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Assessment of Industry Practices for Aircraft Bonded Joints and Structures

July 2005

Final Report

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16. Abstract

Adhesive bonding is used in numerous manufacturing and repair applications for aircraft structures in small airplanes, transport aircraft, rotorcraft, and fighter jets. Many of the technical issues for bonding are complex and require cross-functional teams for successful applications. This report highlights ongoing efforts by the aircraft industry and government agencies to combine their adhesive bonding experiences and technical insights to gain mutual safety benefits.

A large part of this report consists of documentation supplied as part of a survey to benchmark industry practices and collect information on the critical safety issues and certification considerations for bonded aircraft structures and repairs. Representatives from 38 companies with experience and history in adhesive bonding manufacturing and repair practices responded to the survey questionnaire. The questionnaire addresses the use of adhesive bonding in structural applications such as original part or assembly designs and repairs. The results of the questionnaire were also sorted by the functional disciplines of the respondents to highlight any potential differences or critical areas which were particularly important to specific technical areas.

This report also features documentation from an accompanying workshop that was sponsored by the Federal Aviation Administration. The workshop provided additional information to benchmark bonded structures as part of ongoing composite safety and certification initiatives. The primary objective of the workshop was to document the technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. Examples of proven engineering practices used to address specific technical concerns were documented as a secondary objective. The process to benchmark existing technology should also provide directions for future research and developments in the field.

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LIST OF ACRONYMS

AACE	Airworthiness Assurance Center of Excellence
AC	Advisory Circular
AGATE	Advanced General Aviation Transport Experiments
AOG	Aircraft on ground
BVID	Barely Visible Impact Damage
CACRC	Commercial Aircraft Composite Repair Committee
CDC	Cirrus Design Corporation
CFR	Code of Federal Regulations
CS&CI	Composite safety and certification initiatives
DCB	Double cantilever beam
DER	Designated engineering representative
DMA	Dynamic mechanical analysis
DSC	Differential scanning calorimetry
DSTO	Defense Science and Technology Organization
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAW	Fiber areal weight
FEA	Finite element analysis
FEM	Finite element method
FOD	Foreign object damage
FPQ	First part qualification
FTIR	Fourier transform infrared spectroscopy
HPLC	High performance liquid chromatography
LEFM	Linear elastic fracture mechanics
M&P	Material and process
MOL	Maximum operating limit (temperature)
MRO	Maintenance and repair organization
NASA	National Aeronautics and Space Administration
NDE	Nondestructive evaluation
NDI	Nondestructive inspection
NDT	Nondestructive testing
NSE	National Stress Engineers
OEM	Original equipment manufacturer
P/A	Load over area analysis
PAA	Phosphoric acid anodizing
PABST	Primary Adhesively Bonded Structure Technology
PANTA	Phosphoric acid nontank anodizing
QA	Quality assurance
R&D	Research and development
RAAF	Royal Australian Air Force
RT	Room temperature
SEM	Scanning electron microscope
SPC	Statistical Process Control
SRM	Structural repair manual
T_g	Glass transition temperature

TTCP	The Technical Cooperation Program
UMIST	University of Manchester Institute of Science and Technology
USAF	United States Air Force
WSU	Wichita State University

EXECUTIVE SUMMARY

Adhesive bonding is used in numerous manufacturing and repair applications for aircraft structures in small airplanes, transport aircraft, rotorcraft, and fighter jets. Many of the technical issues for bonding are complex and require cross-functional teams for successful applications. This report highlights ongoing efforts by the aircraft industry and government agencies to combine their adhesive bonding experiences and technical insights to gain mutual safety benefits.

A large part of this report consists of documentation supplied as part of a survey to benchmark industry practices and collect information on the critical safety issues and certification considerations for bonded aircraft structures and repairs. Representatives from 38 companies with experience and history in adhesive bonding manufacturing and repair practices responded to the survey's questionnaire. The questionnaire addressed the use of adhesive bonding in structural applications such as original part or assembly designs and repairs. The specific applications that were addressed in the questionnaire were bonded joints with at least one substrate that was precured composite or metal (i.e., joints that include secondary bonds). This included bonding composite-to-composite, metal-to-metal, and composite-to-metal. The questionnaire was divided into three main technical areas, plus two additional areas for background and general inputs. The technical areas were (1) materials and processes; (2) manufacturing and design integration; and (3) product development, substantiation, and support. The results of the survey were also sorted by the functional disciplines of the respondents to highlight any potential differences or critical areas that were particularly important to specific technical areas.

This report also features documentation from an accompanying workshop that was sponsored by the Federal Aviation Administration (FAA). The workshop provided additional information to benchmark bonded structures as part of ongoing composite safety and certification initiatives. The primary objective of the workshop was to document the technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. Examples of proven engineering practices used to address specific technical concerns were documented as a secondary objective. The process to benchmark existing technology should also provide directions for future research and development in the field. Approximately 142 international representatives attended this workshop from industry, academia, and governmental agencies, representing approximately 70 companies, universities, and governmental agencies. The workshop sessions were separated based upon technical issues in (1) material and process qualification and control, (2) design development and structural substantiation, (3) manufacturing implementation and experience, and (4) repair implementation and experience. There was also a session on applications and service experiences. This report summarizes insights gathered in all the sessions and provides technical details of areas that need to be addressed in the future.

The described activities that found a strong interface with the industry, other government groups, and academia is needed to adequately benchmark bonded structures. Such an approach should yield additional documents that provide the industry and governmental agencies with a practical engineering guide, with educational value for personnel new to bonding. Future joint efforts by the FAA, industry, and academia will pursue recommendations on standardization, engineering

guidelines, shared databases, and focused research for bonded structures. The FAA will continue to work with industry and other government agencies in drafting consistent policy and guidance for bonded structures.

1. BACKGROUND.

Bonding is used in numerous manufacturing and repair applications for aircraft structures, including existing commercial and military applications to small airplanes, transport aircraft, rotorcraft, and fighter jets. Many of the technical issues for bonding are complex and require cross-functional teams for successful applications. Collectively, the aircraft industry and government agencies need to combine their adhesive bonding experiences and technical insights to gain mutual safety benefits. Other advantages from sharing information are feasible for improved efficiency in the development and certification of bonded aircraft structure.

1.1 SAFETY AND CERTIFICATION PERSPECTIVES.

The Federal Aviation Administration (FAA) has developed composite safety and certification initiatives (CS&CI) for regulatory work with industry, government agencies, and academia. One objective is to ensure safe and efficient deployment of composite technologies used in existing and future aircraft structure. Another objective was to update related policies, advisory circulars, training, and detailed background used to support standardized composite engineering practices.

Figure 1 illustrates the approach used for CS&CI. Moving from left to right in the figure, internal policies are evolved into mature certification practices over time. The FAA derives initial regulatory policies for composites based on past certification programs and service experiences. Focused research and other industry interfaces are used to transition the initial, often unwritten policies, into documented procedures and guidance for review by regulatory agencies and the aviation industry. Detailed background, which includes engineering standards and training, are also developed to complement and facilitate technology transfer of the regulatory practices recommended for composites.

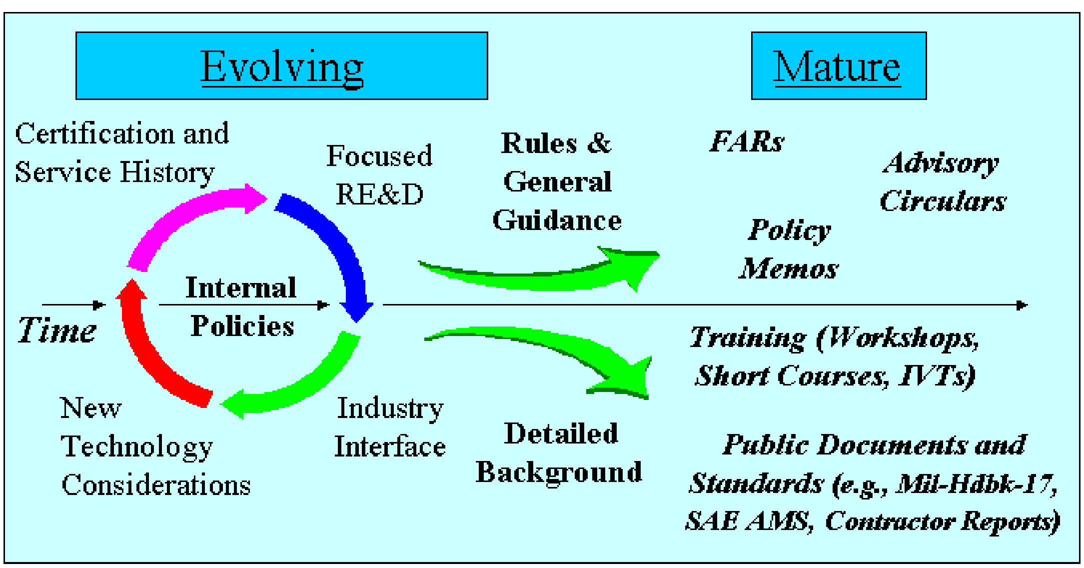

FIGURE 1. THE FAA APPROACH TO CS&CI

Other groups that have supported the approach shown in figure 1 include regulatory agencies from foreign countries, other branches of the U.S. government, and international standards organizations. For example, the National Aeronautics and Space Administration (NASA) was directly involved in a number of CS&CIs, in past years through the program called Advanced General Aviation Transport Experiments (AGATE). The Military Handbook 17 (MIL-HDBK-17) and other standards organizations, such as ASTM and SAE, have helped develop engineering guidelines and standards for the CS&CI. These organizations also provide the necessary forum for composite technical issues and expanding applications.

CS&CI, which are currently active for composite aircraft structures, addresses the technical areas listed in figure 2. Initiatives have been established for these technical areas because they often require considerable attention in development and certification. Advances in engineering practices and future trends in these areas also require the joint efforts of regulatory agencies and industry. Since 2000, considerable progress has been achieved in many of the technical areas shown in figure 2. With help from the NASA AGATE program, the most progress has been gained in material control, standardization, and shared composite databases.

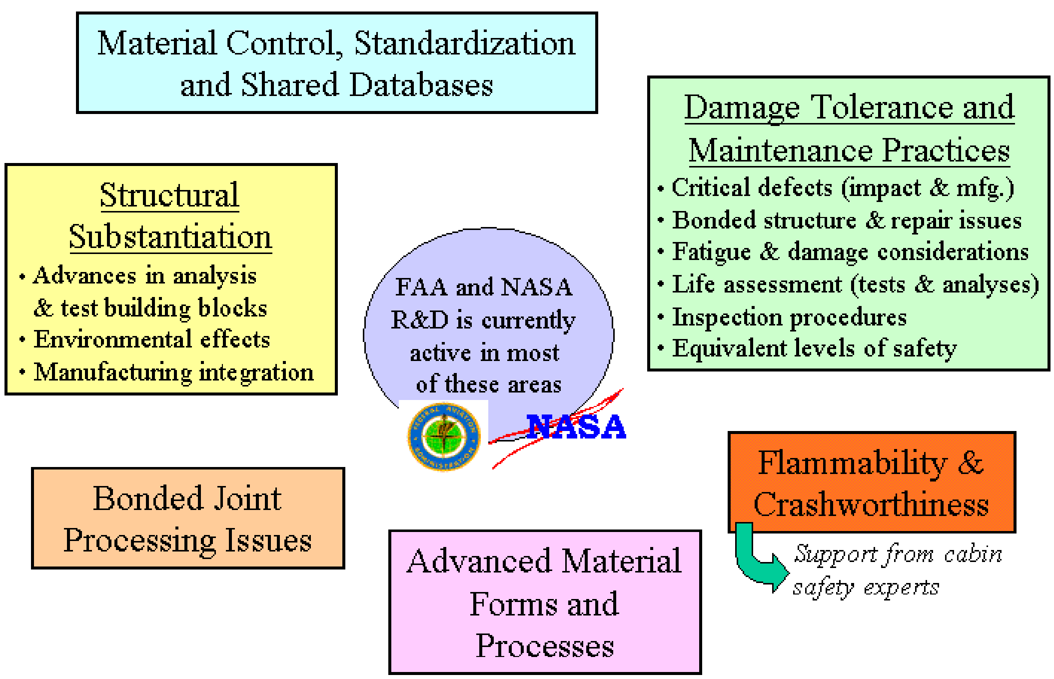

FIGURE 2. TECHNICAL THRUST AREAS FOR CS&CI

Research supporting CS&CI for bonded structures has been active since 1999. Studies were performed on bonded surface preparation and the use of peel plies, as related to service problems from composite applications. Research also led to advancements in adhesive joint shear and peel test methods. Environmental effects, fatigue, and creep were studied for a wide range of adhesive materials used by the industry. Finally, structural analysis methods, which considered realistic bonded joint design detail, were evaluated in problems related to joint stiffness, strength, and damage tolerance.

In addition to the longer-term research, which will continue, this effort was initiated to benchmark industry practices for structural bonding. This includes a survey and bonded structures workshop to engage experts from around the world. The results of these two exercises are documented in this report. The technical scope of these efforts included material and process control, design development, structural substantiation, manufacturing implementation, maintenance practices, and service experiences.

1.2 SURVEY OF THE INDUSTRY.

The initial step in the process of developing adequate recommendations and criteria on adhesive bonded aviation structure was to assess the industry perceptions and practices. To initiate assessment efforts, a survey to benchmark adhesive bonding practices was conducted. This took the form of an e-mailed multiformat survey. The purpose of the survey was to establish detailed background information on the adhesive bonding philosophies that are used by the aircraft industry. The research team identified highly experienced individuals in the bonded structure industry. These individuals were further encouraged to engage other known experts in the field to ensure the broadest industry coverage by the survey. This maximized the breadth of the benchmark effort. The survey addressed the use of adhesive bonding in aviation structural applications, both original manufacturer designs and maintenance repairs.

The survey was constructed to assess both current and preferred practices. This approach allowed the incorporation of lessons learned by current practitioners. The survey participants may have a safe qualified process, but if they were starting a clean sheet of paper, they would modify their currently accepted process. The input was in both multiple-choice and open-ended question format. Most multiple-choice questions allowed for additional input in a comment block. A comment block was also provided at the end of each section and topic area to maximize input of lessons learned and alternate philosophies.

Some questions were asked multiple times with variations in wording. These questions were phrased in different manners to accurately determine the input being given. This is part of a standard surveying technique that asks the question in different ways to eliminate the respondents' bias in interpreting the questions. If the answer is the same with the rephrased question, one knows the respondent was interpreting the question as the surveyor intended. This gives added accuracy to the survey to ensure the responses are addressing the intended issue and provides more accurate conclusions. All multiple-choice questions are provided with a default, No Response, so only the questions an individual respondent answered were included in the survey response.

To identify the type and nature of an individual's input to the survey, a number of questions were asked to classify the organization type, size, perspective of the respondent (individual to corporate), experience level, and expertise area of the respondent. The survey contained three main technical topic areas: (1) materials and processes; (2) manufacturing and design integration; and (3) product development, substantiation, and support. These topic areas follow the major areas of interest and need for control of a bonding process. The final section of the survey encouraged essay responses to five identified general topics in adhesive bonding practice. This allowed the users to voice specific concerns not addressed by specific questions or outside of the scope of any section of the technical topic areas.

The survey information is presented as response numbers and percentage of responses to the multiple-choice questions, and for the open-ended questions, edited text is provided (removing company names and other indicators as to who responded). The survey is discussed in section 3. Details of the survey are shown in appendices A through C.

1.3 BONDED STRUCTURES WORKSHOP.

The primary objective of the Bonded Structures Workshop was to collect and document technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. There were also several secondary objectives for the workshop. Invited speakers were asked to give examples of proven engineering practices for the technical subjects addressed in the workshop. Participants were asked to identify future needs in engineering guidelines, standard tests, and shared databases and specifications. Finally, the participants were asked to provide directions for bonded structure research and technology development, which supports safety and certification.

Figure 3 shows the top-level agenda for the Bonded Structures Workshop, which was held in Seattle, WA, on June 16 to 18, 2004. The FAA opened the workshop with an overview of CS&CI progress with an emphasis on bonded structures initiatives. The survey results collected before the workshop and were shared with the participants. A majority of the participants filled out the survey as a prerequisite for workshop registration. A total of seven sessions were conducted during the rest of the workshop. Sessions 1, 3, 4, 5, and 6 had invited speakers addressing the technical areas shown in figure 3.

FAA Welcome/Overview FAA Survey/Continued Data Collection	Session 3 Material and Process Qualification and Control
Session 1 Applications and Service Experiences Perspectives on critical safety issues, lesions learned and best engineering practice	Session 4 Design Development and Structural Substantiation
Session 2 Four Technical Breakout Sessions Groups in four separate rooms. All participants will attend each session which are run by technical experts (Introduction by leaders, 45 minutes discussion) 1. Materials and processes qualification and control 2. Design development and substantiation 3. Manufacturing implementation 4. Repair implementation	Session 5 Manufacturing Implementation and Experience Session 6 Repair Implementation and Experience Session 7 Summary from day 2 breakout teams, recap, actions, closure and adjourn

FIGURE 3. TOP-LEVEL AGENDA FOR THE BONDED STRUCTURES WORKSHOP

Figure 4 summarizes the technical scope of the Bonded Structures Workshop. The main technical subjects are given in boxes appearing in the four corners of the figure. Regulatory considerations are listed in the center of the figure. The workshop covered all facets of structural bonding from material and process definition through structural design development and certification and manufacturing implementation and maintenance practices. Although these subjects were covered separately, the experts participating in the workshop understood the importance of integrated teamwork for successful bonding applications.

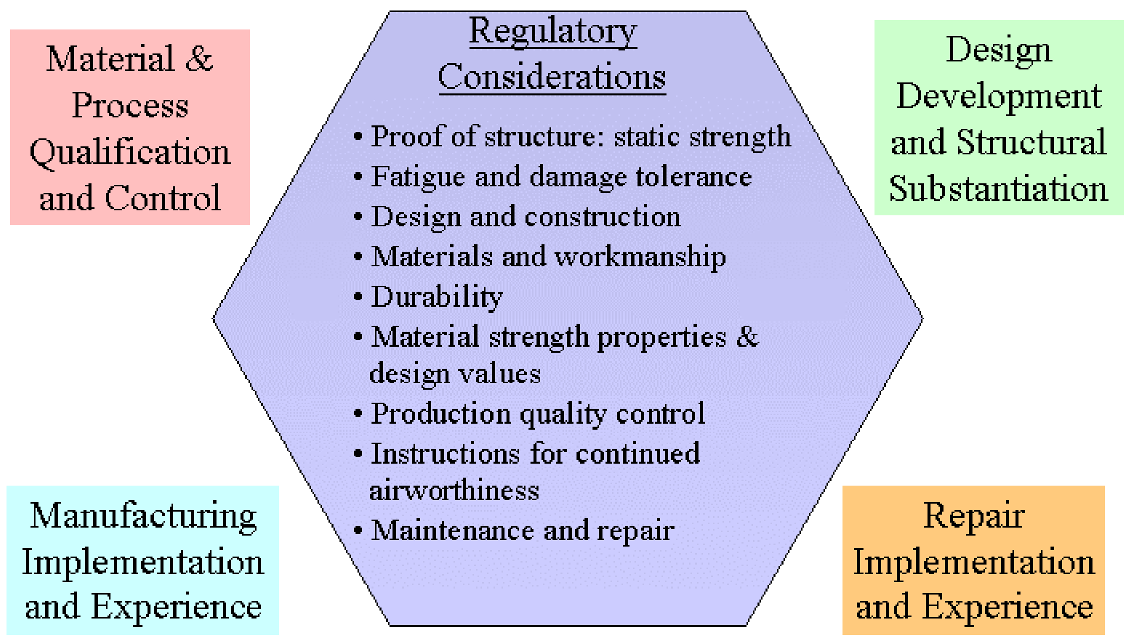

FIGURE 4. TECHNICAL SCOPE OF THE BONDED STRUCTURES WORKSHOP

Teams of technical experts were selected to run the session 2 breakouts, which were held on the morning of the second day. There were separate breakout teams for:

- material and process qualification and control
- design development and substantiation
- manufacturing implementation
- repair implementation

Workshop participants were broken into four groups during the breakout sessions. All groups discussed each of the four different subject areas for approximately 55 minutes. The four teams of facilitators spent the same amount of time with each of the four groups in parallel sessions. Each session started with a brief opening presentation by the responsible facilitators for each subject. This presentation outlined critical technical areas in safety and certification for the particular subject. An open forum on these areas was held after the presentation and the teams of experts collected the information for purposes of future documentation (see section 4.4). Participant comments on future needs in engineering standardization and research were also collected during the breakout sessions. Team leaders at the workshop gave a summary recap of these sessions during session 7 (see section 4.4).

2. THE FAA BONDED STRUCTURES RESEARCH EFFORTS.

2.1 OVERVIEW.

The Bonded Structures Workshop in June 2004 was held prior to drafting the policy in order to gain industry agreement on the critical technical issues for bonding and collect inputs on successful engineering practices. The detailed engineering background on bonding will be documented in a series of FAA William J. Hughes Technical Center reports with the help of industry. The current report represents the first of these documents.

The FAA efforts in bonded structures will continue beyond 2004. The next major milestone for regulatory guidance on bonding is scheduled for 2008. The current plan is to update policy and release an advisory circular for bonded aircraft structure at that time. Training will also be updated by 2008. Focused research on critical bonding issues will remain active to support the FAA efforts in regulatory development and training. The FAA will also continue to support industry and working groups, such as MIL-HDBK-17, SAE, and ASTM, in developing engineering standards for structural bonding in the coming years.

The FAA research in structural bonding from 2000 to 2003 followed a plan outlined by Don Oplinger, who was a composite research project manager at the FAA William J. Hughes Technical Center. This plan included studies to characterize adhesive materials and investigate structural joint details important to existing applications. Some work was performed to evaluate the effects of bondline thickness and environmental conditions on structural integrity. The damage tolerance of bonded structure has been the subject of several studies. This included some NASA and FAA cooperative efforts, which were directed by Dr. Jim Starnes from NASA Langley Research Center. Composite surface preparation processes used for structural bonding have been studied to evaluate qualification and quality control procedures, which ensure suitable materials and processes are used for bonding. Considerable efforts were also applied to evaluate structural analysis methods for adhesive joint design details characteristic of applications. Much of the work completed to date has been published in FAA William J. Hughes Technical Center reports.

Action Group 13 of The Technical Cooperation Program (TTCP) completed a draft document for Certification of Bonded Structure in 2001 [1], following 3 years of coordinated efforts. Dr. Jack Lincoln, of the U.S. Aeronautical Systems Center at Wright Patterson Air Force Base (WPAFB), was the chairman for this action group. This report provided a general guidance for certification, but did not get public distribution. The report recommends future industry interface in forums such as MIL-HDBK-17 to establish certification guidance, which is appropriate for aircraft products, and further research. Individual action group members took this recommendation forward in defining the FAA Bonded Structures Workshop. Former TTCP action group members who helped define and lead the Bonded Structures Workshop included Maxwell Davis (Royal Australian Air Force), James Mazza (WPAFB), and Larry Ilcewicz (FAA). The specific areas of concern are discussed in the next four sections.

2.2 MATERIAL AND PROCESS QUALIFICATION AND CONTROL.

The specific combinations of materials and processes used for bonding must be qualified for structural applications. Bonding processes yield a complex structural system, which includes the adhesive, substrates, and interface regions that are more complex than the individual materials that are bonded. The regulations (e.g., Title 14 Code of Federal Regulations (CFR) 25.603) state that the structural suitability and durability of materials used in aircraft products must account for environmental effects and be established by experience or tests. In addition, the regulations (e.g., 14 CFR 25.605) state "fabrication methods must produce consistently sound structure." The data generated in material and process qualification serves as a basis for subsequent quality control. An approved process specification is used for fabrication methods such as bonding.

The FAA has conducted research in bonding material and process qualification and control with the help of industry. An initial key area of focus has been on composite bonding surface preparation and the ancillary materials (removable surface layers such as peel plies and release fabrics) used by industry. The research showed the importance of qualifying all the materials and process steps used to develop a reliable bond [2]. It also identified different test methods suitable for making such a judgment. This work showed that release fabrics, which contain chemical release agents, should never be used on composite surfaces that will be bonded because subsequent surface preparation steps, such as grit blasting and sanding, cannot remove all the contamination. Peel plies, which do not contain chemical release agents, should have different product designations. The use of peel plies in the bonding process and whether or not subsequent surface preparation steps are needed after their removal appears to depend on the specific substrate and adhesive combinations. Research continues in this important area, and the industry appears to have adopted the practice of distinguishing release fabrics from peel plies.

2.3 DESIGN DEVELOPMENT AND STRUCTURAL SUBSTANTIATION.

The design development and structural substantiation of aircraft products are affected by several regulations. General regulations for design and construction (e.g., 14 CFR 25.601) state: "the airplane may not have design features or details that experience has shown to be hazardous or unreliable." There are also more specific regulations to control the different areas of structural substantiation, including design data and proof of structure for deformation, static strength, fatigue, and damage tolerance. In most cases, these regulations do not have special wording for bonded structure. One exception is the small airplane regulation for damage tolerance and fatigue evaluation of composite airframe structure (14 CFR 23.573). This regulation seeks structural redundancy to ensure residual strength requirements are met in the case of a failed bond or other reliable methods of detecting bonding problems are applied.

A building block approach is typically used for design development and structural substantiation of composite aircraft structure. Figure 5 shows a schematic diagram of the building block approach applied to an airfoil such as a wing or horizontal stabilizer. One of the key components of such an approach is the integration of design details with manufacturing process and tooling constraints. In this case, the building block approach helps gain confidence that scaling issues and manufacturing-induced performance traits can be controlled and are reproducible. A balanced combination of detailed strength and stiffness tests to develop design data and allowables at lower scales with analysis and validation tests at larger scales provides the required structural substantiation. Complex internal load paths may develop in highly integrated bonded structures. Large-scale tests help evaluate secondary loads that may occur in bonded joints and attachments due to the local stability of design details and redistribution of internal loads.

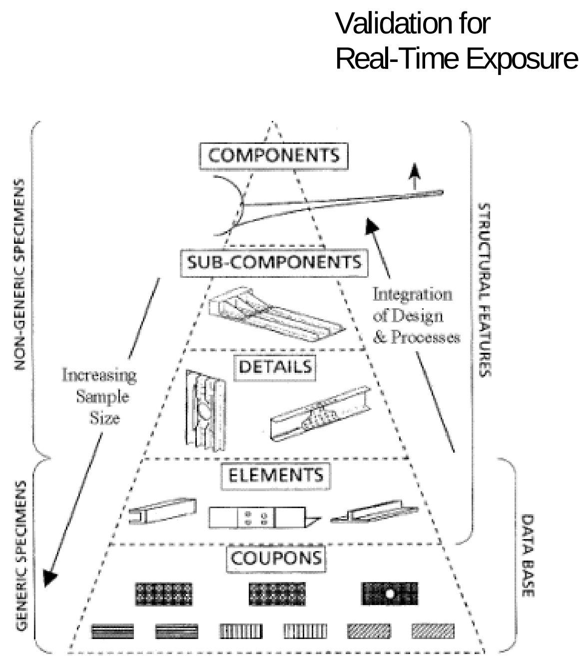

FIGURE 5. BUILDING BLOCK APPROACH TO TECHNOLOGY INTEGRATION

Considerations for manufacturing defects, accidental damage, environmental damage, and repair within the building block approach also provide a basis for subsequent production and service engineering activities. It is not practical to evaluate some of the long-term performance characteristics of bonded structure at the larger scales of the building block approach. As a result, real-time data collected for bonded structure in service is a good complement to the work performed at the time of product certification. Service monitoring programs confirm the continued airworthiness of bonded structure and help identify unreliable design details or process steps that should be avoided in the future.

In working with bonded structures, and composite materials in general, it is important to realize the different design load and damage considerations for structural substantiation, as shown in figure 6. Damage or manufacturing defects that cannot be detected or those deemed acceptable must sustain static strength requirements for ultimate load. Such damage should also be unaffected by repeated loads and environmental conditions occurring throughout the service life of the bonded aircraft structure. Lost ultimate load capability should be rare, with safety covered by damage tolerance and practical maintenance procedures. The structures ability to sustain repeated loads and carry limit load with detectable damage is proven through damage tolerance testing and maintenance procedures (e.g., inspections). Possible sources of detectable damage that will be found with a high degree of probability and repaired through maintenance practices must sustain limit load after experiencing repeated loads in service for a period of time related to the inspection interval. Other damage scenarios such as bird strike, tire tread impact, and rotor burst also have a residual strength requirement.

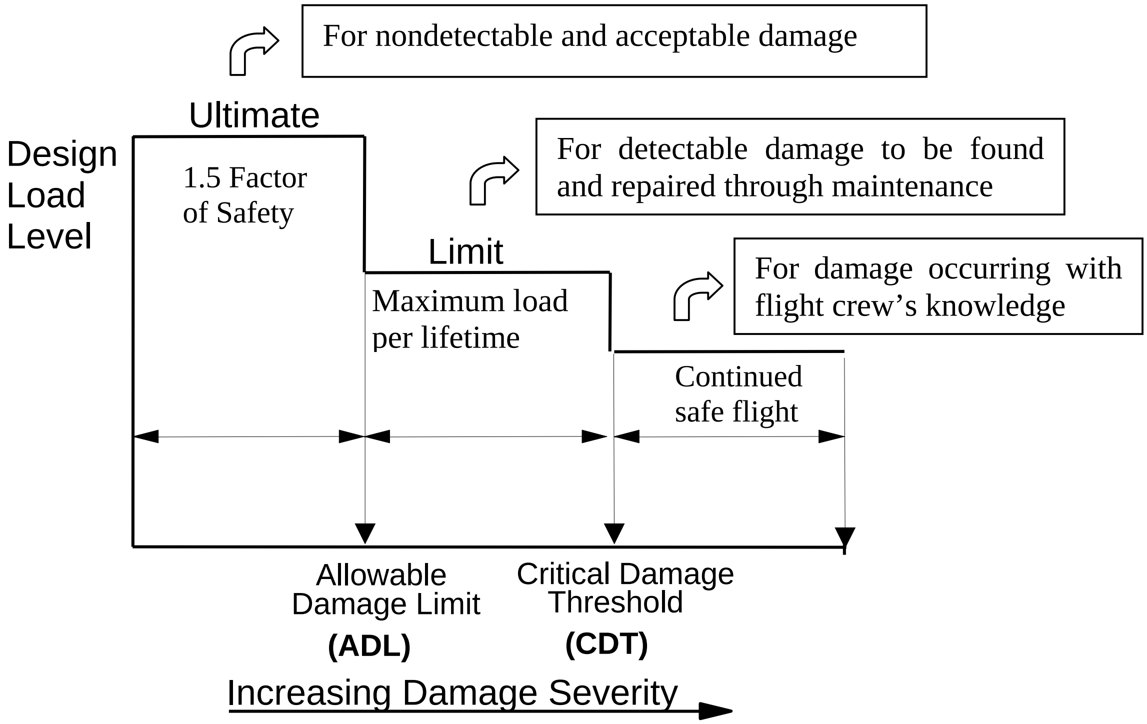

FIGURE 6. DESIGN LOAD LEVELS AND DAMAGE CONSIDERATIONS

It is important to realize that fatigue and damage tolerance methods cannot cover for unacceptable bonding processes and materials. Despite damage tolerance regulations that ensure structural redundancy at the limit load, bonding problems could many times lead to potential loss of ultimate load capability. Qualification and structural substantiation should provide sufficient data to demonstrate reliable bonding processes and materials, including the issues associated with manufacturing scaling. Fatigue and damage tolerance practices remain useful for structure constructed using a well-qualified bonding process that is under control. They will help cover the rare, local disbonding that may occur even for reliable processes. They also provide sufficient fail safety and coverage for accidental damage. An ASTM/FAA Workshop in March 2004 reviewed the state of the art in analysis and test methods used to evaluate the mechanics of delamination and debonding [3]. Some FAA and NASA research in this area was covered in that workshop.

2.4 MANUFACTURING IMPLEMENTATION AND EXPERIENCE.

To get an FAA production certificate, applicants must establish and maintain a quality control system so that each product meets the design provisions of the pertinent type certificate (14 CFR 21.139). Material and process qualification and manufacturing advances that support design development and structural substantiation provide the basis for the quality control system. This includes the requirements and procedures that control production, i.e., acceptance test criteria, key characteristics to monitor processes, manufacturing process control documents, and specifications.

Processes must be scaled to yield reliable adhesive bonds for the structural design detail. Some of the key process steps and processing parameters that must be controlled include bond surface preparation, time limits for adhesive mixing, adhesive out-time, bondline cure temperature, surface contact pressure, and bondline thickness control. Many of these rely on the proper use, control, and maintenance of factory tooling and equipment. Sufficient factory environmental and cleanliness controls for bonding, in-process quality controls, and nondestructive inspection (NDI) are an important part of manufacturing implementation for bonded structures. Finally, the production workforce must be trained to ensure the necessary skills exist to properly execute the different bonding process steps.

2.5 MAINTENANCE IMPLEMENTATION AND EXPERIENCE.

The Instructions for Continued Airworthiness, Structural Repair Manuals and other information used to guide service activities must give special consideration to bonded structures. This includes accessibility for maintenance operations, such as inspection and repair, because disassembly of bonded joints is usually not an option. Inspection procedures are needed to determine the full extent of damage that must be repaired for bonded structures. Even when the design allows detection to apply visual inspection methods, other NDIs are often needed to determine the full extent of damage for repair. A field disposition process must be defined for damage and other defects found in bonded structures. The specific maintenance procedures used for bonded structures must be substantiated for implementation. As with product manufacturing processes, maintenance procedures are usually developed as part of a building block approach to design development and structural substantiation.

The use of bonded repair procedures for composite aircraft structures (e.g., damaged sandwich panels) bring forth many of the same issues that are important to manufacturing implementations of bonding. This includes qualification of the specific materials and processes that are used for bonded repair. The proper use and control of tooling and equipment must be specified. The environment and cleanliness must be controlled in areas where bonded repairs are performed. In combination with in-process quality controls, NDI is an important confirmation that a bonded repair was performed properly. Finally, the maintenance workforce must be trained to ensure the necessary skills exist to properly perform a bonded repair.

The FAA is working with the industry to develop engineering standards and ensure sufficient composite maintenance training exists for a workforce, which meets the needs of expanding applications. The SAE Commercial Aircraft Composite Repair Committee (CACRC) is an international standards group that is leading this effort. The FAA has been performing research to support the CACRC [4]. The results for a bonded repair, indicate that the structural performance depends on proper execution of the bonding processes. Future work is planned in this area, including a 2005 FAA workshop on composite maintenance training.

3. BONDED STRUCTURES SURVEY.

3.1 SURVEY QUESTIONS.

The purpose of the survey was to establish a detailed background on the adhesive bonding philosophies that are used by the aircraft industry. Given this purpose, the multiformat survey was distributed via e-mail and covered a range of topics. The three technical topic areas included (1) materials and processes; (2) manufacturing and design integration; and (3) product development, substantiation, and support. These topic areas address the major areas of interest and need for control in the bonding process.

The survey contained multiple-choice and open-ended questions in addition to comment sections after each set of questions and at the end of each section to provide information on issues not addressed. To accurately determine the input being given, some questions were asked multiple times with variations in wording. This solidifies the answers given by the respondents because it ensures they are addressing the issue in question. The survey questionnaire is shown in appendix A.

3.2 PARTICIPANTS.

The survey was distributed via e-mail to highly experienced individuals in the industry. These individuals were encouraged to solicit other known experts in the field to ensure a range of input from the industry.

Personal background information was collected in the survey to identify the type and nature of the individual's comments, including the organization type, size, perspective of the respondent (individual to corporate), experience level, and the respondent's area of expertise. The background information is shown in appendix B.

3.3 SYNOPSIS OF RESULTS.

A survey was developed to benchmark industry practices and collect information on the critical safety issues and certification considerations for bonded aircraft structures and repairs. Much of the survey used multiple-choice questions, which were simply answered by selecting one or more responses. Some of the multiple-choice questions also allowed an open-ended response. A few questions required open-ended responses. The respondents were encouraged to only answer those questions in which they had experience. The survey was sent to experts in industry, government agencies, and academia. Fifty-three responses were received from forty-two organizations that had extensive experience in commercial and military aircraft bonding applications. The average years of bonding experience for people taking the survey were 18. The responses were based on bonding applications to small airplanes, transport aircraft, rotorcraft, fighter jets, and propellers.

One of the primary areas in the survey questionnaire related to material and process qualification and control. This was broken into a series of questions addressing adhesive qualification, bond process qualification, material control, and process control.

Most respondents agreed that the primary reason for adhesive material qualification is to define requirements for material control. The most common response to a question on the number of adhesive batches used for qualification was three. The respondents provided a long list of different physical, chemical, and mechanical tests for adhesive qualification. The most common mechanical test type used for qualification was some form of a lap shear test. Sixty percent of the respondents did not attempt to characterize the nonlinear stress versus strain behavior of the adhesive. Fifty-three percent of the respondents said they used the thick adherend test and KGR gages, or something similar. Two-thirds of the respondents indicated that bonding process qualification was part of the same test matrix as adhesive qualification. The average number of bonding process runs used for qualification was 6.5. A majority of the respondents agreed that qualification of bonding processes should include durability assessments to ensure adequate adhesion. All the respondents agreed that moisture and temperature environmental effects were included in adhesive and bonded process qualification plans. A majority of the respondents also said their qualification tests can be traced back to both ASTM and their company standards.

The respondents provided information on the types of mechanical, physical, and chemical tests included in specifications for adhesive material procurement and control. This included the types of tests used for acceptance testing. Most respondents indicated that the adhesive material supplier, part manufacturer, or repair facility performed some acceptance testing. There was some difference of opinion between the respondents on whether or not qualification data was used to directly set the acceptance requirements for adhesive material control, with the majority of the respondents in agreement. The majority of the respondents said the adherend and adhesive thickness the responders used for acceptance testing is the same as those being used in production. There was a greater difference in opinions on whether or not to include environmental effects in acceptance testing. Most respondents agreed that adhesive storage and handling should be controlled by freezer temperature and out-time monitoring. The respondents had mixed views on the controls needed for peel ply materials, which are used for composite surface preparation.

The majority of the respondents used in-process monitoring or witness panel tests for bond process control. The different bond surface preparations used by the respondents included sanding (hand and automated), media blasting, peel ply, chemical etch, and others, depending on the substrate and adhesive combinations. The most common methods of monitoring the surface preparation were visual checks, water break tests, witness panels, and surface chemistry tests. Fifty percent of the respondents believed that mechanical tests should be performed for bonding process control purposes. Most respondents agreed with a need to control the prebond moisture of substrate materials. A large majority of the respondents indicated that the components in paste bond mixing are controlled by weight. The respondents, depending on the specific materials and bonding application, used a wide range of bond assembly processing steps. Most respondents had time constraints for the various bond assembly process steps from surface preparation to adhesive cure. The majority of the respondents said that time and temperature were controlled in the bond process cure cycle**,** and 37 of the 49 responses agreed that there are sensors to demonstrate temperature and pressure at the bondline. The majority of the respondents believed that NDI plays a role in bond process control.

Another primary area in the survey questionnaire related to manufacturing and design integration. The first series of questions addressed design and analysis. The respondents used bonding for many parts, including skins, doublers, stringers, and frames. The respondents also said the glass transition temperature (T_g) is measured primarily by dynamic mechanical analysis, followed by differential scanning calorimetry (DSC) and thermo-mechanical analysis. Most people responding to the survey agreed that tooling, manufacturing, and maintenance issues should be integrated into the design process. A slight majority of the respondents used analysis codes. Many believed that cohesive failure in the substrate and adhesive could be predicted. Fifty percent said their predictions distinguish cohesive failures in the adherend or adhesive and they do not agree that adhesion failures between the substrate and adhesive can be predicted. A large majority of the respondents design to minimize peel stresses in a bonded joint. A majority of the respondents indicated that their analysis accounts for residual stresses in the bonded joint. Rivets were the number one fail-safe design feature used to reduce the risk of weak bonds in structures. Most considered damage tolerance, fatigue, and durability in design; however, there was a general disagreement on whether or not analysis methods can be applied for such a purpose.

There were several survey questions related to manufacturing. Most respondents agreed that data from qualification testing or other repetitive bonded joint tests are used to establish statistically based design allowables. The respondents also agreed that a lower minimum bond strength design value is set based on experience and test data (e.g., 500 psi). The majority said they verify the adequacy of the design by considering the peak shear and average shear stresses. In addition, most respondents agreed on a need to control humidity in bond processing. Nearly 50 percent said they used a vacuum bag for adhesive bonding followed by pressure at 23 percent and matched tooling at 20 percent. A majority of the respondents indicated that cured part dimensional tolerance and warpage are controlled. The participants taking the survey were split on the use of Verifilm to confirm the fit of mating surfaces. Most respondents set time constraints during adhesive application. Eight-eight percent agreed that there are handling and storage constraints and disposal guidelines for materials used in surface preparation (e.g., solvents, etc.). In most cases, scaling for production did not result in significant changes in the processes used for surface preparation or adhesive application. The respondents used a number of different methods of controlling bondline thickness. The majority of the respondents said 0.007-0.020 and 0.004-0.007 inch should be used for bonded joint characterization. The majority also said their design has tolerances specified for quality control and that they test far more than just the maximum thickness for allowables characterization. Most respondents used ultrasonic methods and visual inspection to inspect bonded structures following cure. The respondents suggested a number of different methods for training the manufacturing workforce. The majority of the respondents said their company's method for dealing with bonded structure discrepancies was efficient. All respondents agreed on a need to record cure temperature and duration, while most tracked adhesive out time.

There were also several survey questions on allowables and design data. Most respondents used lap shear tests for the former. The results indicated that most companies use the same design data to support the design of their bonded structure. The most commonly used was standard adhesive thicknesses, followed by lap widths and standard joint configurations. MIL-HDBK-17 was the preferred method of calculating allowables. A majority of the participants taking the survey indicated a need to include the effects of environment in bonded joint tests. The desired adhesive layer thickness varied with the application. There were many different thoughts expressed on the data needed for fatigue, damage tolerance, manufacturing defects, and service damage.

Another primary area in the survey questionnaire related to product development, substantiation, and support. Most participants taking the survey indicated that product development lead times for bonded structures were longer than those for conventional structures that use mechanical fastening. Most companies said the scale of testing that yielded the most meaningful data for bonded structure development, substantiation, and support was different in every case. In regards to how critical the bonded joint is classified, responses indicated an equal distribution of loads. The majority of the respondents recommended using a building block approach for product development and substantiation of bonded structure. Most respondents agreed on a need to substantiate strength and damage tolerance in large-scale tests, while most companies have found that small-scale tests have meaning to service experiences. In regard to whether companies have validated accelerated test methods, most neither agreed nor disagreed. Critical defect and damage locations were selected based on stress levels, manufacturing experiences, and susceptibility to impact. Most respondents had good service records with bonded structure, while the rest had mixed success.

The final area of the survey included general questions, which required an open-ended response. Opinions were collected on the major safety concerns and certification hurdles for bonded structures. Views were also expressed on desired design, analysis, manufacturing, and maintenance improvements. Finally, economic and technical barriers to expanded applications were discussed.

4. BONDED STRUCTURES WORKSHOP.

4.1 INTRODUCTION.

As discussed in section 1.1, the FAA approach relies on experience from applications, focused research, and an industry interface as a basis for developing policy, guidance, training, and engineering standards in selected technical thrust areas. Research on bonded structures has been ongoing since 1999. The bonded structure survey and workshop, which are discussed in this report, were used to expand the industry interface in 2004. Efforts to benchmark bonded structures technology through these activities will be used to develop initial regulatory guidance. Future directions for bonding will also be derived from the 2004 studies.

The Bonded Structures Workshop addressed applications in many different aircraft product types, including small airplanes, business jets, transport aircraft, fighter jets, rotorcraft, and propellers. Commercial and military applications of composite and metal bonding were reviewed. Workshop sessions spent time on the technical issues for material and process control, design development, structural substantiation, manufacturing implementation, maintenance practices, and service experiences.

This section of the report provides a summary of the seven technical sessions held at the June 2004 Bonded Structures Workshop. An overview of the FAA CS&CI for bonded structure, including regulatory perspectives shared at the start of the workshop, is provided in section 2. The results from the FAA survey on bonded structures were also summarized at the start of the workshop (see section 3 for more details). The detailed agenda and a list of participants for the workshop are provided in section 4.2. Section 4.3 gives summaries of the invited presentations and related discussions at the workshop. A synopsis of information collected during breakout sessions appears in section 4.4. Workshop presentation materials can be viewed at the website that was setup by the National Institute of Aviation Research at Wichita State University (WSU): http://www.niar.wichita.edu/faa/

4.2 SESSION SUMMARIES.

This section provides summaries of the presentations given at the Bonded Structures Workshop. It is broken into subheadings for sessions 1, 3, 4, 5, and 6. Workshop presentations are posted at the WSU website address given in section 4.1. All speakers were asked to start their talks by summarizing their experiences with bonded structure and the applications they plan to cover. As related to the primary objective of the workshop, they were also asked to provide perspectives on the critical safety issues and certification considerations. In addition, speakers were asked to address secondary objectives for the workshop by giving examples of best engineering practices and commenting on future needs in standardization or research.

Ric Abbott provided a review of the workshop at the end. He felt that there were many excellent presentations given for a wide scope of applications. He also felt that it was good to hear from the users, such as the airlines and the United States Air Force (USAF) as well as suppliers, manufacturers, and regulators. He agreed with the emphasis on bonding surface preparation and cleanliness in many of the presentations as one of the most critical technical issues. A need for repair technicians to be trained and certified for bonded repair and other maintenance activities with bonded structures was also emphasized. He advised the group that scaling issues associated with bonding should be substantiated by full-scale tests. Finally, he suggested the need for more research into reliable quality inspection procedures, damage tolerance analysis methods, and test standards.

In closure, Larry Ilcewicz summarized the key aspects of safety management for bonded structures. The materials and processes used for bonding must meet qualification standards crucial to structural integrity and long-term durability. Once qualified, materials and processes must be controlled to ensure the qualification standards are continuously met through production and maintenance activities. Design development, bonded process scale-up, and substantiation must be coordinated such that manufacturing or maintenance can repeatedly produce the proven structural concept. To this end, a robust implementation of bonded structure manufacturing or maintenance is desired. The Bonded Structures Workshop covered each of these technical areas.

4.2.1 Applications and Service Experiences.

The session on applications and services experiences helped introduce issues critical to the safety of bonded structures. Presentations in this session highlighted some past problems with bonding and the engineering practices needed for successful applications. Examples of bonding applications for military fighter jets, small airplanes, propellers, and transport aircraft helped to gain a complete review of the various technical issues facing different aircraft products. Although there were some differences related to the specific applications, there were also many similar technical issues and engineering solutions.

Max Davis from the Royal Australian Air Force (RAAF) provided some insights on the best engineering practices needed for successful adhesive bonding. He provided a number of examples of bond failures from service for metallic and composite materials. Most of the emphasis for best practices came from his bonded repair experiences for fighter aircraft structure. Prior to 1992, there were numerous metal bond failures in service. These problems were overcome by adopting the principles Davis shared in the workshop. Since 1992, the service history for metal bond repairs in his organization has been excellent. Davis emphasized the need for appropriate bonding process validation as a primary means of avoiding bond failures in service. This included a need to validate the long-term environmental durability of parts using the particular bonding process. Davis stated that lap shear tests are not appropriate for judging long-term durability. Instead, he recommended using a wedge test, which applies peel stress and critical environmental conditions to the bonded joint. Other important areas that were highlighted included surface preparation, adhesive selection, design methods, substantiation testing, quality assurance, and training. The proper application of heat for cure of a bonded repair, while avoiding overheating adjacent structure, was also covered. Finally, Davis suggested some changes to existing regulations or the creation of guidance materials to emphasize a need to demonstrate that selected bonding processes reliably produce structure that is strong and durable.

Jim Krone and Andrew Kasowski summarized 40 years of bonding experiences at Cessna Aircraft, which includes more than 6000 airplanes. Cessna's applications of bonding started with secondary structure before moving to primary structure and a fully bonded airframe as confidence was derived over time. Based on their experiences, Cessna came to realize the applications where bonding could be reliably used. They identified critical safety issues and certification considerations related to joint design, durability, and manufacturing defects. Although Cessna has some experience with composite bonded structure, most of their experience is with bonding of metals. Current metal bond processes for the Citation Aircraft primarily used bare alloys, phosphoric acid anodize surface treatment, chromate bond primer, film adhesives, and autoclave cure. Cessna covered manufacturing implementation in another presentation given in session 5.

Jay Turnberg of the FAA covered bonding experiences from composite propeller applications. He provided a synopsis of two case studies for bonded propeller structure, one involving a service problem and the other related to life evaluation. The former came from a need for field replacement of an erosion shield that is bonded to the propeller blade's edge. Problems in the associated bonding process, including contamination, improper paste adhesive mixing, and skipped processing steps, resulted in poorly repaired blades that had to be removed from service. Improved manuals, extra inspection steps, repair shop audits, and training solved these problems.

The propeller case study on life evaluation was for a primary bonded attachment of the composite blade to metallic retention. This bonded joint has a combination of different materials and complex geometry near the root of propeller blades. Damage from repeated application of high loads is inherent to the design detail of this joint. The structural substantiation used for the joint characterized repeatable damage accumulation, which could be controlled through inspection, leading to blade retirement prior to damage reaching a maximum permissible size. Full-scale testing was essential for life evaluation due to the complex blade root design detail.

John Hart-Smith of Boeing covered some critical issues based on his experience with bonded composite joints. He also has years of experience with metal bonding. As in previous talks, Hart-Smith stated that bonding process specifications must be properly validated and strictly followed. This is essential because, currently, there are no reliable postbond inspection methods that have been used in a production application to prove that an adhesive has adhered properly to the bonding substrate. Hart-Smith started his talk with a summary of the physical and chemical concepts crucial to successful bonding. He emphasized the need for a polymer adhesive to wet the substrate surface, which depends on surface energy. Surface preparation steps to gain cleanliness and sufficient activation of the substrate are essential to this. Hart-Smith recommended that grit blasting was the most reliable means of surface preparation for composite substrate materials. He showed that the use of peel ply ancillary materials, which contained release agents (defined as release fabrics in this report), causes problems. Hart-Smith also discussed prebond surface moisture in the substrate and why it must be eliminated or controlled to levels that are known not to affect the bonding process. He gave evidence of processing problems due to poor surface preparation and prebond moisture from applications. Hart-Smith also showed service examples of how well-bonded structure is tolerant to large damage. Finally, he suggested a need for a composite durability test similar to the metal bond wedge test.

4.2.2 Material and Process Qualification and Control.

The session on material and process qualification and control covered bonding issues crucial to material selection, process verification, and quality control. Speakers covered these issues for a range of product types, including commercial transport aircraft, small airplanes, rotorcraft, and military applications. The presentations spanned more than 40 years of service experience for metal and composite bonding. This provided a complete assessment of the practices used to qualify and control bonding materials and processes.

Kay Blohowiak and Peter Van Voast, who covered metal and composite issues, respectively, presented Boeing perspectives on structural bonding. Boeing used the same systems approach to qualify and control bonding materials and processes for both. All new materials and processes used by Boeing for structural bonding are verified by extensive compatibility tests. Metal bonding experiences dating back to the 1950s has helped Boeing determine materials and processes needed for structural integrity and long-term durability. Early bonding failures for specific material and process combinations were blamed on inadequate verification testing and quality control. Current Boeing efforts focus on how to demonstrate 30 years of service in accelerated tests in the laboratory. Both composite and metal testing at Boeing include some peel testing to help answer this question. A wedge test has been successfully used for metal bonding, whereas composite joints use a double cantilever beam (DCB) test. The presentation focused on surface preparations that have worked for metal and composite bonding. Boeing has successfully used peel plies that have not been treated with release agent (defined as peel ply in this report) for composite surface preparation. They have also explored additional surface preparation steps after peel ply removal to further ensure a good bond. Finally, Boeing showed the degrading effects of prebond moisture on composite bond performance.

Jim Mazza of the USAF provided a presentation that covered bonding surface preparation qualification considerations for metal and composite applications. He started his presentation by highlighting some keys to reliable adhesive bonding that started with validated designs and processes. Mazza indicated that once a good bonding process has been qualified, subsequent success in production is dependent on proper control of materials, technician training, quality inspections, and process control tests. As was the case with other speakers, Mazza indicated that lap shear testing alone is inadequate for validating the long-term durability of bonding materials and processes. He gave some insights on the use of accelerated wedge tests with environmental exposure to duplicate in-service performance, including a detailed assessment on what should be done in applying the test and interpreting results for metal bonding. Mazza also summarized the USAF Primary Adhesively Bonded Structure Technology Program for metal bonding and some service problems involving composite bonding. Finally, he shared perspectives on the use of composite peel tests such as flatwise tension and DCB.

Dave Bond, who is with University of Manchester Institute of Science and Technology (UMIST) in Manchester, U.K., provided his perspectives on the effects of environmental moisture on the performance and certification of adhesively bonded joints and repairs. He is currently involved in research on the subject at UMIST but also has experience in bonding applications from his previous work with Australian and English military groups. Bond covered the various mechanisms where moisture can affect the structural integrity of a bonded joint before, during, and after cure of the bond. Moisture existing before joint curing can affect bond surface wetting and the subsequent development of interfacial bonds. Bond explained that moisture content at the substrate surface drops rapidly under drying conditions, and the time needed to eliminate surface moisture may not be as long as previously thought. This phenomenon follows Fickian diffusion principles and can be accurately modeled. Bond also covered the effects of moisture on interfacial bond strength degradation. He showed test data on degradation, which was most pronounced when joints were created after poor surface preparation. This was consistent with the observations of previous speakers. Bond also showed his research efforts to develop a smart patch that senses bonded joint degradation.

Dieter Koehler from the Lancair Company gave a talk on structural bonding experiences for their aircraft, which are constructed primarily of composite materials. Lancair aircraft, such as the Columbia 300, make extensive use of bonded joints for critical joints such as skin to rib and spar attachment and fuselage longitudinal splices. Koehler explained that the bond gap variations for this aircraft ranged from near zero up to 0.150 inch, which covers the tolerance in material thickness variations. Rods were used to control the minimum bond gap and the maximum gap was controlled by measurements taken prior to applying the adhesive. Paste adhesive that cures in an oven is used for Lancair aircraft. A complete matrix of substrate materials and environmental conditions were used for qualification of the adhesive and bonding process. Bonded strength properties were determined using a thick adherend, lap shear specimen. A version of the traveling wedge test was used to evaluate various bond surface treatments and surface preparation methods. The results from these tests showed bead blasting to be a reliable surface preparation. Koehler recommended more research on the trade offs between adhesive glass transition temperature and toughness.

Mark Chris of Bell Helicopter Textron gave a presentation on his company’s experience with bonded structures, starting with a description of the applications that began in the 1950s with main and tail rotor blades that bonded metallic skins to wood core. Since that time, applications have evolved to include bonded composite airframe structures that use film adhesives. Safety and certification issues covered by Chris included surface preparation, mechanical property characterization, material and process specifications, and damage tolerance. He covered a Bell study to understand the tolerance in the percentages of base epoxy and curing agent in mixing paste adhesives. Chris showed that the sensitivity to mixing ratio depended on the adhesive system. In another study, to determine the effects of variations in bond assembly time, it was also found to depend on the particular adhesive. He felt that insights derived from both studies should be incorporated in specifications and technician training materials.

4.2.3 Design Development and Structural Substantiation.

The session on design development and structural substantiation covered issues crucial to bonded product certification, including the necessary verification analysis and testing and the integration of considerations from other functional disciplines (e.g., material and process control, manufacturing defects, and service damage). Speakers covered these issues for a range of product types, including commercial transport aircraft, small airplanes, rotorcraft, and military applications. These applications used bonding in structure ranging from high-load-transfer/ low-load joints to low-load-transfer attachments with out-of-plane loading considerations. These different applications also provided a range of bonding design details (e.g., bondline thicknesses included tightly controlled gages of up to 0.007 in. for joints using film adhesives and joints using paste adhesives for gap filling, up to 0.20 in.). This provided a complete assessment of the engineering practices used to develop and substantiate bonded structural design details.

D.M. Hoyt (NSE Composites) and Steve Ward (SW Composites) provided perspectives on composite bonded joint analysis, design data, and structural substantiation. The application of bonding in the structure of different product types was considered in developing their assessment of the current state of the art in this area. Many different analysis methods were summarized in their presentation ranging from simple uniaxial, in-plane loading assumptions to complex multiaxial loading, combined with out-of-plane considerations. Their presentation pointed out the need to establish design criteria and analysis methods, which address manufacturing defects and service damage and are consistent with the economic realities associated with the inspection and disposition of defects in the factory and field. This was the thrust in their discussion of analysis methods available to support the design of bonded structure with damage. Without such analysis capability, the industry is forced to rely on testing and conservative design practices. Several engineering methods currently appear practical for applications, but there is still considerable dependence on building block testing at sufficient scale to incorporate real design, loading, and damage complexities. Hoyt and Ward provided a number of recommendations on analysis development and test standardization needed to answer the difficult questions arising with expanded applications of bonded structure (e.g., defect allowances, structural redundancy, and repairable damage limits).

Paul Brey of the Cirrus Design Corporation (CDC) presented thoughts related to the certification, production, and sustaining of their aircraft products, which make extensive use of composites and bonding. Brey started his talk by reviewing the time history of CDC products from development through certification to current production. He also reviewed where structural bonding was used in different parts of the aircraft ranging from fuselage to horizontal stabilizer and wing. Brey identified the structural substantiation issues posing the biggest challenge for bonded structure to be damage, defects, environmental effects, and competing failure modes in built-up structure. He felt that some of these should be addressed by industry working groups. Brey emphasized a need to plan for the transition from certification to production. Service problems, economic considerations, and increased production rates require that engineering groups address many different issues ranging from damage disposition and repair to design and process evolution. Brey explained that production rate increases led to changes in processes, facilities, and tooling, as well as training of an expanding workforce. Similar issues were passed down to suppliers through the CDC quality systems. The examples given in the presentation focused on the material and process control and structural substantiation activities that are needed in the transition.

Allen Fawcett of The Boeing Company presented his structural perspectives on processing issues and related tests for co-bonded primary structure. In this case, co-bonding is a process where precured elements (e.g., stringers and stiffeners) are bonded with uncured elements (e.g., skin and spars) to create stiffened structure. Fawcett’s talk started with a synopsis of Boeing composite applications to transport empennage structure. He gave opinions on the rigorous controls needed for using peel ply in the surface preparation of bonded joints. This included control of single-source materials used for the peel ply, adhesive, and bonding substrate because different combinations of materials yielded undesirable results in the past. Fawcett also felt that intense receiving inspection practices, which include peel tests of bonded coupons and a well-trained workforce, are needed. Another major point of the presentation was a synopsis of what would happen if bondline adhesion failures were discovered in service. As a designated engineering representative to the FAA, he felt that, depending on the ability to trace a problem to a specific manufacturing mistake, immediate directed inspections and the potential for immediate permanent repair may be needed to ensure continued airworthiness. Such a scenario justifies rigorous material and process controls, as well as complete manufacturing records of bonded joint production. Fawcett showed some building block tests needed to develop design data for bonded attachments, including the effects of damage, fatigue, and complex loading.

The final presentation given in this session was by Pierre Harter, representing Adam Aircraft. He started his presentation with a synopsis of the company, which was founded in 1998, and a description of products currently undergoing certification under 14 CFR Part 23 small airplanes. The A500 aircraft is expecting certification to be completed within the year. This airplane makes extensive use of composites and bonding for critical airframe structures. Harter reviewed the important bonding process steps and qualification testing used for bonding materials and processes. He also covered some of the A500 structural design features (e.g., wet lay-up doublers used to gain redundancy at bonded splices) and test data generated for structural and processing details such as bondline thickness, overlap length, and substrate thickness. As a small company, Adam Aircraft was interested in making use of shared composite databases and would like to see more related to structural bonding. Harter also indicated a need to standardize wedge crack testing or the equivalence for composite bonding. Harter emphasized the importance of full-scale tests because it is hard to predict some of the failure modes possible with integrally bonded composite structure.

4.2.4 Manufacturing Implementation and Experience.

The session on manufacturing implementation and experience covered bonding issues crucial to fabrication process scale-up, tooling, equipment, and quality control. Speakers covered these issues for a range of product types, including commercial transport aircraft, small airplanes, rotorcraft, and military applications. The presentations considered process differences for metal bonding, composite sandwich, and integrally stiffened structures. This provided a good overview on some of the manufacturing implementation practices used for bonded aircraft structure.

Jim Krone summarized current metal bond manufacturing processes used at Cessna Aircraft. He also highlighted more than 40 years of fabrication experiences. Some of the key process steps covered in his presentation included phosphoric acid anodizing, bond primer application, doublers lay-up, bagging and tooling, autoclave cure, and postcure inspection. In addition to covering process details, Krone discussed issues affecting rate and process control activities for each step. He made a special point of highlighting that expendable materials used in a lay-up must be closely controlled. Krone emphasized the Cessna philosophy that an end of process inspection alone was insufficient for ensuring structural integrity. This further relates to the safety, customer dissatisfaction, and product liability risks they assume in the event disbonding or delamination occurs in service due to processing problems. In addition to the process control mentality, Krone explained that Cessna has other risk mitigation policies including rigorous personnel training, regular maintenance of facilities, and equipment and process requalifications. In addition, Cessna regularly adopts product design and process improvements based on lessons learned from field experience.

Hal Loken of the DuPont Company provided his perspectives on composite bonding of honeycomb core sandwich panels. Loken began by summarizing applications of sandwich aircraft structures. He also noted a need to collect and document the technology of honeycomb and other bonded structures, including critical safety issues and certification considerations. Loken explained that the failure of bonded honeycomb structures is often due to factors other than the bond, including material systems failures (e.g., microcracking, impact damage, erosion, and sealing problems). This presentation focused on the bonding issues. The industry is familiar with simple honeycomb surface contamination. However, not everyone is aware of the potential for surface contamination due to exuded substances that are wicked to the bonding surface by evaporating rinse solvents. Loken agreed with other speakers that panels showing adhesion failure between the core or substrate and the adhesive must not be accepted. Such failure is poorly understood and impossible to characterize. In tests of challenging bonding conditions using minimum film adhesive, Loken showed examples of good and unacceptable bonded honeycomb failures. An especially noteworthy finding was that film adhesives from different suppliers, and qualified to the same specifications, could give different bonding performance in critical conditions. He also discussed the use of rolling drum peel and flatwise tension tests. The rolling drum peel test, though suitable for process control work, should not be used to compare sandwich structures made with different materials because this test is so sensitive to differences in modulus and fracture toughness. Loken explained that a robust honeycomb bond requires sufficient adhesive fillets on the honeycomb cell wall. Specific adhesive properties during cure were shown to affect the ability to form these fillets.

Steve Forness of The Boeing Company provided some perspectives on the complexities of bonding large integrally stiffened structures, which were derived from experiences with the X-37 program. Forness began his presentation by showing composite design details and the bonded assembly sequence for the X-37. Forness highlighted several problems that occurred during manufacturing development. The honeycomb core selected for skin panels was found to be incompatible with the curing process, resulting in core crush. Forness highlighted warpage and dimensional tolerance problems for longerons and shear clips. He also showed that bagging was a challenge for paste bond assembly of frames to skin panels. In conclusion, Forness pointed out the importance of the integrated efforts of specialists from structures, materials, processes, tooling, and inspection disciplines to derive a producible design.

4.2.5 Repair Implementation and Experience.

The last session, on repair implementation and experience, covered bonding issues important to aircraft maintenance. The two presentations gave the perspectives of customers for bonding technology. This included a representative from an airline maintenance depot and a technical expert from military applications. Both composite and metal bonded repairs were discussed.

Eric Chesmar from United Airlines gave a presentation based on airline experience. He outlined problems and concerns with composites, including bonding issues. Many of his perspectives were consistent with those documented by the SAE CACRC. Chesmar began his presentation with a summary of maintenance concerns with composite and bonded structure design, which was based on CACRC surveys in 1995. Many concerns were with structural design features that did not recognize a need for inspection and repair, leading to unnecessary complexities. In addition, maintenance experts felt that structural repair manuals (SRM) were inadequate, forcing them to lose significant time in coordinating inspection and repair solutions with original equipment manufacturers (OEM). Chesmar showed that structural damage occurring in service is often unforeseen or more severe than covered in an SRM. Without sufficient knowledge available to the airlines for damage disposition and repair, there is a general sense of uncertainty and unnecessary conservatism that leads the industry to worry about some of the wrong things, while potentially missing critical safety issues. For example, for bonded repairs, there is a potential for surface contamination and prebond moisture related to difficulties in removing water, oil, and hydraulic fluids. Other examples relate to vacuum bagging and heat application difficulties when performing on-airplane repairs in certain structural locations and documenting manufacturing-allowable defects and material review board actions. Chesmar highlighted the importance of levels of training for technicians involved in bonded repairs ranging from simple to most difficult.

Andrew Rider of the Defense Science and Technology Organization (DSTO) in Australia made a presentation on the certification of bonded repairs for environmental durability. Much of Rider’s presentation was closely associated with the RAAF experiences shared by Max Davis. Rider began his talk with a summary of the history of bonded composite crack patching on aging metallic structures for military aircraft. Despite early problems with the technology, improved processing has led to very reliable bonded repairs since 1995. This has led the DSTO and RAAF to consider moving from the current fail-safe approach in certifying the repair for primary structure to an approach where the repair is given full credit for maintaining structural integrity for a lifetime [5]. This can only be achieved if there is confidence in the environmental durability over that lifetime. Rider’s presentation gave details on what the DSTO is doing to establish that confidence by correlating wedge test results that meet more rigorous acceptance criteria with the performance of repairs in service. Service performance of repairs will be determined by selected teardown inspection, metal crack growth measurements, and NDI for early indications of bond failure. Rider also showed that the DSTO is trying to further improve the process controls used to ensure good composite to metal bonding practices through the development of surface analytical tools. Future FAA research in this area will be coordinated with the DSTO.

4.3 RESULTS FROM BREAKOUT SESSIONS.

4.3.1 Material and Process Qualification and Control.

There were several goals of the material and process qualification and control breakout sessions. The main goal was to gain agreement on critical safety issues and certification considerations related to material and processing qualification and control. This included discussion on proven engineering practices for addressing these issues and considerations and to establish the needs for material and process qualification and control, such as through additional research, ASTM, SAE, or MIL-HDBK-17. Finally, there was a need to address any additional concerns related to material and process control. The purpose of the sessions was not to solve the critical issues, but simply identify those that needed to be addressed and possibly be considered for future in-depth discussions. For organizational purposes, the discussions were divided into material selection and compatibility, qualification testing, material control, and process control. Each of these will be discussed separately in the following sections.

4.3.1.1 Material Selection and Compatibility.

The goal of this section was to determine how to select an adhesive in relationship to the substrate that is being bonded, and in light of this, how is that going to be used in production. Each of the sessions produced results indicating a need to address specific critical issues. Some of these issues were related to determining how environmental limits were tested in the prequalification stage and whether to use the same criteria for the glass transition temperature (wet) for adhesives as is done for laminated composites.

There was also a discussion and feeling for a need to define the service environment in relationship to the aircraft role and operation environment. The ideal material would be the one that can fit the entire range of environments and operational envelope.

In addition, there was also concern about how to determine certain maximum adhesive temperatures for composites. Furthermore, it was commented that because everyone is trying to reduce costs by cocuring, compatibility should be addressed in the process.

Comments were also obtained expressing a need to find much lower modulus systems and much higher strain to failure systems and enable their use on smaller airplanes.

One issue addressed was whether or not the 50°F rule (T_g 50ºF higher than maximum operating temperature) should be used for adhesives and the relevance of this rule to the actual behavior in the joints.

Comments were also received on other ideas such as the carrier of the adhesive, how the adhesive design criteria may be restricting design, the windows of applications that should be considered during material selection, and safety and handling concerns.

When selecting a material, compatibility issues come into play. To determine compatibility issues, one should consider the system, adhesive, adhered, primer, peel ply, carrier, surface, process, and establish a clear definition of the service environment. The issue of flammability and repairability was addressed in regard to material selection. This was in addition to compatibility with repair structures and the scaling factor with respect to the cure cycle. Materials selection and compatibility must also include items in the manufacturing process, which include potlife, out time, and bond time.

Comments were also made regarding the chemicals used in service and how these should also be taken into consideration during materials selection. Suppliers often make changes based on Environmental Protection Agency standards, which forces changes in production.

Consideration of the impact on adjacent structures and systems should be realized during material selection.

Consideration of desired failure mode should be considered during material selection.

Comments were also made regarding the need for peel tests used for initial screening for material compatibility.

4.3.1.2 Qualification Testing.

Some of the critical issues to consider when qualifying the material include the number of batches to be used, the out time of the adhesive, and the process variables, such as mix ratios. Some concern should also be given to whether the material is new to the industry or just new to the company. In other words, how mature is the material and process specification? The general consensus was that each company should decide how to screen and qualify based on their particular situation. The goal of the sessions was not to dictate how qualification testing should be completed, but to gain some consensus on how material qualification has been accomplished in the past and to take advantage of lessons learned.

Companies must distinguish not only between prepreg and parts qualification, but more importantly, between material and parts certification.

The issues some companies see over and over again are determining what the manufacturer or researcher needs out of the adhesive and being able to generate data to support the design. What needs to be known is what the adhesive can do and how that interacts with the design because, to a certain extent, what is done under qualification depends on what the design practices are going to be, as discussed below.

- Interchangeability issues: An agreement on standardization issues appears to be a major barrier to interchangeability and wider adoption of a shared database methodology. Each company and supplier seems to use a different qualification procedure, test method, joint design, etc., when it comes to adhesive. The solution may be an AGATE approach to adhesives.

- Substrate differences: There was agreement on the performance differences obtained from different adhesives so the qualification tests depend on the substrate material as well as the adhesive. There was also agreement on attempting to isolate the performance of the adhesive in qualification separate from the joint and substrate.

- Qualification testing should also emphasize durability testing (what is the design philosophy—fail safe versus damage tolerant). Currently, most qualifications do not include durability testing.

- A clear definition of the substrate and adhesive should be documented as part of the qualification process.

- During coupon fabrication, the sensitivity of the coupon should be established as to the amount of scaling effect that may be present and the amount of element testing that should be accomplished.

- One of the main points that was emphasized multiple times was the need for a stepped qualification process; it should go in order from adhesive to joint to subelement.

- The qualification process should match the production process, and the key elements should be captured within the qualification.

- Qualification should consider that adhesives have age and process sensitivity.

- Qualification should also establish whether to test on the last day of out time (i.e., how many time intervals in sequence need to be tested at their limits?).

- Clearing House for adhesives: A shared database methodology for adhesives should be pursued. Instead of each company doing things individually, why cannot industry share certain information?

<u>4.3.1.3 Material Control</u>.

Overall environmental control: There are environmental limits and accessibility that determine how the material can be controlled.

Comments were received regarding the requirements and criteria set for material control and change (i.e., has the correct test been identified for material change?).

Comments were received that emphasized protection from contamination: How can you protect the materials from contamination, such as that from the atmosphere and even airborne contaminants, all of which can interfere with the adhesive process?

Consideration of volatile content: One of the variables that effect adhesive performance is the volatile content of the original adhesive and this should be part of the up front screening process.

Additional items discussed were:

- Emphasize control and characterization of ancillary materials
- Control of supplier documentation
- Raw material changes (level of control) should be addressed
- Recertification of material (extended life) should be addressed
- Comment was received on the need for adhesive flow test

4.3.1.4 Process Control.

Environmental controls (clean room, humidity, etc.) should be addressed.

Expendable materials issues (contamination concerns) should be addressed.

Vacuum pressure/adhesive compatibility: A lot of adhesives will cure perfectly if the vacuum bag had a regulator, but some adhesives will not work at full vacuum pressure.

Witness panels should not only include mechanical tests but also physical and chemical tests, and have a frequency of testing specified. Because they are not easily made, it is important to understand up front what information is going to be gained from using witness panels. They are often useful for batch processing, but not for hand grit blasting. In general, the criteria need to be established up front so that the panel will represent the particular part.

The Statistical Process Control (SPC) needs to be representative of production.

At the beginning of process control, coordination between NDI, verifilm, prefit, visual inspection, and destructive tests should be determined.

Comments were received regarding the overuse of NDI and establishing a false sense of security. The groups emphasized the use of a correct NDI technique and that this technique should be quantitative.

Reassessment when the material changes: Strong feelings were expressed on what you need to do when you change things: requalify.

Traceability of materials: Ability to trace where materials have been and where they are going.

Tool qualification and control: When was the last time this was maintained?

Verification of material handling (link between materials and process control): The material handling requirements should be referenced.

Additional items discussed were

- Surface inspection (water break, etc.)
- Operator training
- Emphasize time limits and drying on surface preparation
- Thermal profile of tooling
- Repair control versus production control
- Proof load on actual part
- Safety in handling

4.3.2 Design Development and Structural Substantiation.

4.3.2.1 Bonded Structure Design.

4.3.2.1.1 Design of Parts and Repairs.

Regarding the often-stated criterion to design and size structure to fail outside of a bonded joint, there was general agreement that, while this is desirable and practical to achieve for joints with metal adherends, it is not practical for bonded joints with composite adherends. One participant stated that this criterion is an old concept that comes from welding; the certification basis for welders was to ensure that the weld joint fails outside of the weld. One person stated that this is more of a rule of thumb than a requirement, and that current design and analysis capabilities make it possible to design joints to fail in the joint region.

Several participants agreed that, for composite structure, the criterion should be restated to mean precluding an adhesion failure mode rather than requiring a failure away from the joint. Interlaminar failures in the composite adherend in the surface plies are common, and it may be difficult on some composite designs to achieve failure outside the bondline, especially for pull-off and other out-of-plane loading conditions.

There was agreement that if the adhesive material is going to fail, it should always be in a cohesive failure mode. Adhesion failure modes were agreed to be process failures and thus not acceptable. The preclusion of an adhesion failure mode is principally a process-related issue but material choices could be significant.

A comment was made that, for thicker structures, designing to fail outside the joint is difficult. Another participant remarked that it is easy by using a step lap joint (however, this design only applies to bonded joints transferring loads in the plane of the laminate). For these high-load transfer joints, it was suggested that the design should preclude failure outside the joint area, e.g., in a step lap joint, an adherend failure in one of the steps would not be acceptable.

It was stated that a bond (adhesive) failure is easier to fix than an adherend failure. It was also stated that failures occurring outside the joint (either bonded or bolted) are more consistent than failures occurring within a joint.

There was general agreement that the key issue is predicting the mode and location of the failure. It was pointed out that there is a need to distinguish between design procedures and guidelines and certification approaches to avoid having regulations that state how to design a structure.

A participant suggested that you can learn a lot by designing to fail within the joint, then redesigning it to fail outside. The problem with initially trying to design for failures outside the joint is that you may not be successful. Other participants questioned whether a development program has the time or resources to conduct several design and test cycles.

There was some disagreement over the benefits and drawbacks of cocured composite structure (i.e., without adhesive materials) versus secondarily bonded structure. With cocured structure, failures occur in the laminates. A participant stated that to facilitate repair, the design should have simpler discrete parts that are secondarily bonded; this participant also claimed that this also ends up being cheaper to fabricate in practice. Other participants disputed this statement.

Regarding the often-stated criterion to design to minimize peel stresses, it was pointed out by a participant that one cannot say that there is no peel stress in joints. It is always there to some level, so one needs to design for its presence and understand its effects on joint performance.

There was a discussion on providing for redundant design features and load paths for bonded structure. 14 CFR Part 23 for small aircraft requires proof testing and redundant load paths for limit load. It was stated that separate joints can make up redundant paths (e.g., multispar wing design). The question was asked: Can redundant features be separately processed bonds?

A participant stated that the industry is kidding itself to say redundant features improve safety; if there is a bonding process failure, then all the joints will be bad and redundant design features will not provide the required load capability. A regulatory agency participant stated that (1) 14 CFR Part 23 is not meant to deal with global processing problems, but more with having arrestment feature, and (2) redundancy can deal with localized scale processing problems like contamination at a smaller scale than arrestment features.

An industry participant stated that they do not use adhesive bonds for primary load paths and always use rivets. They gave up on bonded joint designs and now do not have to do NDI of the bondlines.

It was stated that 14 CFR Part 25 does not specifically mention composites or bonded joints and, therefore, implies that you can certify a structure using damage tolerance methods.

Regarding the establishment of defect and damage sizes in bonded joints, it was generally agreed that the sizes should be linked to inspection methods and policies (both factory and in service). There was some disagreement as to whether establishing a defect size is really useful. A participant stated that low stress level structure can accommodate huge defects (e.g., 2- to 5-inch defect sizes). It was stated that it is difficult to intentionally introduce realistic defects—planned versus real in-service defect is different—because the in-service damage tends to be more severe. Defect types and sizes should be linked to manufacturing and in-service threats. It was stated that large damage most often comes from vehicles crashing into the aircraft (e.g., fuel truck or forklift). There was also a concern that it is difficult to inspect for bondline defects, yet industry typically establishes and designates to them—this could lead to difficult in-service issues.

4.3.2.1.2 Design for Repair.

It was stated that repair weight for some structural components is a critical issue. Allowing for repairs in certain areas and accounting for repair weight is necessary in the design process (e.g., for control surfaces). Another important factor to be considered in design is the trade between structural weight efficiency versus repairability.

There ensued a discussion regarding whether there should be a maximum allowable bonded repair size for primary structure. Some participants stated that primary structure with a disbonded repair must sustain limit load. It was also stated that if you have structure that does not have limit load capability without repair, that case should not be treated differently from what is done when designing the airplane. No consensus on repair size criteria was reached. Additional comments regarding bonded repair size limits included:

- A participant with military aircraft experience stated that sometimes damaged parts need to get scrapped.
- A general aviation participant stated that they cannot afford to do this.
- Need to distinguish between flight-critical versus nonflight critical parts.
- There are practical process restrictions on what can be repaired in the field.
- Different construction types permit different damage limits.
- A question was asked: Can different repair shops be identified that can be allowed to do certain repairs versus scrapping the part?
- Another question was asked: Should the repair size limit be an economic one?

It was generally agreed that the specifics of a repair design needed to be considered in specifying maximum defects to be used in the repair design and analysis (e.g., a 2- versus 5-inch repair overlap length can accommodate different defect sizes).

It was also agreed that bonded repair of honeycomb sandwich is easier to do than skin and stringer structure. One participant stated that bonded repairs to skin and stiffener structure will probably need to have fasteners to make it beyond the requirement to sustain limit load with the repair completely disbonded. Further discussion focused on how to design these repairs. The question was asked: How do you determine how much of the repair is bonded in service?

A participant stated that airline repair outfits would like to have correction factors to apply to manufacturer’s (OEM, material supplier?) data for use in repair design.

4.3.2.1.3 Bonded Structure Data and Analyses.

It was generally agreed that bonded structure data must be intimately tied to the analysis methods used to design the structure.

In the areas of material properties and statistical allowables, it was generally agreed that the following data should be obtained:

- Stress-strain response as a function of environment, thickness, etc., for adhesive and possibly composite adherend materials.

- Fracture toughness for adherend and adhesive materials. The data to be obtained will depend on the analytical techniques that are available. This data could give a good basis for comparisons between materials.

In what appears to be a unique case, one company does a lot of thick adherend stress versus strain measurement (at four environments). They do enough tests to get statistical values and have the methodology to take shear stress-strain curves and produce B-basis stress-strain curves. It was commented that having this extensive data helps during certification to document knowledge of properties and failure modes. Another participant commented that having these data are very useful in changing adhesives. However, a different participant suggested that this extent of data generation tends to make companies stick to using the same adhesives—even 30-year-old systems.

A participant asked what tests are available for producing peel stress design data. Another participant commented that pure peel is a mode that is not common and using these data would be very conservative. A comment was made that peel strength data for adhesive does not generally exist; therefore, it is hard to design joints.

It was commented that a big issue is the fact that when testing a composite-bonded joint, it is not a test of the strength of the adhesive, but a test of the joint as a system. Many factors are involved; therefore, allowables data must account for the specific type of joint being designed. Some people feel that this is a problem with thick adherend data and that it does not account for the same amount of peel as the actual joint configuration.

Further problems with the thick adherend shear test were expressed. Depending on which company runs the test, the results can be significantly different. Some participants felt that this indicated that the test procedure had a lot of variability. Comments were made that the mix ratio of paste adhesives affects stress versus strain curves.

The requirement for statistical numbers is a big issue: number of specimens, number of batches, etc. It was generally agreed that adhesive ultimate strength accounts for statistical variation, but adhesive moduli values are average numbers (just like the approach for composite laminates). There was also general agreement that material allowables should take account of material variability as well as production-related variability and be linked to the design methodology.

A small aircraft company participant commented that statistical data is mainly useful for receiving inspection purposes. A small aircraft company cannot afford to perform finite element analysis for every joint; rather, rough design rules of thumb are used, which accept a large margin. Very conservative allowables and rough crude analysis is used for 90% of structure; more aggressive allowables and sophisticated analyses might be used for critical structures.

In the area of manufacturing process data, the following were suggested as needed data:

- Effects of manufacturing variations (surface prep, curing, bondline thickness)
- Effects of manufacturing defects and anomalies

It was agreed that this data should be tied to the specific process used, e.g., vacuum bag, heat blanket, autoclave, etc.

Participants suggested that flaws in the bonded joint should be evaluated to determine whether they are critical. These types of tests are typically done at a full-scale or subcomponent level. A comment was made that flaws near a free edge could cause moisture ingression problems.

In the area of environmental durability data, it was commented that:

- Test protocols should incorporate compounds for inhibiting corrosion.

- Temperature is an important condition for durability tests.

- There is a need to show that you have durability with a combination of realistic operating environments, cyclic loading, and manufacturing defects.

Fatigue (load-cycling) issues should be covered as well as environmental cycling.

There was agreement that point-design data needs are tied in with the planned analysis methods. A comment was made that knockdown factors from element level tests do not necessarily transfer to the full-scale level.

It was agreed that analysis tools for damage tolerance analysis and testing have not been completely linked up. There is a pressing need to validate analysis methods. It was stated that the lack of validated damage tolerance analyses drives the no-damage-growth design philosophy and certification approach.

4.3.2.2 Bonded Structure Substantiation.

4.3.2.2.1 Static Strength.

It was generally agreed that the key to validation of analysis methods is the prediction of failure modes at each level of the building block and the validation of the predictions by test results.

There was no consensus on how to validate manufacturing processes, including process failures. Mostly questions were expressed:

- For certification, are we supposed to go through all the processes and play the “what if” game?
- If so, can you do it analytically?
- How does this affect the need (desire) to make process changes after the structure has been certified?

A participant expressed that the ideal situation would be to design a component that does not have a critical failure in the bondline. It was also suggested that it was important that the failure mode does not change with environmental exposure.

A comment was made addressing the fact that there will always be an unexpected failure mode in the full-scale test, due to a more elaborate structures and complex joints with multiple load paths.

4.3.2.2.2 Durability.

It was suggested by one participant that bond interfacial issues must be resolved before any environmental durability testing is performed; otherwise, confusing or invalid results will be obtained.

The possible need or requirement for large-scale tests at the most severe service environment was seen as a big issue. It was expressed that this is impossible to do for a large airplane, and thus when the aircraft is in service is when it is tested at the most severe environment. Therefore, it is important that in-service durability data and experience get fed back into the loop and adjustments made to account for what is learned.

Some certification programs have used lamina-scale coupon data to create environmental scaling load factors in conducting the full-scale tests. In some cases, intermediate-scale tests have been used to validate the approach. It was commented that this is the approach that produces a lot of information for the lowest cost, but it runs a big risk of missing effects that only show up at the full-scale level.

Regarding the demonstration of the no-growth of damages, it was commented that in many tests, you do not get growth or failure and the test ends, but you still do not know what failure mode is critical. This suggests that solely obtaining no-growth data may not be sufficient to ensure safety.

It was also commented that full-scale tests can be simplified by doing smaller-scale tests to prove no-growth, provided the small- scale tests are successful.

A participant commented that is it important to differentiate between long-term environmental durability and degradation versus short-term loss of structural performance due to an environment. Environmental cycling over the aircraft's lifetime could have a significant effect.

A participant stated that bond interfacial failures should be considered as a failure in certification testing because these joints over time would eventually lose their capability.

4.3.2.2.3 Damage Tolerance.

Issues regarding damage tolerance were discussed throughout the breakout sessions under several topic headings. As such, many of the related comments are interspersed throughout the previous sections. A summary of the key comments from above is given here, along with input from the participants during the discussion of this specific topic.

Regarding design for redundant features and load paths:

- It was stated that 14 CFR Part 23 for small aircraft requires proof testing and redundant load paths for limit load. This generally does not allow for a damage tolerance design approach.

- It was stated that separate joints can make up redundant paths (e.g., multispar wing design). However, can redundant features be separately processed bonds? If the bonds for the redundant load paths are processed simultaneously, is redundancy achieved?

- A regulatory agency participant stated that (1) 14 CFR Part 23 is not meant to deal with global processing problems, but more with having arrestment features and (2) redundancy can deal with localized scale processing problems like contamination at a smaller scale than arrestment features. It also addresses accidental damage threats in service.

- In other applications (non-14 CFR Part 23), crack arrestment features are sometimes used, such as chicken fasteners, or z-pins.

Regarding defect types and sizes:

- Defect types and sizes should be linked to manufacturing and in-service threats. It was stated that large damage most often comes from vehicles crashing into the aircraft (e.g., fuel truck or forklift). There was also a concern that it is difficult to inspect for bondline defects, yet we are establishing and designing to them—this could lead to difficult in-service issues.

- How are manufacturing anomaly or variation threats to be determined? If weak bonds cannot be found at the time of manufacture, how can we ensure the threat is limited to a local area (e.g., one disbonded stringer, etc…)? Again, the issue is how to define a global process failure relative to a local bond failure or anomaly.

It was agreed that the analysis tools for damage tolerance and associated data and testing have not been completely linked up. There is a pressing need to validate the analysis methods. It was stated that the lack of validated damage tolerance analyses drives the no-damage-growth design philosophy and certification approach.

Environmental durability should also be considered with regard to damage tolerance. If a significant bondline defect or damage exists, environmental cycling (including moisture ingress) may lead to damage growth. Do we have the analysis tools and test data required to characterize this?

It was stated that a significant amount of work has been done at DSTO (Australia) using smart patches for health monitoring of bonded repairs. A question was raised: Can health monitoring avoid some of the damage tolerance certification issues?

Several participants stated that there is a need to define the damage tolerance design criteria and philosophy at the start of a program. That is, the objectives of the validation and substantiation effort should be clearly stated before the development program gets underway.

A participant also asked the question: For structural repairs, Should/must a fail safety/damage tolerance analysis be performed?

4.3.2.2.4 Industry Standards, Guidance, and Research Needs.

Only a short amount of time in each of the four breakout sessions was devoted to discussions of standards, guidance, and research needs. In the first two areas, the following items were suggested:

- Reliable environmental durability test standards are needed for bonded joints in composite structure. Some ideas suggested included a wedge-type test or a DCB test.

- Need guidance on how to determine equivalency for different or modified adhesive materials and bonding processes. Need something similar to AGATE program for composite materials. Also need standardization and guidance on evaluating changes to certified materials and processes, including some standardization or definition for the difference between a new material and a change in application.

- Need guidance on developing building block test programs for bonded structure, including where in the building block tests should Barely Visible Impact Damage be incorporated.

- Need guidance on procedures and requirements for statistical allowables for bonded joints. Need to define what an adhesive joint allowable is. Need procedures to be able to apply analysis methods at scales from coupons and elements to full-scale structure.

- Need fracture toughness test standards to support evolving analysis methods.

- More usable data needs to be included in MIL-HDBK-17. This should include adhesive data as well as bonded joint data. Many participants felt that preliminary design data would be acceptable. Material suppliers continue to develop new materials—would like to see a quick turnaround to get new material data into MIL-HDBK-17, as current rate of revision of the document is too slow.

- Some participants expressed a desire for the FAA to publish bonded structures certification guidance (Advisory Circular or policy memo). Need big picture guidance that is application-dependent. However, many participants are concerned that FAA guidance will become requirements, especially by inexperienced FAA personnel. One participant commented that guidance applies to what you already know, not what you have not done yet. This then drives the design philosophy. But when guidance is created, de facto rules are being created, which are generally not desired by industry.

The following areas were suggested as needing further research:

- Inspection methods, both for manufacturing and for in-service evaluation.

- Methods for determining and using effective G_c and *R*-curve data for bonded joint design.

- Investigation of long-term durability of composite and bonded structure, particularly environmental degradation. Possibly obtain old used airplanes, get history on them, and then do teardown studies because these airframes have seen real environmental exposure.

4.3.3 Manufacturing Implementation.

4.3.3.1 Overview.

The primary objective of the manufacturing implementation session was to collect, document, and summarize the industry's consensus of critical issues regarding manufacturing implementation and experience of bonded structures (preferably with ranking). A secondary objective was to document the discussions of the critical issues, including proven engineering practices, provide directions for research and development, and identify the needs for engineering guidelines, standard tests, and specifications.

Prior to the workshop, the manufacturing implementation session panel, in coordination with Larry Ilcewicz, identified categories of issues known to affect bond quality. Using these categories, the panel planned to have workshop members identify key variables within each category and discuss the critical issues. After discussing the category, workshop members were asked to vote for the top three categories they believed were critical in their industry in terms of structural safety.

The initial categories presented for discussion were as follows:

- Handling of the adhesive
- Surface preparation
- Dispensing adhesive
- Dimensional control (adhesive layer thickness)
- Bonding fixtures
- Cure control

- NDI and quality control
- Scaling of processes to larger or smaller structures
- General (other)

4.3.3.2 Discussion Categories and Key Category Variables.

4.3.3.2.1 Surface Preparation.

The discussion of surface preparation was involved and clearly represented a major concern for manufacturers and repair stations. The variables identified as important included adequacy of the surface preparation, especially underprepared surfaces; contamination as related to cross contamination from reused material (grit media, etc.), environment (temperature, humidity, etc.), and time in environment-changing surface conditions; training; standardization of required techniques and environments; and quality control.

The importance of surface preparation seems to be agreed to by all parties. The importance of training and quality control relative to the lack of good NDI techniques to directly measure in-process quality seemed to be the variables that were most discussed.

4.3.3.2.2 Cure Control.

The cure control discussion centered on the large variation in manufacturing approaches; from autoclave processes to heat blankets. The type of approach affected the level of concern with respect to cure control variables. The variables identified as important included local variations in process conditions (temperature, pressure, and porosity); process metrics (in situ process metric versus post process quality assurance (QA)); scaling (laboratory scale versus full scale); and dimensional control of adhesive layer thickness and bonding.

4.3.3.2.3 Fixtures.

The variables identified as important included dimensional control of substrates and verification of fit; application of preloads relative to bondline thickness control and defects; tooling (design, type, flexibility, thermal conductivity, and thermal mass); bondline thickness measuring materials; and the appropriate use of Verifilm.

4.3.3.2.4 NDI and Quality Control.

The variables identified as important included bondline performance relative to thickness, strength, long-term performance, and SPC; the need for visual inspection standards; and NDI—especially adequacy, standardization, new developments, and utilization.

4.3.3.2.5 Scaling of Processes to Larger and Smaller Structures.

The variables identified as important included complexity (including size and number of steps), use of building block approach, and organizational scaling.

4.3.3.2.6 General (Human Factors).

Training was a major variable discussed in all categories. The variables identified as important included automation; equipment maintenance and the handling, storage, and disposal of materials; performance of trained employees; and documentation of processes.

4.3.3.2.7 Handling of the Adhesive.

The variables identified as important included storage and aging—specifically shipping versus manufacturing dates; out time; and requalification.

4.3.3.2.8 Dispensing Adhesive.

The variables identified as important included sequence and timing of the bonding process steps (gap filling and mixing).

4.3.3.3 Ranking of Categories and Variables.

- Surface preparation, 90 votes
  - Environmental cleanliness and control, contamination

- Cure control, 40 votes
  - Local variations in temperature and pressure, porosity

- Dimensional control (adhesive layer thickness) and bonding fixtures, 39 votes
  - Dimensional control of substrates, verification of fit
  - Application of preloads, bondline thickness control, defects

- NDI and quality control, 32 votes
  - Cured bondline evaluation, tracking outcome, and bond process variables

- Scaling of processes to larger and smaller structures, 26 votes
  - Scaling of a developed process to a larger (smaller) structure

- General (Human Factors), 25 votes
  - Equipment maintenance; training of personnel; documentation of process; and handling, storage, and disposal of materials

- Handling of the adhesive, 13 votes
  - Storage, aging

- Dispensing adhesive, 4 votes
  - Sequence and timing of the bonding process steps, gap filling

4.3.3.4 Summary.

In summary, the participants felt that everyone knew what the big issues were, and there was even a rough consensus on prioritization. However, many people were uncomfortable with the concept of ranking. No one was fully comfortable with the techniques available to cope with the current situation. The comfort level was lowest in the areas of training and surface preparation. The consensus was that training was not done well enough, consistently enough, or often enough. It was also the consensus that surface preparation is the issue most in need of one or more good practical solutions.

4.3.4 Repair Implementation and Experience.

4.3.4.1 Repair Design Issues.

The following were the most popular response to the question of what analysis tools were needed.

- Development of software to optimize repair lay-ups: As an example, it was suggested that the existing NSE/Boeing-developed bonded repair analysis method could be further developed and distributed to operators and maintenance and repair organizations (MRO). This would require sharing OEM and repair material databases.

- Development of a fracture mechanics approach to analyze of bonded original structures and repairs: This could be a simple, FAA-approved, PC-based analysis tool to design and substantiate repairs. Finite element method analyses were considered far too cumbersome for repairers.

Any analysis development should be verified by testing.

- CACRC operators' and MIL-HDBK-17 OEM analysis tools: Many repairers were looking forward to these aids. Many attendees commented that development of these analyses had been far too slow.

- Some attendees professed to be disturbed by divergence between analysis tools and structural responses.

- Bondline strength and durability analyses are needed: A4EI, BJAM, or similar type analyses need to be modified to allow for nonuniform shear stresses in the bondlines. It was thought that development of an analysis method to determine long-term durability was remote, but should be pursued as composite parts become larger and more critical for flight safety.

The topic of design values and allowables for repair materials promoted many complaints.

Many small aircraft repairers were using MIL-HDBK-17 material strengths and stiffness values to design their repairs because the MIL-HDBK-17 databases were used to design the aircraft.

This does not help the commercial aircraft repairers because both Boeing and Airbus have not provided their material databases to MIL-HDBK-17.

OEM attendees were asked about the potential for shared databases, both base and repair material allowables. They were concerned about the threat of reverse-engineering and poorly designed replacement parts. There are ITAR/IP issues for OEMs with providing databases.

Many participants thought that standardized engineering guidelines would help reduce the potential for poor design details and difficult repairs. In original designs for example, tapering stiffener flanges can minimize peel stresses. For repairs, the edges of the repair patches should be tapered. This was considered the norm by most repairers.

There was a recommendation that OEMs should provide a sufficient margin of strength to allow for degradation of structure due to repairs, which the OEM said would increase structural weight. There was a suggestion that a strain limit be established for repairs.

There were several responses regarding fail-safe features for primary structures, which are as follows.

- Fasteners in bondlines: The fasteners were to be the fail-safe feature in either original designs or repairs. Most participants thought that this was not a good idea, even though, theoretically, limit load capability could be maintained if the original bondline failed or the bonded repair falls off. The OEM participants thought this would drive up the cost and add complexity for inspection of parts. Repairers thought that these types of repairs would increase costs and repair times, and that these kinds of repairs would need precured patches.

- Damaged limit load capability of components with failed bonded repairs: General aviation and commercial transport OEMs and repair attendees did not consider this potential requirement helpful, even though bonded repairs on USAF composite aircraft require limit load capability of the damaged components without repairs. Currently, commercial aircraft SRMs contain bonded repairs for damaged primary structural components, which require the unrepaired component to retain higher residual strength than the limit load. This is the same for both composite and metal primary structural components. It was considered only an issue for aircraft on-ground repairs for these types of structures. Most commercial SRMs contain bonded repairs for damaged secondary structural parts that require the unrepaired component not retain limit load capability, and repairers did not want this changed for these types of structures, nor did they consider it necessary. It was thought by some that critical-to-flight-safety flight control panels may benefit from this low-risk requirement, until successful service experience drives up the confidence factor in adhesive bonded repairs for these structures.

- Instructions for continued service: Periodic inspection of repairs is typically a requirement for low temperature and some nonautoclave bonded repairs in OEM SRMs. There was some consideration for a similar requirement for bonded repairs to critical-to-safe-flight components. Again, it was suggested that this requirement, if imposed, could be lifted after successful service experience.

4.3.4.2 Repair Material and Process Controls.

- Raw material qualification—adhesives and substrates: The end-user typically runs the receiving inspection tests. This can use up considerable portions of small lots.

  Shared supplier and user databases could provide for statistically based qualification test values. However, material suppliers would need a good business case before providing extensive information.

  There was a comment that material suppliers do not understand the repair environment, and therefore, do not know how to test for it.

  Standardized test coupons and procedures are needed.

  Material equivalency was considered an issue. One OEM representative suggested that the FAA determine an acceptable material equivalency approach.

  It was considered that the AGATE program supplier-owned material database was a good approach.

- Supplier and user relationships: Most small repairers agreed that the material suppliers were not interested in helping them. For example, they were not interested in furnishing small lots of prepreg; therefore, the availability of small quantities of specific repair materials was a problem for small repairers.

- Standardized repair materials and processes: Standardized repair materials would alleviate the availability problem. In order to standardize repair materials and processes, it was thought that OEMs would bear 85% of the development costs, and the business case would need to be understood to expend that kind of expense.

  It was suggested that repair kits be standardized.

  The U.S. military has attempted to standardize repair materials across a multiple supplier fleet of aircraft.

  It was stated that some OEM base materials are not suitable for bonded repairs, specifically the toughened variety. As a result of this discussion, it was recommended that repairability should be an important objective for the material choice of any new airframe.

- Storage and working lives: Obtaining small lots from second tier suppliers can be problematic due to lack of warehouse and shipping controls.

Most general aviation repairers use wet lay-up repair materials and storage was not considered a problem, however, wet lay-up materials working lives could be a problem.

Most large airline repairers and MROs use both wet lay-up and prepreg materials. Storage is somewhat of a problem for prepreg materials as well as the need for retesting material batches every 6 months.

It was suggested that there should be a standardized guide for storage, i.e., containers and environmental controls.

- Surface preparation: Good surface preparation was considered paramount, and numerous attendees thought that most poor bonding is caused by the presence of moisture in the bondline.

  Repair environments need to be controlled to eliminate, as much as possible, moisture from the bonded surfaces. This is not an easy task for field repairs. On the whole, it was thought that depot repair environments were adequate.

  As for eliminating moisture or fluids from the base structure, it was thought to be mostly possible for thin face sheet sandwich, although some fluids, such as hydraulic fluid, were more difficult to eliminate. The consensus was that thicker laminates were next to impossible to dry out.

  At a minimum, it was a consensus that the surfaces to be bonded should be dry and clean.

  There was much discussion as to the best method of roughing the surface to be bonded. It was agreed that some preparation methods can leave a residue on the surface, which can be detrimental to good bonds.

  There was suggestion for a prebond nondestructive evaluation (NDE) capability to assess the surface preparation.

- In-process control: OEM SRMs specify their own process controls for repairs, and approval for these repairs is only granted if the specifications for materials and process control are followed.

  Temperature, vacuum, and pressure monitoring were all considered essential as process controls.

  There was a recommendation that OEMs should open up their processing temperature tolerances to compensate for variations in heat blanket thermocouple readings. F/A-18 E/F repairs were being rejected due to variations in the cure temperature readings. The temperature tolerance was opened up and proved successful. All agreed that processes need to be robust and repeatable.

  One OEM is using T_g via DSC for in-process verification of wet lay-up repairs.

Other suggestions for in-processing control were video monitoring, time sequencing, and in-process inspection buy-offs.

- Postrepair acceptance criteria: All the attendees agreed that there are no NDE methods available to assess bondline strength and durability.

  One participant thought that proof loading was a good method for repair acceptance, although this is not very appropriate for large components. A possible variation of this could be to subject the repair to an energy pulse of the type being investigated at Boeing.

  Companion coupons can be proof of cure but do not guarantee bondline integrity. On the whole, companion coupons were considered of little value.

  Some thought that the wedge test had merit for bondline assessment, but there is apparently no standard for it, and it can be readily misused. As for all other potential bondline tests, it cannot be used to predict life, and it is considered only semiquantitive.

  Most repairers use the tap method for postrepair inspection, although the U.S. Navy has disallowed that method due to lack of reference standards.

  There is potential for some combination of the review of material test properties, surface preparation, repair environment, and in-process controls could provide credible postrepair acceptance criteria. There was a recommendation for the FAA to coordinate a standard for postrepair acceptance criteria.

4.3.4.3 Considerations for Maintenance of Bonded Structures.

- Current field procedures used to inspect bonded structures and repairs: As stated above, most repairers of general aviation and commercial aircraft composites use the tap test for both in-service and postrepair inspections.

  All operators and repairers use a visual approach for both in-service and postrepair inspection.

  NDE methods, such as pulse echo, are used for in-service inspections in some maintenance manuals, but availability of reference standards becomes an issue.

  Due to lack of appropriate standards for repair, NDE performed for postrepair inspection often uses the actual structure for comparisons.

- Robust and repeatable repair processes: It was generally thought that to make sure repair processes are robust and repeatable, the workplace environment and in-process controls need careful attention. Elimination of moisture and humidity are very important. Technicians also need good initial training and periodic retesting.

Max Davis, of the RAAF, indicated that within his repair system, there were good and not so good technicians and inspectors. This all fits in with the suggestion for a certification system.

- Need for hand-held NDE equipment to interrogate bondline strength: Most attendees thought that this is an absolute necessity. The prospect of developing an effective method in the near future seems dim, but it was recommended that the government help with direction and perhaps some funding.

  A representative of the RAAF recommended that not only bondline strength prediction but also bondline durability prediction should be the goal.

- Certification of repair technicians, QA staff, engineering, and regulators: An attendee from Boeing recommended that what is needed is a completely certified repair system that includes materials, workplaces, processing, repair technicians, QA personnel, management, and regulators. This should be coordinated by the FAA and contributed to by OEMs, material suppliers, and repairers.

  There was a suggestion that the cost burden of qualification to, and regulation of such a system, will need to be shared.

  Most agreed that a certified repair system would be appropriate and beneficial.

- Two or more tiers for SRMs: A representative from Bell Helicopters stated that they already employ a multitiered SRM system. They approve repair stations for various levels of repair, and limit SRM distribution to those qualified to each level.

  Qualification to each tier is based on the repairers' experience, workplaces, technical capability and expertise.

  Most thought that this was a great system. Lower tier qualified repairers could qualify for higher tiers as they build experience and capability.

5. CONCLUSIONS.

The Federal Aviation Administration (FAA) is working on composite safety and certification initiatives (CS&CI) with industry, government agencies, and academia. The results of CS&CI, which include regulatory policy, guidance, standards, and training, have a basis in certification and service experiences. An industry interface in new technology considerations and focused research also help evolve the results to best support applications. Technical thrust areas for CS&CI include material standards, process control, structural substantiation, damage tolerance, maintenance practices, and advanced material forms and processes. In 2004, the emphasis was placed on bonded structures for all of these thrust areas.

Bonding is used in numerous manufacturing and repair applications for aircraft structures in small airplanes, transport aircraft, rotorcraft, fighter jets, and propellers. The FAA conducted a survey and workshops in 2004 to benchmark industry practices for structural bonding. The technical scope of these efforts included material and process control, design development, structural substantiation, manufacturing implementation, and maintenance practices and service experiences. Such complete coverage was needed because the technical issues for bonding are complex and require cross-functional teams for successful applications.

The survey developed a point of reference for industry practices and collected information on the critical safety issues and certification considerations for bonded aircraft structures and repairs. The average years of bonding experience for people taking the survey was 18. The responses were based on bonding applications to small airplanes, transport aircraft, rotorcraft, fighter jets, and propellers.

One of the primary areas of questions in the survey related to material and process qualification and control. Most respondents agreed that the primary reason for adhesive material qualification is to define requirements for material control. The respondents provided a long list of different physical, chemical, and mechanical tests for adhesive qualification. The most common mechanical test type used for qualification was some form of a lap shear test. Sixty percent of the respondents did not attempt to characterize the nonlinear stress versus strain behavior of the adhesive. Two-thirds of the respondents indicated that bonding process qualification was part of the same test matrix as adhesive qualification. A majority of the respondents agreed that qualification of bonding processes should include durability assessments to ensure adequate adhesion. All respondents agreed that moisture and temperature environmental effects were included in adhesive and bonded process qualification plans.

The respondents provided information on the types of mechanical, physical, and chemical tests included in specifications for adhesive material procurement and control. This included the types of tests used for acceptance testing. There was some difference in the opinions of the respondents on whether or not qualification data was used to directly set the acceptance requirements for adhesive material control, with the majority of the respondents in agreement. There was a greater difference in opinions on whether or not to include environmental effects in acceptance testing. The respondents had mixed views on the controls needed for peel ply materials, which are used for composite surface preparation.

The majority of the respondents use in-process monitoring or witness panel tests for bond process control. The different bond surface preparations used by respondents included sanding (hand and automated), media blasting, peel ply, chemical etch, and others, depending on the substrate and adhesive combinations. The most common methods of monitoring the surface preparation were visual checks, water break tests, witness panels, and surface chemistry tests. Fifty percent of the respondents believed that mechanical tests should be performed for bonding process control purposes. Most respondents agreed with a need to control the prebond moisture of substrate materials. The respondents, depending on the specific materials and bonding application, used a wide range of bond assembly processing steps. Most respondents had time constraints for the various bond assembly process steps from surface preparation to adhesive cure. The majority of respondents said that time and temperature were controlled in the bond process cure cycle. The majority of the respondents believed that nondestructive inspection (NDI) plays a role in bond process control.

Another primary area of questions in the survey related to manufacturing and design integration. The first series of questions addressed design and analysis. The respondents used bonding for many parts, including skins, doublers, stringers, and frames. Most people responding to the survey agreed that tooling, manufacturing, and maintenance issues should be integrated into the design process. A slight majority of the respondents use analysis codes. Many believed that cohesive failure in the substrate and adhesive could be predicted. A large majority of the respondents design to minimize peel stresses in a bonded joint. Most considered damage tolerance, fatigue, and durability in design; however, there was a general disagreement on whether or not analysis methods can be applied for such a purpose.

There were several survey questions related to manufacturing. Most respondents agreed on a need to control humidity in bond processing. A majority of the respondents indicated that cured part dimensional tolerance and warpage are controlled. People taking the survey were split on the use of Verifilm to confirm the fit of mating surfaces. Most respondents applied time constraints during adhesive application. In most cases, scaling for production did not result in significant changes in the processes used for surface preparation or adhesive application. The respondents used a number of different methods of controlling bondline thickness. Most respondents use ultrasonic methods and visual inspection to inspect bonded structures following cure. The respondents suggested a number of different methods for training the manufacturing workforce. All respondents agreed on a need to record cure temperature and duration, while most tracked adhesive out time.

There were also several survey questions on allowables and design data. Most respondents used lap shear tests. MIL-HDBK-17 was the preferred method of calculating allowables. A majority of people taking the survey indicated a need to include the effects of environment in bonded joint tests. The desired adhesive layer thickness varied with the application. There were many different thoughts expressed on the data needed for fatigue, damage tolerance, manufacturing defects, and service damage.

Another primary area of questions in the survey related to product development, substantiation, and support. Most people taking the survey indicated that product development lead times for bonded structures were longer than conventional structure that uses mechanical fastening. The majority of the respondents recommended using a building block approach for product development and substantiation of bonded structure. Most respondents agreed on a need to substantiate strength and damage tolerance in large-scale tests. Critical defect and damage locations were selected based on stress levels, manufacturing experiences, and susceptibility to impact. Most respondents have had good service records with bonded structure, while the rest have had mixed success.

The final area of the survey included general questions, which required an open-ended response. Opinions were collected on the major safety concerns and certification hurdles for bonded structures. Views were also expressed on desired design, analysis, manufacturing, and maintenance improvements. Finally, economic and technical barriers to expanded applications were discussed.

5.1 BONDED STRUCTURES WORKSHOP.

The Bonded Structures Workshop was held in Seattle, WA on June 16-18, 2004. The primary objective of this workshop was to collect and document technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. As secondary objectives, future needs in engineering guidelines, shared databases, standards, and research for bonded structures were also identified.

Presentations given by technical experts at the Bonded Structures Workshop covered a wide range of aircraft applications and service experiences. Surface preparation for the specific substrate and adhesive material combinations was thought to be a critical process step for both metal and composite bonded joints. Many experts felt that bonding material and process qualification procedures must address any potential for long-term environmental degradation of the bond in addition to mechanical strength and fatigue requirements. Accelerated laboratory tests, which include peel stresses and a moisture environment, were thought to be the best way of judging whether a good bonding process exists. Adhesion failures in qualification testing indicated an unsatisfactory combination of materials and bonding process parameters.

Once qualified, design development and bond process scale-up must be coordinated such that manufacturing and maintenance groups can repeatedly apply the proven process to structural detail. The building block approach to structural substantiation is typically used to address stiffness, static strength, and fatigue and damage tolerance requirements for bonded structures, including considerations for manufacturing defects and service damage. Since it is not practical to address long-term environmental durability in large-scale certification tests, many workshop participants felt that some combination of fail-safe design practices and service monitoring programs were also needed. Finally, most workshop participants believed that rigorous material and process controls and technician training were essential to manufacturing and maintenance implementation of bonding. Workshop presentations can be viewed at the following website, which was setup by the National Institute of Aviation Research at Wichita State University.

http://www.niar.wichita.edu/faa/

Four technical breakout sessions were conducted at the U.S. Bonded Structures Workshop. These included sessions for material and process qualification and control, design development and structural substantiation, manufacturing implementation, and repair implementation. The primary focus of these sessions was to gain agreement on the critical issues and certification considerations that need to be addressed in each area. In addition, best engineering practices were discussed and future needs in standards, shared databases, and research were identified.

In summary, the bonded structures survey and workshops provided a large amount of data to gauge industry practices. There appears to be a general consensus on the critical issues that need to be addressed for safety and certification. Future joint efforts by the FAA, industry, and academia will pursue recommendations on standardization, engineering guidelines, shared databases, and focused research for bonded structures.

6. REFERENCES.

1. "Certification of Bonded Structures," prepared by TTCP Action Group 13, John W. Lincoln, Chairman, February 2001.

2. Jason Bardis, et al., "Effects of Surface Preparation on Long-Term Durability of Bonded Composite Joints," FAA report DOT/FAA/AR-03/53, July 2003.

3. Workshop on Computational Fracture Mechanics for Composites sponsored by FAA-ASTM D 30, March 22-23, 2004, Salt Lake City, UT.

4. John Tomblin, et al., "Bonded Repair of Aircraft Composite Sandwich Structures," FAA report DOT/FAA/AR-03/74, February 2004.

5. Andrew Rider and Roger Vodicka, "Proposed Framework for a Risk-Based Approach for the Environmental Certification of Adhesively Bonded Repairs," DSTO-RR-0282, October 2004, AR-013-224, Commonwealth of Australia.

APPENDIX A—SURVEY QUESTIONNAIRE

The following instructions will assist you in filling out this survey:

Thanks for taking the time to fill out this survey. The survey will lead you through each section. If you wish to return to any section, you can hit the appropriate section button at the bottom of any section to return to that portion of the survey. You may close and reopen this survey as many times as necessary. All information is saved automatically. The "Undo" command only will remember the last action and you will not be able to return to a previously saved version of the survey. For those familiar with FileMaker Pro, all editing commands and functions are available. To capture your current input you may select the print command from the "File" menu and print the current section.

Check boxes (squares) allow for multiple answers on a question, radio buttons (circles) only allow one answer. When "Other" button is available, selecting it opens a window where additional specific answers may be provided for the question.

When complete, close the file and and the survey will be ready to email to WSU. Email the file "Bonded Structure Survey" in the downloaded folder "WSU Survey" to Linda.Greenberg@wichita.edu. Do not email the entire folder as this requires 20 times the memory and email space.

The survey contains the following sections:

(1) Introduction
(2) Endorsement
(3) Background Information
(4) Material and Process Control
(5) Manufacturing and Design Integration
(6) Product Development, Substantiation and Support
(7) General

Next Section

In order to initiate data collection efforts to benchmark adhesive bonding, Wichita State University (WSU), which belongs to the FAA Aircraft Airworthiness Center of Excellence, is conducting this survey as part of ongoing research. The purpose of the questionnaire is to establish detailed background information on the adhesive bonding philosophies that are utilized by the aircraft industry. Information collected in the survey will be summarized and presented at an FAA workshop being scheduled during June 2004 in Seattle (details on the workshop will be provided at a later date). Our Bonded Structures Working Group has identified you as highly experienced in bonded structure and we wish to receive your input for the workshop. The information you provide will guide future efforts. Space at the workshop will be limited, preference for registration will be given to those who provide a response to this questionnaire.

Please fill out the questionnaire as completely as possible. If you do not have a response for specific questions in sections 4, 5, 6 & 7, do not feel obligated to respond. We would like all questionnaires filled out by March 17, 2004 and e-mailed back to:

Linda.Greenberg@wichita.edu

We will continue to collect survey responses but only those received by March 17th will be included in the June Workshop. As a noted expert in the field, you may know of other experts that can help in the benchmarking effort. We encourage you to solicit a response from them. Please CC: Linda Greenberg at the e-mail address from above if you forward the survey to others, so that we have a record of who has been included.

There are some background questions at the start of the survey which identify your individual expertise and whether or not the response provided represents your personal response, functional team experiences or a company policy. Please note that we will not disclose responses that are provided outside of this research and will not identify the author(s) in anything presented at the workshop or in the eventual technical report.

The survey addresses the use of adhesive bonding in structural applications, both original manufacturer designs and maintenance repairs. The survey contains three main technical areas: (1) Materials and Processes, (2) Manufacturing & Design Integration and (3) Product Development, Substantiation and Support and a general questions section. Some questions appear to be asked multiple times; these similar questions are phrased in different manners to accurately determine your experiences and perspectives. All questions are provided with a default “No Response “ so only the questions you answer will be included in your survey response.

We appreciate your efforts in helping making this survey a success.

Thank You,
The Wichita State University Research Team

Dear Bonding Survey Participant,

Bonding is used in numerous manufacturing and repair applications to aircraft structures. This includes existing commercial and military applications: small airplanes, transport aircraft, rotorcraft and fighter jets. Many of the technical issues for bonding are complex and require cross-functional teams for successful applications. Collectively, the aircraft industry and government agencies should be able to combine our adhesive bonding experiences and technical insights to gain mutual safety benefits. Other advantages from sharing insights seem feasible for improved efficiency in the development and certification of bonded aircraft structure.

The FAA has organized an effort to benchmark bonded structures this year, as part of ongoing composite safety and certification initiatives. The primary objective is to document the technical details that need to be addressed for bonded structures, including critical safety issues and certification considerations. Examples of proven engineering practices, which have been used to address selected technical details, will be documented as a secondary objective. The process to benchmark existing technology will also provide directions for future research and development in the field. A strong interface with the industry, other government groups and academia is needed to adequately benchmark bonded structures. Such an approach will yield documents that provide a practical engineering guide, with educational value for an expanding work force. Over time, the FAA will continue to work with industry and other government agencies in drafting consistent policy and guidance for bonded structures, which has a basis in successful industry applications.

Please accept my thanks for responding to this survey. I realize that everyone is very busy in today's work environment.

Larry Ilcewicz

Federal Aviation Administration
Chief Scientific and Technical Advisor, Composites

(3) BACKGROUND INFORMATION

Please provide your contact information:

Your Name ____ Title ____

Company Name ____

Address ____ Mail Code ____

City ____ State ____ Zip Code ____

Phone ____

FAX ____

Email ____

Do you want to be included in informational mailings?

○ Yes ○ No

---

(1) Are perspectives expressed in this survey response based on:

○ Your personal insights
○ Personnel experiences
○ Functional team experiences
○ Company/organizational position
○ Other...

(2) What is your job function as related to adhesive bonding?

○ Materials and Processes
○ Design
○ Manufacturing
○ Analysis(Structural Integrity)
○ Regulator/Customer
○ Other...

(3) How many years has your company/organization been involved in adhesive bonding?

____

(4) How many years have you been involved in adhesive bonding?

____

(5) What is your business area?

○ Original Equipment Manufacturer
○ Bonding Outsourcing Shop
○ Repair Facility
○ Regulatory Agency
○ Customer
○ Researcher/Academia
○ Other...

(6) What aircraft have bonded structures, are manufactured, maintained or controlled by your company or government group?

☐ Primary Structure ☐ Secondary Structure ☐ Tertiary Structure ☐ Other...

(7) Does your company deal with :

☐ Commercial ☐ Military ☐ Other...

If you deal with aircraft commercial products what FAR categories are covered

☐ Part 23 ☐ Part 25 ☐ Part 27 ☐ Part 29 ☐ Part 43 ☐ Other...

(3) BACKGROUND INFORMATION

(8) How many bonded parts does your company process per year?

(9) Approximately how many bonded repairs does your facility perform in a year?

(10) Does your company use:

☐ Film ☐ Paste ☐ Liquid/pour coat ☐ Spray ☐ Primers ☐ Other...

(11) Does your company qualify new materials and/or bonding processes?

○ Yes ○ No

(12) Do you use materials and bonding processes qualified by other companies?

○ Yes ○ No

(13) Do you recieve special training for the use of other company's bonding processes?

○ Yes ○ No

(14) Do you control the quality of materials or processes used for bonded structures?

○ Yes ○ No

(15) Do you certify or approve designs?

○ Yes ○ No

If yes, which of the following are the designs intended

☐ New Products ☐ Product Modifications ☐ Repairs ☐ Other...

(16) Are you involved in maintenance actions that involve bonded repairs or structures?

○ Yes ○ No

(17) If questions arise in interpreting your responses to this survey, may we contact you?

○ Yes ○ No

SUBSECTION: MATERIAL AND PROCESS QUALIFICATION
(also see Allowables and Design Data under Manufacturing and Design Integration)

(1) How many individual adhesive products is your company actively using?

☐

(2) Was qualification testing performed at your company for the adhesives you use?

○ Yes ○ No

(If **adhesive qualification** was performed by another company or as part of an industry standards group, whose specifications and procedures you have adopted, please jump to question 9)

(3) What is the general purpose for the adhesive qualification testing?

☐ Define requirements for material control ☐ Certification requirements
☐ Allowables ☐ Other...

(4) How many "batches" of adhesive were used for the qualification?

☐

How were these "batches" defined?

☐

(5) What tests do you use for adhesive qualification?

☐

What did the typical test matrix consist of?

☐ Hot-wet ☐ Cold ☐ Other...
☐ Hot ☐ Cold-wet
☐ Ambient ☐ Fliud immersion

(6) For multi-part adhesive compounds, did the test matrix consider:

○ Only nominal mix ratios ○ Explore the limits of acceptable mix ratios

should the test matrix consider:

○ Only nominal mix ratios ○ Explore the limits of acceptable mix ratios

(7) Does adhesive qualification include mechanical tests of a bonded joint?

○ Yes ○ No

If yes, are these accomplished with metal or composite adherends?

☐ Aluminum ☐ Steel ☐ CRES ☐ Composite ☐ Hybrid ☐ Other...

(8) Was the adhesive nonlinear shear stress-strain response characterized during testing.

○ Yes ○ No

Did you use KGR gages (or similar) and the thick adherend test?

○ Yes ○ No

(9) Was qualification testing performed at your company for the bond process you use?

○ Yes ○ No

(If **bonding process** qualification was performed by an OEM or as part of an industry standards group, whose specifications and procedures you have adopted, please jump to the next subsection)

(10) How is qualification of the bonding process for specific adhesive and adherend combinations accomplished at your company?

Is it part of the same test matrix as adhesive qualification?

○ Yes ○ No

(11) What tests do you use for bonding process qualification?

☐ Mechanical ☐ Physical ☐ Chemical ☐ Other...

(12) How many different process runs are performed for bonding process qualification?

(13) Surface preparation variables were included in the qualification test plan.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, how?

(14) Qualification of the bonding process does include durability assessments to ensure adequate adhesion.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, what tests are used?

(15) What effects of environment were included in the adhesive and bonding process qualification test plan(s)?

☐ Moisture ☐ Temperature ☐ Other...

What effects of environment should be included in the adhesive and bonding process qualification test plan(s)

☐ Moisture ☐ Temperature ☐ Other...

(16) Can your qualification tests be traced back to:

☐ ASTM ☐ Company specific ☐ Other...

(17) Comments for adhesive and bonding process qualification?

SUBSECTION: MATERIAL CONTROL

(1) Identify which of following are included in the contents of specifications and/or other documents used for adhesive material procurement and control.

☐ Physical properties ☐ Multiple adherends ☐ Resin advancement determination
☐ Mechanical properties ☐ Multiple overlaps ☐ Other...

Please identify major areas are covered in your specifications If you are not part of the original organization that created these documents, please describe any special training received on material procurement and control.

(2) Where are material acceptance tests done?

☐ Supplier ☐ Manufacturer or repair facility ☐ Other...

(3) Which of the following tests do you use for acceptance testing:

☐ Mechanical ☐ Physical ☐ Chemical ☐ Other...

List mechanical tests

For mechanical tests, please indicate the type of specimen, size of specimen, type of adherend, amount of overlap thickness, adhesive thickness, etc. being used

List physical tests

List chemical tests

(4) The limits from adhesive qualification data are used for acceptance requirements defined in the specification.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(5) Can your acceptance tests be traced back to:

☐ ASTM ☐ Company specific ☐ Other...

(6) The adherend type used for acceptance tests is the same as being used in production.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

The adhesive thickness used for acceptance tests is the same as being used in production.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(7) Environmental effects are considered in acceptance testing.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(8) What procedures are used to control adhesive storage and handling from purchase until use?

☐ Freezer temperature monitoring ☐ First-in, First-Out
☐ Out-time monitoring (handling & staging) ☐ Other...
☐ Assembly temperature monitoring

(9) Peel ply materials are used for surface preparation, they are subjected to the same controls as adhesives in items (1) through (9) from above.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

What are the critical controls for peel ply?

(11) Comments on material control?

SUBSECTION: PROCESS CONTROL
(also see Manufacturing under Manufacturing and Design Integration

(1) What controls do you use in processing?

☐ Witness panel ☐ In-process monitoring
☐ Statistical process control ☐ Other...

(2) What type of surface preparation does your company use

☐ Hand sanding ☐ Media blasting ☐ Peel ply
☐ Automated sanding ☐ Chemical etch ☐ Other...

How is it monitored and controlled?

☐ Visual ☐ Water break-free ☐ Chemistry ☐ Witness panel ☐ Other...

(3) Mechanical tests are performed for bonding process control purposes.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, what tests are used?

(4) Pre-bond moisture of the substrates is controlled in your process.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(5) In the case of paste adhesives, how are the mixing variables controlled during production?

☐ Weight ☐ Chemical Analysis ☐ Test coupon ☐ Other...

(6) What is the sequence of processing steps from surface preparation (cleaning and abrasion) through application of primer (if used) and adhesive to bond assembly for cure?

(7) Do you have time constraints for the following steps leading up to cure?

☐ Surface preparation - Adhesive application
☐ Surface preparation - Primer application
☐ Primer application - Adhesive application
☐ Adhesive application - Adhesive cure
☐ Other...

(8) How is the bonding process cure cycle controlled?

☐ Time ☐ Temperature ☐ Other...

There are indicators to demonstrate temperature and pressure at the bond line.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(9) Nondestructive inspection (NDI) plays a role in bond process control.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(10) Comments on process controls?

SUBSECTION : DESIGN AND ANALYSIS

(1) What structural parts, attachments and splices use bonding for manufacture and/or repair?

☐ Skins ☐ Stringers ☐ Spars ☐ Machined parts
☐ Doublers ☐ Frames ☐ Ribs ☐ Other...

(2) How is the maximum operational temperature of your the adhesive established in relation to the Tg?

(3) How do you measure Tg?

☐ DSC ☐ DMA ☐ TMA ☐ Other...

(4) Tooling, manufacturing and maintenance issues are integrated into the design process.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

You have documented design guidelines in these areas.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

These guidelines depend on part criticality.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(6) Briefly describe analysis used for your bonded structures?

You use any analysis codes.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, what analysis code is used?

(7) What failure criteria are used?

Your predictions distinguish cohesive failures in the adherend or adhesive.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

You believe adhesion failures between the substrate and adhesive can be predicted.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(8) You make a concentrated effort to minimize peel stresses in design of bonded joints.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(9) How is the overlap length sized in design?

☐ Geomertically ☐ Stress level ☐ Other...
☐ Design standard ☐ Strain level

(10) Your analysis accounts for residual stresses in the bonded joint.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(11) What basic material properties and joint data are needed for analysis procedures?

(12) Are the following factors considered in design? (check if considered)

☐ Damage tolerance ☐ Fatigue ☐ Durability

(13) What determines the manufacturing flaw and accidental damage sizes considered for fatigue and damage tolerance assessments of bonded structures?

(14) You have had success in applying analysis methods for fatigue and damage tolerance assessments of bonded structures.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(15) What fail-safe design features are used to reduce the risk of weak bonds in your structure?

☐ None ☐ Rivets ☐ Crackstoppers ☐ Other...

(16) Comments on design and analysis?

SUBSECTION : MANUFACTURING

(1) You control humidity.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

You control temperature.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(2) What type of tooling and equipment used for adhesive bonding?

☐ Vacuum bag ☐ Press ☐ Matched Tooling ☐ Other...

(3) Cured part dimensional tolerance and warpage is controlled.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, how?

(4) You perform verifilm runs to confirm the fit of mating surfaces.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(5) The materials and processes qualified for your structures impose strict time limits for adhesive application steps.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If yes, identify how they were derived

☐ Design of Experiment ☐ Calculation ☐ Estimate
☐ Emprical ☐ Full test program ☐ Other...

(6) You handle large-scale surface preparation and adhesive application differently from laboratory scale.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If agree or strongly agree, how?

(7) There are handling/storage constraints and disposal guidelines for materials (e.g., solvents, grit blast media) used in surface preparation.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(8) How is bondline thickness controlled during production?

☐ Shims ☐ Stop blocks ☐ Glass beads
☐ Scrim cloth ☐ Microballoons ☐ Other...

(9) How are the bonded parts inspected after bonding?

☐ Visual ☐ UT ☐ Radiography ☐ Tap ☐ Other...

What classifications are used to control defects?

☐ Size ☐ Number ☐ Proximity ☐ Other...

(10) Is the process for dealing with bonded structure discrepancies in your factory:

☐ Efficient ☐ Inefficient ☐ Rarely used ☐ Other...

(11) Equipment and tooling maintenance is essential to structural bonding.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(12) What types of skills or training are necessary for production personnel?

Hours of training

Types of training ☐ Classroom ☐ Demonstration ☐ Practical ☐ On the Job ☐ Other...

(13) Describe manufacturing documents used for bonding process steps?

(14) What are the significant records taken during bonding process steps?

☐ Cure duration ☐ Out time of adhesive ☐ Cure temperature ☐ Other...

(15) Comments on manufacturing?

SUBSECTION: ALLOWABLES AND DESIGN DATA

(1) What allowables do you use?

☐ Lap shear ☐ Thick Adherend ☐ Bulk properties ☐ Other...

What design data are used to support the design of your bonded structure?

☐ Standard lap widths ☐ Standard joint configurations
☐ Standard adhesive thicknesses ☐ Other...

(2) Effects of environment (moisture, temperature, etc.) were included in the allowables and design data development?

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

Effects of environment (moisture, temperature, etc.) should be included in the allowables and design data development?

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(3) What bond overlap length (in inches) was used for the testing?

If a number of overlap lengths exist in your design, the test plan should be representative of all the overlaps used.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(4) What adhesive layer thickness(es) [in inches] should be used for bonded joint characterization?

☐ 0.002 - 0.004 ☐ 0.004 - 0.007 ☐ 0.007 - 0.020 ☐ 0.020 - 0.050 ☐ 0.050 - 0.100 ☐ Other...

Our design has tolerances specified for quality control:

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

We test only the maximum thickness for allowables characterization:

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(5) What statistics or statistical code is used to develop the allowables?

☐ MIL-HDBK-17 ☐ Average-Standard Deviation ☐ Other...
☐ AGATE ☐ ANOVA

(6) Data from qualification testing or other repetitive bonded joint tests is used to establish statistically based design allowables.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

Alternatively, a lower, "minimum bond strength design value" is set based on experience and test data (e.g., 500 psi).

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

If your adhesive design allowable is based on thick adherend test, do you verify the adequacy of the design by comparing that value to:

☐ Do not verify ☐ Peak shear stresses ☐ Average shear stresses ☐ Other...

(7) What data is collected to support dispositions of manufacturing defects and other discrepancies for bonded structures?

(8) What data is collected for fatigue & damage tolerance assessment of bonded structure?

(9) What data is collected to support service damage disposition and bonded structural repair?

Is the collected data entered in a database for review over time with service experiences?

○ Yes ○ No

(10) Comments on allowables and design data?

(6) Product Development, Substantiation And Support

(1) Based on your experiences, are the product development (through certification) lead times for bonded structure shorter or longer than for conventional structure that uses mechanical fastening?

○ Shorter ○ Longer

If your answer was shorter, This was always the case.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(2) Does the response to question (1) in this section depend on any one functional discipline more than others?

○ Materials and Processes ○ Manufacturing ○ Other...
○ Design ○ Maintenance

(3) How should the building block approach be utilized in adhesively bonded structures?

○ Do not use building block approach ○ Traditional approach
○ Inverted approach, large scale information first ○ Other...

(4) What scale of testing yields the most meaningful data for bonded structure development, substantiation and support?

○ Coupon ○ Subcomponent ○ Full-scale
○ Element ○ Component ○ Different in every case

(If the answer is different in each case, please explain).

(5) How is the criticality of bonded joint for your structure classified?

☐ Loads ☐ Applications ☐ Airworthiness experiences ☐ Other...

You apply a different approach to product development and substantiation based on criticality.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(6) The strength and damage tolerance of the bonded structure should be characterized during a full-scale test.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

Analysis validation takes place at this level.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(7) Long-term environmental exposure and durability should be substantiated for bonded structures.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

You have found that small-scale tests have meaning to service experiences.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

You have validated accelerated tests methods.

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(8) Are critical defect locations and types identified based on the following?

☐ Bond joint stress levels ☐ Susceptibility to impact damage ☐ Other...
☐ Manufacturing process experiences ☐ Damage souce defined from service

(9) What special considerations are important to the maintenance of bonded structure?

☐ Inspection ☐ Scheduled maintenance ☐ Other...

(10) What procedures are used to inspect bonded structures and repairs in the field?

☐ Visual ☐ UT ☐ Radiography ☐ Tap ☐ Other...

(11) Our service experiences with bonded structure and/or repairs has been good?

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

Have these experiences been application dependent?

○ Strongly disagree ○ Disagree ○ Niether agree nor disagree ○ Agree ○ Strongly agree

(12) What is the most common damages or defects found for bonded structure in the field

☐ Impact ☐ Corroision ☐ Moisture egress ☐ Other...

(13) Comments on product development, substantiation and support for bonded structure or repairs?

(7) General Discussion Questions on Bonded Structure

(1) What are your major concerns as to the safety of bonded aircraft structure?

(2) What are your most significant certification hurdles for bonded aircraft structure?

(3) What materials, process, design, analysis, manufacturing and/or maintenance improvements can be made to make bonded structure more economical?

(4) Are there any barriers (economic or technical) that need to be overcome to support the expanding applications of bonded aircraft structure?

(5) Additional general comments on bonded structures and/or repairs?

APPENDIX B—BACKGROUND INFORMATION (SECTION 3)

This appendix contains background information relative to the survey respondents. Table B-1 shows a list of the participating companies in the survey.

TABLE B-1. COMPANIES REPRESENTED IN SURVEY RESPONSES

Abaris Training Resources, Inc.	McClenahan Engineering
Adam Aircraft Industries	Monarch Aircraft Engineering Limited
AFRL/MLS-OL USAF	National Research Council Canada
Aurora Flight Sciences	Naval Air Depot—Cherry Point
Bell Helicopter Textron, Inc.	Naval Air Systems Command
The Boeing Company	NORDAM Europe Ltd
Cessna Aircraft Company	Raytheon Aircraft
Cirrus Design Corporation	Robinson Helicopter Company
Composite Structures Consulting	Rocky Mountain Composites
Concurrent Technologies Corporation	Royal Australian Air Force Directorate General Technical Airworthiness
Cranfield University	Sikorsky Aircraft
Defense Science and Technology Organization, Air Vehicles Division	SW Composites
DuPont Advanced Fibers Systems	Texas Composite Inc.
EADS CASA	The Lancair Company
EMBRAER—Empresa Brasileira de Aeronáutica S.A.	Toyota Motor Sales, Aviation Business Development Office
Federal Aviation Administration	Transport Canada
Goodrich Aerospace—Aerostructures Division	United Air Lines
HEATCON Composite Systems (Europe) Limited	University of Manchester
Korea Aerospace Research Institute	US Air Force Research Laboratory
Lockheed Martin Aeronautics Co.	United State Air Force Academy Center for Aircraft Structural Life Extension
Materials Engineering Research Laboratory Ltd.	Westland Helicopters Ltd.

Perspectives expressed in this survey are based on the following. Of the 53 responses, 22.6 percent said the results were based on personal insights. Approximately 41 percent of the respondents stated personal experience, 18.8 percent said functional team experience, and 15 percent said organizational position.

Job functions of the respondents are related to adhesive bonding as follows. Of the 52 responses, 46 percent said their job function involves materials and processes.

- 30.7 percent said analysis (structural integrity)
- 7 percent said design

- 2 percent said manufacturing
- 3 percent said regulator
- 6 percent said research and development
- 15 percent chose the category Other

The following were the direct responses given from those respondents who chose the category Other.

- Currently in marketing assignment, background is materials science R&D.

- Manufacturer of equipment and provider of training for adhesive bonding.

- I am a retired Structures Group Manager who still does some consulting on mostly composite structures.

- My job function covers regulation, materials and processes, design, manufacturing, analysis, training and quality management in a military repair environment. I have responsibility as a subject matter expert for the development of an engineering standard on composites and adhesive bonding as well as a handbook on design and a handbook on repair fabrication and application.

- Teaching adhesive bonding of composites research and development of failure modes.

- Currently in marketing assignment, background is materials science R&D.

The length of time the respondents have been involved in adhesive bonding was reported as follows. Of the 53 respondents, the minimum number of years stated was 2, the maximum was 47 years, with an average of 17.9 years. The standard deviation was 21.17 years.

The length of time the respondents' companies have been involved in adhesive bonding was stated as follows. Of the 53 responses, the minimum number of years was 4, the maximum was 100 years, with an average of 31.1 years. The standard deviation was 9.33 years.

The respondents represented the following business areas. Of the 50 responses, 46 percent said their business area was an original equipment manufacturer, 18 percent said researcher or academia, and 10 percent said repair facility. Seven percent said consulting and six percent said regulatory agency. Eighteen percent chose the category Other. No responses stated bonding outsourcing shop or customer.

The following were the direct responses given from those respondents who chose the category Other.

- Consultant to Defense Department Research Organizations and Weapon System Program Offices.

- End User, Maintainer, Requirements Developer

- Engineering Services - We evaluate technologies for US Government and US industry clients. One of our specialties is high-performance materials and processes.

- FAA designated engineering regulator Consultant.

- I have done consulting on composites, metal bonding and taught courses in aircraft structures both here in the USA and Europe since retiring. My job included managing a metal bonding research program and the technology development of composites structures. When I answer your question on company experience and usage it will be my experience. Your question that must be answer as to current activities I can not answer because of my long retirement time (17 years). So many of the following questions I can not answer on what they are currently doing.

- Manufacturer - Commercial and Military Aircrafts"

- My primary position is nominally research, but in practice I am involved in technology insertion for establishment of an adhesive bonded repair capability within the Australian Defense Organization.

- Supply of adhesive bonding equipment, materials and training.

The respondents stated of the aircraft that are manufactured, maintained, or controlled by their company or government group, the following have bonded structures. Of the 50 responses, 82 percent said primary, 82 percent said secondary, and 60 percent said tertiary. Eight percent chose the category Other.

The following were the direct responses given from those respondents who chose the category Other.

- As an R&D lab, we typically deal only at the coupon level.

- Composite materials can be found in all classes of aircraft structures.

- Overseeing certification of Seawind 300C which will have bonded joints at all levels (primary, secondary and tertiary).

- We would only be involved in training technicians to carry out composite repair. We are not responsible for any aircraft, or repairs, even though we occasionally help with repairs.

The respondents reported that their companies deal with the following types of aircraft. Of the 52 responders, 78 percent said commercial, 70 percent said military, and 5 percent chose the category Other.

The following were the direct responses given from those respondents who chose the category Other.

- Research and Development
- Marine
- Transportation
- Sporting goods
- Auto/motor sports
- General Aviation
- Other industries (automotive oil and gas)

If the respondents deal with aircraft commercial products, the Title 14 Code of Federal Regulations (CFR) categories were covered as follows. Of the 35 responses, 63 percent said 14 CFR Part 23, 57 percent said 14 CFR Part 25, 26 percent said 14 CFR Part 29, 23 percent said 14 CFR Part 27, and 14 percent said Part 43. Eight percent chose the category Other.

The following were the direct responses given from those respondents who chose Other:

- Academic Awareness of FARs: CAR 8 (ag airplanes)

- Part 145

- The ADF operates aircraft certified to FAR 25 as well as the UK DEF STAN 00 970 and USAF MIL standards. Though my company contributes data and technical expertise, certification is handled by our customers.

The respondents' answers varied considerably when asked how many bonded parts their companies processed per year. The following were the usable responses given: 10, 20, 50, 100, 100, 200, 300, 500(2), 1,000(3), 1,500, 2,000, 2,500, 4,500, 5,000(2), 10,000, 15,000, 16,400, 17,500, 60,000.

The respondents' answers varied considerably when asked how many bonded repairs their facilities performed per year. The following were the usable responses given: zero (5), 10, 12, 25, 50, 80, 100(4), 150, 200(2), 400, 500(2), 1000(3), 2000, 10,000(2)

The respondents' companies use the following types of adhesives: 95 percent of the 47 responses said they use film, 91 percent said paste, 78 percent said primer, 40 percent said liquid, and 25 percent said spray.

When asked whether their company qualified new material and or bonding processes, the respondents replied as follows. Of the 49 responses, 77 percent said yes and 22 percent said no.

When asked whether their company used material and bonding processes qualified by other companies, the respondents replied as follows. Of the 47 responses, 65 percent said yes and 34 percent said no.

When asked whether their company received special training for the use of other companies' bonding processes, the respondents replied as follows. Of the 44 responses, 70 percent said no and 29 percent said yes.

When asked whether their company controlled the quality of materials or processes used for bonded structures, 94 percent of the 49 responses said yes and 6 percent said no.

When asked whether they certified or approved designs, the respondents answered as follows. Of the 51 responses, 70 percent said yes and 29 percent said no.

Of the yes answers, the designs were intended for the following. Of the 37 responders, 81 percent said new products, 56 percent said product modifications, and 73 percent said repairs.

When asked whether they are involved in maintenance actions that involved bonded repairs or structures, the respondents answered: Of the 53 responders, 78 percent said yes and 22 percent said no.

When asked if they could be contacted if questions arose in interpreting their responses, the respondents stated the following. Of the 53 respondents, 98 percent yes and 20 percent said no.

APPENDIX C—SURVEY RESPONSES

This appendix contains a compilation of the responses to the survey.

C.1 MATERIAL AND PROCESS CONTROL SUBSECTION: MATERIAL AND PROCESS QUALIFICATION.

Question 1: The average number of individual adhesive products companies used was 19.34. The highest quantity listed was above 100 and the lowest was 2.

- Material and Process Control Responses
  - The average was 25.5. The highest quantity listed was about 100 and the lowest was 2.
- Design Responses
  - The average was 52.6. The highest quantity listed was over 100 and the lowest was 13.
- Manufacturing Response
  - The respondent indicated 10 or more.
- Analysis Responses
  - The average was 18.25. The highest quantity listed was 100 and the lowest was 2.
- Regulator/Customer Responses
  - Of the three respondents, only one replied, stating four or more.

Question 2: Sixty-one percent of the respondents said qualification testing was performed at their company for the adhesives they used. Thirty-two respondents said qualification testing was not performed at their company.

- Material and Process Control Responses
  - Nineteen percent said qualification testing was performed at their company for the adhesives they used. Eighty percent of the respondents said it was not.
- Design Responses
  - One hundred percent of the respondents said qualification testing was not performed at their company for the adhesives they used.

- Manufacturing Response
  - The respondent said qualification testing was not performed at their company for the adhesives they used.

- Analysis Responses
  - Seventy-eight percent said qualification testing was performed at their company for the adhesives they used. Twenty-one percent of the respondents said it was not.

- Regulator/Customer Responses
  - Of the three respondents, only two replied, stating qualification testing was performed at their company for the adhesives they used.

Question 3: Eighty-six percent of the responders agreed that the general purpose for the adhesive qualification testing is to define requirements for material control. Eighty-four percent said allowables and 81 percent said certification requirements (see figure C-1).

- Material and Process Control Responses
  - Ninety-four percent of the responders agreed that the general purpose for the adhesive qualification testing is to define requirements for material control. Eighty-eight percent said allowables and 70 percent said certification requirements.

- Design Responses
  - No respondents replied to this question.

- Manufacturing Response
  - The respondent did not reply to this question.

- Analysis Responses
  - Ninety-one percent of the responders stated allowables, 83 percent said define requirements for material control, and 83 percent said certification requirements.

- Regulator/Customer Responses
  - Of the three respondents, only two replied. One respondent chose all three options: define requirements for material control, allowables, and certification requirements. The second respondent chose defines requirements for material

control and certification requirements. The category Other response was "establish processing capabilities and application limits."

- Other Category Responses
  - "Establish cure cycle envelope."

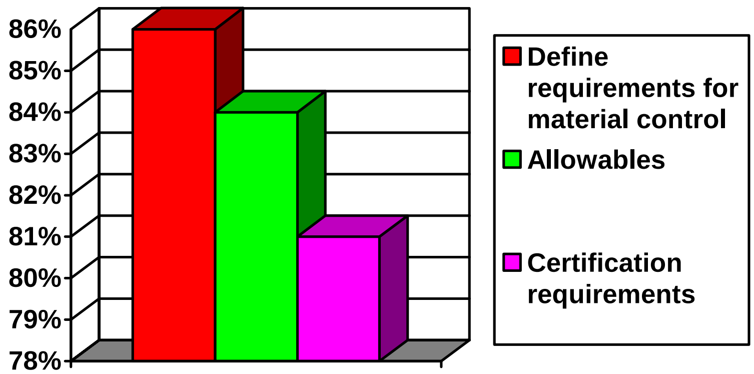

FIGURE C-1. GENERAL PURPOSE FOR THE ADHESIVE QUALIFCATION TEST

Question 4: Of the 29 responses, 68 percent said three batches of adhesive were used for qualification. Two respondents indicated they used one batch, one respondent stated two batches, one respondent indicated five batches, two respondents stated 35 batches, and two respondents stated 13 batches.

- Material and Process Control Responses
  - Of the 15 responses, 80 percent said three batches of adhesive were used for qualification. One respondent stated one batch, one respondent stated one to three batches, and one respondent said three to five batches.
- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of eight responses, 87 percent said three batches of adhesive were used for qualification. One respondent said two.

- Regulator/Customer Responses
  - Of the three respondents, one stated five.

The following were the responses given by the respondents when asked how the batches are defined.

- Material and Process Control Responses
  - "Batch as defined by adhesive manufacturer."
  - "Source, date of manufacture, batch number, form, aerial density."
  - "Separate runs--at least two batches of ingredients."
  - "Usually separate mixes spaced at least two weeks apart. Attempt to spread available raw material batches of components across batches."
  - "Per Mil-17, qualification testing is only done in house when the OEM cannot perform it."
  - "Different raw materials produced at different times."
  - "Generally a quantity of material produced from a single set of raw ingredients and processed at one time with only minor interruptions."
  - "Three different production batches of major chemical constituents."
  - "Depends on the product form."
  - "Varies with OEM specifications."
  - "Resin polymerized in one reaction, in one operation or blended together in one homogeneous mix with traceability to individual components."
  - "Using vendor batch numbers assigned during manufacture of material."
  - "A set with the same processing."
- Analysis Responses
  - "For two part adhesives, three separate batches of mix A and 3 separate batches of mix B."
  - "Separate manufacturing campaigns using unique raw materials."
  - "Resin mix."

- “By three permutations of adhesive manufacturer material batches assembled and cured in three separate oven operations.”

- “By requirement specifications, such as EADS CASA Procedure.”

- “Simply “three separate batches” with no further qualification.”

- “A homogeneous unit of finished adhesive film of the same formulation manufactured under controlled conditions in a continuous operation.”

- “Production date.”

• Design Responses

  - No respondents replied to this question.

• Manufacturing Response

  - The respondent did not reply to this question.

• Regulator/Customer Responses

  - No respondents replied to this question.

• Other Category Responses

  - “RAAF is a small volume user; research and development of design data usually extends over a period that involves several purchases of minimum buy lots. The batches are selected on the basis of supply lots.”

  - “Consecutive individual “lots” or “batches” manufactured at one time under the same conditions and parameters using the same types and quantities of raw materials.”

Question 5: Eighty-six percent of the respondents used some form of lap shear to test for adhesive qualification.

The responses included the following.

• Material and Process Control Responses

  - “Peel” (6)

  - “CD peel”

  - “Metal T-peel”

  - “Honeycomb climbing drum peel”

- “T and FR Peel”
- “Static metal-to-metal peel”
- “Sandwich drum peel”
- “T-Peel”
- “Double Lap shear ”
- “Lap shear” (4)
- “Mechanical testing-lap shear”
- “Metal adherend single lap shear”
- “Metal/metal Single Lap shear and floating roller peel”
- “Honeycomb climbing drum peel and flatwise tensile Tack”
- “Aerial weight”
- “Flow”
- “Volatiles content”
- “Heat of polymerization thick adherend”
- “Metal thick adherend”
- “Thick adherend”
- “T_g”
- “DSC” (2)
- “TMA”
- “FWT” (2)
- “SBS”
- “HPLC”
- “FTIR”
- “CDP”

– “Single lap tensile test”

– “Flatwise tension strength test”

– “Flatwise tension”

– “Flatwise tensile”

– “Flatwise tension wedge”

– “Single lap shear” (2)

– “Flow testing”

– “Thick adherend lap shear”

– “Static and fatigue lap shear”

– “Shear”

– “Lap shear (various l/t ratios)”

– “Wide area lap shear”

– “Peel of cored and skin components”

– “Peel and flow results of full size parts”

– “Climbing drum peel”

– “Creep”

– “Creep rupture”

– “Cyclic creep”

– “Fatigue”

– “Fatigue: Thick adherend lap”

– “Slow cycle fatigue”

– “Environmental durability testing”

– “Durability (wedge, sustained stress, etc)” (2)

– “Fluid exposure”

- “Outdoor exposure”
- “Honeycomb flatwise tension”
- “Metal-to-metal flatwise tension”
- “Metal Static: Lap”
- “Wedge crack”
- “Cyclic stress”
- “Composite & Sandwich bond both pre and co-cured: lap”
- “Aerial weight”
- “Tack” (3)
- “Flow” (3)
- “Rheology”
- “Out time and shelf life”
- “Multiple cure cycles and alternate cure temperatures. Cure time/temp. Response surfaces for lap, & T_g”
- “Mostly ASTM methods, some internally described methods (FTIR, TMA, SEM etc)”
- “Physical properties”
- “Rheology properties”
- “Kinetic properties”
- “Fluid resistance”
- “Durability”
- “Wedge crack”
- “Chemical resistance”
- “Physical and chemical characterization”
- “Shop floor suitability”

- “Shelf life”
- “Out time”
- “Reparability”
- “Inspectability”
- “Sandwich flatwise tension”
- “Block compression”
- “Sag”
- “Density”
- “Percent expansion”
- “Shear Modulus”
- “Out-time studies”
- “Fluid resistance”
- “Workability”

- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - “Lap Shear” (5)
  - “Lap Shear for Phos Anodized Aluminum Substrate and Composite Substrate at CTD, RTD, ETW, and Fluid Immersion (If Wet T_g Is Not 50F Higher Than Maximum Operating Temperature; then A Higher Temperature Wet Test (200F) is included), Shore or Barcol Hardness.”
  - “Beam Shear”
  - “D1002 Lap Shear with Metal Substrate”
  - “Modified D3165 Thick Adherend Lap Shear with Composite Substrate”

- “Double Shear”
- “Shear”
- “Beam Shear”
- “Tensile Shear Strength”
- “Thick Adherend Shear Test”
- “Peel” (3)
- “Honeycomb Peel”
- “Honey-Comb Climbing Drum Peel”
- “Metal To Metal Floating Roller Peel”
- “Metal To Metal Peel”
- “D1876 Peel”
- “FWT”
- “Flatwise Tension”
- “Flat Wise Tension”
- “Flatwise Tensile”
- “Tensile”
- “Fatigue”
- “D3166 Fatigue”
- “FTIR & HPLC for Resin & Hardener”
- “Pot Life”
- “Crack Growth Moisture Uptake”
- “Wet & Dry T_g Via DMA”
- “D4065 T_g”
- “T_g”

- “DCB”
- “Sustained”
- “Stress”
- “Pull Off”
- “D1002 Fluid Immersion”
- “Creep”
- “Non-ASTM Creep”
- “Mechanical Test”
- “Tension in Plane”
- “Temperature”
- “Tack All Types”
- “Adhesive Weight”
- “Adhesive Flow”
- “Volatile”
- “Heat of Polymerization”
- “Hazardousness Grade”

• Regulator/Customer Responses

- “Single Lap Shear” (2)
- “Double Shear”
- “Tension”
- “Element/subcomponent”

Table C-1 shows the breakdown of the typical test matrix.

TABLE C-1. TEST MATRIX CONSIDERATIONS

Response	Percent
Ambient	89
Hot-wet	73
Fluid immersion	60
Cold	65
Hot	47
Cold-wet	7.00
Other	7

- Material and Process Control Responses

  – Of 17 responses, 100 percent said ambient, 88 percent said hot-wet, 82 percent said cold, 70 percent said fluid immersion, 64 percent said hot, and 5 percent said cold-wet.

  The responses from the category Other stated the following.

  – “salt spray”
  – “water soaks”
  – “RT”

- Design Responses

  – No respondents replied to this question.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Ninety-one percent of the respondents said ambient, 83 percent said hot-wet, 66 percent said hot, 66 percent said cold, 58 percent said fluid immersion, and 16 percent said cold-wet.

  One respondent chose the category Other and stated:

  – “Test chambers where spring loaded bonded joints could be exposed to a typical ground – air - ground environment of a typical commercial aircraft was used to expose new bonded joint materials.”

- Regulator/Customer Responses

  – Two of the three respondents replied with the same answers, each chose hot-wet, ambient, cold, and fluid immersion.

Question 6: For multipart adhesive compounds, 72 percent of the responders said the test matrix considered nominal mix ratios and 24 percent said it explored the limits of acceptable mix ratios.

- Material and Process Control Responses

  – For multipart adhesive compounds, 35 percent of the responders said the test matrix considered nominal mix ratios and 64 percent said it explored the limits of acceptable mix ratios.

- Design Responses

  – No respondents replied to this question.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – For multipart adhesive compounds, 37 percent of the responders said the test matrix considered nominal mix ratios and 62 percent said it explored the limits of acceptable mix ratios.

- Regulator/Customer Responses

  – Two of three respondents replied; one said only nominal mix ratios and one said they explore the limits of acceptable mix ratios.

The respondents indicated that the test matrix was accurately characterizing the requirements. Of the 33 responses, 69 percent said it should explore the limits of acceptable mix ratios, while 10 percent who said it should consider only nominal mix ratios.

- Material and Process Control Responses

  – The responses indicated that the test matrix was accurately characterizing the requirements. Of the 17 responses, 72 percent of the responders said the test matrix should only consider nominal mix ratios and 24 percent said it should explore the limits of acceptable mix ratios.

- Design Responses

  – No respondents replied to this question.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Of the eight responses, 25 percent said the test matrix should only consider nominal mix ratios and 70 percent said it should explore the limits of acceptable mix ratios.

- Regulator/Customer Responses

  – Two of the three respondents replied. Both indicated that the test matrix should explore the limits of acceptable mix ratios.

Question 7: Of the 38 responses, 100 percent said adhesive qualification does include mechanical tests of a bonded joint.

The respondents indicated that these are accomplished with metal or composite adherends. Eighty-six percent of the respondents indicated that it was accomplished with aluminum compared to 68 percent who said composites. Table C-2 shows the breakdown of the remaining selections. The category Other responses indicated that testing was done using intended substrates.

TABLE C-2. ADHESIVE QUALIFICATION OF MECHANICAL TESTS OF A BONDED JOINT

Response	Percent
Aluminum	86
Composites	68
Hybrid	21
Titanium	18
CRES	15
Steel	13
Brass	2
Nickel	2
Tungsten	2

- Material and Process Control Responses

  – Seventy-six percent of the respondents indicated that it was accomplished with aluminum compared to 70 percent who said composites. Thirty-five percent stated titanium, 29 percent stated hybrid, and 23 percent said CRES. One respondent indicated brass, nickel, and tungsten.

- Analysis Responses
  - Ninety-one percent said aluminum compared to 66 percent who stated composites; 16 percent said titanium; and 8 percent stated steel, CRES, and hybrid.
- Regulator/Customer Responses
  - Both respondents selected aluminum and composites, with one of the two respondents also selecting hybrid.

Question 8: Sixty-percent of the respondents said the adhesive nonlinear shear stress-strain response was not characterized during testing.

- Material and Process Control Responses
  - Of the 16 responses, 58 percent of the respondents said the adhesive nonlinear shear stress-strain response was characterized during testing. Thirty-five percent of the respondents said it was not.
- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 10 responses, 70 percent said the adhesive nonlinear shear stress-strain response was characterized during testing. Thirty percent said it was not.
- Regulator/Customer Responses
  - Of the two responses, both said the adhesive nonlinear shear stress-strain response was characterized during testing.

Fifty-three percent of the respondents said they used the thick adherend test and KGR gages, or something similar.

- Material and Process Control Responses
  - Of the 20 responses, 65 percent said they used the thick adherend test and KGR gages, or something similar. Thirty-five percent said they do not use these.

- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the eight respondents, 62 percent said they do not use KGR gages and the thick adherend test and 37 percent said they do use them.
- Regulator/Customer Responses
  - Of the two responses, one said they do use KGR gages and the thick adherend test and one said they do not.

Question 9: Of the 52 responses, 65 percent said qualification testing was not performed at their company for the bond process they use. Thirty-four percent said it was performed at their company.

- Material and Process Control Responses
  - Of the 20 responses, 85 percent said qualification testing was performed at their company and 15 percent said it was not.
- Design Responses
  - Of three respondents, 66 percent said qualification testing was not performed at their company and 33 percent said it was.
- Manufacturing Response
  - The respondent said qualification testing was not performed at their company.
- Analysis Responses
  - Seventy-one percent said qualification testing was performed at their company and 28 percent said it was not.
- Regulator/Customer Responses
  - Of the two responses, one said qualification testing was performed at their company and one said it was not.

Question 10: The respondents indicated that the qualification of the bonding process for a specific adhesive and adherend combination was accomplished as stated in the following comments.

- Material and Process Control Responses
  - "We qualify part specific processes with adhesive manufacturer's recommendations."
  - "As a next level in the building block up from material characterization."
  - "Bonding process is carried out with accompanying traveler coupons."
  - "Bonding representative coupons in production environment using representative process parameters."
  - "By means of particularized tests named "process ability tests." The applicable mechanical tests (e.g. laminate or honeycomb) are performed on all of the targeted adherends. We test representative adherend lay-ups, overlap lengths, bondline thickness ranges, bond prep methods and environmental conditioning. Mechanical and physical tests of joints--In-house test program that meets the requirements of a material specification and a process specification."
  - "Coupon, element, and subcomponent level testing, including all substrate and adhesive combinations."
  - "Individual material specifications define the required test methods and procedures."
  - "It is dependent upon the adhesive system, field of use, and product it will be used on. Initial qualification may be specific to a particular program and part configuration, and then expand in scope with additional testing."
  - "Lap shear and T_g tests"
  - "Wedge test"
  - "Process Design, Process Prototype, Destructive Testing"
  - "Repair and remaining qualification is done on a per process basis by developing parameters to evaluate reductions in margin based on repairs. This is only done when it cannot be done at the OEM."
  - "Test adherends used in real parts."
  - "Similar at coupon level but builds up to Verifilm and finally destructive test of first part qualification article(s)."

- Design Responses
  - "Through our parent facility through process specifications."
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - "The applicable mechanical tests (e.g. laminate or honeycomb) are performed on all of the targeted adherends."
  - "Mechanical and physical tests of joints."
  - "Generally perform "point design" testing to validate combination shown on engineering drawing. Not a lot of time is spent evaluating multiple combinations in pursuit of "optimum" combination."
  - "Standard Process"
  - "Academic research only - was not interested in absolute bond performance so repeatability was/is major factor of process qualification."
- Regulator/Customer Responses
  - "Chemical and physical characterization and repetitive testing of shear and peel properties."
- Other Category Responses
  - "Thick adherend double cantilever beam (similar to ASTM D3433)."
  - "Part of the material qualification."
  - "The bonding process follows a dedicated procedure."
  - "Coupon level."
  - "Full scale structural testing including manufacturing defects."
  - "Standard process."
  - "Varies with weapon system."
  - "Academic applications only."

- “Wedge test ASTM D3762 with our own acceptance criteria. The ASTM standard as it currently is written is inadequate for assurance of bond durability.”

- “Generally perform “point design” testing to validate combination shown on engineering drawing. Not a lot of time is spent evaluating multiple combinations in pursuit of “optimum” combination.”

- “Engineering qualification test plans and reports are used for most processes.”

- “Run small scale coupons to develop processes.”

- “Make full size parts.”

- “Destructive test parts.”

- “Fatigue test of parts.”

Of the 36 responses, 66 percent said it was part of the same test matrix as adhesive qualification. Thirty-three percent said it was not part of the same test matrix.

- Material and Process Control Responses

  - Of the 18 responses, 72 percent said it was part of the same test matrix as adhesive qualification. Twenty-seven percent said it was not.

- Design Responses

  - Only one of the three respondents replied to this question, indicating that it was not part of the same test matrix as adhesive qualification.

- Manufacturing Response

  - The respondent did not reply to this question.

- Analysis Responses

  - Of the nine responses, 66 percent said it was part of the same test matrix as adhesive qualification and 33 percent said it was not.

- Regulator/Customer Responses

  - Only one of the three respondents replied, stating it was part of the same test matrix as adhesive qualification.

Question 11: Ninety-seven percent of the respondents said they used mechanical tests for bonding process qualifications, with physical tests at 66 percent and chemical tests at 42 percent.

- Material and Process Control Responses

  – Of the 19 responses, 94 percent said they use mechanical tests for bonding process qualifications, with physical at 76 percent and chemical at 52 percent.

  The following responses were from the category Other.

  – "Non-destructive methods, i.e. ultrasonic, thermography."
  – "Thermal Analysis (T_g)."

- Design Responses

  – Of two responses, 100 percent said mechanical with one respondent also chosing physical and chemical.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Of the 12 responses, 91 percent stated mechanical, 58 percent said physical, and 41 percent said chemical.

  Sixteen percent chose the category Other and provided the following responses.

  – "Storage Conditions"
  – "Life"
  – "Cured conditions"
  – "Destructive Test"
  – "Thermal Profiling"
  – "Prefit"
  – "Verifilm"
  – "NDI"

- Regulator/Customer Responses

  – Only one of the three respondents replied, stating mechanical, physical, and chemical.

- Other Category Responses

  – "Differential Scanning Calorimetry to determine the degree of cure."

Question 12: The average number of different process runs performed for bonding process qualification was 6.5. The highest number listed was 75 and the lowest number was 1.

- Material and Process Control Responses

  – Of the 12 responses, the average number of process runs performed for bonding process qualification was 5.75, with the most common listing as 3. The highest response stated was between five and ten, while the lowest was one.

- Design Responses

  – Only one respondent of three replied, indicating the number of different process runs performed for bonding process qualification was four.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Of the four responses, two stated 3, one stated between 4 and 5, and another stated 12 as the number of different process runs performed for bonding process qualification.

- Regulator/Customer Responses

  – Only one of the three respondents replied, indicating the number of different process runs performed for bonding process qualification was 75.

Question 13: A majority of the respondents agreed that surface preparation was included in the qualification test plan. The responses were broken down as shown in table C-3.

TABLE C-3. SURFACE PREPARATION INCLUDED IN QUALIFICATION TEST PLAN

Response	Percent
Agree	37
Strongly agree	19
Neither agreed nor disagree	17
Disagree	17
Strongly disagree	17
Nickel	2
Tungsten	2

- Material and Process Control Responses

  – Twenty-seven percent agreed, 33 percent disagreed, 27 percent neither agreed nor disagreed, 11 percent strongly agreed, and 5 percent strongly disagreed.

- Design Responses
  - One of three respondents replied, stating they strongly agreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Thirty-three percent agreed, 25 percent neither agreed nor disagreed, 8 percent disagreed, and 8 percent strongly disagreed.
- Regulator/Customer Responses
  - Only one of three respondents replied, stating agreement.

The respondents who either agreed or strongly agreed gave the following responses.

- Material and Process Control Responses
  - "Research was conducted over a number of years investigating affects such as contamination, deviation in specification or leaving of the certain steps on the bond durability as assessed by the wedge test."
  - "The coupons representing a batch of adhesive are also tied to a unique process lot for surface prep and at least two batches of bond primer across the multiple batches of adhesive."
  - "Mesh number of sandpaper."
  - "Typically we use PAAed aluminum for adhesive qualifications. It is possible the results may be different on Ti or stainless and may be different with alternate surface preparations. However, cost limits the amt of testing we can do."
  - "If a process works do not change it."
  - "We evaluated different process methods, i.e. hand sanding versus grit blasting."
  - "Chemical and physical surface characterization test were run on the surface preparation method used including manufacturing tolerances on the surface preparation process parameters."
  - "Used during small scale coupon test."
- Design Responses
  - "To confirm against OEM test specs."

- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - "Especially for environmental testing (long term durability)."
  - "Grit blast, sanding, contamination, and application methods were considered."
  - "Compatibility testing is done with primers and allowed surfaces preparations. My company is more rigorous on metal bond primer and primary structure composites and less rigorous on secondary structure composites."
  - "Influence of surface characteristics and surface preparation evaluated separately and in combination. Particularly those parameters that represent time consuming or cumbersome processes (i.e., sanding versus peel, co-cure versus precure, etc.)."
  - "Introducing all the possible defects taking into account all the possibilities."
  - "Peel ply and other surface preparations influence the bonding strength."
  - "Small scale tests of adherend, surface prep, bond thickness, and environment."
  - "Using different surface preparations and evaluating strength."
- Regulator/Customer Responses
  - "Via repetitive testing within a process window."
- Other Category Responses
  - "Surface preparation tests and manufacturing control are the keys to having good adhesive bonded joints as well as the capability of the adhesive."
  - "Generally use different types of preps such as grits or dwell time."
  - "Wedge tests as stated above. Lap-shear, strain endurance tests and fatigue tests are inadequate for this purpose."
  - "Include the effects of critical environment including temperature and moisture--including Tee Peel Testing."
  - "Surface preparation needs to be taken into account as this can have a great influence on the quality of the adhesive bond."

Question 14: The majority of the respondents agreed that the bonding process does include durability assessments to ensure adequate adhesion. The responses were broken down as shown in table C-4.

TABLE C-4. DURABILITY ASSESSMENTS ENSURE ADEQUATE ADHESION

Response	Percent
Strongly agree	42
Agree	33
Neither agreed nor disagree	9
Disagree	9
Strongly disagree	4

- Material and Process Control Responses
  - Of the 19 responses, 47 percent strongly agreed, 26 percent agreed, 15 percent disagreed, 5 percent strongly disagreed, and 5 percent neither agreed nor disagreed.
- Design Responses
  - One respondent of three replied, stating he strongly agreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 12 responses, 30 percent strongly agreed, 25 percent agreed, 12 percent neither agreed nor disagreed, 8 percent disagreed, and 8 percent strongly disagreed.
- Regulator/Customer Responses
  - Only one of the three respondents replied, stating they strongly agreed.

The following were the responses given by the respondents who either agreed or strongly agreed.

- Material and Process Control Responses
  - "Coupon level and full scale durability and fatigue testing with known manufacturing defects."
  - "Destructive test of coupons, coupons cut from parts, and full size parts."

- “Environmental exposure (salt, acidic salt) lap shear, static and cyclic stress during environmental conditioning.”
- “Typically, lap shear under exposure conditions, sustained stress lap shears, high and slow cycle fatigue (with exposure), beach exposure, DCBs, etc.”
- “Wedge crack testing and destructive testing.”
- “Thick adherend wedge test, wedge test, single lap shear, fatigue using symmetrical skin doublers, double overlap fatigue samples.”
- “Wedge tests with heat and humidity exposure.”
- “Hot-wet wedge crack extension; salt spray; beach exposure and cyclical endurance.”
- “Mesa uses wedge crack for screening and cyclic stress durability for final. Wet and cold peel increasingly used for screening and development.”
- “Sustained stress, cyclic stress, wedge crack, lap shear after wet exposure.”
- “Hot/wet testing, thermal aging.”
- “Lap shear fatigue and cyclic creep tests.”

- Design Responses
  - “Wedge Crack Tests.”
- Analysis Responses
  - “Fatigue crack growth testing under the environment investigating transition from cohesive to interfacial failure.”
  - “For metal bond, GIC, wedge crack, sustained stress, creep, fatigue (high and slow cycle). For secondary structure composites, no durability testing is done. For primary structure composites, DCB, fuel soak, sustained stress, fatigue, creep, prebond humidity.”
  - “Static and flaw growth tests of adherend.”
  - “Cyclic load applications.”
  - “Long term environmental test with both cycle & steady state load.”
  - “Major focus of research is on the durability of bonded joints. A range of mechanical and physical tests are used to characterize the environmental degradation of joints when subjected to hot/wet conditions.”

- “Peel tests considering mode of failure are included in qualification, as well as in process change and process stability testing.”

- Regulator/Customer Responses
  - “Shear and peel testing.”

- Other Category Responses
  - “As already stated, the wedge test is the most reliable test for bond durability.”
  - “In some cases element testing and fatigue testing are used to evaluate structural joints.”
  - “Regular inspection for signs of delamination.”
  - “The environmental testing at both lab and flight environment are truly need for full qualification of bonded structure.”

Question 15: When asked what effects of environment were included in the adhesive and bonding process qualification test plan, the respondents indicated the following. Of the 39 responses, 100 percent of the respondents indicated that moisture and temperature were included in the adhesive and bonding process qualification test plan.

- Material and Process Control Responses
  - Of the 18 responses, 100 percent of the responses indicated that moisture and temperature were included in the adhesive and bonding process qualification test plan.

  The following are the responses from the category Other.

  - “Salt (Materials and Process Control)”
  - “May include SO2 or Acid Assisted Salt Spray”
  - “Beach Exposure (Materials and Process Control)”
  - “Outdoor Exposure”
  - “Aircraft Fluid Exposure”

- Design Responses
  - Only one respondent of three replied, stating moisture and temperature.

- Manufacturing Response
  - The respondent did not reply to this question.

- Analysis Responses

  – Of the 11 responses, 100 percent of the respondents indicated that moisture and temperature were included in the adhesive and bonding process qualification test plan.

  The following were the responses from the category Other.

  – “Fatigue”
  – “Adhesive Thickness”
  – “Fluid Soaks”
  – “Fuel”
  – “Prebond Humidity”
  – “Storage max time”
  – “Aircraft Fluids”

- Regulator/Customer Responses

  – Only one of the three respondents replied, stating said moisture and temperature were included in the adhesive and bonding process qualification test plan.

- Other Category Responses

  – “Fuel”
  – “Hydraulic fluid”
  – “Fluids”
  – “Chemical”
  – “Salt spray”
  – “Salt”
  – “Salt fog”

When asked what effects of environment should be included in the adhesive and bonding process qualification test plan, the respondents indicated the following. Of the 35 responses, 100 percent of the respondents stated moisture and temperatures should be included in the adhesive and bonding process qualification test plan.

- Material and Process Control Responses

  – “Salt Spray”
  – “May include SO2 or Acid Assisted Salt Spray”
  – “Beach Exposure (Materials and Process Control)”
  – “Outdoor Exposure”
  – “Aircraft Fluid Exposure”

- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 12 responses, 91 percent stated both moisture and temperature should be included in the adhesive and bonding process qualification test plan.

  The following were the responses from the category Other.

  - “Adhesive thickness”
  - “Overlap length”
  - “Aircraft Fluids”
  - “Airborne contaminant and particulates”
  - “UV radiation”
  - “Fluids Attack (Oil, Fuel, etc...)”
  - “Fuel/hydraulic fluid exposure”
- Regulator/Customer Responses
  - Of the three respondents, only one replied, indicating moisture and temperature should be included in the adhesive and bonding process qualification test plan.
- Other Category Responses
  - “Cycling effects of deleterious fluids (depends upon application)”
  - “Fluids”
  - “Fuel”
  - “Chemical”
  - “Fatigue”
  - “Aircraft fluids”
  - “Age”
  - “Salt fog”
  - “Salt”

Question 16: When asked whether qualification tests can be traced back to ATSM, company-specific, or Other, the respondents answered as shown in table C-5.

TABLE C-5. TRACABILITY OF QUALIFICATION TESTS

Response	Percent
Company-specific	42
Both	40
ASTM	16
Other	7

- Material and Process Control Responses
  - Of the 19 responses, 84 percent said company-specific, 63 percent stated ASTM, and 30 percent stated both.
- Design Responses
  - One of three the respondents replied, stating company-specific.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Seventy-five percent stated company-specific.
- Regulator/Customer Responses
  - Of the three responses, one indicated both ASTM and company-specific and one stated ASTM.
- Other Category Responses
  - "SACMA"
  - "OEM"
  - "MMM-A-132"
  - "Mil-25463"

Question 17: The following are the respondents' comments on adhesive and bonding process qualification.

- Material and Process Control Responses
  - "For internal qualification of new processes, we develop the process and associated structural information, and then certify a site to perform the process. The certification is typically done with the nominal processing conditions only, while the development evaluates all of the variables of interest."

- "When possible, multiple surface preparations and metals should be included to understand variability of the bonding system."

- "Representative substrate thicknesses should be used to evaluate affect of combined peel and shear loads. For some adhesives, the adhesive is stronger than the base composite substrate epoxy, therefore, substrate failures are often more common then cohesive failures for relatively thin substrates."

- "Successful results - long field history - achieved by including all environmental affects at the coupon level, but not at the full scale structure level for metal bonded structure; however, full environmental exposure for coupon level and full scale structure for composites."

- "Typically the bonding process is very reliant on operator skills and it is essential that adequate training, supervision and quality control processes are in place to insure success. **DSTO** repairs have always been performed by technicians and engineering staff with substantial practical experience, which is crucial for success."

- "Inherently testing a surface preparation, bond primer, adhesive bond system, we have had adhesives fail qualification because the vendor chose a poor bond primer. Structural (not paste usually) adhesive and bond primer qualification scope larger than composite qualification if done thoroughly."

- "Bonding process qualification should include surface preparation variables and periodic threshold contaminant count on the surface prepared in production."

- "Full bonding process qualification may require element and/or full scale test articles specific to a given design configuration/loading scenario that go far beyond what is required to qualify the adhesive to a material specification. The need for tests at multiple levels of the building block approach depends upon the classification of the bonded structure (primary, secondary etc.). Adhesives that have long been "qualified" to an existing material specification are often tested in higher level application specific bonded joint configurations for qualification of new designs."

- Manufacturing Response

  - The respondent did not reply to this question.

- Design Responses

  - No respondents replied to this question.

- Analysis Responses

  - "Most companies want to use the data generated from these tests as 'allowables' for analysis of bonded joints. It should be noted that material/process qualification is separate from an allowables program. However, the user cannot understand the sensitivity of adhesives to bondline thickness and overlap length without additional testing and should be encouraged to do these types of tests."

  - "We have a very rigorous approach to adhesive and bonding process qualification on metal bond partially derived from bad experience. On composites the secondary structure bonding is widespread and varies in approach/rigor. On primary structure composites the approach is rigorous and becoming more so."

  - "Many of these questions are difficult to answer because we treat allowables testing separate from qualification. The allowables testing looks closer at fatigue, defects, environment, and point design testing of the actual structure. This typical does not require multiple batches and uses nominal material. Also some adhesives are treated differently than others depending on application."

  - "For bonded composite structure mechanicals for co-cure should be treated separately from secondary bonding. (Resin mingling in co-cure process can significantly affect adhesive strength/toughness performance.) Core material is significant in composite sandwich structure, core material, cell shape, and cell size should be considered. It should evaluate effect on bond strength of cure contact force variation (vacuum bag versus autoclave may simplify field or OEM repair). Allowed cure cycle variation extremes should be evaluated. As well as minimum cure temperature for full strength bond, bond-line thickness effects, lap length and effects of potential adherend."

- Regulator/Customer Responses

  - "Material qualification should address process control at supplier and establish certifications to be included with the incoming materials, combined with testing upon receiving inspection for mixing and cure characteristics. Process qualification should include training requirements for technicians, environmental controls, bond prep inspections, and witness panel testing for each processing batch."

- Other Category Responses

  - "Adhesive and process qualification is company specific. Test methods identified within the specification or qualification test plan are per ASTM or other industry standards. Requirements vary depending on materials and processes and how they are used."

  - "Air force research labs do qualification of bonding processes."

– "Control of the surface preparation, the adhesive application, the bonding set up tooling, the bonding cure cycle and quality control of these preparation aspects along with the post processing quality control inspections procedures are required to assure a good bond has been made."

– "We seek to understand the technology of bonded structures to ensure that present and future products are suitable for their intended use."

– "For repair there are two aspects that must be qualified and controlled: surface preparation and adhesive cure under field conditions. We have demonstrated that where surface preparation has been validated against stringent wedge test criteria, bond failures are virtually eliminated. The aspect of adhesive cure is managed by validation of the cure cycle temperature's tolerable limits by differential scanning calorimetry and then use of a sophisticated hot bonding unit that is capable of providing assurance that the adhesive in the repair has seen a cure cycle that fits within the cure envelope, while at the same time the structure is not overheated."

C.2 MATERIAL AND PROCESS CONTROL SUBSECTION: MATERIAL CONTROL.

Question 1: When asked about the contents of specifications used, the respondents replied as shown in table C-6.

TABLE C-6. CONTENTS OF SPECIFICATIONS USED FOR ADHESIVE MATERIAL PROCUREMENT AND CONTROL

Response	Percent
Mechanical	96
Physical	92
Resin advancement determination	34
Multiple adherends	32
Multiple overlaps	11

- Material and Process Control Responses

  – One hundred percent of the respondents stated mechanical, 95 percent stated physical, 36 percent stated multiple adherends, 31 percent stated resin advancement determination, and 21 percent stated multiple overlaps. The response from the category Other was "chemical."

- Design Responses

  – One hundred percent of the respondents stated mechanical and physical, 66 percent stated multiple adherends, and 33 percent said resin advancement determination. The response from the category Other was "Packaging."

- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 14 responses, 100 percent stated mechanical, 92 percent said physical, 28 percent said resin advancement determination, and 7 percent said multiple adherends. The response from the category Other was “mixing instruction (if required).”
- Regulator/Customer Responses
  - Only two of the three respondents replied. One hundred percent said physical and resin advancement determination. In addition, one of the two respondents chose multiple adherends and one stated mechanical properties.
- Other Category Responses
  - “Peel tests at R>T> & -100 degrees F RT with moisture margins.”
  - “Controls of the material starts with the materials specification and the test qualification of all the elements of application, manufacturing and quantity control. Each element must have its aspects not only defined but its qualification process well defined and proven.”

The respondents identified the major areas covered in their specifications, if they were not part of the original organization that created these documents, and described any special training received on material procurement and control as follows.

- Material and Process Control Responses
  - “We handle several MIL-A specifications for adhesives, as well as deal with approval of OEM specifications. Typically, material certifications are performed with simple mechanical testing and then physical property testing.”
  - “The supplier provides material control. We can control only shelf life.”
  - “Use supplier standard testing for supplier testing requirements on batches. These are normally standard requirements per Boeing or Airbus specs that the adhesive manufacturer has adopted as ‘standard.’ Control of physical, chemical and mechanical properties are included in the specifications. Control of manufacturing of material is contained in the specifications. Control of material handling, shelf and out life, shipping and storage is included in the specifications.”

- “Shelf life; work life; surface preparation; primer application; adhesive cure application.”

- “Material scope and classification, applicable documents, requirements, quality assurance provisions, qualification, supplier quality conformance inspection, purchaser quality conformance inspection, test methods, preparation for delivery, callout information, certificate of conformity, physical properties, mechanical properties, verification matrix, qualified products list and material update and storage requirements.”

- “No special training usually, just individual experience.”

- “Mechanical: RT FRP, Lap RT & 220 dry (correlated with 180°F/wet); physical/chemical: aerial weight, flow, tack, cure, rheology; packaging/storage, shelf life & extension.”

- “Minimum shear and peel for adhesives and primer system and details of surface preparations.”

• Design Responses

  - “Receiving Inspection - checks for packaging, condition during shipping, remaining shelf-life and out-time.”

  - “Per manufacturer’s data sheets.”

• Manufacturing Response

  - The respondent did not reply to this question.

• Analysis Responses

  - “Material/process requirements (includes strength, physical/chemical, etc. tests); quality control requirements (shelf life, out time, receiving inspection, supplier testing, qualification testing, and re-qualification testing); shipping requirements (packaging, environmental control).”

  - “Adhesive Physicals and Adhesive Mechanicals”

  - “Product qualification, materials, working characteristics, cures requirements, material properties, material identification, packaging instructions, storage, mixing requirements, test methods, supplier and purchaser quality control requirements and recertification requirements.”

• Regulator/Customer Responses

  - No respondents replied to this question.

- Other Category Responses

  - "Composite precursor materials are tested to meet specifications that are set by my company in conjunction with our customers. The purpose of these tests is to ensure consistent and predictable performance of bonded structures made with these materials. We use the term 'release specification' because products must meet these requirements before they can be released for sale."

  - "Material procurement and material control is defined within the material specifications. Only materials on approved source lists of materials specifications may be procured. Strength, Shelf life, shop life and pot life are determined by material specification requirements."

  - "Mechanical testing and flow testing is performed on received adhesives, temperature recording of material during transit is examined to insure life of material."

  - "Purchasing should pay attention to shelf-life. People who handled the material receive dedicated training on procedures."

  - "Use adhesives that perform well with the surface preparations that are recommended and that can handle the mechanical requirements of the design."

  - "We purchase specific adhesives that have been demonstrated to meet our repair requirements and these may not necessarily be those used by the OEM for manufacture. We have a formal procurement standard that defines materials identification, purchase, transport, handling, storage and re-qualification if life-expired."

Question 2: Eighty-two percent of the respondents said material acceptance tests are done through the supplier and 67 percent said they were conducted through the manufacturer or repair facility. Five percent indicated the category Other.

- Material and Process Control Responses

  - Seventy-six percent said manufacturer and 71 percent said supplier.

- Design Responses

  - One hundred percent said supplier and 33 percent stated manufacturer or repair facility.

- Manufacturing Response

  - The respondent did not reply to this question.

- Analysis Responses
  - Ninety-two percent said supplier and 61 percent said manufacturer or repair facility.
- Regulator/Customer Responses
  - Two of the three respondents replied. Both chose supplier and manufacturer or repair facility.
- Other Category Responses
  - "OEM" (Materials and Process Control)
  - "Chemical" (Materials and Process Control)
  - "Supplier"
  - "If supplier details are inadequate or if transport or storage requirements are violated, then we will use a third party to test against acceptance values defined by our organization."

Question 3: When asked what tests were used for acceptance testing, the respondents replied as shown in table C-7.

TABLE C-7. TESTS USED FOR ACCEPTANCE TESTING

Test	Percent
Mechanical	93
Physical	80
Chemical	34
Other	4

- Material and Process Control Responses
  - One hundred percent of the respondents stated mechanical, 88 percent stated physical, and 33 stated chemical.
- Design Responses
  - Sixty-six percent said mechanical, 33 percent said chemical, and 33 said physical.
- Manufacturing Response
  - The respondent did not reply to this question.

- Analysis Responses
  - One hundred percent of the respondents said mechanical, 84 percent said physical, and 46 percent said chemical.
- Regulator/Customer Responses
  - Two of the three respondents replied. Both chose mechanical, while one additionally chose physical and the other chose chemical.
- Other Category Responses
  - “Acceptance of the material is subject to test certificates being provided by the original OEM.”

The respondents identified the following specific mechanical tests.

- Material and Process Control Responses
  - “Lap shear” (13)
  - “WALS” (wide area lap shear)
  - “Flatwise Tensile” (2)
- Design Responses
  - “Lap Shear” (1)
  - “Metal to metal peel”
  - “Interlaminar Shear”
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - “Compressive”
  - “T-Peel for adhesives (all other tests accomplished by suppliers)”
  - “Impact”
  - “Peel”
  - “Lap shear”
  - “Aluminum Lap shear”
  - “Metal to Metal peel”
  - “Fatigue”
  - “Metal to Metal Climbing”
  - “Metal to Metal Climbing Drum Peel”

- Regulator/Customer Responses
  - "Lap shear" (30)
  - "Wedge test"
- Other Category Responses
  - "Flatwise Tensile" (3)
  - "Lap shear" (30)
  - "Required for qualification or acceptance"
  - "Thermal testing (DSC) for some thermoset and two part adhesives"
  - "Aluminum"
  - "By material OEM"
  - "Compressive strength"
  - "Depends on the adhesive: peel"
  - "Double and single"
  - "Tests are typically based on ASTM fiber and paper tests."
  - "Flexural, tension, compression"
  - "Interlaminar shear"
  - "Shear"
  - "Compression"
  - "RT, sub-ambient & elevated temp on two-part adhesives used for structural bond."
  - "Core peel"
  - "Flatwise tensile at ambient for thermoset film adhesives."
  - "Climbing drum peel" (2)
  - "Honeycomb climbing drum" (2)
  - "Honeycomb peel"

- “Flow”
- “Flatwise tension”
- “Typically single and double lap tension”
- “Thick adherend”
- “Tack”
- “Gel time”
- “HPLC”
- “Laminate Tests”
- “Flex”
- “SBS”
- “T-peel, considering using wedge tests in future.” (3)
- “Sandwich drum peel as applicable”
- “Wide Area Single”
- “HCDP” (hydrocarbon dew point)
- “Single over”
- “Single-lap bonding test”
- “Wedge test” (1)

The respondents used the following type of specimen, size of specimen, type of adherend, amount of overlap thickness, adhesive thickness, etc.

- Material and Process Control Responses
  - “2024 T3 FPL etched .5 inch overlap.”
  - “Mostly ASTM D1002, but vendor designed specimens are sometimes used.”
  - “Single-lap, total length 200mm, width 20mm, overlap region 20mm, overlap thickness 1.6mm, adhesive thickness 0.15mm, using composite adherend.”
  - “Standard ASTM methods, adherend is 2024-T3 clad or bare aluminum.”

- “Modified double lap shear, adherend glass pre-preg (25 + plies), overlap thickness 0.75 “adhesive thickness 0.060.”
- “ASTM D1002 with Al-2024T3 clad, 1.6mm thick, overlap of 12.7mm, single layer adhesive controlled through carrier (0.1mm thick).”
- “Lap: standard 1” wide, 0.5” overlap, 0.063” 2024-T3 Al”
- “ASTM WALS”
- “Standard flexural test coupon (ASTM D790). Tension-straight sided 10″ x 0.5″ (occasional need for dogbone specimens). Compression-straight sided w/ tabs-110mm x 10 mm.”
- “Wide area lap shear using PAA aluminum and bond primer.”
- “Composite adherend, .50 inch overlap.”
- “In accordance with ASTMD1002.”
- “3.0 x 75 x .025 2024T3 aluminum. Cleaned anodized and primed adhesive film 004/006.”

• Design Responses

- “BMS specs”

• Manufacturing Response

- The respondent did not reply to this question.

• Analysis Responses

- “ASTM D 1002, no thickness control, aluminum adherend.”
- “Lap Shear: 1/2″ overlap, single, double and wide area. MM Peel: Climbing Drum Peel, FWT: 2″ x 2″ specimens, HC Peel: Climbing Drum Peel”
- “ASTM standards”
- “Lap splice, peel”
- “Varies depending on research programmer.”

• Regulator/Customer Responses

- No respondents replied to this question.

- Other Category Responses

  - "1″ wide 0.5″ overlap aluminum adherends. Adhesive thickness varies with material."

  - "ASTM D3165 with carbon/epoxy substrate (0.1″ thick), 1″ overlap, 0.030″ adhesive thickness"

  - "ASTM D695"

  - "ASTM T-Peel"

  - "By material OEM"

  - "ASTM D1781"

  - "Lap shear - single shear tension per MMM-A-132 / 6″ long x 1″ wide x 0.5″ overlap/ 2024 Aluminum adherends; Metal-to-Metal Peel - 12″ long x 1″ wide/0.025″ thick and 0.063 inch thick 2024 aluminum adherends; Sandwich Drum Peel per MIL-A-25463 - 3″ wide x 12″ long x 0.5″ typical honeycomb core thickness."

  - "Lap shear, T-Peel, aluminum as per ASTM standards, wedge test 0.125 aluminum"

  - "Tests same as MMM-A-132 and MIL-25463"

The respondents identified the following physical tests.

- Material and Process Control Responses

  - "Viscosity" (2)
  - "Volatiles" (2)
  - "Arial weight" (3)
  - "Shear and peel of aluminum to aluminum coupons"
  - "Shore hardness appearance"
  - "Resin content T_g max exothermal volatiles"
  - "Sag percent expansion"
  - "Gel time volatiles tack"
  - "DSC, TMA"

- Design Responses

  - The respondents did not reply to this question.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – "Adhesives: film, weight, volatiles, viscosity."
  – "Gel time T_g"
  – "Pot life, hardness"
  – "Fluid resistance"
  – "Appearance color specific gravity viscosity slump gel time T_g"
  – "Void content failure surface analysis"

- Regulator/Customer Responses

  – "Gel time density viscosity"

- Other Category Responses

  – "Primers: solids, weight per gallon, inhibitor viscosity."

  – "Tack rheology"

  – "Tack aerial weight"

  – "By material OEM"

  – "Check tack of adhesive"

  – "Film weight per sq ft is tested and recorded for film adhesives. Pot life is tested for 2 part mix adhesives."

  – "Test involves determining change in area from a 2″ disk of adhesive after cure correlated with chemical testing to determine when is unsatisfactory. DSC will be performed to determine a cure envelope to enable lower temperature cure for on-aircraft repairs."

  – "Nonvolatile weight per gallon"

  – "Quantitative inhibitor analysis"

  – "Visual"

  – "T_g By DMA"

  – "Volatile content by weight loss by percentage expansion."

- Design Responses
  - No respondents replied to this question.

The respondents listed the following chemical tests.

- Material and Process Control Responses
  - "DSC for enthalpy"
  - "Gel"
  - "Rheology"
  - "Cure"
  - "Volatiles, HPLC" (high performance liquid chromatography)
  - "Durometer hardness"
  - "FTIR"
  - "Performed at adhesive vendor for adhesives and primers"
- Design Responses
  - The respondents did not reply to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - "DSC" (2)
  - "DMA"
  - "XPS"
  - "Epoxide and amine equivalent weight"
  - "Solids testing for paints"
- Regulator/Customer Responses
  - "DSC"
  - "DMA"
- Other Category Responses
  - "OEM"
  - "DMA"
  - "FTIR if required to determine degree of cross linking of resin."
- Design Responses
  - No respondents replied to this question.

Question 4: The participants responded as follows to the statement "The limits from adhesive qualification data are used for acceptance requirements defined in the specification."

Of the 46 responses, 34 percent agreed, and 26 percent strongly agreed. Thirteen percent neither agreed nor disagreed, while 17 percent disagreed, and 8 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 20 responses, 35 percent strongly agreed and 30 percent agreed. Ten percent neither agreed nor disagreed, while 20 percent disagreed and 5 percent strongly disagreed.
- Design Responses
  - Of the two responses, one strongly agreed and one strongly disagreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 11 responses, 36 percent agreed, 18 percent strongly agreed, 27 percent neither agreed nor disagreed, 9 percent disagreed, and 9 percent strongly disagreed.
- Regulator/Customer Responses
  - Two of three respondents replied. One disagreed and one agreed.

Question 5: Eighty-four percent of the respondents said their acceptance tests are company-specific, while 68 percent said ASTM and 6 percent selected the category Other.

- Material and Process Control Responses
  - Ninety-four percent said their acceptance tests are company-specific, while 61 percent said ASTM. Fifty percent of the respondents chose both ASTM and company-specific. The category Other response was "Suppliers of Advanced Composite Materials Association" (SACMA).
- Design Responses
  - One hundred percent of the respondents stated ASTM and company-specific. The category Other response was "OEM."

- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Eighty-three percent said ASTM and 66 percent said company-specific.
- Regulator/Customer Responses
  - Two of the three respondents replied. Both said ASTM.
- Other Category Responses
  - "MMM-A-132"
  - "MIL-25463"

Question 6: The participants responded as follows to the statement "The adherend type used for acceptance tests is the same being used in production."

Of the 43 responses, 27 percent agreed that their acceptance test was the same adherend type that was being used in production. Sixteen percent strongly disagreed, 21 percent disagreed, and 21 percent neither agreed nor disagreed. The remaining 13 percent strongly agreed.

- Material and Process Control Responses
  - Of the 21 responses, 22 percent agreed, 19 percent disagreed, 22 percent neither agreed nor disagreed, 19 percent strongly agreed, and 14 percent strongly disagreed.
- Design Responses
  - Of the four responses, one strongly agreed, one agreed, and two strongly disagreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 11 responses, 36 percent disagreed, 18 percent strongly disagreed, 27 percent agreed, and 18 percent neither agreed nor disagreed.

- Regulator/Customer Responses
  - Two of three respondents replied. One neither agreed nor disagreed and one agreed.

Forty-four percent of the 45 respondents agreed that the adhesive thickness was the same as what is being used in production. Thirteen percent strongly disagreed and 8 percent disagreed. Seventeen percent neither agreed nor disagreed and 20 percent strongly agreed.

- Material and Process Control Responses
  - Of the 19 responses, 42 percent agreed, 21 percent strongly agreed, 21 percent neither agreed nor disagreed, 5 percent disagreed, and 5 percent strongly disagreed.
- Design Responses
  - Of the two responses, one strongly agreed and one strongly disagreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 11 responses, 54 percent agreed, 18 percent disagreed, 18 percent strongly disagreed, and 9 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents replied. One strongly agreed and one agreed.

Question 7: Of the 48 responses, 31 percent disagreed that environmental effects are considered in acceptance testing and 4 percent strongly disagreed. Thirty-three percent of the respondents agreed and 14 percent strongly agreed. The remaining 18 percent neither agreed nor disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 47 percent disagreed and 15 percent strongly disagreed. Fifteen percent agreed, 10 percent strongly agreed, and 10 percent neither agreed nor disagreed.
- Design Responses
  - Of the two responses, both neither agreed nor disagreed.

- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 12 responses, 58 percent agreed, 16 percent disagreed, 16 percent neither agreed nor disagreed, and 8 percent strongly agreed.
- Regulator/Customer Responses
  - Two of the three respondents replied. One disagreed and one neither agreed nor disagreed.

Question 8: The majority of the responses indicated that freezer temperature monitoring and out-time monitoring were the main procedures used in controlling adhesive storage and handling from purchase until use, see table C-8.

TABLE C-8. CONTROLLING ADHESIVE STORAGE AND HANDLING

Response	Percent
Freezer temperature monitoring	93
Out-time monitoring (handling and storage)	87
Assembly temperature monitoring	62
First-in, first-out	24
Automated sanding	15

- Material and Process Control Responses
  - One hundred percent said out-time monitoring, 90 percent said freezer temperature monitoring, 57 percent said assembly temperature monitoring, and 47 percent said first-in, first-out.
- Design Responses
  - Of the three responses, 100 percent stated freezer temperature monitoring and out-time monitoring and 66 percent said assembly temperature monitoring and first-in, first-out. The category Other response was “shelf life.”
- Manufacturing Response
  - The respondent did not reply to this question.

Of the 11 responses, 81 percent said freezer temperature monitoring, 81 percent said out-time monitoring, 54 percent said assembly temperature monitoring, and 45 percent said first-in, first-out.

The following were the responses from the category Other.

- "Shelf life"
- "Assembly humidity monitoring"
- "Assembly cleanliness"

- Regulator/Customer Responses

  - Two of the three respondents replied. One hundred percent said freezer temperature monitoring, first-in, first-out and out-time monitoring. In addition, one of the respondents also said assembly temperature monitoring.

Question 9: Of the 46 responses, 28 percent disagreed that peel ply materials are used for surface preparation and are subjected to the same controls as adhesives in questions 1 through 8 of this section of the survey. Twenty-eight percent agreed and 28 percent neither agreed nor disagreed. The remaining 16 percent strongly disagreed.

- Material and Process Control Responses

  - Of the 21 responses, 19 percent agreed, 9 percent strongly agreed, 38 percent disagreed, 9 percent strongly disagreed, and 23 percent neither agreed nor disagreed.

- Design Responses

  - Of the three respondents, 66 percent agreed and 33 percent neither agreed nor disagreed.

- Manufacturing Response

  - The respondent did not reply to this question.

- Analysis Responses

  - Of the 11 responses, 54 percent agreed, 27 percent neither agreed nor disagreed, 9 percent strongly disagreed, and 1 percent disagreed.

- Regulator/Customer Responses

  - Two of the three respondents replied. One disagreed and one agreed.

The respondents identified the following critical controls for peel ply.

- Material and Process Control Responses

  - "Material weave and surfacing consistency, material storage (esp. WRT (with respect to) humidity)."

- “Cleanliness and bond ability (for bondable peel ply).”
- “Silicone content”
- “Thorough abrasion, cleaning, and water break check of bonding area immediately after removal of the peel ply and immediately prior to application of adhesive.”
- “They are kept clean.”
- “Source of supply and compatibility testing after grit blasting. If not grit blasted, limited to core bond.”
- “Resin content & FAW.”
- “Surface morphology (SEM analysis), Mechanical testing such as FWT and lap shear strength.”
- “Peel ply does not require critical controls, the cleaning process following removal for bonding does.”
- “Storage temperature and humidity.”
- “We do not use peel ply materials.”
- “Fabric type and finish per PCD” (Production Control Document)

• Design Responses
  - “Contamination control. As a rule, a solvent wipe is performed after peel ply is removed.”
  - “Qualified Material, CCA use.”

• Manufacturing Response
  - The respondent did not reply to this question.

• Analysis Responses
  - “These are the same as for a pre-preg.”
  - “DCBs on every roll of every batch using design adherends and adhesive; Single sources are preferable.”
  - “Limiting the possibility of contamination.”
  - “Depends on peel ply type.”

- “For primary structure there is a specification with a QPL. It requires a PCD and DCB testing. For secondary structure, peel plies are listed on the process specification but not controlled by QPL, QC testing, or PCD.”

- “The effects of freezer out-time, and sensitivity to moisture, should be understood for all lamina cured in a laminate, adhesive, pre-preg, or peel ply.”

• Regulator/Customer Responses

  - “Wedge or other form of peel testing.”
  - “Composition, texture, cleanliness”

• Other Category Responses

  - “No change from original qualification.”

  - “Must be free of silicones or other release agents that transfer onto bonding surfaces. Must not be the only treatment prior to bonding.”

  - “Stored in a clean environment.”

Question 10: The respondents gave the following comments on material control.

• Material and Process Control Responses

  - “As an end user with materials in the fleet, we have a need to supply materials in a quick and efficient manner to locations that may not have desirable storage. This can present a real problem for the use of the materials.”

  - “Handle it like film adhesive or pre-preg, but cold storage is not required.”

  - “Maintenance of correct storage conditions for adhesive and pre-preg materials is crucial as is correct recording of age and usage.”

  - “Test approaches are somewhat different for adhesive bond primer qualification and touch-up adhesive bond primer.”

  - “In general, adhesive systems are much more sensitive to material storage life and out-time when compared to conventional pre-preg materials. While it is important to develop applicable design data for each bonded joint configuration using representative adherend materials, bondline thickness ranges and joint geometry, I do not believe that it is practical, efficient or necessary to perform receiving inspection (incoming material control) tests using the same configuration as your actual design. The receiving inspection tests should be done using a simple baseline configuration such as aluminum adherends and baseline test geometry (ASTM or standardized internal test specimen/procedure). To require more than that is neither practical nor economically feasible.”

- “Varies with compliance of individuals. Too easy to pencil whip a report - should be more automated data collection.”
- “Most difficult is shipping and handling between manufacturer and end user; stuff that is manufactured goes into a black hole and shows up at your doorstep.”

- Design Responses
  - The respondents did not reply to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - “My philosophy is to fully characterize the materials in qualification. In QC testing it is important to rely upon tests which are not prone to failure due to variables unrelated to the adhesive or primer. In general, the least QC variability comes from PAA + bond primed adherends. Ideally, a combination of SPC, PCD, good analytical tests (such as rheology, DSC, HPLC), latent chemistry and good shipping control can be used to control the material.”
  - “Have found that some film adhesives are quite insensitive to freezer out time accumulation. Probably worth characterizing level of criticality.”
- Regulator/Customer Responses
  - “Should the OEM conduct chemical analysis on an adhesive if it is not done by the supplier or if it is no longer done on a regular basis by the supplier?”
- Other Category Responses
  - “All time and temperature sensitive thermoset film adhesives and pastes including core splice & potting compounds should be controlled by material specifications for materials acceptance testing, shelf and shop life monitoring and recertification when materials are of the specification parameters. All two part mix adhesives that are used for structural bonding should also be monitored for acceptance and recertification testing and storage life per spec requirements.”
  - “Material control is fundamental to bond integrity. A system must be in place to ensure materials are in prime condition and free of contamination. For vacuum bagging, moisture control is essential through limiting relative humidity. I suggest that we should also have addressed pre-preg materials and dry fiber products.”

- “The industry generally does a poor job storing and handling adhesives and ancillary materials used in bonding. The biggest issues tend to concern moisture ingress into adhesives or hardeners or into the substrate surfaces themselves.”

C.3 MATERIAL AND PROCESS CONTROL SUBSECTION: PROCESS CONTROL.

Question 1: When asked what controls were used in processing, the respondents identified the following: 70 percent of the respondents stated in-process monitoring, 62 percent said witness panel, and 25 percent said statistical process control. Four percent chose the category Other.

- Material and Process Control Responses

  - Eighty-five percent said witness panel, 80 percent stated in-process monitoring, and 19 percent said statistical process control.

  The only response from the category Other was as follows:

  - “Witness panels have not previously been used but we believe there is clear advantage in using them.”

- Design Responses

  - Of the two responses, 33 percent of the respondents chose both witness panel and statistical process control and 33 percent stated in-process monitoring.

- Manufacturing Response

  - The respondent did not reply to this question.

- Analysis Responses

  - Of the 10 responses, 90 percent stated in-process monitoring, 60 percent said witness panel, and 30 percent said statistical process control.

  The following were the responses from the category Other.

  - “Metal bond uses Verifilm”
  - “Sample cure evaluation”
  - “Surface cleanliness”
  - “Witness panel used in bond priming to certify operators”

- Regulator/Customer Responses

  - Two of the three respondents replied. One hundred percent said witness panel and statistical process control.

- Other Category Responses

  – "NDI"

  – "Surface preparation is an up and coming area. This is a real key to a good bonded joint. The surface cleaning is not just the type of cleaning used it is the steps or mechanics of the cleaning process that is the key. Improper cleaning can come from such things as dirty glove on the person cleaning the surface."

  – "The surface preparation spraying needs to be a job for which the applier of the surface preparation is well trained, as well as the post preparation inspection before including the part in the bonding assembly step."

  – "From a repair perspective, we manage our processes by quality management, not quality assurance. Many QC tests are inappropriate for repair scenarios, so it is far better to ensure quality materials, processes and people are used in controlled environments. Then bond integrity will occur."

Question 2: When asked what type of surface preparation their companies used, the majority of responses indicated that 79 percent of the responding companies used hand sanding and 68 percent use media blasting as part of their surface preparation. Fifty-eight percent stated peel ply, 56 percent stated chemical etch, 25 percent chose the category Other, and 16 percent said automated sanding, see figure C-2.

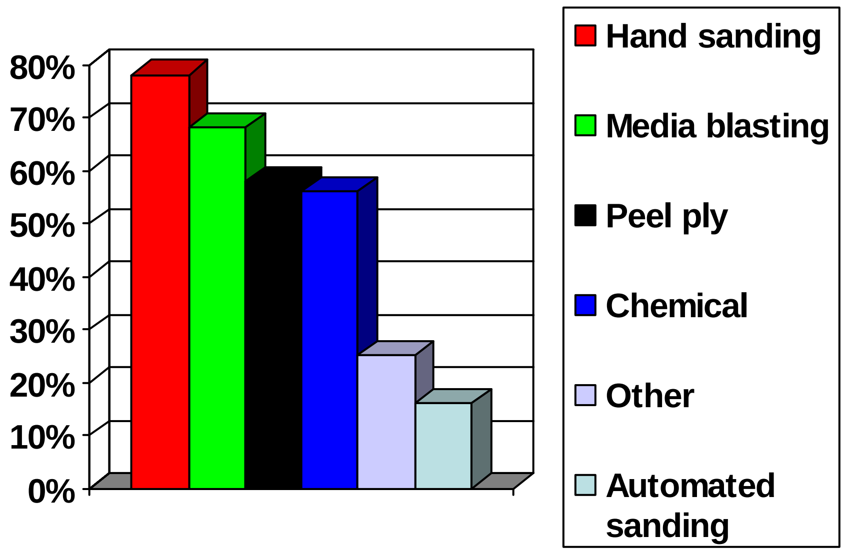

FIGURE C-2. SURFACE PREPARATION

- Material and Process Control Responses

  – Eighty-five percent said hand sanding, 66 percent said media blasting, 62 percent said chemical, 62 percent said peel ply, and 9 percent said automated sanding.

  The following were the responses from the category Other.

  – "Anodizing Sol-Gel Treatments" (2)

  – "Corona/plasma"

  – "Grit blast plus saline"

  – "Grit blasting with 50 micron alumina followed by application of 1% solution of saline coupling agent."

- Design Responses

  – One hundred percent of the respondents stated chemical etch, 66 percent said peel ply, 66 percent said automated sanding, 33 percent said hand sanding, and 33 percent said media blasting.

  Thirty-three percent chose the category Other, stating the following.

  – "Phosphoric Acid Non-tank Anodizing (PANTA)"
  – "SOLGEL"

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Of the 10 responses, 100 percent stated hand sanding, 80 percent said media blasting, 50 percent said peel ply, 50 percent said chemical etch, and 2 percent said automated sanding. The category Other response stated "Chemical etch (Non-structural bond only)."

- Regulator/Customer Responses

  – Two of the three respondents replied. One respondent chose hand sanding, media blasting, chemical etch, and peel ply. Another chose automated sanding and media blasting.

- Other Category Responses

  – "PAA & BR-127 bond primer"

- “PACS (phosphoric acid containment system) for treatment of aluminum in the metal bonding process.”
- “Phosphoric acids anodize and prime for aluminum for structural metal bond is required.”
- “Grit blasting, solvent wipe, and prime for other metals such as steel and titanium.”
- “ScotchBrite abrasives”
- “Solvent degrease, water wipe, dry, aluminum grit blasting, coupling agent, dry then bond.”

Of the 43 responses, 83 percent said surface preparation was monitored and controlled visually. Seventy-two percent said water break-free, 46 percent said witness panel, 25 percent said chemistry, and 11 percent chose the category Other.

- Material and Process Control Responses
  - Of the 21 responses, 85 percent stated water break-free, 66 percent said visual, 62 percent said witness panel, and 38 percent said chemistry.
- Design Responses
  - Of the three responses, 100 percent of the respondents said both visual and water break-free. One respondent also stated chemistry and witness panel. One respondent chose the category Other, stating “polarizing lens (PANTA).”
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 10 responses, 90 percent said visual, 60 percent said water break-free, and 10 percent said chemistry.
- Regulator/Customer Responses
  - Two of the three respondents replied. One hundred percent chose visual and witness panel, with one respondent also choosing water break-free.
- Other Category Responses
  - “Anodize color”

Question 3: Of the 47 responses, 36 percent agreed and 14 percent strongly agreed that mechanical tests are performed for bonding process control purposes. Twenty-three percent neither agreed nor disagreed, while 14 percent disagreed and 10 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 22 responses, 40 percent agreed, 22 strongly agreed, 18 percent neither agreed nor disagreed, 13 percent strongly disagreed, and 4 percent disagreed.
- Design Responses
  - Of the three responses, one respondent agreed, one respondent strongly disagreed, and one strongly agreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 10 responses, 30 percent agreed, 30 percent disagreed, 20 percent neither agreed nor disagreed, 10 percent strongly agreed, and 10 percent strongly disagreed.
- Regulator/Customer Responses
  - Two of the three respondents replied. Both agreed.

The respondents that strongly agreed stated that the following tests were used.

- Material and Process Control Responses
  - "Lap shear" (8)
  - "Flatwise tension" (2)
  - "Peel of witness panels and or panels cut from parts" (2)
  - "Wedge crack for metallic substrates"
  - "Witness panel wedge crack extension"
  - "Crack propagation test"
  - "Tensile shear and peel"
  - "Shear"
  - "T-Peel"
  - "WAL"
  - "Climbing drum peel"
  - "These tests should be done to develop the process and to qualify people"

- Design Responses

  – "Wedge crack"

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – "T_g"
  – "Flatwise tension"
  – "Lap shear" (3)
  – "T-peel tests for metal bonding"
  – "Peel"

- Regulator/Customer Responses

  – "Wedge crack"
  – "ASTM"

Question 4: Of the 48 responses, 39 percent of the respondents agreed that prebond moisture of the substrates is controlled in their process. Eighteen percent strongly agreed, 16 percent neither agreed nor disagreed, while 18 percent strongly disagreed and 6 percent disagreed.

- Material and Process Control Responses

  – Of the 21 responses, 38 percent agreed, 9 percent strongly agreed, 23 percent neither agreed nor disagreed, 23 percent strongly disagreed, and 4 percent disagreed.

- Design Responses

  – Of the three responses, one respondent agreed, one respondent disagreed, and one strongly agreed.

- Manufacturing Response

  – The respondent did not reply to this question.

- Analysis Responses

  – Of the 10 responses, 60 percent agreed, 20 percent strongly disagreed, 10 percent strongly agreed, and 10 percent neither agreed nor disagreed.

- Regulator/Customer Responses
  - Of the four responses, one strongly agreed, one agreed, and one neither agreed nor disagreed.

Question 5: The respondents said that in the case of paste adhesives, mixing variables were controlled during production. Ninety-one percent said weight, 21 percent said test coupon, and 6 percent chose the category Other. No one stated chemical.

- Material and Process Control Responses
  - Of the 21 responses, 90 percent stated weight and 14 percent said test coupon.

  The following responses were from the category Other.

  - "Test coupon" (2)
  - "Sample tested for T_g after cure with part"
  - "Premixed semkits"

- Design Responses
  - Of the three responses, 100 percent stated weight.

- Manufacturing Response
  - The respondent did not reply to this question.

- Analysis Responses
  - Of the 10 responses, 80 percent said weight and 40 percent said test coupon. The response from the category Other stated "Pre-packaged."

- Regulator/Customer Responses
  - Only two of three respondents replied. One hundred percent stated both weight and test coupon.

- Other Category Responses
  - "Pre-weighed packaging"
  - "Static mix tip/fresh materials application"

Question 6: The sequence of processing steps from surface preparation (cleaning and abrasion) through application of primer (if used) and adhesive to bond assembly for cure were identified as follows.

- Material and Process Control Responses

  – "Varies based on class of bond and substrates."

  – "Many different processes used Navy wide."

  – "Solvent degrease, water wipe, water break test, dry, grit blast abrasion to expose a chemically active surface, chemical modification (we use a saline coupling agent) to develop resistance to hydration, drying and then bond. If required a primer is applied after the final drying step."

  – "Composites: Wipe up with MEK; sand; re-wipe with MEK; Aluminum: Chemical strip; chromic acid anodizing, primer within 6 hours."

  – "Clean, deox, surface prep, primer, primer cure, maybe move to location, apply adhesive, bag, cure."

  – "For aluminum substrates: MEK wipe, AlO2 grit blast using N2 gas, N2 gas clean, saline treatment, primer."

  – "Solvent clean part: Abrade (hand sand or grit blast); Solvent clean (if used, water break, dry, clean); Bond within 8 hours."

  – "Check fit, clean, visual inspect, apply adhesive, apply pressure, cure, visual inspect, deflash if required, NDE inspect."

  – "Hand clean as necessary; PAA processing; bond primer application & cure; detail storage."

  – "The procedure involves the following:

    1) Solvent wiping: single wiping of the aluminum surface used methyl ethyl ketone (MEK) soaked lanoline and lint free tissues. A fresh tissue is used after each pass. Single wiping is conducted along the grain direction and at 900 relative to the grain until no observable debris or staining of the tissue can be observed.

    2) ScotchBrite ® abrasion with MEK: following solvent wiping the surface is abraded with ScotchBrite pad soaked in MEK along the grain direction and at 900 relative to the grain until a uniform surface appearance is observed. Single wiping of the aluminum surface then uses MEK soaked lanoline and lint free tissues. A fresh tissue is used after each pass. Wiping is conducted in the direction of the abrasion until no presence of debris or staining of the tissue can be observed.

    3) ScotchBrite ® abrasion with demonized water: following step 2, the surface is abraded with ScotchBrite pad soaked in demonized water along

the grain direction and at 900 relative to the grain until a uniform surface appearance is observed. Single wiping of the aluminum surface then uses demonized water soaked lanoline and lint free tissues. A fresh tissue is used after each pass. Wiping is conducted in the direction of the abrasion until no presence of debris or staining of the tissue can be observed.

4) Water-break testing: The surface is water-break tested by thoroughly wetting the surface prepared in 3) with demonized water and observing that no areas are free of water. The surface is then gradually dried using a hot air gun and moisture should evaporate in a uniform manner without any water-breaks. If water-break areas are present steps 1-3 must be repeated. "Surface preparation-apply adhesive- curing."

5) Drying: The surface is dried in an oven at 1100C for five minutes prior to grit-blasting. Break surface; dry; bond."

6) Grit-blasting: uniform grit-blasting of the surface employs 50 mm aluminum grit and dry nitrogen propellant with a pressure of 450kPa and a working distance of 15 to 20cm.

7) Saline treatment: a 1 percent aqueous solution of g-glycidoxypropyltrimethoxysilane is stirred for 1 hour prior to commencing the surface pre-treatment steps listed above. Distilled water is used to prepare the saline solution. The grit-blasted aluminum surface is "immersed" in the saline solution for 15 minutes by applying the solution regularly to the aluminum surface from clean lanoline and lint free tissues. The surface is then allowed to drain free of excess solution, followed by drying in an 1100C oven for 60 minutes."

– "Degrease surface; Etch or blast surface; Degrease surface; Dry Apply primer; Cure primer; Apply adhesive; Cure adhesive"

– "After all possible forming, machining, and/or drilling options, clean/degrease so have clean panels/details, blast and/or etch, apply/cure adhesion promoters, apply bond primer and cure within hours of prep maintaining cleanliness, wrap in neutral Kraft paper and seal in no-residue bags, unpackaged details in clean room within shelf life, solvent wipe and flash dry, apply touch up bond primer to otherwise acceptable parts w/ nicks/scratches, apply adhesive within time limits, complete/bag assy, begin cure within limits (shelf life), perform approved cure cycle time/temp/pressure/rates, debag, deflash, touch up substrates for corrosion/paint, seal, prime, paint."

– "Surface prep by masking and bead blasting; visual inspection by **Q** personnel; mixing of paste with fillers by weight; application of primer to wet out surface; application of mixed adhesive paste by hand; assembly of part(s) and procure; handling cure and wait for scheduled post cures; post cure; sample cups routed to lab for process tests (T_g)."

- "Metals: clean, abrade, clean, blast, conversion coating, primer, adhesive Composite: peel ply, or clean and blast, or peel ply and blast."
- "We don't use primer on composites."
- "Typical aluminum to aluminum; typical stainless steel to stainless steel; fabricated details parts."
- "Degreasing (if required), PAA. Application of bond primer, adhesive bond (most common). Degreasing (if required), mechanical abrasion, degreasing, silicone primer application, silicone adhesive."
- "Abrasion, solvent wipes, water break, primer, cure if needed, adhesive application."

• Design Responses

- "ALUM SUBSTRATE: Alkaline cleaning, etch, PAA, water-break, primer application, primer bake, (storage possibly), solvent clean, adhesive application, cure. COMPOSITE SUBSTRATES: clean, sand, degrease, water-break test, adhesive application, cure."
- "Final clean using lint free bleached wipes moistened with acetone/MEK, visually inspect wipe to ensure cleanliness, water-break test, dry, primer/adhesive application."
- "Degrease PAA prime, adhesive application, bag and cure."

• Manufacturing Response

- The respondent did not reply to this question.

• Analysis Responses

- "Degrease; Water-break test; Abrade; Couplant (if used); Dry; Primer (if used), Adhesive."
- "The critical parameter is to bond within 4 hrs after surface prep, if no primer is used. If primer is used, the parts may be bagged a stored prior to bonding."
- "For Aluminum: PAA per BAC5555; bond primer within 3 days; MEK wipe after detail storage. For composite: cocure dry peel ply, remove peel ply, bond within 8 hours."
- "For bonding composite parts: General cleaning, grit blast, vacuum, water cleaning, solvent cleaning, final sand, bond; For aluminum parts: Anodize, prime, solvent wipe."

  - "Solvent wipe, light sand."

- Other Category Responses

  - "Keep surface clean and dry prior to surface preparation (in new-part manufacturing), remove peel ply or protective layer from surface, energize surface by abrading, Dry wipe to remove dust and debris, mix & apply adhesive or apply film adhesive, close joint and clamp (mechanical, vacuum bag/autoclave) ASAP, Heat to appropriate cure temperature and monitor /record process. (Pre-cleaning parts with solvents is only required for repairs. No solvents are ever used on freshly energized composite surfaces.)"

  - "Clean bond surfaces (for gross contamination), final surface prep (chemical treatment for most metals, abrasion for most composites), spray or brush application of primer (where required), cure of primer and protection of prepared surface prior to application of adhesive."

  - "Varies depending upon variable(s) to be studied."

  - "Composites: abrade or bead blast; vacuum and solvent wipe; verify no-water."

Question 7: When asked whether they had time constraints for the steps leading up to cure, the respondents' answers were split. Fifty-four percent said surface preparation—adhesive application, 67 percent said surface preparation—primer application, 68 percent said primer application—adhesive application, and 73 percent said adhesive application—adhesive cure.

- Material and Process Control Responses

  - Sixty-three percent said surface preparation—adhesive application, 72 percent said surface preparation—primer application, 60 percent said primer application—adhesive application, and 68 percent said adhesive application—adhesive cure.

- Design Responses

  - Of the three responses, 100 percent stated surface preparation—primer application and 100 percent said adhesive application—adhesive cure. Sixty-six percent said primer application—adhesive application and 33 percent said surface preparation—adhesive application. The response for the category Other stated "PAA to primer application."

- Manufacturing Response

  - The respondent did not reply to this question.

- Analysis Responses

  – Of the nine responses, 88 percent said adhesive application—adhesive cure, 66 percent said primer application—adhesive application, 66 percent said surface preparation—primer application, and 55 percent said surface preparation—adhesive application. The response from the category Other was “Storage time out of bonding humidity limits.”

- Regulator/Customer Responses

  – Of the four respondents, one said surface preparation—adhesive application and adhesive application—adhesive cure. Another said adhesive application—adhesive cure and primer application—adhesive application.

- Other Category Responses

  – “Time constraints should be well defined and the application process and structural assembly designed to meet these time constraints. The characteristics of the bonding material and procedure should be well defined so that if a time constraint is needed it can be well established for each assemble and curing process.”

  – “Open time limits on all amine cured epoxies.”

  – “Our process must be continuous and rapid from start to application of vacuum to bagged part.”

Question 8: The respondents stated that the bonding process cure cycle is controlled. Of the 49 responses, 96 percent said time controlled the bonding process cure cycle. Eighty-seven percent stated temperature and 36 percent chose the category Other.

- Material and Process Control Responses

  – Of the 21 responses, 95 percent said time and 95 percent said temperature.

  The following were the responses from the category Other.

  – “Pressure/vacuum” (7)
  – “Adhesive reaches cure after 7 days at 70°, or adhesive cure may be accelerated.”
  – “Internal bladder pressure”

- Design Responses

  – Of the three responses, 100 percent said both time and temperature. The response from the category Other was “Work Thermocouples.”

- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the ten responses, 100 percent said time and 90 percent said temperature. The response from the category Other was “Tooling pressure.”
- Regulator/Customer Responses
  - Of the four respondents, one replied, choosing time and temperature. The response from the category Other was “Pressure-mechanical clamping.”
- Other Category Responses
  - “Bond process must not only control the time of cure and the cure temperature but the coordination of the time, temperature and the pressure applied to the assembly. The interrelationships between these three are very important to a good bonded assembly. The pressure is just as key as the time and temperature not only in how the pressure is applied but how it sequence matches the other two (time and temperature).”
  - “Parallel Material-state monitoring (Rheology/viscosity)”
  - “Work Thermocouples”
  - “Control is managed by the hottest point on the structure to prevent overheating. A combination of time and temperature as determined by differential scanning calorimetric, is used for acceptance of the bond, based on lowest temperature in the bondline.”
  - “Vent Parameters”
  - “Heat Rise Rate”
  - “Cool Down Rate”

The participants responded as follows to the statement “There are indicators to demonstrate temperature and pressure at the bond line.”

- Material and Process Control Responses
  - Of the 21 responses, 57 percent agreed, 14 percent strongly agreed, 19 percent strongly disagreed, 4 percent disagreed, and 4 percent neither agreed nor disagreed.

- Design Responses
  - Of the three respondents, one strongly disagreed, one strongly agreed, and one agreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 12 responses, 33 percent agreed, 33 percent strongly disagreed, 25 percent neither agreed nor disagreed, 8 percent strongly disagreed, and 8 percent disagreed.
- Regulator/Customer Responses
  - Of the four respondents, one respondent strongly disagreed and one agreed.

Question 9: Of the 51 responses, 50 percent agreed that NDI plays a role in bond process control. Thirty-five percent strongly agreed, while 9 percent neither agreed nor disagreed. Two percent of the respondents disagreed and 2 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 21 responses, 23 percent agreed, 42 percent strongly agreed, while 9 percent neither agreed nor disagreed. Four percent of the respondents disagreed and 4 percent strongly disagreed.
- Design Responses
  - Of the three respondents, two strongly disagreed and one agreed.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - Of the 12 responses, 58 percent agreed, 33 percent strongly agreed, and 8 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents agreed.

Question 10: The following were the respondents' comments on process controls.

- Material and Process Control Responses
  - "We inspect for voids in critical bonds using ultrasonic inspection."
  - "We use different processes for different platforms based on developments at both the OEM and internally."
  - "Period thickness checks required in addition to the above listed process controls."
  - "Pressure is monitored for autoclave cures, but it is not monitored for paste adhesive cure cycles."
  - "Per four, pre-bond (or pre or during cure) moisture effects on your adhesive should be eliminated during qualification or acceptable control limits established. Per 8, there are indicators to demonstrate temp at a bond line if you have performed a thorough heat survey with representative cure details/cure vessel/cure cycle. Pressure is usually indirectly measured by remaining bondline thickness, although pressure sensors can be installed in developmental or FPQ parts for analysis. Per 9, anything you can't find w/ NDI (kissing unbond), you had better figure out how to process control or live with."
  - "Destructive testing of samples which are built into the parts and cut off for testing after bonding is used for critical parts at RHC along with destructive test of parts."
  - Effective process controls in the surface preparation and bonding steps are always difficult to define and maintain. Careful documentation and well defined processes are essential."
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - "NDI is ineffective for kissing bond as a caused by many contaminants. Immersion testing in 160 gallon water tank is useful for detecting "worm hole leaks" in sandwich structure. My company moved away from process control panels due to non-correlation of results and expense."
  - "Mechanical testing of witness coupons is ineffective in a manufacturing setting unless there is a fool-proof way to correlate the coupon and bonded structure manufacturing history and structural performance."

- Regulator/Customer Responses

  – "NDI is a necessary but not a sufficient check of whether the bonding process was successfully achieved."

  – "NDT will only establish presence or absence of adhesive in bond line and degree of porosity. Mix ratio and degree of cure require mechanical/physical/chemical testing."

- Other Category Responses

  – "Mainly use tap-testing."

  – "NDI can only tell if there is a bondline defect. It can not give assurance of bond integrity, especially the condition of the interface. Processes must be managed to produce a reliable product. You can never make a bad bond better by any quality control testing; you can only tell that it is bad. In contrast, if quality is managed into the product it will pass every test possible."

  – "Process controls are extremely important and the level of control depends on the structural importance of the part being bonded."

  – "Some manufacturers use the water-break test as an in-process quality check of the actual substrate's surface preparation/robustness. This practice is self defeating and is ill-advised. The additional time required to then dry the surface reduces the surface free energy to the point that re-abrading would then be required. Solvent wiping can contribute to moisture at the substrate surface prior to bonding. Solvent wiping can also ingress other contaminants into the freshly energized substrate surface. Further investigation into the effects of solvent wiping on composite substrates is necessary. NDI cannot fix an in-process error. It is useful for post-process QA and process assessment only."

C.4 MANUFACTURING AND DESIGN INTEGRATION SUBSECTION: DESIGN AND ANALYSIS.

Question 1: When asked what structural parts, attachments, and splices used bonding, the respondents replied as shown in table C-9.

TABLE C-9. STRUCTURAL PARTS, ATTACHMENTS, AND SPLICES USED FOR MANUFACTURE OR REPAIR

Response	Percent
Skins	85
Doubler	66
Stringers	58
Spars	54
Ribs	54
Frames	54
Machined parts	35
Other	16

- Material and Process Control Responses

  – Of the 18 responses, 94 percent said skins; 66 percent said doublers; 55 percent said stringers, spars, and ribs; 61 percent said frames; 44 percent said machined parts; and 22 percent chose the category Other.

  The following responses were from the category Other.

  – “Control surfaces and doors”
  – “Honeycombs and minor parts, mainly composites”
  – “Skin to spar bond”
  – “Pressure vessel”

- Design Responses

  – Of the three respondents, all three indicated skins, doubles, stringers, spars, and ribs. Two of the three also indicated machined parts.

  One of the two respondents also chose the category Other, stating the following.

  – “Back to back fittings in design”
  – “Transparencies”
  – “Tertiary Brackets”

- Manufacturing Response

  – The respondent chose skins, stringers, frames, spars, and ribs.

- Analysis Responses

  – Of the 13 responses, 100 percent said skins, 77 percent said doublers, 61 percent said stringers, 54 percent said frames, 54 percent said spars, 54 percent said ribs, and 38 percent said machined parts.

- Regulator/Customer Responses

  – Two of the three respondents replied. Both indicated doublers and stringers. The second respondent also indicated skins, frames, spars, and ribs.

- Other Category Responses

  – "Bonded structures can be made for almost all types of structural elements. The tooling and curing process for the structure elements as well as the structure application parameters play a role in selection of the structures that can be manufactured and repaired. The repair aspect need careful review to assure that the design does not make the repair process difficult or not safe. Unsafe repairs are in my mind a real key issue in selecting structures to be bonded."

Question 2: The respondents indicated that the maximum operational temperature of their adhesive was established in relation to the T_g as follows.

- Material and Process Control Responses

  – "25°C below the measured T_g"

  – "50°C below T_g"

  – "It's not. Only strength/stiffness at temperature is a determinant."

  – "50°F - maximum service temperature to original T_g."

  – "50°F"

  – "Approximately 100°F less than the dry T_g."

  – "Component testing at operational temperature."

  – "Knock-down below hot-wet T_g based on shape of the curve."

  – "Sometimes we wish we had a little higher T_g."

  – "Not related"

  – "It is not established in relation to T_g."

- “It is even more important to establish MOL functionally than with just a T_g knockdown for adhesives compared to composites. There are many bonded structures that have a wet T_g at or sometimes below a maximum environmental temperature. This still may not be a deal breaker if you have enough lightly loaded adhesive away from the edges to prevent creep.”
- “Operation temperature not solely defined by T_g. Durability testing at maximum service temperature is used. T_g via DMA is only a relative indicator.”

- Design Responses
  - “Set by OEM as maximum operating temperature.”

- Manufacturing Response
  - The respondent did not answer this question.

- Analysis Responses
  - “30F beyond conservative wet T_g.”
  - “180 ºC”
  - “-50F is a simple guideline, data provides the real number.”
  - “Allowables are temperature dependent.”
  - “It’s not. Only strength/stiffness at temperature is a determinant.”
  - “A safe margin is applied.”
  - “The goal is to have a wet T_g 50F above the maximum operating temperature, but if this is not practical, then an additional high-temperature-wet test (20F above operating) is added to the qualification tests.”
  - “This T_g to use temperature is variable and not clearly defined at our company. However, maximum operational temperature is based on mechanicals.”
  - “Thru structural test data. T_g is relatively meaningless.”
  - “Varies some. Generally = MOL - 50F (wet).”
  - “Well below T_g-20”

- Regulator/Customer Responses

  – Of the three respondents, only one replied. The respondent answered adhesive mechanical characterization and application-specific.

- Other Category Responses

  – "T_g minus 50°F"

  – "Adhesive mechanical characterization and application-specific determinations."

  – "Typically they use temperature should be established at a conservative point below the T_g. Preferably 20 degrees below the onset, depending on the test and the data."

  – "From manufacturer's data and/or independent testing."

  – "Subject of ongoing studies."

  – "From the adhesive data sheets."

  – "Temperature requirements are dictated by the service temperature."

Question 3: When asked how they measured T_g, the respondents replied as shown in table C-10.

TABLE C-10. MEASURING T_g

Response	Percent
DMA	71
DSC	66
TMA	33
Other	17

- Material and Process Control Responses

  – Of the 17 responses, 70 percent said DSC, 58 percent said DMA, and 23 percent said TMA. The response from the category Other was "Varies with material."

- Design Responses

  – None of the three respondents replied to this question.

- Manufacturing Response

  – The respondent indicated DSC and DMA.

- Analysis Responses
  - Of the 11 responses, 90 percent said DMA, 54 percent said DSC, and 27 percent said TMA.
- Regulator/Customer Responses
  - Of the three respondents, only one replied, indicating DMA.
- Other Category Responses
  - "AFRL"
  - "Dynamic Spectrometer (similar to DMA)"

Question 4: Fifty-six percent of the respondents agreed that tooling, manufacturing, and maintenance issues are integrated into the design process. Twenty-four percent strongly agreed, 14 percent neither agreed nor disagreed, and 6 percent disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 52 percent agreed, 21 percent neither agreed nor disagreed, 15 percent strongly agreed, and 10 percent disagreed.
- Design Responses
  - One of the three respondents strongly agreed. Two of the three respondents did not reply to this question.
- Manufacturing Response
  - The respondent strongly agreed.
- Analysis Responses
  - Of the 14 responses, 71 percent agreed, 14 percent strongly agreed, 7 percent disagreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents strongly agreed.

The respondents replied as follows to the statement "You have documented design guidelines in these areas." Forty-two percent of the respondents agreed with this statement and 15 percent strongly agreed. Twenty-six percent neither agreed nor disagreed, 13 percent disagreed, and 4 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 17 responses, 35 percent agreed, 23 percent neither agreed nor disagreed, 17 percent disagreed, 17 percent strongly agreed, and 5 percent strongly disagreed.
- Design Responses
  - One of the three respondents strongly disagreed. Two of the three respondents did not reply to this question.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 14 responses, 57 percent agreed, 28 percent neither agreed nor disagreed, 7 percent strongly agreed, and 7 percent strongly disagreed.
- Regulator/Customer Responses
  - Two of the three respondents agreed.

The respondents replied as follows to the statement "These guidelines depend on part criticality."

- Material and Process Control Responses
  - Of the 19 responses, 47 percent agreed, 21 percent neither agreed nor disagreed, 21 percent strongly agreed, and 10 percent disagreed.
- Design Responses
  - Three respondents replied. One strongly agreed, one strongly disagreed, and one agreed.
- Manufacturing Response
  - Three respondents replied. Two agreed and one strongly disagreed.
- Analysis Responses
  - Of the 12 responses, 66 percent agreed, 16 percent neither agreed nor disagreed, 8 percent strongly agreed, and 8 percent strongly disagreed.
- Regulator/Customer Responses
  - Of the three respondents, one agreed and one strongly agreed.

Question 6: The respondents used the following analysis for bonded structures.

- Material and Process Control Responses
  - "AE4I" (bonded joint analysis program)
  - "Basic P/A (load over area analysis) to FEA, depending upon the application."
  - "For critical joints tensile shear in bond joint equal tensile strength of material being bonded."
  - "Full scale static and fatigue tests on bonded assemblies."
  - "Hand analysis, AYEI, in-house code."
  - "Hand calculations using running shear loads."
  - "In-house analytical tools that have been incorporated into CalcyRep and CRAS software. Designs will always be compared against RAAF Engineering Standard DEF (AUST) 9005-A."
  - "Minimal amount of finite element analysis."
  - "OEM specific"
  - "Shear and Peel stress through FEA."
  - "Using virtual crack closure technique, calculate strain energy release rate."
- Design Responses
  - "Laminate analysis software and physical calculations."
- Manufacturing Response
  - "Customer requirements and published data."
- Analysis Responses
  - "Combination of stress and fracture based analysis."
  - "Detailed FEM and in-house software."
  - "FEA of crack growth (R&D tool only?)"
  - "FEA for overall structure using mechanical properties from notched allowable tests. Localized analysis may be done using CLPT."

- “FEM (particularly for secondarily induced tensile forces), Classical V/A (shear load over area analysis) smeared analysis for simple structures.”

- “Hart smith program. A4EI; assuming elastic - perfectly plastic adhesive properties.”

- “I have no experience with any analysis technique that accurately predicts adhesive performance. Analysis is done with the aid of empirical data and conservative assumptions for adhesive thickness and overlaps. For preliminary design, 500 psi is used with some limitations. Certification is usually accomplished by test, unless the margins of safety are shown to be large.”

- “Lap shear strength or detailed joint test results.”

- “Mostly empirical in the past. VCCT (virtual crack closure technique) approach is currently being adopted for new airplane - still supported by much testing.”

- “Average bond shear stress, with allowable based on adhered stiffness mismatch, overlap length and allowed local bond thickness.”

- “P/A and FEA”

- “Only static analysis”

- “Service experience”

• Regulator/Customer Responses

  - Detailed stress analysis with tools that account for bonded joint design parameters and semiempirical failure criteria.

• Other Category Responses

  - “AE4I evolving to “SIFT methods “(joint analysis program).

  - “The load capacity is calculated using an elastic-plastic analysis. That load capacity is compared against the structural loads. The overlap length is designed such that all loads can be carried by plastic behavior and an additional overlap length is added as precaution against joint creep. This procedure is performed at maximum and minimum service temperatures.”

  - “B-Spline Analysis Method (3D stress analysis tool)”

  - “All bonding would be performed in accordance with the SRM and the adhesive manufacturer’s data sheets.”

  - “The analysis is structural finite element modeling supported by test.”

Forty-two percent of the respondents strongly agreed with the statement "You use analysis codes." Twenty-eight percent neither agreed nor disagreed, 14 percent disagreed, 12 percent strongly agreed, and 4 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 15 responses, 33 percent agreed, 33 percent neither agreed nor disagreed, 13 percent strongly agreed, 13 percent disagreed, and 6 percent strongly disagreed.
- Design Responses
  - One of the three respondents replied that they neither agreed nor disagreed. Two of the three respondents did not reply to this question.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 13 responses, 54 percent agreed, 15 percent strongly agreed, 15 percent disagreed, 7 percent strongly disagreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents agreed.

The respondents that agreed or strongly agreed stated that they use the following analysis codes.

- Material and Process Control Responses
  - "Running-shear model"
  - "Platform specific for repair"
  - "MARC for nonlinear FEM"
  - "NASTRAN" (2)
  - "Patran for fet and various hand calc."
  - "AYEI"
- Analysis Responses
  - "Abaqus" (2)
  - "Various FE and in-house codes"
  - "Non-linear MSC/NASTRAN SOL 600"
  - "NASTRAN/PATRAN"
  - "FEA"

- "P over A"
- "ANSYS"
- "A4EI"

- Regulator/Customer Responses
  - "NASTRAN"

- Other Category Responses
  - "BSAM"

Question 7: The respondents use the following failure criteria:

- Material and Process Control Responses
  - "Platform specific for static (strain based), unlimited life"
  - "Adhesive failure"
  - "Mechanical"
  - "Do they work better than those for composites?"
  - "Mechanical performance, durability, failure mode"
  - "Elastic analysis only"
  - "Limit Load(and fatigue) - Adhesive Yield; Ultimate Load- Ultimate Strength"
  - "Minimum adhesive failure in shear"
  - "Max stress"
  - "Limit load and ultimate load conditions applied to Full-scale test article. Sustainability of the article to withstand ultimate load is evaluated."

- Design Responses
  - "Stiffness and overlap."

- Manufacturing Response
  - "Shear, peel"

- Analysis Responses
  - "Average stress"

- "LEFM, total strain energy"
- "Fracture toughness criteria"
- "EADS CASA criterion"
- "Maximum strain"
- "Max principal stress/strain and fracture mechanics"
- "Generally smeared V/A ultimate"
- "Ultimate strength"
- "Various research"
- "Failure occurs at an average stress (p/a) and is used in conjunction with empirical data generated, considering geometry, overlap, and adhesive thickness."
- "Limit Load(and fatigue) - Adhesive Yield; Ultimate Load- Ultimate Strength"
- "Ultimate shear stress, S-N curves in fatigue"
- "First part"
- "Lap shear, Flatwise tension, Peel strength"

• Regulator/Customer Responses

- "Those conservatively validated by tests."
- "Ultimate strain generally used."

• Other Category Responses

- "Strain based or fracture mechanics based (energy release rate)"
- "Strain and stress limits"
- "Max von mises"
- "Hear strength"
- "Structural criteria must include the effects of time and environment."
- "Depends on joint design"
- "Load capacity calculated as per Hart-Smith is used to compare against loads, with specified margins of safety required."

– “Subject of ongoing study”

– “Result of tap-testing”

Forty-four percent of the responders agreed with the statement “Your predictions distinguish cohesive failures in the adhered or adhesive.” Twenty-seven percent neither agreed nor disagreed, 15 percent strongly agreed, 12 percent disagreed, and 2 percent strongly disagreed.

- Material and Process Control Responses

  – Of the 16 responses, 43 percent disagreed, 31 percent neither agreed nor disagreed; 12 percent strongly disagreed, 6 percent strongly agreed, and 6 percent agreed.

- Design Responses

  – One of the three respondents strongly agreed. Two of the three respondents did not reply to this question.

- Manufacturing Response

  – The respondent agreed.

- Analysis Responses

  – Of the 14 responses, 57 percent agreed, 14 percent disagreed, 7 percent strongly agreed, and 7 percent strongly disagreed.

- Regulator/Customer Responses

  – Of the three respondents, one respondent agreed and one neither agreed nor disagreed.

Thirty percent of the respondents neither agreed nor disagreed that adhesion failures between the substrate and adhesive can be predicted and 30 percent disagreed. Twenty-five percent strongly disagreed, 8 percent agreed, and 7 percent strongly agreed.

- Material and Process Control Responses

  – Of the 14 responses, 35 percent neither agreed nor disagreed, 28 percent agreed, 21 percent disagreed, and 14 percent strongly agreed.

- Design Responses

  – One of the three respondents strongly agreed. Two of the three respondents did not reply to this question.

- Manufacturing Response
  - The respondent disagreed.
- Analysis Responses
  - Of the 14 responses, 36 percent neither agreed nor disagreed, 14 percent strongly disagreed, 14 percent disagreed, and 14 percent agreed.
- Regulator/Customer Responses
  - Of the three respondents, one respondent strongly disagreed and one neither agreed nor disagreed.

Question 8: The responders overwhelming said they make a concentrated effort to minimize peel stresses in the design of bonded joints. Forty-five percent agreed, 47 percent strongly agreed, and 7 percent neither agreed nor disagreed.

- Material and Process Control Responses
  - Of the 17 responses, 47 percent agreed, 41 percent strongly agreed, and 12 percent neither agreed nor disagreed.
- Design Responses
  - None of the three respondents replied to this question.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 15 responses, 60 percent strongly agreed and 40 percent agreed.
- Regulator/Customer Responses
  - Of the three respondents, one respondent agreed and one strongly agreed.

Question 9: Fifty-three percent of the respondents stated that the overlap length is primarily sized in design by stress level. Forty-four percent primarily used a design standard, 33 percent sized geometrically, and 11 percent used strain level. Eleven percent also indicated other methods.

- Material and Process Control Responses
  - Of the 17 responses, 53 percent said stress level, 46 percent said design standard, and 26 percent said geometrically. The response for the category Other was "All for repair, sized by OEM in new design."
- Design Responses
  - Strain level.
- Manufacturing Response
  - The respondent uses design standard.
- Analysis Responses
  - Of the 14 responses, 64 percent said stress level, 57 percent said geometrically, 43 percent said destructive testing, and 21 percent said strain level. The response for the category Other was "Allowance for voids."
- Regulator/Customer Responses
  - Of the three respondents, two chose design standard and one of the two also chose stress level.
- Other Category Responses
  - "Overlap length is affected by the structural stiffness, shape, stress and strain level. Again the overlap length will be effect by the bonding tooling and bonding process. Since in any bonded design the manufacturing process can set how the joint is design and that will of course include the overlap length."
  - "The overlap length has an allowance such that all loads can be carried by plastic behavior in the bond and then an allowance is made for elastic behavior to prevent creep. The overlap length is determined by the hottest service temperature."
  - "As defined by the SRM"

Question 10: Thirty-seven percent of the respondents agreed that their analysis accounts for residual stresses in the bonded joint and 28 percent disagreed. Twenty-one percent neither agreed nor disagreed, 7 percent strongly agreed, and 7 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 14 responses, 42 percent agreed, 21 percent disagreed, 21 percent neither agreed nor disagreed, and 14 percent strongly agreed.

- Design Responses
  - One of the three respondents strongly agreed. Two of the three respondents did not reply to this question.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 14 responses, 36 percent agreed, 36 percent disagreed, 21 percent neither agreed nor disagreed, and 7 percent strongly disagreed.
- Regulator/Customer Responses
  - Of the three respondents, one respondent agreed and one neither agreed nor disagreed.

Question 11: The respondents identified the following basic material properties and joint data needed for analysis procedures.

- Material and Process Control Responses
  - "Adhesive: Tensile modulus, strength, shear modulus, strength, compressive modulus, strength"
  - "Composite: longitudinal & transverse modulus, shear modulus, G12,G31,G23, poissions ratio v12, v31,v23"
  - "Lap Shear Strength Values"
  - "Amount of Overlap"
  - "Adhesive Shear Strength"
  - "Apparent Shear Strength Of Joints With Similar Adherend And overlap Length"
  - "Adhesive: Shear Yield Strength, Tensile Strength, Ultimate Shear Failure Strain, Fatigue Strain Limit, Cure Temp, Operating Temperature Skin: Thickness, Yield Strength, Ultimate Strength, Fracture Toughness, Modulus, Poisson's Ratio, Thermal Expansion Coefficients, Composite Repair Patch: Ultimate Longitudinal Strain, Moduli, Thermal Expansion Coefficients, Thickness"
  - "Adhesive: Tensile Modulus, Strength, Shear Modulus, Strength, Compressive Modulus, Strength, Composite: Longitudinal & Transverse Modulus, Shear Modulus, G12, G31, G23, Poissions Ratio V12, V31, V23"

- “Elastic Modulus, Shear Modulus, Elastic Strain, Plastic Strain”
- “KGR EV. 8”
- “Lap Shear And Bulk Tensile Strength”
- “Minimum Shear Strength And Area”
- “Moduli, Ctes, Failure Loads. Analysis For Composite Joints Requires more information.”
- “Modulus, Elongation, Ultimate Strength”
- “Shear Modulus and Ultimate Stress.”
- “Shear Modulus For Critical Conditions, Representative Elements”
- “Shear Strength And Modulus”
- “Shear Stress-Strain Curve, Flatwise Tensile Strength”

- Design Responses
  - “Ply”
  - “Thickness”
  - “Poissions Ratio”
  - “Young’s Modulus”
  - “Shear modulus”

- Manufacturing Response
  - The respondent did not reply.

- Analysis Responses
  - “A matrix of test results that consider geometry, overlap, and adhesive thickness.”
  - “Adhesive: shear stress, strain, & modulus over temperature range with moisture effects. Adherend: stress, strain, & modulus over temperature range with moisture effects.”
  - “Elastic plastic modulus, Poisson’s tensile and shear fatigue and static strength, fatigue crack growth rate, fatigue threshold”
  - “G1c, G2c, G3 mixed mode.”
  - “Adhesive, and Mechanical allowables (i.e. peeling stress)”

- "Material and adhesive properties"
- "Modulus, Poissions, strength (tensile, shear), adhesive shear strain"
- "Smeared V/A section shear strength and smeared P/A tensile strength"
- "Stiffness of adhesive (linear elastic) and adherends; Strength of adherends and elongation to failure of the adhesive."
- "Stiffness, geometry, strength, impact resistance"
- "Substrate stiffness, adhesive stiffness, empirical adhesive strength, overlap length, bond width, taper/scarf consideration, criticality of joint, presence or absence of failsafe fasteners."

- Regulator/Customer Responses
  - "Nonlinear stiffness and detailed tests/analysis to calibrate "design values.""
  - "Adhesive allowable strain or stress; moduli (shear and extensional); adherend geometry and moduli; and bondline thickness"

Question 12: When considering damage tolerance, fatigue, and durability, the majority of the respondents indicated that two or all three factors were considered in design. Damage tolerance received 35 percent of the responses, fatigue was specified in 34 percent, and durability was indicated in 32 percent of the responses.

- Material and Process Control Responses
  - Of the 12 responses, 58 percent said damage tolerance, 58 percent fatigue, and 58 percent said durability.
- Design Responses
  - Of the three respondents, one indicated damage tolerance, fatigue, and durability. The other two respondents did not reply to the question.
- Manufacturing Response
  - The respondent indicated damage tolerance and fatigue.
- Analysis Responses
  - Of the 15 responses, 93 percent said damage, 86 percent said durability, and 66 percent said fatigue.

- Regulator/Customer Responses
  - Two of the three respondents answered. Both respondents indicated damage tolerance and fatigue; one respondent also indicated durability.

Question 13: The respondents said that the following determined the manufacturing flaw and accidental damage sizes considered for fatigue and damage tolerance assessments of bonded surfaces.

- Material and Process Control Responses
  - "A long and painful coordination between design and stress on one side and manufacturing and m & p (material and process) on the other. They show us their models and we show them our manufacturing history and field failures."
  - "Manufacturing flaw - NDE resolution DT-MIL-STO-1530"
  - "Full scale test article with intentional defects upon sustaining the loads drives the flaw size, durability and the fatigue assessments of the bonded structure."
  - "NDI limits for manufacturing. NDI limits and visual inspection limits for in service structure."
  - "NDT capability and effects of defects testing."
  - "Full scale test and field experience."
  - "Testing"
  - "Loss of area, location of flow and past experience."
- Design Responses
  - "OEM returns back to the original."
- Manufacturing Response
  - The respondent did not reply.
- Analysis Responses
  - "The flaw sizes are determined by the inspection technique and accessibility and can be different for different parts of the structure."
  - "Flaw size leading to unstable growth and/or inspection accuracy."
  - "General design criteria, NDI/NDE capability, process robustness, customer requirements."

- “AC20-107A”
- “Residual strength test data (load capability versus damage size severity).”
- “Experience”
- “Detection sizes for the preferred inspection method.”
- “Secondary structures are determined by visual inspection.”
- “Inspection standards”
- “Currently specification dictates reject flaw size. Also currently investigating flaw size/shape effects.”
- “What can be found by a reliable inspection.”

• Regulator/Customer Responses

- Production and service threat assessment (based on previous experience and engineering judgment), combined with analysis and tests on structural performance.

• Other Category Responses

- “For inspection and damage tolerance issues the effect of the repair is ignored. Pre-repair inspection intervals are maintained.”
- “For manufacturing, eads casa procedure (fix the maximum flaw size and others) for accidental damages is the minimum detectable damage size (depending on damage source).”
- “Twice the NDI detectable flaw size, but moving to the largest flaw size that can be tolerated (acceptable strength reduction) based on empirical “effects of defects” testing.”
- “Type of material used, structural arrangement, stress/strain level the structure see in service, types of damage considered, aircraft usage and type.”
- “Critical structure/aerodynamic considerations.”
- “A critical defect is one that reduces the bond overlap length below that which would permit all loads to be carried by plastic behavior in the adhesive, with a 50% margin of safety on that overlap length.”
- “Tested damage size established by subjective estimation, criteria is damage or defect that can be determined by visual inspection.”

- "As defined by the SRM."

- "NDI detection levels."

Question 14: To the statement "You have had success in applying analysis methods for fatigue and damage tolerance assessments of bonded structures," 21 percent of the 41 respondents agreed, 27 percent disagreed, 24 percent neither agreed nor disagreed, 12 percent strongly agreed, and 7 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 16 responses, 43 percent disagreed, 31 percent neither agreed nor disagreed, 12 percent strongly disagreed, 6 percent agreed, and 6 percent strongly agreed.
- Design Responses
  - One of the three respondents strongly agreed. Two of three respondents did not reply to this question.
- Manufacturing Response
  - The respondent did not reply.
- Analysis Responses
  - Of the 15 responses, 46 percent agreed, 20 percent neither agreed nor disagreed, 20 percent disagreed, and 13 percent strongly agreed.
- Regulator/Customer Responses
  - Of the three respondents, one respondent agreed, and one neither agreed nor disagreed.

Question 15: The respondents used the following fail-safe design features to reduce the risk of weak bonds in their structure. Of the 38 responses, 45 percent said rivets, 18 percent said crackstoppers, and 60 percent chose the category Other.

- Material and Process Control Responses
  - "Of the 14 responses, 35 percent said rivets and 21 percent said crackstoppers.

  The following were the responses from the category Other.

  - "Bolts"
  - "Bolts in some areas of criticality. Wet lay-up to provide an additional load path for redundancy"

- “Multiple redundant load paths”
- “Fasteners”
- “Redundant load paths”
- “Z-pins”
- “None” (3)

• Design Responses

- “None”

• Manufacturing Response

- The respondent did not reply.

• Analysis Responses

- Of the 14 responses, 43 percent said rivets and 14 percent said crackstoppers.

The following were the responses from the category Other.

- “No bonds in single load path elements”
- “Multiple load paths”
- “Blind bolts or Hi-loks”
- “Fasteners”
- “Keep low stresses”
- “Lower allowables/larger bond areas”
- “Self-health monitoring”

• Regulator/Customer Responses

- Two of the three respondents used rivets and crackstoppers.

Question 16: The respondents had the following comments on design and analysis.

• Material and Process Control Responses

- “The design procedures for single sided unsupported repairs require some further review before they can be generally applied.”
- “Wide range of techniques, based on criticality of part.”

- "Of the plane (peel) effects, initiation and growth still seem difficult to model. When asked for small bolts to arrest potential debonds, and got big bolts capable of replacing the entire bond for several hundred hours."

- "Could use help in this area regarding acceptable and accurate analysis methods for joints, especially in predicting substrate (adherend) failures."

- "Analysis makes sure we are in the ball park. All bonded primary structures are qualified by fatigue test or operational test."

- "I am not a designer or analyst, so I could not answer many of the above questions."

* Design Responses

  - None of the three respondents provided comments.

* Manufacturing Response

  - The respondent did not provide comments.

* Analysis Responses

  - "This is the least understood aspect of adhesively bonded structures. The industry needs a reliable analytical tool for bonded joints."

  - "Part of the fail-safe approach used is to provide joint overlaps in which there is enough residual strength to accommodate creep and bond flaws. Fasteners are sometimes used but, with the exception of some peel-stop fasteners, I believe they do more harm than good."

  - "Adhesive properties need more information."

  - "There is a general inconsistency in the design and analysis approach from analyst to analyst."

* Regulator/Customer Responses

  - "Design and detailed stress methods exist to develop bonded joint designs, which conservatively avoid undesirable failure modes. Most analysis applied for bonded joints with damage is dependent on associated databases."

* Other Category Responses

  - "Adhesives are very difficult to model. A standardized technique would at least result in similar errors between different design parties."

  - "Tests and analysis are needed."

- "The issues covered in this section are handled by our customers with minimal input from my company."

- "Static strength of most bonded joints can be predicted if you assume that the as manufactured joint has full strength (not a "weak bond"). Effects of flaws, fatigue life and dadt are still determined using testing."

- "Design can not be based on average shear stress values. Design can not be based on purely elastic analysis. Durability is never a design issue; it is driven purely by processes. The use of "chicken" rivets is a sign that the designer or manufacturer does not know how to design or manufacture an adhesive bond."

- "We have completed more analysis of bonded joint specimen to help determine validity of KGR test etc."

C.5 MANUFACTURING AND DESIGN INTEGRATION SUBSECTION: MANUFACTURING.

Question 1: When asked if they control humidity, the majority of the respondents do control humidity with 39 percent saying that they strongly agreed, and 33 percent agreed, 20 percent neither agreed nor disagreed, 7 percent disagreed, and 1 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 31 percent agreed, 37 percent strongly agreed, 16 percent neither agreed nor disagreed, 10 percent disagreed, 5 percent strongly disagreed.
- Design Responses
  - Of the three respondents, one strongly agreed and one agreed. One respondent did not reply.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 13 responses, 54 percent agreed, 23 percent neither agreed nor disagreed, and 23 percent strongly agreed.
- Regulator/Customer Responses
  - Of the three respondents, two agreed.

The majority of the respondents do control temperature with 40 percent saying they agreed, and 33 percent who strongly agreed, 20 percent neither agreed nor disagreed, and 7 percent disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 47 percent agreed, 47 percent strongly agreed, and 5 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one strongly agreed, and one agreed. One respondent did not reply.
- Manufacturing Response
  - The respondent strongly agreed.
- Analysis Responses
  - Of the 13 responses, 61 percent agreed, 31 percent strongly agreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Of the three respondents, two agreed.

Question 2: Regarding the type of tooling and equipment used for adhesive bonding, 49 percent of the respondents used a vacuum bag, followed by press at 23 percent and matched tooling at 20 percent. Eight percent of the responses indicated other types of tooling and equipment.

- Material and Process Control Responses
  - Of the 19 responses, 78 percent said vacuum bag, 63 percent said matched tooling, and 42 percent said press.

  The following responses were from the category Other.

  - “Bonding jigs with clamps”
  - “Bonding jigs with weight”
  - “Air bladders”
  - “Lofted tools with detail locators”
  - “Positive pressure”
  - “Inflatable mandrel”
  - “Autoclave”

- Design Responses
  - Of the three respondents, one indicated vacuum bag and matched tooling. One respondent indicated vacuum bag and autoclave. The third respondent did not reply.
- Manufacturing Response
  - The respondent indicated vacuum bag and press.
- Analysis Responses
  - Of the 13 responses, 84 percent said vacuum bag, 46 percent said press, 31 percent said matched tooling, and 7 percent said tool pressure.
- Regulator/Customer Responses
  - Of the three respondents, two indicated vacuum bag and press. The response from the category Other was "Matched Tooling with clamps."
- Other Category Responses
  - "Autoclave (five responses)"
  - "Vacuum table"
  - "The process selected is one that is base on the bonded design and can include many approaches."
  - "Tool pressure"

Question 3: Most respondents agreed that cured part dimensional tolerance and warpage is controlled. Forty-six percent of the respondents agreed, 15 percent strongly agreed, 33 percent neither agreed nor disagreed, 4 percent of the respondents disagreed, and 2 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 31 percent agreed, 47 percent strongly agreed, and 5 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one strongly agreed, one strongly disagreed, and one respondent did not reply.

- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 12 responses, 58 percent agreed, 25 percent neither agreed nor disagreed, 8 percent disagreed, and 8 percent strongly agreed.
- Regulator/Customer Responses
  - Of the three respondents, two agreed.

Those who agreed or strongly agreed used the following controls.

- “Fasteners” (4)
- “Wet lay-up to provide an additional load path for redundancy”
- “Lower allowables/larger bond areas”
- “Bolts” (4)
- “Self-health monitoring”
- “Multiple load paths” (4)
- “Z-pins”
- “Hi-loks”
- “Keep low stresses”
- “Load path and expected load level over time are the first keys to selection of the fail safe design features. The ideas of such things as noted as mechanical fasteners backup are only part of the process. The structural arrangement which defines the load paths after the structure is damaged is of significant importance. The inspection procedure to be used to identify damage is part of the elements that determine the type of fail-safe design to be applied to the structure. This is control by the damage being either easy to identify or hard to find. Again all these things must good in to any good safe design as well as in to the manufacturing process selected and the in-service inspection proceeds.”
- “Molded laminate features.”
- “No bonds in single load path elements.”

- Analysis Responses
  - "1) Tooling concept including material selection and size. 2) By understanding composites and their response to the curing process. Sometimes a simulation is performed to determine if there is an issue."
  - "Allowable bond thickness."
  - "Components such as wings cannot be allowed to twist or otherwise deviate from the design shape. Jig fixtures are required to prevent slippage or warping during assembly and cure. Tack rivets are sometimes used."
  - "Electronic measurement."
  - "First article inspections require contour check against 3D model and contour data from Laser Tracker or Faro Arm measurements. Such tolerances are also on the 2D drawings and must conform or part is rejected."
  - "Minimal fit up forces may be used to bring the part to the required contour."
  - "Tooling and process control."

Question 4: Fifty percent of the respondents perform Verifilm runs to confirm the fit of mating surfaces and 50 percent do not.

- Material and Process Control Responses
  - Of the 19 responses, 42 percent agreed, 21 percent neither agreed nor disagreed, 15 percent strongly disagreed, 15 percent strongly agreed, and 5 percent disagreed.
- Design Responses
  - Of the three respondents, one disagreed, and one strongly disagreed. One respondent did not reply.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 12 responses, 41 percent agreed, 25 percent neither agreed nor disagreed, 16 percent disagreed, and 16 percent strongly disagreed.
- Regulator/Customer Responses
  - Of the three respondents, two agreed.

Question 5: Twenty-seven percent of the respondents strongly agreed that the materials and processes qualified for their structures impose strict time limits for adhesive application steps with 52 percent agreeing. Thirteen percent neither agreed nor disagreed, 4 percent disagreed, and 4 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 19 responses, 42 percent agreed, 31 percent strongly agreed, 10 percent neither agreed nor disagreed, 10 percent disagreed, and 5 percent strongly disagreed.
- Design Responses
  - Of the three respondents, one agreed and one strongly agreed. One respondent did not reply.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 13 responses, 69 percent agreed, 23 percent strongly agreed, and 8 percent strongly disagreed.
- Regulator/Customer Responses
  - Of the three respondents, two agreed.

The respondents that answered yes identified how they were derived.

- Empirical and full test program were the most popular responses at 26 percent each. Design of the experiment accounted for 20 percent of the responses, and the category Other identifiers were cited in 16 percent of the responses. Thirteen percent of the responses were for the estimate identifier, and calculation received 3 percent.
- Material and Process Control Responses
- Of the 13 responses, 53 percent stated empirical, 38 percent stated design of experiment, 23 percent stated full test program, 15 percent said supplier, and 15 percent said estimate.

  The following responses were from the category Other.

  - "Supplier recommendation" (2)
  - "Pot life of the paste adhesive"

- Design Responses
  - "OEM of the limits."
- Manufacturing Response
  - The respondent answered "determination was made by estimate."
- Analysis Responses

  Of the 12 responses, 41 percent said empirical, 41 percent said full test program, 25 percent said estimate, 25 percent said design of experiment, and 20 percent said calculation. The response from the category Other was "In process tests."
- Regulator/Customer Responses
  - One respondent said empirical and full test program and one said design of experiment, empirical, and full test program.
- Other Category Responses
  - "Legacy experience"
  - "The control of the process starts with the selection of the application of the bonded design and selection of the bonding material. If the best material for your design requires a control process time wise then the design, and manufacturing proceeds must be so established. We can not forget that everything starts with the design requirement and the design selection. Also in selection of the design there must of course be the understanding of the manufacture process that will be applied if the design is to be a good one."
  - "Common sense"
  - "These are controlled according to the perceived risk of contamination and exposure to humidity. The requirements for a repair on-aircraft are far more severe that for a repair performed in a controlled environment."

Question 6: The respondents stated that they handle large-scale surface preparation and adhesive application differently from laboratory-scale preparation, with 33 percent of the responses showing that the respondents disagreed and 19 percent strongly disagreed. There were 27 percent who neither agreed nor disagreed. Seventeen percent agreed and 4 percent strongly agreed.

- Material and Process Control Responses
  - Of the 18 responses, 27 percent disagreed, 27 percent neither agreed nor disagreed, 22 percent strongly disagreed, 16 percent agreed, and 5 percent strongly agreed.
- Design Responses
  - Of three respondents, one neither agreed nor disagreed and one strongly disagreed. One respondent did not reply.
- Manufacturing Response
  - The respondent disagreed.
- Analysis Responses
  - Of the 13 responses, 46 percent disagreed, 31 percent neither agreed nor disagreed, 15 percent strongly disagreed, and 7 percent agreed.
- Regulator/Customer Responses
  - Of the three respondents, two neither agreed nor disagreed.

The respondents that agreed or strongly agreed handled the difference as follows.

- Material and Process Control Responses
  - "The grit-blast and saline treatment is a process suited to field applications and large area repairs all repairs are relatively small operator periodic certifications, specialized equipment for waste storage and disposal on large scale."
  - "All lab work is FPL. Production is PAA, CAA, etc."
  - "Lab is very carefully controlled, shop is variable."
  - "Operator periodic certifications, specialized equipment for waste storage and disposal on large scale."
  - "For example, anodizing will have careful additional placement of cathodes, work-life for paste adhesives will be controlled, and non-tank processing may be used."
- Analysis Responses
  - No respondents replied to this question.

- Regulator/Customer Responses
  - No respondents replied to this question.
- Other Category Responses
  - "Simply this must be an understood element of the total. For example, anodizing will have careful additional placement of cathodes, work-life for paste adhesives will be controlled, and non-tank processing may be used."
  - "All bonding processes/timing will differ on a large scale compared to the lab scale evaluation. When performing lab sized experiments it is helpful to follow an estimated time-line that may parallel the actual assembly time."
  - "Needed a box for a strong disagreement as well. The process used for any surface preparation must follow the validated processes exactly. If that is not possible, then the modified process must be validated by replication in the laboratory."
  - "We are lab scale only."
  - "Surface preparation and adhesive application on alum or composites is same whether as a lab test or on a large scale production."

Question 7: Eighty-eight percent of the respondents strongly agreed or agreed that there are handling and storage constraints and disposal guidelines for materials (e.g., solvents, grit blast media) used in surface preparation.

- Material and Process Control Responses
  - Of the 17 responses, 64 percent strongly agreed and 35 percent agreed.
- Design Responses
  - Of the three respondents, one agreed and one strongly agreed. One respondent did not reply.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 12 responses, 66 percent agreed, 25 percent neither agreed nor disagreed, and 8 percent strongly disagreed.

- Regulator/Customer Responses

  – Of the three respondents, one respondent agreed and one strongly agreed.

Question 8: Sixty-nine percent of the respondents said bondline thickness is controlled during production by scrim cloth, followed by glass beads at 36 percent, microballoons at 34 percent, shims at 18 percent, and stop blocks at 10 percent. The other 16 percent were responses from the category Other.

- Material and Process Control Responses

  – Of the 15 responses, 80 percent said scrim cloth, 73 percent said glass beads, 33 percent said shims, 33 percent said microballoons, and 20 percent said stop blocks.

  The following responses were from the category Other.

  – “Fishing line”
  – “Bond Rods made of glass epoxy”
  – “Pressure” (2)
  – “Tooling”
  – “Adhesive flow characteristics”
  – “Tool design”
  – “Application technique”

- Design Responses

  – Of the three respondents, one indicated scrim cloth and one indicated both scrim cloth and microballoons. The third respondent did not reply.

- Manufacturing Response

  – The respondent indicated scrim cloth and glass beads.

- Analysis Responses

  – Of the 13 responses, 69 percent said scrim cloth, 31 percent said glass beads, 31 percent said microballoons, 23 percent said stop blocks, and 15 percent said shims.

  The following responses were from the category Other.

  – “Temperature and pressure”
  – “Film”
  – “Tooling position”
  – “Verifilm”
  – “Thickness not controlled at facing to core bondline in sandwich laminates.”

- Regulator/Customer Responses

  – Two of the three respondents replied. One respondent indicated stop blocks and microballoons and the second respondent indicated shims, scrim cloth, microballoons, and glass beads.

- Other Category Responses

  – "Pressure"

  – "Since I have seen and read about all these process, I can only say again there identification for use with your design must review all of them in selection of the one appropriate for your use."

  – "Wire strand"

  – "Non-woven carriers (mat)"

  – "Film thickness"

Question 9: The responses indicated that 80 percent of companies inspect bonded parts after bonding with ultrasonic testing (UT), 79 percent chose visually, 57 percent chose tap, and radiography accounted for 19 percent. Four percent of the responses indicated other methods.

- Material and Process Control Responses

  – Of the 18 responses, 77 percent said UT, 72 percent said visual, 72 percent said tap, and 27 percent said radiography.

  The following responses were from the category Other.

  – "Shearography"
  – "Measure"

- Design Responses

  – Of the three respondents, two chose visual, UT, and tap. The third respondent did not reply.

- Manufacturing Response

  – The respondent chose visual and UT.

- Analysis Responses

  – Of the 13 responses, 77 percent said UT, 69 percent said visual, 38 percent said tap, and 7 percent said radiography.

- Regulator/Customer Responses

  – Two of the three respondents, only two replied. One chose visual and UT and the other indicated visual, UT, radiography, and tap.

One-hundred percent of the respondents classify by size to control defects. Seventy-six percent classify by number and 71 percent use proximity. Seventeen percent of the responses cited other methods.

- Material and Process Control Responses

  – Of the 16 responses, 100 percent said size, 68 percent said number, and 68 percent said proximity.

  The following responses were from the category Other.

  – "Type"
  – "Part criticality: primary structure, secondary structure"
  – "Percent of bonded area"

- Design Responses

  – Of the three respondents, only two responded. One respondent indicated size, number, and proximity. The second respondent chose the category Other, stating "No defects permitted."

- Manufacturing Response

  – The respondent indicated size and number.

- Analysis Responses

  – Of the 12 responses, 100 percent said size, 91 percent said number, and 83 percent said proximity.

  The following responses were from the category Other.

  – "Type"

  – "5 MHz TTU (through transmission ultrasonics) correlated to standards is used on primary structure composites."

  – "Percent area and bondline width"

- Regulator/Customer Responses
  - Two of the three respondents replied. One chose size and proximity and the other indicated size, number, and proximity.
- Other Category Responses
  - “Part criticality: primary structure, secondary structure.”
  - “The amount of total bond length reduced in major load direction.”

Question 10: When asked if the process for dealing with bonded structure discrepancies in their factory was efficient, inefficient, or rarely used, 57 percent of the respondents found their process efficient. Twenty-five percent rarely used their process and 17 percent found their process inefficient. One percent of the respondents indicated the category Other.

- Material and Process Control Responses
  - Of the 13 responses, 54 percent said efficient, 23 percent said inefficient, and 23 percent said rarely used.
- Design Responses
  - Two of the three respondents replied that the process was efficient. The third respondent did not reply.
- Manufacturing Response
  - The respondent replied that the process was efficient.
- Analysis Responses
  - Of the 12 responses, 58 percent said it was efficient, 33 percent said it was inefficient, and 8 percent said it was rarely used.
- Regulator/Customer Responses
  - Of the three respondents, one respondent said the process was efficient and another said the process was rarely used.
- Other Category Responses
  - “Defects outside limits require repeating the process.”
  - “Only involved in assisting with repairs.”

Question 11: The participants responded to the statement “Equipment and tooling maintenance is essential to structural bonding” as follows.

- Material and Process Control Responses
  - Of the 23 responses, 39 percent strongly agreed, 34 percent agreed, and 8 percent neither agreed nor disagreed. No respondents disagreed or strongly disagreed.
- Design Responses
  - Of the four responses, 50 percent agreed and 50 percent strongly agreed.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 13 responses, 54 percent strongly agreed, 38 percent agreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents replied. One strongly agreed and one agreed.

Question 12: The respondents indicated the following necessary hours of training for production personnel.

- Material and Process Control Responses
  - "80" (3)
  - "40" (2)
  - "200"
  - "10"
  - "40 to 80"
  - "Varies"
  - "5 to 10"
- Design Responses
  - "Course dependent"
  - "Continual"
- Manufacturing Response
  - "20"
- Analysis Responses
  - "8" (2)

- "40"
- "ND"
- "80"
- "Years"

- Regulator/Customer Responses

  - "120"

- Other Category Response

  - "Minimum 20"

The respondents indicated the following types of training for production personnel. On the job training was chose in 38 percent of the responses, demonstration was chosen in 33 percent, practical at 30 percent, and classroom at 26 percent. Five percent of the responses cited other types of training.

- Material and Process Control Responses

  - Of the 12 responses, 100 percent said on the job training, 75 percent said demonstration, 66 percent said practical, and 50 percent said classroom. The response from the category Other was "apprentice under supervision."

- Design Responses

  - Of the three respondents, two replied classroom, demonstration, practical, and on the job training. The third respondent did not reply.

- Manufacturing Response

  - The respondent replied demonstration, practical, and on the job training.

- Analysis Responses

  - Of the 12 responses, 83 percent said on the job, 75 percent said demonstration, 75 percent said practical, and 66 percent said classroom.

  The following responses were from the category Other.

  - "Certification of Spray Coat Operators for Priming"
  - "Certification Method for PAA operators"

- Regulator/Customer Responses
  - Two of the three respondents replied. One respondent indicated classroom and on the job training. The second respondent chose classroom, demonstration, and on the job.
- Other Category Responses
  - Seminars and symposiums.

Question 13: The respondents specified the manufacturing documents used for bonding process steps as follows.

- Material and Process Control Responses
  - “Specs for cleaning”
  - “Surface prep of each material”
  - “Adhesive bond primer application”
  - “Bonding lay-up operations”
  - “Cure”
  - “Deflash”
  - “Part specific work descriptions are provided to shop floor personnel for one-off repairs. Heavy interaction with engineering staff is necessary to ensure high quality.”
  - “We have standard WCD’s (work control documents).”
  - “Planning with sign-offs”
  - “Formal visual aids”
  - “Manufacturing work instructions”
  - “Process specification” (5)
  - “Step by step fabrication orders that travel with the parts.”
  - “Controlled and FAA approved process specification for bond prep, adhesive mixing, adhesive application and curing.”

- Design Responses
  - “Approved maintenance data”
  - “Repair schemes”
  - “Manuals”
  - “OEM documentation (i.e. SRM, CMM, AMM, engineering drawings)”

- Manufacturing Response
  - “Work order”

- Analysis Responses
  - “Process Specifications define the requirements of min/max limits, allowable materials, QC, and qualification. Process specifications do not provide how to information.”
  - “Each research program develops a bonding process that is maintained throughout the programmed to ensure repeatability of tests.”
  - “Process manuals”
  - “Manufacturing order”
  - “We prepare computer based video guidance”
  - “Planning documents” (3)
  - “Drawing”
  - “Process Specification (or other document)”
  - “Work orders that list steps in order”
  - “Process controls”

- Regulator/Customer Responses
  - “Work order”
  - “Job card”
  - “Step by step manufacturing plans”
  - “Specifications”

- Other Category Responses
  - “Planning with sign-offs”

- “Adhesive manufacturers’ data sheets.”

- “Details of personnel, temp, humidity, supervisor, batch numbers, lifting, pass/fail steps in process documented, data basing of all work details for ready reference in fault finding or identifying deviations in trends.”

- “Reference standard practice manuals containing this information.”

- “Technique sheets”

- “Detailed processing specifications”

- “Bill of Material”

- “Lay-up charts”

- “Inspections”

- “Typical planning/traveler format with operator, Verification authority, and inspection authority sign-offs (depending on requirements).”

- “A standard generic collection of process specifications is used. These are contained an RAAF publication AAP 7021.016-2 Composite Materials and Adhesive Bonded Repairs: Repair Fabrication and Application Procedures.”

- “Manufacturing policy documents”

- “Quality work instructions”

- “PDS (cure sheets)”

- “Only involved with repairs”

- “Shop order/inspection record for each part with operational steps that includes documentation and verification of each operation.”

Question 14: One hundred percent of the respondents said that cure duration and temperature were the significant records taken during the bonding process steps.

- Material and Process Control Responses

  - Of the 17 responses, 100 percent said cure duration, 100 percent said cure temperature, and 94 percent said out of time of adhesive.

  The following responses were from the category Other.

  - “FOD control records”

- “Lay-up personnel”
- “Lay-up temperature/humidity”
- “Times between solvent wipes and end of flash/application of adhesive”
- “Shelf life of each primed detail”
- “Pressure”
- “Vacuum bag integrity”
- “Time”
- “Process controls for surface treatment”
- “Pot life of mixed adhesive”

- Design Responses

  - Of the three respondents, only two replied. Both respondents chose cure duration, out time of adhesive, and cure temperature.

  The following responses were from the category Other.

  - “Primer thickness”
  - “Pretreatment records out life etc.”
  - “Vacuum”
  - “Pressure”

- Manufacturing Response

  - The respondent chose cure duration, out time of adhesive, and cures temperature.

- Analysis Responses

  - Of the 12 responses, 100 percent said cure duration and cure temperature and 66 percent said out time of adhesive.

  The following responses were from the category Other.

  - “Cleaning warranty”
  - “Thermal/Time History (ramp rates, hold times, hold temps)”
  - “Cure pressure”
  - “Adhesive mix”
  - “Second inspection of prep”
  - “Retained adhesive”

- Regulator/Customer Responses

  - Two of the three respondents replied. One replied cure duration, out time of adhesive, and cure temperature. The other respondent chose cure duration, out time of adhesive, and cure temperature and also chose the category Other, stating “Operator.”

- Other Category Responses
  - "Rates"
  - "FOD control records"
  - "Humidity"
  - "Ambient room-temperature"
  - "Time from application to close"
  - "Times at which surface preparation steps were performed, including surface exposure times."
  - "Temperature charts including maximum cure temperature in heated zone and minimum cure temperature near bondline."
  - "Technician's identification to ensure qualified and competent."
  - "Materials batch numbers."
  - "Independent assessment of water break test."
  - "Pot life of mixed adhesive"
  - "Heat rise"
  - "Leak rate"
  - "Vacuum & vent"
  - "Cool down"

Question 15: The respondents had the following comments on manufacturing:

- Material and Process Control Responses
  - "This complexity, or rather the amazing number of ways to produce scraps or worse, is why many people don't trust bonding. Only for the detail oriented, persistent, and consistent. Even tougher than composites to wade in to."
- Design Responses
  - None of the three respondents replied.

- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - “Adhesive temperature should be measured not oven or press temperature.”
- Regulator/Customer Responses
  - “Process control and training are essential.”
- Other Category Responses
  - “Manufacturing issues are handled by our customers with minimal input from our company.”
  - “Record keeping on the manufacturing steps is a real part of long term quality control. Since this manufacturing history can form a bases for potential solutions to in-service structural bonding problems.”
  - “Humidity / moisture must be controlled up to and during bonding. Open time and carbonate formation on the adhesive can greatly affect the adhesive and ultimate bond strength.”
  - “A method for ensuring competency of technicians is essential.”
  - “Under no circumstances must the bonding process be varied from that used for laboratory tests to qualify a process.”
  - “After bond inspection will not guarantee a durable bond. It only verifies the absence of defects.”
  - “We are a lab environment processing small panels only.”
  - “Only involved with repairs.”

C.6 MANUFACTURING AND DESIGN INTEGRATION SUBSECTION: ALLOWABLES AND DESIGN DATA.

Question 1: When asked what allowable they used, the respondents replied: 77 percent used lap shear, 50 percent used thick adherend, and 31 percent used bulk adherend. Thirteen percent chose the category Other.

- Material and Process Control Responses

  – Of the 15 responses, 73 percent said lap shear, 53 percent said thick adherend, and 40 percent said bulk adherend.

  The following responses were from the category Other.

  – "Durability - cycles to failure"
  – "Tensile Strength"

- Design Responses

  – Of the three respondents, only one replied, stating lap shear.

- Manufacturing Response

  – The respondent did not comment.

- Analysis Responses

  – Of the 15 responses, 93 percent said lap shear, 60 percent said thick adherend, and 33 percent said bulk adherend.

  The following responses were from the category Other.

  – "Tension (pull off)"
  – "In plane shear"
  – "Hardpt, chordwise loading"
  – "Moment (pull off)"
  – "Strain energy parameters"
  – "Sandwich beam shear"
  – "Fracture toughness (GI1, giic, mixed gic/giic)"

- Regulator/Customer Responses

  – Of the three respondents, two listed both lap shear and thick adherend.

- Other Category Responses

  – "Shear strain determined from thick adherend lap shear test."

  – "Basic properties of bonded joints must be defined by testing so that the basic design tools available to the designer and the stress man. However, just like mechanical fastened joints there needs to be tests to cover all aspects of the usage of bonded joints. Example, peel testing of joints, tapered joint testing of lap joints and tension test perpendicular to the bond line. Some of these can be the so called standard testing other will be directed to a specific design."

- “Double lap-shear” (2)
- “Flat wise tension”

The most common design data used to support the design of bonded structure was standard adhesive thickness at 33 percent, followed by lap widths at 32 percent, and standard joint configurations at 27 percent. The category Other responses comprised 6 percent.

- Material and Process Control Responses
  - Of the 14 responses, 78 percent said standard adhesive thickness, 71 percent said standard lap widths, and 64 percent said standard joint configurations.

  The following responses were from the category Other.

  - “Point design for specific areas”
  - “Nonstandard thicknesses and joint configurations”

- Design Responses
  - Of the three respondents, only one replied. The respondent chose standard lap widths, standard adhesive thickness, and standard joint configurations.

- Manufacturing Response
  - The respondent did not comment.

- Analysis Responses
  - Of the 12 responses, 83 percent said standard lap widths, 83 percent said thicknesses, and 75 percent said standard joint configurations. The category Other response was “specific joint test results.”

- Regulator/Customer Responses
  - Of the three respondents, two chose standard lap widths, standard adhesive thicknesses, and standard joint configurations.

- Other Category Responses
  - “Verification testing”
  - “Thick adherend test data is essential”

Question 2: Forty-four percent of the respondents strongly agreed and 42 percent agreed that effects of environment (moisture, temperature) were included in the allowables and design data development. One percent neither agreed nor disagreed, and 2 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 16 responses, 56 percent strongly agreed, 31 percent agreed, and 12 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, only one replied. The respondent strongly agreed.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - Of the 15 responses, 46 percent agreed, 33 percent strongly agreed, 13 percent strongly disagreed, and 6 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Two of the three respondents replied. One respondent agreed and the other neither agreed nor disagreed.

Fifty-one percent of the respondents strongly agreed, and 40 percent agreed that effects of environment (moisture, temperature, etc.) should be included in the allowables and design data development. Four percent neither agreed nor disagreed and an additional 4 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 16 responses, 75 percent strongly agreed, and 25 percent agreed.
- Design Responses
  - Of the three respondents, only one replied. The respondent strongly agreed.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - Of the 15 responses, 46 percent agreed, 40 percent strongly agreed, and 14 percent strongly disagreed.

- Regulator/Customer Responses
  - Two of the three respondents replied. One respondent agreed and the other neither agreed nor disagreed.

Question 3: The respondents said the following bond overlap length (in inches) was used for testing.

- Material and Process Control Responses
  - ".75" (2)
  - ".25-4.0"
  - ".5" (4)
  - ".75 to 5 inches"
  - "1/2"
  - ".78"

- Design Responses
  - "0.5"

- Manufacturing Response
  - The respondent did not comment.

- Analysis Responses
  - "0.5"
  - "1 inch" (2)
  - "Specific joints"
  - "0.5 and others"
  - "0.354-0.5"
  - "Usually 1/2 in. "
  - "0.75"
  - "Various"

- Regulator/Customer Responses
  - "Dependent on mating part thicknesses"
  - "1.0″"

- Other Category Responses
  - "0.78"
  - "2" (3)
  - "3"

- "More than 2"
- "1-2"

Forty-five percent of the respondents agreed and 9 percent strongly agreed that if a number of overlap lengths exist in design, the test plan should be representative of all the overlaps used. Twenty-two percent neither agreed nor disagreed, 12 percent disagreed, and an additional 12 percent strongly disagreed.

- Material and Process Control Responses

  - Of the 14 responses, 35 percent agreed, 21 percent neither agreed nor disagreed, 21 percent strongly disagreed, and 14 percent disagreed.

- Design Responses

  - Of the three respondents, one strongly agreed. The other two did not reply.

- Manufacturing Response

  - The respondent did not reply.

- Analysis Responses

  - Of the 15 responses, 53 percent agreed, 20 percent strongly agreed, 20 percent neither agreed nor disagreed, and 7 percent strongly disagreed.

- Regulator/Customer Responses

  - Two of the three respondents replied. One respondent agreed and the other disagreed.

Question 4: The respondents selected the following adhesive layer thickness(es)—in inches—that should be used for bonded joint characterization: 25 percent of the responders said that 0.007-0.020 inch should be used and an additional 25 percent specified 0.004-0.007 inch. Both 0.002-0.004 and 0.020-0.050 inch were cited in 11 percent of the responses. Fifteen percent chose the category Other, with 7 percent of the responses stating 0.050-0.100 inch.

- Material and Process Control Responses

  - Of the 14 responses, 71 percent said 0.004-0.007, 50 percent said 0.007-0.020, 28 percent said 0.002-0.004, 21 percent said 0.050-0.100, 14 percent said 0.20-0.050, and 7 percent said 0.150-0.250.

  The following responses were from the category Other.

  - "Depends on Joint configuration."
  - "Overlap length is a function of adherend thickness."

  - "Depends upon production adhesive thickness."

- Design Responses

  - Of the three respondents, two replied. One chose a thickness of 0.002-0.004 and the other chose 0.007-0.020. The third respondent did not reply.

- Manufacturing Response

  - The respondent did not comment.

- Analysis Responses

  - Of the 14 responses, 21 percent said 0.004-0.007, 50 percent said 0.007-0.020, 7 percent said 0.002-0.004, and 14 percent said 0.050-0.100.

  The following responses were from the category Other.

  - "Application dependent and tolerance dependent."

  - "Depends on the adhesive, we typically use .008 which is controlled by a scrim. It can vary between .003 and .012 or so."

  - "Whatever is representative of as-fabricated parts."

- Regulator/Customer Responses

  - Of the three respondents, two replied. One chose 0.007-0.020, 0.020-0.050, and 0.050-0.100. The second respondent chose Other, stating "Depends on the adhesive type and application (joint shear stress levels)."

- Other Category Responses

  - "Depends upon the aerial weight of the adhesive film and the pressurization method used."

  - "0.002 to 0.020"

  - "0.150 - 0.250"

  - "Whatever represents your anticipated manufacturing process capability."

  - "The thickness expected in the product although most structural bonds will be in the 0.1mm to 0.2mm range."

Forty-seven percent of the respondents agreed that their design has tolerances specified for quality control and 18 percent strongly agreed. Twenty-five percent neither agreed nor disagreed, 7 percent disagreed, and 2 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 14 responses, 57 percent agreed, 28 percent strongly agreed, and 14 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one strongly agreed. The other two did not reply.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - Of the 15 responses, 46 percent neither agreed nor disagreed, 33 percent agreed, 13 percent strongly agreed, and 6 percent disagreed.
- Regulator/Customer Responses
  - Of the three respondents, one agreed and one neither agreed nor disagreed.

When asked if they test only the maximum thickness for allowables characterization, the respondents answered as follows: 49 percent disagreed, 16 percent strongly disagreed, 30 percent neither agreed nor disagreed, and 4 percent agreed.

- Material and Process Control Responses
  - Of the 15 responses, 53 percent disagreed, 33 percent neither agreed nor disagreed, and 13 percent strongly disagreed.
- Design Responses
  - Of the three respondents, none replied.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - Of the 15 responses, 53 percent disagreed, 20 percent neither agreed nor disagreed, 20 percent strongly disagreed, and 6 percent agreed.
- Regulator/Customer Responses
  - Of the three respondents, two neither agreed nor disagreed.

Question 5: When identifying statistics or statistical code that is used to develop the allowables, the majority of the responses (76 percent) indicated that Mil-Handbook-17 was used. Thirty-eight percent used average-standard deviation, 29 percent cited AGATE, and 5 percent chose ANOVA, seep figure C-3.

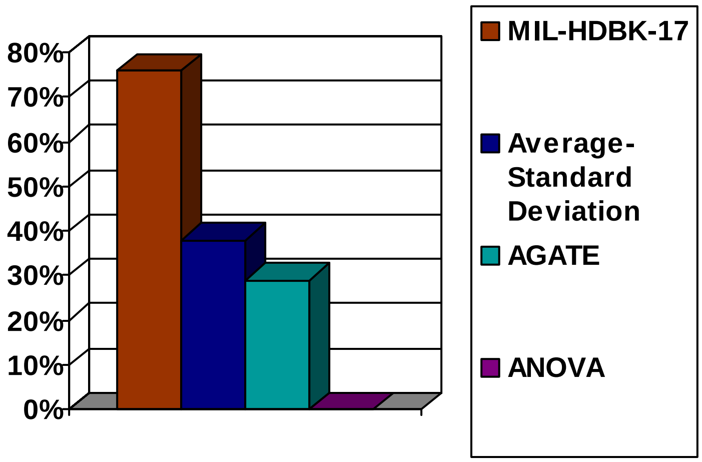

FIGURE C-3. STATISTICAL CODES USED TO DEVELOP ALLOWABLES

- Material and Process Control Responses

  – Of the 12 responses, 75 percent said Mil-Handbook -17, 41 percent said AGATE, and 25 percent said average-standard deviation.

  The following were the category Other responses.

  – "OEM development (Mil-17 variants typically)"
  – "In-house method for thick adherend data to get B-basis stress-strain curve."

- Design Responses

  – Of the three respondents, one respondent indicated Mil-Handbook-17. The other two respondents did not reply. The category Other response was "Software."

- Manufacturing Response

  – The respondent did not comment.

- Analysis Responses

  – Of the 13 responses, 69 percent said Mil-Handbook-17, 38 percent said average-standard deviation, 30 percent said AGATE, and 15 percent said ANOVA.

- Regulator/Customer Responses
  - Of the three respondents, two indicated Mil-Handbook-17.

Question 6: Fifty-two percent of the respondents agreed and 14 percent strongly agreed that data from qualification testing or other repetitive bonded joint tests were used to establish statistically based design allowables. Sixteen percent neither agreed nor disagreed, 14 percent disagreed, and 2 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 14 responses, 35 percent agreed, 35 percent strongly agreed, 21 percent disagreed, and 7 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one agreed. The other two did not reply.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - Of the 14 responses, 71 percent agreed, 14 percent disagreed, 7 percent neither agreed nor disagreed, and 7 percent strongly disagreed.
- Regulator/Customer Responses
  - Of the three respondents, one agreed and one neither agreed nor disagreed.

When asked if alternatively, a lower "minimum bond strength design value" is set based on experience and test data (e.g., 500 psi), 38 percent of the respondents agreed, 7 percent strongly agreed, 30 percent neither agreed nor disagreed, 15 percent disagreed, and 7 percent strongly disagreed.

- Material and Process Control Responses
  - Of the 20 responses, 95 percent strongly disagreed and 5 percent strongly agreed.
- Design Responses
  - Of the three respondents, all three strongly disagreed.
- Manufacturing Response
  - The respondent did not comment.

- Analysis Responses
  - Of the 14 responses, 78 percent strongly disagreed, 14 percent disagreed, and 8 percent agreed.
- Regulator/Customer Responses
  - Of the three respondents, all three strongly disagreed.

The participants responded to the statement "If your adhesive design allowable is based on the thick adherend test, you verify the adequacy of the design by comparing the value to…" The majority at 41 percent chose peak shear stresses, 26 percent chose average shear stresses, and 8 percent said that they do not verify. Twenty-three percent cited the category Other.

- Material and Process Control Responses
  - Of the 11 responses, 45 percent said peak shear stresses, 18 percent said average shear stresses, and 9 percent said they do not verify.

  Thirty-six percent chose the category Other, stating:

  - "Elastic-plastic joint analysis in some cases."
  - "Don't do thick adherend testing."
  - "Don't use this in joint design. Not applicable for thin composite substrates in most cases."
  - "Verified by component and full-scale fatigue tests."
- Design Responses
  - None of the three respondents replied.
- Manufacturing Response
  - The respondent strongly disagreed.
- Analysis Responses
  - Of the 11 responses, 45 percent said average shear stresses, 45 percent said peak shear stresses, and 18 percent said do not verify. The response from the category Other was "Do not use data from the thick adherend test."
- Regulator/Customer Responses
  - "Combination of analysis and tests for the coupon and structural details."

- Other Category Responses
  - "Local peak stresses do not necessarily mean that the design is bad. A combination of the global stresses and the local peak stresses will determine if the design is good."
  - "Calculated load capacity for he bond, together with provision of adequate overlap length."

Question 7: The respondents gave the following comments identifying data collected to support dispositions of manufacturing defects and other discrepancies for bonded structures.

- Material and Process Control Responses
  - "Minimum of process verification coupons up to the maximum of repeating the specification test replicate for a specific process."
  - "Developmental parts include designed in defects for NDI and structural test. Developmental parts with representative defects are collected for archive."
  - "Discrepancy size, location, proximity all related to assembly geometry."
  - "Additional coupon testing with thick adhesive thicknesses."
  - "The defect size, location and proximity are derived from the full scale test article with intentional defects sustaining the ultimate Loads."
  - "Ultrasonic bond tests."
  - "Size of disbonded area."
  - "Full scale tests incorporating manufacturing defects."
  - "Copies of prior dispositions."
- Design Responses
  - None of the three respondents replied.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - "Size of the defect; Thickness and location."
  - "Empirical test data."

- "Tests of actual joint configurations with intentional flaws."
- "HNC (Non-Conformity Sheet) database"
- "If not covered by company standard repair methods, usually perform point design mini program specific to anomalous area."
- "NDI reports of bond flaws and evaluation data."
- "Fracture mechanics analysis"
- "NDI, T_g, Lap shear, flatwise tension"
- "Size, location, type, adherend thickness, adherend stiffness"
- "Much testing"

• Regulator/Customer Responses

- "Design detail tests for a range of specific defects."

• Other Category Responses

- "Adhesive thickness, out time effects."
- "Strength reduction factors for typical/anticipated inclusions/voids."
- "Test articles with simulate types of manufacturing defects needs to be part of the total test program. This information is not only needed for design but for establishing manufacturing inspection and acceptance procedures."
- "Verify that processes were correct, then accept/reject on the basis that a 50 percent MOS exists above the overlap length necessary to carry the design load solely by plastic behavior, provided that the width of the defect does not exceed 10 percent of the bond width."
- "Intentional defects placed in test articles."

Question 8: The respondents gave the following comments, indicating data was collected for fatigue and damage tolerance assessment of bonded structure.

• Material and Process Control Responses

- "On the front end, lifetime (10^7) run out at nominal stress."
- "Double overlap shear and symmetrical skin doublers fatigue specimens."
- "Coupon to element/subcomponent to full scale."

- "Double overlap shear tests."
- "Full scale fatigue test article."
- "The tolerance assessment is derived by full scale test article with intentional defects sustaining the ultimate loads."
- "Fatigue test reports."

• Design Responses

- None of the three respondents replied.

• Manufacturing Response

- The respondent did not comment.

• Analysis Responses

- "Building block testing."
- "Full-scale fatigue tests for critical structures."
- "Empirical test data."
- "Full scale test data."
- "For fatigue, cyclic load tests of basic coupons and actual joint configurations."
- "HNC (non-conformity sheet) database."
- "Continuously growing pool of data (continuous ongoing research)."
- "Da/DN and growth data"
- "Flaw size, Cyclic tests"
- "Size, Location, Type, Adherend thickness, Adherend stiffness"

• Regulator/Customer Responses

- "Elements"
- "Components"
- "Large-scale structure"

- Other Category Responses
  - "Most of our testing is fatigue testing using bonded repairs, crack-growth before and after patching is a critical variable."
  - "In service life analyses are performed on various pieces of hardware."
  - "S-N curves, crack"
  - "Growth rates"
  - "Data from representative test coupons and elements."
  - "Full scale structural tests"
  - "Test data, fleet experience"
  - "Testing of structural segments and total section to validate the design meeting these requirements is a must do. In addition some early test to establish these structural capabilities is required for the development of the design."
  - "Verify that the adhesive shear strain at 60% of limit load is less than twice the elastic limit for ductile adhesives or less than 80% of the elastic limit at dll for brittle adhesive systems."
  - "None"
  - "Environments"
  - "For DT (damage tolerance), tests of actual joint configurations with intentional flaws."
  - "For critical joints, minimum defect detectable by NDI is tested at the element or sub-component level as part of damage tolerance assessment. Damage may also be inflicted during full scale testing."

Question 9: Fifty percent of the respondents do enter collected data into a database for review over time and 50 percent do not. When asked what data is collected to support service damage disposition and bonded structural repair, the respondents replied as follows.

- Material and Process Control Responses
  - "Depends on repair allowable and repair manuals."
  - "Currently we are tearing down old repairs recovered from service including C-130E repairs to wing risers and Mirage repairs to lower wing skins. Repairs to

F-111 honeycomb panels will also be examined and it is hoped a correlation between service life and accelerated laboratory testing will be established."

- "Same as 7 above plus any additional materials/process required due to field/fielded repair constraints (can't etch bonded hardware easily, moisture abs. for core, etc.)."
- "All production and process records on individual assemblies."
- "Full scale fatigue test article with inflicted damage."
- "Size of disbonded area."
- "Field repairs are individually substantiated, case by case."
- "Copies of prior repairs and dispositions."

- Design Responses
  - None of the three respondents replied.
- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - "Design lessons learned."
  - "Size of the defect; Thickness and location."
  - "Repair Manual."
  - "Empirical test data."
  - "Residual strength curves for laminates."
  - "Continuously growing pool of data (continuous ongoing research)."
  - "Flaw size, Surface conditions, Service history."
  - "Frequency, Size, Location, Type, Adherend thickness, Adherend stiffness."
- Regulator/Customer Responses
  - "Design detail tests for known service threats."

- Other Category Responses

  – "The tolerance assessment is derived by full scale test article with intentional defects sustaining the ultimate Loads."

  – "Data from representative test coupons and elements."

  – "Here, various damages are selected as the most likely to occur and be critical to establish the aircrafts inspection requirement as well as develop the repairs for the damage types selected for repair development. It of course must be understood that all type of in-service damage repairs cannot be addressed during the aircrafts design and development. Those that are not covered will have to be reviewed by the aircrafts maintenance organizations and if necessary by the planes manufacture to develop the repair process need for those specific damage."

  – "Service time"

  – "Time since repair"

  – "Type of bond failure (adhesion or cohesion)"

  – "Location and size of defect."

  – "Consequences of failure"

  – "Not sure"

  – "Service history"

  – "Not asked to do this."

  – "Tests of bonded joint configurations: 2D coupons/elements and 3D panel."

Question 10: The respondents made the following comments on allowables and design data.

- Material and Process Control Responses

  – "Mostly handled by OEMs and approved by NAVAIR."

  – "I did not know the answers to many of the questions in this section."

  – "It is very difficult to get statistically meaningful data that can be used reliably for design."

- Design Responses

  – No respondents replied.

- Manufacturing Response
  - The respondent did not comment.
- Analysis Responses
  - "Bond joint thickness depends upon being a paste or a film adhesive. Paste should use 0.005-0.12; film should use 0.002-0.020."
  - "Too often average stress is used in a new design; this could cause problems because it does not reflect reality."
  - "There are questions above about lap length and bondline thickness. The trouble with lap joint coupons is that they are not representative of the loads or boundary conditions within the structure. They are a step for comparing adhesive systems alone."
- Regulator/Customer Responses
  - "I believe that a double lap-shear joint test should be developed to eliminate secondary bending from the single lap shear joint."
- Other Category Responses
  - "Development of mechanical tests that correctly represent the stresses in the adhesive joint are very difficult to design."
  - "Often the failure modes present in composite repairs are quite complex and design to allow for these failure modes is difficult."
  - "Design allowables are set with minimal input from DuPont."
  - "Most "allowables" are not statistically based."
  - "Allowables and design data need to be funded by the design company to make sure that the design will meet all requirements for safe performance."
  - "This coverage is often minimized by the companies but it never even reaches 1% of the aircrafts development cost therefore good management funds the development of this structural data as it should be funded."
  - "In-service defects are an indication of process failures or very bad designs, not fatigue or overload. In-service defects cannot be repaired or bought-off."
  - "Our long-range research project is to develop methods to accurately predict performance under realistic service conditions - helping to reduce allowables testing required and allow for materials substitution."

– "Not involved with calculating allowables or design data."

C.7 PRODUCT DEVELOPMENT, SUBSTANTIATION, AND SUPPORT.

Question 1: Of 47 respondents, 91 percent indicated that, in their experience, product development (through certification) lead times are longer for bonded structure than for conventional structure using mechanical fastening. Nine percent responded that they are shorter.

- Material and Process Control Responses
  - Of the 21 responses, 90 percent said lead times are longer and 10 percent said they are shorter.
- Design Responses
  - Of the three respondents, one replied, stating lead times are longer.
- Manufacturing Response
  - The respondent said lead times are longer.
- Analysis Responses
  - Of the 14 responses, 92 percent said lead times are longer and 7 percent said they were shorter.
- Regulator/Customer Responses
  - Two of three respondent replied. Both said lead times are longer.

For the respondents that answered shorter, 42 percent of seven responses neither agreed nor disagreed that this is always the case, while 28 percent agreed, 14 percent disagreed, and 14 percent strongly agreed.

- Material and Process Control Responses
  - The respondent who stated shorter neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent agreed.
- Analysis Responses
  - The respondent who stated shorter neither agreed nor disagreed.

Question 2: When asked if the response to question 1 in this section was dependent on any one function or discipline more than others, the respondents answered as follows: 50 percent found the lead times were dependent on materials and processes. Twenty-five percent cited design, 19 percent manufacturing, and 5 percent listed maintenance.

- Material and Process Control Responses
  - Of the 12 responses, 50 percent said materials and processes, 25 percent said manufacturing, and 25 percent said design.
- Design Responses
  - Of the three respondents, one replied maintenance.
- Manufacturing Response
  - The respondent said materials and processes.
- Analysis Responses
  - Of the 13 responses, 61 percent said materials and processes, 23 percent said design, 7 percent said manufacturing, and 7 percent said certification and testing.
- Regulator/Customer Responses
  - Two of the three respondents replied. One said manufacturing and one said design.
- Other Category Responses
  - "It depends on the combination of all. M & P because adhesive bonding is different and needs different attitudes. Design because there are still many unknowns. Manufacturing because of all the things that can go wrong using bonding. Inspection and long term durability can only be guaranteed through process control."
  - "NDI methods available."
  - "Certification and testing."
  - "Structural Certification. M and P must be established beforehand. Design is easy. How you certify that design is more difficult. Because there is no method for assurance of bond integrity, current certification approaches (at least for repair) assume bond failure. Hence it is necessary to demonstrate that the repair was not necessary before one can use the repair."

Question 3: Seventy-four percent of the responders advocate using the traditional building block approach in adhesively bonded structures, 19 percent preferred the inverted approach, and 6 percent said that they do not use the building block approach. One percent cited the category Other.

- Material and Process Control Responses

  – Of the 11 responses, 63 percent said traditional approach, 18 percent said they do not use the building block approach, and 9 percent said inverted approach.

  The following were the responses from the category Other.

  – "Traditional approach, realizing that any significant change to the surface prep for any critical substrate, adhesive bond primer, and/or adhesive and you get the opportunity to start over."

  – "Mixture of coupon and subscale articles."

- Design Responses

  – Of the three respondents, one replied. The respondent said inverted approach, large scale information first.

- Manufacturing Response

  – The respondent said inverted approach, large scale information first.

- Analysis Responses

  – Of the 13 responses, 61 percent said traditional approach, 23 percent said inverted approach, large scale information first.

  The following responses were from the category Other.

  – "To better investigate the onset of debonding/delamination as the precursor to failure innovative element testing should become part of the building block approach such that the attention is focused on the initiation of debonding not the final failure. Design should then attempt to be optimized to delay the initiation (not total failure) giving improved overall failure loads."

  – "Depends on the particular application and structure." (2)

- Regulator/Customer Responses

  – Two of three respondents replied. One said traditional approach and one stated "Answer to this question would be design-specific."

- Other Category Responses

  – "Traditional approach is good although there is already a lot of information (both good and bad) for bonded (large) structures."

  – "Manufacturing processes should be part of the certification basis, such that repair durability is demonstrated. Then existing certification methodology is appropriate."

Question 4: The majority (38 percent) of the respondents said that the scale of testing that yields the most meaningful data for bonded structure development, substantiation, and support was different in every case. Twenty-two percent said element, 14 percent said full-scale, 12 percent said subcomponent, 10 percent said coupon, and 2 percent said component.

- Material and Process Control Responses

  – Of the 18 responses, 61 percent said the scale is different in every case, 16 percent said full-scale, 11 percent said element, 5 percent said coupon, and 5 percent said subcomponent.

- Design Responses

  – Of the three respondents, one replied, stating element.

- Manufacturing Response

  – The respondent said coupon.

- Analysis Responses

  – Of the 14 responses, 28 percent said it was different in every case, 21 percent said element, 21 percent said subcomponent, 14 percent said full scale, 7 percent said component, and 7 percent said coupon.

- Regulator/Customer Responses

  – Two of the three respondents replied. One said element and one said subcomponent.

The respondents that replied said it was different in every case, as explained below.

- Material and Process Control Responses

  – "It depends on the part and the way the bonded joint is loaded."

  – "Coupon: Is this a good adhesive/bond primer/surface prep combo? Element/subcomponent: Can the combo support the loadings I'm aware of?

Component: Can I manufacture good quality bondlines over the entire faying surface? Full scale: Are there any complex loadings I'm unaware of?"

– "Joint / adhesive strength is dependant on design. Joint allowables should reflect joint design plus basic adhesive properties."

– "Depends on joint complexity and integration into load path. As an end user, a joint that gives 200 percent of DUL doesn't buy us anything if it is next to a joint that only gives 150 percent of DUL, so it is often not until the full-scale article that we learn how the joints interact when loaded."

– "University perspective! Lot of diversity in what we do."

– "Depends on criticality of part and cost restraints."

– "Each type of test gives different information. Coupon test - material properties for design - subcompound and element - tooling and manufacturing issues. Component/ full scale used for substantiation."

– "For example, it would be different if you are qualifying a paste adhesive for click bonding or a film adhesive for a primary structural bond. I don't know how to answer this except on a case by case basis."

– "Coupon testing is applicable for characterizing adhesive. Subcomponent is more applicable for composite assembly applications. Full-scale is important to identify critical design constraints and focus detailed subcomponent testing in areas."

– "A combination is required."

- Analysis Responses

  – "Joints with high peeling stresses or complex geometry must be tested by subcomponent, component, or full scale. Coupon or element tests may be used for joints without high out-of-plane loads."

  – "An element test will allow local design features to be investigated to delay debond initiation see 3 above, but component testing will be required for final substantiation."

  – "Data at most levels it typically required; can't say one is more meaningful than the others."

  – "For identification of secondary or non-linear effects full scale or component is best, for characterizing local stress state effects of changing joint parameters element is best."

- “For some aspects coupon, for others subcomponent (i.e., Skin plus stringers concept).”

- Other Category Responses

  - “Full scale testing with known loads might be best, but is impractical and expensive!”

  - “Coupon to find a good material and process (esp. surface prep) and durability. Elements to verify if the bonding works in a mechanical way. Depending on the impact of possible failure of the bond component and full-scale may be justified although traditional fatigue testing does not mean that a bond is durable (the coupon testing should provide that (wedge test)).”

  - “Element and subcomponent testing yields the most useful substantiation as the test geometry achieved whilst simplified typically determines the most crucial aspects of the repair design.”

  - “The most effective answer is in designing such that wherever possible the adhesive is not the locus of failure. It is possible to design bonded joints such that the load capacity is greater than the unmatched strength of aluminum, up to about 0.14 inches. That means that the adhesive will never fail by shear, no matter what load case is used. For such designs, testing is meaningless because every test will fail away from the bond or composite structures, that condition can not be readily achieved for laminates over about ten plies, so a coupon, subcomponent, component test may be necessary.”

Question 5: The respondents indicated the criticality of bonded joint for structure is classified equally by loads and applications. Fifty-eight percent said loads and 56 percent said applications. Thirty percent said airworthiness experience and 15 percent chose the category Other.

- Material and Process Control Responses

  - Of the 17 responses, 64 percent said applications, 64 percent said loads, and 64 percent said airworthiness experiences.

  The following responses were from the category Other.

  - “Exposure Environment”
  - “Customer specification. Not sure if this is a clear question?”

- Design Responses

  - Of the three respondents, one replied. The respondent said applications.

- Manufacturing Response
  - The respondent said loads.
- Analysis Responses
  - Of the 12 responses, 58 percent said loads, 50 percent said applications, and 33 percent said airworthiness experiences. The response from the category Other was “Define failures criteria.”
- Regulator/Customer Responses
  - Two of the three respondents replied. One said both loads and airworthiness experience and one said loads and applications.
- Other Category Responses
  - “The reason for selecting other here is the item of usage history. In the time that bonding has been used the success of bonded structure has varied a lot. You must include current information as well as experience to select your design and analysis approach.”
  - “The consequences of failure at maximum load. Consequences of potential failure.”

An overview was not done for the responses to the question “Do you apply a different approach to product development and substantiation based on criticality?”

- Material and Process Control Responses
  - Of the 17 responses, 47 percent agreed, 23 percent strongly agreed, 23 percent neither agreed nor disagreed, and 5 percent disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent disagreed.
- Manufacturing Response
  - The respondent disagreed.
- Analysis Responses
  - Of the 13 responses, 54 percent agreed, 23 percent strongly agreed, 15 percent neither agreed nor disagreed, and 7 percent disagreed.

- Regulator/Customer Responses
  - Two of three respondents replied. One neither agreed nor disagreed and one agreed.

Question 6: Fifty-eight percent of the respondents agreed that the strength and damage tolerance of the bonded structure should be characterized during a full-scale test and 16 percent strongly agreed. Only 8 percent disagreed or strongly disagreed and 18 percent neither agreed nor disagreed.

- Material and Process Control Responses
  - Of the 17 responses, 47 percent agreed, 29 percent strongly agreed, 17 percent neither agreed nor disagreed, and 5 percent disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent agreed.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 14 responses, 57 percent agreed, 21 percent neither agreed nor disagreed, 14 percent disagreed, and 7 percent strongly agreed.
- Regulator/Customer Responses
  - Three respondents replied, two agreed and one disagreed.

Of the 47 responses, 55 percent agreed and 17 percent strongly agreed that analysis validation took place at this level. Twenty-five percent neither agreed nor disagreed and 6 percent disagreed or strongly disagreed.

- Material and Process Control Responses
  - Of the 17 percent, 53 percent agreed, 23 percent strongly agreed, and 23 percent neither agreed nor disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent neither agreed nor disagreed.

- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 13 responses, 61 percent agreed, 15 percent strongly agreed, 15 percent disagreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Three respondents replied. Two neither agreed nor disagreed and one agreed.

Question 7: When asked whether long-term environmental exposure and durability should be substantiated for bonded structures, 50 percent of the 50 responses indicated that participants strongly agreed, 44 percent agreed, 4 percent strongly disagreed, and 2 percent neither agreed nor disagreed.

- Material and Process Control Responses
  - Of the 17 responses, 65 percent strongly agreed and 35 percent agreed.
- Design Responses
  - Of the three respondents, one replied. The respondent strongly agreed.
- Manufacturing Response
  - The respondent agreed.
- Analysis Responses
  - Of the 14 responses, 50 percent agreed, 36 percent strongly agreed, 7 percent neither agreed nor disagreed, and 7 percent strongly disagreed.
- Regulator/Customer Responses
  - Three respondents replied. One agreed, one strongly disagreed, and one agreed.

Of the 49 respondents, 61 percent agreed that small-scale tests have meaning to service experiences and 4 percent strongly agreed. Twenty-nine percent neither agreed nor disagreed and 6 percent disagreed.

- Material and Process Control Responses
  - Of the 17 responses, 53 percent agreed, 35 percent neither agreed nor disagreed, 5 percent strongly agreed, and 5 percent disagreed.

- Design Responses
  - Of the three respondents, one replied. The respondent agreed.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 14 responses, 78 percent agreed, 7 percent strongly agreed, 7 percent disagreed, and 7 percent neither agreed nor disagreed.
- Regulator/Customer Responses
  - Three respondents replied. Two neither agreed nor disagreed and one agreed.

When asked if they have validated accelerated test methods, 30 percent of the respondents disagreed, 4 percent strongly disagreed, 51 percent neither agreed nor disagreed, 11 percent agreed, and 4 percent strongly agreed.

- Material and Process Control Responses
  - Of the 17 responses, 35 percent disagreed, 35 percent neither agreed nor disagreed, 23 percent agreed, and 5 percent strongly disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent neither agreed nor disagreed.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 14 responses, 71 percent neither agreed nor disagreed, 14 percent disagreed, 7 percent agreed, and 7 percent strongly agreed.
- Regulator/Customer Responses
  - Two of three respondents replied. One respondent disagreed and one neither agreed nor disagreed.

Question 8: Twenty-eight percent of the responses indicated that critical defect locations and types are identified based on bond joint stress levels, 26 percent by manufacturing process experiences, and 24 percent by susceptibility to impact damage. Damage source defined from service had 17 percent of the responses. One percent of the responses listed identifiers in the category Other.

- Material and Process Control Responses
  - Of the 15 responses, 73 percent said manufacturing process experiences, 66 percent said bond joint stress levels, 40 percent said susceptibility to impact damage, and 40 percent said damage source defined from service.
- Design Responses
  - Of the three respondents, one replied, stating susceptibility to impact damage and damage source defined from service.
- Manufacturing Response
  - The respondent said bond joint stress levels.
- Analysis Responses
  - Of the 12 responses, 83 percent said bond joint stress levels, 83 percent said susceptibility to impact damage, 50 percent said manufacturing process experiences, and 50 percent said damage source defined from service.
- Regulator/Customer Responses
  - Two of three respondents replied, both stated bond joint stress levels, manufacturing process experiences, and susceptibility to impact damage.
- Other Category Responses
  - "Local cleanliness environment."
  - "Accessibility."
  - "Corrosion protection for metal structure."
  - "Low-load comparative NDI."
  - "Robust quality control that can be validated for the design and application."
  - "Prevention of moisture ingress into sandwich structure. Defect type identification. An interfacial failure (adhesion) has different causes from a cohesion failure, so the repair must be managed differently. Causes of bond failure must always be identified and corrective action taken."

Question 9: The respondents identified special considerations that were important to the maintenance of bonded structure. Inspection was indicated in 62 percent of the responses and scheduled maintenance was indicated in 26 percent. Twelve percent of the responses were from the category Other.

- Material and Process Control Responses

  – Of the 17 responses, 94 percent said inspection and 35 percent said scheduled maintenance.

  The following responses were from the category Other.

  – "Robust quality control that can be validated for the design and application."
  – "Corrosion protection for metal structure."
  – "Accessibility"

- Design Responses

  – Of the three respondents, one replied. The respondent said inspection and scheduled maintenance.

- Manufacturing Response

  – The respondent said inspection.

- Analysis Responses

  – Of the 14 responses, 78 percent said inspection and 35 percent said scheduled maintenance. The response from the category Other was "local cleanliness environment."

- Regulator/Customer Responses

  – Two of three respondents replied. One said inspection and scheduled maintenance and one said inspection.

- Other Category Responses

  – "Low-load comparative NDI."

  – "Prevention of moisture ingress into sandwich structure."

  – "Defect type identification."

  – "An interfacial failure (adhesion) has different causes from a cohesion failure, so the repair must be managed differently. Causes of bond failure must always be identified and corrective action taken."

Question 10: When asked what procedures are used to inspect bonded structures and repairs in the field, the respondents indicated visual—85 percent, UT—76 percent, tap—68 percent, and radiography—19 percent, as illustrated in figure C-4.

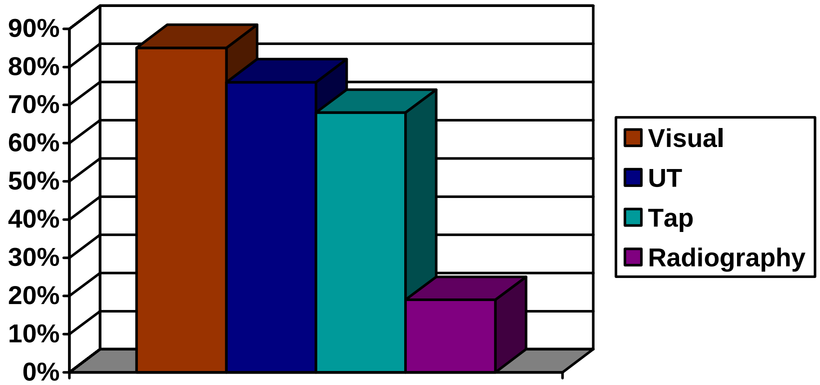

FIGURE C-4. PROCEDURES USED TO INSPECT BONDED STRUCTURES

- Material and Process Control Responses
  - Of the 16 responses, 87 percent said visual, 85 percent said UT, 68 percent said tap, 12 percent said radiography, and 6 percent said thermography.
- Design Responses
  - Of the three respondents, one replied. The respondent said visual, UT, radiography, and tap.
- Manufacturing Response
  - The respondent said visual and UT.
- Analysis Responses
  - Of the 14 responses, 78 percent said visual, 71 percent said tap, 71 percent said UT, and 21 percent said radiography.

The following were the responses from the category Other.

- “Laser shearography is good for large sandwich structures to indicate larger debonds.”
- “Ultrasonic Inspection”

- Regulator/Customer Responses
  - Two of the three respondents replied. Both said visual and UT, with one of the two additionally choosing tap.
- Other Category Responses
  - "The process list can all be used based on the types of flaws being looked for in maintaining the aircraft. Also the type of aircraft will add to defining the approach used."
  - "Thermograph" (4)
  - "Shearography"
  - "Holographic Laser Interferometry"

Question 11: Forty-three percent of the responses indicated that the participants agreed that service experiences with bonded structure and/or repairs have been good and 17 percent strongly agreed. Thirty-three percent neither agreed nor disagreed and 7 percent disagreed.

- Material and Process Control Responses
  - Of the 16 responses, 31 percent agreed, 31 percent strongly agreed, 31 percent neither agreed nor disagreed, and 6 percent disagreed.
- Design Responses
  - Of the three respondents, one replied. The respondent agreed.
- Manufacturing Response
  - The respondent neither agreed nor disagreed.
- Analysis Responses
  - Of the 14 responses, 50 percent agreed, 43 percent neither agreed nor disagreed, and 7 percent disagreed.
- Regulator/Customer Responses
  - Two of three respondents replied. One neither agreed nor disagreed and one agreed.

Of the 47 responses, 52 percent agreed that these experiences have been application-dependent and 12 percent strongly agreed. Twenty-three percent neither agreed nor disagreed, 4 percent disagreed, and 9 percent strongly disagreed.

- Material and Process Control Responses

  – Of the 16 responses, 50 percent agreed, 18 percent strongly agreed, 12 percent strongly disagreed, 12 percent neither agreed nor disagreed, and 6 percent disagreed.

- Design Responses

  – Of the three respondents, one replied. The respondent disagreed.

- Manufacturing Response

  – The respondent neither agreed nor disagreed.

- Analysis Responses

  – Of the 14 responses, 50 percent agreed, 43 percent neither agreed nor disagreed, and 7 percent strongly agreed.

- Regulator/Customer Responses

  – Two of three respondents replied. One neither agreed nor disagreed and one agreed.

Question 12: When asked to identify the most common damages or defects found for bonded structure in the field, the respondents answered as follows: 28 percent said moisture egress and corrosion, 25 percent chose the category Other, and 14 percent indicated impact.

- Material and Process Control Responses

  – Of the 15 responses, 53 percent said corrosion, 40 percent said moisture egress, and 20 percent said impact.

  The following were the responses from the category Other.

  – “Maintenance/Use induced damage”
  – “Erosion”
  – “Poor design/manufacturing”
  – “Not much experience in the field”
  – “Delaminations”

- Design Responses

  – Of the three respondents, one replied. The respondent said impact, moisture egress, and corrosion.

  The following were the responses from the category Other.

- “Fatigue”
- “Lightning strike”

• Manufacturing Response

  - The respondent said impact.

• Analysis Responses

  - Of the 13 responses, 69 percent said moisture egress, 53 percent said impact, and 38 percent said corrosion.

  The following responses were from the category Other.

  - “Disbonding” (2)
  - “Moisture ingress”
  - “Chemical contamination”
  - “Delamination in composite substrates”

• Regulator/Customer Responses

  - Two of the three respondents replied. One said corrosion and moisture egress and one chose the category Other, stating “Local Disbonding (uncertain of specific cause).”

• Other Category Responses

  - “Do not have too much experience with this although a tear down inspection program is being planned. If bonds fail it is typically because the surface preparation was done incorrect. If that is the case they will fail quickly. If done correct proper bonds last very long. Sometimes impact damage or attempts to remove bonded repairs can cause failures.”

  - “Moisture ingress” (4)

  - “Chemical contamination”

  - “Unanticipated load - usually an of the plane event that was not accounted for in the initial design - the joint was loaded in a manner that it was not designed for.”

  - “Almost all bond failures are interfacial, indicating either poor selection and if validation of processes, or poor performance of those processes.”

  - “Impact is not a cause of bond failure unless at sufficient energy levels that other damage has also been caused (dents, delaminations). Corrosion occurs AFTER the bond has failed, it is not the cause.”

Question 13: When asked for comments on product development, substantiation, and support for bonded structure or repairs, the respondents replied as follows.

- Material and Process Control Responses
  - "Need robust processes that repair personnel will likely do correctly."
  - "People are fooled by a run of good cohesive failures because they don't realize that the data that they are getting for the links in the chain that didn't fail (surface prep, adhesive bond primer, and all of the interfaces) may be varying widely just above the strength of their adhesive. It's like run out data for these links that didn't fail. You may have a festering contamination issue building for some time, but it seems like it came of the nowhere because one day all your parts fail cohesively, and then none do."
  - "Criteria for periodic in-service inspection of bonded structures in field should be stringent and all encompassing till a substantial amount of data is obtained."
- Design Responses
  - No respondents replied to this question.
- Manufacturing Response
  - The respondent did not reply to this question.
- Analysis Responses
  - "The current coupon methods for bonded joint durability require an overhaul - at present they are just comparison tests not useful for design eg. lap joint and wedge test."
  - "Designers must consider in-service repair, both interim and permanent, during design because the capability of manufacture exceeds that for repair. If a structure is not repairable it should be designed to be easily and cheaply replaced."
- Regulator/Customer Responses
  - "How are repairs certified? Is it only done at the component or full scale test level? My feeling is that the substantiation process for repairs is not necessarily as rigorous as it is for pristine structure."
- Other Category Responses
  - "Since the industry has build and is build aircraft from private to the space shuttle all of which have highly different design requirements. The first step in all

designs must be to start with a list of design requirements and continue to edit the requirements as we learn more about the specific design and performance requirements. This learning need to be kept open up through flight test. Service experience will be added with time to future version of the aircraft. All design need to be view as a continued learning experience."

- "DOD has funded a large program in bonding composites (Composites Affordability Initiative) -- keep lessons learned from that program."

- "The long term effects of large bond gap, moisture cycling, and thermal cycling of the bond can be studied with stringent periodic in-service inspections."

- "On acquisition of data, simulation of the above mentioned effects on a laboratory scale can be performed from a durability of bonded structure policy standpoint."

- "Still some fear of the "kissing" bond - no validated way to detect this phenomenon using NDI methods."

- "It is important that the process issue is settled before component development occurs, to enable current certification methodologies to be effective. I also stress that adhesive bonds can be designed such that the bond is always stronger than the structure being bonded. That renders any test program (coupon, sub-element, component and full scale) as meaningless because then failure will always occur away from the bond. Thus, for such designs it will be possible to REDUCE the number of tests necessary to verify a bond design, provided that the processing is valid in the first place."

C.8 GENERAL DISCUSSION QUESTIONS ON BONDED STRUCTURE.

Question 1: When asked about their concerns as to the safety of bonded aircraft structure, the respondents stated the following:

- Material and Process Control Responses

  - "Surface prep and bond durability."

  - "It is difficult to apply test results of bonding coupons to structural analysis."

  - "Surface preparation and process control for aluminum substrates."

  - "Durability and how to assess for long-term durability."

  - "Has enough testing been performed to eliminate the need for additional fasteners in bonded joints?"

  - "Identifying cracks in bonds in-service; training of A & P's regarding identifying and repairing bond defects in service."

- “Process control during manufacturing to assure proper bond preparation.”
- “Inspection methods.”
- “Procedures for Design allowables determination; durability; reparability; surface preparation guarantee.”
- “Long term durability.”
- “Long term environmental effects.”
- “Long term service and environmental effects on the bond joints.”
- “Production personnel training and experience.”
- “Quality control of processes applied during manufacture or repair.”
- “The ability to ascertain joint integrity and strength many years after initial fabrication.”
- “The population of people that know what good bonding practice is has been shrinking for some time. The number of people who know why a practice is a good bonding practice has been shrinking since PABST.”

- Design Responses
  - “Corrosion of honeycomb, which is not very detectable until delamination, at which point the corrosion is widespread. This has been the root cause of many of our in-flight failures for parts such as 757 Slats, 767 Slats, etc.”
  - “Inspectability and fatigue of critical composite components such as lugs at primary structure attachments.”
  - “Moisture Ingress.”

- Analysis Responses
  - “Long term durability cannot today be adequately predicted, and it leaves to guesswork or assumption what the quality of bonded joints will be as they age.”
  - “Inability to verify surface preparation and bond integrity. No good method exists to check for “weak” bonds, either as-fabricated or in-service. Methods are needed to validate the fabrication process to ensure adequate bond strength and durability.”
  - “Inability to predict/monitor adhesive bondline degradation due to environmental exposure.”

- “Inadequate surface preparation due to the wrong or incorrect peel ply.”
- “Inspection; fail safety; impact resistance”
- “Quality and reliability of the joint.”
- “Reliability of the bond and pre-bond humidity.”
- “Strength integrity of bonded structure is difficult to ascertain using most current popular NDI methods. Kissing bonds, or bonds of low strength, can exist without being detected using ultrasonic, tap, or thermo NDI methods. Laser and optical inspection methods currently exist in which a subtle stress is applied to the bond-line (such as low vacuum), but these methods have not bee adopted for wide-spread use. In order to improve reliability of detecting existence of a poor bond these methods should be substantiated for wide-spread use and inspection “standards” methodology developed for them.”
- “The difficulty of proving the quality of a bond by NDT.”
- “The long term durability test methods for bonded structures are inadequate for long term life assessment and design.”
- “The major concern is the durability due to different environment conditions.”
- “Understanding criticality and ensuring redundancy if required.”
- “Unknown or unpredicted out-of-plane loads.”
- “Long term effects of stress concentrations in the bonds.”
- “Insufficient testing that accounts for all service loads.”
- “Process creep in production environment that introduces contaminants or degrades surface preparation.”
- “Undetected bond damage during a field incident and subsequent repair.”

- Regulator/Customer Responses
  - “Ensuring consistency / repeatability of the bonding process.”
  - “Effective training of personnel doing the bonding.”
  - “Existence of bonded joint(s) which are not addressed properly by QA.”
  - “Rigorous process controls and technician training.”

  - “Inspection methods and maintenance procedures have not been adequately established.”
  - “Sufficient understanding of the technology by all those involved in manufacturing, design and maintenance (teamwork).”
  - “Conservative design practices that include fail-safe features.”

- Other Category Responses

  - “Process failures.”
  - “Long term effects of environmental cycling.”
  - “Absence of effective NDI procedures.”
  - “Reliance on operator competence.”
  - “Quality of materials allowables used for design.”
  - “Lack of predictive models for assessing bond durability.”
  - “Absence of well defined procedures acceptable to AEO to enable certification of bonded repairs on primary aircraft structure.”
  - “Difficulty in assessing reliability of adhesive bonds on primary structure.”
  - “Correlation between standard laboratory testing (including accelerated durability testing) and service performance.”
  - “Long-term environmental durability; accidental application of adhesives with wrong characteristics (brittle, ductile, etc.) In critical joints.”
  - “Unknowns in some of the analysis.”
  - “Misunderstanding of the analysis.”
  - “Improper training for bonding (quality control).”
  - “Lack of suitable NDI to detect weak interfacial bonds.”
  - “Complex joints and integral structure move usability away from the regime of simple (e.g. Bolted) repairs that can be performed easily.”
  - “Industrial practices do not control every variable in processing, and we do not have adequate guidelines for acceptability of process variation with respect to risk.”

- “Undetected impact damage is a major concern.”

- “Bonded metal structures are subject to corrosion and bonding failure.”

- “Lack of understanding by the designers.”

- “Inability to detect using NDI a “weak bond”. What may look good could have significant strength reduction. Strength of the bond leaving the factory/depot strongly dependent on the care taken in processing particularly surface preparation which can be inconsistent and difficult to verify.”

- “Manufacturing process that is not right or not properly controlled.”

- “Robustness”

- “Inspectability for whether the bonded system was prepared correctly.”

- “Process qualification that includes durability assessments.”

- “Inadequate and/or inappropriate process controls that may compromise long - term durability. (Moisture/humidity. Poor surface prep out-time, open time, etc.).”

- “Peel ply -only surface prep and flock-filled adhesives in small sport-aviation and kit planes.”

- “Lack of basic composite materials knowledge in workforce. (OJT instead of formal training.)”

- “Inappropriate or inadequate process validation testing due to the absence of a requirement to demonstrate bond durability as part of the certification process. Strength and fatigue resistance tests will not prevent interfacial failure.”

- “Inappropriate design methods.”

- “Inadequate failure investigation to identify the true causes of bond failures, coupled with reliance on perceptions that bond failures are fatigue or impact related.”

- “Inadequate and unreliable adhesive design data.”

- “In some cases, it is difficult or impossible to satisfactorily inspect a bond-line using any NDI technique. In these bonded structure applications the best approach is to inspect “in” bond integrity instead of inspecting “for” bond integrity after the fact. This can be accomplished by characterizing the receiving and process parameters in great detail in order to establish critical process inspection points. Historically, industry has processed adhesives per manufacturer's recommendation without taking the time to understand the relative significance of each process step or receiving parameter."

- "Inadequate control of prebond humidity."

- "Consistent bond preparation methods."

- "Improved use and buy-in by the FAA regarding peel-plies for bond preparation."

- "You'd have to review current maintenance experience. The big question has always been meaningful inspections of bonds with inferior strength. Delaminations are relatively easy. Also, environmental durability."

- "Proper surface preparation and bond line thickness."

- "Adhesive bonding is a system: adherends, adhesive, surface preparation, bonding process. A change to any of these items can adversely affect the bond. Post-certification changes to materials and processes must be very carefully monitored and validated. The traditional approach to material control has involved separate adhesive, composite material, process specifications. It is very easy to overlook the bond "system" when a change is made to an individual specification or material, with the result being a significant degradation in the bond capability (rarely does an unintended change make things significantly better). Multiple sources of nominally "equivalent" material must be validated for the bond "system", not just the individual material specification."

- "Need to consider whether there are any services life limits (time, flight hours, flight cycles, #peak loads) for bonded structure. Are there any degradation mechanisms that could limit service life?"

- "Unzipping - we must design with increasing energy release rates."

- "Incorrect surface preparation at time of manufacture/repair."

- "Not using the correct curing parameters, such as temperature, time and vacuum."

- "The repairs are often carried out by technicians who have no formal qualification in composite repair, or who have had very little, or no training."

Question 2: When asked about the most significant certification hurdles for bonded aircraft, the respondents identified the following.

- Material and Process Control Responses

  - "Generation of confidence that we have captured all of the possible processing variants in our allowables calculation. This is critical if we are to have confidence that we can manufacture the structure effectively and be certain that it conforms to the strengths that it was designed to."

- "We know that metallic structures, no matter how well they are surface prepped, will often fail in service because of hydrolytic degradation. We have no way to predict this, nor do we have effective means to inspect for it. Furthermore, we do not have laboratory testing that can be directly linked (phenomenalogically) to the effects of moisture/corrosives in the field."

- "Expense of full scale testing."

- "The certification test would be at the full scale test."

- "Establishing inspection criteria."

- "Effective NDT methods in the field."

- "Cost of allowables."

- "No NDI techniques to detect weak interfacial bonds at time of manufacture."

- "No analytical processes for interfacial failures."

- "Getting FAA buy-in on what is required for certification and design."

- "All this complexity makes bonding a difficult, potentially expensive choice, although the rewards can be substantial."

- "Time and dollar amount spent on testing for the lack of standard practice in analysis software."

- "Certification of adhesive bond long term durability in a humid environment."

- "Military was no single certification authority. Each weapon system used a different approach."

- "Documentation and definition of all manufacturing process and traceability of materials used in test articles."

• Design Responses

  - "As a repair station we are commonly limited as a result of damage size and/or damage proximity in relation to edges, cutouts and fastener holes. In these cases we are forced to refer each issue back to the OEM, whereas we feel there should be scope for repair development IAW baseline documentation."

- Manufacturing Response
  - "Manufactures short cutting known requirements for economic reasons."
- Analysis Responses
  - "Post bond and field inspections of the bond integrity."
  - "Inspections and accelerated methodologies for adhesive and interfacial degradation."
  - "Reliable surface preparation."
  - "Demonstrating compliance on full scale test article."
  - "Proliferation of testing all qualified adhesive and substrate permutations, comparing damage tolerance behavior of new materials to meet baseline requirements, consideration of and testing for critical environments when competing failure modes are present, complexity of bonded structure usually results in a very conservative approach and subsequent weight penalty being enforced by regulatory authority."
  - "Additional tests are required for reliability."
  - "In the past, the biggest hurdle has probably been the time required to perform structural substantiation testing and to have the results approved by the FAA. It is seldom clear exactly what testing is required substantiate bonded structure, so the tendency is to err on the conservative side and an excessive amount of testing is performed. Frequently, the results data spends along time in the hands of the FAA for approval. Presumably, this is due to the limited amount of reference data currently available to them for adhesively bonded structure."
  - "Certification test and approach in the analysis to prove the safety of bonded structures."
  - "Qualification tests - coupons and components."
  - "Inability to predict/monitor adhesive bondline degradation due to environmental exposure."
  - "Proof of long term reliability--25.571 Durability and Damage Tolerance."
- Regulator/Customer Responses
  - "Bond process qualification, substantiation and documentation in specifications."
  - "Building block test substantiation, culminating in large-scale tests."

- “Implementation of efficient bond process control in manufacturing.”
- “Determining the right tests, i.e., chemical, physical and mechanical, that needs to be conducted.”
- “Establishing reliable and robust adhesive and bonding processes.”

- Other Category Responses
  - “Bond preparation and processing.”
  - “Large amounts of testing and validation.”
  - Validation of loads models in fatigue susceptible structure to enable certification of repair design.”
  - “For repairs the USAF has an excellent and conservative guideline. If the structure is treated as if the repair was not applied (inspection intervals and damage tolerance) operation will be safe and inspection intervals will not decrease if the repair works.”
  - “Inspectability.”
  - “Fear of the ‘weak bond.’”
  - “Lack of confidence in consistent processing operations.”
  - “Make sure again that the test program has covered all the safety requirements and that the manufacturing process is receiving the quality control that is needed to insure safety.”
  - “Failure to recognize that demonstration of bond durability must be part of certification.”
  - “The absence of a reliable NDT method to assure of bond integrity. Current methods only indicate the absence of significant defects; they do not interrogate the bond interface and hence can not assure bond durability.”
  - “The absence of reliable statistically sound design data for adhesives.”
  - “Quite obviously, first and foremost, in certification one must prove an understanding of the most taxing load/damage/environment scenarios that can occur at the subject bond, prove an understanding of the effect of the scenario on strength, and show that at the degraded strength the structure is still capable. This is site specific and joint specific. Many variables need to be understood. For example, if a skin develops a crack can it be arrested at features bonded to it, or will the bonded joints fail? Do bonded on stiffeners reliably arrest crack

propagation? Can the bond to honeycomb be designed to arrest cracks emanating from punctures or to arrest disbonds? How do the thickness parameters of bonded joints affect their resilience to impact events? How does facing lay-up and thickness affect joint damage response to impact? In sandwich structure disbonded due to impact, what is strain to induce static damage propagation? Fatigue damage propagation?"

- "Definition of approved, affordable, efficient, in-service bonded repair methods for composites has also been somewhat of a hurdle. Repair types, overlap requirements, cure scenario requirements, etc... All need to be standardized. In addition, in the past, repair research has been centered on wet lay-up. There are other techniques available that should also be standardized."

- "In a major primary load path bond, proving that the bonds formed day-to-day will have indisputably repeatable bond quality and integrity is also a hurdle. Historically, manufacturers process adhesive per manufacturer's specification, without taking the time to characterize the effect of each receiving or process parameter. Proving a reliable process is in place can also be difficult."

- "Getting good design analysis for bonded joints."

- "Substantiating strength of joints, materials and processes."

- "Advanced NDI. Prove that the bond is still holding load (not just that it's not cracked/delamed)."

Question 3: When asked to identify the materials, process, design, analysis, manufacturing, and maintenance improvements that can be made to make bonded structure more economical, the respondents replied as follows.

- Material and Process Control Responses

  - "Room temp storable, long out time, low temp curing film adhesives."

  - "Eliminate honeycomb core, particularly core varieties that are susceptible to water."

  - "More data and publications concerning to success examples should be available and a test and process recommendation specific for adhesives and bonding should be developed."

  - "Define the best combination of mechanical testing and chemical analysis for certification purpose."

  - "Enable the use of more modern improved adhesive systems and take out the old junk of the specifications."

- “Better technical training for the actual bonding process.”
- “Better design and analysis tools that predict joint behavior in real-life applications, i.e. combined peel and shear at the ends of the joints.”
- “Additional stress analysis and bonded joint failure analysis.”
- “Well defined processes with rigid quality control.”
- “The industry can’t standardize on adhesive specs, because we all use different bond primers and surface preparations.”
- “Emphasis on Tooling requirements and max bond thickness restrictions.”
- “Cure monitoring, on-line. Most thermosets are cured for longer than they need to be, that applies to adhesives, too.”
- “Standardization of everything.”
- “There are no test methods or analysis that will give any information on long term service and environmental problems. At best, you can only make comparisons using accelerated test which do a poor job of prediction.”

• Design Responses

- “Wider scope of wet lay-up repairs.”
- “There are no standard materials in use.”
- “Reparability of ALL structures - for example, there are no vacuum-bag cured repairs approved for 350F cured material, or for acoustic panels. These currently require autoclave repairs, which drive more spares and are more expensive for labor and materials.”
- “Approve SolGel surface preparations as equivalent and permanent, or plan for these type repairs form the beginning.”
- “On parts on upper surfaces, make the minimum gage .020 or .025 to eliminate the hail damage.”

• Manufacturing Response

- “A guideline that would give recommendations of what is considered approved practices. If the guideline is adopted by the manufacture facility, then reduce testing.”

- Analysis Responses

  - "There are currently no qualified adhesive vendors, similar to the prepreg vendors such as Toray. The qualification program cost would be lowered if adhesive vendors had qualification products. It is difficult for small businesses to choose an adhesive system. The economical choice tends to be a two part paste adhesive with a low temperature cure. Vendors typically do not supply "hot-wet" data so these companies make their best guess and qualify a material. This may not be the best material but the company must stay with this material because the cost of qualifying another material (that may not be better) is prohibitive. The adhesive vendors could formulate an adhesive that would meet the requirements of the company, if they had an incentive (potential orders)."

  - "Selective use of fasteners in conjunction with bonded joints - e.g. only at stiffener termination not along whole length of a bonded joint."

  - "Use of SPC in adhesive manufacture to reduce end item inspection."

  - "Less sensitive processing/more robust processing. The cheapest bondline is one that does not ever fail!"

  - "Process to validate proper surface preparation."

  - "Procedure to determine in service strength."

  - "Reliable analytical methods to predict fracture growth and bond fracture associated with instability."

  - "Improvement in mechanical properties."

  - "Inspection methods need to be improved so that thorough inspections can be performed in a reasonable amount of time."

  - "Material - standardization adhesive material."

  - "Process - standard process."

  - "Design - Training of the personnel."

  - "Analysis - Supplier adhesive data needs to be in accordance with what the analysis need. For example, curve shear stress versus strain as request by analysis. To choose the easy and friendly software."

  - "Manufacturing - standard manufacturing."

  - "Maintenance - facility adequate to structure bonded and training of the personnel."

- “By far, the best way is to standardize materials, processes, test methods, etc.”
- “Invention of a rapid and reliable NDT method, which demonstrates/measures the shear strength of a bond.”
- “Reliable, low-cost inspection techniques.”
- “Self-health monitoring bonded structures (smart repairs).”

* Regulator/Customer Responses
  - “NDI procedures for chemical confirmation of surfaces that have been prepared for bonding before adhesive application.”
  - “Advances in analysis for bonded joint design.”
  - “Advances in residual strength & fatigue analyses for debond and delamination.”
  - “Advances in test standardization.”
  - “Improved inspection or sensing (in-situ sensors) in critical areas with real-time health monitoring.”

* Other Category Responses
  - “Reduce the vast array of materials implemented in structural repair.”
  - “Introduction of universal material standards.”
  - “Validation of experimental data with available bond analysis techniques is key to reduction in testing costs.”
  - “Testing regimes and validation of processes to enable implementation of a risk based approach to assessing intangibles such as long term adhesive bond durability.”
  - “Techniques to predict/verify durability.”
  - “Easier surface preparation.”
  - “Standardized design techniques/tools.”
  - “A program, similar to the AGATE prepreg program, would be beneficial.”
  - “Improve inspection capability.”

- “Design materials for repair that meet both the requirements of processing in the field (sometimes under austere conditions) and meet the strength requirements for the design.”
- “Results of test are very much scattered.”
- “Improvement in manufacturing process and tooling.”
- “Improve the prediction of failure modes.”
- “We need more automated manufacturing methods where the manufacturing records and controls reduce the need for subsequent inspection and verification steps.”
- “Surface preparation verification tools.”
- “Any NDI method that could verify the joint strength (find the “weak bond”).”
- “Analysis methods that can evaluate the effects of defects on a joint configuration.”
- “If one looks at the introduction of any type of structure you must work the design of the structure with a complete understanding of the manufacturing options.”
- “If the design is to be economical the designer must have as part of his design tools cost information in a form that as the designer goes through the development of the design he can quickly assess the relative cost of various design parameters. To often the design only gets this information though talking to manufacturing people, which means he does not get the information in a true design tradable format. This manufacturing cost parameters information helps him visualize his design as he develops it just like the structural design information.”
- “Find ways to make industry specifications and common best practices more accessible to enable the sharing of costs/data.”
- “Design for manufacturing. Composite structures should be molded with integral features that make them lightweight and enhance stiffness/strength while minimizing multi-piece assembly. (Co-cure and co-bond instead of secondary bonded structures).”
- “Eliminate processes that are capable of producing short term bond strength but not bond durability.”
- “Eliminate the use of average shear stress design methods and use the load capacity approach.”

- "Design adhesive bonds that are stronger than the parent material, hence reducing significantly the number of tests required for certification."

- "Bonded repair techniques need to be standardized in order to streamline the process. (not just wet lay-up repair but also surface ply repair, injection, non-load carrying, etc…)"

- "A fool-proof prep method for surface prep that can be objectively inspected."

- "Introduction of much lower modulus (higher strain to failure) adhesive systems in primary structural applications."

- "Increased reliability of surface preparation using less environmentally harsh prep for aluminum and new materials prep for composite structure."

- "Should already be very economical compared to bolts."

- "Industry standardized adhesive material procurement specifications could help make the process more economical."

- "Improved design/analysis methods that would enable the elimination of "chicken rivets" would save weight in some applications."

Question 4: When asked what barriers (economic or technical) need to be overcome to support the expanding applications of bonded aircraft structure, the respondents replied as follows.

- Material and Process Control Responses

  - "The technical barriers tend to scale with the complexity and amount of bonded structure. The introduction of reproducibly believable analysis and prediction tools has the potential to greatly reduce these barriers."

  - "Mainly technical, concerning to damage tolerance, endurance and reparability."

  - "How to ensure the reliability of bonded structures."

  - "Analysis"

  - "The mindset of using rivets to backup a bonded joint."

  - "A major deficiency in current testing and qualification procedures is the absence of any relationship to field data. It is essential that the bonding community cooperate to develop a coordinated approach to collecting retired bonded repairs or structure and performing teardown inspection. In conjunction with well defined processes used in the original construction, a relationship between accelerated testing a validation procedures used in the laboratory and service performance can be established and a reliable risk model developed for certifying bonded structure."

- "NDI of currently undetectable defects like weak bonds or kissing unbonds."
- "Long term effects of Large bond gaps to be studied extensively."
- "Have an NDI that can verify large bonded strengths."
- "Ways to predict long term effects of service and environment. Currently, you have to fly a fleet all over the world for 20 years to find out what works."
- "In situations non-destructive bond strength determination (still!)."

• Design Responses

- "It is common practice that OEMs call up production materials in structural repairs with long lead times, short shelf lives and large minimum order quantities. More consideration should be given to the practicalities of repair embodiment where a repair station may only perform a particular repair rarely."
- "No standard materials."

• Manufacturing Responses

- "Standardization of surface preparation procedures (sanding, grit blast, peel ply, waterbreak requirements)."
- "The absence of a predictive capability to determine the life of an adhesive bond (in the same manner as fracture mechanics is used to determine the damage tolerance of metallic structure)."

• Analysis Responses

- "The economic barrier is qualification for reasons stated in item 3. The biggest technical barrier is reliable inspection methods and accurate analytical methods."
- "Inspection and long term life prediction methods (durability) to detect early onset of interfacial crack growth or delamination."
- "Understanding of the requirements for prebond moisture."
- "NDI that can detect weak bonds."
- "Significantly different approaches by all OEMs, new entrants, and oversight authorities results in varying and uncertain levels of safety amongst similar products."

  - "Ability of bonded joint to arrest crack propagation in adjacent components needs to be characterized."
  - "The feeling that the structure bonded is safety."
  - "Training and technician understanding must reach new levels to take full advantage of composites. Most of the world is still treating a carbon laminate like black aluminum. This is getting better but too slowly."
  - "The uncertainty of bond quality assurance."
  - "Means to design that will eliminate of the plane loads."
  - "Reliable method to identify bondline deterioration needs to be established."
  - "Understanding of the requirements for prebond moisture."

- Regulator/Customer Responses
  - "The inability of detecting "poor" bonded joint using reliable and inexpensive NDI techniques is the biggest barrier."
  - "Training of resources (engineering and technicians)."
  - "Advances in more efficient process control procedures."
  - "Advances in maintenance repair procedures."
  - "Training at OEMs and end users is inadequate."
  - "Inspection and sensing methods are under development but not common."

- Other Category Responses
  - "Guidelines needed in design to predict and minimize peel stresses."
  - "Do it correct or don't use bonding at all. One failure will lead to a multitude of decisions not to use bonding anymore."
  - "In addition, there should be an effort to reduce the qualification requirements and therefore enhance the economic viability of adhesive bonding. The basic question is, can we reduce the qualification effort and maintain control?"
  - "Development of a design methodology and a sufficiently large supporting database to incorporate the distribution/variation in performance of bonded structures into the design process."

- "Methods to secondarily bond very large pieces of structure need to be established and proven. Because of the low bearing stress of composites we need to eliminate mechanical fasteners in composite structures."

- "In the application of any design the need to feel comfortable with the design both structurally and profitably the information data base available is the key to the specific design process selected for structural and cost performance. The more information available the more likely the procedure will be the one selected. Also most engineer and company management must be sure there is not "NIH" (not invented here") in there organizational structure."

- "Development of new generation adhesives that will wet better and adhere to low energy plastic surfaces must be pioneered to advance adhesive bonding for composites. Low temp and alternative energy/quick-curing systems need to be investigated to reduce processing time of thermoset adhesives. (Few product manufacturers currently seem to be willing to invest in R&D in this area.)"

- "Bonded repair technology must advance to the level where design and certification can give credit for the contribution of the bond to structural integrity. That can only be achieved if the durability of the bond can be assured."

- "From an affordability point of view sandwich construction is superior to discreetly stiffened structure. Crack arrestment via bonds to embedded features need to be demonstrated."

- "A huge amount of damage tolerance data for a multitude of structural configurations is needed."

- "Adhesive/Substrate compatibilities need to be standardized, particularly for co-cured structure. We have seen cases where an adhesive sticks well to "this" cured graphite laminate but not "that one."

- "Lack of load data from OEM's."

- "OEM's will not approve repairs purely for commercial reasons - this does not help the end user, the customer."

- "Improved depth of understanding of the science of the bonded structures by design and regulatory authorities is needed to avoid "practical" mistakes."

- "Lower modulus and lower cure temperature adhesive systems are difficult (impossible?) to certify due to traditional temperature margin requirements."

- "A simple, reliable and cost effective "bond strength" NDT method would resolve most issues and questions."

- “Difficulty in establishing and maintaining a competitive supplier base for “qualified” materials.”

- “There is cultural barrier too.”

- “Development of a more reliable surface preparation than peel ply.”

- “Move away from hostile surface preps for aluminum yet achieves the same high performance.”

- “A rigorous method for composite surface preparations—be it reliable Peel Plies (Hart Smiths experience) reliable training and procedures (human reliability).”

- “Overcoming the philosophy of the use chicken fasteners.”

- “Lack of knowledge on biomaterial joint behavior e.g. composite to Al.”

- “Need methods for rapid, wide-area NDI of aircraft structure (composite and bonded). Tap testing an entire aircraft is not practical.”

- “Need approaches for repairs to aircraft with large areas of “weak” or degraded bonds.”

- “NDI is still a big issue.”

- “Repair limits need to be increased.”

Question 5: When asked for additional general comments on bonded structures and repairs, the respondents replied as follows.

- Material and Process Control Responses

  - “Need a room temp cure primer system for bonded repairs.”

  - “Sorry the information is patchy, but most of the sections are not applicable to university activity.”

  - “We are primarily a Research and Development organization who have pioneered the use of composite bonded repairs to metallic aircraft structure for more than 25 years. Much of this research has been documented in a book entitled: “Advances in Bonded Composite Repair of Metallic Aircraft Structure,” Ed. Baker, A.A., Rose, L.R.F., Jones, R., Vol 1-2, Elsevier, United Kingdom, 2002. Examples of successful repair applications are included in the book. Typically, we will undertake research to develop a repair and then implement the initial repair but subsequently handover to RAAF who will undertake fleet repairs. As the technology has matured, development of RAAF Engineering Standards has enable RAAF to become more self sufficient in the technology, however, our company will provide independent assessment of RAAF standards and provide R+D support for more complex repairs such as to primary structure."

- "I still have a lot to learn about bonded structures."

- Design Responses
  - "Please note that I have answered this survey from a repair station perspective and have not answered most questions applicable to manufacture, testing and development."
- Manufacturing Response
  - No respondents replied to this question.
- Analysis Responses
  - "Adhesive bonding is a very important subject and I believe it is the least understood component of composite construction. Research in this area will be very beneficial to the aviation community."
  - "Show good examples."
  - "Adhesive Manufacturer's provides non reliable data in general."
  - "A general concern that not all new entrants understand the need for good bonded structure design, complete and appropriate testing, and sufficient quality oversight. A significant mistake by any OEM will affect product reputation of all similar manufacturers and likely result in over-reaction by regulatory authorities."
- Regulator/Customer Responses
  - "The technology continues to evolve and depend on rigorous process controls for reliable applications. To date, conservative design practices have helped achieve safety goals despite several examples of problems from production and service experiences."
  - "Bonded structures include ALL sandwich structures, not just bonded joints. This just scratches the surface…"
- Other Category Responses
  - "Open discussion regarding lesson learned."
  - "We need more approved wet lay-up repair methods."

- “Bonded structure can add structural capability and cost reduction but again only if the people doing the design and manufacturing have the data and experience to do the design job.”

- “Fewer separate parts/larger co-cured structures will reduce dependence on secondary assembly (bonding and fastening) for composites. The industry needs to move away from “black aluminum” design concepts and better utilize the ability to mold composite materials. There is evidence that this is happening albeit slowly.”

- “Fracture mechanics can never address the prediction of interfacial failure.”

- “Application of a failure criterion to adhesive bond design will lead to optimized bonds that will then loose any damage tolerance that is inherent in “inefficient” designs.”

- “Finite element or other analyses that do not represent the elastic-plastic behavior of adhesives will not provide reliable designs.”

- “It would be beneficial to tap into CAI efforts. Not all have access due to ITAR and proprietary information.”

- “Am concerned that there are no formal standards used for heater blankets in the repair process.”