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FOR SPACE STANDARDIZATION

Space engineering

Structural materials handbook - Part 1: Overview and material properties and applications

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ECSS Secretariat
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Requirements & Standards Division
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Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

This handbook has been prepared by the ECSS-E-HB-32-30 Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

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Introduction

The Structural materials handbook, ECSS-E-HB-32-20, is published in 8 Parts.

A glossary of terms, definitions and abbreviated terms for these handbooks is contained in Part 8.

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1 Overview

1.1 Scope

1.1.1 General

The structural materials handbook, SMH, combines materials and design information on established polymer matrix composites with provisional information on the emerging groups of newer advanced materials and their composites. Design aspects are described, along with factors associated with joining and manufacturing. Where possible, these are illustrated by examples or case studies.

1.1.2 Polymer composites

The polymer composite materials described are those having continuous fibre reinforcement in a polymer matrix, i.e.:

- Continuous fibre reinforcement, [See: [2-3]
  - Carbon
  - Aramid
  - Glass
- Thermosetting polymer matrix, [See:[2-4]]:
  - Epoxy, [See:2.4,3.2].
  - Polyimide, [See:6.12].
  - Bismaleimide, [See:6.6].
- Thermoplastic polymer matrix, e.g. PEEK, PEI, PES, [See: 6.17].

1.1.3 Advanced materials

Information on the characteristics and applications is given for:

- Magnesium alloys and their composites, [See: Clause 44].
- Aluminium alloys and their composites, [See: Clause 46].
- Titanium alloys and their composites, [See: Clause 47].
- Superalloys and their composites, [See: Clause 48].
- Intermetallic materials, [See: Clause 49].

- Refractory metals, [See: Clause 50].
- Beryllium, [See: Clause 51].
- Technical ceramics, [See: Clause 43]
- Ceramic matrix composites, [See: Clause 52].
- Glass and glass-ceramic matrix composites, [See: Clause 53].
- Carbon-carbon composites, [See: Clause 54].

Data on conventional structural materials is not included in detail. Reference is made to the appropriate documents for aerospace applications.

1.2 Polymer-based composites

1.2.1 Background

1.2.1.1 Development

The advent of high-performance reinforcing fibres in combination with thermosetting polymers was heralded in the 1960's as the arrival of a new group of materials to compete with and, in many cases, replace conventional metals. In retrospect the claims made at that time were somewhat premature, but subsequent development has produced a wide range of materials with useful properties.

The early materials offered were under constant revision by their manufacturers using both the results of their own research and that of other organisations. This was aimed at optimising fibres, polymer resin formulations and manufacturing methods, all of which contribute to the material characteristics. An effect of this constant development was that data on polymer composite materials became redundant rapidly, because the materials themselves changed specification during the research programme. As a result, designers and users, encouraged by the results of initial studies, found it difficult to apply polymer composites.

The main contributing problems in this were:

- Availability of a consistent source of a material.
- Lack of proven characteristics under the whole range of operational or service conditions.
- Lack of design data, since the flexibility of composites enabled materials to be created with highly directional properties. This was a significant departure from traditional metal behaviour and needed the development of methods for measuring properties and correction factors for different environmental degradation mechanisms.
- Poor understanding of the fracture and failure characteristics. Composites differ from metals and fracture mechanics methods are not easily translated to composites with anywhere near the same reliability.
- Scarcity of design tools that enabled the designers to achieve the same level of safety confidence as for metals, given the fact that the design approach needed for composites was significantly different from that for metals.
- New means of testing and verification of materials, components and structures. Those applied to metals needed modification or development. New procedures were also necessary.

- New means of inspecting and correlating findings to structural performance. Again, those techniques applied to metals had to be modified and proven. The types of defects or inconsistencies in composites are completely different in both appearance and effect from those found in metals.

Until these demands were fulfilled, the opportunities for composite materials were severely limited. At about this time, the initial claims made for composites replacing metals were revised and it became accepted that composites complement rather than replace metals in structural applications.

1.2.1.2 Aerospace and defence

As with the development of most 'new materials', their initial applications were foreseen within the aerospace and defence sectors. Here high-value components and structures could tolerate the higher cost of the materials themselves, provided that the perceived performance and weight-saving benefits were realised. The strategic importance of composites was recognised, and considerable budgets were assigned world-wide to develop the necessary technical understanding.

Table 1.2-1 compares composites with conventional materials, Ref.[1-1]. It demonstrates the basis for the interest in their use in high strength, high stiffness to weight applications or where dimensional stability is a crucial demand.

Table 1.2-1 - Comparison of specific strength and stiffness for composite materials and conventional aerospace structural materials

	Specific strength ($\times 10^3$ N/kg/m)	**Specific stiffness** ($\times 10^6$ N/kg/m)	**Density** (g/cm^3)
Unidirectional carbon/epoxy:			
HS - high strength	1850	100	1.5
IM - intermediate modulus	1450	115	1.6
HM - high modulus	550	200	1.7
Aramid/epoxy	1200	50	1.4
Glass/epoxy	980	25	1.8
Aluminium	180	25	2.8
Titanium	240	25	4.4

Table 1.2-2 shows the potential of composites over aluminium in a developed aircraft structure, Ref. [1-1]. Although the costs of the composite replacements were considerably higher than the metal counterparts, in time and with experience of rationalised design and manufacturing processes, the cost-benefit relationships have become more attractive.

Table 1.2-2 - Comparison of early composite and aluminium aircraft structures

L-1011 Aileron Structure	Aluminium	Composite
Weight (kg)	63.9	47.2
Weight-saving	-	26%
Number of ribs	18	10
Part count	398	205
Number of fasteners	5253	2574

Figure 1.2-1 shows the chronological progress in the use of composite materials for military applications, Ref. [1-1].

Some examples of the use of composites in military aircraft, as a percentage of overall structural weight, include:

- F/A-18E 'Hornet' composite content 18%.
- Lockheed F/A-22 composite content 20%.
- AV-Harrier II composite content 26%.
- F-35 Joint Strike Fighter composite content 35%.

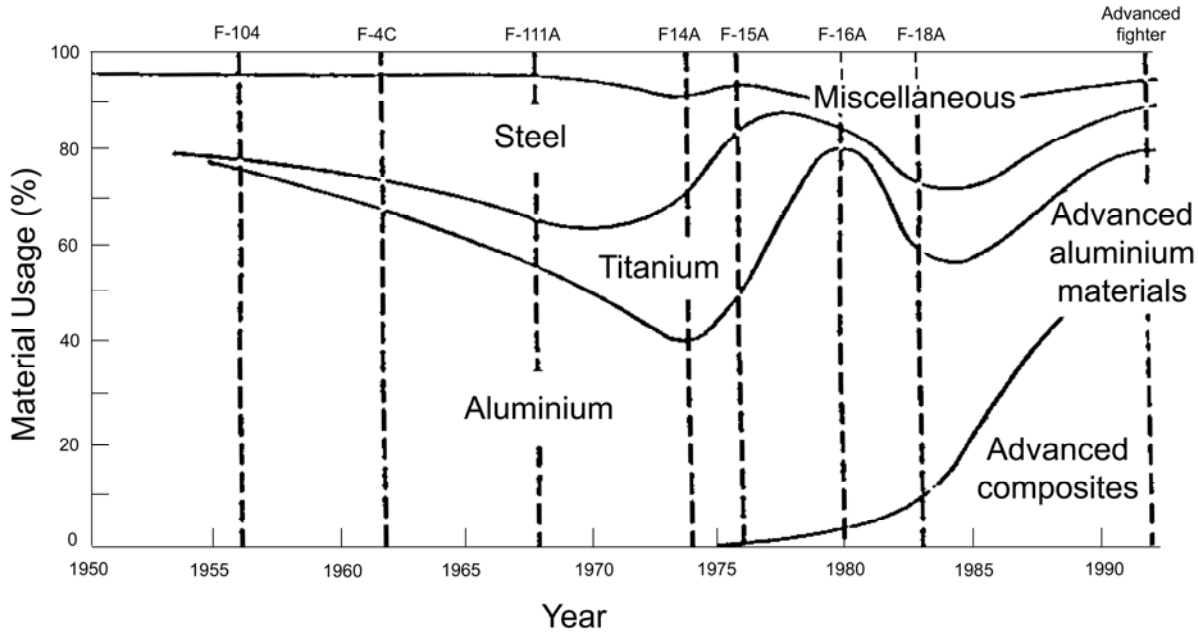


Figure 1.2-1 - Chronological progress of the application of composite materials in military applications

1.2.1.3 Civil aircraft

Application of composites within civil aircraft lagged behind military use owing to:

- Cost.
- Safety; more critical both to manufacturers and certification agencies.
- General conservatism resulting from past experiences of financial penalties from equipment down-time.
- Availability of experience of military flight and service.

Increasing confidence in composite materials, largely from numerous military-based applications, along with extensive work concerned with the development and proving of suitable design and testing approaches, eventually aided their acceptance within civil aircraft. This was, by necessity, a gradual and cautious process.

The aircraft industry sought to use more composites instead of metal to create more fuel-efficient aircraft. In recent commercial aircraft, composites now account for about 10% to 25% of the total weight. Some examples of applications are small fuselage components, tails and selected parts of wings, e.g. trailing-edge flaps.

Within the Airbus-series, in 1985 the tail fin of the A310 was made of composite. About 22% of the A380 is composite, Composite wings are envisaged for the A350.

At the end of 2005, Boeing announced, that 50% of the structural weight of its 787 aircraft is intended to be made of composite, including the fuselage.

1.2.1.4 Space industry

Until the volume use of new materials increased in other unrelated industries, with the benefits of reduction in price and increased knowledge, their use in the smaller volume industries, such as space, was not feasible.

Whilst the value of space-destined structures is high, the volume usage of materials in the space industry is remarkably low. Some of the technical demands are similar to military or civil aircraft, whereas others are very specific to the operational environment of space. The majority of materials used in space structures come from those developed for other industries, but proven to behave in a reliable, predictable manner under the very specific service conditions of space. The basic principles and policies applied to material and process selection are summarised in Table 1.2-3 and Figure 1.2-2, Ref. [1-2].

Table 1.2-3 - Material usage in European space projects

Materials for Space Applications		
Practice:	~90%	Plain commercial materials
	± 9%	Advanced materials developed in other technological areas, e.g. aeronautics, automobiles.
Rationale:		Space application is small, with a high quality demand.
Consequence:		Great effort to be made towards: 1. Establishing suitable test methods to ensure that commercial materials operate satisfactorily in orbit. 2. Screening commercial materials by applying these test methods.

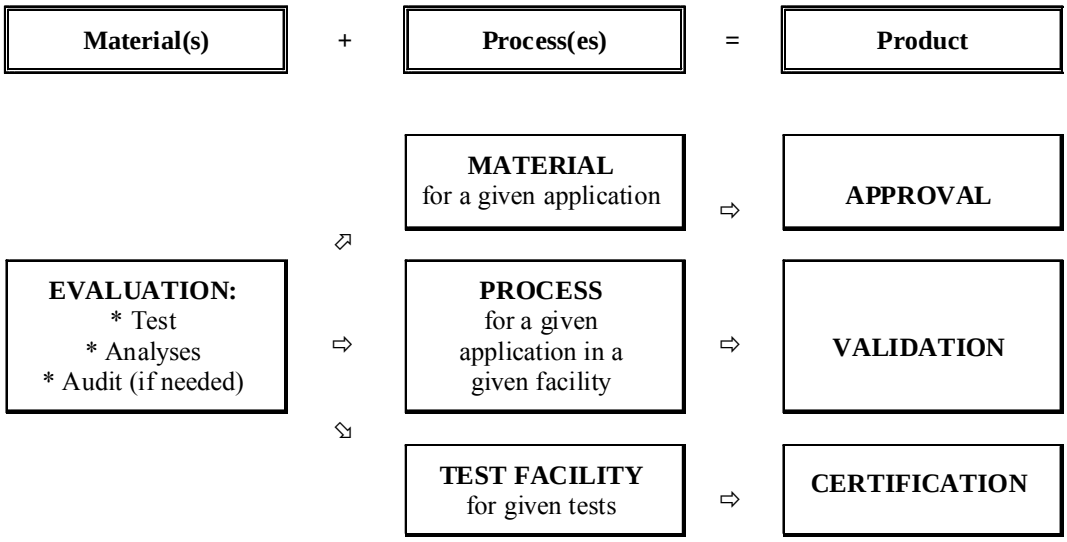


Figure 1.2-2 - Acceptance process for materials, processes and test facilities

For example; In launcher structures that use materials with a proven track-record in other industries, helps not only with material selection, but also for aspects of design, manufacturing processes, and inspection.

Together with the growing experience of military use, composite materials became of greater interest to the space industry as demands increased for mass-efficiency. Thus reducing the cost of launch and deployment, in the increasing number of military, civilian satellites and research payloads. During this period the emphasis placed on 'new technology at any price' shifted to 'new technology at the right price'. This new approach also served to concentrate the minds of the material manufacturers, who consolidated their product ranges and increased the reliability and supply of materials to increase product confidence.

Figure 1.2-3 provides an illustration of the evolution of structural materials within some European space projects, Ref. [1-5].

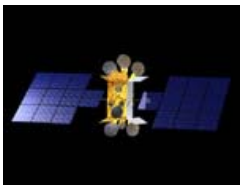
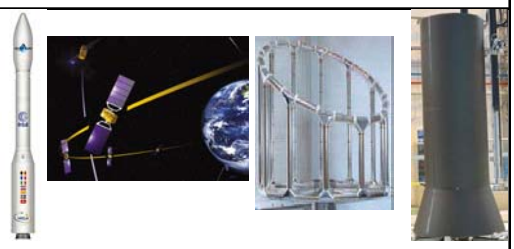
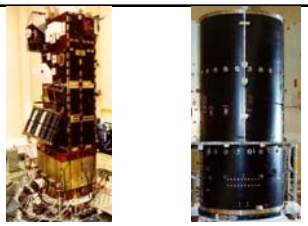
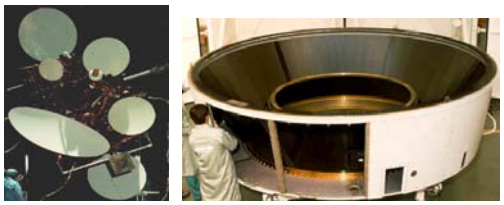
2005 >	Materials: Composite materials re-convergence with civil aircraft (demand for CFRP). Automation of CFRP gridded structures. Emergence of specially-designed 'molecular materials' + nanotechnologies; Multifunctional structures. AlphaBus (large satcom platform).	
2000 >	Composite materials applied to new large projects: Galileo (navigation-positioning); Vega launcher. Monolithic and gridded designs compete with some sandwich structures. New welding processes for metal-based pressurised structures. New material developments: 'Inflatable structures' + optical structures, e.g. SiC ceramics.	
1995 >	'Harmonisation' of material options; convergence of metals and composites used within aircraft. Ariane 5 (ECA interstage): CFRP sandwich + monolithic CFRP (integrated composite rings) conical adapter; both made by fibre placement	
1990 >	Composite materials prevail (except for Hermes and Space Station); First 'smart structures'. Artemis (central tube): Co-cured CFRP sandwich Envisat (Polar Platform): Largest European satellite, to date.	
1985 >	Ariane 5: CFRP all uppers stages; VEB metal cylinder + CFRP sandwich inner cone Hermes: Metals, MMC and CMCs Columbus module (ISS): Metals, MMC an CMCs Satellite primary structures, e.g. telecom: CFRP central tubes	
1980 >	First CFRP components and structures: antenna reflectors, solar arrays, optical benches, truss structures Olympus satellite: CFRP sandwich panels (antennas) Ariane 4: CFRP structures (VEB, fairing and payload adapters).	
1975 >	COS-B satellite: metal sandwich panels + stiffened shell (launcher interface) Ariane 1: metal structures (tanks, stiffened shells-riveted stringers and frames; fairing; equipment bay; payload adapters)	

Figure 1.2-3– Example of the evolution of structural materials in some European space projects

1.2.2 European space industry perspective

1.2.2.1 Approach

Within European aerospace companies, the number of individual organisations working on all aspects of fibre-reinforced composites was, and remains, considerable. ESA was the first to recognise that, where several organisations contributed to a project, there was a need to consolidate the efforts. It is considered that much more can be learnt and progress made effectively if the information developed by one organisation is available to other project members, and eventually to related future programmes. In seeking to improve the performance of aerospace structures, the harmonisation and standardisation of information and design data are crucial. With budgets under more severe scrutiny by the contributing nations, the ability to progress in a more cost-effective manner was an obvious advantage, if it is shown not to interfere with the policies of individual, contributing organisations.

1.2.2.2 Information

With the need for appropriate information identified, work began in 1984 to bring together and disseminate technical information, developed mainly within Europe, on fibre-reinforced polymer composite materials for use on space projects. Under the control of ESA, this massive task was contracted to MBB/ERNO in Germany (which became Astrium and is now part of EADS) who acted as the organisers and recipients of information submitted by other organisations and also developed the framework and 1st edition of ESA PSS-03-1101: Composites Design Handbook; published in 1986. This contained a large amount of information, often unpublished elsewhere. Subsequently, the handbook evolved and enlarged considerably by periodic updating to include relevant innovations in design procedures, testing and analysis for the application of composites.

The methods needed to establish the properties and characteristics of polymer composites are reaching a level of understanding comparable with some conventional aerospace materials, but still have some way to go. One example is the need for standardised, proven methods for ensuring that their integrity is commensurate with that realised by conventional metals, and is maintained throughout their operational life. Composite materials remain under the 'special requirements' of the applicable fracture control documentation in recognition of the fact that linear elastic fracture mechanics technology is generally agreed to be inadequate. Therefore, fracture control currently relies on the techniques of containment, fail-safe assessment, proof and cyclic load testing, [See: ECSS-E-ST-32-01]. Until this subject is considered fully and it is proven that the safety requirements can be met, there remains a restriction on the use of composite materials and the possible mass-saving and performance increases achievable.

The structural materials handbook does not aim to impose a single 'method' for the use of composites. The aim is to provide information and guidance on their application within the framework of materials for space projects; hence the ECSS 'informative' designation.

[See also: Introduction – Source materials; Introduction – Background]

1.3 Metal and ceramic-based composites

1.3.1 Background

The European objectives have grown to include manned, re-usable launch vehicles and long-term deployed, possibly manned, space structures. Very high safety and reliability factors for manned vehicles are additional to those of single-shot launchers and their payloads. Certain parts of these structures are on the performance limit of fibre-reinforced polymer composites and possibly also that of the conventional metals used.

1.3.2 Materials technology

Largely as a result of re-usable structures projects, a further round of materials research, development and proving began with the NASA Space Shuttle, and particularly its external TPS thermal protection system. Research continues today as new projects call for new materials advances and the prospective designs and specifications develop. These new composite materials, also described as 'advanced materials', are no longer based on polymers whose high temperature capabilities are limited, but are either metallic- or ceramic-based.

Figure 1.3-1 summarises the temperature requirements for some future space structures and materials with potential for fulfilling the demands, Ref.[1-3]

The designer, again, is faced with a large number of potential materials, many of which claim to be sufficiently advanced in their development to be considered viable for current or future European space projects, [See also: Introduction – Source materials].

The materials and information presented within the structural materials handbook reflects the relative immaturity of the 'new generation' of composite materials. Validated data is only generated in large quantities by full-scale application of materials and from experience of working with them.

The handbook provides information and guidance on materials application within the framework of materials for space projects; hence the ECSS 'informative' designation.

Depending on the precise requirements, some applications can be fulfilled by several materials. Others, with more demanding temperature or environmental constraints, are limited to perhaps only one or two.

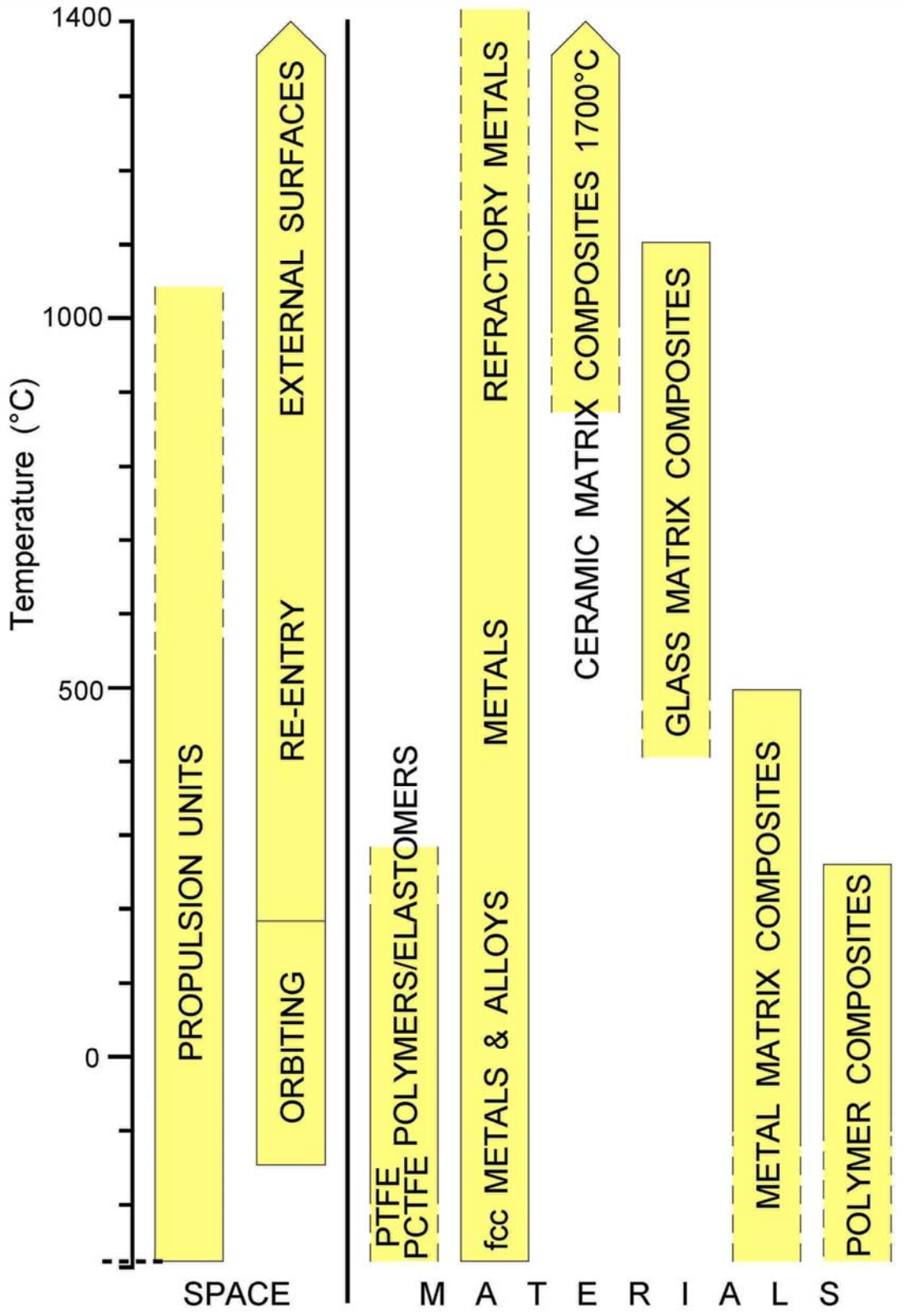


Figure 1.3-1 - Temperature requirements for space structures and potential materials

In the development of metal and ceramic-based composites, some lessons learnt in designing with polymer composites are applicable, whereas others have to be reconsidered. The physical complexity of the newer materials has increased in an attempt to offset some of the recognised deficiencies of polymer-based materials. An example is the need to improve interlaminar characteristics by the use of fibres in three or more directions. This immediately raises the problem of establishing the properties of such a material. Coupon testing and its translation to structural properties are often no longer appropriate other than as a first comparison in the combined material and process development.

In addition, testing and inspection of these materials is often needed for complex geometrical shapes under realistic service conditions, either high temperature or long-term exposure in space. This significantly increases the difficulty, such that dedicated, realistic testing of items becomes the only feasible option. This led to the development of 'Centres of Expertise', in which material and component design, coupled with manufacture and testing, is conducted within one organisation. This is a significant departure from the metal and polymer composite industry, where materials were supplied from one or more sources to known or stated specifications. Components were then manufactured by various organisations, for later integration into the final structure.

Advanced materials also tend to increase the likelihood of single-source components, unless the technology is licensed to other parties. Development of expertise and facilities can be prohibitive on cost alone, hence the limited number of source organisations. Licensing is becoming more common as the associated technology moves from development into standard production processing, although this is not true for all materials. The trend has been set by some of the most technically developed ceramic-based materials, and others, yet to be fully optimised, are likely to follow.

Table 1.3-1 compares the development position of composite materials with traditional metals in aerospace applications. This indicates that whilst 'new' metals can be developed to expand the range of capabilities, the methods needed to establish their properties and characteristics already exist, backed up by many years of experience of other metals. Polymer composites are beginning to move towards this level of understanding, but still have some way to go, [See [1-2]. Considerable work remains to be done before the metal- and ceramic-based composites are at a stage of understanding similar to that of polymer composites. The number of possible applications for the newer advanced composites is limited to those where the other two groups cannot compete, owing to either the service conditions or the stipulated mass-performance.

Table 1.3-1 - Comparison of technology status for composite materials and traditional metals for aerospace applications

Design aspects	Traditional metals	Fibre-reinforced polymer composites	Advanced metal and ceramic-based composites
Material:			
Sources	Numerous	Several	Few
Specifications	Standardised	Established	Few
Basic advantages:	Well established. Known, proven performance history. Very wide range of standard materials available.	Proven mass/ performance benefits over some metal designs. Possibility to 'engineer' properties for the application.	Possible mass-to-performance benefits over some metal designs. Possibility to 'engineer' properties for the application. Structural uses at high temperatures and cryogenic.
Basic limitations	Structural uses limited to low/moderate temperatures, unless special grades applied.	Lower number of materials available. Structural uses limited to low/moderate temperatures. Dictated by the polymer matrix.	Limited number of proven materials available Many types still in development. No service experience.
Manufacturing:			
Methods	Well established	Established	Developing.
Specifications	Standardised	Established	Few
Sources	Numerous	Several	Few
Testing:			
Standard methods	Well established	Established	Developing
Test facilities	Numerous	Several	Few
Inspection	Well established	Established	Developing
Design tools	Well established	Available	Developing
Fracture control	Well established	Needs further development	Developing
Verification	Well established	Established	Developing
Usage and experience:			
Military	> 50 years	~ 25 years	Limited
Aircraft	> 50 years	~ 15 years	None
Space	Extensive	Moderate	Low (developing)

As yet, a comparison on a cost-performance basis is difficult. There is a large body of information on metals, less for polymer composites and only limited data for the recent advanced material groups. Experience of polymer composites has shown that on material cost alone they cannot compete with conventional metals and there is no reason to assume that this is different for the new types of composites. Whilst the newer materials are currently very expensive, partly owing to the influence of low demand, the development of integrated material and component manufacture can provide cost benefits. For example, an integrally formed and joined structural panel reduces the number of manufacturing operations compared with standard sheet fabrication which is reflected in the overall

item cost. Where production runs are small, the extent of this benefit is limited unless the cost of ownership also provides savings.

Table 1.3-2 summarises the technical benefits of the various broad groups within the family of advanced composite materials, Ref. [1-1]

Table 1.3-2 - Comparison of technical aspects of various composite materials

	RELATIVE ADVANTAGE				
Material Properties	Metals	Thermosetting Polymer Composites	Thermoplastic Polymer Composites	Metal Matrix Composites	Ceramic Matrix Composites
Corrosion resistance	X	XXX	XXX	X	XXX
Creep	X	XXX	XX	XX	XXX
Damage resistance	XXX	X	XX	XX	X
Design flexibility	XX	XXX	XXX	XXX	XXX
Fabrication:	XX	XX	XX	XX	XX
Time	X	XX	XX	X	X
Final part cost	XX	X	X	X	X
Moisture resistance	XXX	X	XX	XXX	XXX
Physical properties	XX	XX	XX	XX	XX
Processing cost	X	XX	XX	X	X
Raw material cost	XXX	XX	X	X	X
Reusable scrap	XXX	0	XX	0	0
Shelf life	XXX	X	XXX	XXX	XXX
Solvent resistance	XX	X	XX	XX	XX
Specific strength	X	XXX	XXX	XX	XX
Strength	X	XXX	XXX	XXX	XXX
Stiffness	X	XX	XX	XX	XX
Mass-saving	0	XX	XX	X	XX
Space tolerance:					
Out/off gassing	XXX	X	XX	XXX	XXX
Radiation	XXX	X	XX	XXX	XXX
Vacuum	XXX	X	XX	XXX	XXX
Dimensional Stability	X	XXX	XXX	XX	XXX
Thermal cycling	XXX	XX	XX	XX	XX
Limits for maximum service temperature	Alloy	Matrix type	Matrix type	Alloy matrix + fibre stability	Matrix + fibre stability
Key: XXX- Best; XX-Good; X-Fair; 0-Not Applicable					

Within each main group, there are a number of materials possessing very different characteristics that can both compete with each other and with those in other categories. For example:

- Thermoplastic-based composites can be considered for applications currently fulfilled by thermosetting composites or by metals, such as conventional aluminium alloys.
- Metal matrix composites can compete with higher temperature capability thermosetting resin, thermoplastic composites or conventional metals.

- Ceramic-based composites can be considered for higher temperature applications, possibly displacing Superalloys or other specially developed high temperature alloys with high densities.

In each case the new materials are disadvantaged by the lack of experience in their use.

Purely on a temperature comparison, the possibilities are many. However, other application factors usually reduce the options significantly. These include:

- Loads: Magnitude and direction of both static and dynamic loadings
- Dimensional stability
- Environment: On earth, during launch and in space, as summarised in Table 1.3-3

Table 1.3-3 - Environmental factors for space structures

Environment		
Earth	Launch	Space
Temperature	Vibration	Temperature
Moisture	Acceleration	Vacuum
Atmosphere	Shock	Radiation
Climate	Thermal flux	Debris
Biological	Lightning strike	Micrometeoroids
Physical	Bird strike	Atomic oxygen
	Rain erosion	Man activity

1.4 Structural materials

1.4.1 General

The structural materials handbook, SMH, presents the design teams of European space projects with guidance and information on the application of many types of advanced composite materials; as summarised in Figure 1.4-1.

1.4.2 Materials

The term advanced composite materials describes:

- Polymer matrix composites, where commonly used fibre-reinforced polymer composites, such as carbon/epoxy, have significant engineering data presented, along with information on glass or aramid fibres. Information is also given for the other polymer matrices, e.g. high-temperature resin systems, cyanate ester and thermoplastic-based materials.
- Advanced metals, such as aluminium-lithium, along with:
  - MMC 'metal matrix composites' with either continuous or discontinuous (particulate or whisker) reinforcements. As with polymer-based composites, continuous fibre-reinforced materials are viewed as more appropriate for structural applications.

— Hybrid materials, which are combinations of continuous fibre-reinforcement, polymer matrix and metal, e.g. FML fibre metal laminates (aluminium); HTCL (titanium).

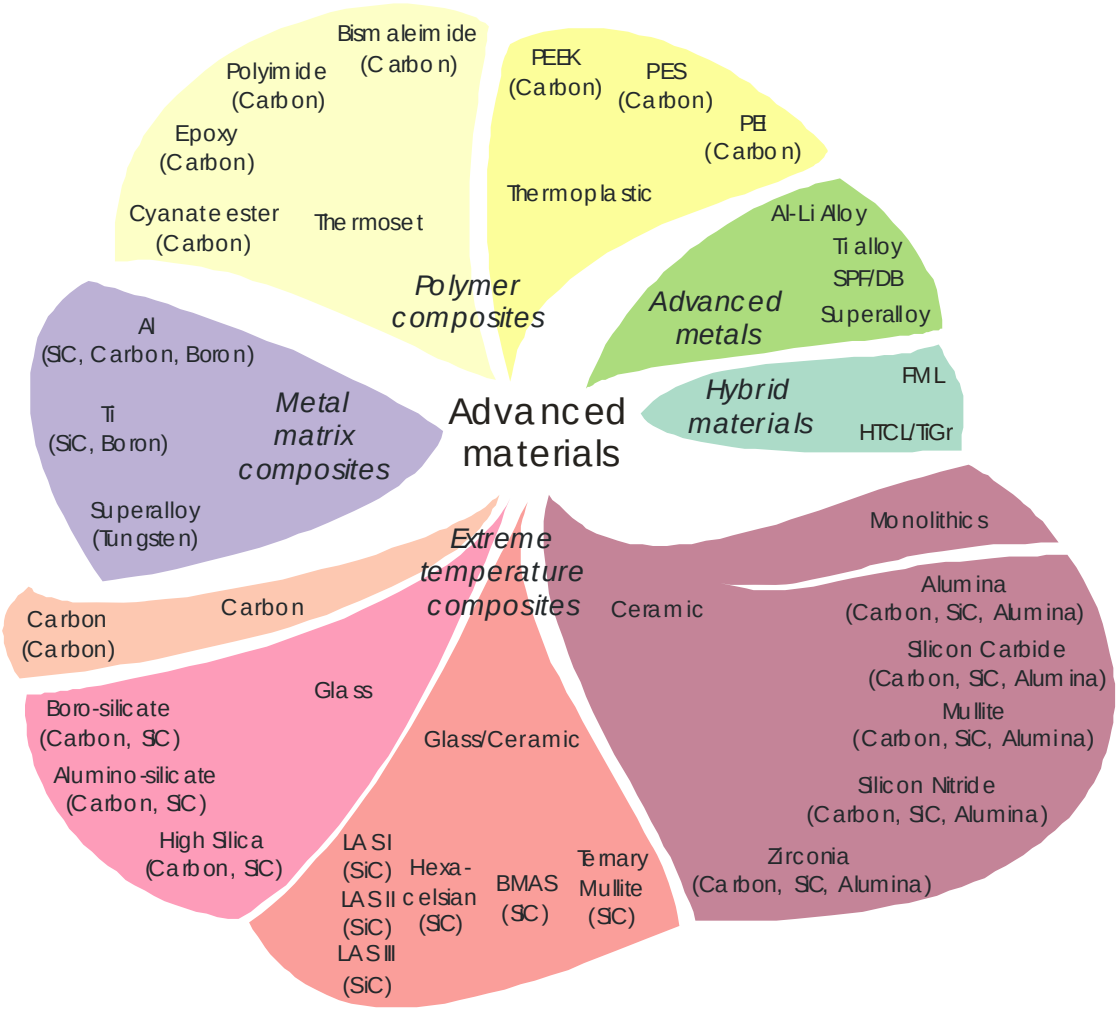
- Extreme temperature materials, originally developed for external surfaces of re-useable spaceplane concepts, but also finding applications within dimensionally-stable structures, e.g.:

  — Ceramics, where some 'monolithic' technical ceramics are applied to structures whereas fibrous forms are for insulation.

  — CMC: Ceramic matrix composites with either continuous or discontinuous reinforcements. Again, the continuous reinforced materials are likely to be used in structural applications.

  — Glass- and glass-ceramics

  — Carbon-carbon composites



Key: Matrix (Reinforcement)

Figure 1.4-1 - Family tree of advanced materials

Information is included on other types of materials which are perceived as acting in supporting roles to composites with structural capability. Examples include, but are not limited to:

- Interest in Europe for specific applications now that availability and experience in its use are Coating systems: To improve environmental resistance of existing or new materials.
- Novel refractory alloy compositions: For high temperature operation.
- Beryllium, which is gaining improving.

For comparison purposes, and to act as a basis for the description of the newer materials, summary information on the more conventional aerospace metals is included, but with extensive referencing to the established source documents, e.g. MIL-handbooks and their successors. Metal development has also progressed, partly in an attempt to fight-off competition from composites, but also to keep pace with the new demands. Examples are aluminium-lithium alloys and titanium alloys with higher temperature capabilities.

1.4.3 Composite terminology

Where alloy development has led to the inclusion of very small refractory particles, the dividing line between what is described as a composite or natural alloy development has become blurred. In this respect, development of ODS oxide dispersion strengthened alloys or the significant anisotropic properties produced by modified solidification techniques, such as directional solidification and single-crystal alloys, can be claimed to be behaving like composites.

Within the context of the SMH, the term composite material applies to those in which the reinforcement is deliberately introduced rather than forming from the matrix under controlled process conditions. Other definitions, which vary between organisations, serve to discriminate on the grounds that within true composites the reinforcement is not usually in chemical equilibrium with the surrounding matrix. ODS alloys are considered the exception, as their reinforcing phases are extremely fine (sub-micron) and interact with the host alloy on a microscopic level, in the same manner as the products of some alloying additions. Nanotechnologies using deliberate additions of fine, structured reinforcing phases to base materials, often polymers, are also promoted as composites.

1.4.4 Simultaneous material and part manufacturing

New material developments no longer concentrate on the characteristics of materials in isolation from their component manufacturing and fabrication methods, which can significantly influence the characteristics of the final material. In some cases it is now impossible to differentiate between material and component manufacture.

The simultaneous manufacture of material and parts was always claimed as a benefit of polymer composites, but has moved a step further in the creation of metal and ceramic-based materials in which manufacture often commences with a reinforcement and some pre-cursor form of the final matrix and, often after several long chemical processes, emerges as a finished section for the leading-edge of a spaceplane, for example.

Where available, basic information is included on the various manufacturing processes applied to the specific materials.

1.4.5 Case studies and examples

As the new materials become of interest for particular applications within space projects, detailed studies are conducted on the design of components and their successful integration into structures. The results of work done so far are included for guidance on:

- General design aspects,
- Joints, often between dissimilar materials,
- Fracture and material modelling,
- Integrity control and inspection,
- Temperature and environmental stability,
- Manufacturing.

Case studies illustrate the design concepts for space applications.

A review of smart technologies, and their possible application to space structures, is included to reflect the need for remote monitoring and control of long-term-deployed or other structures.

NOTE All handbook users are encouraged to submit information for inclusion in handbook revisions, [See: Introduction – User comments].

1.5 References

1.5.1 General

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'Airframe structural design'
Technical Book Company-Commlit Press.
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[1-2] J. Dauphin: ESA-ESTEC
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[1-3] J. Wilson & D.P. Bashford
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ESTEC Contract No. 7090/87/NL(PP)

[1-4] MIL-HDBK-5
'Metallic materials and elements for aerospace vehicle structures'
Department of Defence/F.A.A., Version F, Nov. 1990

[1-5] V. Gomez-Molinero: EADS-CASA Espacio (E)
'General View of the Spacesystem Structures, Evolution and Future Challenges'

European Conference on Spacecraft Structures, Materials and Mechanical Testing, ESTEC, Noordwijk, NL, 10 – 12 May 2005. ESA-SP-581 August 2005 (CDROM)

[1-6] netcomposites (May 2006); website: http://www.netcomposites.com/

1.5.2 ECSS documents

[See: ECSS website]

ECSS-E-ST-32-01 Fracture control; previously ESA PSS-01-401

2
Material characteristics and selection

2.1 Introduction

2.1.1 General

The information presented concentrates on those established composite systems which are applicable to space structures, i.e. satellites, spacecraft, launchers and reusable vehicles. It provides engineers and designers conducting feasibility and design studies with guidelines and data for polymer composite materials.

Established composite systems are primarily those based on epoxy resin matrices. Information is also included on composites with the more common cyanate ester and imide thermosetting resin systems, and those with thermoplastic polymers, [See: 2.4 and Clause 9]. Only selective data is presented to avoid an excessive volume.

For full production items, comprehensive in house materials data is necessary. An important aspect of manufacturing with composites is strict quality assurance coupled to all the procurement and processing methods used. Design allowables are determined for a composite material along with its prescribed method of manufacture.

2.1.2 Material availability

Data is presented on materials appropriate for space use. With time, some commercial products have been withdrawn or superseded by other materials with improved properties. This is particularly true of first generation epoxy CFRP composites.

Before proceeding with detailed design studies, always confirm with the supplier that the material or an equivalent (second source) is commercially available.

2.2 Basic features of composite materials for space use

2.2.1 General

Composites are low density materials, which, if used correctly, provide a number of beneficial properties. For space structures these are primarily:

High specific stiffness High specific strength	}	provide mass savings
Dimensional stability	-	constancy of dimensions under varying thermal environments

A number of other benefits, which can give impetus to the use of composites, include:

- Signal transparency,
- Electrical insulation or conduction,
- Thermal conductivity,
- Integral mouldings with minimum part numbers,
- Impact resistance and debris protection,
- High damping characteristics,
- Fatigue resistance.

2.2.2 Types of composites

Fibre-reinforced plastics are the dominant applied composite materials for structural applications. The main constituents of these are:

Fibres:	Carbon
	Aramid
	Glass (E-, R- and S- grades)
Matrices:	Epoxy resin
	Cyanate ester

Metal- and ceramic-based composites are usually considered for applications where polymer-based composites or conventional aerospace materials cannot compete, usually because of service temperatures, e.g. engine applications and thermal protection systems.

[See: Section XI for MMCs; Section XII for CMCs]

2.3 Reinforcement fibres

2.3.1 General

The tensile properties of some commercially-available continuous reinforcing fibres are shown in Figure 2.3-1 and Figure 2.3-2.

2.3.2 Carbon fibres for CFRP

Some basic characteristics of carbon fibres for CFRP composites are:

- Produced from PAN and pitch based carbon fibres, [See: 3.3]
- Available in many variants to enable optimisation of strength and stiffness; as shown in and Figure 2.3-2.
- Low failure strains in the range 0.25% to 1.8%; as fibre modulus increases, strain to failure decreases; as shown in Figure 2.3-1.
- Small, negative longitudinal CTE coefficients of thermal expansion, but positive coefficients in the transverse direction.

- Electrically and thermally conductive.

2.3.3 Aramid fibres for ARP

Primarily Kevlar 49 (Du Pont), but also Twaron HM (was AZKO, now Teijin) share the basic characteristics of:

- High specific tensile strength,
- Modest specific tensile modulus compared with CFRP,
- Exhibit high tensile strain to failure (~2.3 %),
- Small, negative longitudinal CTE, positive transverse CTE,
- Electrically and thermally insulating,
- Poor compressive strengths,
- Absorb moisture.

Both Twaron and Kevlar 29 have non-Hookean stress-strain responses and are not considered suitable as reinforcements for aerospace structural composites.

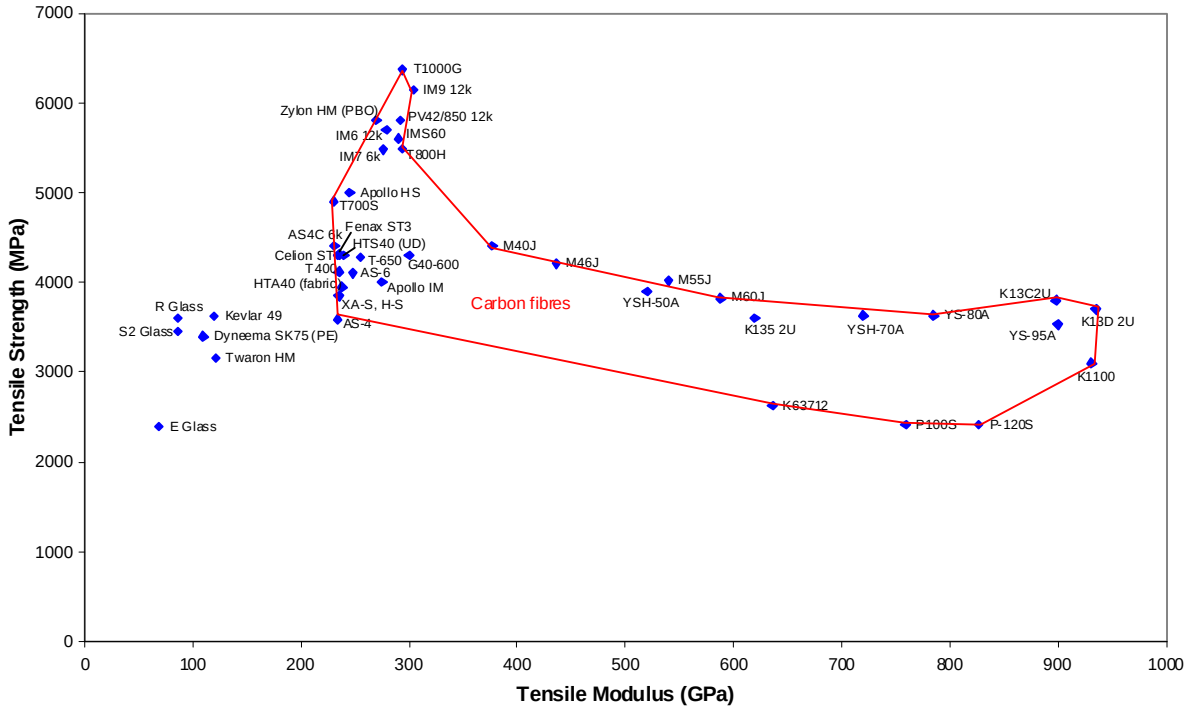


Figure 2.3-1 - Tensile strength and tensile modulus of commercially available continuous reinforcing fibres

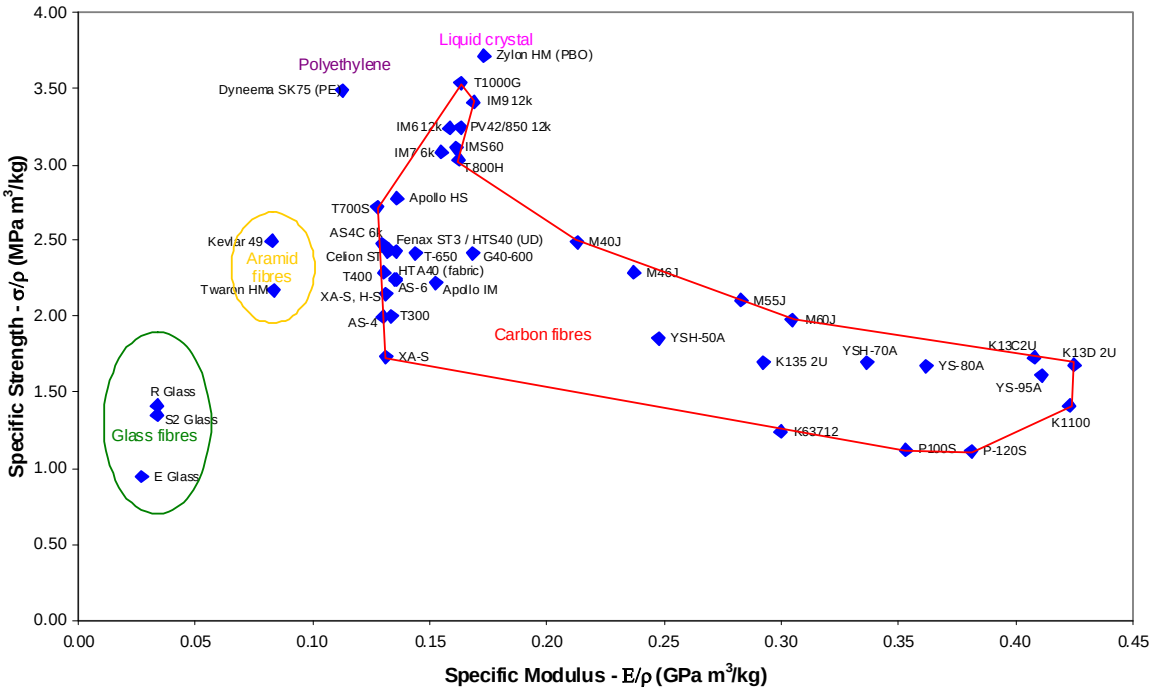


Figure 2.3-2 - Specific tensile strength and specific tensile modulus (for fibres in Figure 2.3-1)

In Europe aramid fibres are available as Kevlar™ (Du Pont), and Twaron™ (initially Enka, then AZKO now Teijin):

- Twaron HM grade is considered as a second-source of Kevlar 49.
- Twaron grade is a competitor to Kevlar 29.

The opportunities for using aramid fibres have diminished, with the arrival of second generation carbon fibres having excellent combinations of intermediate and high modulus, with very high strength and strain to failure.

Nomex™ is also an aramid fibre, but is totally different from Kevlar. Nomex based honeycomb core is used in sandwich constructions. Kevlar is also used in honeycomb core materials in designs that dictate very low thermal expansion characteristics, such as for dimensionally stable structures.

2.3.4 Glass fibres

In general, for space applications:

- The high density of glass reduces the specific tensile properties, making these composites less efficient than CFRP and ARP.
- Low material cost and basic insulating properties enable some use, i.e. for signal transparency and launcher fairings.
- Glass fibres can be used in pressure vessel constructions, somv etimes in combination with aramid fibres.

2.4 Matrix systems

2.4.1 Epoxy resins

Epoxy resins are thermosetting materials that need processing at elevated temperature (120°C to 177°C). They are the most common matrix material with numerous variants for all processing routes. Their basic characteristics include:

- Cured resins have low failure strains (< 2 %).
- Absorb moisture.
- Can meet outgassing requirements for space use,
- CFRP and ARP composites based on epoxies can suffer from microcracking under prolonged thermal cycling, e.g. between +90 °C and -170 °C.

Epoxy resin technology has developed over the years, particularly the processing characteristics, e.g. lower temperature moulding, solventless and zero-bleed prepregs.

The weaknesses of first-generation epoxies, i.e. brittleness and moisture absorption, have been alleviated, Ref.[2-5].

[See also: 6.34 for toughened epoxies]

In most respects, the epoxy matrix is the environmentally-sensitive phase of a composite.

For space structures, the environments encountered can include, [See: Clause 20]:

- Storage prior to launch: Controlled or uncontrolled in terms of moisture absorption.
- Launch: Quasi static loadings and possible heating.
- LEO: Atomic oxygen erosion and high velocity debris impacts in low earth orbit.
- In space: Vacuum (outgassing), radiation and thermal cycling.
- Re entry for reusable vehicles with implications for fatigue and cryogenic fuel storage.

The information presented concentrates on epoxy based composites and their response to likely space environments.

The majority of composite processing equipment used in space programmes is designed for epoxy-based precursor materials.

There are instances where epoxy based composites are inappropriate, and such circumstances are likely to increase as new launch and reusable vehicles are developed.

2.4.2 Cyanate esters

A new generation of thermosetting resins became serious contenders for space use from around 1990, [See: 6.35].

Generally they can be processed in similar ways to epoxies, notably by autoclave moulding in the range 120 °C to 180 °C, [See also: 2.5].

The perceived benefits of cyanate esters over epoxies are:

- lower moisture absorption,
- improved toughness,

- resistance to microcracking.

Cyanate ester CFRP composites are being actively pursued for dimensionally stable structures, such as antennas and solar arrays. Other grades can be appropriate to reusable structures, e.g. cryogenic fuel tanks, [See also: 6.37].

2.4.3 Other thermosetting resins

Composites with -imide matrix systems are used where the elevated temperature (>130°C to 150°C) performance of epoxies is inadequate. The two main resin types are:

- Bismaleimide (BMI), [See also: 6.8].
- Polyimide (PI), [See also: 6.14].

Additional proprietary and high-temperature thermosetting matrix composites offer specialised properties, e.g. moisture resistance, low flammability and low toxicity.

The use of these materials in European space structures is presently limited owing to the lack of elevated temperature applications.

2.4.4 Thermoplastic matrix

Thermoplastic matrix composites are only available from a few sources. They offer increased toughness and low moisture absorption over thermosets and have perceived rapid-forming advantages in manufacturing, [See. 6.19].

Rapid forming is more useful for high unit production runs, rather than the low unit, infrequent process schedules found with space programmes.

Use of thermoplastic composites was inhibited by limited processing expertise and lack of facilities capable of moulding temperatures in the range 250°C to 380°C. The use of fibre-reinforced thermoplastics, for aircraft applications is progressing, Ref. [2-4].

2.4.5 Non-polymer matrix

2.4.5.1 Metal matrix

Metal matrix composites (MMC) have superior elevated temperature performance compared with epoxy composites; higher compressive and shear properties than polymeric matrix composites and exhibit dimensional stability.

[See: Clause 42 - Basic characteristics of new advanced materials, See also: Clause 44 to Clause 51 for specific alloy matrices]

2.4.5.2 Ceramic matrix

Ceramic matrix composites (CMC) and Carbon carbon (C-C) composites have very high temperature capabilities (> 500 °C).

[See: Clause 52 to Clause 54 for ceramic, glass and carbon matrix composites]

2.5 Common fibre, prepreg and resin systems

2.5.1 Commercial products

Commonly used fibres, resins and combined systems applicable to European space structures are given in Table 2.5-1 (This is by no means an exhaustive list).

Table 2.5-1 - Fibres and prepreg and resin systems used in European space programmes

Material	Trade Name [Supplier]	
High-strength carbon fibres	T-300 [Toray] AS-4 [Hercules] HTA [Tenax]	
Intermediate-modulus carbon fibres	IM7 [Hercules] T800H [Toray] T1000 [Toray]	
High-modulus carbon fibres	HM40 [Tenax] M-40J [Toray]	
Ultra-high modulus carbon fibres	M55J [Toray] XN-50 [Nippon Carbon] K135 [Mitsubishi] P-75S [Amoco] K-1100X [Amoco]	
Aramid fibres	Kevlar 49 [Du Pont] Twaron HM [Teijin]	
Prepreg	Fibredux 914 [Hexcel]: Fiberite 977: Narmco 5250 [Cytec]: Brochier M18 [Hexcel]: Cycom 950-1 [Cytec]: Fiberite 934: Fiberite 954-3: RS3 [YLA]: Brochier M22 [Hexcel]:	- 914/T-300 - 977/IM7 - 5250-2/T800H - Vicotex M18/M55J - 950-1/M55J - 934/M55J - 954-3/M55J - RS3/XN-50A - Vicotex M22/M55J
Resin	LY556/HY906/HY960 [Ciba Geigy]: LY1802 [Ciba Geigy]: RTM6 epoxy [Hexcel]: RS14 cyanate ester [YLA]: [See also: Clause 38]	- for filament winding - for RTM - for RTM - for RTM

Open literature tends to refer to materials that were industry standards, but have now been superseded by better materials or, in some instances, discontinued, e.g. BASF GY-70 ultra-high

modulus carbon fibres and Courtaulds Grafil fibres. As a result of commercial rationalisation within the composites industry, some products are sold under their original designations but by different manufacturers.

Data on commercially-available fibres, resins and prepreg systems can be obtained from the particular manufacturer or supplier. Some databases include a limited number of materials, e.g. MatWeb.

2.5.2 Prepreg

The majority of aerospace composite components are moulded from prepregs either in unidirectional fibre tape or woven (fabric) forms. Prepregs consist of fibres impregnated with 'B' stage resins which can be moulded under heat and pressure to induce curing (cross linking) of the resin, Ref. [2-5]. Strict quality control of prepregs is necessary, [See: 36.4 and ESA PSS-03-207; not currently under the ECSS system].

Prepregs are typically characterised by:

- Fibre content, (high: 50% to 70 % by volume),
- Individual ply thicknesses,
- Resin flow characteristics,
- Bleed or zero-bleed options,
- Resin cure temperature,
- Resin tackiness,
- Storage life (usually at -18°C with subsequent factory floor operations at room temperature).

2.5.3 Manufacturing aspects

2.5.3.1 Laminate curing

The chemistry and cure temperature of resins determines the maximum operating temperature of the composite.

A high temperature (170 °C) curing epoxy has a higher glass transition temperature (Tg) than a low temperature (120 °C) curing epoxy. A lower curing temperature however results in a shorter cure cycle and reduced residual stresses within the laminate.

Subsequent moisture absorption by cured epoxies reduces the Tg and hence the maximum operating temperature. The amount of moisture absorption is determined by temperature, prevailing humidity and duration of exposure. The level of moisture absorption varies between individual commercial grades of prepregs.

2.5.3.2 Autoclave moulding

The principal moulding method for prepregs is by autoclave. The high pressures, typically 6 bar, guarantee well-consolidated composite laminates with very low void content (< 1 %). A typical cure cycle with temperature ramp-up, dwell and controlled cool can take 6 hours, [See also: Clause 38 - Manufacturing techniques].

Tool preparation, prepreg lay-up, vacuum de-bulking and bagging is a labour intensive and time consuming exercise. Large mouldings, up to 4 metres in dimension, require large chamber autoclaves which represent considerable capital investments.

2.5.3.3 Filament winding

Filament winding is another common moulding route. It is an efficient process for preparing net-shape structures with optimum fibre orientations. The process is particularly appropriate for closed vessels, cylinders and tubular constructions. Both wet resin fibre rovings and prepreg tape can be used for winding.

[See also: Clause 29 - Filament wound pressure vessels, tanks and structures; Clause 38 - Manufacturing techniques]

2.5.3.4 Fibre placement

A complex technique using a computer controlled band-laying head to place prepreg onto a three-dimensional moulding surface. The bands can be assembled from up to 32 individual tow spools as the layup procedes, enabling mixed fibre bands to be positioned. Individual tows can be stopped and restarted to dynamically vary the width of the band (hence control overlap and part thickness).

[See: 38.14 – Fibre placement]

2.5.3.5 Sandwich panels

Many space structures are fabricated from lightweight, rigid sandwich panel constructions. These are usually in the form of thin laminate skins, formed by autoclave CFRP and ARP prepregs. The skins are adhesively bonded or co-cured to a shaped honeycomb core. The core is often made of aluminium alloy foil, Nomex™, aramid or carbon fibre. More recently, foam cores made from polymer, ceramic or metal are of increasing interest. Each core material gives different mechanical and physical properties. These properties include compressive and shear moduli, strengths plus thermal expansion and conduction characteristics, [See: Clause 26 - Design of sandwich structures].

2.5.3.6 RTM - Resin transfer moulding

RTM processes, of which there are many variants, can be considered for the manufacture of series of complex-shaped, near-net components, [See also: Clause 38 - Manufacturing techniques].

Development RTM components include launcher interface rings, load-introduction fittings for satellite assemblies. Fibre preforms, often made of carbon fibre braids and fabrics, are infiltrated with resins specially adapted for RTM processing. These tend to be epoxy or, more recently, cyanate ester based, Ref.[2-3],[2-4].

2.6 Triaxial woven fabric

2.6.1 Introduction

TWF triaxial woven (weave) fabric describes a range of textiles in which threesets of continuous yarns are arranged at predefined angles within a bi-dimensional fabric ply. These are not 3-D because there are no through-the-thickness yarns, [See: 6.31].

TWFs vary in similar ways to conventional bi-directional fabrics:

- Fibre materials, e.g. carbon, glass or aramid.
- Yarn properties, [See: 95.5].
- Fabric characteristics, e.g. weave type, [See also: 95.6].
- [See also: Clause 95 – Textiles]

2.6.2 TWF weave

2.6.2.1 Types

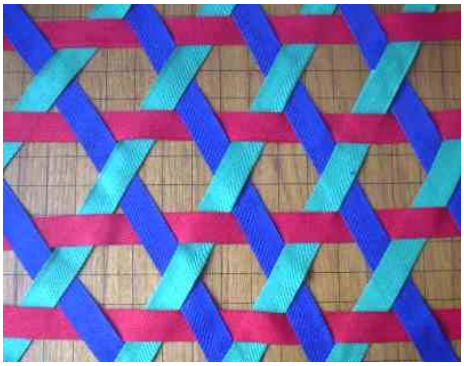
Figure 2.6-1 shows examples of the types of weave, Ref. [2-6]:

- Open, also known as 'sparse'.
- Medium, this is similar to the dense weave, but less symmetrical.
- Dense, where the fabric has three layers of material at any point, making it stronger than a conventional (rectangular) woven fabric, but relatively difficult to manufacture.

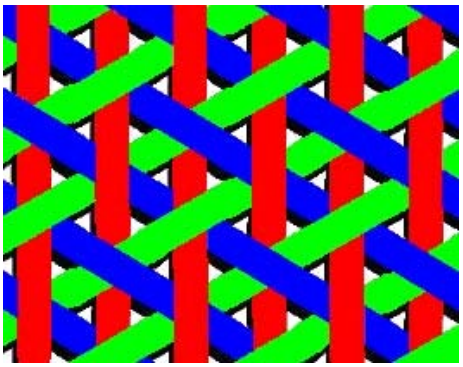
2.6.2.2 Open weave construction

Open or sparse triaxial weaving uses three sets of parallel fibres: known as the warp, whug and weft. The whug is absent in conventional rectangular weaving but in TWF it acts as a second warp. The warp is laid down in simple parallel lines. The whug is then laid down on top of it in simple parallel lines at a predetermined angle. The weft is then woven in and out of both warp and whug layers creating the final fabric, Ref. [2-6].

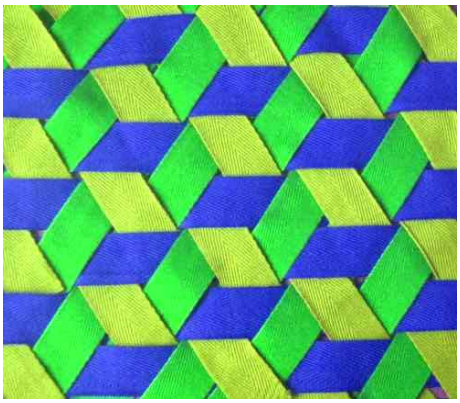
Although the characterisation of TWFs for design purposes is more complicated than for conventional fabric or UD plies, [See: 9.17], composites made using open weaves are considered for space structural applications, [See: 30.13].



Open or sparse weave



Medium weave



Dense weave

Figure 2.6-1 – Triaxial woven fabric: Weave types

2.7 References

2.7.1 General

[2-1] Carbon and High Performance Fibres Directory 6
Published by Chapman Hall, 1995
ISBN 0-412-47020-9.

[2-2] 3rd European Conference on Launcher Technology: Structures and technology challenges for future launchers. Strasbourg 11th - 14th December 2001.

[2-3] International Symposium on Composites Manufacturing for Aircraft Structures. NLR-NL. 30th - 31st May 2002.

[2-4] ESA PSS-03-207 (Dec.1990) - Guidelines for Carbon and other Advanced Fibre Prepreg Procurement Specifications.
NOTE This standard is not currently in the ECSS system.

[2-5] Cytec/Fiberite Technical Bulletin: Cycom 5555 epoxy resin.

[2-6] 'Triaxial weaving' 2008
http://hexdome.com/weaving/triaxial/weaving/index.php

3
Materials data for laminate design

3.1 Introduction

Information is provided for the constituent materials of fibre-reinforced composites:

- Epoxy resin, [See:3.26.34.1]
- Reinforcement fibres, [See: 3.3]
  - Carbon fibres
  - Aramid fibres
  - Glass fibres (E, R and S grades)

Properties of common neat epoxy resins and carbon, aramid and glass fibres are given.

Information on fibre-reinforced epoxy composites, having carbon, aramid or R-glass fibres is provided.

Design allowable data on various epoxy matrix composite systems is also given.

[See also: Clause 9 for data on specific single- and unidirectional-ply epoxy matrix, composite systems, in various states of environmental conditioning, along with similar data on other polymer matrix types]

3.2 Polymer matrices

3.2.1 General

Whilst epoxy resins are the predominant matrix material for space composites, [See also: 6.34], other families of polymers, offering better characteristics under certain conditions, e.g. temperature and moisture, are also used, including:

- Cyanate ester, [See: 6.35].
- Polyimide, [See: 6.12].
- Bismaleimide, [See: 6.6].
- Thermoplastics, [See: 6.17].

3.2.2 Epoxy: Mechanical properties

The properties of neat epoxy resin systems are provided. The data, given in Table 3.2-1 to Table 3.2-8 are typical values for some common epoxy matrix materials, Ref. [3-1].

Fibredux 914 (Ciba Geigy)	1 1.5 4	hour hours hours	at 140°C at 150°C at 190°C
Code 69 (Cyanamid Fothergill)	30 1 3	minutes hours hours	at 130°C at 175°C at 180°C
3501 (Courtaulds, Hercules 3501)	40 30 30	minutes minutes minutes	at 120°C at 150°C at 175°C

For each property, the data are presented in the form:

Standard Deviation
Mean Value
Coefficient of Variation

Some variation in properties can be expected between different batches of the same type of resin system, e.g. see quoted values for Fibredux 914.

The data for the properties of Fibredux 914 down to -180°C were not generated on the same batch of resin as that data listed in Table 3.2-1 to Table 3.2-7.

Considerable scatter in the test results from resin samples is common.

Table 3.2-1 - Epoxy resin: Tensile strength (MPa)

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	6.8 55 12%	10 51 20%	5.9 23 25%	3.2 18 17%	5.2 29 18%	6.1 27 22%
Code 69	9.5 38 25%	14 41 33%	5.8 30 19%	5.5 31 18%	15 37 40%	13 33 40%
Courtaulds 3501	9.6 38 25%	6.8 35 20%	5.4 30 18%	7.0 38 19%	12 38 31%	7.1 46 15%

Table 3.2-2 - Epoxy resin: Tensile modulus (GPa)

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	2.2 5.9 38%	0.3 4.0 8%	0.6 4.0 14%	0.3 3.2 10%	0.3 2.6 12%	0.3 2.5 11%
Code 69	0.5 4.6 11%	14 4.1 8%	0.3 3.7 14%	0.5 4.0 15%	0.6 3.6 16%	13 3.2 13%
Courtaulds 3501	0.7 4.1 16%	0.7 4.1 17%	0.3 3.0 10%	0.7 4.1 18%	0.4 3.2 13%	0.3 3.0 11%

Table 3.2-3 – Epoxy resin: Tensile strain to failure (%)

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	0.5 0.9 51%	10 1.4 19%	0.3 0.68 24%	0.2 0.48 10%	0.1 1.1 25%	0.3 1.2 26%
Code 69	0.3 0.53 51%	0.4 1.1 37%	0.3 0.83 30%	0.2 0.73 23%	0.5 0.96 50%	0.4 0.97 37%
Courtaulds 3501	0.3 0.91 37%	0.2 0.87 28%	0.2 0.93 19%	0.3 0.89 37%	0.5 1.3 35%	0.3 1.7 20%

Table 3.2-4 - Epoxy Resin: Compressive strength (MPa)

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	14 >182 8%	6.1 >153 4%	4.8 >127 4%	6.5 >115 6%	3.9 >97 4%	3.6 >77 5%
Code 69	15 194 8%	6.9 178 4%	4.7 153 3%	3.4 >146 2%	5.6 >128 4%	5.9 115 5%
Courtaulds 3501	15 >182 8%	8.7 170 8%	7.2 >148 5%	4.3 >137 3%	3.8 118 3%	3.5 102 3%

Table 3.2-5 - Epoxy resin: Compressive modulus (GPa)

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	0.1 3.2 4%	0.1 2.7 3%	0.1 2.3 3%	0.1 2.1 3%	0.05 2.1 3%	0.1 1.8 6%
Code 69	0.1 3.3 4%	0.1 2.9 2%	0.1 2.5 3%	0.1 2.5 3%	0.1 2.3 2%	0.1 2.2 5%
Courtaulds 3501	0.2 3.0 5%	0.03 2.7 1%	0.1 2.6 4%	0.1 2.4 2%	0.1 2.3 3%	0.05 2.2 2%

Table 3.2-6 - Epoxy resin: Poisson's ratio (ν), in tension

	-40°C	20°C	70°C	90°C	120°C	150°C
Fibredux 914	0.006 0.40 1%	0 0.39 0%	0.006 0.39 2%	0.012 0.38 3%	0.03 0.39 8%	0.031 0.39 8%
Code 69	0.010 0.38 3%	0.010 0.39 3%	0.010 0.38 3%	0.008 0.38 2%	0.0105 0.39 3%	0.010 0.38 3%
Courtaulds 3501	0.005 0.39 1%	0.006 0.39 2%	0.012 0.38 3%	0.016 0.38 4%	0.016 0.38 4%	0.006 0.40 1%

Table 3.2-7 - Epoxy resin: Density

Resin	Density (kg/m^3)
Fibredux 914	1304
Code 69	1268
Courtaulds 3501	1280

Table 3.2-8 – Epoxy resin Fibredux 914: Mechanical properties

	-180°C	-140°C	-100°C	-40°C	+20°C
Tensile Modulus (GPa)	0.24 6.47 4%	0.58 5.71 10%	1.91 5.28 23%	0.28 4.27 7%	0.18 3.32 5%
Tensile Strength (MPa)	8 46 18%	10 67 15%	10 68 14%	8 56 15%	10 54 18%
Elongation at Break (%)	0.3 0.9 37%	0.1 1.2 10%	0.2 1.5 14%	0.6 1.8 34%	0.5 2.0 23%
	-40°C	0°C	+23°C	+100°C	+150°C
Poisson's Ratio	0.40	0.41	0.39	0.38	0.38

3.3 Reinforcement fibres

3.3.1 General

Common reinforcement fibres for composites are:

- Carbon.
- Aramid, [See: 2.3 and 6.2]
- Glass, [See: 2.3 and 6.2]

[See also: 6.2 for new and development fibres]

3.3.2 Carbon fibres

3.3.2.1 Types of carbon fibres

Carbon fibres are described by the precursor material used to manufacture them:

- PITCH, e.g. oil, coal tar, synthetic.
- PAN Polyacrylonitrile.

Figure 3.3-1 summarises the difference between PAN and pitch-based carbon fibres, Ref. [3-8].

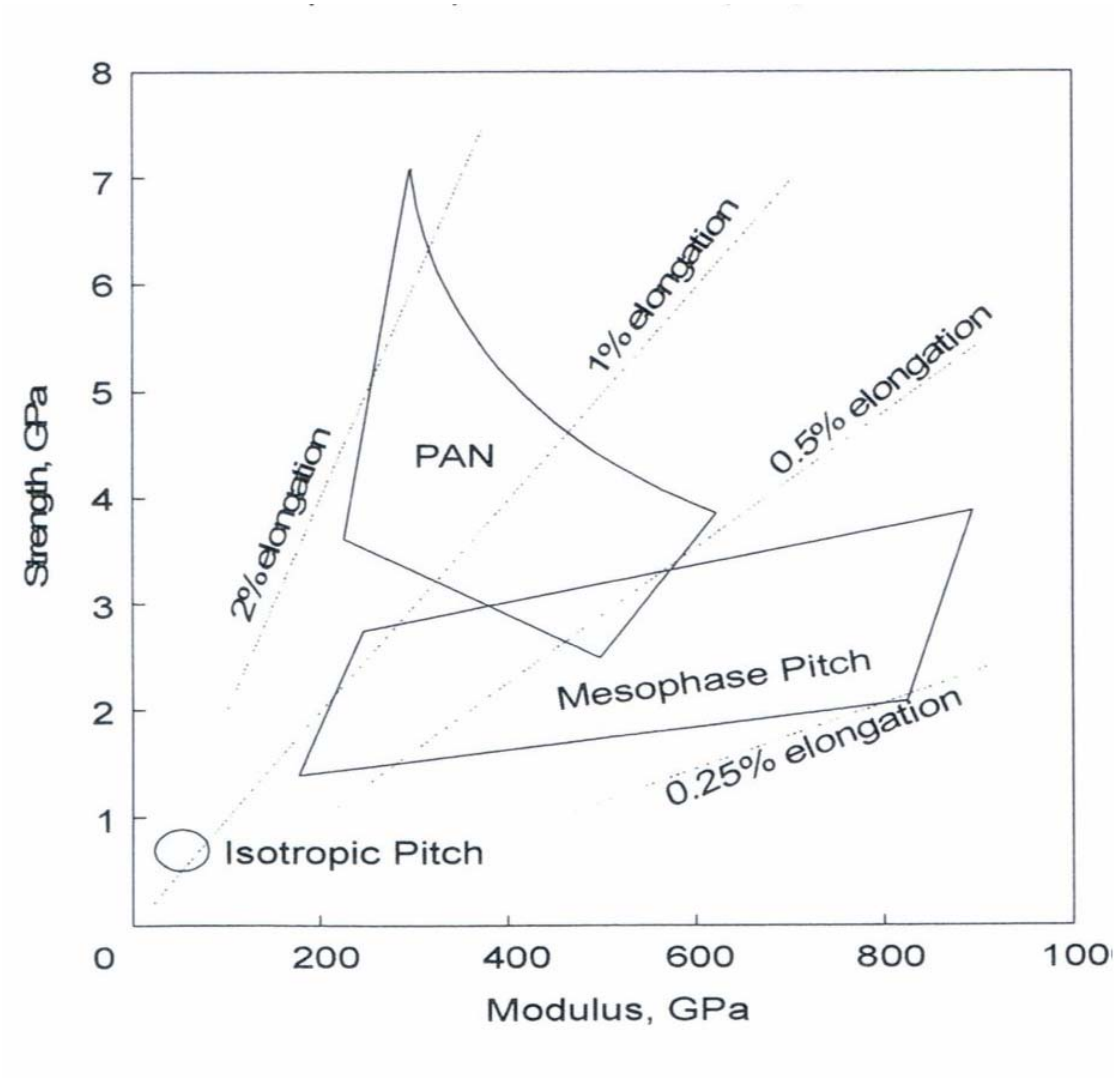


Figure 3.3-1 - Carbon fibres: PAN and pitch-based fibres

The majority of aerospace engineering applications use PAN-based carbon fibres. Pitch-based fibres, although more expensive, are attractive for thermal management or thermal stability applications.

3.3.2.2 Characteristics

Both PAN and pitch-based carbon fibres are usually classified by their mechanical performance into the main groups:

- HT - high tenacity carbon fibres which includes:
  - HS high strength fibres with tensile strengths up to 3500MPa and tensile moduli in the range of 200GPa to 255GPa.
  - high strain or VHS - very high strength fibres with tensile strengths in excess of 3500MPa.
- IM - intermediate modulus carbon fibres, which have tensile moduli in the range of 255GPa to 310GPa.
- HM - high modulus carbon fibres: These all have tensile moduli greater than 310GPa and includes UHM - ultra high modulus fibres with tensile moduli exceeding 395GPa.

Pitch-based fibres normally fall within the HM or UHM class. Nippon GRANOC® XN-series low modulus fibres are exceptions, having tensile moduli between 54 GPa and 155 GPa and failure strains around 2%, Ref. [3-12].

HexTow® IM7 and IM9 and TORAYCA® T800 and T1000 are examples of IM intermediate modulus PAN carbon fibres having very high tensile strengths (around 6000 MPa) and moduli approaching 300GPa. Fibres can be developed to have particular properties for certain applications, e.g. HexTow® PV42/850 is an example of a fibre destined for filament winding of pressure vessels or similar applications where composites need high tensile strength.

Such advances in carbon fibre technology have produced overlap between the main groups.

3.3.3 Mechanical properties

Basic properties for some reinforcing fibres are shown in Table 3.3-1. [See also: Figure 2.3-1 and Figure 2.3-2]. As of 2009, those commercially-available fibres of interest for aerospace are given. Older fibres, with data elsewhere in this handbook, remain for comparison purposes and are shown with a grey background.

The export of some pitch-based fibres, notably from the USA, into European and near-European countries is restricted.

Table 3.3-1 - Reinforcing fibres: Basic properties

Fibre (Manufacturer) Link	Tensile Strength (MPa)	Tensile Modulus (GPa)	Failure Strain (%)	Fibre Density (kg/m^3)	Fibre Diameter (μm)
Carbon HT Fibres					
XA-S (Hysol Grafil)	3100	235	1.31	1790	6.8
T300 (Toray)	3530	235	1.5	1760	7
AS-4 (Hercules)	3590	234	1.53	1800	8
XA-S, H-S (Hysol Grafil)	3850	235	1.64	1790	6.8
HTA40 (fabric) (Toho Tenax)	3950	238	1.7	1760	7
AS-6 (Hercules)	4100	248	1.65	1830	7
T400 (Toray)	4120	235	1.75	1800	7
T-650 (Cytec)	4280	255	1.7	1770	6.8
Celion ST (Celanese)	4300	234	1.84	1770	7
HTS40 (UD) (Toho Tenax)	4300	240	1.8	1770	7
Fenax ST3 (Toho Tenax)	4310	235	1.8	1770	7
AS4C 6k (Hexcel)	4410	231	1.8	1780	6.9
T700S (Toray)	4900	230	2.1	1800	7
Apollo HS (Hysol Grafil)	5000	245	2	1800	-
Carbon IM Fibres					
Apollo IM (Hysol Grafil)	4000	275	1.5	1800	-
IM7 6k (Hexcel)	5480	276	1.8	1780	5.2
IM6 12k (Hexcel)	5700	279	1.9	1760	5.2
IMS60 (Toho Tenax)	5600	290	1.9	1800	5
PV42/850 12k (Hexcel)	5810	292	1.9	1790	5.1
T800H (Toray)	5490	294	1.9	1810	5
T1000G (Toray)	6370	294	2.2	1800	5
G40-600 (Celanese)	4300	300	1.43	1780	-
IM9 12k (Hexcel)	6140	304	1.9	1800	4.4
Carbon HM Fibres					
M40J (Toray)	4410	377	1.2	1770	5
M46J (Toray)	4210	436	1	1840	5
YSH-50A (NGF) [2]	3900	520	0.7	2100	7
M55J (Toray)	4020	540	0.8	1910	5
M60J (Toray)	3820	588	0.7	1930	5
K135 2U (Mitsubishi) [1]	3600	620	0.6	2120	10
K63712 (Mitsubishi) [1]	2626	636	0.4	2120	11
YSH-70A (NGF) [2]	3630	720	0.5	2140	7
P100S (Cytec)	2410	759	0.3	2150	10
YS-80A (NGF) [2]	3630	785	0.5	2170	7
P-120S (Cytec)	2410	827	0.3	2170	10
K13C2U (Mitsubishi) [1]	3800	898	0.42	2200	10
YS-95A (NGF) [2]	3530	900	0.3	2190	7
K1100 (Cytec)	3100	931	-	2200	10
K13D 2U (Mitsubishi) [1]	3700	935	0.4	2200	11
Aramid Fibres					
Kevlar 49 (Du Pont)	3620	120	2.5	1450	11.9
Twaron HM (Teijin)	3150	121	2	1450	12
Glass Fibres					
E Glass (Various)	2400	69	3.5	2540	-
R Glass (Vetrotex)	3600	86	5.1	2550	9 to 13
S2 Glass (Owens Corning)	3450	86	4	2550	-
Other Fibres [See: 6.2]					
Zylon HM (PBO)[3] (Toyobo)	5800	270	2.5	1560	~11
Dyneema SK75 (PE) (Toyobo)	3400	110	3.6	975	-

(1) Europe Distributor: Sumitomo Corporation Europe Ltd. (UK);

(2) Nippon Graphite Fiber (Japan); (3) PBO - Poly (p-phenylene-2,6-benzobisoxazole); See Manufacturers' data sheets & Ref [3-2]; Kevlar 49 data, Ref. [3-7]; [See also: Table 3.2-2 – Thermal properties – Pitch-based carbon fibres] [Manufacturers' data, Revised: April 2009]

3.3.4 Thermal properties

3.3.4.1 Pitch-based carbon fibres

Pitch-based carbon fibres find uses in structures and thermal management systems because they have some better characteristics compared with PAN-based carbon fibres, e.g.:

- Higher thermal conductivity, [See also: [5-9],
- More negative thermal expansion,
- Higher modulus.

Often described as 'mesophase pitch-based fibres' and classed as HM or UHM fibres, the composition can be tailored during carbonisation to enhance thermal properties (high conductivity, low expansion). In general, the higher the graphite content, the higher the thermal conductivity. Properties are directional with significant differences between axial and transverse directions.

Table 3.2-2 summarises suppliers' typical properties for continuous pitch-based carbon fibres, Ref. [3-10], [3-11]. Commercial fibre tow sizes are usually 2k, 4k, 6k, 10k and 12k. A widely-used, PAN-based, HT carbon fibre, T-300 3k, is included for comparison purposes.

The export of some pitch-based fibres, notably from the USA, into European and near-European countries is restricted.

3.3.5 Composite manufacturing aspects

3.3.5.1 General

Continuous tows of reinforcing fibres are normally used for the manufacture of aerospace structural composites, [See: Clause 38]. The most common form is prepreg.

3.3.5.2 Pitch-based carbon fibres

Pitch fibres have low failure strains (typically <0.5%) and large filament diameters, so, to avoid damage during handling or processing, procedures may need to be adapted from those used for PAN carbon fibres, [See also: Clause 38].

European companies involved with the ALMA project have acquired expertise in manufacturing large structures from pitch-based carbon fibres. The European AEM Consortium (Thales Alenia, MT Mechatronics) produce the CABIN and BUS structures for some antennas from Mitsubishi K63712 (12k tow fibre)/HTM57 epoxy prepreg from ACG. The structures are manufactured by Duquiene (France) and Multiplast (France), Ref.[3-9].

Table 3.3-2 – Thermal properties: Pitch-based carbon fibres

Fibre (Manufacturer)	Tensile Strength (MPa)	Tensile Modulus (GPa)	CTE (1) (ppm)	Thermal (1) Conductivity (W/m.K)	Fibre Density (kg/m^3)	Fibre Diameter (μm)
T-300, 3k PAN fibre (Cytec)	3100	235	L –0.6 T +9.0	L 8.5 T 5.0	1750	7
Thornel® (Cytec) (2):						
P-25 2k	1380	159	L - T -	L 22 T 10	1900	11
P-30X 2k	2760	201	L - T -	L 40 T 10	1990	11
P-55S 2k	1900	379	L –1.3 T -	L 120 T 5	2000	10
P-75S 2k	2070	517	L –1.46 T +12.5	L 185 T 2.4	2050	10
P-100S 2k	2410	759	L –1.48 T +12.0	L 520 T 2.4	2150	10
P-120S 2k	2410	828	L –1.5 T +12.0	L 640 T 2.4	2180	10
P-1100S 2k	3100	931	L –1.5 T +12.0	L 1000 T 2.4	2200	10
DIALEAD® (Mitsubishi) (3):						
K1352U 2k	3600	620	-	140	2120	-
K1392U 2k	3700	760	-	210	2150	-
K13C2U 2k	3800	900	-	620	2200	-
K13D2U 2k	3700	935	-	800	2200	-
K63712 10k 12k type	2600	640	-	140	2120	-
GRANOC® (NGF Nippon) (4)						
YSH-50A 1k,3k,6k	3830	520	–1.4	120	2100	7
YSH-60A 1k,3k,6k	3830	630	–1.4	180	2120	7
YSH-70A 1k,3k,6k	3630	720	–1.5	250	2150	7
YS-80A 3k, 6k	3630	785	–1.5	320	2150	7
YS-90A 3k, 6k	3530	880	–1.5	500	2180	7
YS-95A 1.5k, 3k, 6k	3530	920	–1.5	600	2190	7
XN-05 3k	1100	54	+1.4	7.4	1650	10
XN-06 3k	1700	110	–0.1	-	1700	10
XN-07 3k	2400	155	–0.8	6.3	1850	10

(1) L – longitudinal; T – transverse;

(2) Cytec Engineered Materials (USA), includes former BP Amoco products;

(3) Distributor Sumitomo Corporation Europe Ltd. (UK);

(4) Nippon Graphite Fibers (Japan) YSH-A-series high compressive strength for aerospace; YSA-series UHM and high thermal conductivity; XN-series low modulus, high elongation (1.5% to 2.0%).

[DATE: March 2009]

3.4 Woven cloths and fabrics

A fabric is any material of woven construction. A cloth is a fabric more than 150 mm wide. When fabrics are available in widths less than 150 mm, they are called fabric tapes.

All fibres can be converted into fabrics. Single fibre fabrics of either carbon or Kevlar 49 are the most common. The main variables are:

- Weave type, [See: [3-5].
- Areal weight, [See: [3-6].
- Warp and weft characteristics, [See: [3-7].

Mixed fibre fabrics (hybrids) are also available, in combinations of carbon, glass and aramid.

The main reasons for using fabric based prepregs are:

- Ease of handling,
- Drape characteristics,
- Ability to retain fibre position during moulding.

This is particularly important on double curvatures and irregular shapes, e.g. antenna dishes, where unidirectional prepreg can distort.

The mechanical properties of laminates made from woven fabrics are inferior to those from prepreg, [See: [3-8] and Clause 9].

3.5 Weave types

The tows in the warp direction are called ‘ends’ and tows in the weft direction are called ‘picks’, [See also: [3-7]].

The common weave types are:

- Plain or Square: Each warp and weft thread passes over one end (or pick) and under the next.
- Twill: Generally 2x2 or 4x4, in which each warp end and weft pick floats over two (four) crossing threads.
- Satin: Each warp end and weft pick floats over N and under one crossing thread. The weave is described by (N+1), e.g. an 8-harness (8-shaft) satin - SATIN 8 - in which the weft pick passes over 7 and under one warp end, [See: Figure 3.7-1].
- Bias: The weft picks cross the warp ends at 45° or 60° instead of the normal 90°.

The type of weave determines the fibre volume content of the final composite.

Fabric selection is dictated by drape and moulding characteristics. Satin weaves are popular.

3.6 Areal weight

The areal weight is:

- A measurement of the weight per unit area of a fabric or fabric prepreg. The commonly used units are g/m².
- An indication of the individual ply thickness.
- Largely determined by the number of individual fibres in each woven tow.

3.7 Warp and weft characteristics

Some fabrics have a different number of fibre tows per unit width in warp and weft directions.

If end and pick counts are not equal, the mechanical properties of the composite ply are also unequal in the warp and weft directions. Figure 3.7-1 shows three common styles of woven cloths and fabrics.

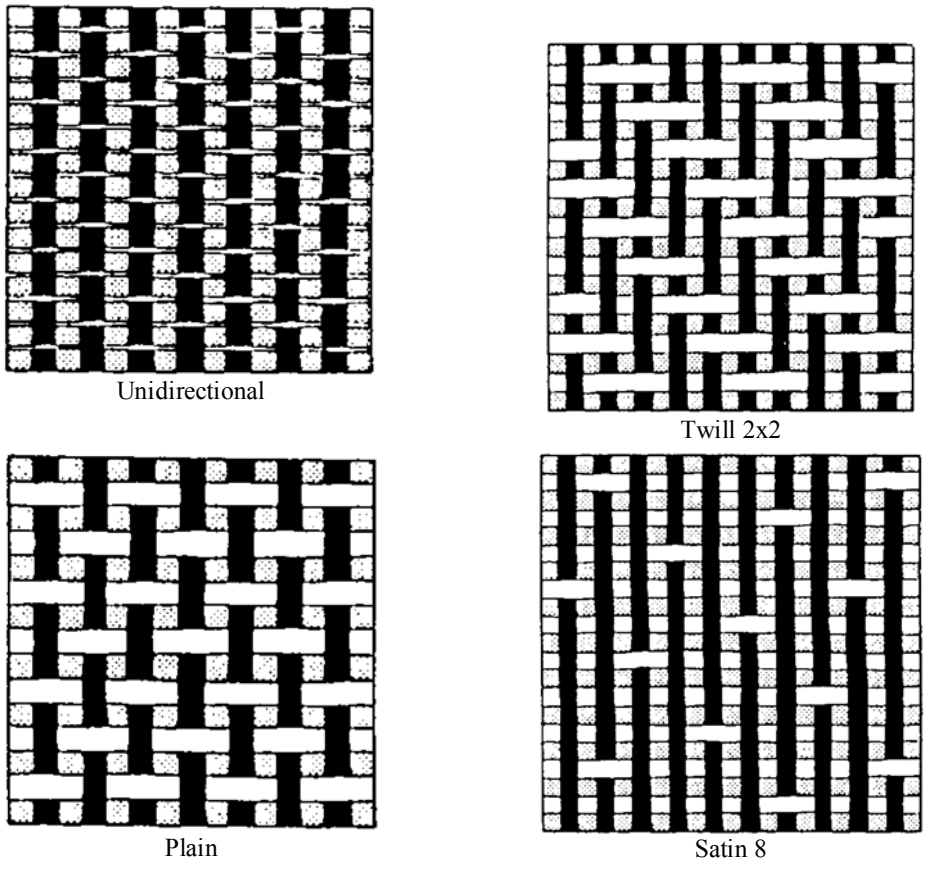


Figure 3.7-1 - Common weave styles

3.8 Single and unidirectional composite plies

Mechanical properties for Fibredux 914/T300 unidirectional carbon fibre tape are given as a function of temperature and moisture content in Figure 3.8-1 to Figure 3.8-7 inclusive, Ref. [3-3].

Similar data for Code 69/T300 and F550/T300 systems are given in Ref. [3-3].

Data which forms the basis for laminate design is given in Clause 9 for various carbon and aramid fibre epoxy matrix materials. The data are for established and fully characterised composite materials used in the aerospace industries.

Clause 9 also contains similar data for less well-established composite materials, including:

- Polyimide resin systems.
- Bismaleimide resin systems.
- Thermoplastic matrix composites.

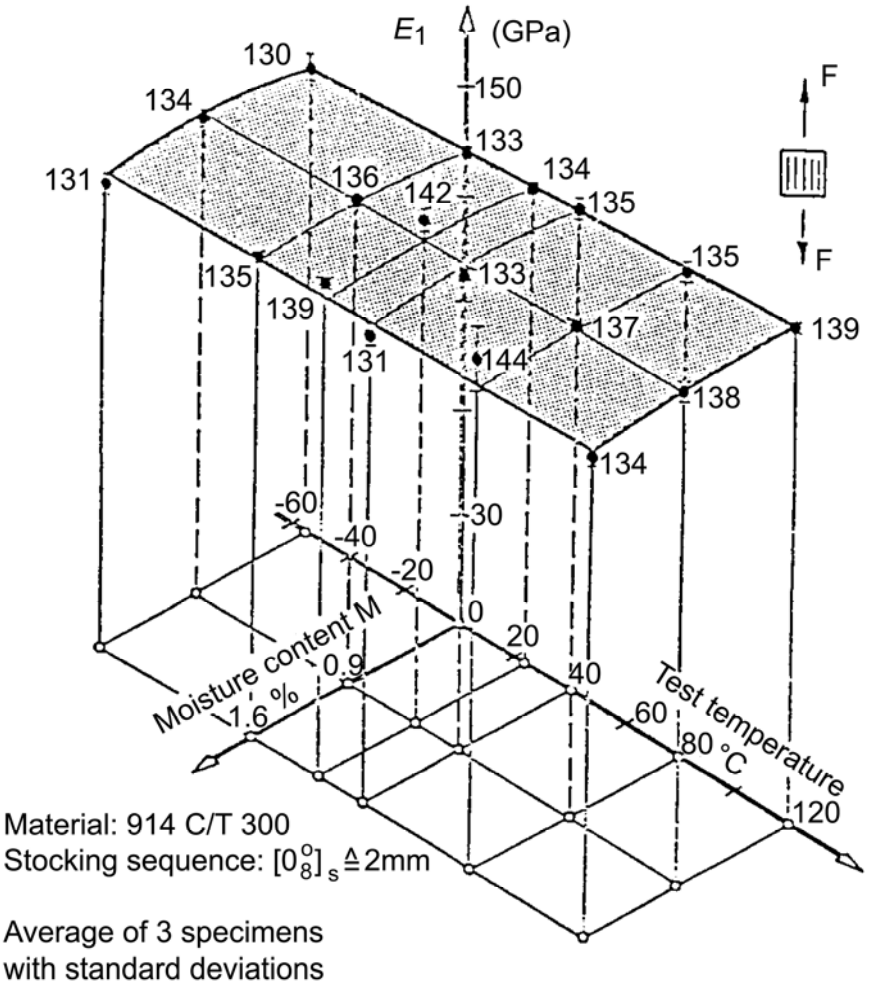


Figure 3.8-1 - Longitudinal modulus of elasticity in tension (E_1)

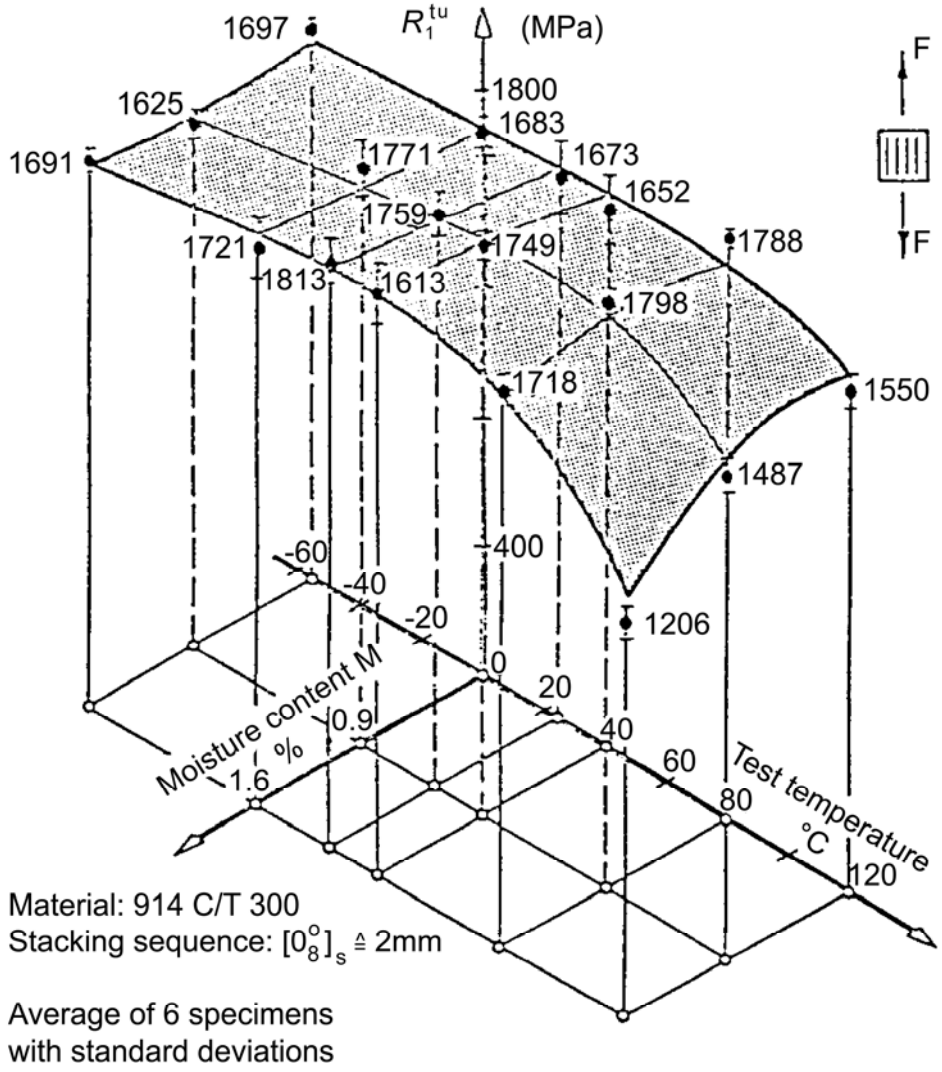


Figure 3.8-2 - Longitudinal tensile strength (R_1^{tu})

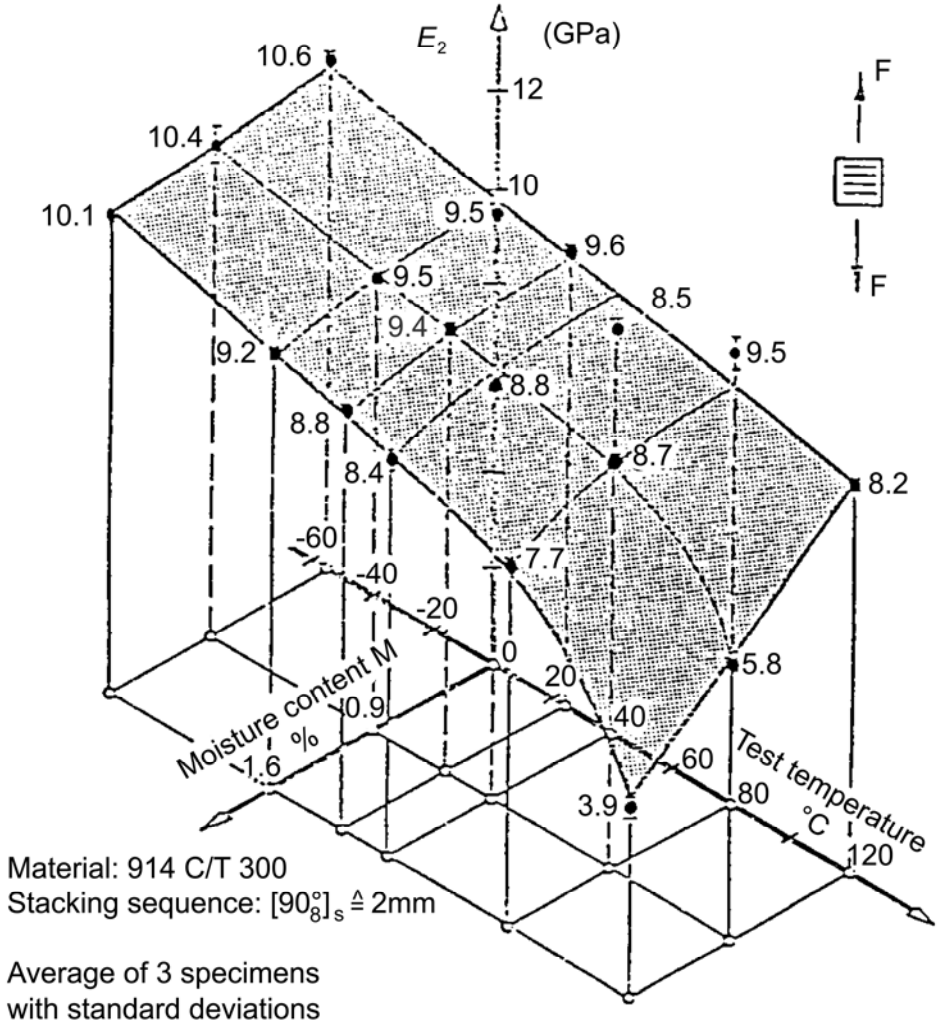


Figure 3.8-3 - Transverse modulus of elasticity in tension (E_2)

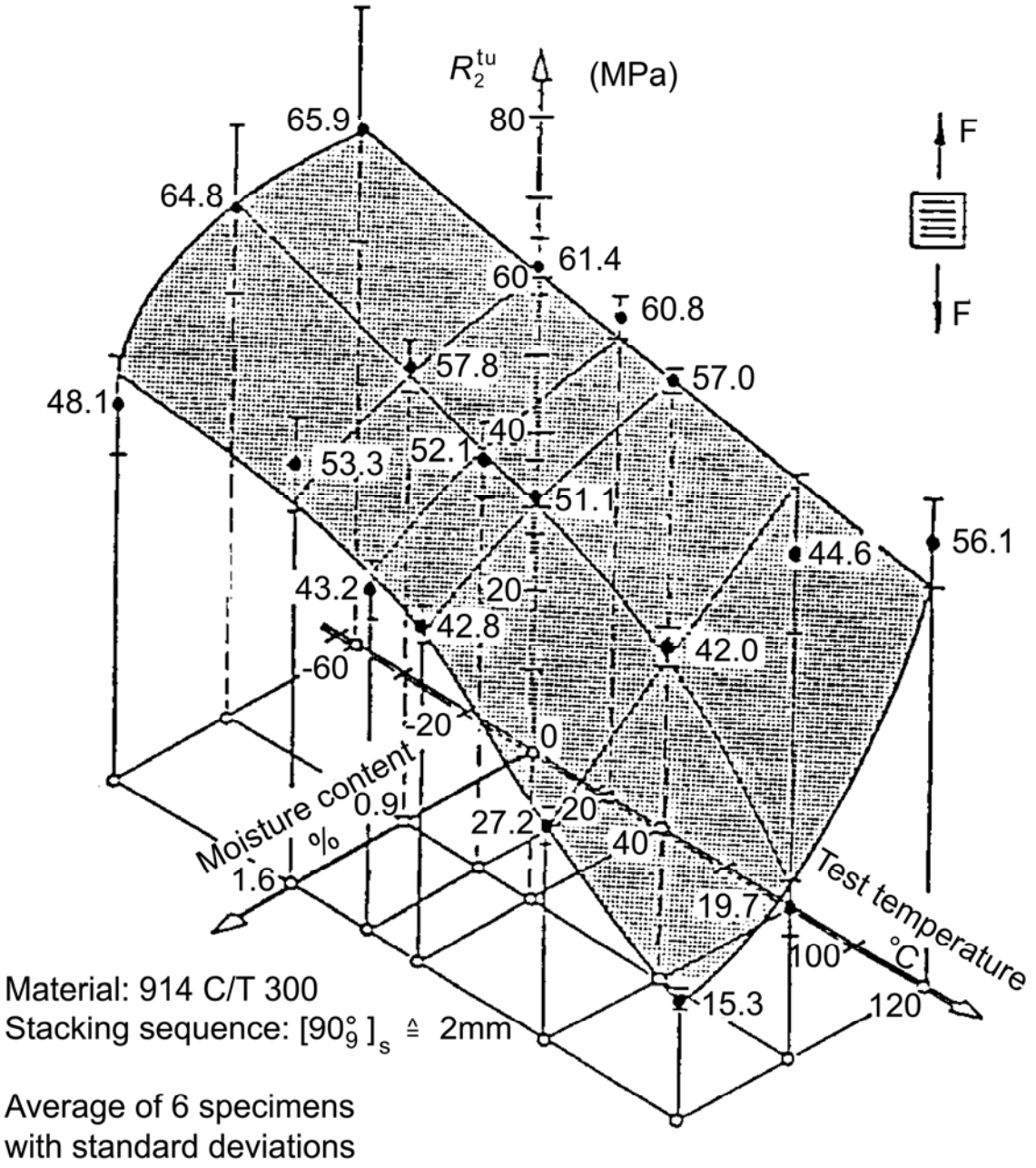


Figure 3.8-4 - Transverse strength in tension (R_2^{tu})

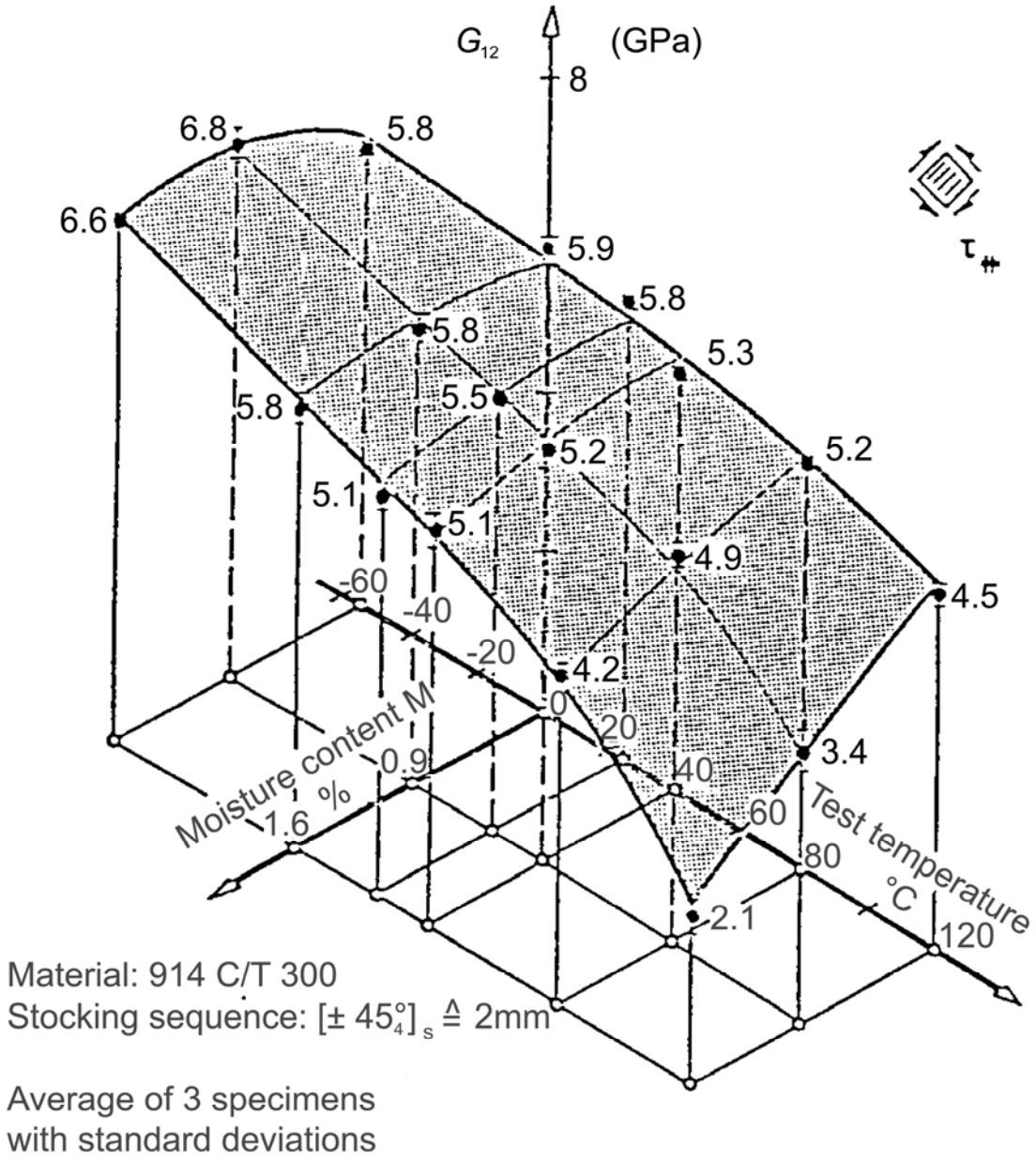


Figure 3.8-5 - In plane shear modulus (G_{12})

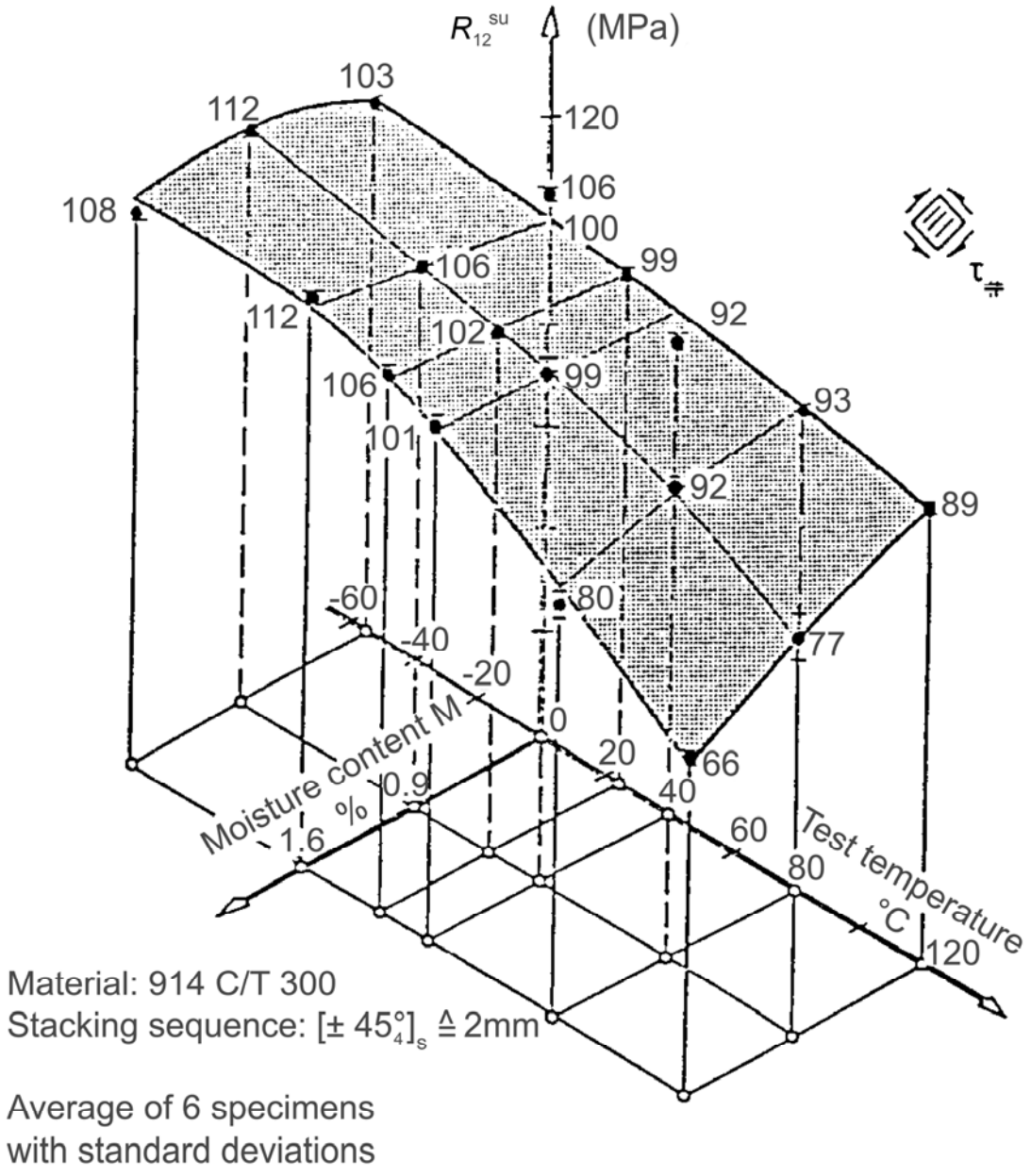


Figure 3.8-6 - In plane shear strength (R_{12}^{su})

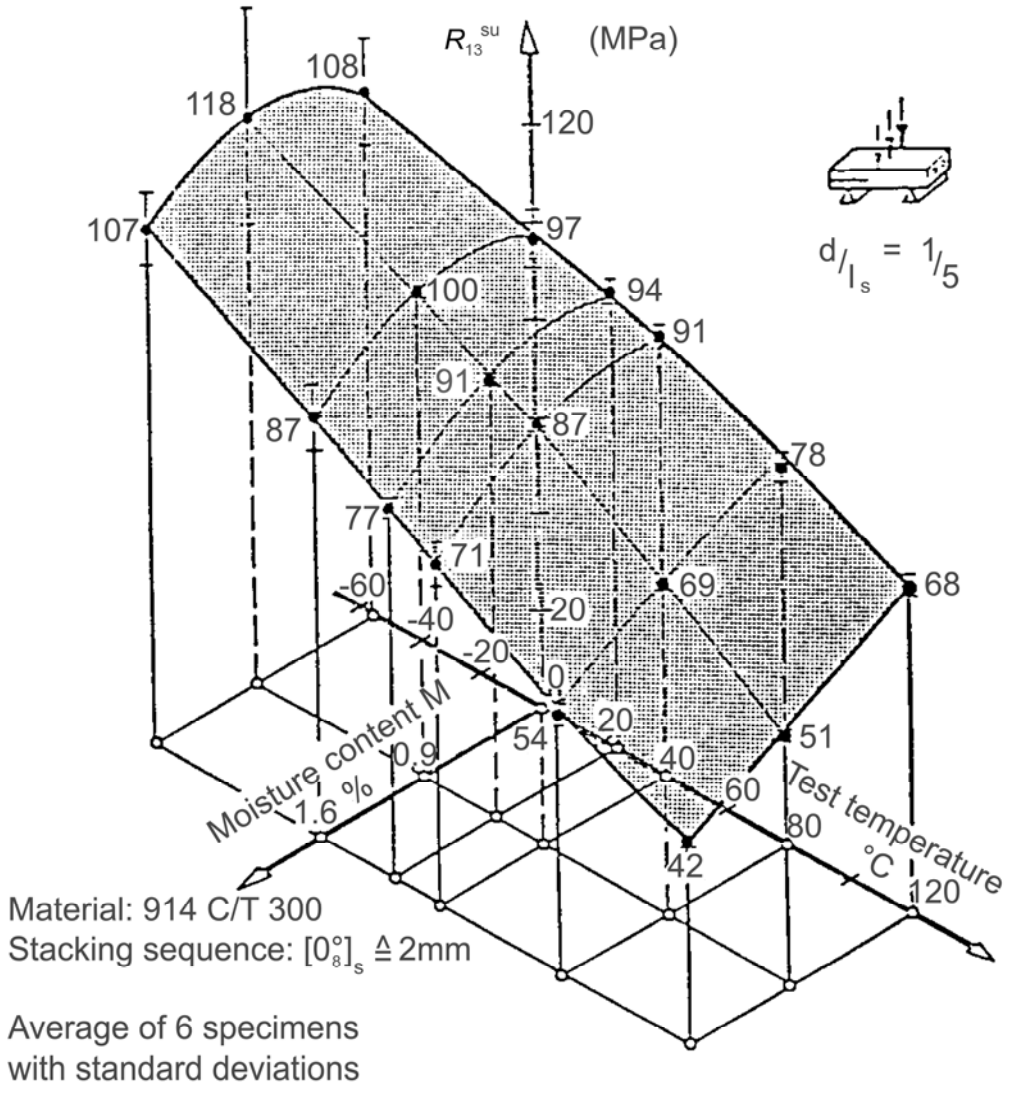


Figure 3.8-7 - Interlaminar Shear Strength (R_{13}^{su})

3.9 Design allowables

3.9.1 General

The data is established by the referenced data source as 'Design Allowables'. The data is obtained from either:

- Open literature, (referenced)
- Supplied directly to ESTEC (data source indicated) for inclusion in the handbook.

The data is from established and fully characterised composite systems used in the aerospace industries.

Points to be noted when using the data is the:

Statistical basis (A-values, B-values),

Fibre content by volume or weight,

Moisture content,

Temperature to which the property is specified,

All data need to be validated by standard procedures before use.

[See: 37.3 for 'A' basis and 'B' basis allowables]

NOTE Data in any given table refer only to the batch of material from which the samples were taken.

Recent experience in some space projects suggests that in-plane characteristics are insufficient for characterising some laminate constructions, particularly in areas of thickened or formed section.

3.9.2 Notation for design allowable data

3.9.2.1 Mathematical notation

Data for tensile and compressive properties are clearly separated in the tables.

E_1 , $E_\parallel$	Young's modulus in 0° direction
E_2, $E_\perp$	Young's modulus in 90° direction
R^u	An ultimate strength
ε^u	An ultimate strain to failure
ν_{12}, $\nu_{\parallel\perp}$	In-plane Poisson's ratio
G_{12}, $G_{\parallel\perp}$	In-plane shear modulus
R_1^{tu}	Ultimate tensile strength, 0° direction
R_1^{cu}	Ultimate compressive strength, 0° direction
R_{12}^{su}	In-plane shear strength
R_{13}^{su}	ILSS, the interlaminar shear strength for 0° unidirectional) laminate
$R_{13}^{su}{}_{[0,\pm45]}$	ILSS for 0°/±45° laminate
R_1^{fu}	Flexural strength for 0° (unidirectional) laminate
$\bar{x}$	Mean value
S.D.	Standard deviation
N	Number of specimens
Suffix:	
1	0° direction (longitudinal)
2	90° direction (transverse)
3	90° direction (through-thickness)

3.9.2.2 Units for design allowable data

1 MPa = 1 N/mm^2

1 GPa = 1000 MPa

3.9.3 Unidirectional carbon HT composite

3.9.3.1 T300 fibre/epoxy resin system

Table 3.9-1 - Design allowables for T300/epoxy system: Hexcel T3T-190-F155, T6C-190-F155

Supplier/Trade Name **Hexcel** **T3T-190-F155** **T6C-190-F155**				**Fibre/Resin System** **T300/Epoxy**				**Data Source** **[3-1]**		
Strength Allowables*										
Basic Value		Multiplication factors for temperature/humidity effects								
Moisture Level										
	Dry	Dry			High moisture level			In-service moisture level		
Temp (°C)	RT	-55	+50	+70	-55	RT	+70	-55	RT	+50
Tension: R_1^{tu} (MPa)										
Mean	1490	0.95		0.95						
"A"	1250	0.9		0.95						
"B"	1050	0.85		0.95						
Compression: R_1^{cu} (MPa)										
Mean	950	1.1		0.75		0.73	0.1			
"A"	790	1.0		0.70		0.7	0			
"B"	660	0.95		0.65		0.67	0			
Flexural; R_1^{fu} (MPa)										
Mean	1650	1.23		0.75	1.31					
"A"	1430	1.22		0.73	1.29					
"B"	1260	1.21		0.71	1.27					
ILSS; R_{13}^{su} (MPa)										
Mean	82	1.41		0.73		0.64	0.31			
"A"	70	1.25		0.71		0.57	-			
"B"	60	1.10		0.70		0.51	-			

* Allowables calculated from data in Clause 9

Table 3.9-2 - Design allowables for T300/epoxy system: Hexcel T6C-190-F593/1a

Supplier/Trade Name **Hexcel** **T6C-190-F593/1a**				**Fibre/Resin System** **T300/Epoxy**				**Data Source** **[3-1]**		
Strength Allowables*										
Basic Value	Multiplication factors for temperature/humidity effects									
Moisture Level										
	Dry	Dry			High moisture level			In-service moisture level		
Temp (°C)	RT	-55	+50	+70	-55	RT	+70	-55	RT	+50
Tension: R_1^{tu} (MPa)										
Mean	1280	0.85		1				0.85	1	1.05
"A"	1075	0.85		1				0.85	1	1.05
"B"	930	0.85		1				0.85	1	1.05
Compression: R_1^{cu} (MPa)										
Mean	1100	1.15		0.75		0.78	0.6	1.15		0.65
"A"	950	1.15		0.70		0.71		1		0.5
"B"	840	1.15		0.65		0.65		0.85		0.35
Flexural: R_1^{fu} (MPa)										
Mean	1590			1						
"A"	1390			1						
"B"	1240			1						
ILSS: R_{13}^{su} (MPa)										
Mean	102	1.25		0.78		0.87				
"A"	86	1.25		0.78		0.87				
"B"	75	1.25		0.78		0.87				

* Allowables calculated from data in Clause 9

Table 3.9-3 - Design allowables for T300/epoxy system: Fiberite HyE 1034C

Supplier/Trade Name Fiberite HyE 1034C	Fibre/Resin System T300 (3K) Epoxy: Fiberite 934	Data Source [3-5]
Fibre Vol (%): 63	t_{ply} (mm): 0.14	Density (kg/m^3): 1600
Areal Weight (g/m^2): -	Year of Test: -	
Specimen Condition: 177 °C Cure. 1% moisture content on laminate.		
Test Environment: 71°C		"In-house" Design Allowables
Tension	E_1^t (GPa)	117.7
	R_1^{tu} (MPa)	1120
	ε_1^{tu} (%)	0.95
	E_2^t (GPa)	8.42
	R_2^{tu} (MPa)	80
	ε_2^{tu} (%)	-
Compression	E_1^c (GPa)	117.7
	R_1^{cu} (MPa)	1000
	ε_1^{cu} (%)	0.85
	E_2^c (GPa)	8.42
	R_2^{cu} (MPa)	71
	ε_2^{cu} (%)	-
Poisson's ratio	ν_{12}	0.34
Shear	G_{12} (GPa)	5.88
	R_{12}^{su} (MPa)	68
Interlaminar shear (ILSS)	R_{13}^{su} (MPa)	59
	R_{13}^{su} $_{(0\pm45)}$ (MPa)	-
Flexural:	R_1^{fu} (MPa)	-

3.9.4 Unidirectional carbon HM composite

3.9.4.1 GY-70 fibre/ epoxy resin system

Ref.[3-4], [3-5].

NOTE Celion GY-70 fibre is no longer commercially available.

Table 3.9-4 - Design allowables for GY-70/epoxy system: GY-70 Code 69

Supplier/Trade Name Cyanamid Fothergill Code 69/GY-70	Fibre/Resin System Celion GY-70 Epoxy: Code 69			Data Source -	
Mechanical Properties - "A" and "B" Allowables					
Test Temperature	(°C)		-183	27	127
Tension	E_1^t (GPa)	A	249	252	-
		B	270	273	-
	R_1^{tu} (MPa)	A	261	400	-
		B	331	506	-
	E_2^t (GPa)	A	6.99	4.70	4.09
		B	8.51	5.72	4.98
	R_2^{tu} (MPa)	A	11.4	15.9	11.9
		B	15.2	21.6	15.9
Compression	E_1^c (GPa)	A	254	263	236
		B	284	294	264
	R_1^{cu} (MPa)	A	589	441	303
		B	713	534	367
	E_2^c (GPa)	A	9.95	7.42	-
		B	10.9	8.12	-
	R_2^{cu} (MPa)	A	126	108	-
		B	152	129	-
Shear	G_{12} (GPa)	A	5.92	4.21	3.98
		B	6.60	4.69	4.44
	R_{12}^{su} (MPa)	A	34.1	41.3	34.4
		B	43.7	53.0	44.2
Interlaminar shear (ILSS)	R_{13}^{su} (MPa)	A	33.1	33.2	32.1
		B	40.6	40.7	39.4

Table 3.9-5 - Design allowables for GY-70/epoxy system: GY-70 Code 95

Supplier/Trade Name Cyanamid Fothergill Code 95	Fibre/Resin System GY-70 Epoxy: Code 95	Data Source -
Fibre Vol (%): 60	t_{ply} (mm): -	Density (kg/m^3): -
Test Environment: RT.		"A" Design Allowables
Tension	E_1^t (GPa)	264
	R_1^{tu} (MPa)	405*
	ε_1^{tu} (%)	-
	E_2^t (GPa)	-
	R_2^{tu} (MPa)	-
	ε_2^{tu} (%)	-
Compression	E_1^c (GPa)	245
	R_1^{cu} (MPa)	470
	ε_1^{cu} (%)	-
	E_2^c (GPa)	-
	R_2^{cu} (MPa)	-
	ε_2^{cu} (%)	-
Poisson's Ratio	ν_{12}	0.3
In-plane Shear	G_{12} (GPa)	3.5
	R_{12}^{su} (MPa)	117
Interlaminar Shear (ILSS)	R_{13}^{su} (MPa)	35
	R_{13}^{su} $_{(0_4 45)}$ (MPa)	-
Flexural	R_1^{fu} (MPa)	-
* Failure at Load Injection.		

Table 3.9-6 - Coefficient of thermal expansion: Design values for GY-70/epoxy system: GY-70 Code 95

	α_1	α_2
CTE: (x 10^{-6} °C^{-1})	-1.0	+30

Table 3.9-7 - Design allowables for GY-70/epoxy system: GY-70 Code 92

Supplier/Trade Name Cyanamid Fothergill Code 92	Fibre/Resin System GY-70 Epoxy: Code 92	Data Source [3-1]
Fibre Vol (%): 60	t_{ply} (mm): 0.06	Density (kg/m^3): 1600
Areal Weight (g/m^2): -	Year of Test: -	
Specimen Condition: Dry.		
Test Environment: RT.		"In House" Design Allowables
Tension	E_1^t (GPa)	275
	R_1^{tu} (MPa)	612
	ε_1^{tu} (%)	0.19
	E_2^t (GPa)	4.6
	R_2^{tu} (MPa)	15
	ε_2^{tu} (%)	0.27
Compression	E_1^c (GPa)	251
	R_1^{cu} (MPa)	391
	ε_1^{cu} (%)	0.13
	E_2^c (GPa)	-
	R_2^{cu} (MPa)	-
	ε_2^{cu} (%)	-
Poisson's Ratio	ν_{12}	0.35
Shear	G_{12} (GPa)	2.7
	R_{12}^{su} (MPa)	-
Interlaminar shear (ILSS)	R_{13}^{su} (MPa)	39
	R_{13}^{su} $_{(0_4 45)}$ (MPa)	-
Flexural	R_1^{fu} (MPa)	695

3.9.5 Unidirectional glass composite

3.9.5.1 R-glass/epoxy resin system

Ref. [3-4].

Table 3.9-8 - Design allowables for glass/epoxy system: R-glass/Fibredux 914G

Supplier/Trade Name Ciba Geigy Fibredux 914G	Fibre/Resin System R-glass Epoxy: Fibredux 914G		Data Source -		
Mechanical Properties - "A" and "B" Allowables					
Test Temperature	(°C)		-183	27	127
Tension	E_1^t (GPa)	A	46.4	46.8	-
		B	54.2	50.2	-
	R_1^{tu} (MPa)	A	804	1390	-
		B	881	1520	-
	E_2^t (GPa)	A	-	10.5	-
		B	-	14.2	-
	R_2^{tu} (MPa)	A	-	2.88	-
		B	-	19.5	-
Compression	E_1^c (GPa)	A	47.4	36.0	-
		B	57.6	43.0	-
	R_1^{cu} (MPa)	A	1210	944	-
		B	1500	1170	-
	E_2^c (GPa)	A	-	13.1	-
		B	-	14.2	-
	R_2^{cu} (MPa)	A	-	190	-
		B	-	200	-
In-plane Shear	G_{12} (GPa)	A	11.6	6.82	4.92
		B	12.4	7.25	5.23
	R_{12}^{su} (MPa)	A	76.0	74.83	55.1
		B	89.2	87.8	64.7
Interlaminar Shear(ILSS)	R_{13}^{su} (MPa)	A	123	85.9	58.0
		B	139	97.1	65.5

3.9.6 Single ply fabric carbon HT composite

3.9.6.1 T300/epoxy resin system

Table 3.9-9 - Design allowables for HT carbon fibre/epoxy system: Hexcel W3T 282 F263 8

Supplier/Trade Name Hexcel W3T 282 F263 8	Fibre/Resin System T300 (3K) Plain Weave Epoxy: F263	Data Source [3-5].
Fibre Vol (%): 60	t ply (mm): 0.21	Density (kg/m^3): 1500
Areal Weight (g/m^2): 322	Year of Test: -	
Specimen Condition: 177 °C cure, balanced laminate, 1 % moisture content.		
Test Environment: 71°C		"In House" Design Allowables
Tension	E_1^t (GPa)	57
	R_1^{tu} (MPa)	280
	ε_1^{tu} (%)	0.49
	E_2^t (GPa)	-
	R_2^{tu} (MPa)	-
	ε_2^{tu} (%)	-
Compression	E_1^c (GPa)	57
	R_1^{cu} (MPa)	284
	ε_1^{cu} (%)	0.47
	E_2^c (GPa)	-
	R_2^{cu} (MPa)	-
	ε_2^{cu} (%)	-
Poisson's Ratio	ν_{12}	0.06
Shear	G_{12} (GPa)	4.80
	R_{12}^{su} (MPa)	36
Interlaminar Shear (ILSS)	R_{13}^{su} (MPa)	33
	R_{13}^{su} $_{(0_4 45)}$ (MPa)	-
Flexural	R_1^{fu} (MPa)	-

Table 3.9-10 - Design allowables for HT carbon fibre/epoxy system: Hexcel F3T 584 42 F263 7

Supplier/Trade Name Hexcel / F3T 584 42 F263 7 Equivalent Material: Cyanamid Fothergill CYCON 985 GF3 135 H8	Fibre/Resin System T300 (3K) SATIN 8 Epoxy: F263	Data Source [3-5].
Fibre Vol (%): 63	t_{ply} (mm): 0.38	Density (kg/m^3): 1500
Areal Weight (g/m^2): 587	Year of Test: -	
Specimen Condition: 177 °C cure, solid laminate, 1 % moisture content.		
Test Environment: 71°C		"In House" Design Allowables
Tension	E_1^t (GPa)	60.4
	R_1^{tu} (MPa)	296
	ε_1^{tu} (%)	0.49
	E_2^t (GPa)	-
	R_2^{tu} (MPa)	-
	ε_2^{tu} (%)	-
Compression	E_1^c (GPa)	60.4
	R_1^{cu} (MPa)	284
	ε_1^{cu} (%)	0.47
	E_2^c (GPa)	-
	R_2^{cu} (MPa)	-
	ε_2^{cu} (%)	-
Poisson's Ratio	ν_{12}	0.06
Shear	G_{12} (GPa)	5.83
	R_{12}^{su} (MPa)	44
Interlaminar Shear (ILSS)	R_{13}^{su} (MPa)	33
	R_{13}^{su} $_{(0\pm45)}$ (MPa)	-
Flexural	R_1^{fu} (MPa)	-

3.9.7 Single ply fabric aramid composite

3.9.7.1 Kevlar 49/epoxy resin system

Table 3.9-11 - Design allowables for aramid fibre/epoxy system: Kevlar 49/ Hexcel K49 285 F161-188

Supplier/Trade Name Hexcel / K49 285 F161-188 Equivalent Material: Cyanamid Fothergill CYCON 985-K285	Fibre/Resin System Kevlar 49 Style 285 Fabric (Satin 4 Crowfoot) Epoxy: F161	Data Source [3-5].
Fibre Vol (%): 48	t_{ply} (mm): 0.25	Density (kg/m^3): 1400
Areal Weight (g/m^2): 354	Year of Test: -	
Specimen Condition: 177 °C cure, solid laminate, 1 % moisture content.		
Test Environment: 71°C		"In House" Design Allowables
Tension	E_1^t (GPa)	28.5
	R_1^{tu} (MPa)	285
	ε_1^{tu} (%)	1.0
	E_2^t (GPa)	27.0
	R_2^{tu} (MPa)	270
	ε_2^{tu} (%)	1.0
Compression	E_1^c (GPa)	27
	R_1^{cu} (MPa)	113
	ε_1^{cu} (%)	0.42
	E_2^c (GPa)	27
	R_2^{cu} (MPa)	113
	ε_2^{cu} (%)	0.42
Poisson's Ratio	ν_{12}	0.05
Shear	G_{12} (GPa)	1.96
	R_{12}^{su} (MPa)	30
Interlaminar Shear (ILSS)	R_{13}^{su} (MPa)	19
	$R_{13}^{su}{}_{(0\pm45)}$ (MPa)	-
Flexural	R_1^{fu} (MPa)	-

3.10 References

3.10.1 General

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4
Laminate mechanical properties

4.1 Introduction

Information on typical load-strain curves for epoxy matrix composites is presented.

Also considered is the effect of stress concentrations and how environmental factors, such as high or low temperatures, moisture and cyclic loading influence the typical properties of laminates.

4.2 Load - strain curves

Typical load-displacement curves for standard carbon epoxy T300/914 composite are shown in Figure 4.2-1,Figure 4.2-2, and. Figure 4.2-3

The curves show the typical response for 0° and 90° unidirectional material and ±45° laminates, Ref. [4-1] In each case the figure shows both a test to failure and the elastic load/unload response.

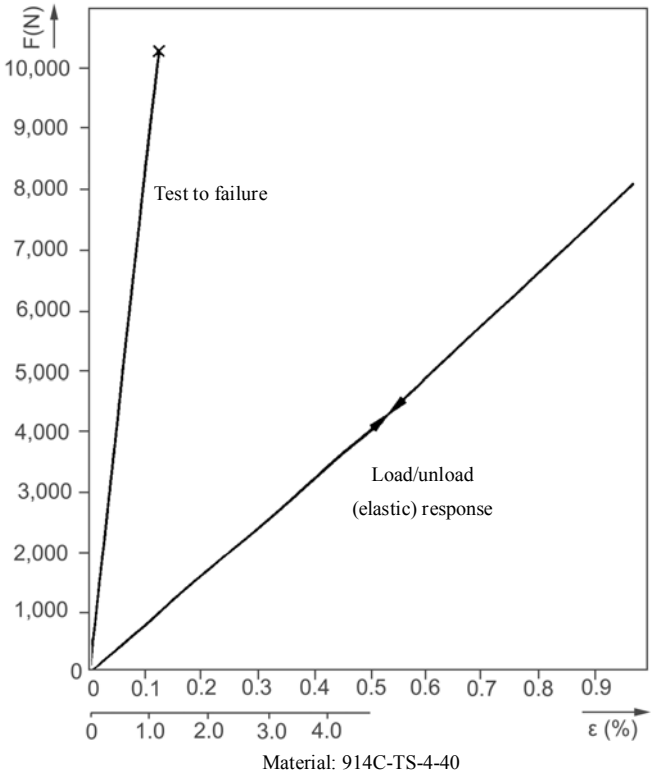


Figure 4.2-1 - Tensile strength 0° UD

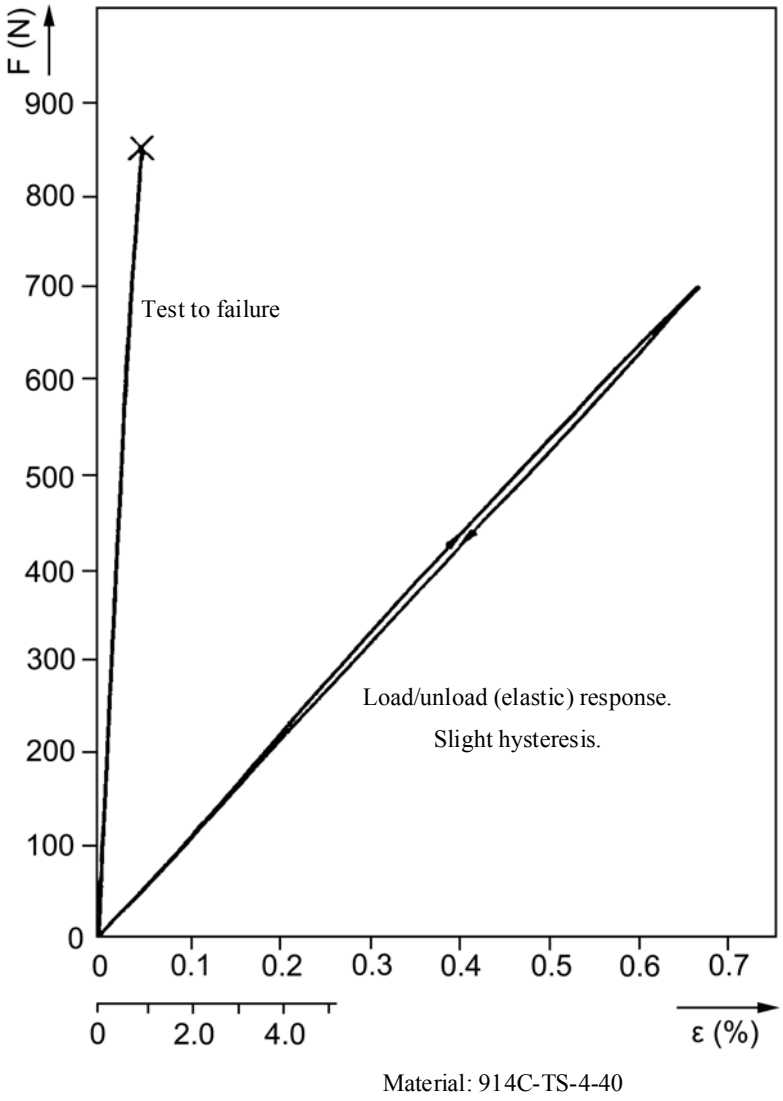


Figure 4.2-2 - Tensile strength 90° UD

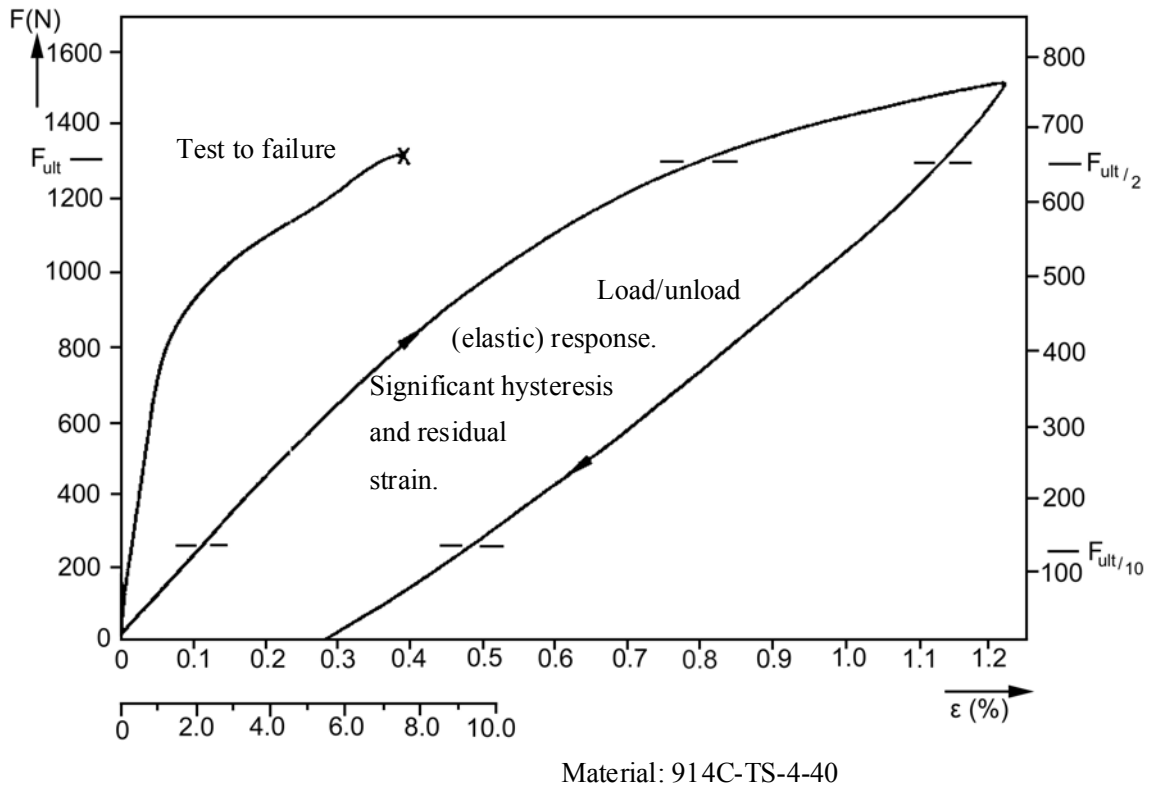


Figure 4.2-3 - Tensile strength ±45° laminates

4.3 Effects of elevated temperature

4.3.1 General

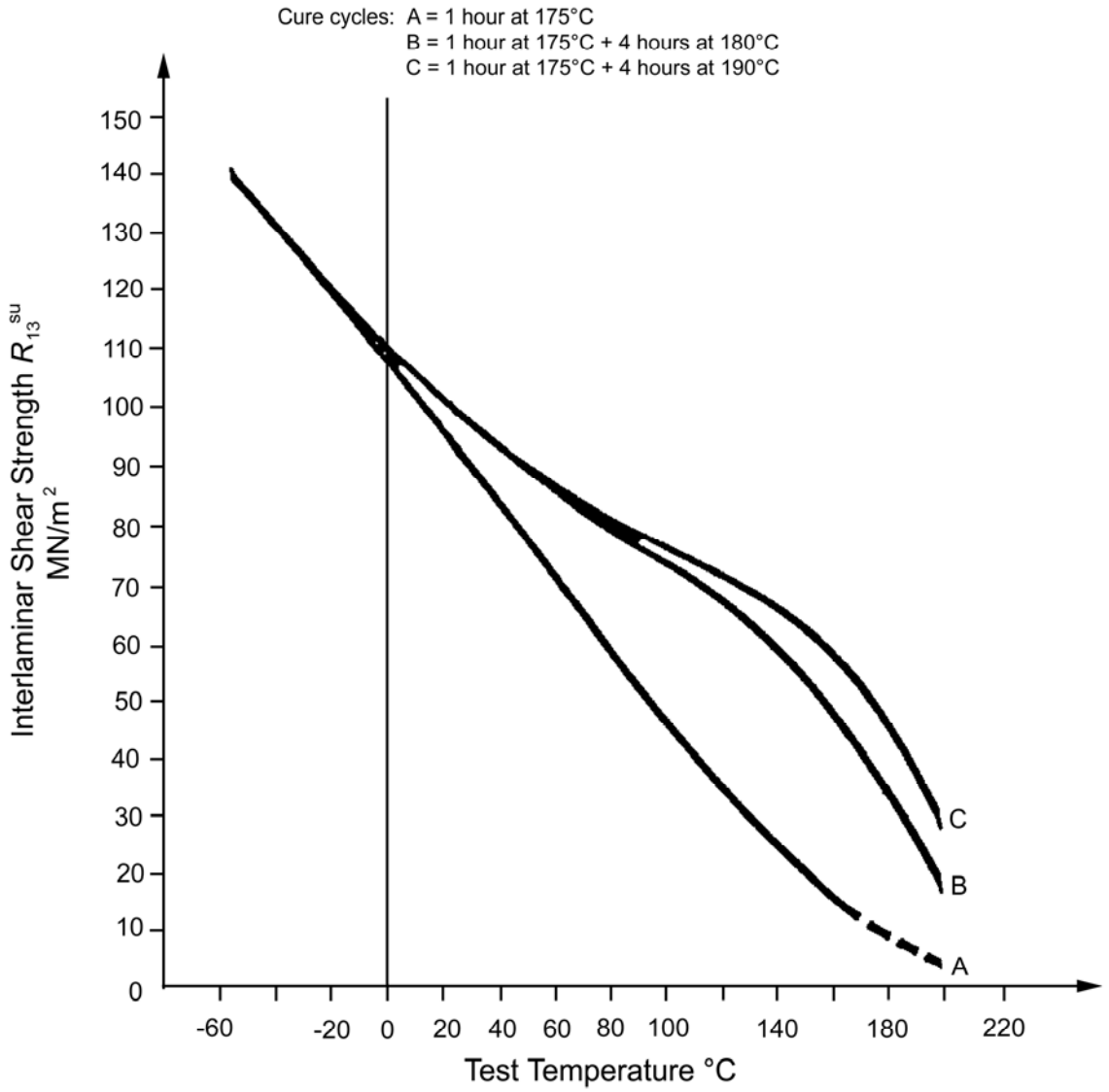
Changes in the properties of carbon/epoxy and aramid/epoxy composites due to elevated temperatures are illustrated.

4.3.2 Carbon/epoxy composites

The effect of temperature on the properties of T300 or XAS carbon fibre-reinforced Fibredux 914C epoxy resin are shown in, Ref. [4-2]:

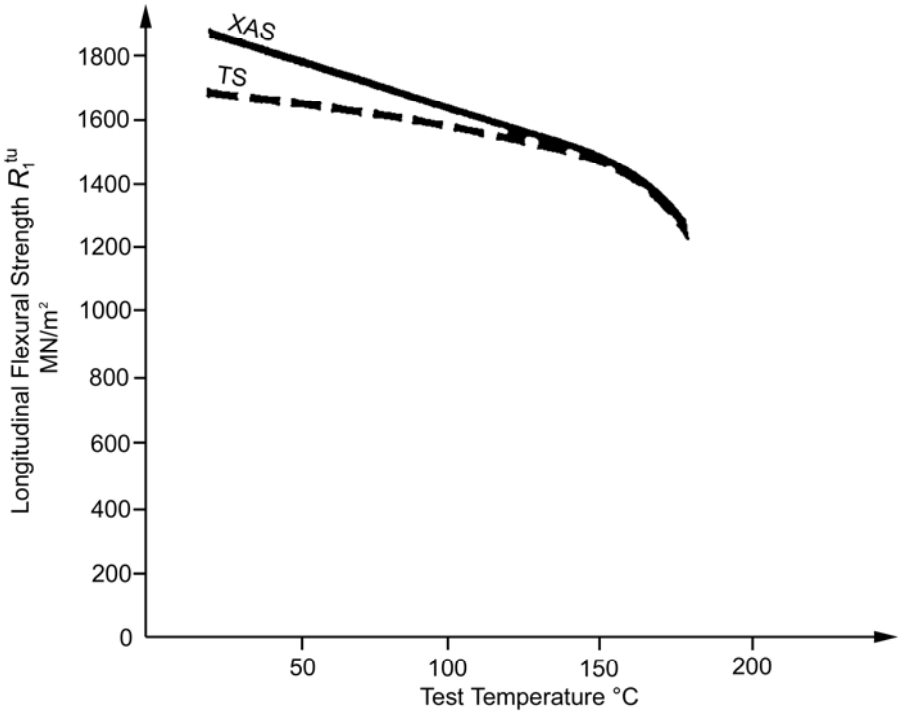
- Interlaminar shear strength, [See: Figure 4.3-1].
- 0° flexural strength, [See:Figure 4.3-2}
- 0° flexural modulus, [See: Figure 4.3-3].
- 90° flexural strength, [See: Figure 4.3-4].
- 90° flexural modulus, [See: Figure 4.3-5].
- 90° strain to failure, [See: Figure 4.3-6].

Manufacturers' data from Ref [4-2] are considered to be typical only.



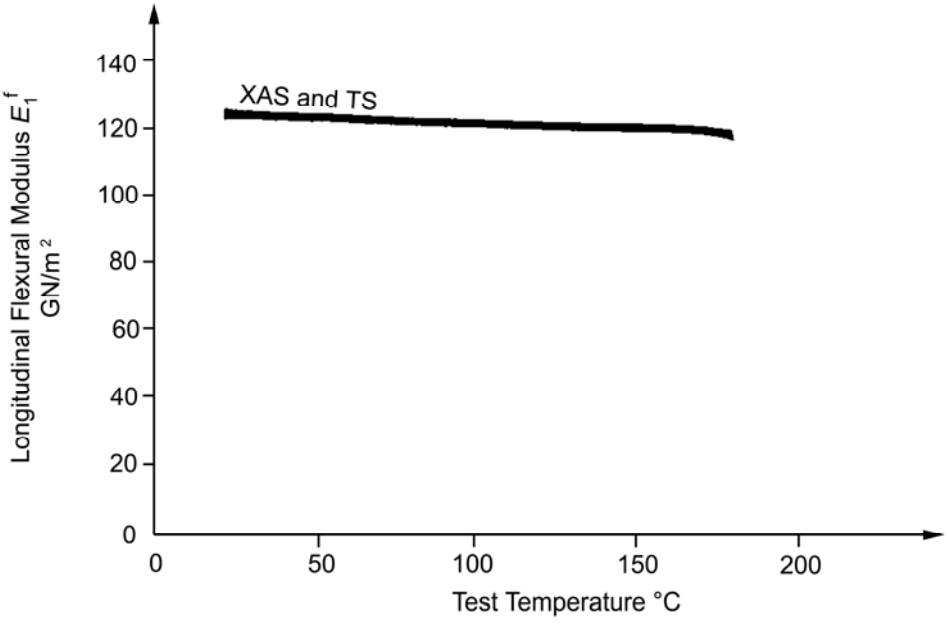
Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-1 - Interlaminar shear strength (ILSS)



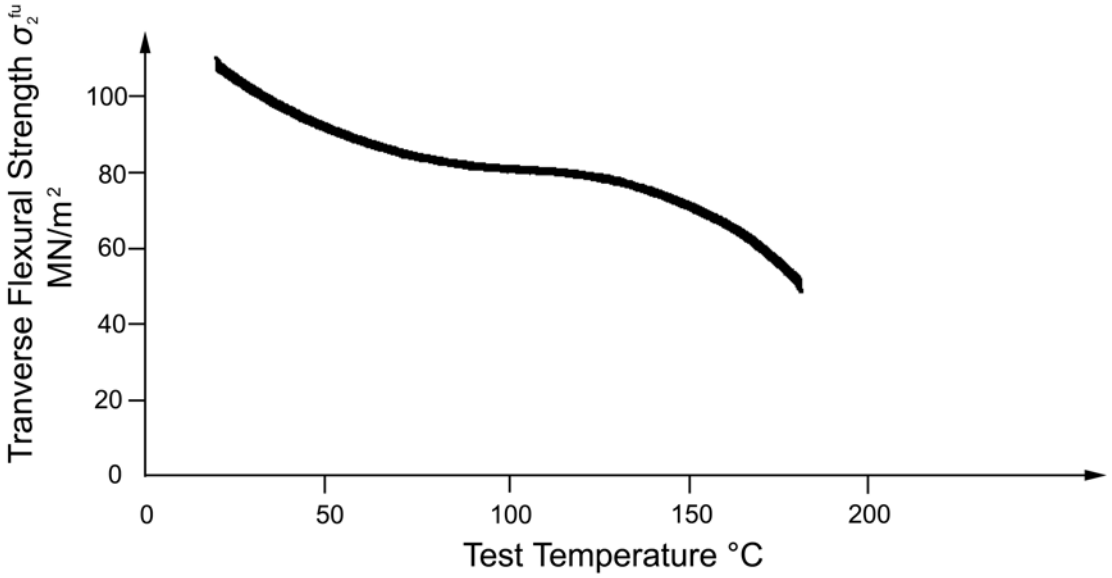
Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-2 - Longitudinal (0°) ultimate flexural strength



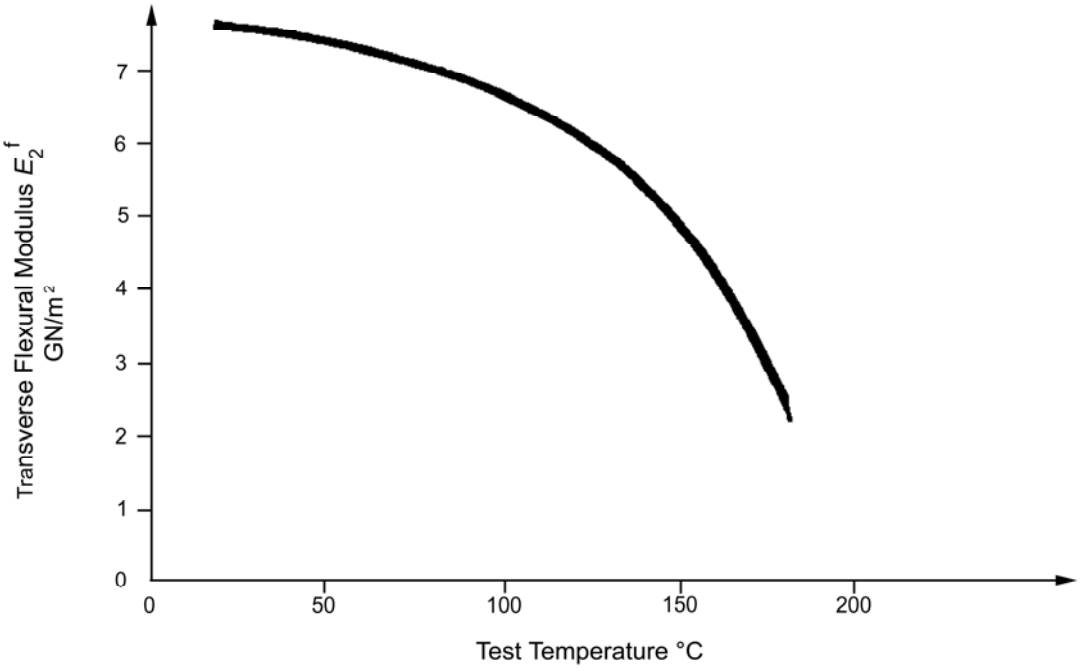
Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-3 - Longitudinal (0°) flexural modulus



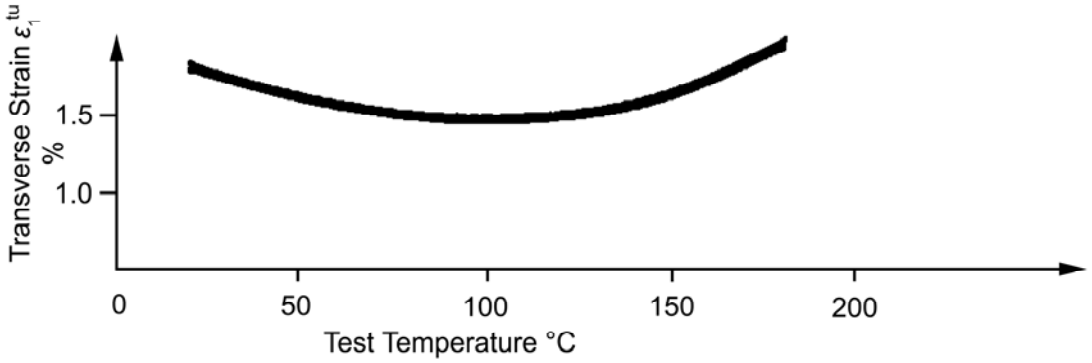
Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-4 - Ultimate transverse (90°) flexural strength



Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-5 - Transverse flexural modulus



Material: Fibredux 914 C (T300 or XAS fibre)

Figure 4.3-6 - Transverse strain to failure (ε_1^{tu})

4.3.3 Aramid/epoxy composite

Table 4.3-1 compares the mechanical properties of Kevlar 49 unidirectional epoxy composite at RT and 121°C. For laminates, guidance on the properties of various ply orientations at 121°C is included in the Du Pont Kevlar 49 manual, Ref.[4-3].

Table 4.3-1 - Unidirectional Kevlar 49/epoxy composite: Comparison of mechanical properties at RT and 121°C

Property		Test Temperature (°C)	
		RT	121°C
Tension	E_1^t (GPa)	78.5	64.8
	R_1^{tu} (MPa)	1379	1172
	E_2^t (GPa)	5.52	4.83
	R_2^{tu} (MPa)	29.6	20.0
Compression	E_1^c (GPa)	78.5	64.8
	R_1^{cu} (MPa)	276	221
	E_2^c (GPa)	5.52	4.83
	R_2^{cu} (MPa)	137.9	107
Poisson's Ratio	ν_{12}	0.34	0.34
Shear	G_{12} (GPa)	2.07	1.79
	R_{12}^{su} (MPa)	43.4	33.1
Material: Kevlar 49/epoxy (type not stated); fibre volume fraction (*Vf*): 60%; density: 1380 kg m^{-3}			

4.4 Effects of low and cryogenic temperatures

4.4.1 Material properties variation

Many space structures operate at low temperatures so the failure behaviour is most important under these conditions. Cryogenic temperatures, where T° <100° K, generate specific reactions in composite materials, including a change in:

- Strength,
- Stiffness, and
- Thermal characteristics.

4.4.1.1 Strength and stiffness

In general, moduli tend to increase with decreasing temperature, but the strength behaviour is subject to greater variability. The strength and modulus properties of angle ply laminates (0°/±60°) are similar in the longitudinal and transverse directions.

4.4.1.2 Thermal expansion

The thermal expansion of the unidirectional materials is small and constant with decreasing temperature along the fibre axis, but is much larger and decreases with falling temperature in the transverse direction. The thermal expansions for angle ply material are small and the same in the two orthogonal directions.

The main reasons for these phenomena are the different properties of resin and fibres. For example, the different coefficient of thermal expansion of the resins and the fibres generates tensile stresses in the matrix when the composite cools down. Reducing the temperature to cryogenic level induces strains within the resin which exceed its failure strain. This causes microcracking which affects the dimensional stability of the composite structure.

4.4.2 Modification to failure criteria

Normally the theoretical values for yield strengths are the ultimate values determined from classical analysis. This assumes that failure in any one ply to be indicative of failure for the complete laminate. To what extent this theory can also be used at low temperature has not yet been proved by experimental data.

4.4.3 Carbon/epoxy composites

4.4.3.1 Courtaulds A-S/Code 69: Calculated values

NOTE Courtaulds A-S fibre is no longer commercially available.

Table 4.4-1 lists the elastic constants calculated for unidirectional and angle ply (0°/±60°) laminates at low temperatures, Ref [4-4].

Table 4.4-1 – Low temperature: Elastic constants

	293K	173K	77K
CTE, ($x10^{-6}$ K^{-1})	2.93	3.82	3.1

Table 4.4-2 gives the calculated low temperature coefficient of thermal expansion, CTE, for angle ply (0°/±60°) laminates, Ref. [4-4].

Table 4.4-2 – Low temperature: CTE for angle ply (0°/±60°)

		Temperature		
		293K	173K	77K
Unidirectional Material (60 Vol %)	Q_{11} (GPa)	105.8	120.9	116.5
	Q_{22} (GPa)	9.01	10.07	6.03
	Q_{12} (GPa)	2.72	3.02	1.81
	Q_{66} (GPa)	3.6	4.6	5.6
	$Q_{16} = Q_{26}$ (GPa)	0	0	0
Angle-ply Material (0°/±60°)	A_{11} (GPa)	45.6	52.27	50.26
	A_{22} (GPa)	45.6	52.27	50.26
	A_{12} (GPa)	15.69	16.33	13.87
Elastic Moduli of Angle-ply Material (0°/±60°)	E_1 (GPa)	40.2	47.2	46.4
	E_2 (GPa)	40.2	47.2	46.4
	ν_{12}	0.34	0.31	0.28
	ν_{21}	0.34	0.31	0.28

4.4.3.2 Courtaulds A-S/Code 69: Experimental results

The measured effects of low temperatures on the properties of laminates are plotted as graphs for, Ref. [4-4]:

- Unidirectional composites:
  - Tensile modulus, [See:Figure 4.4-1].
  - Shear modulus, [See: Figure 4.4-2].
  - Tensile strength, [See: Figure 4.4-3].
  - Compressive strength, [See: Figure 4.4-4].
  - Shear strength, [See: Figure 4.4-5].
  - Angular deflection at failure, [See: Figure 4.4-6].
  - Change in length, [See: Figure 4.4-11].
  - CTE, [See: Figure 4.4-13].
- Angle ply (0°/±60°) composites:
  - Tensile modulus, [See: Figure 4.4-7].
  - Poisson's ratio, [See: Figure 4.4-8].
  - Tensile strength, [See: Figure 4.4-9].
  - Compressive strength, [See: Figure 4.4-10].
  - Change in length, [See: Figure 4.4-12].
  - CTE, [See: Figure 4.4-14].

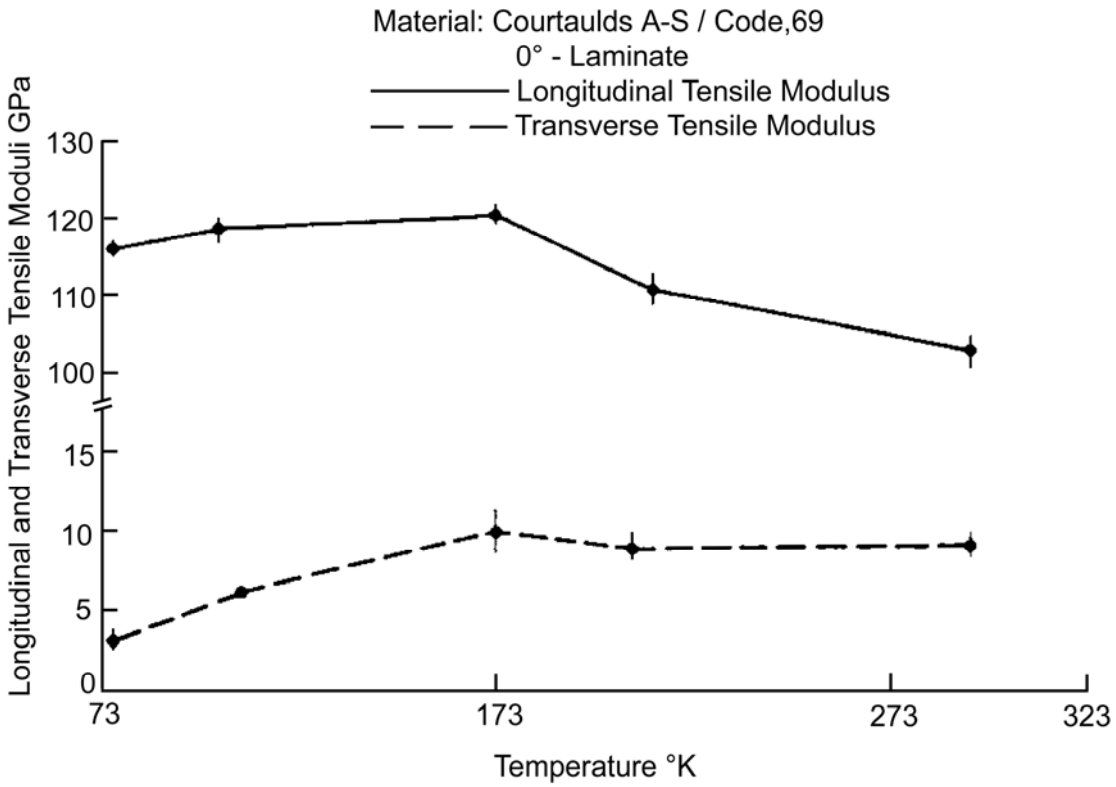


Figure 4.4-1 - Longitudinal and transverse tensile modulus unidirectional carbon fibre composite

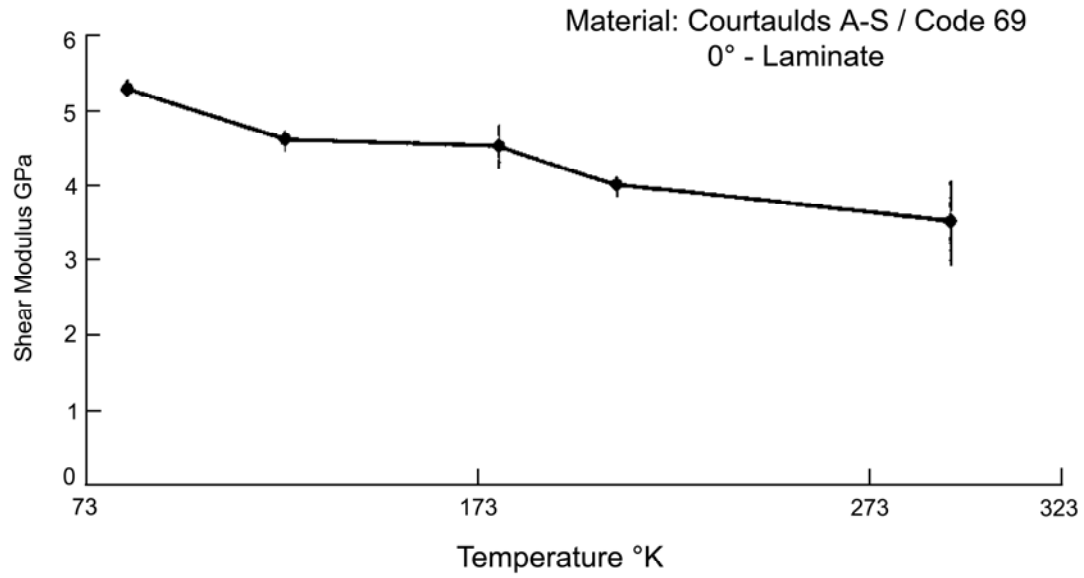


Figure 4.4-2 - Shear modulus: Unidirectional carbon fibre composite

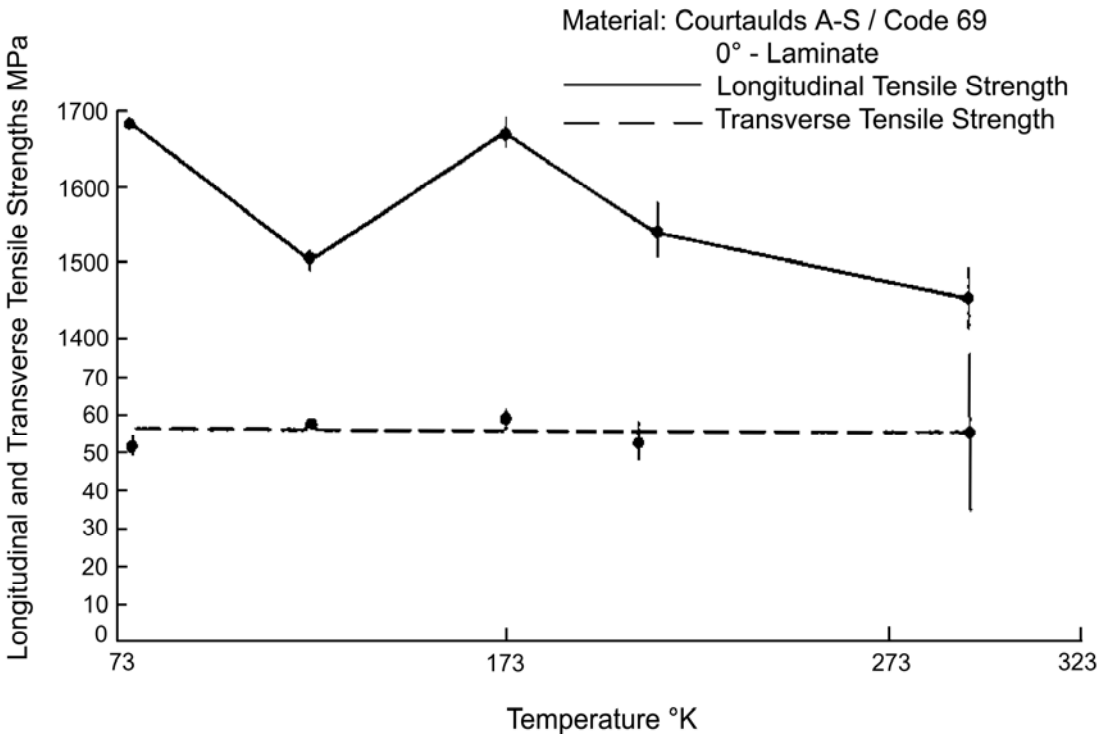


Figure 4.4-3 - Longitudinal and transverse tensile strength unidirectional carbon fibre composite

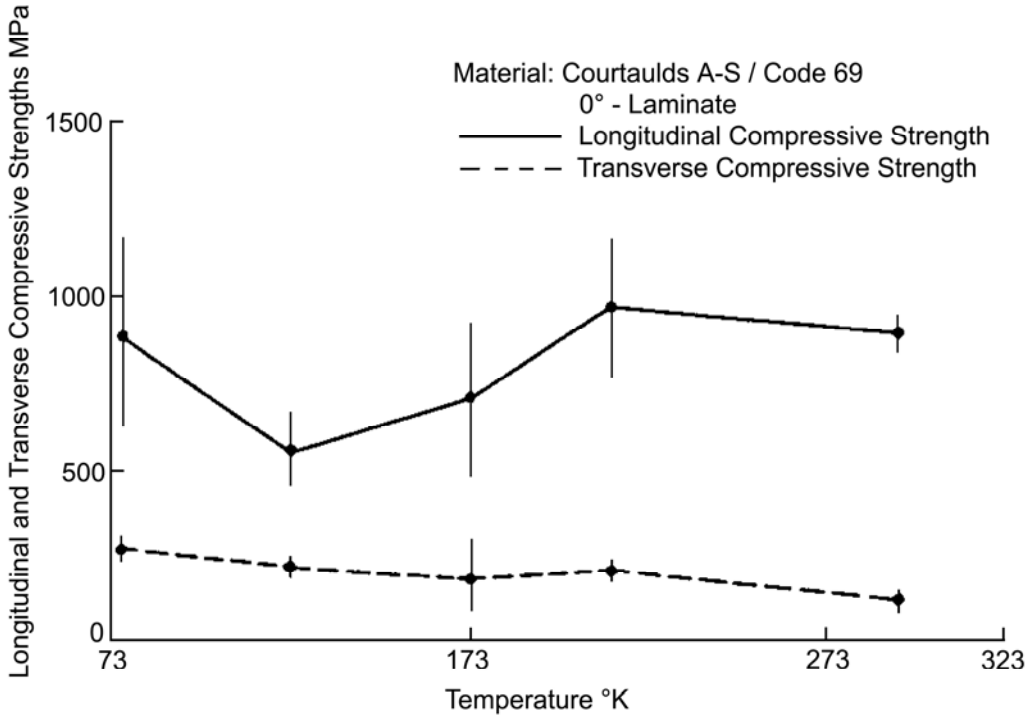


Figure 4.4-4 - Longitudinal and transverse compressive strength unidirectional carbon fibre composite

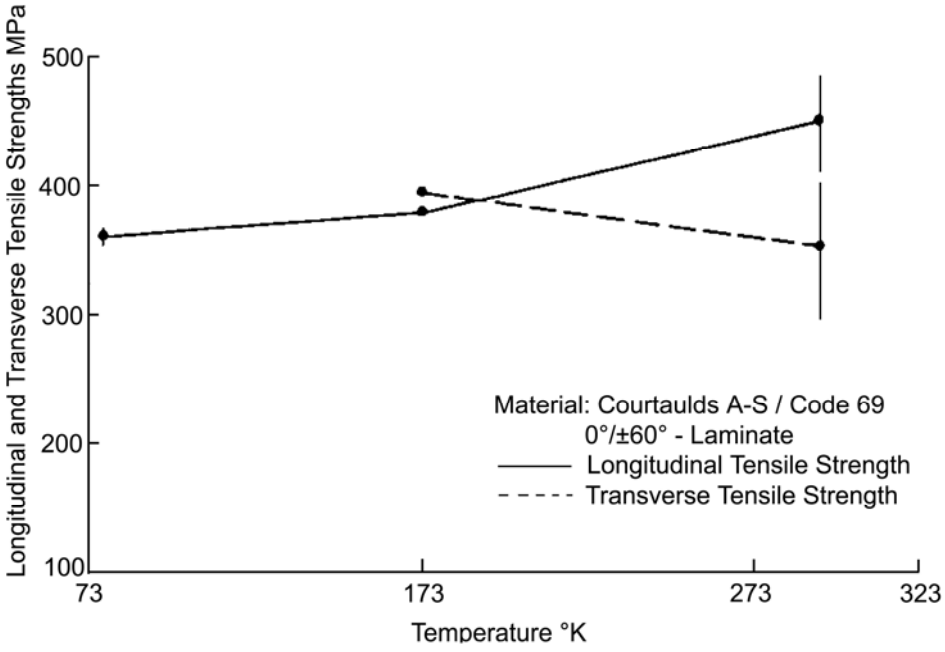


Figure 4.4-5 - Shear strength: Unidirectional carbon fibre composite

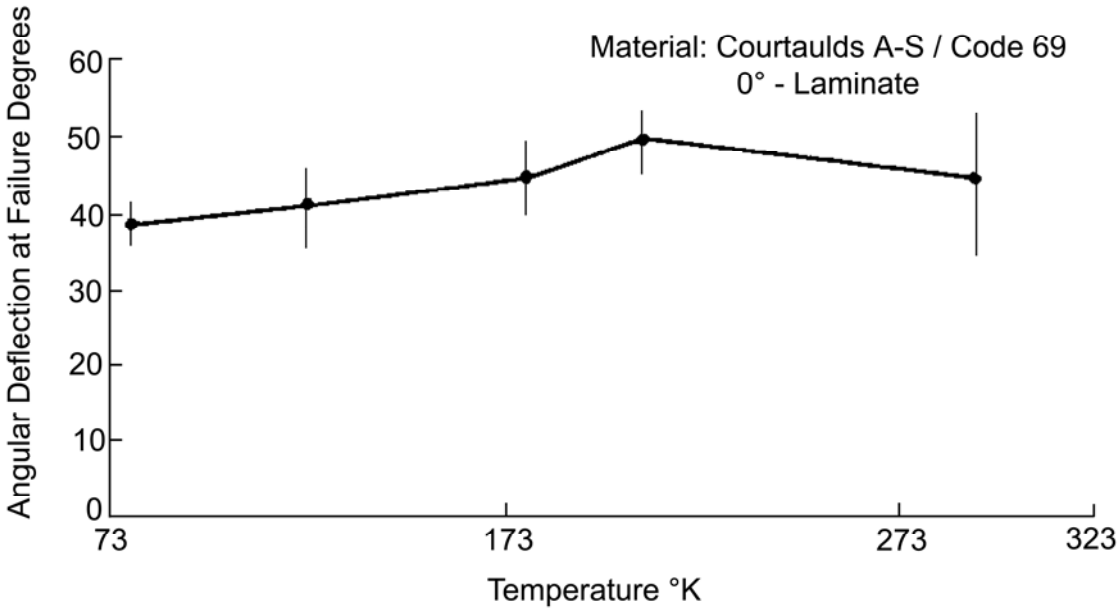


Figure 4.4-6 - Angular deflection at failure unidirectional carbon fibre composite

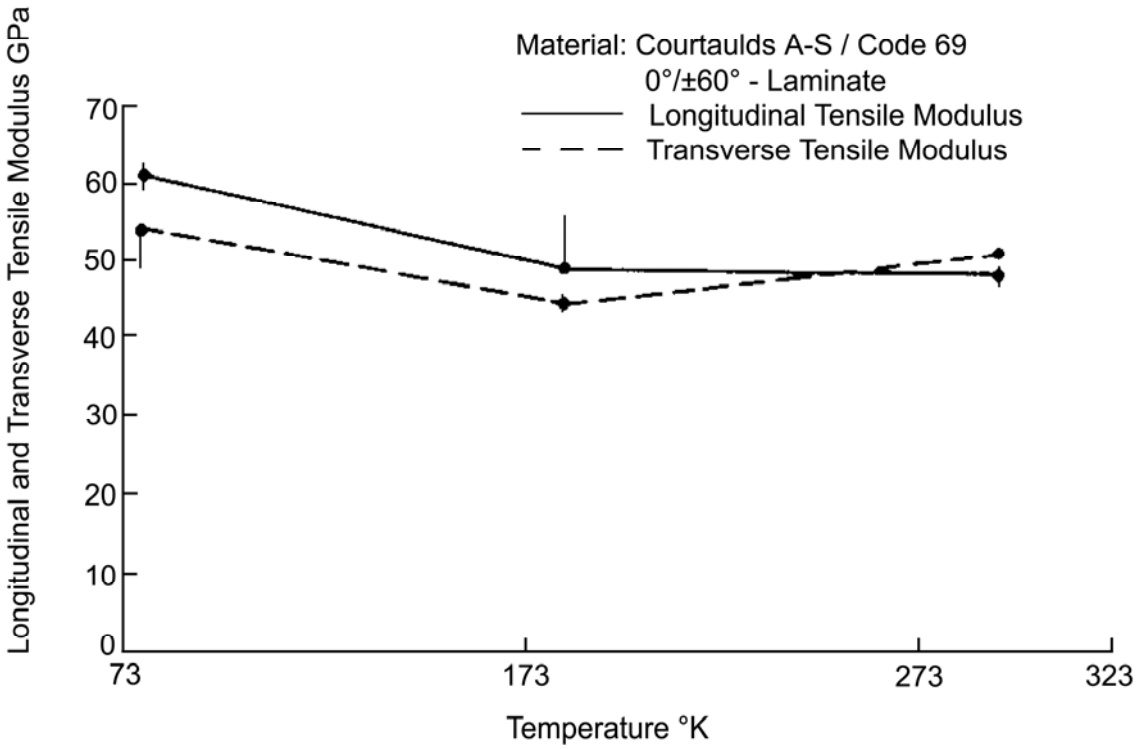


Figure 4.4-7 - Longitudinal and transverse tensile modulus angle ply carbon fibre composite

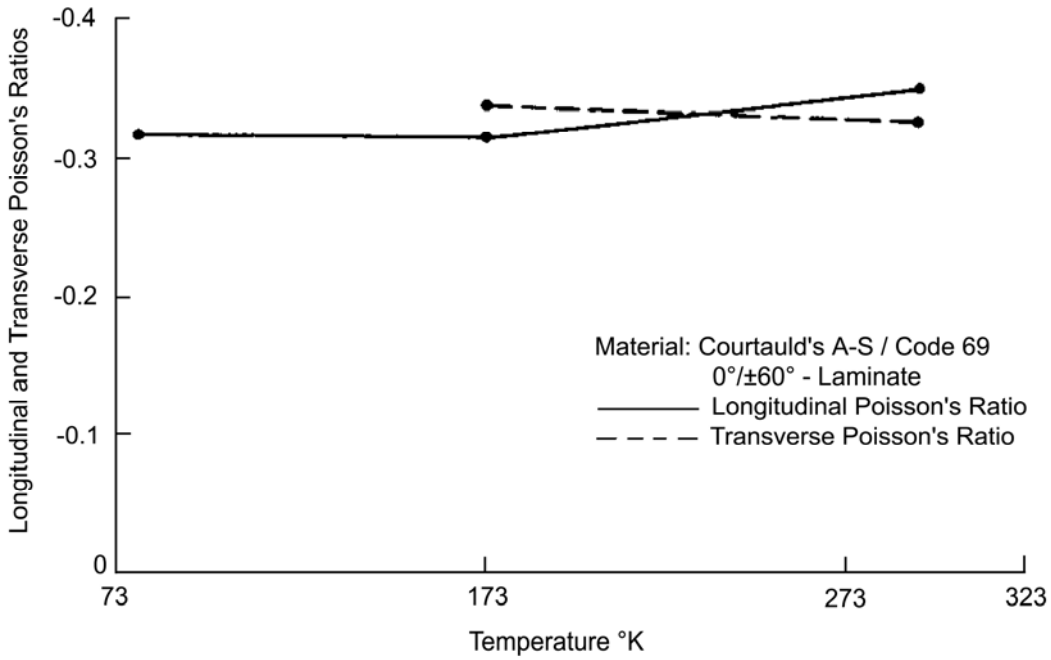


Figure 4.4-8 - Longitudinal and transverse Poisson's Ratio angle ply carbon fibre composite

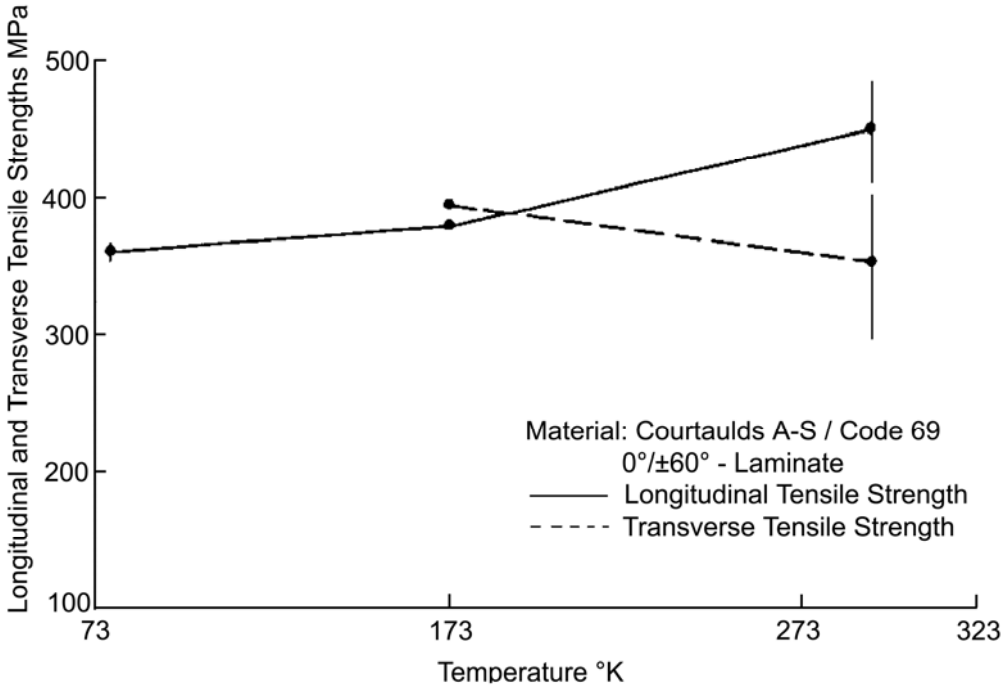


Figure 4.4-9 - Longitudinal and transverse tensile strength

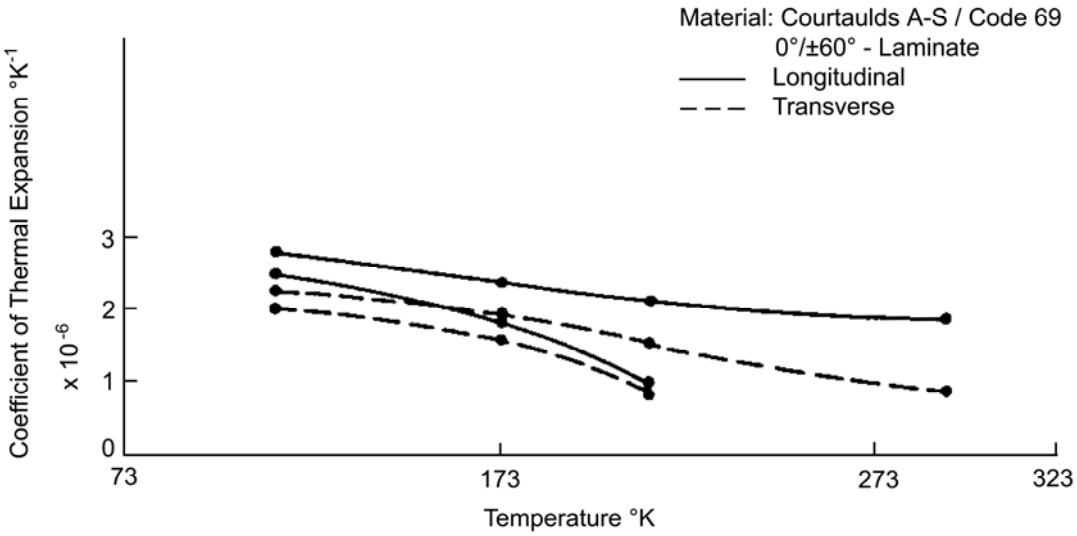


Figure 4.4-10 - Longitudinal and transverse compressive strength angle ply carbon fibre composite

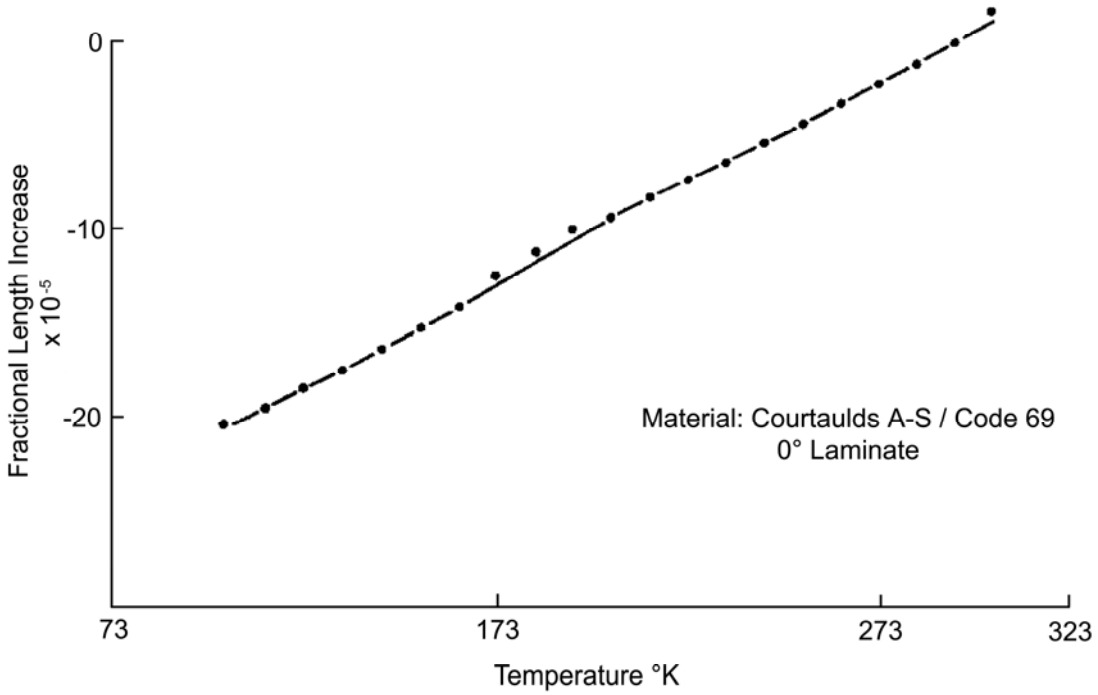


Figure 4.4-11 - Change in length as a function of temperature unidirectional carbon fibre composite longitudinal direction

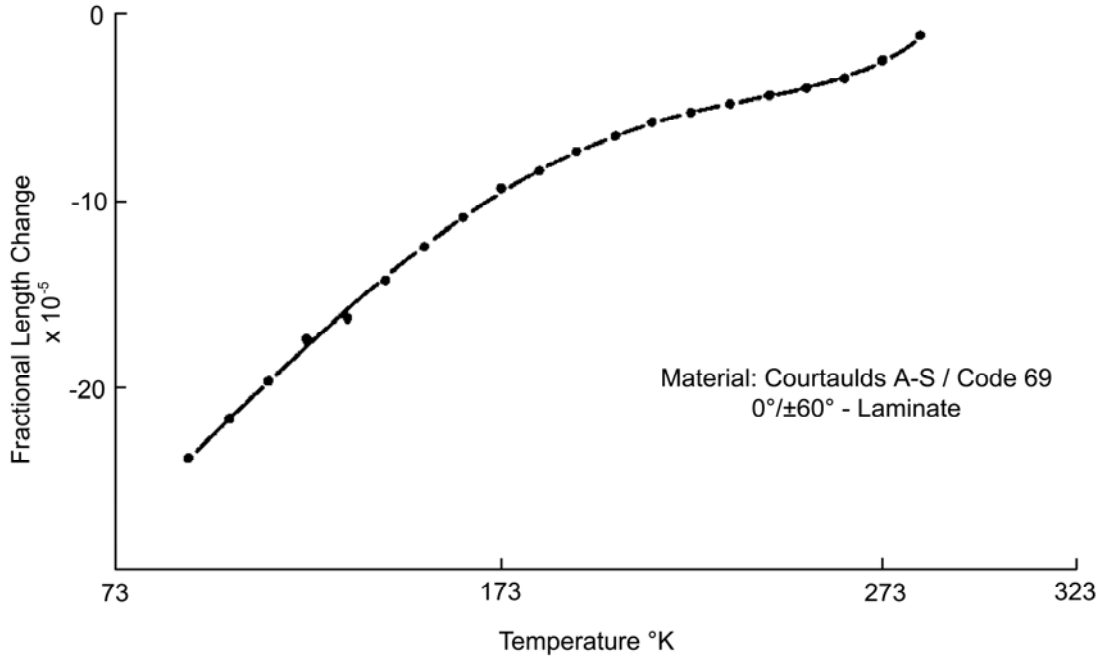


Figure 4.4-12 - Change in length as a function of temperature angle ply carbon fibre composite: Transverse direction

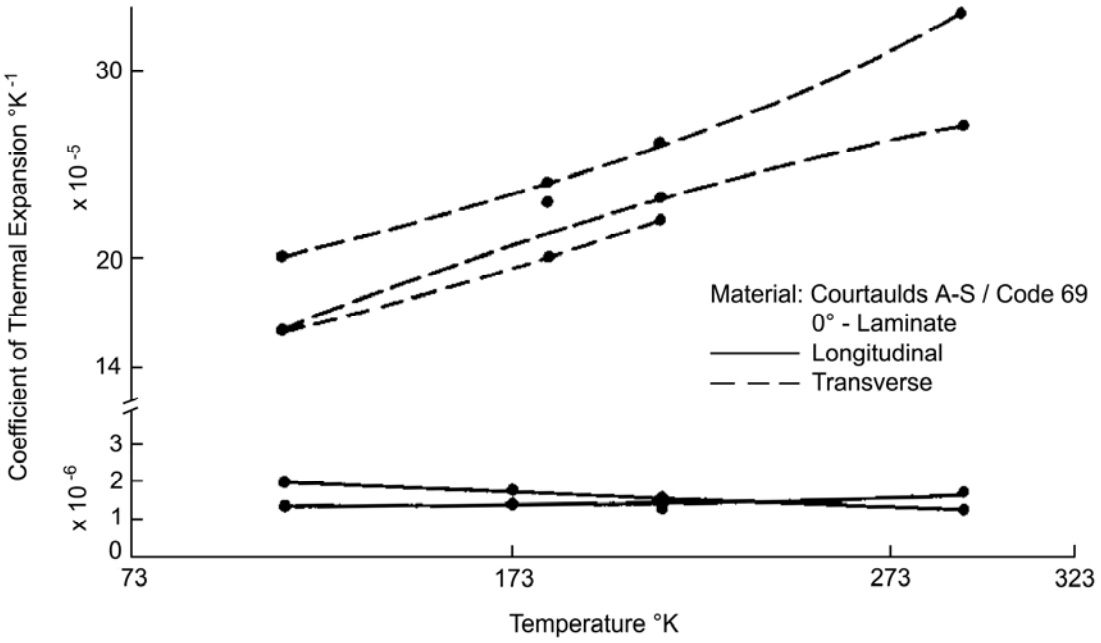


Figure 4.4-13 - Coefficient of thermal expansion unidirectional carbon fibre composite

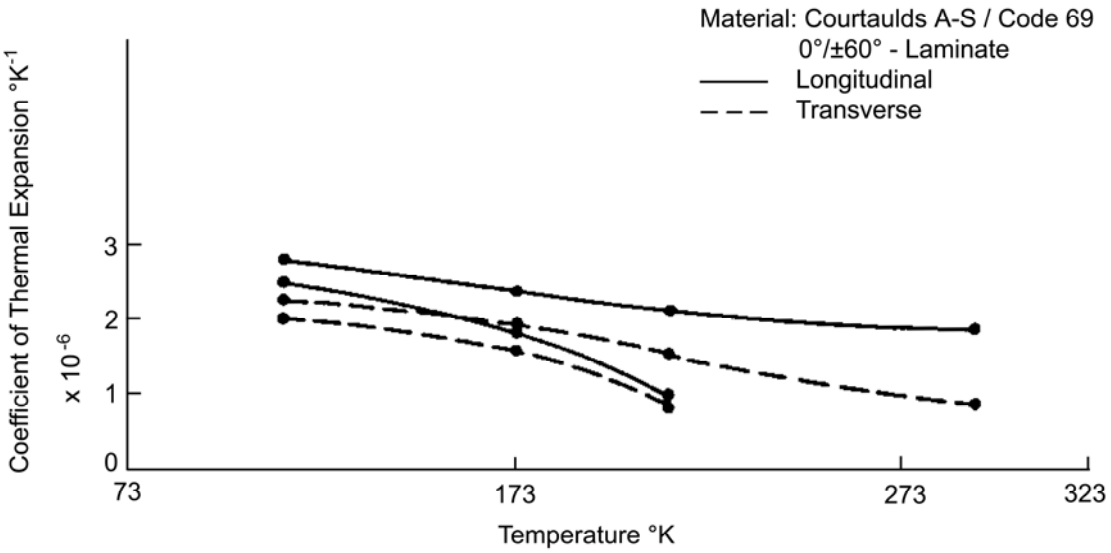


Figure 4.4-14 - Coefficient of thermal expansion angle ply carbon fibre composite

4.4.3.3 T300, M40/epoxy: Test results

Table 4.4-3 gives the properties at low temperatures for the commonly-used epoxy resin systems M10, CY221/HY979 and CY209/HT972, Ref. [4-5]

Table 4.4-3 gives the low temperature properties for commonly used carbon-fibre composites with either HT (T300) or HM (M40A) grade fibre, Ref. [4-5].

Table 4.4-3 - Common epoxy resins: Effect of low and cryogenic temperatures

Resin	M10		CY221/HY979		CY209/HT972
T (K)	77	293	77	293	293
Young's Modulus (GPa)	8.82	4.99	7.7	2.833	3.5
Poisson's Ratio	0.391	0.397	0.37	0.37	0.35

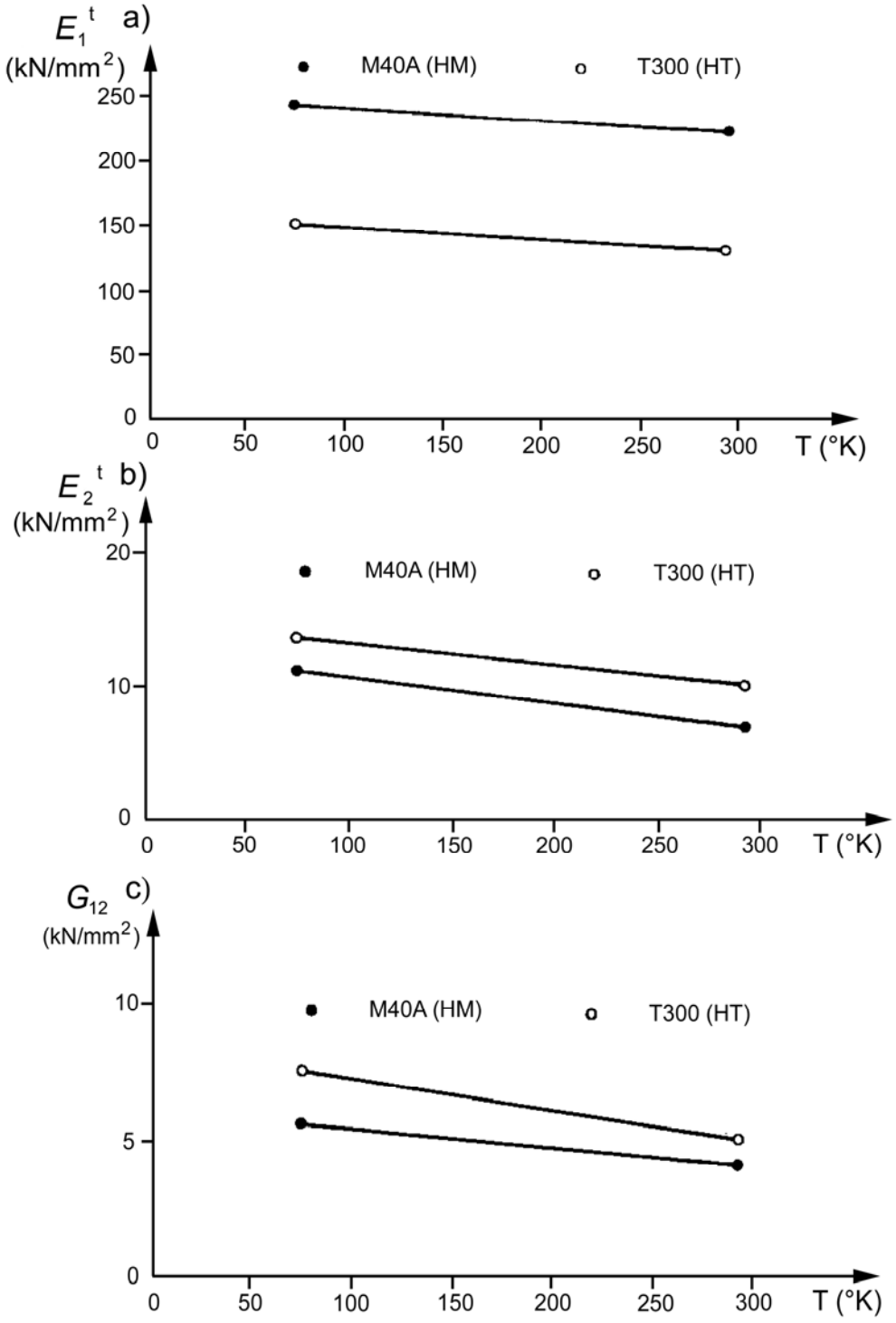
Table 4.4-4 - HT and HM carbon fibre composites: Effect of low and cryogenic temperatures

	Fibre			
60 Vol %	T300		M40A	
T (K)	77	293	77	293
E_1 (GPa)	150.4 (1)	137.54 (1)	240 (2)	225.5 (3)
E_2 (GPa)	13.15 (1)	10.219 (1)	11.45 (2)	7.5 (3)
G_{12} (GPa)	7.584 (1)	5.258 (1)	5.77 (2)	4.3 (3)
ν_{12}	0.295 (1)	0.274 (1)	0.26 (2)	0.26 (3)
R_1^{tu} (MPa)	2208 (2)	1685 (2)	1250 (2)	1422 (3)
R_2^{tu} (MPa)	56 (1)	36 (4)	42.2 (2)	30 (2)
R_{13}^{su} (MPa)	104 (2)	51.4 (2)	76 (2)	52 (2)
$\Delta\varepsilon_1$ (77 - 293K)	2.457×10^{-4}		1.76×10^{-5}	
$\Delta\varepsilon_2$ (77 - 293K)	6.04×10^{-3}		8.72×10^{-3}	

Key:
(1) - M10
(2) - CY221/HY979
(3) - CY209/HY972
(4) - 914C

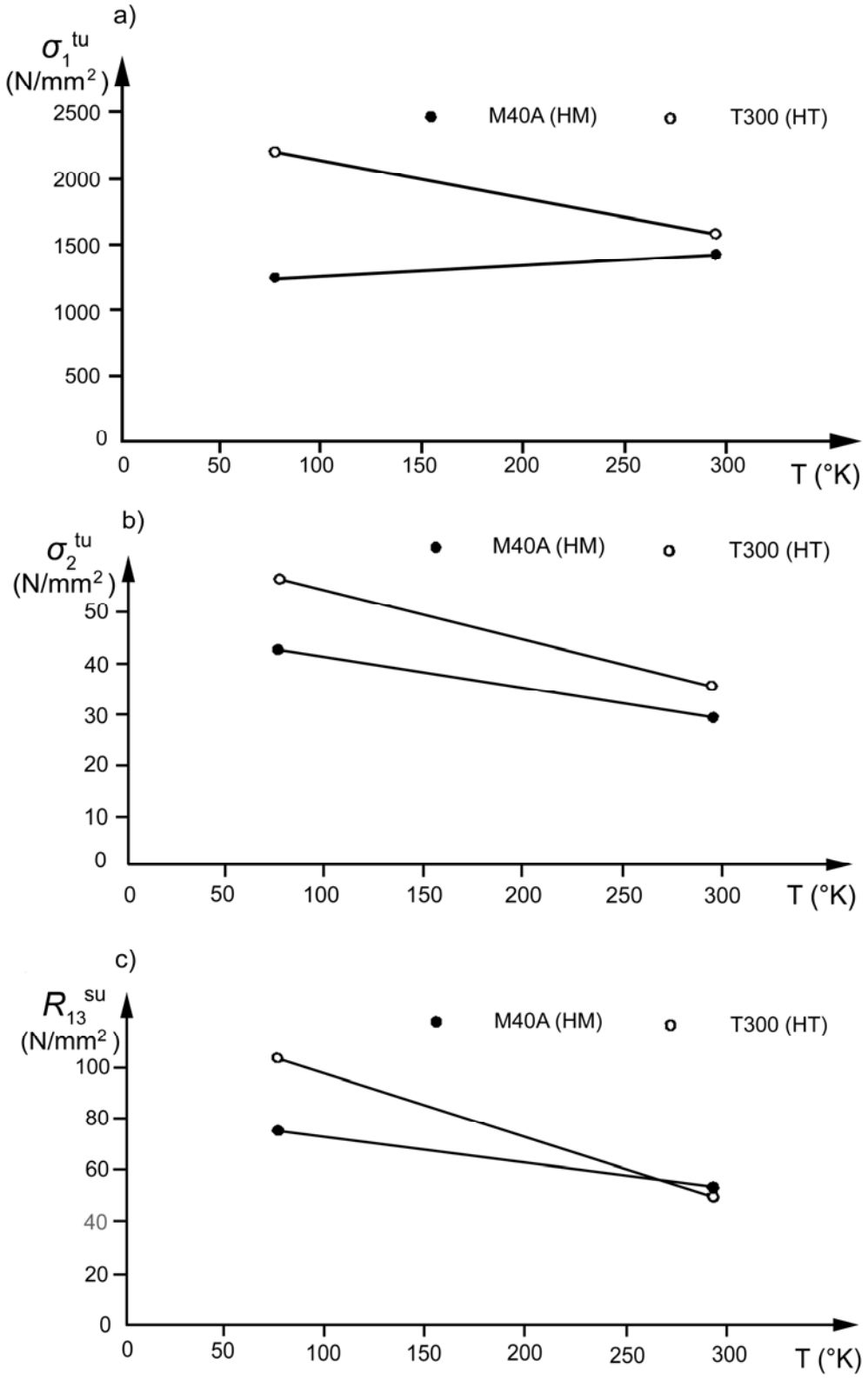
Figure 4.4-15 and Figure 4.4-16 are a graphical representation of the data given in

Table 4.4-4 and show the effect of low temperature on composite moduli and strength values, Ref. [4-5].



Based on Table 4.4-4

Figure 4.4-15 - The change of moduli of carbon fibre composites with temperature



Based on Table 4.4-4

Figure 4.4-16 - The change of strength of carbon fibre composites with temperature

4.4.3.4 XAS/Code 87: Test results

NOTE Courtaulds A-S fibre is no longer commercially available.

Selected material properties of Code 87/XAS laminates were measured at temperature of 300° K, 77° K and 4.2° K (27°C, -196°C, -268.8°C).

Laminate configurations for bending tests were:

- UD - Unidirectional (0°)16
- MD - Multidirectional (90°/±45°/0°/±45°/90°)

Figure 4.4-17 shows that for unidirectional laminates the flexural modulus increased by 13% at temperatures below 300° K and the flexural strength increased by 18%, Ref. [4-7].

For multidirectional laminates the flexural modulus was 7% greater at 4.2° K, but with a flexural strength loss of 8%, Ref. [4-7].

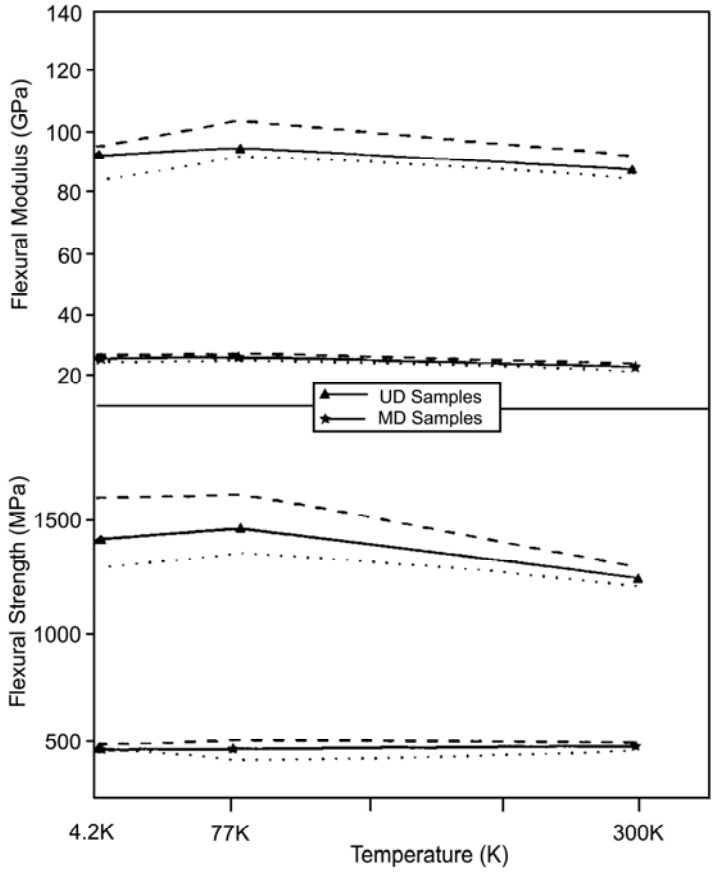


Figure 4.4-17 - Flexural modulus and flexural strength

Figure 4.4-18 shows that tensile test results exhibited a similar increase in modulus at cryogenic temperatures and a small loss in strength, Ref. [4-7].

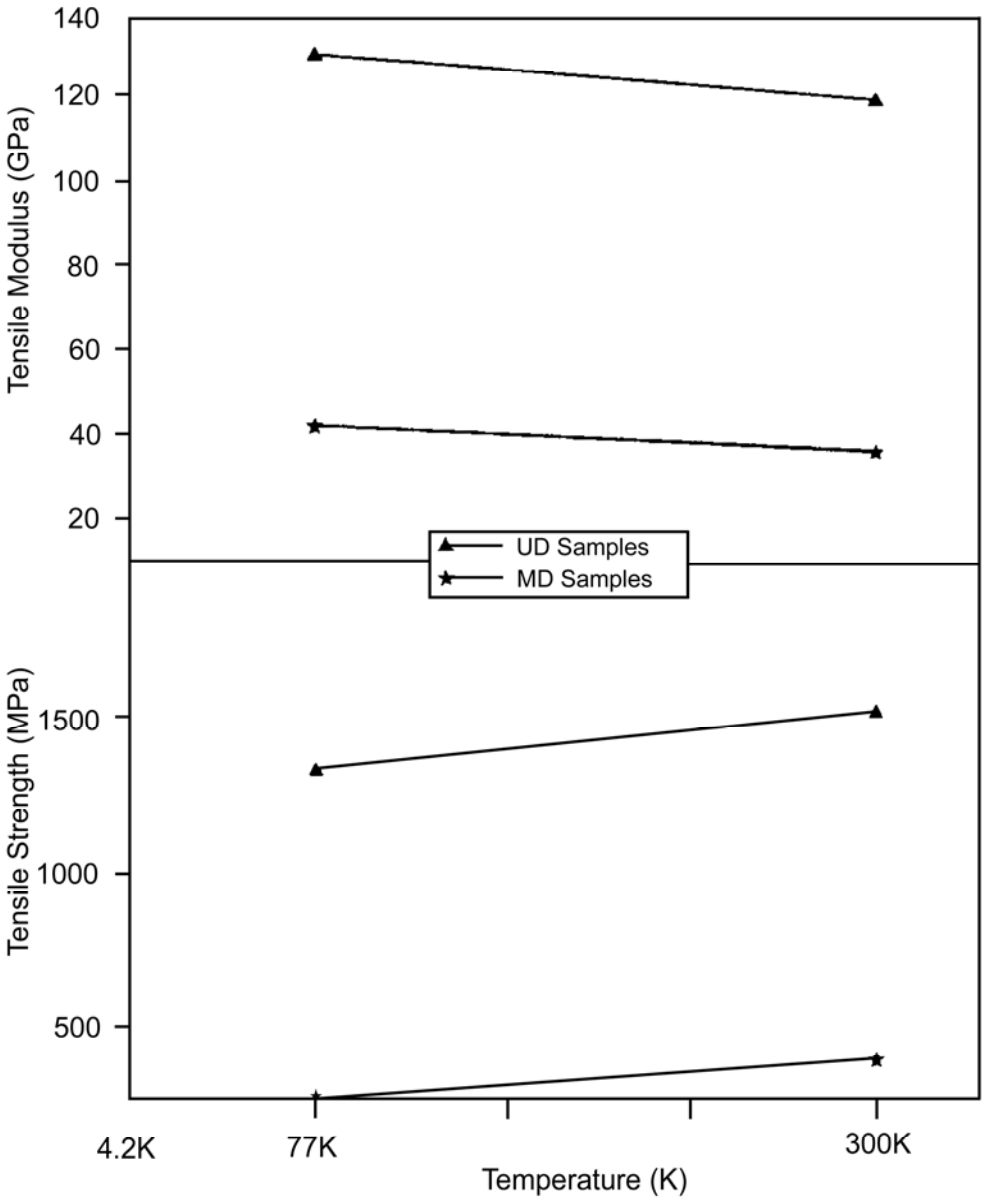


Figure 4.4-18 - Tensile modulus and tensile strength

4.4.3.5 Hercules AS/epoxy: Test results

Table 4.4-5 outlines the AS/Resin 2 laminate configurations used for low temperature testing, Ref. [4-6].

Table 4.4-6 gives average mechanical properties for uniaxial laminates, whereas the equivalent properties for cross-ply 45° laminates are stated in Table 4.4-7, Ref. [4-6].

Table 4.4-5 - Carbon/epoxy materials tested at low temperatures: (AS/Resin 2)

Composite	Lay-up	Number of Plies	Average Ply Thickness (mm)	Specific Gravity at 295 K	Fibre Volume Fraction[1, 2]	Calculated Void Content (%) [1]
AS Graphite Resin 2 [3]	Uniaxial	6	0.185	1.56	0.661	<1
	Uniaxial	15	0.193	1.56	0.682	<1
	±45	10	0.195	1.54	0.618	<1
Key:	1 - Measured by supplier. 2 - Resin removed from graphite by acid digestion. 3 - Resin 2: Epoxy (Epon 828/DSA/Empol 1040/BDMA)					

Table 4.4-6 – Low temperature mechanical properties: AS carbon fibre/Resin 2 (uniaxial laminates)

T	$\sigma_1^{tu}/\sigma_2^{tu}$	E_1^t/E_2^t	ν_{12}/ν_{21}	$\varepsilon_1^{tu}/\varepsilon_2^{tu}$	$\sigma_1^{cu}/\sigma_2^{cu}$	$\varepsilon_1^{cu}/\varepsilon_2^{cu}$	G_{12}
295	1320/12.8	118/7.8	0.324/0.022	0.9/0.2	540/89	0.4/0.7	4.14
76	1230/2.4	101/10.9	0.280/0.030	1.0/0.02	793/136	0.8/1.0	4.50
4	1310/3.1	117/11.3	0.298/0.029	0.9/0.03	690/131	0.7/0.8	5.32
Key:	Strength units: MPa Strain units: % Average values for uniaxial laminates				Moduli units: GPa Temperature units: K		

Table 4.4-7 - Low temperature mechanical properties: AS carbon fibre/Resin 2 (45° cross ply laminates)

T	σ_x^{tu}	E_x^t	ν_{xy}
295	700	15.6	0.706
76	440	17.3	0.800
4	480	18.0	0.690
Notes:	Stressed symmetrically to 45° reinforcement. Strength units: MPa Moduli units: GPa Average values for 45° cross-ply laminates.		

The measured effects of low temperatures on the properties of laminates are plotted as graphs for, Ref. [4-6]:

- Tensile strength, [See:Figure 4.4-19].
- Tensile strain, [See: Figure 4.4-20].
- Compressive strength, [See: Figure 4.4-21].
- Compressive strain, [See: Figure 4.4-22].
- Young's modulus (tensile), [See:Figure 4.4-23]
- In-plane shear modulus, [See: Figure 4.4-24].

- Poisson's ratio, [See: Figure 4.4-25].
- Thermal expansion, [See: Figure 4.4-26].
- Shear stress-strain, [See: Figure 4.4-27].

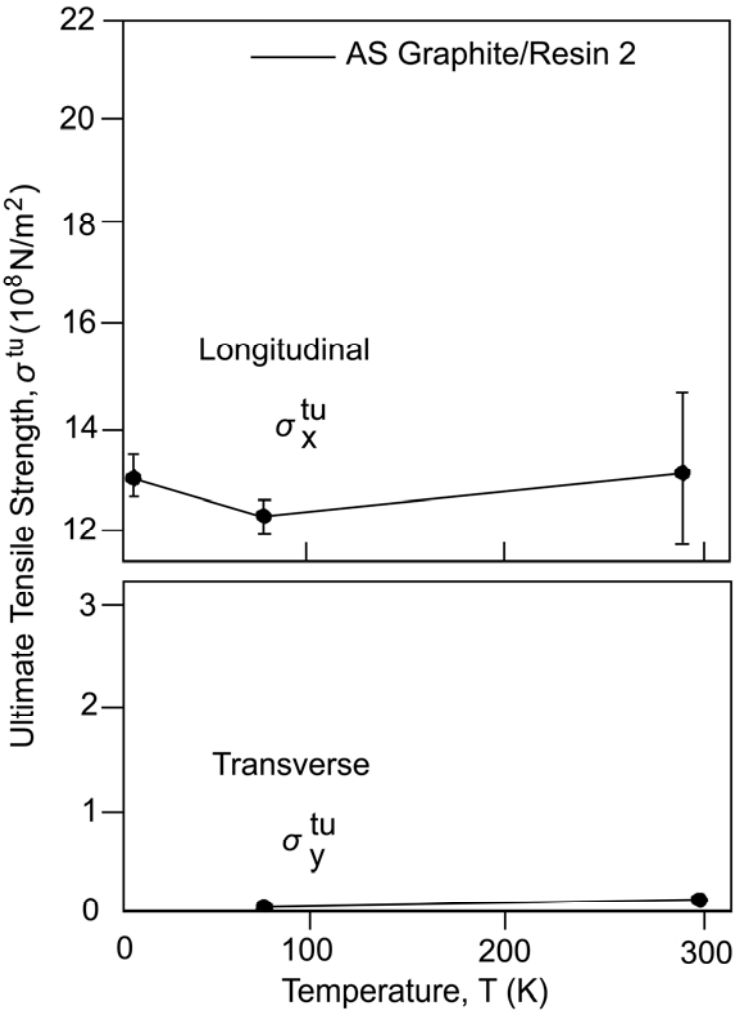


Figure 4.4-19 - Ultimate tensile strength

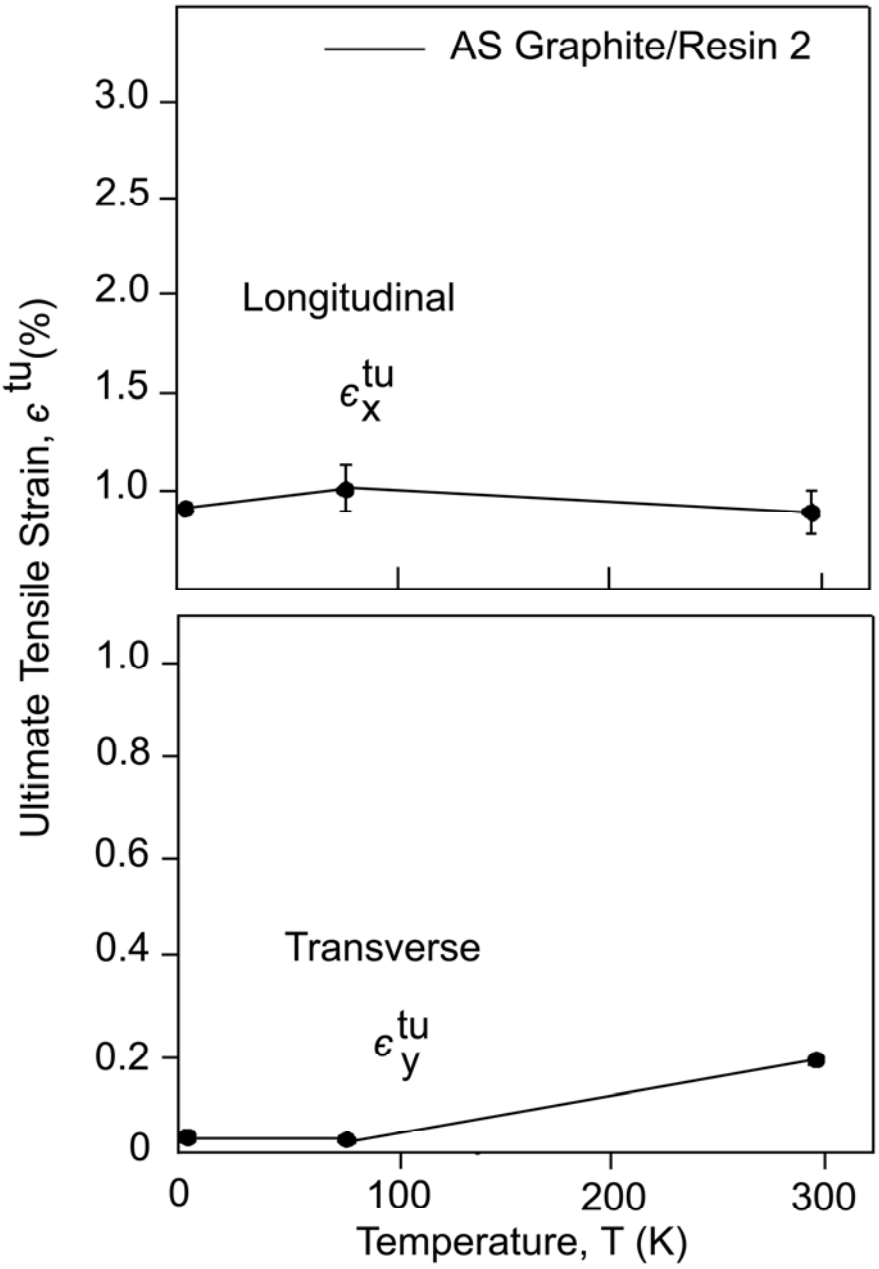


Figure 4.4-20 - Ultimate tensile strain

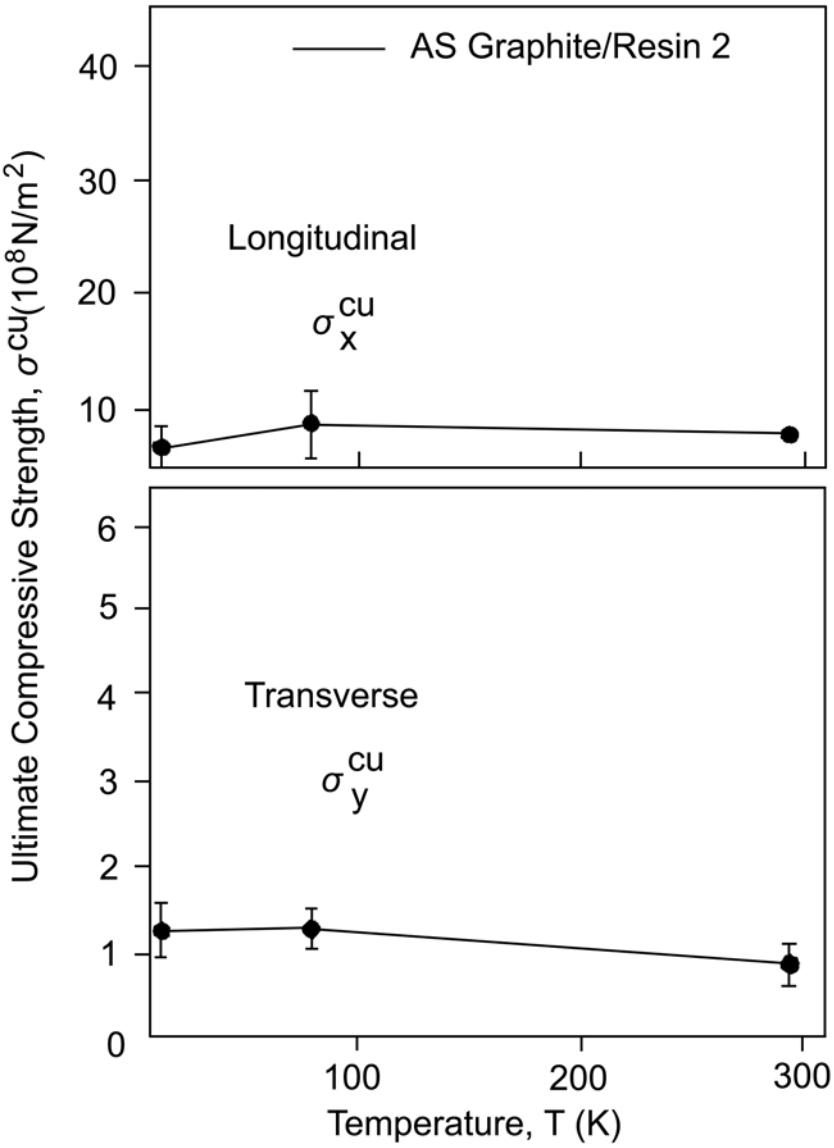


Figure 4.4-21 - Ultimate compressive strength

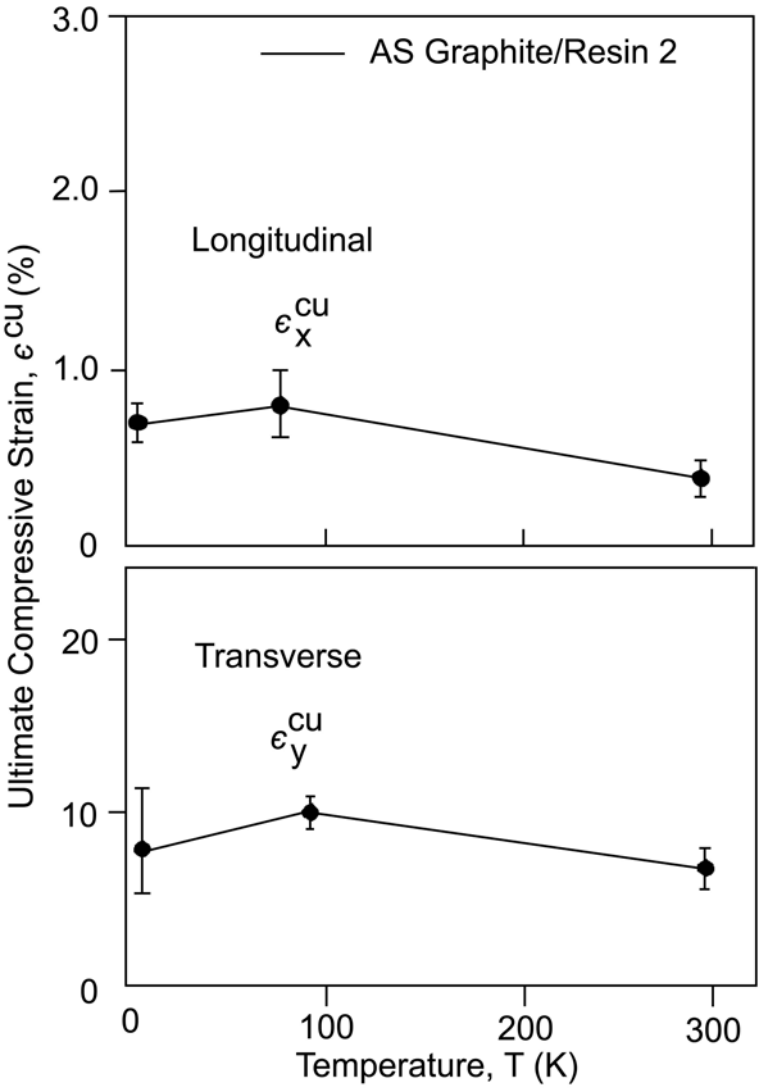


Figure 4.4-22 - Ultimate compressive strain

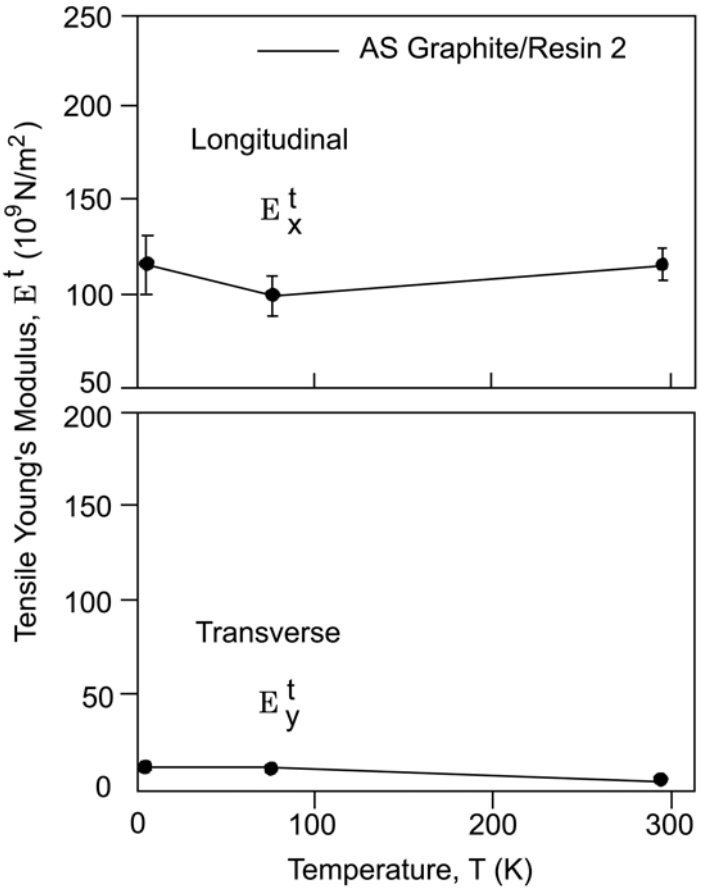


Figure 4.4-23 - Tensile Young's modulus

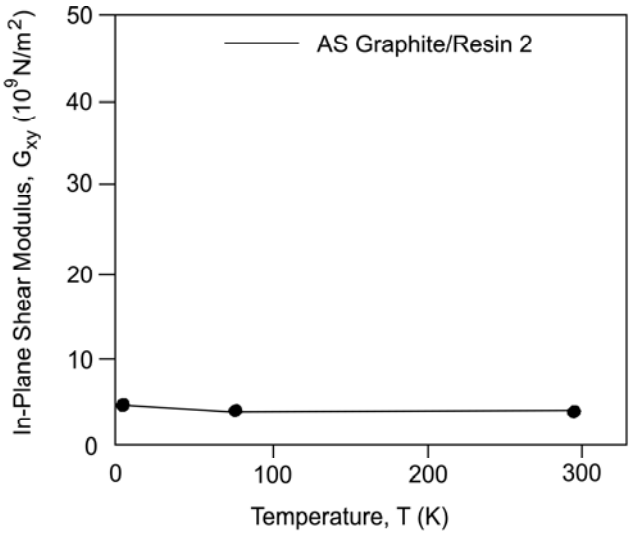


Figure 4.4-24 - In plane shear modulus

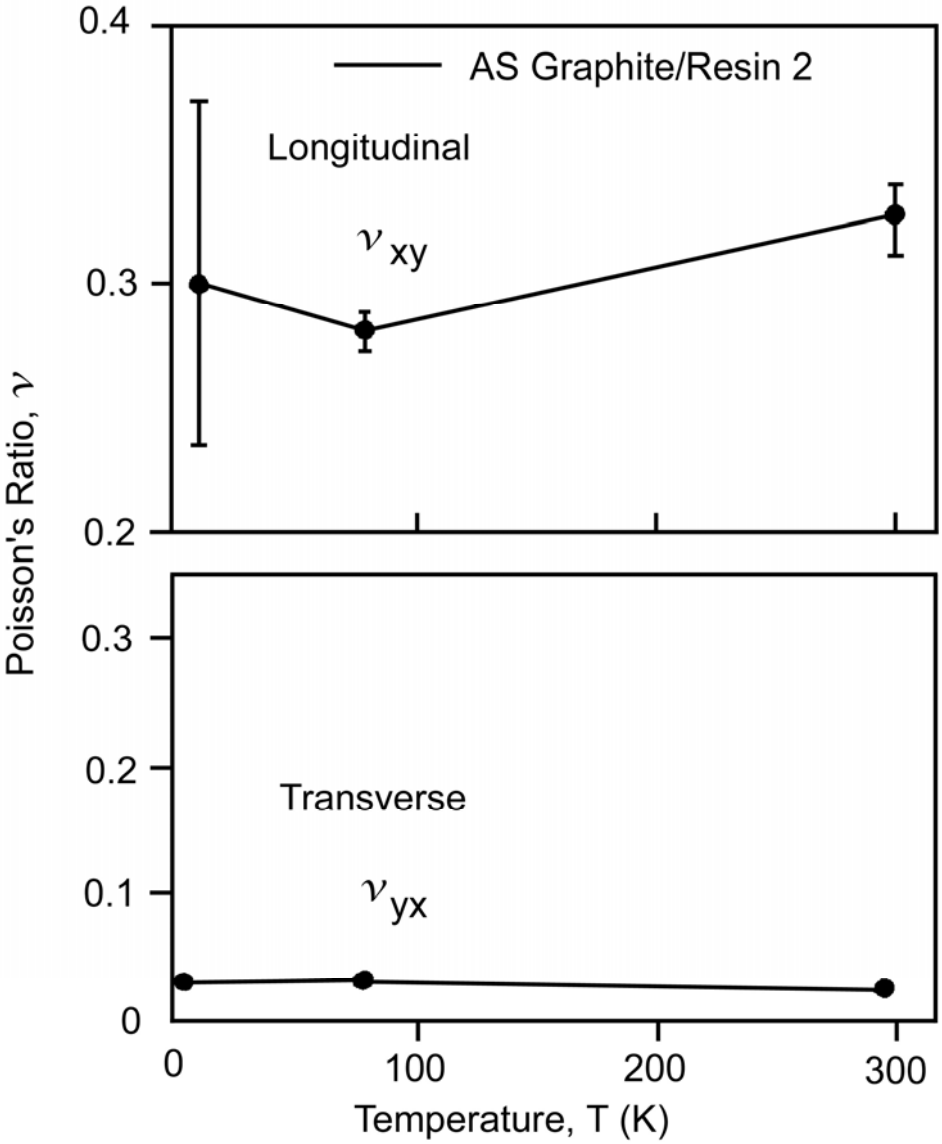


Figure 4.4-25 - Poisson's ratio

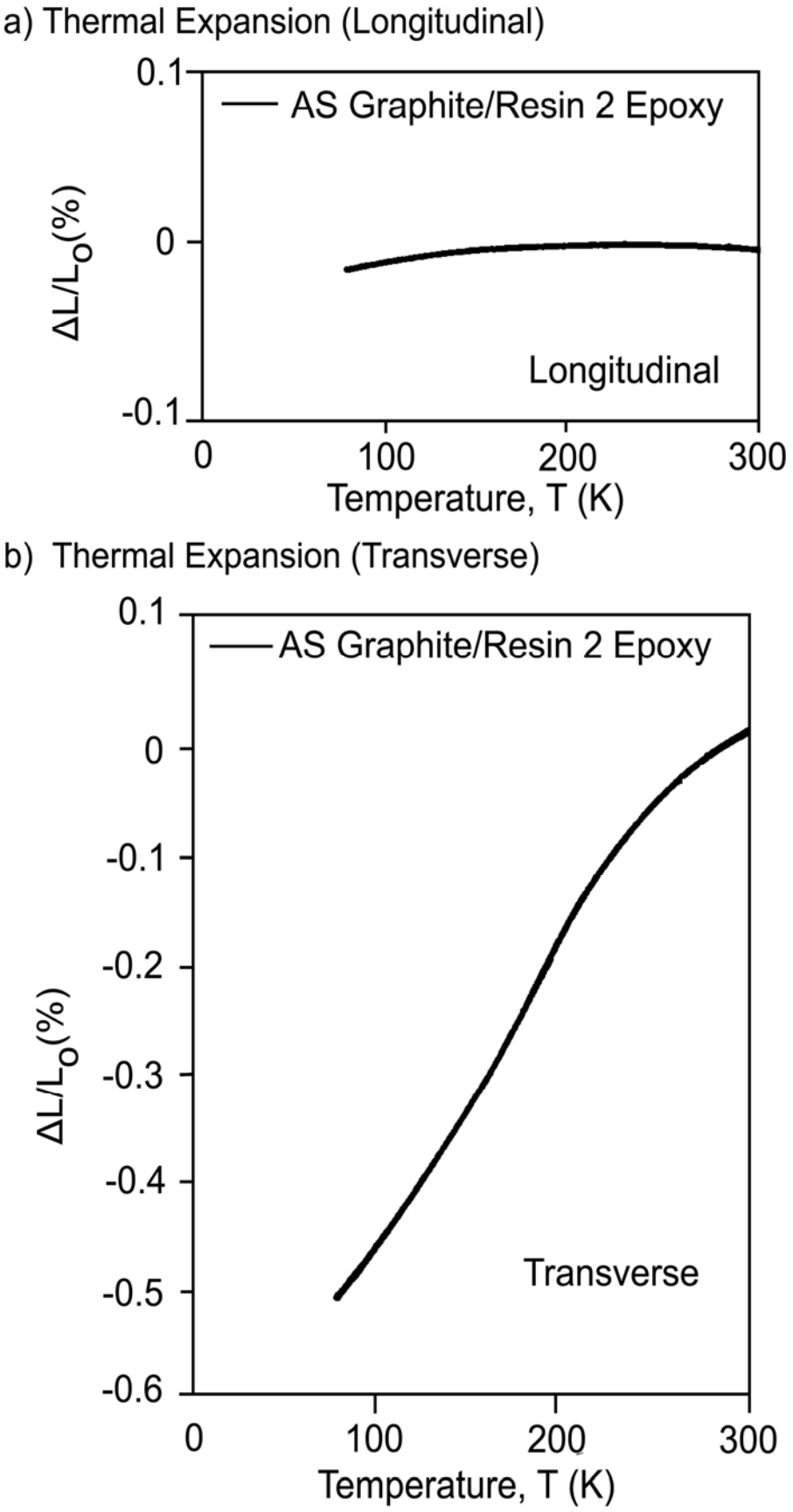


Figure 4.4-26 - Longitudinal and transverse thermal expansion

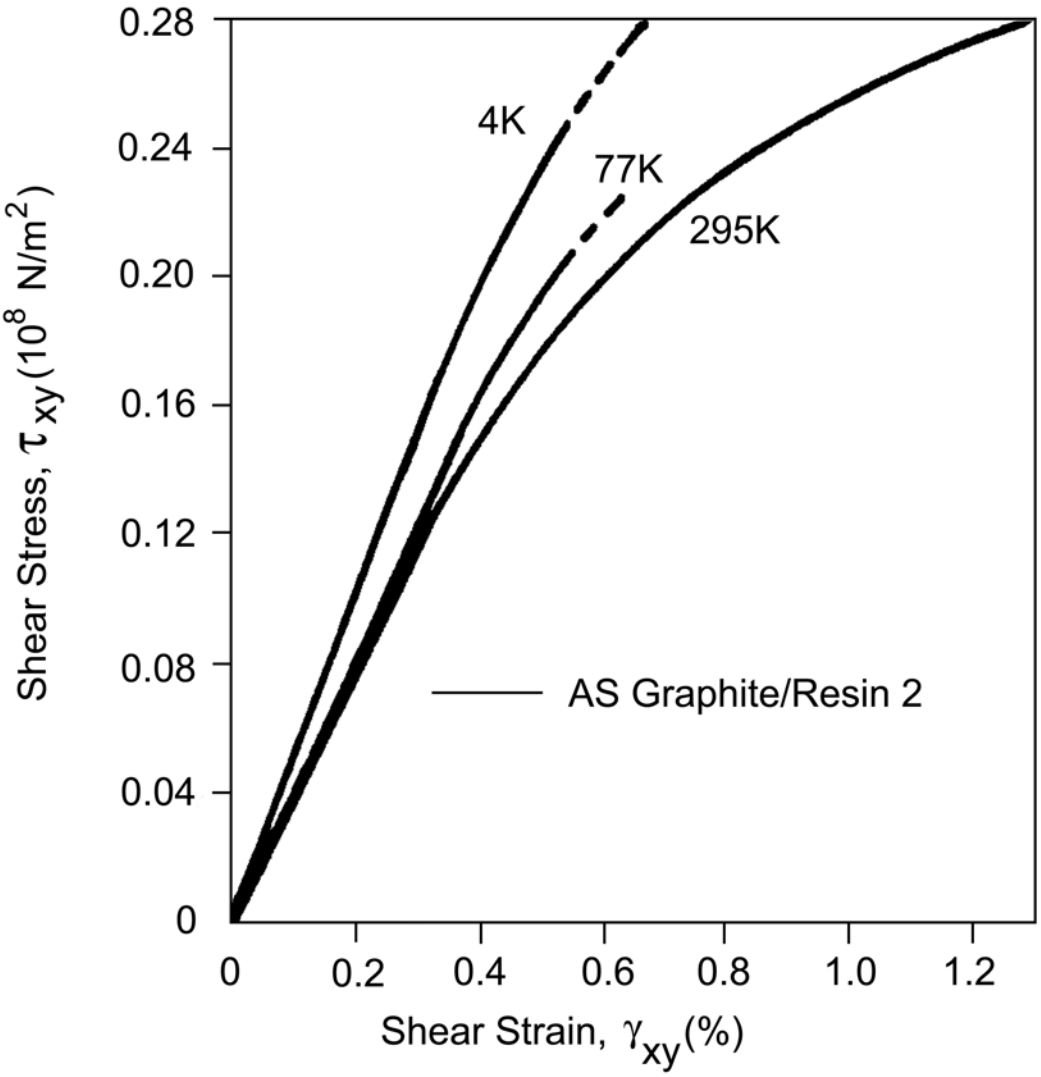


Figure 4.4-27 - Shear stress - strain

4.4.4 Aramid/epoxy composites

Table 4.4-8 provides typical mechanical properties of aramid composites at low and cryogenic temperatures, Ref. [4-8].

A demonstrated low temperature use for aramid fibres is that of the overwrap for metal liners of propellant tanks and pressure vessels, Ref. [4-8]. However, the new generation carbon fibres are becoming attractive for this application, if their thermal and electrical conductivity properties are acceptable. One example is superconductor and magnetic energy storage systems, where electrical and thermal insulating materials are needed, Ref. [4-9].

Table 4.4-8 - Typical mechanical properties of aramid composites at low/cryogenic temperatures

Material (fibre/resin)	Temp (K)	Mechanical Properties			Comments
		Longitudinal Strength (MPa)	Modulus (GPa)	Strain (%)	
Kevlar 49/934	295	1132	71.4	1.58	Tensile: Longitudinal (0°) 6 ply
	76	1154	99.4	1.07	
	4	1142	99.4	1.13	
	295	4.17	2.51	0.16	Tensile: Transverse (90°) 15 ply
	76	3.63	3.59	0.12	
	4	5.56	4.56	0.14	
	295	68.7	6.89	1.52	Tensile: Crossply (±45°) 10 ply
	76	59.1	8.72	1.01	
	4	62.1	9.83	0.85	
	295	225	-	-	Compression: Longitudinal (0°) 30 ply
	76	290	-	-	
	4	366	-	-	
	295	84.4	-	-	Compression: Transverse (90°) 30 ply
	76	109	-	-	
	4	117.2	-	-	
	295	34.3	1.90	-	In-Plane Shear: 10 ply
	76	29.6	2.56	-	
	4	31.2	2.67	-	
Kevlar 49/F155	295	460	-	3.5	Tensile: 4mm thick laminate, 12 ply K_{crit} (MPa√m): 27 @ 296K, 23 @ 77K.
	76	360	-	1	
	4	340	-	1	
Fibre Volume Fraction: Not stated					

4.4.5 Glass/epoxy composites

4.4.5.1 S glass/epoxy: Test results

Table 4.4-9 outlines the S-901 Glass/Resin 2 laminate configurations used for low temperature testing, Ref. [4-6].

Table 4.4-10 gives average mechanical properties for uniaxial laminates, whereas the equivalent properties for cross-ply 45° laminates are stated in Table 4.4-11, Ref. [4-6].

Table 4.4-9 - S901 Glass: Resin 2 composite tested at low/cryogenic temperatures

Lay-up[3]	Number of Plies	Average Ply Thickness (mm)	Specific Gravity at 295 K	Fibre Volume Fraction [1,2]	Calculated Void Content (%)[1]
Uniaxial	6	0.203	2.01	0.659	<1
Uniaxial	15	0.203	-	0.639	<1
±45°	10	0.196	2.03	0.689	<1

Key:
1 - Measured by supplier.
2 - Resin removed by a burn out technique.
3 - Resin 2: Epoxy (Epon 828/DSA/Empol 1040/BDMA).

Table 4.4-10 - Mechanical properties of S901 Glass: Resin 2 composite (average of uniaxial laminates)

T	$\sigma_1^{tu}/\sigma_2^{tu}$	E_1^t/E_2^t	ν_{12}/ν_{21}	$\varepsilon_1^{tu}/\varepsilon_2^{tu}$	$\sigma_1^{cu}/\sigma_2^{cu}$	$\varepsilon_1^{cu}/\varepsilon_2^{cu}$	G_{12}
295	1360/47	57/12.4	0.208/0.058	2.86/0.6	503/98	1.1/3.1	6.19
76	1960/94	58/21.2	0.272/0.098	3.30/0.4	1360/277	2.4/0.9	11.00
4	1940/78	60/22.0	0.289/0.106	3.00/0.4	1420/283	2.0/0.9	12.90

Key: Strength: MPa Moduli: GPa
Strain: % Temperature: K

Table 4.4-11 - Mechanical properties of S901 Glass: Resin 2 composite (average of 45° cross ply laminates)

T	σ_x^{tu}	E_x^t	ν_{xy}
295	139	19.8	0.544
76	238	31.7	0.378
4	234	34.5	0.387

Key: Strength: MPa Moduli: GPa Temperature: K
Stressed symmetrically to 45° reinforcement.

The measured effects of low temperatures on the properties of laminates are plotted as graphs for, Ref. [4-6]:

- Tensile strength, [See: Figure 4.4-28].
- Tensile strain, [See: Figure 4.4-29].
- Compressive strength, [See: Figure 4.4-30].
- Compressive strain, [See: Figure 4.4-31].

- Young's modulus (tensile), [See: Figure 4.4-32].
- In-plane shear modulus, [See: Figure 4.4-33].
- Poisson's ratio, [See: Figure 4.4-34].
- Thermal expansion, [See: Figure 4.4-35].
- Shear stress-strain, [See: Figure 4.4-36].

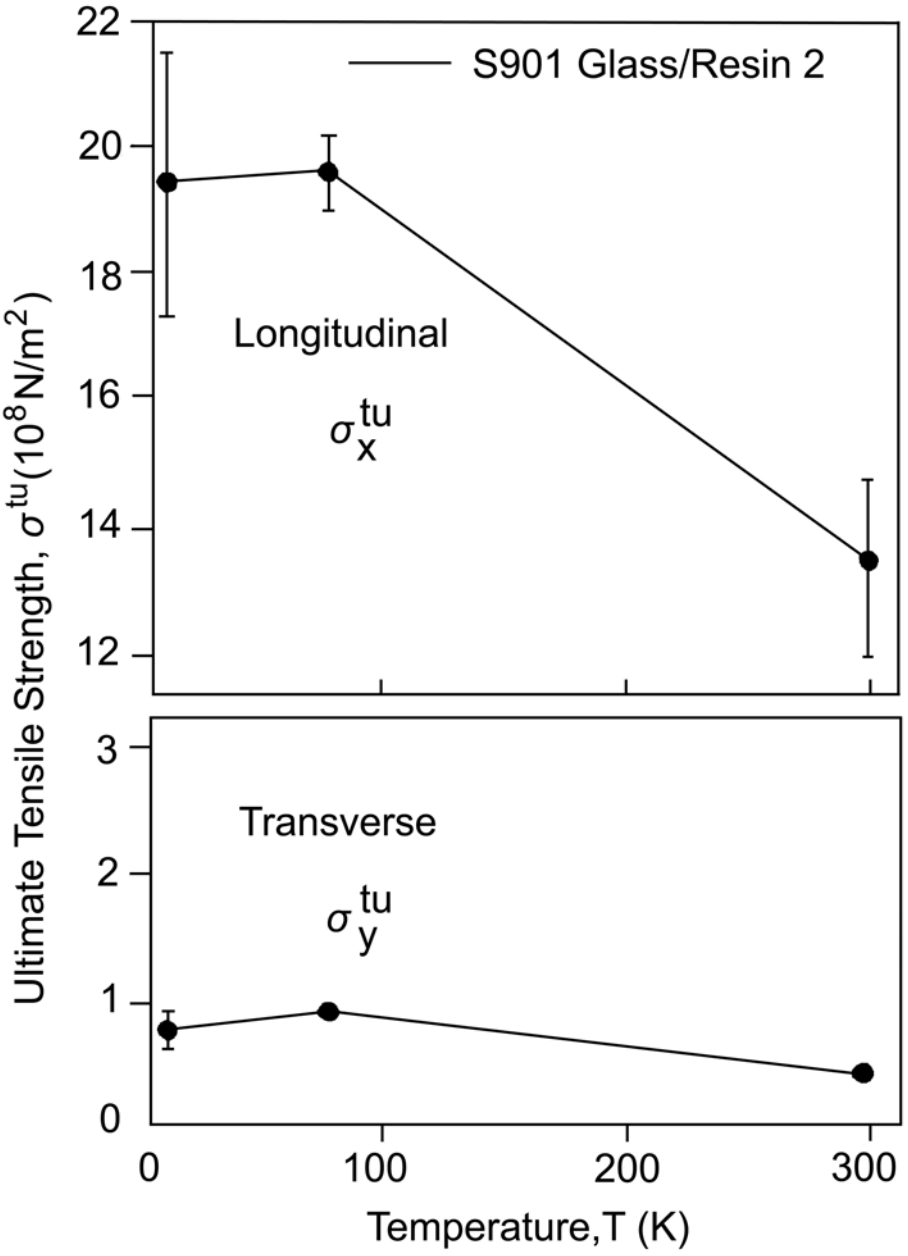


Figure 4.4-28 - Ultimate tensile strength

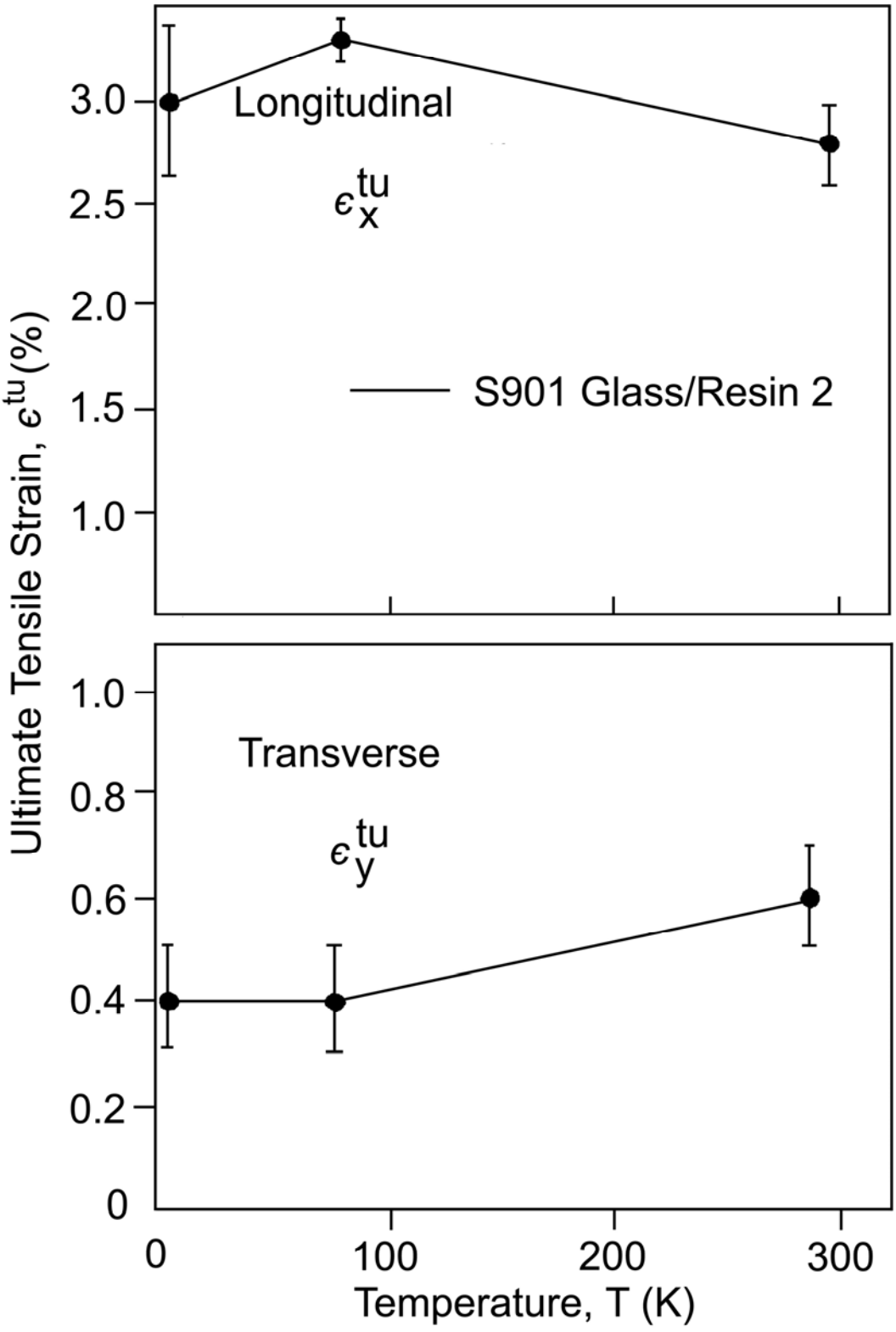


Figure 4.4-29 - Ultimate tensile strain

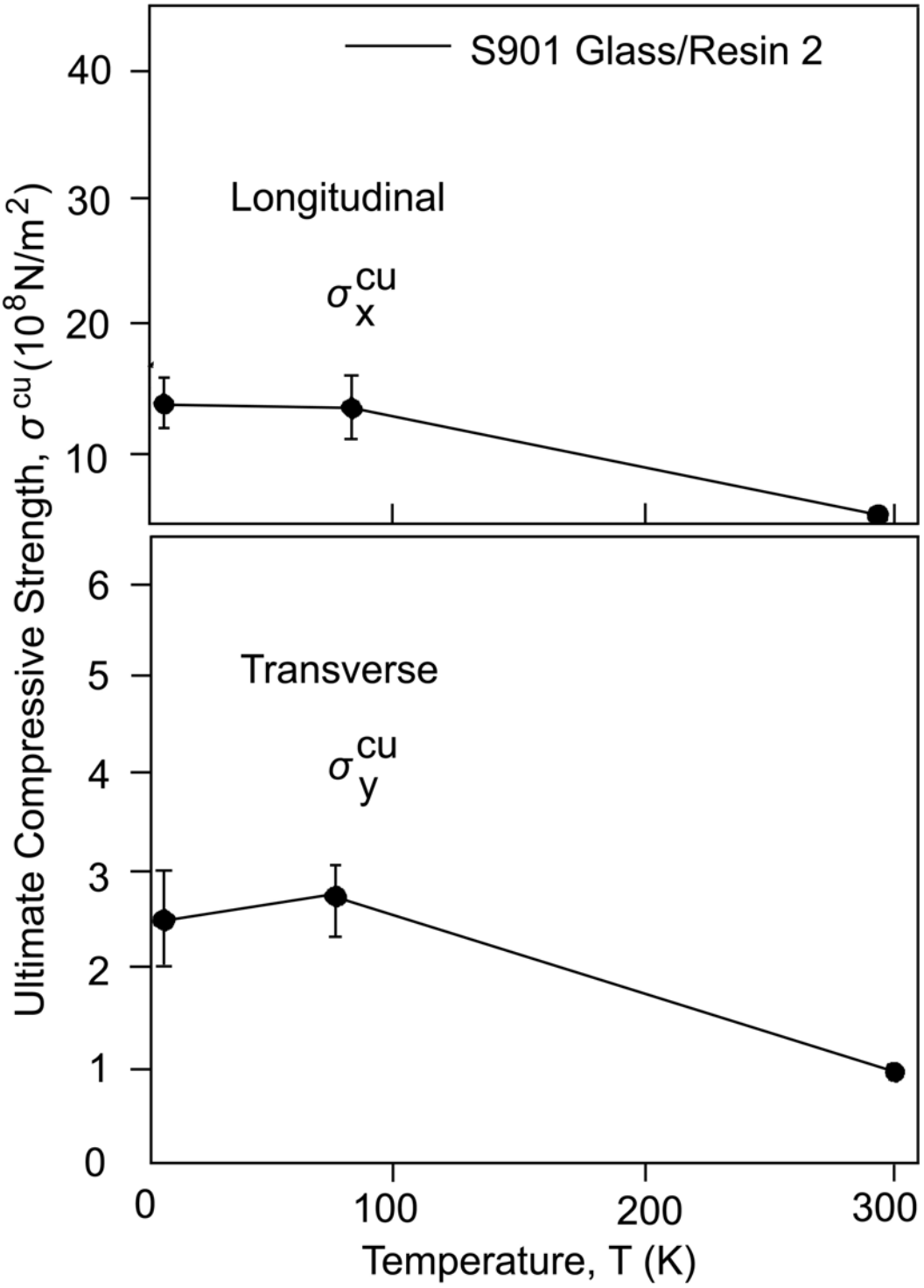


Figure 4.4-30 - Ultimate compressive strength

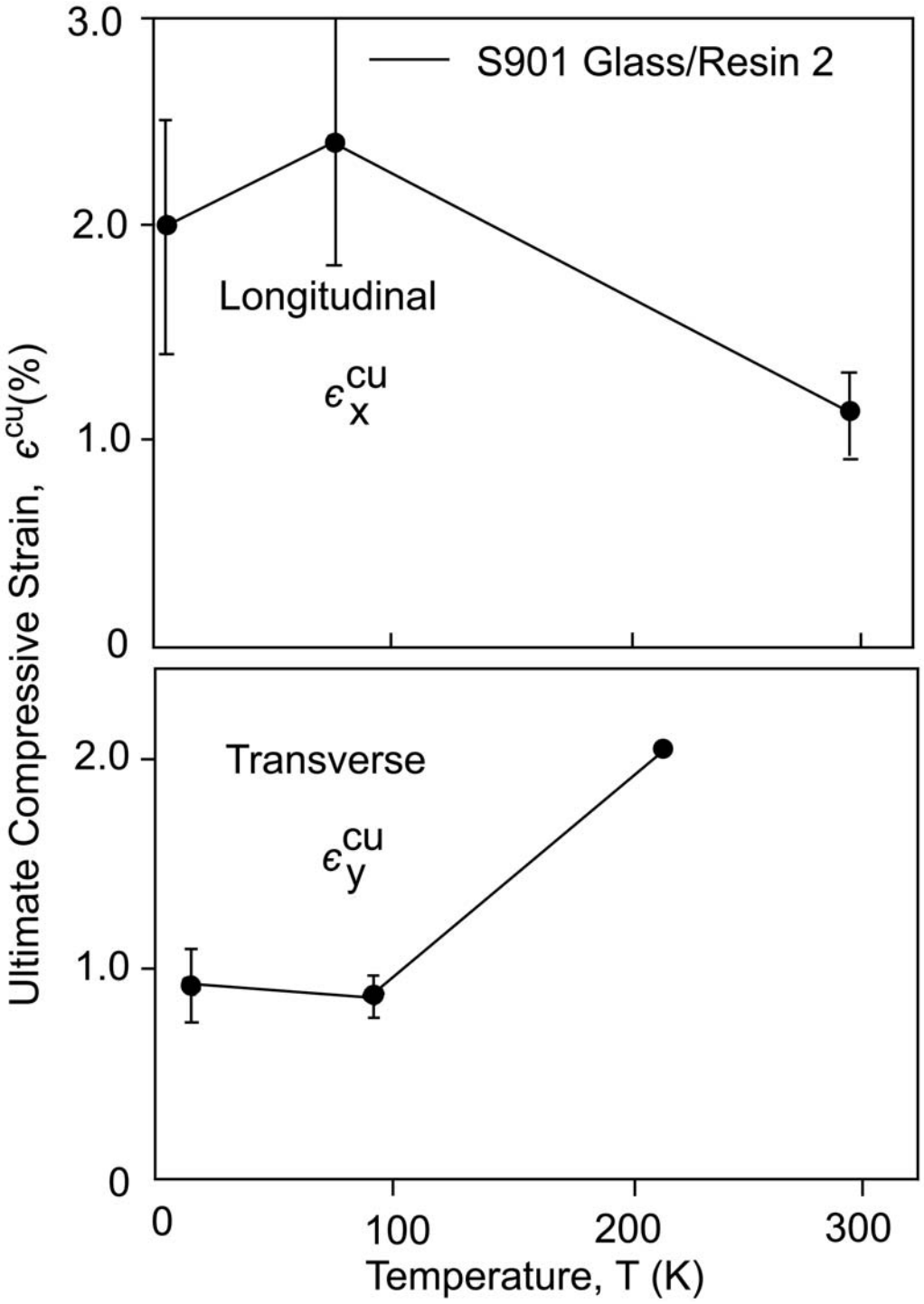


Figure 4.4-31 - Ultimate compressive strain

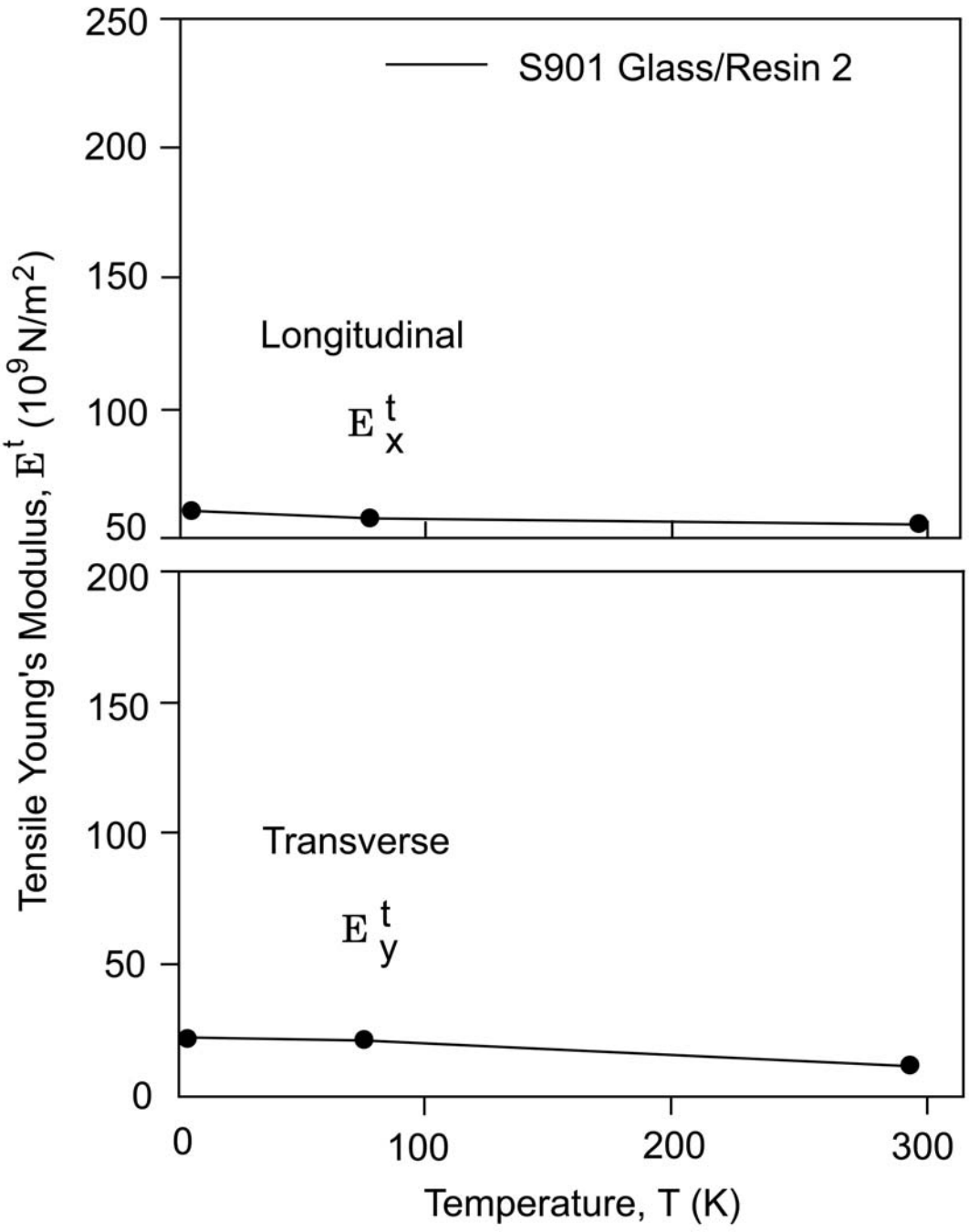


Figure 4.4-32 - Tensile Young's modulus

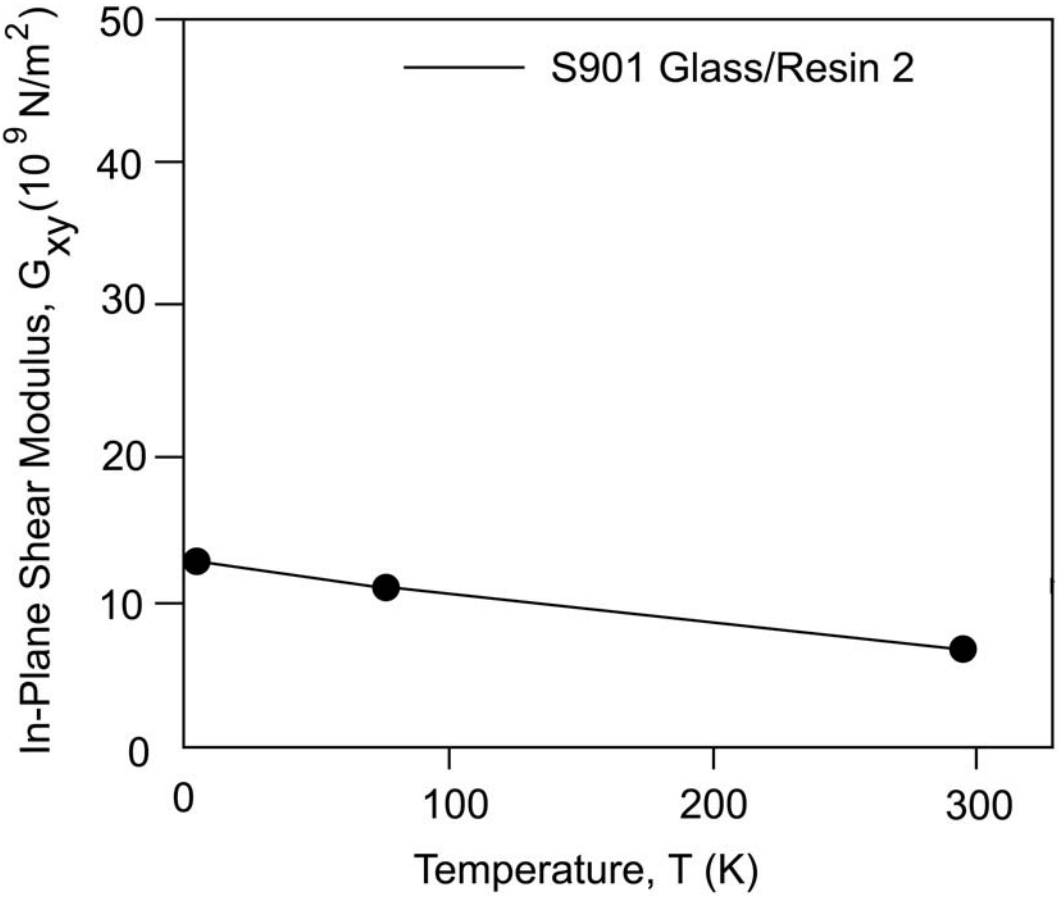


Figure 4.4-33 - In plane shear modulus

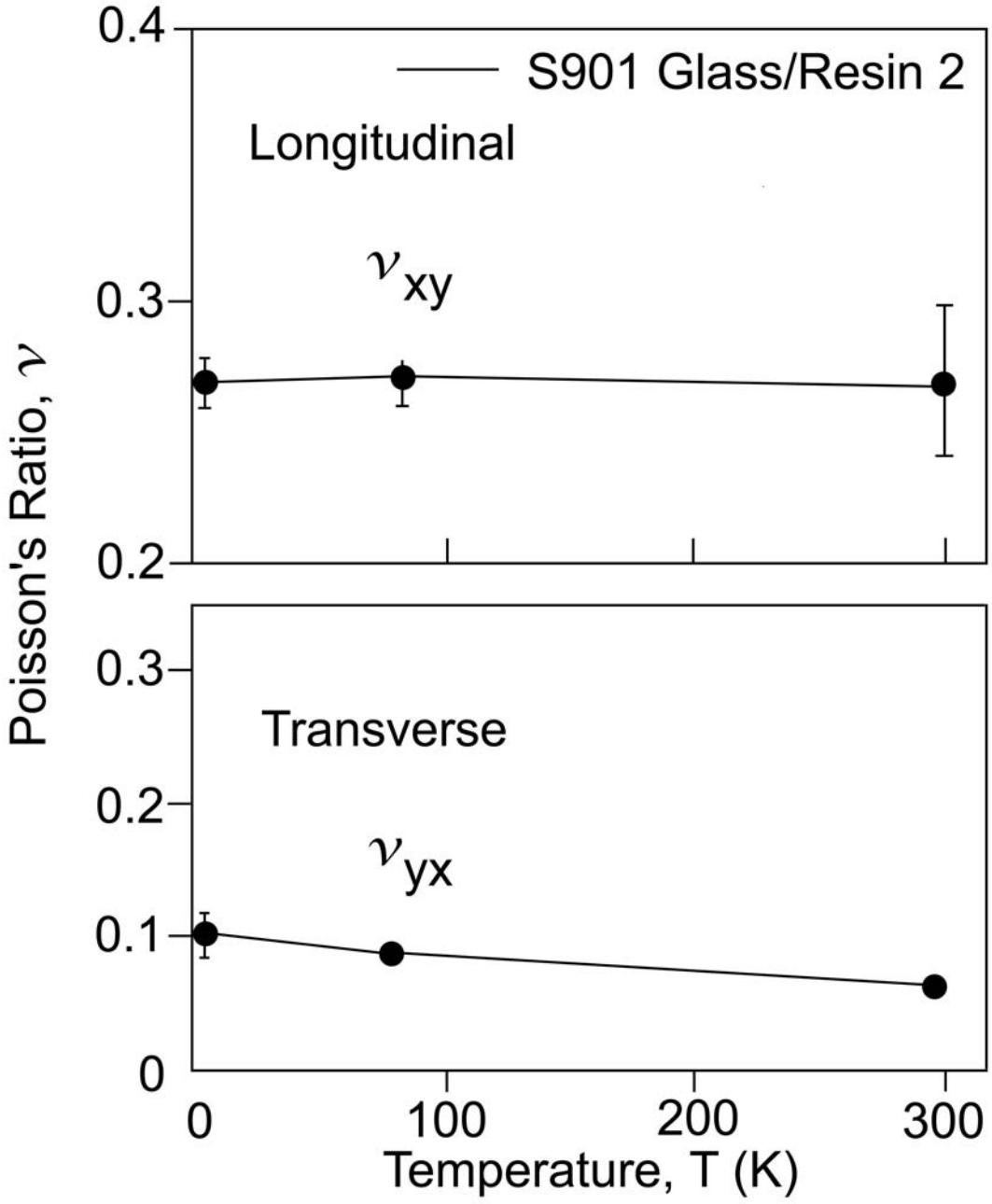


Figure 4.4-34 - Poisson's Ratio

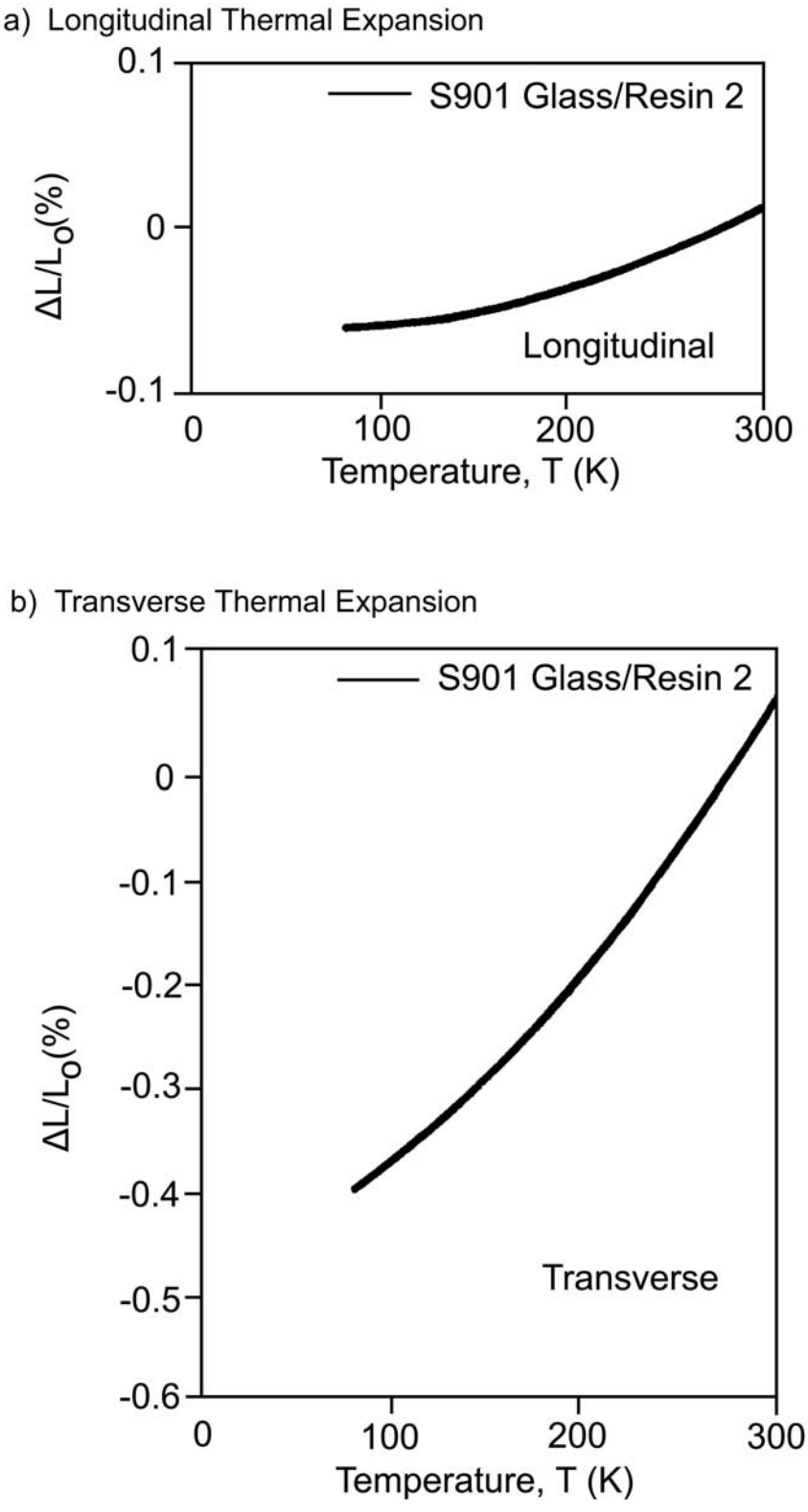


Figure 4.4-35 - Longitudinal and transverse thermal expansion

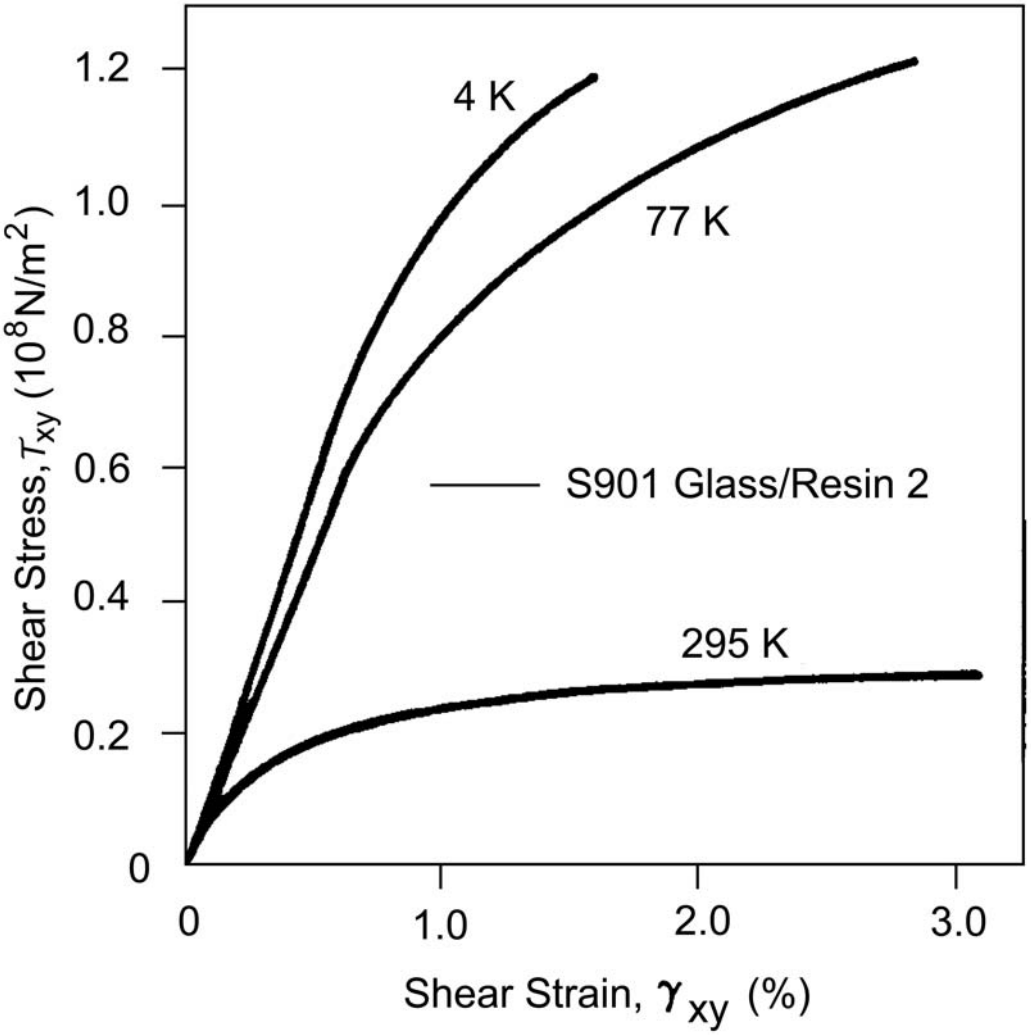


Figure 4.4-36 - Shear stress strain

4.5 Moisture (hygrothermal) effects

4.5.1 Effects of hygrothermal environment

4.5.1.1 General

Absorbed moisture reduces the glass transition temperature (Tg) of a polymeric matrix, e.g. epoxy, and causes a reduction in the composite properties dominated by matrix characteristics, such as:

- Transverse tension
- Longitudinal compression
- Shear

4.5.1.2 Fibre types

Aramid fibres absorb moisture. The level of moisture uptake is dependent on the relative humidity of the environment and the exposure time, Ref. [7-3]. Studies have aimed to understand the mechanisms as well as the effect on the properties of aramid composites, Ref. [7-11], [7-12], [7-13].

The amount of moisture absorbed is matrix dependent. Prior to manufacture, aramid fibres are dried.

4.5.1.3 Matrix resin type

Newer matrix materials have lower moisture absorption. For matrix-only samples, moisture uptakes values are typically up to:

- 7% for first generation (old) epoxies, such as Fiberite 934 and Code 69.
- 5% for second generation (toughened) epoxies, e.g. Vicotex M18.
- 2% for cyanate esters, e.g. Fiberite 954 and YLA RS3.
- 1.5% for high-stability thermoplastics, e.g. PEEK.

4.5.2 Moisture effects on carbon fibre composites

4.5.2.1 General

In a study on an older epoxy system (Courtaulds A-S/Code 69), significant changes to the composite were induced by high levels of moisture absorption, Ref. [7-10], the effects observed are described below.

4.5.2.2 Resin

The matrix resin exhibited, Ref. [7-10]:

- Plasticization,
- Cracking,
- Lowering of glass transition temperature (Tg),
- Swelling.

The moisture sensitivity was dependent on the hydroxyl content. The degree of degradation was related to the local degree of cure.

4.5.2.3 Fibre

High modulus (HM) fibre composites were less susceptible to stiffness and strength degradation than high strength (HT) fibre composites, Ref. [7-10].

4.5.2.4 Resin-to-fibre interface

The interface was degraded. This affects amount of water absorbed, Ref. [7-10].

4.5.2.5 Tensile strength

Moisture produced a small effect on tensile strength for 0° and ± 45° laminates, but a considerable loss (up to 80 %) of tensile strength for 90° laminates, Ref. [7-10].

4.5.2.6 Flexural strength

Moisture induced effects included, Ref. [7-10]:

- Higher levels of degradation than that of tensile strength.
- Effect proportional to amount of water absorbed. Maximum recorded degradation: 60%.
- 50% reduction after 100 hours exposure to steam.

4.5.2.7 Compressive modulus

Moisture-induced effects included, Ref. [7-10]:

- Large effects (≈ 80% degradation) for 90° laminates.
- Small effects on 0° and ± 45° laminates.

When temperature effects were considered, the main observations were that, Ref. [7-10]:

- Saturated room temperature modulus and strength reduced by 20% and 30%, respectively. At 394 K, modulus and strength reduced by 30% and 95%, respectively.
- Large degradations (≈ 80%) at high temperature and humidity appear to be caused more by temperature than water absorption.

4.5.2.8 Shear properties

Hygrothermal effects included, Ref. [7-10]:

- Reduction of shear properties; typically 80% degradation.
- A 50% reduction in shear properties after 200 hours immersion at 373 K.

4.5.2.9 Transverse tensile creep

Moisture-induced effects included, Ref. [7-10]:

- Increase in instantaneous creep strain. Typically 25% at 95% RH, as compared with strain at 19% RH.
- Increased rate of damage accumulation.

4.5.2.10 Torsional and flexural fatigue

Moisture-induced effects included, Ref. [7-10]:

- A reduction in initial torsional stiffness of approximately 30% was found for some specimens, indicating a high degree of matrix plastification.
- An increased rate of damage accumulation with no apparent incubation period.
- Flexural fatigue life, reduced by a factor of 10 for unidirectional material, and by factors of 1.5 to 3 for angle ply material.

4.5.2.11 Coefficient of thermal expansion

The CTE was not affected, Ref. [7-10]:

4.5.2.12 Work of fracture

Hygrothermal effects included, Ref. [7-10]:

- A 25 % reduction in energy to initiate a crack after 375 hours exposure to steam.
- The energy to propagate crack was not affected.
- Work of fracture increased 50% to 100% after 100 hrs exposure to water at 373 K.

4.5.2.13 Pin bearing strength

Hygrothermal effects included, Ref. [7-10]:

- A 40% decrease in strength attributed to a combination of water and temperature at 400 K. The same effect was seen for 3 different lay-ups.
- An 18% decrease in strength was due to moisture alone after 149 days at 98% RH at temperatures between 355K and 422K.

4.5.2.14 Dimensional stability

Very small changes (0.004 %) were noted for very high modulus faced honeycomb sandwich panel after 12 hours exposure to 95% RH at 293 K, Ref. [7-10].

4.5.2.15 Weathering

An accelerated rate of water absorption occurred in the presence of ultraviolet light.

4.5.3 Carbon/epoxy composites

4.5.3.1 Courtaulds A-S/Code 69

The experimental results of hygrothermal effects on composite properties are shown graphically for, Ref. [7-10]:

- Weight gain, [See: Figure 4.5-1].
- Flexural modulus, [See: Figure 4.5-2].
- Flexural strength, [See: Figure 4.5-3].
- Transverse flexural strength, [See: Figure 4.5-4].
- Interlaminar shear strength, [See: Figure 4.5-5].

NOTE Courtaulds A-S fibre is no longer commercially available.

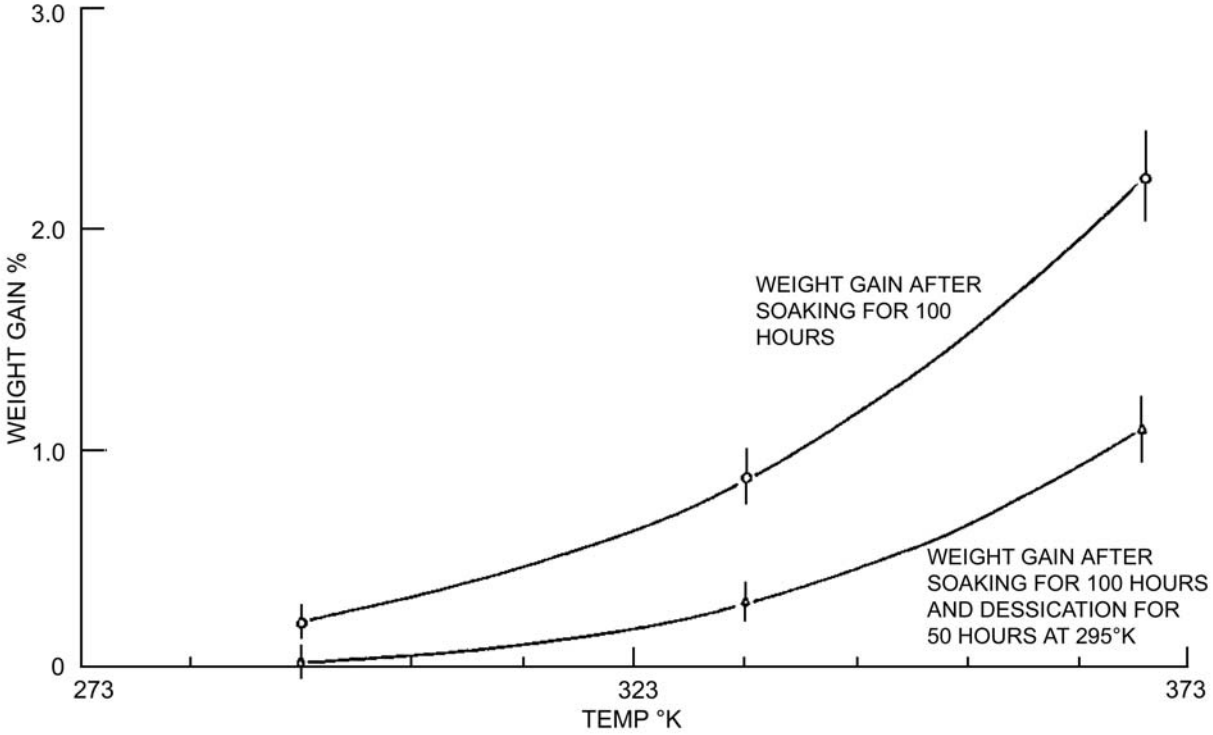


Figure 4.5-1 - Weight gain of composite specimens before and after desiccation

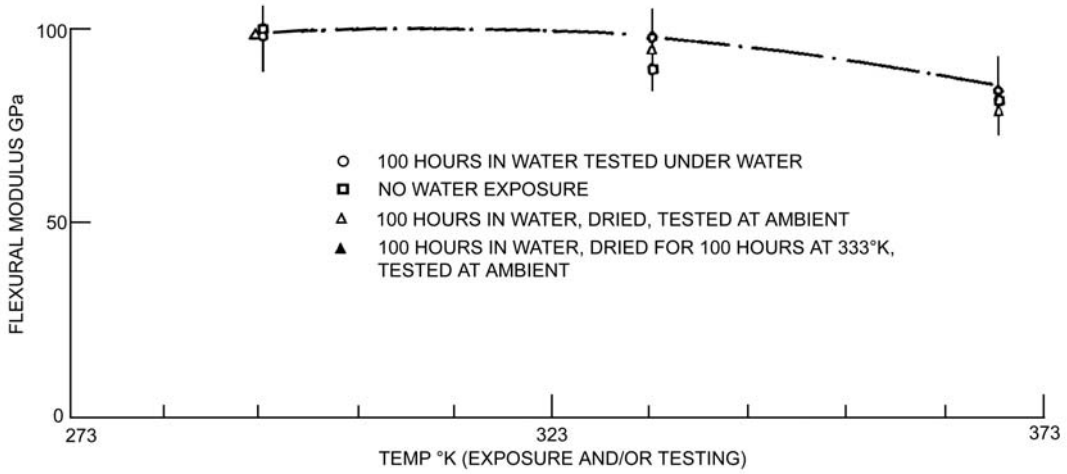


Figure 4.5-2 - Flexural modulus as a function of water exposure/temperature: Unidirectional composite specimens

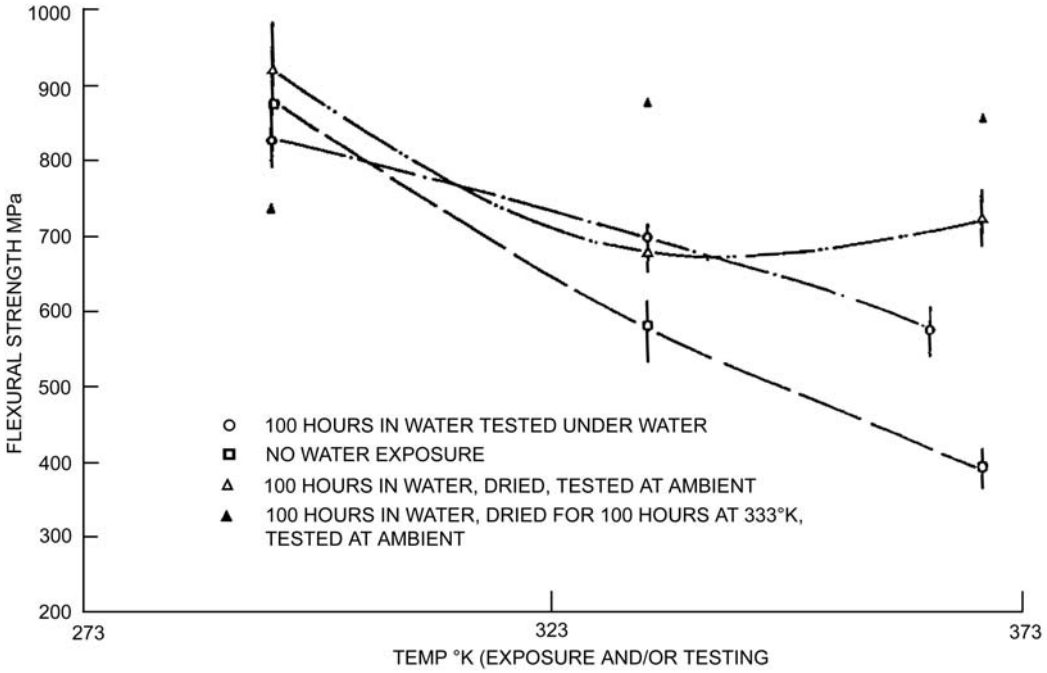


Figure 4.5-3 - Flexural strength as a function of water exposure/temperature: Unidirectional composite specimens

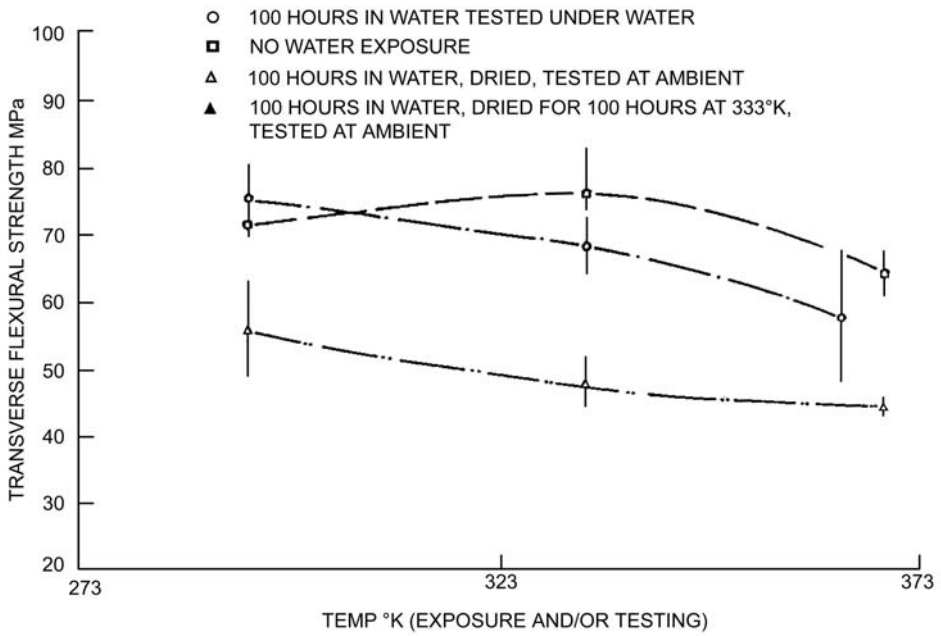


Figure 4.5-4 - Transverse flexural strength as a function of water exposure/temperature: Unidirectional composite specimens

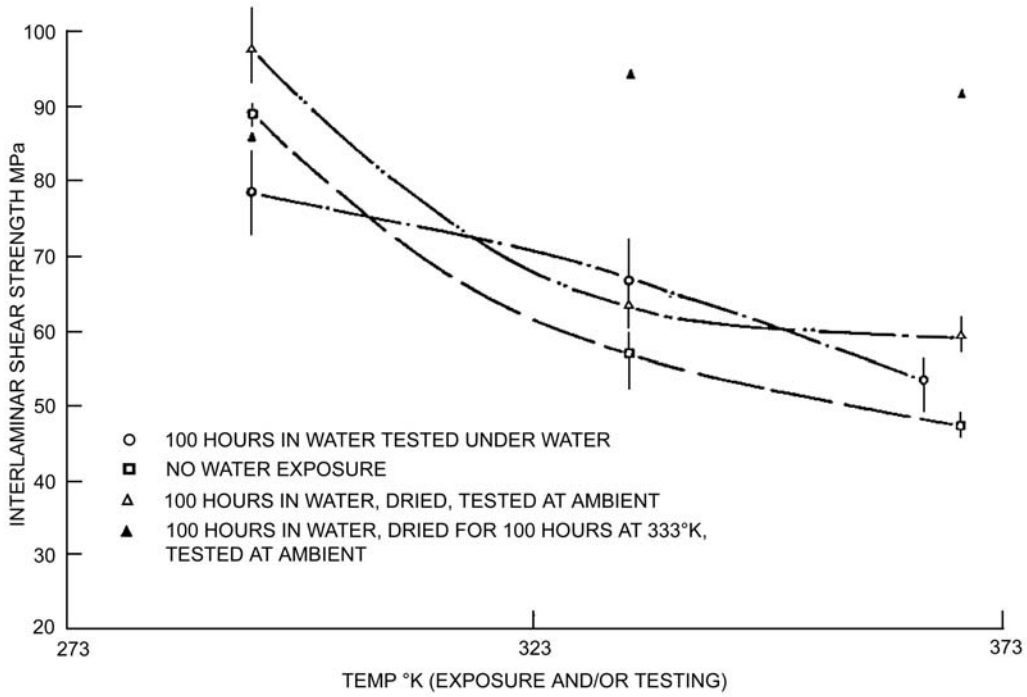


Figure 4.5-5 - Interlaminar shear strength as a function of water exposure/temperature: Unidirectional composite specimens

4.5.4 Aramid/epoxy composites

4.5.4.1 Twaron HM/epoxy

The hygrothermal effects for Twaron HM/LY556/HY917/DY070 Ciba Geigy epoxy composite are shown for, Ref. [7-12]:

- Moisture absorption, [See: Figure 4.5-6].
- Interlaminar shear strength, [See: Figure 4.5-7].
- Transverse tensile strength, [See: Figure 4.5-8].

The fibres were supplied coated in accordance with U.S. Patent No. 4557967 (December 1985). This treatment is standard on Twaron aramid fibres, Ref. [7-12].

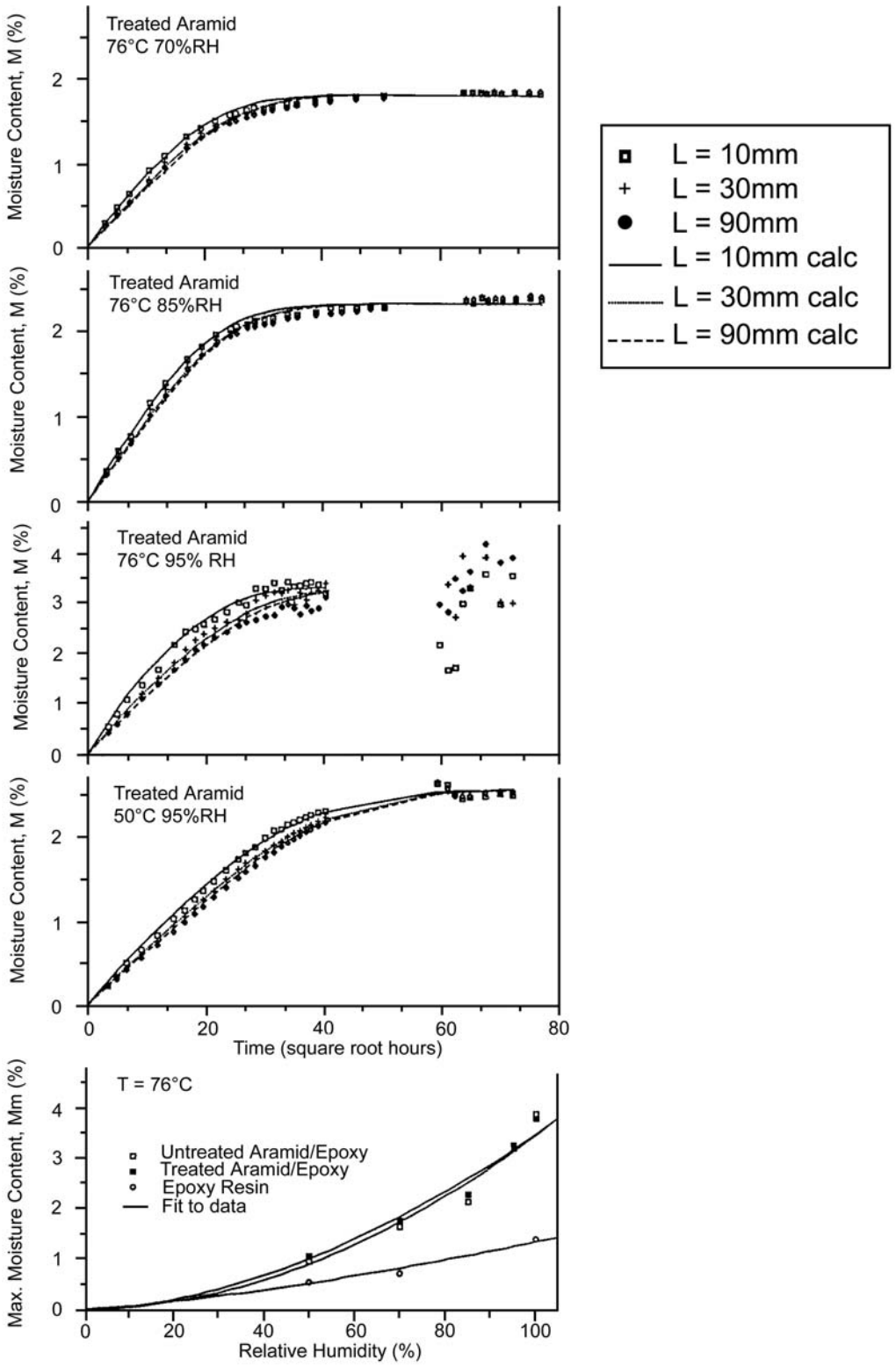


Figure 4.5-6 - Moisture absorption curves for aramid/epoxy composites

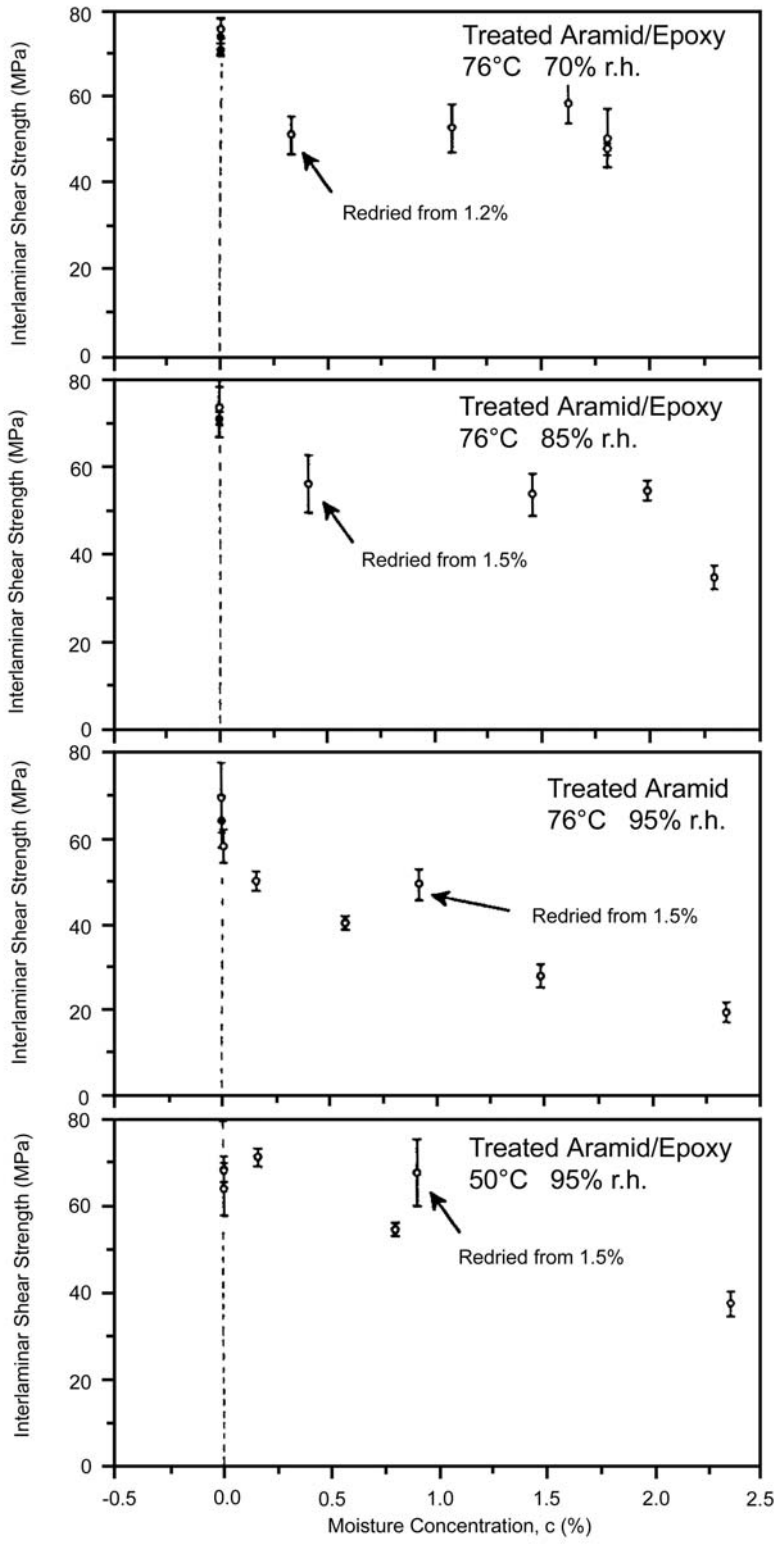


Figure 4.5-7 - Effect of hygrothermal environment on interlaminar shear strength of aramid/epoxy composites

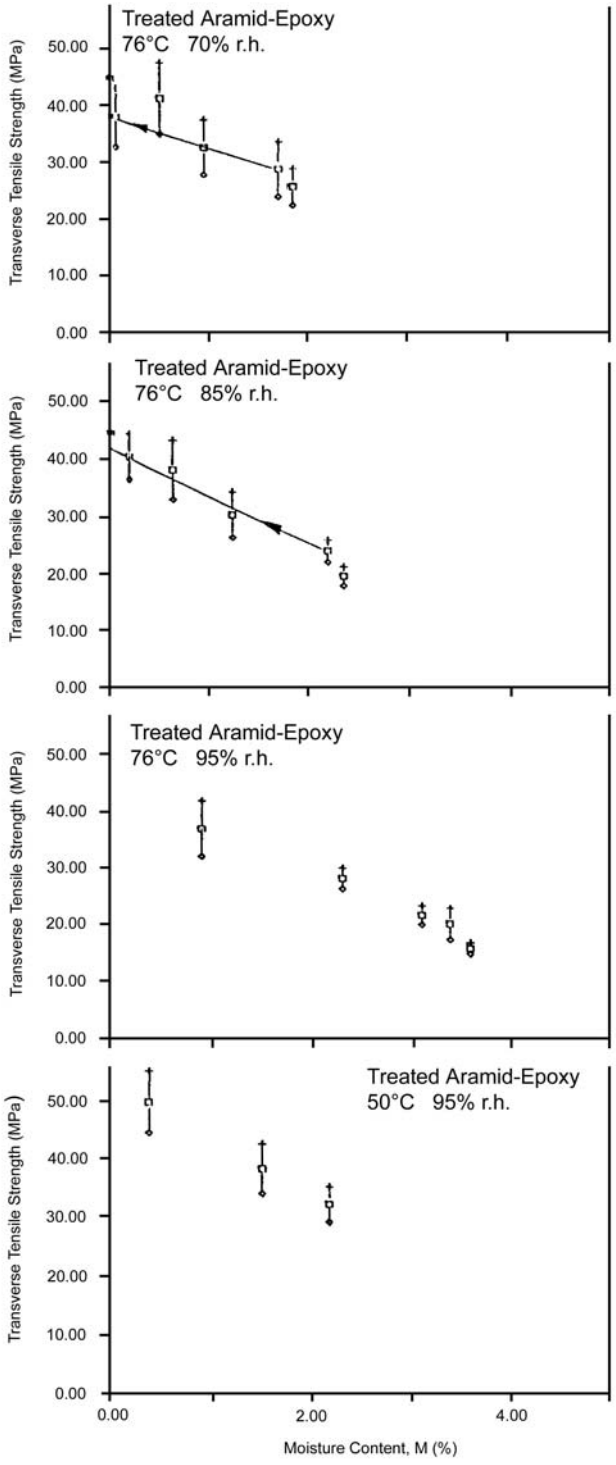


Figure 4.5-8 - Effect of hygrothermal environment on the transverse tensile strength of aramid/epoxy composites

4.5.4.2 Kevlar 49/epoxy

The residual properties of Kevlar 49/epoxy materials after 3 years exposure at various locations in North America are shown for, Ref .[4-13]

- Compressive properties, [See: Figure 4.5-9].
- Shear strength, [See: Figure 4.5-10].

These results are from a study of ground exposure effects on helicopter materials, Ref. [13].

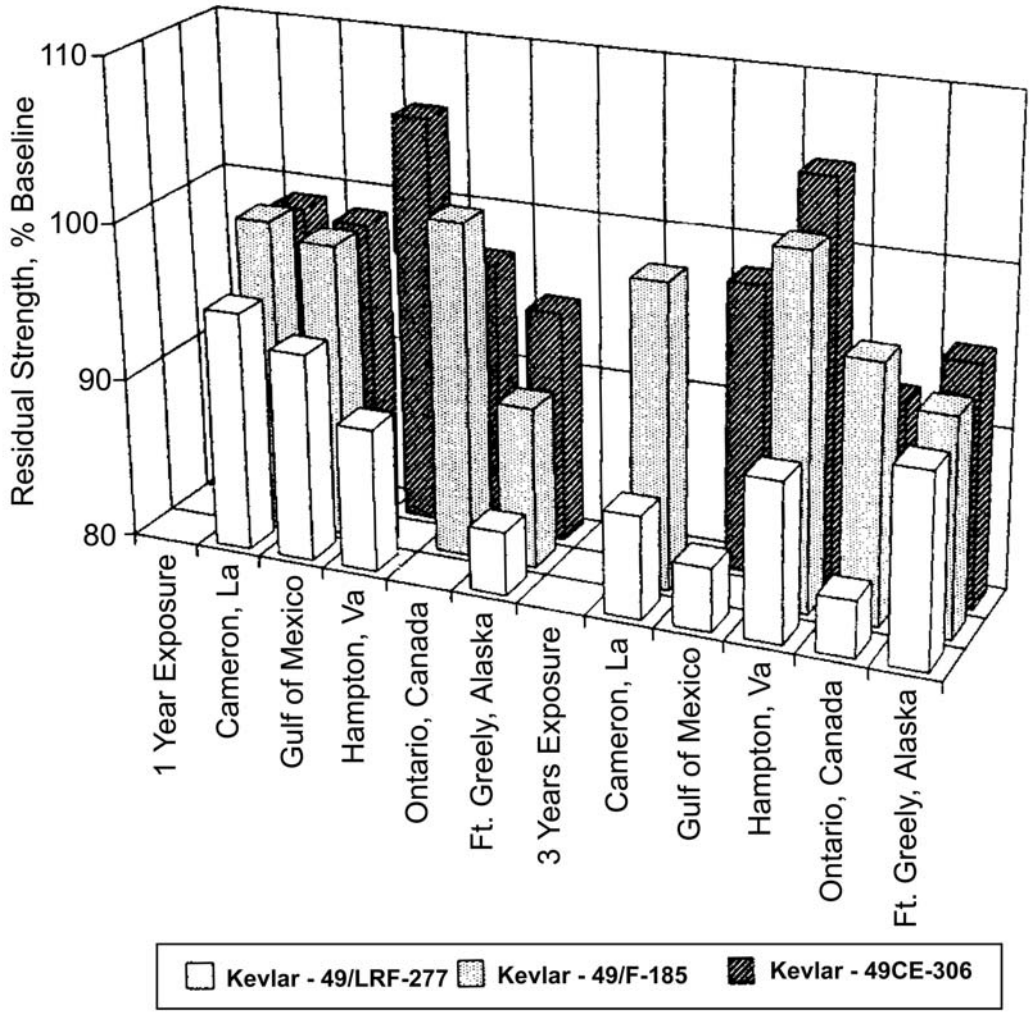


Figure 4.5-9 - Effect of ground exposure on compressive properties of aramid/epoxy composites

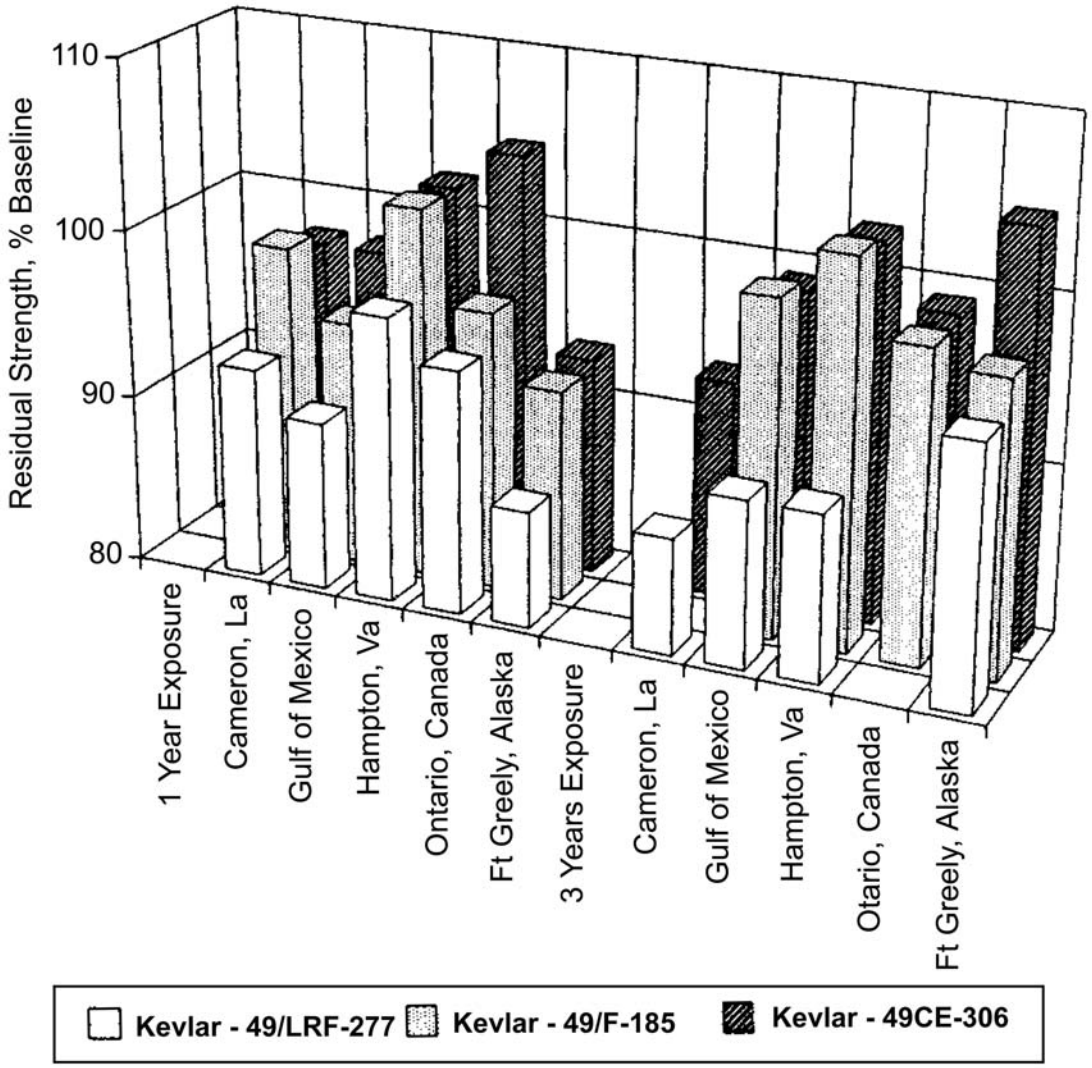


Figure 4.5-10 - Effect of ground exposure on shear strength of aramid/epoxy composites

4.6 Influence of stress concentrations

4.6.1 General

Composites are generally more sensitive to stress concentrations under static loads than metals.

No general guideline can be stated because there are so many possible composite configurations, e.g. fibre, resin, lay-up. Many factors affect stress concentrations in composites.

4.6.2 Carbon/epoxy composites

The sensitivity of CFRP materials is illustrated by considering special cases. Only preliminary information is given. Ref. [4-14] provides more details.

Tests were done on samples having notches of different geometry for typical stacking sequences of a few interesting CFRP materials, Ref. [4-14].

Figure 4.6-1 shows the 4-point bending test configuration on sandwich samples. Hole sizes and delamination zones are shown in Figure 4.6-2, Ref. [4-14].

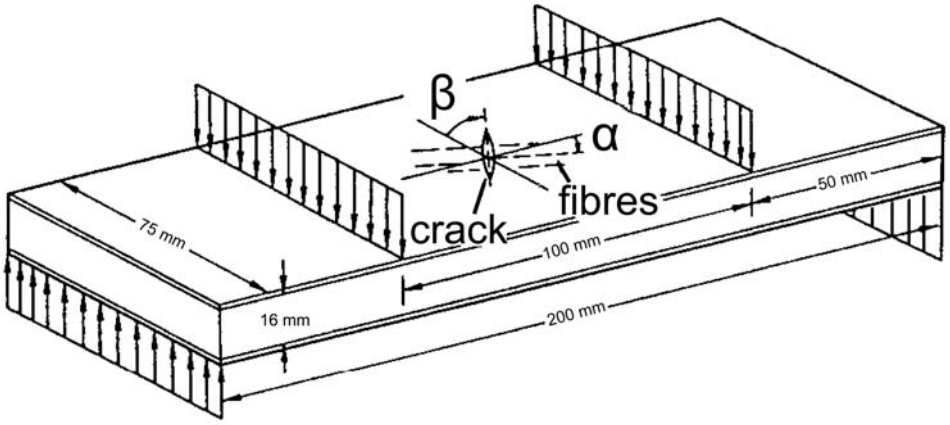


Figure 4.6-1 - Four point bending on sandwich specimen

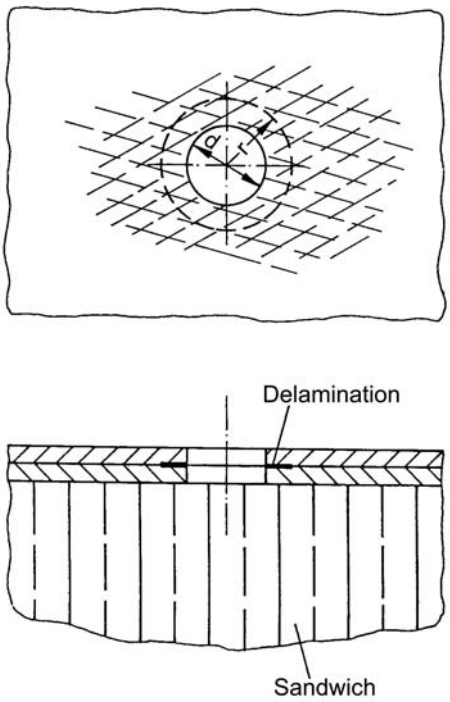


Figure 4.6-2 - Definition of holes and delamination

Table 4.6-1 gives test results for carbon/epoxy 914C-MS-4-40% composite with various holes and delaminations present, whereas Table 4.6-2 provides similar test data for 914C-TS-4-40% carbon epoxy material. Both tables show calculated figures for sensitivity to stress concentrations, Ref. [4-14].

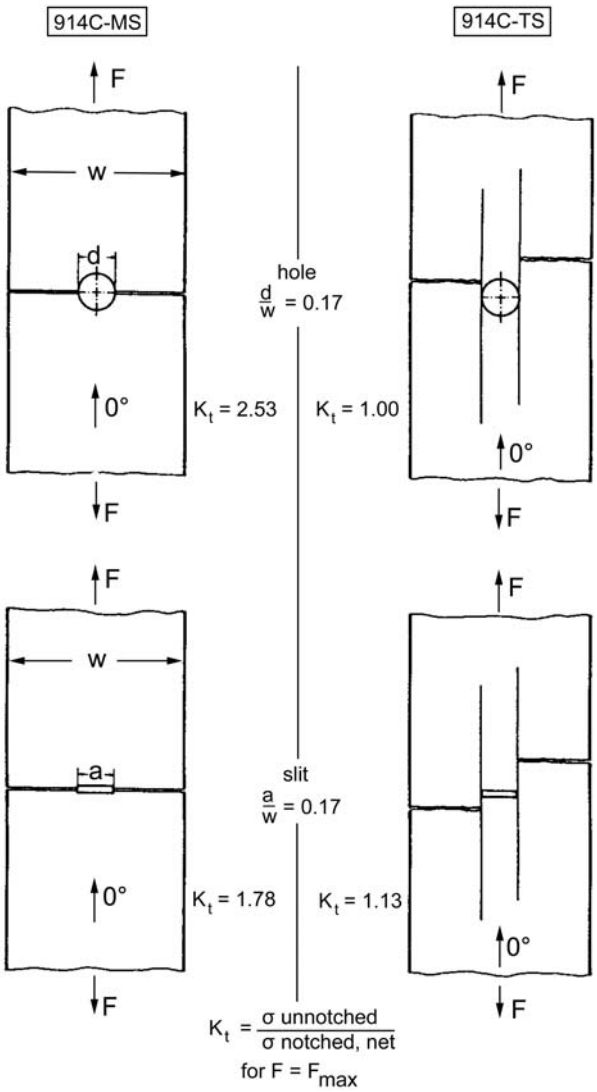
Table 4.6-1 - Test results for 914C-MS-4-40%

	Tests	σ_{WB} *(without hole)*		σ_{not} *(notched)*		Sensitivity $K_t = {}_{WB}/\sigma_{not}$
		Value	S.D.	Value	S.D.	
Un-notched	5	1029	30			
Hole: ∅12mm	3			406	23	2.53
Delamination: ∅12mm	3			1135	144	0.91
Hole: ∅12mm Delamination: ∅20mm	3			477	53	2.16
Slit: 12mm long	3			577	240	1.78
[See also: Figure 4.6-3]						

Table 4.6-2 - Test results for 914C-TS-4-40%

	Tests	σ_{WB} *(without hole)*		σ_{not} *(notched)*		Sensitivity $K_t = {}_{WB}/\sigma_{not}$
		Value	S.D.	Value	S.D.	
Un-notched	3	1766	53			
Hole: ∅12mm	3			1762	98	1.00
Delamination: ∅12mm	3					
Hole: ∅12mm Delamination: ∅20mm	3			1633	17	1.08
Slit: 12mm long	2			1565	82	1.13
[See also: : Figure 4.6-3]						

Figure 4.6-3 compares the effects of hole type on the stress concentration sensitivity of both composite materials, Ref. [4-14].



[See also: Table 4.6-1 and Table 4.6-2]

Figure 4.6-3 - Sensitivity of HM/HT UD laminate to stress concentrations

The sensitivity of a UD laminate to stress concentrations under longitudinal loadings can be summarised as, Ref. [4-14]:

- The material tends to split and is not considered as highly sensitive to stress increases.
- The material tends to experience fibre breakage under a stress below the ultimate strength, in the net section.

In the latter situation, notch geometry plays a role. Holes have been found to have a more severe effect than slits.

4.7 Effects of fatigue loading

4.7.1 Introduction

The failure mechanisms of composite laminates are totally different from those of metals. Whereas metals under fatigue loading can fail as a result of initiation and growth of a single crack, composite laminates fail progressively by the accumulation of many cracks.

Damage in composites can be of various forms [See: Clause 8 and Clause 19]:

- Fibre breaks
- Resin cracks
- Interfacial debonds
- Delaminations

Whilst categorised separately, they are highly interconnected and depend on the types of:

- Loading,
- Fibre/matrix system,
- Laminate lay-up, and
- Environmental conditions.

4.7.2 General damage mechanisms

4.7.2.1 Cyclic tension loading

The results of tests on un-notched specimens indicate that the progression of events follows a more or less distinct pattern:

- The first discernible damage usually consists of microcracks at certain intervals in the cross-plies (0°, 90°) of the laminates; as shown in Figure 4.7-1, Ref. [4-15].
- With increasing load cycles, more microcracks develop, which tend to turn at the interface with adjacent plies to form small delaminations, both inside and at the free edges of a laminate; as shown in Figure 4.7-2, Ref. [4-15].
- Additional delaminations start from the locations of fibre breakage.
- The degree of cracking stabilises at a certain level; known as the ‘characteristic damage state’ or CDS.

The extent of free edges in real composite structures is limited mainly to holes and cut-outs. For small samples, this leads to conservative predictions of the fatigue strength.

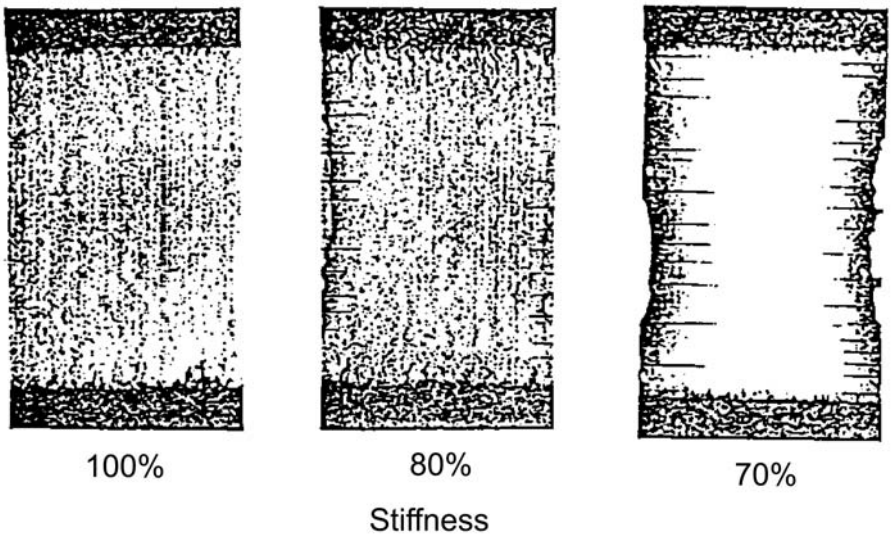


Figure 4.7-1 - Origin of cracks at free-edges in quasi-isotropic laminates after tension/compression fatigue, R = -1.0

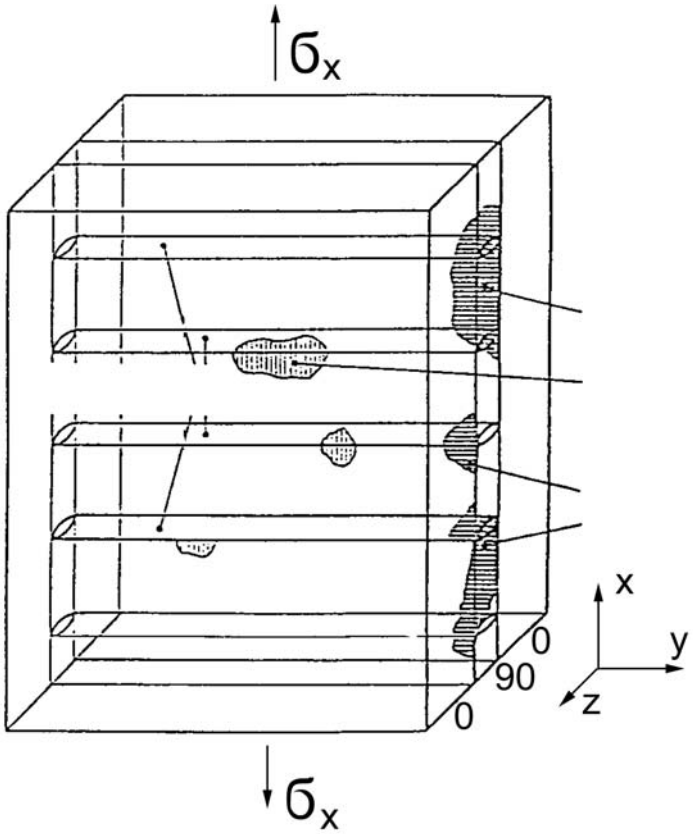


Figure 4.7-2 - Matrix cracks in cross plies and onset of delamination

4.7.2.2 Cyclic compressive loading

The critical conditions can arise in the presence of delaminations caused by:

- Manufacturing faults
- Impact damage
- Previously experienced high tensile loads.

If the compressive stresses are sufficiently high, local buckling of the laminate sections (separated by delamination) occur due to their reduced stiffness.

When the cycling is continued, the delamination acts as a crack front; causing damage growth by massive separation of the laminate, culminating in overall specimen failure.

The reduction of stiffness (increase of strain) with increasing damage is shown in Figure 4.7-3 for a matrix-controlled [±45°] laminate. Figure 4.7-4 shows a fibre-controlled laminate that failed suddenly at the start of loss of stiffness, Ref. [4-15].

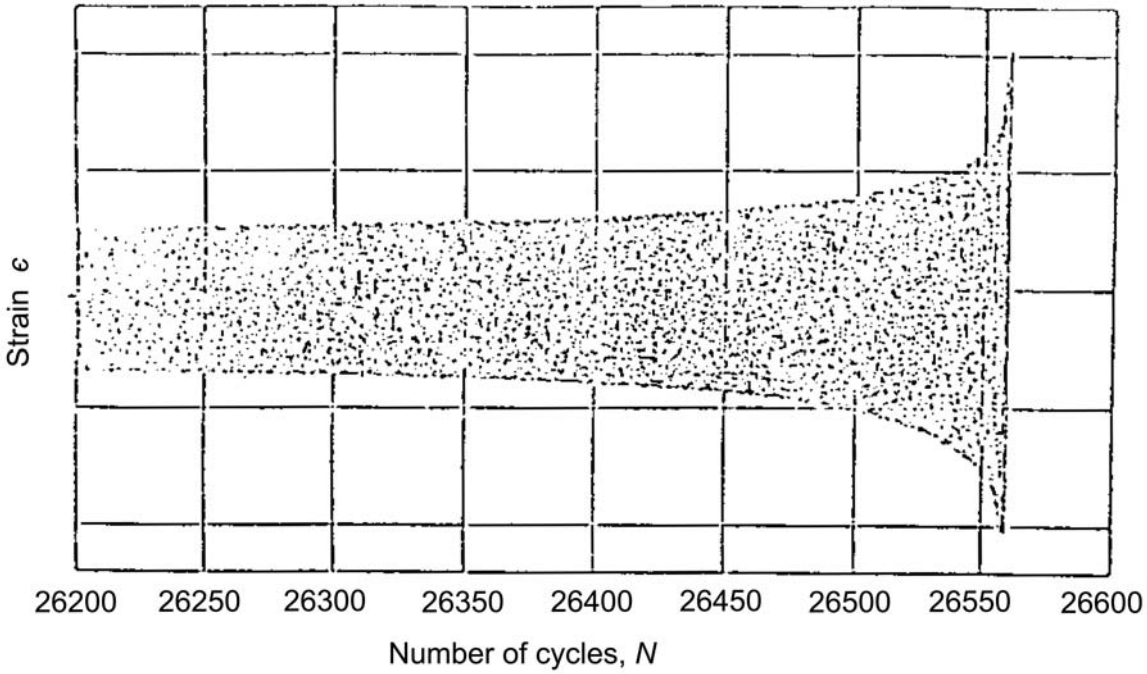


Figure 4.7-3 - Gradual increase in strain in a [±45°]s laminate during load controlled tension/compression test, R = -1.0

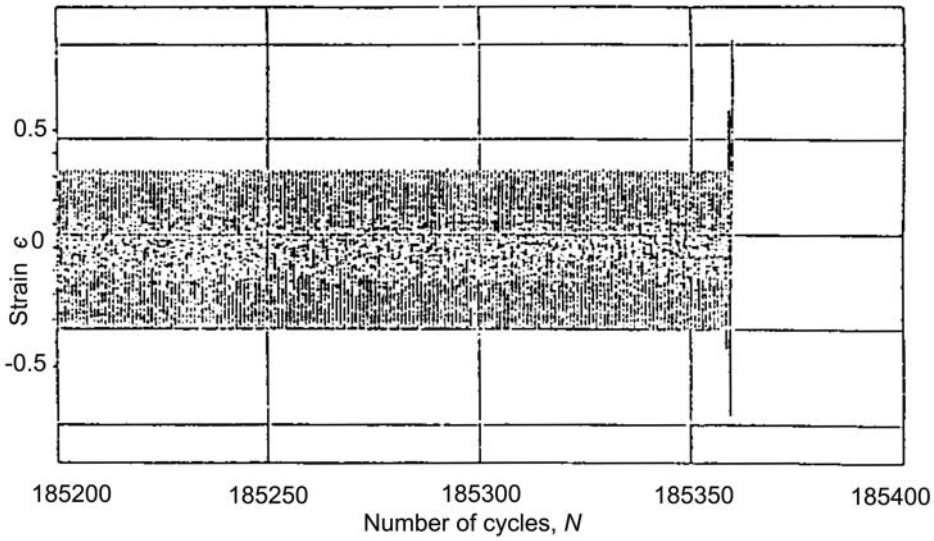


Figure 4.7-4 - Sudden increase in strain in a [0_2/+45/0_2/-45/0_2/90]s laminate during load controlled tension/compression tests, R = -1.0

4.7.3 Effect of lay-up

The fatigue strength of multi-directional laminates is mainly determined by the proportion of 0° plies. A small variation of the angle results in a significant drop in stiffness when the laminate is cycled, as shown in Figure 4.7-5, Ref. [4-16].

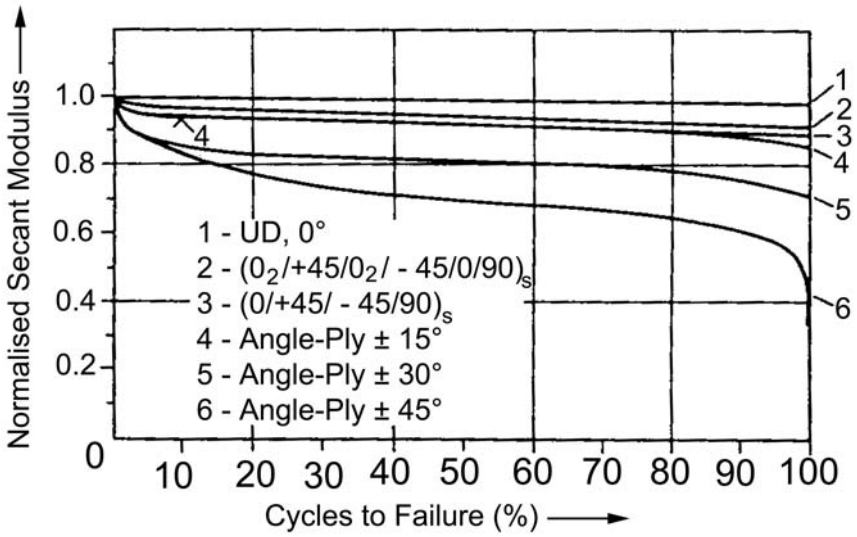


Figure 4.7-5 - Stiffness degradation due to cyclic loading for various laminates, R = 0.1

As shown in the Wöhler curves, Ref. [4-2], [4-3], the change to a 5° off-axis load results in less than 50% of the fatigue strength of a 0° on-axis load, [See: Figure 4.7-6], Ref. [4-16], [4-17].

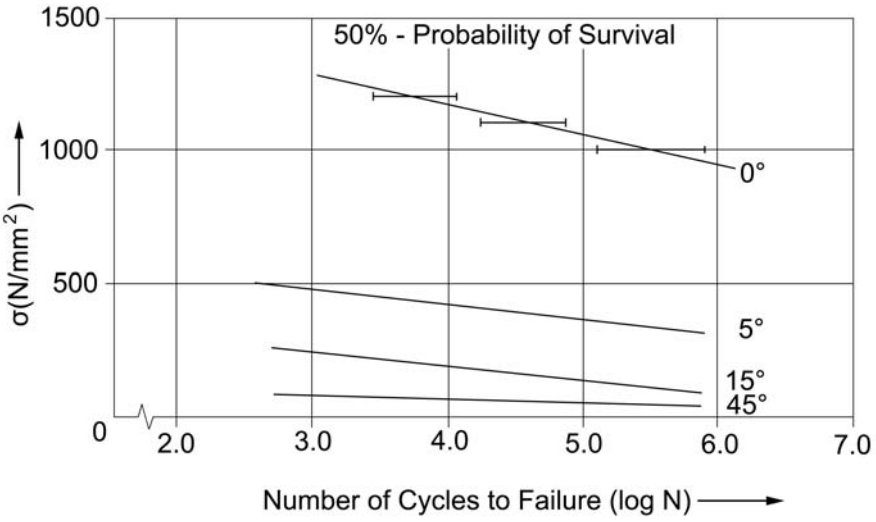


Figure 4.7-6 - Fatigue strength of unidirectional CFRP laminates, R = 0.1

Plies of 45° or 90° only improve the transverse stiffness of a laminate but do not contribute to the fatigue strength.

Figure 4.7-7 shows that angle-ply laminates (without 0° plies) also have much lower fatigue strength than unidirectional 0° laminates, Ref. [4-16].

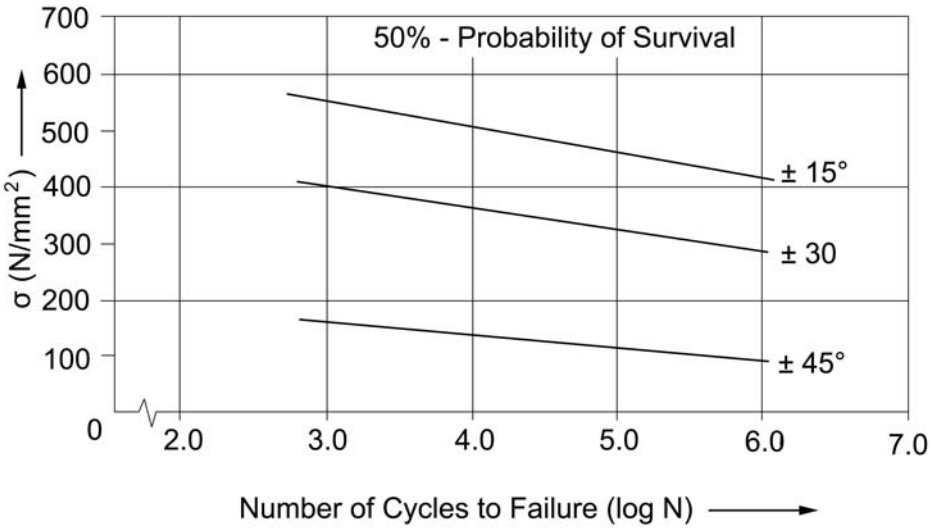


Figure 4.7-7 - Fatigue strength of angle ply CFRP laminates, R = 0.1

The reduction of fatigue strength due to an alteration in the ply angle is obvious, [See:Figure 4.7-8], Ref. [4-16],[4-17], for both tension/tension fatigue (R = 0.1) and tension/compression (R = 1.0).

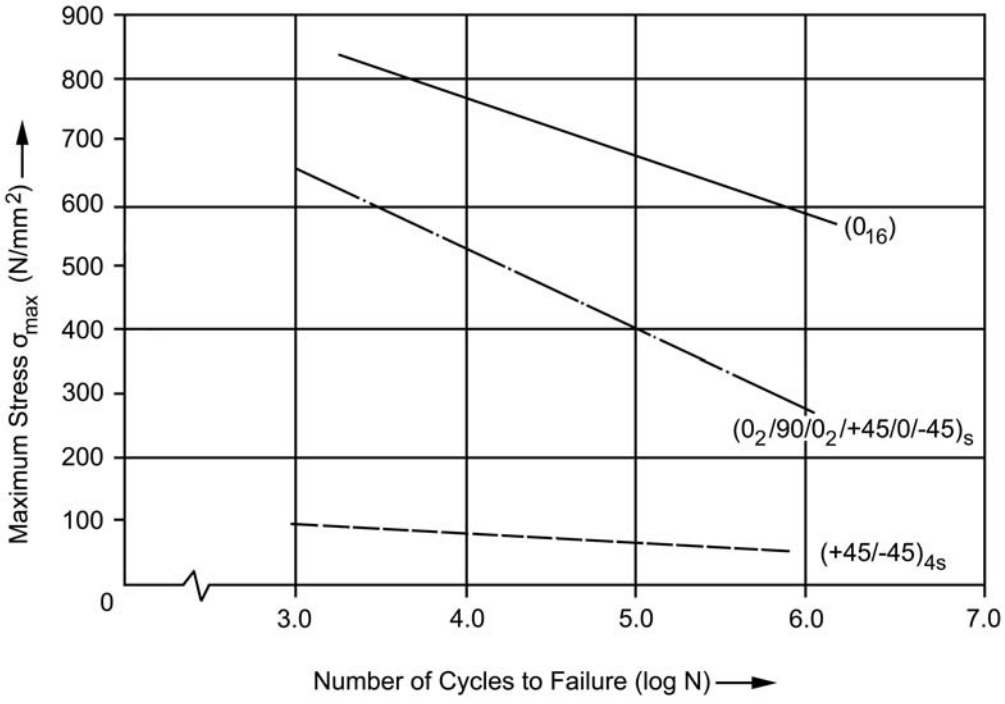


Figure 4.7-8 - Fatigue strength of various laminates under tension/compression loading, R = -1.0

4.7.4 Effects of type of loading

4.7.4.1 General

Comparing Figure 4.7-9 with Figure 4.7-10 shows the fatigue strength of angle-ply and multidirectional laminates under similar cyclic loading conditions, Ref. [4-16]. The severity of cyclic loading can be seen for the same multi-ply laminate by comparing the fatigue strengths in Figure 4.7-10 and Figure 4.7-11, Ref. [4-16].

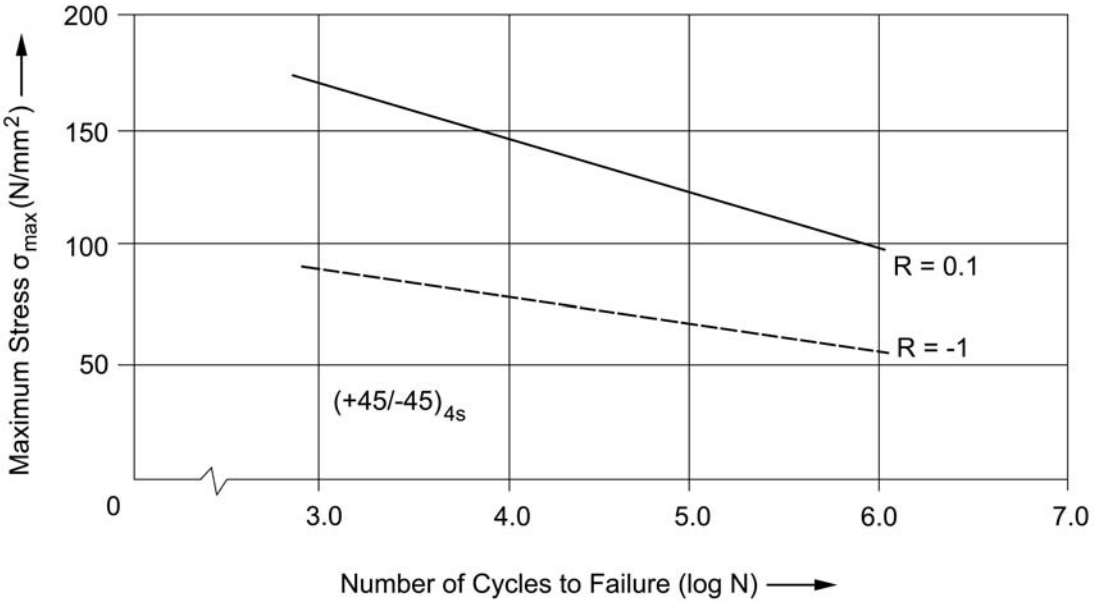


Figure 4.7-9 - Degradation of fatigue strength of angle ply laminates subjected to different loading conditions, R = -1 and R = 0.1

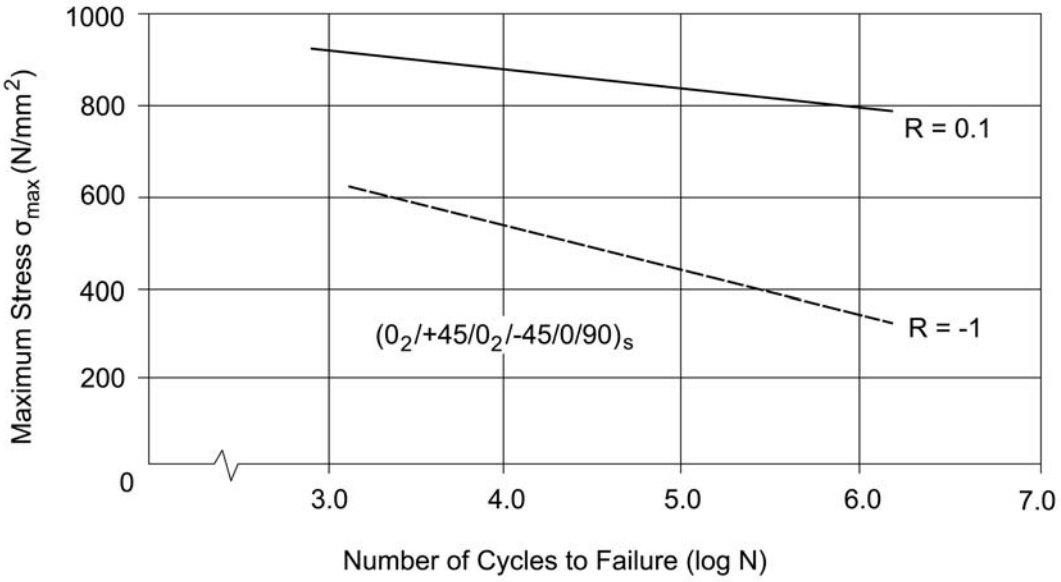


Figure 4.7-10 - Degradation of fatigue strength of multidirectional laminates subjected to different loading conditions, R = -1 and R = 0.1

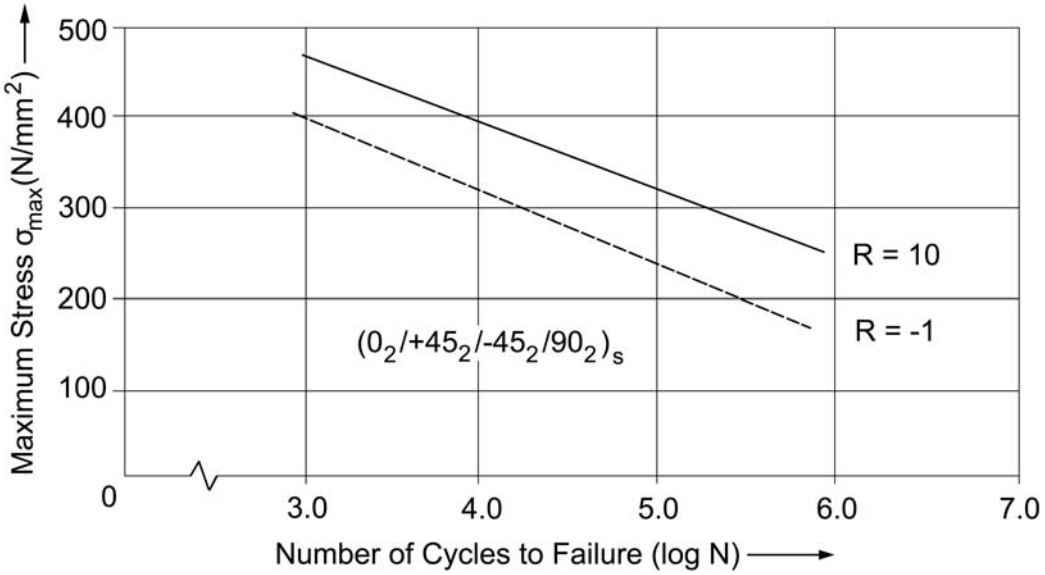


Figure 4.7-11 - Degradation of fatigue strength of multidirectional laminates subjected to different loading conditions, R = -1 and R = 10

4.7.4.2 Tension/tension cyclic loading

CFRP laminates have much higher tension/tension fatigue strength than metals, even under the influence of temperature and moisture.

4.7.4.3 Compressive cyclic loading

The number of cycles to failure reduces significantly. The reason for this is a higher stressing of the matrix under compressive loading.

Ref. [4-16] states that the degradation in fatigue strength for tension/compression cycling ($-5 \leq R \leq -0.5$) is higher than for compression/compression fatigue ($1.0 < R < \infty$) and very much higher than for tension/tension fatigue ($0 \leq R \leq 1.0$).

NOTE The static strength of a structure does not cover dimensioning for tension/compression fatigue.

4.7.5 Effects of hygrothermal environment

4.7.5.1 General

In general, composite materials are strongly affected by environmental conditions such as:

- Temperature
- Moisture.

In particular, the matrix-dominated properties tend to change under their influence, because of:

- Different CTE between fibre and matrix, and
- Swelling effects in the matrix.

[See: 4.4, 4.5, Clause 12 and Clause 13]

These effects lead to changes in the composite inner stress distribution. This, in turn, influences the mechanisms of crack initiation and growth under fatigue loading.

Ref. [4-15], [4-16], [4-17] provide some data on carbon/epoxy unidirectional, angle-ply and multidirectional laminates subjected to tension/tension (R = 0.1) or tension/compression (R = -1) fatigue load and a hygrothermal environment.

NOTE Material: T300/914C.

4.7.5.2 Summary of tension/tension (R=0.1) composite properties

The main effects can be summarised as, Ref. [4-15]:

- Unidirectional specimen: The compressive stresses induced by the moisture offset the residual stresses remaining after the curing process, which results in improved fatigue properties, [See: Figure 4.7-12], Ref[4-15].
- Matrix-controlled laminates: Temperature combined with moisture appears to be the worst case, but the degradation tends to decrease as the number of cycles increases, [See: Figure 4.7-13], Ref. [4-15].

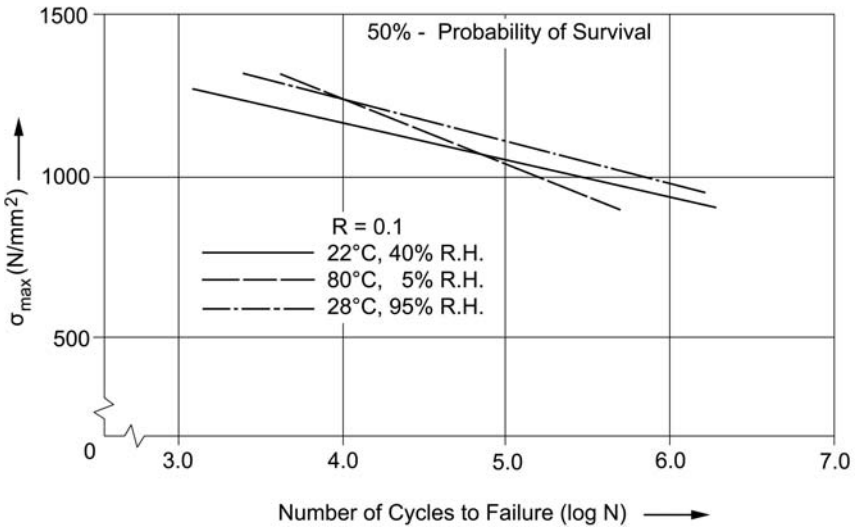


Figure 4.7-12 - Effects of temperature and moisture on the fatigue strength of a 0° bidirectional laminate, R = 0.1

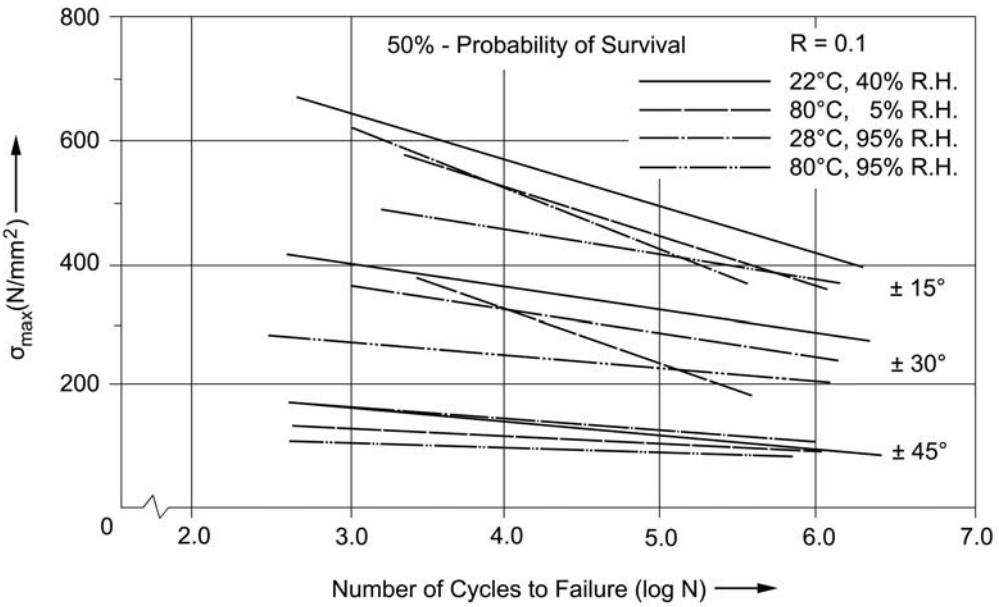


Figure 4.7-13 - Effects of temperature and moisture on the fatigue strength of angle-ply laminates, R = 0.1

4.7.5.3 Multi-directional composite properties

Figure 4.7-14 and Figure 4.7-15 show results for tension/tension and tension/compression loaded multidirectional (fibre-controlled) specimens. The main features can be summarised as, Ref. [4-15]:

- Tension/Tension (R = 0.1): Figure 4.7-14 shows that both laminates have increased fatigue strength for high moisture contents and moderate temperature. This is due to moisture affecting the residual stresses from the curing process. Furthermore, laminate Type 1 is less affected by high temperatures because it is more strongly fibre-controlled than laminate Type 2.
- Tension/Compression (R= -1): Figure 4.7-15 show that the fibre-controlled laminates are less affected by moisture and temperature than matrix-controlled ones, but the general degradation of fatigue strength is seen to continue more significantly as the number of load cycles increases.

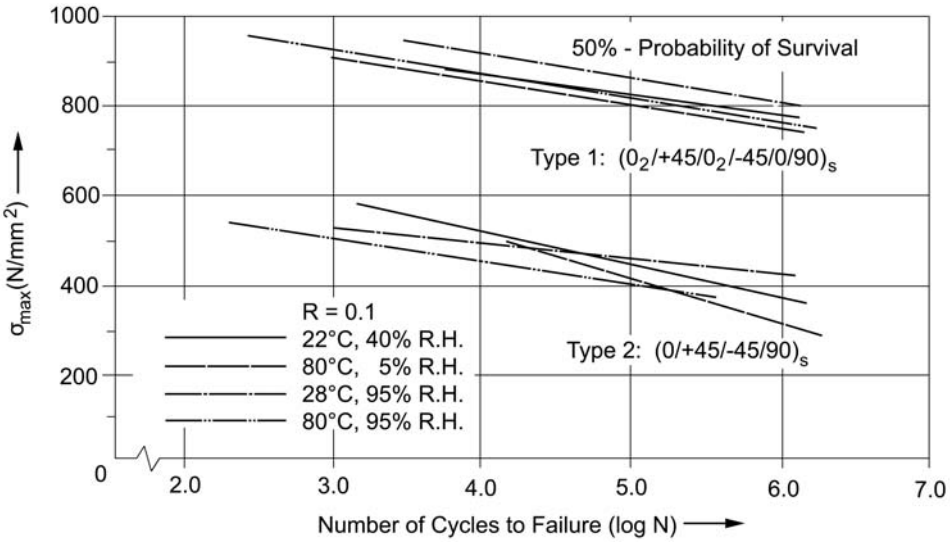


Figure 4.7-14 - Effects of temperature and moisture on the fatigue strength of multidirectional laminates, R = 0.1

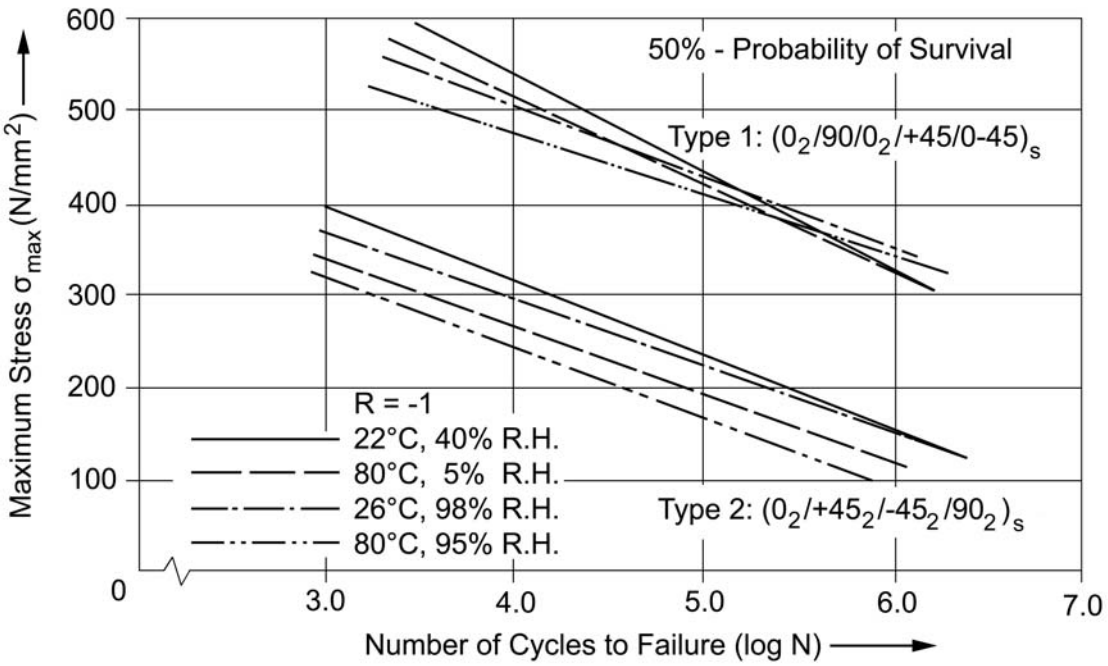


Figure 4.7-15 - Effects of temperature and moisture on fatigue strength of multidirectional laminates, R = - 0.1

The worst case for the tested quasi-isotropic specimens under tension/compression loading is:

Temperature + Moisture

It indicates that the softening of the matrix reduces fatigue strength, due to the weaker support of the fibre. Whereas in tension/tension loading, an improvement in the fatigue strength is seen.

4.7.6 Effects of central holes

4.7.6.1 General

Fibre-reinforced components often have holes, notches or irregularities causing stress concentrations which can lead to structural damage.

Investigation of damage mechanisms for holes enables the initiation location and propagation direction to be known. The behaviour has been investigated in a series of tests on T300/914, Ref.[4-17].

The investigation considered both, Ref. [4-17]:

- Static tension and compression strength of the test specimens, their fatigue lives at different stress amplitudes (σ - N-curves).
- Their residual static strengths after various numbers of load cycles.

The dominant test parameters were the:

- Laminate stacking order,
- Hole diameter, and
- Moisture content of the specimens.

4.7.6.2 Influence of stacking order

Figure 4.7-16 shows that the, Ref. [4-17]:

- Static compression strength of the laminate Types I and II, which contain the same number of 0° plies, is approximately the same.
- Compression strength of laminate Type III, having fewer 0° plies (4 instead of 10 in Types I and II), is considerably less.

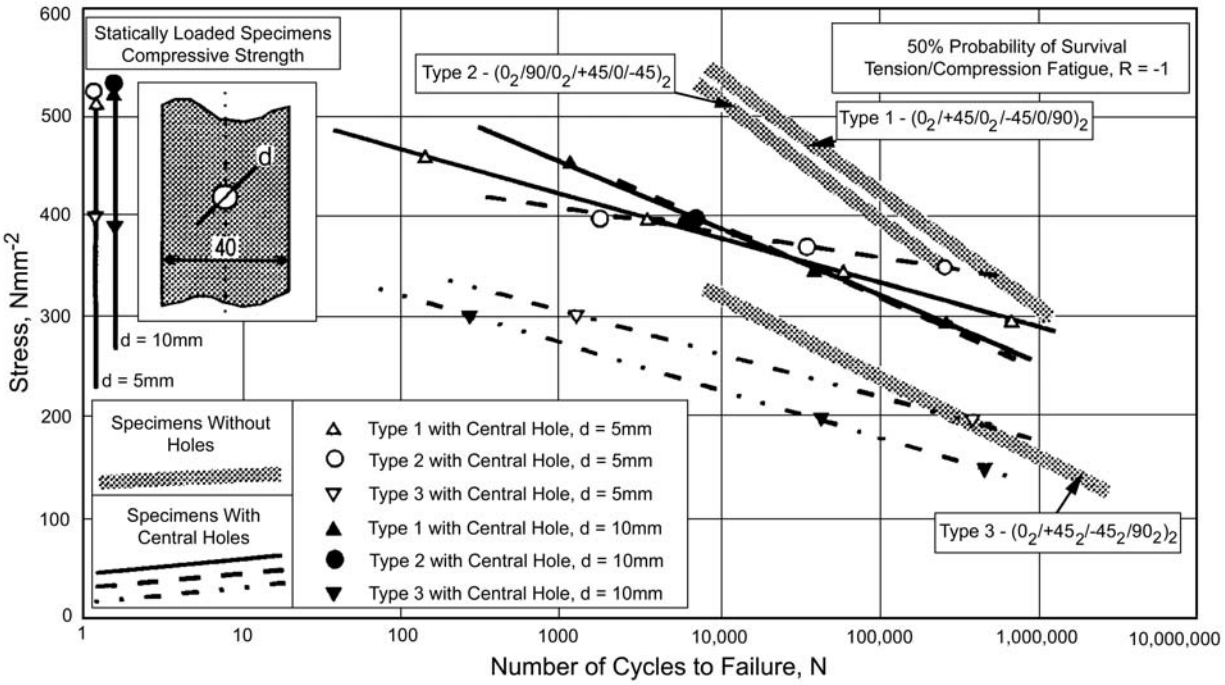


Figure 4.7-16 - Influence of stacking order and hole diameter

The fatigue strength tests show a similar trend:

- Laminate Types I and II had comparable strengths.
- Type III displayed considerably fewer load cycles to failure; a reduction by a factor of 10^{-2} to 10^{-3}, [See: Figure 4.7-16].

Since σ-*N*-curves for all laminate types have a similar slope, similar reductions can be expected for different stress amplitudes.

4.7.6.3 Influence of hole diameter

Holes in laminates reduce their static and fatigue strengths.

For static load, the reduction in compressive strength is shown in Table 4.7-1, Ref. [4-17]

Table 4.7-1 - Laminate compressive strength: Effect of hole

Laminate	Compression strength without hole	Reduction of static compression strength by holes	
		d = 5 mm	d = 10 mm
Type I	(100%)	(88%)	(91%)
Type II	(100%)	(87%)	(89%)
Type III	(100%)	(81%)	(80%)1

The influence of holes on fatigue strength is shown in Figure 4.7-16 Ref. [4-17]:

- σ-*N* curves for laminate Types I, II and III with 5mm and 10mm diameter holes, and
- σ-N curves for the same laminates without holes.

The curves show higher values as well as a much steeper slope for laminates without holes, indicating that at:

- High stress amplitudes, the presence of holes greatly reduces fatigue strength.
- Lower stress amplitudes (and correspondingly higher load cycles) the reductions are much smaller.

4.7.6.4 Effect of number of cycles

For example, at $N = 104$, a hole lowers the fatigue strength of:

- Type I and Type II laminates by 28 %, and.
- Type III laminates by 24 %.

At $N = 106$, in comparison, the same laminates with and without holes have very similar fatigue strengths.

NOTE Stress amplitudes for laminates with holes are based on net cross-sections.

[See: Figure 4.7-16]

4.7.6.5 Effect of hole size

Figure 4.7-16 shows the effect of hole diameter on fatigue strength, Ref. [4-17].

Depending on the stacking order and the stress amplitude, laminate Types I and II with 5 mm holes failed at lower numbers of load cycles than specimens with 10 mm holes.

A similar response was seen in the static compression tests, giving lower strengths for specimens with 5 mm holes than for 10 mm holes.

At low stress amplitudes, specimens with 5 mm holes failed at higher numbers of load cycles ($N = 102 \rightarrow 10^6$).

The same is valid for the static compression strength, in contrast to laminates Type I and II.

4.7.6.6 Influence of moisture

To investigate the influence of moisture on the strength of laminates containing holes, specimens were conditioned at 100% relative humidity and 70°C for 1650 hours and then tested under ambient conditions, Ref. [4-17].

The tests with fully saturated specimens show that the presence of moisture has only a minor influence on their static and fatigue strengths. Figure 4.7-17 and Figure 4.7 18 compare the test results for dry specimens and moisturised specimens, Ref. [4-17]. The former are shown as mean values for static compression strength and in terms of 50% survival probabilities for fatigue strength, and the latter in the form of individual test results.

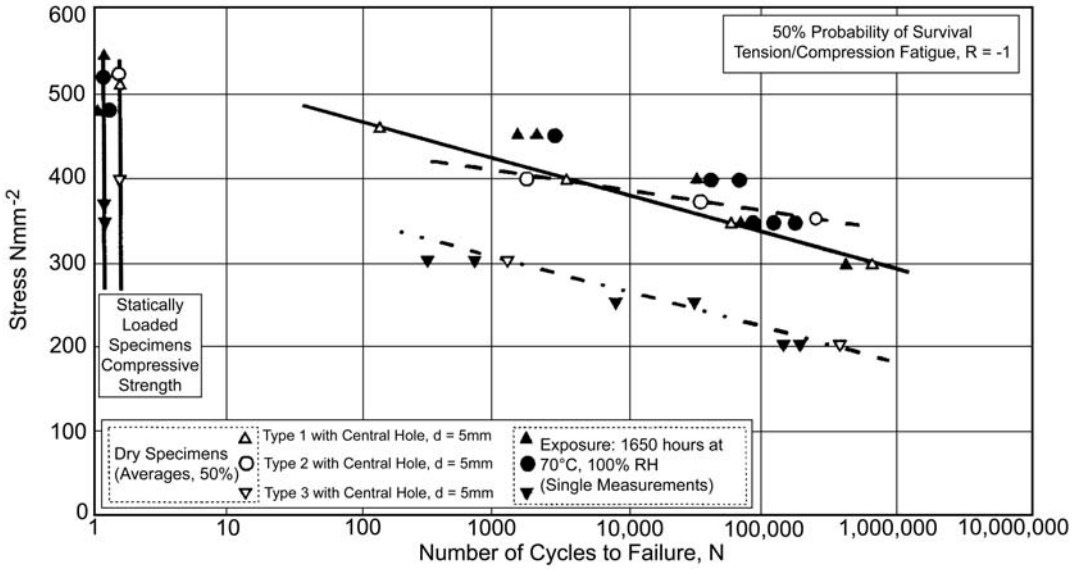


Figure 4.7-17 - Influence of moisture, hole diameter, d = 5 mm

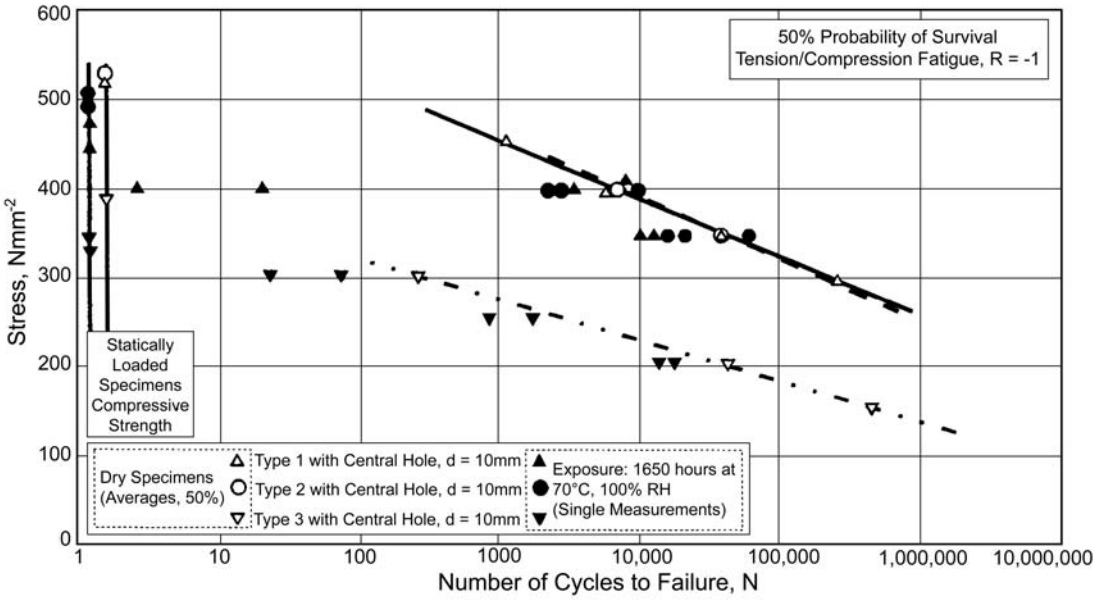


Figure 4.7-18 - Influence of moisture, hole diameter, d = 10 mm

The static strength of the conditioned specimens is only 6% to 15% lower than that of the dry specimens. Similarly the number of cycles to failure of the conditioned specimens was only slightly less than those of the dry specimens. This trend was observed in all laminate types and for both hole diameters.

4.8 References

4.8.1 General

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5
Specialist properties of composites

5.1 Introduction

Information is provided for the specialist properties and characteristics of composite materials that are of particular relevance to space structures:

- Outgassing and offgassing, contains data on materials which have acceptable outgassing characteristics, [See: 5.2]
- Thermal characteristics: CTE, [See: 5.3], thermal conductivity, [See: 5.9].
- Damping properties provides data on the damping properties of various types of UD and multidirectional carbon-, glass- and aramid-reinforced materials, [See: 5.4].
- Radiation effects for aramid-based composites, [See: 5.7].
- RF radio frequency transparency, with guidelines on the use of aramid-based composites, [See: 5.8].

5.2 Outgassing and offgassing

5.2.1 General

5.2.1.1 Types of gaseous products

Depending on the application, there are restrictions on the gaseous products released from materials or finished articles in operational vacuum conditions that can contaminate:

- Other equipment, known as 'outgassing'.
- Air during preparatory or operational conditions for manned spacecraft, known as 'offgassing'.

5.2.1.2 Outgassing test

Testing procedures to determine outgassing levels are given in ECSS-Q-ST-70-02 and NASA STD 6001; previously ESA PSS-01-702 and NASA NHB-8060 1A.

Table 5.2.1 shows examples of materials that passed the above outgassing test procedures, when using the limits below, however the tests only subjected the materials to 24 hours at 125°C and $<10^{-5}$ torr. Long term out gassing 'ageing' tests were not performed, and therefore the materials listed are for guidance only,as these tests should also be considered .

The acceptance limits that were used for assessment were:

- Test A: For materials used in general spacecraft applications:
  - TML - total mass loss: <1.0%.
  - CVCM - collected volatile condensable material: <0.1%.
- Test B: For materials used in the fabrication of optical devices or used in their vicinity:
  - RML - recovered mass loss: 0.1%
  - CVCM - collected volatile condensable material: <0.01%.

In general, epoxy resins and epoxy matrix composites should pass the outgassing criteria.

5.2.1.3 Offgassing test

ECSS-Q-ST-70-29 provides the test method for materials and assembled articles to be used in a manned space vehicle crew compartment. The test involves monitoring the evolution of gaseous products for an assembled article subjected to slight radiant heat in the specified test atmosphere.

5.2.2 Materials with satisfactory outgassing characteristics

Table 5.2-1 lists the materials that have passed the 24hr test cycle outgassing test.

Table 5.2-1 - Materials with satisfactory outgassing characteristics

Resin/Composite System	Comments
Fibredux 914 Code 69 Code 87 Code 92	Commonly used for epoxy prepreg systems for space structures.
Courtaulds 3501 Epoxy Epikote DX210 + BF3400 Epikote 828/Versamid 140 Araldite CY209/HT972	Resin systems. Older variants now largely redundant or no longer known by these names.
LY556/HY906/DY063	Filament winding resin.
Hexcel F155, F584, F593 epoxies Fiberite 976	177°C cure. Usually with T300 fibres as prepregs.
Fibredux 6376 Cyanamid Cycom 1806 Cyanamid HST-7 Narmco Rigidite 5245	New generation prepregs. 5245 has good outgassing characteristics.
ICI APC2	Carbon fibre AS4/thermoplastic PEEK, excellent outgassing characteristics.

For further information See: ECSS-Q-70-71: Data for selection of space materials and processes; 6.21 for thermoplastic matrix composites.

5.3 Thermal expansion

5.3.1 General

Dimensional stability is important for many space structures that experience changes in their service temperature.

Carbon or aramid fibre composites can be designed to exploit the low longitudinal coefficients of thermal expansion, CTE, of the fibres.

Thermal expansion characteristics can be summarised as:

- Carbon and aramid fibres:
  - longitudinal CTE is slightly negative, but
  - transverse CTE is positive.
- Glass fibres:
  - positive CTE's
- Resins:
  - large positive CTE's which are not constant with temperature.

[See also: 4.4; Clause 12 for assessment of coefficients of thermal expansion; 21.2 for recommended bonding materials; 28.6 for environmental effects dimensionally stable structures]

5.3.2 CTE data on the constituents of composite materials

5.3.2.1 General

Table 5.3-1 provides typical data for some constituents of composite materials.

Table 5.3-1 - Coefficients of thermal expansion for the constituents of composite materials

	CTE (10^{-6} °C^{-1})		Temperature Range (°C)
	Longitudinal	Transverse	
Carbon fibres	-0.5 to -1.3*	10 to 30*	-
Kevlar 49 fibre	-2 -4 -5	+59 - -	0 to 100 100 to 200 200 to 260
S2 Glass fibre	+5	+5	
Epoxy resins	+30* (Not constant with temperature)		-
* Precise value is dependant on the specific commercial material.			

5.3.2.2 Carbon fibres

The longitudinal CTE of carbon fibres varies with tensile stiffness. CTE becomes more negative as fibre stiffness increases, as shown in Table 5.3-2

Table 5.3-2 - Variation of CTE with carbon fibre stiffness

Carbon Fibre Type	α_1 (x 10^{-6} °C^{-1})	
XN50A	-1.3	↑ Increasing Stiffness
M46J	-0.7	
T300	-0.4	

5.3.2.3 Epoxy resins

Coefficients of thermal expansion for Fibredux 914 resin are shown in Table 5.3-3, Ref. [5-1].

Table 5.3-3 - CTE for Fibredux 914 epoxy resin

Temperature Range (°C)	CTE (x10^{-6} °C^{-1})
-150 to -130	28.5
-130 to -110	27.0
-110 to -90	29.2
-90 to -70	32.0
-70 to -50	31.8
-50 to -30	31.9
-30 to -10	31.8
0 to 20	37.5
20 to 40	36.5
40 to 60	39.4
60 to 80	43.2
80 to 100	45.4
100 to 120	48.5
120 to 140	50.2
140 to 160	52.1
160 to 180	66.7
180 to 200	92.1
200 to 220	87.0

5.3.2.4 Effect of cure schedule

The effect of the cure schedule on CTE for Code 92 and CY209/HT972 resin systems is shown in Table 5.3-4 and Table 5.3-5, respectively, Ref. [5-1].

Table 5.3-4 - Effect of cure schedule on CTE of Code 92 epoxy resin

Temp. (°C)	CTE (10^{-6} °C^{-1})		
	Cure Cycle 1	**Cure Cycle 2**	**Cure Cycle 3**
	4 hours/50°C, 2 hours/125°C	6 hours/60°C, 4 hours/120°C	6 hours/60°C, 4 hours/120°C and 4 hours/140°C
90	-	-	102.4
80	-	96.5	-
70	103.6	90.5	85.7
50	85.7	82.2	78.6
30	75.0	76.2	70.3
10	73.8	71.5	66.7
-10	66.7	65.5	59.5
-30	59.5	58.4	52.4
-50	54.8	52.4	46.4
-70	42.9	41.7	42.9

Table 5.3-5 - Effect of cure schedule on CTE of CY209/HT972 epoxy resin

Temp. (°C)	CTE (10^{-6} °C^{-1})		
	Cure Cycle 1	**Cure Cycle 2**	**Cure Cycle 3**
	4 hours/50°C, 2 hours/125°C	20 hours/45°C, 7 hours/120°C	20 hours/45°C, 7 hours/120°C and 4 hours/140°C
90	97.4	76.2	66.7
70	76.1	67.9	63.2
50	66.2	59.5	61.9
30	56.7	54.8	59.5
10	55.5	50.0	53.5
-10	50.0	45.3	48.8
-30	47.2	41.7	44.4
-50	42.5	38.1	42.4
-70	37.8	36.9	40.5

5.3.3 CTE data on unidirectional composites

5.3.3.1 Carbon fibre UD materials

Table 5.3-6 provides CTE data for unidirectional materials with various types of carbon fibres.

Table 5.3-6 - CTE for carbon fibre unidirectional material

Fibre	Resin	Volume of Fibre	CTE (10^{-6} °C^{-1})	
			Longitudinal	Transverse
UD Materials with High Strength Carbon Fibres				
T300 (1)	Fibredux 914	?	-0.45	+29
UD Materials with High Modulus Carbon Fibres				
MS (1)	Fibredux 914	?	-0.80	+38 (60°C)
P55 (2)	ERL-1962	60%	-0.76	+30
P75 (2)	ERL-1962	60%	-0.97	+30
P100 (2)	ERL-1962	60%	-1.15 (±1%)	+31 (±0.3%)
UD Materials with Carbon IM Fibres				
T50 (2)	ERL-1962	60%	-0.54	+30
Key:	Data from suppliers:	(1) Ciba Geigy	(2) Union Carbide	

5.4 Damping properties

5.4.1 General

Damping is one of the most structure-sensitive properties. Thus, slight differences in composition, stress history or test conditions can lead to significantly different results. Publications rarely detail information of these features.

Although, theoretically, as composite damping is linear, the structural damping measured equals the material damping, the total damping energy absorbed per cycle by a test specimen is, for a low damping material, very small compared with that generally dissipated within conventional grips, joints and other features of the testing apparatus.

Extreme care is needed to minimise such extraneous effects to prevent errors of an order of magnitude occurring. Some of the high damping values observed in the data can be directly attributed to extraneous losses.

Use of this damping data requires interpolation or extrapolation. However, changes in predominant mechanisms with stress level, frequency, temperature, etc., make such processes inaccurate.

The data presented is divided into:

- Unidirectionally reinforced composites, [See:5.5]:
  - carbon fibre reinforced
  - glass fibre reinforced
  - aramid fibre reinforced

- Multidirectional composites,[See:5.6]:
  - carbon fibre reinforced
  - glass fibre reinforced
  - aramid fibre reinforced
- Theoretical methods [See: Clause 15] for:
  - predicting the damping properties,
  - approximated data for Loss Factors of various composites,
  - definitions of specific terms.

5.4.2 Analytical notation

Ψ Specific damping capacity, $\Psi = \eta \times 2\pi$

η Loss factor

ξ Damping ratio, $\xi = \dfrac{\omega_2 - \omega_1}{2\omega_n}$

ω_1, ω_2 Frequencies at which energy dissipated

ω_n Resonance frequency

V_f Fibre volume content

CFRP Carbon fibre reinforced plastic

GFRP Glass fibre reinforced plastic

Subscripts:

1 Longitudinal

2 Transverse

12 Shear

Superscripts:

f Flexure

S Shear

T Torsion

5.5 Damping: unidirectional composites

5.5.1 Carbon/epoxy

5.5.1.1 Notation

[See: 5.4 for analytical notation]

5.5.1.2 HM-S/DX209 and HT-S/DX210

Table 5.5-1 summarises the material and test method, Ref.[5-10]. The results of damping tests on these materials are given in Table 5.5-2, Ref.[5-10].

The effects of fibre orientation within the composite on the damping properties are shown for, Ref. [5-10]:

- Flexural damping, Figure 5.5-1 and Figure 5.5-2
- Torsional damping, Figure 5.5-3 and Figure 5.5-4.

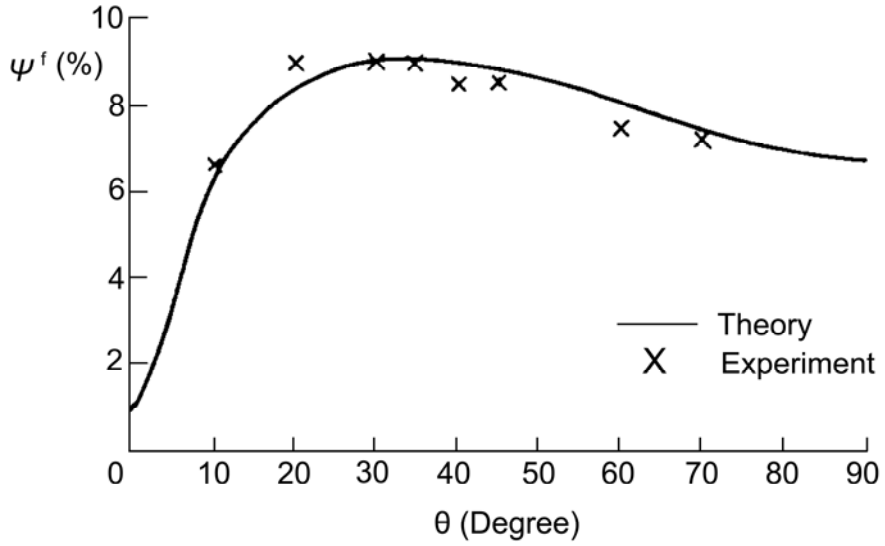
Table 5.5-1 - Material and test method

Material:	Carbon/epoxy laminate: HM-S/DX209 HT-S/DX210, Ref. [5-10].
Method:	Measurement of energy input stored in a free-free beam vibrating in flexure and a cantilevered beam in shear.

[See: Data in, Table 5.5-2, Figure 5.5-1, Figure 5.5-2, Figure 5.5-3 and Figure 5.5-4]

Table 5.5-2 - Damping data for UD carbon/epoxy: HM-S/DX209 and HT-S/DX210

Materials	ψ_1^f %	ψ_2^f %	ψ_{12}^f %
HM-S/DX209, Vf = 0.5	0.64	6.9	10
HT-S/DX210, Vf = 0.5	0.49	5.48	6.75



[See: Table 5.5-1 for material and test method]

Figure 5.5-1 - Variation of flexural damping with fibre orientation for HM-S/DX209, V_f = 0.5

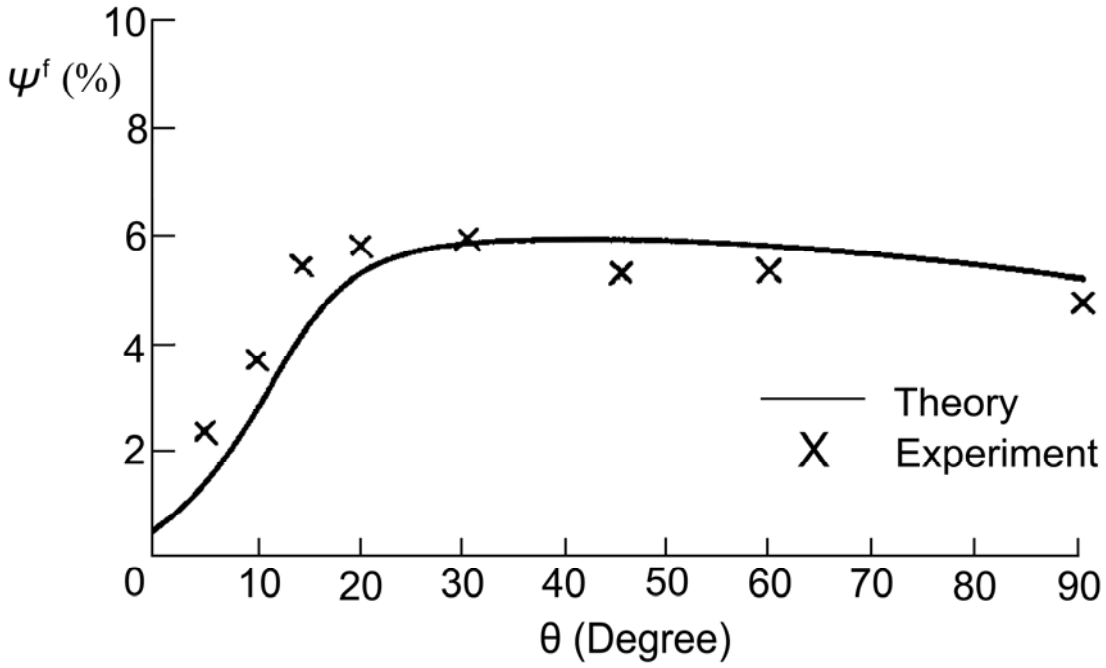


Figure 5.5-2 - Variation of flexural damping with fibre orientation for HM-S/DX210, V_f = 0.5

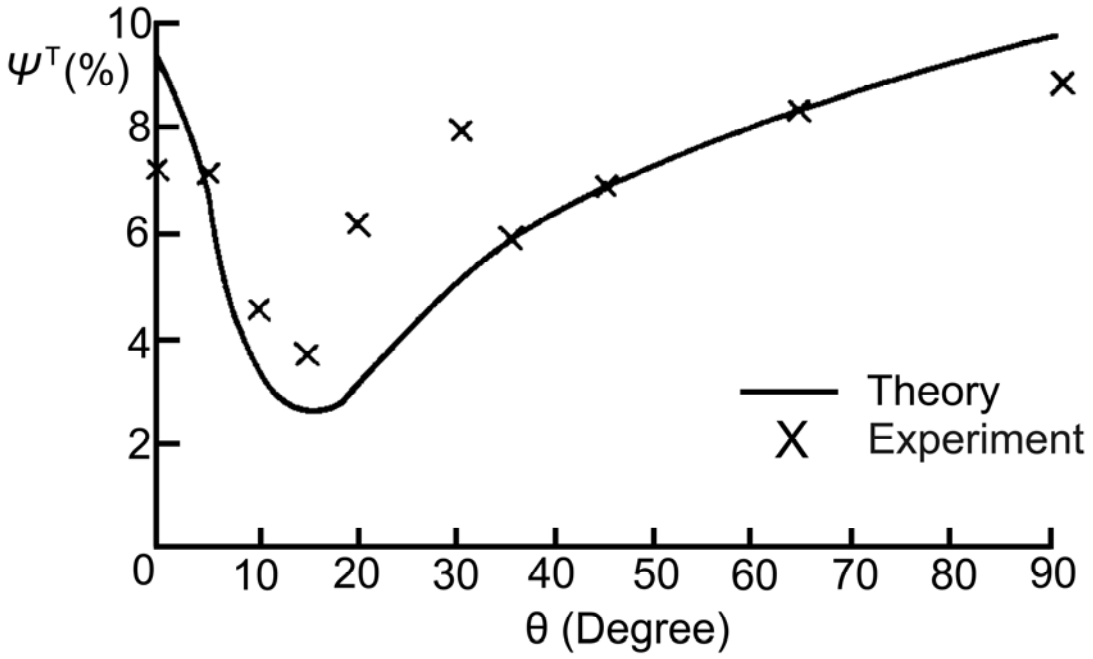


Figure 5.5-3 - Variation of torsional damping with fibre orientation for HM-S/DX209, V_f = 0.5

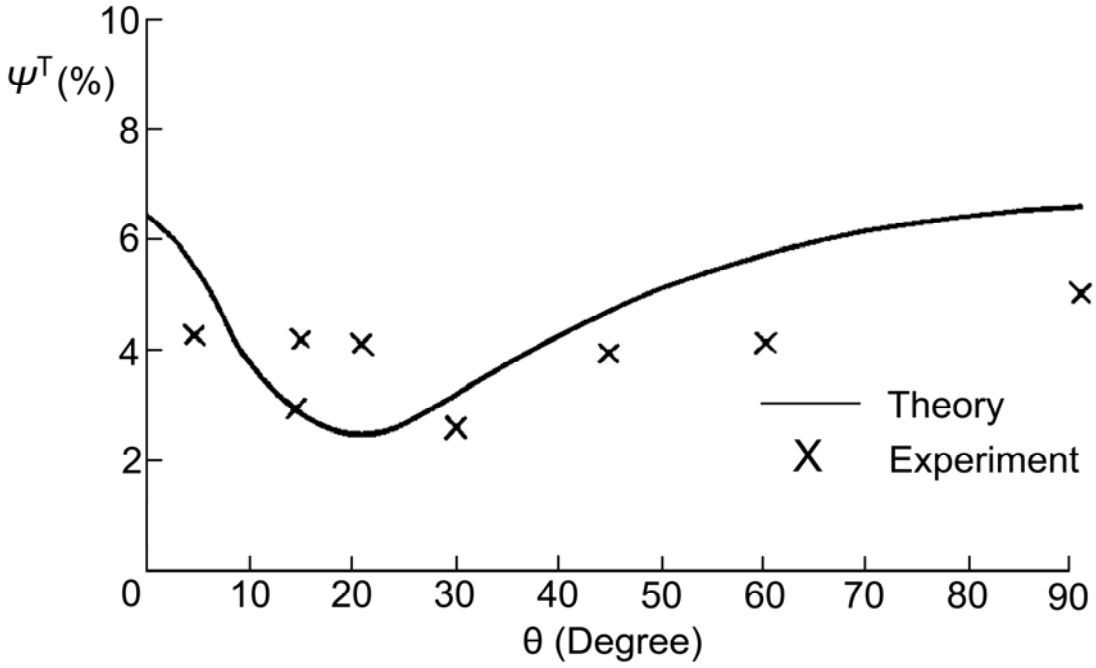


Figure 5.5-4 - Variation of torsional damping with fibre orientation for HM-S/DX210, V_f = 0.5

Table 5.3-3 summarises the material, test and viscous damping data for a carbon/epoxy composite, Ref. [5-9].

Table 5.5-3 - Material, test method and ξ for carbon/epoxy: HT-S/DX210, V_f = 0.6

Material:	Carbon/epoxy laminate: HT-S/DX210, V_f = 0.6, Ref. [5-9]
Method:	Free decay of a free-free beam in flexure and clamped-clamped beams in shear
Result:	Viscous damping ratio: ξ = 6.8 x 10^{-4} (1st mode flexure)

5.5.1.3 A-S fibres/EPON 826

Table 5.5-4 summarises the material, test method and damping test data, Ref. [5-7].

Table 5.5-4 - Material, test method and η for carbon/epoxy: A-S fibres/EPON 826, V_f = 0.607

Material:	Carbon/epoxy laminate: A-S Fibres/EPON 826, V_f = 0.607, Ref. [5-7]
Method:	Free decay of thin cantilevered beam in flexure
Result:	η = 0.0017(flexure)

5.5.2 Glass/epoxy

5.5.2.1 Notation

[See: 5.4 for analytical notation]

5.5.2.2 S-994/EPON 826

Table 5.5-5 summarises the material, test method and damping test data, Ref. [5-7].

Table 5.5-5 - Material, test method and η for glass/epoxy: S-994/EPON 826, V_f = 0.613

Material:	Glass/epoxy laminate: S-994/EPON 826, V_f = 0.613, Ref. [5-7]
Method:	Free decay of thin cantilevered beam in flexure
Result:	η = 0.0029(flexure)

5.5.2.3 E-glass/DX210

Table 5.5-6 summarises the material and test method, Ref. [5-10].

The results of damping tests on this material are given in Table 5.5-7, Ref. [5-10]. The effect of fibre angle on damping is shown in Figure 5.5-5, Ref. [5-10].

Table 5.5-6 - Material, test method

Material:	Glass/epoxy laminate: E-Glass/DX210, V_f = 0.5, Ref. [5-10]
Method:	Measurement of energy input and stored energy in a free-free beam vibrating in flexure and cantilever beam in shear

[See: Data in Table 5.5-7]

Table 5.5-7 - Damping data for glass/epoxy: E-Glass/DX210

ψ_1^f %	ψ_2^f %	ψ_{12}^f %
0.87	5.05	6.91

[See: Table 5.5-6 for material and test method]

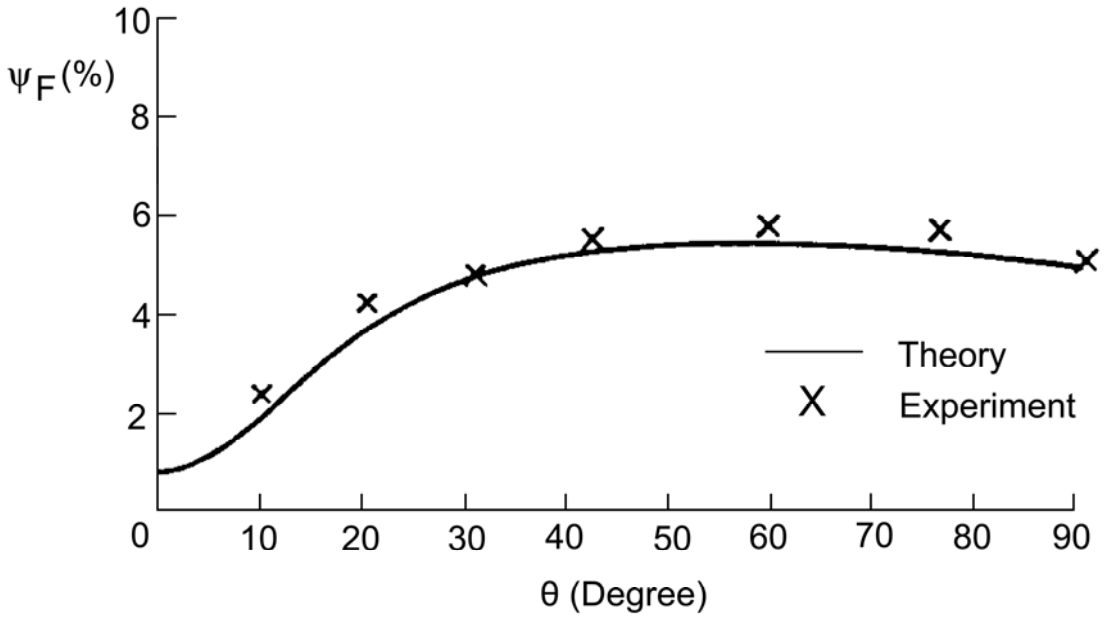


Figure 5.5-5 - Variation of damping with fibre orientation for E-Glass/DX210, V_f = 0.5

Table 5.5-8 summarises the material, test method and damping test data, Ref. [5-9]

Table 5.5-8 - Material, test method and ξ for glass/epoxy: E-Glass/DX210, V_f = 0.5

Material:	Glass/epoxy laminate: E-Glass/DX210, V_f = 0.5, Ref. [5-9]
Method:	Free decay of a free-free beam in flexure and clamped-clamped beams in shear
Result:	$\xi = 12.8 \times 10^{-4}$ (1st mode flexure)

5.5.2.4 3M-1009 265 prepreg

Table 5.5-9 summarises the material, test method and damping test data, Ref. [5-11].

Table 5.5-9 - Material, test method and η for glass/epoxy: 3M-1009 265 prepreg, V_f = not stated

Material:	Glass/epoxy laminate: 3M-1009 265 prepreg, V_f: Not stated, Ref. [5-11]
Method:	Free decay method applied to a thin beam in flexure
Results:	Loss factor, $\eta = 10^{-3}$ (flexure)

5.5.3 Aramid/epoxy

5.5.3.1 Notation

[See: 5.4 for analytical notation]

5.5.3.2 Kevlar 49 (Type 968)/EPON 826

Table 5.5.10 summarises the material, test method and damping test data, Ref. [5-7].

Table 5.5-10 - Material, test method and η for aramid/epoxy: Kevlar 49 (Type 968)/EPON 826, V_f = 0.685

Material:	Aramid/epoxy laminate: Kevlar 49 (Type 968)/EPON 826, V_f = 0.685, Ref. [5-7]
Method:	Not stated.
Results:	η = 0.018 (flexure)

5.6 Damping: multidirectional composites

5.6.1 Carbon/epoxy

5.6.1.1 HM-S/DX209 and HT-S/DX210

Table 5.6-1 summarises the materials and test method, Ref. [5-6]. Table 5.6-2 gives the 'general plate' construction, Ref. [5-6].

With respect to Table 5.6-1, Table 5.6-2 and Figure 5.6-1 to Figure 5.6-8, inclusive:

- Cross plies are defined as having 'n' layers, where:
  - all the odd layers are at 0° and of the same thickness, and
  - all the even layers are at 90° and of the same thickness, which can be different from that of the odd layers.
  - The cross-ply ratio is thus defined as:

$$m = \frac{\text{total thickness of odd layers}}{\text{total thickness of even layers}}$$

- The lay-up of the 10 ply 'General Plate' was [0°/0°/30°/30°/45°]s, [See: Table 5.6-2].

- Orientation of 'General Plate' is relative to the outermost laminate fibre direction.

Table 5.6-1 - Material and test method

Material:	Carbon/epoxy laminates: HM-S/DX209 HT-S/DX210 V_f = 0.5, Ref. [5-6]
Form:	Angle plies, cross-plies and general plate.
Method:	Measurement of energy input stored in a free-free beam vibrating in flexure and a cantilevered beam in shear.

[See: Figure 5.6-1,Figure 5.6-2,Figure 5.6-3,Figure 5.6-4,Figure 5.6-5,Figure 5.6-6,Figure 5.6-7 and Figure 5.6-8 for variation of damping with ply angle, cross-ply ratio and orientation of general plate]

Table 5.6-2 - Lay-up for general plate

Ply No.	Fibre Type	Description
1	GR-A-S	Grafil high strain treated fibre
2	MOD-111-S	Modmor high strain treated fibre
3	GR-HM-S	Grafil high modulus treated fibre
4	MOD-I-NS	Modmor high modulus treated fibre
5	GR-A-NS	Grafil high strain untreated fibre
6	GR-A-NS	-as above-
7	MOD-I-NS	
8	GR-HM-S	
9	MOD-111-S	
10	GR-A-S	

[See: Figure 5.6-1,Figure 5.6-2,Figure 5.6-3,Figure 5.6-4,Figure 5.6-5,Figure 5.6-6,Figure 5.6-7 and Figure 5.6-8 for damping data.]

The variation of damping with composite construction is shown for, Ref. [5-6]:

- Flexural damping: Figure 5.6-1,Figure 5.6-2,Figure 5.6-3 and Figure 5.6-4.
- Shear damping: ,Figure 5.6-5,Figure 5.6-6,Figure 5.6-7 and Figure 5.6-8.

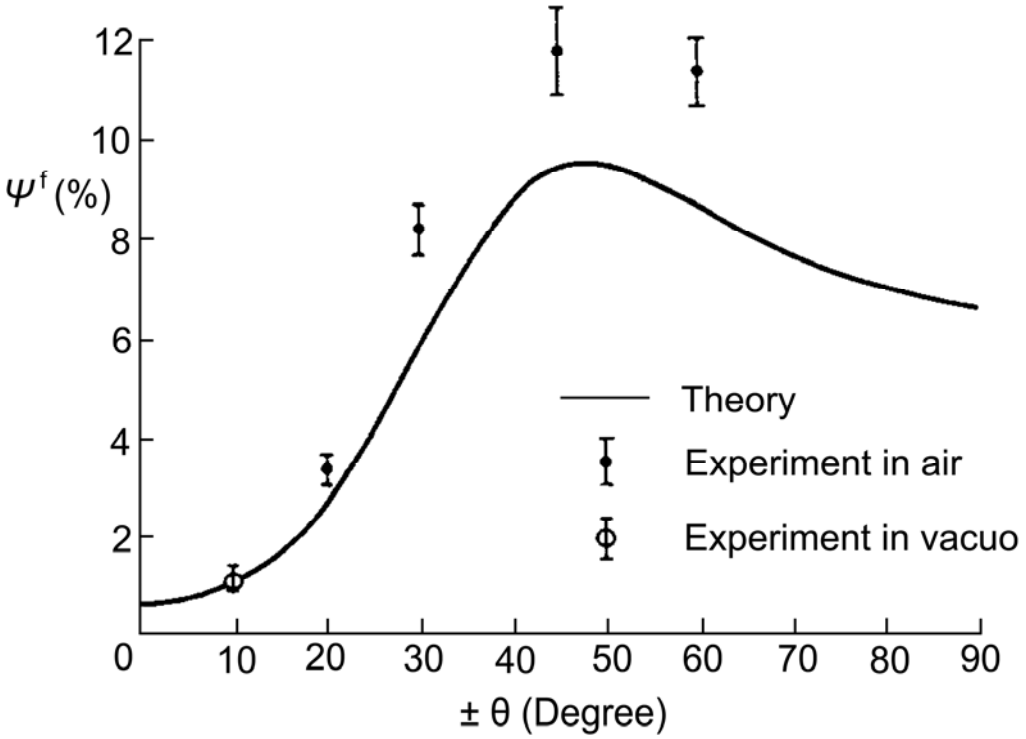


Figure 5.6-1 - Effect of ply angle on flexural damping of HM-S/DX209, V_f = 0.5

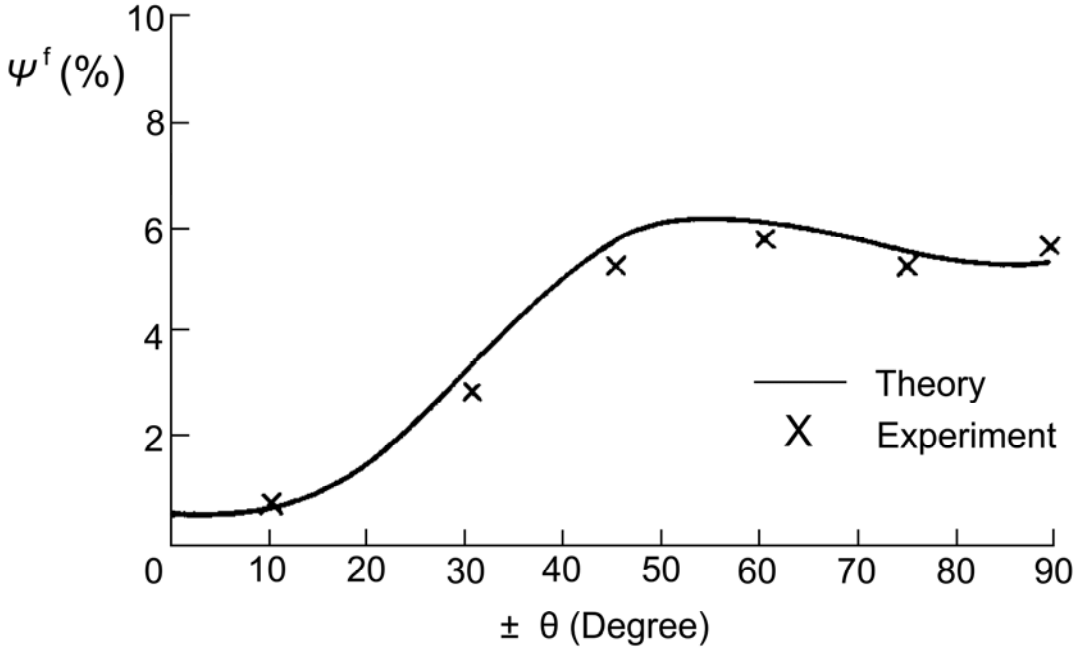


Figure 5.6-2 - Effect of ply angle on flexural damping of HM-S/DX210, V_f = 0.5

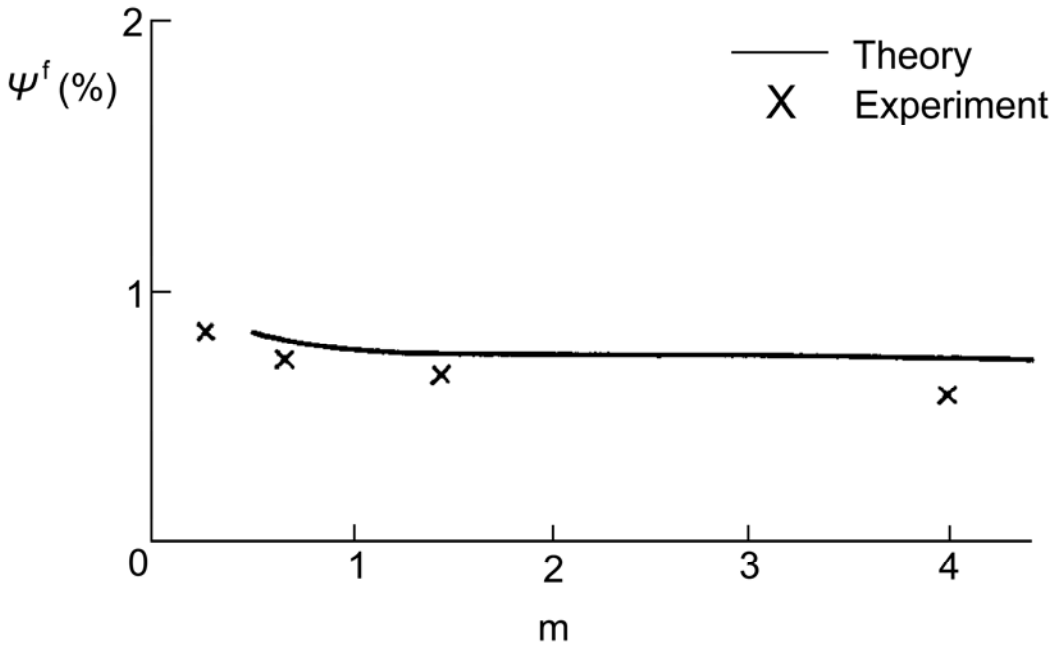


Figure 5.6-3 - Effect of cross-ply ratio on flexural damping of HM-S/DX209, V_f = 0.5

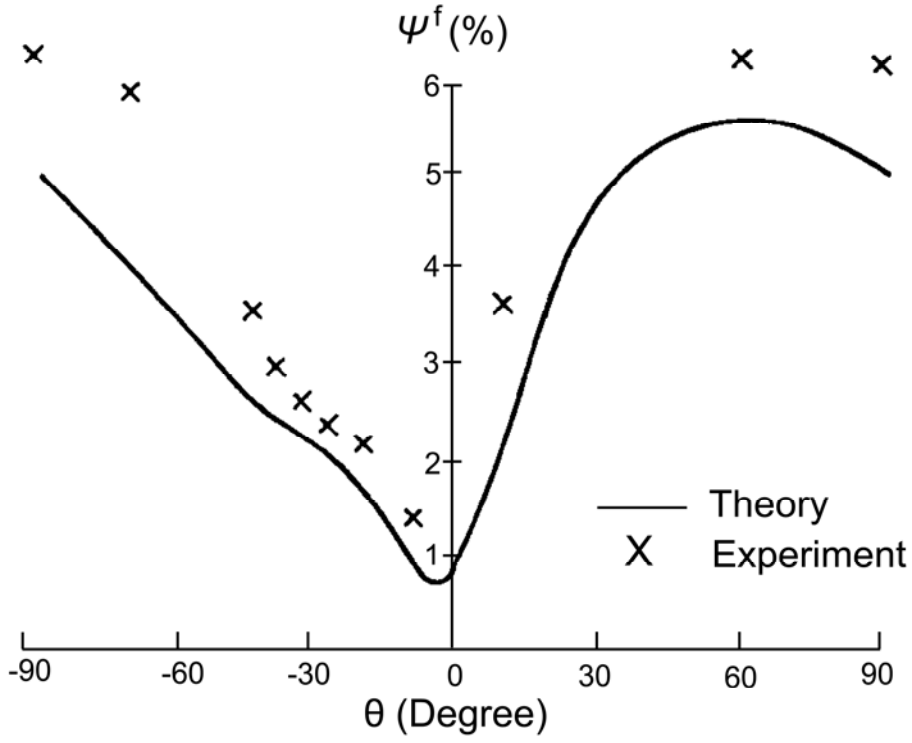


Figure 5.6-4 - Effect of orientation on flexural damping

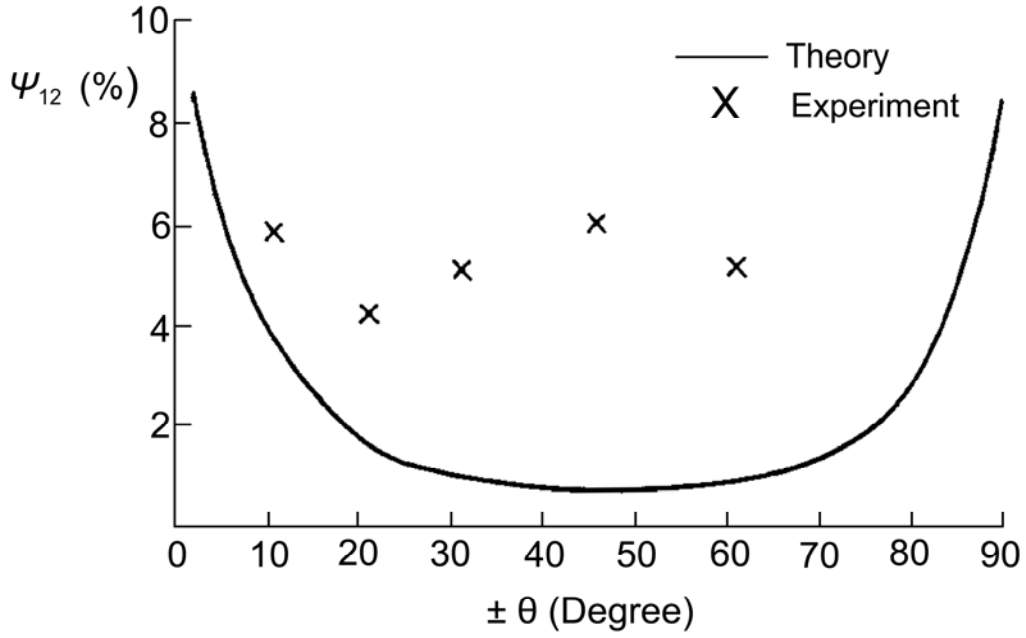


Figure 5.6-5 - Effect of ply angle on shear damping of HM-S/209, V_f = 0.5

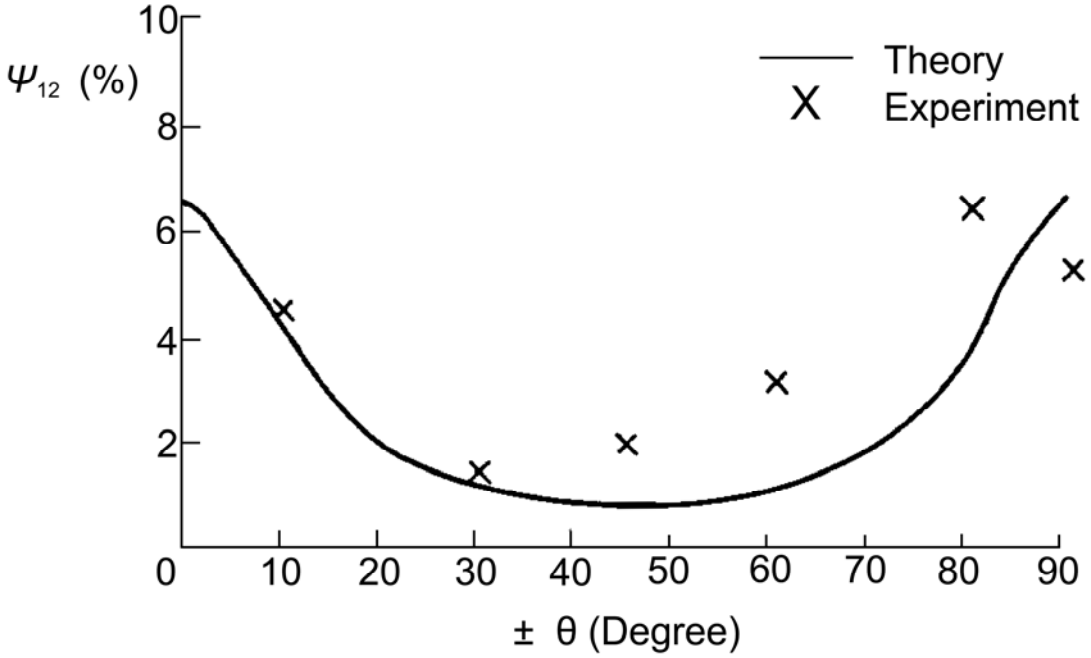


Figure 5.6-6 - Effect of ply angle on shear damping of HM-S/210, V_f = 0.5

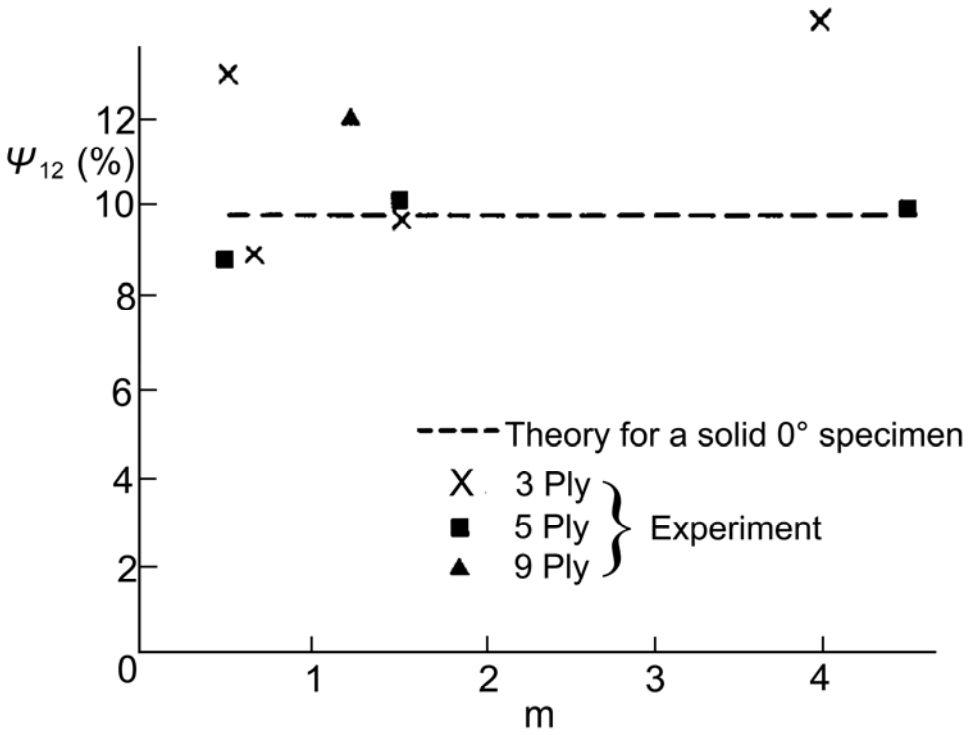


Figure 5.6-7 - Effect of cross-ply ratio on shear damping of HM-S/209, V_f = 0.5

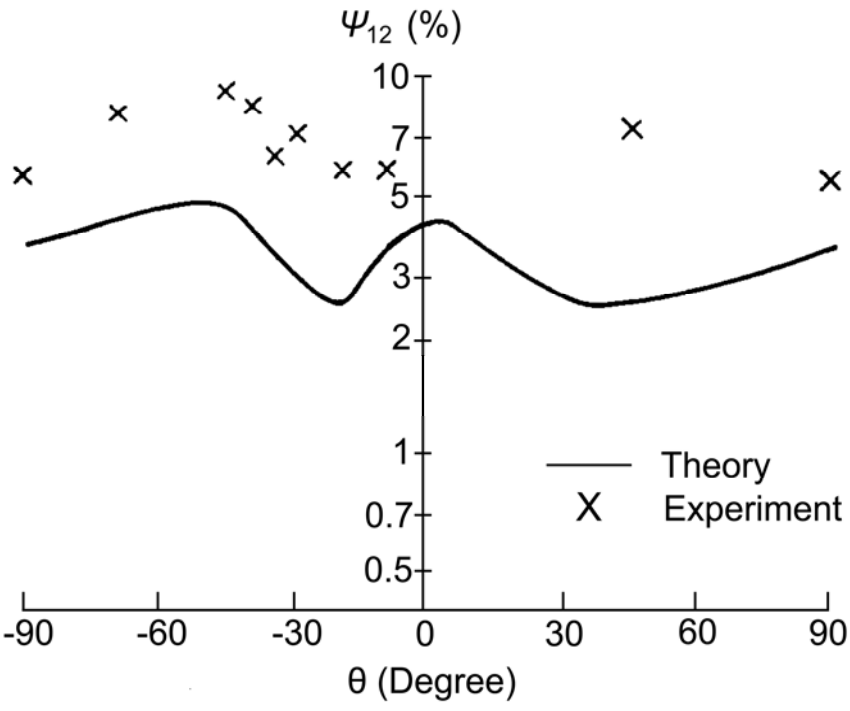


Figure 5.6-8 - Effect of orientation of general plate on shear damping

5.6.1.2 T300/Fiberite 934 fabric

Table 5.6-3 summarises the material, test method and damping data, Ref. [5-7].

Table 5.6-3 - Material, test method and η for carbon/epoxy: T300/Fiberite 934 fabric, V_f = not stated

Material:	Carbon/epoxy laminate: T300/Fiberite 934 fabric, V_f: Not stated, 6 plies, Ref. [5-7]
Method:	Free decay of a thin cantilevered beam in flexure.
Result:	η = 0.0046 (flexure, warp aligned)

5.6.1.3 T300/P305 prepreg

Table 5.6-4 summarises the material and test method, Ref. [5-14].

The natural frequencies are given in Table 5.6-5 for various specimen types, Ref. [5-14]. Flexural damping factors are shown in Figure 5.6-9, Ref. [5-14].

Table 5.6-4 - Material and test method for carbon/epoxy: T300/P305, V_f = not stated

Material:	Carbon/epoxy laminates: T300/P.305 prepreg, Ref. [5-14]
Method:	Free decay of a thin cantilever in flexure.

[See: Table 5.6-5 for natural frequencies and Figure 5.6-9 for damping data]

Table 5.6-5 - Natural frequencies for carbon/epoxy: T300/P305, V_f = as stated

Specimen Description			V_f	Natural Frequencies		
Specimen No.	No. of Plies	Fibre Orientation		1st Mode	2nd Mode	3rd Mode
1	20	0°	.51	18.0	114	319
2	20	(0 ±60°)s	.509	14.7	92.9	262
3	20	(90°, ±30°)s	.507	9.37	59.4	169
4	20	(0, 90°)s	.505	14.7	93.6	262
5	20	(±45°)s	.523	7.64	48.4	138

[See: Table 5.6-4 for material and test method]

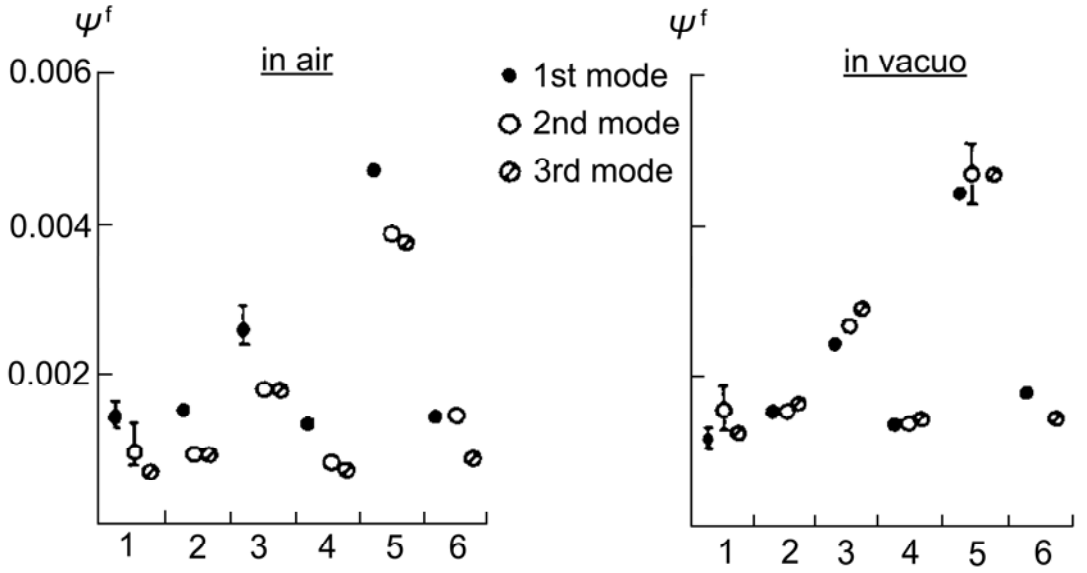


Figure 5.6-9 - Flexural damping factors of CFRP strip specimen, 6 = Al

5.6.1.4 HM-S/DX210 prepreg

Table 5.6-6 summarises the material and test method, Ref. [5-12].

The test specimen construction is given in Table 5.6-7, Ref. [5-12].

Table 5.6-6 - Material and test method for carbon/epoxy: HM-S/DX210 prepreg

Material:	Carbon/epoxy laminates: HM-S/DX210, prepreg [0°/90°]s, [0°/±60°]s, and [0°/90°/±45°]s , Ref. [5-12]
Method:	Measurement of energy input and stored in a free-free beam vibrating in flexure and a cantilevered beam in shear.

[See: Table 5.6-7, for specimen description, Figure 5.6-10, Figure 5.6-11 and Figure 5.6-12 for damping data]

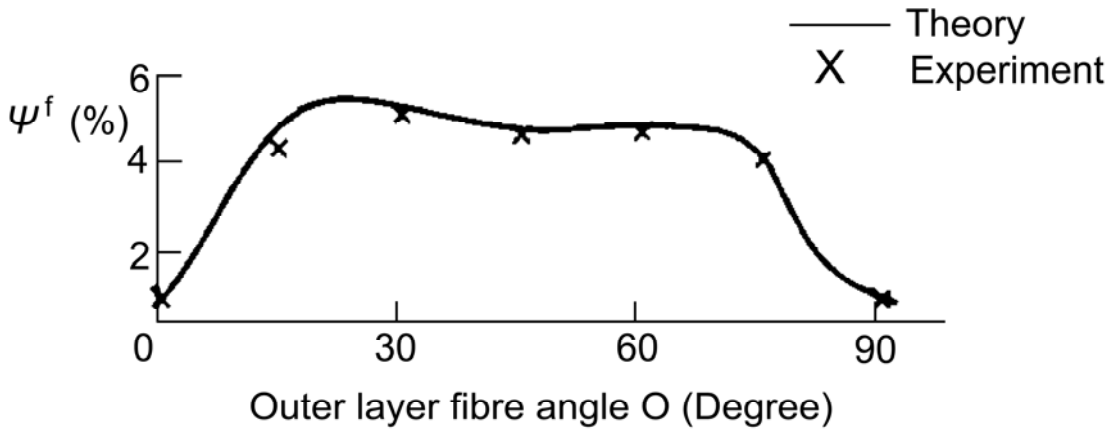
Table 5.6-7 - Specimen description for carbon/epoxy: HM-S/DX210 prepreg

Specimen No.	Orientation	No. of Plies	V_f
1	(0, 90)s	8	0.465
2	(0, ±60)s	6	0.464
3	(0, 90, ±45)s	8	0.480

[See: Table 5.6-6, Figure 5.6-12 and Figure 5.6-13 for damping data]

The variation in damping with outer layer fibre direction is shown for the types of specimens, Ref. [5-12]:

- type '1' cross-ply in Figure 5.6-10.
- type '2' [0°/±60]s in Figure 5.6-11.
- type '3' [0°/90°/±45]s in Figure 5.6-12.



[See: Table 5.6-7 for specimen description]

Figure 5.6-10 - Variation of damping with outer layer fibre orientation for cross ply CFRP "1"

[See: Table 5.6-7 for specimen description]

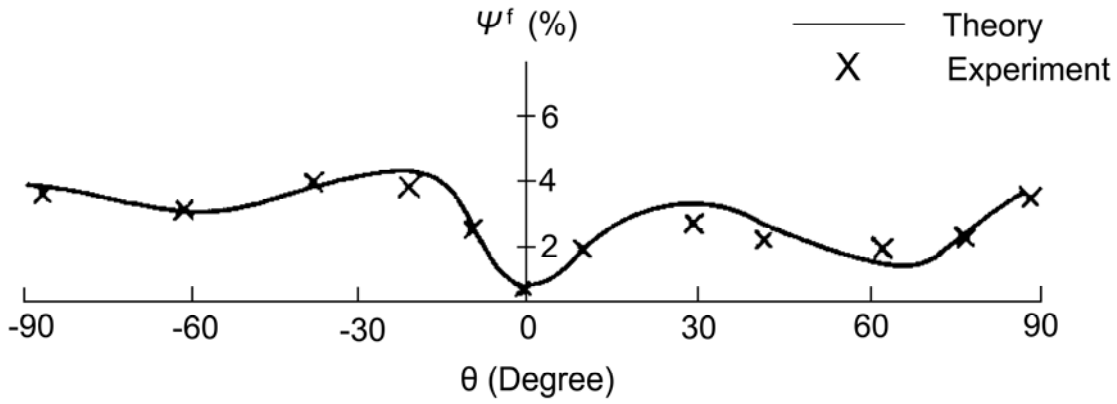
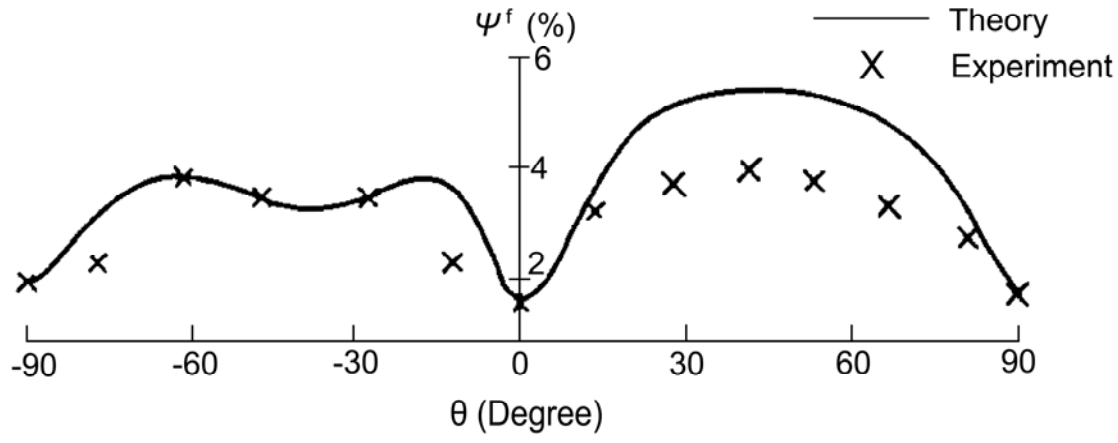


Figure 5.6-11 - Variation of damping with outer layer fibre orientation for [0°/±60]s CFRP "2"



[See: Table 5.6-7 for specimen description]

Figure 5.6-12 - Variation of damping with outer layer fibre orientation for [0°/90°/±45]s CFRP "3"

5.6.2 Glass/epoxy

5.6.2.1 E-glass/F-155 prepreg fabric

Table 5.6-8 summarises the material, test method and damping data, Ref. [5-7].

Table 5.6-8 - Material, test method and η for glass/epoxy: E-Glass/F155 prepreg fabric

Material:	Glass/epoxy laminate: E-glass F-155 prepreg fabric, V_f: Not stated, 30 plies, Ref. [5-7]
Method:	Free decay of a thin cantilevered beam in flexure.
Result:	η = 0.0065 (flexure)

5.6.2.2 E glass/3M Scotchply prepreg (cross-ply)

Table 5.6-9 summarises the material and test method, Ref. [5-12].

The test specimen construction is given in Table 5.6-10, Ref. [5-15].

Table 5.6-9 - Material and test method for glass/epoxy: E Glass/3M Scotchply, prepreg cross-ply

Material:	Glass/epoxy laminate: E-glass/3M Scotchply, prepreg cross-ply, V_f = 0.5, Ref. [5-15]
Method:	Measurement of energy input and stored in a free-free beam vibrating in flexure and a cantilevered beam in shear.

[See: Table 5.6-10 for specimen description and Figure 5.6-13, Figure 5.6-14 and Figure 5.6-15 for damping data]

Table 5.6-10 - Specimen description for glass/epoxy: E Glass/3M Scotchply, prepreg cross-ply

Specimen No.	Orientation	No. of Plies	V_f
4	(0, 90)s	12	0.45
5	(0, ±60)s	6	0.434
6	(0, 90, ±45)s	8	0.555

[See: Table 5.6-9 for test method and Figure 5.6-13, Figure 5.6-14 and Figure 5.6-15 for damping data]

The variation in damping with outer layer fibre direction is shown for the types of specimens, Ref. [5-15]:

- type '4' cross-ply in Figure 5.6-13.
- type '5' [0°/±60]s in Figure 5.6-14.
- type '6' [0°/90°/±45]s in Figure 5.6-15.

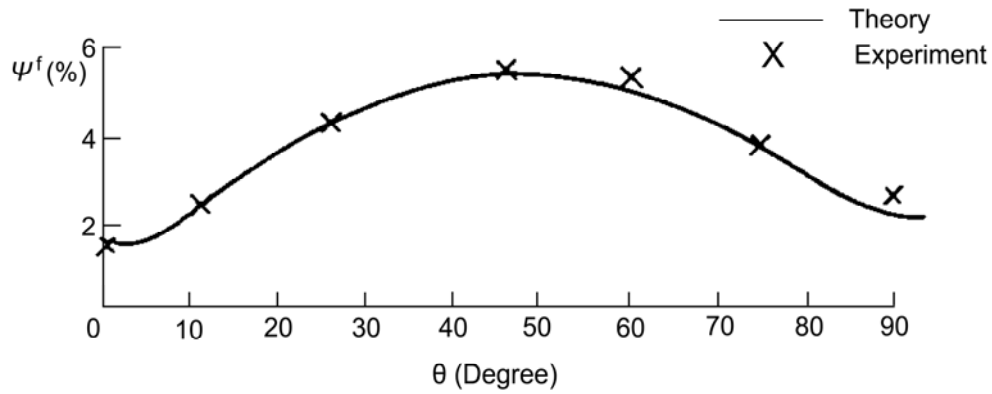


Figure 5.6-13 - Variation of damping with outer layer fibre orientation for cross-ply GFRP "4"

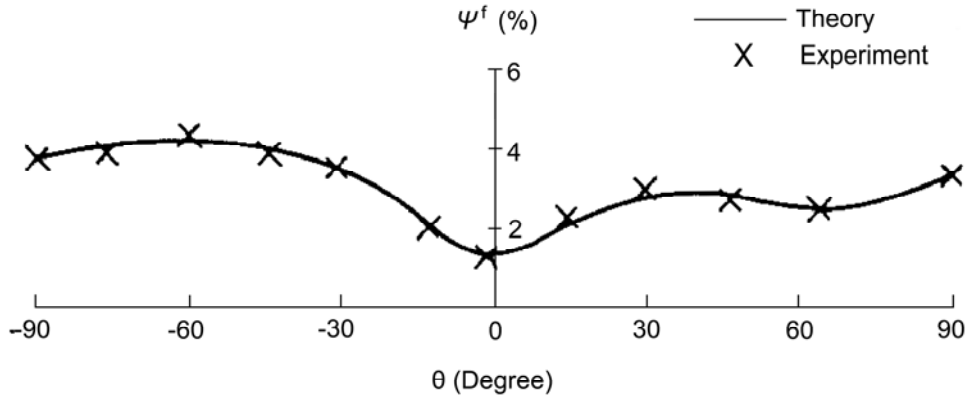


Figure 5.6-14 - Variation of damping with outer layer fibre orientation for [0°/±60°]s GFRP "5"

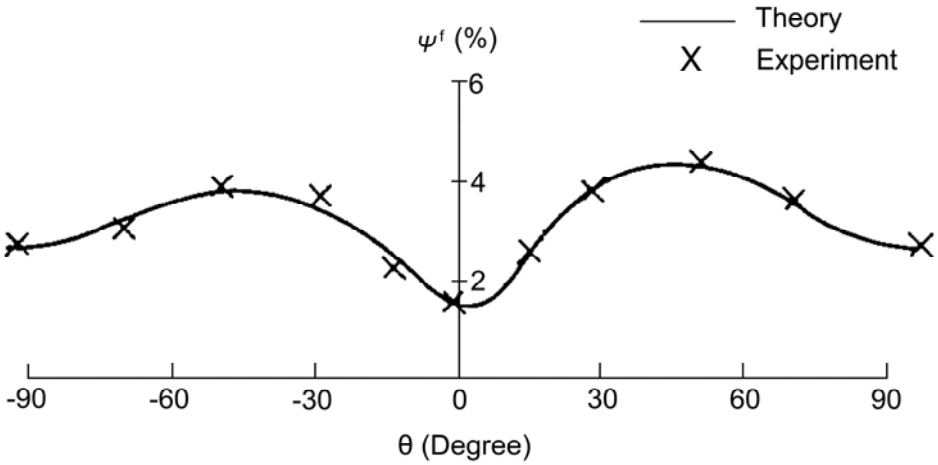


Figure 5.6-15 - Variation of damping with outer layer fibre orientation for [0°/90°/±45°]s GFRP "6"

5.6.2.3 3M-1009/26S prepreg cross-ply

Table 5.6-11 summarises the material, test method and damping data, Ref. [5-11].

Table 5.6-11 - Material, test method and η for glass/epoxy: 3M-1009/26S prepreg cross-ply, V_f= not stated

Material:	Glass/epoxy laminates: 3M-1009/26S, prepreg cross-plies, V_f: Not stated, Ref. [5-11]
Method:	Free decay method applied to a thin beam in flexure.
Result:	Loss factor $\eta = 2.5 \times 10^{-3}$ (1st mode flexure)

5.6.2.4 E-glass/epoxy (type not stated)

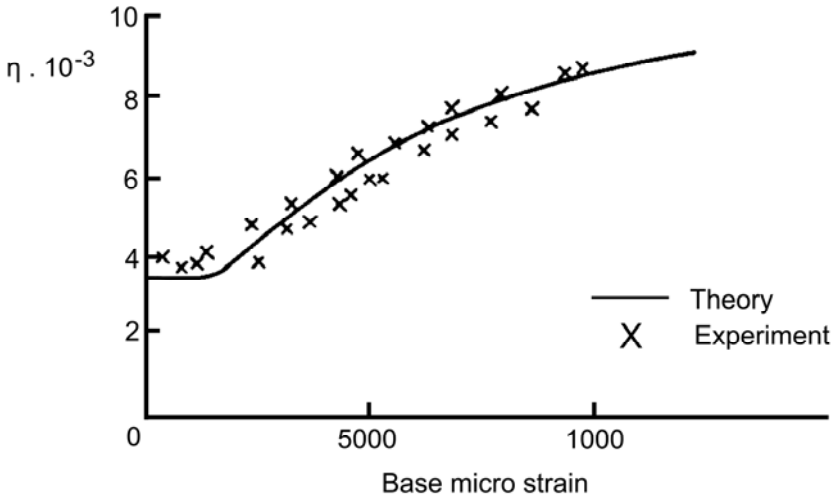
Table 5.6-12 summarises the material and test method, Ref. [5-16].

Damping as a function of peak bending strain for this material is shown in Figure 5.6-12, Ref. [5-16].

Table 5.6-12 - Material and test method for E-Glass/epoxy cross-ply, V_f= not stated

Material:	Glass/epoxy laminates: E-glass/epoxy, cross-plies, V_f: Not stated, Ref. [5-16]
Method:	Free decay in a thin cantilevered beam in flexure.

[See: Figure 5.6-16 for the effect of high strain and interfacial slip]



[See: Table 5.6-12 for material and test method]

Figure 5.6-16 - Damping as a function of peak bending strain; load monotonically increasing; GFRP cross plies

5.6.2.5 3M Scotchply 1002

Table 5.6-13 summarises the material and test method, Ref. [5-17].

Damping data (ξ) for various modes and frequencies are given for, Ref. [5-17]:

- Specimen types [0°/±60°]s and [0°/90°/±45°]s in Table 5.6-14.
- Specimen types [0°/90°/±45°]s in Table 5.6-15.

Damping ratio is shown for, Ref. [5-17]:

- π/3 laminates in Figure 5.6-17.
- π/4 laminates in Figure 5.6-18.

Table 5.6-13 - Material and test method for 3M Scotchply 1002, [0°/±60°]s and [0°/90°/±45°]s

Material:	Glass/epoxy laminates: 3M Scotchply 1002, [0°/±60°]s and [0°/90°/±45°]s, V_f: Not stated. Ref. [5-17]
Method:	Half-power bandwidth method on double cantilevered thin beams in flexure.

[See: Table 5.6-14 and Table 5.6-15 for damping data, and Figure 5.6-17 and Figure 5.6-18]

Table 5.6-14 - ξ for glass/epoxy: 3M Scotchply 1002 [0°/±60°]s

Mode	Frequency (Hz)	$\xi \times 10^2$
1	41.8	0.83-1.07
2	264	0.34
3	735	0.24
5	2370	0.34
7	4910	0.55

Axis at 0° to outer fibre direction.

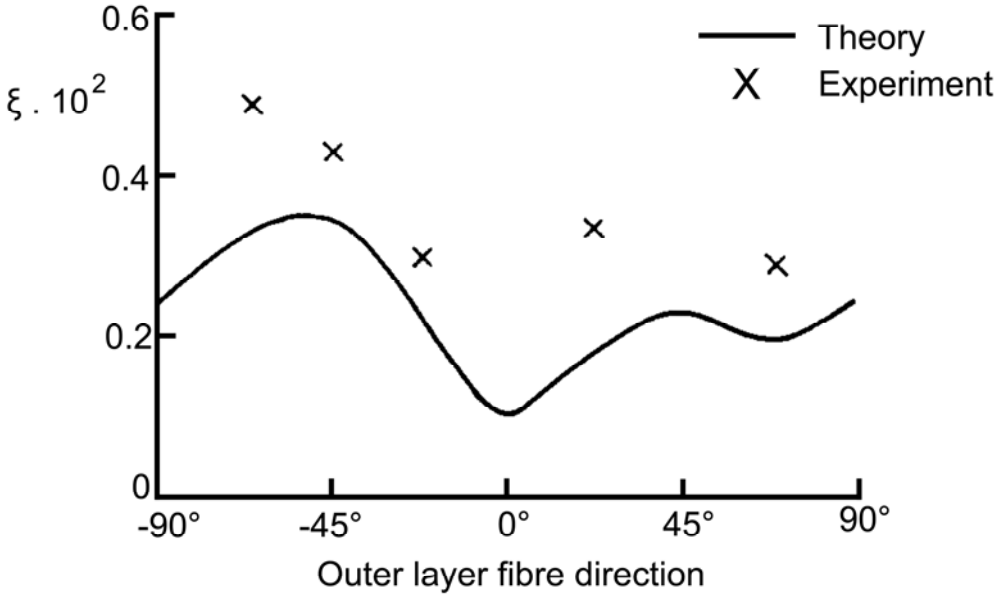
[See: Table 5.6-13 for material and test method]

Table 5.6-15 - ξ for glass/epoxy: 3M Scotchply 1002 [0°/90°/±45°]s

Mode	Frequency (Hz)	$\xi \times 10^2$
1	51.7	1.35
2	329	0.33
3	915	0.28
5	2940	0.44
9	9360	1.18

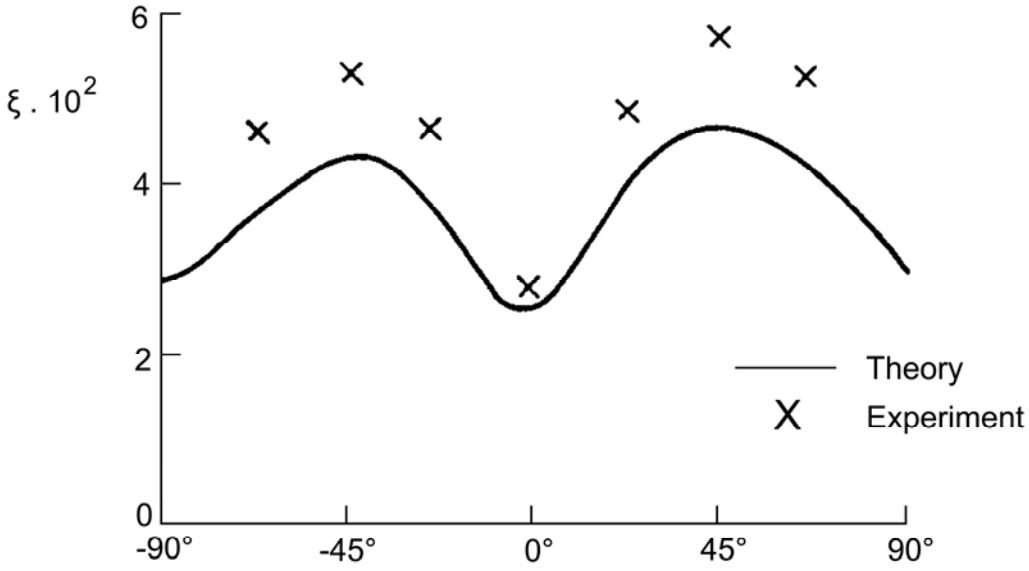
Axis at 0° to outer fibre direction.

[See: Table 5.6-13 for material and test method]



[See: Table 5.6-13 for material and test method]

Figure 5.6-17 - Damping ratio for π/3 laminates (GFRP)



[See: Table 5.6-13 for material and test method]

Figure 5.6-18 - Damping ratio for π/4 laminates (GFRP)

5.6.3 Aramid/epoxy

5.6.3.1 Kevlar 49/Fiberite 934 fabric

Table 5.6-16 summarises the material, test method and damping data, Ref. [5-7].

Table 5.6-16 - Material, test method and η for aramid/epoxy: Kevlar 49/Fiberite 934 fabric (warp aligned), V_f= not stated

Material:	Aramid/epoxy laminates: Kevlar 49/Fiberite 934 fabric (Warp aligned), V_f: Not stated, Ref. [5-7]
Method:	Free decay of a thin cantilevered beam in flexure.
Result:	0.020 η Flexure

5.6.3.2 Kevlar 49 + T300/Fiberite 934 hybrid 50/50

Table 5.6-17 summarises the material, test method and damping data, Ref. [5-7].

Table 5.6-17 - Material, test method and η for aramid + carbon hybrid/epoxy: Kevlar 49+T300/Fiberite 934 (warp aligned), Vf= not stated

Material:	Aramid/epoxy laminates: Kevlar 49 + T300/Fiberite 934 hybrid 50/50 (Warp aligned) V_f: Not stated, Ref. [5-7].
Method:	Free decay of a thin cantilevered beam in flexure.
Result:	0.013 η Flexure

5.7 Radiation effects

5.7.1 Aramid composites

Aramid fibres are sensitive to ultraviolet radiation. Aramid-based materials need light-proof storage conditions to avoid property degradation. UV-affected aramid undergoes a colour change from yellow (normal) to a golden brown.

In composites, the fibres are largely protected by the matrix material, although those on the surface can be affected.

Fibres exposed to electron radiation show no property degradation, Ref. [5-18].

5.8 Radio frequency transparency

5.8.1 General

Certain aerospace applications need materials which offer high specific mechanical properties coupled with good dielectric characteristics. These applications include:

- radomes
- antenna support structures
- sub-reflectors

In reflector antenna design and their supports, benefits in overall antenna electrical performance can be achieved by using RF-transparent materials, Ref. [5-19].

Glass or aramid fibre composites can be preferable to electrically-conducting reinforcements, such as carbon or boron.

5.8.2 Aramid composites

The dielectric properties of aramid fibres make them of interest for RF transparent structures. The electrical properties are the:

- Relative dielectric constant (ε).
- Loss factor (tan δ).

These properties, in particular ε, vary for different resin matrix systems.

Table 6.8-1 gives typical values for aramid composites, Ref. [5-19], [5-20].

Table 5.8-1 - Typical dielectric properties for aramid composite materials

Composite [Note]	Electrical Property	Value	Comments
Laminates (1)	ε	3.2 to 3.7	Typical range
		4.0	High temperatures
	tan δ	0.01 to 0.02	Typical range
		0.04	High temperatures
Cores (2)	ε	1.05 to 0.02	-
	tan δ	0.001 to 0.003	-
Sandwich Panels (3)	ε	-	-
	tan δ	-	-

Key:
(1) Anisotropy for UD composite, typically 10% to 20% difference in longitudinal and transverse directions.
(2) Depending on density. 2% to 3% difference between values along and across ribbon. (Larger value along ribbon). Nomex cores have slightly higher values for the same cell size.
(3) Calculation of ε depends on accurate thickness measurement. Surface roughness does not cause diffraction up to ~ 30GHz.

5.9 Thermal conductivity

5.9.1 General

Some applications need materials that provide high specific mechanical performance coupled with good thermal conductivity and thermal stability.

Some examples of these applications include:

- Antenna reflectors and support structures, both in-orbit and terrestrial, Ref. [5-25], [5-26].
- Thermal management (electronics and optoelectronics)
- Optical payload structures

5.9.2 Materials

5.9.2.1 General characteristics

Most monolithic materials have near-isotropic thermal conductivity. However, the thermal conductivity of carbon varies widely between particular allotropes, [See: 43.10], and some show highly-directional thermal conductivity, e.g. graphite.

[See also: 43.17 – CVD diamond; 43.12 – silicon carbide]

The thermal conductivity of particulate-reinforced composites tends to be near-isotropic, whereas that of continuous fibre CFRP is highly directional. Both glass and aramid fibre composites have low-no thermal conductivity. Table 5.09.1 summarises the thermal conductivity of some engineering materials for thermal management applications, Ref.[5-21], [5-24], [5-30].

For the thermal characteristics of other materials used in thermo-structures and thermal protection systems, e.g. some MMCs, CMCs and C-C, [See: Section XVI; Clause 82].

Table 5.9-1 - Thermal conductivity: Typical values for some engineering materials

Material		Density (g/cm^3)	In-plane			Out of plane
Matrix	**Reinforcement** (1)		**Modulus, (GPa)**	**CTE, (ppm/K)**	**Thermal Conductivity, (W/m.K)**	**Thermal Conductivity, (W/m.K)**
Epoxy	E-glass fibres	2.1	23	10	0.9	0.6
Carbon fibres [See also: 2.3, 3.3]						
Epoxy	Carbon IM PAN fibre	1.6	63	2.3	6.0	0.5
Epoxy	Carbon UHM PAN fibre	1.7	110	0.4	23.0	0.5
Epoxy	Carbon PITCH fibre (2)	-	520 [0°] 5.6 [90°]	-	-	-
Epoxy	Carbon PITCH fibre (3)	1.72	381	-	77	-
Carbon	Carbon PITCH fibre	1.9	240	–0.1	350-400	40
Aluminium [See: Clause 46]		2.7	70	23	200	200
Al	SiC particles	3.0	115-265	6.2-16.2	170-220	170-220
Al	Diamond particles	2.9-3.1	220-250	6-10	325-450	325-450
Copper [See: Clause 45]		8.9	130	17	400	400
Cu	Tungsten	15-17	230-255	5.7-8.9	157-190	157-190
Cu	Diamond particles	5.0-5.5	225-410	4.0-7.7	465-550	465-550
Diamond [See: 43.17]		3.5	1000	1.0	2000	-
Graphite [See: 43.10]		1.8	15	4	1000	5.5

(1) continuous fibre; (2) NGF YS-90A/120°C epoxy, 60% Vf; (3) ACG Ltd. K63712/MTM57120°C epoxy 312gsmUD; 55% Vf norm.

5.9.2.2 Pitch-based carbon fibres

Pitch-based carbon fibres have much higher thermal conductivities than PAN carbon fibres, [See: 3.3]. Both types have much lower transverse values compared with the axial direction, Ref. [5-22], [5-23].

5.9.2.3 Carbon nanotubes

The thermal conductivity of carbon nanotubes is directional, with the highest value in the axial direction and the lowest in the transverse direction. Although the thermal conductivity of carbon nanotubes is widely quoted as 6000 W/m.K, there is a significant temperature-related effect and also a dependency on the particular nanoparticle structure, Ref. [5-27], [5-28]. In bundles, the thermal conductivity falls to about 900 W/m.K (axial) and 5.5 W/m.K (radial).

[See also: Section XXIII - Nanotechnologies]

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[See: ECSS website]

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6
Options in polymer composites

6.1 Introduction

Some of the newer advances in polymer composite materials are introduced which aim to improve on the known characteristics of the existing range of epoxy-based materials.

Developments in reinforcement fibres are described, [See: 6.2], along with the newer matrix systems, [See: 6.6, 6.12, 6.35]. These include imide-based thermosetting systems for use at higher temperatures than epoxy-based formulations, and thermoplastics, [See: 6.17], which can be a means of improving composite damage tolerance, as well as higher temperature use.

The manufacturing processes associated with thermoplastic matrix composites differ from those for thermoset systems. A basic description of possible techniques is included, [See: 6.25]. Some are of interest because they can reduce the cost of manufacture.
The information presented is for materials which are under development, and have not been fully evaluated for space applications, as the epoxy-based materials have.

The information is advisory only and is likely to change due to continuing materials development.

6.2 New and development reinforcement fibres

6.2.1 Types of new fibres

6.2.1.1 Carbon fibres

New commercial grades of carbon fibres are continually being produced, primarily with higher strengths and higher strain to failures. To the designer, this offers:

- A general improvement in the damage tolerance of composites, especially those using HS high strength or IM intermediate modulus fibres.
- The ability to use fibres of higher stiffness than was previously possible because strength is no longer compromised.

For fibres with failure strains approaching 2%:

- Composites can be produced with very high tensile strengths, but are not necessarily achieved in compression.
- With a high strength IM intermediate modulus fibre, such as T800, the compressive strength of the unidirectional (0°) composite can be less then 50% of the tensile performance.

- In the case of quasi-isotropic composites, compressive strengths can be from 60% to 80% of the tensile properties.

6.2.1.2 Aramid fibres

Du Pont's Kevlar™ 49 has been the traditional reinforcing fibre for structural composites. There is a complementary fibre in Twaron HM from Teijin Twaron. A wider range of aramid fibres is possible because the processing enables different grades to be formulated.

Table 6.2-1 gives basic material properties for comparative purposes.

Table 6.2-1 - Basic mechanical properties of new aramid fibres

Fibre (Manufacturer)	σ^t (MPa)	E^t (GPa)	ε^t (%)	Density (kg m^{-3})	Comments
Kevlar 49 (Du Pont)	3620	124	2.75	1450	Equivalent, standard reinforcing fibres.
Twaron HM (Teijin)	3150	121	2.0	1450	
Kevlar 149 † (Du Pont)	3440	175	1.8	1470	High stiffness variant for structural use.
Kevlar 29 (Du Pont)	4175	88	3.3	1440	Primary use for ballistic protection.
Technora (Teijin)	3000	70	4.4	1390	Similar to Kevlar 29. Low modulus.

Key: † discontinued.

6.2.1.3 Glass fibres

E- and S-glass remain the options because no new glass fibres have been introduced recently.

6.2.1.4 Polyethylene fibres

These fibres can offer high strength and modulus, which makes them suitable for reinforcing polymer matrix composites.

[See: 6.3]

6.2.1.5 Polyether ether ketone (PEEK) fibres

PEEK fibres have poor mechanical properties. They are suitable for co-mingling with reinforcing fibres, such as carbon, and thermoforming to give a consolidated composite.

[See: 6.17, 6.18]

6.2.1.6 Liquid crystal polymer fibres

An example is Vectran LCP from Celanese of which its typical characteristics include:

- Modest modulus (~79GPa),
- Modest strength(~2700MPa)
- Density of 1400 kg/m3.

It is largely untried in composite materials.

6.2.1.7 Polybenzimidazole (PBI) fibre (Celanese)

PBI has poor mechanical properties.

6.2.1.8 Ceramic and refractory fibres

Included in this group are:

- Boron and 'Borsic' filaments.
- Silicon carbide fibres and filaments.
- Si-Ti-C-O fibres.
- Alumina fibres and filaments.
- Alumina-boria-silica fibres.

This is a fairly large group of speciality fibres, Ref.[6-2]. Several have been applied as reinforcements in polymer matrix composites, e.g. boron filaments. However, their utilisation in aerospace components is very low compared with that of carbon, aramid and glass fibres.

Their basic refractory nature makes them more appropriate to metal matrix and ceramic matrix composites. [See: Clause 43 - Fibres].

NOTE A fibre is a material with a diameter of 5µm to 10µm, whilst filaments are 100µm to 250µm in diameter.

6.2.1.9 Quartz fibres

Quartz fibres are specified as the reinforcement for composites in some satellite constructions. For example, the dielectric properties of Astroquartz II fibres proved more important than the low fibre strength and modulus modest (69 GPa) mechanical properties.

6.2.1.10 Metallized fibres

Metallized fibres are speciality fibres which are coated with a fine metallic layer, primarily to enhance electrical properties in composites. The metallization provides:

- High electrical conductivity, e.g. for earthing purposes.
- Shielding from electromagnetic radiation.

NOTE Some examples are shown in Table 6.2-2.

Table 6.2-2 - Types of metallized fibres

Substrate Fibre	Metal Coatings
Carbon	nickel, silver, gold
Aramid	nickel
Glass	aluminium, silver
Polyester*	nickel, copper
Key: * Limited interest for structural composites but possible applications for electrical/signal components.	

6.2.1.11 Metal fibres

Metal fibres (2 μm to 80 μm) can be specified for inclusion in a composite for some applications. These can be co-woven with carbon fibres. Examples of fibre materials include:

- Stainless steel,
- Inconel,
- Hastelloy,
- Titanium.

6.3 Polyethylene fibres

6.3.1 General

High modulus, high strength polyethylene fibres suitable for composite reinforcements became available from 1985. They are not to be confused with the general purpose polymer of the same name.

6.3.2 Fibre characteristics

The fibres get their excellent mechanical properties from the high molecular and crystal alignment produced by gel-spinning. The polyethylenes have a very high molecular weight (>10^6). In addition to good stiffness and strength, other characteristics include:

- Low fibre density compared with all other reinforcing fibres, hence very high specific strength.
- Non-Hookean behaviour:
- High failure strain, but
- Modest strengths.
- High failure strain.
- Maximum use temperature: ~120°C. (Tm ~150°C).
- Very high resistance to ultraviolet (UV) radiation.
- Non-conducting, electrically insulative.
- Tough fibre, implying damage tolerant composite.
- Low moisture absorption.
- Table 6.3-1 shows the commercially available polyethylene fibres.

Table 6.3-1 - Commercially available polyethylene fibres

Fibre (Manufacturer)	Density (kg m^{-3})	Fibre dia. (μm)	Tensile Modulus (GPa)	Tensile Strength (MPa)	Elongation (%)
Spectra 900 (Allied)	970	38	117	2650	3.5
Spectra 1000 (Allied)	970	27	172	3090	2.7
Dyneema SK 60 (Dyneema Vof)	970	-	87	2700	3.5
Tekmilon 1000/100 (Mitsui)	960	38	88	2450	3.0
U.H.M.P.E. (Snia Fibre)	960	16	45	1300	-

The specific properties of polyethylene fibres are compared with the more common reinforcing fibres in Table 6.3-2.

Table 6.3-2 - Comparison of specific properties of polyethylene fibres and common fibre reinforcements

Fibre	Specific Stiffness †	Specific Strength ‡
T300	133.5	2006
T800	162.4	3088
Kevlar 49	85.6	2497
Spectra 1000	177.3	3186
Dyneema SK60	89.7	2783
Key: † GPa/density (g cm-3) ‡ MPa/density (g cm-3)		

6.3.3 Fibre applications

Early indications suggested that polyethylene fibre could compete with aramids for applications needing:

- Very high specific tensile strength, e.g. pressure vessels, and
- Impact resistance.

The polyethylene fibres have gained interest for:

- Ropes, and other tensioned items.
- Ballistic armours.

6.3.4 Composite development

Polyethylene fibre/epoxy structural composites are under development. A limitation on the cure temperature of 120°C is imposed to avoid de-stabilising the fibre.

Polyethylene polymers are renowned for poor bonding characteristics, so considerable work is deleted to optimise the level of interfacial bonding between matrix and fibre. A low level of bonding can:

- Produce composites with good impact performance in terms of apparent toughness.
- Limit the maximum strengths obtainable, particularly in compression and shear.

6.3.5 Potential space applications

For space structures, stiffness is usually the prime criteria for composites. Spectra 1000 appears more attractive than Dyneema SK60. Since polyethylene fibres do not exhibit elastic, Hookean behaviour, they have high failure strains but modest strengths. For all high strain to failure (>2%) fibres, the matrix failure strains can be a limiting factor on the strength levels acceptable for design purposes. There are considerable gains to be made in improving strength and new commercial variants are likely to be developed.

The obvious advantage of polyethylene is its low density which is some 33% less than aramids and 46% lower than carbon.

Polyethylene fibre composites also have attractive damping and dielectric properties, e.g.:

- Dielectric constant at 10 GHz is 2.3.
- Loss tangent of 4x10-4 for the fibre.

Two potential areas for concern with polyethylene-fibre-reinforced composites are:

- Flammability.
- Uncertain creep characteristics under load.

6.4 Ceramic and refractory fibres

The use of ceramic and refractory fibres in polymer matrix composites is very low. They have been overshadowed by the commitment to carbon fibres as the predominant reinforcement.

Carbon fibres are preferred to boron, silicon carbide and alumina reinforcements because they possess a better performance profile with respect to:

- Stiffness and strength,
- Formability in composites,
- Availability (multi-source), and
- Acceptable cost.

This leaves a number of single source ceramic fibres with limited commercial outlets.

Table 6.4-1 shows the properties of the two boron-based fibres which have been used in matrix polymer composites.

Table 6.4-1 - Properties of two boron-based reinforcements used for polymer matrix composites

Fibre [Manufacturer]	Fibre ∅ (μm)	Density (kg m^{-3})	Modulus (GPa)	Tensile Strength (MPa)	Failure Strain (%)
Boron † [TEXTRON]	102 142	2580	400	3520	0.88
CI Boron [CI]	101 142 203	2380 - 2610	-	2700	0.7
SiCaBo ‡ [CI]	147	2580	400-414	3790	0.9
Key: † Boron on tungsten wire substrate. ‡ SiC coated boron on tungsten wire substrate.					

Various types of ceramic and refractory high-cost fibres are of interest for reinforcements in metal matrix and ceramic matrix composites. These are used at higher temperatures.

[See: Clause 43 for reinforcing fibres]

Ceramic fibres which can be readily woven into fabrics are of interest for their refractory characteristics in thermal insulation and fire protection applications.

6.5 Characteristics of bismaleimide composites

6.5.1 Characteristics

Basic characteristics of bismaleimide resin systems, [See also: 6.6], are:

- Improved thermal stability compared with epoxies.
- Poorer thermal stability than polyimides.
- Improved hydrolytic stability over epoxies.
- Thermosetting resin, which, like epoxy resins, can be processed in the form of:
  - prepregs, and
  - filament winding.

The commercial significance of bismaleimide-based composites has increased as applications have arisen for composites capable of operating at 200°C. They were considered for the main structure of the Hermes spaceplane. A number of bismaleimide-based prepregs are commercially available.

Some of the prepregs are development materials whose properties are subject to change and their continued availability cannot be guaranteed.

6.6 Bismaleimide resins

6.6.1 Resin chemistry

Bismaleimides are addition polymerised resins where no by-products, such as water, are formed during the cross-linking reaction.

The resins are formulated from low molecular weight bisimide pre-polymers which are end-capped with reactive maleimide rings. Heat induced polymerisation forms highly cross-linked, heat-resistant polymer networks. Such networks form the basis for good thermal and hydrolytic stability.

Refinement of bismaleimide resin chemistry was necessary to overcome problems with:

- Solvent retention in prepregs.
- High uncured resin melting points.
- High curing temperatures of the monomer.
- High cross-link density, which resulted in brittleness that was conferred on the composite.
- Low fracture toughness and excessive microcracking, which were reported in comparison with conventional carbon fibre reinforced epoxy laminates.

Later commercial prepregs included modifiers in the resin formulation to give greater toughness in the cured composites.

6.6.2 Commercial resin systems

Table 6.6-1 lists commercially available bismaleimide resins used in prepregs.

Table 6.6-1 - Commercially available bismaleimide resins used in prepregs

Resin System	Prepreg Supplier
V378	U.S. Polymeric (HITCO)
F178	Hexcel
F650	Hexcel
CP12272	Ferropreg
Rigidite 5245	Narmco (BASF)
Rigidite 5250	Narmco (BASF)
SX5564	Ciba Geigy
HG9107	Hysol
BMI-1	Hyfil
Compimide 796	Technochemie
Resin systems are trade names or designations. Different formulations are available based on these systems.	

6.6.3 Toughened bismaleimide systems

As an example of the toughening of bismaleimide matrices, modification to Technochemie 796 resin was by additions of co-monomer, arylene-ether-ketones (TM123). This gave improvements in neat resin properties.

6.6.3.1 Mechanical properties

Mechanical property data on cured resin is given in Table 6.6-2. Compared with the basic resin, the main points to note are:

- A significant increase in strength.
- A slight reduction in modulus (stiffness).
- Significant improvements in:
  - failure strain,
  - fracture energies (G_{1C}), and
  - stress intensity factor (K_{1C}).
- Reduced moisture absorbency and a marginal reduction in glass transition temperature (Tg).

Table 6.6-2 - Mechanical properties of toughened bismaleimide neat resins

			Mechanical Properties						
Composition (%)		**Test Temp**	σ^f	E_f	ε^f	G_{1C}	K_{1C}	WA	Tg
C796	TM123	(°C)	(MPa)	(GPa)	(%)	(J/m^2)	(kN/m$^{-3/2}$)	(%)	(°C)
100	-	23	76	4.64	1.70	63	526	4.30	>300
		250	31	3.03	1.03	-	-	-	-
80	20	23	106	3.96	2.34	191	847	3.66	266
		250	65	2.66	2.52	-	-	-	-
70	30	23	132	3.61	3.88	397	1188	3.37	265
		250	90	2.47	5.00	-	-	-	-
60	40	23	132	3.70	3.75	439	1209	2.59	249
		250	56	1.71	4.86	-	-	-	-

Abbreviations:

σ^f	Flexural strength	WA	Water absorption, 1000h at 70°C, 94% RH
Ef	Flexural modulus	Tg	Glass transition temperature
ε^f	Flexural strain	C796	COMPIMIDE 796
G1C	Fracture energy	TM123	4,4'-bis(o-propenylphenoxy) benzophenone
K1C	Stress intensity factor		

The cure schedules for Compimide 796/TM123 blends are shown in Table 6.6-3

Table 6.6-3 - Cure schedule for Compimide 796/TM123 blends

Cure	Post Cure
2 hours @ 170°C	5 hours @ 245°C
2 hours @ 190°C	
4 hours @ 210°C	

6.6.4 Cured neat resin properties

Table 6.6-4 compares the properties of a conventional epoxy (5208) with two modified bismaleimides (X5250 and 5245C). The differing thermal capabilities for the bismaleimide resins result from their cure chemistries. All are Narmco products.

Particularly noticeable are the higher failure strain and fracture toughness for the bismaleimides.

Table 6.6-4 - Comparison of resin properties for two bismaleimides and an epoxy

Property	Bismaleimide Resins		Epoxy Resin
	X5250	5245C	5208
Maximum service temperature (°C)	204	149	149
Cure schedule	6 hours @ 177°C and 12 hours @ 227°C	4 hours @ 210°C	1½ hours @177°C 1 hour @ 204°C
Tg (°C) - Dry	321°C	199 - 210°C	232°C
Tg (°C) - Wet	-	165°C	165°C
Tensile strength (MPa)	62.7 - 69.0	57.2	54.5
Tensile modulus (GPa)	3.93	3.59	3.93
Tensile strain (%)	1.7	2.0	1.0
Flexural strength (MPa)	135.8 - 168.9	122.7	121.4
Flexural strain (%)	3.3 - 4.4	3.7	3.7
G_{1C} (J m^{-2})	85.9 - 96.4	157.8	71.9

Key: Tg
Glass transition temperature

6.7 Fibres for bismaleimide composites

The majority of bismaleimide composites use carbon fibre reinforcement as opposed to glass or aramid.

The commercial carbon fibres used are those for epoxy resins. However, new grades of carbon fibres are continually being introduced; most notably very high strength (VHS) and intermediate modulus (IM). There are therefore prepreg systems being introduced which combine new fibres and new bismaleimide matrices. Such prepreg systems, e.g. T800/5250-2 and T800/SX5534 were evaluated for the main structures of Hermes.

Table 6.7-1 provides a listing of references which give information on certain resin/fibre combinations.

Table 6.7-1 - Fibres used with bismaleimide resins

Resin Matrix	Carbon Fibre	Comments	Ref.
Narmco 5250-2 Ciba Geigy SX5564	Toray T800	Measured mechanical properties for Hermes use.	[6-1]
Narmco X5250 Narmco 5245C	G40-600 T-300 AS-4 T300	Comparison between BMI and Epoxy (5208) composites.	[6-2] [6-10]
USP V378A	T300	Mechanical characteristics of composites.	[6-3] [6-5]
Narmco 5245C Kerimid 601 Kerimid 353 Ciba Geigy XU292	Various	Assessment of microcracking phenomena.	[6-4] [6-10]
Hysol HG910	Apollo IM	Development of a semi-IPN bismaleimide.	[6-6]
Technochemie Compimide 796	T300 XAS	Improved toughened Bismaleimides	[6-7]
Kerimid derivatives	Not stated	Development of solvent-free resins.	[6-8]
BMI-1 and MBMI-I derivatives	Not stated	Copolymer systems.	[6-9]
Narmco 5245C USP V378A	IM6 T300	Impact characteristics of new composite systems.	[6-12]
Narmco 5250-2 5250-3	Celion 12000 IM (various) T300	Assessment of composite properties.	[6-11]

6.8 Bismaleimide composites

6.8.1 Basic materials data for laminate design

Basic mechanical property data has been generated as part of the LTPP program, Ref. [6-3]

Specific emphasis has centred on:

- T800/Narmco 5250-2
- T800/Ciba-Geigy SX5564

6.8.2 Single composite plies

6.8.2.1 Hysol GH9107/Apollo IM

Table 6.8-1 summarises the material and processing method. Typical mechanical properties are given in Table 6.8-2

Table 6.8-1 - Carbon fibre/bismaleimide material description: Apollo IM/Hysol GH107 prepreg

Prepreg Material:	Apollo IM Fibre: σ^t = 3.98 GPa E^t = 296 GPa Resin: Hysol GH 107 V_f: 69%
Cure:	179°C / 3 hrs
Post-cure:	227°C / 6 hrs

[See: Table 6.8-2 for mechanical properties]

Table 6.8-2 - Mechanical properties of carbon fibre/ bismaleimide: Apollo IM/Hysol GH107 prepreg

Property		Strength (MPa)	Modulus (GPa)
0° Tension:	R.T.	2067	176.4
0° Compression:	R.T.	1344	179.8
	R.T./Wet	1226	161.9
	177°C	1089	178.5
	177°C/Wet	827	151.6
	218°C/Wet	503	136.4
	232°C	779	177.1
0° ILSS:	R.T.	93.7	-
	R.T./Wet	84.1	-
	177°C	74.4	-
	177°C/Wet	44.1	-
	204°C/Wet	6.9	-
	232°C	50.3	-
±45° In-plane shear (G_{12}):	149°C/Wet	90.9	2.27
	163°C/Wet	71.2	1.38
	177°C	45.5	1.31
DCB:	G1C (Jm-2)	333	-

6.8.2.2 USP V378A/T300-6K

Table 6.8-3summarises the material and processing method. Typical mechanical properties at various temperatures are given in Table 6.8-4.

Table 6.8-3 - Carbon fibre/bismaleimide material description: T300/V378A

Prepreg Material:	Fibre: T300-6K Resin: V378A V_f: 69 - 72%
Cure:	177°C / 4 hrs
Post-cure:	246°C / 4 hr 288°C / 1 hr

[See: Table 6.8-4 for comparison with T300-3K/5208 epoxy system]

Table 6.8-4 - Mechanical properties of carbon fibre/ bismaleimide: T300/V378A

Strength Property (Statistical Data)	**Bismaleimide T300-6K/V378A (Epoxy T300-3K/5208)**		
	-54°C	**24°C**	**177°C**
0° Flexural (MPa):			
$\bar{x}$	2069 (2115)	1972 (1902)	1517 (1400)
C.V. (%)	4.5 (8.0)	6.1 (4.6)	7.8 (4.6)
N	220 (5)	234 (912)	240 (912)
90° Flexural (MPa):			
$\bar{x}$	88.3 (80.6)	97.2 (106)	54.5 (81.3)
C.V. (%)	16.9 (12.4)	15.3 (13.3)	14.3 (14.7)
N	220 (18)	239 (912)	238 (912)
ILSS (MPa):			
$\bar{x}$	128 (139)	113 (121)	78 (70)
C.V. (%)	6.5 (8.6)	7.0 (7.7)	7.4 (9.8)
N	59 (18)	66 (912)	62 (912)

Key: $\bar{x}$: Mean;
C.V: Coefficient of variation (%)
N: Number of tests.

[See: Table 6.8-1 for material description]

6.8.3 Unidirectional composites

[See:9.10 for 'Data Sheets' for unidirectional IM carbon fibre bismaleimide composites]

6.8.4 Quasi-isotropic laminates

6.8.4.1 T800/5250-2 laminates

Table 6.8-5 summarises the material and processing method, Ref. [6-3]

Table 6.8-5 -Material description of carbon fibre/bismaleimide: T800/5250-2 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Material:	Fibre: T800 Resin: 5250-2 V_f: Not stated
Lay-up:	$(0/+45/90/-45_2/90/+45/0)_2$
Cure:	Not stated
Post-cure:	Not stated

[See: Table 6.8-6- Tensile and Table 6.8-7- Compressive properties]

Typical tensile mechanical properties at various temperatures and conditions are given in Table 6.8-6 and typical compressive properties in Table 6.8-7, Ref. [6-3]

Table 6.8-6 - Tensile mechanical properties of carbon fibre/bismaleimide: T800/5250-2 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Tensile Properties				
Temperature (°C)	**E^t (GPa)**	**R^{tu} (MPa)**	**ε^{tu} (%)**	**ν**
-60	55.8 ± 1.1	555 ± 38	1.02 ± 0.09	0.147
RT	59.1 ± 2.6	603 ± 33	1.06 ± 0.08	-
RT (Wet)	59.8 ± 2.3	695 ± 33	1.14 ± 0.07	-
200	57.5 ± 1.4	671 ± 46	1.11 ± 0.03	0.32
RT: (After 360 cycles)	56.9 ± 1.9	688 ± 20		
RT: (After 3000 cycles)	55.4 ± 2.2	690 ± 58	1.25 ± 0.06	0.32
RT: (After 3000 cycles and wet)	55.6 ± 1.7	743 ± 91	1.37 ± 0.13	0.33

Key: E^t : Tensile modulus; ε^{tu} : Ultimate tensile strain; R^{tu} : Tensile strength; ν : Poisson's ratio

Thermal cycle: -60°C to +80°C

Wet: 750 hrs @ 75°C and 95% relative humidity

[See: Table 6.8-5 - Description and Table 6.8-7 - Compressive properties]

Table 6.8-7 - Compressive properties of carbon fibre/ bismaleimide: T800/5250-2 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Compressive Properties		
Temperature	**E^c (GPa)**	**R^{cu} (MPa)**
-60°C	63.0 ± 0.4	537 ± 87
RT	58.9 ± 2.0	501 ± 64
RT: (Wet)	56.2 ± 0.6	490 ± 14
200°C	58.6 ± 2.9	445 ± 103
RT: (After 360 cycles)	54.5 ± 4.0	543 ± 28
RT: (After 3000 cycles)	53.2 ± 5.8	450 ± 3
RT: (After 3000 cycles and wet)	55.7 ± 5.3	473 ± 12
Key:	E^c : Compressive modulus	R^{cu} : Compressive strength
	Thermal cycle: -60°C to +80°C	
	Wet: 750 hrs @ 75°C and 95% relative humidity	

6.8.4.2 T800/SX5564 laminates

Table 6.8-8 summarises the material and processing method.

Table 6.8-8 - Material description of carbon fibre/bismaleimide: T800/SX5564 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Material:	Fibre: T800 Resin: SX5564 V_f: Not stated
Lay-up:	$(0/+45/90/-45_2/90/+45/0)_2$
Cure:	Not stated
Post-cure:	Not stated

[See: Table 6.8-9 - Tensile, and Table 6.8-10 - Compressive properties]

Typical tensile mechanical properties at various temperatures and conditions are given in Table 6.8-6 and typical compressive properties in Table 6.8-7.

Table 6.8-9 - Tensile properties of carbon fibre/bismaleimide: T800/SX5564 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Tensile Properties				
Temperature (°C)	**E^t (GPa)**	**R^{tu} (MPa)**	**ε^u (%)**	**ν**
-60	54.4 ± 1.3	665 ± 23	1.20 ± 0.06	0.289
RT	54.8 ± 2.6	682 ± 17	1.40 ± 0.06	0.305
RT (Wet)	57.3 ± 1.0	727 ± 12	1.32 ± 0.04	0.319
200	57.8 ± 2.6	640 ± 10	1.40 ± 0.20	-
RT: (After 360 cycles)	56.1	701	1.08	0.32
RT: (After 3000 cycles)	54.2	663	1.23	0.30
RT: (After 3000 cycles and wet)	54.0	694	1.28	0.30
Key:	E^t : Tensile modulus		ε^{tu} : Ultimate tensile strain;	
	R^{tu} : tensile strength		ν : Poisson's Ratio	
	Thermal cycle: -60°C to +80°C			
	Wet: 750 hrs @ 75°C and 95% relative humidity			

[See: Table 6.8-8 - Description, Table 6.8-10 - Compressive]

Table 6.8-10 - Compressive properties of carbon fibre/ bismaleimide: T800/SX5564 laminate $(0/+45/90/-45_2/90/+45/0)_2$

Compressive Properties		
Temperature	**E^c (GPa)**	**R^{cu} (MPa)**
-60°C	52.3 ± 1.5	464 ± 53
RT	49.1 ± 2.2	536 ± 45
RT: (Wet)	51.2 ± 1.4	538 ± 47
200°C	51.2 ± 1.7	494 ± 49
RT: (After 360 cycles)	53.2	476
RT: (After 3000 cycles)	51.9	603
RT: (After 3000 cycles and wet)	51.4	459
Key:	E^c : Compressive modulus	R^{cu} : Compressive strength
	Thermal cycle: -60°C to +80°C	
	Wet: 750 hrs @ 75°C and 95% relative humidity	

[See: Table 6.8-8 - Description and Table 6.8-9 - Tensile properties]

6.9 Typical properties of bismaleimide composites

6.9.1 Elevated temperature hygrothermal stability

6.9.1.1 T300-3K/V-378A fabric

Table 6.9-1 summarises the material and processing method, Ref. [4-7]. Typical mechanical properties for various temperatures and conditions are given in Table 6.9-2, Ref. [6-7].

Table 6.9-1 - Material description for carbon fibre/bismaleimide: T300/V-378A 8 ply satin fabric V_f: 61%

Material:	Fibre: T300-3K, 8-harness satin fabric Resin: V-378A V_f: 61%
Lay-up:	8 plies
Cure:	177°C / 4 hrs
Post-cure:	232°C / 4 hrs.

[See: Table 6.9-2 - Mechanical properties]

Table 6.9-2 - Mechanical properties of conditioned carbon fibre/ bismaleimide: T300/V-378A 8 ply satin fabric V_f: 61%

y	Mechanical Properties	
Tension		
RT	E^t (GPa)	71.0
	R_w^{tu} (MPa)	507.5
177°C	E^t (GPa)	71.7
	R_w^{tu} (MPa)	553.7
ILSS		
RT	R_{13}^{su} (MPa)	62.1
177°C	R_{13}^{su} (MPa)	53.1
232°C	R_{13}^{su} (MPa)	42.7
316°C	R_{13}^{su} (MPa)	31.0
371°C	R_{13}^{su} (MPa)	19.3
Compression		
RT: (Dry)	E^c (GPa)	62.7
	R_w^{cu} (MPa)	513.0
RT: (Wet) {30 days, 100% R. H., 71°C}	E^c (GPa)	59.3
	R_w^{cu} (MPa)	481.3
177°C:(Dry)	E^c (GPa)	57.9
	R_w^{cu} (MPa)	468.2
177°C: (Wet)	E^c (GPa)	62.7
	R_w^{cu} (MPa)	343.4

6.9.1.2 T300/V-378A UD tape

Typical mechanical properties of aged unidirectional tape composites are given in Table 6.9-3, Ref.[6-7].

Table 6.9-3 - Mechanical properties for aged carbon fibre/ bismaleimide: T300/V-378A UC039 UD tape composites

Property		As Made	Aged 6 months @ 177°C	Aged 9 months @ 232°C
0° Flexure				
RT	E_1^f (GPa)	125.5	137.9	145.5
	R_1^{fu} (MPa)	2055	2206	1841
177°C	E_1^f (GPa)	120.0	145.5	-
	R_1^{fu} (MPa)	1689	1869	-
232°C	E_1^f (GPa)	120.0	-	147.6
	R_1^{fu} (MPa)	1607	-	1413
ILSS				
RT	R_{13}^{su} (MPa)	108.9	-	106.9
177°C	R_{13}^{su} (MPa)	69.6	-	-
232°C	R_{13}^{su} (MPa)	53.1	-	59.3

6.9.1.3 Apollo IM/Hysol HG107

The effect of moisture and temperature on the mechanical properties of IM/HG107 composite is shown in:

- Figure 6.9-1 for 0° compressive strength.
- Figure 6.9-2 for 0° short beam shear strength. for ±45° shear modulus.

NOTE Courtaulds Apollo IM fibre is no longer commercially available.

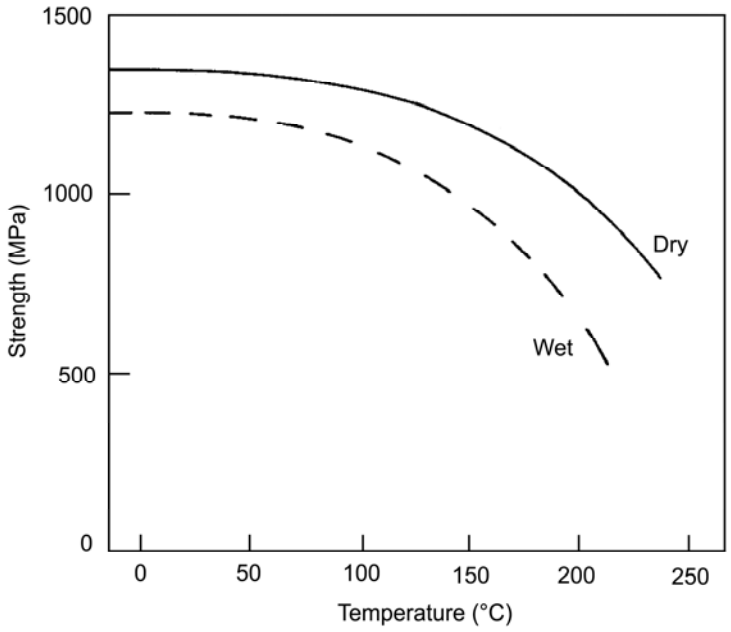


Figure 6.9-1 - (0°) compressive strength with temperature for carbon fibre/bismaleimide composite: Apollo IM/ Hysol HG107

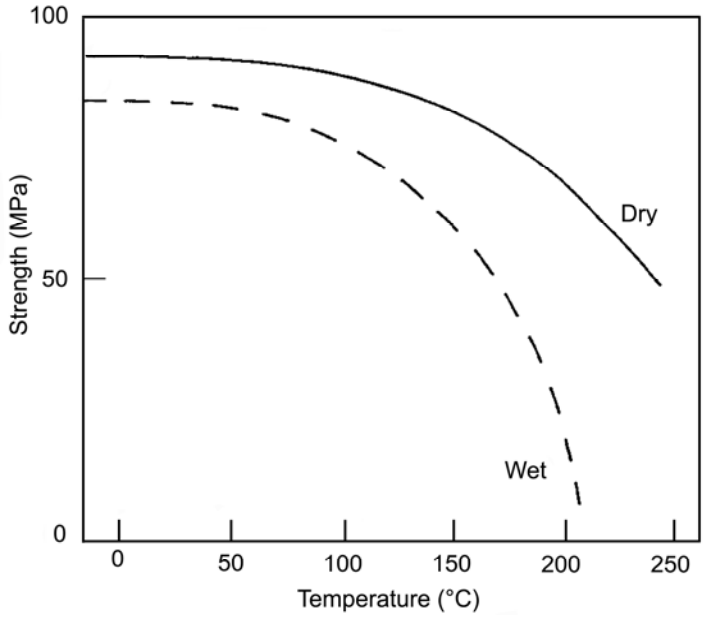


Figure 6.9-2 - (0°) short beam shear strength with temperature for carbon fibre/bismaleimide composite: Apollo IM/ Hysol HG107

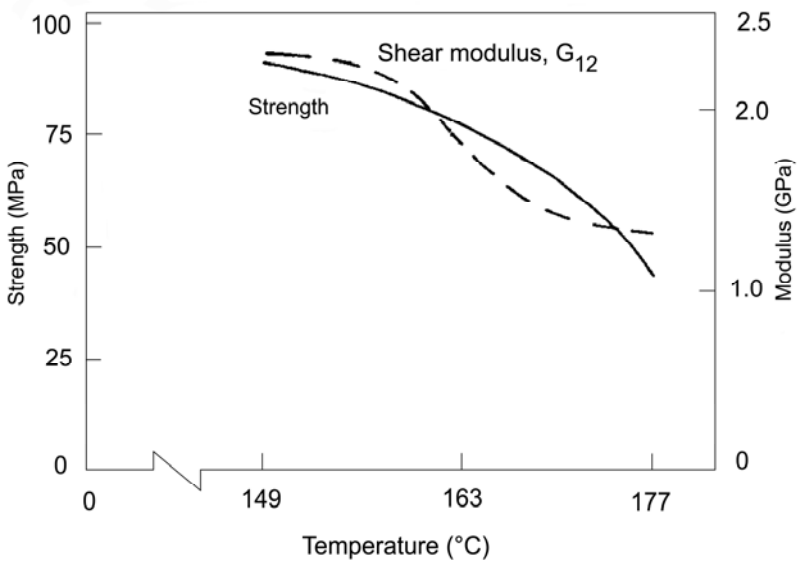


Figure 6.9-3 - (±45°) hot/wet shear modulus with temperature for carbon fibre/bismaleimide composite: Apollo IM/ Hysol HG107

6.9.2 Toughness

Before 1985, emphasis was placed on achieving better thermal stability than epoxies. This tended to produce brittle resins that gave composites:

- Low toughness, and
- Great susceptibility to microcracking.

In 1982, the problem of microcracking was seen in an ESTEC study of T300/Hexcel F178, Ref.[6-15] Excessive microcracking occurred after a modest number of thermal cycles.

Modifying the resin chemistry, primarily through the introduction of co-monomers, improved the toughness without compromising thermal stability. Table 6.9-4 lists the newer generation bismaleimides which exhibit improved toughness, often beyond that of epoxies.

Table 6.9-4 - Newer generation of tougher bismaleimide resins

Manufacturer	Resin
Narmco	5245C 5250
Ciba Geigy	SX5564 XU-292
Hysol	HG9107

Improvements in toughness are seen in impact tests. Programmes to assess delamination levels against impact energies, ranked the impact resistance of composites as shown in Table 6.9-5, Ref. [6-14].

Table 6.9-5 - Impact resistance of bismaleimide-based composites

Service		Composite System (Fibre: Resin)
120°C	↑ Better	IM6 : Narmco 5245C Celion HS : Narmco 5245 AS4 : Hercules 3501-6 AS4 : Hercules 2220-1
176°C	↑ Better	T300 cloth : USP V378A HX : Hexcel 1516 XAS : Hysol 9101-3 T300 : Hexcel 81-5 T300 : Avco 130B
Key: Incipient damage energy level:		AS4: Hercules 3501-6 = 1.6J. IM6: Narmco 5246C = 3.7J.

6.9.3 Microcracking

Table 6.9-6 considers the cracking tendency for a particular laminate, Ref. [6-6]. This provides an indication of the microcracking behaviour of different bismaleimide systems.

Table 6.9-6 - Microcracking behaviour of carbon fibre/ bismaleimide cross-ply composites

Composite System (Resin: Fibre)		Cracking Tendency in 0° Layer	Transverse Tensile Strain to Failure (%)
USP 378A:	HiTex 42	Severe	0.65
USP 378A:	T50	Severe	0.65
Hercules 4502:	AS-4	Severe	0.59
Ferro CPI-2272:	Celion 6000	Severe	0.60
Avco 151-2A:	Celion 6000	Moderate	0.74
Cyanamid X3100:	Celion 6000	Severe	-
5245C:	HiTex 42	None	0.72
5245C:	IM6*	None	0.72
Hexcel 1516:	Celion 6000	Severe	-
Avco 130:	AS-4	Severe	0.34
Key: i) Laminate construction: $(90°_2/0°16/90°_2/0°16, 90°_2)$ ii) Maximum cure temperature: 177°C for 4 hours * Maximum cure 204°C for 8 hours.			

This work concluded that:

- changes in cure and post cure cycles in the 5245C/HiTex42 cross-ply composites (90°/0°) are not effective in preventing microcracking in most balanced configurations.
- microcracking can be prevented irrespective of the cure or post cure cycle in the composites consisting of a multiple of (90°4/0°2/90°4) in a balanced configuration.

6.9.4 HERMES development programme

An exercise to evaluate bismaleimide and polyimide composites for potential use in Hermes constructions was concluded in 1990. Four CFRP materials were evaluated for load-bearing applications experiencing temperatures in the range of 200°C to 250°C. Two were bismaleimides and two polyimides, [See: [6-15]].

The bismaleimide composites were:

- Narmco 5250-2/T800H: Table 6.9-7 provides property data.
- Ciba/Brochier SX 5564-1/T800H: Table 6.9-8 gives property data.

The data was collated at the conclusion of the programme, Ref. [6-73]. Earlier bismaleimide data from the Hermes programme was from Ref. [6-3].

Open hole tension and filled hole compression tests were conducted on 28 ply quasi-isotropic laminates : [0,±45,0,90,0,±45,0,90,0,±45,0]s.

[See also: 9.10 for further data on bismaleimide composites]

Table 6.9-7 - Narmco 5250-2/T800H: Single and multidirectional composite data

Supplier/Tradename: Narmco-BASF	**Fibre/Resin System: Toray T800 12K Narmco R 5250-2**			**Data Source: HERMES Programme**
Fibre volume (%): 60	t_{ply} (mm): 0.125			Density (kg m^{-3}): 1600
Areal weight of prepreg (g m^{-2}): 208	Number of batches tested: 5			
Areal weight of fibre (g m^{-2}): 135	Volatile content (%): 2			Year of test: 1988/89
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension	Strength (MPa) Modulus (GPa)	2687* 168*	231* 1.9*	4
MD open hole tension: 5mm ∅	Strength (MPa)	734	5.1	3
MD filled hole compression: 5mm ∅	Strength (MPa)	440.6	19.9	3
UD interlaminar shear	Strength (MPa)	102.7	1.5	3
Key: UD: Unidirectional MD: Multidirectional *: Manufacturer's data on the batch supplied				

Table 6.9-8 - Ciba SX5564-1/T800H: Single and multidirectional composite data

Supplier/Tradename: **Ciba Brochier**	**Fibre/Resin System:** **Toray T800 12K** **Ciba SX 5564-1**		**Data Source:** **HERMES Programme**	
Fibre volume (%): 60	t_{ply} (mm): 0.125		Density (kg m^{-3}): 1600	
Areal weight of prepreg (g m^{-2}): 210	Number of batches tested: 4			
Areal weight of fibre (g m^{-2}): 137.7	Volatile content (%): LT5		Year of test: 1989	
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension	Strength (MPa) Modulus (GPa)	2370 176.6	175 111	4
MD open hole tension: 5mm ∅	Strength (MPa)	838.8	4.8	5
MD filled hole compression: 5mm ∅	Strength (MPa)	455.7	12.8	3
UD interlaminar shear	Strength (MPa)	100.5	0.97	6
Key: UD: Unidirectional MD: Multidirectional				

6.10 Manufacture of bismaleimide composites

6.10.1 Product forms

Bismaleimide systems can be supplied in similar prepreg forms to epoxies. Specification requirements include:

- Resin content.
- Tack.
- Resin flow.
- Viscosity.
- Solvent release.
- Voidage.

[See: 36.4 and ESA PSS-03-207; currently not under the ECSS document system]

6.10.2 Autoclave

Many of the refinements to bismaleimide resin systems are related to easing the production of high-quality, low voidage, composite mouldings by autoclave processing.

The basic manufacturing difference between epoxies and bismaleimides is the marginally longer cure cycle for the latter, due to:

- Higher cure temperatures, and
- Longer dwell times.

Another factor to consider is the capability of processing materials to withstand the upper cure temperature, which is usually no more than 175 to 180*C, this includes:

- vacuum bagging,
- Release Film, and
- Breather plies.

Table 6.10-1 shows examples of processing cycles.

Figure 6.10-1 shows a typical cure cycle.

Table 6.10-1 - Processing cycles for bismaleimide composites

Process Conditions	**Bismaleimide Composite Systems (Resin : Fibre)**				
	5250-2: T800	**SX5564: T800**	**H9107: Apollo IM**	**V378A: T300-6K**	**5245C: HiTex-42**
Heat-up rates (°C min^{-1})	1	2.5	2	1.7	1.1
Pressure (MPa)	None to start	None to start	0.69 throughout	0.59	0.69
Vacuum	Full throughout	Full throughout	Full throughout	Full	Full
Dwell D1 (Hrs/Temp°C)	1 / 150 then 0.62 MPa applied	Not used	1.5 / 120	2 / 80 with vacuum removed	Not used
Dwell D2 (Hrs/Temp°C)	4 / 190	0.69 MPa applied then 4 / 180	3 / 179	4 / 175 and 0.69 MPa	3 / 177, no vacuum after 1 hr
Total Time (hr)†	9	7.5	7.5	9	8
Post-cure (Hrs/Temp°C) ‡	6 / 243	2 / 200 6 / 250	6 / 227	4 / 246 1 / 288	4 / 204
Key: † In Autoclave ‡ Free standing			Applied Pressures:	0.59MPa (85 psi) 0.62 MPa (90 psi) 0.69 MPa (100 psi)	

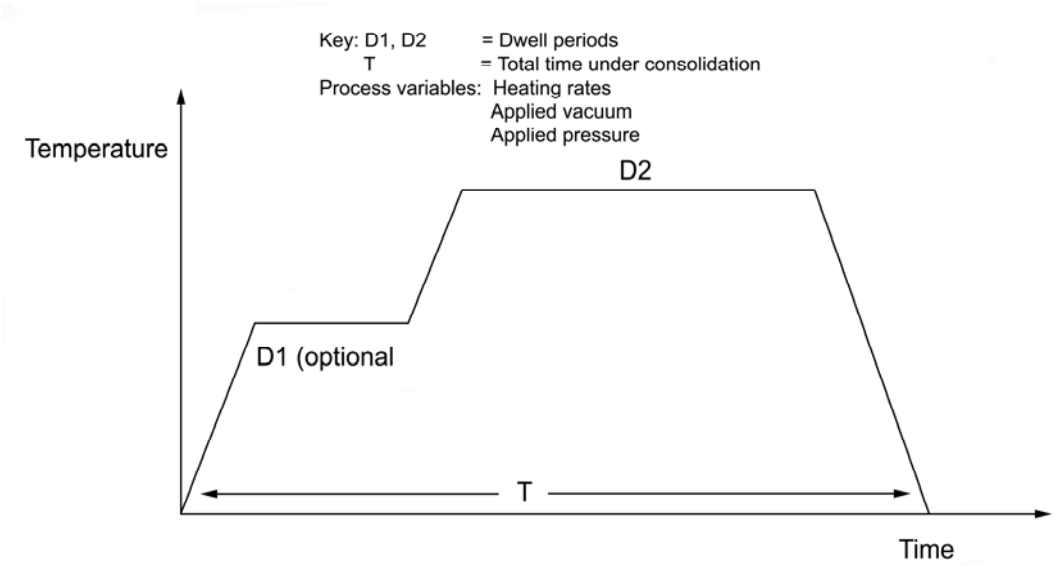


Figure 6.10-1 - Typical cure cycle for bismaleimide composite

6.11 Characteristics of polyimide-based composites

6.11.1 Characteristics

Polyimide composites have thermal capabilities which exceed those of epoxy-based systems for long-term use. The stability of polyimide composites at high temperatures is a subject of on-going research, coupled with development work in resin formulation.

One objective is to produce a polyimide composite material which has:

- Cost-effective fabrication.
- Useful mechanical properties at elevated temperatures and after thermal cycling.
- Thermal oxidation resistance when exposed to:
  - 317°C for 100 hours, and
  - 170°C to 260°C for 50,000 hrs to 70,000 hrs.

These figures were determined from sub- and supersonic flight data.

6.11.2 Potential applications

Technology demonstration items have concentrated on applications where service temperatures normally exceed 200°C, Ref. [6-17], [6-21], [6-22].

Examples of polyimide-based composite components include:

- Space shuttle orbiter aft body flap, and
- Aircraft engine ducts and cowls.

For reusable space planes, the higher temperature capacity of polyimide based materials is attractive for structures beneath the thermal protection system (TPS) which experience thermal soak after re-entry.

6.12 Polyimide resins

6.12.1 General

From initial development work, compared with epoxy systems, the polyimide group of polymers offered:

- Improved hydrolytic properties.
- Thermo-Oxidative stability.

However, manufacture was difficult and components were of inconsistent quality, Ref. [6-17]. The cure process is now understood and acceptable aerospace quality items can be fabricated.

Subsequently, various polyimide systems were investigated and improved with the aim of producing composite systems having higher temperature (>200°C) capabilities for structural use in aerospace applications. Initially this work was centred in the USA, at NASA-Langley and NASA-Lewis Research Centers, Ref. [6-16], [6-17].

6.12.2 Resin chemistry

Polyimide resins can be grouped in terms of their molecular structure, dictated by their chemistry and formulation. The basic groups are:

- Condensation.
- Addition.
- Thermoplastic.

The first two classes describe their cure method, whereas thermoplastic describes the polymer properties after cure.

Condensation polyimides were developed commercially in the 1970's and have been superseded by the ‘addition’ type of which PMR-15 and LaRC-160 are the most advanced in availability and understanding.

The term ‘thermoplastic’ is somewhat misleading because polyimide materials initially have incomplete chemistries, needing cross-linking during the cure process. In the fully cured condition they show ‘thermoplastic tendencies’.

[See also: [6-19] for thermoplastic-based composites]

Table 6.12-1 summarises groups, general characteristics, material supplier and product codes for polyimide polymers suitable for continuous fibre reinforcement.

Table 6.12-1 - Development status and availability for various polyimide resins for advanced composites

General Characteristics [Group]	Development Status	Trade Name	Supplier [code]	Notes
[Condensation]				
* High Tg * Excellent chemical resistance * Excellent thermal stability * Difficult to process * Cure reaction causes high voidage	Initial development in 1970's, followed by commercial products in mid to late 1970's. Processing difficulties resulting in high levels of voidage >>l%. No longer available.	NR150 Skybond	No longer offered in commercial quantities	NR150 resin system may be used as a sizing agent on reinforcement.
[Addition]				
* High Tg * Lower volatile content * Improved processibility	Developed by NASA-Langley. Commercially available in Europe and USA.	LARC-160	Fiberite/ICI [978]	Available in prepreg form in USA and Europe. Numerous sources.
* Good thermal stability * Good chemical resistance	Developed by NASA-Lewis. Commercially available in Europe and USA.	PMR 15	Fiberite/ICI [966] BP Advanced Composites [PMR-15]	Available in prepreg form in USA and Europe. Numerous sources.
	Developed by Hughes Aircraft Co.	Thermid	National Starch and Chemical Corp [Thermid 600]	European source unknown.
	Developed by Rhone-Poulenc.	Kerimid	Rhone Poulenc [Kerimid 601]	-
[Thermoplastic]				
* High Tg * Low outgassing * Good toughness	Newer group at present still in development stage.	AVIMID	Du Pont [AVIMID N]	Available in prepreg form in commercial quantities.
* Good chemical resistance/moisture			Du Pont [AVIMID KIII]	Available in prepreg form in development quantities.
		JD861	BP Advanced Composites [JD861]	Available in prepreg form in development quantities.

6.12.3 Commercial resin systems

There are both US and European commercial sources of polyimide based prepreg with various carbon fibre reinforcements; both unidirectional and bidirectional, Ref.[6-1].

[See also: Table 6.12-1 for supplier and product codes]

6.12.4 Cure reaction

The cure reactions of polyimide resins are complex and certain precautions are needed to ensure that the fully cured component meets aerospace standards.

A summary of the cure process is presented in Table 6.12-2 along with advisory notes, Ref. [6-2].

Table 6.12-2 - Summary of cure processes and advisory notes

Cure Reactions	Potential Problems	Advisory Notes
	Condensation	
One Stage: [340 kPa/177°C] Water evolution	Excessive voidage (~9% vol.) Moisture pickup	High voidage. Limited use in structural applications but of use in sound suppression panels (aircraft engine zone)
N-methyl 1-2-pyrrolidone solvent	Difficult to remove. Reduced strength of composite if retained	
Arsenic compound catalyst	Health and Safety Requirements	
Post cure: [288°C]	Long periods to increase Tg	
Addition: PMR-15, LaRC-160		
Two stage: Imidisation (condensation): Water evolution Volatiles (alcohol)	Voidage "Puffing" or expansion (Thick sections)	Apply vacuum. Typical range: 15kPa to max. in-service (i.e. space) Restrain laminate to avoid expansion and wrinkling by tool design
Polymerisation: Low viscosity of resin	Excessive resin bleed	Minimise bleeder system Good mould design Pressure application cycle
Post cure: [307°C for PMR-15]	Overheating (manufacturing losses)	Seek advice on upper temperature capability

6.12.4.1 Microcracking

For components likely to experience thermal cycling, it was shown that a cure temperature of 280°C to 290°C is beneficial in reducing matrix microcracking and subsequent loss of mechanical and environmental performance in PMR-15 materials, Ref. [6-23].

6.12.5 Manufacturing techniques

Polyimide composites can be cured by either:

- Autoclave.
- Press Moulding, depending on the geometry of the part.

Sample cure cycles for process methods are shown in Figure 6.12-1 for autoclave and for press moulding. A post-cure cycle is shown in Figure 6.12-3, Ref. [6-17].

The process temperatures are higher than those for epoxy based materials. This affects the suitability of processing equipment and ancillary materials, e.g. bagging film.

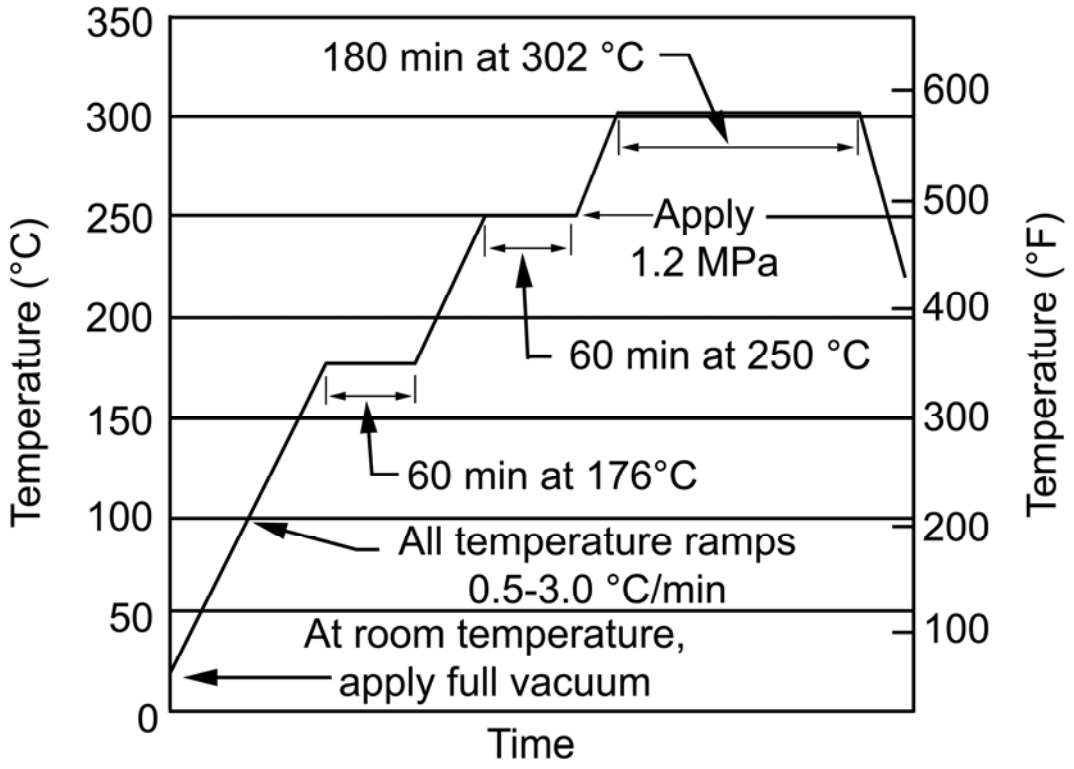


Figure 6.12-1 - Autoclave cure cycle for polyimide PMR-15 composites

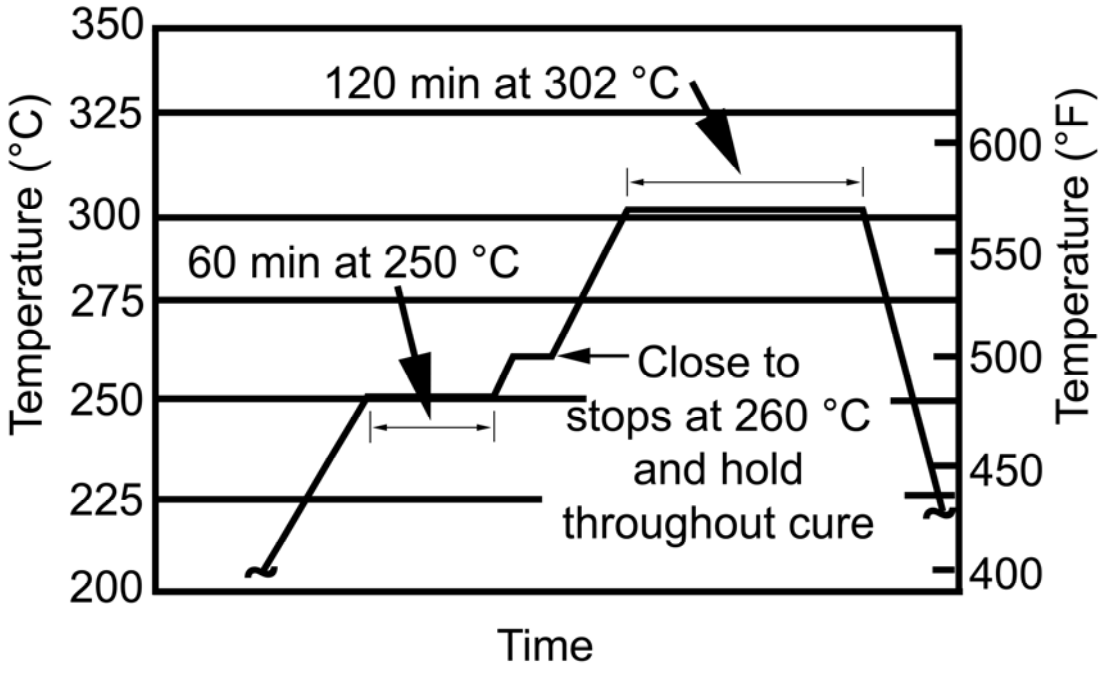


Figure 6.12-2 - Press moulding cure cycle for polyimide PMR-15 composites

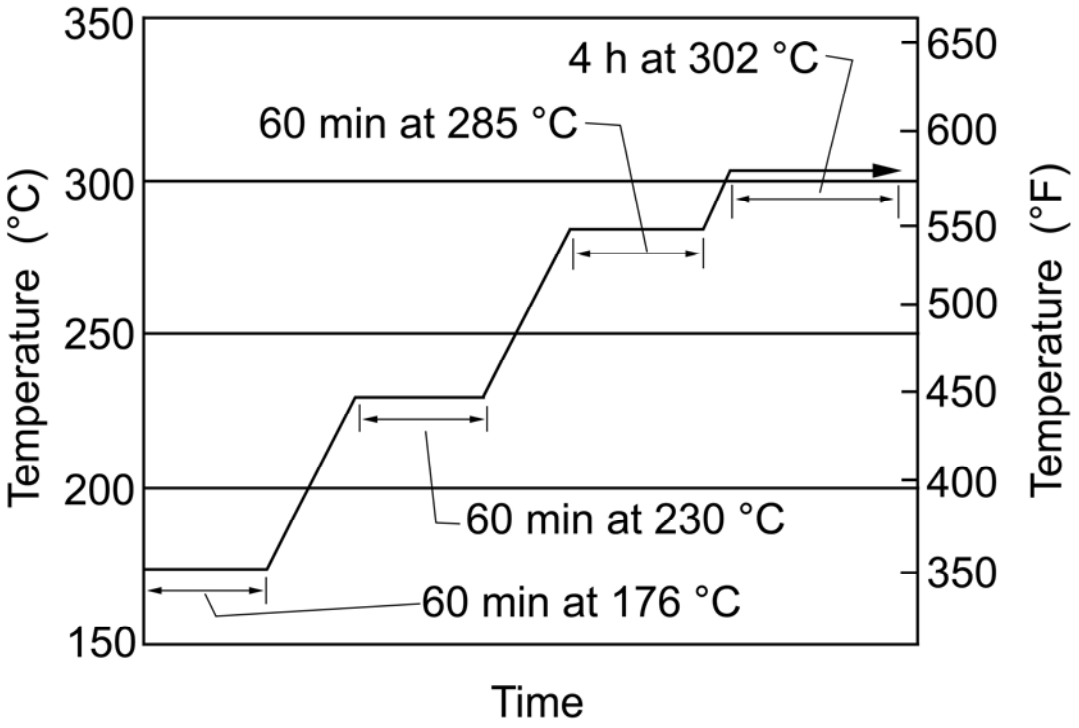


Figure 6.12-3 - Post cure cycles for polyimide PMR-15 composites

6.12.5.1 Autoclave

A schematic diagram showing the steps to achieve a full autoclave consolidation is given in Figure 6.12-4, Ref. [6-17].

It is possible to reduce the autoclave time by completing the imidisation part of the cure in an oven (under vacuum; temperature range 177°C to 23°C for PMR-15) before autoclave polymerisation.

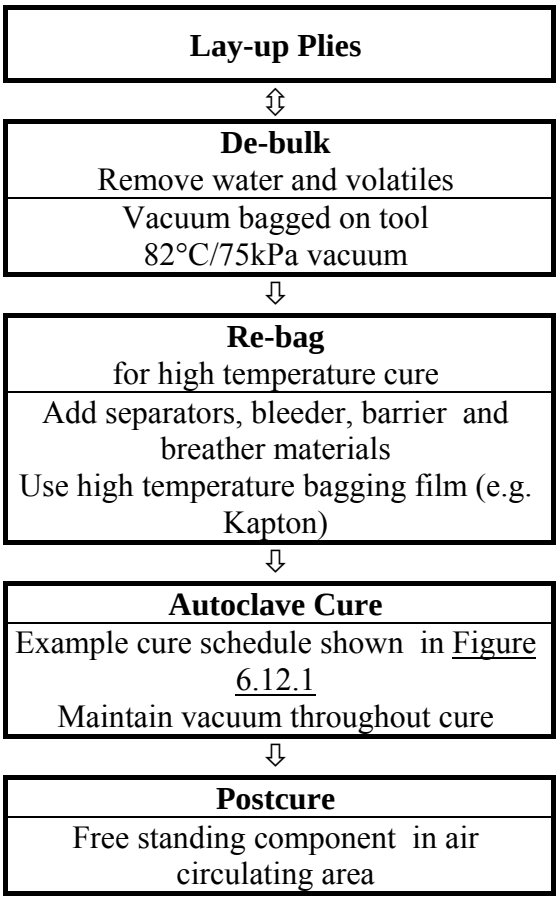


Figure 6.12-4 - Autoclave processing of polyimide PMR-15 composites

6.12.5.2 Press moulding

Oven imidisation also reduces the time in the press because it avoids the necessity to cool the mould in the press.

To avoid excessive resin bleed, the pressure stage in the cure cycle can be selected by batch testing of prepreg to counteract any variations in resin viscosity.

6.13 Fibres for polyimide composites

6.13.1 General

Many studies have concentrated on polyimide resins combined with continuous carbon fibre reinforcement, although glass and aramid (Kevlar™) fibres have also been investigated, Ref. [6-18].

6.13.2 Carbon fibres

As with all composite materials, the fibre to matrix compatibility is important for both mechanical properties and environmental tolerance. Initial studies identified that the surface morphology of the Celanese Celion 6000 fibre was beneficial, Ref. [6-18]. Hence the majority of published work on polyimide/carbon has been with this fibre.

As the number of carbon fibre/polyimide combinations increased, so did the number of sources for PMR-15 or LaRC-160 resin systems combined with various proprietary carbon fibres.

Table 6.13-1 summarises a range of carbon fibre/polyimide materials with supplier data, Ref. [6-1].

Table 6.13-1 - Carbon fibre/polyimide materials

Resin Matrix Type [Cure Temp]	Fibre	Product Trade Name [Product Code]	Forms	Supplier
PMR-15 [316°C]	Besfight	HY-E [1666AD]	T	Fiberite
	3k	HMF [1133/66A]	S8	Fiberite
	T300/3k	Ferropreg [CP12237/2] †	S8	Ferro Corp.
	HTA7	Hyfil [C475]	S5	Hyfil Ltd
	HTA7	Hyfil [C498]	S8	Hyfil Ltd
	Various	USP [USPMR-15]	Various	Hitco Material Div. (USP)
LaRC-160 [288°C]	Besfight	HY-E [1678D]	T	Fiberite
	3k	HMF [1133/76]	S8	Fiberite
	1k	HMF [1176/78]	S5	Fiberite
	T300 3,6k	Ferropreg [CP12274/T3]	T fabric	Ferro Corp.
401 [190°C]	DIN65184 FandG	Sigrafil [CT1020]	UD	Sigri Elektro-graphit
Not stated [≤180°C]	3-24kDIN	Krempel [KIHG3312]	T	A. Krempel Soehne GmbH and Co.
	LN	Krempel [KGHG4006]	twill	
	LN	Krempel [KCHG3708]	S	
	LN	Krempel [KCHG2010L]	P	
	LN	Krempel [KGHH2007H]	P	

Key: † : Abbreviated Code
T: Tape (not woven)
P: Plain weave
S: Satin weave
UD: Unidirectional

6.13.3 Aramid fibres

Table 6.13-2 summarises Kevlar 49/polyimide materials, Ref. [6-1].

Table 6.13-2 - Aramid fibre/polyimide materials

Resin Matrix Type	Fibre	Product Trade Name [Product Code]	Form	Supplier
Polyimide ‡	Kevlar 49	Not stated [AGBD series] †	P S4 S4/8	A. Krempel Soehne GmbH & Co.
Key:	† : Abbreviated code ‡ : Grade not stated		P : Plain weave S : Satin weave	

6.14 Polyimide composites

6.14.1 Basic materials data for laminate design

The evaluation of polyimide-based materials has concentrated on property retention at elevated temperatures, i.e. exceeding 200°C.

Much of the work reported is linked to the resin development activities, where the effect of an adjustment to the resin constituents was investigated with respect to property retention.

For guidance, typical properties of some unidirectional and bidirectional polyimide composites are provided.

Care is needed when interpreting results from resin development programmes because the data does not always correspond to those resin systems currently available commercially.

Data presented are for guidance only. For full production items a comprehensive in-house material evaluation study is necessary. In many cases this is likely to need significant resources.

6.14.2 Unidirectional

6.14.2.1 Celion 6000/LaRC-160

Table 6.14-1 summarises the material and processing, Ref. [6-19]. Typical mechanical properties at various temperatures are given in Table 6.14-2, Ref. [6-19].

Table 6.14-1 - Carbon fibre/polyimide material description

Material:	Fibre: Celanese Celion 6000 Resin: LaRC-160 V_f: 58%
Cure:	Not stated
Post-cure:	Not stated
Condition:	As manufactured, un-aged

[See: Table 6.14-2 for mechanical properties]

Table 6.14-2 - Mechanical properties for carbon fibre/polyimide: Celion 6000/LaRC-160

		$\bar{x}$ (MPa)	S.D.	N
ILSS †	RT	103.4	-	8
	232°C	72.4	-	8
	288°C	60.0	-	8
Flexural Strength ‡	RT	1755	-	3
	232°C	1295	-	3
	288°C	1135	-	3
Key: †: ASTM D2344-76 Short beam method ‡: ASTM D790-71 (1978)		Tg: 350°C; Voids: <1% Year of test: 1983		

[See: Table 6.14-1 for material description]

6.14.2.2 Celion 6000/PMR-15

Table 6.14-3 summarises the material and processing, Ref. [6-19]. Typical mechanical properties at various temperatures are given in Table 6.14-4, Ref. [6-19].

Table 6.14-3 - Carbon fibre/polyimide material description

Material:	Fibre: Celanese Celion 6000 Resin: PMR-15 V_f: 61%
Cure:	Not stated
Post-cure:	Not stated
Condition:	As manufactured, un-aged

[See: Table 6.14-4, for mechanical properties]

Table 6.14-4 - Mechanical properties for carbon fibre/polyimide: Celion 6000/PMR-15

		$\bar{x}$ (MPa)	S.D.	N
ILSS †	RT	97.2	-	8
	232°C	54.0	-	8
	288°C	38.4	-	8
Flexural Strength ‡	RT	1670	-	3
	232°C	1172	-	3
	288°C	1145	-	3
Key: †: ASTM D2344-76 Short beam method ‡: ASTM D790-71 (1978)		Tg: 333°C; Voids: <1% Year of test: 1983		

[See: Table 6.14-3 for material description]

6.14.3 Bidirectional

6.14.3.1 Carbon fibre/PMR-15

Table 6.14-5 summarises the material and processing, Ref. [6-23]. Typical mechanical properties at various temperatures are given in Table 6.14-6, Ref. [6-23].

Table 6.14-5 - Carbon fibre/polyimide material description

Material:	Fibre: Carbon (grade not stated) Resin: PMR-15 V_f: Not stated
Cure:	288°C
Post-cure:	Not stated
Condition:	Not stated

[See: Table 6.14-6 for mechanical properties]

Table 6.14-6 - Mechanical properties for carbon fibre/polyimide PMR-15

		$\bar{x}$	S.D.	N
Tensile modulus (GPa)	RT	65.6	-	-
	230°C	61.7	-	-
Tensil strength (MPa)	RT	649	-	-
	230°C	475	-	-
Compressive modulus (GPa)	RT	57.7	-	-
	230°C	58.9	-	-
Compressive strength (MPa)	RT	569	-	-
	230°C	449	-	-
In-plane shear modulus (GPa)	RT	4.3	-	-
	230°C	3.2	-	-
In-plane shear strength (MPa)	RT	81.0	-	-
	230°C	72.0	-	-
ILSS	RT	61.7	-	-
	230°C	47.3	-	-
Key: Tg: 322 to 326°C		Year of test: 1985		

[See: Table 6.14-5 for material description]

[See also: Clause 9 for 'Data Sheets' on polymer composite materials]

6.15 Typical properties of polyimide composites

6.15.1 Effects of elevated temperatures

Polyimide-based composites have potential uses in aerospace components where temperatures exceed the capabilities of established epoxy-based materials.

To be accepted, polyimide-based composites should demonstrate for their intended life:

- Adequate mechanical properties at elevated temperatures.
- Acceptable thermo-oxidative resistance.
- Adequate properties during thermal cycling.

The normal target temperatures and life criteria are:

- 320°C for life of 100 hrs.
- 170°C to 260°C for life of 50,000 hrs to 70,000 hrs.

Many research and development programmes, primarily conducted in the USA, have considered the high-temperature performance of several fibre/resin combinations, coupled with various resin formulations.

The cure schedule used, especially the cure temperature, affects the mechanical properties and thermo-oxidative resistance achievable for polyimide-based composites. This factor also influences the integrity of the composite when it is exposed to thermal-cycling. The effect is attributed to high cure temperatures promoting microcracks, Ref. [6-23].

Temperature effects on the properties of carbon fibre/polyimide composites are shown for, Ref. [6-19], [6-20], [6-23] (The data presented are for guidance only.):

- Interlaminar shear strength in Figure 6.15-1, Ref. [6-19].
- Flexural strength in Figure 6.15-2, Ref. [6-19]
- Flexural strength with thermal ageing in Figure 6.15-3, Ref. [6-19].
- Interlaminar shear strength, with weight loss and thermal ageing at:
  - 204°C in Figure 6.15-4, Ref. [6-19].
  - 232°C in Figure 6.15-5, Ref. [6-19].
  - 260°C in Figure 6.15-6, Ref. [6-19].
  - 288°C in Figure 6.15-7, Ref. [6-19].
- High temperature flexural strength and interlaminar shear strength, with weight loss and thermal ageing in Figure 6.15-8, Ref. [6-20].
- Effect of thermal cycling on mechanical properties in Figure 6.15-9, Ref. [6-23].

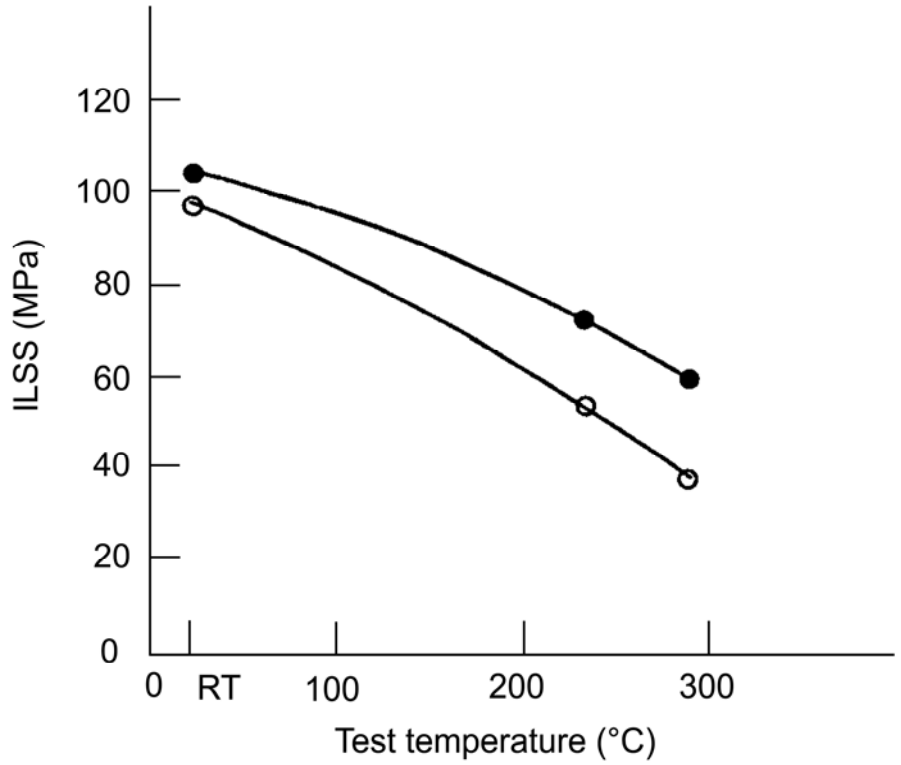


Figure 6.15-1 - Carbon fibre/polyimide composite: Effect of elevated temperature on ILSS

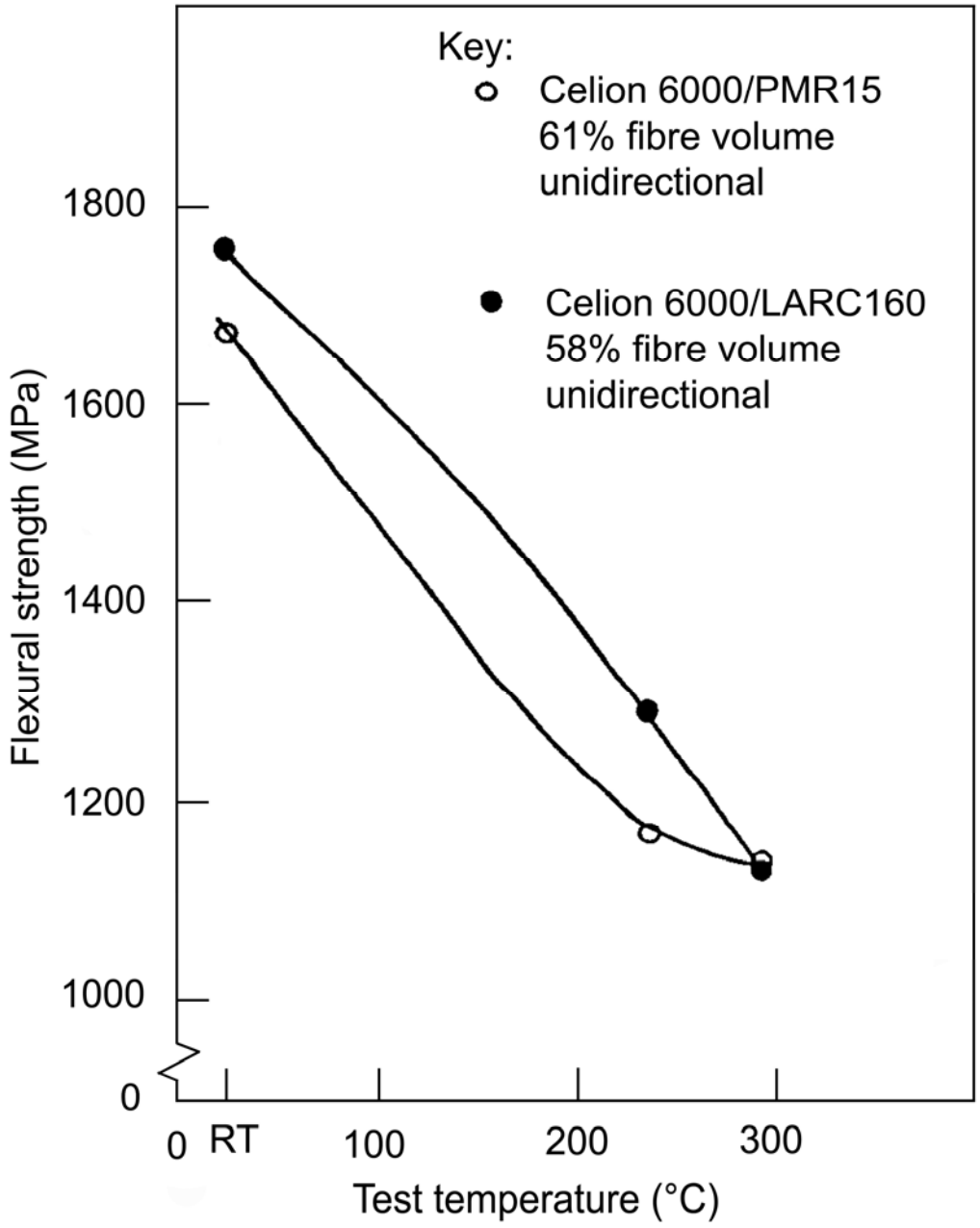
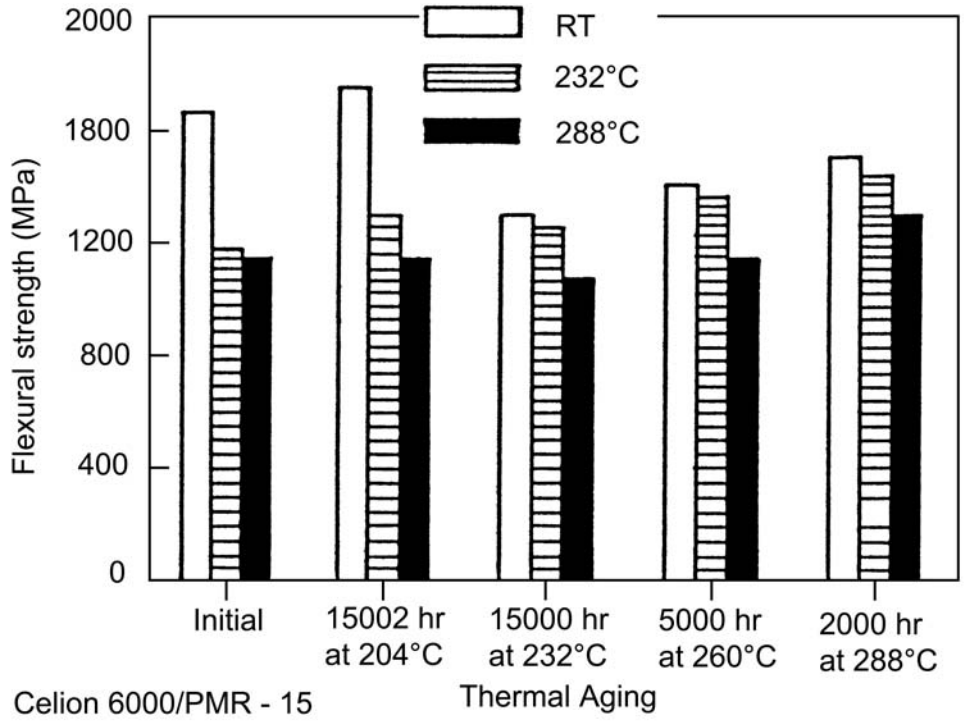


Figure 6.15-2 - Carbon fibre/polyimide composite: Effect of elevated temperature on flexural strength



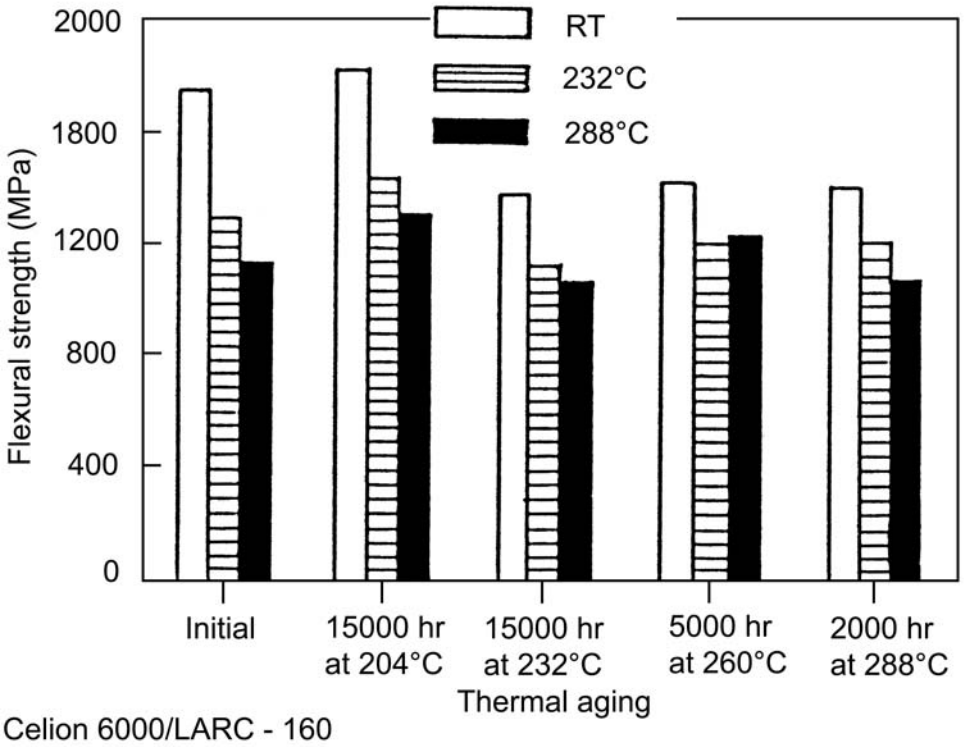


Figure 6.15-3 - Carbon fibre/polyimide composite: Thermal ageing and elevated temperature effect on flexural strength

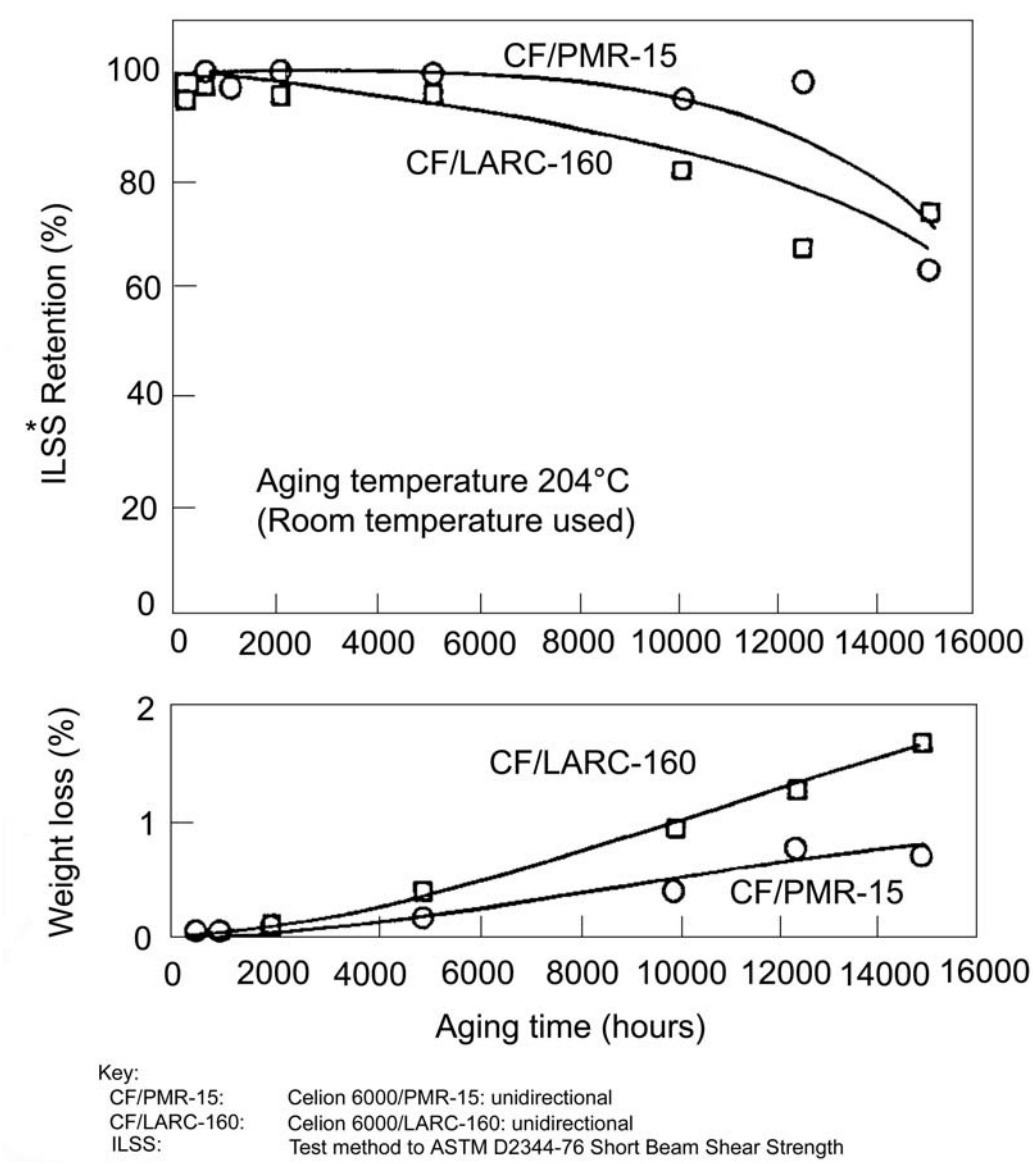


Figure 6.15-4 - Carbon fibre/polyimide composite: Weight loss and effect of thermal ageing at 204°C on ILSS

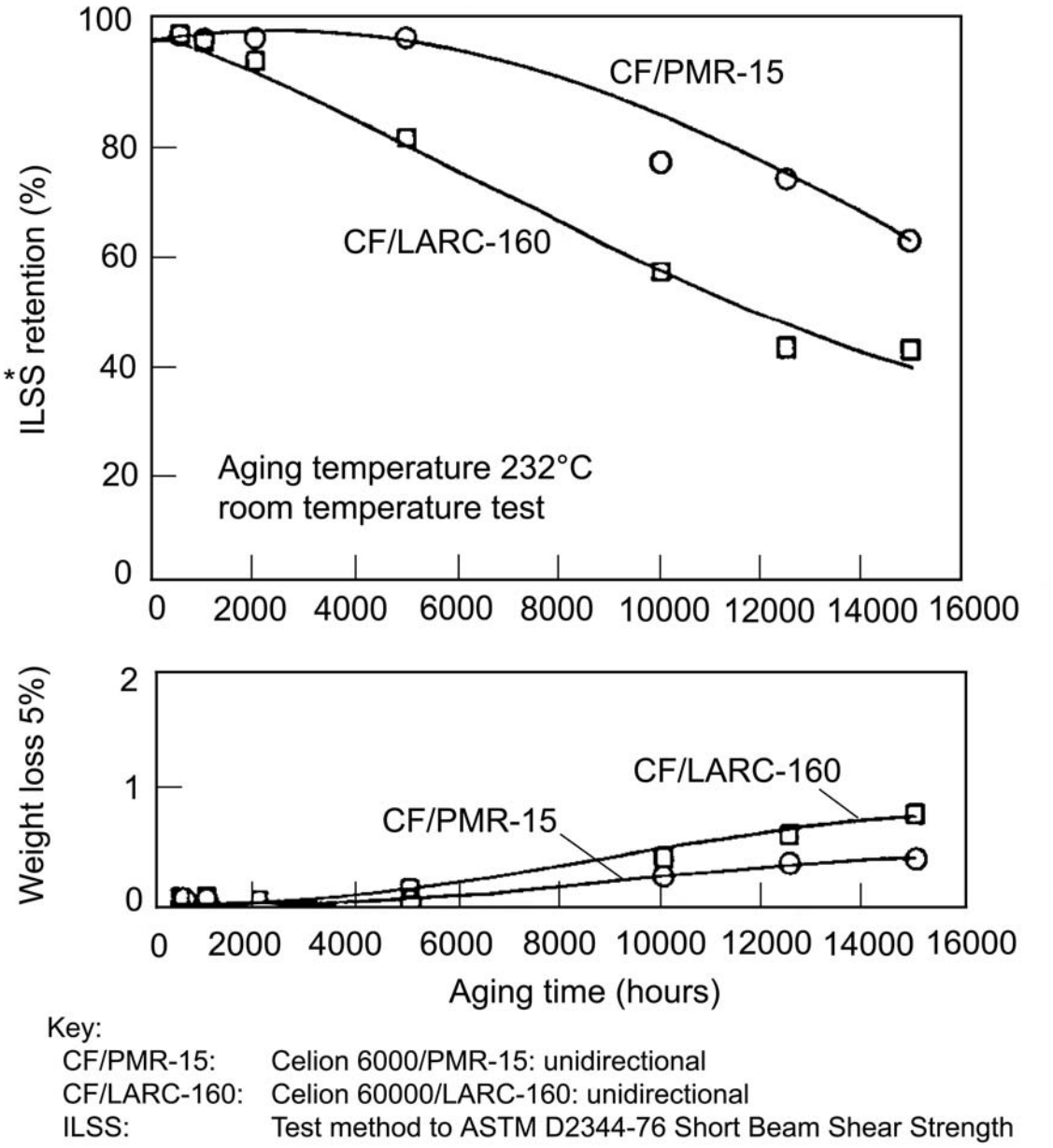


Figure 6.15-5 - Carbon fibre/polyimide composite: Weight loss and effect of thermal ageing at 232°C on ILSS

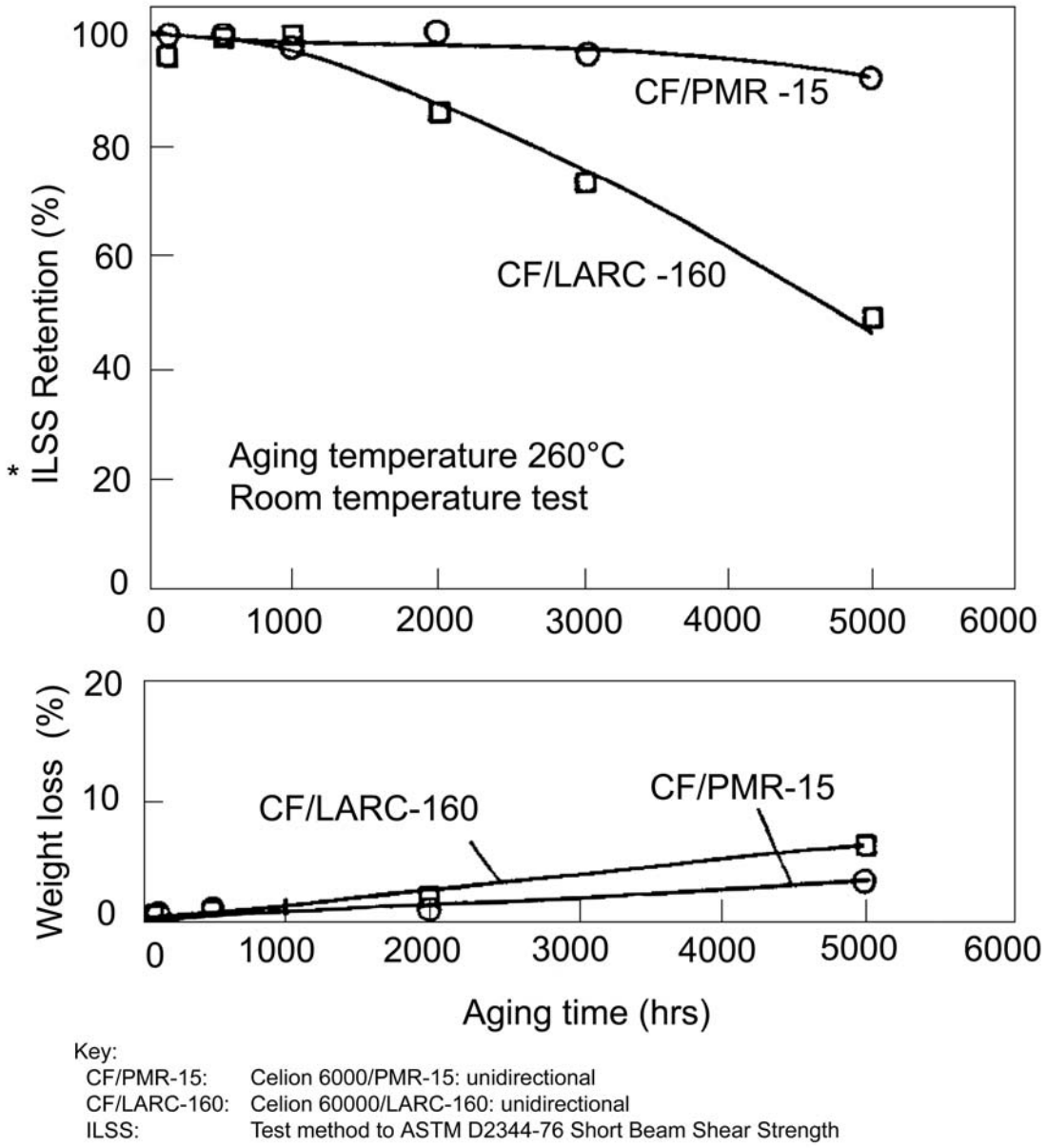


Figure 6.15-6 - Carbon fibre/polyimide composite: Weight loss and effect of thermal ageing at 260°C on ILSS

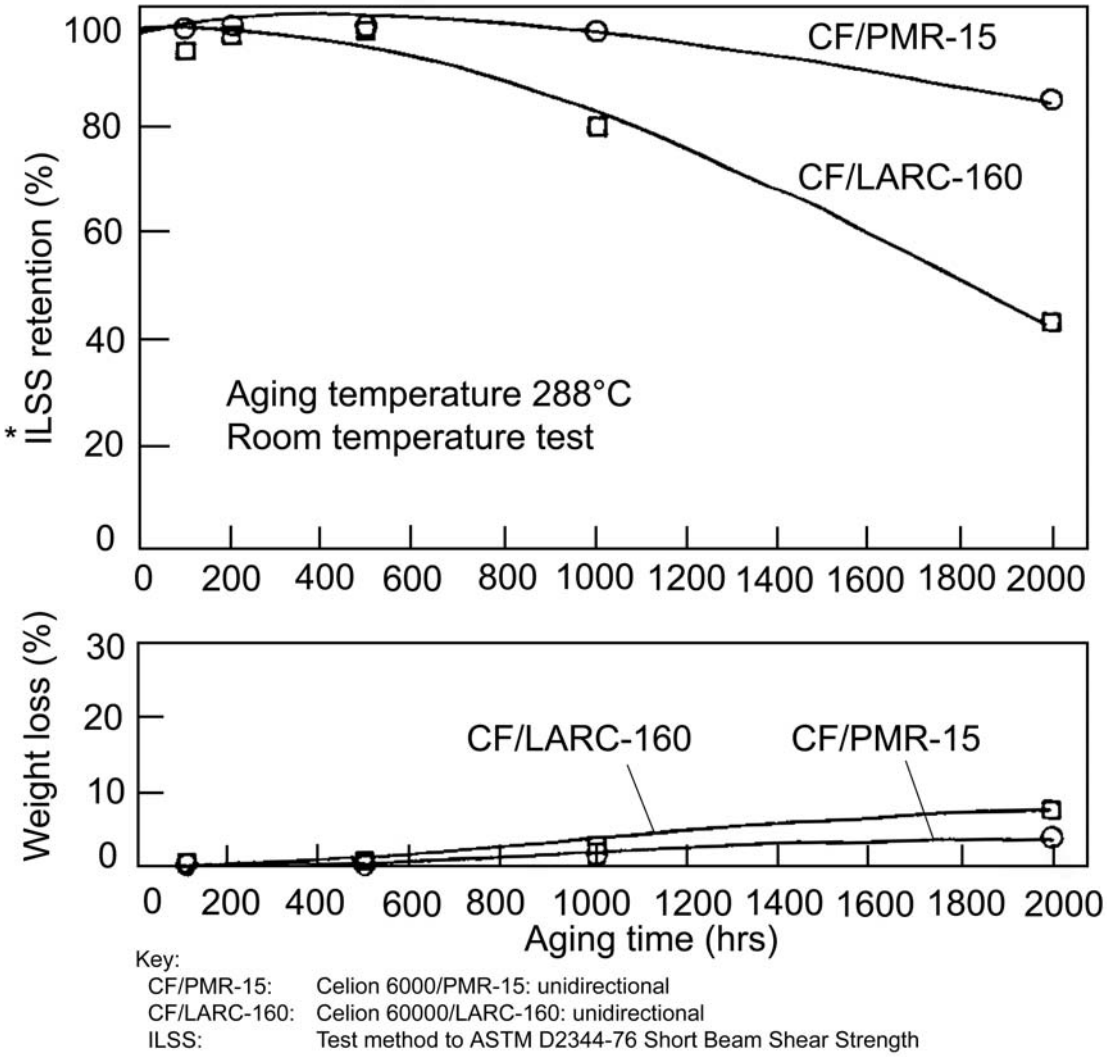


Figure 6.15-7 - Carbon fibre/polyimide composite: Weight loss and effect of thermal ageing at 288°C on ILSS

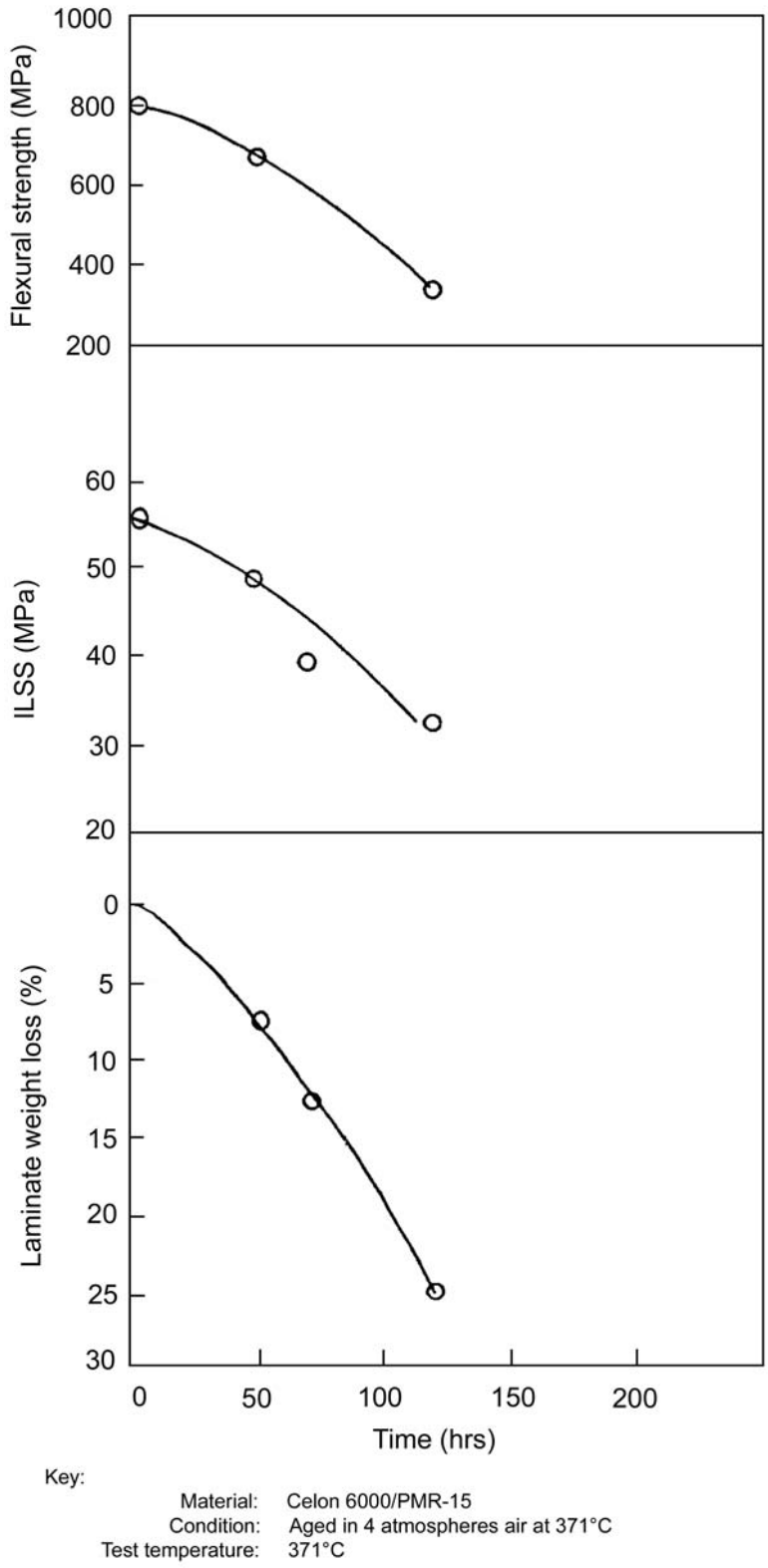


Figure 6.15-8 - Carbon fibre/polyimide composite: High temperature test, weight loss and thermal ageing on flexural strength and ILSS

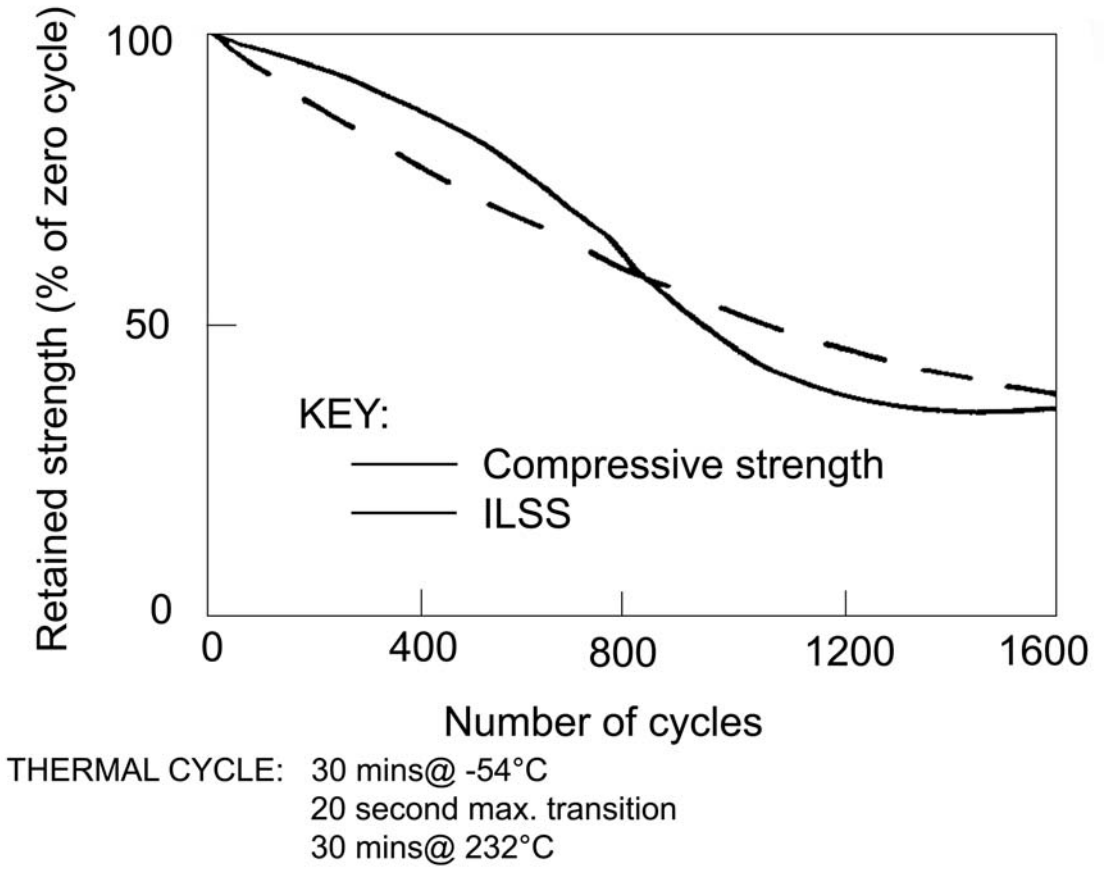


Figure 6.15-9 - Carbon fibre/polyimide PMR-15 composite: Effect of thermal cycling on mechanical properties

6.15.2 Coefficient of thermal expansion

Table 6.15-1 gives typical CTE data for various carbon/polyimide lay-ups, Ref. [6-24].

Table 6.15-1 - Typical CTE for carbon/polyimide laminates

Material System [Fibre : Resin]	Lay-up	Fibre Content (%)	CTE @ 24°C (10^{-6}°C^{-1})
Celion 6000 : PMR-15	$[0]_8$	60 - 65	-0.213
	$[90]_8$	60 - 65	22.432
	$[0_2/90_2]_8$	60 - 65	1.635
	$[0/+45/90/-45]_8$	60 - 65	1.529

6.15.3 HERMES development programme

An exercise to evaluate both bismaleimide and polyimide composites for potential use in Hermes constructions concluded in 1990, Ref. [6-73]. Four CFRP materials were evaluated for load-bearing applications experiencing temperatures in the range 200°C to 250°C.

[See also: 6.9 for the bismaleimide-based composites].

The two polyimide-based composites were, Ref. [6-73]:

- Alsthom Ferro PMR 15 T/T800H: Table 6.15-2 gives property data.
- Alsthom Ferro LaRC 160/T800H: Table 6.15-3 gives property data.

The data presented was collated at the conclusion of the programme, Ref. [6-73].

Table 6.15-2 - PMR-15T/T800H: Single and multidirectional composite data

Supplier/Tradename: Alsthom Ferro Composites	Fibre/Resin System: Toray T800 12K PMR-15 T		Data Source: HERMES Programme		
Fibre volume (%): 60	t_{ply} (mm): 0.125		Density (kg m^{-3}): 1600		
Areal weight of prepreg (g m^{-2}): 231	Number of batches tested: 5				
Areal weight of fibre (g m^{-2}): 133	Volatile content (%): 10.2		Year of test: 1989/90		
Specimen condition: Standard cure cycle. Dry state. RT values					
Test environment: (1) RT; (2) 250°C					
			$\bar{x}$	SD	N
UD tension	Strength (MPa) Modulus (GPa)		2198 159	146 11	5
MD open hole tension: 5mm ∅	Strength (MPa)		672	-	10
MD filled hole compression: 5mm ∅	Strength (MPa)		397.9	6.4	3
UD interlaminar shear	Strength (MPa) RT 250°C		 100.6 59.3	 6.4 2.5	 25 25
Key: UD: Unidirectional MD: Multidirectional					

Table 6.15-3 - LaRC 160/T 800H: Single and multidirectional composite data

Supplier/Tradename: Alsthom Ferro Composites	Fibre/Resin System: Toray T800 12K LaRC 160		Data Source: HERMES Programme		
Fibre volume (%): 60	t_{ply} (mm): 0.125		Density (kg m^{-3}): 1600		
Areal weight of prepreg (g m^{-2}): 242	Number of batches tested: 1				
Areal weight of fibre (g m^{-2}): 134	Volatile content (%): 10.7		Year of test: 1989		
Specimen condition: Standard cure cycle. After ageing*. RT values					
Test environment: (1) RT; (2) 250°C					
			$\bar{x}$	SD	N
UD tension	Strength (MPa) Modulus (GPa)		- -	- -	-
MD open hole tension: 5mm ∅	Strength (MPa)		679	12	3
MD filled hole compression: 5mm ∅	Strength (MPa)		440	24	3
UD interlaminar shear	Strength (MPa) RT 250°C		 102 51	 7 0.1	 3 3
KEY: UD: Unidirectional MD: Multidirectional *: Wet ageing + Vacuum thermal cycling (-120°C,+250°C) + Wet ageing					

Open hole tension and filled hole compression tests were conducted on 28 ply quasi-isotropic laminates : [0,±45,0,90,0,±45,0,90,0,±45,0]s

The presence of methylene dianiline amine (MDA), a known carcinogen, and alcohol solvent gives rise to health concerns when using these polyimide prepregs; particularly PMR 15.

[See also: 9.12 and 9.13 for further data on polyimide composites]

6.16 Characteristics of thermoplastic-based composites

6.16.1 General

Composites with thermoplastic polymer matrices underwent serious development and as a result commercial products became available in 1985.

They are viewed as complementing the existing and established epoxy thermoset composites used in space structures.

6.16.2 Characteristics

Thermoplastic-based composites have a number of perceived advantages which can be listed but are not necessarily proven or guaranteed; as summarised in Table 6.16-1.

Table 6.16-1 - Characteristics of thermoplastic-based composites

Advantages	
Proven	Infinite shelf life at room temperature [No cold storage needed] Significant reduction in process cycle time over thermosets No exothermic problems with thick sections Reprocessible, repeated thermoforming possible
Conditional on specific thermoplastic matrix	More damage tolerant than epoxy-based Lower moisture absorption than epoxy based composites Good resistance to aviation fuels and hydraulic fluids Good outgassing characteristics
Possible but unproven	Use of fusion bonding for fabrication Component manufacturing costs less than those of thermoset composites, using thermoforming techniques
Disadvantages	
Identified	High material processing temperatures Modest adhesive bond strengths Limited material options available Creep at elevated temperatures Misalignment of fibres during forming Precise process control (cooling phase) No ‘tack’

Only the most commercially advanced materials are described, together with their mechanical and physical properties appropriate to space use.

For full production items, comprehensive in-house materials data is necessary for a successful project, in many cases this is likely to be a very large evaluation exercise.

[See also: 6.17, 6.18, 6.19, 6.20 and 6.21]

6.17 Thermoplastic matrix materials

6.17.1 General

The properties of thermoplastics differ significantly from those of epoxies. They are governed by the:

- Molecular structure.
- Morphology.
- Crystallinity.

These have a strong influence on the mechanical and thermo-mechanical performance of the material.

The manufacturing cycle for thermoplastics can be considerably shorter than that of thermosets.

A guaranteed source of consistent quality material is necessary for a full-scale production of aerospace hardware. Experience is needed in manufacturing with a particular material such that its suitability is proven and acceptance is gained for each application.

There are only a few thermoplastic matrices which have been studied for long enough for confidence to be placed in them and their composites. A ranking is given for those matrix materials which have been closely evaluated as aircraft structural materials. None of these have yet reached full aircraft certification.

Studies, mainly within SDI programmes, considered the space applications of thermoplastic composites although detailed information is not available in open publications. The first carbon fibre/thermoplastic satellite components were to be launched in 1992, Ref. [6-3].

There are a large number of engineering thermoplastics that are being developed as composite matrices that could one day come to fruition as available prepreg materials.

In addition to prepreg materials a new group of thermoplastic continuous fibre materials are becoming available. These consist of reinforcing fibre and matrix mixed at the fibre level and supplied in unidirectional and woven forms. These are described as ‘mixtures’ and are undergoing process optimisation.

6.17.2 Chemistry

The main difference between thermoset and thermoplastic matrices is their chemistry and the effect of this on the manufacture of composite components.

To a production engineer, thermosetting matrices have an incomplete chemistry which needs cross-linking at elevated temperatures and under pressure. Thermoplastics, however, have a completed chemistry, but can be softened by heat and shaped under pressure. This is known as thermoforming.

6.17.3 Influence of processing conditions

6.17.3.1 Morphology

The molecular structure of thermoplastic polymers can take four different forms, depending on their:

- Molecular weight,
- Supercooling, and
- Orientation mechanisms during solidification and post-treatment.

These molecular structures, shown in Figure 6.17-1, are:

- Amorphous: Long range and only very limited short range order due to rapid quenching from the melt. Degree of crystallinity is almost zero.
- Semi-crystalline:
  - Spherulitic, resulting from lamellae growing radially from nucleation agents or nuclei. The material has a certain degree of crystallinity and isotropic mechanical properties.
  - Lamella (fibre texture), consisting of oriented lamellae (containing chain folded macromolecules) with their crystallographic C-axis being parallel to the orientation direction. The mechanical (E, σ) properties in orientation direction are better than those in perpendicular direction.
  - Needle-like, having macromolecules fully extended and arranged in parallel bundles aligned along the orientation direction. Owing to the resemblance to macroscopic fibres, e.g. carbon and glass; the material having such needle crystals is also called self-fibre reinforced.

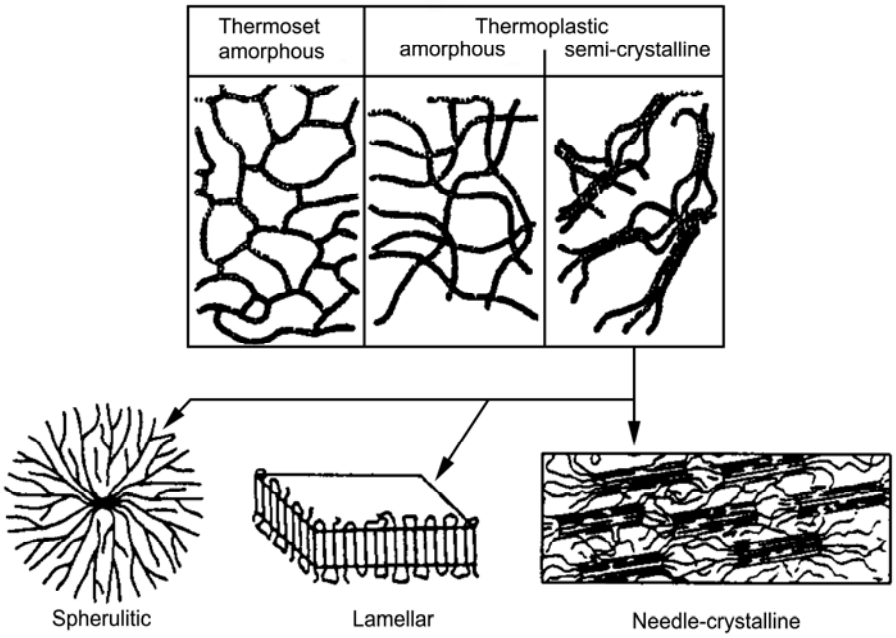
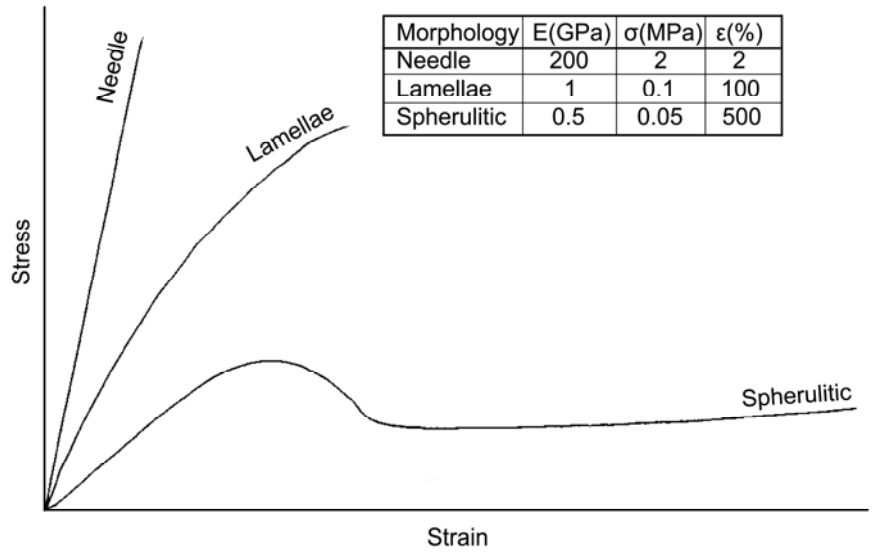


Figure 6.17-1 - Macromolecule arrangement in thermoset and thermoplastic polymers

The rules for mechanical properties of conventional fibre/matrix systems apply also to this purely polymeric composite. Needle crystal length variation greatly affects the mechanical behaviour, as shown in Figure 6.17-2.



Morphology	E(GPa)	σ(MPa)	ε(%)
Needle	200	2	2
Lamellae	1	0.1	100
Spherulitic	0.5	0.05	500

Figure 6.17-2 - Schematic stress-strain curves for different thermoplastic morphologies

6.17.3.2 Degree of crystallinity

The morphologies described imply that the polymer is able to arrange its macromolecules in a three-dimensional, periodic, long range order, i.e. crystallise. The degree of crystallinity can be summarised as:

- Variable between 0 % (amorphous) up to almost 80 %, having significant effect on physical properties of the polymer.
- Strength and stiffness are increased with increasing crystallinity.
- Melting temperature and resistance to other media increases.
- Elongation to break and fracture toughness reduces when the fraction of crystallites increases within the material.
- The effect of different cooling rates, i.e. the control of degree of crystallinity within a thermoplastic matrix, on the mechanical behaviour of APC-2 is depicted in: Figure 6.17-3 and Figure 6.17-4.
- Figure 6.17-3 for fracture properties.
- Figure 6.17-4 for transverse modulus.
- Figure 6.17-5 for transverse ultimate strain.
- Figure 6.17-6 for shear modulus.

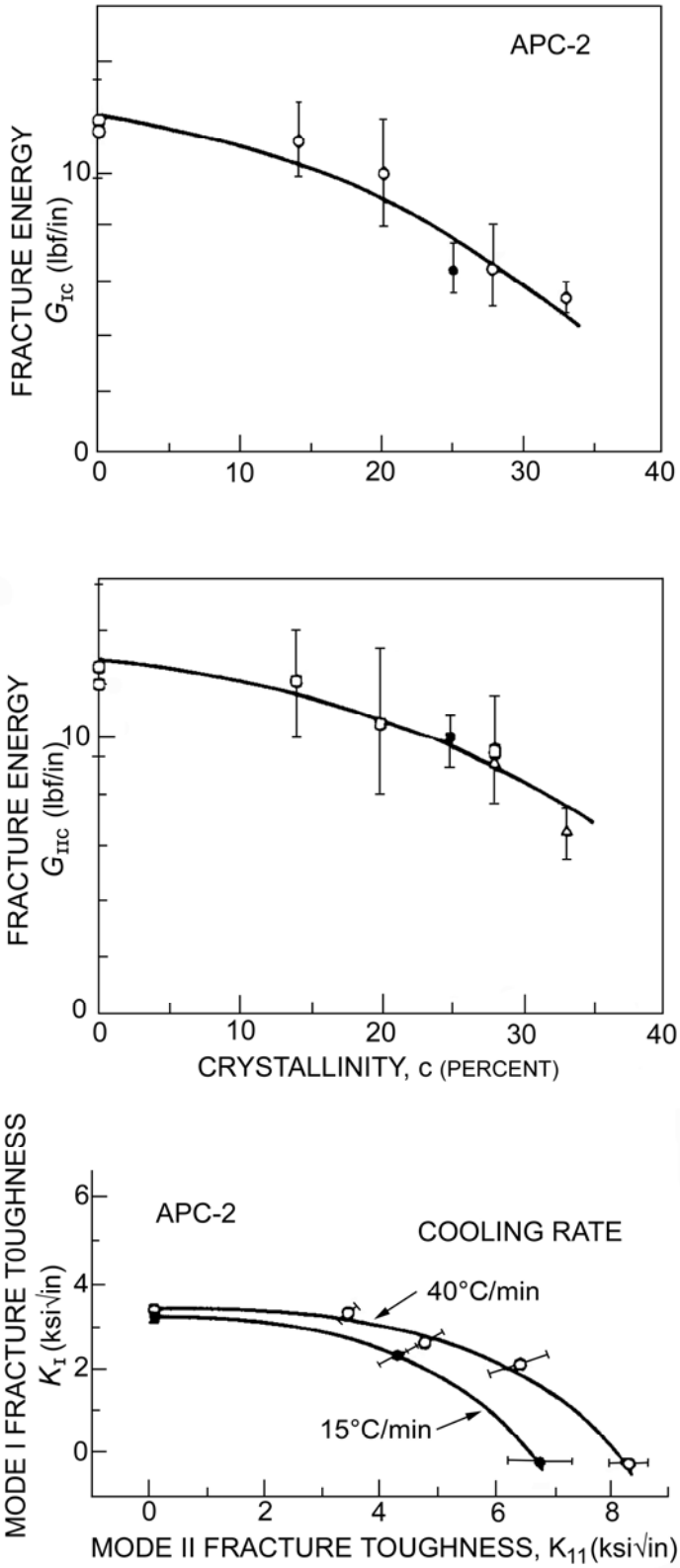


Figure 6.17-3 - Influence of cooling rate (crystallinity) on the fracture properties of carbon/PEEK: APC2

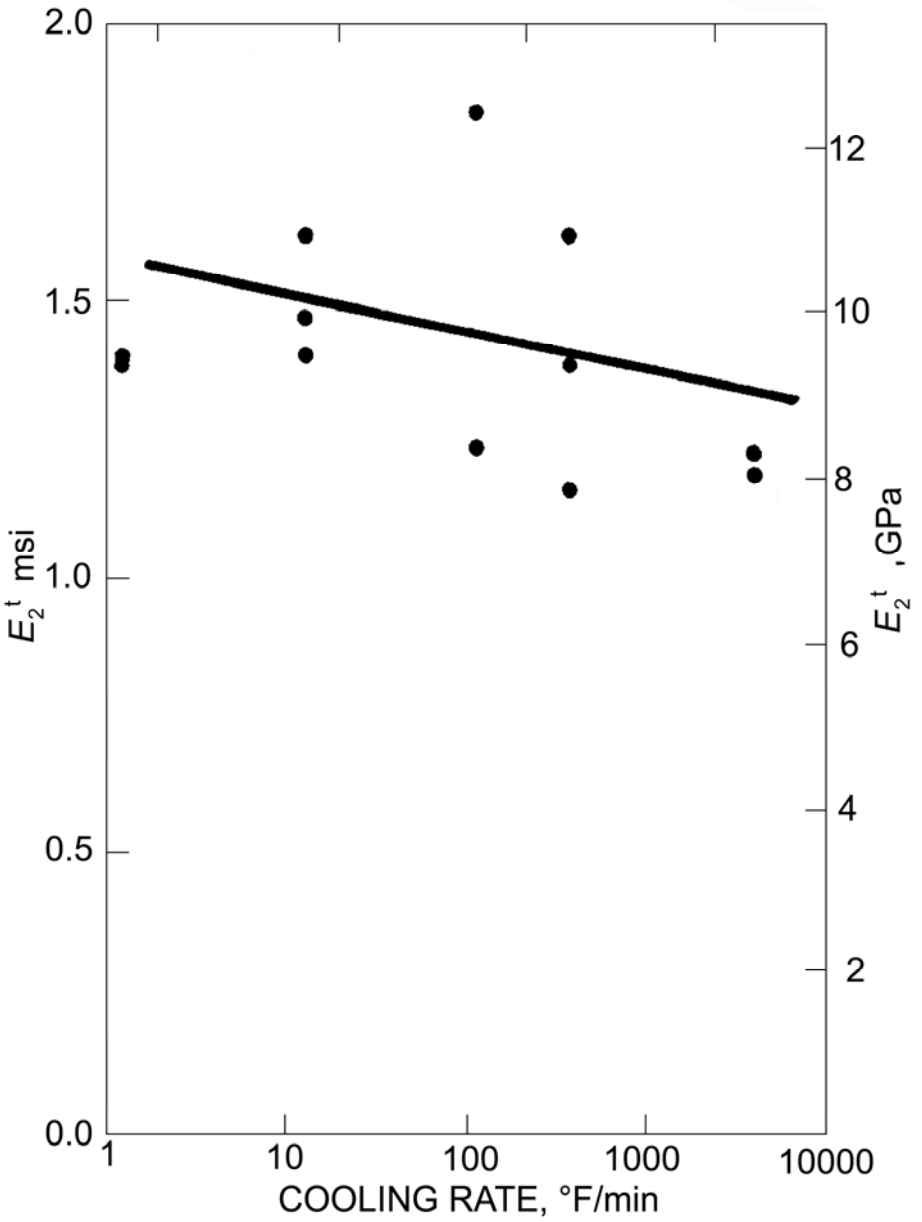


Figure 6.17-4 - Influence of cooling rate (crystallinity) on the transverse modulus of carbon/PEEK: APC2

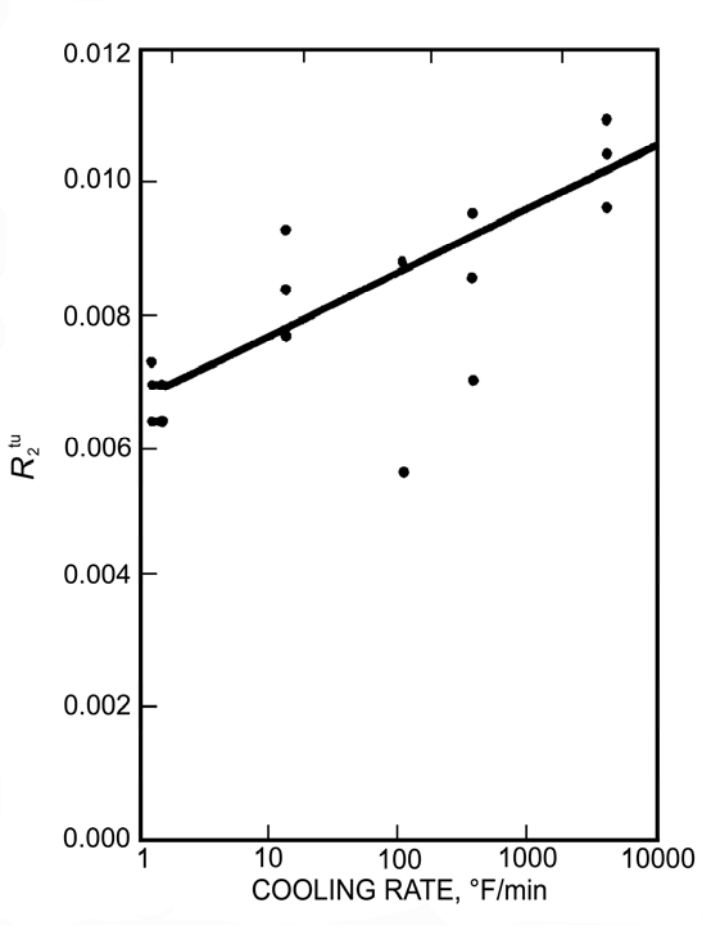


Figure 6.17-5 - Influence of cooling rate (crystallinity) on the transverse ultimate strain of carbon/PEEK: APC2

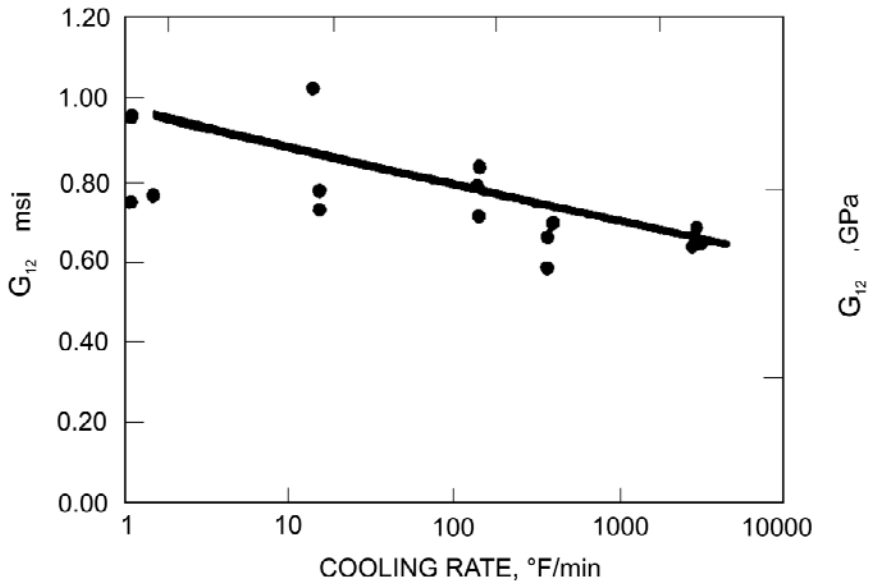


Figure 6.17-6 - Influence of cooling rate (crystallinity) on the shear modulus of carbon/PEEK: APC2

6.17.4 Commercial thermoplastic matrix

6.17.4.1 General

Thermoplastic materials can be grouped in terms of their molecular structure, which is dictated by their polymer chemistry and processing method, [See also: [6-17] - Chemistry].

Table 6.17-1 summarises the development status of those thermoplastics under consideration as composite matrices, with material supplier and product name codes. Included in the table are brief descriptions of the attributes of each polymer group. The descriptions are generalised and variations do exist between the polymer types in a particular group. Of the primary contenders for aerospace use, the greatest emphasis has been placed on the polyether ether ketone PEEK-based composites. This polymer is attractive because of its resistance to moisture absorption and aviation fluids.

Table 6.17-1 – Development status and availability for potential matrices for thermoplastic based composites

Status	Thermoplastic Polymer Group					Notes
	Semi-crystalline	**Crystalline**	**Amorphous**	**Amorphous Polyamide**	**Liquid Crystal**	
Primary	Polyether Ether Ketone (PEEK/ICI)		Polyether Imide (PEI/GE Plastics)			All these materials are available as prepreg.
	Polyphenylene Sulphide (PPS/RYTON/ Phillips Petroleum)		Polyether Sulphone (PES/ICI)			Spinable polymers are mixed with reinforcement fibres and supplied as UD or woven form.
	Polyamide-imide (TORLON/ Amoco)					-
Potential		Polyamylene Sulphide (PAS-1, PAS-2/ Phillips Petroleum)	(J2/Du Pont) Polyamylene Sulphide (PAS-2/ Phillips Petroleum)	(AVIMID N, AVIMID K111/ Du Pont)	(XYDAR SRT 300, XYDAR SRT 500/ Dart Industries)	Limited availability as Prepregs: The majority of these materials are still under development.
		Polyether Ketone (PEK/ICI)	High Temperature Amorphous (HTA/ICI)	(JDB61/BP)	(Vectra/Celanese)	
		High Temperature Crystalline (HTX,HTC/ICI)		(EYMYD/-)	(-/DSM)	
				(LARC-I -TP1/ NASA Langley)		
Attributes	High Toughness High Solvent and Chem. Resistance	Good Mech. Properties Excellent Chem. Resistance Medium/High Tg	Good Toughness Medium/High Tg	Good Toughness High Tg	Good Strength High Tg Dimensional stability Chemical Resistance	General properties. Variations exist between polymer types in a particular group.
Drawbacks	Low Tg		Processibility Solvent Resistance	Processibility	Processibility	

6.17.4.2 Carbon fibre/PEEK

PEEK is combined with Hercules AS4 carbon fibre to give APC-2, sold by ICI as unidirectional prepreg. The characteristics of APC2 include:

- Fibre/matrix compatibility.
- Matrix Tg of 143°C.
- Processing temperature circa. 360°C.
- Resistance to moisture.
- Resistance to chemicals (solvent, organic and inorganic).
- Low flammability rating (V-0 without additives).
- Low emission of thermoplastic combustion products:
  - smoke, and
  - toxic acid gases
- Resistance to gamma-radiation.
- Good electrical properties.
- Damage tolerance to impact.

APC2 exhibits useful properties for aerospace components. It is the most advanced regarding availability and understanding. A combined property evaluation and manufacturing exercise was made by Westland Helicopters, Ref. [6-29], and various aerospace companies in the USA.

The Westland evaluation, Ref. [6-29], included a woven carbon fibre reinforcement in a PEI matrix (Ultem 1000, supplied by Ten Cate Glass, NL). This material was chosen as it too has comparatively consistent quality and availability with a woven reinforcement, whereas woven carbon fibre/PEEK was not available at an acceptably reproducible quality. Data generated on the PEI material is also included.

6.17.5 Polymer forms

6.17.5.1 Filaments

Some polymers can be spun to produce filaments, including:

- PEEK,
- PEI,
- PE,
- PPS.

These are mixed with carbon reinforcements to produce ‘hybrid’ or a ‘mixture’ type fibre.

[See also: 6.18]

6.17.5.2 Polymer powders

Pre-impregnation of yarns using powdered polymers (PEEK, PAS-2) is under development.

[See also: 6.18]

6.18 Fibres for thermoplastic composites

6.18.1 General

It is necessary to differentiate between reinforcement fibres used in:

- Prepreg, and
- Mixture, which contain both reinforcement and polymer filaments.

Table 6.18-1 summarises the availability status of both prepreg and mixture products.

Table 6.18-1 - Thermoplastic matrices and fibre reinforcement types with availability status

Matrix	Fibre	Product Code [Supplier]	Note
Prepreg			
PEEK	AS4	APC2/AS4 [ICI/Fiberite]	Available in UD prepreg form.
	IM6	APC2/IM6 [ICI/Fiberite]	Late development/early production stage.
	IM7 IM8	[ICI/Fiberite] [ICI/Fiberite]	Early development, likely to supersede APC2/IM6.
	P75 P100	[ICI/Fiberite] [ICI/Fiberite]	Experimental. High *E*, low CTE space applications development.
PEI	AS4	Ultem 1000/AS4 [CETEX Ten Cate Glass]	Available with woven carbon fibre reinforcement.
	Aramid	[Ferro]	Fabric.
PPS	AS4 IM6	[Phillips Petroleum]	Available in prepreg form and satin weave fabric.
	Aramid	[Quadrax]	Interlaced, UD prepreg tape.
	Aramid	[Ferro]	Fabric.
Mixture			
PEEK	Carbon	FILMIX [Courtaulds Advanced Materials]	Development: Filaments are nominally 75mm - 100mm long and twisted. (HELTRA Process).
	AS4	[BASF]	Commingled yarn.
		[Textile Technologies]	Commingled fabric.
	P75	[Textile Products] (USA)	Commingled fabric.
	P100	[Textile Technologies]	Co-woven.
PEI	Aramid	[Textile Products] (USA)	Development: Commingled fabric.
TPI	IM8	[BASF]	Early development: Powder prepreg.
PEEK PAS-2	Carbon	FIT series: [Ciba Geigy]	Powder prepreg.

6.18.2 Prepreg

6.18.2.1 General

The fibres used to reinforce thermoplastic matrices are similar to those used with traditional thermosetting resins, e.g. epoxy.

[See: 3.3 for fibre properties]

Thermoplastic prepreg characteristics include:

- Inherent rigidity (do not drape easily).
- No tack, which can cause problems during lay-up.

6.18.2.2 Carbon fibres

The choice of fibre reinforcement for a particular thermoplastic matrix is very limited, [See: Table 6.18-1], but suppliers attempt to keep pace with the arrival of new fibre reinforcements; for example, APC2/IM6 is likely to be superseded by the newer IM7 and IM8 fibres.

The combination of PEEK with P75 and P100 fibres is aimed primarily at high stiffness, low thermal expansion space applications.

The term APC now describes a family of ICI composites in which the fibre types can vary. Therefore the precise fibre should also be specified.

6.18.2.3 Aramid fibres

Aramid fibre composites are intended for satellite applications needing RF transparency.

Thermoplastic fibre/matrix compatibility needs evaluation. New fibre surface treatments can be needed for adequate fibre-to-matrix bonding. This has been established for the carbon AS4/PEEK (APC2/AS4).

6.18.3 Mixtures

6.18.3.1 Filaments

To assist lay-up, fibres containing reinforcement (usually carbon) and polymer filaments have been developed. These are subsequently used for unidirectional, fabrics and 3-D products. Figure 6.18-1 shows methods of mixing polymer and reinforcement, Ref. [6-32].

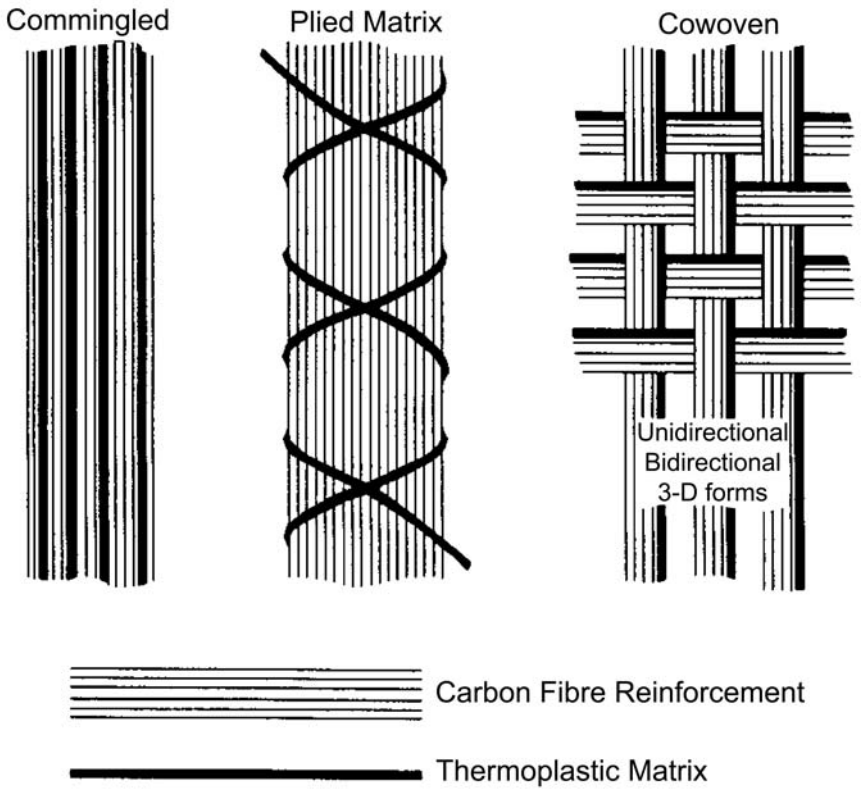


Figure 6.18-1 - Development thermoplastic mixture product forms

Commingled fibres contain 60% carbon and 40% polymer (PEEK) typically. Unidirectional forms and fabrics are being evaluated for aerospace applications, Ref. [6-31].

6.18.3.2 Powders

The pre-impregnation of reinforcement tows with polymer powders aims to provide flexible materials, where matrix polymers are not limited by their ability to be spun. A tacky agent is also incorporated to aid lay-up.

Weaving and subsequent consolidation operations need to show benefits over prepreg thermoplastics.

In unidirectional product forms, carbon fibre and thermoplastic are used in the warp direction, and thermoplastic only in weft direction.

6.19 Thermoplastic matrix composites

Mechanical property data for APC2/AS4 and PEI/AS4 with uni and bidirectional carbon fibre reinforcement, respectively, were generated by Westland UK in an in-house evaluation programme as part of their aerospace materials investigations, Ref.[6-29].

[See also: 9.15 and 9.16 for data on unidirectional and bidirectional plies]

6.20 Typical properties of thermoplastic composites

6.20.1 Effects of elevated temperatures

6.20.1.1 Unfilled thermoplastic materials

With increasing temperature, thermoplastic materials soften and exhibit a loss in mechanical properties.

Figure 6.20-1 shows the tensile strength of some unfilled materials with respect to temperature.

The effect on flexural modulus is shown in Figure 6.20-2.

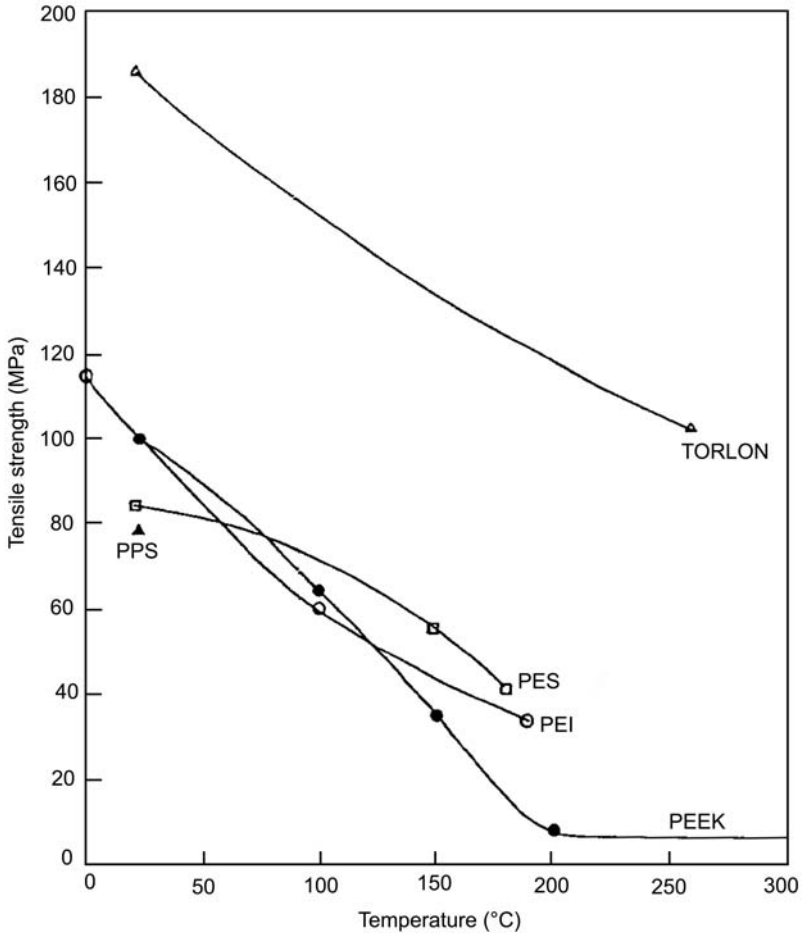


Figure 6.20-1 - Effect of temperature on the tensile strength of various unfilled thermoplastics

Manufacturers' information

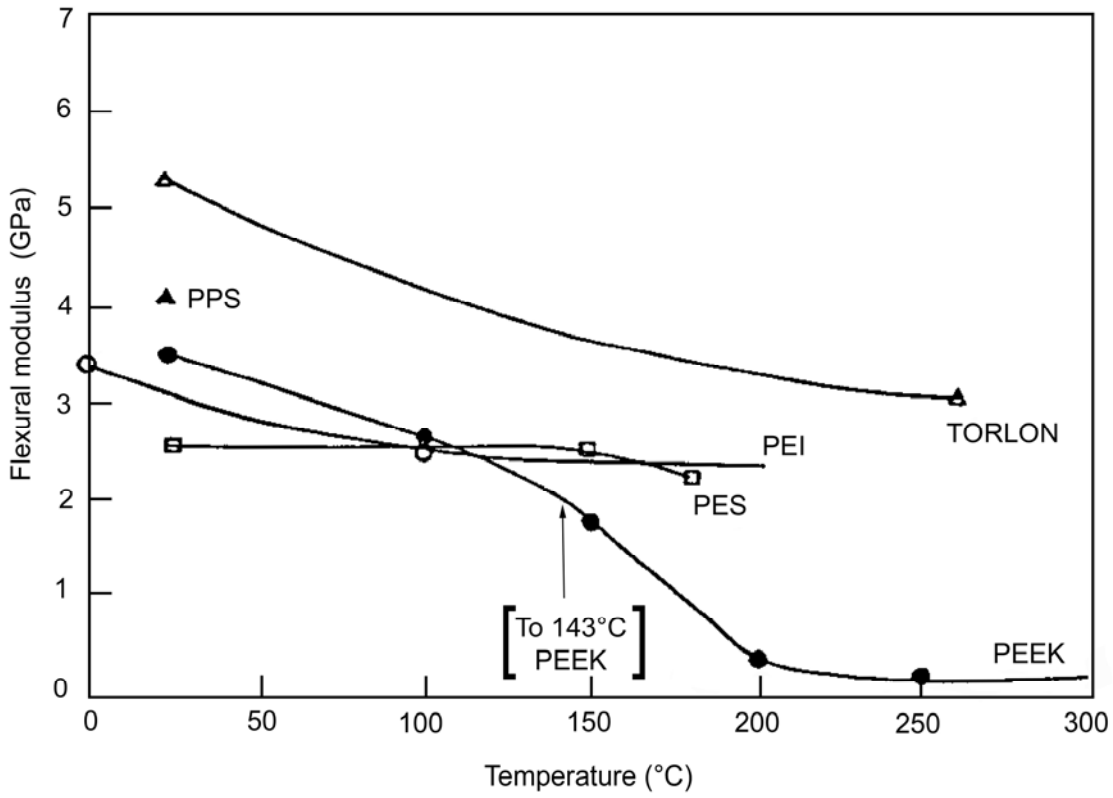


Figure 6.20-2 - Effect of temperature on the flexural modulus of various unfilled thermoplastics

As the glass transition temperature (Tg) is reached, property loss is more pronounced, [See: Figure 6.20-2- PEEK curve].

A histogram of the Tg points for the whole range of unfilled thermoplastics described is shown in. Figure 6.20-3 Those materials classified as 'primary contenders' are highlighted.

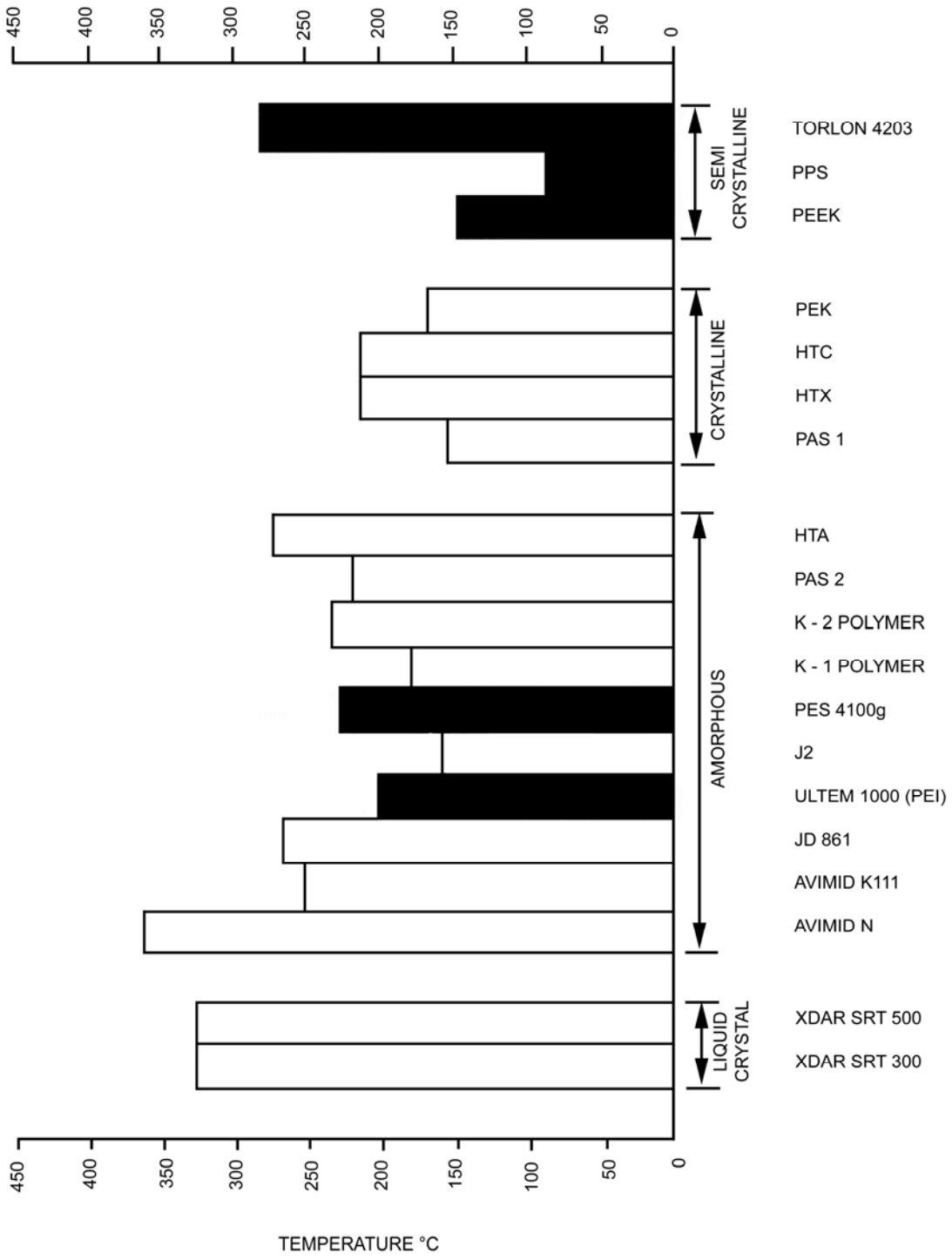


Figure 6.20-3 - Glass transition temperature (Tg) for various unfilled thermoplastics

For guidance only, Figure 6.20-4 shows the melting temperature and Figure 6.20-5 the long-term service temperature of unfilled thermoplastic matrices data provided by the manufacturers.

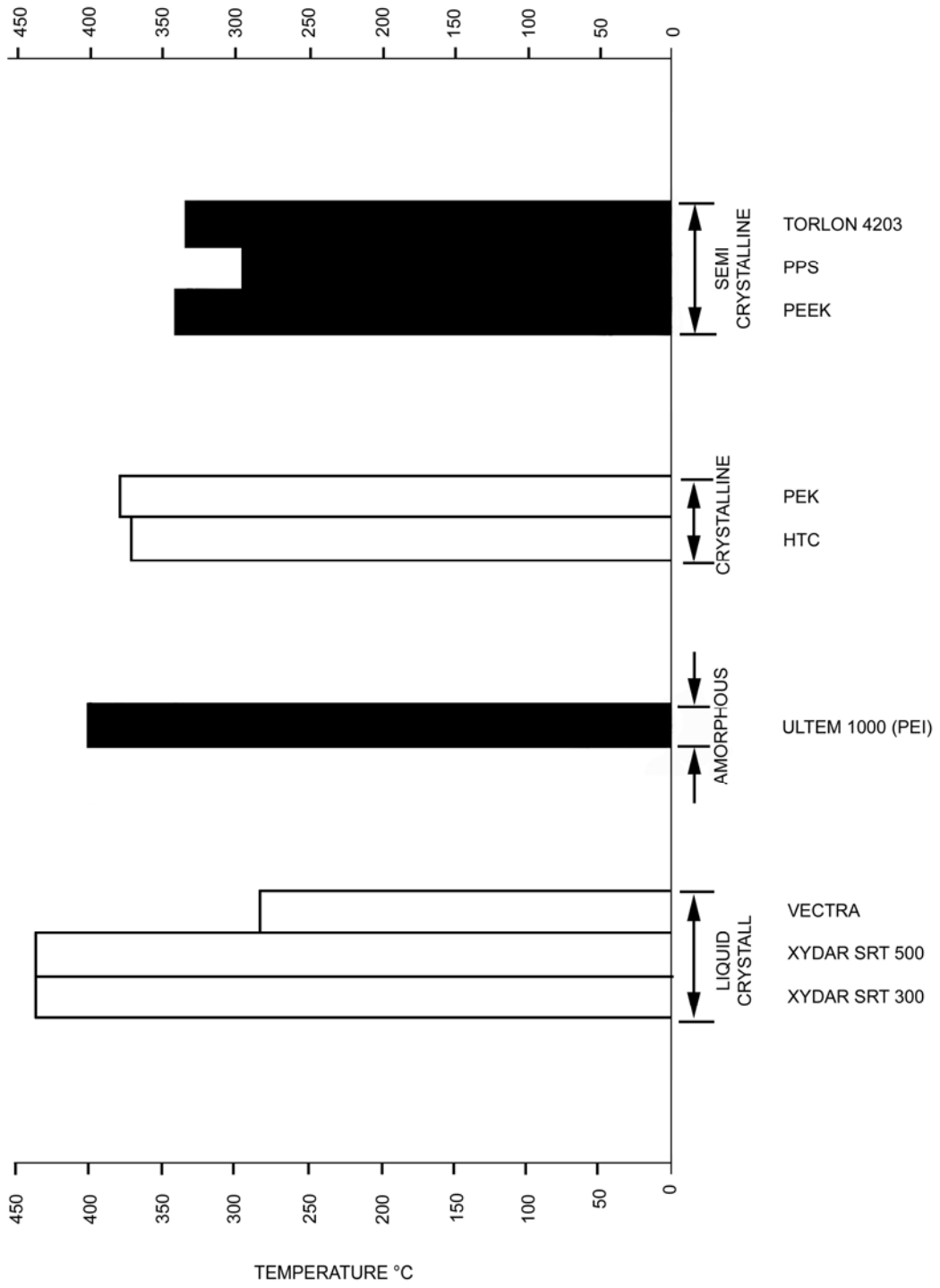


Figure 6.20-4 - Melting temperature for various unfilled thermoplastics

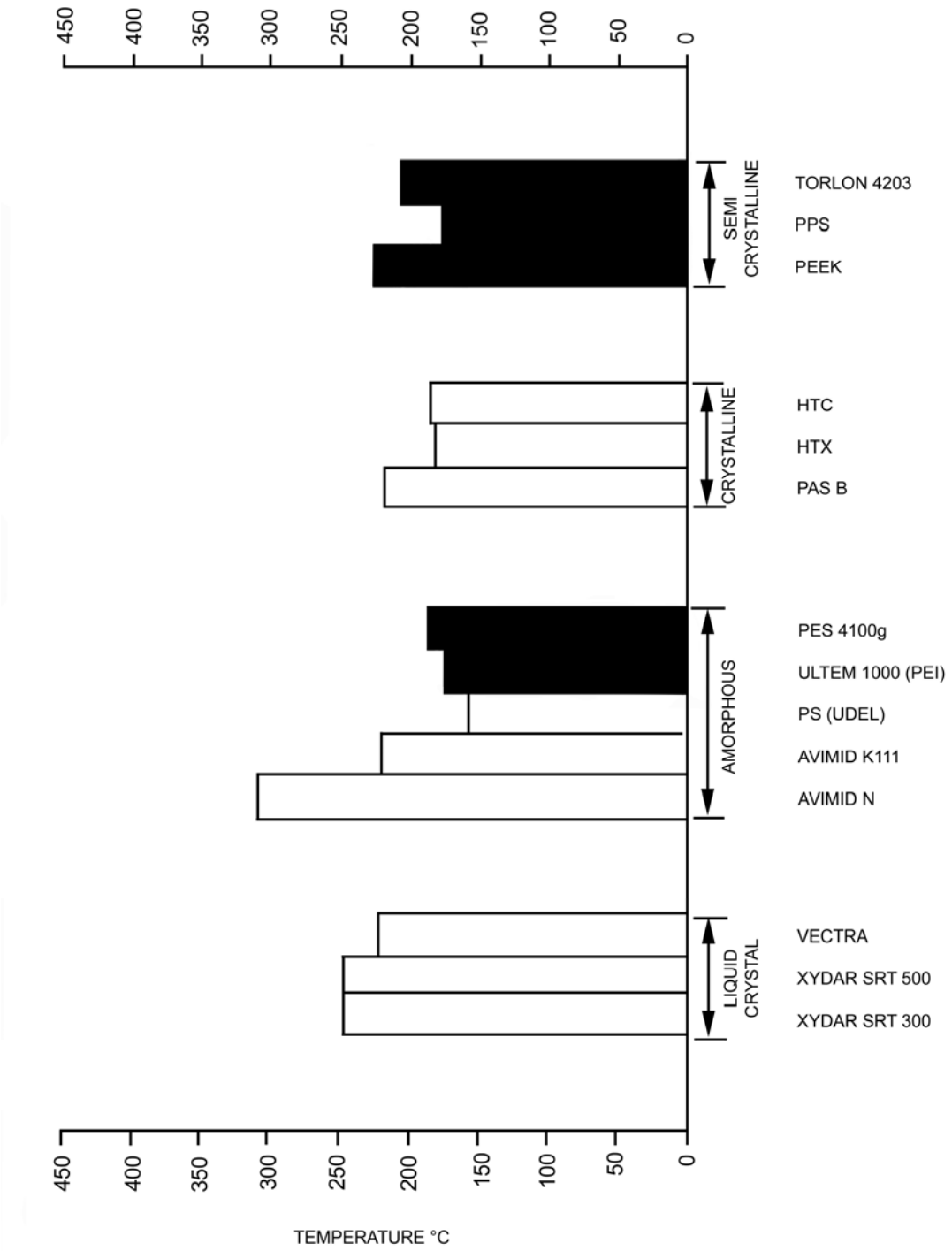


Figure 6.20-5 - Perceived long term use temperature for various unfilled thermoplastics

The properties can be recovered to some level after cooling. The property levels depend on the cooling rate which in turn dictates the polymer structure. For PEEK, the cooling rate affects the crystallinity, [See: 6.17].

6.20.2 Effects at low and cryogenic temperatures

The properties of thermoplastic-based composites are not fully characterised for use in the low temperatures associated with space. The results of initial studies indicated that:

- Thermal cycling: PEEK based composites, cycled 500 times between -157°C and +121°C indicate low microcracking; (1 microcrack/cm2 compared with 8 microcracks/cm2 for epoxy composite), Ref. [6-34].
- Cryogenic temperatures: Promising performance of thermoplastics at -196°C; with a continuous operating temperature for APC2 (AS4/PEEK) of -268°C claimed by ICI, Ref. [6-34].

Further work is needed to provide confidence in material performance over prolonged:

- Cycling between Earth shadow and full sunlight. (30 years life/175000 cycles).
- Containment of liquid oxygen and liquid hydrogen propellants at cryogenic temperatures. Ref. [6-46].

6.20.3 Moisture (hygrothermal) effects

6.20.3.1 General

The fundamental differences in the chemistry of thermosetting and thermoplastic polymers [See: 6.17] gives a different tolerance to moisture uptake and subsequent ageing by hygrothermal degradation.

The advantages of thermoplastic matrix composites, notably PEEK, compared with thermosets, are shown in Table 6.20-1.

Thermoplastic matrices with known lower tolerance to moisture are given in Table 6.20-2.

Table 6.20-1 - Comparison of hygrothermal effects on carbon fibre thermosetting and thermoplastic matrix composites

Material/ Constituent	Comments on Effect of Moisture	
	Thermosetting Matrix (Epoxy)	Thermoplastic Matrix (PEEK)
Absorbed Moisture (%)	1.5	0.1
Matrix	Plasticisation	No plasticisation
	Micro-cracking	No micro-cracking
	Degree of degradation depends on local level of cure	Not applicable
	Lowering of Tg	No lowering of Tg
	Swelling	No swelling
	Sensitivity related to Hydroxyl content	Not applicable
Fibre	High-modulus fibres (HM) less susceptible than high strength (HT) fibres	Unknown
Fibre/Matrix Interface	Degraded Affects amount of water absorbed	Relies on correct and reproducible surface chemistry of fibre, and matrix compatibility

Table 6.20-2 - Basic guide on the moisture tolerance of thermoplastic matrix materials

Status (1)	Thermoplastic (Trade Name/Supplier)	Moisture Tolerance
Primary	Polyetheretherketone (PEEK/ICI)	Good
	Polyphenylenesulphide (PPS/Phillips Petroleum)	Good
	Polyamide-imide (TORLON/Amoco)	Modest
	Polyetherimide (PEI/General Electric Plastics)	-
	Polyethersulphone (PES/ICI)	Modest
Potential	The majority of these thermoplastics are still under development; their properties are variable and have not been established in a systematic manner.	Unknown
Key: (1) As classified in 6.17		

6.20.3.2 Carbon fibre composites

For thermosetting matrices, i.e. epoxy, absorbed moisture primarily affects matrix-dominated properties. Since moisture absorption for PEEK is considerably lower, matrix-dominated property degradation is reduced.

When direct comparisons are made between epoxy and PEEK-based carbon fibre composites, the inherent mechanical properties of the matrices are different. Therefore their respective contributions to the composite mechanical properties also differ.

6.20.3.3 Aramid fibre composites

Total moisture absorption is a combined effect of epoxy matrix and fibre property, Ref. [6-35].

Thermoplastic matrix/aramid composites show significantly reduced moisture uptake and associated hygroscopic strain, as shown in Figure 6.20-6 and Table 6.20-3., Ref. [6-36].

Table 6.20-3 - Moisture absorption characteristics of aramid composites with various thermoplastic matrix materials

Composite	Weight Change† (%)	Transverse Hygroscopic Strain (%)	Diffusivity x 10^{-5} ($mm^2 s^{-1}$)
Kevlar 49/PES	2.41	1.06	1.2
Kevlar 49/PPS	1.18	0.39	0.16 ‡
Kevlar 49/PEI	2.28	0.87	1.2
Kevlar 149/PEI	1.38	0.46	2.5
Kevlar 49/5208 Epoxy	4.6	2.15	0.176

Key: † : Equilibrium moisture gain ‡ : Low diffusivity attributed to crystallinity of PPS

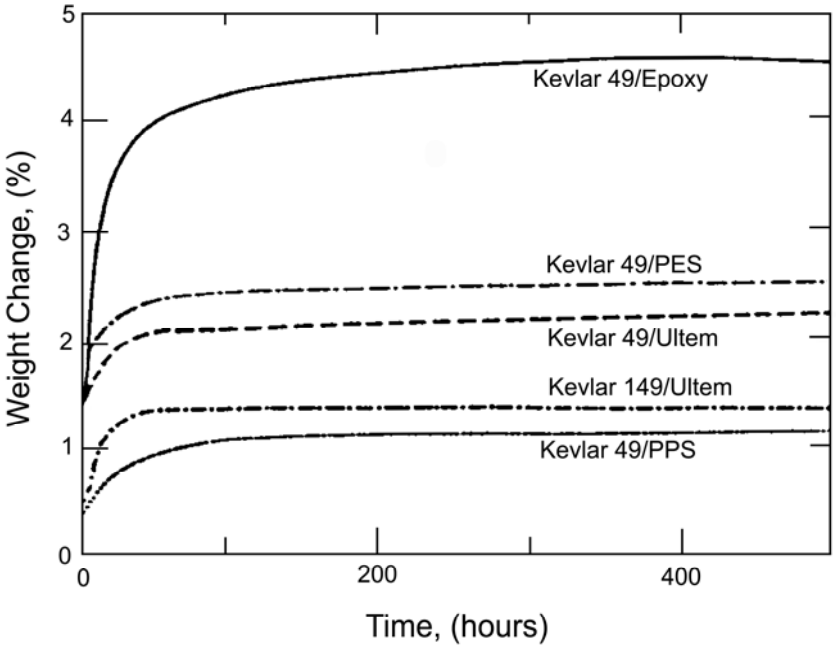


Figure 6.20-6 - Water absorption characteristics of aramid composites with various thermoplastic matrix materials

6.20.4 Influence of stress concentrations

For guidance only, thermoplastic matrix composites are likely to react in a similar manner to stress concentrations as thermosetting materials.

There is little data regarding the effect of stress concentrations on APC-2 (AS4/PEEK) composites, although initial indications are:

- PEEK-based composites are similar to epoxy in notch sensitivity tests.
- Trials with 5 mm holes indicate that incorrect crystal morphology of the thermoplastic can produce unacceptable stress states. This implies careful control of the processing cycle.

6.20.5 Impact resistance

6.20.5.1 Low energy impact

Data on the damage tolerance of APC-2 with low energy impacts comes from the aircraft industry research programmes on thick section laminates. When PEEK-based composites are compared with epoxy, these studies indicate,

- Delamination and damage areas are smaller and more localised around impact site.
- The residual tensile and compressive properties of impact damaged PEEK composites are higher.

Information from aircraft programmes is useful for European reusable spacecraft programmes.

6.21 Specialist properties of thermoplastic composites

6.21.1 Outgassing and offgassing characteristics

Outgassing characteristics for thermoplastic-based composites can be measured using the same test methods as for thermosets, [See:5.2]. Table 6.21-1 shows the outgassing and offgassing of APC2.

Table 6.21-1 - Outgassing and offgassing of APC2 (AS4/PEEK)

Material	Parameters					Comments
	Outgassing (1)			Offgassing (2)		
	VCM (%)	WLT (%)	WLR (%)	Total Organic (µg/g)	CO_2 (µg/g)	
APC2	0	0.17	0.07	0.3	0.40	Excellent (1) Passed Test
Key: (1): ECSS-Q-ST-70-02 (2): ECSS-Q-ST-70-29 (PEEK matrix only).						

Those thermoplastics with a higher tendency to absorb moisture [See: 6.16] have poorer outgassing characteristics than APC2.

Other thermoplastic matrix composites have yet to have their outgassing characteristics established.

6.21.2 Thermal expansion characteristics

The combination of carbon fibres with a thermoplastic matrix can produce composite materials with a near zero CTE.

6.21.3 Thermal cycling

6.21.3.1 AS4/PEEK

Initial results on the effect of thermal cycling on the CTE of APC2 (AS4/PEEK) indicate:

- No hysteresis experienced in temperature range 23°C to 100°C.
- Initial variability on first cycle in temperature range -100°C to +120°C, stabilised after fourth cycle.

Indicative CTE values after thermal cycling are given in Table 6.21-2. A full evaluation programme is needed to establish the thermal performance of thermoplastic materials.

Table 6.21-2 - Typical CTE after thermal cycling for APC2 (AS4/PEEK)

Lay-up	Temperature Range	CTE ($x10^{-6}°C^{-1}$)
0°	23 to 143°C	0.5
90°	23 to 143°C	30

6.21.4 Damping properties

In general, the damping properties are influenced by the matrix and the orientation of the reinforcement.

Figure 6.21-1 compares the damping properties of unidirectional and bidirectional APC2 (AS4/PEEK) with those of unidirectional epoxy based composite over a range of frequencies, Ref. [6-36].

Test: Cantilever beam specimens; extensional vibration.

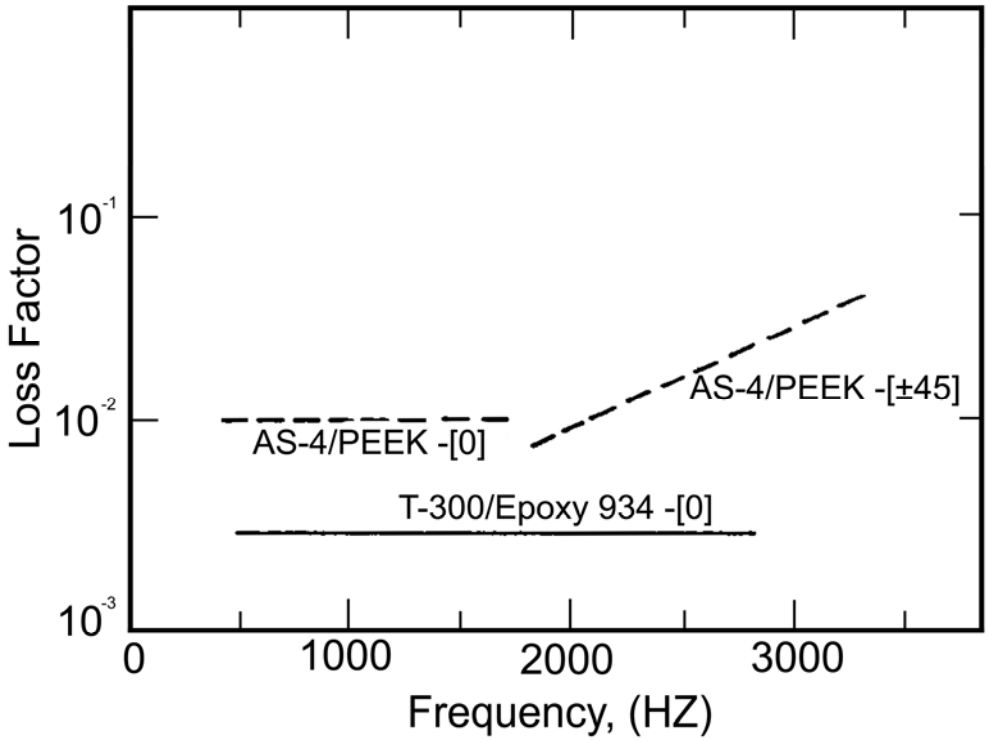


Figure 6.21-1 - Comparison of loss factor for APC2 (AS4/PEEK) and T300/epoxy 934 at various frequencies

6.21.5 Radiation effects

The types of radiation experienced by spacecraft include:

- Ultraviolet.
- Alpha.
- Proton.
- Electron.
- Gamma.

The levels of each type of radiation exposure vary depending on the position and mission of the spacecraft.

Table 6.21-3 summarises the limited information available on the tolerance of thermoplastic matrix composites to the various forms of radiation experienced in space.

Table 6.21-3 - Effect of radiation on thermoplastic matrix composites

	Type of Radiation				
Thermo-plastic	**Ultra-violet**	**Alpha**	**Electron**	**Proton**	**Gamma**
PEEK	High resistance	>10000 Mrads	>1000 Mrads	-	-
PES	-	-	Lowers elongation	-	High dose gives high loss in elongation
TORLON	-	-	-	-	Good resistance
Key: Indicative properties only. Manufacturers' information and requires a full evaluation study with respect to the particular space environment or mission.					

6.22 Thermoplastic composites test methods and standards

6.22.1 Standard procedures

6.22.1.1 General

There are no standard testing methods established specifically for thermoplastic matrix composites.

Those procedures devised for thermoset composites and testing of fibres are relevant. For the mechanical properties of the thermoplastic matrix alone, the test methods devised for testing plastics are appropriate, [See: Clause 7].

Thermoplastic test samples need to be produced by the same processing route as that intended for the final composite material. Otherwise the thermoplastic structure, i.e. crystal morphology, can have a different mechanical response.

6.22.1.2 Delamination behaviour

In general, delamination is assumed to result from interlaminar stresses created by impacts, eccentricities in structural load paths or from discontinuities in the structure.

Some of the design details which can induce local out-of-plane loads leading to interlaminar stresses are:

- Straight or curved (near holes) free edges,
- Ply terminations or ply drop for tapering the thickness,
- Bonded or co-cured joints,
- Bolted joints
- Cracked lap shear specimen.

Besides mechanical loads, moisture and temperature can also cause interlaminar stresses in a laminate. These can result from:

- Residual thermal stresses due to cool-down,
- Residual stresses due to moisture absorption in the laminate
- Moisture level gradient through the laminate thickness
- Impact

The crucial point is the delamination caused by impact where the laminate is hit by a projectile or impactor, such as a stone, bird, tool, meteorites, and locally compressed under the projectile, i.e. a very short time compared with the response of the structure.

The highly localised deformation gradient causes large transverse shear and normal stresses or the formation of compression stress waves which travel through the laminate and destroy the first weak interface found.

Both internal stresses and out-of-plane deformations can initiate delamination at interfaces where there is major changes in the angle between plies.

The amount and type of damage in the laminate depends upon the size, type and geometry of the laminate, impact energy and the loading at the time of impact, [See also: Figure 6.23-1].

In order to assess the delamination behaviour of thermoplastic composites, different test methods have been established. The use of fracture mechanics tests to determine toughness values has been shown to be a useful approach. In principal, these tests are the same as those for general fibre reinforced plastics. While not yet standardised, applicable test methods include DCB (double cantilever beam). The specimen is widely used to determine Mode I (opening mode) delamination resistance. Mode II (shear) testing is more controversial; however, a range of tests has been applied to composites. Two different Mode II tests can be used for thin and thick specimens, respectively:

- ENF: end notch flexure.
- ELS: end loaded split.

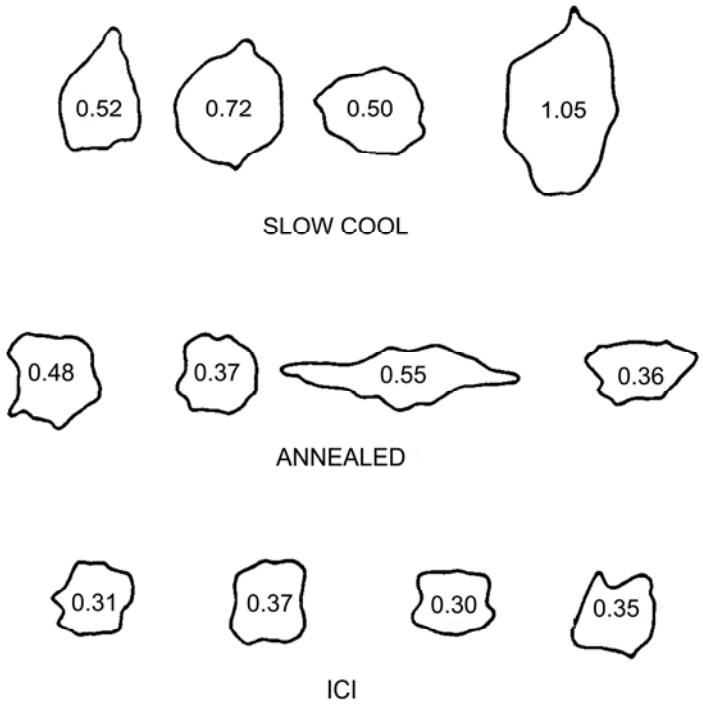
6.22.1.3 Impact behaviour

Composites, even thermoplastic-based ones, are sensitive to delamination failure. It is therefore necessary to expose specimens to impact testing and subsequently test their strength behaviour in tension and compression loading.

[See also: Figure 6.23-2and Figure 6.23-3]

Standard impact tests are in general the same as for all other composites. These are performed using a drop weight instrument with an impact mass in the range of 1.3 kg to 10 kg, an indentor diameter of 15.7 mm and a sample size of 100 mm x 150 mm. The actual impact energy can be varied by selecting different drop heights.

Figure 6.22-1 shows schematically the influence of process cooling rate on impact behaviour.



Key: ICI procedure is fast cooling.

Numbers indicate damage areas in cm^2

Figure 6.22-1 - Schematic diagram of influence on process cooling rate on impact behaviour of thermoplastic composite APC2 (AS4/PEEK)

6.22.1.4 Shear strength determination

The shear testing of fibrous composite laminates has, for a long time, been a difficult task. Even the short-beam-shear coupon (ASTM D-2344) for measuring interlaminar shear strength (a resin dominated property) under 3-point bending is regarded with suspicion because the failure mode is often influenced by failure of the fibres.

For thermoplastic composites, the same problems have been identified. The ductile matrix further complicates identification of the matrix failure (interlaminar shear failure). Consequently, an alternative specimen has been developed in the form of an off-axis tensile test shown in Figure 6.22-2. Stress from axial tension on a long ±45° coupon is equivalent to biaxial tension in the 0° and 90° directions.

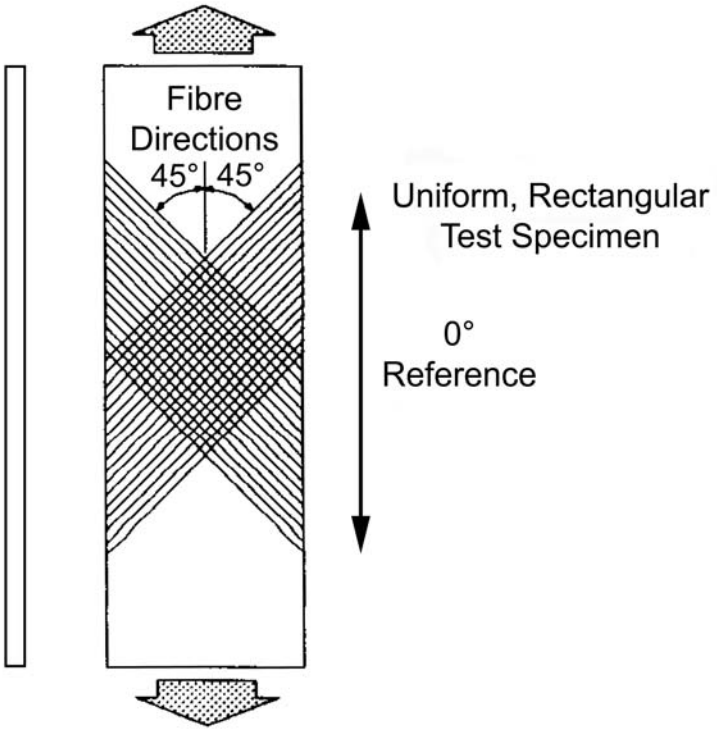


Figure 6.22-2 - ASTM D-3518: Off-axis tensile test on ±45° coupon to simulate 0/90° coupon

The in-plane shear strength is taken to be one half of the tensile stress at failure of the Iosipescu in-plane shear test coupon. In-plane shear strength is, in turn, taken to be the interlaminar strength of fibrous composites as well as the in-plane shear strength of uni-directional monolayers. It is important to test a laminate with fibres in both the +45°and -45° directions to represent the shear strength of a 0/90° laminate, rather than to test a specimen with all of the fibres in one direction only. In the latter case, failure is triggered by the onset of cracking in the resin, whereas, in a real structure, cross plies arrest those initial inter-fibre cracks and delay the failure of the laminate until some fibres become overloaded or the crack density in the resin becomes excessive.

The failure criterion associated with off-axis testing is the maximum shear stress theory customarily used for ductile metal alloys. The theory is applied in this case because the resin, which is failing, is isotropic.

The off-axis coupon [See: Figure 6.22-2] is becoming increasingly popular and is standardised as ASTM D-3518 because it is simple to fabricate and test and it gives repeatable results. It is also preferred because it generates higher allowable strengths than other coupons employed for the same purpose. The Iosipescu (or double V-notched) coupon also received considerable attention. However, it is more difficult to fabricate, it needs special test equipment and its strength is greatly affected by the geometry of the notch at each end of the test section.

Special problems concerning testing of thermoplastic composites are not reported widely in the literature.

6.22.2 Matrix characterisation

6.22.2.1 Morphology

The morphology has a significant effect on the mechanical properties, especially if the molecules are oriented in a preferred direction.

The material morphology can be determined by:

- Light microscopy: Imaging of spherulites using polarised light. Molecule orientation can be investigated using birefringence measurements.
- Scanning electron microscopy (SEM): Imaging of specimen surfaces, revealing crystallite arrangements if the contrast caused by secondary electron or backscattered electron intensities is sufficient for image forming.
- Transmission electron microscopy (TEM): Where high magnifications are needed for microstructural characterisation of structures using only a few nanometers, TEM is the most suitable tool. Even if little contrast is present in the sample to be investigated (as is often the case in polymers consisting of only an amorphous and a crystalline phase), sophisticated staining techniques enable the imaging of structures smaller than 0.2nm.
- Small angle X-ray scattering (SAXS): This X-ray diffraction method uses the scattered intensity of the X-rays (due to crystallites within the sample) appearing at small angles with respect to the primary beam. The diffraction patterns obtained (recorded either photographically or with position sensitive detectors) enable the determination of lamella or needle crystals in the sample, additionally providing information regarding the length of the crystals.

6.22.2.2 Crystallinity

The determination of the crystallinity is a useful tool for acceptance testing of thermoplastic-based composites.

The degree of crystallinity, i.e. the volume fraction of crystallites within the polymer, is generally determined under the assumption of a 2-phase model, where:

- Phase 1: Crystalline regions
- Phase 2: Amorphous regions

Two practical methods are:

- Density gradient column method: This is the simplest method for crystallinity determination. Two suitable fluids are mixed together in a column in such a way that the resulting density varies linearly over height of the fluid in the column. The polymer to be investigated is dropped into the column and reaches a state of equilibrium, i.e. density of fluid and density of polymer are equal. The degree of crystallinity is then calculated according to:

$$w_c = \frac{\rho_c(\rho - \rho_a)}{\rho(\rho - \rho_a)} \qquad [6.22\text{-}1]$$

Where:

ρ = measured density

ρ_c = density of crystallite

ρ_a = density of amorphous regions

- Wide angle X-ray scattering (WAXS): The crystalline areas of the polymer scatter X-rays according to the Bragg Law (Eq.[6.22-3), resulting in a diffraction pattern as shown in Figure 6.22-3.

$$2d \sin\theta = n \cdot \lambda \qquad [6.22\text{-}2]$$

Where:

d = lattice spacing

θ = scattering angle

λ = wavelength of rays n = 1, 2,

The sharp peaks are due to scattering at crystalline areas while the broad background curve results from diffuse scattering at amorphous regions.

The ratio, determined by Eq [6.22-3], is a measure of the degree of crystallinity and can be precisely determined. Additionally, the peak shape provides information regarding crystallite size and perfection.

$$R = \frac{\text{crystalline peak area}}{\text{overall scatter area}} \qquad [6.22\text{-}3]$$

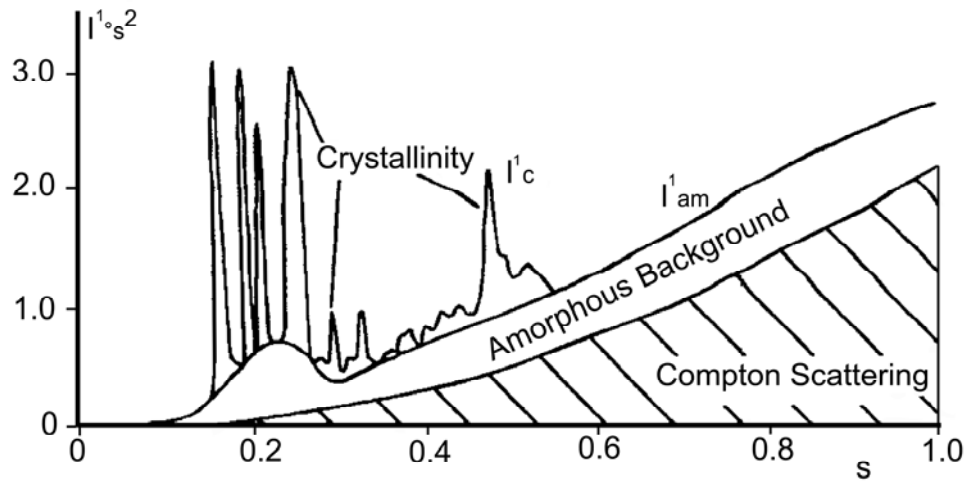


Figure 6.22-3 - Determination of crystallinity by wide-angle x-ray scattering (WAXS)

6.22.2.3 Transition temperatures

The performance of thermoplastics is significantly influenced by their transition temperatures, i.e.

Tg: Glass transition temperature at which the material changes from a glassy to ductile state, giving a steep increase in free volume.

Tm: Melting temperature at which the material changes from the solid state to the molten state.

The Tg is roughly the temperature which limits dimensional stability in a hot environment. The melting temperature (Tm) is important for processing conditions and re-solidification performance.

Typical glass transition and melting temperatures for PEEK are:

Tg = 154°C

Tm = 367°C

In general, the more complex the backbone and attached side-groups of the polymer molecule, the higher the Tg and Tm of the thermoplastic.

The tools to determine these relevant parameters are:

- Differential scanning calorimetry (DSC): where the sample, along with a reference with a known response is heated with a constant heating rate, then the difference in heat flow in the two is recorded. Internal, temperature-dependant, molecular transitions in the thermoplastic (Tg and Tm) appear as a sudden absorption or release of heat energy.
- Dynamic mechanical analysis (DMA): where the sample is exposed to torsional vibration while heating occurs. The response of the material to the forced deformation is recorded and gives curves for the storage and loss modulus and the damping of the material as a function of temperature. Internal, temperature-dependant, molecular transitions in the thermoplastic (Tg and Tm) appear as a variation in the shape of these curves.

6.22.2.4 Stress crack formation

If an aggressive environment is combined with internal or external stress on a polymer, rapid failure can occur due to crack formation.

The main loading mechanisms used for testing the stress cracking resistance of thermoplastic polymers are:

- Creep (constant tensile load).
- Relaxation (constant strain).
- Tensile test (variable strain rate).

The selection of the most suitable test method depends on the specific use for which the material is envisaged. In many cases the creep test enables the correct assessment of the material behaviour against stress cracking.

It has been commonly acknowledged that stress cracking resistance is improved by:

- A high degree of cross-linking,
- Increase of molecular weight,
- Increase in crystallinity, provided that spherulite phase boundaries do not develop weak points,
- Short side groups,
- Single stiff chain segments in the backbone,
- Decrease of interaction between polymer and media, e.g. owing to co-polymerisation.

6.23 General design aspects of thermoplastic composites

6.23.1 Adequate design

The principles applied to designing with thermosetting composites are equally applicable to thermoplastic-based materials.

Opportunities to exploit certain beneficial properties of thermoplastic composites need a full evaluation exercise to establish criteria for design and appropriate material allowables.

6.23.2 Residual stresses

It is likely that the levels of stresses differ from those found with thermosetting matrix materials because:

- Curing Stresses are not appropriate to thermoplastic-based materials. Thermoplastics do not cure.
- Residual Stresses are related to the basic material properties in conjunction with processing temperatures. In general, thermoplastics are processed at higher temperatures than thermosets.

6.23.3 Effect of manufacturing practices on material properties

6.23.3.1 Effect of defects on failure of composites

The prime differences between thermoplastic- and thermosetting-based composites are:

- Thermoplastic chemistry is complete and does not need the complex and long-term cure schedules associated with thermosetting resin systems.
- The ability to be shaped using heat (thermoforming), by a variety of techniques, giving time and cost savings.

These two factors can result in types of defects different from those defined for thermosetting materials. For example:

- Reduced tendency to delaminate.
- Fibre motion during thermoforming and joining by fusion methods.
- Increased tendency for matrix rich zones.
- Variations in crystal morphology due to differences in cooling rates within components.

Methods for the inspection of thermoplastic composites are undergoing development by modifying existing techniques:

- Inspection by ultrasonics (C-scan): In laminates, detection of void contents to 1% and 5 mm delaminations.
- X-ray: Fibre distribution and inclusions.
- Bonded assemblies: Modification of existing techniques has revealed voids of down to 1mm.

Effort is needed to further enhance and prove inspection methods to enable structures to be examined.

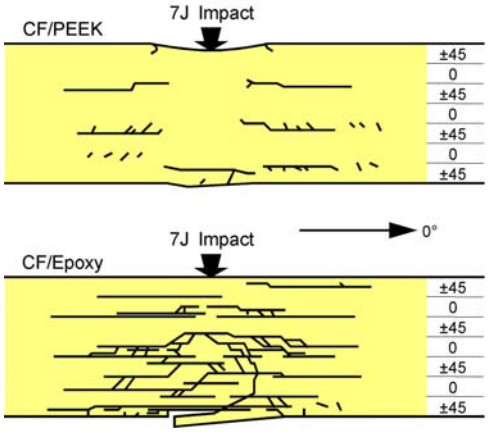
6.23.4 Manufacturing faults and damage tolerance

[See also: 6.23 for effect of manufacturing practices on material properties]

Investigation on the damage tolerance of thermoplastic-based composites is largely from the aircraft industry research programmes. To date the PEEK-based materials (initially APC1 superseded by APC2 as it became available) have been the topic of most evaluation.

Figure 6.23-1, compares the damage zones produced by drop weight impact tests on carbon/PEEK with carbon fibre/epoxy laminates. The post-impact residual tensile strength for both materials is shown in Figure 6.23-2 and residual compressive properties in Figure 6.23-3, Ref. [6-29], [6-45] and [6-47].

A Internal damage due to dropweight impact of 7J on (±45°, 0°) laminates of carbon fibre/PEEK and carbon fibre/epoxy.



B Variation of delaminated area due to dropweight impact in carbon fibre/PEEK and carbon fibre/epoxy laminates (±45, 0_3, ±45, 0_2) lay-up.

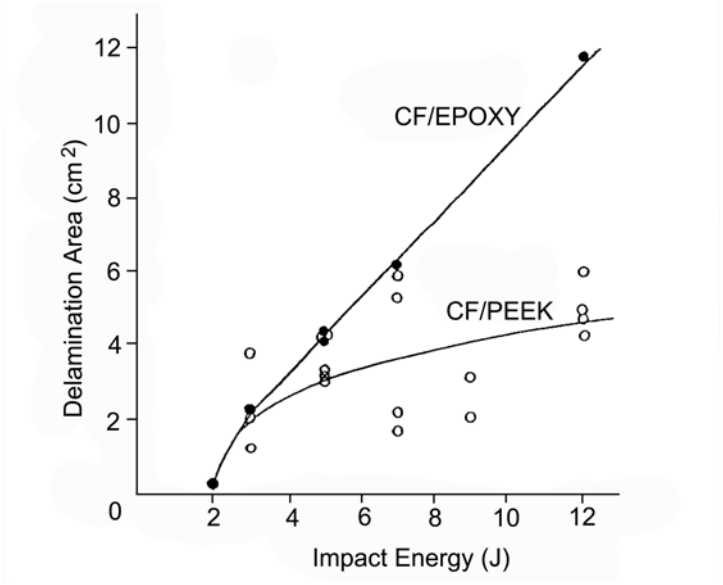


Figure 6.23-1 - Damage zone comparison for drop weight impact test on carbon/PEEK and carbon/epoxy laminates

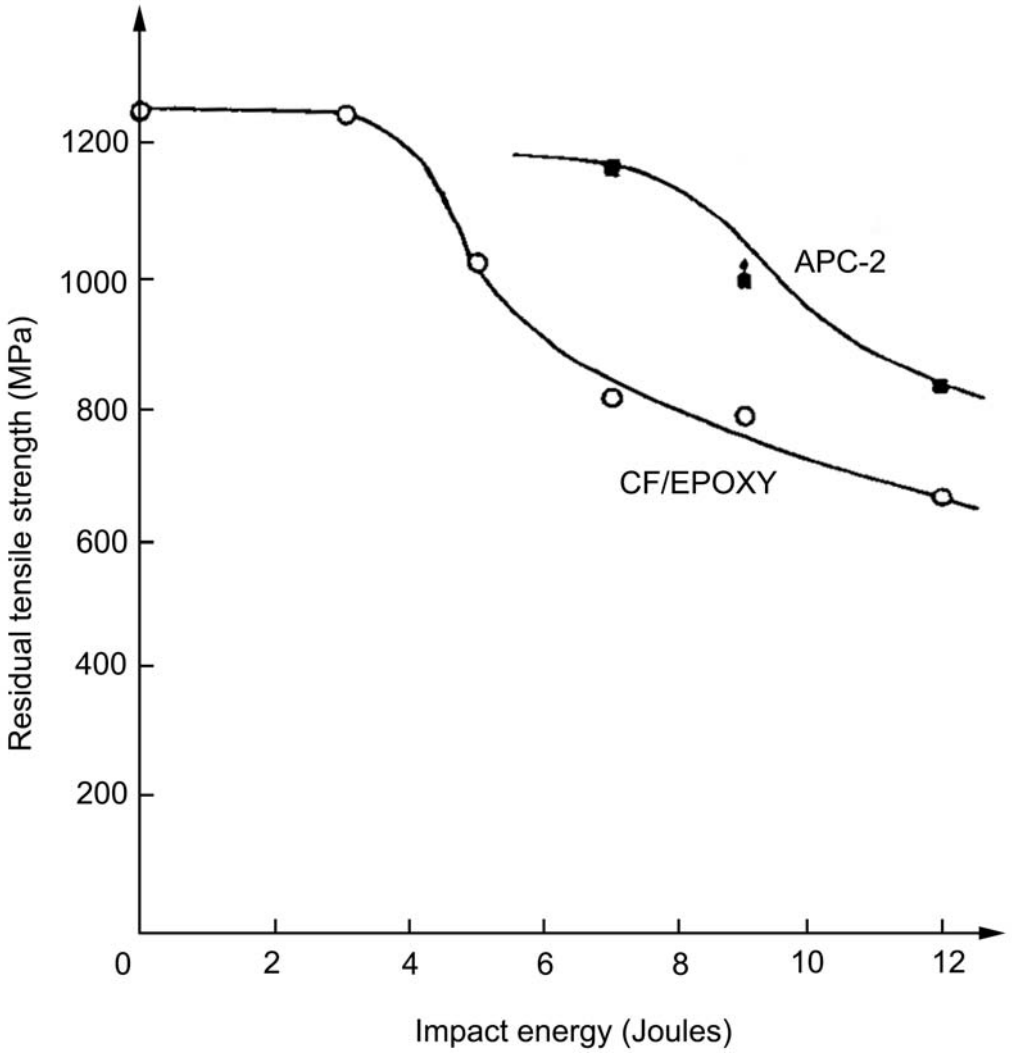


Figure 6.23-2 - Residual tensile strength comparison after impact on carbon/PEEK and carbon/epoxy laminates

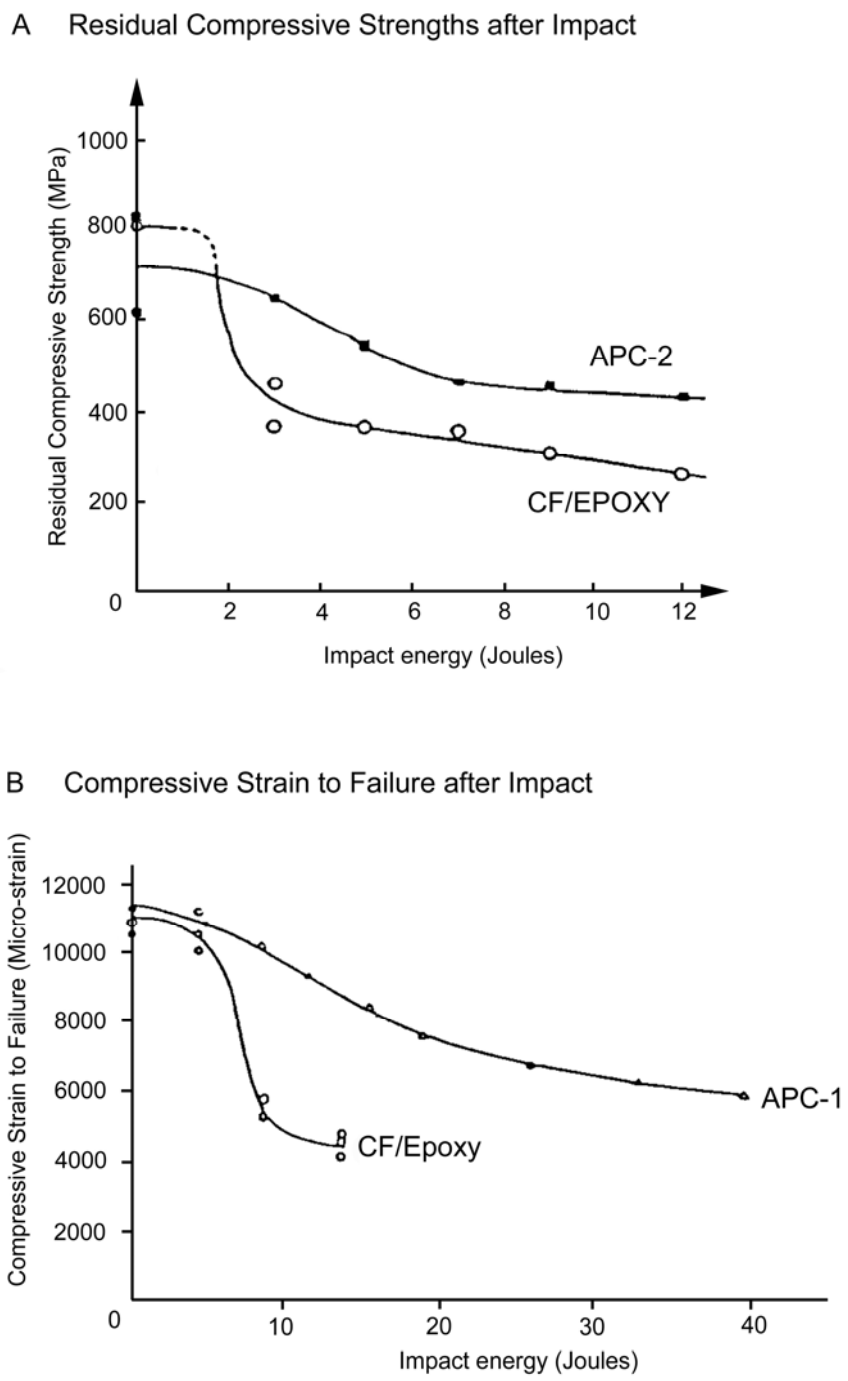


Figure 6.23-3 - Residual compressive strength and strain to failure comparison after impact on carbon/PEEK and carbon/epoxy laminates

Table 6.23-1 compares aspects of damage tolerance for PEEK-based carbon fibre materials with carbon fibre/epoxy thermoset composites Ref. [6-29],[6-45],[6-47]. The composite stacking/ply orientation needs to be considered.

Table 6.23-1 - Summary of damage tolerance aspects for thermoplastic and thermosetting composites

Topic	Aspects of Damage Tolerance	
	Thermoplastic PEEK/Carbon fibre APC1 and APC2	**Thermoset Epoxy/Carbon fibre**
Fibre/ply orientation	For component areas with high risk of impact damage, use of lay-up of plies in sequence used for epoxy composites.	
Processing method	Follow 'Optimum' processing method to achieve correct crystal morphology.	-
Notch sensitivity	Similar behaviour for PEEK and epoxy for 16 ply $(90/\pm45/0)_{2S}$. Apparent lower performance of PEEK with 5mm holes. Presumed linked to poor crystal morphology.	
Interlaminar fracture toughness	Improved performance two crack growth phases. G_{IC} 1.9 and 3.8 kJ m^{-2}, tougher matrix and high fibre/matrix bonding.	Lower performance, G_{IC} 0.29 kJ m^{-2}
Low energy impact (1) Damage zone (2)	Tendency to localise damage zone around site of impact. Less damage (delamination) for equivalent impact on epoxy.	Tend to delaminate - to give large damage zone, increases with impact energy.
Residual tensile strength (3)	Retains higher tensile strength compared to epoxy.	-
Residual Compressive Strength (4)	Retains higher compressive strength compared to epoxy.	-
Residual Compressive strain to failure (5)	Higher strain to failure compared to epoxy.	-
Barely visible impact damage (BVID)	Surface denting and surface cracking at low impact energies, but with improved integrity of internal structure (localised damage zone).	No or low surface damage but internal integrity impaired (damage zone, delamination).

Key:
(1) General statements to be interpreted with known stacking/ply orientation of composite.
(2) See Figure 6.23-1 A and Figure 6.23-1 B
(3) See Figure 6.23-2
(4) See Figure 6.23-3A
(5) See Figure 6.23-3B

6.24 Joints in thermoplastic composites

6.24.1 Bonded joints

6.24.1.1 General

The production of adequate strength and reproducible quality bonded joints for thermoplastic based composites, notably PEEK, is the subject of various research and development activities.

6.24.1.2 Bonding methods

Bonding can be achieved by:

- Adhesives, normally a thermosetting epoxy-type.
- Fusion techniques, where local heating is used to re-melt the thermoplastic matrix, or additional polymer placed in the bond line.

The quality, hence strength, of adhesive bonds is largely dictated by proper surface preparation. This is more complicated than for epoxy thermosetting composites.

Fusion is being investigated to exploit the melting characteristics of thermoplastics and, hopefully, avoid the extensive surface preparation demanded by adhesive bonding practices.

General guidelines on bonding are given in Table 6.24-1.

Table 6.24-1 - General guidelines on bonding technology for thermoplastic based composites

Topic	Technology Steps/Status for Bonding Thermoplastic Composites	
	Present	**Future**
Recommended Bonding Materials	None recommended for thermoplastics. Initially those developed for thermosetting composites (Epoxy based paste and film adhesives). [See: Surface Preparation]	New adhesives with higher temperature capability. Thermoplastic 'adhesives' compatible with matrix/fibre. Use of matrix phase alone Fusion Techniques.
Design of Bonded Joints	Methods developed for thermosetting composites.	Enhanced methods to exploit material attributes.
Bonding Defects and Failure Modes	Under investigation, including inspection methods.	Dependent on ultimate bonding method selected.
Calculation methods	Methods developed for thermosetting composites.	Enhanced methods to exploit material attributes
Surface Preparation	Under investigation: Abrasion: Differs from thermosets Bond Promoters: Organo-silanes Specialist Treatments: Corona discharge, acid or plasma etch.	Dependent on findings of R and D programmes.
Bonding Methods:	Under investigation: Adhesive bonding, fusion techniques. [See: Table 6.24.3]	Dependent on findings of R and D programmes.

Table 6.24-2 summarises various fusion techniques, Ref. [6-37],[6-38],[6-39].

Table 6.24-2 - Development fusion techniques for thermoplastics

Technique	Summary of Method	Comments
Resistance Heating	A resistive 'element' is placed in the bond line; * High resistance wires * Carbon fibre tow * Carbon fibre prepreg Adherends clamped together, a current passed through the 'element' then heats the bond line.	Elements remain in bond line. Using adherends as the element produces excessive warpage outside clamped area.
Ultrasonic Welding	Static pressure plus superimposed dynamic vibration (Low amplitude/ High frequency. e.g. 0.013 to 0.25mm amplitude at 20 to 40 kHz).	Thermal conductivity of carbon fibres reduces bond line heating and longer weld times result. Commercial equipment available, (in USA).
Focused Infra-Red Heating	Heat is focused at the bond interfaces, once molten, pressure is applied to produce a bond, and maintained until cool.	Commercial equipment available (in USA).
Thermobonding with PEI film. †	PEI film either placed on bond line or 'moulded' to surface of PEEK composite to be joined. Secondary heating under pressure melts PEI film in bond line, forming a joint.	Principle based on PEI 'melting' occurs at a lower temperature than PEEK, therefore reducing fibre movement in the bond region.
Induction Welding	Heating by induction coil passed over clamped adherends. Typical frequency required to heat APC2: 2 to 2.5MHz.	Frequency/time selection critical parameters to ensure correct heating.
Key:	†: Developed by ICI for APC2 composites.	

Table 6.24-3 provides a ranking of certain bonding techniques judged by requirements identified for aerospace components, Ref. [6-37],[6-38].

Table 6.24-3 - Ranking of bonding techniques for thermoplastic composites

Requirements	Techniques					
	Adhesive Bonding	Adhesive + Rivet	Resistance Heating	Ultrasonic Welding	Focused Infra Red	Thermo-bonding
Reproducibility	10	10	5	5	10	10
Adaptable to various joint configurations	10	10	8	5	6	10
Suitable for small and large bond areas	10	10	8	5	4	10
Minimal surface preparation	2	1	10	10	10	10
Minimal equipment use	9	8	7	5	5	10
Automation possible	YES	YES	YES	YES	YES	YES
On-line inspection	10	10	5	10	5	10
Reworkable	NO	NO	YES	YES	YES	YES
Production use	YES	YES	NO(1)	NO(2)	YES	YES

Key: 0 = Lowest 10 = Highest

(1) Difficult for cross-ply, angle-ply and large parts.

(2) Suitable for small bond areas and long, thin bond lines.

6.24.2 Mechanically fastened

The basic aspects of producing adequate strength and quality fastened joints for thermoplastic-based composites are essentially the same as those used for thermosetting composites.

Further development of techniques could provide joints with greater strength by improved resistance to stress concentrations. Thermoplastic fasteners are also under evaluation.

6.25 Manufacture of thermoplastic composites

6.25.1 General

Any technique which melts the thermoplastic with instantaneous consolidation to component shape offers scope for exploitation. The rapidity of these processes is the largest difference between thermoplastic and thermosetting composites.

Table 6.25-1 introduces the technologies associated with the fabrication of thermoplastic-based composites.

The objective of research and development programmes notably that at Westland (UK), has been to consider the available technology and modify it to be suitable for thermoplastic composites. The materials are primarily PEEK and PEI-based because these are the most advanced and available, Ref. [6-29].

The final choice of fabrication method depends on the size of the component and the availability of equipment for the higher processing temperatures required.

Table 6.25-1 - Summary of technology terms associated with fabrication of thermoplastic composite materials

Fabrication Techniques	Comments	Current Status
Hand Lay-up:		
Fibres direct in mould.	Requires liquid matrix phase.	Not applicable
Prepreg tapes/fabrics.	Requires local heat source to 'tack' prepreg in place.	Laminate production
Bag Moulding	Higher temperature bag moulding material required. Limited use of autoclaves.	Development
Press Clave	Intermediate autoclave/hot press technique.	Initial development
Vacuum Consolidation	Higher temperature ancillary materials required.	Development
Diaphragm Moulding	Modified metal forming technique.	Development
Press Forming:		
Hot compression forming	Hot tooling, small presses available, large press availability limited in UK and Europe.	Preferred method, preproduction
Cold compression forming	Cold tooling, composite pre-heated. Cooling rate defines ultimate crystal morphology hence properties.	Preferred method, preproduction
Deep drawing	Variation on press forming applicable to thin laminates and small components.	Development
Incremental Forming	Large components formed in stages. Smaller presses but complex tooling.	Development
Filament Winding	Modified technique requiring melting of matrix. Limited commercial equipment for thermoplastics.	Development
Tape Laying	Modified technique requiring melting of matrix. Limited commercial equipment for thermoplastics.	Development
Injection Moulding	Not appropriate for continuous reinforcement. Random fibre or particulate reinforcement only.	Production
Pultrusion	Requires higher temperatures (modifications to dies and heaters).	Development

6.25.2 Prepreg and laminates

From a production point of view, the attractive features of thermoplastic materials include:

- Supplied in a ready to use form, either as prepreg or laminate.
- Easy to store and do not need cold storage.
- Lay-up of prepreg needs a temperature-controlled heat source (soldering iron, ultrasonic or hot air gun) to locally melt polymer for tacking into place. Inherent stiffness (no drape) of prepregs can cause difficulties with the lay-up of complex geometry parts. Local heating is used to lay-up tight curves, but springback can still occur.
- Working areas should be clean and dry, but air conditioning and temperature control are not necessary.
- Processing is significantly faster than curing thermoset (epoxy) composites. Thermoplastics need:
  - heat to melt the polymer,
  - pressure to consolidate the prepreg, and
  - heating to soften the laminate prior to forming operations. Autoclave processing is not necessary.

6.25.3 Mixture products

Variants of thermoplastic materials (reinforcement and matrix polymer mixed at the fibre level) are supplied as unidirectional or fabrics that offer improved drape characteristics for complex geometries.

The processing of 'mixture' products should be optimised because it is different from those used for the stiffer prepregs.

[See also: 6.18 – Mixtures]

6.26 Fabrication techniques for thermoplastic composites

6.26.1 Choice of fabrication method

6.26.1.1 Prepreg and laminates

From the range of techniques offered for processing thermoplastic composites, the exact technique selected is dependent upon the structure to be produced, including:

- Precise material:
  - fibre, and
  - thermoplastic.
- Structure or component design.
- Finished laminate thickness.
- Exact size and shape.
- Availability of equipment.

Table 6.26-1 provides guidelines to assist in the choice of processing technique. These come from extensive development work at Westland UK and are representative of the technology status of PEEK and PEI-based carbon fibre materials, Ref. [6-29].

The types of components produced are secondary and tertiary structures associated with helicopters, although some are representative of those found in space vehicles.

For primary structures, it is envisaged that automatic filament winding and tape-laying are necessary with various press techniques, possibly combined.

As other materials become available in prepreg form, development work is needed on combining and optimising the possible techniques.

Table 6.26-1 - Guidelines on preferred fabrication methods for components manufactured from PEEK and PEI-based thermoplastic prepreg laminates

Fabrication Method	Component Type	Comments
Press forming	Laminates.	-
	Skins with integral stiffeners co-moulded.	Preferred method, either hot or cold tooling.
	Sandwich construction.	-
	Channel sections.	-
Hydroforming	'Small' components.	-
Diaphragm moulding	Shallow pans.	-
Filament winding	Thin section.	-
	Thick section.	-
	Starter sections (near net shape) for channels.	Press formed to final shape.

6.26.1.2 Mixture products

Processing techniques are under development, but need optimising, [See: [6-32] for 3-D composites]

6.26.2 Autoclave

This is the first technique that most engineers consider for thermoplastic materials. However, the practical difficulties in using this technique are quite significant. There are very few autoclave facilities available with the temperature ability to handle these materials.

No tack and the general stiffness of the prepreg material, make laying up both difficult and costly. This is especially true when it involves double curvature. When laying-up in a mould, natural tackiness cannot be relied on; the material tends to spring back. Localised spot tacking with heat appliances does not retain the prepreg to the shape. These difficulties are compounded by the lack of adequate ancillary materials to make the process viable, i.e. bagging film and sealing materials for the high temperatures involved.

'Mixture' products are easily draped but processing cycles are not yet optimised, [See also: 6.18 - Fibres].

High processing temperatures, 260°C to 427°C typically, need tooling materials which not only withstand the processing cycle but have expansion characteristics which do not cause unacceptable fibre motion, buckling or breakage, Ref. [6-40]. Low CTE tool materials include (in order of cost):

- Monolithic graphite.
- Bonded ceramic.
- Cast ceramic.

These are very expensive and have short lives compared with steel tools.

The quality of components produced by the autoclave techniques is excellent and repeatable, as the process does involve high pressures. However, the manufacture of components is limited to those of a relatively flat nature, unless major developments in the ancillary materials are made.

Autoclave moulding does not exploit the quick processing capability which thermoplastics possess and as the basic materials (prepreg, laminates, 'mixture' products) are more expensive than thermosets, the autoclave technique is always significantly more expensive.

6.26.3 Press clave

The press claving technique, as shown in Figure 6.26-1, Ref. [6-29], is an interim measure which was adopted mainly as a means of achieving autoclave type conditions in available platen presses. Hot tooling is used.

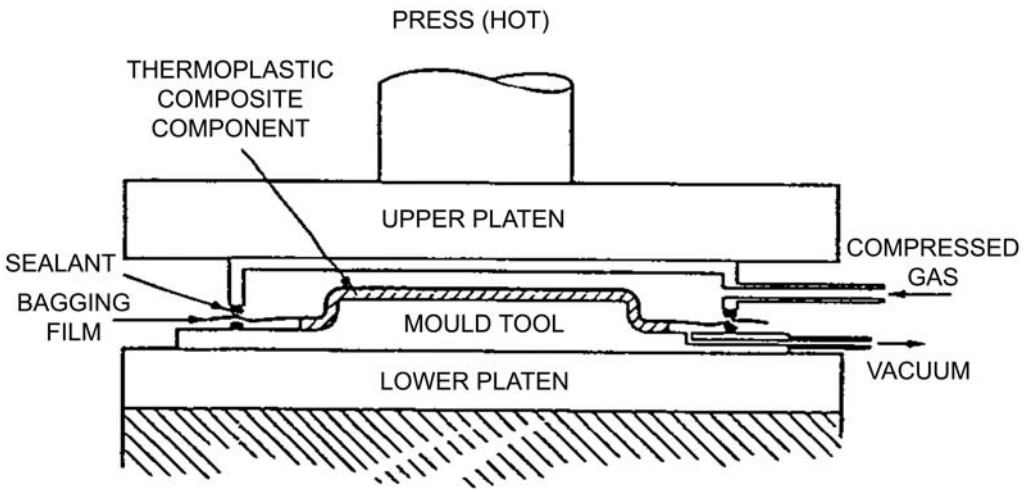


Figure 6.26-1 - Press clave for thermoplastic prepreg

The same basic conditions apply as for autoclave moulding:

- Handling,
- Lay-up,
- Quality, and
- Ancillary materials.

A restriction imposed by the press clave is the depth of the components that can produced. This is because of the size limitation of the jaws on the available heated platen presses. There is a need for safe pressure and temperature chambers, which tend to be bulky in order to retain the consolidating gases.

A large number of presses are available but few with the temperature capability that the new materials need. The tooling is made of metal because of the high process temperatures, i.e. 380°C, and pressures needed. The heating and cooling cycles are similar to autoclave moulding.

Components produced tend to be of relatively flat geometry but of excellent and repeatable quality, owing to the high pressures used for consolidation; typically 0.7 MPa to 1.4 MPa (100 to 200 psi).

It is not viewed as a truly commercial process because it is fairly expensive.

6.26.4 Vacuum consolidation

The success of vacuum consolidation as a fabrication process for PEEK and PEI is dependent on the quality of the prepreg. The guidelines used for quality are the number of voids that are developed in the consolidated laminate. This is established prior to deciding upon the technique to be used. Ancillary materials are available to make this process viable, but tend to lack the necessary stretch and sealing to make this a repeatable process.

Metal tooling is needed because of the process temperatures. A reduction in the overall process time can be achieved by loading the material into preheated equipment and removing the formed component as soon as possible. Distortion due to thermal stresses within the laminate, brought about by uneven cooling, can cause problems that need to be quantified.

The process equipment exists, with only air circulating ovens needed, which are relatively low-cost items. The cost of manufacturing by this technique offers little saving when compared with that of thermoset materials, where bagging and lay-up has a similar labour content.

6.26.5 Diaphragm moulding

The diaphragm moulding technique for composites is adapted from a metal forming process, as shown in Figure 6.26-2, Ref. [6-29].

This process sandwiches the flat composite lay-up between two superplastic aluminium sheets. After the composite laminate has been heated to the appropriate processing temperature, it is deformed to shape by the application of a differential pressure. The pressure deforms the diaphragm, which forces the composite into the required shape.

Components of complicated shapes can be made from unidirectional materials, which otherwise do not exhibit the natural drawing properties necessary. Normally, complicated shapes are made from woven fabrics, which do not have the same strength and stiffness properties as unidirectional materials.

Lay-up is simplified because flat sheet prepreg is used. The subsequent blowing operation forces the fibres into shape.

Consolidation and quality of mouldings produced by this technique are excellent. Some problems can be experienced because the overall control of fibre orientation is lost. This technique is quite slow, owing to the heating cycles and the blowing process needed for superplastic forming.

With the two metal components being discarded, it appears to be an expensive operation. However, it does enable the manufacture of shapes which are not otherwise possible with unidirectional materials.

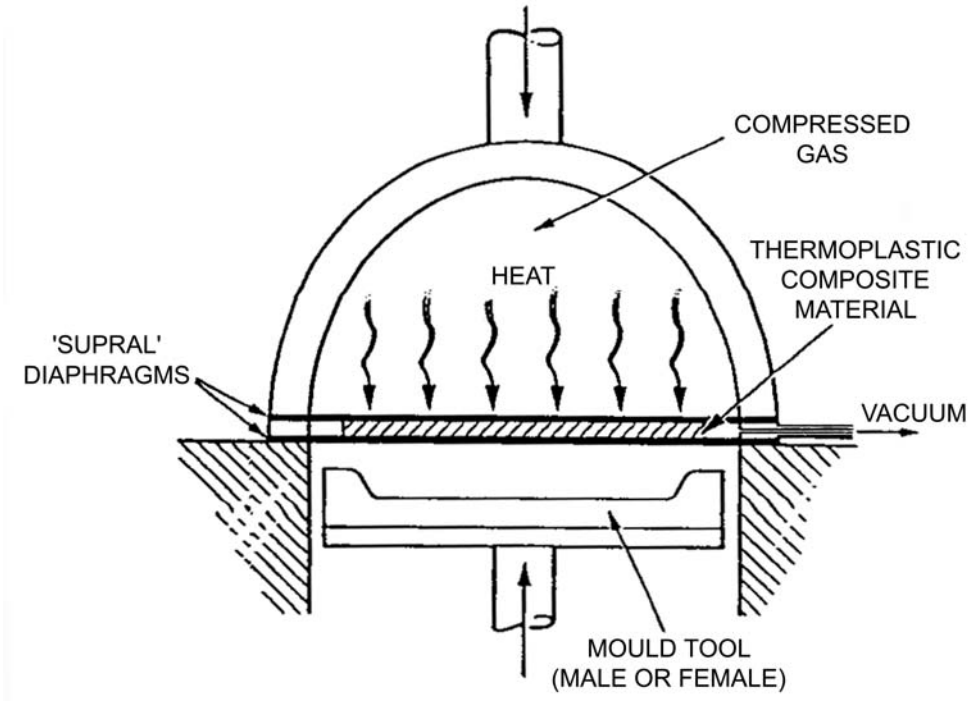


Figure 6.26-2 - Diaphragm forming of components from thermoplastic prepreg

The equipment availability is the same as for the heated platen presses, although a larger press opening is necessary for the diaphragm technique.

Metal tooling is needed because of the process temperatures and the large pressures involved.

The advent of non-metallic diaphragms could eventually reduce the required pressures, but studies have shown that lower stiffness diaphragms reduce the quality of the component produced, Ref. [6-41].

In general this technique is seen to be an expensive one and only used where the complexity of the component is such that it cannot be manufactured by other means.

6.26.6 Press forming

6.26.6.1 General

Figure 6.26-3 summarises the press forming technique, Ref. [6-29]. It can be either a hot or cold process.

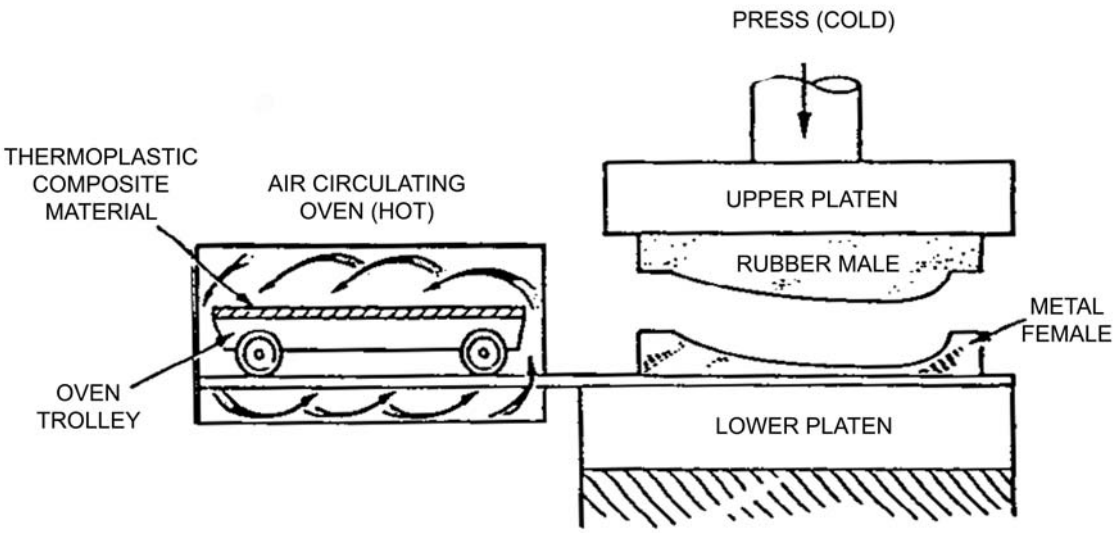


Figure 6.26-3 - Press forming of pre-consolidated thermoplastic laminates

6.26.6.2 Hot compression forming

The impact strength of a finished laminate is dependent upon the degree of crystallisation within the laminate and this in turn is directly affected by the cooling rates during forming. Therefore control of the cooling rate is necessary. The component is produced by either:

- Laying the prepreg directly into the tool.
- Pre-laying the sheet and transferring (in lay-up form) into matched-metal tooling which is mounted on the press platens.

In either case, reduction of overall process times can be achieved by using preheated presses. Cooling to below the material melt temperature is carried out under pressure. This is an inherently slow process.

The quality of components made by this technique is excellent and indicative of the high pressures used. Equipment availability depends upon component size. A large number of small presses are available, each with up to 300mm. square capability. There are few large presses with the temperature capability in Europe but a greater number operate in the USA.

6.26.6.3 Cold compression forming

When cold compression moulding is employed, only the component material is heated and quickly transferred to cold tooling.

Turn-round times of 15 minutes per component are possible. The process time is dictated by the period required to heat the sheet to the process temperature in the air circulating oven, and not the actual press operation time. Heating time can be reduced further by multi-stacking sheets in the oven. Fast closing of two halves of the tool is necessary.

Since the tooling is not heated, any material capable of carrying the compression load can be used. It is advisable that even pressures are maintained. For large numbers of components, use of a male or female metallic former to maintain quality throughout the production run is advisable.

This technique makes full use of the quick processing capability of thermoplastic materials, and so results in cheaper component manufacture.

There is an obvious restriction on the amount of double curvature which can be produced. This can be eased by slight heating in the tools and use of woven prepreg materials. Cold pressing relies on the availability of consolidated sheet of the correct lay-up for the component being made. The demonstrated cost savings in manufacture can be increased with an automated process for sheet manufacture. Two such techniques are filament winding and tape-laying.

The hydroforming variant of this process is shown in Figure 6.26-4, Ref.[6-29].

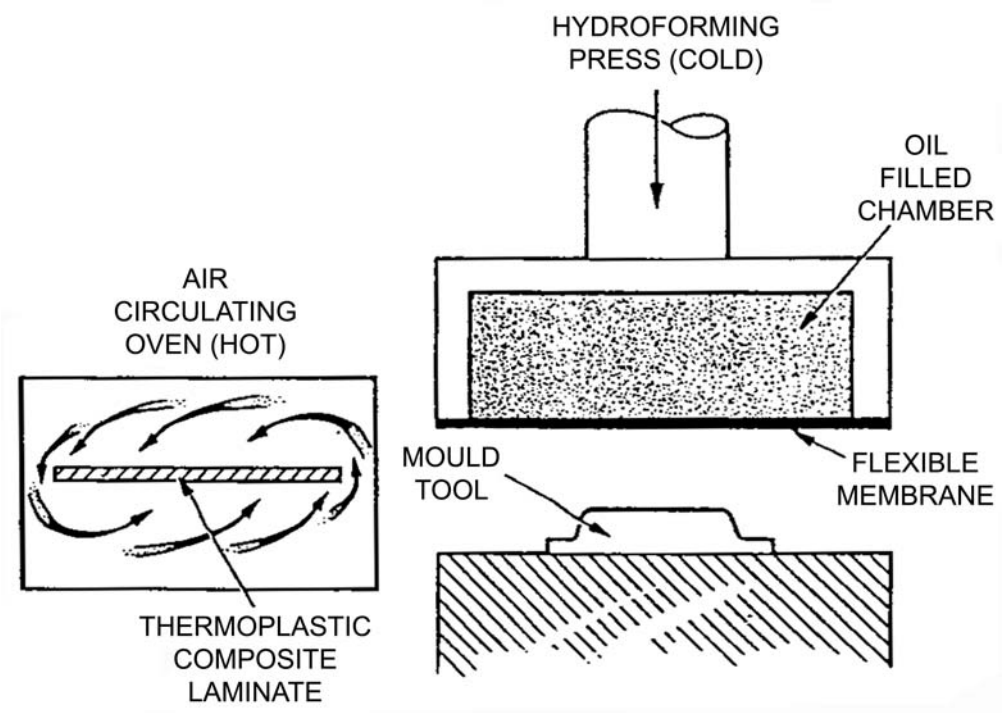


Figure 6.26-4 - Hydroforming of pre-consolidated thermoplastic laminates

6.26.6.4 Deep drawing

This technique is a variation on press forming and is shown in Figure 6.26-5, Ref. [6-29]. It can be used for thin laminates and small components.

The demonstrated cost savings in manufacture can be increased when an automated process for sheet manufacture is available, i.e. by filament winding and tape-laying.

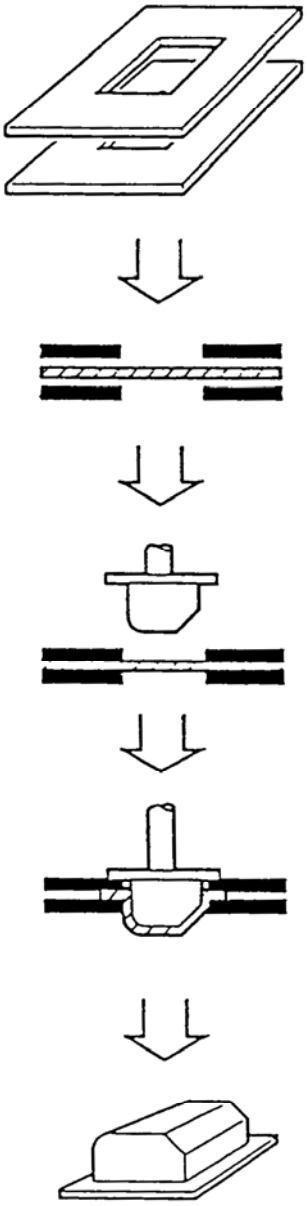


Figure 6.26-5 - Deep drawing of woven fabric thermoplastic component

6.26.6.5 Incremental forming

This development process is shown in Figure 6.26-6, Ref. [6-42]. It involves forming a large component in stages rather than in a single operation.

The need for large capacity presses and ovens is avoided as only the section currently being formed needs heating or pressing.

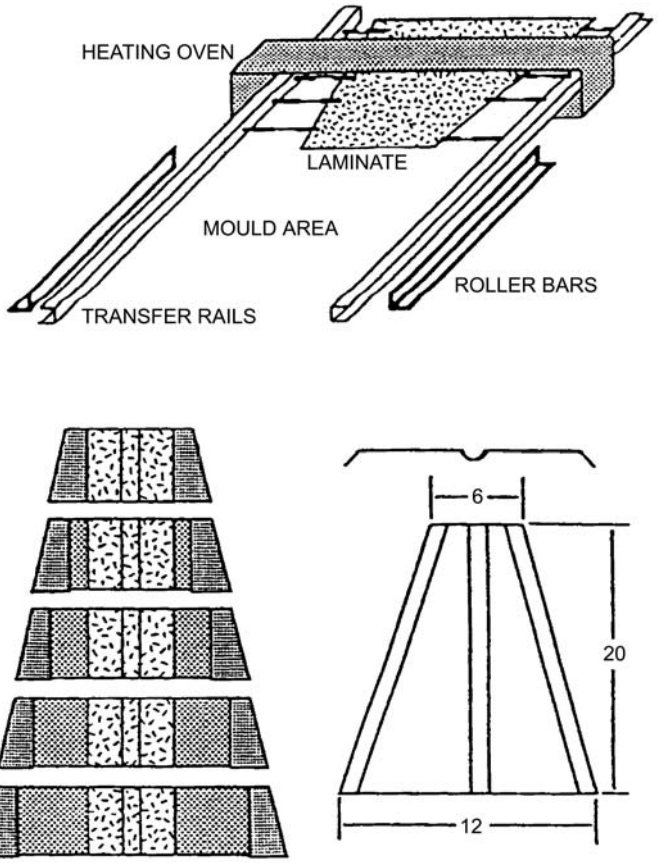


Figure 6.26-6 - Incremental forming

The main elements of the system are:

- Heater.
- Transfer system.
- Press.
- Matched moulds for the section to be formed.

Incremental forming is appropriate to large, relatively simple geometry parts. For complex geometry components, the tooling is likely to be considerable, although it can be reduced by using modular moulds. A cooling system is advisable to reduce expansion of tools and loss of dimensional tolerance. Demonstration components have defect free surfaces and tight dimensional tolerances, Ref. [6-42].

6.26.7 Filament winding

The full benefits of filament winding thermoplastics, can only be realised when localised heating is used during winding. Consolidation is achieved by back tension on the pre-impregnated tape or tow, or a second heated roller.

Acceptable consolidation is very much dependent upon the quality of the material received from the suppliers. This aspect improves as more materials become available.

Winding a finished component shape is possible, with no subsequent operations being required, whereas, with thermoset materials, long cure cycles are needed. Typical winding rates, for tow or tape, are 1m per minute to 2m per minute, depending on the particular polymer melting temperature.

Although no commercially available equipment is specifically for thermoplastics, existing equipment can be modified.

A large amount of development work into tooling materials is necessary. Tooling materials tend to be rigid and as such, only simple tube components can be made.

Fully-automated processing of what is inherently an expensive material can eventually make this technique cost effective when compared with thermoset materials.

6.26.8 Tape-laying

The tape-laying process is shown in Figure 6.26-7. The development of tape laying has demonstrated speeds up to 6m per minute with the higher temperature materials, such as PEEK. However, low melting temperature materials can increase the laying rate.

Overall panel times are dictated by the number of stops and starts. The intention is to have full automation with no operator involvement, although in practice this is rarely achieved. Cost savings naturally occur if laying and consolidating are combined successfully.

It is considered that the ability to lay directly to component shape can be achieved; although unproven. Concern is expressed as to the distortion obtained from the built-in thermal stresses within the lay-up, but provided that re-melting and pressing to shape is employed, this effect can be ignored.

No commercial equipment is available, although flat tape laying is in an advanced stage of development.

The quality of development laminates are marginally acceptable for aircraft use, but re-processing by quick pressing enables excellent quality components. The laminates produced by tape-laying form the starting materials for the rapid shaping processes.

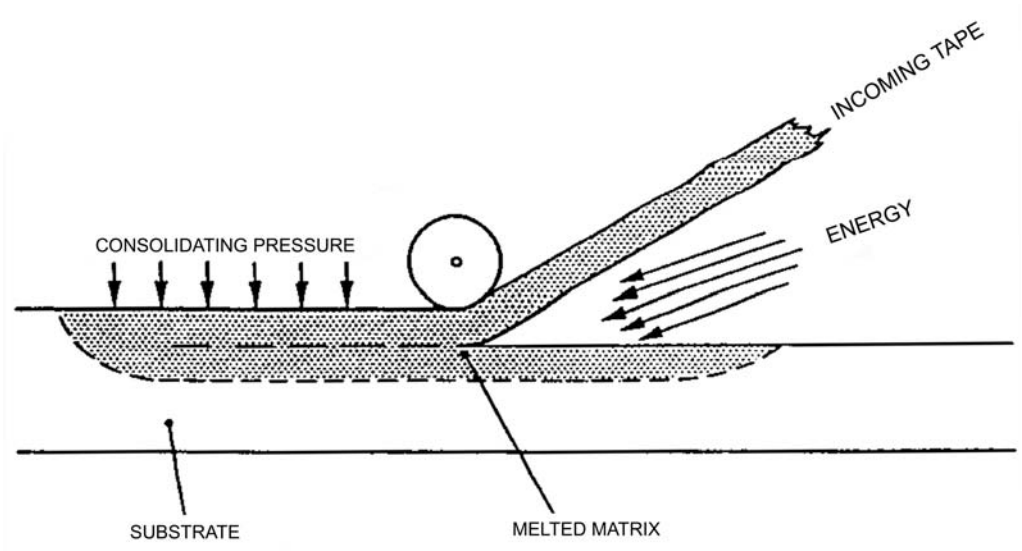


Figure 6.26-7 - Filament winding/tape laying of thermoplastic components

6.26.9 Injection moulding

The injection moulding process is applicable to thermoplastic design and suitable for high-volume production and complex, relatively solid shapes, [See also: 38.11].

The disadvantage is that injection moulding uses random fibre fillers to strengthen the basic polymer; producing a polymer with low modulus and tensile strength compared with unidirectional and woven laminates.

It has limited scope for space application where mass-saving is important, but can be very useful for inserts, bolts, control rods and other small items. Manufacturing techniques are relatively simple; the molten polymer together with random, chopped carbon filler is fed directly into a two part mould, with or without a core.

6.26.10 Pultrusion

Pultrusion involves drawing composite material through a heated die to form continuous lengths of constant cross-section. It is analogous to extrusion of metals, [See also: 38.8].

It is an accepted industrial process for low-performance thermoset composites, for tube, channel and structural sections. It is also appropriate for certain carbon fibre reinforced thermosets, provided that the resin chemistry is fast curing, i.e. within the die heated zone.

Specific equipment is not available for processing high-performance thermoplastics, but existing equipment can be modified for pultrusion of APC2, Ref. [6-33].

6.26.11 Machining techniques

The machining of thermoplastic composites is similar to that of thermosetting materials. No additional techniques are envisaged.

[See: Clause 39 - Machining techniques]

6.27 Manufacturing economic factors for thermoplastic composites

6.27.1 General

Thermoplastic composites have certain attributes which, when fully quantified and exploited, can provide cost savings over thermosetting materials, Ref. [6-29]. Table 6.27-1 provides a summary of some of the possible cost savings.

Table 6.27-1 - Possible cost saving factors associated with use of thermoplastic-based composite materials

Parameter	Thermoplastic-based Composite Components	
	Advantage	**Disadvantage**
Commercial Prepreg Availability	Increasing sources	Limited at present.
Commercial Mixture Fibre Availability	-	Development.
Materials Cost	Infinite shelf life.	More expensive than CF/epoxy, should reduce with increased output from suppliers.
Quality	-	Variable but improving with volume availability.
Storage	No cold storage. Infinite shelf life.	-
Plant Environment	No specialist requirements other than cleanliness.	-
Lay-up	Mixture: Drapable.	Prepreg: Inherent stiffness. No tack.
Process cycle	Shorter process time.	Higher process temperature. Limited equipment. Limited consumables for processing.
Component Complexity	Shaped components. Bonding, welding or fastening appropriate.	-
Automation	Decrease labour content.	Long-term development activity.
Inspection	May be inspected by existing techniques with modifications.	Development activity.

6.27.2 Material costs

Material suppliers offer a wide range of product forms, from fibre goods, prepreg and semi-processed sheets to consolidated laminates of customer specification.

Material costs are highly variable; reflecting the amount of pre-processing carried out, but tends to be higher than those of thermosets because of the low consumption.

6.27.3 Equipment costs

The adoption of a new material is a costly exercise as the various manufacture, inspection, quality control and qualification procedures are developed. This is compounded for thermoplastics by the need to re-equip or modify machinery for the higher process temperatures. However, this can be done as existing equipment reaches the end of its useful life.

It is envisaged that adoption of thermoplastic composites is likely to be slow. Existing facilities and locations of expertise can be sought.

6.27.4 Component costs

Various development programmes producing demonstrator aircraft parts, show that the levels of cost saving are encouraging if rapid processing techniques are used. These can be summarised as:

- Cost analysis studies have confirmed that autoclave processing is competitive for flat or single curvature parts, Ref. [6-40], [6-43], [6-44]
- Channel and angle sections produced by forming processes and tubular struts by filament winding carbon fibre thermoplastics (IM7/PEEK) show significant cost savings (20% to 40%) over equivalent autoclaved thermoset parts, Ref. [6-44].
- Process automation, particularly for tape-laying and filament winding, is viewed as having the highest potential for reducing costs if the finished product is then thermoformed.

6.28 Multi-directional (3-D) composites

Composite materials and structures manufactured by standard laminate techniques are denoted as two-dimensional, or 2-D, because the orientation of the reinforcing fibres is planar. This applies to composites produced from unidirectional prepreg tapes or fabrics.

The lack of through-thickness fibres means that out-of-plane loads (either tensile or shear) are borne by the matrix phase. As matrix properties are considerably lower than fibre properties, the interlaminar properties of such composites are significantly inferior.

Whilst modifications to resin chemistries are helpful, they do not contribute at the level and magnitude to that of placing properly oriented fibres in the composite. Hence, fibre placement to create continuous fibre 3-D composites is being evaluated.

Table 6.28-1 compares 2-D and 3-D composites, highlighting properties perceived as beneficial for 3-D materials.

Techniques developed to create 3-D fibre structures by weaving or braiding have enabled complex geometry shapes (solely fibrous) to be produced, e.g. cones, cylinders and structural sections. These are denoted as ‘fibre preforms’ and are subsequently consolidated with a matrix to form the final component. The processes apply to all types of high-performance fibres or combinations thereof (except boron) having either polymer, metal or ceramic matrices.

[See also: Clause 42 for non-polymer matrix composites]

Interest in thermoplastic matrix 3-D composites is largely the result of the ability to create a weaving yarn containing both reinforcement and matrix. These ‘co-mingled yarns’ enable a means of controlling fibre volume fraction. That, coupled with inherently better toughness of certain thermoplastics over thermosetting resins, makes their potential for improving composite damage tolerance attractive.

Initial material evaluation studies indicate that improvements in through-thickness characteristics are promising. Further studies optimising fibre orientation and manufacturing processes are needed.

Table 6.28-1 - Comparison of 2-D and 3-D composite structures

2-D Construction	3-D Construction
Reinforcing fibres in planes (laminar)	Reinforcing fibres in all principal directions
Planes held together with matrix Poor through-thickness properties (matrix dominated) - interlaminar shear stress	No interlaminar planes (reinforced in all planes) - High tensile strength - High shear strength
Poor resistance to out-of-plane loads - delamination resistance	Improved delamination resistance
Poor impact/damage tolerance	Improved 'after-impact' properties Improved performance allowing mass savings
New or high-reliability applications possibly limited by matrix dominated properties	Potential new applications for composites
Extensive performance data available on carbon/epoxy systems.	Technology demonstrator parts produced
Analytical tools available	Limited analytical tools available
Manufacturing/process technology established for thermoset matrix materials	Limited performance data available
Experience for aerospace applications	Technology centred in France and USA in specialist companies offering complete design and manufacture service

6.29 Potential applications for 3-D composites

Several applications for 3-D composites have been suggested. All of these aim to improve through-thickness characteristics or to locally enhance properties, such as around fastener holes or bonded joints, Ref.[6-57].

More ambitious applications include complex curved parts for thermal protection or nozzles, Ref. [6-58].

Table 6.29-1 summarises some applications under development which are appropriate to the aerospace industries.

Table 6.29-1 - Potential applications for 3-D composites

Application	Requirements	Material (Fibre/Matrix)	Characteristics Obtained	Current Status [Reference]
Sandwich panels	Improve resistance to out-of-plane loads Improve delamination resistance	E-glass (warp and weft) Aramid (pile)/ epoxy	Reduced density (compared to 'standard' sandwich constructions Compression strength; lower (~1/2) than that of 'standard' sandwich construction Improved flexural strength over standard sandwich constructions Reduced shear modulus, shear strength but comparable shear energy to total failure	Initial results of development study. Future work to include different foam strengths/stiffnesses Ref. [1]
Structural shapes	Improve bending characteristics Improve delamination resistance	Not stated Thermoplastic	Modification to standard Cartesian MAGNAWEAVE braider to incorporate thermoplastic fibres into preform No loss of loom capacity	Manufacturing facility BRAIDTECH INC, USA Ref. [3]
I-beams	Determine mechanical response (flexural and compressive loading). Failure characteristics Fibre architecture effect	E-glass, carbon + hybrid/ polyester resin	Improved flexural strengths with axial laid yarns No delamination evident demonstrating through-thickness strength	Initial study (U.S. Dept. of Transport/US Army Res.) Ref. [4]
Rectangular bar, I-beams	Improved delamination resistance Retained longitudinal mechanical properties	Carbon, aramid (hybrid) Epoxy resin	Two-step braiding process most suitable for thicker sections. (Near net shapes)	Initial study now requires automation. (General Motors/Du Pont) Ref. [5]
Near net shapes Blocks Rocket/missile nozzles. Rocket exit cones Rocket case-nozzle adapters ITE Hypersonic aircraft leading edges Spacecraft attachment parts on space booster tanks End fittings on truss tubes Meteoroid and debris bumpers (space platforms or stations) Automobile connecting rod	Improved mechanical performance (strength, stiffness, stability)	Carbon, silicon carbide, aramid glass/epoxy, carbon	Demonstrator parts manufacture possible, mechanical performance improved allowing weight savings	Initial studies (1972) produced automated wearing machines for blocks and contoured shapes (1977) by AEROSPATIALE, France. Licensed HERCULES AEROSPACE CO, Utah, USA. Machines for producing large contoured cylindrical structures installed late 1985. Also demonstrator parts produced by MAGNAWEAVE braiding by BRAIDTECH Inc, USA. Ref. [2, 4]

6.30 Reinforcements for 3-D composites

3-D polymer composite technology can be applied to continuous yarns of:

- Carbon fibre,
- Aramid fibre, and
- Glass fibre.

Use of carbon, silicon carbide and alumina fibres are of interest to metal and ceramic matrix material systems, [See: Clause 43].

Yarns can be single type or mixed to produce hybrid reinforcements.

6.31 3-D fibre architecture

6.31.1 General

Various textile processes for the production of composite reinforcement have been considered for providing 3-D multiaxial reinforcement, damage tolerance and reduced manufacturing costs, Ref [6-105]. A variety of methods have been developed as part of 3-D fibre reinforcement preform technology for manufacturing polymer matrix composites, e.g. by RTM and derivative processes, [See: 38.7], or for composites having metal- or ceramic matrices, [See also: 54.2; 54.3; Clause 88].

Details vary, but the methods can be grouped as:

- Triaxial.
- Braided.
- Woven structures.

Despite the perceived advantages, textile composites are yet to challenge laminated composites for the majority of applications.

In order to advance the use of 3-D reinforcements, the interactions between reinforcement architecture, processing and properties need to be investigated using a combination of experimentation and modelling. Any advantages in cost reduction also need to be quantified, along with the trade-off between cost, weight and performance for the whole manufacturing cycle. As with many manufacturing processes, serial production of high numbers of identical parts normally yields the highest potential cost savings, and for space structures, this is rarely possible.

A UK government funded survey of 3-D fibre technologies in the USA showed that nearly all of the work is funded by the military. 3-D weaving appears to be the first choice for preforms because it achieves high volume fractions of fibre and hence better performance. It is also a very versatile process allowing a very wide range of weave types. For all processing routes, e.g. weaving or braiding, accurate tension control is vital to ensure quality.

Nearly all the work in the USA is directed towards producing long lengths of constant sections, e.g. structural I, T, Pi profiles. Little progress has been made on component preforms apart from work on fan blades, Ref.[6-108].

The development of an accurate modelling and analysis design system for preform selection is also essential, Ref. [6-108].

6.31.2 Triaxial fabrics

6.31.2.1 General

The term triaxial is used to describe:

- Joining together layers of biaxial fabrics using continuous yarns, e.g. stitching, angle-interlocking, use of pile fibres or Z-pinning [See: 6.40]. These types tend to be of limited thickness, e.g. 3 layers, for use as thin section composites or skins.

- Weaving of yarns in three direction within a single layer. These are commonly known as TWF triaxial woven fabric, [See also: 2.6; 6.41; 9.17; 30.13 – case study].

6.31.2.2 Stitching

In its simplest form, a triaxial fabric is made by stitching layers of conventional fabric together. This can result in needle damage to the yarns.

6.31.2.3 Angle-interlocked

When the through-thickness yarns are woven at the same time as the base fabric layers using modified looms, these are known as 'integrally woven' or angle interlocked, Ref. [6-62]. Figure 6.31-1 shows examples of this type of fibre architecture, Ref. [6-63].

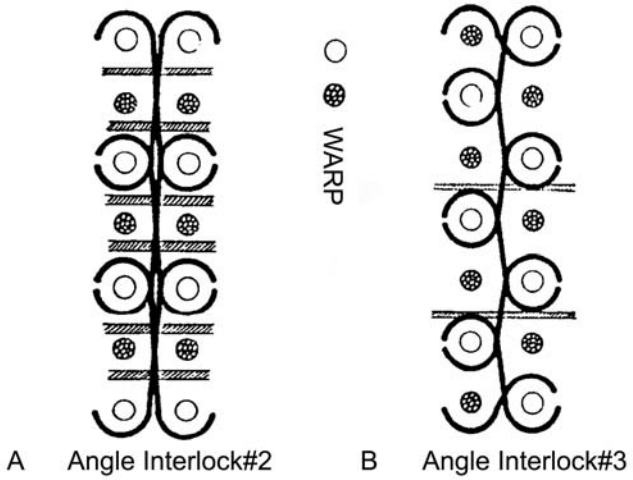


Figure 6.31-1 - Examples of fibre architecture of triaxial fabrics

6.31.2.4 Pile fibres

Also described as quasi-3-D or 2.5-D fabrics, Ref. [6-57], these triaxial fabrics consists of a bi-directional fabric with discontinuous or 'pile' fibres in the through-thickness direction.

6.31.2.5 TWF - triaxial woven fabrics

TWF are lightweight and more shear resistant than conventional bi-direction fabrics. TWFs can comprise either yarns or ribbons made of a range of materials (textiles, reinforcing fibres). The openness of the weave can also be varied, [See: 2.6]. Their mechanical and physical properties are more difficult to characterise by testing or modelling than conventional fabrics, [See: 6.41]. An ESA-funded study characterised a 0°±60° T300 carbon fibre TWF for space applications, [See: 9.17].

6.31.3 Braided

Braiding technology enables three or more continuous yarns to be progressively crossed in a predetermined pattern and angle to produce a complex network. Figure 6.31-2 is an example of a braiding process, Ref. [6-61].

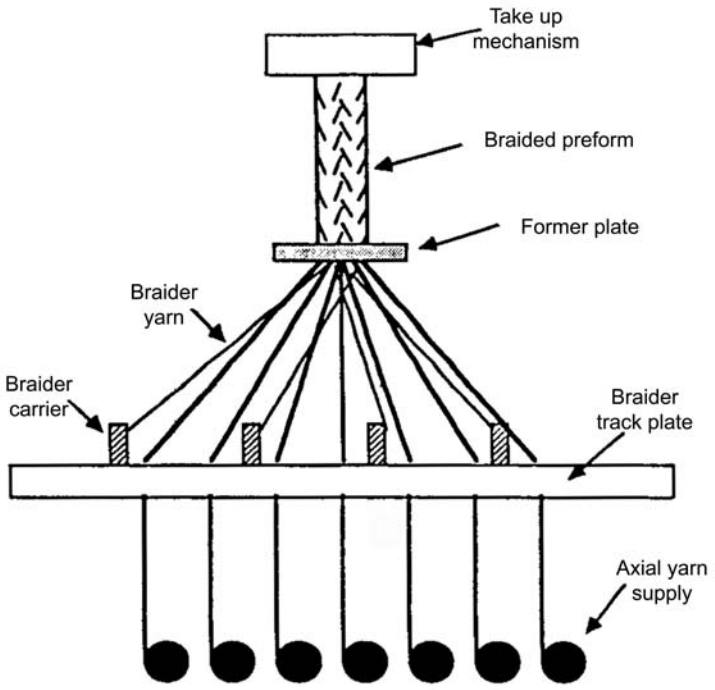


Figure 6.31-2 - Fibre architecture: Braiding process

Braiding techniques can provide both:

- Thicker sections (greater than 3 yarn thickness),
- Specific structural shapes. (I -beams, cylindrical and rectangular tube or bar). These are described as near net-shape preforms.

Figure 6.31-3 shows the yarn path within a braid, Ref. [6-64].

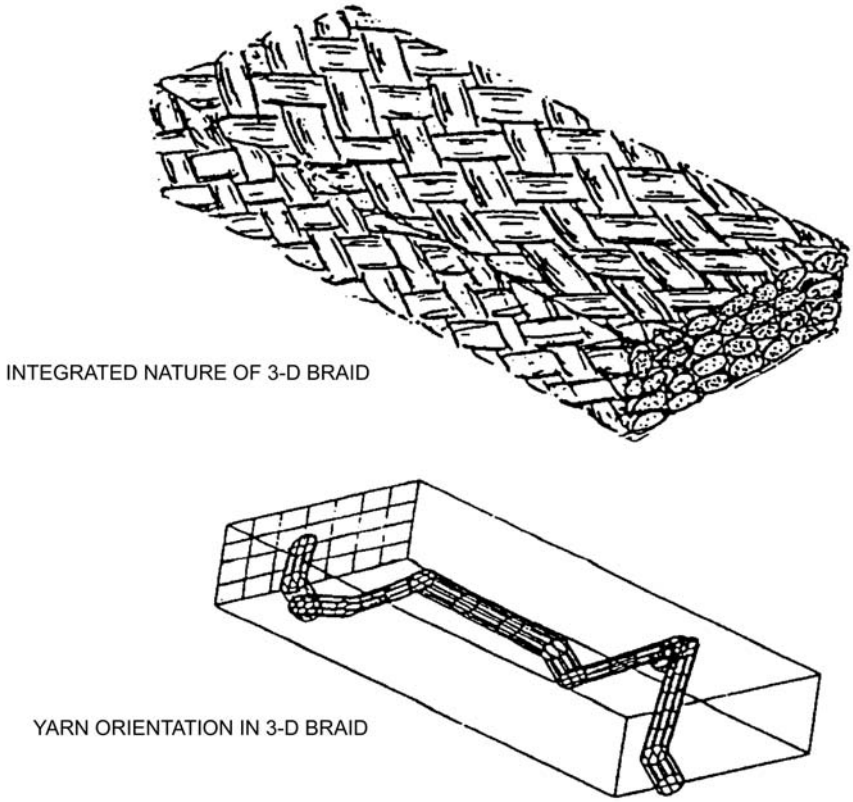


Figure 6.31-3 - Example of yarn path within a braid

6.31.4 Woven structures

6.31.4.1 General

The techniques (pioneered by Aerospatiale) are capable of producing large, thick section fibre preforms by either:

- Cylindrical weaving, where the yarns are oriented in radial, circumferential and axial or meridional directions, as shown in Figure 6.31-4 for cylinders, cones, frustrums or other thick or thin-walled contoured bodies, Ref. [6-58].
- Orthogonal weaving, where the yarns are oriented in the X, Y, Z directions, as shown in Figure 6.31-5 to produce blocks, Ref. [6-58].

Fibre preforms can be shaped prior to impregnation to minimise final machining operations.

[See also: 54.2; 54.3]

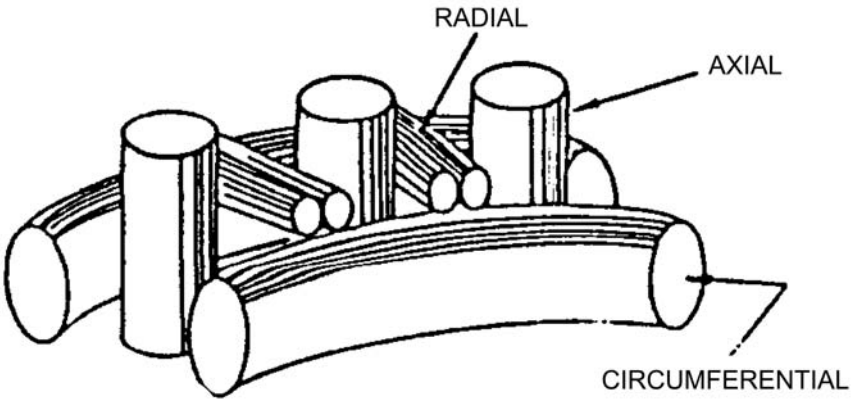


Figure 6.31-4 - Fibre architecture: Cylindrical weaving

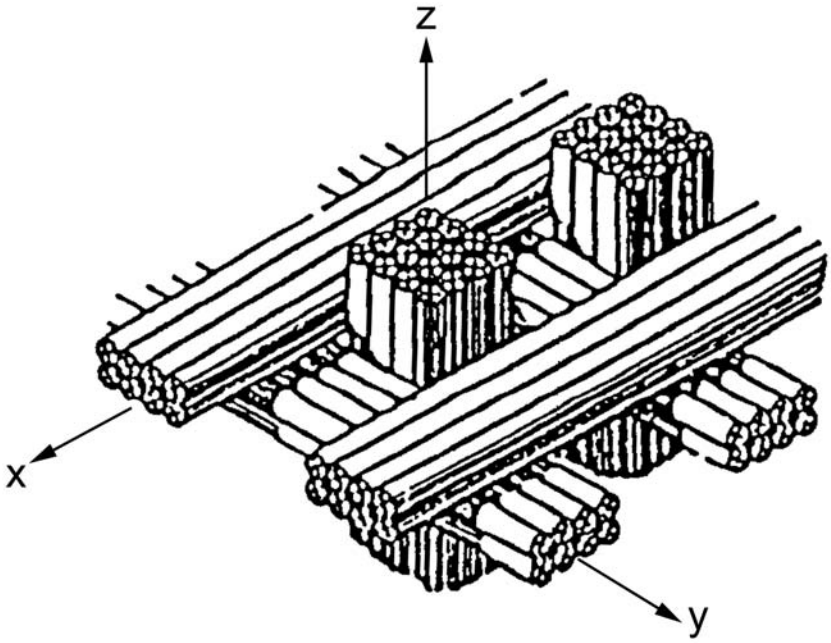


Figure 6.31-5 - Fibre architecture: Orthogonal weaving

6.31.4.2 Woven sandwich panel structures

Sandwich panel structures are based on triaxial fabrics having comparatively long through-thickness yarns. These subsequently become the internal structure of the panel with the fabric outer layers forming the skins. The internal fibres, after impregnation, need support by, for example, foam, Ref. [6-57].

6.31.4.3 DIRIS - thermoplastic woven sandwich panels

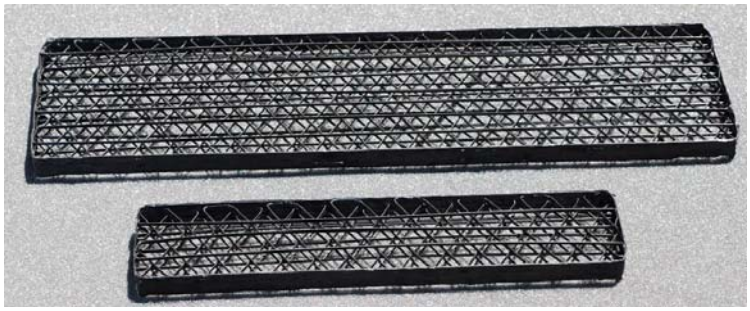
DIRIS - *DIrectionally Reinforced Integrated Single-yarn* is a multi-layered honeycomb panel comprising of a honeycomb core and two skins all made of fibre-reinforced thermoplastic matrix composite, Ref. [6-106].

The isogrid core is made by winding a single tape of carbon fibre/PEEK in successive layers in 0°, +60°, -60° directions to form equilateral triangles. Triangular prismatic cells, made of the same composite material but having a 45° fibre direction with respect to the edges of the prism, are then inserted in the

triangular gaps, as shown in Figure 6.31-6. Ref. [6-107]. The skins, made of 0°/90° thermoplastic composite, are then heat-bonded under pressure to the core and the ends of the triangular cells.

Under ESA-funding carbon fibre/PEEK DIRIS panels have been investigated, Ref. [6-107]. Some potential space applications for the panels include membrane connectors for tension fabrics, satellite floors and structural elements, Ref. [6-106].

Triangular prismatic cells



Isogrid core

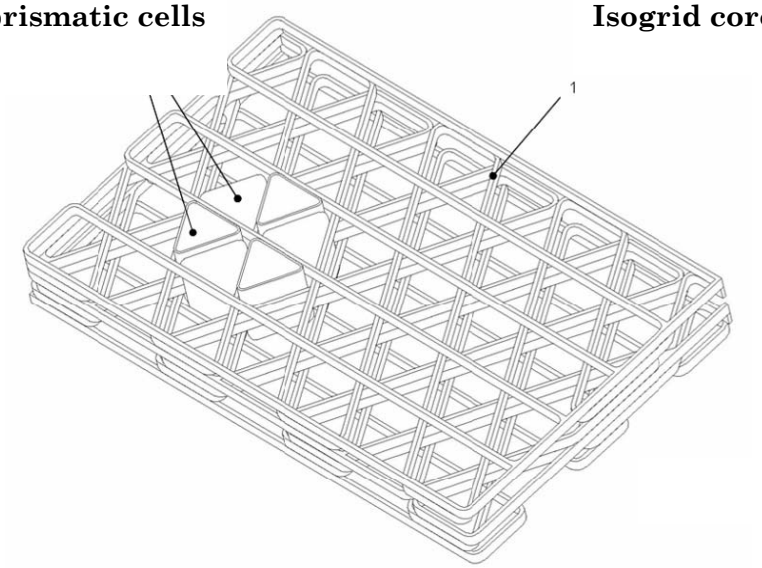


Figure 6.31-6 – DIRIS - woven thermoplastic sandwich panels

6.32 Matrix systems for 3-D composites

6.32.1 Thermosetting resins

Impregnation by a liquid resin matrix is undertaken by vacuum assisted techniques in shaped moulds. It is important to extract entrapped air in dense fibre preforms to achieve a properly consolidated composite.

6.32.2 Thermoplastics

The availability of thermoplastics in fibre form, notably PEEK, enables yarns to be produced containing both reinforcement and matrix. These 'co-mingled' yarns, as shown in Figure 6.32-1, are then used to produce the 3-D fibre preform, Ref. [6-64][6-64]. The preform is subsequently hot moulded to melt the matrix fibres and consolidate the composite, Ref. [6-64][6-64].

Table 6.32.1 lists some of the features of 'co-mingled' manufacturing, Ref. [6-63], [6-64], [6-70], [6-71] and[6-72].

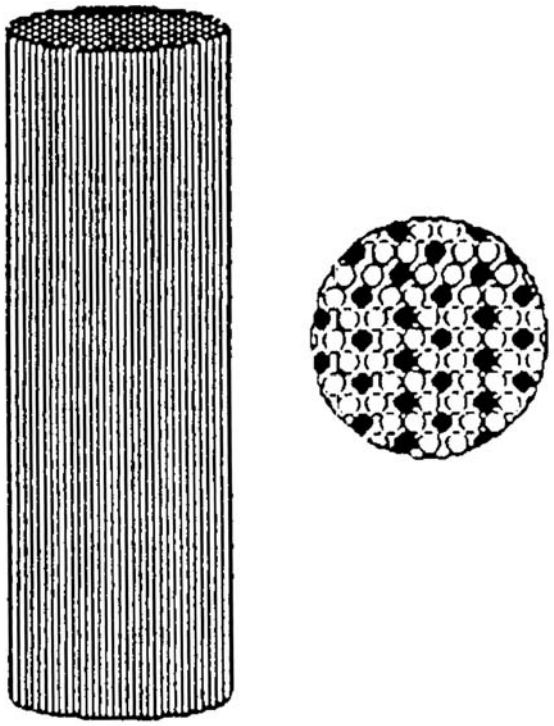


Figure 6.32-1 - Co-mingled yarns: Thermoplastic matrix and reinforcement fibre

Table 6.32-1 - Features of 'co-mingled' thermoplastic matrix 3-D composites

Advantages		Disadvantages
Good control of volume fraction (V_f) of composite by co-mingling reinforcement and matrix at yarn level.		Fibre/matrix interface needs consideration.
Preform includes both reinforcement and matrix (reducing composite consolidation processes).		Non-uniform fibre and matrix distribution (characteristic of 3-D composites).
Secondary thermal shaping possible.		Pockets of matrix phase may have variable properties. (Crystallinity variations noted).
		Vacuum assisted manufacture required to remove air pockets (modified autoclave).
Materials:	Fibre: Celion 6K, Celion G30-500-3K	Matrix: PEEK 380, Celanese 175/20 PEEK, SP-301-A (175 denier, 20 filament)

6.32.3 Metal matrix

Liquid metal infiltration techniques, as used for uni- or bidirectional metal matrix composites (MMC's) are applicable to 3-D preforms, Ref. [6-67]. One example is alumina fibre-reinforced aluminium-lithium alloys, known as Fibre FP/Al-2.5 Li, Ref[6-65] and [6-66].

[See also: Clause 46 for aluminium-based MMC's]

6.32.4 Ceramic matrix

Chemical vapour infiltration (CVI) and pitch impregnation techniques are used for 2-D ceramic matrix composites (CMC's), Ref. [6-68]. These processes are also appropriate for 3-D preforms to produce carbon-carbon (C-C) or silicon carbide (SiC-SiC) composites, Ref. [6-58] and [6-69].

[See also: Clause 52 for CMC's and Clause 54 for C-C composites]

6.33 Properties of 3-D composites

As with all composites the properties obtained are dependent on the interrelationships of fibre, matrix and conditioning. For 3-D composites, Ref. [6-68], this is further complicated by the:

- Density of through-thickness connections,
- Braid angle, and
- Effects of local matrix-rich regions.

Consequently mechanical property data is very material specific and is often limited to a few mechanical (often impact) tests as part of feasibility studies. The results, if encouraging, then lead to further research and development programmes to optimise fibre placement and processing techniques. Using fibres in a third dimension reduces the strength-to-weight and stiffness-to-weight ratios of the composite in the other two dimensions.

Mechanical property data can be included as and when the results of comprehensive evaluations are available.

For near net-shape preforms, property data is specific to the component produced and therefore the standardised data sheets available for 2-D laminate systems are not appropriate.

[See also: Clause 42 for non-polymer composite materials]

6.34 Toughened epoxy composites

6.34.1 Introduction

Epoxy resin technology has improved greatly over the years. Early epoxies tended to be very brittle which was undesirable, particularly in aircraft construction where impact damage was of acute concern. The later generations of epoxies have increased toughness, and better hot-wet strength retention.

There remains a need to have an acceptable glass transition temperature (Tg) above the operating temperature. However, the desire to lower processing temperatures from 175°C to 120°C has increased. This has produced a further generation of prepreg resins.

For space structures, toughened resins and low-temperature curing are known to reduce the occurrence of microcracking. Some examples of useful epoxy resins for European space programmes are:

- Hexcel [Ciba/Brochier] Vicotex M18 (175°C cure),
- Fiberite 977-2 (175°C cure),
- Fiberite 977-6 (135°C or 177°C cure),
- Cyanamid Cycom 950-1 (120°C cure).

M18, 977-6 and 950-1 are particularly appropriate for use with UHM carbon fibres.

For space applications where the effects of moisture are important, [See: 13.1], some new epoxy resins are formulated with low moisture absorbency, whilst retaining useful processing characteristics, e.g. cure temperatures, handling and composite processing by prepregging or by resin transfer moulding, Ref. [6-92]. These epoxy resins are competitors to the low moisture, cyanate ester formulations, [See also: 2.4; [6-35]. An example is Cycom 5555.

6.34.2 M18/M55J

6.34.2.1 General

Alenia Spazio characterised M18/M55J as a replacement for M18/GY70 for use with spectrometer constructions, Ref. [6-75]. M18 is a system regularly used for dimensionally stable structures. Table 6.34-1 shows the outgassing characteristics of this system, Ref. [6-75].

Table 6.34-1 - Outgassing characteristics of M18/M55J

Outgassing Criteria	M55J/M18	Acceptance Limits
TML: Total mass loss (%)	0.43	1.00
CVCM: Collected volatile condensable material (%)	0.01	0.10
RML: Recovered mass loss (%)	0.25	1.0

6.34.2.2 Mechanical properties

Mechanical properties were measured for UD and quasi-isotropic laminates. The properties are given in Table 6.34-2, Ref. [6-75].

Table 6.34-2 - M18/M55J: Unidirectional and multidirectional composite data

Supplier/Tradename: Brochier [now Hexcel]	Fibre/Resin System: Toray M55J Vicotex M18		Data Source: Alenia Spazio
Fibre volume (%): 60	t_{ply} (mm): -		Density (kg m^{-3}): -
Areal weight of prepreg (g m^{-2}): -			Number of batches tested: 1
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1994
Specimen condition: Standard cure cycle. Dry state. RT values			
Test environment: RT			

		$\bar{x}$	SD	N
UD tension $(0°)_{16}$ to ASTM D 3039	Strength (MPa) Modulus (GPa) Strain (%)	1784 301 0.57	111 13 0.03	- - -
UD tension $(90°)_{16}$ to ASTM D 3039	Strength (MPa) Modulus (GPa) Strain (%)	21 5.9 0.36	0.3 0.05 0.01	- - -
MD longitudinal tension $[(+60°0°-60°)_S]_2$	Strength (MPa) Modulus (GPa) Strain (%)	695 109 0.61	23 3 0.03	- - -
UD compression $(0°)_{16}$ to ASTM D 3410	Strength (MPa) Modulus (GPa) Strain (%)	602 293 0.24	50 13 0.02	- - -
MD longitudinal compression $[(+60°0°-60°)_S]_2$	Strength (MPa) Modulus (GPa) Strain (%)	299 102 0.35	14 3 0.02	- - -
In-plane shear $(\pm45°)_6$ to ASTM D 3518	Strength (MPa) Modulus (GPa)	53 4.6	0.5 0.14	- -
UD interlaminar shear $(O°)_{16}$: to ASTM D 2344	Strength (MPa)	68	4	-

Key: UD: Unidirectional MD: Multidirectional

6.34.2.3 Coefficient of thermal expansion

Table 6.34-3 gives the measured CTE values of unidirectional UD and multi-directional MD laminates in the temperature range 17°C to 65°C, Ref. [6-75].

Table 6.34-3 - CTE of M18/M55J laminates

Laminate	CTE: x 10^{-6}°C^{-1}	
	At 40°C	At 60°C
0° UD laminate	-0.9 ± 0.1	-1.02 ± 0.06
90° UD laminate	34 ± 2	35 ± 1
Longitudinal $[(+60°0°-60°)_S]_2$	-0.17 ± 0.03	-0.16 ± 0.03

6.34.3 977-6/M46J

This thermoplastic toughened resin system under development with the aim of having a versatile curing system, i.e. 3 hours at 135°C or 2 hours at 177°C with a controlled flow system.

Table 6.34-4 shows the variation of glass transition temperature (Tg) with cure conditions.

Table 6.34-4 - Glass transition temperatures of Fiberite 977-6 in relation to cure conditions

977-6 Cure Study	
Cure Schedule	T_g (°C)
2 hrs/135°C	77
3 hrs/135°C	156
4 hrs/135°C	163
5 hrs/135°C	164
2 hrs/135°C and 2 hrs/163°C	178

Initial studies with 977-6/M46 prepreg produced the mechanical properties for unidirectional UD laminates shown in Table 6.34-5.

Table 6.34-5 - 977-6/M46J: Unidirectional composite data

Supplier/Tradename: Fiberite.	Fibre/Resin System: Toray M46J 977-6		Data Source: Fiberite
Fibre volume (%): -	t_{ply} (mm): -		Density (kg m^{-3}): -
Areal weight of prepreg (g m^{-2}): -		Number of batches tested: 1	
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -	Year of test: 1996	
Specimen condition: Cure cycle of 135°C for 5 hours. Dry state. RT values			
Test environment: RT			

		$\bar{x}$	SD	N
UD 0° tension to ASTM D 3039	Strength (MPa)	2172	-	-
	Modulus (GPa)	273	-	-
UD 90° tension to ASTM D 3039	Strength (MPa)	57.9	-	-
	Modulus (GPa)	7.4	-	-
UD 0° compression to ASTM D 3410 [IITRI]	Strength (MPa)	1083	-	-
	Modulus (GPa)	239	-	-
UD 0° interlaminar shear to ASTM D 2344	Strength (MPa)	97.9	-	-

6.35 Cyanate ester composites

6.35.1 General

Cyanate ester resin systems are a recent addition to the thermosetting range, which includes epoxies and bismaleimides. They offer physical characteristics that are attractive in both aircraft and spacecraft construction.

In particular, the improvements over epoxies in producing carbon fibre composites are:

- Good toughness.
- Lower moisture absorption.
- Increased resistance to microcracking, particularly in UHM CFRP.

These are most noticeable in comparisons with first generation brittle epoxies, e.g. Code 69 and Fiberite 934. Improvements are less pronounced compared with the second generation epoxies, such as the toughened systems, [See:6.34]. Cyanate ester resins have lower densities than epoxies and this reduces CFRP density by around 5%.

6.35.2 Prepreg processing

The cyanate ester prepregs are intended to be processed by autoclaving at the cure temperatures indicated. They also have post-cure capabilities, if needed. The newer generation cyanate esters and toughened epoxies have the ability to attain glass transition temperatures (Tg) in excess of the indicated cure temperature. This is particularly important for those with low cure temperatures in the 120°C to 130°C range.

Whilst cyanate ester prepregs can be processed by vacuum bagging and autoclaving, initial experience indicates that process cycles need to be optimised for individual prepregs; particularly with regard to:

- Moisture absorption by exposed uncured prepreg resin prior to moulding.
- Resin flow characteristics and viscosity changes during initial cross-linking.
- Laminate consolidation to remove voids.

6.35.3 Resin mechanical properties

The stiffness and strength of neat cyanate ester resins are comparable with the traditional epoxies. The differences are in the higher neat resin failure strains which are in the 2% to 5% range. This, in theory, confers good toughness on the composite; by improved transverse ply strain to failure and delamination resistance. The level of resin-to-fibre bonding is important. Fibre and resin compatibility is optimised through appropriate fibre sizing.

6.35.4 Low moisture absorption

High moisture absorption in epoxies can be equated to a reduction in Tg and a high coefficient of moisture expansion (CME), [See: 13.7]. A high CME is undesirable in dimensionally stable structures, hence the interest in changing to cyanate esters.

The moisture absorbency of YLA RS3 and Fiberite 934 neat resins are compared in Table 6.35-1. The amount absorbed by RS3 is only 20% that of 934. However, in a composite containing only 40% by volume resin, the capacity of the composite to absorb moisture is very low. The improvement in CME is thus less pronounced.

Table 6.35-1 - Cyanate ester resins: Moisture absorption of matrix resins

	Moisture Diffusivity, K^H ($m^2 s^{-1}$)		**Max. Moisture Content, C_m (%)**		**Coeff. of Moisture Expansion, β (m/m)**	
	RT	93°C	RT	93°C	RT	93°C
RS-3	8.94×10^{-13}	1.34×10^{-11}	1.2	1.5	0.149	0.156
F934	8.31×10^{-14}	2.69×10^{-12}	6	7	0.261	0.267

The rate of moisture absorption at room temperature is shown in Figure 6.35-1 and desorption under vacuum in Figure 6.35-2. Cyanate esters absorb and desorb moisture more quickly than epoxies.

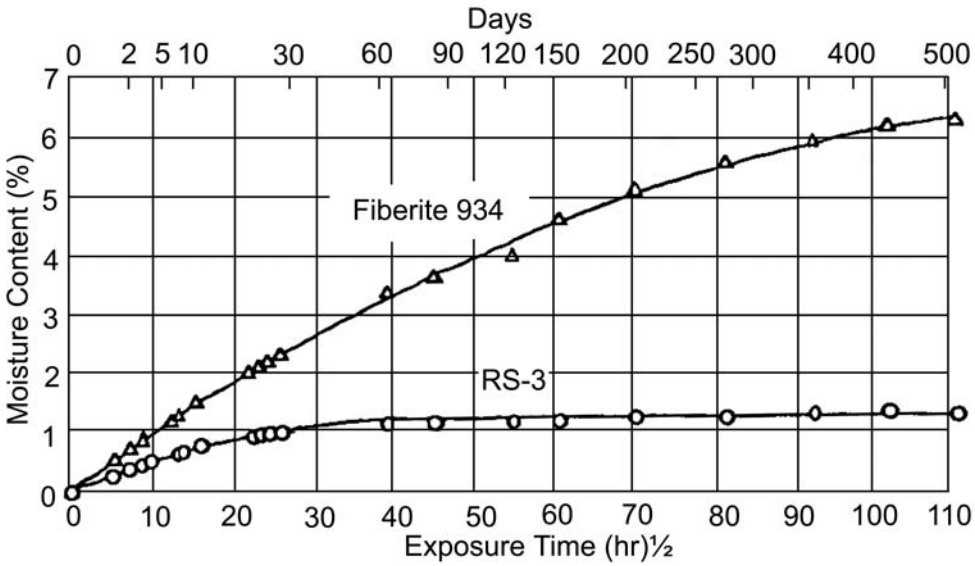


Figure 6.35-1 - Cyanate ester resins: Moisture absorption of matrix resins at RT, 100% RH

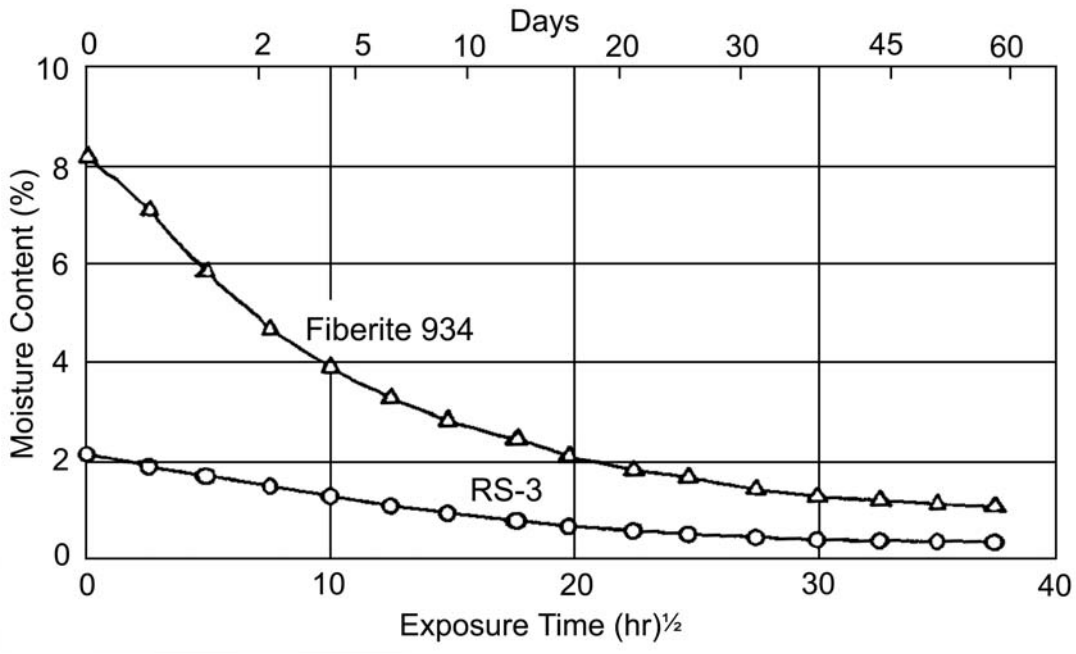


Figure 6.35-2 - Cyanate ester resins: Moisture desorption of resins at 37°C, in vacuum

6.35.5 Microcracking resistance

Under repeated and severe thermal cycling, e.g. from -180°C to +130°C, epoxy UHM CFRP shows a tendency to microcrack. This is undesirable for dimensionally structures. Microcracking is most prevalent in 90° plies adjacent to 0° plies in cured laminates. Evidence shows that cyanate ester composites have a much-reduced tendency to microcrack. Questions remain as to whether this is true of all cyanate ester UHM CFRP composites or is only seen in specific resin and fibre combinations. The interfacial adhesion between resin and pitch-based fibres, such as XN50A and K135, can differ from composites made with PAN based fibres, e.g. M55J. The level of any microcracking is dependent upon:

- Laminate processing,
- Laminate construction and thickness,
- Extremes of temperature,
- Number of thermal cycles.

6.35.6 European space programmes

6.35.6.1 General

Prepreg systems with UHM carbon fibres are needed for dimensionally stable structures, antennas, reflectors and optical devices, Ref. [6-88],[6-89] and [6-90].

The use of cyanate esters with high-strength, intermediate-modulus fibres has been studied for cryogenic fuel tanks in future launcher programmes, Ref. [6-76] and [6-77].

6.35.6.2 UHM CFRP

Within European space programmes the principal prepreg systems either applied or being studied are 954-3/M55J, RS3/M55J, M22/M55J, 954-3/K135, M22/K135, RS3/XN50A, and RS3/Kevlar 49.

6.35.6.3 RTM CFRP

The high-strength Toray HTA fibre combined with cyanate ester resin systems RS3 or RS14RTM from YLA have been evaluated for load-introduction components on EOS earth observation satellites. The study compared the cyanate ester systems with a Hexcel epoxy resin RTM6. The development components were manufactured by a resin transfer moulding (RTM) process, Ref. [6-91].

6.36 Cyanate ester availability

6.36.1 General

Table 6.36-1 and Table 6.36-2 indicate a range of commercial cyanate esters products available. The fewer number of products compared with that of epoxies reflects their current market share and continuing evolution.

Table 6.36-1 - Cyanate ester prepreg resin products

Product Designation	Manufacturer	Processing Characteristics	Comments/Applications
954-2A	Fiberite, Germany/USA	177°C cure with optional 232°C postcure	Low flow, toughened system for complex structures. Usually with high strength and intermediate modulus carbon fibres.
954-3		177°C cure with optional 232°C postcure	High flow cyanate system. Principally for space structures with UHM carbon fibres.
954-6		135°C cure	Low temperature curing system, with 155°C T_g., for dimensionally stable structures.
996		177°C cure	Cyanate siloxane with extremely low moisture absorption (low CME) for dimensionally stable structures. Low resin density.
M22	Hexcel, France/UK*	180°C cure	Low moisture absorption. Intended for space applications and use with UHM carbon fibres.
RS-3	YLA, Inc. USA	177°C cure	Good balance of toughness and hot/wet performance. Suitable for satellite structures, airframe/missile structures and radomes.
RS-9		193°C cure plus 315°C post-cure.	High temperature resin for use to 287°C. RTM processible.
RS-12		121°C cure	Low temperature curing system for space applications.
EX-1515	Bryte Technologies, Inc. USA	107 to 120°C cure	Ultra-high conversion, extremely low moisture absorption, self-adhesive and high resistance to microcracking. Specifically for space programmes.
EX-1505		177°C cure	T_g of 316°C, high char yield, low moisture absorption. Aircraft radome and rocket nozzles.
BTCy-1		177°C cure	177°C to 204°C hot/wet service.
BTCy-1A		177°C cure	Toughened version of BTCy-1.
BTCy-2		177°C cure	Very good electrical properties for ultra low dielectric/low loss radomes.
BTCy-3		121°C cure	Excellent electrical and structural properties.
BTCy-3A		121°C cure	Toughened version of BTCy-3.
LTM 110	Advanced Composites Group, UK	70°C initial autoclave cure.	Tooling prepreg for high temperature applications with T_g of 375°C when postcured.

Key: * includes Ciba Geigy and Brochier prepreg products.

Table 6.36-2 - Cyanate ester adhesives, resins and sundry materials

Product Designation	Product Form	Manufacturer	Processing Characteristics	Comments/Applications
A54	Film adhesive	Fiberite, Germany/USA	177°C cure	Lightweight unsupported film for co-curing cyanate prepreg skins. 163°C service temperature. Film weights from 70 to 210 g/m^2.
RS-4A	Film adhesive	YLA, Inc. USA	177°C cure	Ultra lightweight adhesive. 203°C T_g.
RS-14	Resin		RT + 177°C cure and 274°C post cure	Low viscosity for RTM and filament winding applications.
RS-16	2 part resin		RT + 135°C cure and 149°C post cure	For RTM applications.
MicroPly SF-5	Syntactic film		177°C cure	Hollow microsphere filled film, with thickness from 250µm to 3.175 mm (1/8″). Use with RS3.
MicroPly EM-5	Expanding syntactic film		232°C cure	Thickness from 178µm to 3.175 mm (1/8″). For high temperature skin consolidation.
EX-1516	film adhesive	Bryte Technologies, Inc. USA	121°C cure	Outstanding electrical performance.
EX-1543			121°C cure	Good electrical performance and very good thermal resistance.
EX-1502-1	paste adhesive		121°C cure	Paste adhesive with similar properties to EX-1516.
EX-1537			177°C cure	Paste adhesive with high thermal resistance and excellent structural properties.
EX-1537-1			177°C cure	Low viscosity paste adhesive.
EX-1510	resin		RT with 177°C cure	Low viscosity RTM and filament winding resin. Room temperature processible (long pot life) with high T_g after full cure.
EX-1545			RT with 149 to 177°C cure	High performance single component RTM resin for room temperature injection.
EX-1530	2 part resin		43 to 49°C processing. 177°C cure	High temperature matrix, with high char yield. Excellent ablative characteristics. 8 hour pot life.
EX-1532			54 to 60°C processing. 177°C cure	4 hour pot life. Differs from EX-1530 with higher viscosity, T_g and char yield.
EX-1541	syntactic foam		121 to 177°C cure	160-192 kg/m^3 density. Low CTE, high temperature resistance and good electrical performance. Other densities available.

6.36.2 Prepreg

YLA's RS3 and Fiberite's 954-3 prepregs have been commercially available from about 1991. Both use the same base resin (XU 71787) from Dow Chemicals but with differing cure systems. Prepregs in UHM cyanate esters are available in thicknesses from 60μm upwards and with fabric reinforcements.

The more recent M22 system uses a different proprietary base resin. M22 can be processed as a prepreg or injected for RTM. A number of the systems given in Table 6.36.1 are intended for specialised uses such as aircraft radomes, rocket nozzles and tooling prepregs. For radomes, the resins are selected on electrical characteristics. The latter applications demand high Tg values and char yields.

6.36.3 Adhesives

As cyanate ester composites became accepted for structures, secondary issues were addressed. It was found that epoxy adhesives were in some instances inappropriate for bonding cyanate ester laminates. The reasons cited were incompatibility in achieving satisfactory bond strength and higher moisture absorption by the epoxy adhesive. Cyanate ester adhesives were therefore developed. One such example is the Fiberite A54 material whose features can be summarised as:

- Lightweight unsupported film adhesive.
- Designed for co-curing cyanate prepregs skins to sandwich core or laminates.
- Applicable to secondary bonding requirements.

6.36.4 Resins

6.36.4.1 General

Cyanate esters are available as formulated low-viscosity resin systems intended for processing by filament winding and resin transfer moulding. This increases the opportunity for using these resins in thicker section constructions.

6.36.4.2 Resin transfer moulding (RTM)

The EX-1510 resin system from Bryte Technologies has been used by CASA Space Division to manufacture demonstrator profiles for use with thermal protection systems on future launcher configurations.

[See also: 6.35 - European space projects]

6.37 Space applications for cyanate ester composites

6.37.1 Introduction

Cyanate ester composites are relatively new (circa 1990) so there are only a few definitive applications in European space programmes. The technology is under active development at major European contractors including Matra Marconi, Fokker, Aerospatiale, CASA, Dornier, Contraves and ORS.

The arrival of cyanate esters coincided with the commercial withdrawal of GY70 UHM carbon fibre. The opportunity was taken to develop composites based on PAN- and pitch-based fibres offering improved mechanical properties.

The process of characterising materials and qualifying structures for space use is on-going.

6.37.2 Examples

6.37.2.1 Future launcher programmes

SONACA evaluated high-temperature resins and RTM resin transfer moulding techniques for future launcher programmes, Ref. [6-80]. The study included YLA's RS9 reinforced by Brochier E4354 T800H fabric.

6.37.2.2 FESTIP

CASA manufactured CFRP omega profiles by RTM, Ref. [6-77]. EX1510 resin system and 0°/90°/90°/0° preforms were combined. These omega-shaped profiles were designed for interfaces with the TPS thermal protection system support structures mounted on a polymer composite cryogenic fuel tank, Ref. [6-77].

SABCA manufactured representative cryogenic tank sections based on sandwich constructions of 954-2A/IM7 face skins on Rohacell 71 WF foam core, Ref. [6-79]. Cryogenic and omega profile attachments testing was undertaken.

6.37.2.3 Artemis CLRD

The common large reflector dish CLRD development for ARTEMIS was undertaken by CASA Space Division, Ref.[6-78]. The main features can be summarised as:

- Used three prepreg systems: one unidirectional (RS3/XN50A) and two fabrics (RS3/K49 and RS3/T300).
- The configuration consisted of a dish sandwich stiffened with back structure rib sandwich, each with a HRH 49 Kevlar core.
- The CLRD was up to 3.265m at its largest dimension, with a total mass of 24.8kg.

6.37.3 Wider uses of cyanate esters

6.37.3.1 General

Some examples of the wider potential for using cyanate ester composites can be cited.

6.37.3.2 Radiator panel

Development of a high-conductivity composite face sheet with aluminium honeycomb radiator panel without heat pipes to replace a baseline all aluminium sandwich radiator panel with heat pipes, Ref. [6-81].

High-conductivity pitch fibre systems, RS3/P100 and RS3/K1100 were studied. By matching thermal performance, a mass saving of 22% was identified over the existing all metal construction.

6.37.3.3 Optical mirrors

Optical quality mirrors have been manufactured with K135/EX-1515, Ref. [6-82]. These are intended as replacements for glass mirrors, considerable mass savings are the obvious attraction.

The optimisation of surface coatings and smoother mould surfaces needed further development to provide the CFRP with sufficiently low surface roughness for optical use.

6.37.3.4 Bus structure

The bus structure of a small satellite, 975mm x 737mm x 737mm was manufactured in 954-3/K1100 face skinned sandwich panels, Ref. [6-83].

With a composite mass of 55kg, the K1100 fibre was specified for thermal control purposes. Additional 954-3/T50 material was used for carrying compressive loads. An RS3/XN50A reflector was integrated with the structure.

6.38 Typical properties for cyanate ester composites

6.38.1 Introduction

Data are given on a range of cyanate ester composites that have been characterised within space programmes.

6.38.2 RS3/XN50

6.38.2.1 General

In developing the CLRD common large reflector dish for ARTEMIS, CASA characterised RS3/XN50 material in the form of unidirectional and multidirectional laminates, Ref. .[6-78].

The mechanical properties are summarised in Table 6.38.1, Ref. .[6-78].

Table 6.38-1 - YLA RS3/XN50: Unidirectional and multidirectional composite data

Supplier/Tradename: **YLA Inc.**	**Fibre/Resin System:** **Granoc XN50 RS3**		**Data Source:** **ARTEMIS Programme (CASA)**	
Fibre volume (%): 58±2	t_{ply} (mm): 0.065		Density (g cm^{-3}): -	
Areal weight of prepreg (g m^{-2}): -		Number of batches tested: 1		
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1995	
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension $(0°)_{14}$ to ASTM D 3039	Strength (MPa)	1707	157	12
	Modulus (GPa)	318	11	12
UD tension $(90°)_{14}$ to ASTM D 3039	Strength (MPa)	18	1.0	10
	Modulus (GPa)	5.7	0.2	10
MD longitudinal tension $[(+60°0°-60°)_S]_3$	Strength (MPa)	476	59	10
	Modulus (GPa)	103	1.1	10
MD transverse tension $[(+60°0°-60°)_S]_3$	Strength (MPa)	478	20	10
	Modulus (GPa)	89	1.2	10
UD compression $(0°)_{30}$ to ASTM D 695	Strength (MPa)	364	37	10
	Modulus (GPa)	211	3.4	10
UD compression $(90°)_{30}$ to ASTM D 695	Strength (MPa)	148	12	10
	Modulus (GPa)	6.2	0.1	10
MD longitudinal compression $[(+60°0°-60°)_S]_5$	Strength (MPa)	211	3	12
	Modulus (GPa)	68	2.6	12
MD transverse compression $[(+60°0°-60°)_S]_5$	Strength (MPa)	226	6	12
	Modulus (GPa)	66	0.3	12
In-plane shear $(±45°)_8$ to ASTM D 3518	Strength (MPa)	91	3	10
	Modulus (GPa)	4.8	0.3	10
UD interlaminar shear $(0°)_{30}$ to ASTM D 2344	Strength (MPa)	67	5	12
MD interlaminar shear $[(+60°0°-60°)_S]_5$	Strength (MPa)	51	2	8
Key: UD: Unidirectional MD: Multidirectional				

From the basic data, 'B'-basis allowables were used for CFRP modulus values and 'A'-basis allowables for strength, as shown in Table 6.38-2, Ref. [6-78].

Table 6.38-2 - Design allowables for RS3/XN50

"A" and "B" Design Allowables for RS3/XN50			
Test environment: RT			
		Type	Value
UD tension $(0°)_{14}$	Strength (MPa) Modulus (GPa)	A B	1120 293
UD tension $(90°)_{14}$	Strength (MPa) Modulus (GPa)	A B	12 5.1
MD longitudinal tension $[(+60°0°-60°)_S]_3$	Strength (MPa) Modulus (GPa)	A B	240 100
MD transverse tension $[(+60°0°-60°)_S]_3$	Strength (MPa) Modulus (GPa)	A B	395 86
UD compression $(0°)_{30}$	Strength (MPa) Modulus (GPa)	A B	221 203
UD compression $(90°)_{30}$	Strength (MPa) Modulus (GPa)	A B	98 6.0
MD longitudinal compression $[(+60°0°-60°)_S]_5$	Strength (MPa) Modulus (GPa)	A B	197 62
MD transverse compression $[(+60°0°-60°)_S]_5$	Strength (MPa) Modulus (GPa)	A B	202 62
In-plane shear $(\pm 45°)_8$	Strength (MPa) Modulus (GPa)	A B	79 4.2
UD interlaminar shear $(0°)_{30}$	Strength (MPa)	A	46
MD interlaminar shear $[(+60°0°-60°)_S]_5$	Strength (MPa)	A	43

6.38.2.2 RS3/K49 and RS3/T300

In addition to RS3/XN50, the CLRD called for Kevlar™ 49 aramid fibre and T300 carbon fibre fabric prepregs. Their properties are summarised in Table 6.38-3 for Kevlar and Table 6.38-4 for carbon, Ref. [6-78].

Table 6.38-3 - YLA RS3/K49: Multidirectional fabric composite data

Supplier/Tradename: YLA Inc.	Fibre/Resin System: Kevlar 49 Fabric RS3		Data Source: ARTEMIS Programme	
Fibre volume (%): 44	t_{ply} (mm): 0.100		Density (kg m^{-3}): -	
Areal weight of prepreg (g m^{-2}): -			Number of batches tested: 1	
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1995	
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
MD longitudinal tension $(0°/90°)_{20}$ to ASTM D 3039	Strength (MPa) Modulus (GPa)	373 25.7	18 0.4	8 4
MD transverse tension $(0°/90°)_{20}$ to ASTM D 3039	Strength (MPa) Modulus (GPa)	341 26.7	12 0.3	9 5
MD interlaminar shear $(0°/90°)_{20}$	Strength (MPa)	32	5	8

Table 6.38-4 - YLA RS3/T300: Multidirectional fabric composite data

Supplier/Tradename: **YLA Inc.**	**Fibre/Resin System:** **T300 Fabric RS3**		**Data Source:** **ARTEMIS Programme**	
Fibre volume (%): 43	t_{ply} (mm): 0.130		Density (kg m^{-3}): -	
Areal weight of prepreg (g m^{-2}): -			Number of batches tested: 1	
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1995	
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
MD longitudinal tension $(0°/90°)_{20}$ to ASTM D 3039	Strength (MPa)	710	20	10
	Modulus (GPa)	63.3	0.6	5
MD transverse tension $(0°/90°)_{20}$ to ASTM D 3039	Strength (MPa)	747	30	10
	Modulus (GPa)	64.3	0.8	6

'A'-basis and 'B'-basis design allowables were calculated for the fabric prepregs, the properties for these are shown in Table 6.38-5, Ref. [6-78].

Table 6.38-5 - Design allowables for RS3/K49 and RS3/T300 fabric laminates

"A" and "B" Design Allowables for RS3/K49 Fabric			
Test environment: RT			
		Type	Value
MD longitudinal tension $(0°/90°)_{20}$	Strength (MPa)	A	293
	Modulus (GPa)	B	24.1
MD transverse tension $(0°/90°)_{20}$	Strength (MPa)	A	290
	Modulus (GPa)	B	25.7
MD interlaminar shear $(0°/90°)_{20}$	Strength (MPa)	A	14
"A" and "B" Design Allowables for RS3/T300 Fabric			
MD longitudinal tension $(0°/90°)_{20}$	Strength (MPa)	A	627
	Modulus (GPa)	B	61.4
MD transverse tension $(0°/90°)_{20}$	Strength (MPa)	A	629
	Modulus (GPa)	B	61.7

6.38.2.3 Effects of thermal cycling

Mechanical tests were undertaken to assess any changes in performance after 20 thermal cycles from -140°C to +110°C were applied to laminates. These are given in Table 6.38-6, Ref. [6-78].

The effect of thermal cycling on design allowables, were calculated and the results given in Table 6.38-7, Ref. [6-78].

Table 6.38-6 - Properties of YLA RS3/XN50 after thermal cycling

Properties of RS3/XN50 laminates before and after thermal cycling.				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension $(0°)_{30}$ Before thermal cycling	Strength (MPa) Modulus (GPa)	1694 282	- -	2 2
UD tension $(0°)_{30}$ After thermal cycling	Strength (MPa) Modulus (GPa)	1483 277	107 8.2	12 12
MD longitudinal tension $[(+60°0°\text{-}60°)_S]_5$ Before thermal cycling	Strength (MPa) Modulus (GPa)	673 105.4	- -	3 3
MD longitudinal tension $[(+60°0°\text{-}60°)_S]_5$ After thermal cycling	Strength (MPa) Modulus (GPa)	689 107.5	40 2.8	6 6
MD transverse tension $[(+60°0°\text{-}60°)_S]_5$ Before thermal cycling	Strength (MPa) Modulus (GPa)	466 79.1	- -	2 2
MD transverse tension $[(+60°0°\text{-}60°)_S]_5$ After thermal cycling	Strength (MPa) Modulus (GPa)	459 81.5	13 2.2	10 10
MD longitudinal tension $[(0°+60°0°\text{-}60°90°)_S]_3$ Before thermal cycling	Strength (MPa) Modulus (GPa)	675 113.2	41 3.2	10 10
MD longitudinal tension $[(0°+60°0°\text{-}60°90°)_S]_3$ After thermal cycling	Strength (MPa) Modulus (GPa)	605 114.3	41 2.5	10 10
UD interlaminar shear $(0°)_{30}$ After thermal cycling	Strength (MPa)	56	2	8
MD ILSS $[(+60°0°\text{-}60°)_S]_5$ After thermal cycling	Strength (MPa)	51	2	8
Key: UD: Unidirectional MD: Multidirectional				

Table 6.38-7 - Design allowables for YLA RS3/XN50 after thermal cycling

"A" and "B" Design Allowables for RS3/XN50 laminates after thermal cycling			
Test environment: RT			
		Type	Value
UD tension $(0°)_{30}$	Strength (MPa) Modulus (GPa)	A B	1083 259
MD longitudinal tension $[(+60°0°\text{-}60°)_S]_5$	Strength (MPa) Modulus (GPa)	A B	487 99.0
MD transverse tension $[(+60°0°\text{-}60°)_S]_5$	Strength (MPa) Modulus (GPa)	A B	407 76.3
MD longitudinal tension $[(0°+60°0°\text{-}60°90°)_S]_3$	Strength (MPa) Modulus (GPa)	A B	442 108.3
UD interlaminar shear $(0°)_{30}$	Strength (MPa)	A	47
MD interlaminar shear $[(+60°0°\text{-}60°)_S]_5$	Strength (MPa)	A	42

6.38.2.4 Properties at -130°C and +110°C

To reflect the operational conditions for Artemis, the effect of extremes of temperature were studied. Mechanical properties for multidirectional laminates at -130°C and +110°C were measured after laminates had been subjected to 20 thermal cycles from -140°C to +110°C.

Table 6.38-8 shows these results and Table 6.38-9 the consequent reductions in design allowables.

Table 6.38-8 - Properties of YLA RS3/XN50 at extremes of temperature after thermal cycling

Properties of RS3/XN50 laminates at 110°C and -130°C after thermal cycling.				
		$\bar{x}$	SD	N
Test environment: +110°C				
MD longitudinal tension $[(+60°0°\text{-}60°)_S]_5$	Strength (MPa) Modulus (GPa)	573 110.9	29 3.1	6 6
MD longitudinal tension $[(0°+60°0°\text{-}60°90°)_S]_3$	Strength (MPa) Modulus (GPa)	545 102.6	32 3.7	10 10
Test environment: -130°C				
MD longitudinal tension $[(+60°0°\text{-}60°)_S]_5$	Strength (MPa) Modulus (GPa)	399 96.7	24 4.0	6 6
MD longitudinal tension $[(0°+60°0°\text{-}60°90°)_S]_3$	Strength (MPa) Modulus (GPa)	455 104.6	52 3.7	8 8

Table 6.38-9 - Design allowables for YLA RS3/XN50 at extremes of temperature after thermal cycling

"A" and "B" Design Allowables at extremes of temperature for RS3/XN50 laminates after 20 thermal cycles.			
		Type	Value
Test environment: +110°C			
MD longitudinal tension $[(+60°0°-60°)_S]_5$	Strength (MPa)	A	426
	Modulus (GPa)	B	101.5
MD longitudinal tension $[(0°+60°0°-60°90°)_S]_3$	Strength (MPa)	A	417
	Modulus (GPa)	B	94.0
Test environment: -130°C			
MD longitudinal tension $[(+60°0°-60°)_S]_5$	Strength (MPa)	A	278
	Modulus (GPa)	B	84.6
MD longitudinal tension $[(0°+60°0°-60°90°)_S]_3$	Strength (MPa)	A	229
	Modulus (GPa)	B	95.0

6.38.2.5 CTE tests

The CTE behaviour of dried RS3/XN50 laminates was measured before and after 100 thermal cycles from +100°C to -50°C.

Samples representative of the sandwich constructions for Artemis CLRD were also assessed and are given in Table 6.38-10, Ref. [6-78].

Table 6.38-10 - CTE characteristics for YLA RS3/XN50 laminates and sandwich constructions

Configuration		CTE, x 10^{-6}°C^{-1}					
		Before thermal cycling			After thermal cycling		
		min	$\bar{x}$	max	min	$\bar{x}$	max
$(0°)_{30}$	L	-1.23	-1.10	-0.96	-1.25	-1.112	-0.868
	T	34.6	36.4	37.9	-	-	-
$[(+60°0°-60°)_S]_5$	L	0.152	0.183	0.214	0.095	0.125	0.160
	T	0.187	0.194	0.210	0.106	0.133	0.161
$[(0°+60°0°-60°90°)_S]_2$	L	0.303	0.332	0.400	0.253	0.325	0.436
	T	0.297	0.413	0.464	0.252	0.349	0.475
Sandwich: Dish	L	0.306	0.444	0.620	0.324	0.380	0.430
	T	0.454	0.549	0.630	0.431	0.470	0.509
Sandwich: Rib	L	-	-	-	0.243	0.362	0.437
	T	-	-	-	0.343	0.418	0.501

Key: L indicates Longitudinal and T is Transverse direction.

The dish sandwich configuration was a 6mm HRH49 Kevlar 49 honeycomb with face skins of adjacent 0°/90° RS3/K49 fabric layer and outer -60°0°+60° RS3/XN50 ply lay-up.

The back structure rib sandwich configuration was a 10mm HRH49 Kevlar 49 honeycomb with face skins of adjacent 0°/90° RS3/T300 fabric layer and outer 90°-60°0°+60°0° RS3/XN50 ply lay-up.

6.38.3 954-2A/IM7

6.38.3.1 General

The FESTIP programme examined aspects of performance for the 954-2A/IM7 system. The proposed application was the containment of cryogenic fuels in future launchers, Ref.[6-76],[6-86].

The basic laminate properties measured are shown in Table 6.38-11, Ref. [6-76].

Table 6.38-11 - Fiberite 954-2/IM7: Unidirectional composite data

Supplier/Tradename: Fiberite	Fibre/Resin System: Hercules IM7 Fiberite 954-2		Data Source: INTA FESTIP Programme	
Fibre volume (%): 60	t_{ply} (mm): 0.125		Density (kg m^{-3}): 1540	
Areal weight of prepreg (g m^{-2}): -		Number of batches tested: 1		
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1997	
Specimen condition: Standard cure cycle. Dry state. RT values				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension $(0°)_{16}$ to prEN 2561	Strength (MPa)	2157	35	5
	Modulus (GPa)	153	2.5	5
	Strain (%)	1.38	0.03	5
UD tension $(90°)_{16}$ to prEN 2597	Strength (MPa)	27.7	3.0	5
	Modulus (GPa)	7.5	0.3	5
	Strain (%)	0.37	0.05	5
UD compression $(0°)_{16}$ to prEN 2580	Strength (MPa)	1148	99	5
	Modulus (GPa)	154	3.4	5
	Strain (%)	-	-	-
In-plane shear $(\pm 45°)_{2S}$ to AITM 1.0002	Strength (MPa)	111	3.4	5
UD interlaminar shear $(0°)_{16}$ to prEN 2563	Strength (MPa)	86.8	1.6	10
Key: UD: Unidirectional MD: Multidirectional *: Manufacturer's data on the supplied batch				

6.38.3.2 Residual strength properties

In the context of considering 954-2/IM7A for a reusable launcher configuration of up to 100 flights, laminate strength reduction was investigated, Ref. [6-76].

A multidirectional laminate configuration was tested in tension to assess the effects of open hole, thermal cycling and mechanical fatigue.

- A *Kt* value equal to 0.70 for reference tensile strength divided by open hole strength was determined.
- Thermal cycling conditions:
  - 50 cycles between -140°C and +100°C.
  - 30 minutes at minimum and maximum temperatures.

— Rapid 'thermal shock' between maximum and minimum.

- Mechanical fatigue cycling conditions:
  — 400 cycles between 0 and 60% of mean tensile strength.
  — 0.5 Hz sinusoidal-type wave.

The residual laminate properties are shown in Table 6.38-12, Ref. . [6-76].

Table 6.38-12 - Residual properties of 954-2/IM7 laminates

954-2/IM7 MD laminate : $[(\pm 45°)_2(90°)_4 0]_S$				
Test environment: RT				
		$\bar{x}$	SD	N
Tension to ASTM D3039	Strength (MPa)	460	14	5
Tension open hole to ASTM D3039	Strength (MPa)	345	2.9	5
Tension after thermal cycling to ASTM D3039	Strength (MPa)	422	16	5
Tension after fatigue to ASTM D3039	Strength (MPa)	434	8	5

6.38.3.3 Fracture toughness

As shown in Table 6.38-13, the Mode I GIC values are around twice that for the base resin, Ref. [6-76]. Mode II GIIC values of over 1000 J/m2 are expected for IM7 with a toughened epoxy matrix.

Table 6.38-13 - Fracture toughness of 954-2/IM7 laminates

954-2/IM7 UD laminate : $(0°)_{24}$				
Test environment: RT				
V_f = 60%		$\bar{x}$	SD	N
Mode I fracture toughness to AITM 1.0005	G_{IC} (J/m^2)	714	65	5
Mode II fracture toughness to AITM 1.0006	G_{IIC} (J/m^2)	914	94	5

6.38.3.4 LH2 and LOX compatibility

The response of 954-2/IM7 unidirectional laminates to 100 hours immersion in liquid fuels was assessed for changes in interlaminar shear strength. These are shown in Table 6.38-14, Ref. [6-76].

Specimen temperatures were 87.7 K±0.8 K for LOX and 19.4 K±0.2 K for LH2.

Table 6.38-14 - ILSS of 954-2/IM7 laminates after immersion in cryogenic fuels

954-2/IM7 UD laminate : $(0°)_{16}$				
Test environment: RT				
V_f = 60%		$\bar{x}$	SD	N
ILSS as manufactured [1] to prEN 2563	ILSS (MPa)	86.8	1.6	10
ILSS as manufactured [2] to DIN EN 2563	ILSS (MPa)	86.5	1.9	10
ILSS after LOX exposure [2] to DIN EN 2563	ILSS (MPa)	85.0	1.9	5
ILSS after LH2 exposure [2] to DIN EN 2563	ILSS (MPa)	84.2	2.0	5

Key: [1] indicates tests by INTA and [2] by ARC Seibersdorf.

6.38.3.5 Hydrogen permeability

Tests performed by ARC Seibersdorf measured the hydrogen permeability on circular, 954-2/IM7 laminate specimens (1372 mm2) at room temperature under two pressures. The results were:

- Mean permeation rates:
  - 1.56 x 10-9 mbar 1/cm2 s at 1 bar GH2 (gaseous hydrogen).
  - 3.28 x 10-9 mbar 1/cm2 s at 2 bar GH2 (gaseous hydrogen).
- GH2 permeability: 3.59 x 10-9 mbar 1 mm/cm2 s bar (i.e. 3.59 x 1014 m2/s).

This indicates low permeability behaviour.

6.38.3.6 Reactivity with oxygen

The results of testing at BAM indicate 954-2A/IM7 can be safely used below 60°C and 20 bar oxygen pressure:

- Ignition temperature: 152±4 °C.
- Artificial ageing (200 bar/ 100°C / 100 hours):
- No change in ignition temperature.
  - 0.2% mass gain.
- Ignition sensitivity to gaseous oxygen pressure pulses:
  - None for 60°C/20 bar.
- Reactivity with LOX on mechanical impact:
  - Reaction beyond 375 Nm impact energy.

6.38.3.7 Cryogenic testing

The results of testing of 954-2/IM7 unidirectional laminates at a very low temperature of 20K (-253°C) are shown in Table 6.38-15, Ref. [6-76].

Table 6.38-15 - Properties of 954-2/IM7 laminates at 20 K

954-2/IM7 UD laminate : $(0°)_{16}$				
Test environment: 20 K				
V_f = 60%		$\bar{x}$	SD	N
ILSS to prEN 2563	(MPa)	135	4.8	10
Compressive strength to prEN 2850	(MPa)	1031	63	5

Testing at 20K indicates that the:

- ILSS increased by 60% at 20K compared with RT values.
- Compression strength reduced by 10%.
- Tensile strength is reduced slightly, but modulus is maintained.
- In-plane shear strength improves slightly.

6.38.3.8 Test data for panel performance predictions

S.A.B.C.A Limburg N.V. produced the data in Table 6.38-16 to support buckling prediction techniques for shells under mechanical and thermal load, Ref. [6-84].

Table 6.38-16 - Fiberite 954-2/IM7: Unidirectional composite data at differing temperatures

Test	**Temperature (°C)**	**Property**	**Value**
0° Tension	RT	Strength (MPa) Modulus (GPa) Poisson's Ratio	2544 156 0.34
	70	Strength (MPa) Modulus (GPa) Poisson's Ratio	2605 157 0.31
	150	Strength (MPa) Modulus (GPa) Poisson's Ratio	1916 166 0.30
90° Tension	RT	Strength (MPa) Modulus (GPa) Poisson's Ratio	48 9.2 0.023
	150	Strength (MPa) Modulus (GPa) Poisson's Ratio	43 7.4 0.010
0° Compression	RT	Strength (MPa) Modulus (GPa) Poisson's Ratio	660 155 0.34
	150	Strength (MPa) Modulus (GPa) Poisson's Ratio	481 160 0.29
90° Compression	RT	Strength (MPa) Modulus (GPa) Poisson's Ratio	203 9.0 0.015
Fibre Volume Fraction = 62%. Tensile testing by ASTM D-3039 and compression by D-695.			

6.38.4 954-2A/M55J

Table 6.38-17 shows the measured effect of thermal cycling on the residual tensile properties of a quasi-isotropic laminates, Ref. [6-85].

The as-manufactured laminates had localised microcracks in the outer 0° plies. Both of the thermal cycling regimes induced these microcracks to grow in length.

Table 6.38-17 - Properties of 954-2/M55J laminates before and after thermal cycling

954-2/M55J :Eight ply 0°/+45°/90°/±45°/90°/-45°/0° laminate				
Specimen condition: Standard cure cycle. Dry state.				
Test environment: 22°C				
Tested to DIN EN 2561		$\bar{x}$	SD	N
Longitudinal tension	Strength (MPa)	577	12	4
	Modulus (GPa)	134	44	4
As manufactured	Strain (%)	0.47	0.05	4
	Poisson's Ratio	0.35	0.03	4
Longitudinal tension	Strength (MPa)	612	28	4
	Modulus (GPa)	140	17	4
Thermal cycle state I	Strain (%)	0.52	0.03	4
	Poisson's Ratio	0.34	0.02	4
Longitudinal tension	Strength (MPa)	622	20	4
	Modulus (GPa)	153	11	4
Thermal cycle state II	Strain (%)	0.48	0.08	4
	Poisson's Ratio	0.37	0.04	4

Key: State I equates to 100 cycles from -50°C to +100°C and State II to the same but with an additional 100 cycles from -55°C to +100°C.

6.38.5 954-2/P-100X HTS

P-100X HTS is an enhanced version of the Amoco P-100S pitch-based fibre, with UTS in the range 3100MPa to 3750MPa and tensile modulus of 724GPa to 793GPa.

The characterisation of this fibre combined with Fiberite 954-2A is shown in Table 6.38-18, Ref. [6-86].

Table 6.38-18 - 954-2/P-100X HTS: Unidirectional and multidirectional composite data

Supplier/Tradename: Fiberite	Fibre/Resin System: Amoco P-100X HTS 954-2A		Data Source: University of Dayton, Ohio	
Fibre volume (%): 57	t_{ply} (mm): 0.070		Density (kg m^{-3}): -	
Areal weight of prepreg (g m^{-2}): 84			Number of batches tested: 1	
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1995	
Specimen condition: Standard cure cycle. Dry state.				
Test environment: 21°C				
		$\bar{x}$	C V	N
UD tension $(0°)_{16}$ to SACMA	Strength (MPa)	1806	6.1%	5
	Modulus (GPa)	414	6.3%	5
UD tension $(90°)_{14}$ to SACMA	Strength (MPa)	17.0	15%	5
	Modulus (GPa)	5.52	2.0%	5
MD longitudinal tension $[(0°+45°90°-45°)_S]_2$	Strength (MPa)	550	8.6%	5
	Modulus (GPa)	135	3.5%	5
UD compression $(0°)_{32}$ to ASTM D 3410 [IITRI]	Strength (MPa)	320	15%	5
	Modulus (GPa)	349	8.2%	5
UD compression $(90°)_{44}$ to ASTM D 3410 [IITRI]	Strength (MPa)	124	6.6%	5
	Modulus (GPa)	5.58	4.4%	5
In-plane shear $(\pm45°)_8$ to SACMA	Strength (MPa)	69	3.0%	5
	Modulus (GPa)	4.21	10%	5
UD interlaminar shear $(0°)_{30}$ to SACMA	Strength (MPa)	42.7	9.2%	5

Key: UD: Unidirectional
MD: Multidirectional
C V: Coefficient of Variation

The improved fibre enhances handleability and processibility for the prepreg.

For 0° laminates, the fracture toughness values obtained at 21°C are:

- Mode I = 236 Jm-2 (±20%).
- Mode II = 327 Jm-2 (±13%).

6.38.6 954-6/M40J

This low-temperature curing cyanate ester system is a recent addition to the Fiberite range. It has a Tg of 150°C.

Table 6.38-19 shows the properties of UD laminates.

Table 6.38-19 - Properties of unidirectional 954-6/M40J laminates

Supplier/Tradename: Fiberite	Fibre/Resin System: Toray M40J 954-6		Data Source: Fiberite
Fibre volume (%): 62	t_{ply} (mm): -		Density (kg m^{-3}): -
Areal weight of prepreg (g m^{-2}): -			Number of batches tested: 1
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1996
Specimen condition: Cure cycle of 121°C for 3 hours. Dry state.			
Test environment: 21°C			

		$\bar{x}$	SD	N
UD 0° tension	Strength (MPa)	2356	-	-
	Modulus (GPa)	196	-	-
UD 90° tension	Strength (MPa)	71.7	-	-
	Modulus (GPa)	7.52	-	-
UD 0° compression	Strength (MPa)	1206	-	-
	Modulus (GPa)	222	-	-
UD 0° interlaminar shear	Strength (MPa)	98.4	-	-

6.38.7 M22/K135

Table 6.38-20 shows the property results from initial tests by Aerospatiale on M22/K135.

Table 6.38-20 - Properties from initial tests on M22/K135 laminates

M22/K135 UD laminate				
Test environment: 23 °C				
60% V_f		$\bar{x}$	SD	N
0° Longitudinal tension	Strength (MPa)	1900	-	-
	Modulus (GPa)	370	-	-
0° Longitudinal compression	Strength (MPa)	380	-	-
	Modulus (GPa)	286	-	-
0° ILSS	(MPa)	73	-	-

M22 does not use the same base resin as 954-3 and RS3. Observations on M22 behaviour include:

- M22 has good tack characteristics for prepreg lay-up.
- Curing of M22 at 180°C for 2 hours achieves 100% cross-linking conversion.
- At 25°C and 50% RH, M22/K135-2U laminates (2mm thick) absorb 0.08% water at equilibrium.

6.38.8 CME Behaviour

6.38.8.1 General

The lower moisture absorption of cyanate esters compared with epoxies is attractive for dimensionally stable structures as it reduces physical expansion due to moisture uptake.

Data correlating absorbed moisture with physical expansion, i.e. CME, coefficient of moisture expansion, is given in Table 6.38-21. Moisture strains are given for material systems in Table 6.38-22. The major contribution is from a CASA study, Ref. [6-87].

Table 6.38-21 - CME data for UHM CFRP composites

Laminate Configuration	m_{sat} (%)	CME (µm/m/%)	Coefficient of Variation on CME (%)
954-3/M55J			
0°	0.17 (60°C/60%RH)	29.0 [1]	8.4
90°	0.18 (60°C/60%RH)	1998 [1]	3.0
$[0°,\pm60°]_s$	0.19 (60°C/60%RH)	64.6 [1]	6.8
954-3/K135			
90°	~0.18 (25°C/50%RH)	2800 [2]	-
M22/M55J			
0°	0.15 (60°C/60%RH)	47.5 [1]	9.2
90°	0.17 (60°C/60%RH)	1942 [1]	1.9
$[0°,\pm60°]_s$	0.19 (60°C/60%RH)	123 [1]	4.0
M22/K135			
90°	0.08 (25°C/50%RH)	1600 [2]	-
RS3/XN50A			
0°	0.29 (60°C/60%RH)	40.4 [1]	26
90°	0.26 (60°C/60%RH)	1570 [1]	13
$[0°,\pm60°]_s$	0.30 (60°C/60%RH)	85.3 [1]	16
996/M55J *			
0°	0.15 (60°C/60%RH)	80.4 [1]	30
90°	0.14 (60°C/60%RH)	1585 [1]	10
$[0°,\pm60°]_s$	0.15 (60°C/60%RH)	97.7 [1]	21
950-1/M55J**			
0°	0.97^+ (60°C/60%RH)	30.8 [1]	19
90°	0.95^+ (60°C/60%RH)	3866 [1]	8
$[0°,\pm60°]_s$	0.94^+ (60°C/60%RH)	90.4 [1]	17

Key: m_{sat} (%) = equilibrium saturated moisture absorption at defined conditions.

CME calculated from increase in specimen length at saturation.

* indicates cyanate siloxane system.

** indicates epoxy system, $^+$ not saturated.

[1] data from CASA, Ref. [6-87]; [2] from Aerospatiale.

Table 6.38-22 - Moisture strains for 90° and quasi-isotropic UHM CFRP laminates for absorption at 70°C to 60°C / 60% R.H

Material	Moisture Strain (μm/m)	
	90°	$(0°\pm60°)_S$
Fiberite 954-3/M55J	360	12.3
Hexcel-Brochier M22/M55J	330	23.4
YLA RS3/XN50	408	25.6
Fiberite 996/M55J	222	14.7
Cytec 950-1/M55J (not saturated)	3673	85.0

Some comments with respect to the data in Table 6.38-21 and Table 6.38-22 include:

- CME values should be viewed with caution.
- The relationship between moisture absorbed and moisture strain is material dependent.
- The affect of moisture absorption and moisture strain on the dimensional stability of hardware depends on:
  - — laminate construction,
  - — laminate processing conditions,
  - — prelaunch storage conditions.

6.38.8.2 Retention of absorbed moisture

The absorption and desorption of moisture by epoxy laminates is a reversible process. This is not necessarily true for some cyanate esters. It has been observed that under certain conditions, these cyanate esters retain moisture when subsequently dried, i.e. rather than a physical effect, moisture is retained by chemical bonding. This has been observed in 954-3 and RS3 laminates. It is attributed to incomplete cross-linking and the type of catalyst used in the resin formulation. The temperature and relative humidity at which moisture is absorbed is important. Chemically-retained moisture does not desorb under orbiting conditions.

Laminates are pre-dried before the moisture absorption and moisture expansion CME's are measured. Moisture uptake is typically measured at 20°C to 70°C, under varying humidity, to establish a saturated condition. The corresponding changes in dimensions enable a CME value to be determined. The validity of the value quoted depends on whether or not chemically retained moisture is present.

6.38.9 Low temperature moulding (LTM) systems

6.38.9.1 XLTM 123

Table 6.38-23 gives some typical properties of ACG development cyanate ester system XLTM 123 (EF20098 resin/M55J UHM carbon fibre). This material was the most promising of several formulations examined for potential use in high stability structures, Ref. [6-90].

The main study objectives were to develop a prepreg with, Ref. [6-90]:

- A low temperature cure and post cure to reduce residual stress in laminates.
- A Tg (dry laminate) of about 130°C for an anticipated service temperature of 90°C.
- Processing by both autoclave and oven bagging moulding. (continued)

- Very low moisture absorbency at 60°C and 50% RH. With a CFRP laminate not exceeding 0.2% saturation after 90 days, typically.
- Resistance to microcracking within cross-ply laminates.

Both 0°/90° and 90° laminates were manufactured with 145g/m2 unidirectional prepreg and a nominal 60% fibre volume fraction. The laminate configurations are typical of those used as sandwich panel face skins in high stability antennas and reflectors, Ref. [6-88].

Table 6.38-23 - Low temperature moulding Cyanate ester systems: Typical properties of XLTM 123 (EF20098 resin/M55J UHM carbon fibre)

Supplier/Tradename: **ACG/ XLTM 123**	**Fibre/Resin System:** **EF20098 resin/M55J UHM carbon fibre**	**Data Source:** **Ref. [88, 89, 90]**
Fibre volume (%): 60†	t_{ply} (mm): -	Density (kg m^{-3}): -
Areal weight of fibre (g m^{-2}): 145	Volatile content (%): -	Year of test: 1999
Voidage (%): 4 ply 0°/90° (vac. bag) <0.02 8 ply 0°/90° (vac. bag) <0.8	Tg (°C): 140	Test environment: -
Specimen condition:	70°C / 16 hrs initial cure + 120°C / 3 hrs postcure.	
Typical mechanical properties:		
0°/90° Tension	Strength (MPa)	>760.1
0°/90° Compression	Strength (MPa)	379.5
0°/90° Interlaminar shear	Strength (MPa)	36.3
±45° In-plane shear	Strength (MPa)	55.9
0° Transverse flexural (90° direction)	Strength (MPa) Modulus (GPa) Strain (%)	37.4 7.2 0.52
Typical environmental properties:		
0°/90° Laminate shrinkage. Postcure 125°C.	Shrinkage (%)	0.0125
0°/90° Absorbed moisture: exposure 83 days/60°C/50%RH	Absorbed moisture (%) - initial cure only - cure + postcure	 0.15 0.11
Saturated moisture content: 60°C/60%RH	Saturated moisture content (%)	0.22
Typical environmental properties:		
0° Coefficient of thermal expansion (90° direction). Postcure 120°C/4hrs	CTE ($°C^{-1}$)	40.6
0°/90° Coefficient of thermal expansion. Postcure 120°C/4hrs	CTE ($°C^{-1}$)	0.2
0° Coefficient of moisture expansion (0° direction).	CME ($x10^{-6}$/%)	28
0° Coefficient of moisture expansion (90° direction).	CME ($x10^{-6}$/%)	2978
0° ±60° Coefficient of moisture expansion.	CME ($x10^{-6}$/%)	97
Key: † : All properties normalised to 60% fibre volume fraction, except ILSS.		

6.39 Cyanate siloxane composites

6.39.1 General

Siloxane chemistry has been introduced into polymer composites to modify their physical behaviour. For space programmes, moisture absorption by thermosetting resins is strictly controlled and minimised where possible. The combination of cyanate ester and siloxane chemistry is intended to reduce moisture absorption to very low levels.

For operation in low Earth orbit (LEO), the presence of atomic oxygen erodes hydrocarbon-based resins. The introduction of silicon-containing resins can help to reduce erosion by the formation of a protective silicon dioxide surface layer, [See: 20.14].

6.39.2 Fiberite 996

This resin system is intended for dimensionally stable structures needing very low moisture absorption characteristics. The features indicated by Fiberite include:

- Moisture absorption by 996 neat resin:
  - 0.20% weight gain at RT and 50% RH. Compared with 0.40% for 954-3 resin.
  - At 70°C and 95% R.H. moisture absorption for 996 increases to 0.90% and 954-3 to 1.3%.
- Resin Tg is 169°C.
- Autoclave cure of 2 hours at 177°C.
- Minimum viscosity of 130 cp, compared with 50 cp for 954-3 and 1500 cp for 954-2A.
- The thermal cycling of 996/M55J and 954-3/M55J quasi-isotropic laminates, (±45°0°90°)4S, from -157°C to +121°C for 100 cycles gave the same microcrack density. This was 0.5 cracks/cm in the 90° plies.
- CME data for 996/M55J, [See: Table 6.38-21 and Table 6.38-22].

The mechanical properties of unidirectional UD 966/M55J are given in Table 6.39-1.

Table 6.39-1 - 966/M55J: Unidirectional composite data

Supplier/Tradename: Fiberite HyE 3496J	Fibre/Resin System: Toray M55J Fiberite 996		Data Source: Fiberite	
Fibre volume (%): 62	t_{ply} (mm): -		Density (kg m^{-3}): -	
Areal weight of prepreg (g m^{-2}): -			Number of batches tested: 3	
Areal weight of fibre (g m^{-2}): -	Volatile content (%): -		Year of test: 1995/6	
Specimen condition: Standard cure cycle, 177°C for 2 hours. Dry state.				
Test environment: RT				
		$\bar{x}$	SD	N
UD tension 0° to ASTM 3039	Strength (MPa) Modulus (GPa)	2080 320	140 8.3	18 18
UD tension 90° to ASTM 3039	Strength (MPa) Modulus (GPa)	37.2 4.1	5.79 0.5	18 18
UD compression 0° to SACMA SRM-1R94	Strength (MPa) Modulus (GPa)	896 312	38.6 22.9	18 18
In-plane shear ±45° to SACMA SRM-7R94	Strength (MPa) Modulus (GPa)	75.1 4.27	- -	- -
UD interlaminar shear 0° to ASTM 2344	Strength (MPa)	67.6	4.8	18

6.40 Z-pinning

6.40.1 Introduction

Laminated composite materials have low through-thickness strength because there is no fibre reinforcement in this direction. Hence, emphasis has been placed on the understanding and prevention of interlaminar delamination. A new technology for through-thickness reinforcement using Z-pins has been developed that helps provided fibre-reinforcement in this direction. The technique has attracted considerable attention for applications where delaminations cannot be tolerated, Ref. [6-93],[6-94],[6-95] and [6-96]. Z-pinning is an alternative to the through stitching of composites in the z-direction where the laminates are sewn together prior to curing, Ref. [6-97]. Other forms of z-direction reinforcement that have been considered include metal stapling of the prepreg and one-sided stitching ('tufting').

The Z-pins, (trade name Z-Fibers®), are inserted orthogonally to the plane of the prepreg plies during the manufacturing process, before the resin matrix is cured. They are small diameter continuous rods which need to be sufficiently strong to resist the insertion process into the laminate. The materials which have been investigated for use as Z-pins include:

- SiC/BMI,
- T650/BMI,
- T300/Epoxy,
- T300/BMI,
- P100/Epoxy,
- S-Glass/Epoxy,
- Titanium,
- Stainless steel,
- Aluminium.

The pin diameters range from 0.15 mm to 1 mm and are driven through the uncured laminate in a two-stage process. This involves the use of a specialised ultrasonic insertion gun and a sequential removal of the collapsible foam sandwich in which the Z-pins are held prior to insertion. The procedure has been applied successfully to unidirectional tape or fabric prepreg-based laminates, but is applicable to other forms of reinforcement and processes.

The cured products exhibit high delamination resistance, Ref. [6-95] and [6-96], increased compression-after-impact resistance Ref. [6-98] and [6-99] and increased resistance to delamination fatigue crack growth, Ref. [6-100], compared with non-Z-pinned control specimens. However, as with other forms of z-reinforcement, the Z-pins do reduce some of the in-plane properties, specifically, the tensile and compression strengths of the laminates. The magnitude of the reduction is dependent on the lay-up of the laminate and the areal density of the pinning, Ref. [6-101].

6.40.2 Manufacturing process

6.40.2.1 Z-pin performs

The more common Z-pins are 1k tows of carbon fibre, impregnated in a bath of liquid BMI bismaleimide resin. The impregnated tows are pultruded into continuous rods, in a range of diameters between 0.15mm and 1mm. BMI resin is used because its high glass transition temperature ensures sufficient rigidity of the Z-pins during the subsequent manufacturing operations. The blocks of Z-pins, contained in double-layer foam, are known commercially as the 'preform'. The preform is manufactured by a patented process, developed from an original concept at Foster–Miller (USA). The pultruded rods are cut to the appropriate perform length and inserted into the double layer foam; as shown in Figure 6.40-1. The cutting device leaves an acute angle at the ends of the pins which assists pin penetration and minimises fibre breakage in the parent laminate during insertion.

Figure 6.40-1 - Z-Fiber® preforms containing 0.28mm diameter pins at densities of 0.5%, 2% and 4%

The top layer is a low-density foam (typically polystyrene) whereas the bottom layer is a medium density closed-pore type (base foam). These support foams hold the pins in position prior to use. It is designed to collapse under pressure. The base foam prevents the pins buckling during their insertion into the laminate. The preform is characterised by the material of the Z-pins and by the ratio between the combined cross-sectional area of the Z-pins and the total cross-sectional area of the preform (areal density). The areal density usually ranges from 0.5% to 10%.

6.40.2.2 Z-pin insertion

To insert the pins into the prepreg, the preform is positioned on top of the uncured laminate area that is being reinforced. A layer of Teflon® coated glass fabric is placed between the laminate and the perform to protect the laminate from contamination and damage.

Originally, the heat and pressure of the autoclave cycle was used to insert the pins. The disadvantage with this method is the low available pressure limiting the process to very low density pins. While large areas of pins can be inserted in one autoclave run, the panels needed significant post-process cleaning to remove the discarded foam.

The use of ultrasonic vibration to assist pin insertion has advantages over the autoclave method. An ultrasonic hammer, vibrating at 20kHz, has heads (or horns) of different shapes and sizes depending on the application. These units can be hand-held or fully-automated robotic insertion machines with the preforms fed into a cartridge in 25mm × 25mm blocks. The insertion process is shown in Figure

6.40-2. Ultrasonic vibration is modulated by a series of boosters and the insertion pressure and speed are controllable.

After insertion, the compacted foam is removed and at the same time the excess pin length is shear cut, flush with the surface of the laminate.

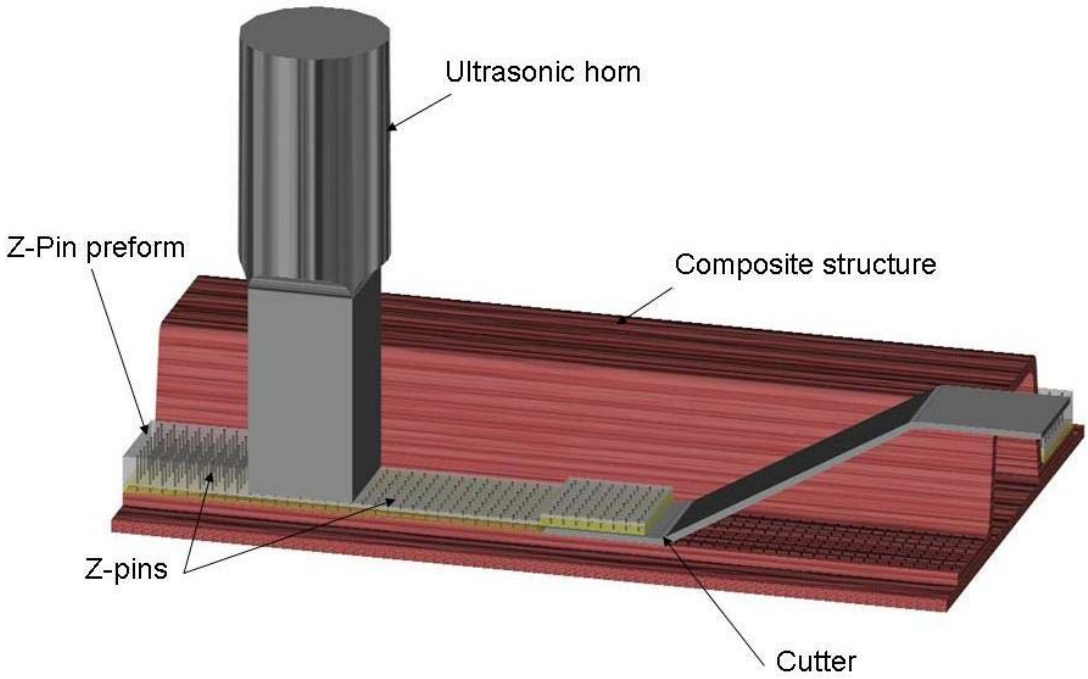


Figure 6.40-2 - Z-Fiber® insertion: Schematic of ultrasonic hammer

6.40.3 Testing

6.40.3.1 General

Little experimental work has been done to quantify the in-plane properties. Most of the experimental work has focused on the delamination characteristics. The reduction in the longitudinal modulus is considered to be approximately 10%. Compression strength can be affected most because the Z-pins can cause local misalignment of the laminate fibres. The compression knockdown was approximately 30 %, Ref [6-102].

6.40.3.2 Mode I delamination characterisation

A DCM 'double cantilever beam' specimen is used for Mode I delamination, [See also: 7.18]. The Z-pins serve to bridge delaminations giving a significant improvement in delamination resistance. The micro-mechanisms of the bridging by Z-pins have been characterised by single pin pullout experiments. Modelling the behaviour of simple structures such as double cantilever beam has proved to be successful, Ref. [6-103].

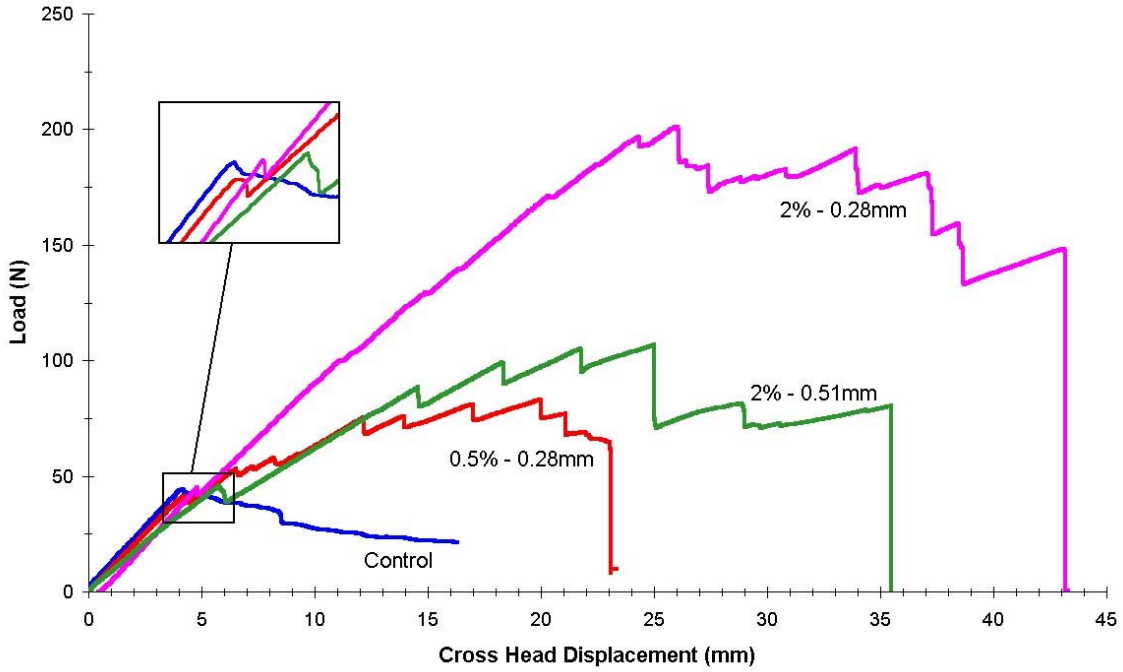


Figure 6.40-3 – Z-pins: DCB load-displacement curve for pinned samples and control

A comparison of load-displacement traces for Mode I tests of pinned and control samples is shown in Figure 6.40-3. The load at delamination initiation is unaffected by the presence of the Z-pins 5mm ahead of the crack tip. However, the propagating delamination encounters the discrete rows of Z-pins and the fracture load increases significantly in comparison with the control samples.

The tests show that the presence of the Z-pins has no effect on the ability of the laminate to resist Mode I delamination initiation but resistance to propagation can be more than doubled with only 0.5% areal density of Z-pins. The load-carrying capability of the specimens is improved up to four times by using Z-pins at 2% areal density. Increasing the areal density gives increased resistance to delamination propagation but can progressively compromise other in-plane properties.

6.40.3.3 Mode II delamination characterisation

Mode II testing of Z-pinned laminates is generally characterised using 3-point End Notched Flexure (ENF) or 4-point ENF (4ENF), [See also: 7.18]. Again significant improvement in delamination propagation resistance occurs; as shown in Figure 6.40-4, Ref. [6-104].

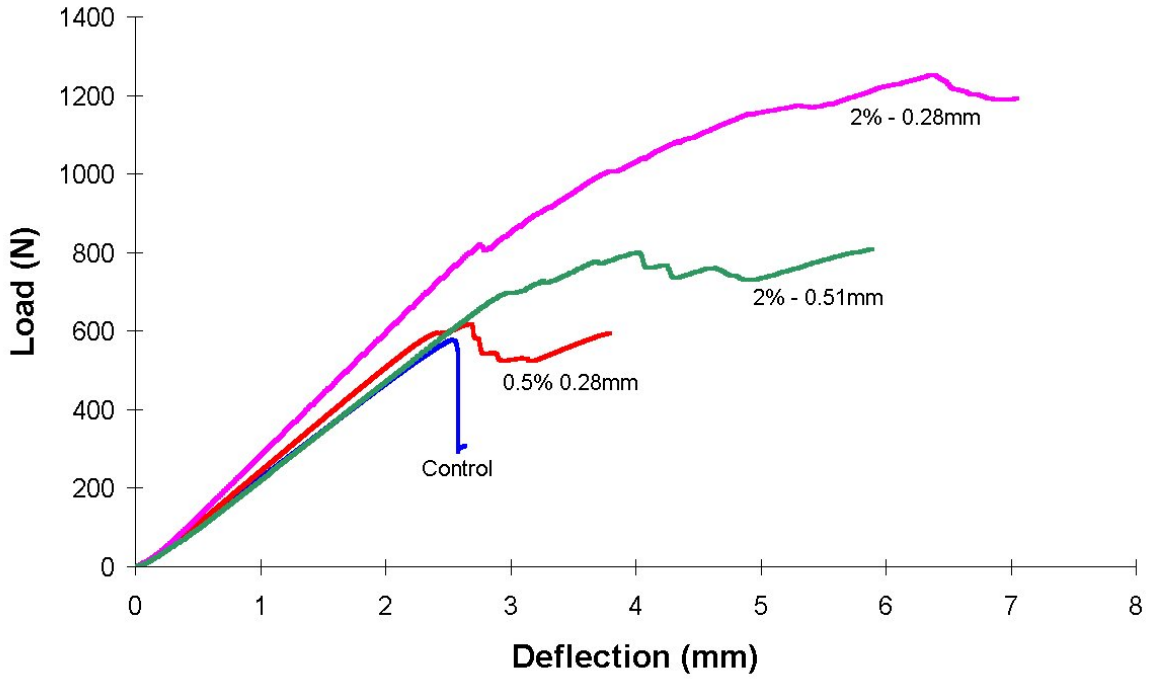


Figure 6.40-4 – Z-pins: Load-deflection curves from Mode II 3-point ENF on pinned samples and control

The presence of the z-direction reinforcement raises some questions about the validity of the normal beam-theory based data-reduction schemes used in these delamination tests. The pinned region gives rise to a large scale bridging effect violating the beam theory used. Therefore, the exact values of strain-energy release calculated using these methods cannot be used for design. It can, however, be used for a qualitative comparison between pinned- and non-Z-pinned laminates in order to demonstrate the increased resistance to delamination propagation.

6.41 Triaxial woven fabric composites

6.41.1 Materials

TWFs have numerous applications in various industry sectors, e.g. filters, technical textiles, geotextiles and clothing. The basic characteristics of fabrics vary widely, e.g. materials, yarn dimensions, weave styles and density, [See also: 2.6].

For structural applications, TWFs tend to comprise continuous strips of UD composite material, usually carbon fibre, interlaced in three directions (usually 0° and $\pm$60°, impregnated with thermosetting resin and then cured like a conventional composite. [See: 9.17 - TWF evaluation study]

6.41.2 Basic characteristics

6.41.2.1 General

Macroscopically, TWF has quasi-isotropic mechanical properties; hence it can be used to construct single-ply structural elements with very low areal mass.

[See: 30.13 – Case study for ULR ultra lightweight antenna reflector]

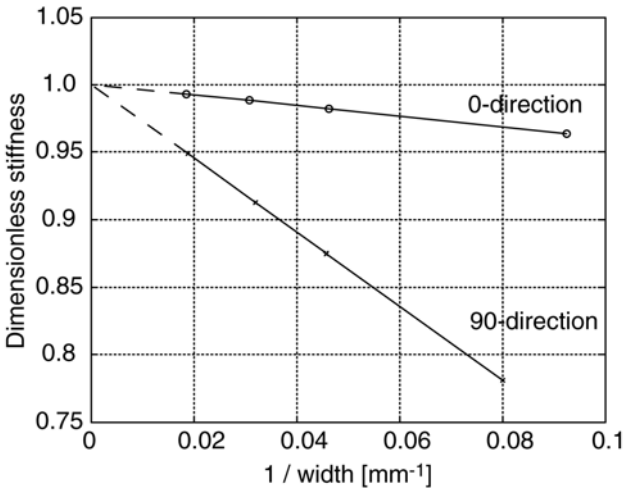
6.41.2.2 Effect of weave

The behaviour of single-ply TWF is more complex than standard laminated composites because the weave produces a significant through-the-thickness contribution in the stress and strain response.

6.41.2.3 Comparison with conventional single ply composite

Differences between the behaviour of single-ply TWF composites and standard composites include:

- Three-dimensional behaviour, with coupling between in-plane and out-of-plane effects. Hence modelling TWF as a continuum gives poor results Ref. [6-1].
- Geometrically non-linear variation of in-plane stiffnesses, at higher strains the TWF becomes stiffer due to straightening of the woven tows.
- Variation in Poisson's ratio.
- Free edge effects, giving reduced in-plane stiffness for strips of material that are not aligned with one of the tows; summarised in Figure 6.41-1. Such effects need consideration with respect to both modelling techniques and the experimental verification of the numerical models. Ref. [6-2], [6-3], [6-4].
- Thermally-induced twist.



Ratio between in-plane axial stiffness of finite-size and infinite TWF specimens

Figure 6.41-1 TWF characteristics: Summary of edge effects

6.41.3 Analytical approach

6.41.3.1 General

To fully characterise TWF, some key features of the 3-dimensional microstructure need to be considered. But, as a fully-detailed analysis is impractical in engineering applications, it can be shown that good predictions of stiffness can be obtained using a suitably defined, 2-dimensional, homogenised, continuum.

[See: 9.17- TWF evaluation study]

6.41.3.2 Stiffness

The measurement and analytical prediction of stiffness can be summarised as:

- At the macroscopic scale, TWF is modelled by a homogenized continuum whose constitutive relationship is represented by a 6 × 6 ABD stiffness matrix. This matrix relates suitably defined in-plane and out-of-plane mean strains and curvatures to corresponding force and moment stress resultants per unit length.
- Neglecting the geometric non-linearities mentioned above, the ABD matrix is constant.
- Free edge effects are neglected, and hence it is assumed that the behaviour of TWF is translationally symmetric in two perpendicular directions. Hence it is sufficient to analyse the deformation of a unit cell subject to periodic boundary conditions.
- The full ABD stiffness matrix is derived from a finite-element analysis of a representative unit cell. Here each tow is modelled as a three-dimensional beam, whose geometry is obtained from direct measurement of the tows and whose material properties are based on the elastic properties of the fibres and matrix and their volume fractions.
- The ABD matrix can be used to model the material for structural analysis, leading to estimates of the generalized stresses and strains in the structure which can be compared with experimentally obtained failure parameters.
- Experimental validation of a subset of the coefficients of the ABD matrix obtained from a finite-element analysis, against directly measured stiffness parameters.

6.41.3.3 Failure parameters

The measurement and analytical prediction of failure parameters includes:

- Maximum force per unit width, under in-plane compression.
- Maximum force per unit width, under in-plane tension.
- Maximum shear force per unit width.
- Maximum bending moment per unit width and maximum curvature.

6.41.3.4 Thermo-mechanical behaviour

The measurement and analytical prediction of thermo-mechanical behaviour include:

- Linear coefficient of thermal expansion.
- Coefficient of thermal twist.

[See also: 2.6; 9.17 – evaluation study; 30.13 – case study]

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6.42.2 Sources

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6.42.3 ECSS documents

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ECSS-Q-ST-70-02	Thermal vacuum outgassing test for the screening of space materials; previously ESA PSS 01-702
ECSS-Q-ST-70-29	Determination of offgassing products from materials and assembled articles to be used in a manned space vehicle crew compartment; previously ESA PSS-01-729

7
Test methods and standards

7.1 Introduction

7.1.1 General

As composites have developed, a better understanding of their fracture characteristics has been gained. This has led in turn to an evolution in mechanical test methods. It is also reflected in the wide range of standards and test methods available to characterise composites for design data or for quality control. Test methods aim to enable measurement of the fundamental properties of the composite as a whole, rather than the properties defined by the use of individual specimen geometry. Problems stem from the anisotropic characteristics of composites and uncertainties in failure criteria. This gives a large number of test methods from which to select appropriate ones to produce accurate and consistent results.

The various appropriate standard test methods are described along with comments on their use. A comprehensive list of standards and test methods for the mechanical and physical assessment of composites is provided for reference.

Most mechanical test methods assess composites in flat laminate form, typically from moulded prepregs. Test methods are also available which use filament wound cylinders, Ref. [7-1], textile-based composites, Ref. [7-2] and sandwich panel specimens, which can be appropriate in some circumstances.

7.1.2 International standards

Standards relating to composite testing are numerous and at various stages of evolution, Ref. [7-63]. Harmonisation of standards is the ultimate objective in obtaining global acceptance of international standards under the ISO series. National, European and American standards bodies are endeavouring to seek agreement on wording ISO standards to be acceptable for international trade purposes. It is generally viewed that good agreement exists on the basic philosophy behind test methods within the present standards and that any differences are generally not technically justifiable, Ref. [7-63].

7.1.3 Engineering and design data for composites

From an engineering perspective, there are valid arguments, in some instances, for modifying mechanical test procedures to ensure that the results are representative of a specific grade of composite and the intended application. With respect to space structures, it has been established that high modulus CFRP materials behave differently compared with high strength CFRP. Therefore testing can be tailored to those conditions specified in international standards. Test methods should be reviewed regulary to give confidence in their reproducibility and provide design data that can verify

and produce consistently efficient structures. Also, testing of composites used in thin-skin sandwich constructions needs careful consideration based on the structures application and environment.

7.1.4 Failure criteria in fibre-reinforced-polymer composites

The anisotropic nature of composites makes predicting their strength extremely difficult, especially when compared with metals. A 12-year WWFE 'worldwide failure exercise' study involved evaluation of 19 theories and their application in several examples. The accuracy of predictions and the performance of the theories were assessed and advice provided on their use in engineering design. The overall approach used in the WWFE can also be applied to 'benchmark' any new theories, Ref. [7-65].

An ESA-funded study provided detailed guidelines for the proper use of failure criteria during the different stages of design of spacecraft composite structures, both for fibre-reinforced polymer composites and ceramic-based materials, Ref. [7-66].

7.2 Test method selection

7.2.1 Introduction

Many organisations involved in testing of composites have historical allegiances to particular test methods. Often, their material databases are built up by consistently using the same method and retaining confidence in the results.

There is also considerable evidence to indicate that results from mechanical tests can be operator dependent, giving inconsistencies when results from differing organisations are compared, Ref. [7-3], [7-4].

Different organisations place different emphasis on the expectations of test methods. Their selection is influenced by several criteria, which can include:

- Comparing materials for selection,
- Generation of design data (UD unidirectional material),
- Quality control procedures,
- Damage tolerance investigations (MD multidirectional or quasi-isotropic laminates), and
- Collaborative data exchange.

7.2.2 Basic guidelines

The points to be considered when selecting mechanical test methods are:

- Is there demonstrable confidence in the method chosen for measuring modulus and strength values? Does it give reproducible results between sample batches?
- Is the test specimen configuration representative of the final composite product form? The main product forms are:
  - flat laminate,
  - sandwich constructions, and
  - filament wound lay-ups.

- Does the test method need to generate design data or fulfil quality control requirements? Cost is often a serious implication to consider, particularly where specimen preparation is concerned.
- Has the ultimate strength of unidirectional (UD) 0° laminates measured for design requirements been given close examination, particularly in compression?
- Are test data to be exchanged within a project? Then it is preferable for all contractors to be using the same test methods and fixtures.

7.2.3 Material specifications

In conjunction with established test methods, particular industries, and in some cases projects, can produce individual material specifications which define the material form and performance. The most obvious of these are for aircraft construction with collaborative arrangements between contractors, e.g. Airbus Industries. Test methods are included for generating material design data and meeting quality control requirements, Ref.[7-5].

7.3 Test method standards

7.3.1 General

The available test method standards are mainly International, American or European in origin.

To date, limited success has been reached with generating international ISO standards to assist with global acceptance of materials data. Traditionally, the aerospace industries have relied on national standards. In particular, ASTM standards offer very comprehensive coverage of test methods for aerospace composites. ASTM standards have been significantly revised in recent years and are accepted within the USA and partially by European companies.

The picture is more complex on a national and collective scale in Europe. Various harmonisation exercises are under way to move towards collective EN standards.

In some cases in-house methods developed over time by one company can become more broadly accepted as de-facto standards by other organisations facing similar problems.

[See also 7.20 for International; 7.21 for ASTM; 7.22 for European standards]

A differentiation can be made between standards for high-performance aerospace composites and those for engineering composites and plastics. Only those standards appropriate for aerospace materials are considered here; in particular those with carbon fibres.

7.3.2 International ISO standards

ISO standards applicable to high-performance composites are being prepared and, in some cases, finalised.

From a European perspective, national and CEN bodies are moving towards adopting ISO standards and relinquishing their previous standards; giving a common designation with a national prefix, e.g. BS EN ISO XXXX.

The generation of a full range of applicable ISO standards for all mechanical and physical tests will not happen for an appreciable period of time. CEN are actively involved in leading the preparation of some ISO standards. The main technical committee for generating standards for all plastics is ISO TC61:

- Sub-committee SC13 of TC61 covers 'composites' and 'reinforcement fibres'.
- European countries provide all but one of the ISO convenors on this sub-committee.

7.3.3 American ASTM standards

The ASTM standards on CFRP are produced by the D30 committee responsible for 'high modulus fibres and their composites', Ref. [7-6]. ASTM Standards are regularly updated and re-issued as agreement is reached on the most appropriate testing philosophies.

Recently amended test methods have become available in metric units and are suffixed by the letter M, e.g. ASTM D 3039M.

Detailed guidance is provided within each standard on specimen preparation, test techniques, acceptable failure modes and calculation methods.

7.3.4 European EN standards

There are presently a range of issued and draft European test method standards and material performance specifications (ENs and prENs) for aerospace composites. These are being drawn up by AECMA (Association Européenne des Constructeurs de Matériel Aérospatial) Committee C7/SC5 for testing high modulus composites in carbon, aramid and glass fibres.

Additional documentation has also been proposed by Airbus Industries to cover particular aspects of composite performance with respect to aircraft construction.

In addition to AECMA and Airbus Industries, a further forum for generating standards is:

- CEN TC249/SC2 – 'General standards for composites, reinforcements and prepregs', which:
  - collaborates with ISO (via Vienna Agreement) on standards for general engineering uses of composites.
  - principally concerned with material specification standards.
  - generally follow ISO for test methods and then to other existing European and national standards.

Full EN standards for glass fibre and general engineering composites started to become available from 1989.

As harmonisation of international standards proceeds, the EN standards are rationalised gradually. As of early 1997, AECMA, CEN and Airbus Industries all retain their portfolios of standards.

7.3.5 Airbus Industries

As a collaborative exercise within the Airbus consortium, a number of additional test method and material specifications have been drawn up to cover aspects of composite behaviour of relevance to aircraft construction. These include:

- Compression after impact (CAI),
- Bearing strength,
- Notch effects and interlaminar fracture toughness.

These are being tabled as potential EN standards.

7.3.6 German DIN standards

DIN standards are being updated and expanded to cover composites appropriate for aerospace use. They form part of a series related to aerospace applications and are written as 'Technical Specifications', or in some cases as 'Test Methods'. Aspects of these methods appear in the prENs.

Ultimately, all DIN standards will become equivalent to individual EN and ISO documents.

7.3.7 UK aerospace test method recommendations

Agreement was reached within the UK aerospace community (~1990) on a set of test methods introduced under the CRAG (Composite Research Advisory Group), Ref. [7-7], [7-8].

Aspects of these methods appear in the prENs and subsequently in the drafting of ISO standards.

Ultimately, BS standards will become equivalent to individual EN and ISO documents.

7.3.8 In-house test methods and specifications

Many companies and organisations, wherever they are, have their own 'In-House' test methods. These are derived either from standards already identified or from modifications thereof. They are prepared to provide solutions for generating design data and meeting quality control demands.

Test methods can be modified to accommodate specific construction materials and their associated manufacturing techniques. Individual organisations have confidence in their own material databases and methods of design. However, such practices can cause problems in that there can be a lack of confidence when materials data and results are exchanged between organisations having different test methods.

7.4 Sample and specimen preparation

Guidance is provided for the preparation of samples and specimens in some standards in order to assist in the acquisition of reproducible test results. These standards are:

- ISO 1268: a multi-part standard incorporating aspects of available prENs.
- ASTM D 5687/ D 5687M – 95.
- EN 2374, EN 2375, prEN 2565, (prEN 4177, preparation suspended)

Traditionally, the prENs have differentiated between glass and carbon fibre composites with individual standards.

ISO 1268 is now more appropriate as it includes prEN 2565 for CFRP test panels.

ASTM D 5687 covers the preparation of laminates from fibre reinforced organic matrix composite prepregs, either in UD tape or orthogonal weave patterns.

The standard guide provides a detailed eight-step preparation process covering:

- Lay-up,
- Laminate consolidation,
- Initial cutting,
- Tab bonding,
- Specimen machining,
- Application of coatings and treatments,
- Specimen conditioning,
- Strain gauging,
- Non-destructive examination: Guidance for checks ensuring acceptable laminate and specimen quality.

7.5 Tensile testing

7.5.1 Use of tensile tests

Tensile testing is an appropriate technique for providing:

- UTS ultimate tensile strength.
- Tensile modulus.
- Poisson's ratio.
- Ultimate tensile strain to failure.
- ‘A’ design allowables.
- ‘B’ design allowables.

It is applicable to:

- Material characterisation.
- Material procurement.
- Quality control in production.

7.5.2 Tensile test method standards

Table 7.5-1 lists test method standards appropriate for tensile testing of high-performance composites suitable for aerospace structures.

Table 7.5-1 - Tensile test method standards

Tension Test Method (Standard)	Comments
EN ISO/F-DIS 527-4: for MD laminates. **EN ISO/F-DIS 527-5**: for UD laminates.	Based on ISO 3268. Mainly harmonised with ASTM D 3039, but differences do exist Mainly harmonised with ASTM D 3039 (but differences do exist), prEN 2561, prEN 2597 and prEN 2747
ASTM D 3039/D 3039 M - 95: Suitable for all advanced resin matrix composites of laminar construction. Preferred method in majority of cases. **ASTM D 5450/D 5450 M - 93**: Suitable for high modulus composites.	Recommends specimen dimensions Recommends end tabs of E-glass UD composite Indicates tapered end tabs Indicates the use of strain gauges Provides codes for describing specimen failure Uses a hoop wound composite cylinder
EN 2561: Longitudinal tensile properties (0°) of unidirectional CFRP. **prEN 2597:** Transverse tensile properties (90°) of unidirectional CFRP.	Restricted to 0° and 90° properties of Unidirectional epoxy (thermosetting) CFRP Tab material the same as that under test
DIN 29971: Unidirectional epoxy CFRP. **DIN 65146, Part 2**: Woven fabric epoxy CFRP. **DIN 65453, Part 2**: Unidirectional bismaleimide CFRP. **DIN 65426, Part 2**: Fabric epoxy aramid composite. **DIN 65090**: E-glass fabric epoxy composite.	DIN standards are classified by materials rather than test method, i.e. by fibre and matrix type
UK CRAG Methods: **300**: 0° UD FRP. **301**: 90° UD FRP. **302**: Multi-directional FRP. **303**: Notched multi-directional FRP.	Applicable to all resin matrix continuous fibre composites, particularly carbon and aramid fibre epoxies GRP end tabs for moist/hot conditions Aluminium tabs suitable for dry conditions For design data, in this standard a failure is recorded when fault had occured in the central portion of the gauge

The most significant development is the new harmonised version of ISO 527, first issued as a discussion draft EN ISO/F-DIS 527 parts 4 and 5, for testing fibre-reinforced composites, Ref. [7-63].

These parts have inputs from ISO 3268, ASTM D 3039, JIS 7073, CRAG 300, EN 61 and EN aerospace ENs 2561, 2597 and 2747.

Except for ASTM D 5450, all the tests use flat, parallel-sided coupons, similar to those given in Table 7.5-2 (for ASTM D3039).

Table 7.5-2 - ASTM D3039/D 3039M: Tensile specimen geometry recommendations

A: Recommended specimen dimensions

Fibre Orientation	Recommended Specimen Width (mm)	Overall Length (mm)	Thickness (mm)
0° unidirectional	15.0	250	1.0
90° unidirectional	25.0	175	2.0
balanced and symmetric	25.0	250	2.5

B: Recommended tab dimensions

Fibre Orientation	Tab Length (mm)	Tab Thickness (mm)	Tab Bevel Angle (°)
0° unidirectional	56	1.5	7 or 90
90° unidirectional	25	1.5	90
balanced and symmetric	emery cloth	-	-

Tensile testing is not a particularly contentious issue, as the basic method is common worldwide, Ref. [7-9]. Good agreement between different testing organisations can be reached provided that certain issues are considered, including:

- Specimen failure occurs within the gauge length and not at the gripped ends.
- Bonded end tabs need to be used with unidirectional laminates (0° and 90°) to ensure the maximum strength is attained. A tough, high-strain variety of adhesive is used.
- Tab material is typically a glass fibre based laminate, e.g. 0°/90° aligned at 45° to the loading direction. Friction tabs, e.g. emery paper, can be used with multidirectional laminates.
- The adhesive does not soften or fail at the test temperatures so avoiding premature and unrepresentative specimen failure.
- If possible, tapered end tabs are used to reduce stress concentrations at the beginning of the gauge length.
- The quality of the specimen is representative of the final composite structure with respect to permissible defects, such as voidage, matrix cracking and delaminations. This requires some non-destructive inspection.
- Care should be taken when cutting specimens to avoid unnecessary damage to cut edges. Ideally cut edges are milled or ground to remove damaged material.
- A minimum of five specimens are tested from the same material batch.
- To generate design allowables, more than one material batch needs to be tested; giving a total of more than 10 results.

Good agreement on elastic modulus properties between different organisations occurs. These are defined by the earlier part of the load/strain profile. With the use of bonded strain gauges and automated data plotting, good reproducibility can be achieved.

Agreement between different organisations of the ultimate tensile strength, particularly of UD 0° laminates, can be hindered because:

- Very high strength composites with carbon fibres of >5500 MPa tensile strength, ~2% failure strain, do not always fail in the gauge length.
- Tab designs can influence localised stress concentrations which initiate failure.
- Gripping arrangements can influence ultimate failure modes.
- Specimen alignment can vary.

Recent agreement between ISO, CEN, EN aerospace and ASTM has standardised on a specimen width of 15mm. In addition, a glass-fibre fabric/epoxy, aligned at ±45° to the specimen axis, was chosen as the preferred tab material. Alternatives are permitted provided that it can be shown that the ultimate strength is at least equal to that obtained with the preferred tab material and there is no increase in scatter.

Table 7.5-3 highlights the remaining differences between the respective international standards on tensile testing, Ref. [7-63].

Table 7.5-3 - Remaining differences of tensile test methods retained in international standards

Parameter	Options	Standards
Modulus	strain based (EN ISO 0.05%-0.25% or ASTM 0.1%-0.3%)	ISO, EN General, ASTM, JIS, CRAG
	load limited (cf allowable strain design limits used)	EN Aerospace
Material Scope	all fibres covered by one standard	ISO, EN General, ASTM, JIS, CRAG
	fibre specific, several versions involved	EN Aerospace
Application Area	all	ISO, EN General, ASTM, JIS, CRAG
	aerospace only	EN Aerospace
Tab Angle	90°	ISO, EN General, JIS, CRAG EN Aerospace
	tapered (7 to 90°)	ASTM

7.5.3 Additional tensile related tests

7.5.3.1 General

In addition to characterising the basic laminate, parallel sided specimens can also be used for:

- Notched tensile strength: With a drilled hole in the centre of the gauge length.
- Assessing tensile fatigue performance, using either notched or un-notched. In fatigue, the cyclic frequency is controlled to avoid induced specimen heating. As a guide, matrix dependent coupons, e.g. ±45°, are cycled at 5Hz or less but for other coupons 10Hz is more appropriate.

Table 7.5-4 lists additional tensile test methods.

Table 7.5-4 - Additional tensile tests

Standard	Subject
ASTM D 3479 ASTM D 3552 ASTM D 5766	Tension-tension fatigue (based on D3039 method) Tensile test for metal matrix composites Open hole tension test
Airbus prEN 6035	Notched (open hole) and unnotched tensile test
CRAG 303	Notched tensile strength of MD laminates

7.5.3.2 Waisted coupons

Some exponents of composite testing propose waisted coupons to ensure that specimen failure occurs within the gauge length. However, mean strength values were found to be higher for thickness-waisted 0° samples than that actually achieved by the 0° plies within multidirectional coupons and corresponding components. In addition, the specimens are more expensive to prepare and for this reason are not appropriate for quality control purposes. It is usual to standardise on one specimen configuration for both approval of a material and undertaking quality control in composite component production.

7.5.3.3 Hoop wound cylinders

For filament wound composites, flat coupons are not the most appropriate form of test configuration. Wound cylinders can be tested to provide tensile, compressive and shear characteristics.

ASTM D 5450 provides a means of quantifying the transverse tensile properties of hoop wound (90°) cylinders; nominally 100mm diameter, 140mm long and 2mm wall thickness.

A common test specimen configuration employed is that as also used in ASTM D 5448 for in-plane shear and ASTM D 5449 for transverse compression.

The procedure used for the tensile test is:

- Two metallic end fixtures are bonded to each end of the cylinder.
- Three strain gauge rosettes (three directional, 0°/45°/90°) are bonded to the outer surface of each cylinder, 120° apart.
- Five specimens are axially loaded to failure.
- The results from the three gauges in each orientation are then averaged to provide values for:
  - transverse tensile strength,
  - strain to failure,
  - modulus, and
  - Poisson's ratio.

7.6 Compression testing

7.6.1 Use of compression tests

Compression testing provides:

- Ultimate compressive strength.
- Compressive modulus.
- Ultimate compressive strain to failure.
- Poisson's ratio.
- 'A' design allowables.
- 'B' design allowables.

It is applicable to:

- Material characterisation.
- Material procurement.
- Quality control in production (if necessary).

Table 7.6-1 indicates those standards which are available and cover compressive testing; also techniques developed to assess the compressive performance of composites.

As with tensile testing, there is a new ISO draft standard (EN ISO/DIS-2 14,126) for compression testing, Ref. [7-63]. This standard is based on ISO 8515, with inputs from EN 2850, ASTM D 3410, CRAG 400 and ASTM D695 (modified).

7.6.2 Evolution in compressive test methods

Compressive testing of laminates has proved a contentious issue since the advent of composites, Ref. [7-8],[7-10] to [7-19]. Various reviews and 'round robin' tests have been made that compare different methods, Ref [7-9], [7-20]. to [7-22], [7-62].

The aim has been to identify a specimen configuration and testing jig that truly characterises the composite and avoids failure modes which are specimen configuration dependent. The problem stems from load transfer into the specimen and the need to avoid, either individually or together:

- localised buckling,
- crushing in the specimen ends, and
- localised stress concentrations around edges and tabs.

Various elaborate test techniques have been developed to obtain the maximum quantifiable compressive strength from the composite. A number of comparative exercises have been reported, which sought to identify the attributes of respective methods, Ref. [7-9], [7-19].

The characteristics of a good compressive test method are, Ref. [7-16]:

- The test fixture or jig is simple and economical.
- The specimen is easily mounted, aligned and tested.
- The mode of specimen failure and the failure region are repeatable.
- Testing at non-ambient temperatures and high humidities is possible, Ref. [7-18].
- The specimen is insensitive to edge effects.

EN ISO 14, 126 and ASTM D 3410, more recent standards, concentrate on the quality of the test regardless of the test jig used. Failure has to occur within a maximum allowable bending strain of 10%, as monitored by strain gauges on both faces of the sample.

Important aspects in testing for ultimate compressive strength are:

- Avoiding specimen buckling through the use of side constraints or very short gauge lengths.
- Preventing 'brooming' or crushing at the end of the specimens (end-loaded configurations).
- UD (0°) composites pose greater problems in obtaining the ultimate strength from the composite than do MD laminates.

Specimen failure, at the lowest possible strength, occurs either as a result of buckling, brooming or by longitudinal splitting of plies (delamination); by shear failure or local fibre buckling.

Fibre buckling within the specimen is a fundamental mode of material failure and is not to be confused with specimen buckling.

Table 7.6-1 describes features of various compression test method standards.

Table 7.6-1 - Compression test methods for polymer composites

Compression Test Method (Standard)	Comments
EN ISO/DIS-2 14, 126 : Suitable for all fibre-reinforced plastics.	Mainly harmonised with ASTM D 3410 and prEN 2850. Permits shear and end-loaded jigs, with two types of specimen. Allows 10% maximum bending strain in obtaining strength values.
ASTM D 3410/D 3410M - 94: Suitable for all high modulus fibre reinforced plastics of unidirectional (0° and 90°) and balanced crossply (0°/90°) construction. Preferred method for majority of cases. **ASTM D 5467 - 93**: Suitable, in theory, for all laminate composites. **ASTM D 5449/D 5449M**: Measures transverse compressive properties.	Uses the Celanese test fixture (with conical grips) and IITRI configuration. Narrow rectangular laminate specimen with bonded, tapered end tabs, preferably GRP. Uses a sandwich beam to determine the compressive properties of the composite making up the face-skins. Appropriate in a limited number of cases, due to specimen construction. Uses a hoop wound polymer composite cylinder. Suitable for assessing filament wound composites.
prEN 2850 : Compression test for unidirectional CFRP	Type A : Modified Celanese type with wedge grips, plus tabbed or co-cured doubler test specimens Type B : End-loaded modified ASTM D 695 type with tabbed and untabbed (modulus only) test specimens
Applicable **DIN** Standards: **DIN 29971**: Unidirectional epoxy CFRP. **DIN 65375**: Compression test transverse to fibre direction for unidirectional laminates **DIN 65380:** Testing of unidirectional and woven fabric laminates	Recommends the Celanese type testing configurations. Uses Celanese type rig, with wedge grips, symmetrical alignment pins and cocured doublers for gripping specimen
CRAG Methods: **400**: 0° UD FRP **401**: Multidirectional FRP **402**: Notched MD FRP **403**: Residual strength of impacted MD FRP	Recommends a modified Celanese jig or equivalent offering 'accurate alignment and rotational restraint', e.g. ASTM D695 type. Rectangular specimen with bonded, non-tapered end tabs. Recommends different specimen dimensions dependent on test, i.e. 400, 401, 402 or 403. More wide ranging than ASTM D3410, but more is left to the discretion of the tester.

Test Options	
Shear loading (e.g.Celanese type)	Generic test method with many variants, test fixture typically 5 kg. Original version has conical grips
End loading - ASTM D695 or ISO 8515 type	Generic test method with variants. Originally for testing plastics, it is regaining acceptance in modified forms for testing high modulus composites
IITRI (Illinois Institute of Technology Research Institute) - shear loading	Generic test method, using wedge grips in two steel blocks with two large alignment pins between the blocks. The test fixture is heavy (25 kg or 10 kg in modified versions), making testing tiring.
Ring/cylindrical specimens.	Seeking uniform stress conditions, but inconvenient specimen form unless filament winding is applicable.
Skinned honeycomb sandwich panels	Seeking uniform stress conditions but with an inconvenient specimen form unless final application is a sandwich. Deemed costly.
Waisted specimens.	Costly and prone to shear failures.

From the material perspective alone, composite compressive strength is dependent on:

- Fibre characteristics, i.e. actual strength potential (3500MPa to 6000+ MPa), modulus and fibre diameter,
- Matrix support to the fibres, which is determined by matrix modulus, resin content, porosity and resin distribution,
- Fibre orientations, i.e. 0°, 90° and multidirectional MD.

Under hot/wet conditions the strength becomes more matrix dependent, Ref. [7-23]. Also, as new fibres develop with their increased potential strengths and strain to failures, so have problems with measuring compressive strength.

7.6.3 Factors in compression testing

The selection of specimen geometry is often influenced by the composite manufacturing route used and the intended applications, Ref [7-16]. Specimen configurations evaluated include:

- Rectangular laminate coupons,
- Reduced (machined) section coupons,
- Circular rod and bar specimens (pultrusions),
- Tubular, filament wound specimens,
- Filament wound ring specimens,
- Sandwich specimens.

The measured composite modulus of elasticity is not usually test method dependent, provided that the initial, low strain, modulus of the specimens is taken for this parameter.

The relative merits and disadvantages of individual test methods are:

- Most tests use shear loaded (Celanese rigs or modified derivatives) or end-loaded arrangements, Ref. [7-10], . [7-15], [7-18][.
- With different laminate thickness and construction (fibre type and orientations in quasi-isotropic laminates), it is possible to find deficiencies in all test methods in instances where ultimate compressive strength is not achieved. The highest strengths are usually attained through greater sophistication, effort and skill.
- All compressive tests depend on the exact specimen and loading jig alignment applied in each test laboratory.

7.6.4 Comparison of test methods

Some 30 combinations of specimen configuration and loading arrangement have been evaluated over the years. Some have only subtle variations over others.

In comparative exercises when testing the same UD composite, but by different methods, the highest strengths attained have exceeded the lowest values by up to 50%. A position has been reached where the desired test method characteristics are basically known, but difficult to achieve in a single method applicable to all composites. It is now accepted that a single method does not meet all requirements, so options, i.e. several test method standards, are available from which to choose.

The points to be considered are:

- UD (0°) composites pose greater problems than MD laminates in attaining the ultimate strength from the composite.
- UD laminates lose true linear elasticity as they approach compressive failure, such that failure strains can reach 2.5% which is greater than their potential in tension.
- Specimens can be either, Ref. [7-16]:
- End-loaded,
- Shear loaded, or
- Combined end- and shear-loaded.
- Bonded tabs, or co-cured doublers, Ref. [7-18], are widely used to eliminate end-brooming and aid gripping in shear loaded rigs to prevent damage to the specimen surface.
- Correct specimen and test fixture alignment is critical for all compressive tests, Ref. [7-16]. Monitoring alignment with strain gauges on both faces of the specimen reveals any out-of-plane bending. Strain gauges are now mandatory in international standards to ensure that bending strain does not exceed 10%.
- Some test jigs produce results which can be operator dependent, not least is monitoring and correcting alignments, Ref. [7-19].
- Unsupported gauge lengths should be as short as possible whilst retaining a valid stress regime, Ref. [7-18], [7-24], [7-25]. As laminate thickness increases so can the unsupported gauge length, Ref. [7-22].
- With Celanese-type specimens, it is important to use the particular thickness specified. Other thicknesses can cause jamming.
- The use of bonded tabs assists with load introduction in the case of shear loaded specimens. It also induces stress concentrations at the start of the gauge length.
- Good specimen preparation is essential to ensure the test is valid and not influenced by:
  - misaligned fibre orientation with respect to specimen edges, Ref. [7-17].
  - variations in laminate thickness.
- Shear loaded grips should be clean, with well-serrated surfaces to maintain consistent results, Ref. [7-19], and avoid severe through-thickness stress concentrations.
- Combining 90° plies with 0° plies to give an MD laminate, e.g. [90°/0°/0°/90°]s , higher strengths (of the order of 20% to 50%) can be obtained from the 0° plies than if they were alone, Ref. [7-26], [7-27]. This has been proposed as a means of overcoming the problems of testing UD laminates, Ref. [7-28].
- The most widely accepted test techniques are:
  - shear-loaded 'modified Celanese' fixtures and specimens, [See: 7.7],
  - end-loaded arrangements, e.g. 'Modified ASTM D695 or ISO 8515' types, [See: 7.8], and
  - shear-loaded IITRI, principally used in USA, [See: 7.09].
- Both EN ISO 14,126 (Draft) and ASTM D 3410 are now in agreement on specimen width and gauge length:
  - 10mm x 10mm for UD laminates, and
  - 25mm x 25mm for MD and fabric laminates.

7.6.5 Additional compression-related tests

7.6.5.1 General

These are listed in Table 7.6-2.

Table 7.6-2 - Compression-related tests

Test Standard	Subject
ASTM D 5449/ D 5449M	Transverse compressive properties of hoop wound cylinder
Airbus prEN 6036 Airbus prEN 6038	Filled hole and unnotched compression test Compression after impact (CAI)
CRAG 402 CRAG 403	Notched compression strength of MD laminates Compression after impact (CAI)

7.6.5.2 Compression after impact (CAI)

The compression properties after impact provide an important criterion in aircraft construction by defining the maximum allowable compressive strains for structures, Ref.[7-18].

Figure 7.6-1 shows a representative CAI testing rig, Ref. [7-18]. This takes into account the larger specimen width needed for a valid test.

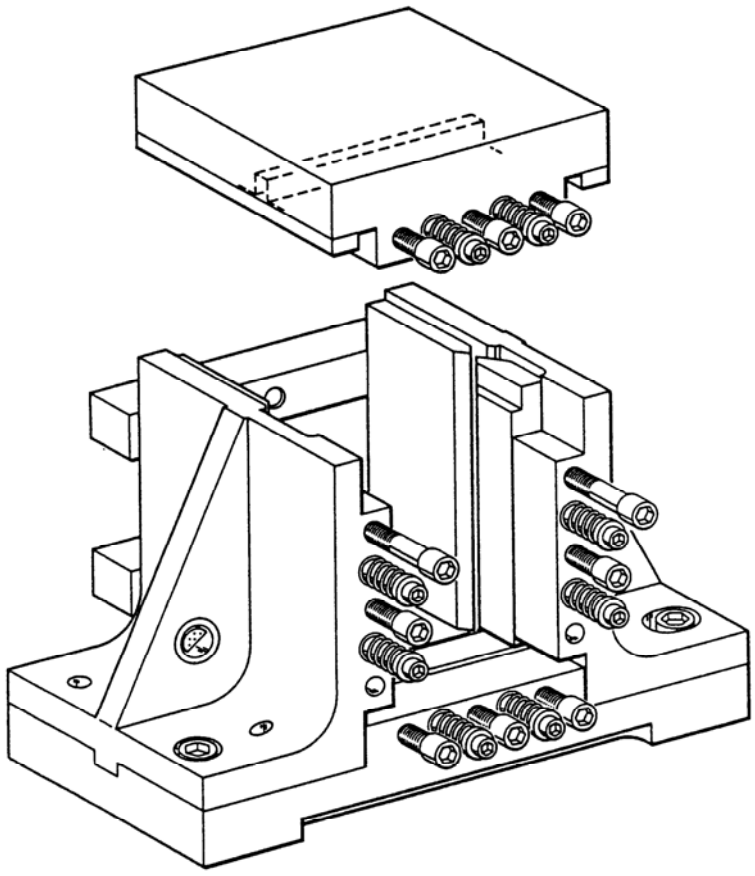

Figure 7.6-1 - Compression after impact (CAI) test rig

7.7 Celanese methods (shear loaded specimens)

7.7.1 Introduction

7.7.1.1 General

The Celanese method arose in the early 1970s. Although most publications use this name, it does not necessarily appear in standards, e.g. in ASTM D 3410 it is under Procedure A.

It is recognisable from the distinctive cylindrical shell enclosing two tapered sleeves with split collets. These grip the specimen tabs during compression and the load is transferred by shear into the specimen.

Over the years the original test arrangement, retained in ASTM D 3410, has been altered by many organisations to produce 'Modified Celanese' methods.

Variations in specimen details have also appeared, notably:

- gauge length,
- specimen width,
- laminate thickness, and
- tabbing arrangements.

7.7.1.2 Compression test specimen

The basic specimen configuration and fixture, shown in Figure 7.7-1, are characterised by:

- Tabbed and untabbed specimens, with the latter only suitable for measuring initial compressive modulus.
- Tabs of steel, glass/epoxy or CFRP.
- Toughened adhesive for bonding tabs.
- Strain gauging, on both faces of the specimen to check for bending strain (up to 10% permitted).

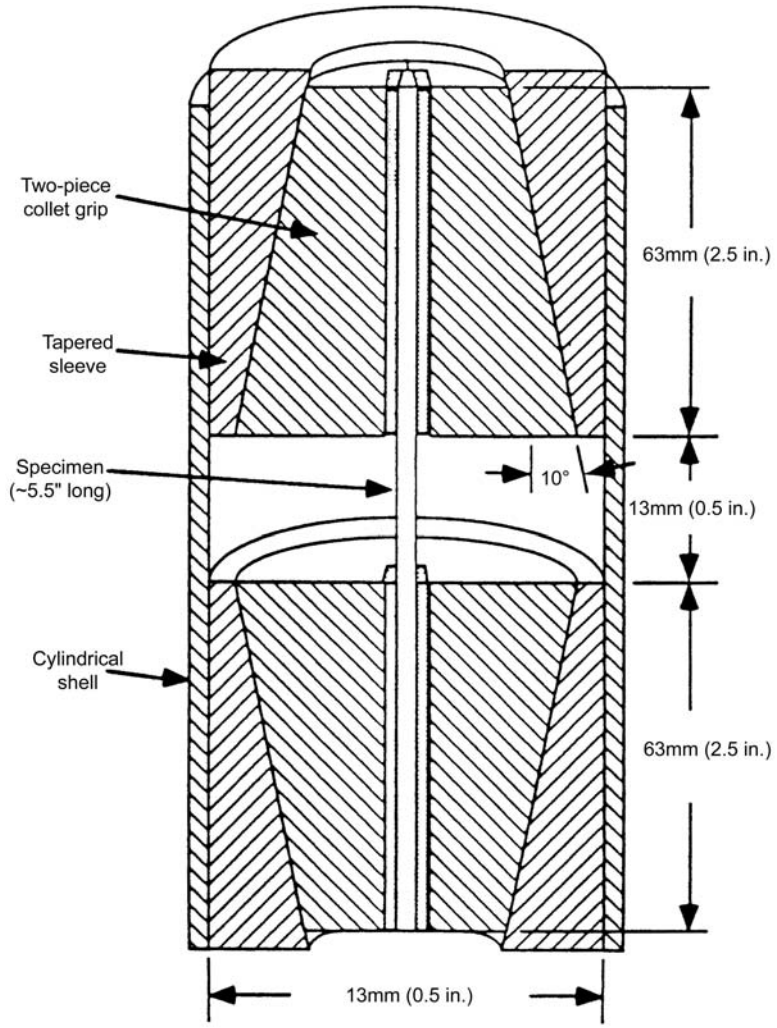

Figure 7.7-1 - ASTM D3410/D 3410 M: Procedure A (Celanese type) compression test fixture

ASTM D 3410 states minimum required specimen thickness values in relation to the longitudinal modulus of the composite and the anticipated compressive strength, as shown in Table 7.7-1.

The values are calculated using an equation provided in the text. They apply to both Celanese-type tests under Procedure A and the IITRI-type tests under Procedure B, [See also: 7.9 for IITRI].

Table 7.7-1 - Compression specimen dimensions as recommended by ASTM D 3410M for Celanese and IITRI type tests

Compression Specimen Geometry Recommendations for Procedure B						
	Fibre Orientation	**Width (mm)**	**Gauge Length**	**Tab Length (mm)**	**Overall Length (mm)**	**Tab Thickness (mm)**
	0°, Unidirectional	10	10-25	65	140-155	1.5
	90°, Unidirectional	25	10-25	65	140-155	1.5
	Orthotropic	25	10-25	65	140-155	1.5
Minimum Required Specimen Thickness (mm) for Procedures A & B - Gauge Length = 10 mm						
Longitudinal	**Anticipated Compressive Strength (MPa)**					
Modulus (GPa)	300	600	900	1200	1500	1800
25	1.27	1.89	2.45	3.02	3.64	4.36
50	1.00	1.33	1.73	2.14	2.58	3.08
75	1.00	1.09	1.41	1.74	2.10	2.52
100	1.00	1.00	1.22	1.51	1.82	2.18
200	1.00	1.00	1.00	1.07	1.29	1.54
300	1.00	1.00	1.00	1.00	1.05	1.26
400	1.00	1.00	1.00	1.00	1.00	1.09
500	1.00	1.00	1.00	1.00	1.00	1.00
Minimum Required Specimen Thickness (mm) for Procedures A & B - Gauge Length = 20 mm						
25	2.53	3.77	4.90	6.04	7.28	8.72
50	1.79	2.67	3.46	4.27	5.15	6.17
75	1.46	2.18	2.83	3.49	4.21	5.04
100	1.27	1.89	2.45	3.02	3.64	4.36
200	1.00	1.33	1.73	2.14	2.58	3.08
300	1.00	1.09	1.41	1.74	2.10	2.52
400	1.00	1.00	1.22	1.51	1.82	2.18
500	1.00	1.00	1.10	1.35	1.63	1.95
Minimum Required Specimen Thickness (mm) for Procedures A & B - Gauge Length = 25 mm						
25	3.17	4.72	6.12	7.55	9.10	10.91
50	2.24	3.33	4.33	5.34	6.44	7.71
75	1.83	2.72	3.53	4.36	5.26	6.30
100	1.58	2.36	3.06	3.77	4.55	5.45
200	1.12	1.67	2.16	2.67	3.22	3.86
300	1.00	1.36	1.77	2.18	2.63	3.15
400	1.00	1.18	1.53	1.89	2.28	2.73
500	1.00	1.05	1.37	1.69	2.04	2.44
Procedure A based on specimen length = 140 mm, gauge length = 10 mm and specimen width = 10 mm.						

7.7.1.3 Compression test fixture

The Celanese loading rig is shown in Figure 7.7-2. For dimensions refer to specification.

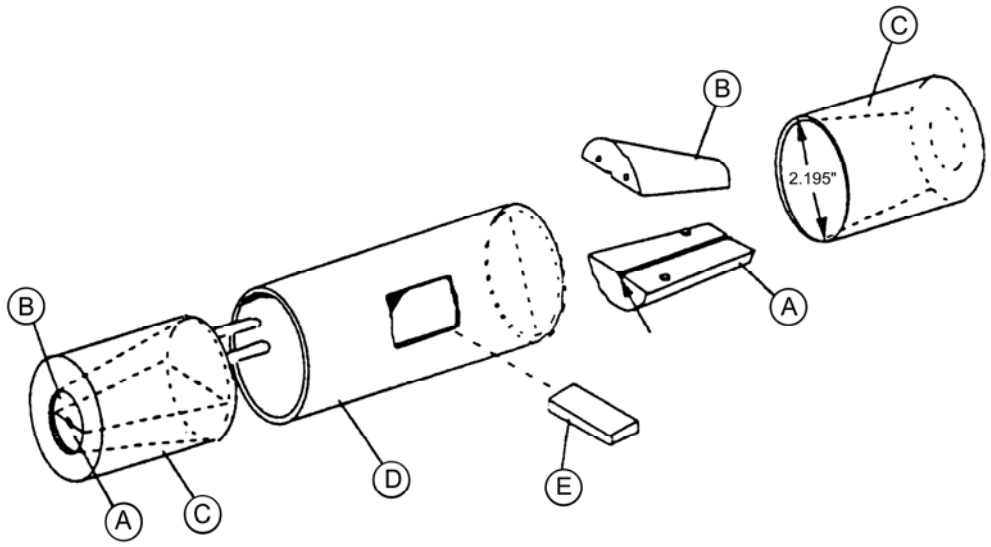

Figure 7.7-2 - ASTM D3410/D 3410 M: Celanese compression test fixture

The tabbed specimen is located in a circular collet grip which fits in a tapered sleeve. This fits inside a cylindrical shell which provides the necessary lateral support for the entire loading jig. A port within the cylindrical sheet provides access for strain gauge leads to the specimen. Under load, the collets lock into the taper and grip the specimen. Load is transferred by shear into the specimen through the tabs. The active gauge length is 10mm with a width of 10mm for ASTM D 3410.

The jig relies on free-sliding surfaces between metal components, but in some cases the outer sleeve can sustain load which it should not. The conical wedges are known to be prone to cone-to-cone seating problems, as stated in ASTM D 3410.

Many failures occur where the gauge length meets the end tabs, particularly in the case of steel tabs. This shows an undesirable stress concentration. Attempts to prevent this tend to transfer failure to the tab/grip interface particularly if GRP or CFRP tabs are used.

7.7.2 Modified Celanese methods

7.7.2.1 General

The original Celanese method was criticised for not providing symmetrical specimen loading leading to out-of-plane bending.

To improve the original method, various modifications have been made, i.e.:

- Pyramidal wedge grips replace the conical collets, Ref [7-18].
- Different alignment pin arrangements to improve specimen loading conditions.
- Modified 0° UD test specimens, as in the use of bonded doublers, Ref. [7-18], enable higher compressive strengths to be achieved.

7.7.2.2 European compression testing study

A European 'round robin' exercise was reported in 1993 under the auspices of GARTEUR (Group for Aeronautical Research and Technology in Europe), Ref. [7-20], [7-29].

The European organisations that participated were DLR, ONERA, DRA, NLR, Fokker, Deutsche Aerospace and Westland helicopters.

Each used their own preferred compression test method and specimen type (at that time). Five of the organisations used Celanese type fixtures (standard or modified).

The conclusions included:

- The measured strength of 0° UD laminates varied significantly between establishments. The highest measured values were between 50% and 75% greater than the lower values in some cases where the same composite material was tested.
- A Celanese type set-up, as shown in Figure 7.7-3, Ref. [7-18], gave the highest compressive values. However, this needs a small area of a special lay-up to be available or prepared to execute the test, and as such is not widely accepted.
- Quasi-isotropic (MD) laminates gave fewer problems with smaller standard deviations than UD laminates.

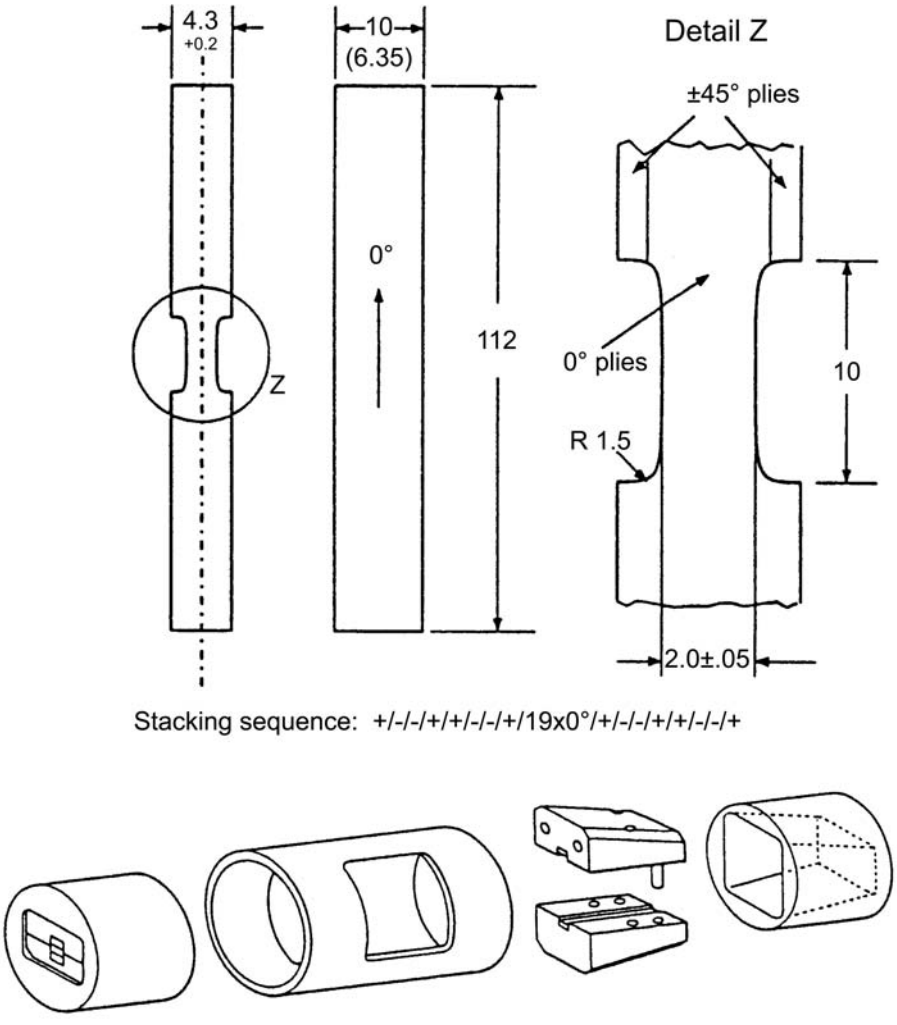

Figure 7.7-3 - Modified Celanese test rig and specimen according to DIN 65380

7.8 End-loaded specimens

7.8.1 Introduction

End-loaded untabbed specimens, without face support, were the original means of testing both unreinforced and reinforced plastics; as defined by ASTM D 695M-91 for general plastics. This was later deemed an inappropriate means of measuring the ultimate strength of high-performance composites. Ultimate strength values were typically 30% lower than for shear-loaded specimens. For this reason ASTM D 695 does not come under the auspices of Committee D 30, although it is still used by aerospace companies because of its simplicity.

The use of end-loaded tabbed specimens, but with face support, is now seeing a resurgence and wide acceptance. The method has been refined to alleviate the original weaknesses, Ref. [7-19], [7-30]. It appears in EN ISO 14125. Although the term 'modified ASTM D 695' has been used, in many cases the proposed methods bear no resemblance to the original ASTM D 695. A simple tabbed specimen configuration is an obvious attraction, coupled with the face support provided to the specimen which inhibits specimen bending, Ref. [7-19].

As potential compressive strengths increase with new fibres, unsupported gauge lengths become increasingly prone to buckling, Ref. [7-25]. An end-loaded configuration appears in ISO 8515, prEN 2850 and CRAG 400 series.

The simplicity of face-supported and end-loaded specimen arrangements has attractions over the most complex Celanese shear loaded configurations.

7.8.2 Compression test specimens and fixtures

The original ASTM D 695 fixture is inappropriate for obtaining high strength values from untabbed unidirectional (0°) constructions, because the end of specimen fails by either 'brooming', 'splitting' or 'crushing'. This is particularly so of CFRP but less so of GRP. The use of end tabs can improve strengths.

Advisory guidelines for compression test specimens are:

- The original waisted, untabbed ASTM D 695 specimen is inappropriate for high-performance composites, Ref. [7-11].
- A straight-sided, untabbed specimen can be used for measuring compressive modulus only.
- Tabbed rectangular specimens with strain gauges are used for measuring ultimate strength.

NOTE Face supports should accommodate access for strain gauges.

The test fixture can also be redesigned in a number of ways so that side restraints and end-loading plates can be bolted to the specimen, e.g.:

- prEN 2850,
- CRAG 400 series,
- ISO 8515: 1991,
- ICSTM, the Imperial College of Science, Technology and Medicine method is shown in Figure 7.8.1, Ref. [7-30]:

— further improved by PTFE shims placed beneath the tab immediately adjacent to the gauge length.

— shims reduce the stress concentration by introducing a delamination and increase in measured strength.

- Birmingham University rig, Ref. [7-30],
- Various from individual methods tried in the USA; NBS, Lockheed, SWRI, Northrup, AFWAL, NASA, Ref. [7-16], [7-21],
- Boeing, SACMA SRM-1, Ref. [7-26],
- Canadian Institute for Aerospace Research, Ref. [7-23].

Imperial College ICSTM version.

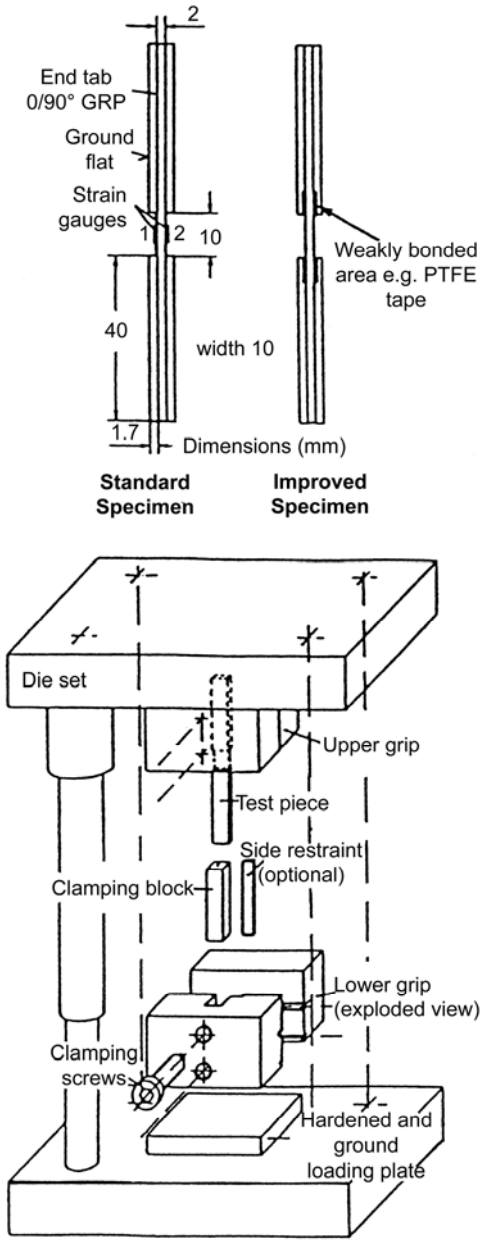

Figure 7.8-1 - End-loaded compression test specimen and fixture

7.8.3 Combined end- and shear-loaded specimens

7.8.3.1 General

Most compressive tests are conducted on relatively thin laminates; approximately 2mm thick. The transfer of compressive load into the specimen causes problems. As specimen thickness increases, so does the load making the exercise more difficult.

Further modified test methods are therefore needed to measure the maximum compressive strength of thick laminates. A means of achieving this is to design a loading arrangement which transmits the initial load through the tabs by shear loading and thereafter engaging the ends to apply further load, Ref. [7-31].

7.8.3.2 Compression tests for thick laminates

Early reported work includes, Ref. [7-32]:

- compression test fixture, a modified IITRI, which has been applied to 16 ply, 48 ply and 72 ply laminates with 1600MPa potential compressive strength, Ref. [7-31]:
  - 10% to 25% load transmitted by shear.
  - steel end-caps applied to glass/epoxy tabbed CFRP laminates
- DTRC thick-section compression fixture, which has been applied to 48 ply (6.4mm), 96 ply (12.7mm) and 192 ply (25.4mm) ply CFRP laminates, Ref. [7-33]:
  - Tabbed specimen with clamping blocks either end.
  - A self-aligning lubricated spherical loading seat to align specimen and loading axes.
  - Four strain gauge rosettes, one on each face of the laminate specimen.
  - Applied load for thickest specimen of 100mm width and 25.4mm thickness was 2150kN for ultimate strength of 840MPa on a [0°/0°/90°]32S construction.

The through-thickness behaviour of composites is attracting attention as sectional thicknesses increase, Ref. [7-34].

7.9 IITRI

7.9.1 Introduction

The IITRI method originated at the Illinois Institute of Technology Research Institute. It has been adopted as Procedure B in ASTM D 3410.

7.9.2 Compression test specimen and fixture

The specimen is essentially the same as for the Celanese Method, Ref. [7-14], [See also: 7.7].

The specimen sits between wedge grips which in turn lock into large blocks, as shown in Figure 7.9.1.

These blocks are directly fixed to the cross-heads of the test machine and with large guide pins between the two. The physical bulk of the end blocks ensure the stability of the test rig in avoiding specimen buckling. However, the weight of the unit makes handling difficult.

[See also: Table 7.7.1 for recommended specimen dimensions for Procedure B]

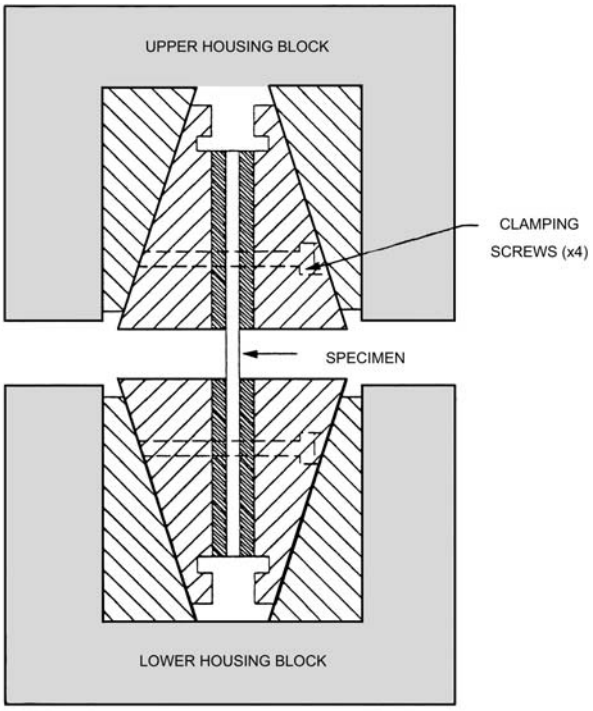

Figure 7.9-1 - ASTM D3410/D 3410 M: Procedure B (IITRI type) compression test fixture

In reported comparisons between the 'modified Celanese' and IITRI methods, IITRI gave marginally higher ultimate compressive strengths with similar coefficients of variation to that of Celanese. For this reason the lITRI method was included in ASTM D 3410 in 1987.

7.10 Other compression tests

7.10.1 Test specimen configurations

7.10.1.1 General

Attempts have been made to introduce test configurations which claim pure compressive stresses within the composite under test. These specimens are usually of an inconvenient form if the intended structure is a monolithic sheet laminate. They are more convenient if the intended application resembles the test specimen. Some of the proposed specimen types are described.

7.10.1.2 Sandwich beam or panel

Providing that the correct specimen configuration is used in a 4-point bending mode, it is possible to generate uniform compressive stresses in one of the face skins. The face skin is therefore the composite under test and the sandwich (honeycomb core) provides the lateral support to avoid buckling, Ref. [7-35]. This is a suitable test method for thin section CFRP laminates.

ASTM C364-94 'Edgewise compressive strength of sandwich constructions' is applicable to co-cured constructions. It measures face skin strength as well as indicate wrinkling and dimpling effects.

7.10.1.3 Tubular specimens

Tubular specimens are beneficial in that they avoid free edges and are self supporting, Ref. [7-12]. The tubes have a predominance of 0° fibres longitudinally with some 90° fibres (circumferentially) to stabilise the specimens near the ultimate compressive strength.

The winding and consolidation of these specimens is not easy. Also, bonded steel end fittings are needed as the means of loading the specimen. End fittings and specimen preparation are costly. This type of test-fixture is appropriate for multi-axial loading (stress states).

7.10.1.4 Ring specimens

The methods developed induce external compressive forces on a ring of composite, usually by means of a diaphragm, Ref. [7-13]. These produce hoop and transverse stresses in the specimens which are monitored with strain gauges.

7.11 In-plane shear testing

7.11.1 Introduction

As with compressive testing, it is generally accepted that more than one test method can be used for measuring shear characteristics. A true state of shear is difficult to achieve in specimens with free edges and criticism in one form or another can be levelled at all of the widely used methods, Ref. [7-9]. Simplicity and lower cost techniques tend to take precedence where commercial pressures prevail.

7.11.2 Use

In-plane shear testing is used to quantify:

- In-plane shear modulus (G),
- In-plane shear strength (τ),
- 'A' design allowables.
- 'B' design allowables.

Unless the simpler specimen configurations are used, such testing is not suitable for:

- Material characterisation,
- Material procurement ,
- Production quality control.

In-plane shear properties are difficult to obtain and are subject to some disagreement as to the best means of achieving a state of pure shear in a test specimen, Ref. [7-36].

The various specimen configurations and test fixtures available for providing shear data are given in Table 7.11.1, Ref. [7-9]. This also identifies the appropriate standards. ISO 14,129 (draft EN ISO/F-DIS 14,129) is a recent addition, Ref. [7-63].

The recognised standards, i.e. ISO, prEN, ASTM, DIN and CRAG, all use the symmetrical ±45° laminates tested in tension for prepreg-based composites. This is simple and effective. There are other specimen and test configurations which are promoted. Of these, the double V-notched beam (Iosipescu) type, plate-twist and rail shear tests are the more appropriate ones.

If it were solely a case of using a specimen which produced the purest state of shear, then the torsional loading of a thin-walled cylinder can be selected. However, this is an inconvenient and costly test unless filament winding is the preferred manufacturing technique.

7.11.3 Test method comparisons

The attributes of the various test methods are summarised in Table 7.11.2, where an evaluation of the various test methods has produced a 'ranking' with respect to each other, Ref. [7-37]. The weightings given to each criterion should be considered rather than the actual rankings of the methods.

Several studies have analysed loaded specimens to determine shear distribution, Ref. [6-38], [7-39].

Table 7.11-1 - In-plane shear standards and test methods

In-Plane Shear Test Method (Standard)	Comments
EN ISO/F-DIS 14,129: Suitable for all fibre-reinforced plastics.	Test based on symmetrical ±45° laminate, 2.0 mm in thickness. Test terminated after 5% strain. Standard based on ASTM D3518 as source document. Warning included on the effect of the number of shearing planes when ply thickness exceeds 0.125 mm.
ASTM D3518/D3518 M - 91: Suitable for all high modulus fibre-reinforced plastics of unidirectional construction. **ASTM D4255/D 4255M - 83 (1994):** Suitable for all high-modulus composites. **ASTM D5379/D 5379M - 93:** Suitable for all high modulus composites.	Test based on symmetrical ±45° laminate tested in tension to ASTM D3039. Inexpensive test. 2 mm thick specimen with strain gauges. Tests based on two- or three-rail shear loading. Uses a notched beam (laminate) commonly referred to as the Iosipescu method. Preferred for measuring shear strength. ASTM D 5379 to be redrafted and submitted as an ISO.
Airbus prEN 6031	Indicates tensile testing of ±45° laminate similar to ASTM D3518, but with 1.0 mm thick sample. No applicable European (prEN) standard from AECMA.
Applicable **DIN** Standards: **DIN 29971:** For unidirectional epoxy CFRP. **DIN 65466**: Testing of unidirectional laminates in tension for determining shear strength and modulus.	Indicates tensile testing of ±45° laminate as for ASTM D3518.
CRAG Methods: **101**: In-plane modulus and strength for UD FRP.	The ±45° laminate specimen is used, with two strain gauges in 0° and 90° orientations. End tabs either aluminium alloy or GRP, but without end-tabs permissible as specimen is of low strength.
Test Options	
±45° laminate in tension.	Long-standing, simple tabbed tensile specimen widely used due to low cost and valid results.
losipescu shear test.	Double notched specimen undergoing two counteracting moments to induce shear.
10° off-axis tensile specimen.	Simple tensile specimen of unidirectional laminate of 10°
Two-rail and three-rail shear test.	Rectangular specimen loaded via parallel rails. Can be applied to MD laminates.
Thin-walled tube.	Tube loaded in torsion to induce pure state of shear, i.e. desirable for accuracy yet most inconvenient.
Slotted-tensile specimen.	Tensile specimen with two axial slots undergoing both tensile and compressive, hence biaxial, loading.
Cross-beam sandwich.	Cross shaped sandwich specimen with +ve and -ve bending to induce biaxial state of tension and compression.
Picture frame panel.	Essentially a sandwich panel held in a four-bar linkage frame, undergoing biaxial tensile or compressive loading.
Plate twist.	Simple test for measuring shear modulus. To appear as ISO/CD 15,310.

Table 7.11-2 - Evaluation of in-plane shear methods

Criterion	Weighting (Rating)	In-plane Test Method								
		2 Rail	3 Rail	45° Tensile	10° off-axis	Cross Beam	Picture Frame	Thin-walled Tube	Slotted Tensile	Iosipescu
Cost of Fabrication:										
Material Quality	20 (10)	7	6	9	10	2	4	1	8	9
Processing Equipment	50 (10)	10	10	10	10	8	10	8	10	10
Specimen Processing	40 (10)	10	10	10	9	7	10	2	10	10
Specimen Preparation	40 (10)	6	7	10	10	8	8	7	7	10
Cost of Testing:										
Test Equipment	100 (10)	10	10	10	10	7	10	2	10	10
Special Fixture	50 (10)	5	4	10	10	7	6	2	3	7
Specimen Testing	50 (10)	10	10	10	10	3	4	2	4	10
Auxiliary Instrumentation	50 (10)	10	10	10	10	10	10	7	10	10
Data Producibility:										
Strength	150 (10)	6	7	7	7	6	7	10	8	8
Stiffness	150 (10)	7	7	8	7	7	6	10	8	8
Accuracy of Experimental Results:										
Comparison †	200 (10)	7	8	9	9	6	7	10	7	9
RATING		**6**	**4**	**1**	**3**	**9**	**7**	**8**	**5**	**1**

Key: † Compared with experimental results of thin-walled tube.

7.12 ±45° laminate tensile specimen

7.12.1 General

The main advantage of this configuration is that it is simple, whilst retaining sufficient accuracy to be valid for quantifying the shear modulus of UD material.

7.12.2 ±45° specimen

Features of the ±45° specimen are, Ref. [7-37], [7-40]:

- Mathematical expressions from laminate plate theory enable the in-plane 0° shear properties to be calculated from longitudinal and transverse stress/strain curves.
- The specimen provides an adequate but not true measurement of shear strength, owing to the Poisson's ratio not being exactly 1.0, the presence of small tensile strains and some edge effects.
- For highly shear-sensitive laminates, the ±45° method is the most suitable means of determining the in-plane shear modulus to represent the response of the material within laminates, Ref. [7-40].
- International standards are available.

7.12.3 10° off-axis specimen

The 10° off-axis specimen is shown in Figure 7.12-1, Ref. [7-12]. Features of this specimen are, Ref. [7-37]:

- A biaxial stress state consists of two stresses on the 10° plane - transverse and in-plane shear. When the specimen fails, the in-plane shear stress is near its critical value and so the strength can be determined.
- Suitable for measuring environmental, temperature, fatigue and impact effects.
- Specimens free from laminate residual stresses.
- Owing to sensitivities, the fibre direction, strain-gauge positioning and load alignment need to be kept within ±1%.
- Certainly appropriate for CFRP, but evidence suggests that inaccuracies occur with aramid fibre/epoxy composites.

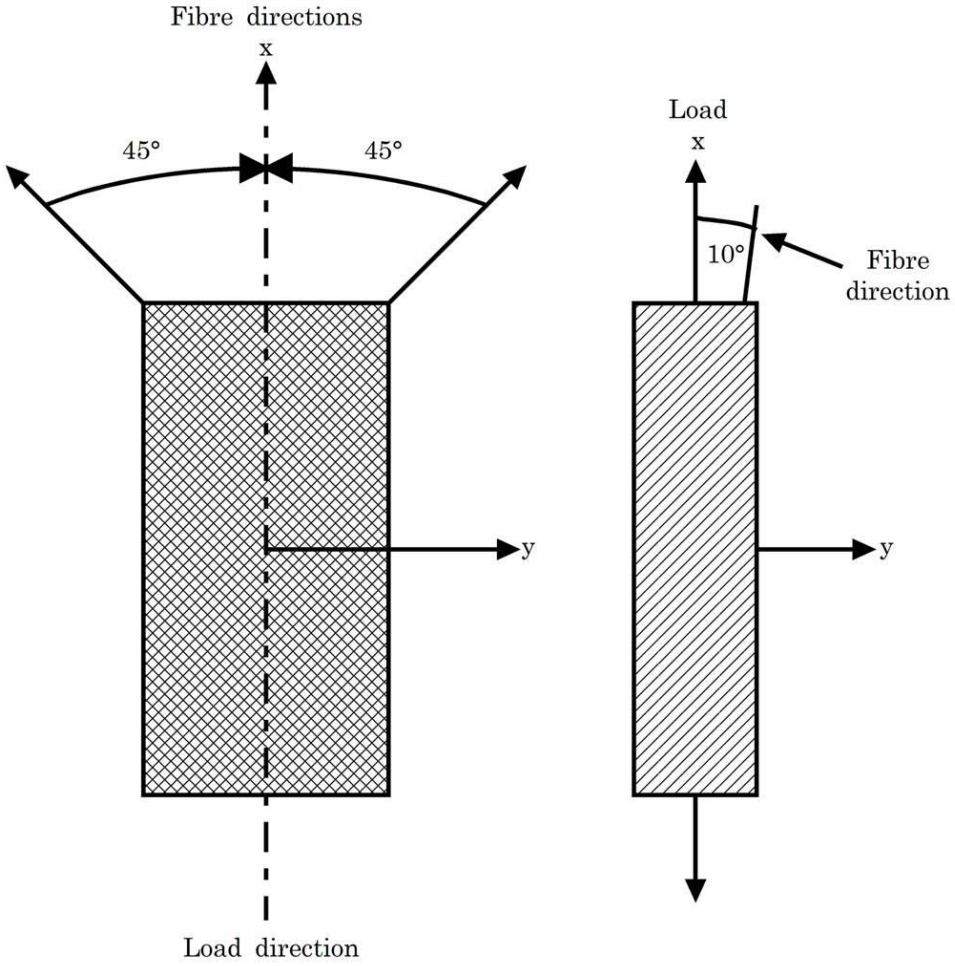

Figure 7.12-1 - Specimens for ±45° and 10° off-axis shear

Whilst being a credible test method for measuring shear properties, it is not an accepted manufacturing practise to prepare specimens with 10° orientations when 0°, 90° and 45° are the more commonly used. This appears to be the main reason that commercial organisations rarely use the 10° specimen for generating shear data.

7.13 Double V-notched beam shear test

7.13.1 Introduction

The V-notched beam method, previously called the Iosipescu shear test, was derived by the University of Wyoming, USA in the early 1980s and adopted in ASTM D 5379 from 1993, Ref. [7-41].

Various reviews have compared the Iosipescu test with the more established ±45° laminate and rarely used 10° off-axis method, Ref. [7-40], [7-42], [7-43], [7-44].

[See: 7.12 for ±45° and 10° off-axis]

It is generally accepted that similar results for in-plane shear modulus are obtained by the three methods with respect to secant and tangent interpretations of the stress/strain curve. This is true for 90° specimens tested by the V-notched beam route, but not necessarily so for 0° specimens, Ref. [7-45].

7.13.2 Specimen and fixture

The test and specimen configurations are shown in Figure 7.13.1.

From a number of reviews, Ref. [7-37], [7-46], [7-47], [7-48], this method is identified as coming close to the ideal state of pure shear when a state of constant shear force is induced through the middle section of the specimens at the 90° V-notches. This is proven by finite element analysis.

In the rankings [See: Table 7.11.2], it appears first, along with the ±45° specimen. The two criteria on which it suffers are the need for a special test fixture and facilities for machining precise V-notches.

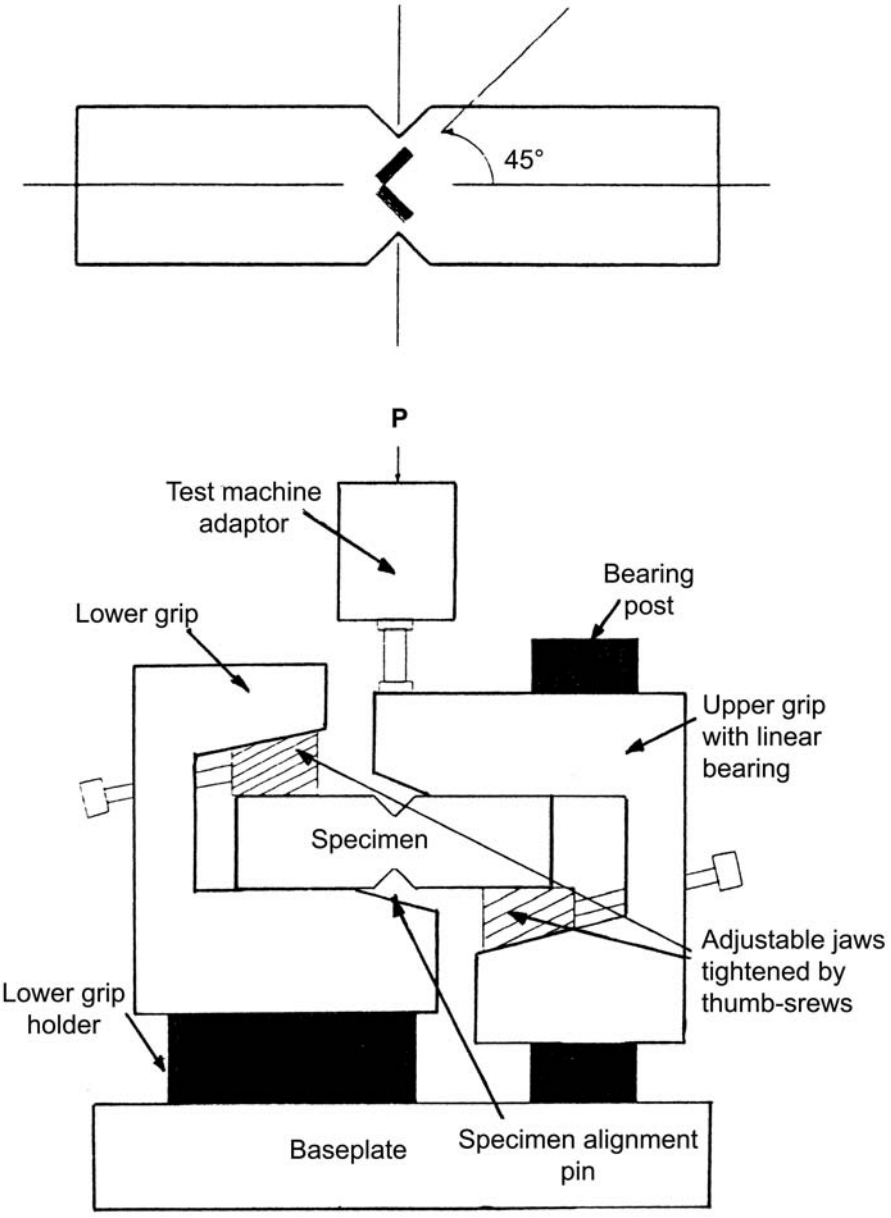

Figure 7.13-1 - ASTM D 5379/D 5379 M: V-notched beam (Iosipescu type) in-plane shear test fixture and specimen

7.13.3 Test

The test provides a complete shear stress-strain curve to failure, and thus strength, modulus, and strain to failure, for both in-plane and interlaminar shear loadings can be determined, Ref. [7-41].

Features of the method are:

- Adjustable test fixture with tightening jaws.
- The four loading surfaces are ground parallel and smooth for the test to be valid, Ref. [7-45].
- ±45° strain gauge rosette bonded between the notches.
- Specimen dimensions: 76mm long and 20mm wide.
- Suitable for:
  - laminates with 0° and 90° fibre orientations,
  - woven fabric laminates with warp direction either parallel or perpendicular to the loading axis,
  - 0°/90° laminates with balanced and symmetric stacking sequence, with fibres parallel or perpendicular to loading direction.

The techniques for machining the notches are published in ASTM D 5379 and elsewhere, Ref. [7-45], [7-49].

The outputs from both strain gauges are monitored separately to ensure that they are similar and a pure shear state is achieved, Ref. [7-45].

Moiré interferometry has been used to determine the surface displacement fields in 10° off-axis, ±45° and 0° Iosipescu CFRP specimens, Ref. [7-50], [7-51].

A comparison of the Moiré data on one face of the specimens with data from a strain gauge rosette on the other face has been made. This revealed that strain gauging only one face can give erroneous results. The use of rosettes on both faces provides confidence that a uniform shear state does really exist when each specimen is tested.

The interferometry patterns also revealed inconsistencies in the shear strain distribution in both ±45° and Iosipescu configurations, depending on fibre distribution (for ±45°), proximity to specimen edge (for ±45°) and Iosipescu specimen-to-fixture interactions.

7.14 Two-rail and three-rail shear test

7.14.1 Introduction

These are well established tests but cannot be recommended in the first instance, due to doubts on reproducibility in inter-laboratory tests. The simpler ±45° laminates and double V-notched beam arrangements are preferred, [See: 7.12 for ±45°; 7.13 for V-notched].

ASTM have retained the rail shear methods but within a ‘standard guide’. In 1981, the ASTM sub-committee D-30.04 concluded that the:

- Variation in averages was large enough to cast doubt on the validity of data from the two- and three-rail tests,
- Spread of the data between the two tests did not indicate a preferred test system.

7.14.2 Specimens and fixtures

Figure 7.14.1 shows how the specimens are configured, and how loading is achieved. Both techniques are fairly popular but have deficiencies in accurate measurement of shear strength; noticeably in the two-rail method, Ref. [7-37].

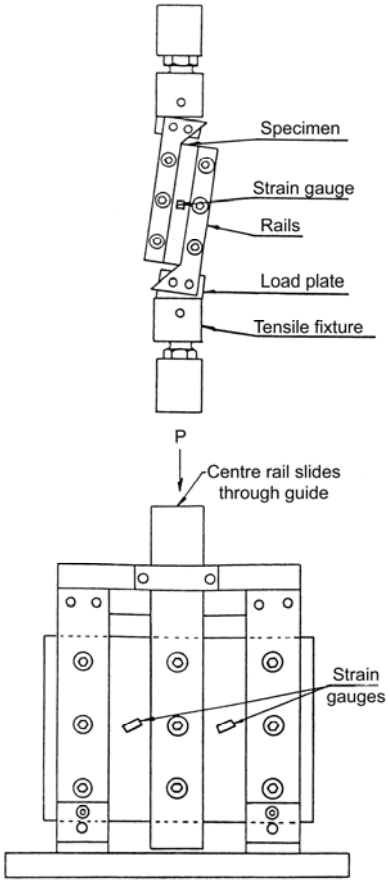

Figure 7.14-1 - Two and three-rail shear test configurations from ASTM D 4255/D 4255M

7.14.3 Two-rail test

The features of the test include:

- The length-to-width ratio should be be at least 10 to measure shear modulus. ASTM D 4255 states a specimen design where the ratio is 2 on a length of 152mm and width of 76mm.
- The effective Poisson's ratio of the laminate with respect to the edges should be less than unity. For high Poisson's ratio laminates, e.g. ±45°, the method gives unacceptably low strength values.
- If design allowables are being sought, care is needed to use the proper laminate orientations. Otherwise the values are too conservative.

7.14.4 Three-rail test

The features of the test include:

- It provides a better approximation to a state of pure shear.
- The specimen has two independent calculations for shear response.
- Significant normal stresses can occur depending on the stiffness of the rails, the method of load application and the laminate properties.

7.15 Other in-plane shear tests

7.15.1 Introduction

Some examples are included to illustrate the developments made in the overall quest for valid test methods. They can be used if the specimen form is appropriate for in-house applications.

7.15.2 Thin walled torsion tube test

In this test, a thin-walled circumferentially wound cylindrical tube, as shown in Figure 7.15.1, is subjected to a pure torque about its longitudinal axis, Ref. [7-37], [7-52].

Since the wall thickness is small compared with the mean radius of the tube, the shear strain gradient through the thickness is negligible. In addition the specimen has minimal normal stresses in the test section. Care is taken to ensure that only pure torque is applied to the specimen. Therefore, to prevent the development of bending moments, the specimen is mounted concentrically.

Axial forces that result as the specimen undergoes shearing deformation can be prevented by enabling one end of the specimen to move axially. The wall thickness to diameter ratio is less than 0.03 to ensure a uniform stress distribution.

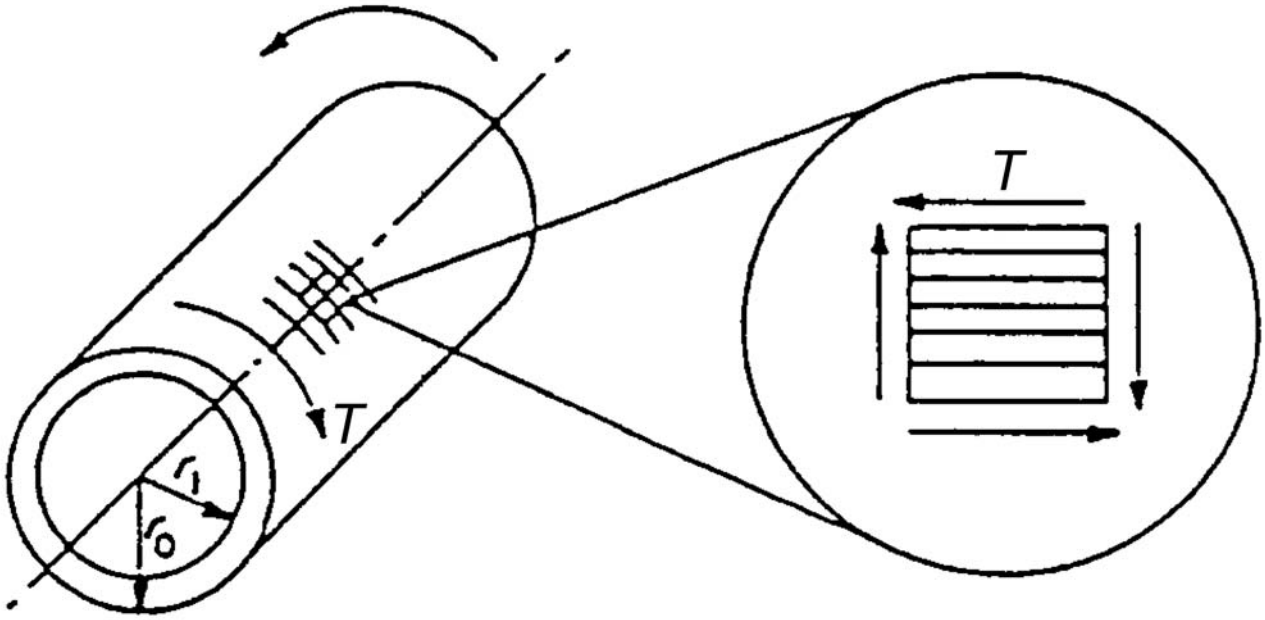

Figure 7.15-1 - Thin-walled torsion tube

7.15.3 Slotted tensile test

A conventional tensile coupon is modified by the addition of two axial slots which terminate 25mm apart along the centreline of the specimen, Ref. [7-37]. The configuration is shown in Figure 7.15.2.

Tensile and compressive stresses are provided by applying axial and transverse loads in a ratio governed by the specimen width and the distance between slots. Good agreement was reached between testing and finite element theory with a [±45°]s CFRP coupon.

For [0°/90°]s laminates, the material tended to fail in tension which did not reflect a valid shear strength result. Few studies have been conducted on this method.

7.15.4 Cross beam sandwich test

The composite being assessed forms the facings of the cross-shaped sandwich panel shown in Figure 7.15.3, Ref. [7-37].

The cross-beam shear specimen is loaded in positive and negative bending to produce a biaxial state of tension and compression over the test area at the centre of the specimen. Laminates commonly used with the cross beam are [0°/90°]s and [±45°]s.

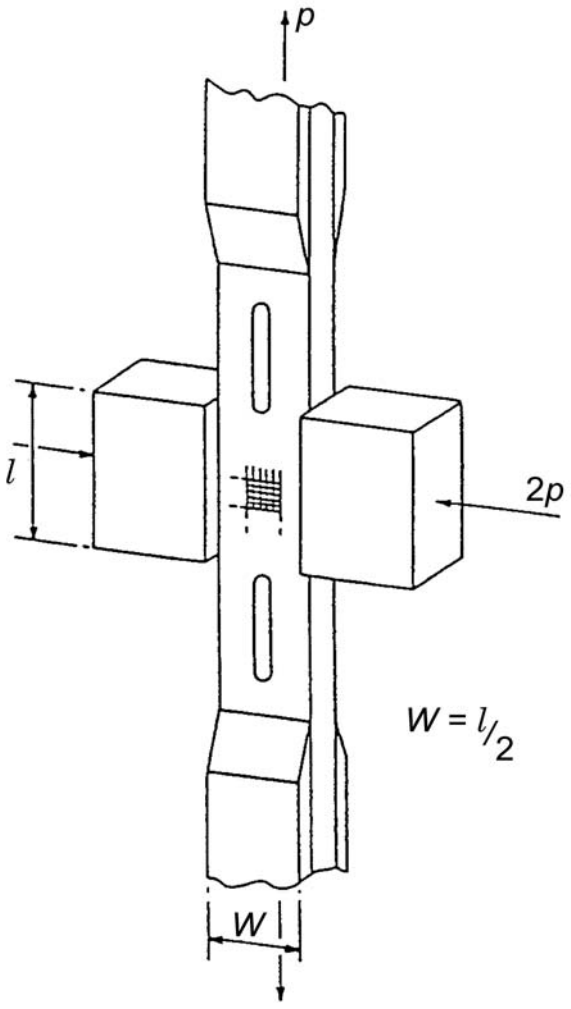

Figure 7.15-2 - Slotted tensile specimen

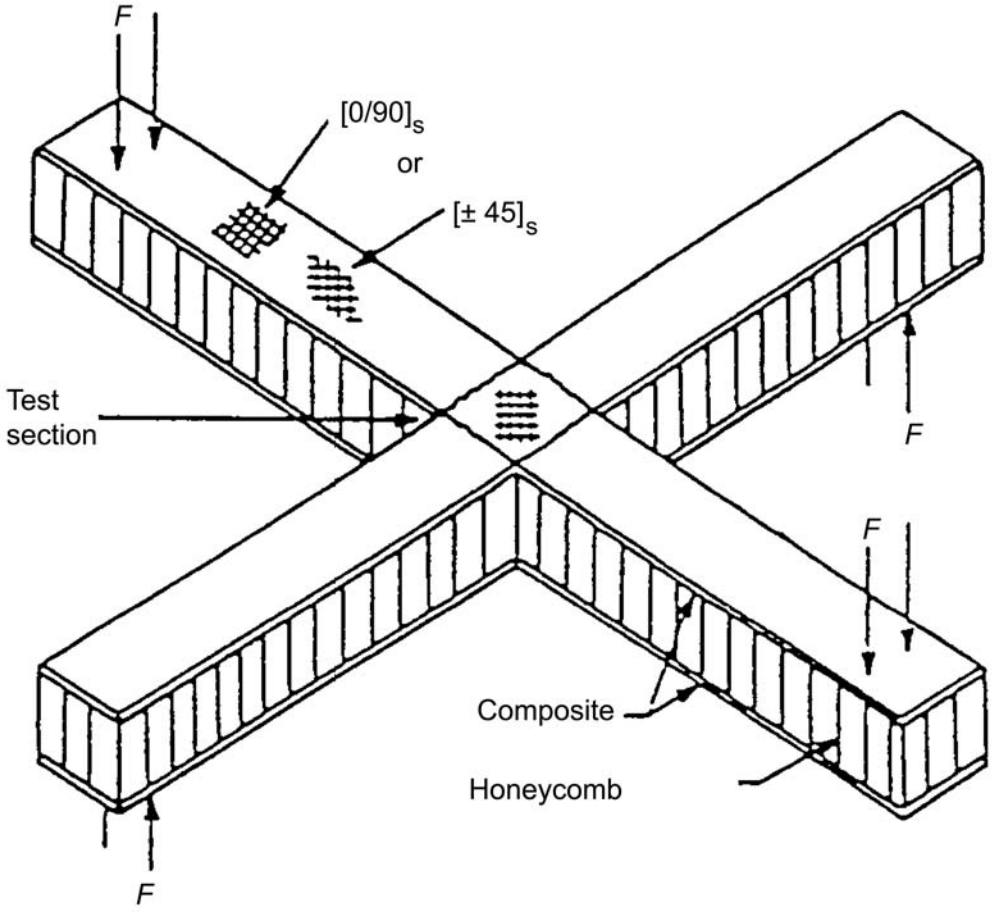

Figure 7.15-3 - Cross-beam sandwich specimen for in-plane shear tests

The specimen configuration tends to produce normal stresses within the test section which contribute to errors in the shear strength; reportedly as high as 13% to 20%. These are attributed to corner effects adjacent to the test section.

The cross-beam specimen receives the lowest rating in comparative test method studies, [See: Table 7.11.2].

7.15.5 Picture frame panel test

A sandwich panel specimen is used in which the face skins are under test, Ref. [7-37].

Figure 7.15.4 shows the configuration with a rigid four-bar linkage frame bolted or bonded to the panel for load introduction. To reduce high corner stresses, these areas are usually cut out and have doublers bonded on or near the resulting free edges.

The load is introduced by a combination of tension and/or compression forces in pairs on opposite corners. Thus, the specimen is subjected to shear loading along planes at 45° to the diagonals.

Some opinion suggests that this method is appropriate for measuring in-plane shear strength but is not appropriate for measuring the modulus. Generally a sandwich specimen is inconvenient unless the intended application is for a similar construction.

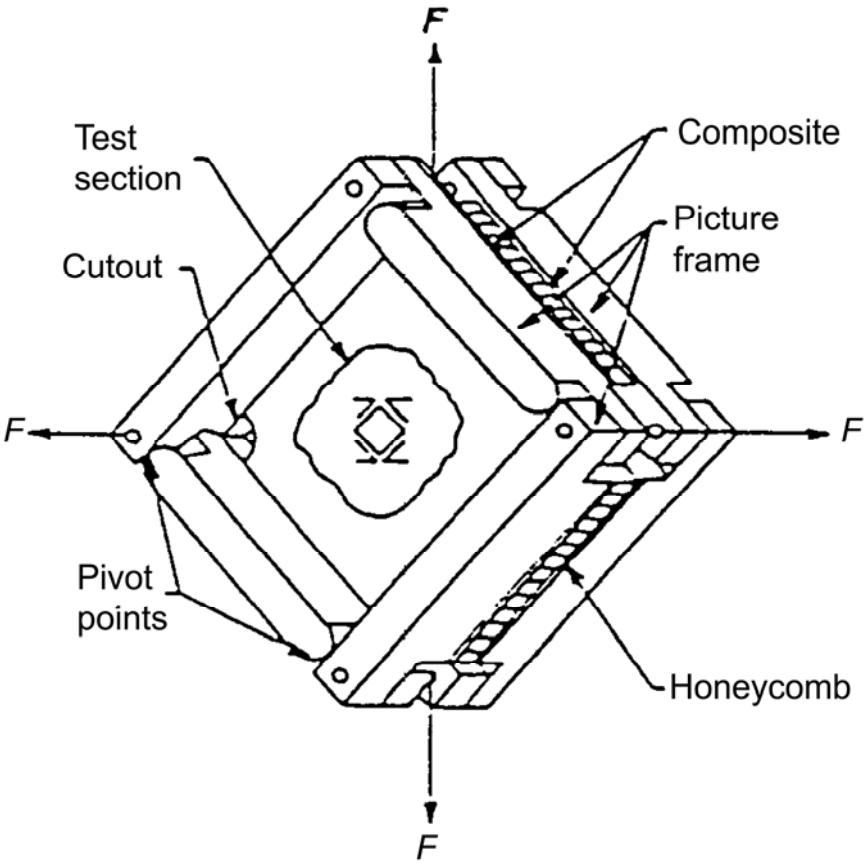

Figure 7.15-4 - Picture frame panel test

7.16 Flexural testing

7.16.1 Uses

Flexural testing of flat coupons is appropriate for:

- Material procurement.
- Quality control.

The non-uniform stress state that exists in the specimen, i.e. compressive, tensile and shear, or combinations there of, means that fundamental design values cannot be measured, Ref. [7-53]; although strength and modulus values are often quoted as results.

Flexural testing demands a sufficiently high span-to-depth ratio to avoid shear failure. Both three-point and four-point bend testing can be used. The three-point is more popular, but the four-point produces strength and modulus values closer to the directly measured tensile values. The basic test is simple and cheap to perform, hence its widespread use for comparison between materials and in quality control.

Table 7.16.1 gives the appropriate test standards. It includes the recent ISO 14,125 (draft EN ISO/F-DIS 14,125), Ref. [7-63], which is based on ISO 178 applied to general plastics.

In that all standards are effectively undertaking the same test, some common points can be identified. These are:

- The span-to-depth ratio determines the value of the apparent flexural modulus. In this case depth is the specimen thickness.
- Tensile and compressive failures are acceptable but shear is not.
- The radius of the specimen supports can be important in determining the failure mode.
- Claims are made that a transverse flexural test for 90° laminates is not as sensitive to surface flaws as a conventional tensile specimen and consequently produces higher, more realistic tensile strength values, Ref. [7-44].

Table 7.16-1 - Flexural test standards

Flexural Test Method (Standard)	Comments
EN ISO/F-DIS 14,125: Suitable for all fibre-reinforced plastics.	Four classes of composites with different specimen sizes and spans. 4-point loading included. Equivalent to ISO 178 for plastics.
ASTM D790-92: Flexural properties of reinforced plastics.	Not a D-30 standard but general to plastics. Covers 3-point and 4-point loading. Recommended test dimensions given.
prEN 2562: Covers unidirectional epoxy CFRP.	Three point bending only.
Applicable **DIN** standards: **DIN 29971**.	Three point bending. Attention given to supports of smooth profile.
CRAG Methods: **200**: Flexural strength and modulus of FRP.	Three point bending. Recommended test dimensions. Calculation methods provided.

7.17 Short-beam interlaminar shear test

7.17.1 Uses

Short-beam interlaminar shear tests are suitable for:

- Material procurement.
- Quality control.

As with the flexural test, [See: 7.16], primarily it provides a qualitative assessment of laminates, Ref. [7-9], [7-54].

The method is simple, low cost and quick to undertake. As defined in ASTM D 2344, it is a three-point bend test where the span-to-depth ratio is:

- 4:1 for fibre modulus up to 100GPa, e.g. glass, and
- 5:1 for greater than 100GPa, e.g. carbon.

This ensures that shear failure occurs. Likely failure modes can be classified as shown in Table 7.17.1.

Table 7.17-1 - Short beam / interlaminar shear test: Likely failure modes

Failure Mode	
Single shear	VALID
Multiple shear	VALID
Plastic deformation with evidence of shear failure	VALID
Flexural failure (tensile or compressive)	INVALID

Under hygrothermal conditions, this test provides a good indication of the matrix characteristics, e.g.:

- State of cure,
- Interlaminar integrity, and
- Shear stability.

The shear strength values from the ILSS method are usually an overestimation of the actual interlaminar strengths. More accurate measurement of true interlaminar shear strength of laminates is best obtained using other test methods, i.e.

- In-plane shear testing, [See: 7.11].
- ±45° laminate tensile specimen, [See: 7.12].
- Double V-notched beam shear test, [See: 7.13].
- Two- and three-rail shear test, [See: 7.14].

7.17.2 Standards

The appropriate standards are:

- ISO 4585 for GRP, with 2.0mm default thickness.
- EN ISO/F-DIS 14,130, with 2.0mm default thickness, but scaling factors for other thicknesses. This is based on ISO 4585 with inputs from other standard, i.e.:
  - ASTM D2344-84 (1989),
  - prEN 2563,
  - CRAG Method 100.

7.18 Interlaminar fracture toughness testing

7.18.1 Interlaminar toughness of composites

7.18.1.1 General

Delaminations, or interlaminar cracking, are considered to be the most common types of damage in composite materials.

Aircraft constructors are particularly keen to quantify the relationship between interlaminar toughness of laminate constructions and loading modes; either independently or combined. The fracture toughness modes are described as:

- Mode I - opening, cleavage,
- Mode II - sliding, shear,
- Mode III - tearing.

7.18.1.2 Test methods

Various test methods have been devised to assess fracture behaviour, Ref. [7-55], [7-56], [7-57], [7-58]. These include:

- DCB double cantilever beam, as shown in Figure 7.18.1, used for Mode I (GIC). This is most commonly used for CFRP materials.
- CN centre notch for Mode I.
- DT double torsion for Mode I.
- ENF end notch flexure for Mode II (GIIC).
- ENS end loaded split for Mode II used for thin laminates.
- ENCB end notched cantilever beam used for thick laminates.
- CBEN cantilever beam enclosed notch for Mode II.
- EDT edge delamination tension test for mixed Modes I and II, Ref. [7-54].
- CLS cracked lap shear for mixed Modes I and II. This was developed for assessing adhesives.
- DSDCB double split double cantilever beam for Mode III, Ref. [7-54].
- Arcan test arrangement.

For Mode I (G_{IC})

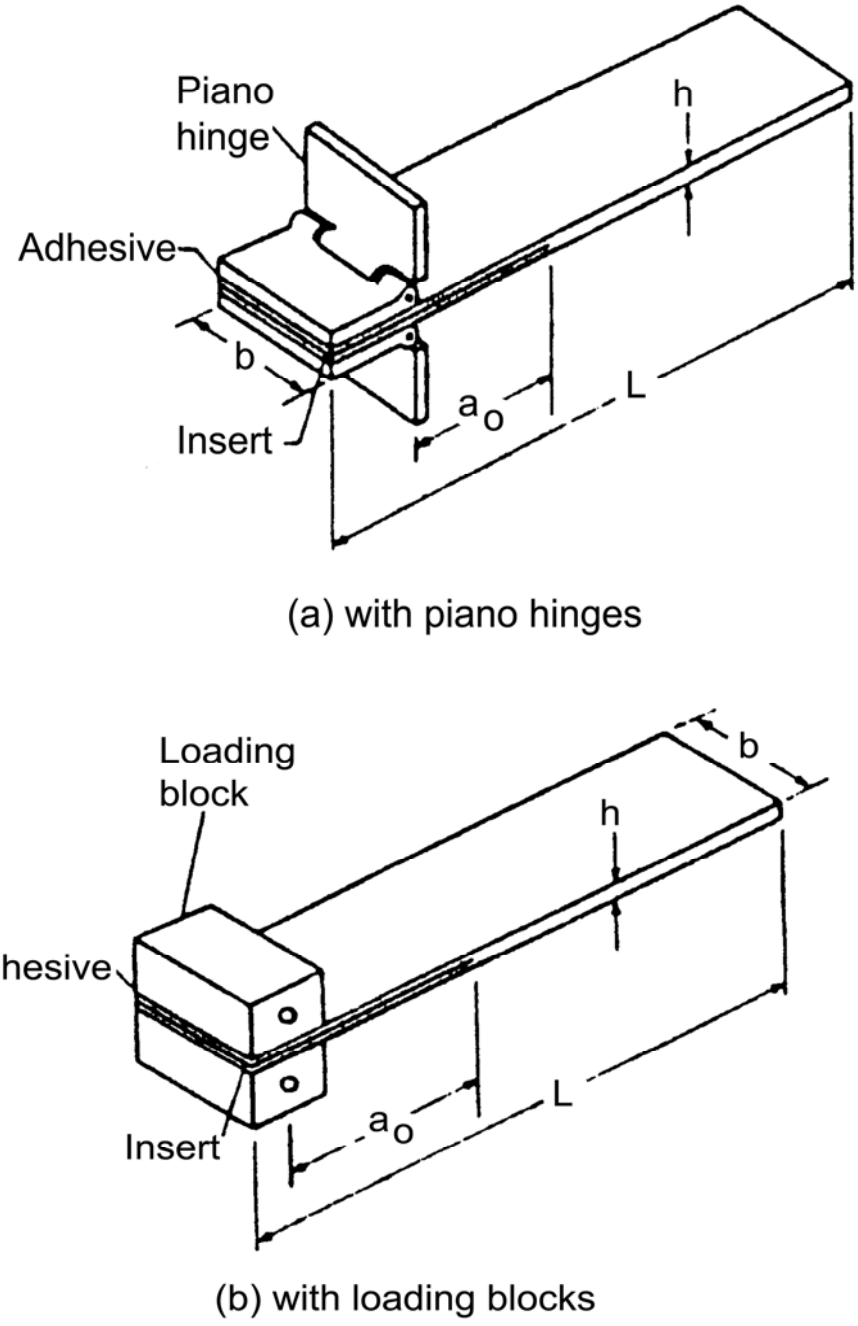

Figure 7.18-1 - ASTM D5528: Double cantilever beam (DCB)

Some of the test methods are covered in the standards given in Table 7.18.1.

NOTE International collaboration in pre-standards research for the development of a Mode II test method is being undertaken via a VAMAS lead project.

Table 7.18-1 - Interlaminar fracture toughness test standards

Test Method (Standard)	Comments
ISO/CD 13,586	Mode I assessment based on ESIS document from USA. (Mode II being studied in VAMAS lead project).
ASTM D 5528 - 94a:	Double cantilever beam - Mode I
Airbus prEN 6033	Determination of Mode I (G_{1c}) for CFRP
Airbus prEN 6034	Determination of Mode II (G_{2c}) for CFRP

7.19 Cyclic load testing

7.19.1 Introduction

Fatigue testing is strongly influenced by the:

- Failure criteria applied,
- Stress state applied (multiaxial, uniaxial),
- Control mode applied (load, displacement),
- Other factors, including:
  - R ratio,
  - specimen shape,
  - test frequency, and
  - waveform.

See Refs. [7-59], [7-60], [7-61]

This makes the generation of international standards somewhat slow, Ref. [7-57]. In many respects, these tests fulfil secondary design requirements and are awaiting the full acceptance of the static mechanical tests.

7.19.2 Standards

The standards worth noting are:

- ISO/CD 13,003, which is intended to cover general principles for fatigue testing.
- ASTM 3479-76 (1990): Test methods for tension-tension fatigue of oriented fibre, resin matrix composites. This is basically an extension of ASTM D-3039 for testing a flat coupon with cycling between either two tensile load limits or two tensile strain limits.
- CRAG Method 500: Preparation of test specimens for the measurement of fatigue properties of FRP either in interlaminar shear, flexural, compressive or tensile loading.

  NOTE This is an advisory document.
- AFNOR T51-120 (1986): Bending fatigue test for reinforced plastics with non-stretch specimens.

7.20 International standards

7.20.1 Introduction

The number of organisations preparing test methods, specifications and standards for aerospace composites exceeds 20 worldwide. These, along with their collaborative activities, can be grouped as:

- Worldwide:
  - ISO.
  - Vienna Agreement for collaboration between ISO and CEN,
  - VAMAS global initiatives for preparing ISO standards.
- USA:
  - ASTM.
  - Others include: SACMA, DoD, NASA, Boeing, SAE, AIAA, NIST.
- Europe:
  - CEN.
  - Others include: AECMA, DIN, BSI, AFNOR, CRAG, GARTEUR, ETAC, Airbus, EFA, BAe, DASA, ESIS.
- Japan: JIS.

It takes a very long time to reach agreement on an accepted international test method standard. In some cases, agreement is never reached and methods are discarded as composite technology moves on.

Ideally, globally-accepted standards are preferable, i.e. ISO. Until recently, these were the least comprehensive in their coverage of standards applicable to aerospace composites.

ISO now publish several draft standards on mechanical testing applicable to CFRP materials in general. These augment other documents applicable to all composites. Where agreement is reached on technical issues, new ISO standards are harmonised with the EN 'general series' and ASTM procedures.

The ASTM aerospace series of test method standards for higher modulus composites is very comprehensive and regular revisions are published.

The European perspective is more complicated because the EN and prEN standards are aligned to different classes of composites, i.e. carbon, aramid and glass. Some of these appear to be perpetually in draft form. The picture is further confused by the overlap between the EN 'general series' produced by CEN and the 'aerospace series' controlled by AECMA and, more recently, Airbus Industries.

The drive towards international ISO standards eventually enforces their adoption as EN equivalents for some test methods.

7.20.2 ISO standards

Table 7.20.1 summarises the standard test methods that are recognised for the assessment of fibre-reinforced composites.

NOTE Contact the issuing authorities for document issue status.

Table 7.20-1 - ISO standards for fibre-reinforced composites

Standard	Title
ISO 291	Test and conditioning atmospheres
ISO 527-4: 1996 (Draft)	Plastics - determination of tensile properties for isotropic and orthotropic fibre reinforced plastic composites
ISO 527-5: 1996 (Draft)	Plastics - determination of tensile properties for unidirectional fibre reinforced plastic composites
ISO 1183-A (70):	Plastic method for determining the density and relative density (specific gravity) of plastics excluding cellular plastics
ISO 1268 Parts 1 to 9	Fibre reinforced plastics - Test plate manufacturing methods. Multiple parts depending on materials and moulding route
ISO 1889 (Draft)	Reinforcement fibres: Determination of twist
ISO 1890 [94] (Draft)	Determination of twist for reinforcing yarns
ISO 3344 (Draft)	Reinforcement products: Determination of moisture content
ISO 3951 [89]	Sampling procedures and charts for inspection of variables
ISO 4602 (Draft)	Woven fabric: Determination of the number of yarns for warp and weft
ISO 4065 (Draft)	Woven fabrics: Determination of mass per unit area
ISO 5025 (Draft)	Woven fabrics: Determination of width and length
ISO 8515 [91]	Determination of compressive properties of GRP materials
ISO 9782 (Draft)	Determination of prepreg volatiles content
ISO 10119 [92]	Determination of density of carbon fibres
ISO 10120 [91]	Determination of linear density of carbon fibres
ISO 10352: 1995(Draft)	Fibre-reinforced plastics - Moulding compounds and prepregs - Determination of mass per unit area
ISO 10548 [94]	Determination of size content of carbon fibres
ISO 10618 [94]	Determination of tensile properties of resin-impregnated carbon fibre yarns
ISO 11566 [96]	Determination of tensile properties of single-filament carbon fibres
ISO 11567 [94]	Determination of filament diameter and cross-sectional area for carbon fibres
ISO 11667 (Draft)	CFRP - measurement of fibre volume fraction
ISO 12114 (Draft)	Prepregs - determination of curing characteristics
ISO 12115 (Draft)	Prepregs - determination of flowability, maturation and shelf life
ISO 13002 (Draft)	Carbon fibre designations
ISO 13003 (Draft)	General principles of fatigue testing for composites
ISO 13586 (Draft)	Measurement of Mode I fracture toughness
ISO 14125: 1996 (Draft)	Fibre-reinforced plastic composites - Determination of flexural properties
ISO 14126: 1996 (Draft)	Fibre-reinforced plastic composites - Determination of compressive properties in the in-plane direction
ISO 14127 (Draft)	Carbon fibre composites - determination of resin and fibre content
ISO 14128 (Draft)	Reactivity of carbon fibre prepregs
ISO 14129: 1996 (Draft)	Fibre-reinforced plastic composites - Determination of the in-plane shear stress strain response, the in-plane shear modulus and strength by the ±45° tension test method
ISO 14130: 1996(Draft)	Fibre-reinforced plastic composites - Determination of apparent interlaminar shear strength by short beam method
ISO 15034 (Draft)	Measurement of resin flow
ISO 15310: 1996 (Draft)	Fibre-reinforced plastic composites - Determination of in-plane shear modulus by the plate-twist method

7.21 ASTM standards

7.21.1 High modulus fibres and composites

Table 7.21.1 summarises all the standard test methods, assembled by ASTM Committee D-30, which are considered suitable for high-modulus, aerospace grade composites.

NOTE Contact the issuing authorities for document issue status.

Table 7.21-1 - American ASTM standards: For high modulus fibres and aerospace composites

A: Guidance and Specimen Preparation

Standard	Title
ASTM D 3544-76 (1989)	Guide for reporting test methods and results on high modulus fibres
ASTM D 3878-95	Terminology of high-modulus reinforcing fibers and their composites
ASTM D 5687/D 5687M-95	Guide for preparation of flat composite panels with processing guidelines for specimen preparation

B: Test Methods

Standard	Title
ASTM C 613-67 (1990):	Test method for resin content of carbon and graphite prepregs by solvent extraction
ASTM D 2290-92	Test method for apparent tensile strength of ring or tubular plastics and reinforced plastics by split disk method
ASTM D 2344-84 (1989):	Test method for apparent interlaminar shear strength of parallel fibre composites by short beam method
ASTM D 2585-68 (1990):	Test method for preparation and tension testing of filament-wound pressure vessels
ASTM D 3039/ D 3039M-95:	Test method for tensile properties of polymer matrix composite materials
ASTM D 3171-76 (1990)	Test method for fibre content of resin-matrix composites by matrix digestion
ASTM D 3379-75 (1989)	Test method for tensile strength and young's modulus for high-modulus single-filament materials
ASTM D 3410/ D 3410M - 94:	Test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading
ASTM D 3479-76 (1990):	Test methods for tension-tension fatigue of orientated fibre, resin matrix composites
ASTM D 3518/D 3518M -91:	Test method for in-plane shear response of polymer matrix composite material by tensile test of a ±45° laminate
ASTM D 3529/D 3529M -90:	Test method for resin solids content of epoxy-matrix prepreg by matrix dissolution
ASTM D 3530/ D 3530M-90:	Test method for volatiles content of epoxy-matrix prepreg
ASTM D 3531-76 (1989):	Test method for resin flow of carbon fibre-epoxy prepreg
ASTM D 3532-76 (1989):	Test method for gel time of carbon fibre-epoxy prepreg
ASTM D 3552-77 (1989)	Test method for tensile properties of fibre-reinforced metal matrix composites
ASTM D 3553-76 (1989)	Test method for fibre content by digestion of reinforced metal matrix composites

Standard	Title
ASTM D 3800-79 (1990):	Test method for the density of high-modulus fibres
ASTM D 4018-93	Test methods for properties of continuous filament carbon and graphite fibre tows
ASTM D 4255/D 4255M-83 (1994)	Guide for testing in-plane shear properties of composite laminates
ASTM D 5229/D 5229M-92	Test method for moisture absorption properties and equilibrium conditioning of polymer matrix composite materials
ASTM D 5300-93	Test method for measurement of resin content and other related properties of polymer matrix thermoset prepreg by combined mechanical and ultrasonic methods
ASTM D 5379/D 5379M-93	Test method for shear properties of composite materials by the V-notched beam method
ASTM D 5448/D 5448M-93	Test method for inplane shear properties of hoop wound polymer matrix composite cylinders
ASTM D 5449/D 5449M-93	Test method for transverse compressive properties of hoop wound polymer matrix composite cylinders
ASTM D 5450/D 5450M-93	Test method for transverse tensile properties of hoop wound polymer matrix composite cylinders
ASTM D 5467-93	Test method for compressive properties of unidirectional polymer matrix composites using a sandwich beam
ASTM D 5528-94a	Test method for mode 1 interlaminar fracture toughness of unidirectional fibre-reinforced polymer matrix composites
NASA NHB8060.lB:	Flammability, odour and offgassing requirements and test procedures for materials in environments that support combustion

7.22 European standards

7.22.1 Introduction

Given the national and commercial interests within Europe, the drafting and acceptance of test methods standards is proving a protracted exercise. The coverage of topics in the 'aerospace series' from AECMA (Association Européenne des Constructeurs de Matériel Aérospatial) and Airbus in 1995 has improved since 1990.

The EN 'general series' now has several new standards, mainly harmonised with ISO which are triple prefixed, i.e. National EN ISO.

NOTE For the current status of standards, contact the issuing authorities.

7.22.2 AECMA aerospace series

The 'aerospace series' EN and prENs, compiled by Committee C7/SC5 of AECMA, are given in Table 7.22.1. The status of standards varies and some are likely to be superseded when new ISO standards are adopted as equivalents.

Table 7.22-1 - AECMA standards for aerospace composites

SAMPLE AND SPECIMEN PREPARATION	
EN 2374: 1991	Production of test panels for glass fibre reinforced mouldings and sandwich constructions (to be replaced by 4177?)
EN 2375: 1992	Sampling procedures for reinforced plastics made from resin pre-impregnated materials
EN 2565: 1987	Preparation of unidirectional carbon fibre reinforced resin panels for test purposes (to be replaced by 4177?)
prEN 2743 ‡	Standard atmospheres for conditioning and testing reinforced plastics
prEN 4177-1 ‡*	Fibre reinforced moulded half-finished products - Preparation of test panels of yarns and rovings by unidirectional winding
prEN 4177-2 ‡*	Fibre reinforced moulded half-finished products - Preparation of test panels of plane reinforcement products
prEN 4177-3 ‡*	Preparation of honeycomb/prepreg sandwich test panels
TEST METHODS - ALL COMPOSITES	
EN 2310: 1992	Requirements and methods for testing inflammability for the qualification of non-metallic materials
EN 2378: 1995	Fibre reinforced plastics - Determination of water absorption by immersion in demineralised water
EN 2489: 1995	Fibre reinforced plastics - Determination of the effects of liquid chemicals
prEN 2823 ‡	Test method for the determination of the effect of exposure to humid atmosphere on physical and mechanical characteristics
prEN 3615 ‡	Fibre reinforced plastics - Test method for the determination of the conditions of exposure to humid atmosphere and the determination of moisture absorption (continued)
prEN 3783 ‡	Procedure of the normalisation of test results of fibre dominated composite mechanical properties

prEN 4238 ‡	Fibre reinforced plastics - Determination of the effect of dry heat on physical and mechanical characteristics
TEST METHODS - GLASS FIBRE COMPOSITES	
EN 2329: 1993	Test method for the determination of mass per unit area of woven textile glass fibre pre-impregnate
EN 2330: 1993	Test method for the determination of the percentage of volatile matter in woven textile glass fibre fabric pre-impregnate
EN 2331: 1993	Test methods for the determination of the resin content of woven textile glass fibre fabric pre-impregnate
EN 2332: 1993	Test method for the determination of the resin flow of woven textile glass fibre fabric pre-impregnate
EN 2377: 1989	Test method for the determination of interlaminar shear properties for glass fibre reinforced plastics
prEN 2746: ‡	Glass fibre reinforced plastics. Determination of flexural properties of 3-point bend method (drafted 1990)
prEN 2747 ‡	Glass fibre reinforced plastics - Determination of tensile properties (drafted 1990)
TEST METHODS - CARBON FIBRE COMPOSITES	
prEN 2557: ‡	Test method for the determination of mass per unit area of a carbon fibre pre-impregnate (drafted 1988)
prEN 2558: ‡	Test method for the determination of percentage of volatile matter in a carbon fibre pre-impregnate (drafted 1988)
prEN 2559: ‡	Test method of the determination of resin and fibre content of a carbon fibre-pre-impregnate (drafted 1988)
prEN 2560: ‡	Test method for the determination of resin flow of a carbon fibre pre-impregnate (drafted 1988)
EN 2561: 1995	Test method for the determination of tensile properties of unidirectional carbon fibre reinforced epoxy resin composites
prEN 2562 ‡	Test method for the determination of flexural properties of unidirectional carbon fibre reinforced epoxy resin composites (drafted 1989)
prEN 2563: ‡	Test method for the determination of interlaminar shear strength of unidirectional carbon fibre reinforced epoxy resin composites (drafted 1989)
prEN 2564: ‡	Test method for the determination of fibre, resin and porosity content of a carbon fibre reinforced resin laminate (drafted 1988)
prEN 2597: ‡	Test methods for the determination of transverse tensile properties of unidirectional carbon fibre reinforced epoxy resin composites
prEN 2598: ‡	Test methods for the qualification and inspection of carbon fibre reinforced thermo-setting plastics
prEN 2850: ‡	Test method for the determination of longitudinal compressive properties of unidirectional carbon fibre reinforced epoxy resin composites
QUALITY AND PRODUCT SPECIFICATIONS	
EN 2000: 1992	Quality Assurance requirements for manufacture and procurement of EN-aerospace standard products
prEN 2833-1: ‡	Technical specification for glass fibre thermosetting preimpregnates – Part 1: General (continued)

prEN 2833-2: ‡	Technical specification for glass fibre thermosetting preimpregnates – Part 2: Glass fabric / epoxy resin preimpregnates curing at up to 125°C for continuous use up to 80°C
prEN 2833-3: ‡	Technical specification for glass fibre thermosetting preimpregnates – Part 3: Qualification/batch release requirements for fabric reinforced epoxy resin cured at up to 180°C for continuous use up to 120°C
prEN 2833-4: ‡	Technical specification for glass fibre thermosetting preimpregnates – Part 4: Qualification/batch release requirements for unidirectional reinforced epoxy resin cured at up to 125°C for continuous use up to 80°C
prEN 2833-5: ‡	Technical specification for glass fibre thermosetting preimpregnates – Part 5: Qualification programme and batch release testing of fabric reinforced phenolic resin preimpregnates for aircraft interiors
prEN 2962: ‡	Technical specification for carbon fibre filament yarn (polyacrylonitrile precursor)
prEN 2963: ‡	Technical specification for high strength carbon fibre yarns with: tensile strength of 3900 MPa, Tensile Modulus of 235 GPa, strain to failure of 1.4% - fibre class F4

STATUS KEY:	EN: Full standards	prEN: Draft standards of which:	† : Officially approved and released ‡ : Under discussion * : Drafting suspended

7.22.3 Airbus standards

Table 7.22.2 summarises documentation from Airbus Industries (as of end-1995). It is proposed that some or all of these become prENs.

Table 7.22-2 - Airbus Industries documentation proposed as prENs

Test Methods	
prEN 6030 ‡	Fibre reinforced plastics - Determination of mechanical degradation due to chemical paint stripper
prEN 6031 ‡	Fibre reinforced plastics - Determination of in-plane shear properties by ±45° tensile test
prEN 6032 ‡	Fibre reinforced plastics - Determination of glass transition temperature
prEN 6033 ‡	Carbon fibre reinforced plastics - Determination of interlaminar fracture toughness energy, Mode I
prEN 6034 ‡	Carbon fibre reinforced plastics - Determination of interlaminar fracture toughness energy, Mode II
prEN 6035 ‡	Fibre reinforced plastics -Determination of notched and unnotched tensile properties
prEN 6036 ‡	Fibre reinforced plastics -Determination of filled hole and unnotched compressive properties
prEN 6037 ‡	Fibre reinforced plastics -Determination of bearing strength
prEN 6038 ‡	Fibre reinforced plastics -Determination of compressive strength after impact (CAI)
prEN 6039 ‡	Fibre reinforced plastics -Determination of exothermic reaction during curing of prepreg materials
prEN 6040 ‡	Non-metallic materials - Analysis of thermoset systems by high pressure liquid chromatography (HPLC)
prEN 6041 ‡	Non-metallic materials - Analysis of uncured material by differential scanning calorimetry (DSC)
prEN 6042 ‡	Analysis of organic compounds by infrared spectroscopy
prEN 6043 ‡	Fibre reinforced plastics -Determination of gel time and viscosity of matrix resins
Quality and Product Specifications	
prEN 6044-1 ‡ **prEN 6044-2 ‡**	AIMS - Carbon fibre reinforced epoxy prepreg
Status Key:	‡ : Under discussion

7.22.4 German DIN standards

Table 7.22.3 gives DIN standards for aerospace composites.

Table 7.22-3 - German DIN standards for aerospace composites

TEST METHODS FOR COMPOSITES	
DIN 65375 (1989)	Fibre reinforced plastics; testing of unidirectional laminates; compression test transverse to fibre direction.
DIN V 65380 (Current 1987) (Draft November 1991)	Fibre reinforced plastics; testing of unidirectional and woven-fabric laminates; compression test.
DIN 65466 (December 1993)	Fibre reinforced plastics; testing of unidirectional laminates; determination of shear strength and shear modulus in tension.
SPECIFICATIONS - GLASS FIBRE COMPOSITES	
DIN 60850 Part 1 (March 1987)	Textile glass; glass filament yarns; designation and types.
DIN 60850 Part 2 (March 1987)	Textile glass filament yarns; technical delivery conditions.
LN 9103 (December 1981)	Aerospace; textile glass; rovings for reinforcement of plastics; dimensions and masses.
DIN 65060 (July 1991)	Aerospace; textile glass; filament rovings for reinforcement of plastics; technical specifications.
LN 9169 (December 1993)	Aerospace; textile glass; E- glass filament fabric; dimensions and masses.
DIN 65066 (August 1991)	Aerospace; textile glass; E- glass filament fabric; technical specification.
LN 29549 (December 1981)	Aerospace: textile glass: pre-impregnated filament glass cloth from E-glass (prepreg): dimensions and masses.
DIN 65090 (July 1979)	Aerospace: textile glass cloth from E-glass (prepreg): technical specification.
SPECIFICATIONS - ARAMID FIBRE COMPOSITES	
DIN 65356 Part 1 (November 1988)	Aerospace; aromatic polyamide (aramid) high tenacity aramid filament yarns; dimensions and masses.
E DIN 65356 Part 2 (November 1988)	Aerospace; aromatic polyamide (aramid); high tenacity aramid filament yarns: technical specification.

SPECIFICATIONS - ARAMID FIBRE COMPOSITES	
DIN 65426 Part 1 (July 1985)	Aerospace; aromatic polyamide (aramid); pre-impregnated woven fabric of high modulus filament yarns (prepreg); dimensions and masses.
DIN 65426 Part 2 (June 1989)	Aerospace; aromatic polyamide (aramid); pre-impregnated fabric of high modulus filament yarns (prepreg) and epoxy resins; technical specification.
DIN 65427 Part 1 (September 1984) (+ Draft November 1990)	Aerospace; aromatic polyamide (aramid); fabric of high-modulus filament yarns - dimensions and masses.
DIN 65427 Part 2 (September 1991)	Aerospace; aromatic polyamide (aramid); fabric of high-modulus filament yarns; technical specification.
SPECIFICATIONS - CARBON FIBRE COMPOSITES	
DIN 65184 (December 1993)	Aerospace; carbon fibres; high performance carbon fibre filament yarns; dimensions and masses.
DIN 29965 (November 1992)	Aerospace; carbon fibres; high performance carbon fibre filament yarns; technical specification.
DIN 65147 Part 1, (April 1987)	Aerospace; carbon fibres; fabric of carbon fibre filament yarns; dimensions and masses.
DIN 65147 Part 2, (April 1987)	Aerospace, carbon fibres; fabric of carbon fibre filament yarns; technical specification.
E LN 29656 (Expired Draft July 1983)	Aerospace; pre-impregnated unidirectional sheets of carbon fibre; dimensions and masses.
DIN 29971 (September 1991)	Aerospace; pre-impregnated unidirectional sheet of carbon fibres and epoxy resin, technical specification.
DIN 65146, Part 1 (September 1991)	Aerospace; pre-impregnated woven fabric of carbon filament yarn and epoxy resin; dimensions and masses.
DIN 65146, Part 2 (September 1991)	Aerospace; pre-impregnated woven fabric of carbon filament yarn and epoxy resins; technical specification.
DIN 65453 (February 1993)	Aerospace; pre-impregnated unidirectional sheet of carbon fibre and bismaleimide - polyimide resin; technical specification.
Status Key:	'E' prefix denotes Draft.

7.22.5 United Kingdom test methods

CRAG, the UK composites research advisory group, test methods for the 'Measurement of the Engineering Properties of Fibre-reinforced Plastics' are listed in Table 7.22.4.

Table 7.22-4 - United Kingdom CRAG test methods for composites

Shear Test Methods:	
Method 100	Method of test for interlaminar shear strength of fibre reinforced plastics (QC)
Method 101	Method of test for in-plane shear strength and modulus of fibre reinforced plastics (PDD)
Method 102	Method of test for lap shear strength of fibre reinforced plastics (SDD)
Flexural Test Methods:	
Method 200	Method of test for flexural strength and modulus of fibre reinforced plastics (QC)
Tensile Test Methods:	
Method 300	Method of test for the longitudinal tensile strength and modulus of unidirectional fibre reinforced plastics (PDD)
Method 301	Method of test for the transverse tensile strength and modulus of unidirectional fibre reinforced plastics (PDD)
Method 302	Method of test for the tensile strength and modulus of multidirectional fibre reinforced plastics (PDD)
Method 303	Method of test for the notched tensile strength of multidirectional fibre reinforced plastics (SDD)
Compression Test Methods:	
Method 400	Method of test for longitudinal compression strength and modulus of unidirectional fibre reinforced plastics (PDD)
Method 401	Method of test for longitudinal compression strength and modulus of multidirectional fibre reinforced plastics (PDD)
Method 402	Method of test for notched compression strength of multidirectional fibre reinforced plastics (SDD)
Method 403	Method of test for residual compression strength after impact of multidirectional fibre reinforced plastics (SDD)
Test Methods for Fatigue Properties:	
Method 500	Methods for the preparation of test specimens for the measurement of fatigue properties of fibre reinforced plastics (SDD)
Test Methods for Toughness:	
Method 600	Method of test for interlaminar fracture toughness of fibre reinforced plastics (SDD)
Test Methods for Bearing Properties:	
Method 700	Method of test for bearing properties of multi- directional fibre reinforced plastics (SDD)
Physical Properties Test Methods:	
Method 800	Method of test for the density of fibre reinforced plastics (QC)
Method 801	Method of test for the determination of the coefficient of linear thermal expansion of fibre reinforced plastics
Method 802	Method of test for the outgassing of fibre reinforced plastic
Environmental Effects:	

Method 900	Background information on environmental effects
Method 901	Method of assessment of diffusivity properties of fibre reinforced plastics
Method 902	Method of conditioning of fibre reinforced plastics under hot/wet environments
Miscellaneous Tests:	
Method 1000	Methods of assessment of fibre volume fraction of fibre reinforced plastics (PDD)
Method 1001	Method of assessment of void volume fraction of fibre reinforced plastics by ultrasonic scanning (PDD)
Key: Intended uses for test method: PDD - Primary Design Data; SDD - Secondary Design Data; QC - Quality Control.	

7.22.6 European space standards

Prior to 1993, ESA published a comprehensive series of standards and specifications under the PSS documentation system.

The European Cooperation for Space Standardization (ECSS), of which ESA is an active participant, began developing a uniform system of space standards and requirements across Europe, Ref. [7-64]. These are replacing the ESA PSS documents covering the same subject matter. A number of ECSS standards have been released and many more under development. ECSS standards do not yet have the same comprehensive coverage of the previous PSS documents.

[See also: Annex A]

NOTE During the period of transition from PSS to ECSS, the status of European space standards can be ascertained from the ECSS secretariat website.

Table 7.22.5 summarises the ECSS of direct relevance to the testing of composite materials.

[See also: ECSS-Q-ST-70 - Space product assurance - Materials, mechanical parts and processes; ECSS-Q-70-71 - Space product assurance - Data for selection of space materials and processes]

Table 7.22-5 - ECSS standards for aerospace composites

Number	Title
ECSS-Q-ST-70-02	Thermal vacuum outgassing test for the screening of space materials
ECSS-Q-ST-70-04	Thermal testing for the evaluation of space materials, processes, mechanical parts and assemblies
ECSS-Q-ST-70-21	Flammability testing for the screening of space materials
ECSS-Q-ST-70-22	Control of limited shelf-life materials
ECSS-Q-ST-70-29	Determination of off-gassing products from materials and assembled articles to be used in a manned space vehicle crew compartment

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7.23.2 Sources

Websites for some of the organisations having relevant test methods and standards for aerospace composite materials include:

ISO	International Organization for Standardization
AECMA	Association Européenne des Constructeurs de Matériel Aerospatial
ASTM	American Society for Testing and Materials

NOTE Nationally-based standards organisations also offer advice on the status of particular European standards.

7.23.3 ECSS documents

[See: ECSS website]

ECSS-Q-ST-70	Space product assurance - Materials, mechanical parts and processes; previously ESA PSS-01-70.
ECSS-Q-70-71	Space product assurance - Data for selection of space materials and processes; previously ESA PSS-01-701.
ECSS-Q-ST-70-02	Thermal vacuum outgassing test for the screening of space materials; previously ESA PSS-01-702.
ECSS-Q-ST-70-04	Thermal testing for the evaluation of space materials, processes, mechanical parts and assemblies; previously ESA PSS-01-704.
ECSS-Q-ST-70-21	Flammability testing for the screening of space materials; previously ESA PSS-01-721.
ECSS-Q-ST-70-22	Control of limited shelf-life materials; previously ESA PSS-01-722.
ECSS-Q-ST-70-29	Determination of off-gassing products from materials and assembled articles to be used in a manned space vehicle crew compartment; previously ESA PSS-01-729.

8
Effect of manufacturing practices

8.1 Introduction

The influence of defects on the strength of polymer-based composites is described, Ref. [8-1].

Defects are grouped as:

- Microcracking due to differential thermal expansion of layers and exposure to moisture and sub zero temperatures.
- Residual stresses [See: Clause 18].
- Gaps between tows which produce resin rich seams parallel to the fibres.
- Distorted, broken or cut fibre tows.
- Inclusions, in particular swarf or pieces of backing paper from the preimpregnated layers.
- Voids.
- Kinked plies.

A summary of the types of defect that can occur and the methods used for their detection is also given, [See: 8.3].

[See also: Clause 19 for manufacturing faults and damage tolerant design; Clause 34 for inspection and quality assurance, Clause 17 for some basic design rules and Section VI for more detail on the design of structures]

8.2 Material defects and their effects on strength

8.2.1 General

The effect of defects is considered with respect to:

- Interlaminar shear strength
- Tensile strength
- Compressive strength

[See also: 8.1 for defect groups]

In general, apart from broken or cut tows, none of the defects have a major effect on the structural properties.

In compression, the effect of minor defects on strength is unlikely to be greater than 10%. However, a significant reduction in interlaminar shear strength can be expected in regions of high void content.

[See also: Section VII for damage tolerance and the effect of defects on structural integrity]

8.2.2 Interlaminar shear strength

Figure 8.2.1 shows that voids, moisture and freeze cycling decrease the interlaminar shear strength, Ref. [8-1]. A reduction of more than 16% occurs if the voiding is as high as 7%.

Definition	Void Content
Low Voiding	< 0.9%
Medium Voiding	0.9 - 3.0%
High Voiding	> 3.0%

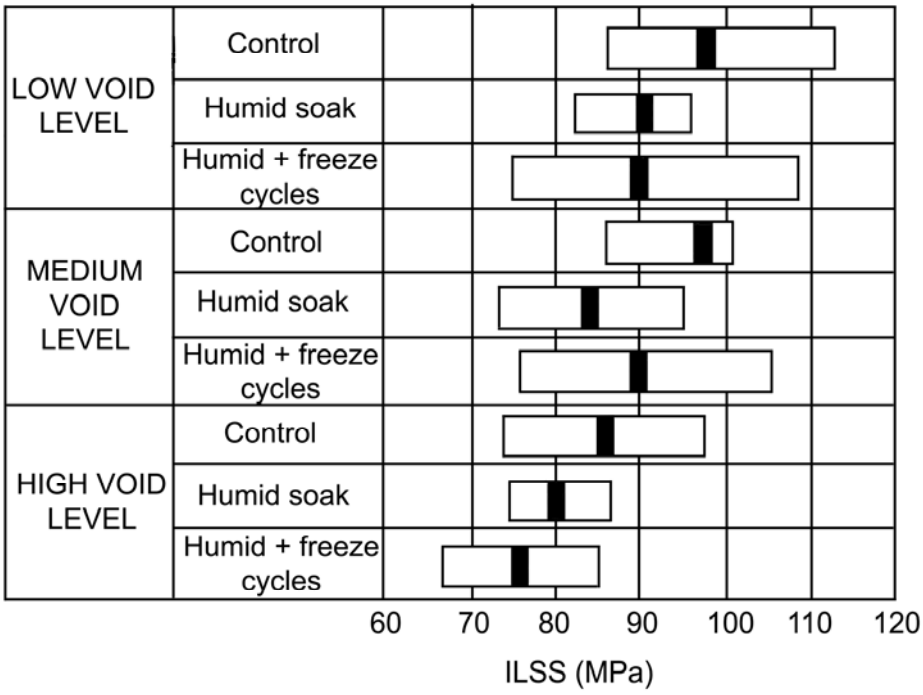


Figure 8.2-1 - Variation of interlaminar shear strength with void content and preconditioning

Paper inclusions with exposure to moisture reduce the interlaminar shear by approximately 20%, as shown in Figure 8.2.2, Ref. [8-1].

Paper inclusions which completely traverse the specimens produce defects more severe than are likely in practice.

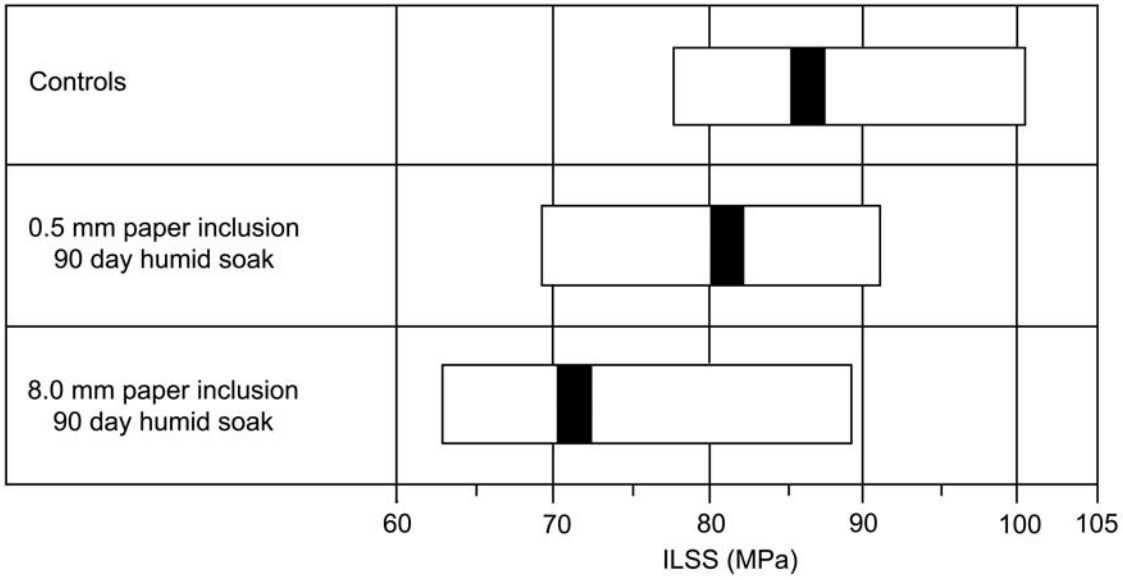


Figure 8.2-2 - Effect of inclusions at mid depth on the interlaminar shear strength

8.2.3 Tensile strength

Figure 8.2.3 shows that the tensile strength of thin skins on sandwich beam specimens with a distorted tow decreases by 15%, Ref. [8-1].

A decrease of 25% occurs for a cut tow; where the tow width was 8% of the specimen width. A significant recovery in strength occurs in this case after fatigue because 0° crack growth reduces the stress concentration at the cut.

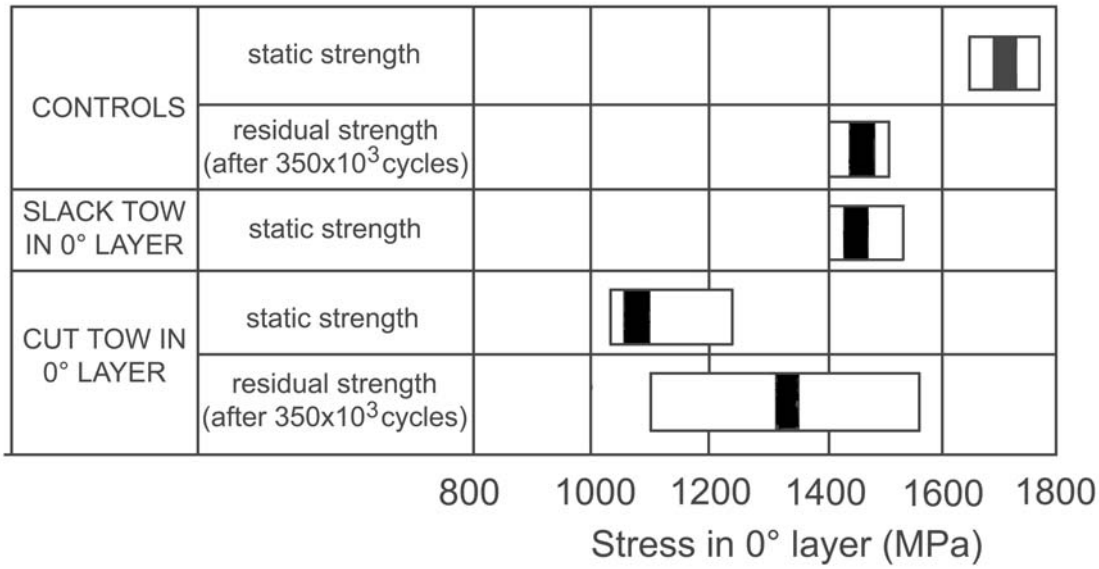


Figure 8.2-3 - Effect of defects in 0° layer on tensile strength of a 0°, ± 45° skin of a sandwich beam

Effects produced by discontinuous and kinked plies in unidirectional carbon fibre reinforced plastic under tension are shown in Figure 8.2.4, Ref. [8-1]. This shows the mean stress at failure on the continuous plies compared with increasing numbers of discontinuous plies and increased ply kinking.

Comparison with the failure stress for specimens without ply defects shows that in all cases discontinuous plies reduce the mean failure stress in the continuous plies by 15%. This is attributed to a stress concentration effect which is independent of the number of discontinuous plies.

A further reduction in the failure stress in the continuous plies occurs with kinking due to the decrease in load-carrying ability of the kinked ply and increased stress concentration. The reduction is greater for increased amounts of kinking and it is associated with delamination as the kinks straightened out. An overall reduction of 28% is obtained for kinking around three discontinuous plies.

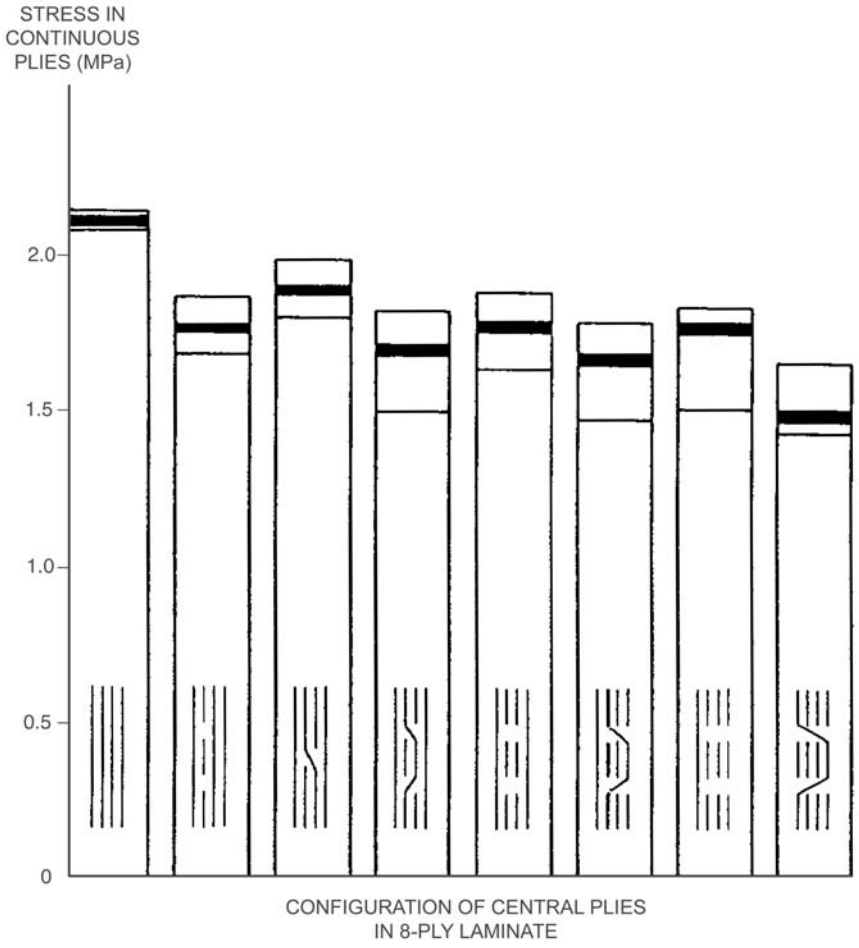


Figure 8.2-4 - Effect of discontinuous and kinked plies on the tensile strength of unidirectional CFRP

8.2.4 Compressive strength

The effects of various defects on the compressive strength of thin skins are shown in Figure 8.2.5, Ref. [8-1].

Gaps in the 0° layer have no significant effect even after exposure to moisture or freeze cycling. There is only a small decrease for a gap in the 45° layer.

A cut tow reduces the strength by about 11% but the residual strength after fatigue is only 7% below the control values.

The most significant decrease is obtained for paper inclusions, which cannot be detected by ultrasonic inspection. Decreases in compressive strength up to 25% are obtained and delamination failures occur. However, for a single 10mm paper inclusion the decrease is only 10%.

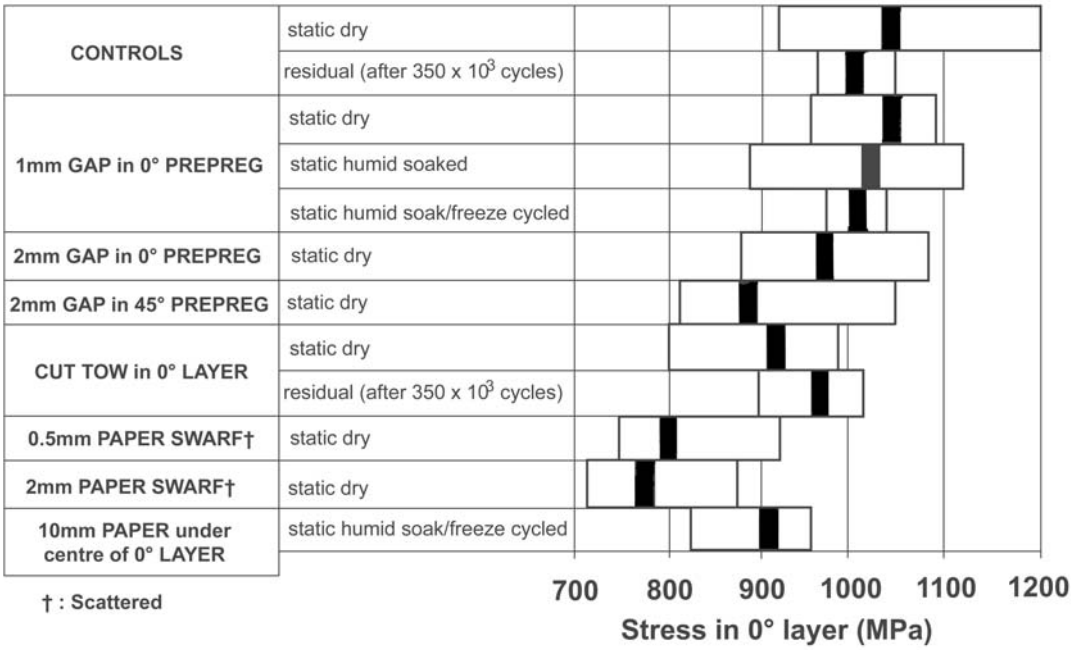


Figure 8.2-5 - Effect of defects on compressive strength of a 0°, ± 45° skin of a sandwich beam

8.3 Defects and their detection

Table 8.3.1 lists defect types and their possible detection by various non-destructive evaluation NDE techniques, Ref. [8-2].

[See also: Clause 19 for manufacturing faults and damage tolerant design; Clause 34 for inspection and quality assurance and Section VII for damage tolerance and the effect of defects on structural integrity]

Table 8.3-1 - Detection of defects by various NDE techniques

Visual	Coin Tapping	Ultrasonic C-scan	X-ray	Holography ‡	Fokker Bond Tester	Acoustic Flaw Detector
Porosity						
Detected if extending to outer surface	Not successful	Preferred method ①②	Successful for severe porosity †	Not successful	Successful for severe porosity †	Not successful
Prepreg Gaps						
Successful on outer surface	Not successful	Preferred method ①②	Successful for severe porosity †	Successful Decreased with increased thickness	Not successful	Not successful
Solvent Contamination						
Not successful	Not successful	Not successful	Not successful	Not successful	Not successful	Not successful
Solid Contamination						
Successful on outer surface	Not successful	Detection ③	Preferred method	Detection ③ and surrounding material	Detection ③ and surrounding material	Detection possible ④
Backing Sheet Contamination						
Detection in thin laminates	Detection in thin laminates	Preferred method for paper backing ⑤	Preferred method for polyethylene backing ⑥	Preferred method	Successful provided ⑦	Successful
Fibre alignment / Lay-up order						
Detection on outer surface	Not successful	Detection of lay-up order by pulse-echo	Preferred method Microfocus	Not successful	Not successful	Not successful
State of Matrix Cure						
Not successful	Not successful	Possibly successful for severe undercure	Not successful	Not successful	Possibly successful for severe undercure	Not successful
Fibre/Resin Ratio						
Successful on outer surface	Not successful	Preferred method	Detection possible	Not successful	Successful for severe variations	Not successful
Prepreg Joints						
Successful on outer surface	Not successful	Detection in thin laminates	Preferred method in thin laminates	Detection in thin laminates	Not successful	Not successful

Visual	Coin Tapping	Ultrasonic C-scan	X-ray	Holography ‡	Fokker Bond Tester	Acoustic Flaw Detector
Interply Delaminations						
Successful in thin laminates	Successful in thin laminates	Preferred method ① ②	Not successful	Preferred method	Good detection	Good detection
Skin-to-Core Debonding						
Successful if outer surface is disturbed	Successful for thin skins	Preferred method ① ②	Not successful	Preferred method	Good detection	Preferred method
Resin Microcracks						
Successful on outer surface	Not successful	Possible detection ③	Preferred method Microfocus ③	Not successful	Not successful	Not successful
Damaged Honeycomb Core						
Successful if outer surface is disturbed	Not successful	Possible detection	Preferred method Conventional	Possible detection	Not successful	Not successful
Honeycomb Joints						
Not successful	Not successful	Possible detection	Preferred method	Possible detection	Not successful	Not successful
Misplaced Potting Compound						
Successful for thin skins only	Successful for thin skins only	Good location	Preferred method Conventional	Good location	Good location	Good location
Edge Member/Shear Disbond						
Not successful	Not successful	Not successful	Preferred method	Possible detection	Possible detection Depends upon structure	Not successful

Key:
† Pore size >0.1 mm dia.
‡ Non-contact
① Water-coupled probes
② Dry-coupled roller probes
③ Depending on size and orientation
④ If damage is caused when the composite is strained
⑤ Less suitable for polyethylene backing
⑥ Less suitable for paper backing
⑦ If backing sheet does not adhere to prepreg

8.4 References

8.4.1 General

[8-1] 'The significance of defects on the failure of composites'
AGARD Report No. 690

[8-2] 'Guidelines for the non destructive examination of advanced fibre composite materials for spacecraft applications'
Fulmer Research Laboratories, UK
ESA Contract 4389/80/NL/AK(SC)

9
Data for polymer composite materials

9.1 Introduction

The data given here form the basis for laminate design, [See also: Clause 3].

The materials described are either used in the aerospace industry or are viewed as having significant use in future projects.

The data are for:

- Epoxy-based composite systems: established and fully characterised with reinforcing fibres of:
- Carbon high strength HT fibres, [See: 9.3; 9.4; 9.7].
- Carbon high modulus HM fibres, [See: 9.5; 9.8].
- Aramid, [See: 9.6].
- Bismaleimide-based composite systems: emerging materials needing further evaluation, [See: 9.9; 9.10 for carbon intermediate modulus IM fibres].
- Polyimide-based composite systems: emerging materials needing further evaluation, [See: 9.11; 9.12; 9.13].
- Thermoplastic matrix composite systems: emerging materials needing further evaluation, [See: 9.14; 9.15; 9.16].

The data were compiled from openly published literature (as referenced) or were submitted directly for inclusion in the handbook from the sources indicated. The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative only.

The data in any given data sheet refer only to the batch of material from which the samples were taken. When using a data sheet, always take into account:

- Uni- or bidirectional material
- Fibre content
- Cure schedules: cure and post cure
- Moisture content, and conditioning
- Temperature at which the property is stated.

[See also: 9.2 for notation used on data sheets]

9.2 Data sheet notation

E_x	Young's modulus in 0° direction. ($Ex = E_1$ for other notations)
E_y	Young's modulus in 90° direction. ($Ey = E_2$ for other notations)
σ	An ultimate strength.
ε	An ultimate strain to failure.
ν_{xy}	In-plane Poisson's ratio.
G_{xy}	In-plane shear modulus.
τ_{xy}	In-plane shear strength.
$\tau_{[0]}$	Interlaminar shear strength for 0° (unidirectional) laminate.
$\tau_{[0,\pm45]}$	Interlaminar shear strength for 0°/±45° laminate.
$\tau_{(flex)}$	Flexural strength for 0° unidirectional laminate.
$\bar{x}$	Mean value.
S.D.	Standard deviation.
C of V %	Co-efficient of variation. (thermoplastic composites)
N	Number of specimens.
Suffix x	0° or longitudinal direction.
Suffix y	90° or transverse direction.

Units:

1 MPa = 1 N/mm²
1 GPa = 1000 MPa

NOTE 1 I. H indicates an 'in-house' evaluation test method. If known, the test standard used is stated for the particular property.

NOTE 2 All data are presented to the stated notation. Data for tensile and compressive properties are separated in the various tables.

9.3 Epoxy matrix composites

9.3.1 Resin systems

Various epoxy resins combined with a reinforcement fibre are established structural materials for aerospace use.

[See: Clause 2]

9.3.2 Fibre reinforcements

Epoxy resins are combined with either carbon, aramid, glass fibres. In some cases, 'hybrid' reinforcements are used which are a mix of two or more types of fibres.

[See: 2.3; 3.3 and 6.2 for new and development fibres]

9.4 Unidirectional carbon HT/epoxy composite

9.4.1 General

Materials data sheets are provided for:

- Cytec: T300/Fiberite 976; previously Fiberite
- Hexcel:
  - T300/Fibredux 914; previously Ciba Geigy
  - T300/Hexcel F593
  - T300/Hexcel F115
  - T300/Hexcel F593-7

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative only.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.4.2 T300/Fiberite 976

Table 9.4-1 - Data sheet for UD carbon HT/epoxy (Fiberite HY-E 1076-E)

Supplier/Trade Name Fiberite HY-E 1076E	Fibre/Resin System T300 (6K) Epoxy: Fiberite 976		Data Source 1	
Fibre vol (%): 70	t_{ply} (mm): 0.14		Density (kg/m^3): 1620	
Areal weight (g/m^2): -		Year of test: 1984/85		
Specimen condition: 177°C cure. Aged 70°C/88% RH - saturated, 0.45 wt% moisture				
Test environment: 80°C		$\bar{x}$	S.D.	N
Tension:	E_x (GPa)	161	6.3	15
I.H.	σ_x (MPa)	1745	65.5	15
	ε_x (%)	1.04	0.045	15
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	146.8	2.7	10
I.H.	σ_x (MPa)	1028	75.4	5
	ε_x (%)	0.75	0.2	7
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio: I.H.	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	4.40	0.353	9
I.H.	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS): $l/t = 5$	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.4-2 - Data sheet for UD carbon HT/epoxy (Fiberite HY-E 1076-E)

Supplier/Trade Name Fiberite HY-E 1076E	Fibre/Resin System T300 (6K) Epoxy: Fiberite 976			Data Source 1
Fibre vol (%): 70	t_{ply} (mm): 0.14			Density (kg/m^3): 1620
Areal weight (g/m^2): -		Year of test: 1984/85		
Specimen condition: 177°C cure. Aged 60°C/95% RH - saturated, 0.8 wt% moisture				
Test environment: 95°C		$\overline{X}$	S.D.	N
Tension: I.H.	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression: I.H.	E_x (GPa)	149.3	3.21	15
	σ_x (MPa)	963	57.9	15
	ε_x (%)	0.69	0.046	15
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio: I.H.	ν_{xy}	-	-	-
Shear: I.H.	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	63.8	1.83	10
(ILSS): $l/t = 5$	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.4-3 - Data sheet for UD carbon HT/epoxy (Fiberite HY-E 1076-E)

Supplier/Trade Name Fiberite HY-E 1076E	Fibre/Resin System T300 (6K) Epoxy: Fiberite 976	Data Source 1
Fibre vol (%): 70	t_{ply} (mm): 0.14	Density (kg/m^3): 1620
Areal weight (g/m^2): -	Year of test: 1984/85	
Specimen condition: 177°C cure. Specimen dry.		

Test environment: 95°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	161	4.1	18
	σ_x (MPa)	1693	87.8	18
	ε_x (%)	1.01	0.042	18
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	146.1	3.33	15
I.H.	σ_x (MPa)	1141	87.7	50
	ε_x (%)	0.83	0.06	15
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.31	0.017	18
Shear:	G_{xy} (GPa)	4.407	0.141	9
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	94	8.1	10
(ILSS): $l/t = 5$	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	1876	106	15

9.4.3 T300/Hexcel F593-7

Table 9.4-4 - Data sheet for UD carbon HT/epoxy (Hexcel T3T-190-12-F593-8)

Supplier/Trade Name Hexcel T3T-190-12-F593-8	Fibre/Resin System T300 (3K) Toughened Epoxy: Hexcel F593-7		Data Source 2	
Fibre vol (%): 55	t_{ply} (mm): 0.207		Density (kg/m^3): 1500	
Areal weight (g/m^2): 305			Year of test: 1984	
Specimen condition: 177°C cure. Specimen Dry.				
Test environment: RT.		$\bar{X}$	S.D.	N
Tension:	E_x (GPa)	135	4.81	5
I.H.	σ_x (MPa)	1613	122	5
	ε_x (%)	1.21	0.096	5
	E_y (GPa)	7.0	-	-
	σ_y (MPa)	40	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	115	3.19	5
I.H.	σ_x (MPa)	1259	138.3	5
	ε_x (%)	1.09	0.105	5
	E_y (GPa)	-	-	-
	σ_y (MPa)	246	-	-
	ε_y (%)	-	-	-
Poisson's ratio: I.H.	ν_{xy}	0.3	-	-
Shear: I.H.	G_{xy} (GPa)	4.5	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	112	7.5	5
(ILSS): I.H.	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	-	-	-

9.4.4 T300/ Fibredux 914

Table 9.4-5 - Data sheet for UD carbon HT/epoxy (Ciba Geigy 914C-TS-5-42)

Supplier/Trade Name Ciba Geigy 914C-TS-5-42	Fibre/Resin System T300 (3K) Epoxy: Fibredux 914		Data Source 4	
Fibre vol (%): 61.5	t_{ply} (mm): 0.125		Density (kg/m^3): 1580	
Areal weight (g/m^2): 225		Year of test: 1985		
Specimen condition: Autoclave cure cycle. 1 hr - 120°C, 1 hr - 175°C, pressure 3.5 bar, vacuum 20 mbar.				
Test environment: 20°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	138.1	7.3	5
ASTM D3039-76	σ_x (MPa)	1573	117	5
	ε_x (%)	1.07	0.07	5
	E_y (GPa)	8.92	0.36	5
	σ_y (MPa)	36.6	6.0	5
	ε_y (%)	0.42	0.07	5
Compression:	E_x (GPa)	120.6	0.82	6
ASTM D3039-76	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	10.25	0.91	6
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio: D3039	ν_{xy}	0.37	0.02	5
Shear:	G_{xy} (GPa)	4.97	0.24	5
ASTM D3518-76	τ_{xy} (MPa)	87.0	0.77	5
Interlaminar shear	$\tau_{(0)}$ (MPa)	81.6	5.2	8
(ILSS): I.H.	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.4-6 - Data sheet for UD carbon HT/epoxy (Ciba Geigy 914C-TS-4-40)

Supplier/Trade Name Ciba Geigy 914C-TS-4-40	Fibre/Resin System T300 (6K) Epoxy: Fibredux 914			Data Source 3
Fibre vol (%): 60	t_{ply} (mm): 0.1			Density (kg/m^3): 1560
Areal weight (g/m^2): -	Year of test: 1984			
Specimen condition: 170°C cure. Batch 75/51891. Humidity 50%.				
Test environment: RT. (23°C)		$\overline{X}$	S.D.	N
Tension: DAN 432	E_x (GPa)	128.7	2.09	25
(E_x, σ_x - Reduced specimen width.)	σ_x (MPa)	1646	93	25
	ε_x (%)	-	-	-
(E_y,σ_y - Waisted specimen)	E_y (GPa)	9.12	0.1	25
	σ_y (MPa)	101	15	25
	ε_y (%)	-	-	-
Compression: I.H.	E_x (GPa)	-	-	-
	σ_x (MPa)	996	74	25
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS): DAN 432	$\tau_{(0\pm45)}$ (MPa)	97	7	25
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.4.5 T300/Hexcel F155

Table 9.4-7 - Data sheet for UD carbon HT/epoxy (Hexcel T3T-190-F155 and T6T-190-F155)

Supplier/Trade Name Hexcel T3T-190-F155/T6T-190-F155	Fibre/Resin System T300 Toughened epoxy: Hexcel F155	Data Source 1
Fibre vol (%): 54	t_{ply} (mm): 0.2	Density (kg/m^3): 1530
Conditions: 120°C cure. High moisture level: 1.7 % wt. (Ageing 70°C/88% RH) Saturated. 'In-service' moisture level: 0.85 % wt. (Ageing 70°C/70% RH) Saturated.		

Mechanical Properties (Average values)

	Basic Value	Multiplication factors for temperature/humidity effects								
Moisture	Dry	Dry			High Moisture Level			In-Service Moisture Level		
Temp(°C)	RT	-55	+50	+70	-55	RT	+70	-55	RT	+50
Tension										
E_x (GPa)	126	0.97		0.97						
σ_x (MPa)	1490	0.95		0.95	0.9	0.95	0.6	0.95	0.95	0.95
ε_x (%)	1.13	0.95		1						
E_y (GPa)	7.1	1		0.6		0.78	0.03			
σ_y (MPa)	48	1		0.75		0.7	0.1			
ε_y (%)	0.65	1		1.25		0.95	4.5			
Compression										
E_x (GPa)	115	1		1		0.95				
σ_x (MPa)	950	1.1	0.85	0.75	1	0.73	0.1	1.1	0.85	0.7
ε_x (%)	0.88	1.2		0.73		0.73				
E_y (GPa)	7.1									
σ_y (MPa)	220									
ε_y (%)										
Poisson's ratio										
ν_{xy}	0.3	1		1						
Shear										
G_{xy} (GPa)	4									
τ_{xy} (MPa)		1.41	0.77	0.73		0.64	0.3			
ILSS										
$\tau_{(0)}$ (MPa)	82									
Flexural										
$E_{(flex)}$ (GPa)	110	1		1	1					
$\sigma_{(flex)}$ (MPa)	1650	1.23		0.75	1.31					

9.4.6 T300/ Hexcel F593

Table 9.4-8 - Data sheet for UD carbon HT/epoxy (Hexcel T6T-190-F593/1a)

Supplier/Trade Name Hexcel T6T-190-F593/1a	Fibre/Resin System T300 Toughened Epoxy: Hexcel F593	Data Source 1
Fibre vol (%): 55	t_{ply} (mm): 0.195	Density (kg/m^3): 1530
Conditions: 177°C cure. High moisture level: Aged at 60°C/90% RH) until saturated 'In-service' moisture level: Aged at 70°C/85% RH) until saturated.		

Mechanical Properties (Average values)										
	Basic Value	Multiplication factors for temperature/humidity effects								
Moisture	Dry	Dry			High Moisture Level			In-Service Moisture Level		
Temp (°C)	RT	-55	+80	+95	-55	RT	+95	-55	RT	+80
Tension										
E_x (GPa)	124	1		1				1	1	1
σ_x (MPa)	1280	0.85		1				0.85	1	1.05
ε_x (%)	0.99	0.9		1				0.9	1	1.05
E_y (GPa)	8.4	1.09								
σ_y (MPa)	46	1.05								
ε_y (%)	0.55	0.95		>1				0.95	>1	>1
Compression										
E_x (GPa)	116	1.05		1		1	1	1.05		1
σ_x (MPa)	1100	1.15		0.75		0.78	0.6	1.15		0.65
ε_x (%)	1.09	1.15		0.75		0.78	0.6	1.1		0.65
E_y (GPa)	100									
σ_y (MPa)	225									
ε_y (%)	3.5									
Poisson's ratio										
ν_{xy}	0.3	1		1						
Shear										
G_{xy} (GPa)	4.7	1.16	0.88	0.85				1.04	0.88	0.77
τ_{xy} (MPa)										
ILSS										
$\tau_{(0)}$ (MPa)	102	1.25		0.78		0.87	0.56			
Flexural										
$E_{(flex)}$ (GPa)	114			1						

9.5 Unidirectional carbon HM/epoxy composite

9.5.1 General

Materials data sheets are provided for:

- Hexcel: HM-S/Fibredux 914; previously Ciba Geigy
- Cytec:
  - GY-70/Code 92; previously Cyanamid Fothergill
  - HMS/Code 69; previously Cyanamid Fothergill
  - P75S/Fiberite 934; previously Fiberite

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.5.2 HM S/ Fibredux 914

Table 9.5-1 - Data sheet for UD carbon HM/epoxy (Ciba Geigy 914C-MS-4-40)

Supplier/Trade Name Ciba Geigy 914C-MS-4-40	Fibre/Resin System Grafil E/HM-S (10K) Epoxy: Fibredux 914		Data Source 3	
Fibre vol (%): 60	t_{ply} (mm): 0.1		Density (kg/m^3): 1640	
Areal weight (g/m^2): -		Year of test: 1984		
Specimen condition: 170°C cure. Batch 75/51487. Humidity 50%.				
Test environment: RT. (23°C)		$\overline{X}$	S.D.	N
Tension: DAN 432	E_x (GPa)	221.7	3.27	6
(E_x, σ_x - Reduced specimen width)	σ_x (MPa)	1121	122	25
	ε_x (%)	-	-	-
(E_y,σ_y - Specimen waisted)	E_y (GPa)	7.31	0.131	6
	σ_y (MPa)	46	6	25
	ε_y (%)	-	-	-
Compression: I.H.	E_x (GPa)	-	-	-
	σ_x (MPa)	898	45	25
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS): DAN 432	$\tau_{(0\pm45)}$ (MPa)	65	8	25
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.5.3 GY - 70/Code 92

Table 9.5-2 - Data sheet for UD carbon HM/epoxy (Cyanamid Fothergill: Celion GY70/Code 92)

Supplier/Trade Name Cyanamid Fothergill	Fibre/Resin System Celion GY-70 Epoxy: Code 92		Data Source 1	
Fibre vol (%): 60	t_{ply} (mm): 0.06		Density (kg/m^3): 1600	
Areal weight (g/m^2): -		Year of test: -		
Specimen condition: 120°C cure.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	298.8	12.7	20
	σ_x (MPa)	788.9	67.3	10
	ε_x (%)	0.251	0.011	9
	E_y (GPa)	4.30	0.2	18
	σ_y (MPa)	18	2.2	18
	ε_y (%)	0.436	0.062	18
Compression:	E_x (GPa)	274.9	12.2	20
	σ_x (MPa)	433.2	53.5	20
	ε_x (%)	0.159	0.027	20
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Celion GY-70 fibre is no longer commercially available.

Table 9.5-3 - Data sheet for UD carbon HM/epoxy (Cyanamid Fothergill: Celion GY70/Code 92)

Supplier/Trade Name Cyanamid Fothergill	Fibre/Resin System Celion GY-70 Epoxy: Code 92	Data Source 1
Fibre vol (%): 60	t_{ply} (mm): 0.06	Density (kg/m$^{3)}$: 1600
Areal weight (g/m^2): -		Year of test: -
Specimen condition: 120°C cure. Specimen dry.		

Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	300.7	13.0	19
	σ_x (MPa)	711.6	67.3	9
	ε_x (%)	0.223	0.011	9
	E_y (GPa)	5.2	0.3	18
	σ_y (MPa)	8.6	1.7	18
	ε_y (%)	0.368	0.048	18
Compression:	E_x (GPa)	275.8	12.6	20
	σ_x (MPa)	509.6	61.3	20
	ε_x (%)	0.196	0.035	20
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.39	0.019	19
Shear:	G_{xy} (GPa)	3.48	0.34	10
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	47.3	4.3	20
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	767.7	30.5	10

Celion GY-70 fibre is no longer commercially available.

9.5.4 HMS/Code 69

Table 9.5-4 - Data sheet for UD carbon HM/epoxy (Cyanamid Fothergill: Courtaulds HMS/Code 69)

Supplier/Trade Name Cyanamid Fothergill		Fibre/Resin System Courtaulds HMS Epoxy: Code 69		Data Source 6
Fibre vol (%): 60±3	t_{ply} (mm): -		Density (kg/m^3): 1600	
Areal weight (g/m^2): -		Year of test: 1986		
Specimen condition: 175°C cure. Specimens as made.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	194.5	9.36	9
	σ_x (MPa)	923	131.0	9
	ε_x (%)	-	-	-
	E_y (GPa)	7.30	0.75	8
	σ_y (MPa)	25.1	5.31	9
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	184.5	17.2	10
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	5.15	0.043	10
	τ_{xy} (MPa)	60.7	2.63	10
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Courtaulds HMS fibre is no longer commercially available.

Table 9.5-5 - Data sheet for UD carbon HM/epoxy (Cyanamid Fothergill: Courtaulds HMS/Code 69)

Supplier/Trade Name Cyanamid Fothergill		Fibre/Resin System Courtaulds HMS Epoxy: Code 69		Data Source 6
Fibre vol (%): 60±3	t_{ply} (mm): -			Density (kg/m^3): 1600
Areal weight (g/m^2): -		Year of test: 1986		
Specimen condition: 175°C cure. Specimens as made.				
Test environment: 150°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	191.4	4.84	14
	σ_x (MPa)	997.4	160.7	15
	ε_x (%)	-	-	-
	E_y (GPa)	6.1	0.38	15
	σ_y (MPa)	27.5	3.57	15
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	167.1	9.66	15
	σ_x (MPa)	694.6	42.3	15
	ε_x (%)	-	-	-
	E_y (GPa)	6.36	0.47	14
	σ_y (MPa)	122.7	17.2	14
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.373	0.054	13
Shear:	G_{xy} (GPa)	2.86	0.041	6
	τ_{xy} (MPa)	50.0	1.51	15
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Courtaulds HMS fibre is no longer commercially available.

9.5.5 P75S/Fiberite 934

Table 9.5-6 - Data sheet for UD carbon HM/epoxy (Fiberite: Thornel P75S/Fiberite 934)

Supplier/Trade Name Fiberite	Fibre/Resin System Thornel P75S Epoxy: Fiberite 934		Data Source 6	
Fibre vol (%): 60±3	t_{ply} (mm): -		Density (kg/m^3): 1780	
Areal weight (g/m^2): -			Year of test: -	
Specimen condition: 180°C cure. Specimens as made.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	271.2	22.35	4
	σ_x (MPa)	853	35.4	4
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	338	38.5	4
	σ_x (MPa)	123.5	4.8	4
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	36.4	4.85	10
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.5-7 - Data sheet for UD carbon HM/epoxy (Fiberite: Thornel P75S/Fiberite 934)

Supplier/Trade Name Fiberite		Fibre/Resin System Thornel P75S Epoxy: Fiberite 934		Data Source 6
Fibre vol (%): 60±3	t_{ply} (mm): -			Density (kg/m^3): 1780
Areal weight (g/m^2): -			Year of test: 1986	
Specimen condition: 180°C cure. Specimens as made.				
Test environment: 100°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	298.8	3.50	4
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	340	27.9	4
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.6 UD aramid/epoxy composite

9.6.1 General

Materials data sheets are provided for:

- Twaron HM/Bakelite VE3543.
- Hexcel: Twaron HM/Ciba Geigy 913; previously Ciba Geigy.

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.6.2 Twaron HM/Bakelite VE3543

Table 9.6-1 - Data sheet for UD aramid/epoxy (Twaron HM 1055/Bakelite VE3543)

Supplier/Trade Name -	Fibre/Resin System Twaron HM 1055 Epoxy: Bakelite VE3543		Data Source 8	
Fibre vol (%): 63.9	t_{ply} (mm): 0.122		Density (kg/m^3): -	
Areal weight (g/m^2): 106			Year of test: 1989	
Specimen condition: 177°C cure, dry, no artificial ageing.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension: DIN	E_x (GPa)	63.9	2.1	6
	σ_x (MPa)	1308	57	6
	ε_x (%)	1.95	0.06	6
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression: DIN	E_x (GPa)	50.2	3.1	6
	σ_x (MPa)	259	4.8	6
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	5.72	0.51	6
	τ_{xy} (MPa)	93.2	2.08	6
Interlaminar shear	$\tau_{(0)}$ (MPa)	55.2	1.77	6
(ILSS): $l/t = 5$	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	637	12.4	6

Table 9.6-2 - Data sheet for UD aramid/epoxy (Twaron HM 1055/Bakelite VE3543)

Supplier/Trade Name -	Fibre/Resin System Twaron HM 1055 Epoxy: Bakelite VE3543		Data Source 8
Fibre vol (%): 63.9	t_{ply} (mm): 0.122		Density (kg/m^3): -
Areal weight (g/m^2): 106		Year of test: 1989	
Specimen condition: 177°C cure, aged 14 days at 70°C in water.			

Test environment: 70°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression: DIN	E_x (GPa)	54.5	3.0	6
	σ_x (MPa)	208	3.9	6
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	1.85	0.43	6
	τ_{xy} (MPa)	38.8	0.97	6
Interlaminar shear	$\tau_{(0)}$ (MPa)	43.9	1.56	6
(ILSS): $l/t = 5$	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	540	25.3	6

9.6.3 Twaron HM/Ciba Geigy 913

Table 9.6-3 - Data sheet for UD aramid/epoxy (experimental product: Ciba Geigy SX913/45/100)

Supplier/Trade Name Ciba Geigy SX913/45/100 (Experimental Product)		Fibre/Resin System Twaron HM 1057 Epoxy: Ciba 913		Data Source 8
Fibre vol (%): 52.2		t_{ply} (mm): 0.113		Density (kg/m^3): -
Areal weight (g/m^2): 106			Year of test: 1989	
Specimen condition: 120°C cure, dry, no artificial ageing.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	66.2	3.5	5
	σ_x (MPa)	1159	71.3	5
	ε_x (%)	1.68	0.11	5
	E_y (GPa)	5.28	3.5	4
	σ_y (MPa)	19.2	71.3	4
	ε_y (%)	0.37	0.11	4
Compression: DIN	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	73.5	-	4
Interlaminar shear (ILSS): $l/t = 5$	$\tau_{(0)}$ (MPa)	59.0	3.85	14
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: $l/t = 40$	$\sigma_{(flex)}$ (MPa)	516	12.4	14

9.7 Single ply fabric carbon HT/epoxy composite

9.7.1 General

Materials data sheets are provided for:

- Hexcel: T300/Hexcel F593.

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.7.2 T300/F593

Table 9.7-1 - Data sheet for single ply fabric carbon HT/epoxy (Hexcel W3T-282-42-F593-1)

Supplier/Trade Name Hexcel W3T-282-42-F593-1		Fibre/Resin System T300 (3K) Plain Weave (282) Epoxy: F593		Data Source 2
Fibre vol (%): 44		t_{ply} (mm): 0.237		Density (kg/m^3): 1450
Areal weight (g/m^2): 345			Year of test: 1984	
Specimen condition: Dry.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	52.4	2.65	5
x = warp	σ_x (MPa)	554	42.6	5
y = weft	ε_x (%)	1.05	0.094	5
	E_y (GPa)	50.6	0.86	5
	σ_y (MPa)	553	41.8	5
	ε_y (%)	1.09	0.079	5
Compression:	E_x (GPa)	45.1	2.84	5
	σ_x (MPa)	574	50.1	5
	ε_x (%)	1.28	0.167	5
	E_y (GPa)	46.0	2.28	5
	σ_y (MPa)	625	33.3	5
	ε_y (%)	1.39	0.101	5
Poisson's ratio:	ν_{xy}	0.06	-	-
Shear:	G_{xy} (GPa)	3.5	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	73.1	6.51	5
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.8 Single ply fabric carbon HM/epoxy composite

9.8.1 General

Materials data sheets are provided for:

- Cytec: GY-70/Fiberite 934; previously Fiberite.
- Hexcel; previously Brochier:
  - M40/Fibredux 914.
  - M40 (warp):T300 (weft)/Fibredux 914.

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.8.2 M40/Fibredux 914

Table 9.8-1 - Data sheet for single ply fabric carbon HM/epoxy (Brochier SA: Vicotex 914-44% G821)

Supplier/Trade Name Brochier S.A. Vicotex 914-44% G821	Fibre/Resin System Toray M40B (3K) Satin 4 Weave Epoxy: Fibredux 914			Data Source 3
Fibre vol (%): 50	t_{ply} (mm): 0.233		Density (kg/m^3): 1560	
Areal weight (g/m^2): 375		Year of test: 1984		
Specimen condition: 170°C cure, Batch 4.04.25.P. Humidity 50%.				
Test environment: 23°C		$\overline{X}$	S.D.	N
Tension: I.H.	E_x (GPa)	95.3	1.5	12
x = warp	σ_x (MPa)	34.1	39	12
y = weft	ε_x (%)	-	-	-
	E_y (GPa)	88.1	4.7	12
	σ_y (MPa)	352	34	12
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	-	-	-
	σ_x (MPa)	312	32	12
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	298	41	12
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	37	4	12
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.8.3 M40 (warp):T300 (weft)/Fibredux 914

Table 9.8-2 - Data sheet for single ply fabric carbon HM/epoxy (Brochier SA: Vicotex 914-34% G829)

Supplier/Trade Name Brochier S.A. Vicotex 914-34% G829	Fibre: Toray M40B (3K) warp 90% Toray T300 (1K) weft 10% Resin : Epoxy: Fibredux 914			Data Source 2
Fibre vol (%): 58	t_{ply} (mm): 0.18		Density (kg/m^3): 1500	
Areal weight (g/m^2): 318		Year of test: 1988		
Specimen condition: 177°C cure, Specimen dry.				
Test environment: RT.		$\bar{x}$	S.D.	N
Tension:	E_x (GPa)	195.1	1.66	6
x = warp	σ_x (MPa)	-	-	-
y = weft	ε_x (%)	-	-	-
	E_y (GPa)	19.7	0.39	6
	σ_y (MPa)	146	7.3	6
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	167.1	3.55	6
	σ_x (MPa)	668	33.3	6
	ε_x (%)	-	-	-
	E_y (GPa)	16.4	0.4	6
	σ_y (MPa)	269	9	6
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.155	-	-
Shear:	G_{xy} (GPa)	4.1	0.19	6
	τ_{xy} (MPa)	73	9.2	6
Interlaminar shear	$\tau_{(0)}$ (MPa)	70.2	2.0	6
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.8.4 GY-70 SE/Fiberite 934

Table 9.8-3 - Data sheet for single ply fabric carbon HM/epoxy (Fiberite: Celion GY70-E/Fiberite 934)

Supplier/Trade Name Fiberite	Fibre/Resin System Celion GY-70E. 8 Harness Satin Epoxy: Fiberite 934			Data Source 6
Fibre vol (%): 54±4	t_{ply} (mm): -			Density (kg/m^3): 1700
Areal weight (g/m^2): -			Year of test: 1986	
Specimen condition: 180°C cure, Specimen as made.				
Test environment: RT.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	123.3	1.97	5
	σ_x (MPa)	208.9	31.5	5
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	182.5	7.77	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	108.7	21.9	4
	σ_x (MPa)	255.1	24.5	4
	ε_x (%)	-	-	-
	E_y (GPa)	79.6	16.1	5
	σ_y (MPa)	171.6	20.9	5
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	27	2.28	10
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Celion GY-70 fibre is no longer commercially available.

Table 9.8-4 - Data sheet for single ply fabric carbon HM/epoxy (Fiberite: Celion GY70-E/Fiberite 934)

Supplier/Trade Name Fiberite	Fibre/Resin System Celion GY-70E. 8 Harness Satin Epoxy: Fiberite 934			Data Source 6
Fibre vol (%): 54±4	t_{ply} (mm): -			Density (kg/m^3): 1700
Areal weight (g/m^2): -				Year of test: 1986
Specimen condition: 180°C cure, Specimen as made.				
Test environment: 100°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	135.0	6.67	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	102.6	8.9	5
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	111.5	12.9	4
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	83.9	16.7	5
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	-	-	-
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.9 Bismaleimide matrix composites

9.9.1 Resin systems

Bismaleimides are thermosetting resin systems which offer improved thermal and hydrolytic stability over epoxy-based resin systems. They are addition polymerisation resins and produce no by-products, such as water during the cross-linking reaction. Modifications to resin formulations have reduced the brittle tendency of earlier resins, [See: 6.6].

9.9.2 Reinforcement fibres

Carbon fibres are most commonly used with bismaleimide resin systems. These are either the commercial fibres used with epoxy resins or the newer IM intermediate modulus fibres, as they become available, [See: 6.7].

9.10 Unidirectional carbon IM/bismaleimide composite

9.10.1 General

Materials data sheets are provided for:

- Cytec: T800/Narmco 5250-2; previously Narmco BASF
- Hexcel : Vicotex: T800/Ciba Geigy SX 5564; previously Brochier

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.10.2 T800/Narmco 5250-2

Table 9.10-1 - Data sheet for UD carbon IM/bismaleimide (Narmco: Toray T800/Narmco 5250-2)

Supplier/Trade Name Narmco (BASF)		Fibre/Resin System Toray T800 Narmco 5250-2		Data Source Ref. [1]
Fibre vol. (%): 59±1	t_{ply} (mm): -		Density (kg/m^3): 1600	
Areal weight (g/m^2): -		Year of test: 1987		
Specimen condition: 190°C cure + 6 hour post-cure at 243°C. Dried at 70°C.				
Test environment: -60°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	162.4	0.66	5
	σ_x (MPa)	2474	161	5
	ε_x (%)	1.48	0.08	5
	E_y (GPa)	9.96	0.13	3
	σ_y (MPa)	31.8	4.0	3
	ε_y (%)	0.34	0.05	3
Compression:	E_x (GPa)	155.3	2.8	4
	σ_x (MPa)	1010	82.8	5
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.33	0.01	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-2 - Data sheet for UD carbon IM/bismaleimide (Narmco: Toray T800/Narmco 5250-2)

Supplier/Trade Name Narmco (BASF)	Fibre/Resin System Toray T800 Bismaleimide: Narmco 5250-2		Data Source: Ref. [1]
Fibre vol. (%): 59 ± 1	t_{ply} (mm): -	Density (kg/m^3): 1600	
Areal weight (g/m^2):		Year of test: 1987	
Specimen condition: Cured at 190°C with 6-hour post-cure at 243°C. Dried at 70°C			

Test environment: R.T		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	163.6	3.49	6
	σ_x (MPa)	2601	116	6
	ε_x (%)	1.53	0.05	6
	E_y (GPa)	9.72	0.04	3
	σ_y (MPa)	36.0	5	3
	ε_y (%)	0.37	0.05	3
Compression:	E_x (GPa)	156.9	4.7	7
	σ_x (MPa)	884	140	9
	ε_x (%)	-	-	-
	E_y (GPa)	10.17	0.46	5
	σ_y (MPa)	304	24	4
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.31	0.005	5
Shear:	G_{xy} (GPa)	50.8	7.0	2
	τ_{xy} (MPa)	82.2	1.7	7
Interlaminar shear	$\tau_{(0)}$ (MPa)	116.2	3.34	6
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-3 - Data sheet for UD carbon IM/bismaleimide (Narmco: Toray T800/Narmco 5250-2)

Supplier/Trade Name: Narmco (BASF)	Fibre/Resin System: Toray T8OO Bismaleimide: Narmco 5250-2		Data Source: Ref. [1]	
Fibre vol. (%): 59 ±1	t_{ply} (mm): -		Density (kg/m^3): 1600	
Areal weight (g/m^2):		Year of test: 1987		
Specimen condition: Cured at 190°C with 6-hour post-cure at 243°C. Boiled in water for 120 hours.				
Test environment: R.T.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	178.6	2.5	5
	σ_x (MPa)	2627	229	5
	ε_x (%)	1.41	0.11	5
	E_y (GPa)	9.31	0 14	4
	σ_y (MPa)	28	5	4
	ε_y (%)	0.3	0.05	4
Compression:	E_x (GPa)	151.1	4.2	5
	σ_x (MPa)	872.6	79.3	5
	ε_x (%)	-	-	-
	E_y (GPa)	9.7	0.46	5
	σ_y (MPa)	225	-	1
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-4 - Data sheet for UD carbon IM/bismaleimide (Narmco: Toray T800/Narmco 5250-2)

Supplier/Trade Name: Narmco (BASF)	Fibre/Resin System: Toray T800 Bismaleimide: Narmco 5250-2		Data Source: Ref. [1]	
Fibre vol. (%): 59 ±1	t_{ply} (mm): -		Density (kg/m^3): 1600	
Areal weight (g/cm^2): -			Year of test: 1987	
Specimen condition: Cured at 190°C with 6-hour post-cure at 243°C. Dried at 70°C				
Test environment: 100°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	162.3	5.3	9
	σ_x (MPa)	2318	298	9
	ε_x (%)	1.4	0.16	5
	E_y (GPa)	8.78	0.27	5
	σ_y (MPa)	24	3	5
	ε_y (%)	0.28	0.03	5
Compression:	E_x (GPa)	141.9	6.8	4
	σ_x (MPa)	965.6	85.6	5
	ε_x (%)	-	-	-
	E_y (GPa)	8.95	0.53	5
	σ_y (MPa)	216.5	17.7	5
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.33	0.012	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	90.7	15.5	6
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-5 - Data sheet for UD carbon IM/bismaleimide (Narmco: Toray T800/Narmco 5250-2)

Supplier/Trade Name: Narmco (BASF)	Fibre/Resin System: Toray T800 Bismaleimide: Narmco 5250-2		Data Source: Ref. [1]	
Fibre vol. (%): 59 ± 1	t ply (mm): -	Density (kg/m^3): 1600		
Areal weight (g/m^2): -		Year of test: 1987		
Specimen condition: Cured at 190°C with 6-hour post-cure at 243°C. Dried at 70°C				
Test environment: 200°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	169.5	3.6	5
	σ_x (MPa)	2499	242	5
	ε_x (%)	1.41	0.12	5
	E_y (GPa)	7.74	0.01	3
	σ_y (MPa)	38.8	4.9	3
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	149.8	25.3	2
	σ_x (MPa)	638	35.9	4
	ε_x (%)	-	-	-
	E_y (GPa)	8.32	0.10	2
	σ_y (MPa)	170	8.64	4
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-		
Shear:	G_{xy} (GPa)	21.9	-	1
	τ_{xy} (MPa)	66.5	5.2	6
Interlaminar shear	$\tau_{(0)}$ (MPa)	70.0	5.12	6
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.10.3 T800/SX 5564

Table 9.10-6 - Data sheet for UD carbon IM/bismaleimide Brochier Vicotex (Toray T800/Ciba Geigy SX5564)

Supplier/Trade Name: Brochier Vicotex NCIM 5564/137/T800H	Fibre/Resin System: Toray T800 Bismaleimide: Ciba-Geigy SX5564		Data Source Ref. [2]
Fibre vol. (%): 60 ± 1	t_{ply} (mm): 0.135	Density (kg/m^3): 1570	
Areal weight (g/m^2): -	Year at test: 1987		
Specimen condition: 180°C cure Post cure 2 hours at 200°C and 6 hours at 250°C. Dried at 70°C.			

Test environment: -60°C		$\overline{X}$	S. D.	N
Tension:	E_x (GPa)	160.2	3.5	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	9.09	1.11	5
	σ_y (MPa)	36	6.6	5
	ε_y (%)	0.40	0.07	5
Compression:	E_x (GPa)	136.7	6.33	5
	σ_x (MPa)	1078	46	5
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.327	0.03	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-		-

Table 9.10-7 - Data sheet for UD carbon IM/bismaleimide Brochier Vicotex (Toray T800/Ciba Geigy SX5564)

Supplier/Trade Name: Brochier Vicotex NCIM 5564/137/T800H	Fibre/Resin System: Toray T800 Bismaleimide: Ciba-Geigy SX5564		Data Source: Ref. [2]
Fibre vol. (%): 60 ± 1	t_{ply} (mm): 0.135		Density (kg/m^3): 1570
Areal weight (g/m^2): -		Year of test: 1987	
Specimen condition: 180°C cure. Post cure 2 hours at 200°C and 6 hours at 250°C. Dried at 70°C			

Test environment: R.T.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	161.2	6.6	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	8.60	0.24	5
	σ_y (MPa)	39.7	2.5	5
	ε_y (%)	0.45	0.04	5
Compression:	E_x (GPa)	137.0	6.9	5
	σ_x (MPa)	986	143	5
	ε_x (%)			
	E_y (GPa)	9.48	0.17	4
	σ_y (MPa)	197	13	4
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.286	0.033	5
Shear:	G_{xy} (GPa)	4.87	0.20	5
	τ_{xy} (MPa)	67.3	0.9	5
Interlaminar shear	$\tau_{(0)}$ (MPa)	92.5	0.9	5
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-8 - Data sheet for UD carbon IM/bismaleimide Brochier Vicotex (Toray T800/Ciba Geigy SX5564)

Supplier/Trade Name: Brochier Vicotex NCIM 5564/137/T800H	Fibre/Resin System: Toray T800 Bismaleimide: Ciba-Geigy SX5564		Data Source: Ref. [2]
Fibre vol. (%): 60 ± 1	t_{ply} (mm): 0.135		Density (kg/m^3): 1570
Areal weight (g/m^2): -		Year of test: 1987	
Specimen condition: 180°C cure. Post cure 2 hours at 200°C and 6 hours at 250°C. Dried at 70°C.			
Test environment: 100°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	163.4	8.4	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	8.04	0.34	5
	σ_y (MPa)	27.0	3.2	5
	ε_y (%)	0.33	0.05	5
Compression:	E_x (GPa)	140.6	3.08	5
	σ_x (MPa)	1133	106	5
	ε_x (%)	-	-	-
	E_y (GPa)	8.11	0.18	5
	σ_y (MPa)	184	6	4
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.33	0.03	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	76.2	4.8	5
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-9 - Data sheet for UD carbon IM/bismaleimide Brochier Vicotex (Toray T800/Ciba Geigy SX5564)

Supplier/Trade Name: Brochier Vicotex NCIM 5564/137/T800H	Fibre/Resin System: Toray T800 Bismaleimide: Ciba-Geigy SX5564			Data Source: Ref. [2]
Fibre vol. (%): 60 ± 1	t_{ply} (mm): 0.135			Density (kg/m^3): 1570
Areal weight (g/m^2): -			Year of test: 1987	
Specimen condition: 180°C cure. Post cure 2 hours at 200°C and 6 hours at 250°C. - Dried at 70°C.				
Test environment: 200°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	159.0	15.4	4
	σ_x (MPa)	-	-	-
	ε_x (%)			
	E_y (GPa)	7.41	0.36	5
	σ_y (MPa)	25.1	3.6	5
	ε_y (%)	0.34	0.05	5
Compression:	E_x (GPa)	154.0	7.95	5
	σ_x (MPa)	772	27	5
	ε_x (%)	-	-	-
	E_y (GPa)	7.72	0.34	5
	σ_y (MPa)	136	8	5
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}			
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	60.7	1.9	4
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	58.2	2.2	5
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.10-10 - Data sheet for UD carbon IM/bismaleimide Brochier Vicotex (Toray T800/Ciba Geigy SX5564)

Supplier/Trade Name Brochier Vicotex NCIM 5564/137/T800H	Fibre/Resin System: Toray T800 Bismaleimide: Ciba-Geigy SX5564			Data Source: Ref. [2]
Fibre vol. (%): 60 ± 1	t_{ply} (mm): 0.135		Density (kg/m^3): 1570	
Areal weight (g/m^2): -		Year of Test: 1987		
Specimen condition: 180°C cure. Post cure 2 hours at 200°C and 6 hours at 250°C. Saturated with moisture by immersion in boiling water.				
Test environment: R.T.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	159.7	5.65	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	9.09	0.25	5
	σ_y (MPa)	30	*2*	5
	ε_y (%)	0.33	0.02	5
Compression:	E_x (GPa)	139.2	5.6	5
	σ_x (MPa)	698	134	5
	ε_x (%)	-	-	-
	E_y (GPa)	9.32	0.24	5
	σ_y (MPa)	199	16.7	5
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.315	0.02	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	-	-	-
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.11 Polyimide matrix composites

9.11.1 Resin systems

Polyimides are thermosetting resin systems which offer improved hydrolytic and thermo-oxidative stability over epoxy-based resin systems. Structural uses at temperatures exceeding 200°C are possible.

Types of resins are:

- Addition
- Condensation
- Thermoplastic, which describes the polymer characteristics after curing, [See: 6.12; 6.17].

9.11.2 Reinforcement fibres

Carbon fibres are most commonly used with polyimide resin systems. In particular Celanese Celion 6000 which was shown to have an acceptable surface morphology. Aramid and glass fibres have also been considered, [See: 6.13].

9.12 Unidirectional carbon IM/polyimide composites

9.12.1 General

Materials data sheets are provided for:

- Du Pont: T800/Avimid N

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.12.2 T800/AVIMID N

Table 9.12-1 - Data sheet for UD carbon IM/polyimide (Toray T800/Du Pont AVIMID N)

Supplier/Trade Name: Du Pont	Fibre/Resin System: Toray T800 Polyimide: Du Pont AVIMID N		Data Source: Ref. [3]	
Fibre vol. (%): 60 ± 2	t_{ply} (mm): 0.136		Density (kg/m^3): 1570	
Areal weight (g/m^2): -		Year at test: 1987		
Specimen condition: Fully cured to Du Pont specification. Dried at 70°C.				
Test environment: -60°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	155.7	5.9	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	6.78	1.44	5
	σ_y (MPa)	31	-	5
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	145.3	12.1	5
	σ_x (MPa)	804	126	5
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	0.286	0.028	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.12-2 - Data sheet for UD carbon IM/polyimide (Toray T800/Du Pont AVIMID N)

Supplier/Trade Name: Du Pont	Fibre/Resin System: Toray T800 Polyimide: Du Pont AVIMID N			Data Source: Ref. [3]
Fibre vol. (%): 60 ± 2	t_{ply} (mm): 0.136			Density (kg/m^3): 1570
Areal weight (g/m^2): -			Year of test: 1987	
Specimen condition: Fully cured to Du Pont specification. Dried at 70°C.				
Test environment: R.T.		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	155.2	4.95	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	6.79	1.20	5
	σ_y (MPa)	29	-	5
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	135.6	10.1	5
	σ_x (MPa)	629	127	5
	ε_x (%)	7.37	0.59	5
	E_y (GPa)	174	3	5
	σ_y (MPa)	-	-	-
	ε_y (%)	0.30	0.018	5
Poisson's ratio:	ν_{xy}	4.17	0.72	5
Shear:	G_{xy} (GPa)	58.7	3.4	5
	τ_{xy} (MPa)	60.7	2.6	5
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.12-3 - Data sheet for UD carbon IM/polyimide (Toray T800/Du Pont AVIMID N)

Supplier/Trade Name: Du Pont	Fibre/Resin System: Toray T800 Polyimide: Du Pont AVIMID N			Data Source: Ref. [3]
Fibre vol. (%): 60 ± 2	t_{ply} (mm): 0.136		Density (kg/m^3): 1570	
Areal weight (g/m^2): -		Year of test: 1987		
Specimen condition: Fully cured to Du Pont specification.				
Test environment: 100°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	155.5	3.32	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	5.51	0.52	5
	σ_y (MPa)	25	-	5
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	140.6	15.6	5
	σ_x (MPa)	642	48	5
	ε_x (%)	-	-	-
	E_y (GPa)	6.04	0.55	5
	σ_y (MPa)	172	11	4
	ε_y (%)			
Poisson's ratio:	ν_{xy}	0.30	0.03	5
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	53	2.9	5
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.12-4 - Data sheet for UD carbon IM/polyimide (Toray T800/Du Pont AVIMID N)

Supplier/Trade Name: Du Pont	Fibre/Resin System: Toray T800 Polyimide: Du Pont AVIMID N		Data Source: Ref. [3]
Fibre vol. (%): 60 ± 2	t_{ply} (mm): 0.136	Density (kg/m^3): 1570	
Areal weight (g/m^2): -	Year of test: 1987		
Specimen condition: Fully cured to Du Pont specification.			

Test environment: 200°C		$\overline{X}$	S.D.	N
Tension:	E_x (GPa)	169.8	9.03	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	5.08	0.61	5
	σ_y (MPa)	19	-	5
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	142.7	16.6	5
	σ_x (MPa)	438	46	5
	ε_x (%)	-	-	-
	E_y (GPa)	4.65	0.03	5
	σ_y (MPa)	135	14	5
	ε_y (%)	-	-	-
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	53.1	1.0	4
Interlaminar shear	$\tau_{(0)}$ (MPa)	44.5	2.5	5
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

Table 9.12-5 - Data sheet for UD carbon IM/polyimide (Toray T800/Du Pont AVIMID N)

Supplier/Trade Name: Du Pont	Fibre/Resin System: Toray T800 Polyimide: Du Pont AVIMID N			Data Source: Ref. [3]
Fibre vol.(%): 60 ± 2	t_{ply} (mm): 0.136			Density (kg/m^3): 1570
Areal weight (g/m^2): -		Year of test: 1987		
Specimen condition: Fully cured to Du Pont specification. Saturated with moisture by immersion in boiling water.				
Test environment R.T.		$\overline{X}$	S. D.	N
Tension:	E_x (GPa)	157.9	2.50	5
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	7.19	0.87	5
	σ_y (MPa)	25	-	5
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	137.1	15.1	5
	σ_x (MPa)	575	97	5
	ε_x (%)	7.89	0.42	5
	E_y (GPa)	197	13.5	5
	σ_y (MPa)	-	-	-
	ε_y (%)	0.287	0.027	5
Poisson's ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	-	-	-
(ILSS):	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural:	$\sigma_{(flex)}$ (MPa)	-	-	-

9.13 Bidirectional carbon fibre polyimide composites

9.13.1 General

Materials data sheets are provided for:

- BP Advanced Composites:
  - Carbon 5HS fabric/PMR-15.
  - Carbon 8HS fabric/PMR-15.

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.13.2 5HS carbon fabric/PMR-15

Table 9.13-1 - Data sheet for bidirectional carbon fabric/polyimide (5HS fabric/PMR-15)

Supplier/Trade Name: BP Advanced Composites Ltd.	Fibre/Resin System: 5HS Carbon fibre fabric/PMR15 polyimide resin		Data Source: Ref. [4] Preliminary Data.	
Fibre vol. (%): 55 †	t_{ply} (mm): -		Density (kg/m^3): -	
Areal weight (g/m^2): -	Year of Test: -			
Specimen condition: -				
Test environment: 22°C		$\overline{X}$	S.D.	N
Tension: I.H.	E_x (GPa)	66	-	-
	σ_x (MPa)	620	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	62	-	-
	σ_y (MPa)	730	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS):	$\tau_{(0)}$ (MPa)	52	-	-
I.H (at R.T)	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: I.H. (0°)	$\sigma_{(flex)}$ (MPa)	830	-	-
Key: † Typical value				

Table 9.13-2 - Data sheet for bidirectional carbon fabric/polyimide (5HS fabric/PMR-15)

Supplier/Trade Name: BP Advanced Composites Ltd.	Fibre/Resin System: 5HS Carbon fibre fabric/PMR15		Data Source: Ref. [4] Preliminary Data	
Fibre vol. (%): 55 †	t_{ply} (mm): -		Density (kg/m^3): -	
Areal weight (g/m^2): -		Year of Test: -		
Specimen condition: -				
Test environment: 288°C		$\overline{X}$	S.D.	N
Tension: I.H.	E_x (GPa)	63	-	-
	σ_x (MPa)	620	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	62	-	-
	σ_y (MPa)	640	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	43	-	-
(ILSS): I.H. (at R.T.)	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: I.H. (0°)	$\sigma_{(flex)}$ (MPa)	630	-	-
Key: † Typical value				

9.13.3 8HS carbon fabric/PMR-15

Table 9.13-3 - Data sheet for bidirectional carbon fabric/polyimide (8HS fabric/PMR-15)

Supplier/Trade Name: BP Advanced Composites Ltd.	Fibre/Resin System 8HS Carbon fibre fabric PMR15 polyimide resin		Data Source: Ref. [4] Preliminary Data
Fibre vol. (%): 55 †	t_{ply} (mm): -	Density (kg/m^3): -	
Areal weight (g/m^2): -	Year of Test: -		
Specimen condition: -			

Test environment: 22°C		$\overline{X}$	S.D.	N
Tension: I.H.	E_x (GPa)	66	-	-
	σ_x (MPa)	670	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	65	-	-
	σ_y (MPa)	700	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-		-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	45	-	-
(ILSS): I.H. (at R.T.)	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: I.H. (0°)	$\sigma_{(flex)}$ (MPa)	930	-	-

Key: † Typical value

Table 9.13-4 - Data sheet for bidirectional carbon fabric/polyimide (8HS fabric/PMR-15)

Supplier/Trade Name: BP Advanced Composites Ltd.	Fibre/Resin System 8HS carbon fibre fabric PMR15 polyimide resin		Data Source: Ref. [4] Preliminary Data	
Fibre vol. (%): 55 †	t_{ply} (mm): -		Density (kg/m^3): -	
Areal weight (g/m^2): -		Year of Test: -		
Specimen condition: -				
Test environment: 288°C		$\bar{x}$	S.D.	N
Tension:	E_x (GPa)	68	-	-
I.H.	σ_x (MPa)	700	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	65	-	-
	σ_y (MPa)	700	-	-
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	-	-	-
	σ_x (MPa)	-	-	-
	ε_x (%)	-	-	-
	E_y (GPa)	-	-	-
	σ_y (MPa)	-	-	-
	ε_y (%)	-	-	-
Poisson ratio:	ν_{xy}	-	-	-
Shear:	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	-	-	-
Interlaminar shear (ILSS): I.H.	$\tau_{(0)}$ (MPa)	40	-	-
	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: (0°) I.H.	$\sigma_{(flex)}$ (MPa)	690	-	-
Key: † Typical value				

9.14 Thermoplastic matrix composites

9.14.1 Thermoplastic matrix

Numerous thermoplastics have been considered for the matrix phase of structural composite materials, [See: 6.17].

In 1988, the polymers considered by Westlands Aerospace to be sufficiently advanced, both technically and commercially for aerospace items, were Ref. [9-5]:

- PEEK – polyetheretherketone, [See: 9.15].
- PEI – polyetherimide, [See: 9.16].

9.14.2 Reinforcement fibres

Carbon fibres are most commonly combined with thermoplastic polymers, [See: 6.18]. In particular the surface of AS4 has been optimised for use with PEEK matrix.

9.15 Unidirectional carbon/PEEK (APC2) composites

9.15.1 General

Materials data sheets are provided for:

- ICI: AS4/PEEK

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.15.2 AS4/PEEK

Table 9.15-1 - Data sheet for UD carbon/thermoplastic composites (ICI: AS4/PEEK)

Supplier/Trade Name: ICI APC2	Fibre/Resin System Hercules AS4 Carbon fibre/Polyetheretherketone (PEEK)			Data Source 9
Fibre vol. (%): 61	t_{ply} (mm): -			Density (kg/m^3): -
Areal weight (g/m^2): -		Year of Test: -		
Specimen condition: -				
Test environment: 23°C		$\overline{X}$	C of V %	N
Tension: I.H.	E_x (GPa)	139	1.0	-
	σ_x (MPa)	2131	3.3	-
	ε_x (%)	-	-	-
	E_y (GPa)	10.4	3.1	*
	σ_y (MPa)	64	15.8	*
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	102	9.9	-
I.H.	σ_x (MPa)	1116	13.9	-
	ε_x (%)	-	-	-
	E_y (GPa)	5.7	14.9	*
	σ_y (MPa)	253	27.4	*
	ε_y (%)	-	-	-
Poisson ratio: I.H.	ν_{xy}	0.33	-	-
Shear: I.H.	G_{xy} (GPa)	4.5	10.8	-
	τ_{xy} (MPa)	175	1.7	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	110	1.6	-
(ILSS): I.H.	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: I.H.	$\sigma_{(flex)}$ (MPa)	-	-	-
Key: * Small sample size.				

9.16 Bidirectional carbon/PEI composites

9.16.1 General

Materials data sheets are provided for:

- Ten Cate: AS4/PEI

The inclusion of data for any particular material within the handbook does not imply that it is commercially available. Always establish the availability with the supplier. The emerging materials are subject to modification. Therefore, the data are considered as indicative.

References are indicated within data sheets as Ref. [x].

'Data Sources' cited within data sheets are digits only.

NOTE See: 9.2 for data sheet notation.

9.16.2 AS4/PEI

Table 9.16-1 - Data sheet for bidirectional carbon fabric/thermoplastic composites (Ten Cate Glass: AS4/PEI)

Supplier/Trade Name: Ten Cate Glass, Netherlands.	Fibre/Resin System: Hercules AS4 Carbon fibre/ 5-Shaft Satin Ultem 1000 (Polyetherimide)			Data Source: 9
Fibre vol. (%): 61	t_{ply} (mm): -		Density (kg/m^3): -	
Areal weight (g/m^2): -		Year of Test: -		
Specimen condition: -				
Test environment: 23°C		$\bar{x}$	C of V %	N
Tension: I.H.	E_x (GPa)	56.8	-	-
	σ_x (MPa)	709.	7.9	-
	ε_x (%)	-	-	-
	E_y (GPa)	41.8	-	*
	σ_y (MPa)	565	11.6	*
	ε_y (%)	-	-	-
Compression:	E_x (GPa)	65.2	-	-
I.H.	σ_x (MPa)	648	1.1	-
	ε_x (%)	-	-	-
	E_y (GPa)	63.8	5.6	*
	σ_y (MPa)	620	10-8	*
	ε_y (%)	-	-	-
Poisson ratio: I.H.	ν_{xy}	-	-	-
Shear: I.H.	G_{xy} (GPa)	-	-	-
	τ_{xy} (MPa)	112	0.5	-
Interlaminar shear	$\tau_{(0)}$ (MPa)	79	8.3	-
(ILSS): I.H.	$\tau_{(0\pm45)}$ (MPa)	-	-	-
Flexural: I.H.	$\sigma_{(flex)}$ (MPa)	706	4.6	-
Key: * Small sample size.				

9.17 Triaxial woven fabric composites

9.17.1 Introduction

TWF triaxial weave fabrics are of interest in many applications because they are considered structurally superior to most types of conventional, orthogonal weaves. Structural elements run in three directions providing a fabric that is much more resistant to shearing forces, [See also: 2.6; 6.41].

TWF is potentially useful for space applications as it has macroscopically quasi-isotropic mechanical properties, and hence can be used to construct single-ply structural elements of very low areal mass, [See: 30.13]. However, characterisation of TWFs for design purposes is more complicated than conventional composite plies.

An ESA-funded study, conducted in 2006, investigated an open (sparse) weave single-ply carbon fibre TWF. This provided insight into the characterisation and modelling of such materials for space structures, Ref. [9-19].

The results of the study, summarised here, showed that:

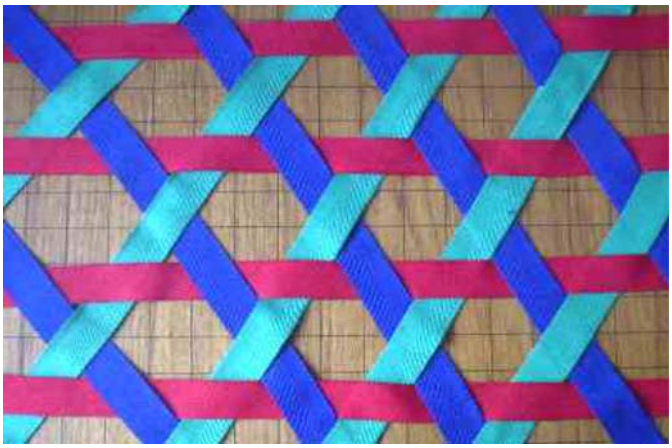
- TWF behaviour differs from standard laminated composites in many important respects, so appropriate models are needed to predict stiffness and strength.
- Linear-elastic response of single-ply TWF composites can be modelled accurately in terms of a homogenised Kirchhoff plate. The ABD matrix for this plate is computed from an assembly of transversely isotropic 3-D beams whose unit cell is analysed using standard FE analysis, assuming periodic boundary conditions.
- Thermal deformation of TWF composites comprises two separate effects: a biaxial linear expansion that is characterised by the coefficient of linear expansion, plus the development of a thermally-induced twist that is characterised by the coefficient of thermal twist. The value of these two coefficients can be estimated accurately by analytical or numerical models.

9.17.2 Materials

9.17.2.1 Fabric

The triaxial weave fabric (TWF) examined in the ESA-funded study is based on SK-802 carbon-fibre fabric, produced by Sakase-Adtech Ltd., Fukui, Japan. Using the basic weave shown in Figure 9.17.1, Ref. [9-23]. This is a very open but stable weave, having fill yarns perpendicular to the direction of weaving and warps yarns at +60° and □-60°.

Figure 9.17.2 shows a schematic representation of a roll of this fabric with the weave directions indicated.



Courtesy of www.hexdome.com

Figure 9.17-1 – TWF study: Weave

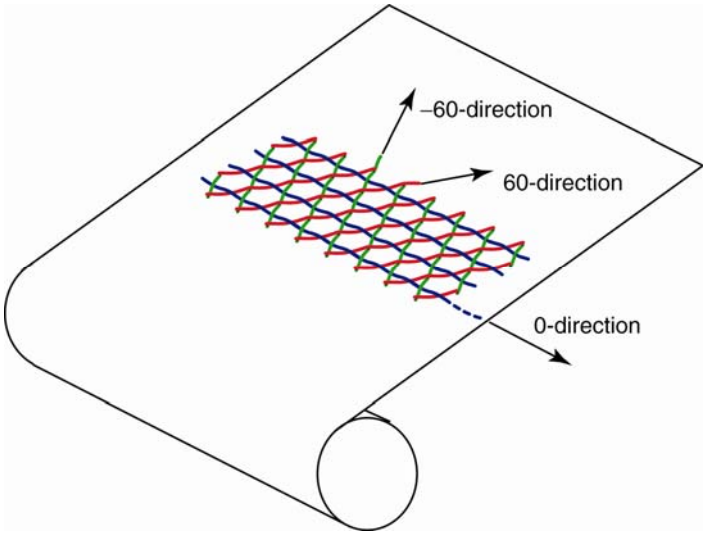
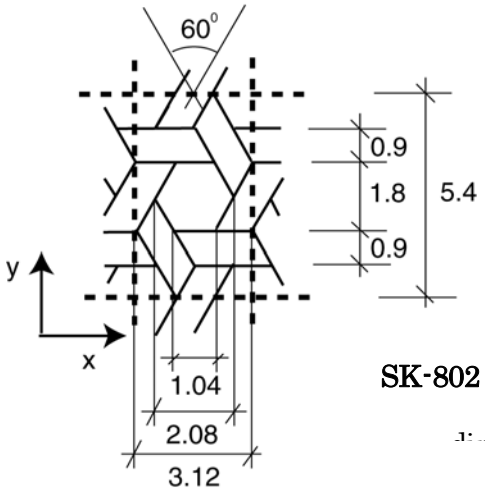


Figure 9.17-2 – TWF study: Orientation of weave

The yarns in this fabric each consist of 1000 filaments of T300 carbon fibre, produced by Toray Industries Inc., Japan, [See: Table 9.17.1 for fibre characteristics].

In the basic weave pattern the hexagonal holes occupy about half of the surface area. SK-802 has a dry mass of 75 g/m2 and a thickness of about 0.15 mm. The repeating unit cell of the fabric is defined in Figure 9.17.3.



SK-802 triaxial woven fabric

dimensions in mm

Figure 9.17-3 - TWF study: Fabric unit cell

9.17.2.2 Matrix

The matrix consists of the space-qualified resin, Hexcel® 8552, from Hexcel Composites, UK. Physical and mechanical properties of the matrix are given in Table 9.17.1; [See also: Ref. [9-10]].

Table 9.17-1 - TWF study: Fibre and matrix properties

Properties	T300 fibre	Hexcel 8552 matrix
Density, ρ [kg m^{-3}]	1760	1301
Longitudinal stiffness, E_1 [N/mm^2]	233000	4670
Transverse stiffness, E_2 [N/mm^2]	23100	4670
Shear stiffness, G_{12} [N/mm^2]	8963	1704
Poisson's ratio, ν_{12}	0.2	0.37
Longitudinal CTE, α_1 [°C^{-1}]	-0.54×10^{-6}	65.0×10^{-6}
Transverse CTE, α_2 [°C^{-1}]	10.08×10^{-6}	65.0×10^{-6}
Maximum strain, ε^{tu} [%]	1.5	1.7

9.17.2.3 Volume fractions

The volume fractions of fibre and resin in the composite are defined with respect to the total volume of composite material, excluding the voids in the weave. In particular, the volume fraction of fibre, V_f, is defined as:

$$V_f = \frac{\text{Vol.fibre}}{\text{Vol.fibre} + \text{Vol.matrix}} \qquad [9.17\text{-}1]$$

Which can be calculated from:

$$V_f = \frac{\rho_f W_f}{\rho_r W_f + \rho_f W_r} \qquad [9.17\text{-}2]$$

Where:

W_r = *weight per unit area of resin film*
W_f = *weight per unit area of dry fabric*
ρ_r = *density of resin*
ρ_f = *density of dry fibres*

The volume fraction of matrix, V_m, can be calculated from:

$$V_m = 1 - V_f \qquad [9.17\text{-}3]$$

The fibre volume fraction needed to fully embed the fibres in the matrix is about 0.65. Hence the weight of resin per unit area is around 30 g/m² (without resin in the hexagonal voids in the fabric).

9.17.3 Composite ply manufacture

Vacuum bagging was used in order to achieve good compaction of the fibres and to control the temperature profile of the curing process. The composite lay-up is shown in Figure 9.17.4. Preparation of the prepreg, lay-up and curing procedures were as follows:

a. Adhesively tape the edges of the dry fabric and the cutting lines to prevent fibre misalignment when cutting the fabric. Cut fabric along the centre line of the tape.

b. Place TWF dry fabric on Tygaflor® release fabric sheet and apply 30 g/m2, paper-backed, Hexcel 8552 resin film to the top side (resin in contact with the fabric).

c. Tack the resin to the TWF fabric using an electric iron at 100°C. Remove the paper backing sheet.

d. Place a sheet of Tygaflor® release fabric on top of a steel plate with the resin/fabric sample on top (resin side up).

e. Seal the lay-up using standard vacuum bagging techniques; Aerovac A500RP3 perforated release film, a breather blanket and a Capran® bag, shown in Figure 9.17.4.

f. Place bagged lay-up in an autoclave.

g. Apply the following consolidation and cure schedule:

   1. Increase temperature to 110°C, at a heating rate of 2°C /min, and pressure to 6 bar.

   2. Hold temperature at 110°C for 1 hour, to enable the resin to be drawn by capillarity action into the fibres. At 110°C the viscosity of the resin is minimised while the gel rate is still very low.

   3. Increase temperature to 180°C, at a heating rate of 2 °C/min.

   4. Hold temperature for 2 hours, to fully cure the resin.

   5. Depressurise autoclave and let lay-up to cool down. Ideally, the cooling rate is 3°C min-1or 4°C min-1.

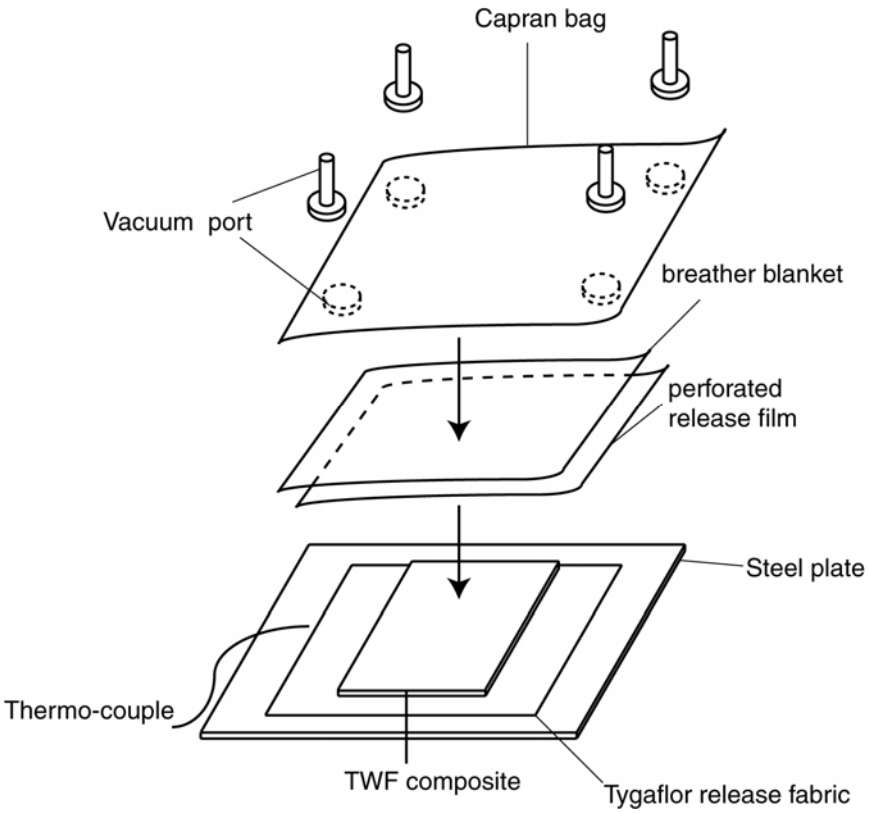


Figure 9.17-4 - TWF study: Lay-up for curing

The two-step cure cycle described above differs slightly from the standard Hexcel 8552 cure cycle. In the standard cycle, the lay-up is heated to 180°C and cured in a single step. The dwell at 110°C in the above schedule ensures enough time for the resin to melt and infiltrate the fabric before it begins to harden, maximising fibre wetting and minimising resin in the hexagonal holes.

If insufficient resin is provided, the surface of the cured tows is matt. Excessive resin is visible around the edges of the hexagonal holes (It is normal for a small amount of resin to be absorbed by the breather blanket). The amount of resin applied to the fabric should be carefully controlled to avoid starved areas or excessive bleed into the perforated release film.

The technique of ironing the resin film onto the fabric is only suitable for a few square metres of material. An electric laminator can be used for larger quantities, and, for industrial scale prepregs, conventional impregnation techniques are necessary.

Prepregs prepared by the 2-step method have been successfully laid on double-curvature moulds.

9.17.4 Cured composite

Figure 9.17.5 shows a photograph of the cured single-ply composite, highlighting the unit cell.

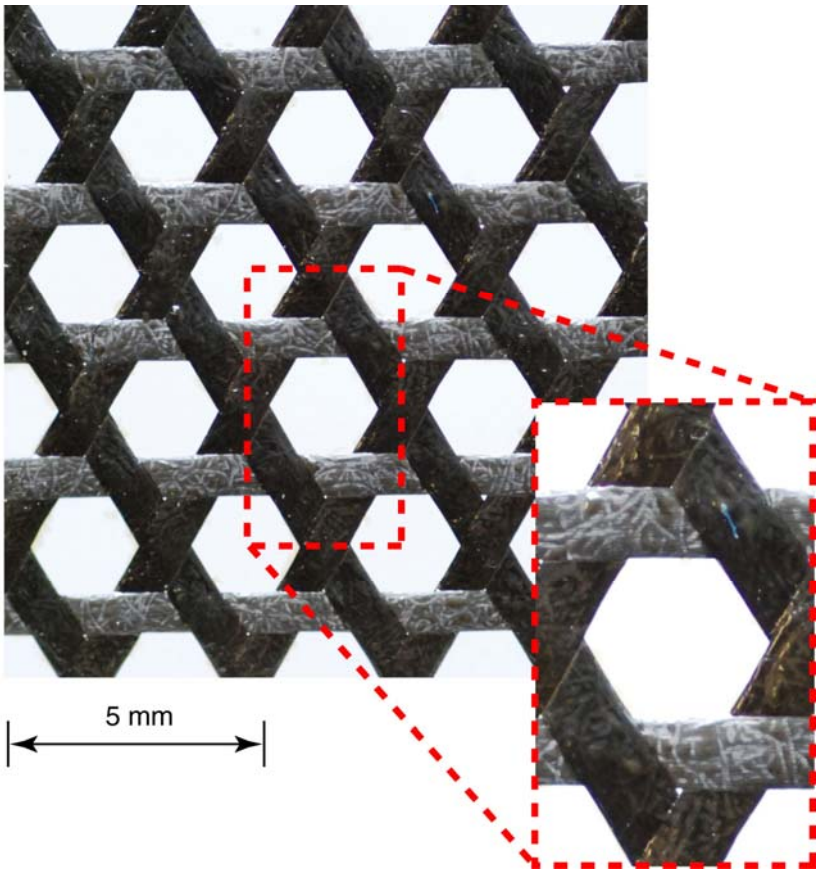


Figure 9.17-5 - TWF study: Single-ply composite

Five 50 mm × 50 mm pieces of single-ply TWF composite were weighed and their areal weights are shown in Table 9.17.2. The average value (Wc) was 111.7 g/m2, giving a corresponding average weight per unit area of resin of:

$$W_r = W_c - W_f = 111.7 - 75 = 36.7 \text{ g/m}^2 \qquad [9.17\text{-}4]$$

Since this value is larger than the weight of resin film that had been used, five larger samples were weighed and a new set of weights per unit area were obtained. Their values are listed in Table 9.17.3. The average weight per unit area for the new set was Wc = 97.4 g/m2.

The overall average weight per unit area, considering both sets of samples, is Wc = 104.5 g/m2, corresponding to a weight per unit area of resin of Wr= 29.5 g/m2. This value is plausible as it is less than the weight of resin film used.

The fibre volume fraction for the tows is obtained by substituting Wr and the standard values of Wf , ρf and ρr into Equation [9.17-2], giving:

$$V_f = \frac{1301 \times 0.075}{1301 \times 0.075 + 1760 \times 0.0295} = 0.65 \qquad [9.17\text{-}5]$$

Table 9.17-2 - TWF study: Areal weight of Set 1 samples

Specimen	W_c [g/m²]
1	104.62
2	112.35
3	112.31
4	114.20
5	115.08
Average	111.71
Std. dev.	4.143
Variation [%]	3.71

Table 9.17-3 -TWF study: Areal weight of Set 2 samples

Specimen	weight/area [g/m²]
1	98.13
2	99.73
3	97.79
4	95.05
5	96.10
Average	97.36
Std. dev.	1.82
Variation [%]	1.87

9.17.5 Tows

9.17.5.1 Geometry

The micrograph in Figure 9.17.6 shows a section along the 0-direction tows. This section also cuts across two +60 tows (A and C) and one □-60 tow (B). In this view the sections of the tows are not perpendicular to their axes, and hence appear elongated by a factor of 1/Cos 30°. Also, the profiles of the tow sections are generally curved, except where the lower tows were in contact with a flat surface during the curing process.

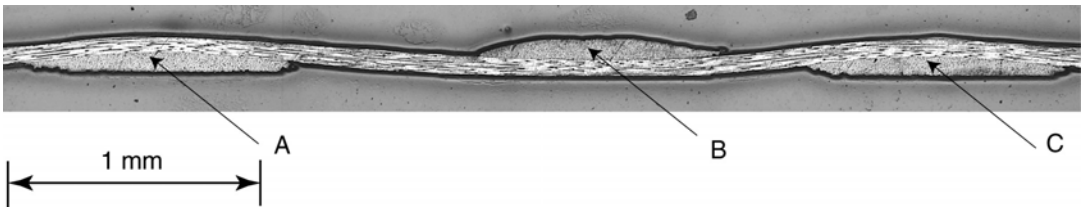


Figure 9.17-6 - TWF study: Micrograph of cured TWF composite

To determine the cross-sectional area of a tow, the outline of the tows in this and similar micrographs were traced using Adobe Illustrator®, Ref. [9-11]. Each trace was then converted into a region using Autocad®, Ref. [9-12] and the enclosed area was determined using the Autocad® 'mass property' function. This analysis was carried out on sections of six different tows in the ±60° direction. Finally the areas, At, were corrected for tow angle using the equation:

$$A_t = A\cos 30 \qquad [9.17\text{-}6]$$

Where:

A is the area computed using Autocad®.

Table 9.17.4 lists the cross sectional areas obtained.

Table 9.17-4 - TWF study: Tow cross-sectional areas

Specimen	A_t [mm²]
1	0.0612
2	0.0607
3	0.0618
4	0.0608
5	0.0670
6	0.0640
Average	0.0626
Std. dev.	0.002
Variation [%]	3.97

An alternative, and more direct, way of determining the cross-sectional area of the tows is to sum the cross-sectional areas of the fibres and matrix in a tow.

The total cross sectional area of the fibres within a tow, A_f, satisfies the following mass relationship:

$$L\rho_f A_f = W_f A_{cell} \qquad [9.17\text{-}7]$$

Where:

L = total length of tow centre line lying in the unit cell

A_{cell} = area of unit cell

Hence, solving for A_f:

$$A_f = \frac{W_f A_{cell}}{L\rho_f} \qquad [9.17\text{-}8]$$

Substituting Acell = 3.12 × 5.4 mm2 = 16.85 × 10-6 m2, see Figure 9.17.3, and L = 18.71 × 10-3 m, which assumes the tow centre lines to be coplanar, into Equation [9.17-8] gives:

$$A_f = \frac{0.075\times 16.85\times 10^{-6}}{18.71\times 10^{-3}\times 1760} = 3.838\times 10^{-8}\ \text{m}^2 = 3.838\times 10^{-2}\ \text{mm}^2 \qquad [9.17\text{-}9]$$

The next step is to determine the cross-sectional area of the matrix (resin), Ar, embedding the fibres in a tow. Here, the key relationship is:

$$L\left(\rho_f A_f + \rho_r A_r\right) = W_c A_{cell} \qquad [9.17\text{-}10]$$

Solving for Ar and substituting all known terms:

$$A_r = \frac{W_c A_{cell} / L - \rho_f A_f}{\rho_r} \qquad [9.17\text{-}11]$$

$$= \frac{\frac{104.53\times16.85\times10^{-9}}{18.71\times10^{-3}} - 1760\times3.838\times10^{-8}}{1301} = 2.044 \times 10^{-2}\ \text{mm}^2 \qquad [9.17\text{-}12]$$

Finally, the tow cross-sectional area is calculated from:

$$A_t = A_f + A_r = 5.882 \times 10^{-2}\ \text{mm}^2 \qquad [9.17\text{-}13]$$

This gives a value 6% lower than the average cross-sectional area measured from the micrographs.

The thickness of the cured composite is defined as the maximum thickness that is measured from the micrographs. Six measurements were taken and their values are listed in Table 9.17.5. The average value is 0.156 mm.

Table 9.17-5 - TWF study: Measured sample thickness

Specimen	Thickness [mm]
1	0.157
2	0.154
3	0.156
4	0.167
5	0.152
6	0.152
Average	0.156
Std. dev.	0.006
Variation [%]	3.59

In the analytical models presented in the next section the tows are represented as beams of uniform rectangular cross section. The height of these rectangles is assumed to be half the measured thickness of the cured specimens. The width is calculated from a rectangle of this height, having a cross-sectional area equal to that measured on the tow samples.

Therefore, the rectangle height is half the average thickness in Table 9.17.5, i.e. 0.078 mm. Taking the average tow area from Table 9.17.4, At = 0.0626 mm2, the rectangle width is 0.803 mm.

9.17.5.2 Thermo-mechanical properties

Analysis of the behaviour of TWF composites starts from the thermo-mechanical behaviour of the tows. Each tow is modelled as a three-dimensional continuum having transversely isotropic properties. The modulus in the fibre direction is higher than the two transverse directions, where the modulus is assumed to remain constant. Five independent elastic constants are needed to model a transversely isotropic solid, Ref. [9-13]:

- longitudinal stiffness, E_1
- transverse stiffness, E_2
- longitudinal Poisson's ratio, ν_{12}
- shear modulii, G_{12} and G_{23}

The thermal properties of the tow are also assumed to be transversely isotropic.

The independent engineering constants are determined as follows, Ref. [9-13]:

The longitudinal extensional modulus, E1, and Poisson's ratio, ν, are calculated using the rule of mixtures:

$$E_1 = E_{1f}V_f + E_r(1-V_f) \qquad [9.17\text{-}14]$$

$$\nu_{12} = \nu_{13} = \nu_{12f}V_f + \nu_r(1-V_f) \qquad [9.17\text{-}15]$$

The transverse extensional modulus, E_2, is calculated from the Halpin-Tsai semi-empirical relation:

$$E_2 = E_3 = E_r\frac{1+\xi\eta V_f}{1-\eta V_f} \qquad [9.17\text{-}16]$$

Where:

$$\eta = \frac{E_{2f}-E_r}{E_{2f}+\xi E_r} \qquad [9.17\text{-}17]$$

and where the parameter ξ is a measure of reinforcement of the composite which depends on the fibre geometry, packing geometry, and loading conditions. For this exercise a value of 2.0 has been used, Ref. [9-13].

The shear modulus $G_{12} = G_{13}$ is also found using the Halpin-Tsai semi-empirical relation, Ref. [9-13]:

$$G_{12} = G_{13} = G_r\frac{(G_{12f}+G_r)+V_f(G_{12f}-G_r)}{(G_{12f}+G_r)-V_f(G_{12f}-G_r)} \qquad [9.17\text{-}18]$$

The in-plane shear modulus, G_{23}, is obtained by solving the following quadratic equation, Ref. [9-14]:

$$\left(\frac{G_{23}}{G_r}\right)^2 A + \left(\frac{G_{23}}{G_r}\right) B + C = 0 \qquad [9.17\text{-}19]$$

Where:

$$A = 3V_f(1-V_f)^2\left(\frac{G_{12f}}{G_r}-1\right)\left(\frac{G_{12f}}{G_r}+\zeta_f\right) + \left[\left(\frac{G_{12f}}{G_r}\right)\zeta_r + \zeta_r\zeta_f - \left(\left(\frac{G_{12f}}{G_r}\right)\zeta_r - \zeta_f\right)(V_f)^3\right] \times\left[\zeta_r V_f\left(\frac{G_{12f}}{G_r}-1\right) - \left(\left(\frac{G_{12f}}{G_r}\right)\zeta_r + 1\right)\right] \qquad [9.17\text{-}20]$$

$$B = -6V_f(1-V_f)^2\left(\frac{G_{12f}}{G_r}-1\right)\left(\frac{G_{12f}}{G_r}+\zeta_f\right) + \left[\left(\frac{G_{12f}}{G_r}\right)\zeta_r + \left(\frac{G_{12f}}{G_r}-1\right)V_f + 1\right] \times\left[(\zeta_r - 1)\left(\frac{G_{12f}}{G_r}+\zeta_f\right) - 2(V_f)^3\left(\left(\frac{G_{12f}}{G_r}\right)\zeta_r - \zeta_f\right)\right] + (\zeta_r+1)V_f\left(\frac{G_{12f}}{G_r}-1\right)\left[\frac{G_{12f}}{G_r} + \zeta_f + \left(\left(\frac{G_{12f}}{G_r}\right)\zeta_r - \zeta_f\right)(V_f)^3\right] \qquad [9.17\text{-}21]$$

$$C = 3V_f(1-V_f)^2\left(\frac{G_{12f}}{G_r}-1\right)\left(\frac{G_{12f}}{G_r}+\zeta_f\right) + \left[\left(\frac{G_{12f}}{G_r}\right)\zeta_r + \left(\frac{G_{12f}}{G_r}-1\right)V_f + 1\right] \times\left[\frac{G_{12f}}{G_r} + \zeta_f + \left(\left(\frac{G_{12f}}{G_r}\right)\zeta_r - \zeta_f\right)(V_f)^3\right] \qquad [9.17\text{-}22]$$

And:

$$\zeta_r = 3 - 4\nu_r \qquad [9.17\text{-}23]$$

$$\zeta_f = 3 - 4\nu_{12f} \qquad [9.17\text{-}24]$$

ν_{23} is calculated from the equation:

$$G_{23} = \frac{E_2}{2(1+\nu_{23})} \qquad [9.17\text{-}25]$$

The longitudinal coefficient of thermal expansion is derived from, Ref. [9-15]:

$$\alpha_1 = \frac{E_{1f}\alpha_{1f}V_f + E_r\alpha_r V_r}{E_{1f}V_f + E_r V_r} \qquad [9.17\text{-}26]$$

And the transverse coefficient of thermal expansion from, Ref. [9-15]:

$$\alpha_2 = \alpha_3 = V_f\alpha_{2f}\left(1+\nu_{12f}\frac{\alpha_{1f}}{\alpha_{2f}}\right) + V_r\alpha_r(1+\nu_r) - (\nu_{12f}V_f + \nu_r V_r)\alpha_1 \qquad [9.17\text{-}27]$$

Using the measured volume fraction, Vf = 0.65, the material properties of a tow made of T300/Hexcel 8552 have been calculated using these relationships. The values obtained are shown in Table 9.17.6.

Table 9.17-6 - TWF study: Tow material properties

Material properties	Value
Longitudinal stiffness, E_1 [N/mm²]	153085
Transverse stiffness, $E_2 = E_3$ [N/mm²]	12873
Shear stiffness, $G_{12} = G_{13}$ [N/mm²]	4408
In-plane shear stiffness, G_{23} [N/mm²]	4384
Poisson's ratio, $\nu_{12} = \nu_{13}$	0.260
Longitudinal CTE, α_1 [°C^{-1}]	0.16×10^{-6}
Transverse CTE, α_2 [°C^{-1}]	37.61×10^{-6}

9.17.6 Derivation of homogenised elastic properties from finite elements

9.17.6.1 Homogenised plate model

An analytical model for the linear-elastic behaviour of single-ply TWF composites is described. This is developed from a detailed finite-element analysis of a repeating unit cell.

The kinematic description is a standard, Kirchhoff thin plate, where deformation of the plate is described by the deformation of its mid-surface. Hence the kinematic variables for the plate are the mid-plane strains:

$$\varepsilon_x = \frac{\partial U}{\partial x} \qquad [9.17\text{-}28]$$

$$\varepsilon_y = \frac{\partial V}{\partial y} \qquad [9.17\text{-}29]$$

$$\varepsilon_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \qquad [9.17\text{-}30]$$

Where: ε = engineering shear strain.

The mid-plane curvatures:

$$\kappa_x = -\frac{\partial^2 W}{\partial x^2} \qquad [9.17\text{-}31]$$

$$\kappa_y = -\frac{\partial^2 W}{\partial y^2} \qquad [9.17\text{-}32]$$

$$\kappa_{xy} = -2\frac{\partial^2 W}{\partial x \partial y} \qquad [9.17\text{-}33]$$

Twice the surface twist is used because this is the standard variable defining the twisting curvature in the theory of laminated plates, Ref. [9-13].

The corresponding static variables are the mid-plane forces and moments per unit length N_x, N_y, N_{xy} and M_x, M_y, M_{xy}.

In analogy with classical composite laminate theory, the 6 × 6 matrix relating these two sets of variables can be written as an *ABD* stiffness matrix, as follows:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ -- \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & | & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & | & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & | & B_{61} & B_{62} & B_{66} \\ -- & -- & -- & -- & -- & -- & -- \\ B_{11} & B_{21} & B_{61} & | & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{62} & | & D_{21} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & | & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ -- \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \qquad [9.17\text{-}34]$$

Where: A_{ij}, B_{ij}, and D_{ij} represent the in-plane (stretching and shearing), coupling, and out-of-plane (bending and twisting) stiffness of the material, respectively.

This matrix is symmetric, and so the 3 × 3 submatrices *A* and *D* along the main diagonal are symmetric ($A_{ij} = A_{ji}$ and $D_{ij} = D_{ji}$), however (unlike the *B* matrix of a laminated plate) the *B* matrix is not guaranteed to be symmetric.

The inverse of the *ABD* stiffness matrix, useful when comparing with measured stiffness values, is:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ -- \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = \left[\begin{array}{ccc|ccc} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{21} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{61} & a_{62} & a_{66} & b_{61} & b_{62} & b_{66} \\ \hline b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{21} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{61} & d_{62} & d_{66} \end{array}\right] \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ -- \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} \qquad [9.17\text{-}35]$$

9.17.6.2 Unit cell of TWF composite

The tows of TWF are modelled in ABAQUS®, Ref. [9-16], using 3-node, quadratic beam elements (element B32). These elements are based on Timoshenko beam theory, which takes into account transverse shear deformation. The beams are isotropic in the transverse direction; their properties are defined in Table 9.17.6.

The unit cell is shown in Figure 9.17.7. The global z-axis is perpendicular to the mid plane of the unit cell. The edges of the unit cell are parallel to the axes and have dimensions (based on Figure 9.17.3) Δlx = 3.12 mm and Δly = 5.4 mm.

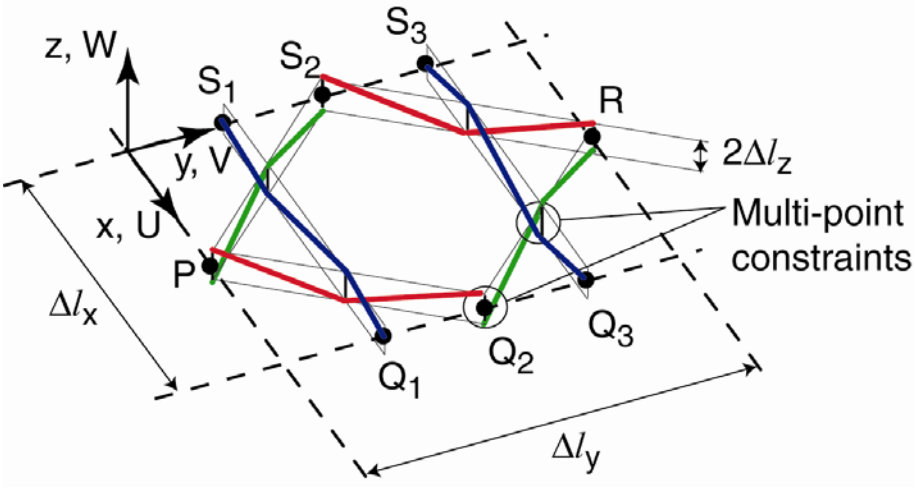


Figure 9.17-7 - TWF study: Perspective view of TWF unit cell

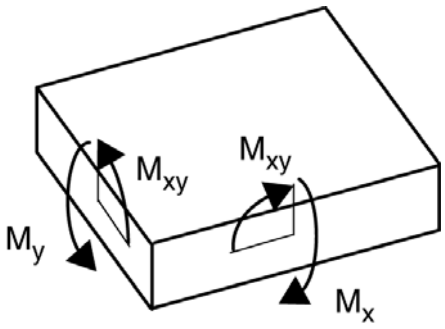


Figure 9.17-8 - TWF study: Moments sign convention for plate

The beam cross section is rectangular, with uniform width of 0.803 mm and uniform height of 0.078 mm, [See: 19.17.5.1 - geometry]. The centroidal axis of each beam undulates in the z-direction; the undulation has a piece-wise linear profile with amplitude Δ_{lz}. This value is set equal to one quarter the thickness of the cured composite, [See: 19.17.5.1 - geometry], and hence $\Delta_{lz} = 0.156 / 4 = 0.039$ mm.

At the cross-over points the beams are connected with rigid elements parallel to the z-direction. These connections are set up using multi-point constraints, in ABAQUS®, i.e. with the command *MPC of type *BEAM. The *BEAM constraint defines a rigid beam between the connected points, and so constrains both the displacements and rotations at one node to those at the other node.

The whole TWF unit cell model consisted of 494 nodes and 248 elements.

9.17.6.3 Periodic boundary conditions

Periodic boundary conditions are a standard tool in the computation of homogenised models for composites, so there is an extensive literature on this subject. A recent paper by Tang and Whitcomb, Ref. [9-17] explains the key ideas involved in this approach, in the context of semi-analytical solutions based on assumed displacement fields within the unit cell. Of particular relevance to the present study is the direct micro-mechanics method introduced by Karkainen and Sankar for plain weave textile composites, Ref. [9-18]. The approach presented here is essentially the same as this reference, but:

- Extended to a triaxial weave and
- 'Discretising' the TWF into a mesh of beam elements, instead of solid elements.

The idea is to assume that the average deformation of a TWF composite should match that of a plate, over a length scale defined on the basis of the weave geometry. The stiffness properties of the homogenised plate are defined such that this match is achieved. More precisely, any changes in deformation between corresponding points on opposite boundaries of the TWF unit cell will match the deformation of the plate over the same length. These conditions of geometric compatibility are known as periodic boundary conditions (PBC), and are imposed on the four pairs of nodes lying on the edges of the unit cell.

The more intuitive case is that of the mid-plane strains only, which are explained first. The in-plane stretching and shearing of the mid plane are described by the functions U(x,y) and V(x,y), where the origin of the coordinate system is a corner of the unit cell, as shown in Figure 9.17.7. Expanding each of these functions into a Taylor series:

$$U = U_0 + \left(\frac{\partial U}{\partial x}\right)_0 x + \left(\frac{\partial U}{\partial y}\right)_0 y \qquad [9.17\text{-}36]$$

$$V = V_0 + \left(\frac{\partial V}{\partial x}\right)_0 x + \left(\frac{\partial V}{\partial y}\right)_0 y \qquad [9.17\text{-}37]$$

where: subscript '0' denotes the origin of the coordinate system.

The derivatives $\delta U/\delta x$ and $\delta V/\delta y$ are equal to the normal strain components, εx and εy respectively, see Equations [9.17-27] and [9.17-28]. Each of the derivatives $\delta U/\delta y$ and $\delta V/\delta x$, are set equal to half the shear strain εxy, in order to satisfy Equation [9.17-29].

Hence Equations [9.17-35] and [9.17-36] become:

$$U = U_0 + \varepsilon_x x + \frac{1}{2}\varepsilon_{xy} y \qquad [9.17\text{-}38]$$

$$V = V_0 + \frac{1}{2}\varepsilon_{xy} x + \varepsilon_y y \qquad [9.17\text{-}39]$$

Consider a general pair of nodes lying on boundaries of the TWF unit cell. The change in in-plane displacement between these two nodes is set equal to the deformation of two corresponding points on the homogenised plate.

In the present case, because the boundaries are parallel to the x- and y-directions, the pairs of nodes to be coupled have either the same x- or y-coordinate and so the compatibility equations are specialised to:

$$U^{Q_i} - U^{S_i} = \varepsilon_x \Delta l_x \qquad [9.17\text{-}40]$$

$$V^{Q_i} - V^{S_i} = \frac{1}{2}\varepsilon_{xy} \Delta l_x \qquad [9.17\text{-}41]$$

for i = 1, 2, 3 and

$$U^R - U^P = \frac{1}{2}\varepsilon_{xy} \Delta l_y \qquad [9.17\text{-}42]$$

$$V^R - V^P = \varepsilon_y \Delta l_y \qquad [9.17\text{-}43]$$

Next, the effects of out-of-plane bending and twisting of the mid-plane are considered. The (small) out-of-plane deflection of the mid-plane is described by the function *W(x,y)*. A Taylor series expansion, up to the second order, gives:

$$W = W_0 + \left(\frac{\partial W}{\partial x}\right)_0 x + \left(\frac{\partial W}{\partial y}\right)_0 y + \frac{1}{2}\left(\frac{\partial^2 W}{\partial x^2}\right)_0 x^2 + \left(\frac{\partial^2 W}{\partial x \partial y}\right)_0 xy + \frac{1}{2}\left(\frac{\partial^2 W}{\partial y^2}\right)_0 y^2 \qquad [9.17\text{-}44]$$

Where: subscript '$_0$' denotes the origin of the coordinate system.

Noting that the deflection at the origin, W_0, can be made equal to zero by a rigid-body translation, defining the slopes at the origin $\theta_{x0} = (\delta W/\delta y)_0$ and $\theta_{y0} = (\delta W/\delta x)_0$ and substituting Equations [9.17-30] and [9.17-32], Equation [9.17-43] becomes:

$$W = -\theta_{y0} x + \theta_{x0} y - \frac{1}{2}\kappa_x x^2 - \frac{1}{2}\kappa_{xy} xy - \frac{1}{2}\kappa_y y^2 \qquad [9.17\text{-}45]$$

Hence, the slopes are:

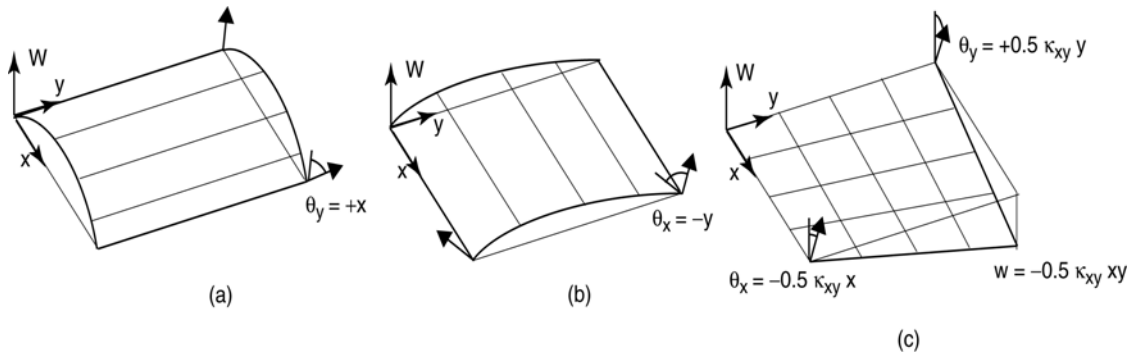
$$\theta_x = \frac{\partial W}{\partial y} = \theta_{x0} - \frac{1}{2}\kappa_{xy}x - \kappa_y y \qquad [9.17\text{-}46]$$

$$\theta_y = -\frac{\partial W}{\partial x} = \theta_{y0} + \kappa_x x + \frac{1}{2}\kappa_{xy}y \qquad [9.17\text{-}47]$$

Three separate deformation modes are now considered; pure bending, in both x and y directions, and pure twisting, as shown in Figure 9.17.9.

The bending mode in the x-direction has $\kappa_x \neq 0$, $\kappa_y = 0$, $\kappa_{xy} = 0$; for simplicity the slope θ_{y0} is chosen such that $w = 0$ on two opposite edges, see Figure 9.17.9 (a).

Similarly, the bending mode in the y-direction has $\kappa_x = 0$, $\kappa_y \neq 0$, $\kappa_{xy} = 0$ and the slope θ_{x0} is chosen such that $w = 0$ on two opposite edges, shown in Figure 9.17.9 (b).



(a) $\kappa_x = 1$; (b) $\kappa_y = 1$; (c) $\kappa_{xy} = 1$
Three uniform deformation modes and associated rotations of normal vectors

Figure 9.17-9 - TWF study: Bending and twisting deformation modes

Several observations can be made from Figure 9.17.9:

- Bending deformation modes do not result in a change in W for points on opposite boundaries. This only occurs in the twisting mode.
- Bending in the x-direction results in a rotation of the normal between points lying on boundaries parallel to the y-axis, but no rotation of the normal between points lying on boundaries parallel to the x-axis.
- Bending in the y-direction results in a rotation of the normal between points lying on boundaries parallel to the x-axis, but no rotation of the normal between points lying on boundaries parallel to the y-axis.
- Twisting results in a rotation of the normal between any pair of points lying on opposite boundaries.

Therefore, the equation of compatibility between the change in out-of-plane displacement, ΔW, between two corresponding points on opposite boundaries of the TWF composite and the deformation of a plate subject to uniform bending and twisting is:

$$\Delta W = -\frac{1}{2}\kappa_{xy}\Delta x\Delta y \qquad [9.17\text{-}48]$$

And the equations of compatibility for the rotation components are:

$$\Delta\theta_x = -\kappa_y\Delta y - \frac{1}{2}\kappa_{xy}\Delta x \qquad [9.17\text{-}49]$$

$$\Delta\theta_y = \kappa_x\Delta x + \frac{1}{2}\kappa_{xy}\Delta y \qquad [9.17\text{-}50]$$

Substituting the coordinates of the relevant pairs of boundary nodes these equations can be specialised to:

$$W^{Q_i} - W^{S_i} = -\frac{1}{2}\kappa_{xy}y_i\Delta l_x \qquad [9.17\text{-}51]$$

$$W^{R} - W^{P} = -\frac{1}{2}\kappa_{xy}\frac{\Delta l_x}{2}\Delta l_y \qquad [9.17\text{-}52]$$

And:

$$\theta_x^{Q_i} - \theta_x^{S_i} = -\frac{1}{2}\kappa_{xy}\Delta l_x \qquad [9.17\text{-}53]$$

$$\theta_y^{Q_i} - \theta_y^{S_i} = \kappa_x\Delta l_x \qquad [9.17\text{-}54]$$

$$\theta_x^{R} - \theta_x^{P} = -\kappa_y\Delta l_y \qquad [9.17\text{-}55]$$

$$\theta_y^{R} - \theta_y^{P} = \frac{1}{2}\kappa_{xy}\Delta l_y \qquad [9.17\text{-}56]$$

In addition to the above conditions, all relative in-plane rotations between opposite nodes are prevented by setting:

$$\theta_z^{R} - \theta_z^{P} = 0 \qquad [9.17\text{-}57]$$

And:

$$\theta_z^{Q_i} - \theta_z^{S_i} = 0 \qquad [9.17\text{-}58]$$

for i = 1, 2, 3.

9.17.6.4 Virtual deformation modes

To derive the *ABD* matrix, six unit deformations are imposed on the unit cell, in six separate ABAQUS® analyses. In each case, one average strain/curvature is set equal to one and all others are set equal to zero. For instance, in the first analysis, $\varepsilon_x = 1$ while $\varepsilon_y = \varepsilon_{xy} = 0$ and $\kappa_x = \kappa_y = \kappa_{xy} = 0$. In the five subsequent analyses ε_y, ε_{xy}, κ_x, κ_y, and κ_{xy} are set equal to 1, one at a time, while the other deformations are set equal to zero.

From each of the six analyses one set of deformations are obtained, including displacement and rotation components at the 8 boundary nodes, and one set of corresponding constraint forces and moments.

9.17.6.5 Virtual work computation of *ABD* matrix

Six unit deformations are imposed on the unit cell, in six separate ABAQUS® analyses; these are referred to as Case A, …, Case F. In each case, one average strain/curvature is set equal to one and all others equal to zero. For instance, in the first analysis, $\varepsilon_x = 1$ while $\varepsilon_y = \varepsilon_{xy} = 0$ and $\kappa_x = \kappa_y = \kappa_{xy} = 0$. From each of the six analyses one set of deformations, including displacement and rotation components at the 8 boundary nodes, and one set of corresponding constraint forces and moments, are obtained.

Next, virtual work is used to compute the entries of the *ABD* matrix. For example, entry 1,1 is obtained by writing the equation of virtual work for Case A (i.e. $\varepsilon_x = 1$) and the forces/moments also in the first mode. Hence the equation is:

$$N_x \varepsilon_x \Delta l_x \Delta l_y = \sum_{b.n.} \left(F_x U + F_y V + F_z W + M_x \theta_x + M_y \theta_y + M_z \theta_z \right) \qquad [9.17\text{-}59]$$

Where the summation is extended to the 8 boundary nodes (b.n.).

Substituting $\varepsilon_x = 1$ and comparing with Equation [9.17-33] gives:

$$A_{11} = \frac{\sum_{b.n.} \left(F_x U + F_y V + F_z W + M_x \theta_x + M_y \theta_y + M_z \theta_z \right)}{\Delta l_x \Delta l_y} \qquad [9.17\text{-}60]$$

The calculation of the whole *ABD* matrix is best done by setting up two matrices with 48 rows, i.e. 6 degrees of freedom per node times 8 boundary nodes, and 6 columns, i.e. the six deformation modes.

The first matrix, *U*, contains in each column the displacement and rotation components at all boundary nodes for each particular case:

$$U = \begin{bmatrix} U_{PA} & U_{PB} & U_{PC} & U_{PD} & U_{PE} & U_{PF} \\ V_{PA} & V_{PB} & V_{PC} & V_{PD} & V_{PE} & V_{PF} \\ W_{PA} & W_{PB} & W_{PC} & W_{PD} & W_{PE} & W_{PF} \\ \theta_{PxA} & \theta_{PxB} & \theta_{PxC} & \theta_{PxD} & \theta_{PxE} & \theta_{PxF} \\ \theta_{PyA} & \theta_{PyB} & \theta_{PyC} & \theta_{PyD} & \theta_{PyE} & \theta_{PyF} \\ \theta_{PzA} & \theta_{PzB} & \theta_{PzC} & \theta_{PzD} & \theta_{PzE} & \theta_{PzF} \\ U_{Q_1A} & U_{Q_1B} & U_{Q_1C} & U_{Q_1D} & U_{Q_1E} & U_{Q_1F} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \theta_{S_3zA} & \theta_{S_3zB} & \theta_{S_3zC} & \theta_{S_3zD} & \theta_{S_3zE} & \theta_{S_3zF} \end{bmatrix} \quad [9.17\text{-}61]$$

The second matrix, *F*, contains in each column the forces and couples at all boundary nodes for each particular deformation case:

$$F = \begin{bmatrix} F_{PxA} & F_{PxB} & F_{PxC} & F_{PxD} & F_{PxE} & F_{PxF} \\ F_{PyA} & F_{PyB} & F_{PyC} & F_{PyD} & F_{PyE} & F_{PyF} \\ F_{PzA} & F_{PzB} & F_{PzC} & F_{PzD} & F_{PzE} & F_{PzF} \\ C_{PxA} & C_{PxB} & C_{PxC} & C_{PxD} & C_{PxE} & C_{PxF} \\ C_{PyA} & C_{PyB} & C_{PyC} & C_{PyD} & C_{PyE} & C_{PyF} \\ C_{PzA} & C_{PzB} & C_{PzC} & C_{PzD} & C_{PzE} & C_{PzF} \\ F_{Q_1xA} & F_{Q_1xB} & F_{Q_1xC} & F_{Q_1xD} & F_{Q_1xE} & F_{Q_1xF} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ C_{S_3zA} & C_{S_3zB} & C_{S_3zC} & C_{S_3zD} & C_{S_3zE} & C_{S_3zF} \end{bmatrix} \quad [9.17\text{-}62]$$

Equation [9.17-59] can then be extended to the following expression for the *ABD* matrix:

$$ABD = \frac{U^T F}{\Delta l_x \cdot \Delta l_y} \quad [9.17\text{-}63]$$

And, substituting *U* and *F* (the detailed expressions are given in, Ref. [9-19]), gives:

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ \hline M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \left[\begin{array}{ccc:ccc} 3312 & 1991 & 0 & 0.00 & 0.00 & -0.62 \\ 1991 & 3312 & 0 & 0.00 & 0.00 & 0.62 \\ 0 & 0 & 660 & 0.62 & -0.62 & 0.00 \\ \hdashline 0.00 & 0.00 & 0.62 & 2.11 & 0.59 & 0.00 \\ 0.00 & 0.00 & -0.62 & 0.59 & 2.11 & 0.00 \\ -0.62 & 0.62 & 0.00 & 0.00 & 0.00 & 0.76 \end{array}\right] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \hline \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \quad [9.17\text{-}64]$$

Where the units are N and mm.

This matrix has several symmetry properties:

- The matrix itself is symmetrical.
- The sub-matrices A and D are both symmetric.
- B is antisymmetric (unlike the B matrix for a laminated plate).

Aoki and Yoshida, Ref. [9-7] have explained this result by noting that, because TWF composites are quasi-isotropic, both the A and D matrices have to satisfy the conditions met by an isotropic plate, namely $A_{11} = A_{22}$, $A_{66} = (A_{11} - A_{12})/2$ and $D_{11} = D_{22}$, $D_{66} = (D_{11} - D_{12})/2$.

In more detail:

$$A = \begin{bmatrix} a & b & 0 \\ b & a & 0 \\ 0 & 0 & \dfrac{a-b}{2} \end{bmatrix} \qquad [9.17\text{-}65]$$

And

$$D = \begin{bmatrix} c & d & 0 \\ d & c & 0 \\ 0 & 0 & \dfrac{c-d}{2} \end{bmatrix} \qquad [9.17\text{-}66]$$

Both of these properties are satisfied by the *ABD* matrix in Equation [9.17-63].

The inverse of the *ABD* matrix in Equation [9.17-63] is:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} = 10^{-6} \times \left[\begin{array}{ccc:ccc} 473 & -284 & 0 & 0 & 0 & 614 \\ -284 & 473 & 0 & 0 & 0 & -614 \\ 0 & 0 & 1515 & -614 & 614 & 0 \\ \hdashline 0 & 0 & -614 & 514086 & -143070 & 0 \\ 0 & 0 & 614 & -143070 & 514086 & 0 \\ 614 & -614 & 0 & 0 & 0 & 1314268 \end{array}\right] \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} \qquad [9.17\text{-}67]$$

9.17.7 Thermo-mechanical modelling

9.17.7.1 General

Single-ply TWF composites show counter-intuitive behaviour when subjected to even the simplest kind of thermal loading. An initial, purely numerical, study was carried out by Zhao and Hoa, Ref. [9-20], who observed that rectangular panels including different numbers of unit cells deform in bending and twisting by different amounts. Although no fully general relationship or experimental validation of the results was obtained, a series of approximate formulas for estimating average mid-plane thermal strains and curvatures were proposed.

Kueh and Pellegrino, Ref. [9-9] carried out a set of experiments and finite-element simulations aimed at establishing the key effects that had resulted in the complex behaviour reported by Zhao and Hoa. Tests on rectangular single-ply TWF panels hanging from a wire attached to a single point of the panel showed the panel bending into a cylindrical shape when its temperature was raised.

It was conjectured that twisting had been prevented by geometrically non-linear effects and, to minimise this constraint, tests were conducted on narrow specimens. Thermally-induced twisting was observed on these narrow specimens. Time-dependent behaviour was also observed in these tests which resulted in additional work, prior to the present study, on resin selection, the curing process and the moisture content of the specimen.

As a result of this additional work, it is now believed that the time-dependent effects reported by Kueh and Pellegrino, Ref. [9-9], can be avoided by the use of a more stable resin system and by ensuring that it is fully cured.

A separate activity, Ref. [9-9], was a series of detailed finite-element simulations that linked the observed, thermally-induced twist to the out-of-plane deformation that develops at the interface between tows in different directions that are bonded in the cross-over region. This approach has been further developed in, Ref. [9-19].

9.17.7.2 Analytical prediction of CTE

A simple analytical model is presented to predict the linear CTE of single-ply TWF composites. The idea is that the (small) CTE in the direction of a tow is increased by the (much larger) CTE of the tows bonded above and below this tow; the longitudinal and transverse stiffness of these transverse tows cannot be ignored in the analysis.

Consider a straight tow with longitudinal CTE, α_1, and stiffness $(EA)_1$, perfectly bonded to a series of tows that are perpendicular to it. Only those sections of these perpendicular tows that overlap the first tow are considered; the rest of the material is neglected. Their CTE in the direction of the first tow is α_2 and their stiffness is $(EA)_2$. Poisson's ratio effects are neglected.

It is assumed that bending effects, resulting from the eccentricity between the axis of the main tow and the perpendicular ones, can be neglected so that the problem can be formulated in one dimension, as shown in Figure 9.17.10.

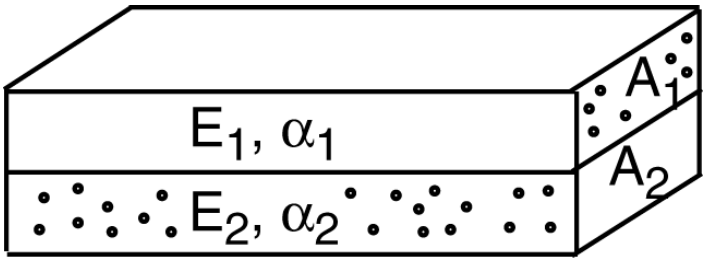


Figure 9.17-10 - TWF study: CTE analysis 2-tow system

The overall CTE of this two-tow system is of interest. There will be a thermal strain mismatch when the system is subject to a uniform change of temperature, ΔT, resulting in equal and opposite axial forces, x, acting on the two separate tows. The resulting strains are:

$$\varepsilon_1 = \alpha_1 \Delta T + \frac{x}{(EA)_1} \qquad [9.17\text{-}68]$$

$$\varepsilon_2 = \alpha_2 \Delta T - \frac{x}{(EA)_2} \qquad [9.17\text{-}69]$$

Setting $\varepsilon_1 = \varepsilon_2$ for compatibility and solving for x gives:

$$x = (\alpha_2 - \alpha_1)\frac{(EA)_1(EA)_2}{(EA)_1 + (EA)_2}\Delta T \qquad [9.17\text{-}70]$$

And, substituting into Equation [9.17-67]:

$$\varepsilon_1 = \left[\alpha_1 + \frac{(EA)_2(\alpha_2 - \alpha_1)}{(EA)_1 + (EA)_2}\right]\Delta T \qquad [9.17\text{-}71]$$

Dividing by ΔT gives the following expression for the *CTE* of the two-tow system:

$$\alpha_c = \left[\alpha_1 + \frac{(EA)_2(\alpha_2 - \alpha_1)}{(EA)_1 + (EA)_2}\right] \qquad [9.17\text{-}72]$$

9.17.7.3 CTE values

There are a number of effects that are not described by this simple model; hence there is little value in estimating its parameters with great accuracy. For example, what value of CTE should be used for the cross tows, given that they are at ±60° and not at right angles? For simplicity it is assumed that the effects of the change of angle are small and that the cross-sectional areas are equal, $A_1 = A_2$. Substituting the values in Table 9.17.6 into Equation [9.17-71] gives:

$$\alpha_c = \left[0.16 + \frac{12,873(37.61 - 0.16)}{153,085 + 12,873}\right] \times 10^{-6} = 3.06 \times 10^{-6}\ {}^{\circ}\mathrm{C}^{-1} \qquad [9.17\text{-}73]$$

Then, assuming that only two-thirds of the main tow are covered by the cross tows the effective value of the CTE will be the average of α_1 and $2\alpha_c/3$, giving:

$$\overline{\alpha}_c = (0.16 + \frac{2}{3}3.06)\times 10^{-6} = 2.20\times 10^{-6} \ {}^{\circ}\mathrm{C}^{-1} \qquad [9.17\text{-}74]$$

9.17.7.4 Finite element model

Solid-element models are used to simulate the thermo-mechanical behaviour of single-ply TWF composites, in order to capture the three-dimensional deformation of the tow cross-over regions. The model of the unit cell is shown in Figure 9.17.12. A single tow is modelled as a 3D continuum with the properties defined in Table 9.17.6. The thermo-mechanical properties of each tow are assumed to be transversely isotropic.

The unit cell comprises 2760 nodes and 2048 elements. The tows are modelled as having a uniform, rectangular cross-section, 0.803 mm wide and 0.078 mm high, with four elements through the thickness. The tow undulation is modelled in a piece-wise linear fashion; the tow cross-over regions are modelled as flat rhombuses, where it is assumed that the tows are fully joined together, connected by sloping regions that are straight in the longitudinal direction of the tow. Thus, the surface of each tow is continuous, but with localised slope changes when the tow meets a crossing tow. At this point there is a step change in thickness of the model. Importantly, the presence of these step changes in the thickness of the model results in each hexagon having six-fold rotational symmetry about an axis perpendicular to the mid plane of the unit and each triangle has three-fold rotational symmetry, however the model is not symmetric about the mid-plane.

An equal-sided triangular gap with a 0.169 mm length of side has been introduced to give space for tow crossing; this is circled in Figure 9.17.11.

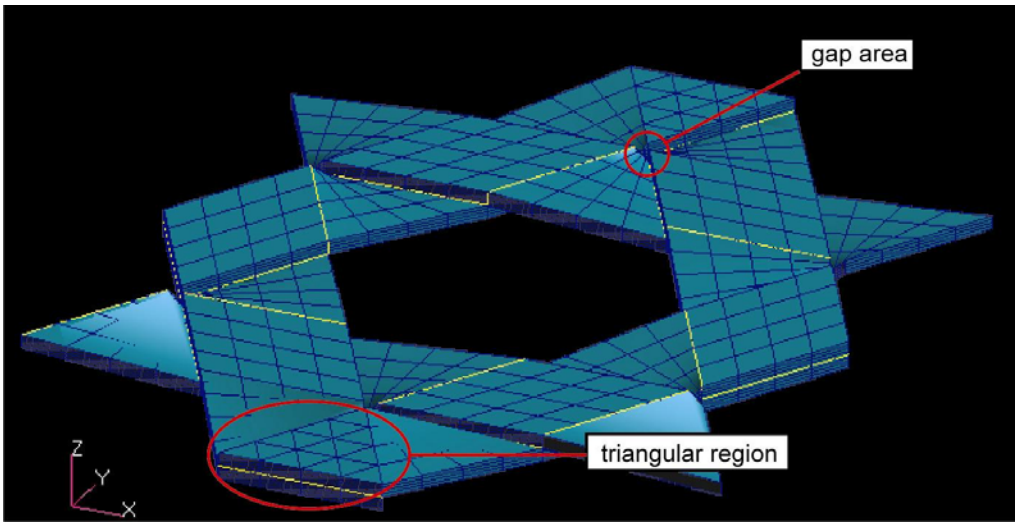


Figure 9.17-11 - TWF study: Unit cell solid element model

A local Cartesian coordinate system is created for each piece of tow and the material properties of the tow are defined according to this local coordinate system. The coordinate system for a flat piece of tow

has its 1-axis aligned with the fibre direction. The coordinate system for a sloping piece, joining two flat pieces, is such that the 3-axis is perpendicular to the surface of the sloping piece. The 1-axis is defined by joining corresponding points on the end cross-sections of the flat pieces. The material properties for the solid elements are defined based on this local coordinate system. The 1-axis is aligned to the direction of the fibres. After determining the local coordinate systems for a number of elements, due to symmetry, the remaining elements are defined, including their own coordinate systems, using the copy function and by rotation about the central point of the unit cell. The material properties of each element are then set equal to the values defined in Table 9.17.6.

An 8-node linear brick element with incompatible modes, C3D8I, is used to model the prismatic regions of the tows. The triangular regions are meshed with 6-node linear triangular prisms, C3D6. It has been found that the incompatible modes included in the formulation of this element lead to better performance in bending, and hence a lower mesh density is needed to achieve convergence compared to a standard 8-node linear brick element.

9.17.7.5 Thermo-mechanical behaviour

Figure 9.17.12 shows two one unit-wide strips of TWF composite. These two strips are obtained by cutting the TWF:

- In the direction of the 0-direction tows, and
- Perpendicular to the 0-direction tows.

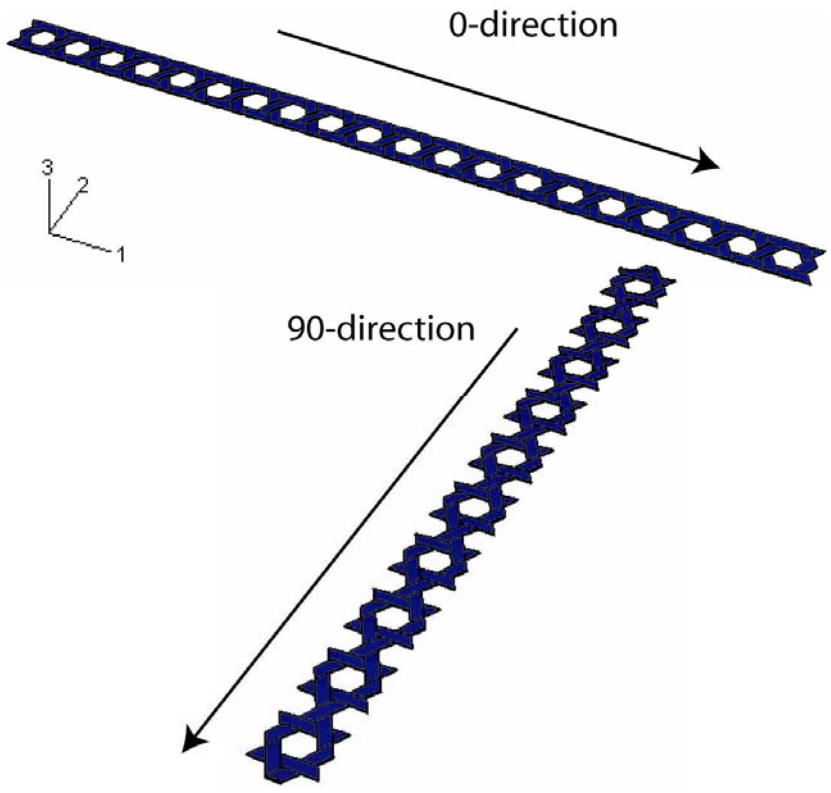
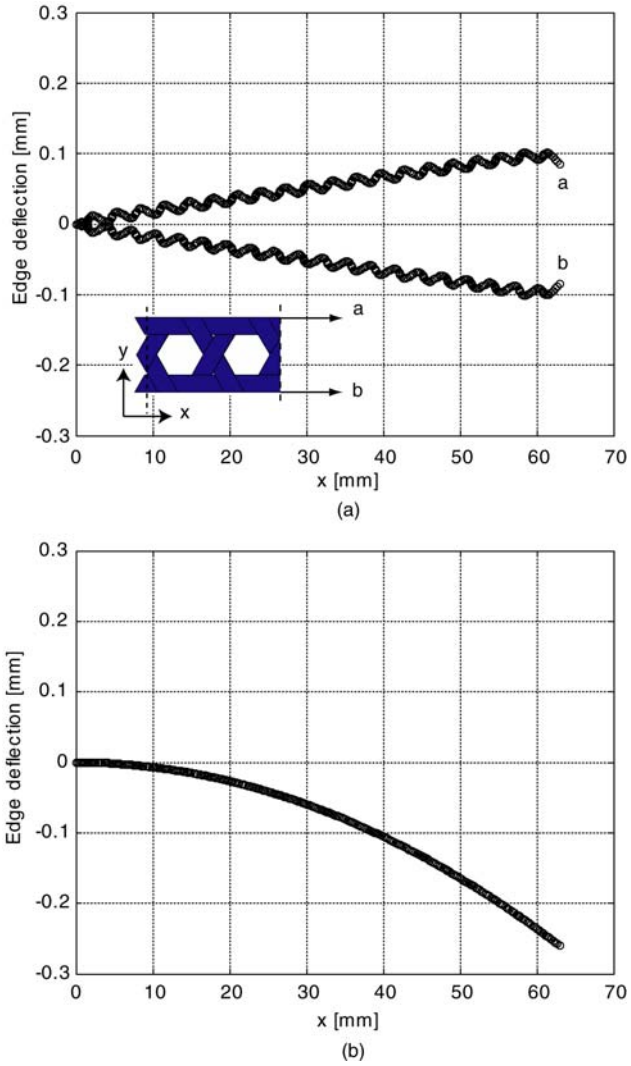


Figure 9.17-12 - TWF study: 0-direction and 90-direction strips

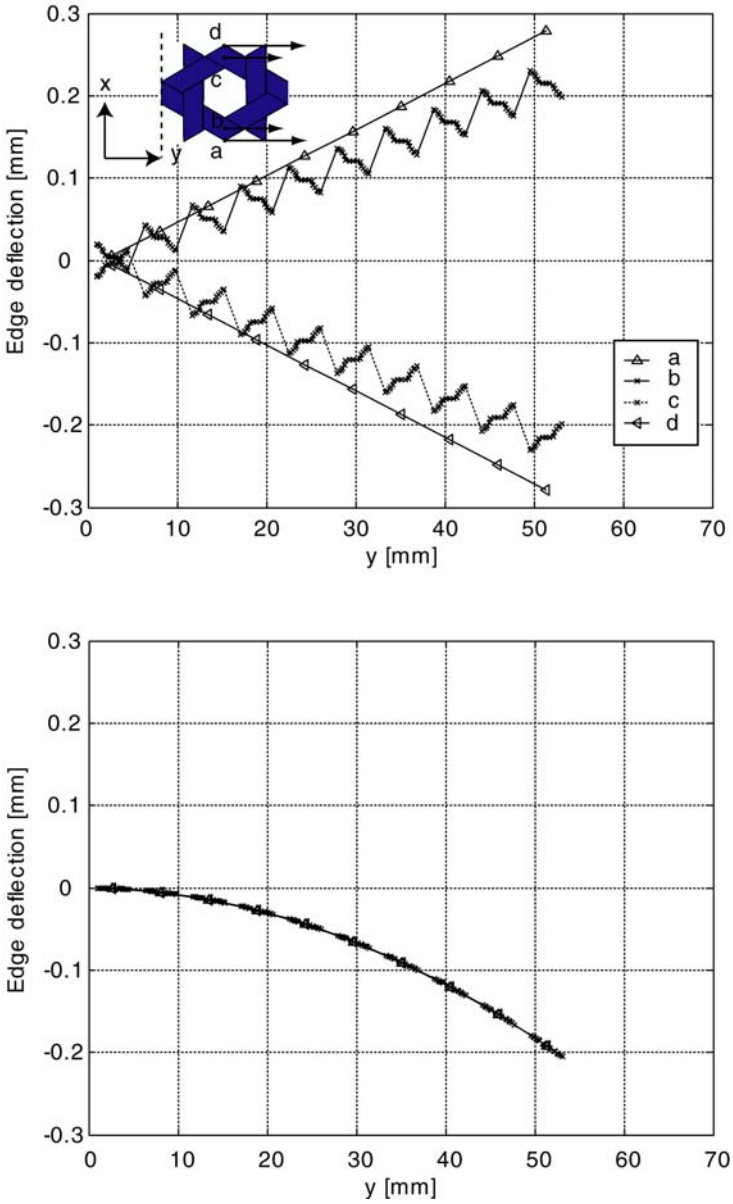
The behaviour of these two types of TWF strip, subjected to two different thermal loading cases, has been analysed. In the first case a uniform temperature increase of 100°C was applied. In the second case, a thermal gradient of ±2°C was applied in three uniform steps; the temperatures of the outer thirds of the thickness of the structure were subjected to +2°C and □2°C and the temperature of the

central third was 0°C. The mechanical boundary conditions were fully clamped at the left-hand side end of the strip. A linear elastic analysis was performed in all cases.



Deformation of 0-direction strip subject to: (a) uniform temperature rise of 100°C; (b) thermal gradient of ±2°C

Figure 9.17-13 - TWF study: Thermal deformation of 0-direction strip



Deformation of 90-direction strip subject to: (a) uniform temperature rise of 100°C; (b) thermal gradient of ±2°C

Figure 9.17-14 - TWF study: Thermal deformation of 90-direction strip

9.17.8 Test programme

9.17.8.1 General

Both mechanical and thermal properties were established under the test programme:

- Mechanical: tensile, compression, bending, shear.
- Thermal: linear CTE, thermal twist.

Some of the test methods used were developed specifically for TWF composites.

9.17.9 Tensile properties

9.17.9.1 Method

The coupon layout is shown in Figure 9.17.15. To minimise edge effects, an aspect ratio of 1:1 was adopted for the unreinforced area.

Each specimen was 90 mm wide × 190 mm long (including tabs) and consisted of a sheet of single-ply TWF, with the 0-direction arranged in the main loading direction, sandwiched between rectangular aluminium tabs (90 mm long × 50 mm wide and 1 mm thick) and additional 60 mm × 90 mm sheets of single-ply TWF. These extra reinforcements, tabs and outer layers are to reduce Poisson's ratio mismatch effects that lead to premature failure near the clamped area.

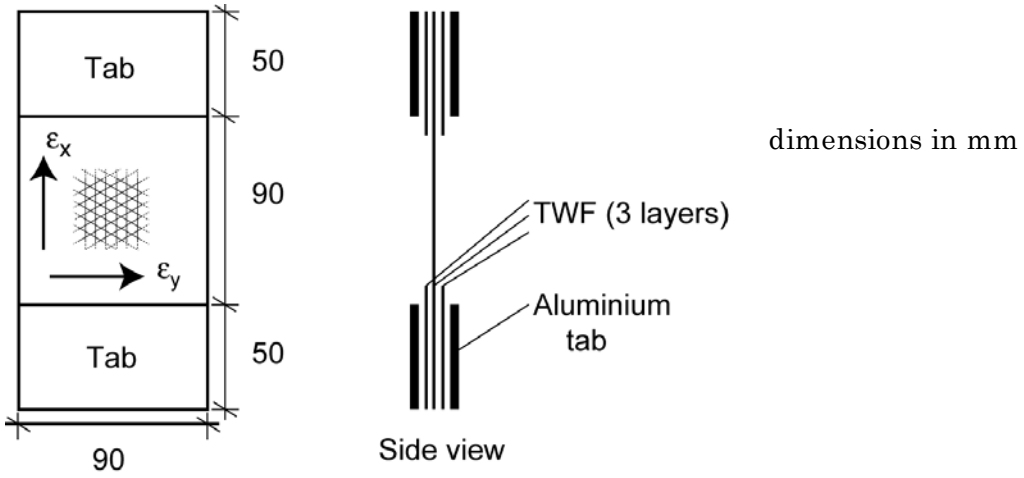


Figure 9.17-15 - TWF study: Tensile test sample

9.17.9.2 Results

A typical load-deformation plot from the tension tests shows non-linear effects associated with tow waviness changes (crimp interchange).

Figure 9.17.16 shows a plot of force/width vs. longitudinal strain for one of the test specimens (T6). Two straight lines (in red) have been superimposed on the plot. The strain at the intersection of these lines is defined as the transition strain. The slope increases after the transition strain.

A more significant non-linearity is seen in a plot of transverse strain vs. longitudinal strain, from which a strain-dependent Poisson's ratio can be calculated.

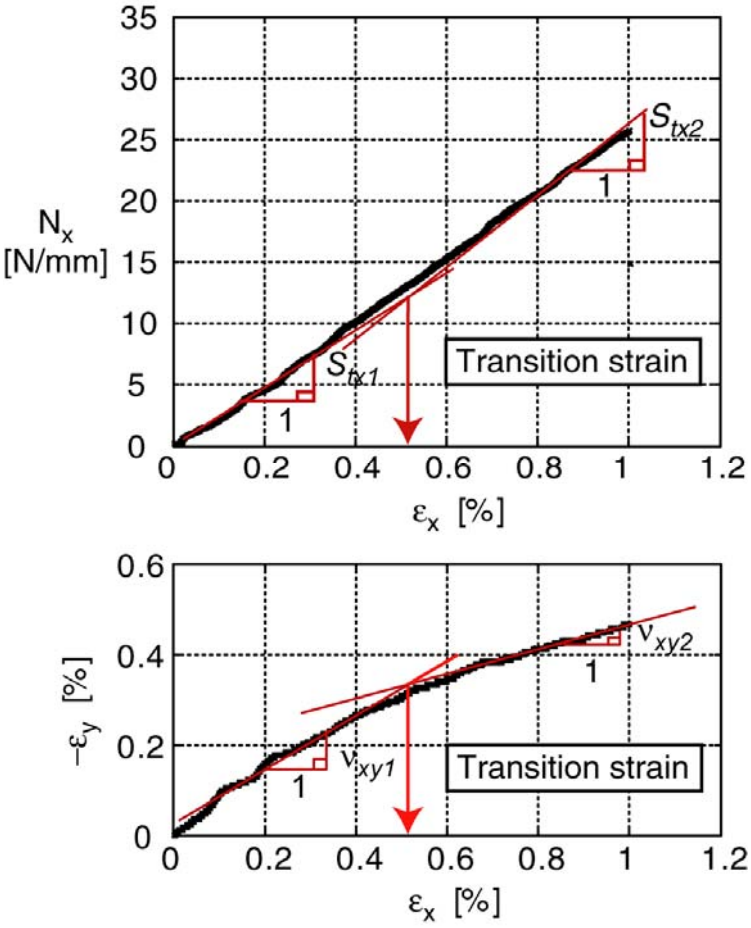


Figure 9.17-16 - TWF study: Definition of transition strain

Both of these effects are due to the fact that the tows are not straight. Straightening of the tows in tension has the effect of increasing the weave extensional stiffness while decreasing the Poisson's ratio. The stiffness continues to increase, although much less rapidly, up to failure of the material. The opposite is true for the Poisson's ratio.

The extensional stiffness in the 0-direction, Stx, in N/mm, can be computed from the initial slope:

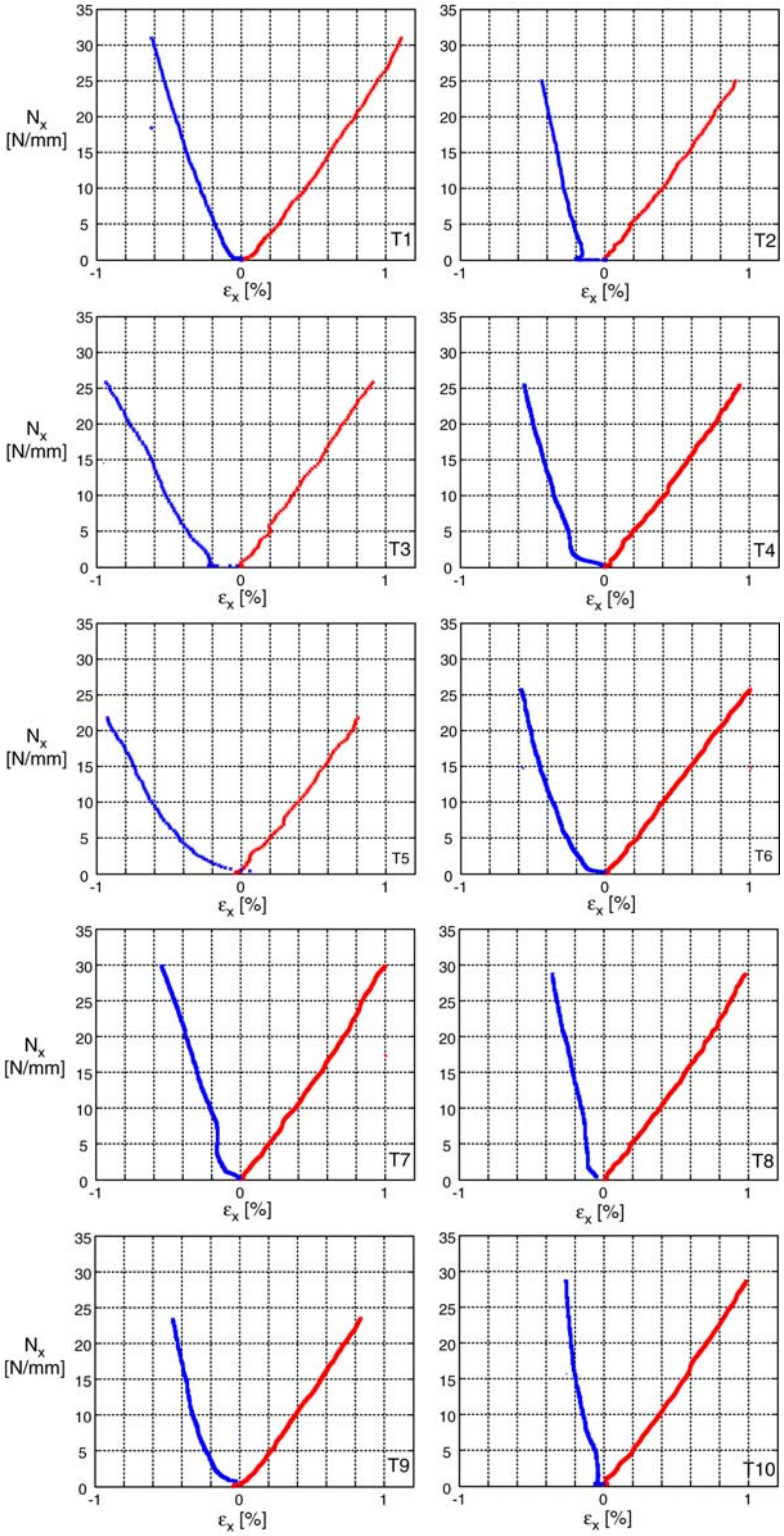
$$S_x^t = \frac{\Delta N_x}{\Delta \varepsilon_x} \qquad [9.17\text{-}75]$$

The longitudinal Poisson's ratio, ν_{xy}, can be determined from:

$$\nu_{xy} = -\frac{\Delta \varepsilon_y}{\Delta \varepsilon_x} \qquad [9.17\text{-}76]$$

where: $\Delta\varepsilon_y$ is the change of transverse strain.

The force per unit width at failure, N_x^{tu}, and the failure strain, ε^{tu}, were also measured during the test.



Measured force per unit width vs. strain response from tension tests

Figure 9.17-17 - TWF study: Tensile test plots

Ten, force/width vs. strain plots, from the tension tests are shown in Figure 9.17.17. The values for stiffness and Poisson's ratio calculated from these plots, both before and after the transition strain (denoted by subscripts 1 and 2 respectively), are listed in Table 9.17.7.

Table 9.17-7 - TWF study: Tensile test results

Specimen	S^t_{x1}	S^t_{x2}	ν_{xy1}	ν_{xy2}	N_x^{tu}	ε^{tu}
	[N/mm]	[N/mm]			[N/mm]	[%]
T1	2100.3	3278.7	0.564	0.428	30.97	1.11
T2	2062.8	3015.1	0.541	0.360	24.99	0.90
T3	2067.0	3028.0	0.663	0.422	25.83	0.91
T4	2069.5	3129.7	0.561	0.408	25.44	0.93
T5	2245.8	3088.0	0.658	0.466	21.75	0.81
T6	2250.0	3075.6	0.564	0.358	25.73	1.00
T9	2069.5	3066.5	0.558	0.421	23.46	0.84
T10	2024.8	3098.0	0.690	0.388	28.62	1.08
Average	2111.2	3097.5	0.600	0.406	25.85	0.95
Std. dev.	86.80	81.96	0.060	0.036	2.86	0.11
Variation [%]	4.11	2.65	9.92	8.98	11.07	11.36

Results deemed anomalous are excluded.

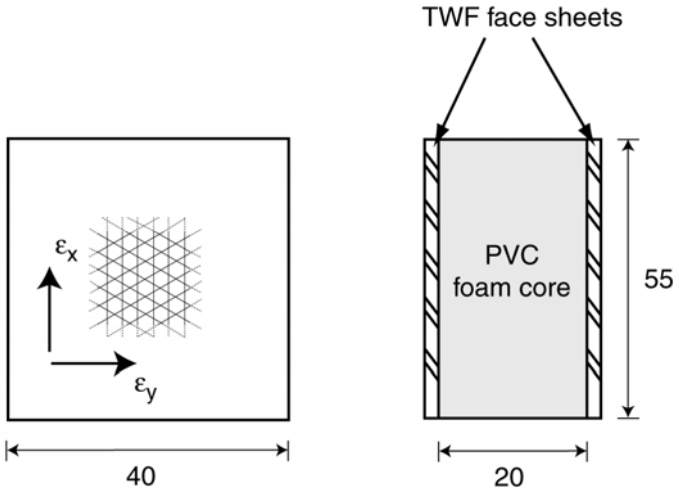
Some of the specimens gave an anomalous initial response, e.g. T7. This is a feature of testing specimens of small thickness, where a small initial curvature in the longitudinal direction would result in zero initial stiffness and a small transverse curvature would result in a very large apparent Poisson's ratio. To obtain the Poisson's ratio the horizontal part has been neglected. Since the initial slope of the longitudinal response is constant up to a strain of, in most cases, 0.5%, the initial transverse response is also computed up to this strain. This is done after omitting the horizontal part. The response after the transition strain is stable, thus making the computation of the Poisson's ratio easier.

9.17.10 Compressive properties

9.17.10.1 Method

Compression tests on thin composite plates are notoriously difficult, as the failure mode of interest is fibre microbuckling, but other test-dependent failure modes tend to occur at lower loads. Following Fleck and Sridhar, Ref. [9-21], the compression tests are carried out on short sandwich columns, comprising two TWF face sheets bonded to a closed-cell PVC foam core, as shown in Figure 9.17.18. Fleck and Sridhar have shown that by suitable choice of the properties of the foam the lateral restraint provided by the core can be optimised to prevent failure by Euler buckling, core shear macrobuckling, and face wrinkling so that the specimen fails by fibre microbuckling. The particular foam used was Divinycell®, a closed-cell polyvinyl chloride (PVC) foam sandwich core having the following properties:

- Density = 186 kg m-3
- Extensional modulus, Ecore = 295 MPa
- Shear modulus, Gcore = 110 MPa



dimensions in mm

Front view Side view

Figure 9.17-18 - TWF study: Compression test sample

The specimens were designed such that failure occurred by fibre microbuckling.

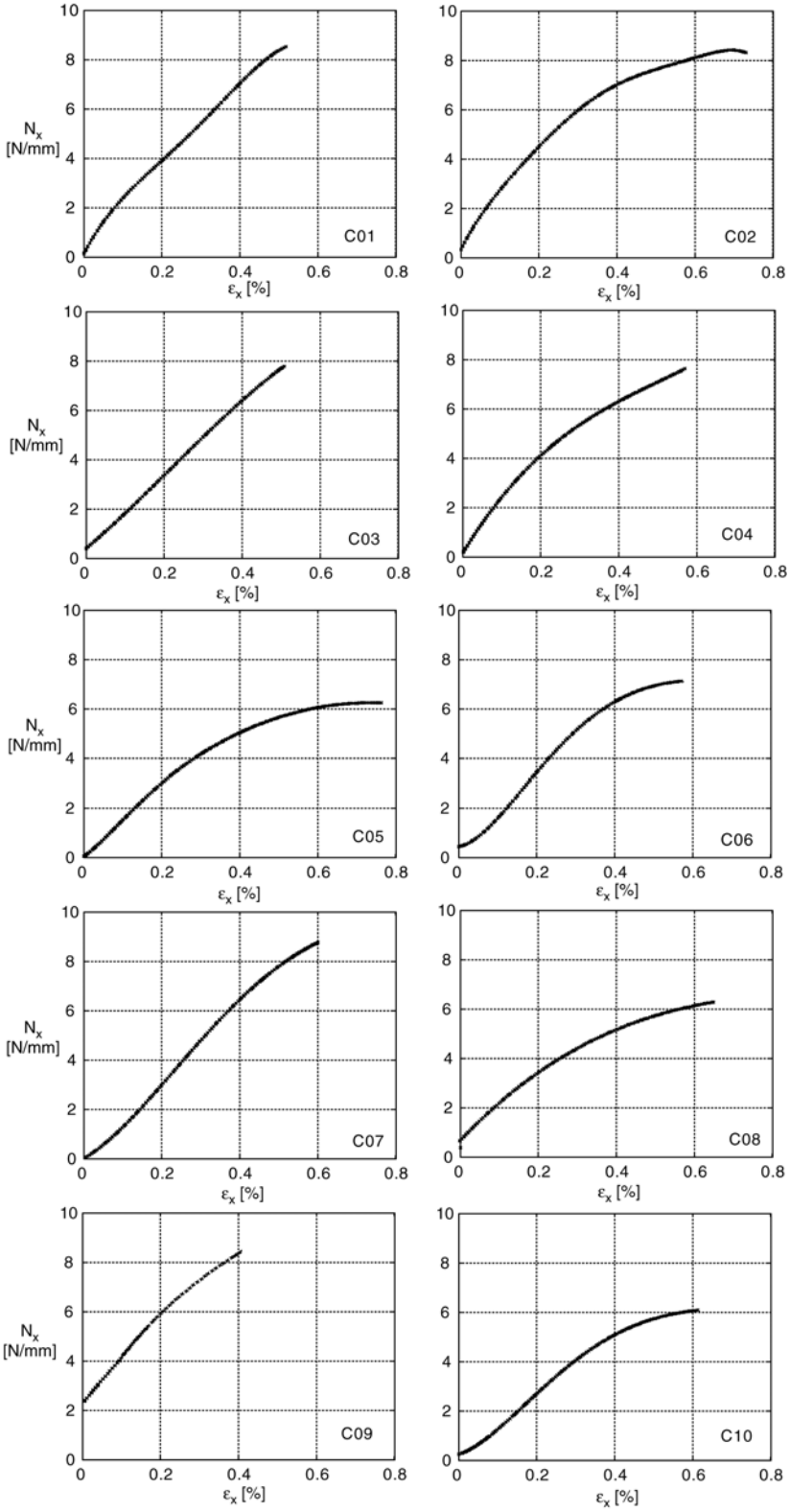
Each specimen was 40 mm wide × 55 mm long and consisted of two 40 mm × 55 mm TWF sheets, with the 0-direction tows aligned with the longer direction, and a 20 mm foam sandwich core.

9.17.10.2 Results

Ten plots of measured force per unit width vs. strain from the compression tests are shown in Figure 9.17.19. In general, the axial stiffness in compression, S^c_x in the fibre direction, can be computed from the initial slope, as follows:

$$S_x^c = \frac{\Delta N_x}{\Delta \varepsilon_x} \qquad [9.17\text{-}77]$$

Some specimens, e.g. C06, showed a softer response at the beginning of the test. It is believed that this behaviour occurred when the specimen did not make full contact with the load platens at the beginning. The force per unit width at failure, N_x^{cu}, and the failure strain, ε^{cu}, were also measured in each compression test.



Measured force per unit width vs. strain response from compression tests

Figure 9.17-19 - TWF study: Compression test plots

The measured compression properties are summarized in Table 9.17.8. The data for specimen C09 has been omitted from the table, as the initial part of this test was not recorded. There is a larger variation, 13.86%, in the failure strain in compression than in tension, 11.36%.

Table 9.17-8 – TWF study: Compression test results

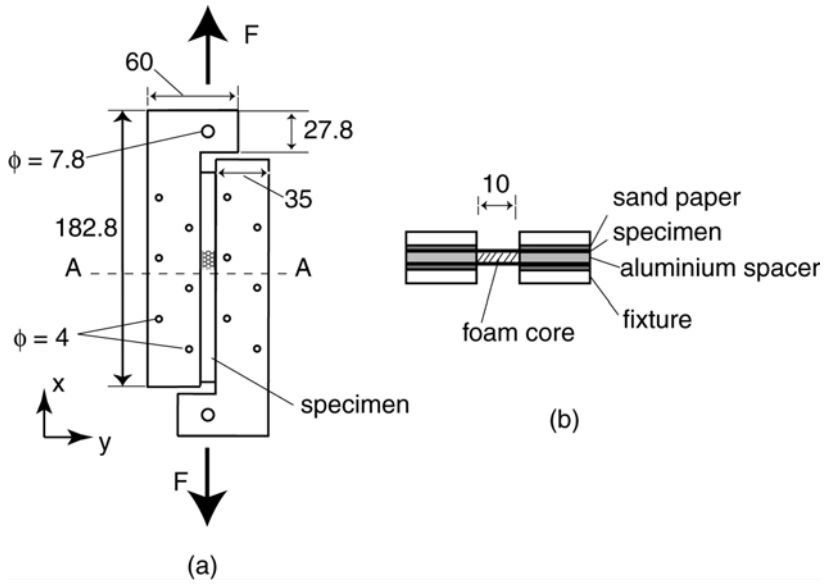
Specimen	S^{c}_{x} [N/mm]	N_x^{cu} [N/mm]	ε^{cu} [%]
C01	2178.8	8.59	0.52
C02	2218.7	8.46	0.72
C03	2220.9	7.87	0.52
C04	2290.3	7.48	0.57
C05	2299.4	6.85	0.77
C06	2280.5	7.85	0.57
C07	2346.2	8.63	0.6
C08	2328.7	6.81	0.64
C10	2036.9	6.23	0.62
Average	2244.5	7.64	0.61
Std. dev.	95.18	0.87	0.09
Variation [%]	4.24	11.33	13.86

Results deemed anomalous are excluded.

9.17.11 Shear properties

9.17.11.1 Method

To prevent wrinkling of the specimen, an analogous approach to that of the compression tests of Fleck and Sridhar, Ref. [9-21] was followed. Hence a sandwich plate consisting of TWF face sheets and a thin foam core was used, instead of a single sheet as suggested in ASTM D4255, Ref. [9-22]. The standard two-rail shear test rig was modified as shown in Figure 9.17.20. The modification includes increasing the number of bolts from three to six and using sandpaper between the specimen and the steel rails. Also, the unconstrained width of the specimen was reduced from 12.7 mm to 10 mm to increase the wrinkling load.



dimensions in mm

(a) Modified shear rig (b) Cross section AA

Figure 9.17-20 – TWF study: Shear test rig and sample

The shear strain in the specimen was calculated from linear strain measurements from two clip gauges, one across the rails and one at 45°.

Each specimen was 80 mm wide × 130 mm long with an unsupported width of 10 mm. Specimens comprised of two TWF sheets bonded to a 130 mm long by 10 mm wide, 3 mm thick strip of PVC foam core, between 3 mm thick aluminium spacers, see Figure 9.17.20 (b). The PVC foam is of the same type used in the compression specimens.

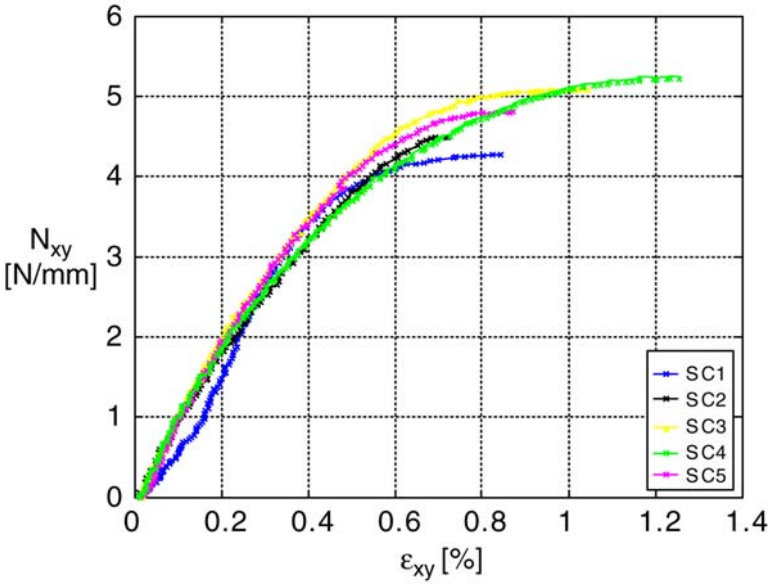
9.17.11.2 Results

Plots of measured shear force/length vs. shear strain (measured with the clip gauges) are shown in Figure 9.17.21. The force per unit width values refer to one sheet of TWF and the force carried by the core has already been subtracted. The behaviour under test is broadly similar. The key parameters obtained from each test are summarised in Table 9.17.9. The shear failure force per unit width and strain are represented by N^{u}_{xy} and ε^{u}_{xy}, respectively.

No premature failures near the clamped region of the specimens were observed, indicating that the sandwich specimen configuration worked well.

The shear stiffness, S_{xy}, can be determined from the initial slope of the shear load vs. shear strain plot, as follows:

$$S_{xy} = \frac{\Delta N_{xy}}{\Delta \varepsilon_{xy}} \qquad [9.17\text{-}78]$$



Shear force per unit length vs shear strain

Figure 9.17-21 – TWF study: Shear test plots

Table 9.17-9 – TWF study: Shear test results

Specimen	S_{xy} [N/mm]	N^u_{xy} [N/mm]	ε^u_{xy} [%]
SC1	666.0	4.38	0.84
SC2	737.5	4.79	0.72
SC3	828.6	5.33	1.02
SC4	839.7	5.69	1.21
SC5	813.8	5.02	0.86
Average	777.12	5.04	0.93
Std. dev.	73.874	0.501	0.189
Variation [%]	9.51	9.94	20.37

9.17.12 Bending stiffness

9.17.12.1 Method

To measure the bending stiffness, a 4-point bending configuration was used instead of 3-point because it gives a central region with a uniform bending moment.

The outer span was 60 mm and the inner one was 20 mm, to give an aspect ratio of 0.5 in the region subject to uniform bending moment. The deflections imposed during this test were very small, the maximum value of δ being about 0.6 mm, corresponding to a deflection-to-span ratio of 33; the maximum value of applied load was about 0.1 N. Friction effects associated with longitudinal deflections at the supports were negligible.

Rectangular test specimens were 100 mm long × 40 mm wide, with the 0-direction tows aligned with the longer edge were tested. A specimen width, w = 40 mm, was chosen to match the width of the compression specimens.

9.17.12.2 Results

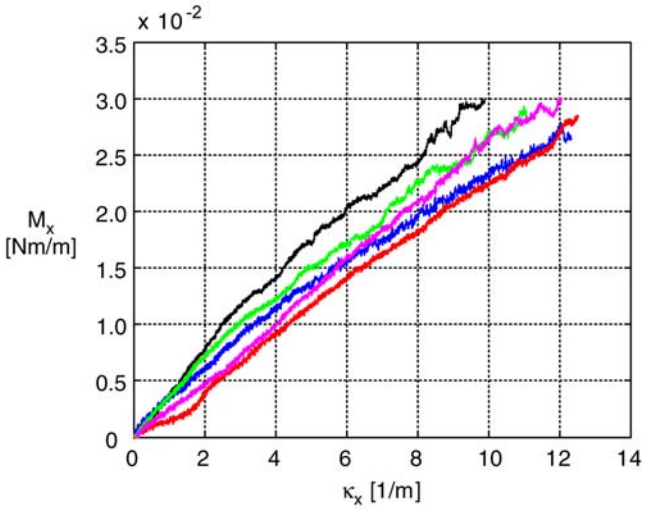
Plots of bending moment per unit width, M_x, vs. curvature, κ_x, are shown in Figure 9.17.23. All plots show a gradual decrease in slope.

The bending stiffness in the 0-direction, D_{11}, is given by the initial slope of these plots: , after discarding any anomalous response:

$$D_{11} = \frac{\Delta M_x}{\Delta \kappa_x} \qquad [9.17\text{-}79]$$

Curves deemed to show an anomalous response were excluded.

The measured bending stiffnesses obtained from this calculation are listed in Table 9.17.10. There is only a small scatter in the experimental data.



Bending moment per unit width vs. curvature
from 4-point bending tests

Figure 9.17-22 – TWF study: 4-point bending test plots

Table 9.17-10 – TWF study: Bending stiffness (measured)

Specimen	Bending stiffness, D_{11} [N mm]
B01	2.008
B02	2.046
B03	2.092
B04	2.108
B05	2.132
Average	2.077
Std. dev.	0.050
Variation [%]	2.40

9.17.13 Bending curvature at failure

9.17.13.1 Method

Figure 9.17.22 shows the test set-up to determine the smallest radius to which single-ply TWF composites can be folded before breaking. This, so-called, 'squashing test' enables the sample curvature at failure to be determined.

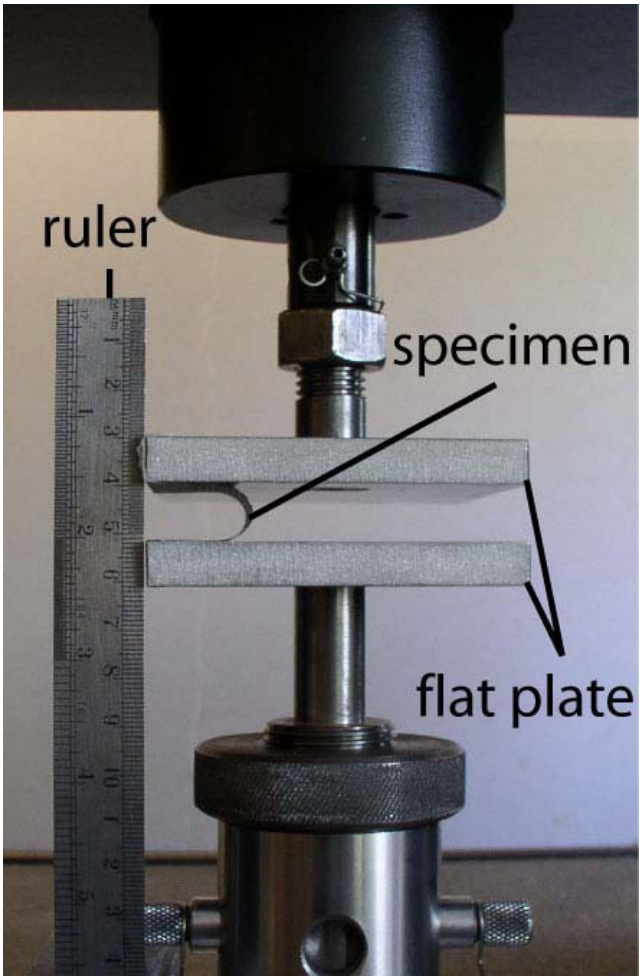


Figure 9.17-23 – TWF study: 'Squashing test' set-up

Test specimens were rectangular, 40 mm wide by 50 mm long, with the 0-direction tows aligned with the longer edge of the coupon. Each test was recorded with a digital video camera. Images recorded just before the failure of the specimen were analysed in detail. The minimum radius to which the specimen can be folded without failure is judged to be half of the distance between the two plates just before the specimen fails. The results are given in Table 9.17.11.

9.17.13.2 Results

The minimum radii and failure curvatures, measured from 10 squashing tests on 0-direction specimens, are listed in Table 9.17.11. The average radius at failure was 2.6 mm, with only a small variation.

Table 9.17-11 – TWF study: 'Squashing test' results

Specimen	Minimum radius, R_{min} [mm]	Failure curvature, κ^u [1/mm]
1	2.554	0.392
2	2.672	0.374
3	2.716	0.368
4	2.716	0.368
5	2.601	0.385
6	2.503	0.400
7	2.601	0.385
8	2.713	0.369
9	2.692	0.372
10	2.592	0.386
Average	2.636	0.380
Std. dev.	0.076	0.011
Variation [%]	2.88	2.91

9.17.14 Linear coefficient of thermal expansion

9.17.14.1 Method

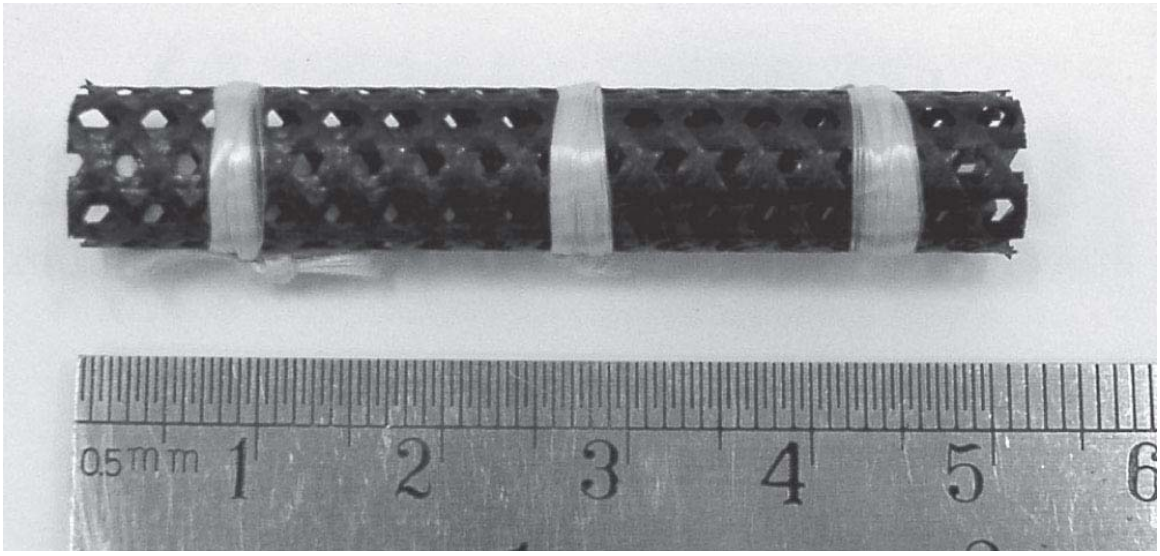
The aim of the test was to determine the linear coefficient of thermal expansion. It was decided to focus on the 0-direction as previous work, Ref. [9-8] has shown that the CTE in the 90-direction has a similar value.

TWF is too thin to carry out CTE tests on flat strips, as a flat strip cannot be guaranteed to remain straight under the load applied by the dilatometer. Hence, the coupon layout previously used in, Ref. [9-8], was adopted.

The TWF was cured on a 20 mm diameter mandrel. Coupons were made by cutting 50 mm long cylinders and wrapping them with Kevlar fibres down to a diameter just below 8 mm, see Figure 9.17.24.

Cylindrical specimens with a nominal length of 50 mm (actual lengths between 49.6 mm and 50.5 mm) were tested. The results from one of the cylinders were not repeatable and were discarded.

The dry appearance of specimen surfaces indicated that the fibre volume fraction, although not measured, was higher than in the flat specimens used for all other tests.



A WSK TMA 500 dilatometer was used for the CTE measurements.

Figure 9.17-24 – TWF study: CTE cylindrical test sample

9.17.14.2 Results

Plots of the measured relationship between thermal strain and temperature for the cylindrical coupons with the 0-direction aligned with the axis of the cylinder are shown in Figure 9.17-25. The plot for specimen TE3 shows an anomalous behaviour at colder temperatures. Excluding this specimen, the other plots show uniform behaviour. Generally, the slope is greater above room temperature, but becomes less at lower temperatures.

The CTE of a specimen can be determined from:

$$\alpha = \frac{\Delta \varepsilon_x}{\Delta T} \qquad [9.17\text{-}80]$$

An overall average of the measurements shown in Table 9.17.12 gives a value of 0.957 x 10^{-6}°C^{-1}.

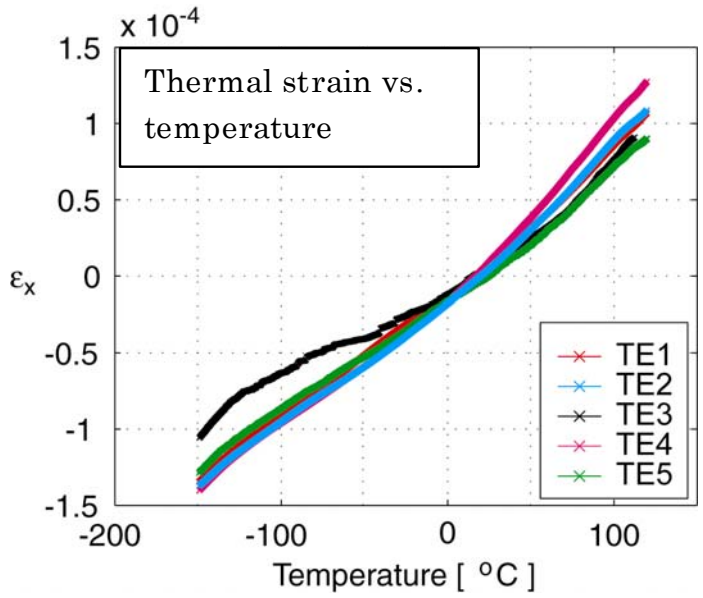


Figure 9.17-25 - TWF study: Thermal measurements

Table 9.17-12 – TWF study: CTE test results

Specimen	CTE × 10^{-6} [/°C]
TE1	1.067
TE2	0.664
TE3	0.969
TE4	0.969
TE5	1.117
Average	0.957
Std. dev.	0.176
Variation [%]	18.38

Results deemed anomalous are excluded

9.17.15 Thermal twist

9.17.15.1 Method

The aim of these tests was to measure the relationship between twist and temperature in narrow 0-direction and 90-direction strips of TWF composite that were fixed at one end. The reason for testing narrow strips of material is to avoid the complex buckle patterns that have been observed in wider specimens, Ref. [9-9].

The torsional stiffness of the strips is small and hence a non-contact measurement technique was adopted. The twist of the end section of the strips was obtained by measuring the deflection of two points close to the edges of the strip, using laser displacement sensors. To further amplify these readings, the ends of the strips were widened by attaching small composite plates.

Figure 9.17-26 shows the thermal twist test specimens. Single-unit-wide coupons, approximately 80 mm long, were prepared. The 0-direction specimen was 5.4 mm wide; the 90-direction specimen was 3.1 mm wide. The coupons were cut from a flat sheet of cured material using a pair of scissors for composite materials, under a magnifying glass. When cutting these strips it is important to avoid cutting through the interweaved regions in order to ensure that they are not damaged.

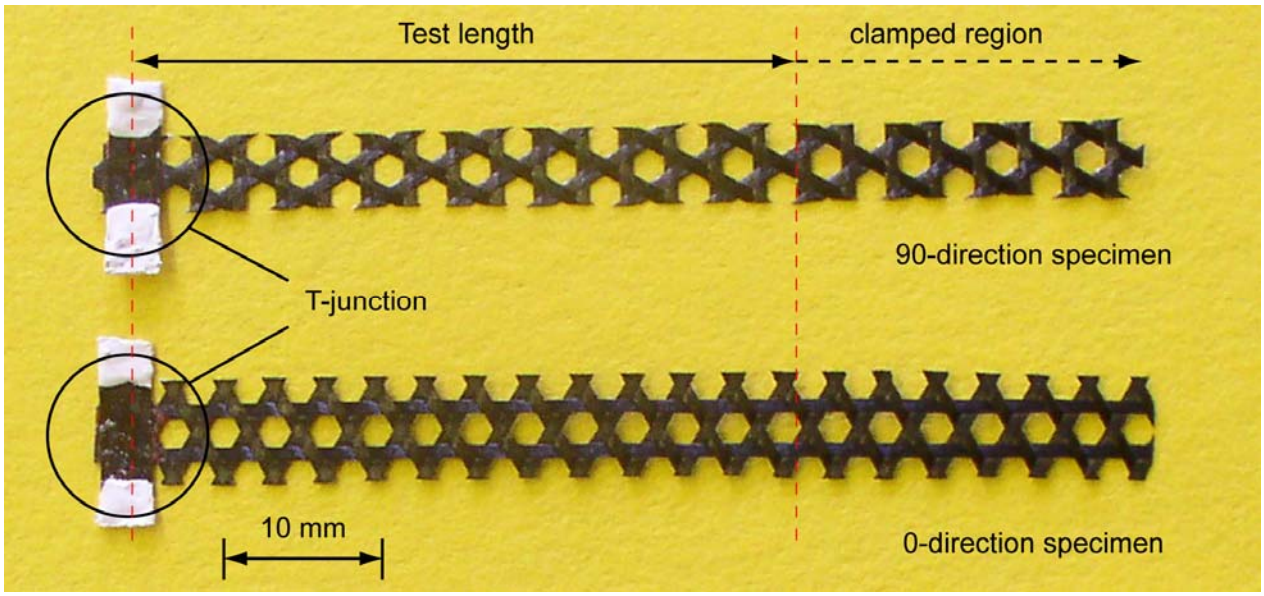


Figure 9.17-26 - TWF study: Thermal twist specimens

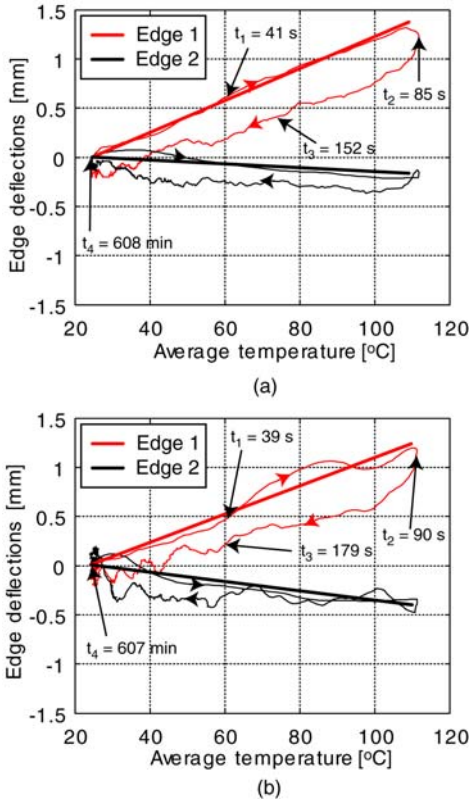
A 12 mm long, flat plate of single-ply T300/Hexcel® 8552 composite material (3 mm wide × 0.22 mm thick) was attached to the end of each strip using Loctite® 3608 adhesive.

All specimens were held under vacuum for 24 hours to ensure a low moisture content. Three thermal cycles were applied to each specimen in an environment with a relative humidity of 15 % at room temperature.

9.17.15.2 Results

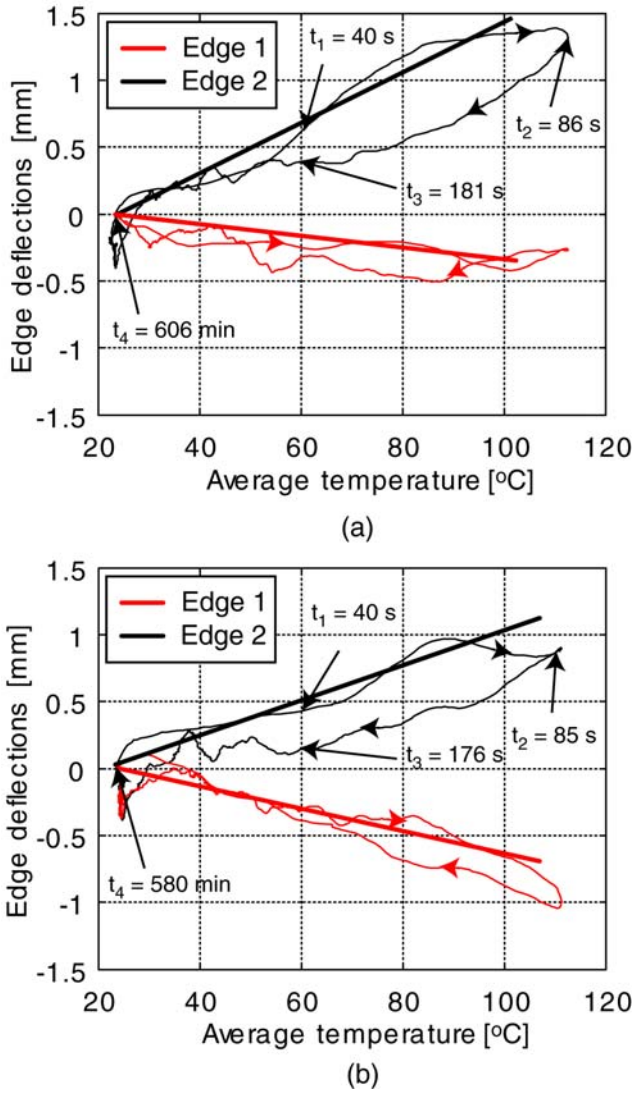
Figure 9.17.27 and Figure 9.17.28 show plots of the displacements of two points at the tip of a 0-direction strip and a 90-direction strip, vs. the average temperature during the third and final thermal cycle.

The edge that moves up in Figure 9.17.27 is edge 1, but in Figure 9.17.28 it is edge 2.



Tip edge deflections vs. average temperature
measurements for two nominally identical 0-direction strips

Figure 9.17-27 - TWF study: 0-direction thermal twist plots



Tip edge deflections vs. average temperature measurements
for two nominally identical 90-direction strips

Figure 9.17-28 – TWF study: 90-direction thermal twist plots

The experimental data defining the deflection of points on two opposite edges of two nominally identical strips, during the temperature increase part of the cycle, has been fitted with straight lines in both Figure 9.17.27 and Figure 9.17.28.

The corresponding twist per unit length of each strip, or coefficient of thermal twist, β, can be determined by dividing Equation 9.17.32 by the total temperature change, hence:

$$\beta = -2\frac{\Delta W}{dL\Delta T} \qquad [9.17\text{-}81]$$

Where:

ΔW = difference in out-of-plane deflection between two tip edges

d = distance between edge points measured by two lasers (9.1 mm in both strips)

L = strip length

ΔT = change of temperature

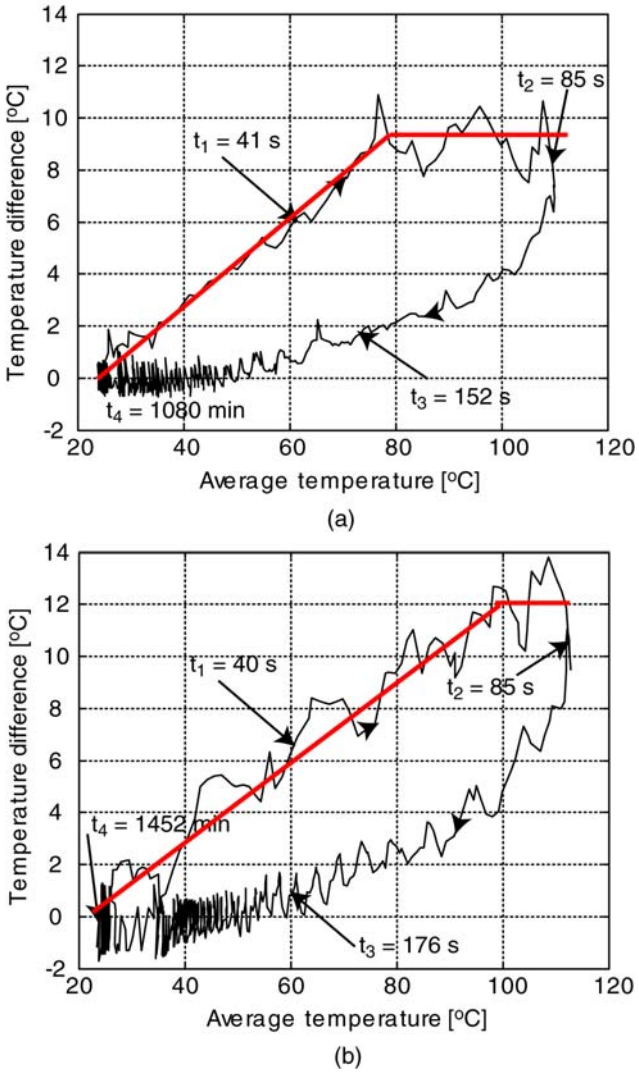
Table 9.17.13 lists the values of the CTT for the 0-direction and 90-direction strips, all measured from the 'heat up' part of the test. The table indicates that the 90-direction strip twists more than the 0-direction strip. All of the values of ⊚ are negative, indicating that a negative twisting curvature develops in a TWF composite when it is heated. The average CTT's are:

- 0-direction $\beta_0 = -7.082 \times 10\text{-}5\ \text{mm-}1°\text{C-}1$
- 90-direction $\beta_{90} = -9.010 \times 10\text{-}5\ \text{mm-}1\ °\text{C-}1$

Table 9.17-13 – TWF study: Thermal twist test results

Specimen	Cycle	β_0	β_{90}
		$(mm^{-1}°C^{-1})$	$(mm^{-1}°C^{-1})$
1	1	-7.442×10^{-5}	-8.334×10^{-5}
	2	-6.378×10^{-5}	-8.224×10^{-5}
	3	-6.910×10^{-5}	-9.868×10^{-5}
2	1	-8.098×10^{-5}	-8.992×10^{-5}
	2	-6.578×10^{-5}	-8.772×10^{-5}
	3	-7.086×10^{-5}	-9.868×10^{-5}
Average		-7.082×10^{-5}	-9.010×10^{-5}
Std. dev.		3.113×10^{-6}	3.610×10^{-6}
Variation [%]		8.79	8.02

Figure 9.17.29 shows the variation between the two surfaces of each specimen, as a function of the average temperature of the specimen. The thermal gradient increased approximately linearly in both tests, and then remained approximately constant.



Measurements of temperature difference between two surfaces of (a) 0-direction strip; (b) 90-direction strip

Figure 9.17-29 – TWF study: Surface temperature differences

9.18 References

9.18.1 General

Indicated within data sheets as: Ref. [x]. [See also: Data Sources].

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9.18.2 Data sources

Digits only indicated within Data Sheets under Data Sources. [See also: References].

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2 CASA (S)
3 MBB/ERNO (G)
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