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Laminate Statistical Allowable Generation for Fiber-Reinforced Composite Materials: Lamina Variability Method

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16. Abstract

Substantiation of composite structures often requires analysis as well as tests conducted at multiple building-block levels. Typically, as one proceeds up the building block and becomes more confident with the analytical design methods, the number of samples or replicates is reduced since the structural complexity increases. As the complexity of higher-level tests increases, more variables are introduced; i.e., fastener holes and multidirectional laminates. Currently, there is no standardized statistical methodology that allows progression up the pyramid of tests with a concurrent reduction of the number of tests while maintaining statistical reliability established at the lower replicate level. Therefore, conservative approaches are exercised at the higher level of building-block tests to be able to use the material variability of lower levels to represent the higher levels. Because a reduction in the number of samples results in excessively low or overly conservative material allowables, this research program explores the use of lamina-level variability to generate B-basis allowables for fiber-reinforced laminated composites. A multibatch laminate database was created to form baseline B-basis values. Then, B-basis allowables were obtained from single-batch data sets and compared with multibatch data to investigate the statistical reliability of the proposed small-sample B-basis method—the lamina variability method (LVM). This investigation included six material systems from three prepreg manufacturers: Toray Composites, FiberCote Industries, and Advanced Composites Group. In addition to the proposed methodology, two additional small-sample, B-basis methods proposed by Steve Ward were compared. Analysis of lamina and laminate test data for six different prepreg materials showed that LVM works well and gives conservative B-basis allowables that are about 90% of the three-batch laminate allowables. Caution should be exercised if the laminate data exhibits unusual variability due to test methods. If the variability is due to the material, the LVM method should be used with caution. If test variability is too high, for example, bearing strength, then three batches of laminate tests should be performed for that property to obtain B-basis allowables. It is imperative to realize the advantages as well as the risks associated with small-sample methods, and the data may need to be validated with additional tests based on specific applications.

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LIST OF SYMBOLS AND ACRONYMS

t/D	Thickness-to-diameter ratio
w/D	Width-to-diameter ratio
t	specimen thickness
w	specimen width
D	Hole diameter
e	Edge distance
BB (50%) T	Single-shear, two-fastener bearing (50% bypass) test
BB (50%) C	Single-shear, two-fastener bearing (50%) bypass) compression
in.-lbf	Inch pound force
5HS	Five-harness fabric
ACG	Advanced Composites Group
ACO	Aircraft Certification Office
AGATE	Advanced General Aviation Transport and Experiments
ANOVA	ANalysis Of VAriance
ASAP	AGATE Statistical Allowable Program
ASTM	American Society for Testing and Materials
CTD	Cold-dry tests
CV	Coefficient of variation
DAR	Designated Airworthiness Representative
DMIR	Designated Manufacturing Inspection Representative
DSBT	Double-shear bearing test
ETW	Hot-wet tests at 200° ±5°F
ETW2	Hot-wet tests at 250° ±5°F
FAA	Federal Aviation Administration
FHC	Filled-hole compression
FHT	Filled-hole tension
LVM	Lamina variability method
MIL-HDBK	Military Handbook
NAS	National Aerospace Standards
NASA	National Aeronautics and Space Administration
NHC	No-hole compression
NHT	No-hole tension
OHC	Open-hole compression
OHT	Open-hole tension
PB	Pin bearing (with stabilizing fixture)
PMC	Polymer matrix composite
PW	Plain weave
RECIPE	Regression Confidence Intervals on Percentiles
RH	Relative humidity
RTD	Ambient laboratory conditions
SACMA	Suppliers of Advanced Composite Materials Association
SSBT	Single-shear, one-fastener bearing test
VNRS	V-notched rail shear
WSU	Wichita State University

EXECUTIVE SUMMARY

With the application of composite materials in aircraft structural components, material qualification requirements have been a costly burden to airframe manufacturers. Substantiation of such structures often requires analysis and multiple levels of building-block tests. Typically, as one proceeds up the building block and becomes more confident in the analytical design methods, the number of samples or replicates is reduced since structural complexity increases. For example, the greatest number of specimens is usually tested at the lowest level when factors such as batch variability and environment are included in the test. Typically, the number of specimens approaches 1000 mechanical tests at this lower level. In contrast, only one test article is used at the highest level of the building block, which usually consists of a full-scale test.

As the complexity of higher-level testing increases, more variables are introduced; i.e., fastener holes and multidirectional laminates. Due to the increased cost of higher-level testing, the number of samples must be reduced. Currently, there is no standardized statistical methodology that allows progression up the pyramid of tests with a concurrent reduction of the number of tests while maintaining statistical reliability established at the lower replicate level. Therefore, conservative approaches are exercised at the higher-level, building-block tests to be able to use the material variability of lower levels to represent the higher levels. Because a reduction in the number of samples results in excessively low or overly conservative material allowables, this research program explores the use of lamina-level variability to generate B-basis allowables for fiber-reinforced laminated composites. A multibatch laminate database was created to form baseline B-basis values. Then, B-basis allowables were obtained from single-batch data sets and compared with multibatch data to investigate the statistical reliability of the proposed small-sample B-basis method—Lamina Variability Method (LVM). This investigation included six material systems from three prepreg manufacturers: Toray Composites, FiberCote Industries, and Advanced Composites Group. In addition to the proposed methodology, two additional small-sample, B-basis methods proposed by Steve Ward were compared. Analysis of lamina and laminate test data showed that using LVM produced conservative B-basis allowables that were about 90% of the three-batch laminate allowables.

1. INTRODUCTION.

The testing and analysis of composite materials at all levels of the building-block tests are crucial to ensure the structural integrity and the reliability of their applications. As one progresses from lamina level to laminate level, the cost of testing escalates. Thus, in comparison to lamina-level tests, a reduced amount of testing is usually proposed. This research work was intended to investigate the lamina and laminate statistics and appropriate data reduction procedures to ensure safety and statistical reliability of laminate design allowable generation. A statistical methodology to analyze small-sample laminate data sets with the use of lamina level variability was proposed and is detailed in sections 2 and 3. These research details are meant to provide guidelines and to develop statistical methodology for the use of laminate (notched and unnotched) data in future designs, while maintaining an acceptable level of safety. Reliability of the B-basis allowables generated using this method was investigated by comparing them with the three-batch laminate data sets fabricated from various material systems.

In addition to the statistical reliability of the small-sample method proposed, several issues related to the design of composite structural joints were also investigated. The use of mechanically fastened joints in composite materials differs considerably from that of metallic joints. Many programs have investigated the use of mechanically fastened composite joints, with resulting guidelines for their use, which is documented in Military Handbook 17 (MIL-HDBK-17) [1]. MIL-HDBK-17 provides some guidance of the test methods and procedures to characterize the laminate behavior of a material and its associated notched and unnotched behavior under various parameters. Open-hole, filled-hole, and bolted joints were chosen for testing the notched properties of this program.

This research was conducted under Federal Aviation Administration (FAA) special project number SP3650WI-Q. Panel fabrication was conformed by an FAA Designated Manufacturing Inspection Representative (DMIR) at the Toray Composites and FiberCote Industries facilities. Specimen conformity and torque verification were performed by an FAA Designated Airworthiness Representative (DAR) at Wichita State University (WSU). Some of the tests were witnessed at WSU by an engineer from the FAA Aircraft Certification Office (ACO), Wichita, Kansas.

1.1 BACKGROUND.

In general, analysis alone is not considered adequate for substantiating composite structures used in aircraft designs; commonly, a building-block approach is used in conjunction with the analysis. This approach basically consists of lower-level, building-block tests that characterize material performance, usually at the coupon level. Then, the complexity of the test gradually increases to include structural details, usually at the element or subcomponents level, as one progresses toward a full-scale components test. Figure 1 shows the building-block approach schematically as a pyramid of tests.

Typically, as one proceeds up the building block and becomes more confident of the analytical design methods, the amount of samples or replicates is reduced since structural complexity increases. For example, the greatest number of coupons is usually tested at the lowest level when factors such as batch variability and environment are included in testing. Typically, the number of specimens approaches 1000 mechanical tests at this lower level. In contrast, only one test article is used at the highest level of the building block, which usually consists of a full-scale test. Currently, there is no standardized statistical methodology that allows one to progress up the pyramid of tests and, at the same time, reduce the number of tests while maintaining statistical reliability established at the lower replicate level. The intent of this research is to propose a statistical methodology that uses lamina-level information to produce B-basis allowables that are not excessively low due to the reduced number of samples.

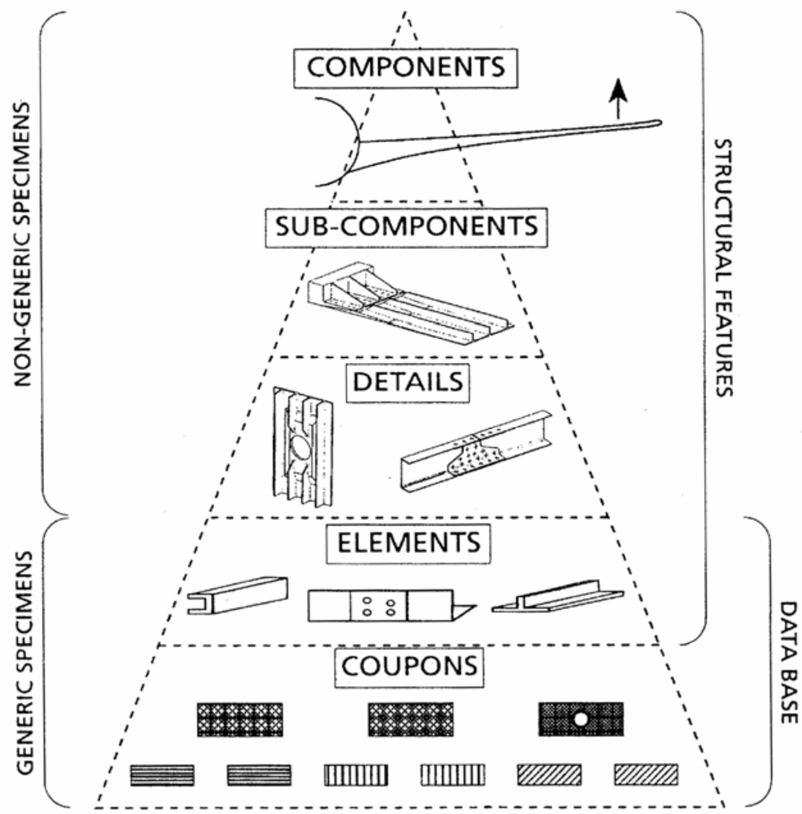


Figure 1. Building-Block Approach Showing the Pyramid of Tests Used for Structural Substantiation

1.2 OBJECTIVES AND SCOPE OF WORK.

The major objective of this research was to attempt to link steps at the lowest level of the building block, consisting of lamina tests, with the next level in the building block, consisting of notched and unnotched laminate tests. To validate the statistical assumptions required to reduce the number of tests at the next higher level, a three-batch laminate test program was performed, which is outlined in section 2. While using the larger number of tests at this higher laminate level, comparisons were made that evaluated the reliability of the reduced testing methodology as one proceeded higher in the building block. One must notice that, typically, such large data sets are not available at the laminate level. Also, small-sample, statistical methodologies must be sufficiently robust and conservative to increase the likelihood that the calculated B-basis values represent a high-confidence, lower-bound estimate of the true population B-basis value.

However, the methodologies should not be so conservative that the basis values are excessively low.

A number of other objectives and goals were also addressed in the program, as follows:

- Generate a multibatch, nested database of notched and unnotched laminate properties for four typical, commonly used composite material systems (unidirectional tape and plain weave (PW) fabric) in which lamina-level statistics already exist. Two additional material systems were added later to broaden the investigation.

- Evaluate common ASTM International test methods, which are used to generate the notched properties for database generation, develop guidelines for use, and make recommendations to the MIL-HDBK-17 committee for possible inclusion in the handbook.

- For bolted joint designs, generate typical effects of width, thickness, and notch diameter, with respect to ultimate strength, for inclusion in the laminate database.

- Use lamina and laminate databases to compare multiple statistical methodologies that are currently proposed, which show the effects of using smaller sample sizes of statistical reliability at the laminate level of the building block.

- Generate notched and unnotched laminate data, which may be used in future design efforts, for inclusion into MIL-HDBK-17.

- Recommend a reduced laminate qualification test matrix and statistical methodology for inclusion into MIL-HDBK-17.

2. TECHNICAL APPROACH.

The primary goal of this investigation was to propose a statistically reliable methodology for determining allowables for laminated composites with small-sample (one-batch) data sets without producing excessively low B-basis values. The increased use of composite materials in aircraft structures leading to shared database development programs, such as the National Aeronautics and Space Administration (NASA) Advanced General Aviation Transport Experiments (AGATE) consortium, has resulted in a growing number of lamina databases with multibatch data sets. At the first level in the building block, shown in figure 1, the number of samples in lamina-level testing is relatively large; i.e., more than 18 per environmental condition. Some statistical methodologies [2] allow the pooling of data across environments for the same failure modes, thus increasing the sample size to estimate material variability for obtaining basis values. At this level in the building block, specimens are selected so the data sets include batch variability and process variability. The large sample (population) variability for particular failure modes has implications for the statistical significance of design allowables for higher-level, building-block tests, i.e., notched and unnotched laminates, in which the test samples are historically small. This lays the foundation for the lamina variability method (LVM) proposed in this investigation to obtain the B-basis allowable for laminated composites (small data sets) detailed in section 3.1. To calculate laminate basis values without generating excessively low B-basis values, laminate population variation must be assumed or estimated, since it cannot be accurately determined from a small data set. The basic assumptions for LVM are that there is substantial data (e.g., from lamina specimens) and the intrinsic strength variability of the higher complexity specimens (for which only a small data set is available) is no greater than the variability of the lamina specimens.

The main data set in this investigation consists of three batch data sets for unidirectional tape and PW laminates from Toray[1]. Specimens were selected with at least two process cycles incorporated. Furthermore, two data sets from Advanced Composites Group's (ACG) unidirectional tape and five-harness fabric (5HS) were included in the analysis to further verify statistical reliability of small-sample, B-basis allowable calculations. Program data generation focused on the carbon-reinforced material systems from these three prepreg material suppliers, as listed in table 1. Typically, at the laminate level in the building block, multibatch tests to obtain allowables are not performed. However, to assess the reliability of the small-sample basis calculations, i.e., determine the level of conservatism, basis values from the small-sample method were compared against multibatch allowables. Multibatch B-basis values were obtained using an AGATE Statistical Allowable Program (ASAP) [3] that pools the data. These values exhibit similar failure modes and variability across all available environments. Then, for each environment and for each material batch, B-basis allowables were generated using the LVM. Figure 2 shows an example calculation of B-basis values for a material property that has test data from three material batches and three different environments: cold-dry testing (CTD), ambient laboratory conditions (RTD), and hot-wet testing (ETW). For each batch and test condition, LVM B-basis values were calculated separately and compared with ASAP B-basis values that were obtained by pooling test data from all three environments (if available) and three material batches. Therefore, for cases with three test environments, the ASAP population was at least nine times (6 x 3 x 3 = 54) the number of replicates for small data sets.

The chosen methods and sample sizes for laminate-level tests must have a representative unit volume of materials in the gage section of the test samples. Violation of this practice can cause high data scatter that may appear to have batch or process variability. Several standard test methods are available through ASTM for no-hole, open-hole, filled-hole tension, compression, and bearing. During this investigation, a test method for determining unnotched shear by rail shear loading was developed as a research project funded by the FAA [4]. This test method was used in this investigation because of its attractive features, such as a larger gage section and improved loading conditions, compared to the commonly used ASTM D5379 standard test method. A small secondary matrix was developed to compare the shear properties obtained from both test methods. ASTM standard test methods (along with Suppliers of Advanced Composite Material Association (SACMA) equivalent test methods) used for laminate testing are listed in table 2. Additional details of test specimen geometry and fixture requirements are discussed in section 2.1.

[1] FiberCote and ACG data were also investigated, but because this data was generated later, it was added in Appendix B.

Table 1. Investigated Prepreg Materials

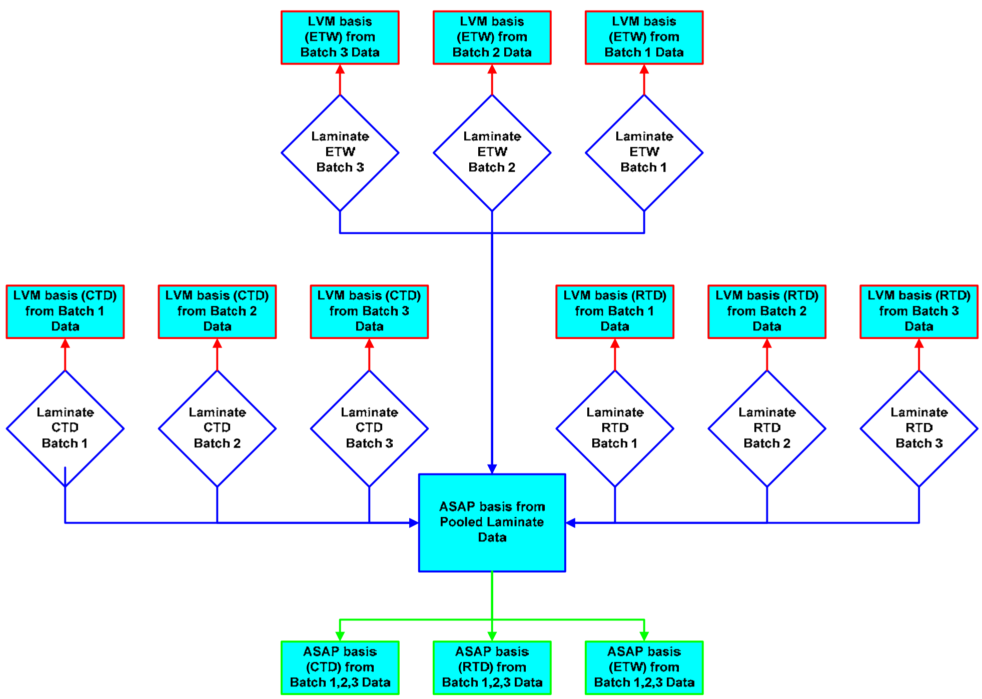
Manufacturer	Fiber/Resin	Material Form	Nominal Cured Ply Thickness (in.)
Toray (America), Inc.	T700G/#2510	150 g/m^2, unidirectional carbon tape	0.0060
	T700S/#2510	190 g/m^2, PW carbon fabric	0.0086
FiberCote Industries, Inc.	T700/E765	150 g/m^2 24K graphite unidirectional tape	0.0056
	T300/E765	190 g/m^2 3K PW fabric	0.0089
Advanced Composites Group (ACG), Inc.	AS4C/MTM45*	145 g/m^2 12K unidirectional tape	0.0055
	AS4C/MTM45*	375 g/m^2 6K 5HS	0.0153

*Stacking sequences and test matrices are different for ACG materials.

In addition to basis-value calculations, the effects of specimen and joint geometries with respect to joint behavior were evaluated. As noted in MIL-HDBK-17, Volume 1, Chapter 7 [1], joint geometry has a significant effect on the bearing strength of laminated composites. Two parameters that have the greatest effect on the joint are the width-to-diameter ratio (*w/D*) and the thickness-to-diameter ratio (*t/D*). In the main test matrices, the joint geometries had a *w/D* and *t/D* ratio of 6 and 0.48, respectively. In this task, the effects of the specific joint geometry with respect to *w/D* and *t/D* were investigated using open-hole tension (OHT) and 50% bypass (tension) test configurations, respectively. It should also be noted that the effects of these variables are not generic, and the generation of similar data would be required for each specific application and/or material. Also, failure mode and loads can significantly change for different parameters, such as hole clearance and fastener clamp-up, for the same material system. The *t/D* study was conducted by merely changing the hole diameter rather than changing the specimen thickness.

Table 2. Laminate Test Methods

Test Description	Test Method	Test Fixture
Tension No Hole	ASTM D 5766 (Modified) SACMA SRM 5 (Modified)	No
Tension Open Hole	ASTM D 5766 SACMA SRM 5	No
Tension Filled Hole	ASTM D 6742 SACMA SRM 5 (Modified)	No
Compression No Hole	ASTM D 6484 (Modified) SACMA SRM 3 (Modified)	Yes
Compression Open Hole	ASTM D 6484 SACMA SRM 3	Yes
Bearing, Double-Shear, Stabilized Tension	ASTM D 5961 (Procedure A)	Yes
Bearing, Single-Shear Stabilized, Tension	ASTM D 5961 (Procedure B)	Yes
50% Bearing-Bypass, Single-Shear, Tension	ASTM D 5961 (Procedure B)	No
50% Bearing-Bypass, Single-Shear, Compression	ASTM D 5961 (Procedure B)	Yes
V-Notch Rail Shear	ASTM D 7078	Yes



Note: For each batch and environment, LVM basis values were calculated separately.
ASAP basis values were based on three-batch pooled data across all available environments.

Figure 2. Comparison of Laminate B-Basis Values

The tests were performed on laminates representative of the range of stacking sequences used for prepreg tape and fabric in typical airframe design. The stacking sequences selected for this test program are presented in tables 3 through 6, and are consistent with the laminate stacking sequences recommended in MIL-HDBK-17. The 0^o direction on the tables indicates the fiber direction for unidirectional material and the warp direction for fabrics.

Table 3. Laminate Configurations for Unidirectional Tape (Toray and FiberCote)

Layup % 0°/45°/90°	Ply Stacking Sequence	Total Plies	Nominal Thickness* (in.)	
			Toray	FiberCote
50/40/10	$[45/0/\text{-}45/90/0/0/45/0/\text{-}45/0]_S$	20	0.120	0.112
25/50/25	$[(45/0/\text{-}45/90)_3\ ]_S$	24	0.144	0.134
10/80/10	$[45/\text{-}45/90/45/\text{-}45/45/\text{-}45/0/45/\text{-}45]_S$	20	0.120	0.112

*Based on cured-ply thicknesses for Toray and FiberCote materials shown in table 1.

Table 4. Laminate Configurations for Pw Fabric (Toray and FiberCote)

Layup % 0°/45°/90°	Ply Stacking Sequence	Total Plies	Nominal Thickness* (in.)	
			Toray	FiberCote
40/20/40	$[0/90/0/90/45/\text{-}45/90/0/90/0]_S$	20	0.172	0.178
25/50/25	$[\ (45/0/\text{-}45/90)_2\ ]_S$	16	0.138	0.142
10/80/10	$[45/\text{-}45/90/45/\text{-}45/45/\text{-}45/0/45/\text{-}45]_S$	20	0.172	0.178

*Based on cured-ply thicknesses for Toray and FiberCote materials shown in table 1.

Table 5. Laminate Configurations for ACG Unidirectional Tape

Layup % 0°/45°/90°	Ply Stacking Sequence	Total Plies	Nominal Thickness* (in.)
50/40/10	$[0/0/45/0/90/\text{-}45/0/45/0/\text{-}45]_S$	20	0.110
25/50/25	$[(45/0/\text{-}45/90)_3]_S$	24	0.132
10/80/10	$[45/\text{-}45/0/45/\text{-}45/90/45/\text{-}45/45/\text{-}45]_S$	20	0.110

*Based on cured-ply thickness for ACG materials shown in table 1.

Table 6. Laminate Configurations for ACG 5HS Fabric

Layup % 0°/45°/90°	Ply Stacking Sequence	Total Plies	Nominal Thickness* (in.)
40/20/40	[0/0/0/45/0/0/-45/0/0/0]	10	0.153
25/50/25	[45/0/-45/90/90/45/0/-45]	8	0.122
10/80/10	$[45/\text{-}45/0/45/\text{-}45]_2$	10	0.153

* Based on cured-ply thickness for ACG materials shown in table 1.

Laminate layup configurations shown in tables 3 through 6 cover the recommendation in MIL-HDBK-17, including hard (50/40/10 for unidirectional tape and 40/20/40 for fabric), quasi-isotropic[2] (25/50/25), and soft (10/80/10) laminate constructions. Both the layup configuration and test condition can severely affect material performance, and the test matrices are designed to characterize the properties for different variables that affect those properties; i.e., layup, test environment, and specimen geometry (*w/D*, *t/D*). Figure 3 graphically illustrates the selected laminate-stacking sequences with respect to lamina-level test layups.

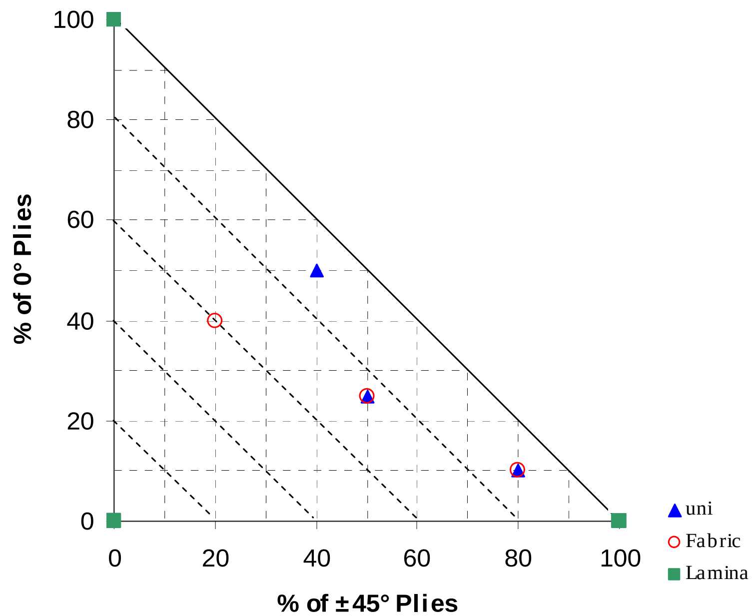


Figure 3. Layup Sequences Investigated

2.1 TEST METHODS FOR LAMINATED COMPOSITES.

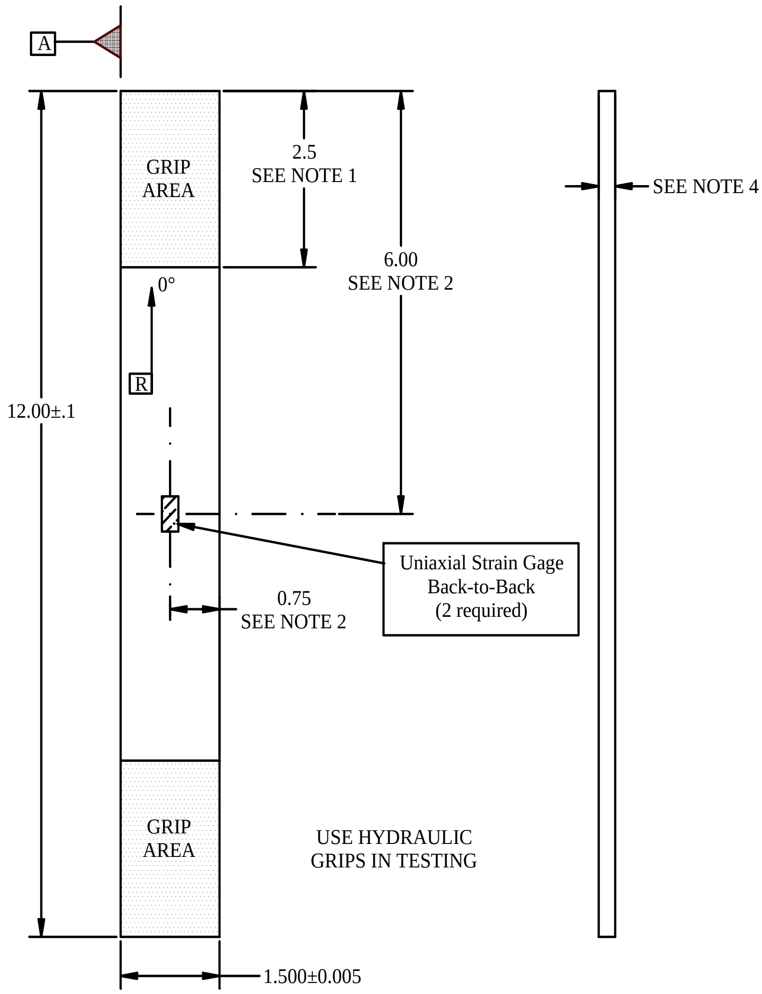
This section describes the specific standard and specimen geometry used to produce each individual mechanical property. Specific dimensions and tolerances are provided for each specimen taken from the referenced test method, as well as the requirements on parallelism and perpendicularity. Specific changes and additions to the referenced test methods are also presented. Test specimen geometry and tolerance, as well as torque applications, were conformed by a FAA DAR to meet specifications in the test plan [5].

When testing for laminated composite material properties, it is important to select specimen sizes that represent a sufficient amount of material in the gage section. No countersunk holes were used for bearing test specimens. Hole diameter and specimen width for the main test matrix were 0.25 and 1.5 inches, respectively, which resulted in a *w/D* ratio of 6, as recommended in ASTM standards, unless otherwise specified; i.e., *w/D* and *t/D* ratio studies. To avoid damage to the laminate upon fastener installation, hole tolerances of +0.003/-0.000 inch (class 3) were used throughout the program. Fasteners used in this investigation were cadmium-plated alloy steel bolts per National Aerospace Standards (NAS) 6603 through 6606. Bolts with the correct grip sizes were used to prevent damage to the bolt holes from the threads.

[2] Material properties are similar in all in-plane directions.

2.1.1 No-Hole Tension.

Currently, there is no standard test method specifically for no-hole tension (NHT). Therefore, NHT tests were conducted according to the ASTM D 5766 standard test method for OHT strength of polymer matrix composite laminates. The test specimen was modified by omitting the center hole in the ASTM D 5766 specimen. Test parameters and failure mode identification were used from ASTM D 5766. This test method does not require a test fixture. Due to the large gage section, either biaxial extensometers or strain gages can be mounted to determine the laminate modulus and Poisson's ratio. Test specimens were untabbed, and the dimensions are shown in figure 4.



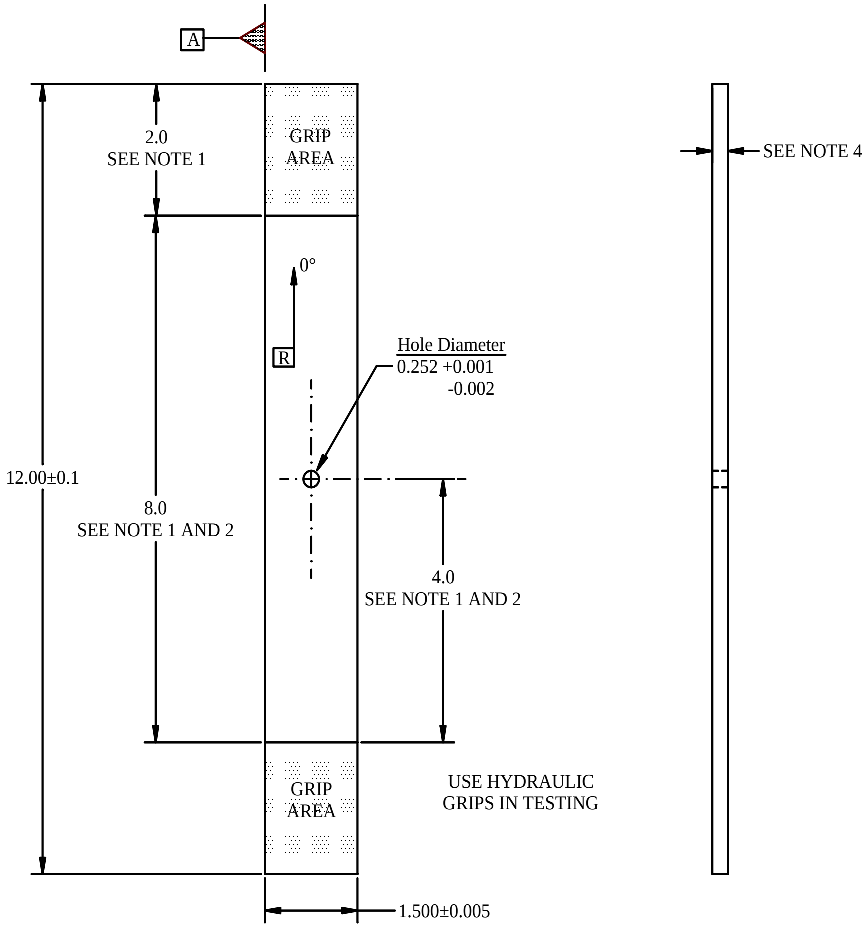
Notes:

1. Cannot be verified on specimen basis.
2. Nominal dimension; no tolerance requirement.
3. Datum "A" parallell to reference edge within 0.25°; cannot be verified on specimen basis.
4. Laminate thickness within ±15% of nominal value.
5. All dimensions are in inches.

Figure 4. No-Hole Test Specimen Configuration

2.1.2 Open-Hole Tension.

OHT tests were conducted according to ASTM D 5766. Test specimen geometry is shown in figure 5. OHT strength was calculated based on the gross cross-sectional area (disregarding the hole) as recommended in ASTM D 5766. Stiffness reduction due to the presence of the hole can be measured by mounting an extensometer at the edge of the specimen. This specimen typically does not require tabbing, and therefore, an emery-cloth can be used to avoid damage to the specimen from grip pressure.



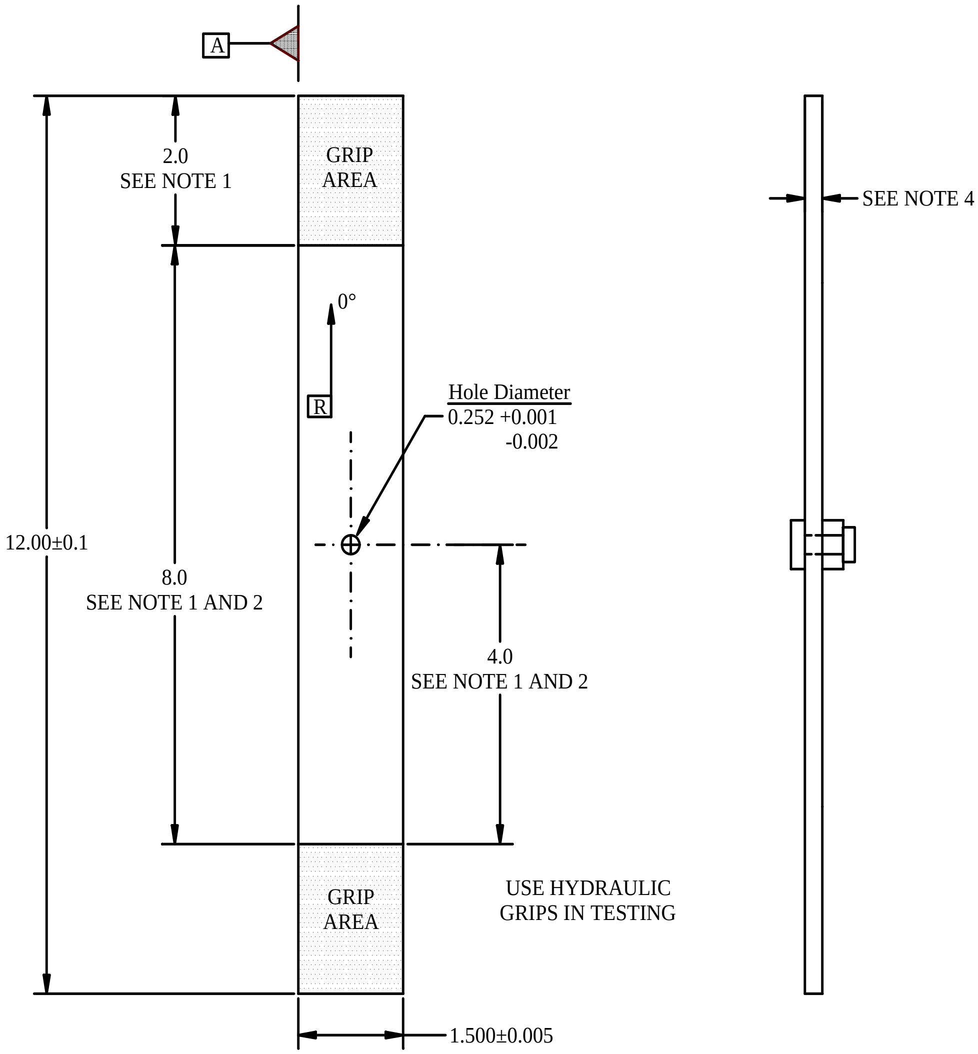
Notes:

1. Cannot be verified on specimen basis.
2. Nominal dimension; no tolerance requirement.
3. Datum "A" parallell to reference edge within 0.25°; cannot be verified on specimen basis.
4. Laminate thickness within ±15% of nominal value.
5. All dimensions are in inches.

Figure 5. Open-Hole Tension Test Specimen Configuration

2.1.3 Filled-Hole Tension.

Filled-hole tension (FHT) tests were conducted according to the ASTM D 6742 standard test method for FHT testing of polymer matrix composite laminates. Figure 6 shows the recommended specimen geometry for this test. A fastener for each specimen was installed with a torque of 70 ±5 inches pound force (in.-lbf) using a calibrated torque wrench. The FHT strength was calculated based on the gross cross-sectional area, as recommended in ASTM D 6742.



Notes:

1. Cannot be verified on specimen basis.
2. Nominal dimension; no tolerance requirement.
3. Datum "A" parallell to reference edge within 0.25°; cannot be verified on specimen basis.
4. Laminate thickness within ±15% of nominal value.
5. All dimensions are in inches.

Figure 6. Filled-Hole Tension Test Specimen Configuration

2.1.4 No-Hole Compression.

Currently, there is no standard test method specifically for no-hole compression (NHC). Therefore, NHC tests were conducted according the ASTM D 6484 standard test method for open-hole compression (OHC) strength of polymer matrix composite laminates. The test specimen was modified by not drilling the center hole. Test parameters and failure mode identification were used from ASTM D 6484. The support fixture shown in figure 7 was used to prevent buckling during compressive loading. Test specimen dimensions were the same as the NHT tests (as shown in figure 4).

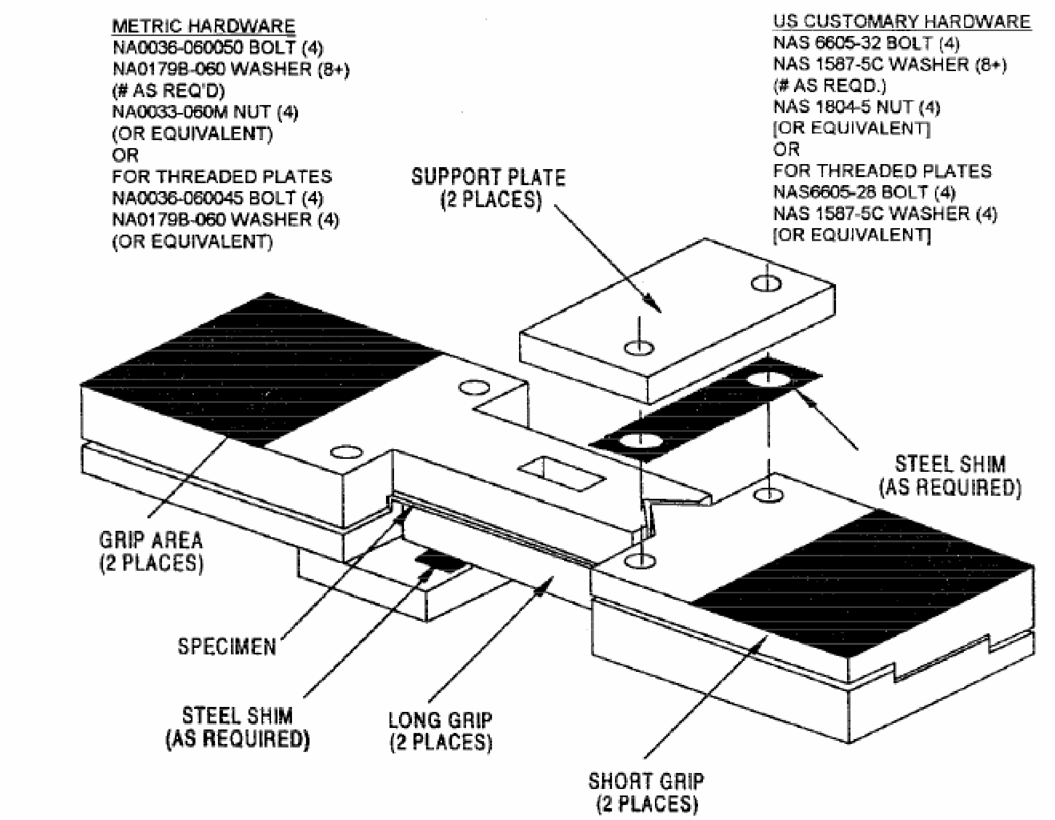


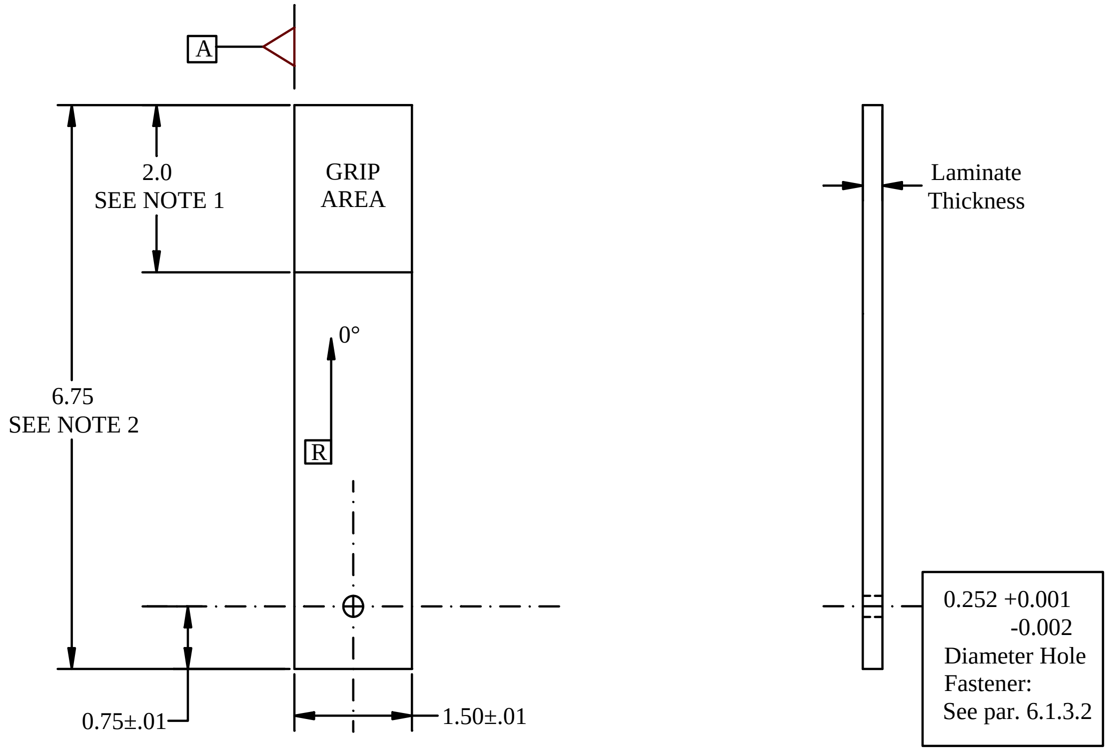
Figure 7. Support Fixture for Compression Tests (ASTM D 6484)

2.1.5 Open-Hole Compression.

OHC tests were conducted according to ASTM D 6484. Test specimen dimensions were the same as for OHT tests (as shown in figure 5). The support fixture shown in figure 7 was used to prevent buckling during compressive loading. The OHT strength was calculated based on the gross cross-sectional area (disregarding the hole), as recommended in ASTM D 6484.

2.1.6 Double-Shear Bearing.

The double-shear bearing test (DSBT) was conducted according to Procedure A (figure 8) of the ASTM D 5961 standard test method for bearing response of polymer matrix composite laminates. Once the specimen was mounted in the test fixture, a torque of 35 ±5 in.-lbf (low clamp-up) was applied using a calibrated torque wrench. An axial extensometer, mounted in the test fixture, measured hole deformation. The test fixture was designed by WSU to accommodate various hole diameters and to accommodate the extensometer (see figure F-1 in appendix F).



See ASTM D 5961 procedure A for fixture loading plate and fixture assembly configuration.

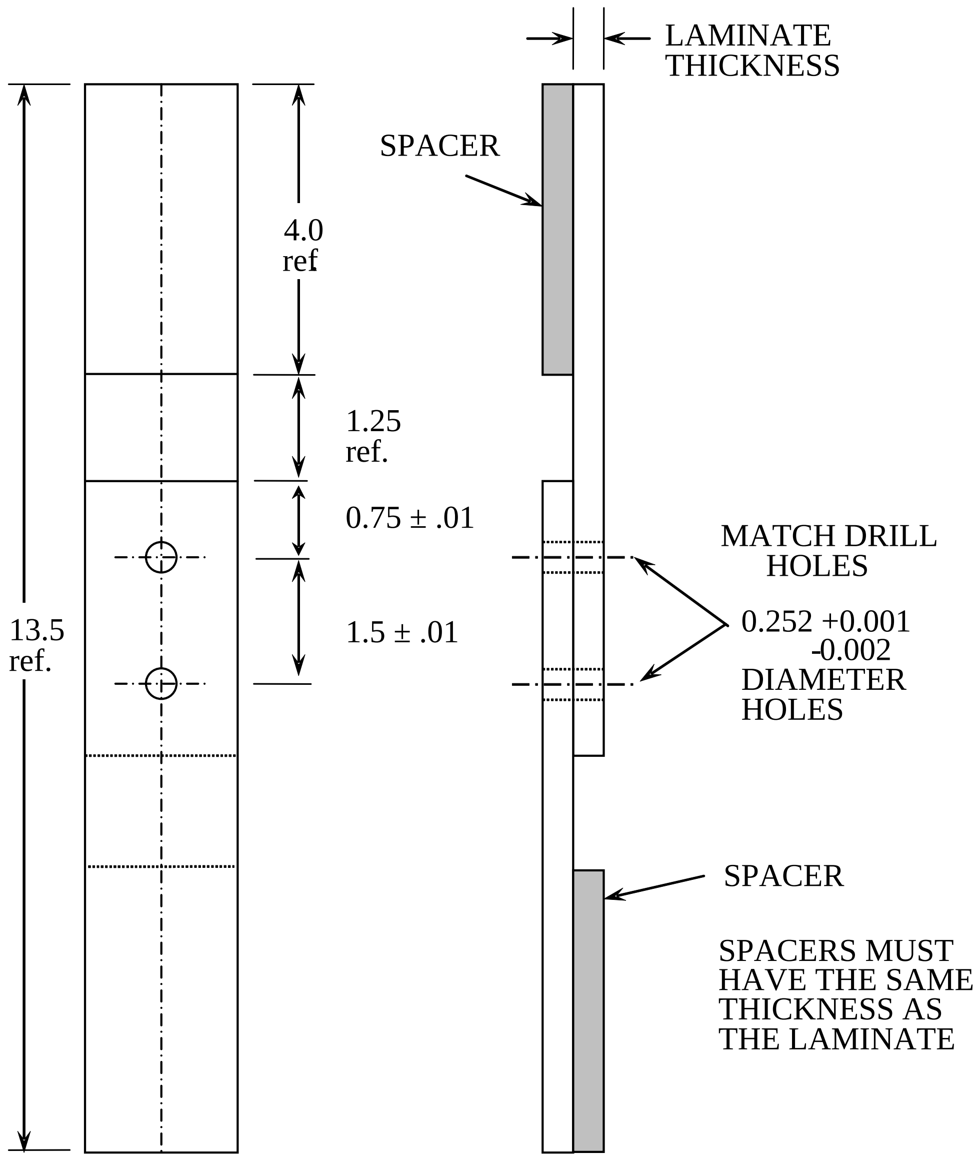
Notes:

1. Cannot be verified on specimen basis.
2. Nominal dimension; no tolerance requirement.
3. Datum "A" parallell to reference edge within 0.25°; cannot be verified on specimen basis.
4. Laminate thickness within ±15% of nominal value.
5. All dimensions are in inches.

Figure 8. Double-Shear Bearing Test Specimen Configuration

2.1.7 Single-Shear, Two-Fastener Bearing (50% Bearing-Bypass).

A single-shear, two-fastener bearing test was conducted according to Procedure B of ASTM D 5961. Figure 9 shows the recommended specimen geometry for this test method. Fastener torque for both tension and compression bearing testing was 35 ±5 in.-lbf. Two axial extensometers were mounted on the sides of the test specimen to measure (average) hole deformation. The support fixture shown in figure 10 was used only for compression loading.



Dimensions are in inches.
Test using stabilization fixture.

Figure 9. Stabilized Single-Shear 50% Load Transfer Test Specimen Assembly

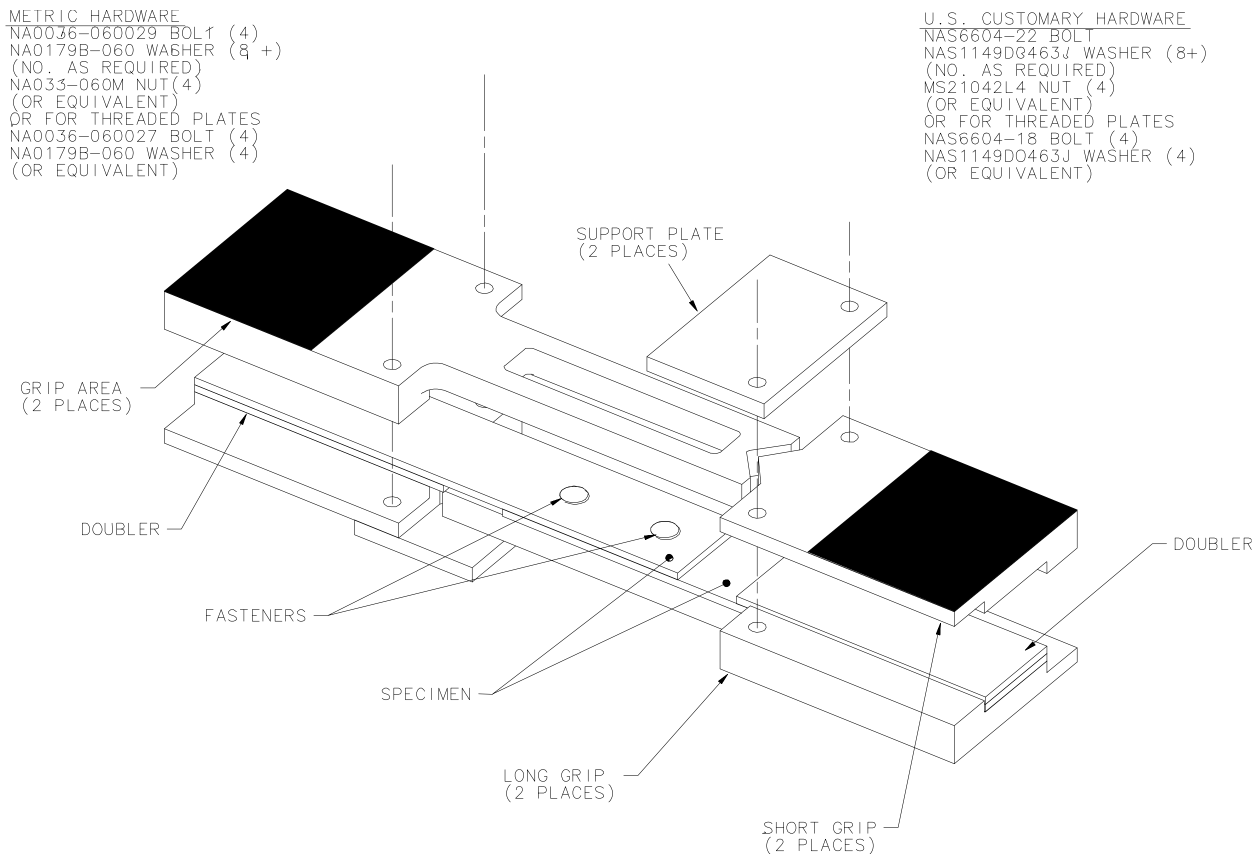
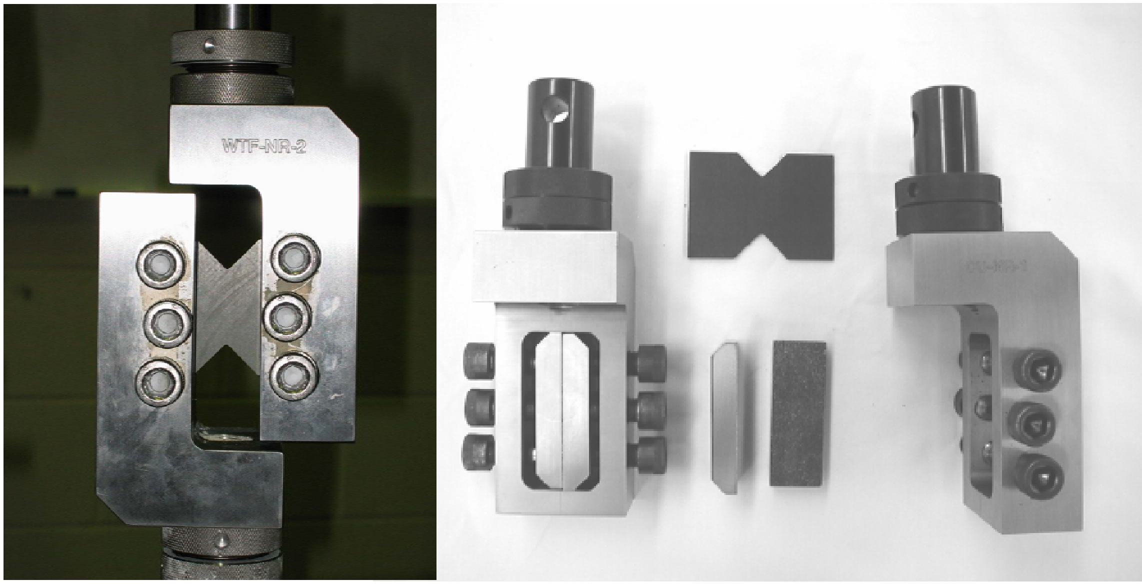


Figure 10. Support Fixture Assembly for ASTM D 5961 Procedure B

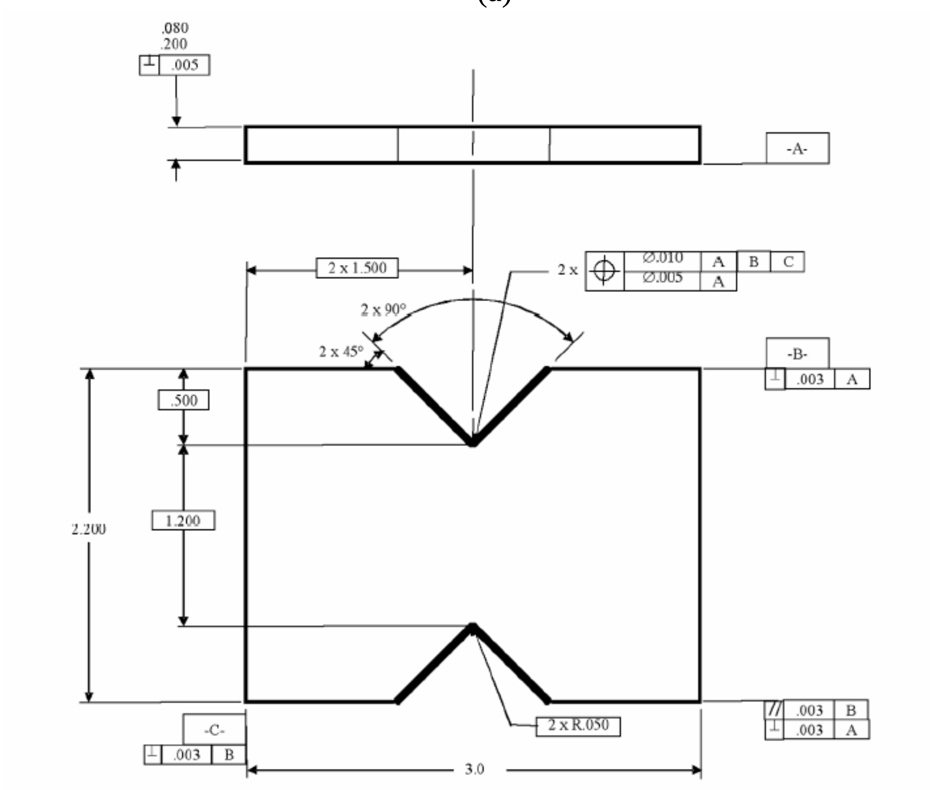
2.1.8 Laminate In-Plane Shear.

The Iosipescu shear test according to the ASTM D 5379 standard test method for shear properties of composite materials by the V-notched beam method is commonly used to obtain the in-plane shear properties of lamina that have fibers parallel and/or perpendicular to the loading direction. The gage section of the test specimen is approximately 0.45 inch. For laminated composites with multiple-fiber orientations and larger repeated unit cell[3] sizes, a specimen geometry with a larger gage section than that of ASTM D 5379 is desired. Therefore, in-plane shear testing of laminated composites used in this investigation was conducted according to the ASTM D 7078[4] standard test method for shear properties of composite materials by the V-notched rail shear (VNRS) method, as shown in figure 11. This test specimen has a gage section of approximately 1.22 inches [6].

[3] Smallest repetitive geometry of lamina.
[4] This test method was under development during the initial testing phase of this research.



(a)



(b)

Figure 11. (a) V-Notched Rail Shear Test Fixture and
(b) Test Specimen (ASTM D 7078)

2.2 ENVIRONMENTAL CONDITIONING.

Humidity-aged specimens typically use accelerated conditioning to simulate long-term exposure to humid air and to establish the moisture saturation of the material. Accelerated conditioning of the specimens at 85% ±5% relative humidity (RH) and 145° ±5°F for Toray and FiberCote (160° ±5°F for ACG) material was used until moisture equilibrium was achieved. ASTM D 5229 and SACMA SRM 11 provide general guidelines regarding environmental conditioning and moisture absorption.

Specimens tested in the dry, as-fabricated, condition were exposed to ambient laboratory conditions until mechanically tested. Ambient laboratory conditions are defined as an ambient temperature range of 65°~75°F. Since the moisture absorption or desorption rate of epoxy is very slow at ambient temperatures, maintaining relative humidity levels in the mechanical test laboratory was not necessary.

Effective moisture equilibrium was achieved when the average moisture content of the traveler specimen changed by less than 0.05% for two consecutive readings within a span of 7 ±0.5 days this may be expressed by

$$\frac{W_i - W_{i-1}}{W_b} < 0.0005$$

where W_i is the weight at the current time, W_{i-1} is the weight at the previous time, and W_b is the baseline weight prior to conditioning.

When the traveler specimens passed the criteria for two consecutive readings, which were 7 ±0.5 days apart, the specimens were removed from the environmental chamber and placed in a sealed bag along with a moist paper towel for no more than 14 days prior to mechanical testing. Specimens were not dried prior to conditioning. Strain-gaged specimens were removed from the controlled environment for less than 2 hours to apply gages under ambient laboratory conditions.

2.3 TEST MATRICES.

Detailed test matrices for Toray and FiberCote materials are found in the test plan for FAA special project number SP3650WI-Q [5], and ACG test matrices for FAA special project number SP3505CPN are found in reference 7. Test matrices are based on the recommendation in MIL-HDBK-17 with modifications to reduce test requirements. Panel and specimen conformity documentation is available on request. All test panels and machined specimens underwent FAA conformity inspection, and the documentation and data packages for each material are available on request. The primary goal in this investigation was to evaluate small-sample, statistical methodology for obtaining B-basis. Therefore, test matrices, especially for Toray and FiberCote cases, were tailored to evaluate the LVM for unnotched and notched laminate (small data sets) B-basis values. Each property was tested using three material batches that included two process cycles per batch, as shown in figure 12.

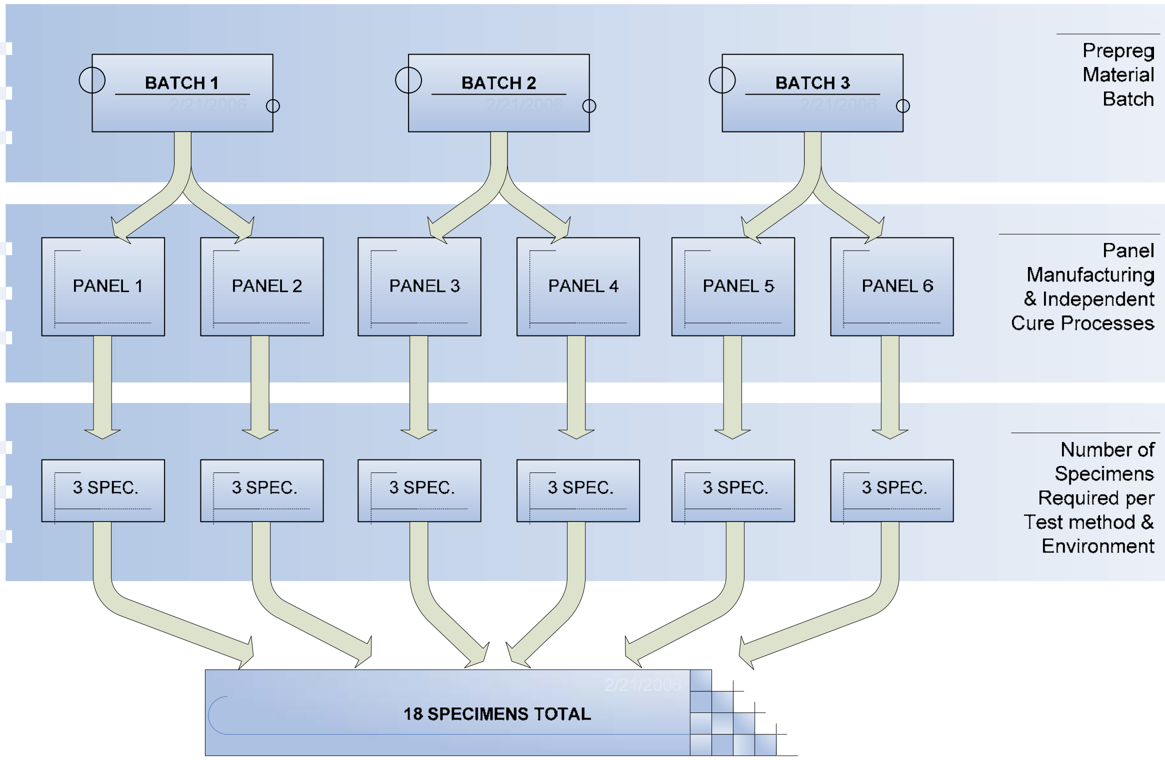


Figure 12. Specimen Selection and Batch Traceability

The test matrix for the properties discussed in this section have the following notation cited in each column

x # x

where the first # represents the required number of prepreg batches, the second # represents the required number of panels, and the third # represents the number of replicates. For example, 3 x 2 x 3 refers to three prepreg batches of material and six specimens per prepreg batch, for a total requirement of 18 test specimens.

2.3.1 Test Matrices for Toray and FiberCote Material Systems.

Multibatch laminate tests were conducted for a wide range of unnotched and notched laminate properties (tables 7 through 12) of Toray and FiberCote material systems listed in table 1. Mechanical tests were performed under the following conditions for Toray and FiberCote materials:

- CTD—cold-dry testing at -65° ±5°F with an as-fabricated moisture content
- RTD—ambient laboratory conditions with an as-fabricated moisture content
- ETW—hot-wet testing at 180° ±5°F (equilibrium moisture weight gain at 145°F and 85% RH)

Table 7. Laminate Tension Tests for Unidirectional Tape

Layup	Specimen Type	Number of Material Batches	Environment			Total
			CTD	RTD	ETW	
50/40/10	No hole[1]	3		3 x 2 x 3		18
	Filled hole[2,3]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
25/50/25	No hole[1]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
	Open hole	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
10/80/10	No hole[1]	3		3 x 2 x 3		18
	Open hole	3		3 x 2 x 3		18
					Total =	216

Notes:
[1] No-hole specimens instrumented with back-to-back strain gages
[2] Fasteners: NAS 6604 hardened alloy steel
[3] Fastener torque: 70 ±5 in.-lbf (high clamp-up critical)

Table 8. Laminate Tension Tests for PW Carbon Fabric

Layup	Specimen Type	Number of Material Batches	Environment			Total
			CTD	RTD	ETW	
40/20/40	No hole [1]	3		3 x 2 x 3		18
	Open hole	3		3 x 2 x 3		18
	Filled Hole [2,3]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
25/50/25	No hole [1]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
	Open hole	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
10/80/10	No hole [1]	3		3 x 2 x 3		18
	Open hole	3		3 x 2 x 3		18
					Total =	234

Notes:

[1] No-hole specimens instrumented with back-to-back strain gages
[2] Fasteners: NAS 6604 hardened alloy steel
[3] Fastener torque: 70 ±5 in.-lbf (high clamp-up critical)

Table 9. Laminate Compression Tests (Tape and Fabric)

Layup	Specimen Type	Number of Material Batches	Environment			Total
			CTD	RTD	ETW	
50/40/10 or 40/10/40**	No hole*	3		3 x 2 x 3		18
	Open hole	3		3 x 2 x 3		18
25/50/25	No hole*	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
	Open hole	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
10/80/10	No hole*	3		3 x 2 x 3		18
	Open hole	3		3 x 2 x 3		18
					Total =	180

* No-hole specimens instrumented with back-to-back strain gages
** For fabric

Table 10. Laminate Bearing Tension (Tape and Fabric)

Layup	Specimen Type	Number of Material Batches	Environment			Total
			CTD	RTD	ETW	
50/40/10 or 40/10/40**	Double shear [1,2]	3		3 x 2 x 3		18
	Single shear stabilized [1,2]	3		3 x 2 x 3		18
25/50/25	Double shear [1,2]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
	Single shear stabilized [1,2]	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
					Total =	144

Notes:
[1] Fastener torque: 35 ±5 in.-lbf (low clamp-up critical)
[2] Fasteners: NAS 6604 hardened alloy steel
** For Fabric

Table 11. Laminate 50% Bearing-Bypass Interaction (Tape and Fabric)

Layup	Bearing-Bypass Ratio	Specimen Type	Loading	Environment	No. of Specimens
50/40/10 or 40/20/40**	0.5 (50% load transfer)	Single shear	Tension*	RTD	3 x 5
			Compression*	RTD	3 x 5
25/50/25	0.5 (50% load transfer)	Single shear	Tension*	RTD	3 x 5
			Compression*	RTD	3 x 5
10/80/10	0.5 (50% load transfer)	Single shear	Tension*	RTD	3 x 5
			Compression*	RTD	3 x 5
					Total = 90

* Fastener torque: 35 ±5 in.-lbf (low clamp-up critical)
** For fabric

Table 12. Laminate In-Plane Shear (Tape and Fabric)

Layup	Specimen Type	Number of Material Batches	Environment CTD	RTD	ETW	Total
50/40/10 or 40/20/40*	VNRS	3		3 x 2 x 3		18
25/50/25	VNRS	3		3 x 2 x 3		18
10/80/10	VNRS	3	3 x 2 x 3	3 x 2 x 3	3 x 2 x 3	54
						Total = 90

*For fabric

In addition, tables 13 through 15 show the test matrices for *w/D* and *t/D* effects investigations. The OHT strength test was selected to investigate the *w/D* study, and the BB(50%) test was selected to investigate the *t/D* effects. For these studies, 50/40/10 and 40/20/40 layup configurations were selected for tape and PW laminates, respectively. Fastener torque was 35 ±5 in.-lbf as low clamp-up is the more critical condition.

Table 13. *w/D* Ratio Investigation Matrix (Tape and Fabric)

w (in.)	*D* (in.)	*w/D*	Environment	Replicates	No. of Specimens
0.75	0.250	3	RTD	3 x 2 x 3	18
1.00	0.250	4	RTD	3 x 2 x 3	18
1.50	0.250	6	RTD	3 x 2 x 3	18
2.00	0.250	8	RTD	3 x 2 x 3	18
				Total =	72

This *w/D* ratio of 6 was tested and characterized in table 8 for PW fabric.

Table 14. *t/D* Ratio Investigation Matrix for Unidirectional Tape

t (in.)	*D* (in.)*	*t/D*	*D/t*	*W* (in.)	Environment	Replicates	No. of Specimens
0.120	0.3750	0.320	3.125	2.250	RTD	3 x 2 x 3	18
0.120	0.3125	0.384	2.604	1.875	RTD	3 x 2 x 3	18
0.120	0.2500	0.480	2.083	1.500	RTD	3 x 2 x 3	18
0.120	0.1875	0.640	1.563	1.125	RTD	3 x 2 x 3	18
						Total =	72

*NAS 6603 = 0.1900; NAS 6605 = 0.3125; NAS 6606 = 0.375
t/D ratio of 0.480 was tested and characterized in table 11.

Table 15. *t/D* Ratio Investigation Matrix for PW Fabric

t (in)	*D* (in.)*	*t/D*	*D/t*	*W* (in.)	Environment	Replicates	No. of Specimens
0.178	0.375	0.475	2.107	2.250	RTD	3 x 2 x 3	18
0.178	0.3125	0.570	1.756	1.875	RTD	3 x 2 x 3	18
0.178	0.250	0.712	1.404	1.500	RTD	3 x 2 x 3	18
0.178	0.1875	0.949	1.053	1.125	RTD	3 x 2 x 3	18
						Total =	72

* NAS6603 = 0.1900; NAS6605 = 0.3125; NAS6606 = 0.375
t/D ratio 0.712 was tested and characterized in table 11.

2.3.2 Test Matrices for ACG Material Systems.

In addition to the previous four material systems, two additional material systems from ACG were evaluated using LVM (tables 16 and 17). To compare the LVM B-basis values with the multibatch data for the corresponding test method, only multibatch data sets were extracted from ACG material qualification data packages [8 and 9]. Moisture-conditioning parameters for ACG materials were 160° ±5°F and 85% ±5% RH. Mechanical tests were performed under the following conditions for Toray and FiberCote materials:

- CTD—cold-dry tests at -65° ±5°F with an as-fabricated moisture content
- RTD—ambient laboratory conditions with an as-fabricated moisture content
- ETW—hot-wet tests at 200° ±5°F (equilibrium moisture weight gain at 160°F and 85% RH)
- ETW2—hot-wet tests at 250° ±5°F (equilibrium moisture weight gain at 160°F and 85% RH)

Table 16. Laminate Test Matrix for ACG Unidirectional Tape

Layup	Specimen Type	Environment			
		CTD	RTD	ETW	ETW2
25/50/25	OHT	3 x 2 x 3	3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
10/80/10		3 x 2 x 3	1 x 2 x 3		1 x 2 x 3
50/40/10		3 x 2 x 3	1 x 2 x 3		1 x 2 x 3
25/50/25	OHC		3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
10/80/10			1 x 2 x 3		3 x 2 x 3
50/40/10			1 x 2 x 3		3 x 2 x 3
25/50/25	Unnotched tension	3 x 2 x 3	3 x 2 x 3		1 x 2 x 3
25/50/25	Unnotched compression		3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
25/50/25	FHT	3 x 2 x 3	1 x 2 x 3		
25/50/25	FHC		--		--
10/80/10			1 x 2 x 3		3 x 2 x 3
50/40/10			1 x 2 x 3		3 x 2 x 3
25/50/25	Single-shear bearing		3 x 2 x 3		3 x 2 x 3
10/80/10			1 x 2 x 3		3 x 2 x 3
50/40/10			1 x 2 x 3		3 x 2 x 3

Table 17. Laminate Test Matrix for ACG 5HS Fabric

Layup	Specimen Type	Environment			
		CTD	RTD	ETW	ETW2
25/50/25	OHT	3 x 2 x 3	3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
10/80/10		3 x 2 x 3	1 x 2 x 3		1 x 2 x 3
40/20/40		3 x 2 x 3	1 x 2 x 3		1 x 2 x 3
25/50/25	OHC		3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
10/80/10			1 x 2 x 3		3 x 2 x 3
40/20/40			1 x 2 x 3		3 x 2 x 3
25/50/25	Unnotched tension	3 x 2 x 3	3 x 2 x 3		1 x 2 x 3
25/50/25	Unnotched compression		3 x 2 x 3	1 x 2 x 3	3 x 2 x 3
25/50/25	FHT	3 x 2 x 3	1 x 2 x 3		
25/50/25	FHC		1 x 2 x 3		3 x 2 x 3
10/80/10			1 x 2 x 3		3 x 2 x 3
40/20/40			1 x 2 x 3		3 x 2 x 3
25/50/25	Single-shear bearing		3 x 2 x 3		3 x 2 x 3
10/80/10			1 x 2 x 3		3 x 2 x 3
40/20/40			1 x 2 x 3		3 x 2 x 3

3. SMALL SAMPLE B-BASIS MATERIAL ALLOWABLE GENERATION.

3.1 INTRODUCTION.

As testing progressed through the building block shown in figure 1, it was important to reduce the sample size to lower cost. This may have lead to unstable basis values and higher variance in data sets. Compared to conventional metals, laminated composite materials exhibit a larger dispersion of their material properties—both mechanical and physical. This can be attributed to process parameters, such as cure temperature, pressure, out-time of prepreg material, and fiber misalignment; specimen fabrication; and test parameters; as well as environment. Furthermore, the variability in constituents, i.e., fibers and matrix, affects the mechanical and physical properties of composite materials. Some of these parameters can significantly increase the variability of mechanical properties. Therefore, it is vital to control such variables to minimize the scatter in mechanical properties. Nevertheless, the design value of a composite structure must account for the stochastic nature of material properties caused by batch-to-batch variability and process variability and, thus, must be statistically generated to ensure safe operation of the structure throughout its life. Since the material property of interest is a random variable that changes from one test specimen to another, some statistical method must be used to approximate the true material distribution. Thus, a statistical method to reduce the test data to obtain design allowables or design values must be exercised.

B-basis material properties are defined as the tenth percentiles of a material property distribution. However, the true population (probability distribution of an infinite number of samples) is an unknown. By testing *n* specimens, one observes *n* numbers and, if *n* is large enough, a histogram of these numbers will approximate the unknown probability distribution for the strength property. This probability distribution is referred to as a population, and the *n* numbers are a realization of a random sample of this population. A statistically based B-basis material property is a statistic calculated from a random sample of size *n*, such that if one were to repeatedly obtain random samples of *n* specimens and calculate many of their basis values, 95% of the time the calculated values would fall below the (unknown) tenth percentile (see figure 13). In statistical terminology, basis values are 95% lower confidence limits on prescribed percentiles, which are also sometimes referred to as tolerance limits. Basis values from a set of repeated samples will form a histogram, as shown in figure 13, rather than a fixed value. The mean and variance of the distribution of the basis values will be a function of the sample size and the strength property variance [10].

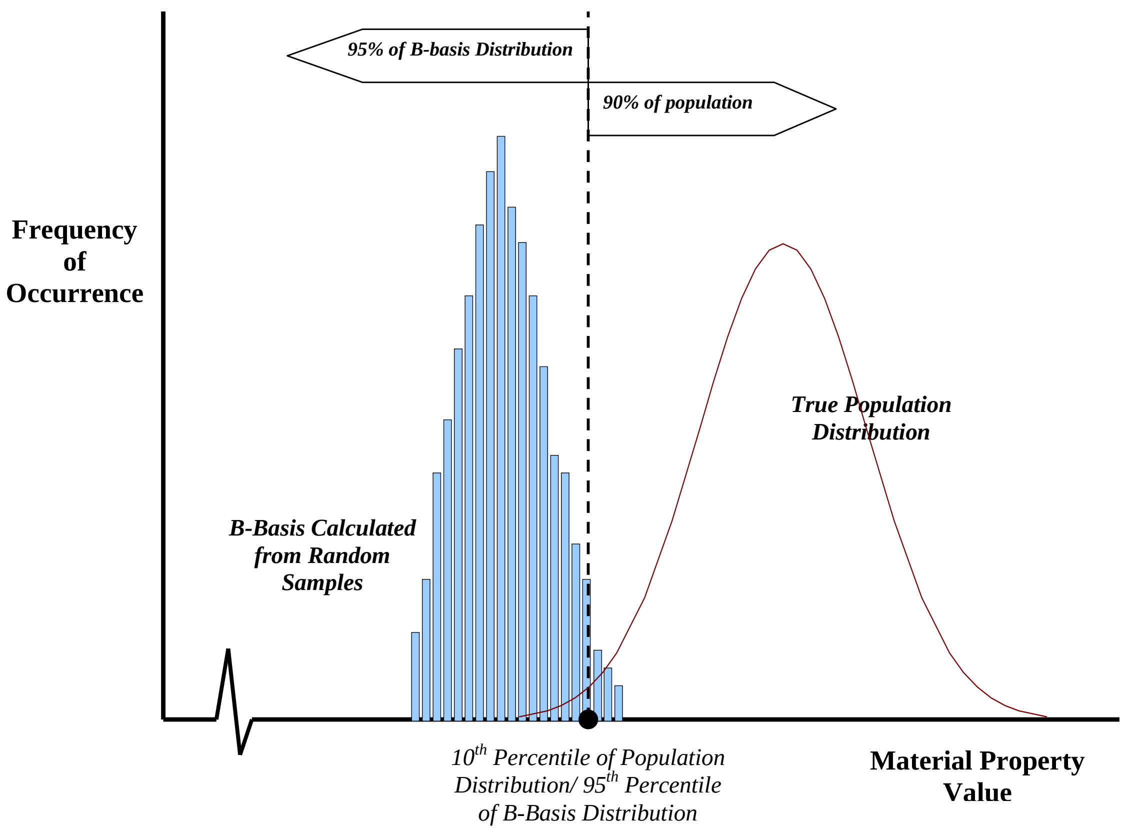


Figure 13. B-Basis Allowable

Several statistical methods for obtaining design allowables of composites in the lamina level were developed under the MIL-HDBK-17 Polymer Matrix Composite (PMC) Statistics Working Group [1]. As a result of the AGATE consortium, general aviation communities, along with federal authorities (FAA and NASA), and academia developed a pooling method to establish large samples (population) to obtain more stable allowables from a limited number of batches. A detailed description of the ASAP is included in reference 3 with an example B-basis calculation. This approach [2 and 10] pools data for a specific failure mode across all test environments, thus creating a large population to establish population variability. This method requires relatively small samples at different environments and assumes normal distribution of the test data. The intent of this research was to evaluate small-sample B-basis allowable calculation methods and compare them to large-population B-basis values to determine the statistical reliability or the degree of conservatism of such methods. Section 3.1 primarily discusses the LVM, and appendix D includes a comparison of the 1-Batch Normal (Ward) method [11] for small-sample B-basis calculations for Toray unidirectional tape and PW fabric materials [12]. This comparison also includes data analyzed using the Regression Confidence Intervals on Percentiles (RECIPE) code, which was developed by Dr. Vangel as a general purpose code for determining basis values with or without additional random effects; such as batch variability [13, 14, 15, and 16].

Statistical methods, such as ASAP, are intended for data sets that have sample sizes greater than 50 and for multibatch data sets with different environmental conditions. Unlike the data evaluated in this section, in practice, laminate data sets may contain only one batch of data for one environment, and the variance of such data undoubtedly will not be representative of the large population. Therefore, the intent of the study outlined in this section was to explore the capability of LVM to obtain conservative basis values from a small data set. Data analyzed by LVM was then compared to basis values obtained using a multibatch data set (large population) to assess the likelihood that calculated basis values represent a high-confidence, lower-bound estimate of the true population basis values.

3.2 LAMINA VARIABILITY METHOD.

LVM assumes that the intrinsic strength variability of a laminate (small) data set is no greater than the strength variability of the specimen for which considerable (lamina) data is available. The *N*1+*N*2-2 method [17] proposed by Dr. Vangel in 1989 makes this assumption and obtains the B-basis values as

$$\mathrm{B-Basis\,Value} = \mathrm{X_1} - \mathrm{K}_{(\mathrm{N_1},\mathrm{N_2})} \cdot \sqrt{(\mathrm{N_1}-1)\cdot \mathrm{S_1}^2 + (\mathrm{N_2}-1)\cdot \mathrm{S_2}^2 \Big/ (\mathrm{N_1}+\mathrm{N_2}-2)} \tag{1}$$

where *X*, *N*, *K*, and *S* correspond to the mean, standard deviation, and number of specimens, respectively, while the subscripts 1 and 2 refer to small-sample data sets (laminate) and large population (lamina), respectively. $K_{(N_1,N_2)}$ is obtained from a two-sided statistical table (table 18), which is shown graphically in figure 14, where $\mathrm{K}_{(N_1,N_2)}$ = B-basis factor.

Table 18. B-Basis Factors $\left(K_{(N_1,N_2)}\right)$ for Small Data Sets Using Variability of Corresponding Large Data Set

	N1													
N1+N2-2	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	4.508	0	0	0	0	0	0	0	0	0	0	0	0	0
4	3.827	3.607	0	0	0	0	0	0	0	0	0	0	0	0
5	3.481	3.263	3.141	0	0	0	0	0	0	0	0	0	0	0
6	3.273	3.056	2.934	2.854	0	0	0	0	0	0	0	0	0	0
7	3.134	2.918	2.796	2.715	2.658	0	0	0	0	0	0	0	0	0
8	3.035	2.820	2.697	2.616	2.558	2.515	0	0	0	0	0	0	0	0
9	2.960	2.746	2.623	2.541	2.483	2.440	2.405	0	0	0	0	0	0	0
10	2.903	2.688	2.565	2.484	2.425	2.381	2.346	2.318	0	0	0	0	0	0
11	2.856	2.643	2.519	2.437	2.378	2.334	2.299	2.270	2.247	0	0	0	0	0
12	2.819	2.605	2.481	2.399	2.340	2.295	2.260	2.231	2.207	2.187	0	0	0	0
13	2.787	2.574	2.450	2.367	2.308	2.263	2.227	2.198	2.174	2.154	2.137	0	0	0
14	2.761	2.547	2.423	2.341	2.281	2.236	2.200	2.171	2.147	2.126	2.109	2.093	0	0
15	2.738	2.525	2.401	2.318	2.258	2.212	2.176	2.147	2.123	2.102	2.084	2.069	2.056	0
16	2.719	2.505	2.381	2.298	2.238	2.192	2.156	2.126	2.102	2.081	2.063	2.048	2.034	2.022
17	2.701	2.488	2.364	2.280	2.220	2.174	2.138	2.108	2.083	2.062	2.045	2.029	2.015	2.003
18	2.686	2.473	2.348	2.265	2.204	2.158	2.122	2.092	2.067	2.046	2.028	2.012	1.999	1.986
19	2.673	2.459	2.335	2.251	2.191	2.144	2.108	2.078	2.053	2.032	2.013	1.998	1.984	1.971
20	2.661	2.447	2.323	2.239	2.178	2.132	2.095	2.065	2.040	2.019	2.000	1.984	1.970	1.958
21	2.650	2.437	2.312	2.228	2.167	2.121	2.084	2.053	2.028	2.007	1.988	1.972	1.958	1.946
22	2.640	2.427	2.302	2.218	2.157	2.110	2.073	2.043	2.018	1.996	1.978	1.962	1.947	1.935
23	2.631	2.418	2.293	2.209	2.148	2.101	2.064	2.033	2.008	1.987	1.968	1.952	1.938	1.925
24	2.623	2.410	2.285	2.201	2.139	2.092	2.055	2.025	1.999	1.978	1.959	1.943	1.928	1.916
25	2.616	2.402	2.277	2.193	2.132	2.085	2.047	2.017	1.991	1.969	1.951	1.934	1.920	1.907
26	2.609	2.396	2.270	2.186	2.125	2.078	2.040	2.009	1.984	1.962	1.943	1.927	1.912	1.900
27	2.602	2.389	2.264	2.180	2.118	2.071	2.033	2.003	1.977	1.955	1.936	1.920	1.905	1.892
28	2.597	2.383	2.258	2.174	2.112	2.065	2.027	1.996	1.971	1.949	1.930	1.913	1.899	1.886
29	2.591	2.378	2.252	2.168	2.106	2.059	2.021	1.990	1.965	1.943	1.924	1.907	1.893	1.880
30	2.586	2.373	2.247	2.163	2.101	2.054	2.016	1.985	1.959	1.937	1.918	1.901	1.887	1.874
40	2.550	2.337	2.211	2.126	2.063	2.015	1.977	1.946	1.919	1.897	1.877	1.860	1.845	1.832
50	2.528	2.315	2.189	2.104	2.041	1.993	1.954	1.922	1.896	1.873	1.853	1.836	1.820	1.807
60	2.514	2.301	2.175	2.089	**2.026**	1.978	1.939	1.907	1.880	1.857	1.837	1.819	1.804	1.790
70	2.504	2.291	2.164	2.079	2.016	1.967	1.928	1.896	1.869	1.846	**1.825**	1.808	1.792	1.778
80	2.496	2.283	2.157	2.071	2.008	1.959	1.920	1.887	1.860	1.837	1.817	1.799	1.783	1.769
90	2.491	2.277	2.151	2.065	2.002	1.953	1.913	1.881	1.854	1.830	1.810	1.792	1.776	1.762
100	2.486	2.273	2.146	2.060	1.997	1.948	1.908	1.876	1.849	1.825	1.805	1.787	1.771	1.757
125	2.478	2.264	2.138	2.051	1.988	1.939	1.899	1.867	1.839	1.816	1.795	1.777	1.761	1.747
150	2.472	2.259	2.132	2.046	1.982	1.933	1.893	1.861	1.833	1.809	1.789	1.770	1.754	1.740
175	2.468	2.255	2.128	2.042	1.978	1.929	1.889	1.856	1.828	1.805	1.784	1.766	1.750	1.735
200	2.465	2.252	2.125	2.039	1.975	1.925	1.886	1.853	1.825	1.801	1.781	1.762	1.746	1.732

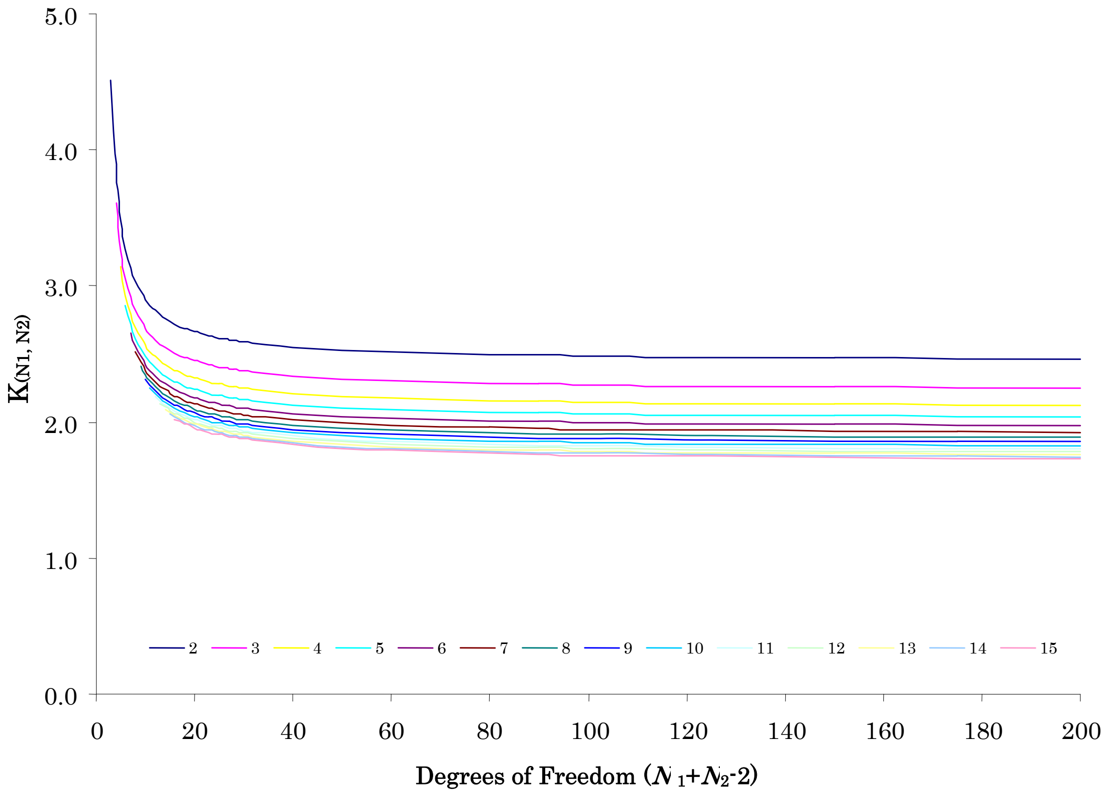


Figure 14. B-Basis Factors for a Small Data Set Using Variability of Corresponding Large Data Set

For LVM, N_2 is assumed to be significantly large compared to N_1, and thus, the contribution from N_1 to B-basis was neglected. Once the large population data set is normalized by the corresponding mean (X_2), the standard deviation is equal to the coefficient of variation (CV_2), and the mean is equal to 1. Therefore, equation 1 was modified as

$$k_{LVM} = 1 - K_{(N_1, N_2)} \cdot CV_2 \tag{2}$$

where k_{LVM} is defined as the B-basis allowable factor for LVM, and the B-basis value is calculated as

$$B - basisvalue = k_{LVM} \cdot X_1 \tag{3}$$

It is imperative to note that the B-basis values obtained by LVM for small-sample data sets is merely affected by the number of samples and the CV of the large population, and the number of samples and the mean of the small-sample data set. Therefore, for a particular lamina data set (CV_2 and N_2 are known) and the corresponding laminate (small data set, N_1), the B-basis allowable factors can be graphically presented, as shown in figure 15. This example shows the effects of N_1 and CV_2 on B-basis, considering an N_2 of 84. Although the effects of N_1 in equation 2 are not apparent, K_{LVM} is a function of the degree of freedom (N_1+N_2 -2). As shown in figure

16, the effects of N_2 on K_{LVM} are reduced for values of N_2 more than 70. Therefore, K_{LVM} becomes more dependent on N_1 for such cases.

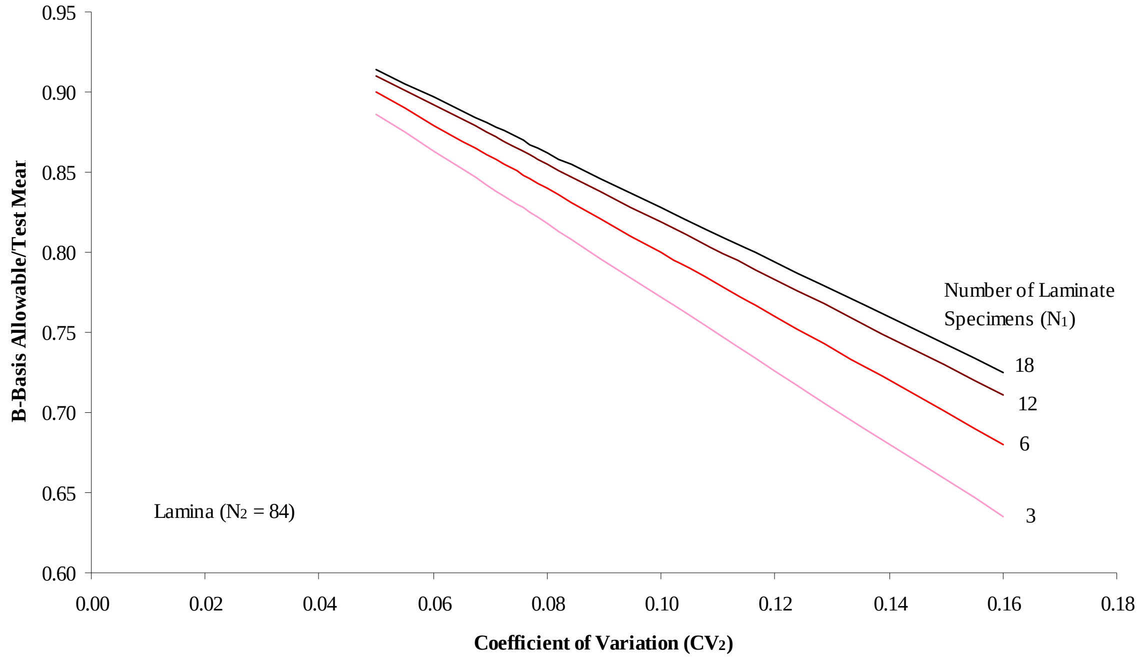


Figure 15. B-Basis Allowable Factors for $N_2 = 84$

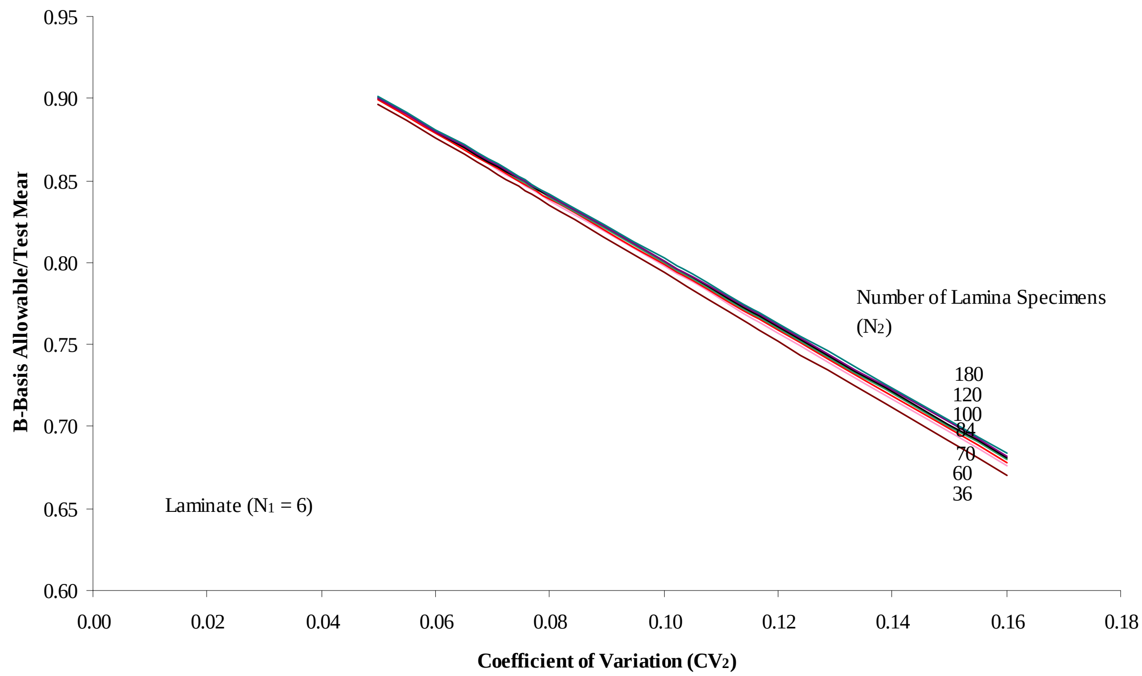


Figure 16. B-Basis Allowable Factors for $N_1 = 6$

In addition to the CVs of lamina and laminate data, the failure modes between them must be alike and, for each environment, should not significantly change. If the failure modes or the CVs change significantly, traditional methods in MIL-HDBK-17 must be used to generate laminate B-basis values.

4. BEARING-BYPASS TESTS.

Any joint in a composite structure is a potential failure site or damage-initiation point. Therefore, it is important to consider the bearing allowables of composite materials. However, typical joints are designed with multiple fasteners and encounter both bearing loads as well as loads that bypass the fastener and do not fully react at the fastener hole. The bearing and bypass ratios are typically a function of joint stiffness and configuration, and remain fairly constant until damage occurs around the hole and produces different failure modes. A range of tests conducted on different bearing-bypass ratios form an empirical curve that can be used for multifastener joints encompassing several failure modes, as shown in figure 17.

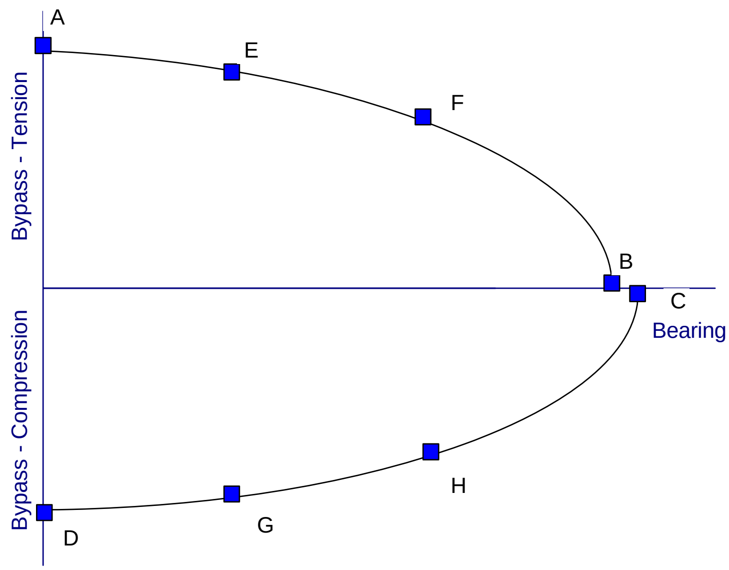


Figure 17. Typical Bearing-Bypass Interaction Curve

Points A and D represent pure-bypass (no bearing loads) cases identified as net tension and net compression failures, respectively. Open-hole and filled-hole specimens (typically at critical environmental conditions to reduce test requirements) are used to obtain the properties. Lines from point A to B and point D to C represent the reduction of net tension and compression strength due to fastener loads, respectively. Points B and C represent the pure-bearing case obtained from one-fastener loading (single-shear or double-shear bearing), where the entire load is reacted by the fastener. Typically, the bearing value for tension and compression loading are not much different, and therefore, tests are only conducted in tension, since it requires minimal test fixture requirements. Several test methods are currently available to achieve different bearing-bypass ratios (points E, F, G, and H), and some may require intricate instrumentation to calculate the load measured directly without backing out a value from strain gage readings on joining members [18] and/or added calibrations. Several test methods are listed in MIL-HDBK-17 (Volume 1: Chapter 7) for testing composites for different bearing-bypass ratios. In this investigation, single-shear, two-fastener specimens from this investigation were used to obtain a 50% bearing-bypass loading condition. This is a relatively simple test. However, based on the clamp-up pressure applied through fastener torque, layup configuration, and specimen geometry, the failure modes may differ. Typically, a specimen that has *w/D* = 5 with high clamp-up can experience bypass failure mode, while *w/D* = 8 with low clamp-up results in a bearing failure mode. In addition to the parameters mentioned above, the test environment may cause different failure modes for a particular test configuration. The MIL-HDBK-17 testing working group together with ASTM International has developed several standard test methods for obtaining the above-mentioned properties [19]. Further, single-batch laminate bearing-bypass test results for several Toray and FiberCote material systems are included in references 20 through 22.

Historically, bearing strength and failure mode show some dependency on the specimen geometry, namely hole diameter (*D*), specimen width (*w*), specimen thickness (*t*), and edge distance (*e*). As part of this investigation, both *t/D* ratio and *w/D* ratio effects on 50% bearing-bypass and OHT strength, respectively, were investigated.

5. RESULTS AND ANALYSIS.

Both Toray unidirectional tape and PW laminate data [20] for this investigation consisted of three batches for all test methods. Laminate data for several FiberCote cases were not available for 3 batches, and the analysis was conducted using only two batches. For most cases, both ACG unidirectional tape and 5HS data has test data from three batches for most cases [8 and 9].

5.1 VARIATION OF LAMINA AND LAMINATE TEST DATA.

The prime assumption for applying the LVM is the intrinsic strength variability of the laminate (small) data set is no greater than the strength variability of the specimen for which considerable (lamina) data is available. To investigate the validity of this assumption, CVs of laminate data are paired with lamina CVs for the same loading and environmental conditions. The NHT, OHT, and FHT tests exhibit general tension loading of the laminate test specimens, and the failure modes are primarily in tension failure of fibers, as observed previously in lamina testing (figure 18). Therefore, the CVs of those test results are compared against the 0° tension lamina CVs corresponding to individual environments. Similarly, the NHC, OHC, and FHC laminate CVs are compared to the 0° compression lamina CVs.

Figure 18. Typical Tension Failure Modes of Laminate Tension Tests

Unlike the above-mentioned two loading cases, bearing and in-plane shear failure modes require vigilance when determining the appropriate failure modes for comparison. Regardless of the global loading condition of a bearing specimen, there exists a highly localized compressive load at the bearing contact surface of the fastener hole. In some cases, the failure occurs at locations closer to the washer on the compression side. Failure modes of these specimens indicate a localized compressive failure of the laminate (figure 19). For the case of in-plane shear, the failure mode analysis becomes more challenging. As the V-notch specimens are loaded in in-plane shear, typically the portion of the specimen that is loaded in compression mode fails due to instability of the fibers (figure 20). Therefore, both bearing and in-plane shear laminate CVs are compared against lamina 0° compression CVs.

Figure 19. Localized Compression Failure of Laminate Bearing Tests

Figure 20. Compressive Failure of Laminates During Shear Loading

From the Toray products AGATE material qualification test program [23 and 24], lamina CVs are obtained for individual environments and compared with the laminate CVs for the corresponding environment and loading condition. Figures 21 and 22 show a comparison of results for the Toray tape and PW laminate tests conducted in this investigation, respectively. Lamina CV’s for FiberCote materials were obtained from AGATE data [25 and 26], while ACG lamina data were obtained from the ongoing test programs that included lamina and laminate data [8 and 9]. A detailed comparison of variation for all six material systems under investigation is included in appendix A. Except for some bearing cases and in-plane shear cases, overall test data indicated lower CVs for laminate compared to corresponding lamina CVs. After 2% or more hole deformation of single-shear bearing tests, bolts tend to dig into the specimens because of excessive rotation caused by load eccentricity. Therefore, the tests were manually stopped after sufficient hole deformation, and 2% offset strength was reported for most cases according to the recommended ASTM D 5961 test procedure. The high CV in some of the bearing cases can be attributed to the data reduction process; 2% offset was determined using hole deformation that was measured using extensometers mounted on the side of the specimen. Such variation cannot completely be attributed to material behavior. It must be investigated individually and may require further testing based on the application. High CVs for laminate-bearing tests are more apparent for tape materials. In-plane shear tests were conducted using the new VNRS test method, which was developed using thinner specimens than those used in this investigation. Therefore, they required bolt torques ranging from 700 to 900 in.-lbf to prevent specimen slippage. These through-the-thickness clamping forces may have resulted in damage closer to the gripping area that resulted in a higher variability in the unnotched in-plane shear test data, especially for tape laminates with a high percentage of ±45° plies and at CTD environmental condition.

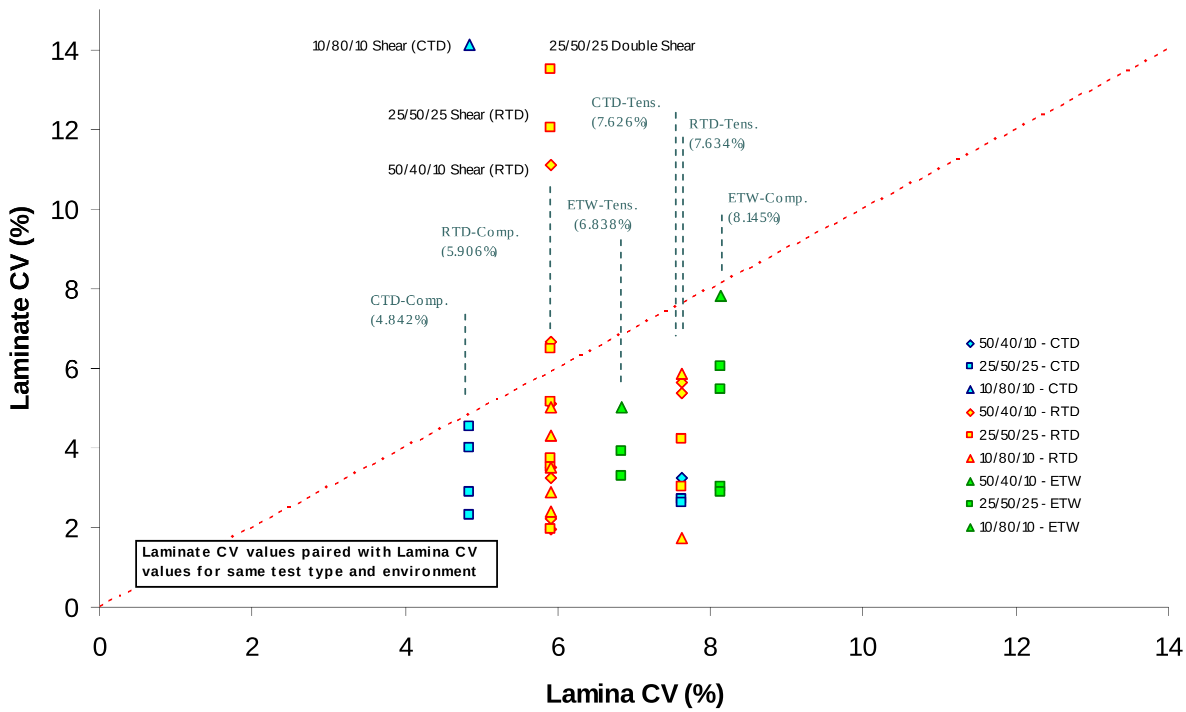


Figure 21. Toray Tape Data CV Comparison

Laminate test data for ACG 5HS also indicated lower CVs for laminate than for lamina, except for one bearing case and one unnotched compression case. Since the current investigation was limited to the analysis of prepreg material listed in table 1, the CV comparison was limited to these materials. It was noted that for cases where the laminate CV is high, the pooled three-batch, B-basis values were low. Since LVM does not account for laminate variability (only the number of samples and mean), LVM B-basis values for such cases were higher than the three-batch, B-basis values and appeared unconservative. Therefore, further analysis of the cause of the variability in a large population (three-batch laminate data set) that resulted in the lower-pooled ASAP values must be investigated. If the variability is caused by the test parameters, then that must be corrected and retested; for example, the complication encountered while testing thick laminates in shear is not relevant for material variability. If the small sample test data continues to produce high CVs (batch to batch or within batch), multibatch data is required and alternative statistical analysis methodologies proposed in MIL-HDBK-17, Volume 1, Chapter 8 may be used.

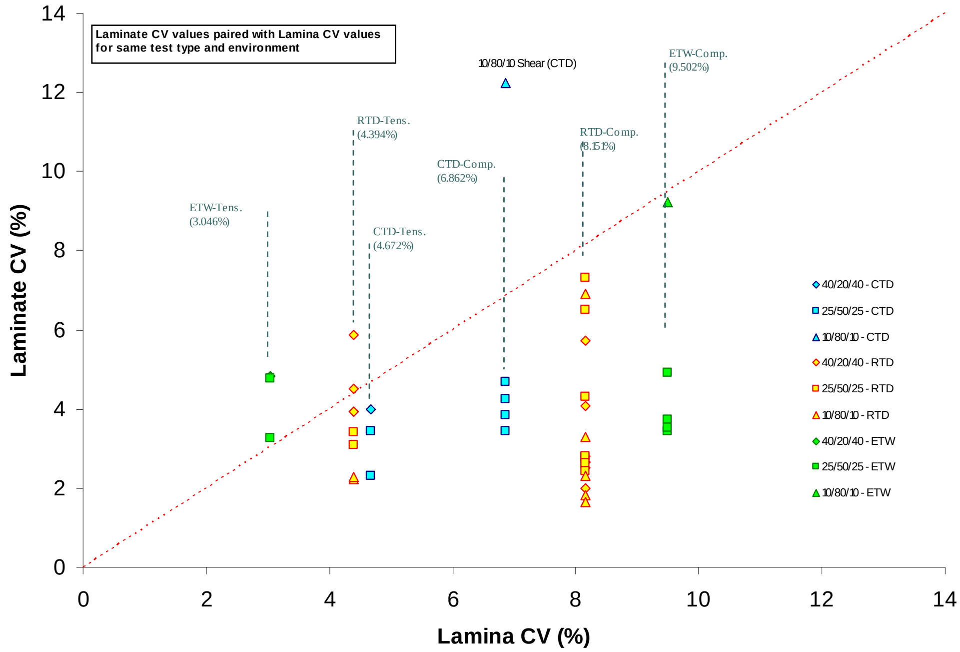


Figure 22. Toray PW Data CV Comparison

5.2 ANALYSIS OF TORAY T700/#2510 THREE-BATCH LAMINATE DATA.

B-basis allowables for three-batch data that were pooled across environments were calculated using the ASAP program. This program performs the following checks and reports the applicability of the pooling method to generate the basis values [3]:

- Maximum normed residual test for outliers
- k-sample Anderson Darling test for batch equivalence
- Anderson-Darling test for normality
- Check for normality based on graphical method
- Levene's test for equality of CVs

Statistical data for both Toray unidirectional tape and PW fabric materials are shown in tables 19 and 20. Once the LVM analysis was conducted on a single-batch data for each environment, B-basis values were then compared with three-batch ASAP data. ASAP is programmed specifically for obtaining allowables by pooling data across three or more environments. Therefore, for the cases with data from only one environment, the normal B-basis method was used [1]. As shown in table 19, for three cases of Toray tape materials (10/80/10 in-plane shear, 25/50/25 double-shear bearing, and 25/50/25 single-shear bearing), the CVs were not equivalent at the alpha = 0.05 significant level using Levene's test that was caused by failing the batch-to-batch variability at the alpha = 0.01 significance level using the Anderson-Darling test at one environment. This resulted in overly conservative ASAP or normal B-basis values. Consequently, as will be shown later, the LVM basis values for these individual batches resulted in being unconservative. Other batch-to-batch variability failures were ignored as they were caused by too low variability and did not cause any problems. As an example, if one considers VNRS test results for 10/80/10 in table 19, the CTD had significant batch-to-batch variation, which showed up as three-batch CV of 14.71. When CTD data was pooled with RTD and ETW, failure of Levene's test occurred and a very high ASAP-pooled CV resulted, leading to unconservative LVM values.

For the fabric material (see table 20) all CV equivalency tests passed, although for the VNRS test of 10/80/10, the batch-to-batch variability tests failed, resulting in very high CVs that lead to unconservative LVM values.

It should be noted that the 10/80/10 has very high shear capability that resulted in grip failures, especially at CTD.

Table 19. Toray T700G-12K-31ES/#2510 Unidirectional Tape Data Summary

Test	Layup	Env	Average (ksi)	ASAP Pooled or Normal B-Basis	Batch Variation?	CVs not Equal ?	3-Batch CV (%)	ASAP-Pooled CV (%)	Lamina CV (%)
NHT	50/40/10	CTD							
		RTD	159.5	143.4	**Y**		5.16		7.63
		ETW							
	25/50/25	CTD	88.0	84.1			2.71	2.49	7.63
		RTD	95.2	91.0	**Y**		3.02	2.49	7.63
		ETW	99.0	95.5	**Y**		3.29	2.49	6.84
	10/80/10	CTD							
		RTD	53.1	46.9	**Y**		5.85		7.63
		ETW							
FHT	50/40/10	CTD	66.8	61.4			3.25	4.56	7.63
		RTD	72.0	66.2			5.37	4.56	7.63
		ETW	85.1	78.2	**Y**		5.01	4.56	6.84
OHT	25/50/25	CTD	44.2	41.4			2.60	3.60	7.63
		RTD	49.5	46.4			4.23	3.60	7.63
		ETW	61.4	57.6			3.92	3.60	6.84
	10/80/10	CTD							
		RTD	41.0	39.6			1.72		7.63
		ETW							
NHC	50/40/10	CTD							
		RTD	116.4	109.0			3.24		5.91
		ETW							
	25/50/25	CTD	93.3	86.3			4.51	4.24	4.84
		RTD	81.1	75.0			5.15	4.24	5.91
		ETW	65.9	61.0			3.01	4.24	8.15
	10/80/10	CTD							
		RTD	52.4	47.9			4.31		5.91
		ETW							
OHC	50/40/10	CTD							
		RTD	56.0	50.5	**Y**		5.08		5.91
		ETW							
	25/50/25	CTD	47.3	43.9			2.86	4.15	4.84
		RTD	41.7	38.7			3.74	4.15	5.91
		ETW	33.5	31.1	**Y**		5.48	4.15	8.15
	10/80/10	CTD							
		RTD	35.4	33.4			2.88		5.91
		ETW							
VNRS	50/40/10	CTD							
		RTD	44.1	34.4			11.07		5.91
		ETW							
	25/50/25	CTD							
		RTD	31.0	23.5	**Y**		12.03		5.91
		ETW							
	10/80/10	CTD	48.9	40.8	**Y**	**Y**	14.71	9.85	4.84
		RTD	59.3	49.5		**Y**	5.00	9.85	5.91
		ETW	32.5	27.1		**Y**	4.99	9.85	8.15
DSBT	50/40/10	CTD							
		RTD	147.8	140.9	**Y**		2.41		5.91
		ETW							
	25/50/25	CTD	158.2	136.3		**Y**	3.98	5.45	4.84
		RTD	135.3	116.3	**Y**	**Y**	8.64	5.45	5.91
		ETW	120.9	103.8		**Y**	2.87	5.45	8.15
SSBT	50/40/10	CTD							
		RTD	94.0	89.9			2.22		5.91
		ETW							
	25/50/25	CTD	98.8	89.8		**Y**	2.33	5.18	4.84
		RTD	86.7	78.8	**Y**	**Y**	6.47	5.18	5.91
		ETW	79.2	72.0		**Y**	6.01	5.18	8.15
BB(50%)T	50/40/10	RTD	90.7	87.2			1.89		5.91
	25/50/25	RTD	82.0	79.5			1.48		5.91
	10/80/10	RTD	88.7	85.6			1.68		5.91
BB(50%)C	50/40/10	RTD	91.0	85.2			3.46		5.91
	25/50/25	RTD	83.9	80.4			1.97		5.91
	10/80/10	RTD	90.5	86.0			2.41		5.91

Table 20. Toray T700SC-12K-50C/#2510 PW Fabric Data Summary

Test	Layup	Env	Average (ksi)	ASAP Pooled or Normal B-Basis	Batch Variation?	CVs not Equal ?	3- Batch CV (%)	ASAP-Pooled CV (%)	Lamina CV (%)
NHT	40/20/40	CTD							
		RTD	124.7	115.0			3.94		4.39
		ETW							
	25/50/25	CTD	93.9	89.2	Y		2.30	2.86	4.67
		RTD	96.5	91.6			3.10	2.86	4.39
		ETW	93.7	88.9	Y		3.26	2.86	3.05
	10/80/10	CTD							
		RTD	56.9	54.4			2.22		4.39
		ETW							
FHT	40/20/40	CTD	59.6	54.5			3.98	4.87	4.67
		RTD	62.9	57.5			5.87	4.87	4.39
		ETW	75.2	68.8			4.82	4.87	3.05
OHT	40/20/40	CTD							
		RTD	66.5	60.7			4.52		4.39
		ETW							
	25/50/25	CTD	50.8	47.3			3.45	3.92	4.67
		RTD	54.5	50.8			3.42	3.92	4.39
		ETW	61.1	56.9	Y		4.78	3.92	3.05
	10/80/10	CTD							
		RTD	41.1	39.3	Y		2.28		4.39
		ETW							
NHC	40/20/40	CTD							
		RTD	77.3	68.6			5.73		8.15
		ETW							
	25/50/25	CTD	86.4	80.4	Y		3.86	3.92	6.86
		RTD	74.4	69.2			4.32	3.92	8.15
		ETW	47.5	44.6			4.91	3.92	9.50
	10/80/10	CTD							
		RTD	49.4	46.2			3.29		8.15
		ETW							
OHC	40/20/40	CTD							
		RTD	43.4	40.0	Y		4.08		8.15
		ETW							
	25/50/25	CTD	48.9	46.1			3.43	3.30	6.86
		RTD	40.4	38.0			2.79	3.30	8.15
		ETW	28.0	26.4	Y		3.72	3.30	9.50
	10/80/10	CTD							
		RTD	34.4	32.8			2.32		8.15
		ETW							
VNRS	40/20/40	CTD							
		RTD	30.2	29.0			1.99		8.15
		ETW							
	25/50/25	CTD							
		RTD	46.1	39.4			7.31		8.15
		ETW							
	10/80/10	CTD	41.6	34.6	Y		12.23	9.47	6.86
		RTD	46.9	39.1	Y		6.91	9.47	8.15
		ETW	23.4	19.5	Y		9.22	9.47	9.50
DSBT	40/20/40	CTD							
		RTD	109.7	104.9			2.50		8.15
		ETW							
	25/50/25	CTD	161.5	151.1	Y		4.68	3.63	6.86
		RTD	139.4	130.5			2.79	3.63	8.15
		ETW	115.7	108.3	Y		3.44	3.63	9.50
SSBT	40/20/40	CTD							
		RTD	72.5	68.6	Y		2.67		8.15
		ETW							
	25/50/25	CTD	106.7	97.5			4.24	4.84	6.86
		RTD	84.0	76.8	Y		6.51	4.84	8.15
		ETW	69.8	63.8			3.52	4.84	9.50
BB(50%)T	40/20/40	RTD	69.5	65.6			2.67		8.15
	25/50/25	RTD	83.1	78.6			2.64		8.15
	10/80/10	RTD	72.9	70.2	Y		1.81		8.15
BB(50%)C	40/20/40	RTD	74.4	70.1			2.80		8.15
	25/50/25	RTD	85.8	81.5			2.44		8.15
	10/80/10	RTD	76.8	74.1			1.65		8.15

5.3 COMPARISON OF POOLED AND LVM B-BASIS VALUES.

LVM analysis was performed on all six material systems. Some of the FiberCote test batches were unavailable at the time this report was generated, and ACG data had a limited number of cases that could be analyzed. Therefore, this section mainly discusses the Toray material data. Pooled B-basis allowables for Toray data were generated using ASAP and compared with LVM B-basis in the following two sections. Available FiberCote and ACG material data were analyzed using LVM and compared with ASAP pooled data in appendix B. At the time of the analysis, ACG lamina 0° compression data was not available, and therefore, LVM was only calculated for tension-loading cases of tape material. Both Toray and FiberCote laminate data packages, containing details of statistical analysis, summary sheets, and conditioning chats, etc., will be released separately.

5.3.1 Toray T700G-12K-31E/#2510 Unidirectional Tape Data Summary.

Previous unnotched tension tests conducted on Toray T700/#2510 systems [20 and 23] showed an increase in strength as the test temperature increases. The same behavior was observed for the unnotched tension cases as well as for open- and filled-hole tension cases. Improved alignment of fibers during tension tests, along with matrix softening, may have caused this phenomenon.

Tables 21 and 22 compare the B-basis values obtained from the LVM for each batch and each environment with the pooled B-basis values for the corresponding environments (see appendix B for nomenclature used in these tables). Based on the data in these tables, LVM values were normalized by pooled basis values and compared to evaluate the degree of conservatism in the proposed method. Except for NHT (50/40/10 and 10/80/10), double-shear bearing, and in-plane shear, LVM produced conservative B-basis allowables that were not excessively low (figures 23 through 32). LVM also produced conservative B-basis for compressive bearing strengths. However, for laminate bearing and in-plane shear cases, three or more test batches may be required for basis values generation to ensure confidence. Double- shear bearing data for 50/40/10 layup indicated a high outlier in batch 3. Outlier was dispositioned for three-batch, B-basis calculation, but left in the LVM B-basis calculation for batch 3 data. Similarly, in-plane shear data for 10/80/10 indicated a high outlier in ETW batch 1 data and removed for three-batch, B-basis calculation, but left in the LVM B-basis calculation for ETW batch 1 data.

Since LVM does not account for laminate variability (only the number of samples and mean), LVM B-basis values for cases where the laminate variability is large were higher than the three-batch B-basis values. Therefore, further analysis of the cause of the variability in a large-population laminate (three-batch data set) that resulted in the lower-pooled ASAP values were investigated. For example, the complication encountered while testing thick laminates in shear, figure 32, is not a good measure of material variability.

Table 21. Toray Unidirectional Tape B-Basis Allowable Comparison (50/40/10)

			Laminate Properties (3 Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
50/40/10	NHT	RTD	19	159.534	143.364	5.157	6	165.535	142.557	5.056	6	161.628	139.193	3.103	7	152.596	131.937	3.413
	OHT [w/D=3]	RTD	18	70.229	63.809	4.588	6	69.901	60.198	3.212	6	69.123	59.528	5.022	6	71.664	61.716	5.246
	OHT [w/D=4]	RTD	18	75.443	66.961	5.641	6	75.703	65.194	4.857	6	77.870	67.061	4.781	6	72.755	62.656	5.894
	OHT [w/D=8]	RTD	19	80.413	74.610	3.672	6	79.723	68.657	3.421	6	81.018	69.772	1.961	7	80.486	69.590	5.123
	FHT	CTD	18	66.826	61.443	3.251	6	66.988	57.689	3.496	6	67.566	58.187	1.094	6	65.924	56.773	4.385
		RTD	18	71.991	66.192	5.375	6	74.275	63.965	7.668	6	72.355	62.311	2.298	6	69.344	59.718	1.348
		ETW	19	85.050	78.235	5.011	6	85.315	73.472	3.034	6	88.973	76.622	4.333	7	81.461	70.433	3.016
	NHC	RTD	19	116.424	109.012	3.239	7	113.657	98.780	2.427	6	118.337	102.457	2.538	6	117.738	101.939	3.382
	OHC	RTD	21	55.991	50.532	5.082	7	54.155	47.066	4.644	8	56.559	49.305	5.207	6	57.378	49.678	3.939
	DSBT	RTD	20*	147.801	140.882	2.411	7	148.897	129.407	3.427	7	147.513	128.204	1.803	7	141.062	122.597	10.978
	SSBT	RTD	19	94.043	89.946	2.216	6	93.925	81.321	1.706	6	93.323	80.800	1.982	7	94.762	82.358	2.773
	BB(50%)T [t/D=0.32]	RTD	18	87.276	81.510	2.629	6	88.520	76.641	2.526	6	86.983	75.311	2.689	6	85.878	74.354	5.585
	BB(50%)T [t/D=0.384]	RTD	18	88.800	84.233	2.581	6	89.448	77.445	2.140	6	87.900	76.105	3.313	6	29.982	24.975	2.293
	BB(50%)T [t/D=0.48]	RTD	15	90.725	87.130	1.889	5	90.218	77.728	2.008	5	91.208	78.580	1.702	5	90.748	78.184	2.184
	BB(50%)T [t/D=0.64]	RTD	17	91.081	86.144	2.679	6	89.921	77.855	4.150	5	91.633	78.947	1.346	6	91.782	79.466	1.291
	BB(50%)C	RTD	15	91.041	85.216	3.051	5	92.315	79.534	2.821	5	91.839	79.124	1.179	5	88.971	76.653	3.705
	VNRS	RTD	18	44.094	34.363	11.074	6	41.922	39.209	9.480	6	45.033	42.119	13.449	6	45.327	42.393	9.879

Env.= environment n = number of specimens

Table 22. Toray Unidirectional Tape B-Basis Allowable Comparison (25/50/25 and 10/80/10)

			Laminate Properties (3 Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHT	CTD	18	88.009	83.403	2.713	6	89.896	77.418	1.284	6	87.541	75.389	3.560	6	86.591	74.571	1.361
		RTD	18	95.227	90.243	3.020	6	97.513	83.977	1.789	6	95.306	82.076	1.160	6	92.862	79.972	3.550
		ETW	18	98.958	93.779	3.291	6	99.480	85.671	1.446	6	99.787	85.935	1.817	6	97.606	84.057	5.358
	OHT	CTD	18	44.165	41.362	2.605	6	44.403	38.239	2.381	6	44.125	38.000	3.226	6	43.967	37.864	2.530
		RTD	18	49.513	46.370	4.226	6	50.265	43.288	5.069	6	50.089	43.136	3.870	6	48.186	41.497	2.494
		ETW	21	61.449	57.606	3.919	6	63.568	54.744	2.991	7	61.994	53.602	2.544	8	59.383	51.508	2.832
	NHC	CTD	18	93.328	86.338	4.507	6	90.454	78.316	3.316	6	92.293	79.908	3.574	6	97.237	84.189	3.373
		RTD	18	81.121	75.046	5.152	6	80.424	69.632	5.777	6	80.025	69.286	5.176	6	82.916	71.790	4.633
		ETW	18	65.930	60.992	3.011	6	64.871	56.166	2.806	6	66.985	57.996	2.508	6	65.934	57.086	3.248
	OHC	CTD	21	47.254	43.863	2.864	8	46.725	40.733	2.778	6	47.044	40.731	2.545	7	48.039	41.751	2.799
		RTD	18	41.692	38.655	3.741	6	40.249	34.848	2.107	6	41.722	36.124	2.428	6	43.104	37.320	2.964
		ETW	22	33.547	31.150	5.476	8	32.295	28.153	5.726	6	34.623	29.977	3.761	8	33.992	29.633	4.637
	DSBT	CTD	22	158.237	136.301	3.978	7	159.862	138.937	2.480	7	158.733	137.956	2.109	8	156.380	136.325	6.031
		RTD	19	135.276	116.264	13.475	7	136.777	118.874	7.276	6	132.935	115.097	22.579	6	135.866	117.635	9.490
		ETW	18	120.933	103.846	2.866	6	118.199	102.338	2.381	6	121.554	105.243	1.898	6	123.045	106.534	2.909
	SSBT	CTD	18	98.838	89.792	2.327	6	98.142	84.972	2.212	6	98.867	85.600	1.162	6	99.506	86.153	3.307
		RTD	18	86.699	78.765	6.475	6	84.019	72.744	3.217	6	85.779	74.268	3.769	6	90.300	78.183	8.872
		ETW	18	79.198	71.950	6.015	6	78.070	67.594	6.644	6	81.620	70.668	5.392	6	77.905	67.451	5.785
	BB(50%)T	RTD	15	82.018	79.466	1.484	5	82.297	70.904	1.363	5	81.947	70.602	1.980	5	81.810	70.484	1.304
	BB(50%)C	RTD	15	83.887	80.424	1.968	5	83.685	72.099	1.720	5	83.254	71.728	2.182	5	84.721	72.992	1.956
	VNRS	RTD	18	30.974	23.549	12.028	6	28.264	26.435	3.868	6	32.041	29.967	15.809	6	32.615	30.504	8.069
10/80/10	NHT	RTD	18	53.107	46.913	5.852	6	54.789	47.184	2.401	6	51.402	44.266	2.085	6	53.130	45.755	9.042
	OHT	RTD	18	41.017	39.613	1.718	6	41.239	35.515	1.268	6	41.300	35.567	1.311	6	40.511	34.888	1.720
	NHC	RTD	18	52.398	47.897	4.310	6	51.619	44.692	5.029	6	53.600	46.407	2.748	6	51.974	45.000	4.615
	OHC	RTD	18	35.424	33.392	2.879	6	34.908	30.223	1.922	6	35.682	30.894	2.713	6	35.683	30.895	3.620
	BB(50%)T	RTD	15	88.700	85.581	1.677	5	89.368	76.996	1.575	5	88.005	75.821	1.459	5	88.727	76.444	1.937
	BB(50%)C	RTD	15	90.507	85.957	2.397	5	90.118	77.642	1.857	5	90.625	78.078	2.905	5	90.778	78.210	2.797
	VNRS	CTD	18	48.884	40.834	14.707	6	48.739	45.585	12.873	6	53.627	50.156	14.063	6	44.113	41.257	7.481
		RTD	18	59.303	49.537	4.997	6	57.226	53.522	3.585	6	61.539	57.556	5.735	6	59.143	55.315	2.379
		ETW	17*	32.534	27.146	4.990	6	33.360	31.201	12.193	6	33.451	31.286	4.943	6	32.236	30.150	4.648

Env. = environment n = number of specimens

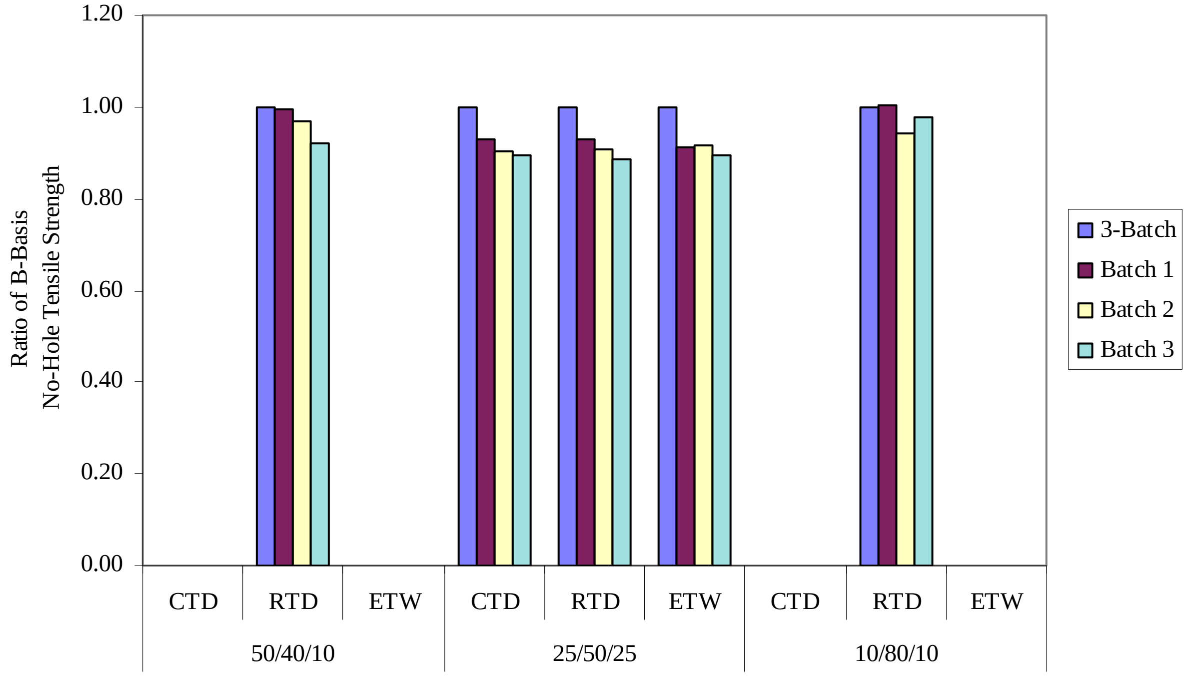


Figure 23. Ratio of LVM to Laminate B-Basis for NHT Strength of Toray Tape

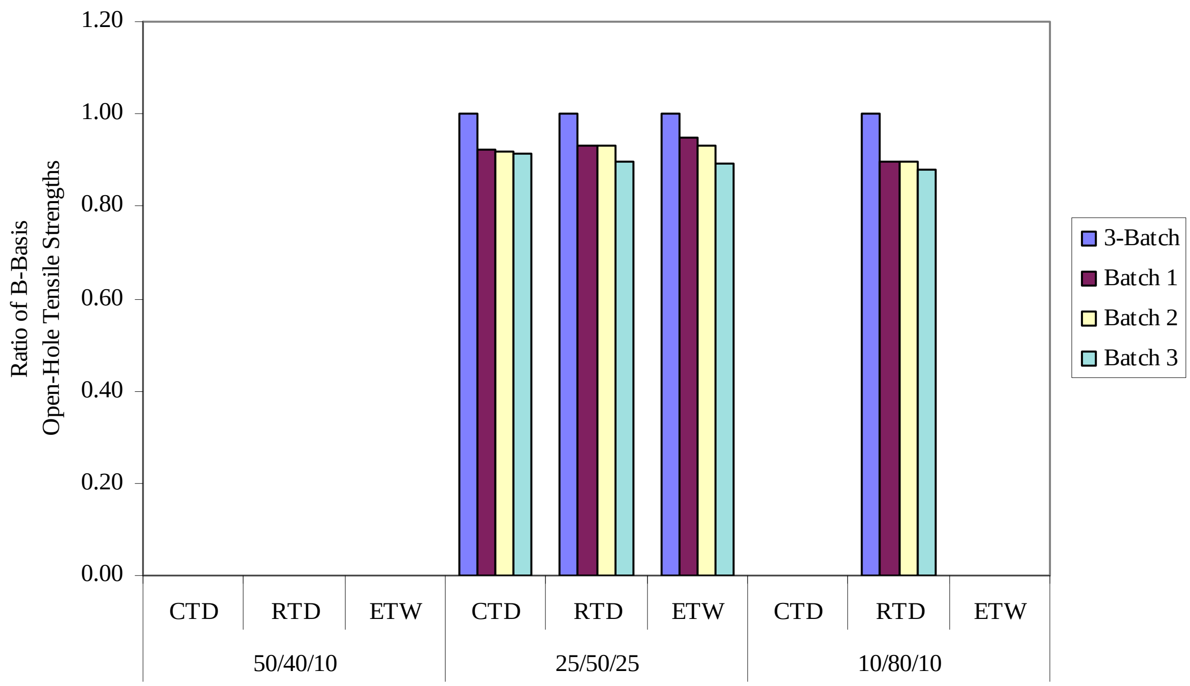


Figure 24. Ratio of LVM to Laminate B-Basis for OHT Strength of Toray Tape

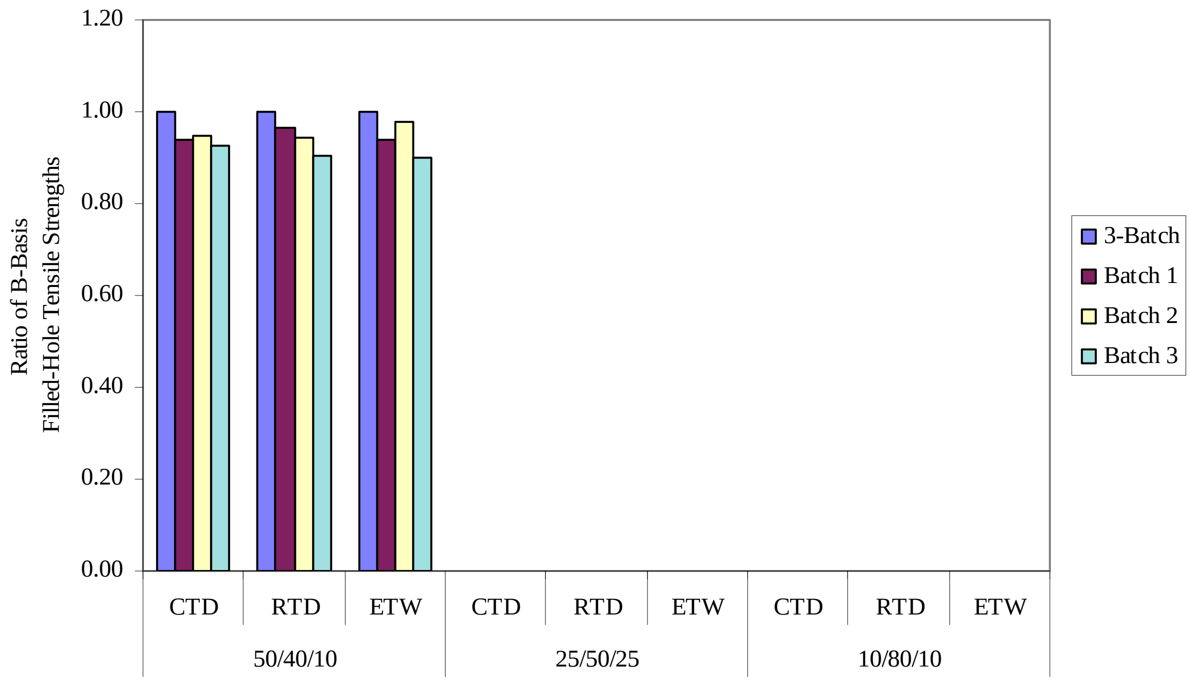


Figure 25. Ratio of LVM to Laminate B-Basis for FHT Strength of Toray Tape

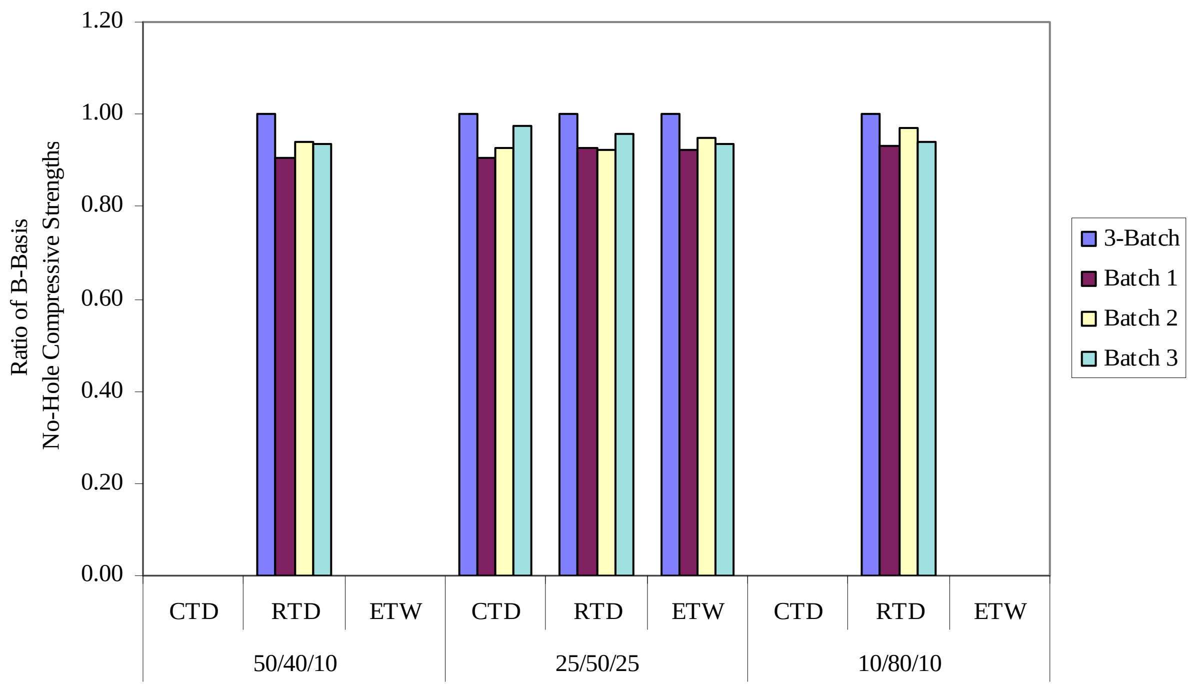


Figure 26. Ratio of LVM to Laminate B-Basis for NHC Strength of Toray Tape

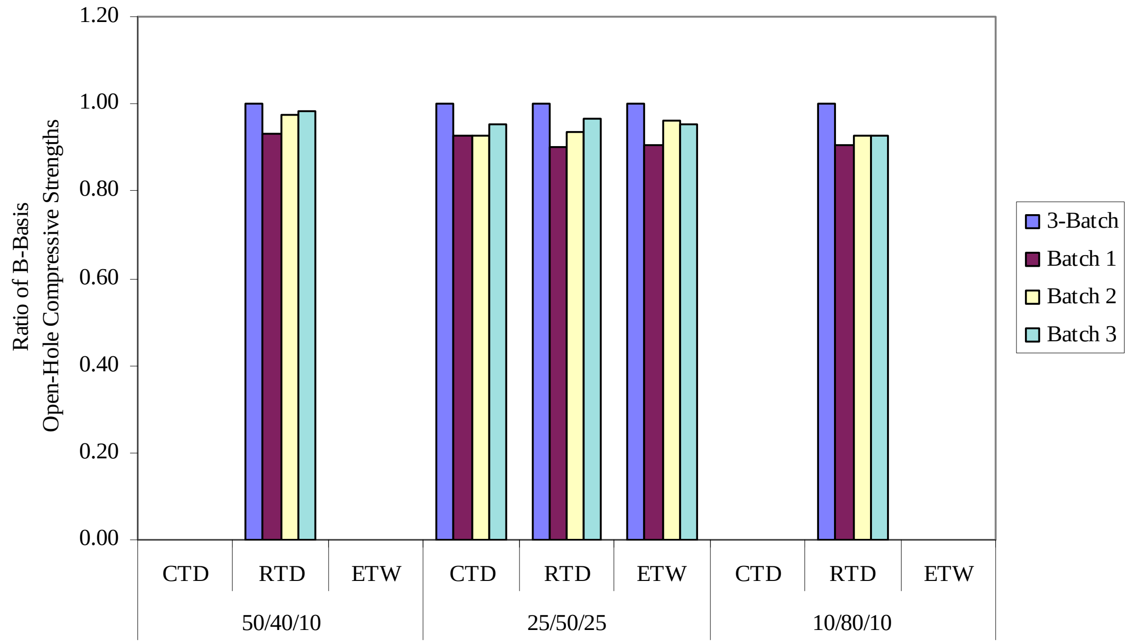


Figure 27. Ratio of LVM to Laminate B-Basis for OHC Strength of Toray Tape

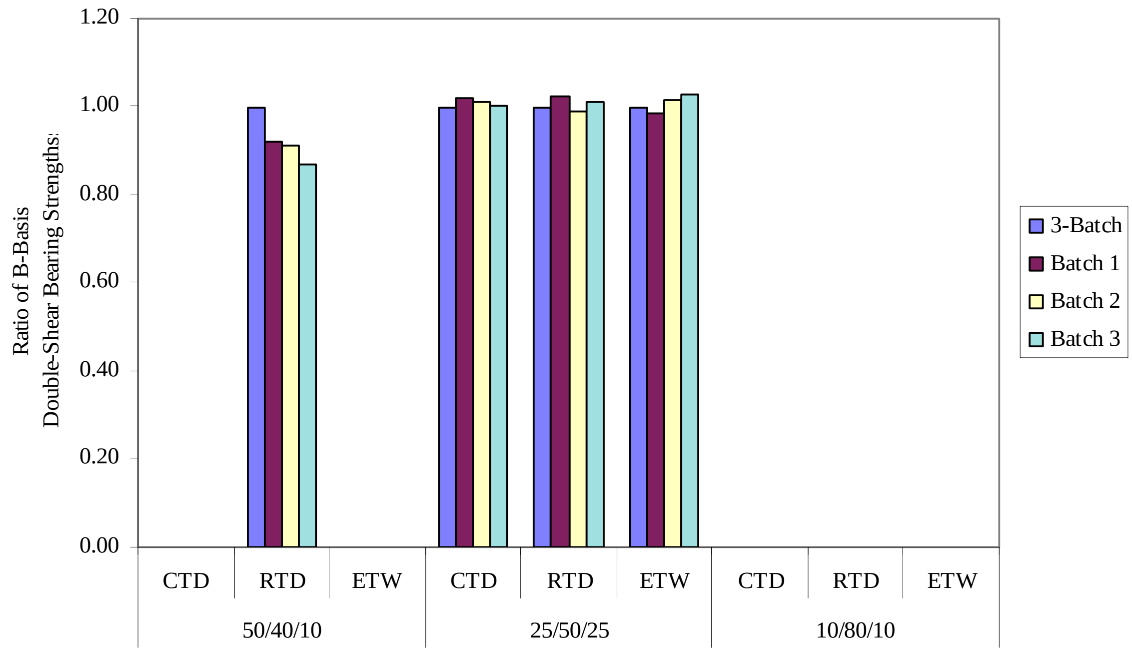


Figure 28. Ratio of LVM to Laminate B-Basis for Double-Shear Bearing Strength of Toray Tape

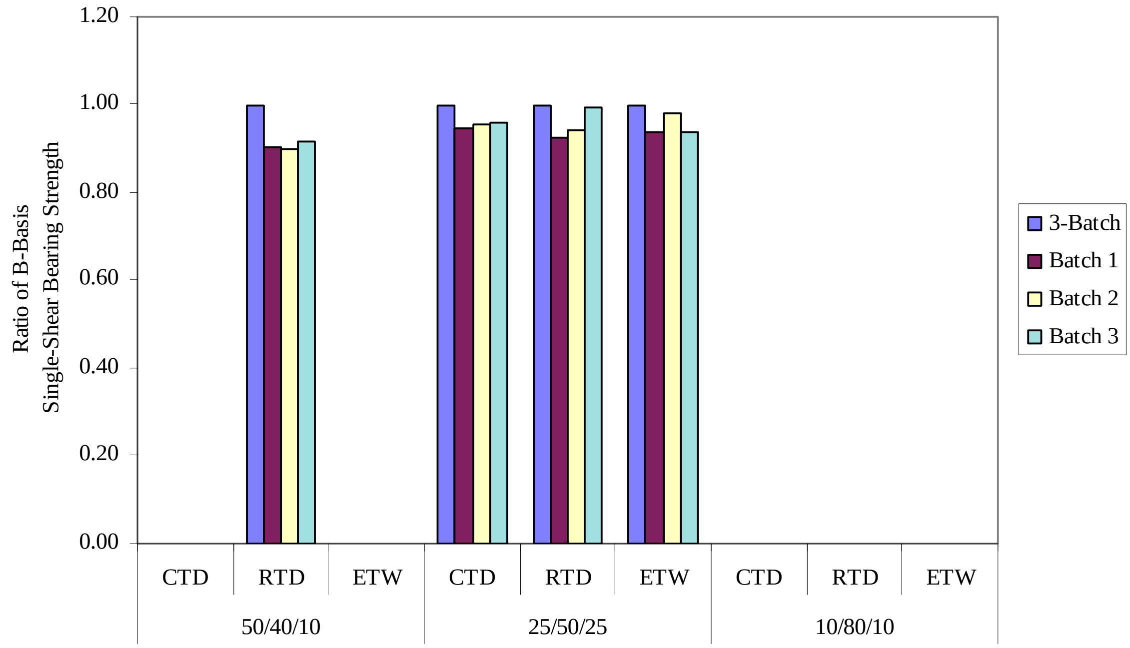


Figure 29. Ratio of LVM to Laminate B-Basis for Single-Shear Bearing Strength of Toray Tape

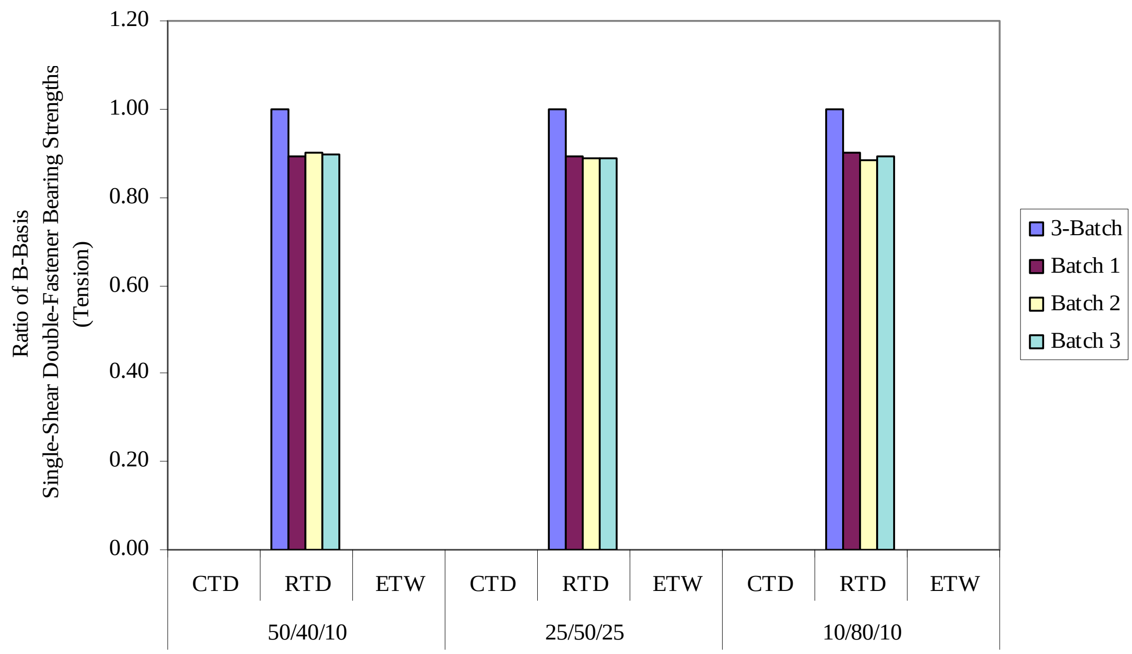


Figure 30. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Tension Strength of Toray Tape

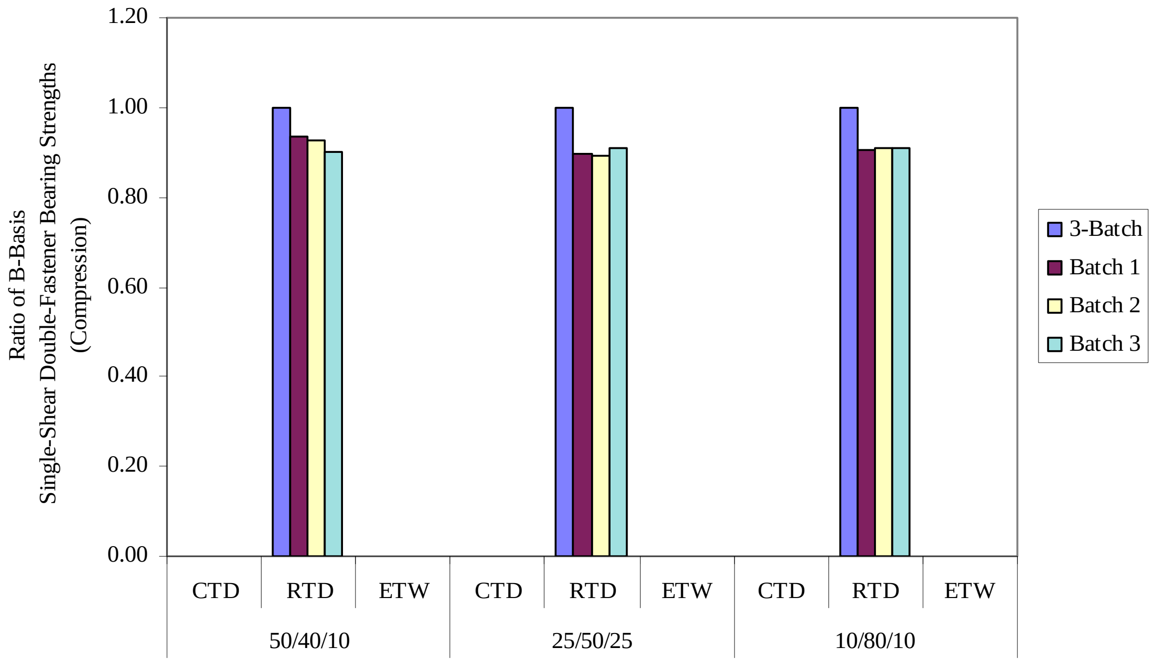


Figure 31. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Compressive Strength of Toray Tape

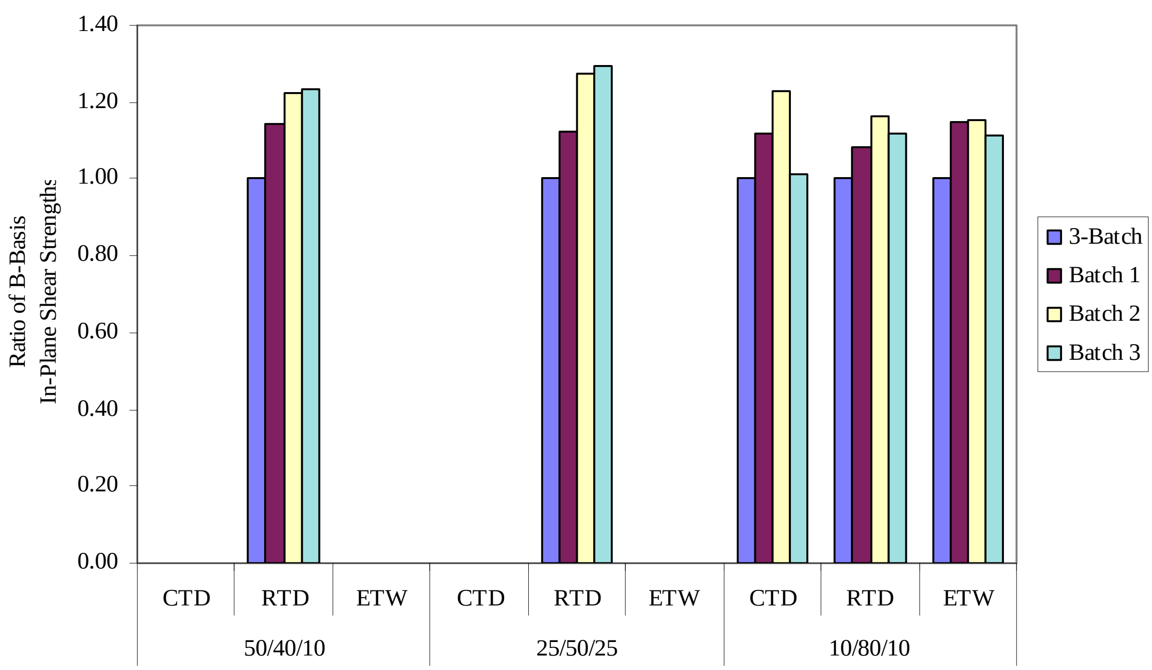


Figure 32. Ratio of LVM to Laminate B-Basis for In-Plane Shear Strength of Toray Tape

5.3.2 Toray T700SC-12K-50C/#2510 PW Fabric Data Summary.

Previous unnotched tension tests conducted on Toray T700/#2510 systems [20 and 24] showed an increase in strength as the test temperature increases (warp and fill directions for lamina). The same behavior was observed for the unnotched tension cases, except for 25/50/25 PW NHT batches 2 and 3 hot-wet data, as well as for open and filled-hole tension cases.

Tables 23 and 24 compare the B-basis values obtained from the LVM for each batch and for each environment with the pooled B-basis values for the corresponding environments. Based on the data in these tables, LVM values were normalized by pooled basis values and compared to evaluate the degree of conservatism in the proposed method. Except for 40/20/40 single-shear, 25/50/25 single-shear two-fastener bearing, and in-plane shear, LVM B-basis values are conservative and not excessively lower than that of the pooled values (figures 33 through 42).

The conservatism of the LVM method appears to be greatest for OHC and double-shear bearing, about 10%-15%. This implies that the variability of the laminate compressive and bearing strength is less than for compressive laminate strength. This is not surprising since obtaining compressive strength of lamina involves difficult testing. The difficulty of using the new ASTM D 7078 standard for shear when the loads are large is also apparent, as only the laminate with the fewest 45-degree plies had reasonable variability, and hence, the B-basis values were comparable to LVM B-basis values.

Table 23. Toray PW Fabric B-Basis Allowable Comparison (40/20/40)

			Laminate Properties (3 Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
40/20/40	NHT	RTD	18	124.688	114.903	3.938	6	119.304	109.627	3.037	6	126.899	116.606	2.676	6	127.861	117.490	1.674
	OHT [w/D=3]	RTD	18	59.638	52.621	5.903	6	57.619	52.945	3.461	6	63.310	58.175	3.408	6	57.984	53.281	5.218
	OHT [w/D=4]	RTD	18	63.222	57.660	4.414	6	63.770	58.598	4.033	6	65.164	59.878	2.762	6	60.731	55.805	3.411
	OHT [w/D=6]	RTD	20	66.530	60.692	4.521	7	66.357	61.106	3.362	7	68.656	63.223	4.828	6	64.253	59.041	2.527
	OHT [w/D=8]	RTD	18	69.266	63.212	4.386	6	67.254	61.799	3.202	6	70.710	64.974	4.913	6	69.835	64.170	3.769
	FHT (Critical)	CTD	19	59.583	54.495	3.984	7	57.880	53.301	5.241	6	60.382	55.484	1.042	6	60.772	55.843	2.511
		RTD	19	62.854	57.486	5.871	6	62.908	57.806	5.012	7	64.602	59.491	5.250	6	60.760	55.831	6.529
		ETW	18	75.250	68.789	4.824	6	75.010	68.926	3.795	6	75.884	69.729	5.793	6	74.855	68.783	5.449
	NHC	RTD	18	77.347	68.519	5.727	6	77.239	64.060	3.269	6	76.245	63.235	6.312	6	78.555	65.151	7.417
	OHC	RTD	19	43.435	39.954	4.077	6	42.687	35.403	2.330	6	43.458	36.042	5.381	7	44.056	36.723	3.942
	DSBT	RTD	30	109.745	104.848	2.502	12	110.270	93.282	3.552	6	108.641	90.103	1.577	12	109.773	92.862	1.364
	SSBT	RTD	18	72.457	68.603	2.669	6	72.405	60.050	1.878	6	72.857	60.425	3.456	6	72.108	59.804	2.837
	BB(50%)T [t/D=0.475]	RTD	18	71.187	67.040	2.923	6	70.546	61.080	4.014	6	71.501	61.907	2.755	6	71.512	61.916	2.018
	BB(50%)T [t/D=0.570]	RTD	18	68.907	65.033	2.821	6	70.613	61.137	1.904	6	67.363	58.324	2.325	6	68.746	59.521	2.162
	BB(50%)T [t/D=0.712]	RTD	15	69.481	65.594	2.667	5	70.203	60.484	1.671	5	69.695	60.047	3.594	5	68.544	59.055	2.335
	BB(50%)T [t/D=0.949]	RTD	18	64.945	60.737	3.251	6	63.892	55.319	2.087	6	65.659	56.849	4.688	6	65.283	56.523	2.070
	BB(50%)C	RTD	15	74.429	70.052	2.804	5	74.231	63.954	3.380	5	74.305	64.018	3.366	5	74.752	64.403	2.114
	VNRS	RTD	18	30.184	28.985	1.993	6	30.279	28.224	1.487	6	30.237	28.185	2.256	6	30.036	27.997	2.405
	VNRS (0.2%)	RTD	18	21.200	19.606	3.773	6	20.741	19.333	2.553	6	21.597	20.131	3.159	6	21.263	19.820	4.660

Env. = Environment n = Number of specimens

Table 24. Toray PW Fabric B-Basis Allowable Comparison (25/50/25 and 10/80/10)

Laminate	Material Property	Env.	Laminate Properties (3 Batch) n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	Laminate Batch 1 n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	Laminate Batch 2 n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	Laminate Batch 3 n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHT	CTD	18	93.917	89.165	2.302	6	92.176	84.699	2.404	6	93.444	85.864	0.643	6	96.133	88.335	0.945
		RTD	18	96.476	91.594	3.099	6	95.127	87.411	3.895	6	96.559	88.726	2.082	6	97.742	89.814	2.984
		ETW	18	93.661	88.921	3.260	6	96.676	88.834	2.595	6	91.177	83.781	1.484	6	93.130	85.576	2.382
	OHT	CTD	18	50.825	47.315	3.454	6	51.382	47.214	2.876	6	50.145	46.078	2.701	6	50.949	46.816	4.610
		RTD	18	54.519	50.754	3.422	6	54.607	50.177	3.614	6	55.217	50.738	1.489	6	53.735	49.376	4.533
		ETW	21	61.109	56.950	4.784	7	63.053	58.064	3.860	8	58.213	53.701	2.605	6	62.701	57.615	2.315
	NHC	CTD	18	86.407	79.826	3.856	6	83.877	69.565	2.279	6	89.486	74.217	3.228	6	85.859	71.208	2.931
		RTD	18	74.367	68.703	4.316	6	74.027	61.396	2.186	6	76.472	63.423	2.908	6	72.601	60.213	5.887
		ETW	19	47.543	43.941	4.913	6	47.226	39.168	4.112	6	48.621	40.325	4.016	7	46.890	39.085	6.140
	OHC	CTD	19	48.901	46.073	3.429	6	48.062	39.861	4.807	7	48.919	40.776	2.875	6	49.720	41.236	1.756
		RTD	18	40.398	38.050	2.786	6	39.770	32.984	1.419	6	40.989	33.995	3.377	6	40.437	33.537	2.685
		ETW	21	27.980	26.377	3.725	6	28.207	23.394	5.209	7	27.436	22.869	2.117	8	28.286	23.673	3.212
	DSBT	CTD	18	161.484	151.059	4.678	6	155.149	128.675	2.526	6	162.897	135.101	5.236	6	167.393	137.926	2.011
		RTD	18	139.411	130.461	2.794	6	138.671	115.009	2.136	6	136.584	113.278	2.116	6	142.978	118.581	2.091
		ETW	18	115.711	108.283	3.438	6	114.228	94.737	3.122	6	114.163	94.683	3.657	6	118.742	98.481	2.246
	SSBT	CTD	18	106.687	97.487	4.242	6	103.514	85.851	4.022	6	109.600	90.898	3.107	6	106.999	88.164	3.943
		RTD	18	84.034	76.829	6.512	6	77.127	63.967	2.530	6	87.899	72.900	2.572	6	87.076	72.218	2.956
		ETW	18	69.790	63.806	3.523	6	70.278	58.286	3.773	6	70.897	58.799	2.068	6	68.195	56.559	3.758
	BB(50%)T	RTD	15	83.116	78.514	2.640	5	83.851	72.243	1.774	5	82.537	71.110	1.388	5	82.962	71.476	4.211
	BB(50%)C	RTD	15	85.849	81.450	2.443	5	85.511	73.673	3.325	5	85.663	73.804	1.587	5	86.373	74.415	2.572
	VNRS	RTD	18	46.084	39.367	7.314	6	43.823	40.848	8.044	6	47.311	44.099	6.660	6	47.118	43.920	5.634
10/80/10	NHT	RTD	19	56.866	54.381	2.223	7	56.723	52.235	2.162	6	57.031	52.405	2.775	6	56.866	52.253	2.068
	OHT	RTD	18	41.108	39.236	2.285	6	41.585	38.212	2.271	6	40.605	37.311	2.536	6	41.134	37.797	1.666
	NHC	RTD	18	49.397	46.160	3.287	6	50.061	41.519	3.726	6	48.580	40.291	3.268	6	49.549	41.094	2.558
	OHC	RTD	18	34.373	32.783	2.322	6	34.628	28.719	2.450	6	34.498	28.612	1.252	6	33.994	28.194	2.929
	BB(50%)T	RTD	15	72.914	70.139	1.815	5	73.308	63.159	1.517	5	71.623	61.707	1.306	5	73.810	63.591	1.161
	BB(50%)C	RTD	15	76.755	74.095	1.652	5	76.960	66.305	1.125	5	75.851	65.350	1.161	5	77.455	66.732	2.008
	VNRS	CTD	18	41.587	34.627	12.232	6	44.475	41.456	13.886	6	40.650	37.891	4.580	6	39.635	36.944	13.990
		RTD	19	46.859	39.058	6.911	6	44.231	41.229	3.825	6	50.130	46.727	4.356	7	46.307	43.241	5.771
		ETW	18	23.401	19.485	9.217	6	25.127	23.422	8.146	6	21.945	20.455	6.958	6	23.131	21.561	7.594

Env. = Environment n = Number of specimens

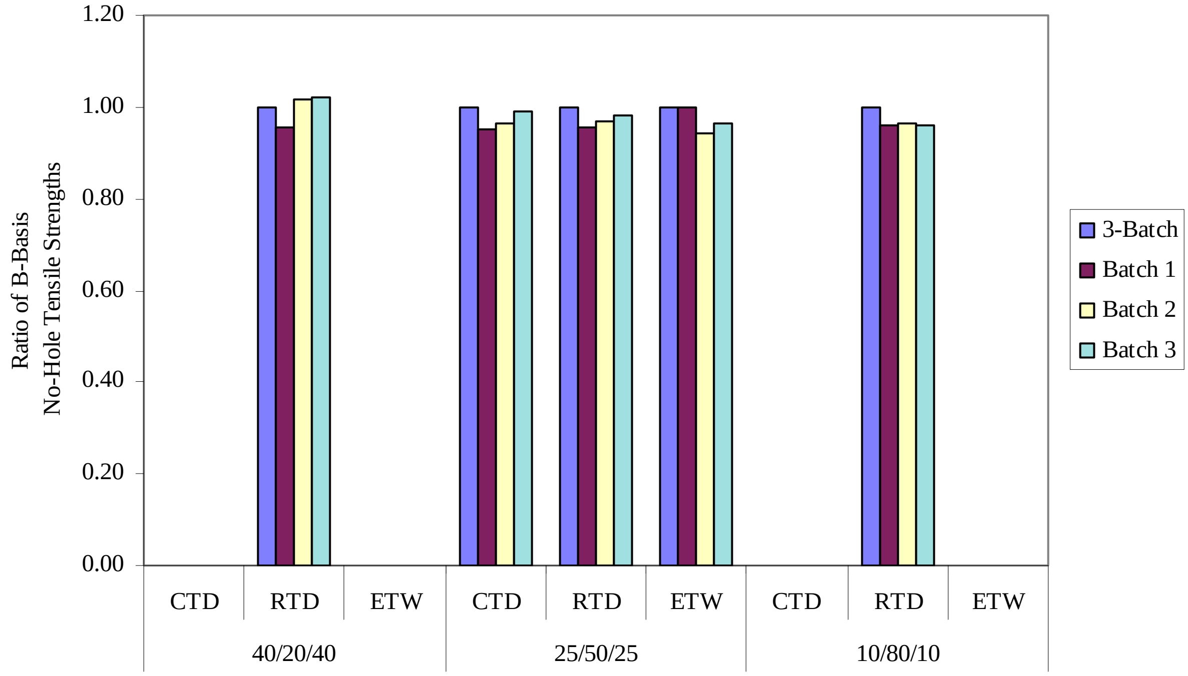


Figure 33. Ratio of LVM to Laminate B-Basis for NHT Strength of Toray PW

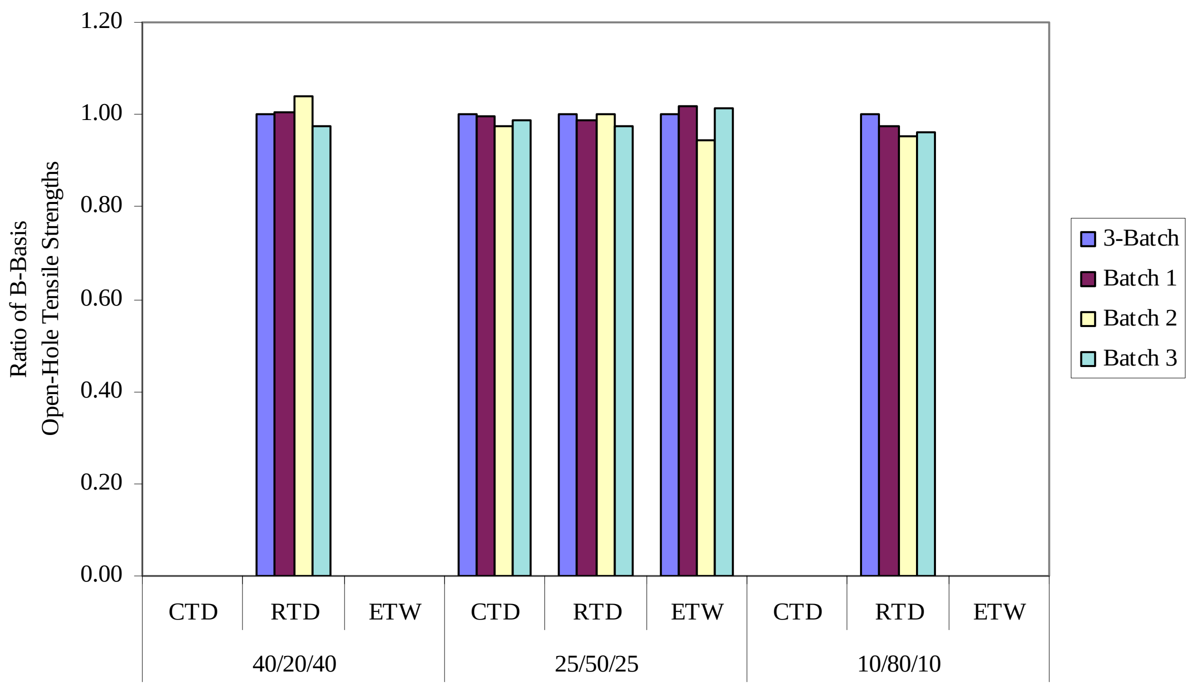


Figure 34. Ratio of LVM to Laminate B-Basis for OHT Strength of Toray PW

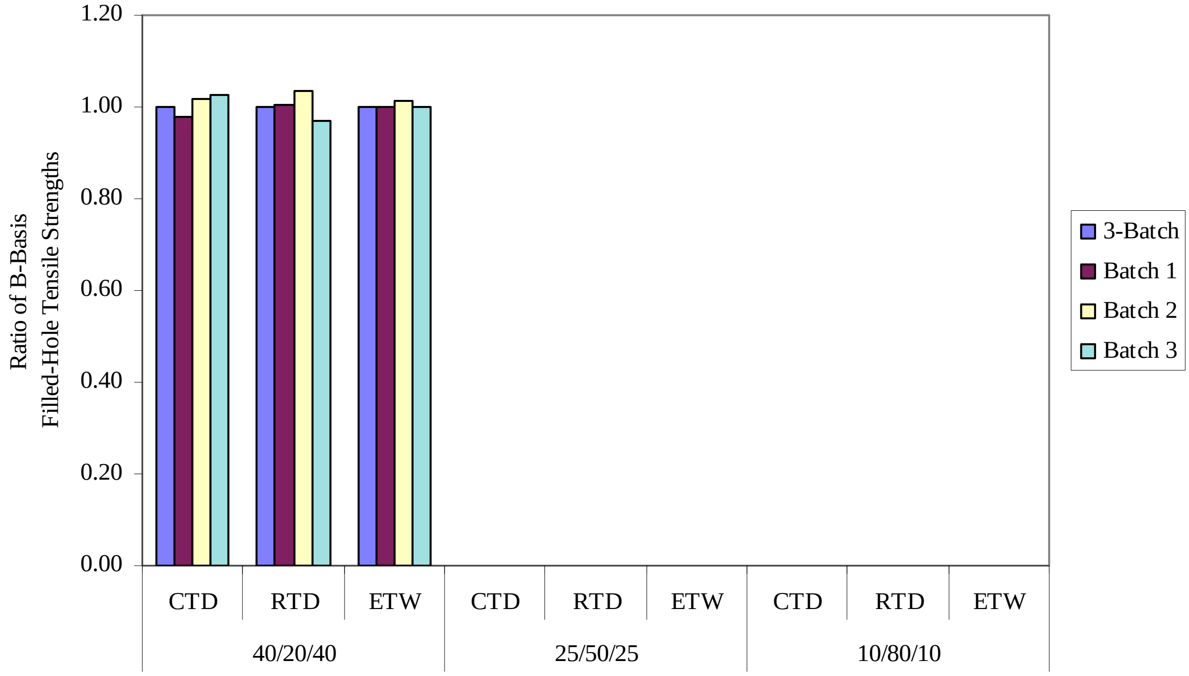


Figure 35. Ratio of LVM to Laminate B-Basis for FHT Strength of Toray PW

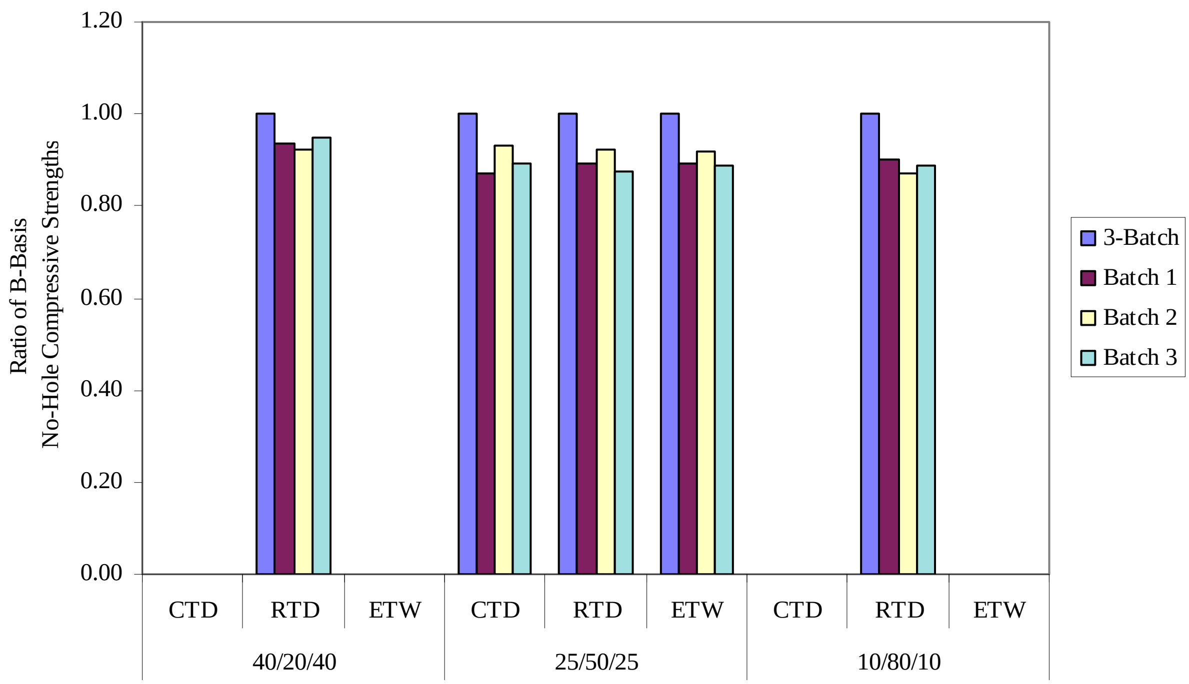


Figure 36. Ratio of LVM to Laminate B-Basis for NHC Strength of Toray PW

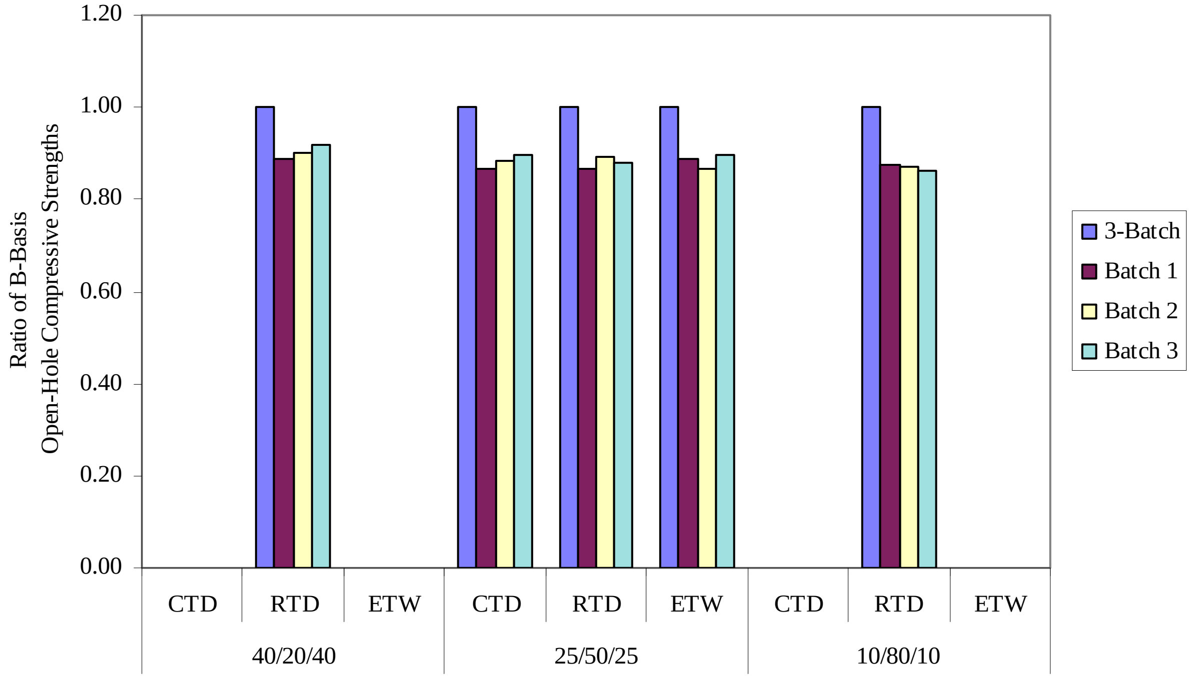


Figure 37. Ratio of LVM to Laminate B-Basis for OHC Strength of Toray PW

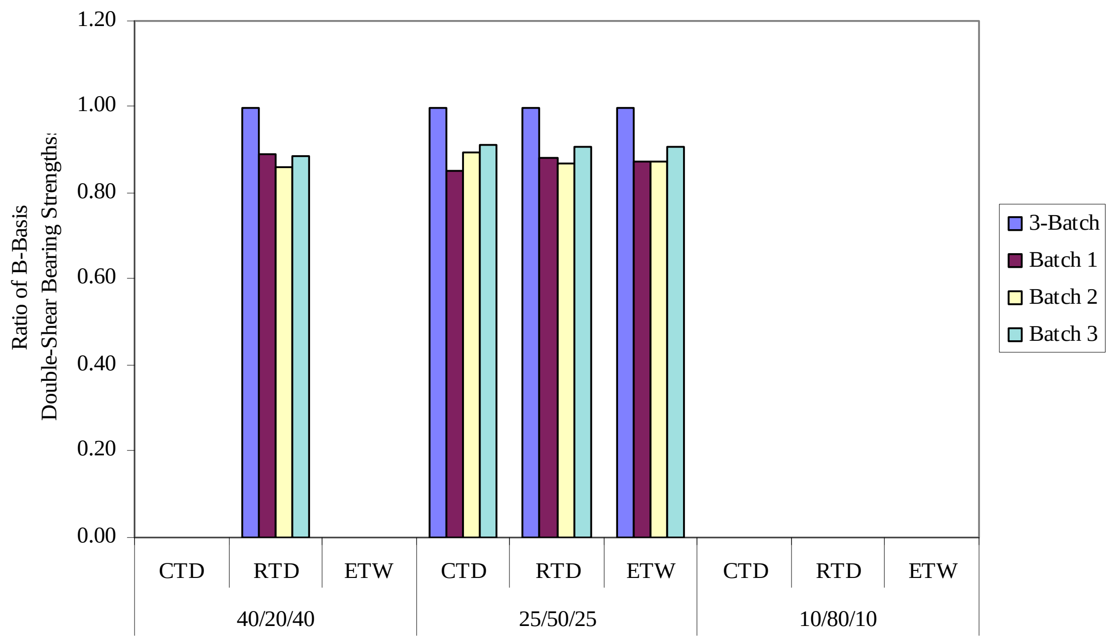


Figure 38. Ratio of LVM to Laminate B-Basis for Double-Shear Bearing Strength of Toray PW

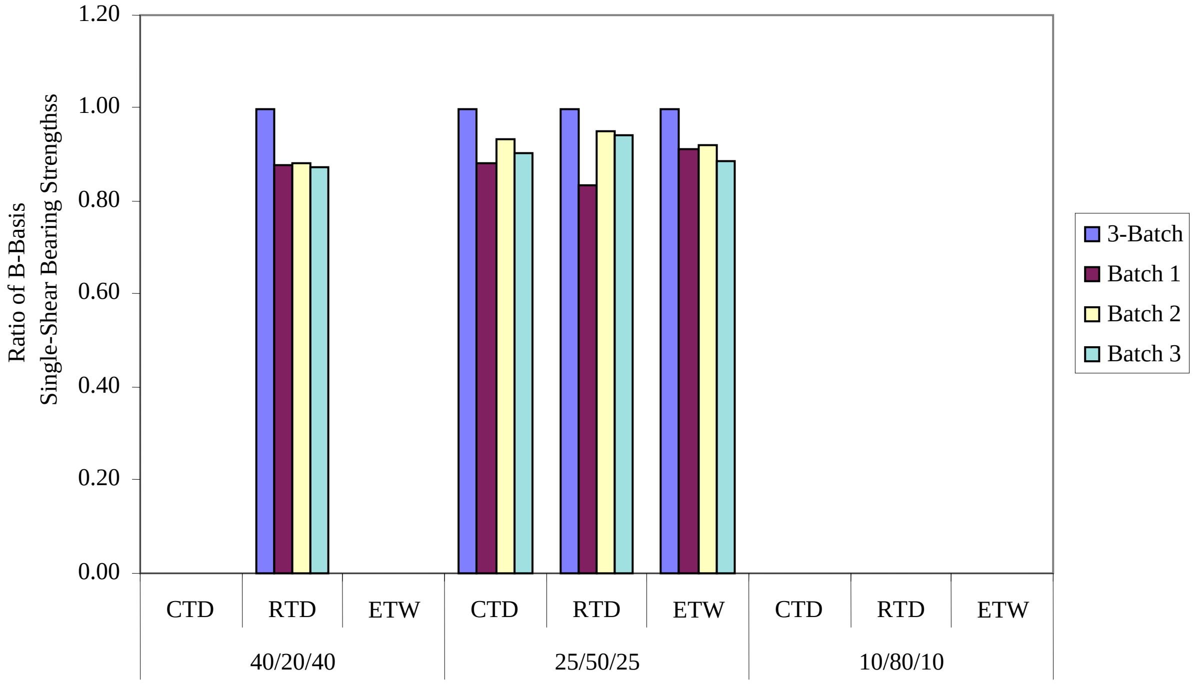


Figure 39. Ratio of LVM to Laminate B-Basis for Single-Shear Bearing Strength of Toray PW

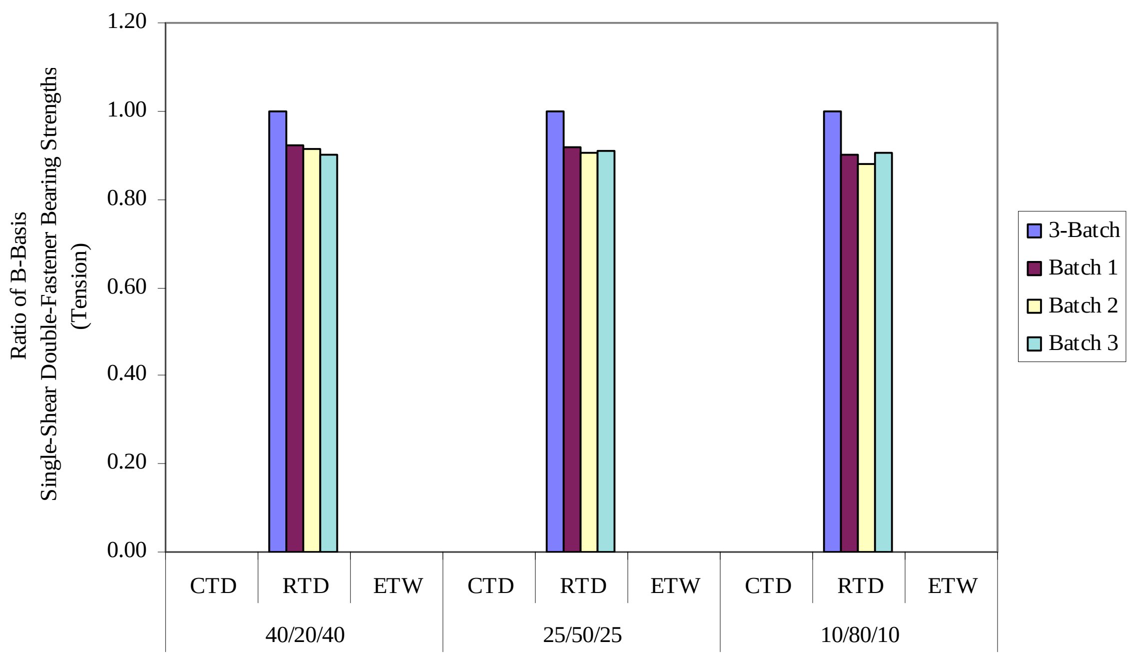


Figure 40. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Tension Strength of Toray PW

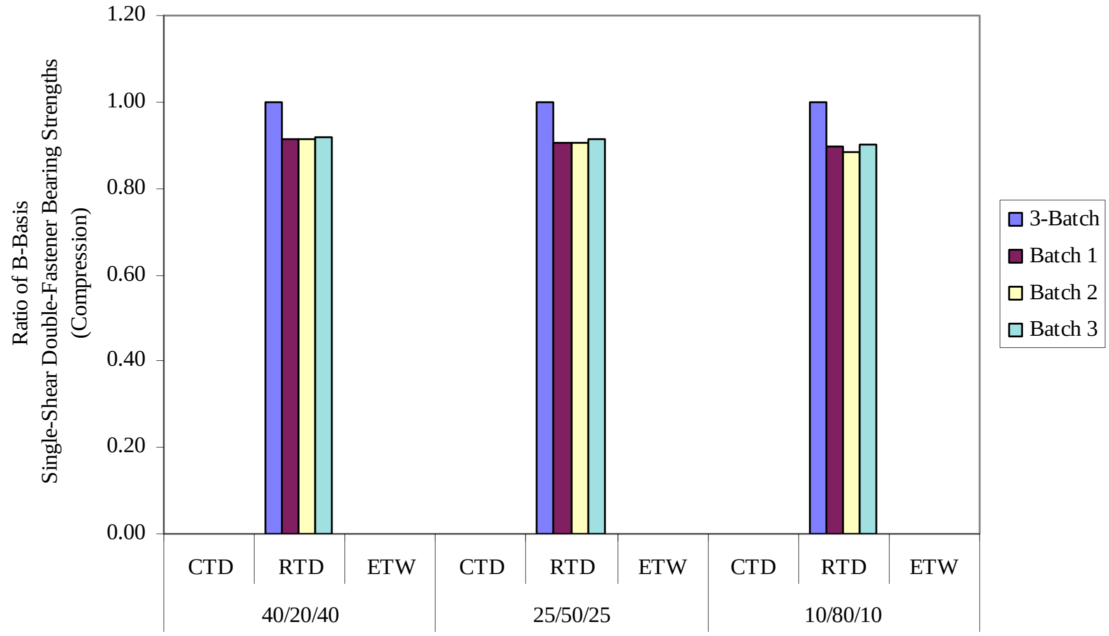


Figure 41. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Compressive Strength of Toray PW

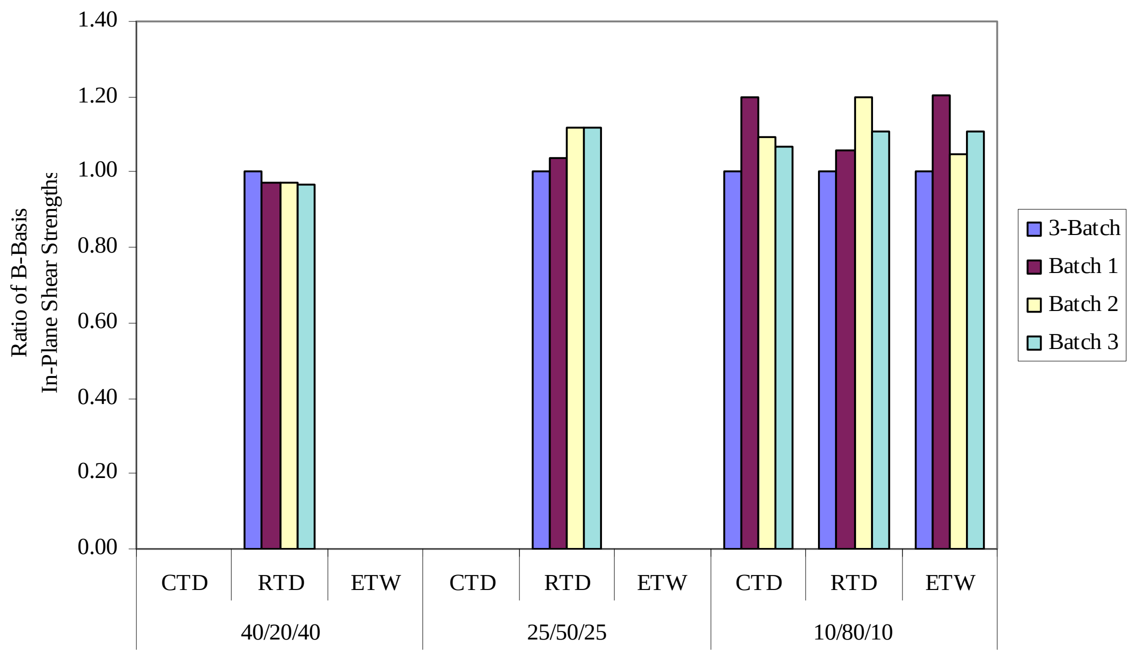


Figure 42. Ratio of LVM to Laminate B-Basis for In-Plane Shear Strength of Toray PW

5.4 CONCERNS RELATED TO THE APPLICATION OF LVM.

As shown in figures 23 through 42 and in appendix B for the six material systems from Toray, FiberCote, and ACG, LVM B-basis values were generally lower than those for pooled multibatch B-basis allowables. For the cases where batch variation was observed in three-batch laminate data, as shown in figure 43, pooled B-basis allowables resulted in low values due to cumulative high variation. Although there are data from two process cycles for each batch, within a material batch, data shows low variation. Such variation can be attributed to material batch variability and must be further investigated to isolate the cause. In some cases, due to the process cycle, only one of the data sets within a batch may have considerably high or low values that can result in a high cumulative variation. Both of these cases can cause excessively low pooled B-basis values and the comparison portrays unconservative LVM B-basis values. Therefore, such cases must be examined to isolate the variability before applying LVM and may require multibatch testing to obtain safe and reliable B-basis allowables.

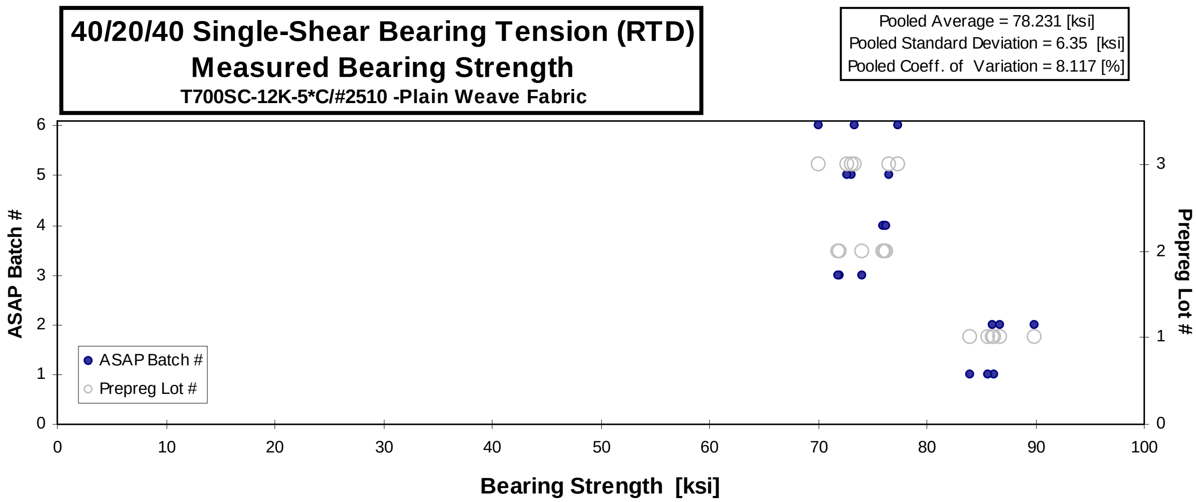


Figure 43. Material Batch-to-Batch Variation

Further, variability that can be mostly attributed to test complications, as shown in figure 44, may be observed throughout the multibatch data set. Such variations also can cause excessively low ASAP B-basis values across all environments. Since LVM does not account for laminate-level variation in materials, allowables result in higher values than those of pooled B-basis values shown in figure 45.

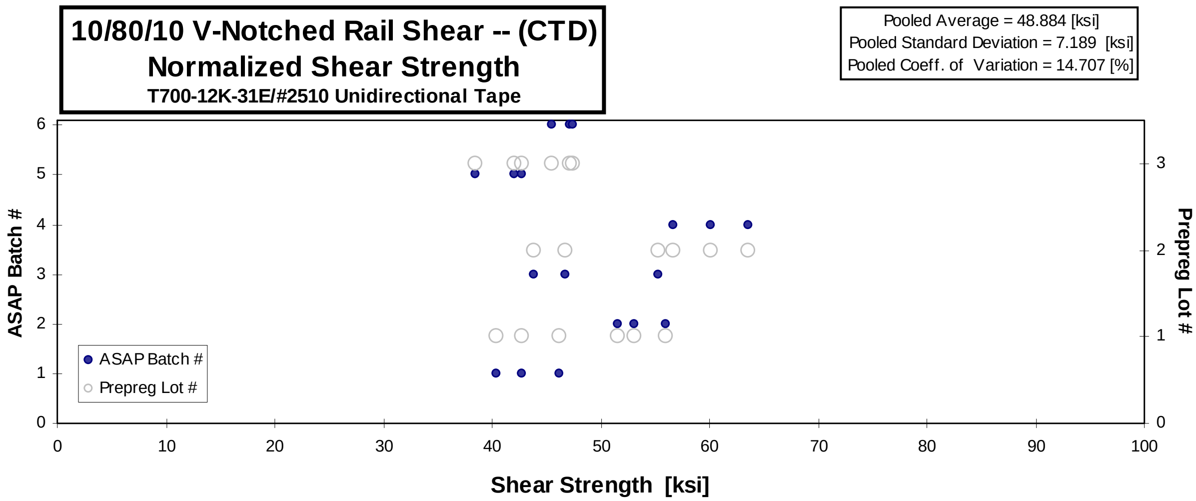


Figure 44. Data Variability Due to Test Method

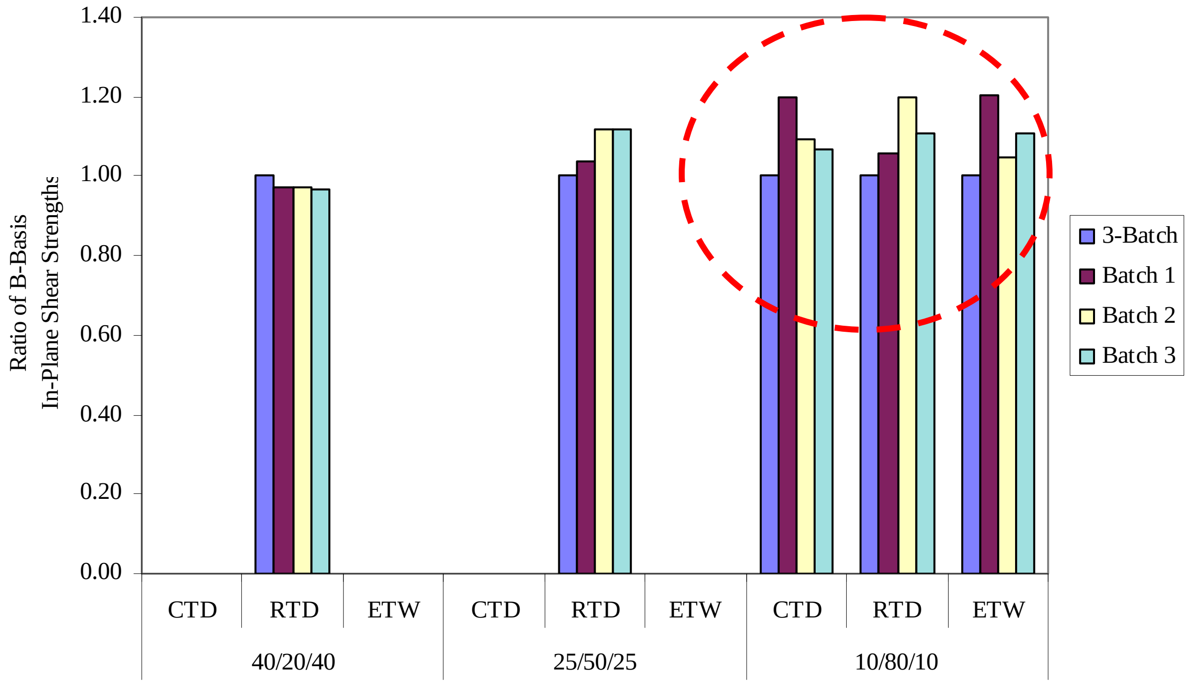
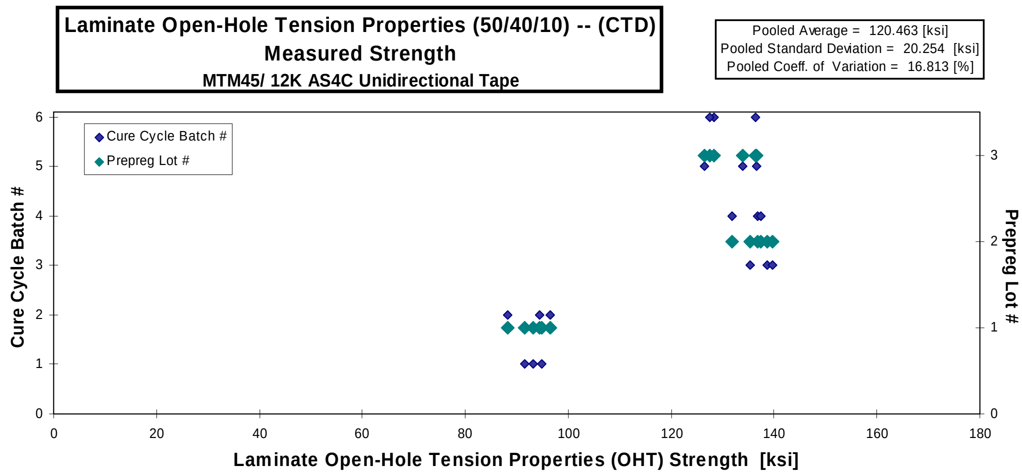


Figure 45. Comparison of ASAP and LVM B-Basis for Toray PW

Figure 46 shows that the B-basis values obtained from the LVM for 50/40/10 OHT strength in a CTD environment has significant batch variability. This caused the ASAP B-basis values to be considerably lower than those of LVM and affected all environmental conditions, since ASAP B-basis values were calculated by pooling laminate data from all three environmental conditions (typically, these cases are analyzed using single-point statistical methodologies presented in MIL-HDBK-17 rather than environment pooling methods).



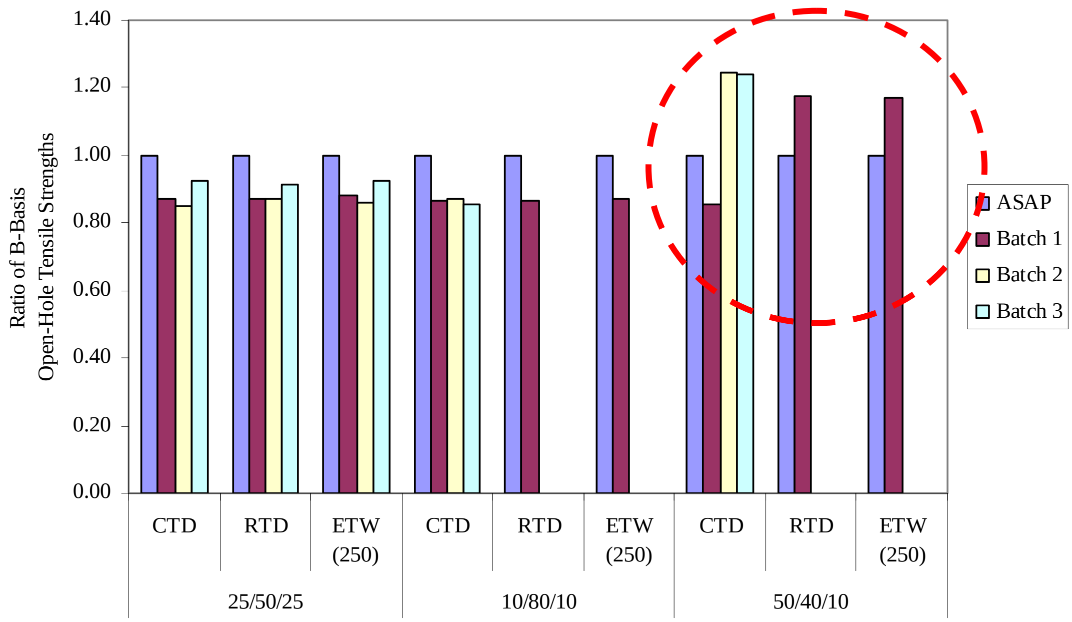


Figure 46. Comparison of ASAP and LVM B-Basis for ACG Unidirectional Tape

The LVM and three-batch B-basis comparison included approximately 4000 (excluding FiberCote batch 3) data points for six different material systems from three different prepreg manufacturers. Overall, the LVM produced conservative B-basis values that were not excessively low compared to the three-batch data sets. However, for the cases that exhibited either considerable material variability or variability caused by the test method or data reduction methodology, the LVM data may seem unconservative due to the low three-batch, pooled B-basis produced by such variability. This observation is not limited to LVM, but is observed for other small-sample methods, as shown in figure 47 (additional data in appendix D). For such cases, engineering judgment must be applied to determine the appropriate statistical methodology to generate safe and reliable allowables. The VNRS specimens must be resized to obtain correct failure modes and to reduce variability caused by specimen slippage and high through-the-thickness stresses due to excessive bolt torque.

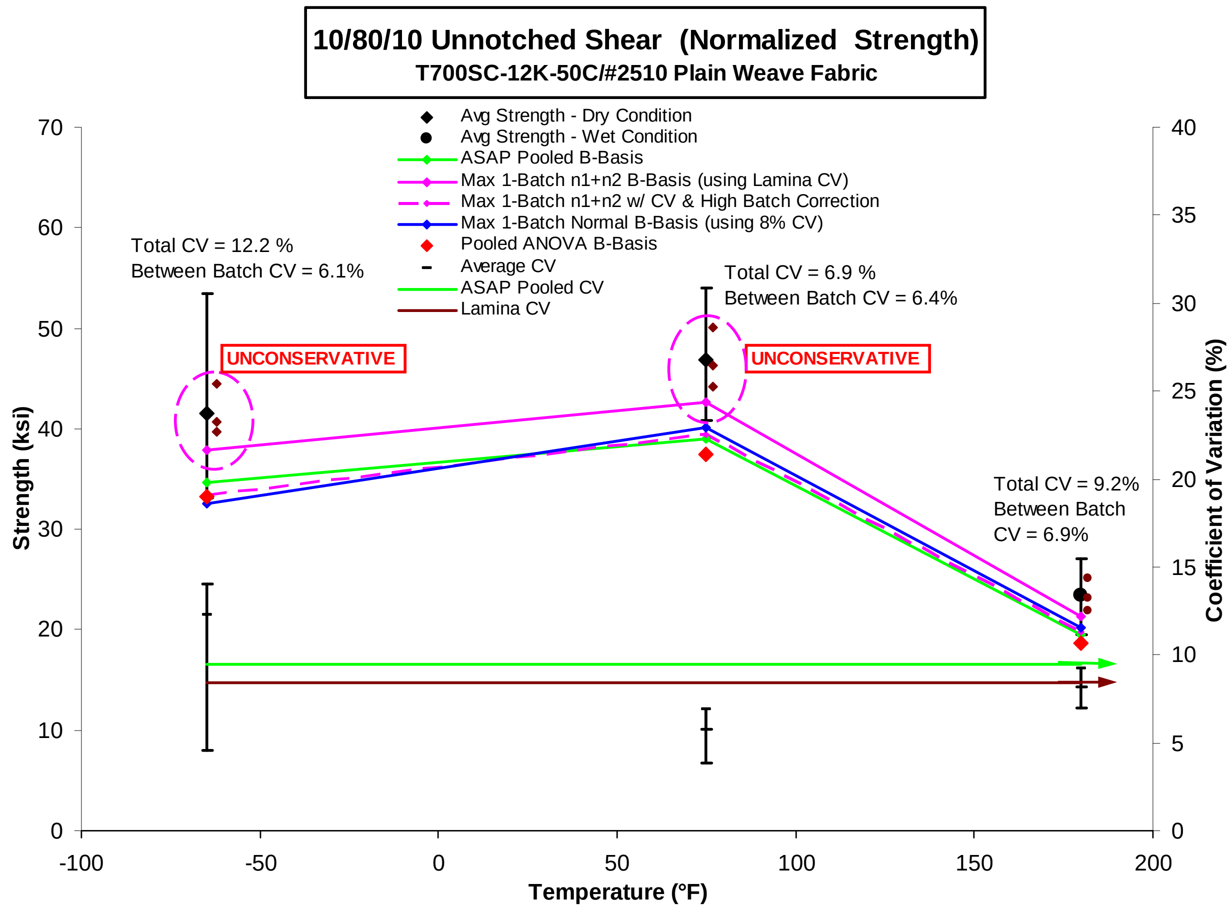


Figure 47. Small Sample B-Basis Affected by Data Set Variability

5.5 BEARING-BYPASS INTERACTION CURVES.

Bearing-bypass interaction curves were generated for both Toray and FiberCote material systems. At the time this report was written, only Toray test data was completed, and therefore, this section only contains Toray data. Appendix C contains bearing-bypass interaction curves, hole diameter effects[5], and *w/D* ratio effects for the available FiberCote unidirectional tape and PW test data. Figures 48 through 53 shows the bearing-bypass interaction curves for Toray tape and PW materials. Fifty percent of the bearing-bypass test data corresponds to bearing failure. Overall, bearing data does not indicate significant changes for different stacking sequences, but bypass strengths, i.e., OHT, FHT, and OHC, are reduced as the percentage of 0° plies decreases.

[5] *D/t* or *t/D* ratio effects were studied only by changing the diameter for one laminate thickness; therefore, this data is presented as the effects of hole diameter.

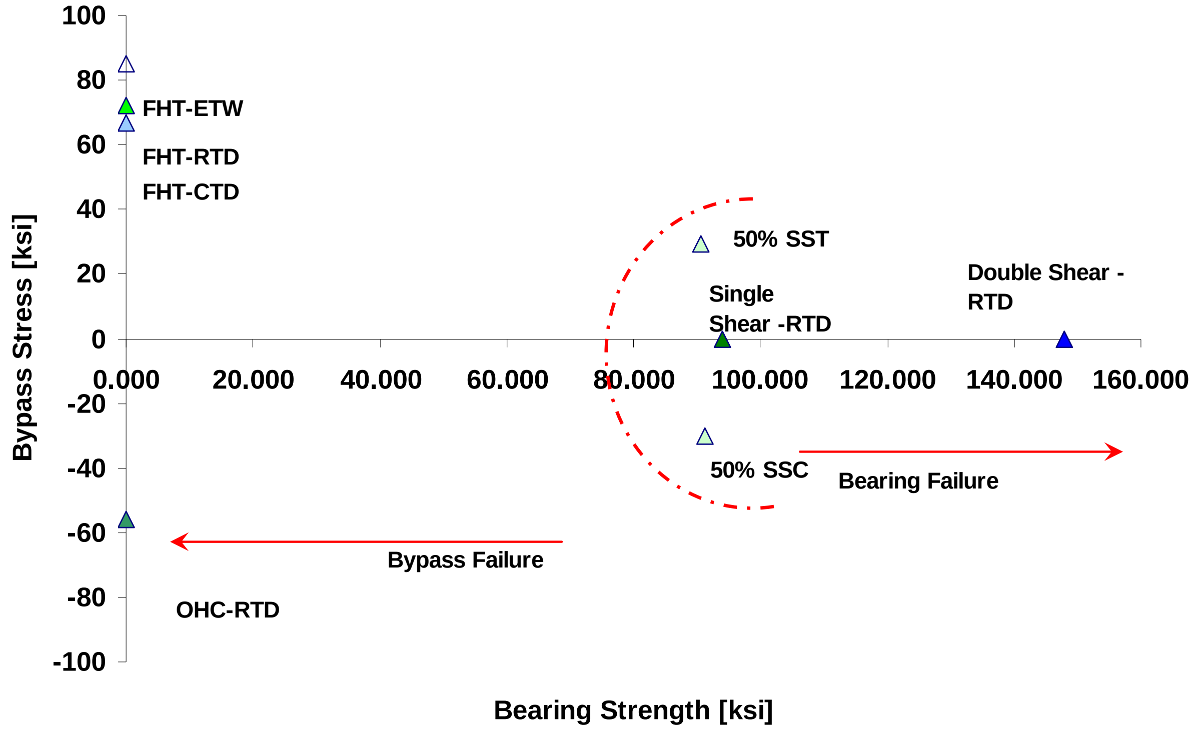


Figure 48. Bearing-Bypass Interaction Curve for Toray 50/40/10 Tape

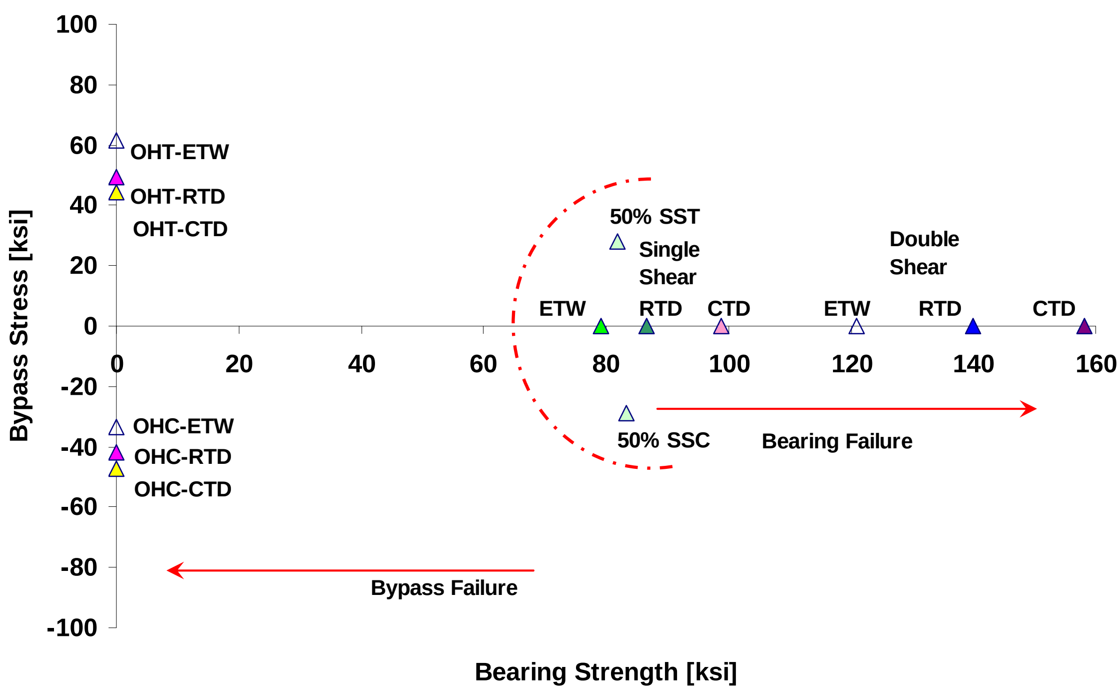


Figure 49. Bearing-Bypass Interaction Curve for Toray 25/50/25 Tape

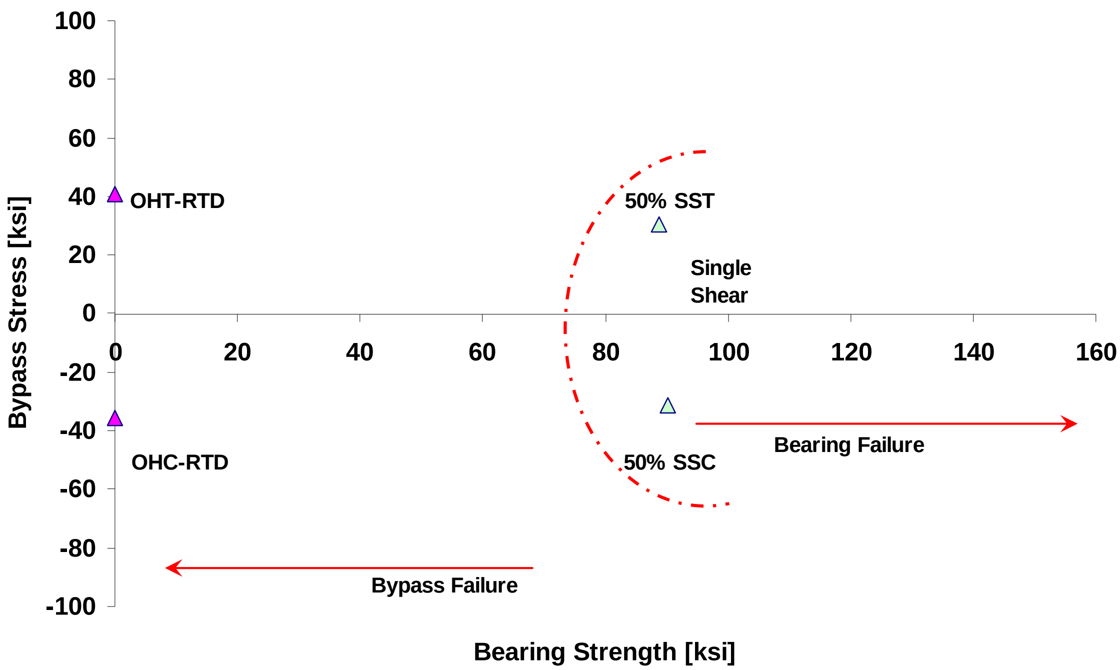


Figure 50. Bearing-Bypass Interaction Curve for Toray 10/80/10 Tape

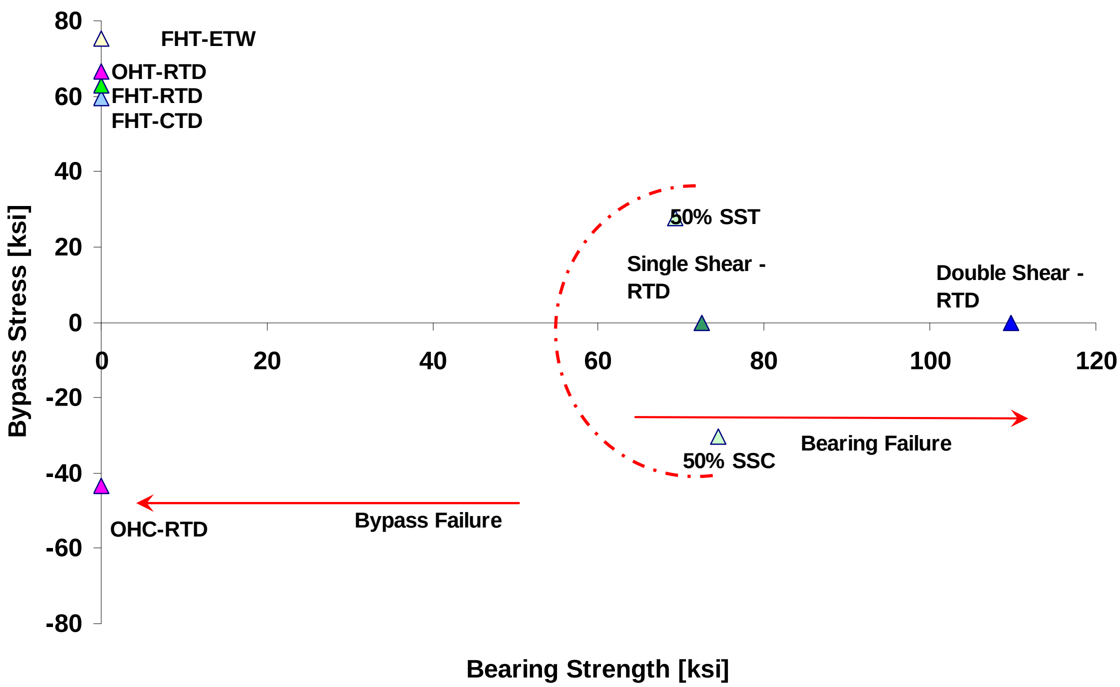


Figure 51. Bearing-Bypass Interaction Curve for Toray 40/20/40 PW

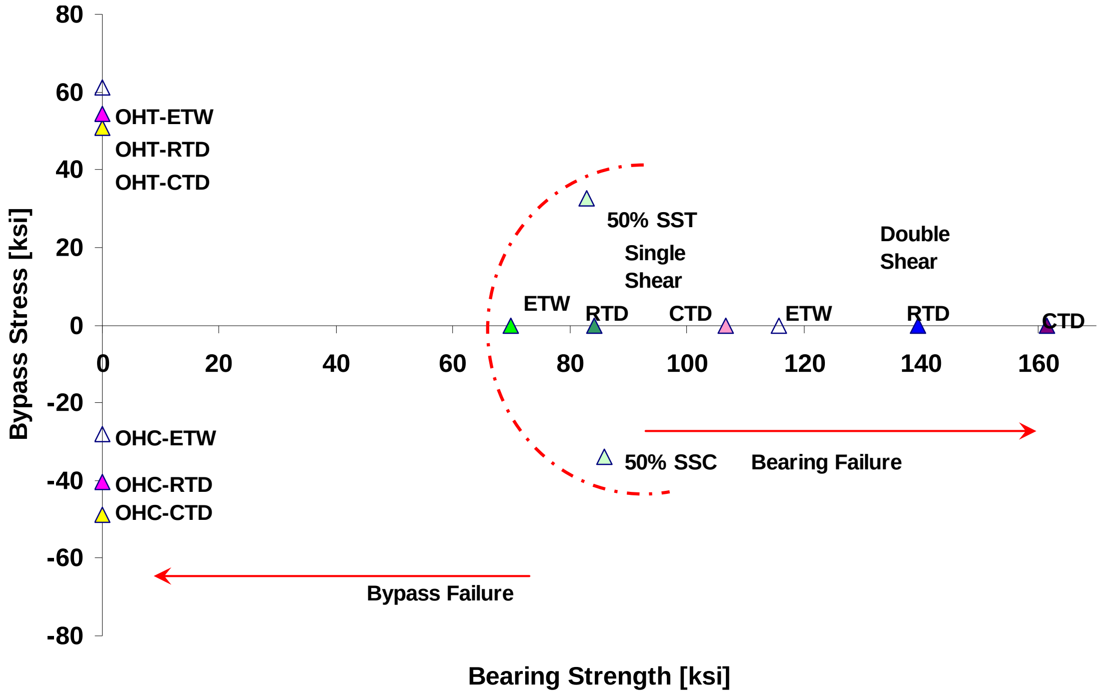


Figure 52. Bearing-Bypass Interaction Curve for Toray 25/50/25 PW

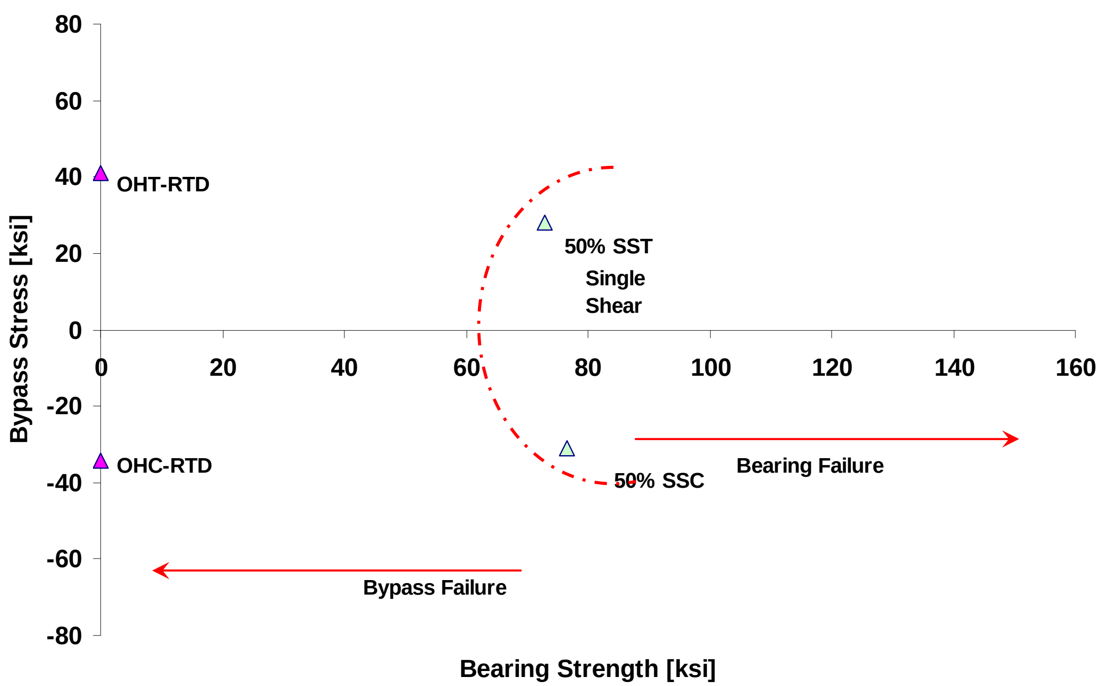


Figure 53. Bearing-Bypass Interaction Curve for Toray 10/80/10 PW

Hole diameter and *w/D* effects on bearing and OHT strength, respectively, for Toray tape 50/40/10 and fabric 40/20/40 layups are shown in figures 54 through 57. OHT test results showing hole-size effects (*w/D* ratio) are compared to predicted values using the classical finite width correction equation shown in appendix C. The baseline OHT values are defined as *w/D* = 8 for unidirectional tape and *w/D* = 6 for fabric material. Corresponding finite width correction values are calculated based on these *w/D* ratio values.

The bearing data does not follow the trend seen for other carbon fiber/epoxy material, where strength decreases with increasing fastener diameter [12]. Inconsistent trends in the Toray data may be due to the effects of relatively stiff layups, as a result of limited test data, or the fact that this data is 2% offset bearing strength rather than maximum strength. Note that the data is not plotted here as a function of *D/t* ratio for two reasons: (1) all the data is for one laminate thickness, and (2) composite bearing data is not a strong function of *D/t* [12].

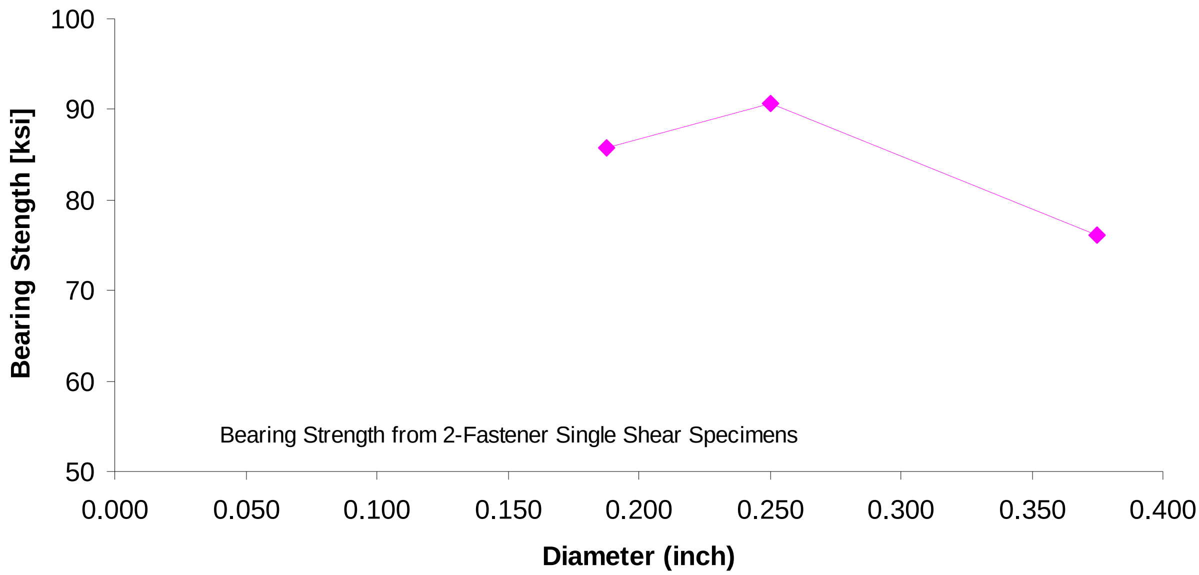


Figure 54. Effects of Hole Diameter on Toray Tape 50/40/10 Bearing Strength

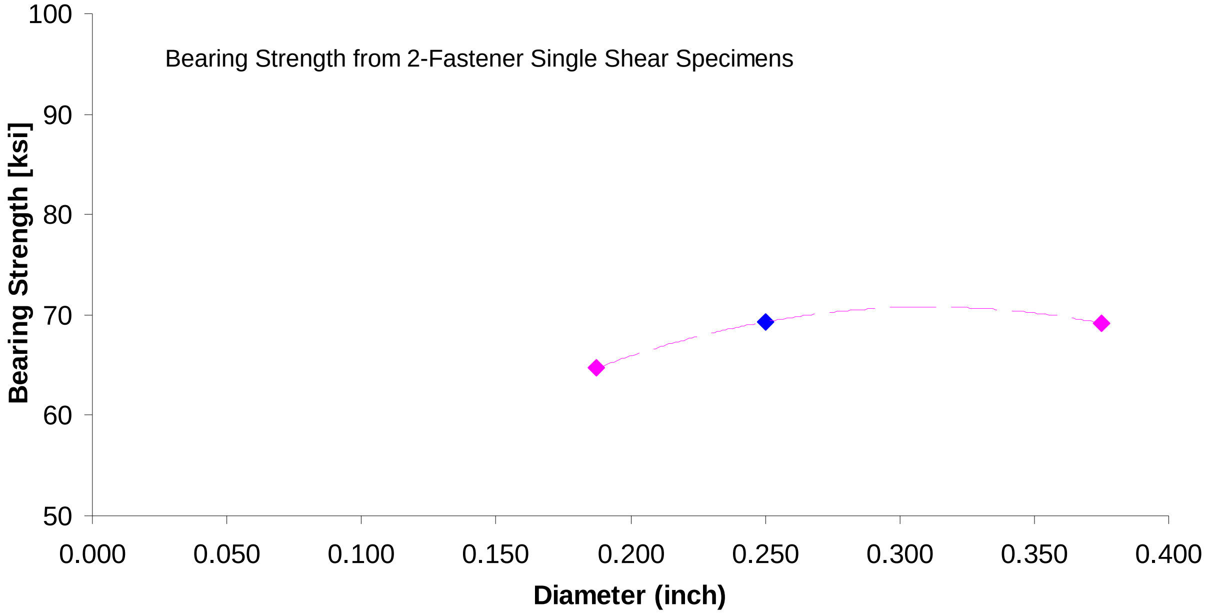


Figure 55. Effects of Hole Diameter on Toray PW 40/20/40 Bearing Strength

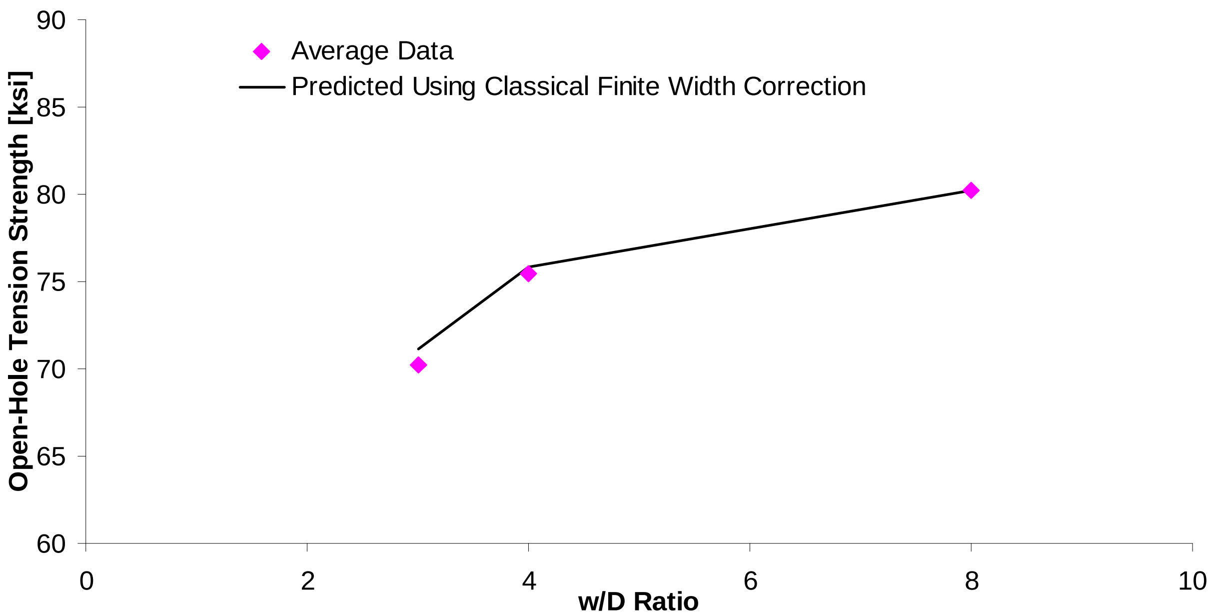


Figure 56. Effects of *w/D* Ratio on Toray Tape 50/40/10 OHT Strength

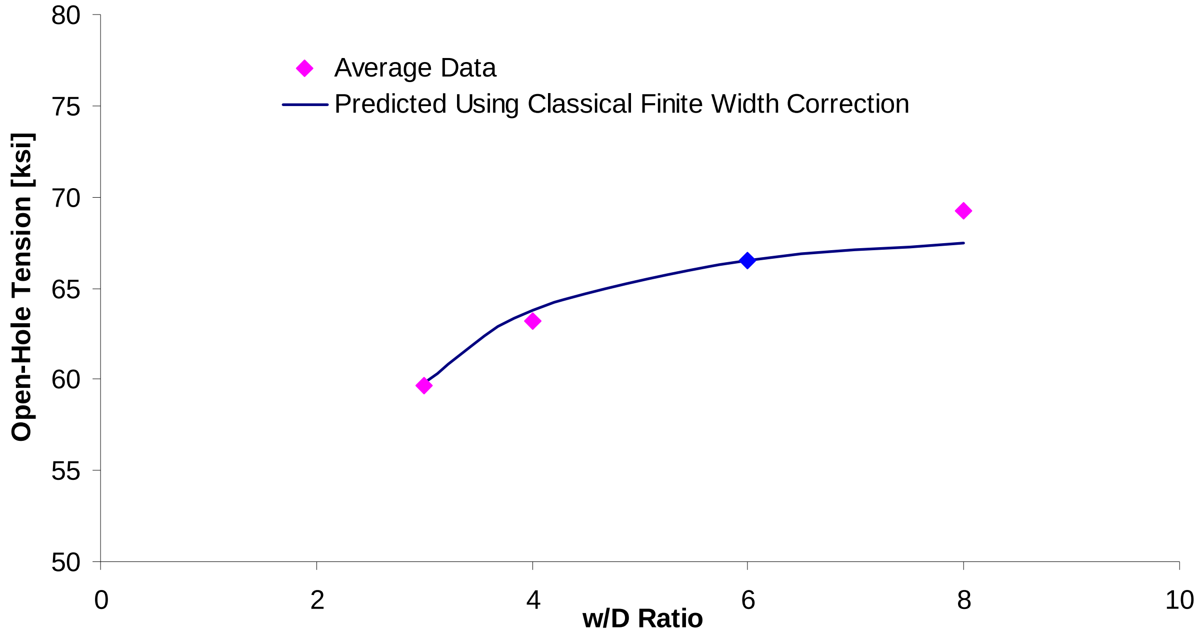


Figure 57. Effects of *w/D* Ratio on Toray PW 40/20/40 OHT Strength

6. CONCLUSIONS.

This report includes laminate test data generated on six different materials from three different prepreg manufacturers. The primary goal of this investigation was to evaluate the small-sample B-basis allowable generation using the lamina variability method (LVM) for generating B-basis allowables at higher (laminate) levels of building-block tests. Lamina versus laminate variation of the material under investigation indicated that the lamina coefficient of variation (CV), in most cases, are higher than laminate CVs. Therefore, when applying LVM for obtaining laminate B-basis allowables, only lamina variation is considered. Analysis of lamina and laminate test data for six different prepreg materials showed that LVM worked well and gave a conservative B-basis allowable that was about 90%, with extremes of 5% and 85% of the AGATE Statistical Allowable Program laminate allowable. Caution should be exercised if the laminate data exhibits unusual variability due to test methods. If variability is due to the material, the LVM method should be used with caution. If test variability is too high, for example bearing strength, then three batches of laminate tests should be performed for that test method to obtain B-basis allowables.

Generating composite design allowables can be costly, and thus, it is imperative to create a database of these materials, especially at higher levels of building-block tests. To establish such databases, it is vital that the process and test parameters be kept consistent and documented in detail.

Bearing data indicated minimal effects on the layup sequence. However, the bypass strength values decreased with decreasing percentage of 0° plies. The bearing data reported in this investigation were lower than that of Toray 2002 single-batch data, because they were reported as 2% offset bearing strength, and the specimens were not loaded to maximum load level, while

Toray 2002 data were reported with 4% offset. Single-shear, one-fastener, and two-fastener bearing data, for both tape and fabric, indicated a similar bearing strength and bearing failure mode. Bearing failure on two-fastener test specimens as opposed to possible net-section bypass failure mode may be due to the premature stoppage of these tests after 2% hole deformation. Higher clamp-up and continuous loading until complete failure of the specimen may be required to obtain bypass failure, and thus, the interaction curve may be completed for intermediate bearing-bypass ratios. Overall, bearing data indicated high variability, and therefore, further (multibatch) tests may require establishing data sets that encompass laminate-level material variability. Since bearing strength was not significantly affected by the layup sequence and since the most common layup sequence used in bolted joint areas is 25/50/25 (quasi-isotropic), multibatch bearing tests can be conducted for this layup only. The test specimen used for the BB(50%)T or C is not very useful for obtaining bearing/bypass data. Independent loading of the bolt is recommended.

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26. "B-Basis Design Allowables for Epoxy-Based Prepreg: FiberCote Graphite Fabric T300 3KPW/E765," AGATE-WP3.3-033051-103, September 2001 (http://www.niar.twsu.edu/agate).

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28. Tomblin, J. and Seneviratne, W., "Multibatch Laminate Design Allowables for FiberCote T700/E765 Unidirectional Tape and T300/E765 Plain Weave Fabric," NIAR Report, Wichita, KS.

APPENDIX A—LAMINA AND LAMINATE COEFFICIENTS OF VARIATION

This appendix contains laminate coefficient of variations (CV) plotted against lamina CVs for the Toray, FiberCote, and Advanced Composites Group (ACG) material systems. The nomenclature used in figures A-1 through A-8 is as follows:

5HS	Five-harness fabric
ACG	Advanced Composite Group
ASAP	AGATE Statistical Allowable Program
BB(50%)T	Single shear, double-fastener bearing (50% bypass) tension
BB(50%)C	Single-shear, double fastener bearing (50% bypass) compression
CV or CoV	Coefficient of variation
DSBT	Double-shear bearing tension
FHC	Filled-hole compression
FHT	Filled-hole tension
LVM	Lamina Variability Method
n	Number of test specimens
NHC	No-hole compression
NHT	No-hole tension
OHC	Open-hole compression
OHT	Open-hole tension
PB	Single-shear, single-fastener (with stabilizing fixture)
PW	Plain Weave
SSBT	Single-shear, single-fastener bearing tension
VNRS	V-notched rail shear

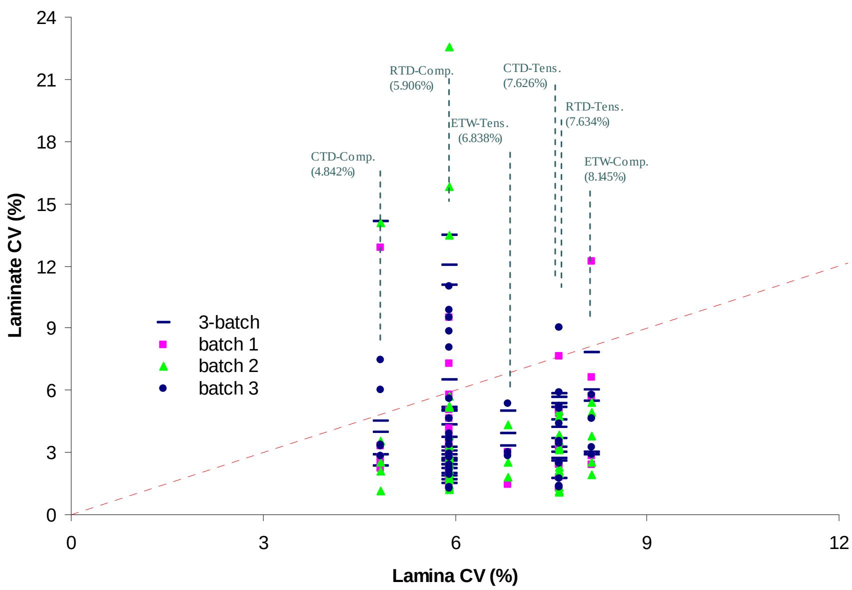

Figure A-1. Comparison of CV for Toray Tape

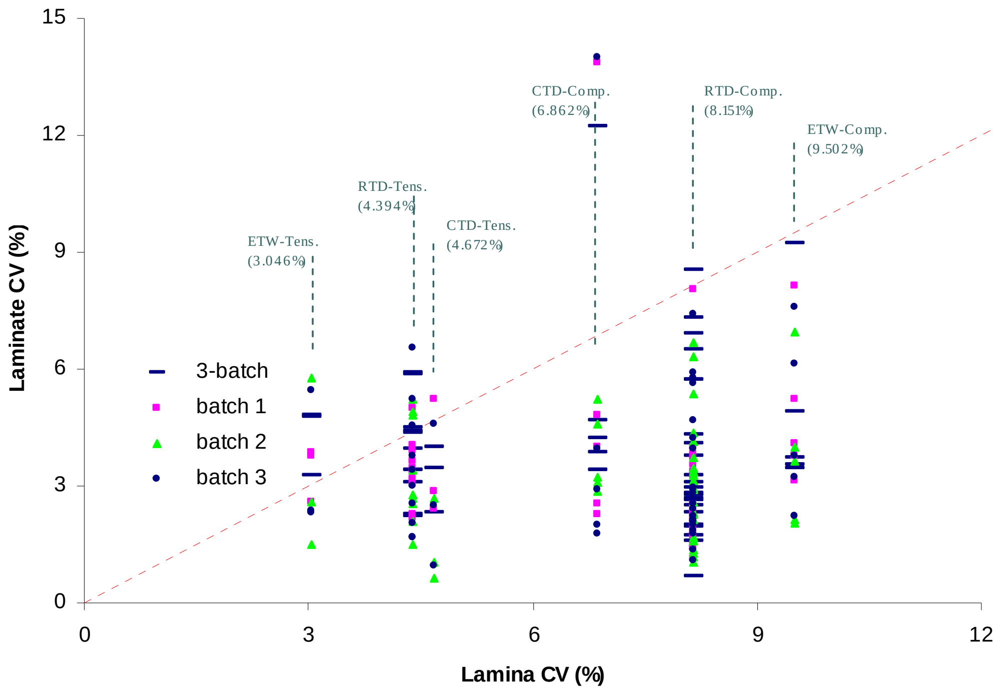

Figure A-2. Comparison of CV for Toray PW

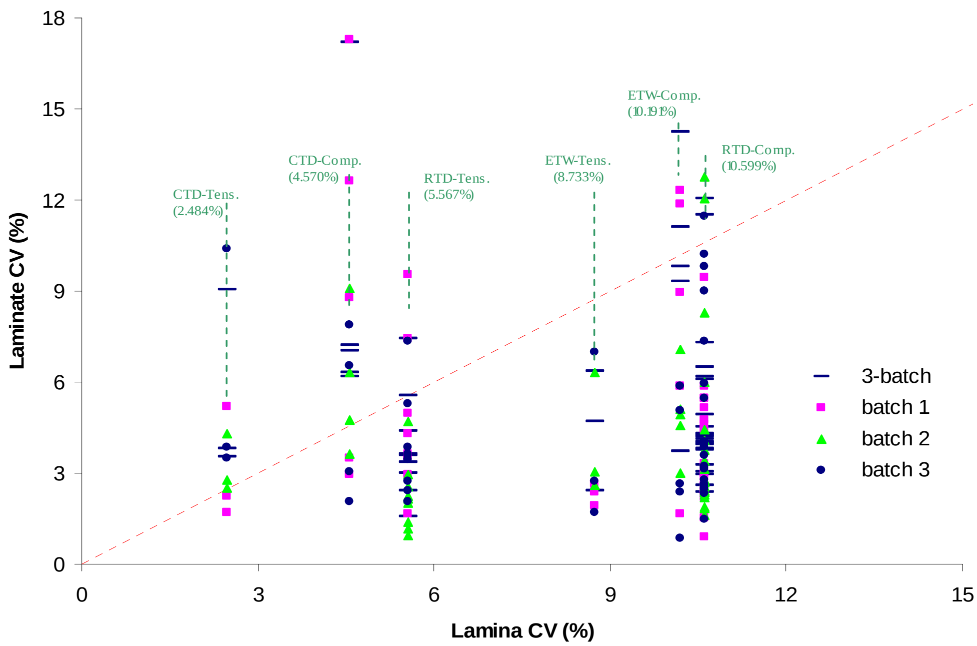

Figure A-3. Comparison of CV for FiberCote Tape

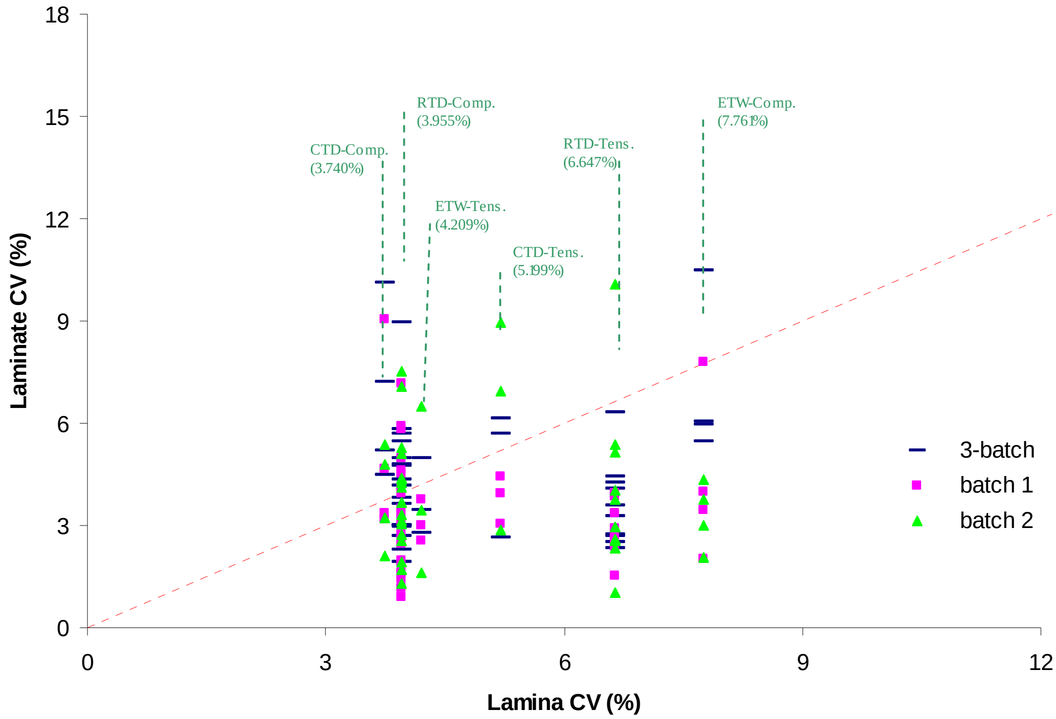

Figure A-4. Comparison of CV for FiberCote PW

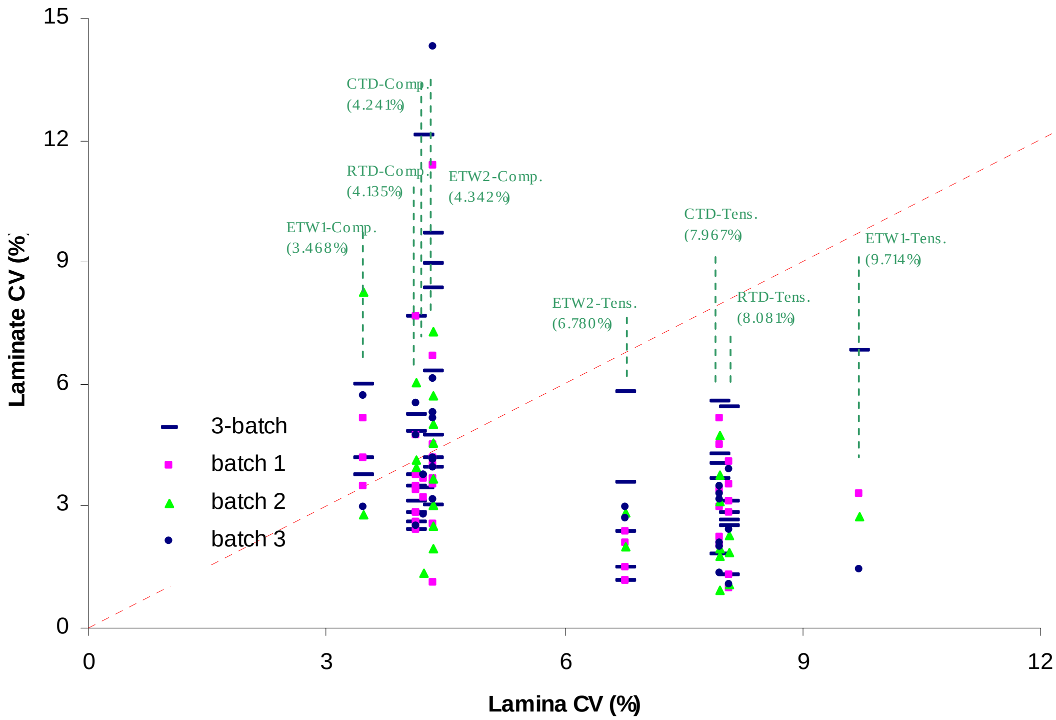

Figure A-5. Comparison of CV for ACG Tape

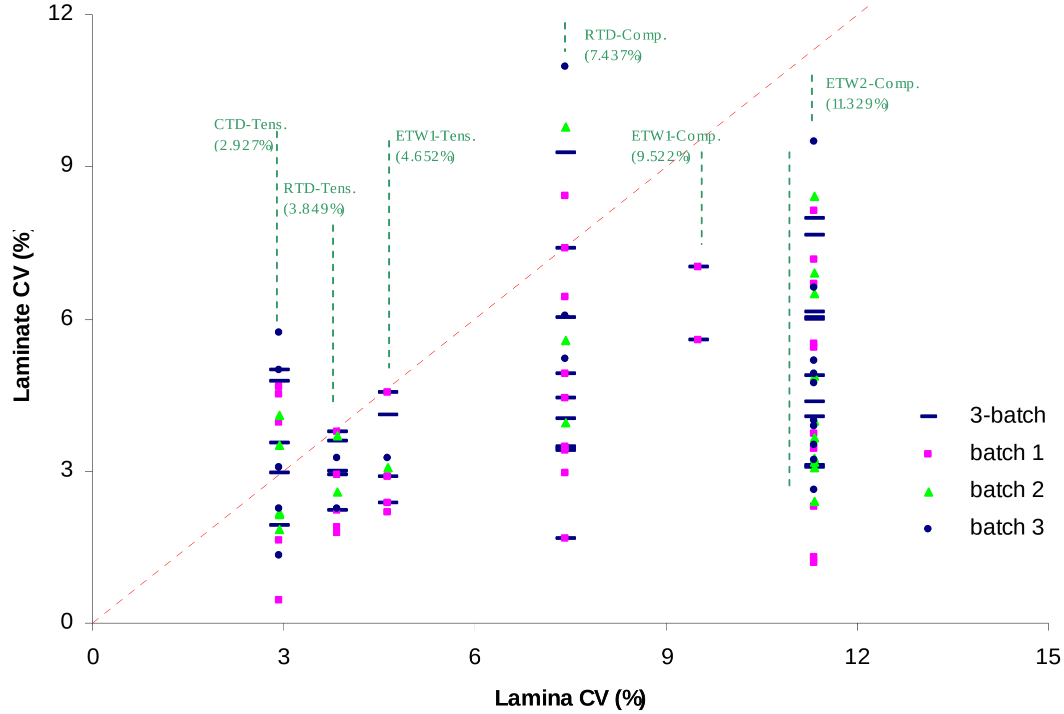

Figure A-6. Comparison of CV for ACG 5HS Weave

A.1 LAMINATE CVS SUMMARY.

Variations for each batch within the three-batch data set and the pooled three batches were calculated [A-1]. Figures A-7 and A-8 compare the maximum of the one-batch CVs to the corresponding three-batch CVs. The values are relatively low (2% to 6%) for the tension, compression, and two-fastener bearing bypass tests. CVs are significantly higher for some of the in-plane shear and bearing tests due to possible complications introduced during testing.

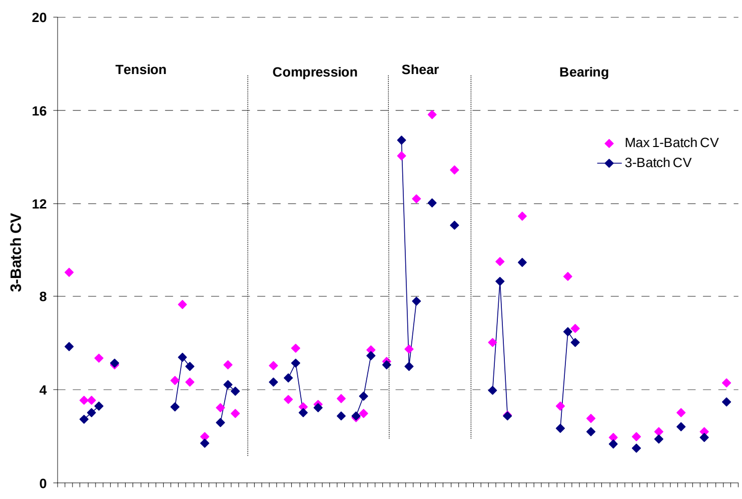

Figure A-7. Comparison of Maximum One- and Three-Batch Laminate CVS for Toray Tape

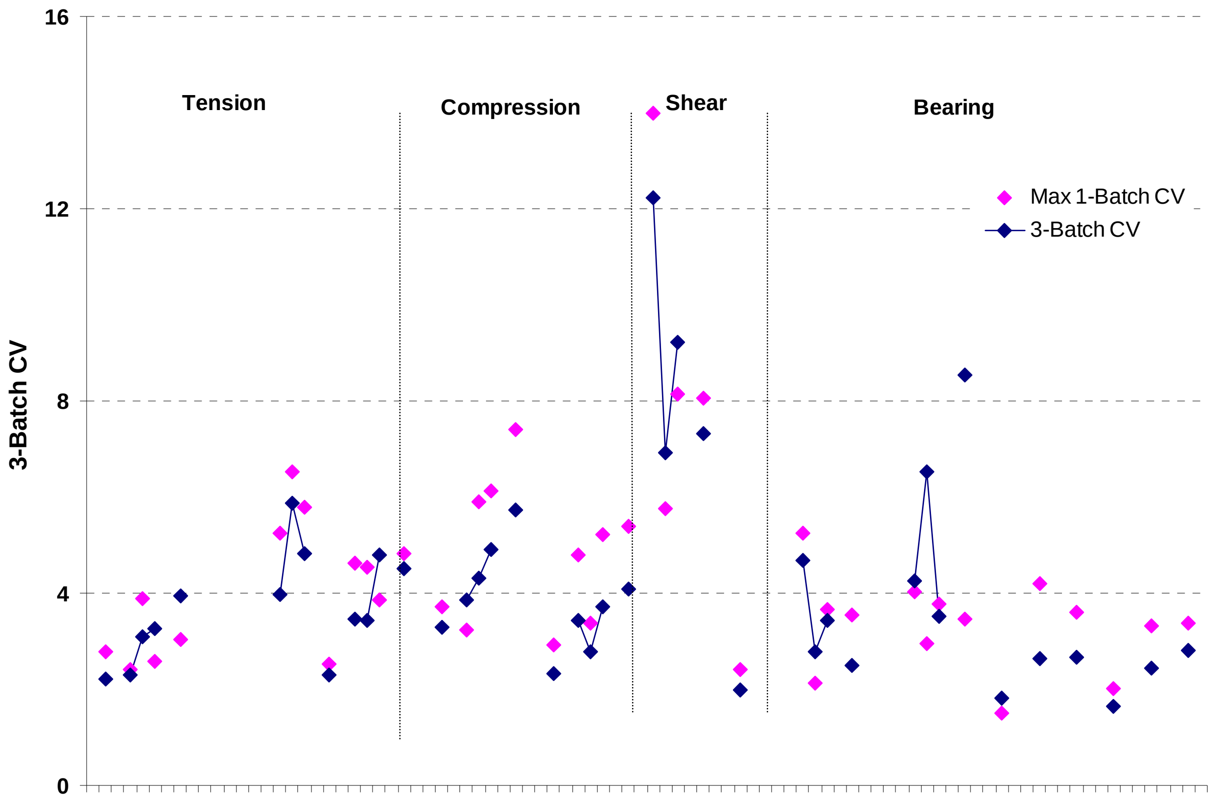

Figure A-8. Comparison of Maximum One- and Three-Batch Laminate CV for Toray PW

A.2 REFERENCES.

A-1. Ward, S.H., "Development and Assessment of Procedures for Generating Statistical Allowables From Composite Laminate Test Data–Analysis of Toray T700/#2510 Uni Tape and PW Fabric Data," Report SWC-2005-01, SW Composites, Taos, NM, February 2005 (http://www.niar.twsu.edu/agate)

APPENDIX B—B-BASIS VALUE COMPARISON OF ASAP AND LVM

This appendix contains the B-basis values obtained from ASAP for multibatch data and from LVM for one-batch, small-sample data sets of FiberCote and ACG [B-1] material systems. Graphical comparisons of ASAP and LVM B-basis values are included. The nomenclature used in tables B-1 through B-6 and figures B-1 through B-28 is as follows:

5HS	Five-harness fabric
ACG	Advanced Composite Group
ASAP	AGATE Statistical Allowable Program
BB(50%)T	Single shear, two-fastener bearing (50% bypass) tension
BB(50%)C	Single-shear, two-fastener bearing (50% bypass) compression
CV or CoV	Coefficient of variation
DSBT	Double-shear bearing tension
FHC	Filled-hole compression
FHT	Filled-hole tension
LVM	Lamina Variability Method
n	Number of test specimens
NHC	No-hole compression
NHT	No-hole tension
OHC	Open-hole compression
OHT	Open-hole tension
PB	Single-shear, single-fastener (with stabilizing fixture)
PW	Plain weave
SSBT	Single-shear, single-fastener bearing tension
VNRS	V-notched rail shear

Table B-1. Comparison of FiberCote Unidirectional Tape B-Basis Allowables (50/40/10 Layup)

		Laminate (3 Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
NHT	RTD	17*	201.217	170.893	7.448	7	188.192	157.120	7.437	3	212.187	171.317	2.246	7	209.541	174.944	3.589
OHT [w/D=3]	RTD	18	107.369	100.146	3.376	6	104.142	86.515	3.649	6	109.610	91.057	2.134	6	108.354	90.014	2.077
OHT [w/D=4]	RTD	16*	112.238	108.592	1.578	6	114.168	94.844	3.537	6	111.336	92.491	0.949	6	115.265	95.755	5.272
OHT [w/D=8]	RTD	18	123.538	112.772	4.373	6	122.149	101.474	3.522	6	121.318	100.784	4.714	6	127.146	105.625	3.865
FHT	CTD	18	114.495	105.054	3.784	6	113.083	93.942	5.178	6	114.448	95.076	2.492	6	115.956	96.329	3.496
	RTD	18	112.064	102.823	3.638	6	111.853	92.921	4.950	6	112.800	93.707	2.574	6	111.538	92.659	3.631
	ETW	18	129.884	119.174	6.343	6	131.710	109.417	2.634	6	121.315	100.781	6.296	6	136.628	113.502	2.712
NHC	RTD	18	122.229	94.157	11.524	6	125.497	102.396	4.444	6	107.564	87.764	12.781	6	133.626	109.029	3.944
OHC	RTD	20	65.180	57.497	6.073	6	67.926	55.422	4.492	8	62.402	51.427	2.755	6	66.137	53.963	7.345
DSBT	RTD	21	155.122	135.760	6.505	6	142.426	116.209	5.854	6	125.965	102.778	4.446	9	145.940	120.715	4.016
SSBT	RTD	18	98.669	91.189	3.804	6	101.469	82.791	2.350	6	98.618	80.465	3.157	6	123.728	100.952	3.873
BB(50%)T [t/D=0.32]	RTD	17*	93.631	86.485	3.772	6	93.782	76.519	5.477	6	95.003	77.516	2.174	6	95.223	77.695	9.021
BB(50%)T [t/D=0.384]	RTD	18	96.937	91.893	2.611	6	96.986	79.133	2.608	6	96.516	78.749	2.404	6	97.308	79.396	3.186
BB(50%)T [t/D=0.48]	RTD	15	96.143	87.332	4.018	5	99.432	80.547	2.438	5	92.053	74.570	4.083	5	96.945	78.532	2.639
BB(50%)T [t/D=0.64]	RTD	18*	94.680	85.376	4.931	6	99.828	81.452	2.873	6	88.072	71.860	8.270	8	89.489	73.750	11.459
BB(50%)C	RTD	13	95.492	87.098	4.003	4	97.329	78.072	2.582	4	93.088	74.670	1.830	5	95.945	77.722	5.466
VNRS	RTD	18	52.510	46.055	6.169	6	50.444	41.158	9.434	6	53.341	43.523	3.419	6	53.746	43.853	2.577

* Outliers were removed
Env. = Environment
n = Number of specimens

Table B-2. Comparison of FiberCote Unidirectional Tape B-Basis Allowables (25/50/25 and 10/80/10 Layups)

			Laminate (3 Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHT	CTD	19	130.609	115.136	9.067	6	132.929	110.430	2.230	6	119.395	99.186	2.770	7	138.233	115.409	10.367
		RTD	14*	135.794	119.193	5.537	6	129.514	107.593	9.519	3	130.695	105.522	1.164	6	139.484	115.875	7.345
		ETW	18	130.362	114.837	4.689	6	133.422	110.839	2.390	6	127.294	105.748	2.598	6	130.369	108.303	7.006
	OHT	CTD	18	70.446	66.967	3.532	6	69.227	57.509	1.693	6	71.318	59.246	4.297	6	70.795	58.812	3.855
		RTD	18	74.985	71.282	2.427	6	74.308	61.731	2.971	6	75.354	62.600	2.014	6	75.294	62.550	2.396
		ETW	18	83.137	79.031	2.440	6	82.372	68.430	1.938	6	82.592	68.612	3.039	6	84.448	70.155	1.681
	DSBT	CTD	17*	177.132	147.145	6.327	6	179.040	146.083	17.262	6	196.173	160.062	6.315	7	174.471	143.147	3.046
		RTD	18	164.808	137.067	4.215	6	161.807	132.022	4.761	6	171.899	140.256	1.630	6	160.719	131.134	1.480
		ETW	21	121.082	100.998	14.251	8	100.760	83.039	5.880	7	137.323	112.668	3.004	6	129.228	105.440	2.643
	SSBT	CTD	18	105.765	96.029	7.202	6	115.147	93.951	2.937	6	99.014	80.788	3.612	6	103.133	84.148	2.041
		RTD	18	84.140	76.395	4.535	6	88.176	71.945	2.172	6	83.268	67.941	3.758	6	80.975	66.070	2.328
		ETW	20	67.961	61.768	3.737	8	67.491	55.621	1.650	6	67.848	55.359	4.581	6	68.701	56.055	5.060
	BB(50%)T	RTD	16	84.143	78.882	3.038	5	83.997	68.044	0.893	5	82.728	67.016	2.386	6	85.444	69.715	4.052
	BB(50%)C	RTD	15	86.891	79.739	3.925	5	86.936	70.425	5.445	5	85.624	69.362	3.392	5	88.113	71.378	2.778
	NHC	CTD	18	108.884	93.696	7.045	6	112.108	91.471	8.785	6	105.403	86.000	4.733	6	109.141	89.050	6.548
		RTD	17*	94.437	81.189	4.296	6	91.979	75.048	4.605	6	94.359	76.990	2.753	6	99.462	81.153	5.949
		ETW	18	63.193	54.379	11.086	6	55.942	45.644	11.885	6	65.198	53.197	7.088	6	68.440	55.842	0.860
	OHC	CTD	19	55.759	49.321	6.163	6	57.246	46.709	3.504	7	56.733	46.548	4.751	6	53.135	43.354	7.879
		RTD	18	49.497	43.751	2.378	6	49.585	40.457	2.452	6	49.653	40.513	2.567	6	49.252	40.186	2.483
		ETW	20	33.725	29.850	9.313	7	33.423	27.422	12.305	7	31.794	26.086	4.942	6	36.330	29.642	2.352
	VNRS	RTD	18	60.445	45.912	12.065	6	54.475	44.448	4.748	6	61.308	50.022	12.042	6	65.552	53.486	10.195
10/80/10	NHT	RTD	15	67.618	63.392	2.980	3	68.952	55.671	4.280	6	68.271	56.716	1.401	6	66.298	55.077	2.741
	OHT	RTD	18	47.957	44.542	3.573	6	49.246	40.910	1.658	6	48.175	40.021	2.938	6	46.449	38.587	3.428
	BB(50%)T	RTD	15	96.671	90.084	3.249	5	99.500	82.125	2.985	5	95.122	78.511	2.355	5	95.392	78.734	2.489
	BB(50%)C	RTD	14	96.920	90.829	4.379	5	96.892	78.489	2.977	4	97.570	78.265	2.686	5	96.429	78.115	3.603
	NHC	RTD	18	61.215	56.028	4.252	6	62.463	50.965	1.519	6	63.042	51.437	1.888	6	58.139	47.437	3.212
	OHC	RTD	20	38.202	35.154	4.111	6	38.641	31.528	3.313	8	39.168	32.279	2.303	6	36.474	29.760	3.112
	VNRS	CTD	18	76.396	60.251	17.189	6	60.695	49.523	12.612	6	82.236	67.098	9.075	6	86.258	70.380	4.996
		RTD	18	69.774	55.029	7.310	6	67.490	55.067	5.161	6	71.544	58.374	6.010	6	70.288	57.350	9.806
		ETW	18	40.275	31.763	9.817	6	36.216	29.549	8.967	6	43.259	35.296	5.089	6	41.349	33.738	5.882

* Outliers were removed
Env. = Environment
n = Number of specimens

Table B-3 Comparison of FiberCote PW Fabric B-Basis Allowables (40/20/40 Layup)

			Laminate Properties (Multi batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
40/20/40	NHT	RTD	13	90.925	82.475	4.232	6	91.166	80.195	3.348	7	90.719	80.071	5.140				
	OHT [w/D=3]	RTD	12	40.902	37.867	3.285	6	41.283	36.316	2.746	6	40.521	35.645	3.773				
	OHT [w/D=4]	RTD	13	44.355	42.067	2.349	6	44.344	39.008	2.574	7	44.364	39.157	2.348				
	OHT [w/D=6]	CTD	12	41.997	38.513	5.676	6	42.762	37.617	3.954	6	41.231	36.270	6.960				
		RTD	12	45.832	42.030	4.079	6	46.529	40.930	3.836	6	45.135	39.704	4.048				
		ETW	12	48.190	44.193	3.450	6	48.285	42.475	3.772	6	48.094	42.307	3.442				
	OHT [w/D=8]	RTD	12	47.420	43.597	3.568	6	46.832	41.196	3.954	6	48.009	42.232	2.975				
	FHT	CTD	12	47.603	44.896	2.517	6	47.962	42.191	2.425	6	47.243	41.558	2.589				
	NHC	RTD	13	66.491	59.211	4.986	7	64.527	55.915	4.524	6	68.783	59.372	3.067				
	OHC	RTD	12	39.396	35.993	3.823	6	39.112	33.761	1.609	6	39.680	34.251	5.288				
	DSBT	RTD	13	102.51	95.76	3.00	6	99.895	86.227	1.896	7	104.747	90.767	1.707				
	SSBT	RTD	15	70.460	57.205	8.970	8	66.342	57.668	4.990	7	75.167	65.135	7.522				
	BB(50%)T [t/D=0.475]	RTD	12	62.231	58.999	2.299	6	61.916	53.444	2.723	6	62.547	53.989	1.906				
	BB(50%)T [t/D=0.570]	RTD	12	61.689	57.927	2.699	6	62.158	53.654	1.962	6	61.219	52.843	3.300				
	BB(50%)T [t/D=0.712]						6	68.178	58.850	5.803								
	BB(50%)T [t/D=0.949]	RTD	12	61.623	55.812	4.174	6	60.301	52.050	4.617	6	62.946	54.333	2.564				
	BB(50%)C	RTD					9	68.017	59.276	3.487								
	VNRS	RTD	12	26.889	25.729	1.909	6	26.962	23.273	2.476	6	26.815	23.146	1.300				

Env. = Environment
n = Number of specimens

Table B-4. Comparison of FiberCote PW Fabric B-Basis Allowables (25/50/25 and 10/80/10 Layups)

			Laminate Properties (Multi Batch)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHT	CTD	18	72.738	69.304	2.662	6	73.866	64.977	3.037	6	72.263	63.567	2.864	6	72.085	63.411	1.472
		RTD	18	76.403	72.796	2.711	6	76.869	67.619	3.919	6	76.549	67.337	2.559	6	75.791	66.671	1.273
		ETW	21	74.258	70.804	2.795	8	74.310	65.766	2.536	7	75.506	66.644	1.593	6	72.731	63.979	3.235
	OHT	CTD	18	36.865	33.129	6.151	6	37.773	33.227	4.421	6	35.956	31.629	8.970	6	36.865	32.429	4.123
			18	38.582	34.672	6.320	6	39.873	35.075	2.927	6	37.498	32.985	10.062	6	38.374	33.757	2.796
		ETW	18	40.756	36.626	4.963	6	41.579	36.576	2.985	6	38.979	34.289	6.505	6	41.711	36.692	1.185
	NHC	CTD	18	70.716	64.717	4.468	6	73.043	63.049	3.161	6	70.091	60.501	3.242	6	69.014	59.571	5.226
		RTD	15	65.840	60.149	3.630	6	66.951	57.791	3.944	6	65.371	56.427	3.691	3	64.555	54.504	1.670
		ETW	18	41.740	38.199	6.034	6	38.894	33.573	2.035	6	41.744	36.032	2.075	6	44.581	38.482	1.983
	OHC	CTD	18	43.001	37.116	7.205	6	41.364	35.705	3.371	6	41.960	36.219	4.794	6	45.680	39.430	8.048
		RTD	18	37.192	32.102	4.780	6	37.785	32.615	3.136	6	36.672	31.654	7.061	6	37.120	32.041	3.697
		ETW	19	26.637	23.011	10.462	6	25.505	22.015	3.980	6	24.031	20.743	4.353	7	29.840	25.858	4.080
	DSBT	CTD	20	130.717	119.498	5.173	7	135.382	117.314	4.638	6	131.676	113.660	2.123	7	125.231	108.517	4.884
		RTD	20	120.536	110.191	4.352	6	122.110	105.402	3.287	7	119.018	103.133	3.668	7	120.707	104.597	5.827
		ETW	19	98.462	89.970	5.479	6	98.519	85.040	7.800	6	99.898	86.230	3.745	7	97.182	84.212	4.876
	SSBT	CTD	18	100.635	87.561	10.139	6	107.572	92.854	9.027	6	104.652	90.334	5.384	6	89.683	77.412	2.929
		RTD	18	78.539	68.335	5.457	6	80.090	69.132	5.918	6	78.725	67.954	4.256	6	76.801	66.293	6.134
		ETW	18	66.278	57.667	5.976	6	69.612	60.088	3.446	6	67.285	58.079	2.987	6	61.937	53.463	4.075
	BB(50%)T	RTD	10	73.506	68.307	3.004	5	72.030	61.862	1.573	5	74.982	64.397	2.745				
	BB(50%)C	RTD					4	78.308	66.793	0.876	4	81.449	69.472	4.388				
	VNRS	RTD	18	40.924	36.283	5.690	6	40.984	35.377	7.182	6	41.542	35.858	5.089	6	40.246	34.739	5.146
10/80/10	NHT	RTD	18	48.891	46.302	2.682	6	48.723	42.057	1.525	6	49.813	42.997	1.048	6	48.137	41.550	3.765
	OHT	RTD	18	36.699	33.483	4.438	6	36.441	32.056	2.371	6	36.420	32.038	5.376	6	37.235	32.754	5.320
	NHC	RTD	18	47.235	44.450	2.959	6	47.494	40.996	2.549	6	46.882	40.467	3.123	6	47.330	40.854	3.531
	OHC	RTD	18	33.787	31.777	2.984	6	34.492	29.773	1.445	6	33.499	28.915	4.100	6	33.369	28.804	1.932
	BB(50%)T	RTD													6	61.138	52.773	15.81
	BB(50%)C	RTD	13	71.597	64.118	4.757	4	73.969	63.092	4.124	7	71.358	61.834	4.325	2	67.693	56.168	1.282
	VNRS	CTD	12	45.935	39.291	8.957	6	44.672	38.560	11.891					6	47.198	40.740	4.831
		RTD	17	42.906	36.929	6.369	6	43.287	37.364	3.808	5	42.855	36.805	7.709	6	42.568	36.744	8.182
		ETW	15	34.131	29.315	8.612	6	33.733	29.117	4.553	3	31.419	26.527	5.583	6	35.886	30.976	9.775

Env. = Environment
n = Number of specimens

B.1 FIBERCOTE UNIDIRECTIONAL TAPE.

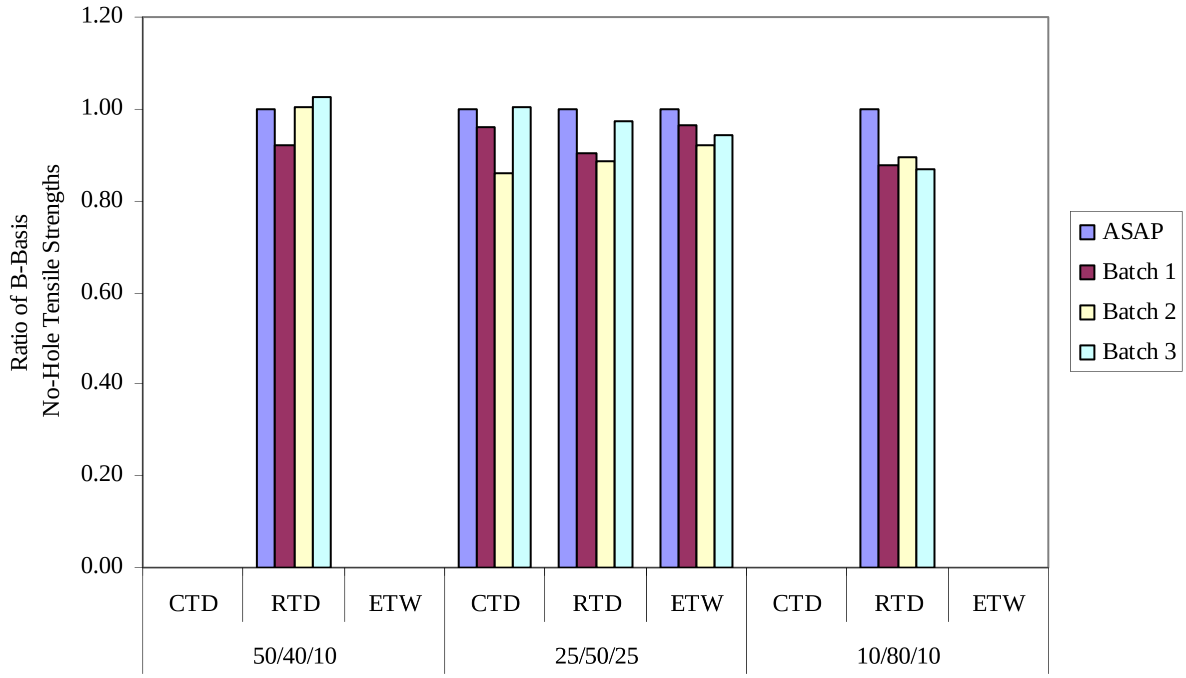

Figure B-1. Ratio of LVM to Laminate B-Basis For NHT Strength of FiberCote Tape

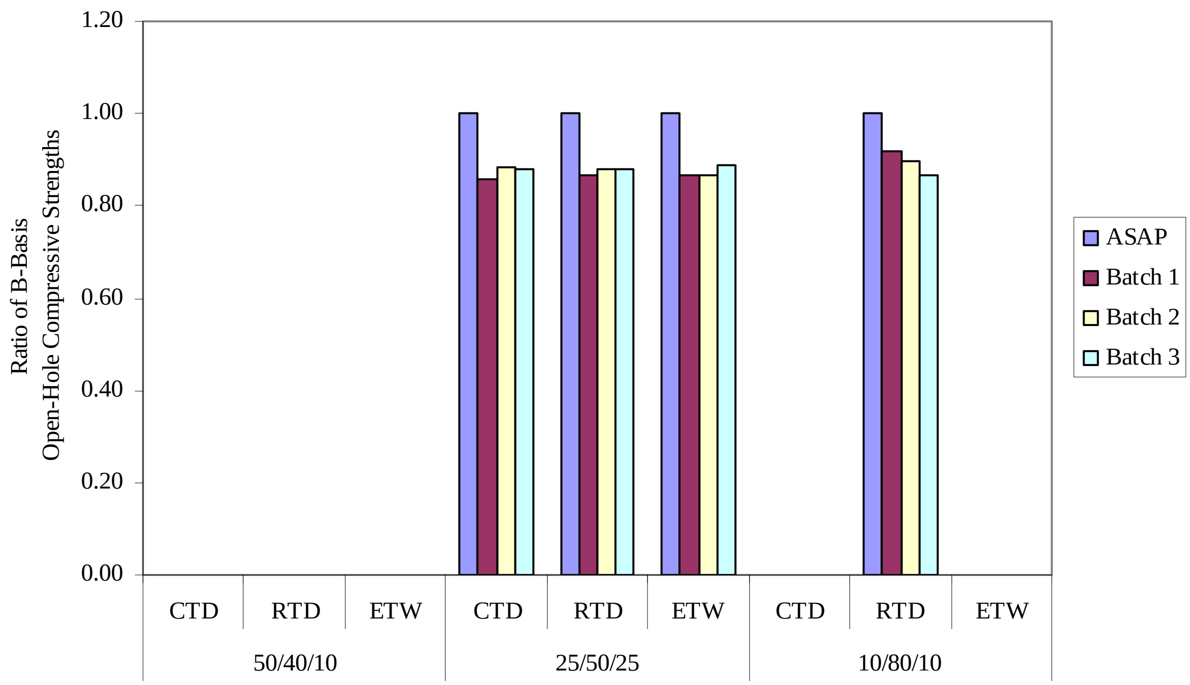

Figure B-2. Ratio of LVM to Laminate B-Basis For OHT Strength of FiberCote Tape

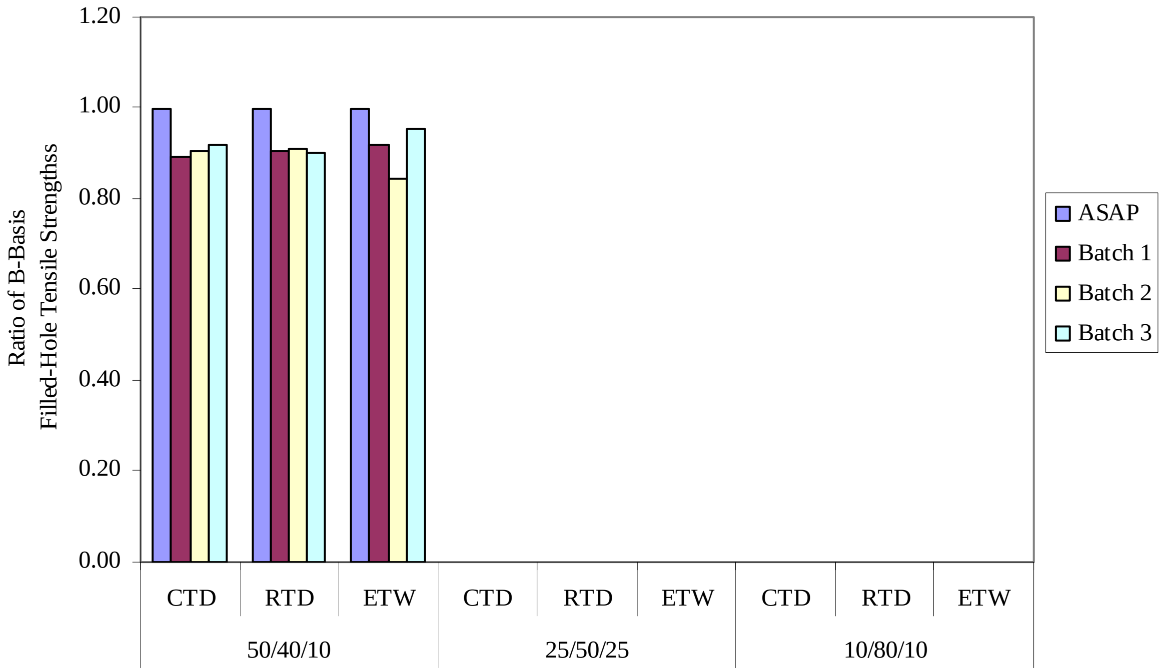

Figure B-3. Ratio of LVM to Laminate B-Basis For FHT Strength of FiberCote Tape

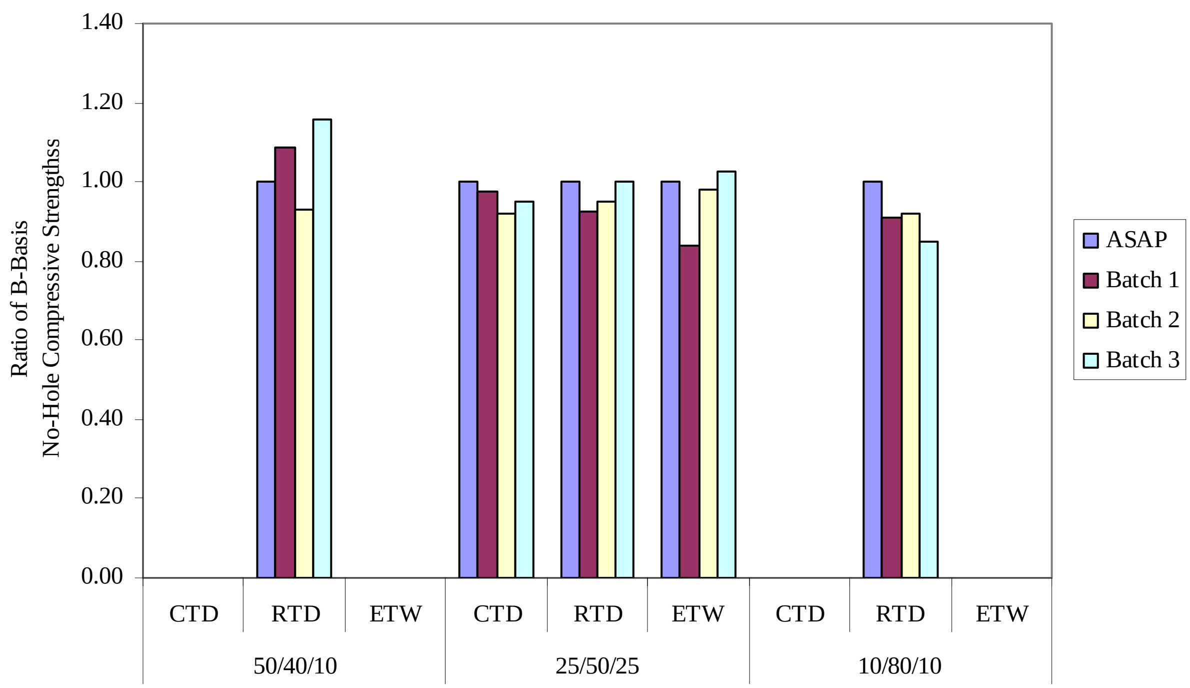

Figure B-4. Ratio of LVM to Laminate B-Basis for NHC Strength of FiberCote Tape

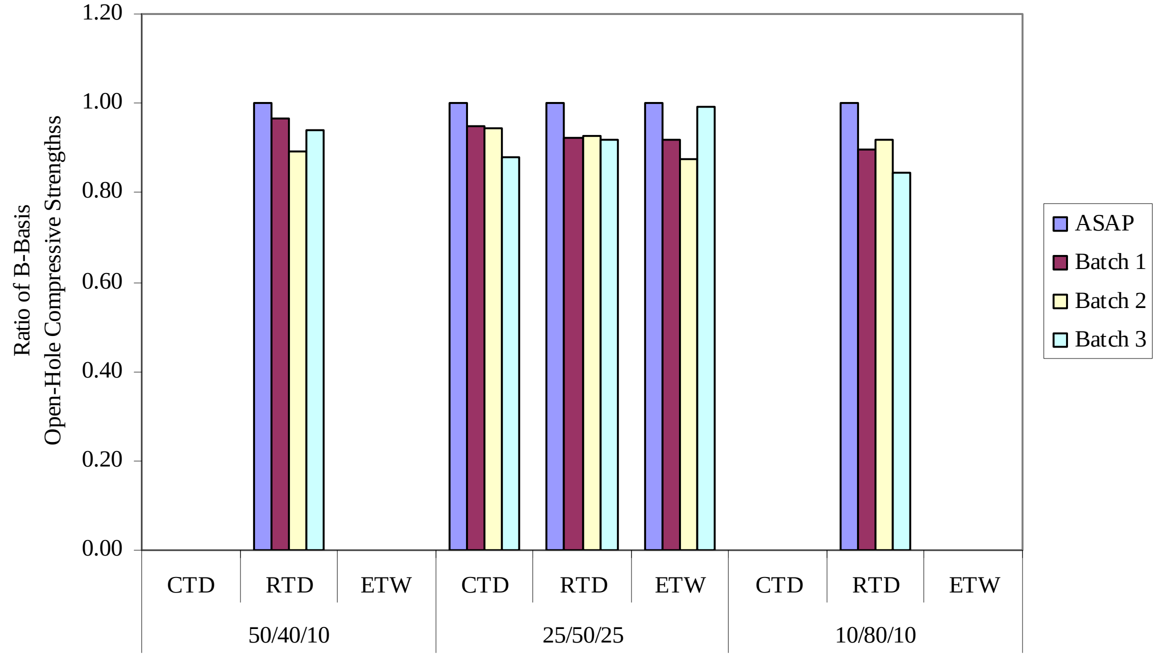

Figure B-5. Ratio of LVM Compressive to Laminate B-Basis OHC Strength of FiberCote Tape

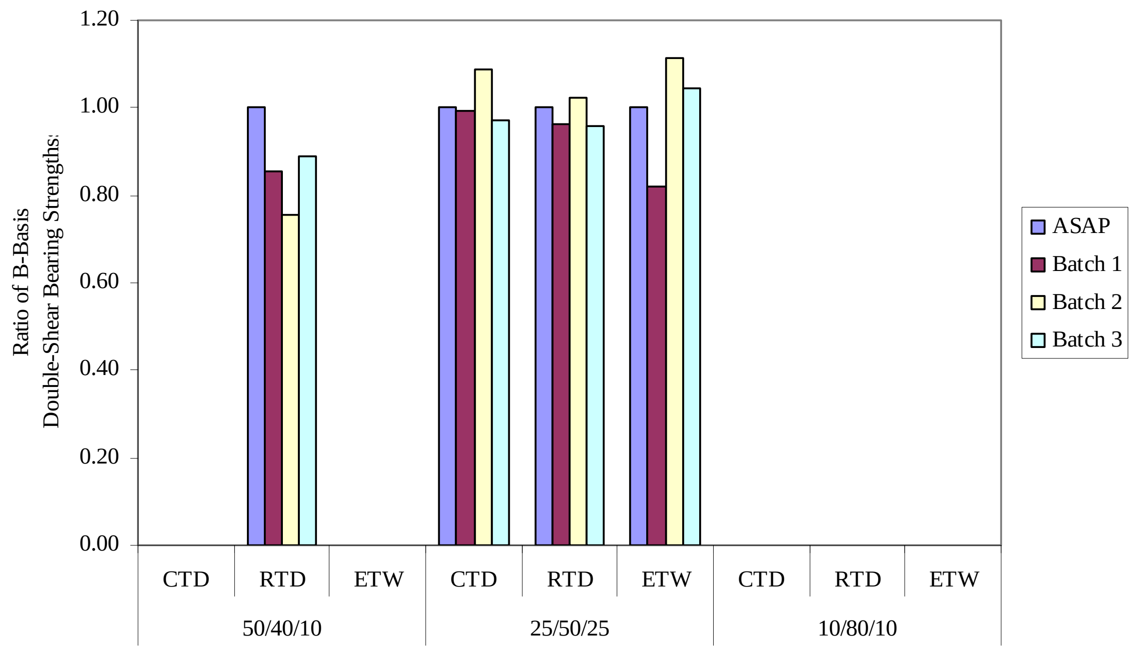

Figure B-6. Ratio of LVM to Laminate B-Basis for Two-Shear Bearing Strength of FiberCote Tape

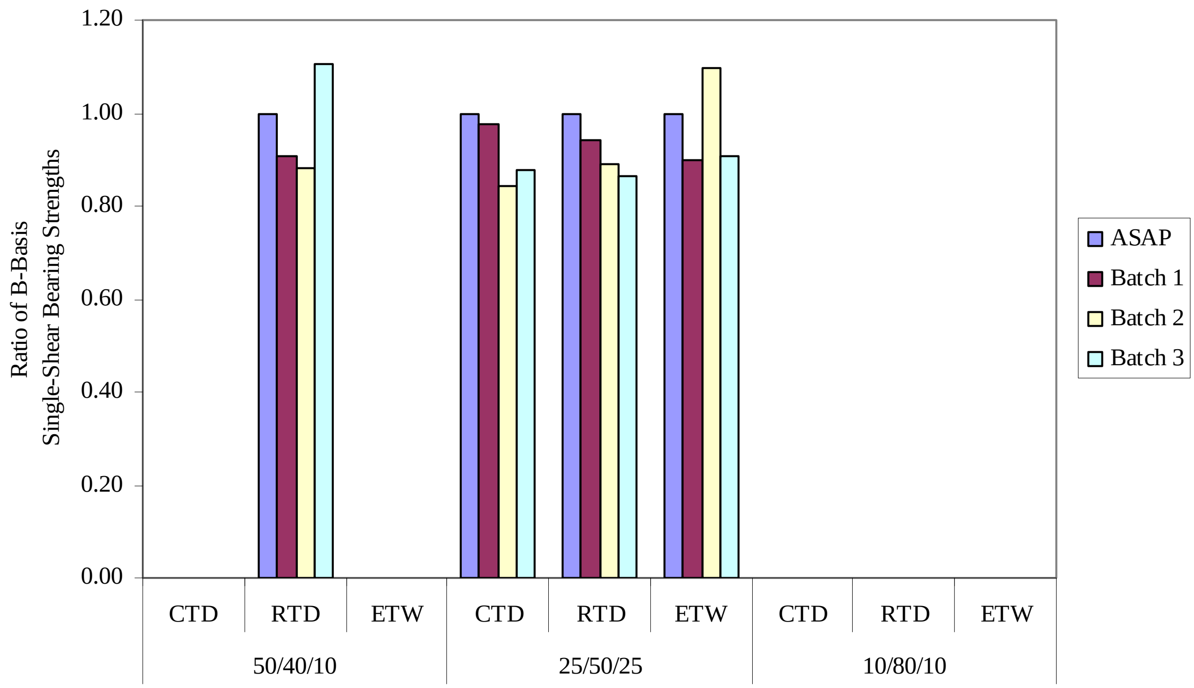

Figure B-7. Ratio of LVM to Laminate B-Basis for Single-Shear Bearing Strength of FiberCote Tape

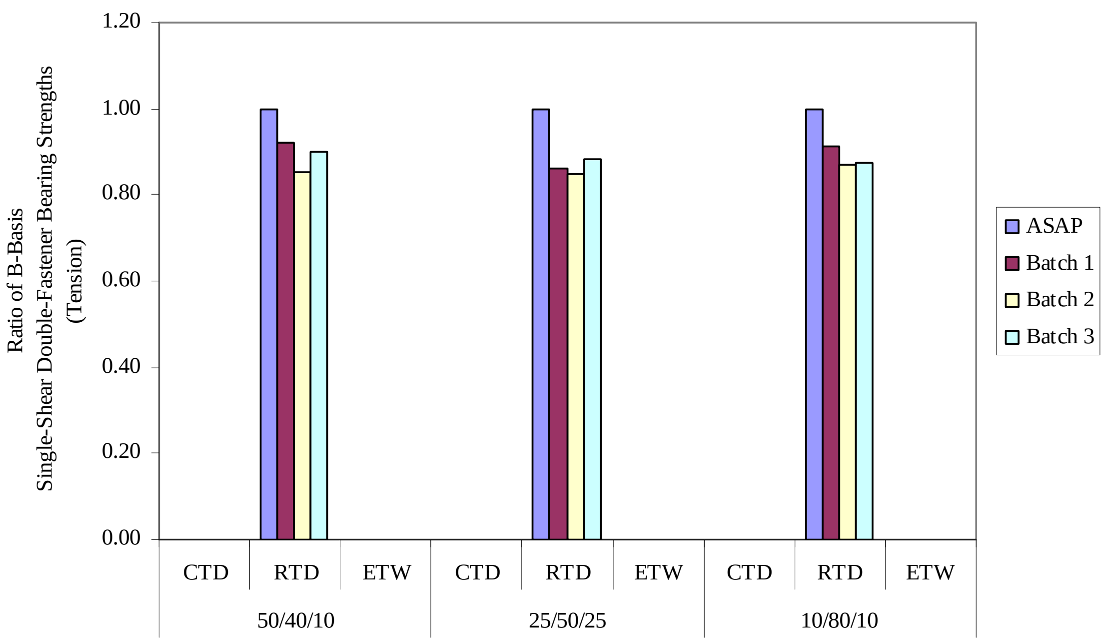

Figure B-8. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Tension Strength of FiberCote Tape

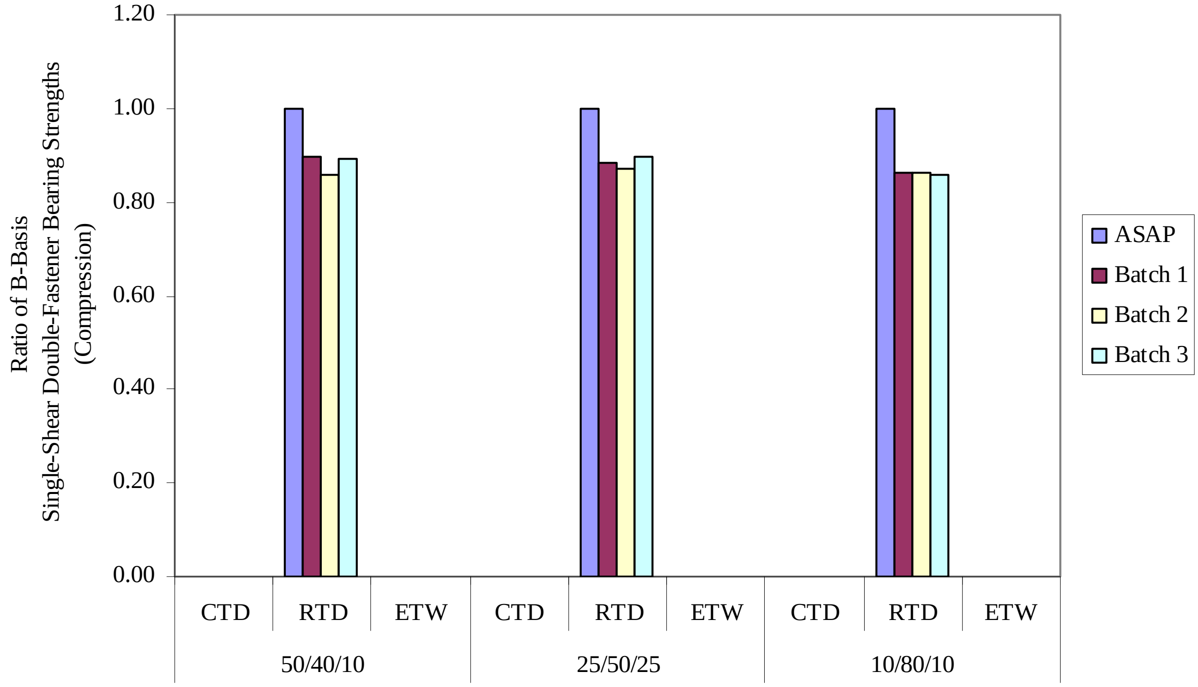

Figure B-9. Ratio of LVM to Laminate B-Basis for 50% Bearing-Bypass Compressive Strength of FiberCote Tape

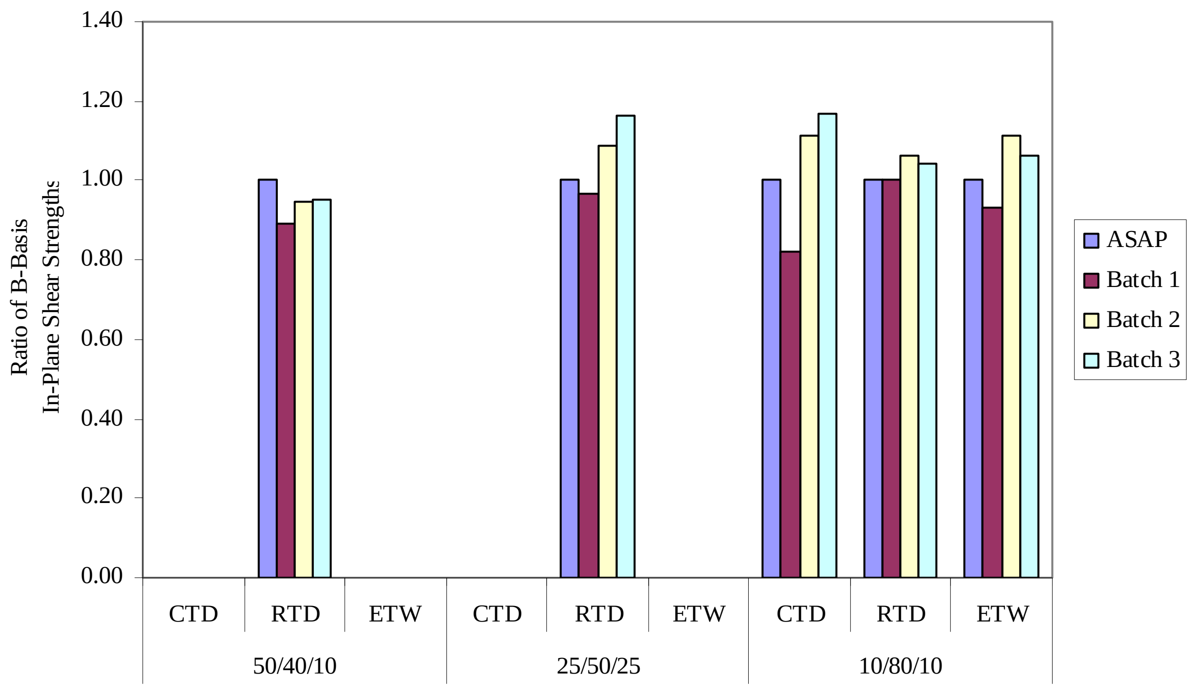

Figure B-10. Ratio of LVM to Laminate B-Basis for In-Plane Shear Strength of FiberCote Tape

B.2 FIBERCOTE PW FABRIC.

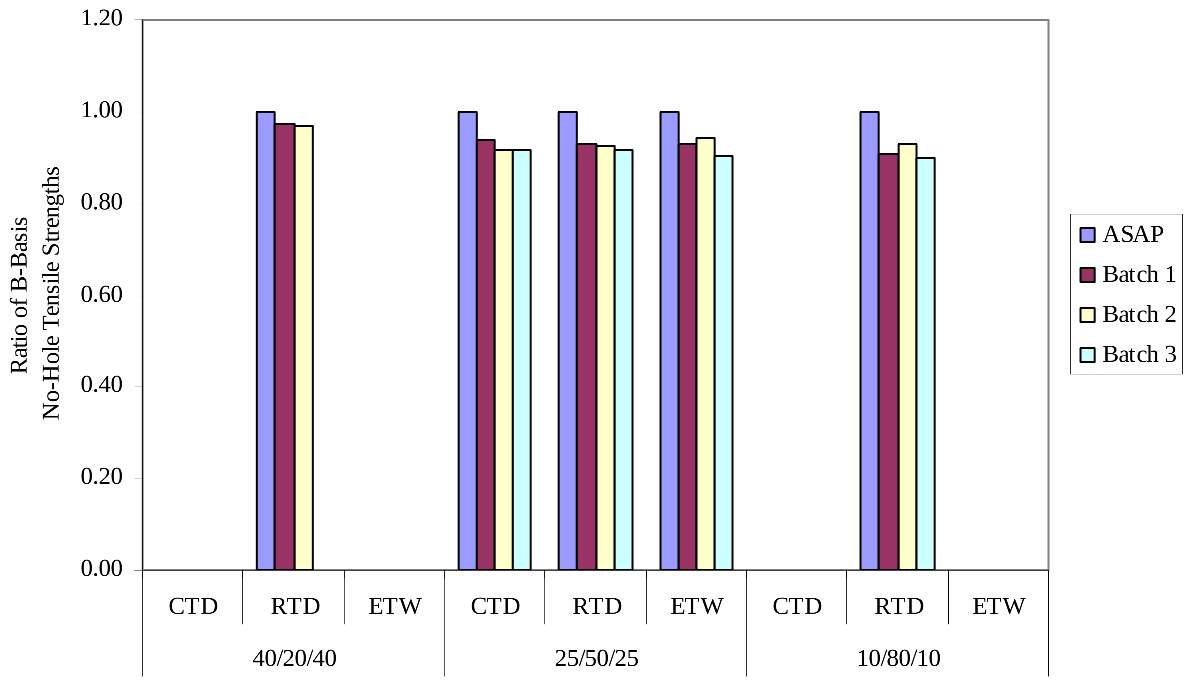

Figure B-11. Ratio of LVM to Laminate B-Basis for NHT Strength of FiberCote PW

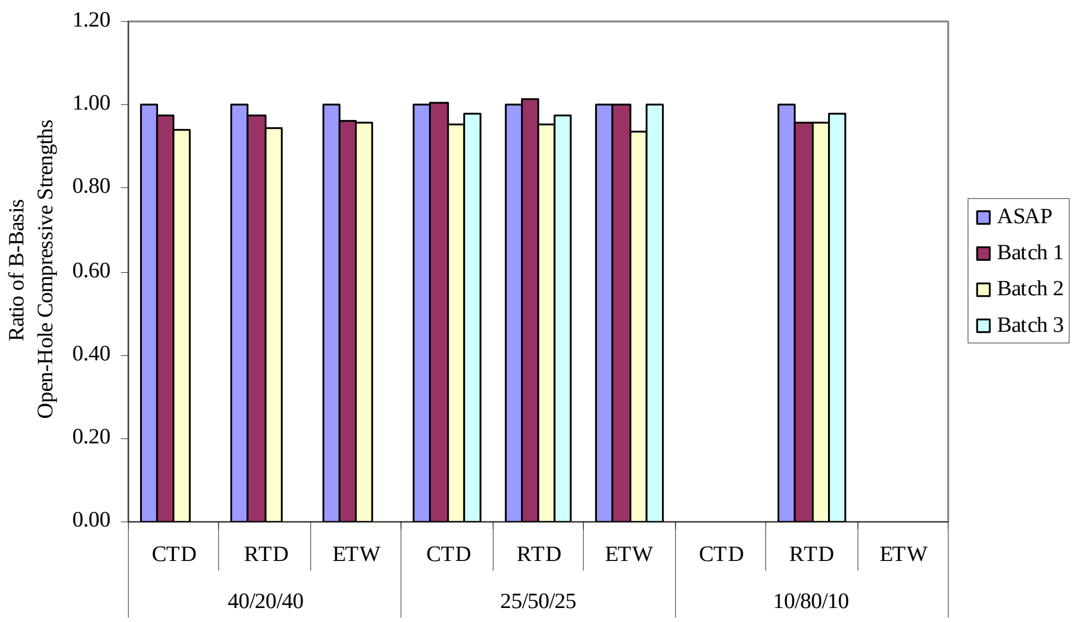

Figure B-12. Ratio of LVM to Laminate B-Basis for OHT Strength of FiberCote PW

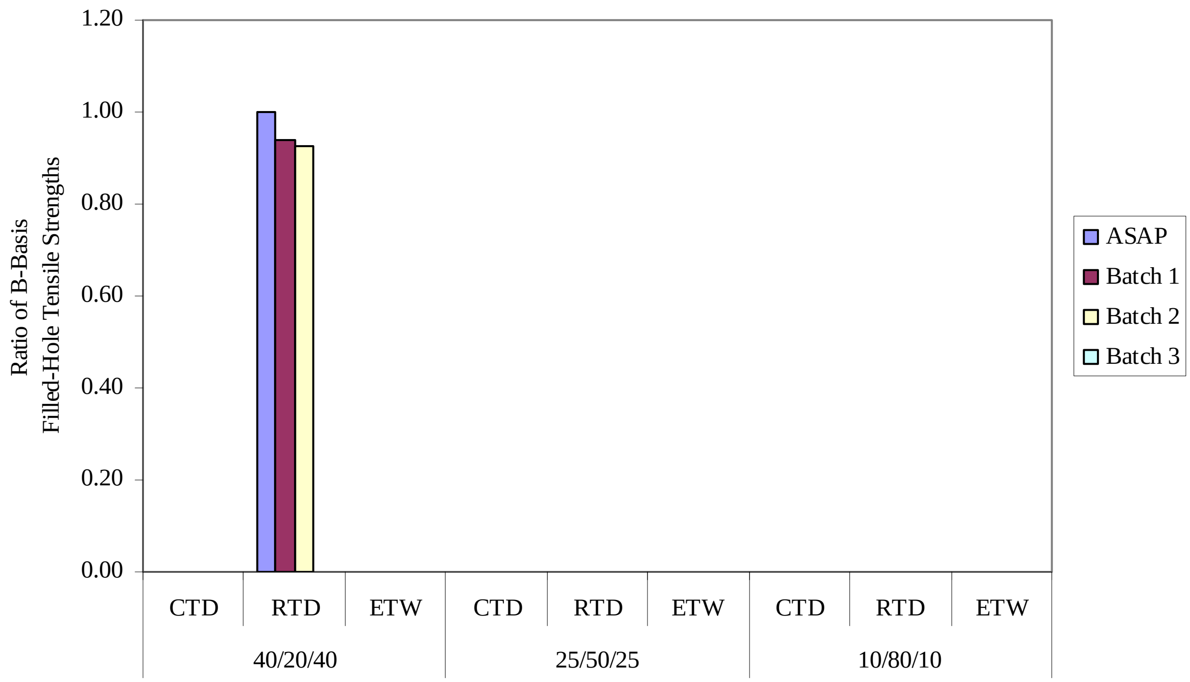

Figure B-13. Ratio of LVM to Laminate B-Basis for FHT Strength of FiberCote PW

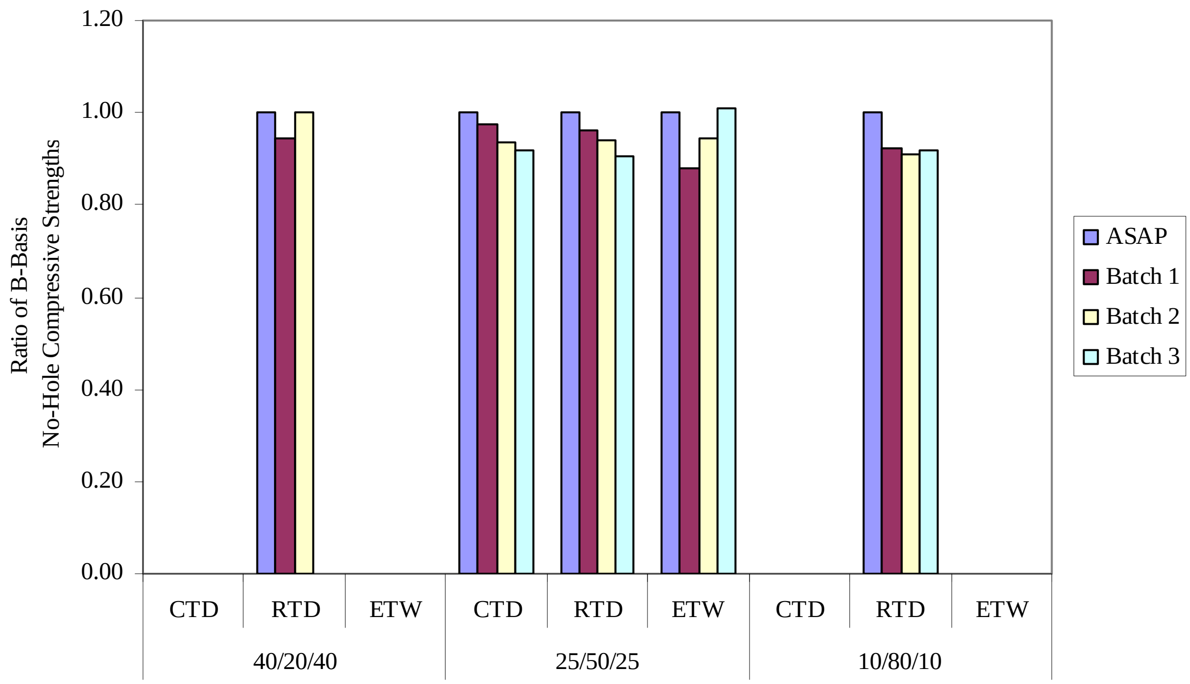

Figure B-14. Ratio of LVM to Laminate B-Basis for NHC Strength of FiberCote PW

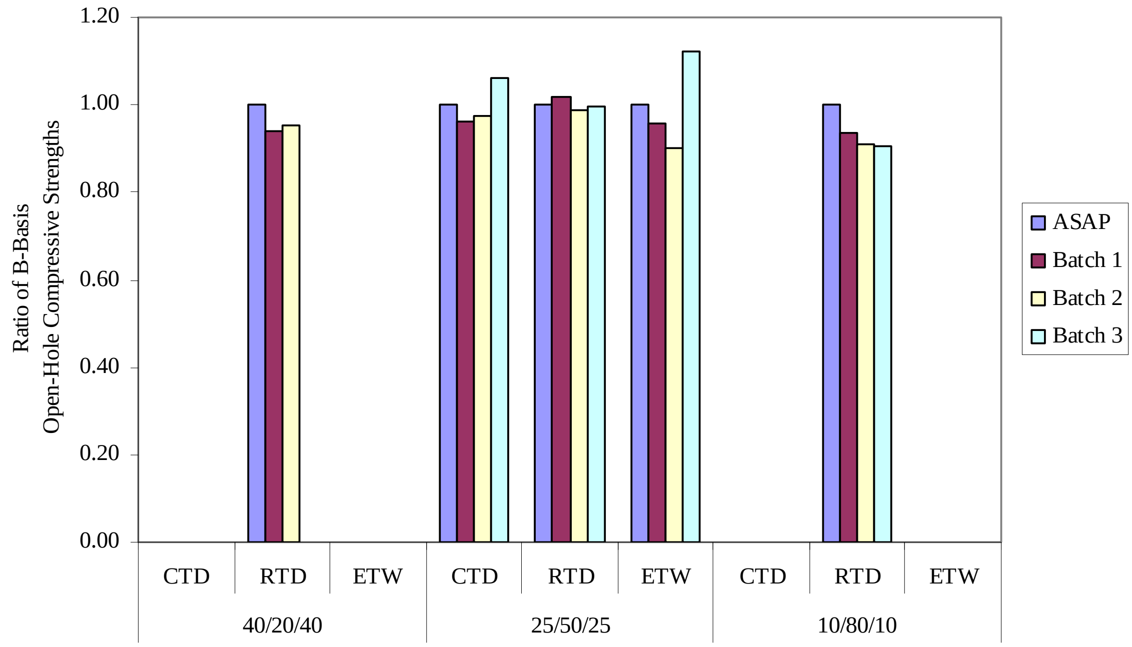

Figure B-15. Ratio of LVM to Laminate B-Basis for OHC Strength of FiberCote PW

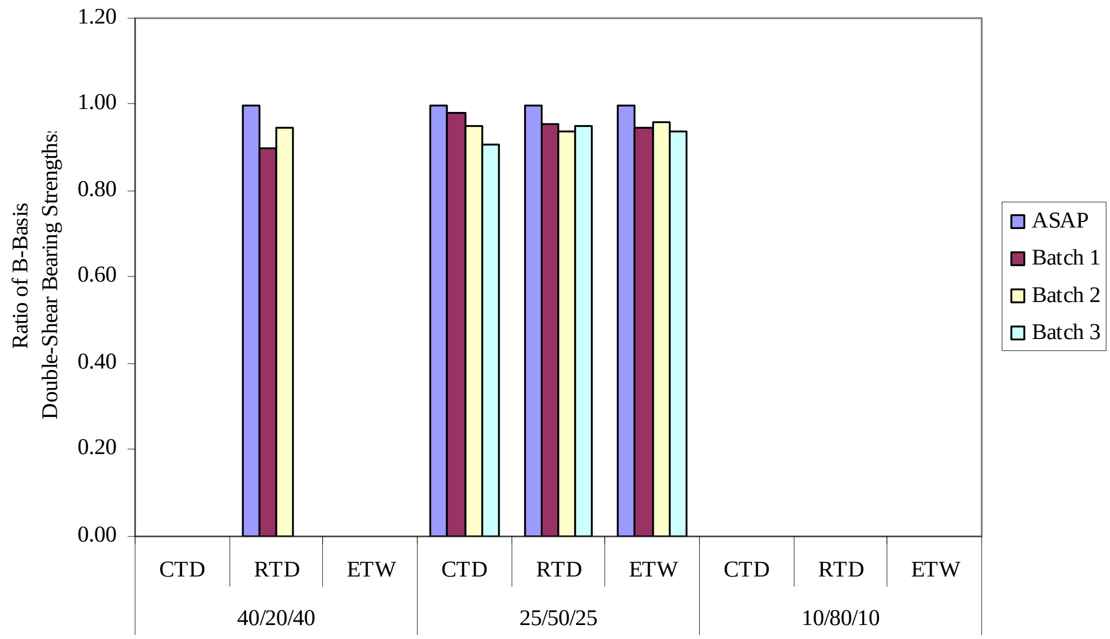

Figure B-16. Ratio of LVM to Laminate B-Basis for Double-Shear Bearing Strength of FiberCote PW

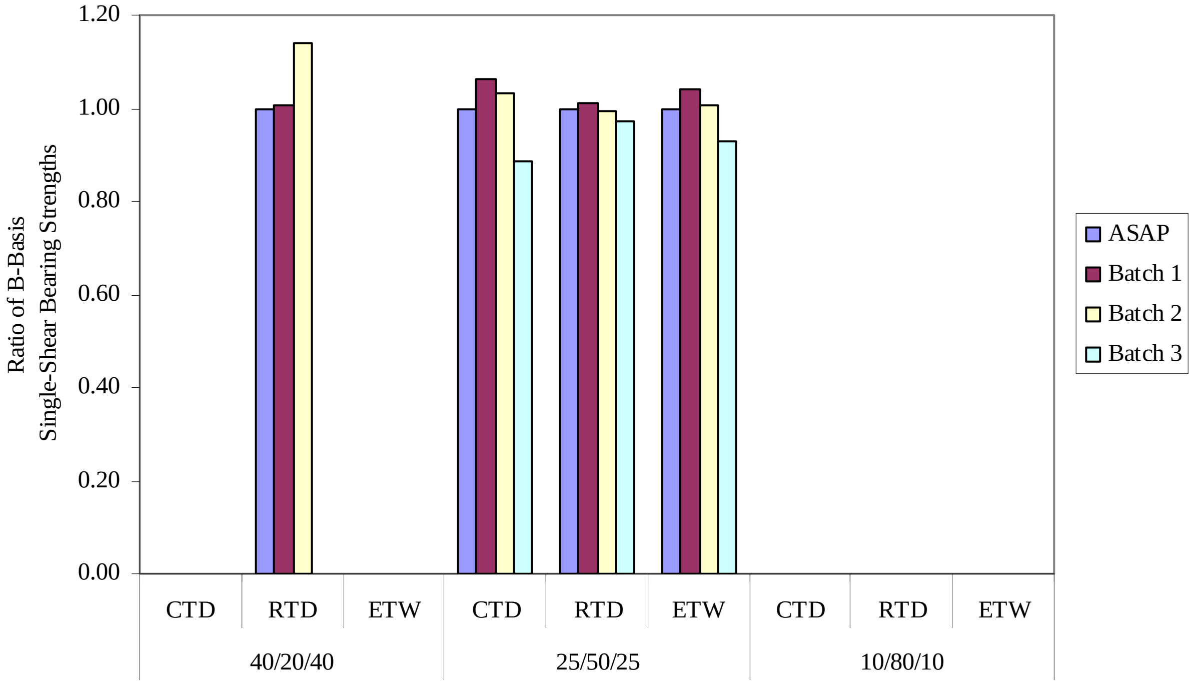

Figure B-17. Ratio of LVM to Laminate B-Basis for Single-Shear Bearing Strength of FiberCote PW

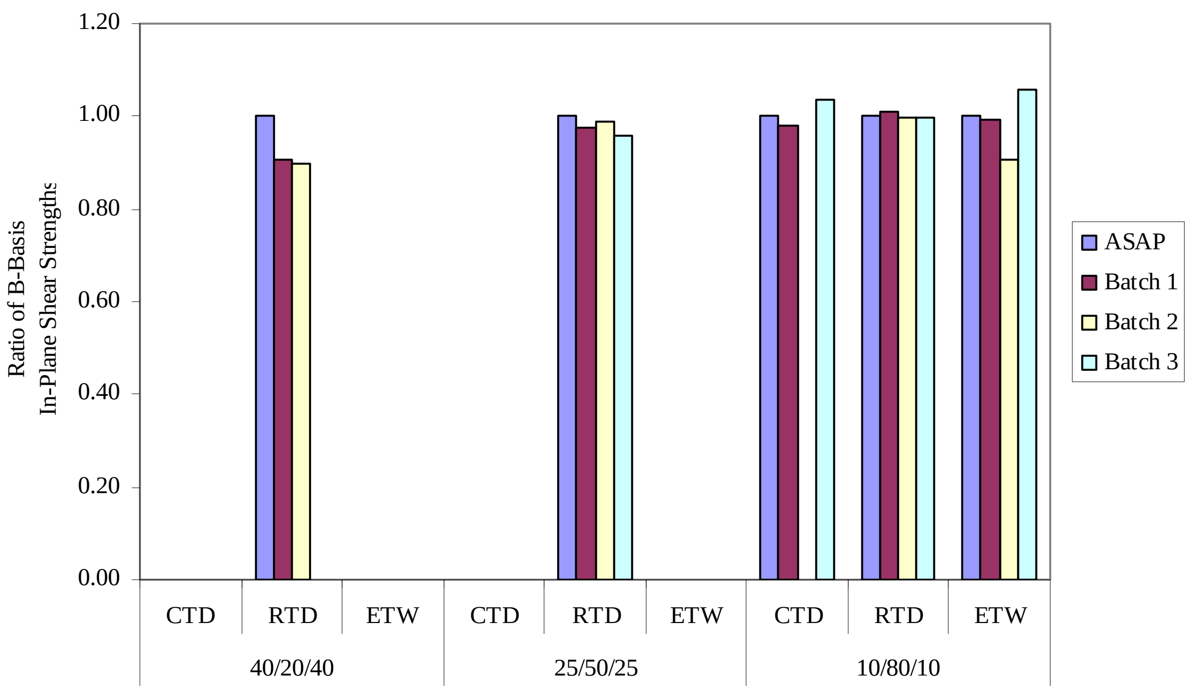

Figure B-18. Ratio of LVM to Laminate B-Basis for In-Plane Shear Strength of FiberCote PW

Table B-5. Comparison of ACG Unidirectional Tape B-Basis Allowables Comparison

			Laminate Properties (Available Batches)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHT	CTD	18	116.375	110.240	3.663	6	115.804	96.796	5.177	6	116.196	97.124	3.771	6	117.124	97.900	2.011
		RTD	18	116.908	110.745	2.627	6	116.644	97.498	3.514	6	115.116	96.221	1.870	6	118.964	99.438	1.074
		ETW2	6	108.754	102.177	1.174	6	108.754	90.903	1.174								
	NHC	CTD	19	84.988	79.591	3.457												
		RTD	7	68.086	63.214	2.395												
		ETW2	18	62.279	58.304	4.172												
	FHT	CTD	18	62.804	58.354	4.044	6	64.061	53.547	2.058	6	63.432	53.021	4.739	6	60.919	50.920	3.493
		RTD	6	62.980	57.924	2.845	6	62.980	52.643	2.845								
	PB	RTD	18	104.883	93.921	5.265												
		ETW2	18	93.978	84.155	6.332												
	OHT	CTD	15	58.899	55.208	4.259	4	58.460	48.148	3.397	5	56.617	47.029	3.112	6	61.092	51.065	2.092
		RTD	15	58.029	54.392	2.524	5	56.993	47.341	0.962	4	57.356	47.239	1.055	6	59.340	49.600	2.410
		ETW2	18	56.604	53.121	3.577	5	56.385	46.836	1.150	6	54.707	45.728	2.007	7	58.385	49.037	2.962
	OHC	RTD	14	45.326	42.646	3.130												
		ETW	6	35.991	33.616	4.187												
		ETW2	17	34.531	32.529	3.039												
10/80/10	PB	RTD	6	97.042	80.646	2.853												
		ETW2	18	86.011	73.183	8.979												
	FHC	RTD	5	51.134	47.015	3.498												
		ETW	21	35.319	32.913	3.782												
	OHT	CTD	17	46.519	44.958	1.796	5	46.820	38.891	2.224	6	46.775	39.098	1.957	6	45.893	38.361	1.326
		RTD	5	42.366	40.711	1.287	5	42.366	35.191	1.287								
		ETW2	6	36.415	35.033	2.365	6	36.415	30.438	2.365								
	OHC	RTD	5	37.079	33.378	3.783												
		ETW2	18	24.878	22.744	4.754												
50/40/10	PB	RTD	6	101.726	90.073	7.671												
		ETW2	20	90.834	81.747	4.716												
	FHC	RTD	7	84.424	63.099	18.719												
		ETW2	21	59.817	46.403	9.721												
	OHT	CTD	18	123.341	92.522	17.152	6	94.596	79.069	2.957	6	138.068	115.406	1.760	6	137.360	114.814	3.280
		RTD	5	95.152	67.301	3.101	5	95.152	79.039	3.101								
		ETW2	6	95.142	68.080	1.485	6	95.142	79.526	1.485								
	OHC	RTD	6	60.663	55.969	2.599												
		ETW2	19	47.125	43.924	3.929												

Env. = Environment
n = Number of specimens

Table B-6. Comparison of ACG 5HS B-Basis Allowables

			Laminate Properties (Available Batches)				Laminate Batch 1				Laminate Batch 2				Laminate Batch 3			
Laminate	Material Property	Env.	n	Mean [ksi]	ASAP or Normal B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)	n	Mean [ksi]	LVM B-Basis [ksi]	CV (%)
25/50/25	NHC	RTD	18	71.046	63.628	6.027	6	70.439	57.207	6.436	6	72.783	59.111	5.578	6	69.915	56.782	6.060
		ETW1	6	50.860	44.769	5.560	6	50.860	41.306	5.560								
		ETW2	18	44.276	39.654	5.990	6	44.752	36.346	8.130	6	45.514	36.964	3.061	6	42.563	34.568	4.906
	OHC	RTD	18	40.94	37.45	4.01	6	41.333	33.569	2.949	6	41.127	33.401	3.947	6	40.368	32.785	5.200
		ETW1	6	33.023	29.789	7.018	6	33.023	26.820	7.018								
		ETW2	18	28.097	25.698	4.881	6	29.325	23.816	3.739	6	27.597	22.413	3.182	6	27.368	22.227	4.729
	FHC	RTD	6	62.161	56.740	4.414	6	62.161	50.484	4.414								
		ETW2	18	40.257	37.158	4.047	6	39.330	31.942	2.294	6	41.616	33.799	3.997	6	39.824	32.343	3.526
	NHT	CTD	23	88.791	84.667	1.928	6	88.630	81.990	1.628	6	88.895	82.234	1.847	11	88.822	82.745	2.261
		RTD	18	89.297	85.057	3.568	6	92.017	85.123	1.884	6	89.162	82.481	3.690	6	86.713	80.216	2.238
		ETW2	6	79.610	75.265	2.360	6	79.610	73.645	2.360								
	OHT	CTD	18	53.448	49.641	4.997	6	55.438	51.284	4.652	6	52.281	48.364	2.179	6	52.625	48.682	5.735
		RTD	18	55.716	51.747	2.979	6	56.006	51.810	1.782	6	56.677	52.431	2.580	6	54.465	50.384	3.256
		ETW2	18	55.274	51.336	4.092	6	57.524	53.214	2.186	6	54.751	50.649	3.047	6	53.546	49.534	3.257
	FHT	CTD	18	55.282	51.783	3.532	6	57.197	52.912	0.445	6	54.226	50.163	3.493	6	54.293	50.225	3.056
		RTD	6	58.215	54.040	2.907	6	58.215	53.853	2.907								
	PB	RTD	18	92.182	79.642	9.264	6	91.590	74.385	8.423	6	91.375	74.210	9.767	6	93.580	76.001	10.962
		ETW2	23	83.066	72.008	6.111	8	83.478	68.495	7.171	8	84.015	68.936	4.870	7	81.512	66.577	6.596
10/80/10	OHT	CTD	18	42.348	40.261	2.962	6	42.291	39.122	3.957	6	43.139	39.906	2.125	6	41.615	38.497	1.342
		RTD	9	39.062	36.986	2.234	9	39.062	36.314	2.234								
		ETW2	6	31.932	30.135	2.883	6	31.932	29.539	2.883								
	OHC	RTD	6	32.850	30.671	3.442	6	32.850	26.679	3.442								
		ETW2	18	21.027	19.796	3.052	6	21.029	17.079	1.282	6	21.192	17.211	3.662	6	20.862	16.943	3.893
	FHC	RTD	6	47.093	44.260	1.672	6	47.093	38.246	1.672								
		ETW2	18	28.349	26.844	3.114	6	28.040	22.772	1.187	6	29.126	23.655	3.266	6	27.881	22.643	2.613
	PB	RTD	6	98.579	83.200	4.911	6	98.579	80.061	4.911								
		ETW2	24	79.678	69.018	7.973	8	79.215	64.998	5.492	8	83.394	68.427	6.888	8	76.424	62.708	9.485
40/20/40	OHT	CTD	21	62.544	57.551	4.774	9	63.345	58.889	4.519	6	63.340	58.594	4.083	6	60.548	56.011	4.999
		RTD	7	68.398	62.220	3.767	7	68.398	63.400	3.767								
		ETW2	6	77.336	70.188	4.554	6	77.336	71.541	4.554								
	OHC	RTD	6	32.761	29.875	3.489	6	32.761	26.606	3.489								
		ETW2	18	33.459	30.858	4.357	6	32.908	26.726	3.430	6	34.855	28.307	2.386	6	32.616	26.489	4.002
	FHC	RTD	6	68.095	59.071	7.374	6	68.095	55.303	7.374								
		ETW2	20	48.071	42.508	6.015	6	47.135	38.281	5.446	7	48.907	39.946	8.415	7	48.038	39.237	3.196
	PB	RTD	6	90.597	77.307	3.397	6	90.597	73.578	3.397								
		ETW2	24	69.984	61.180	7.638	8	65.903	54.075	6.669	8	69.852	57.315	6.483	8	74.198	60.881	5.168

Env. = Environment
n = Number of specimen

B.3 ADVANCED COMPOSITE GROUP UNIDIRECTIONAL TAPE.

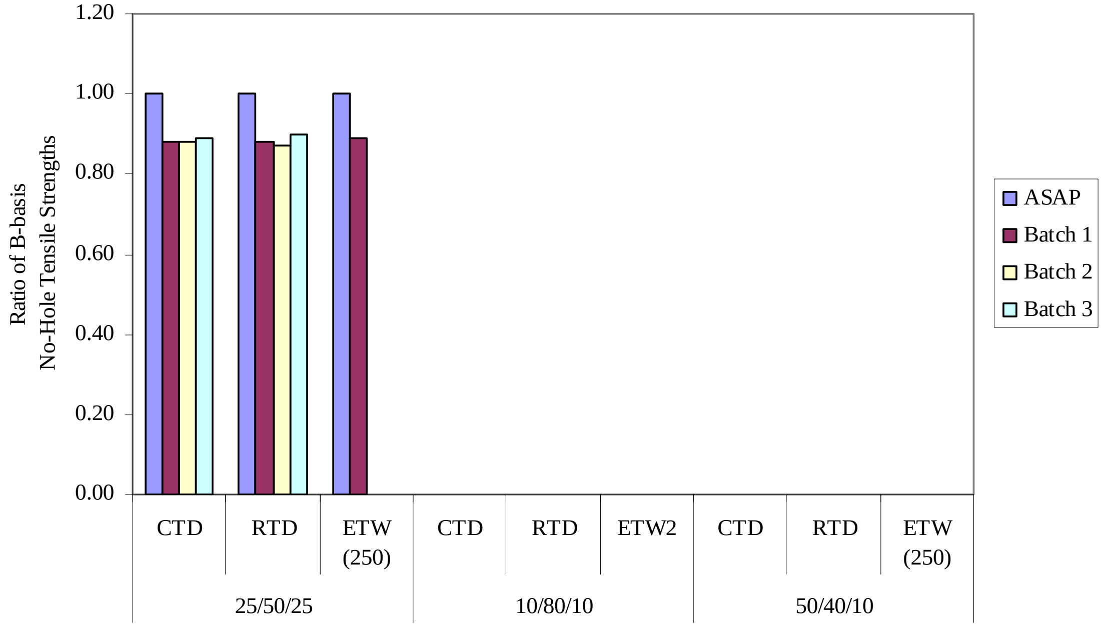

Figure B-19. Ratio of LVM to Laminate B-Basis for NHT Strength of ACG Tape

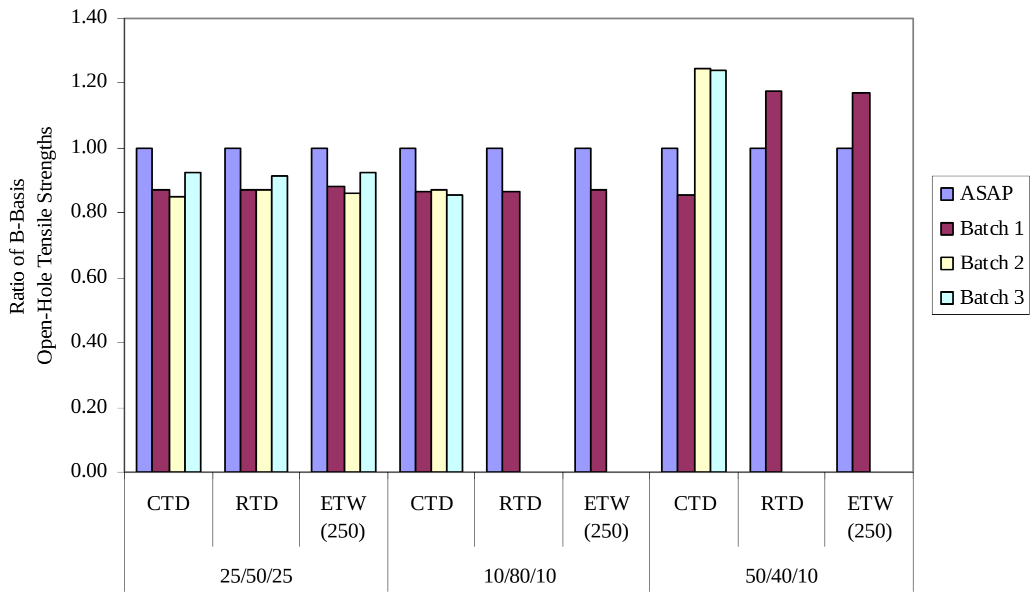

Figure B-20. Ratio of LVM to Laminate B-Basis for OHT Strength of ACG Tape

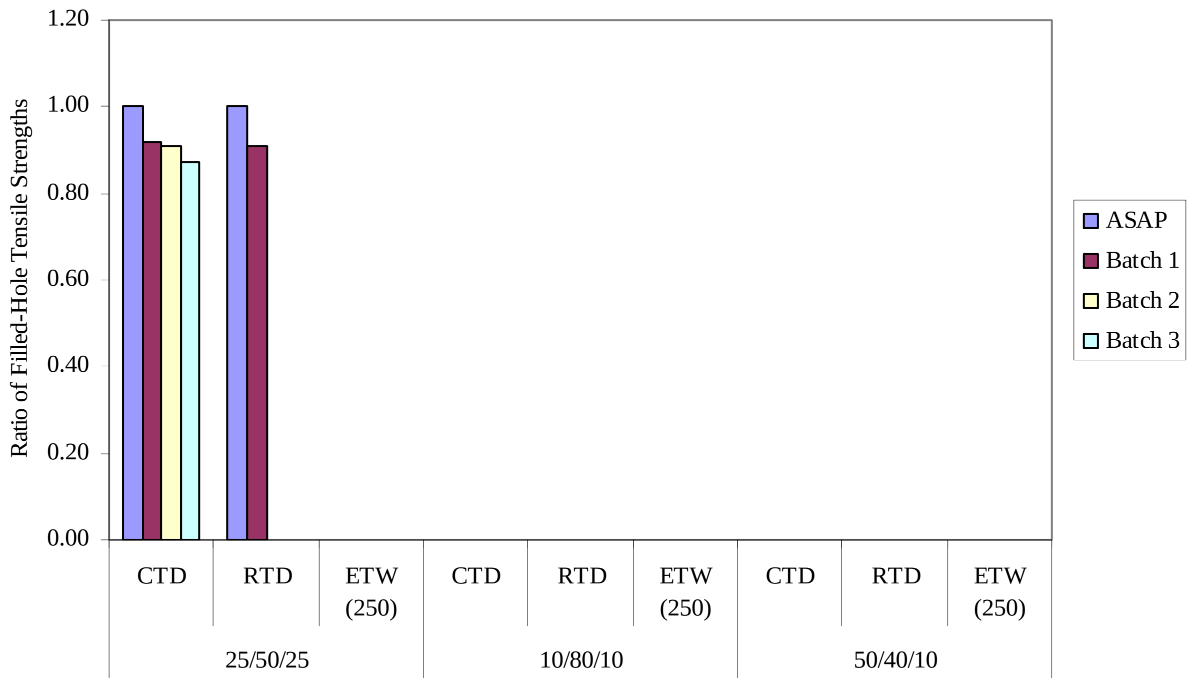

Figure B-21. Ratio of LVM to Laminate B-Basis for FHT Strength of ACG Tape

B.4 ADVANCED COMPOSITE GROUP PW FABRIC.

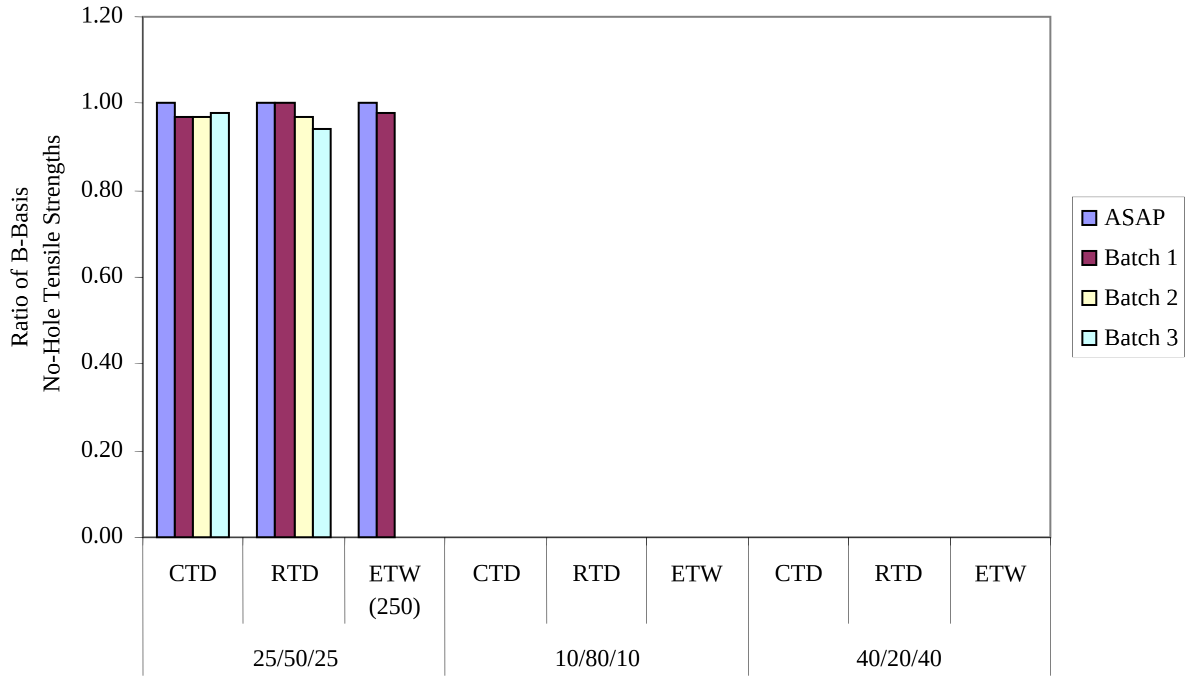

Figure B-22. Ratio of LVM to Laminate B-Basis for NHT Strength of ACG 5HS

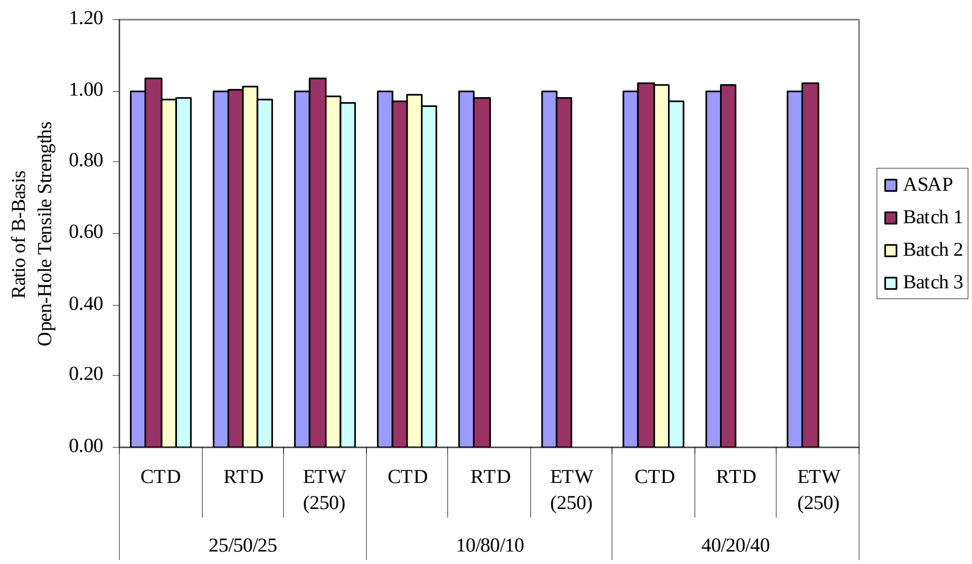

Figure B-23. Ratio of LVM to Laminate B-Basis for OHT Strength of ACG 5HS

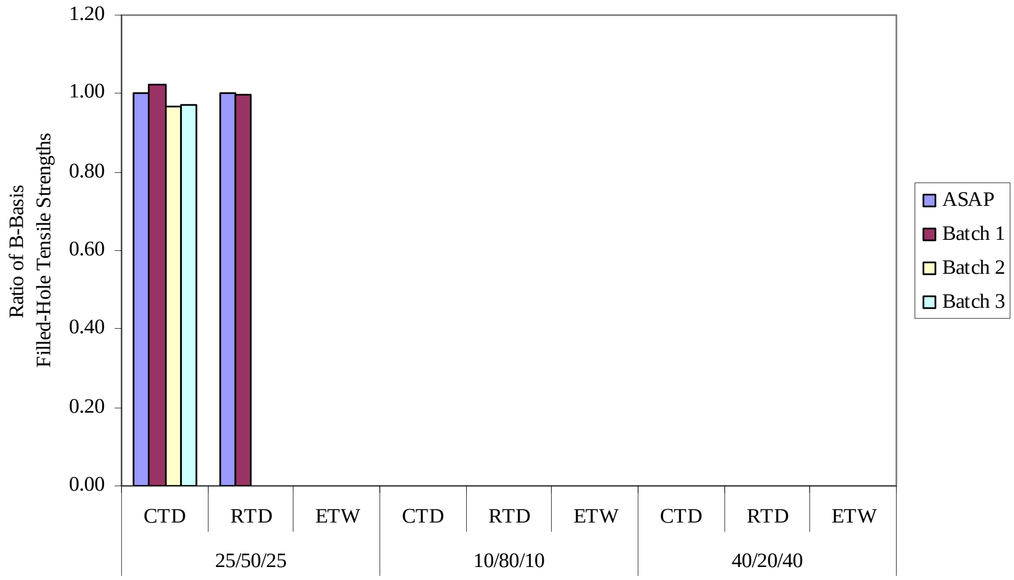

Figure B-24. Ratio of LVM to Laminate B-Basis for FHT Strength of ACG 5HS

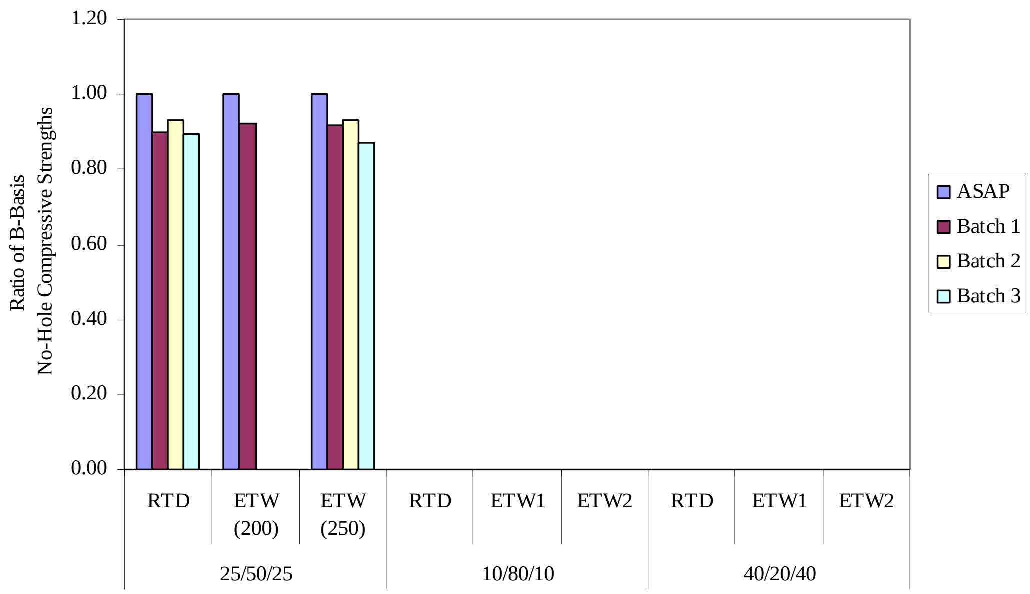

Figure B-25. Ratio of LVM to Laminate B-Basis for NHC Strength of ACG 5HS

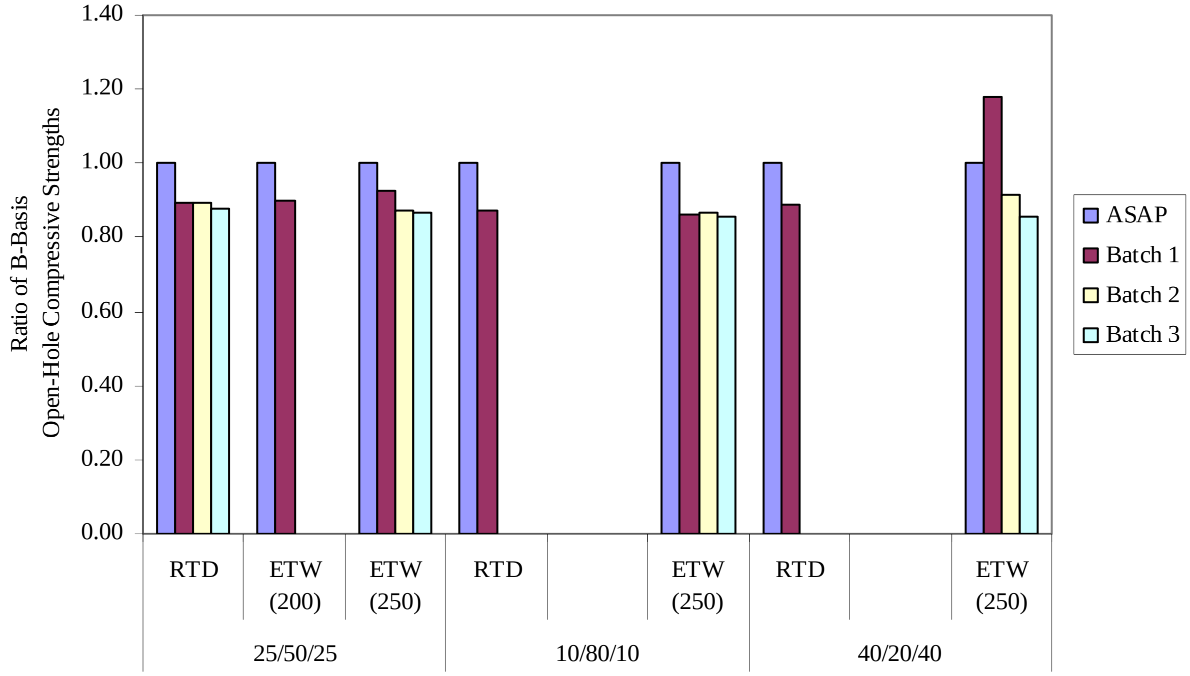

Figure B-26. Ratio of LVM to Laminate B-Basis for OHC Strength of ACG 5HS

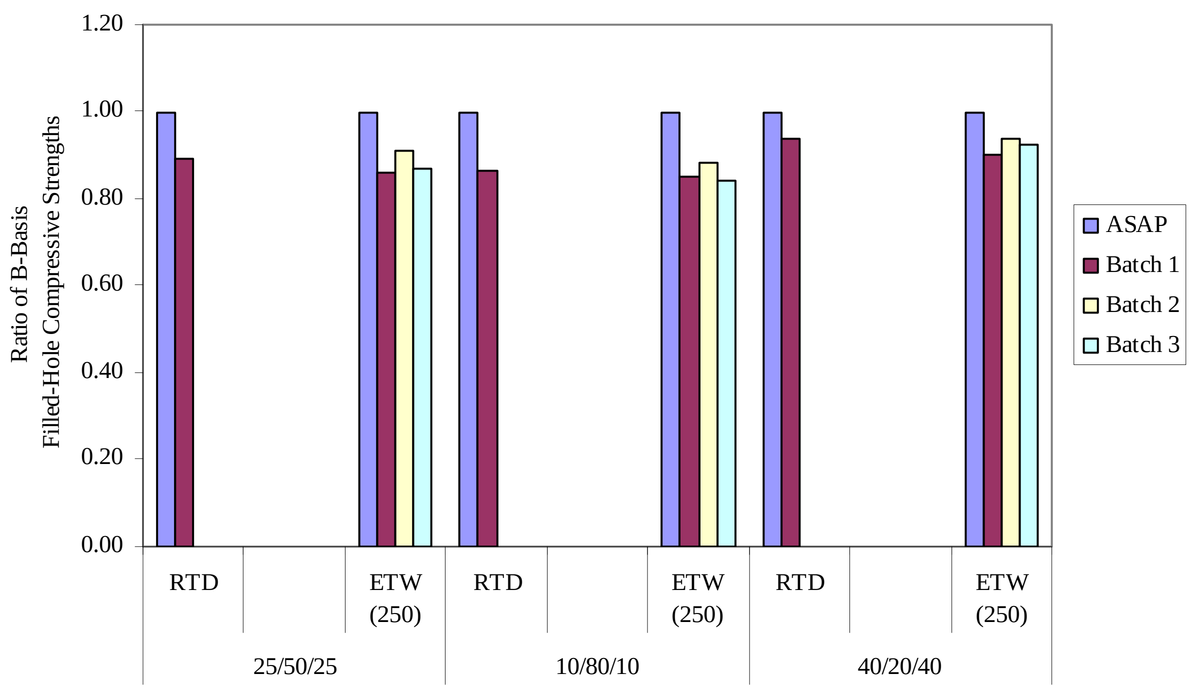

Figure B-27. Ratio of LVM to Laminate B-Basis for FHC Strength of ACG 5HS

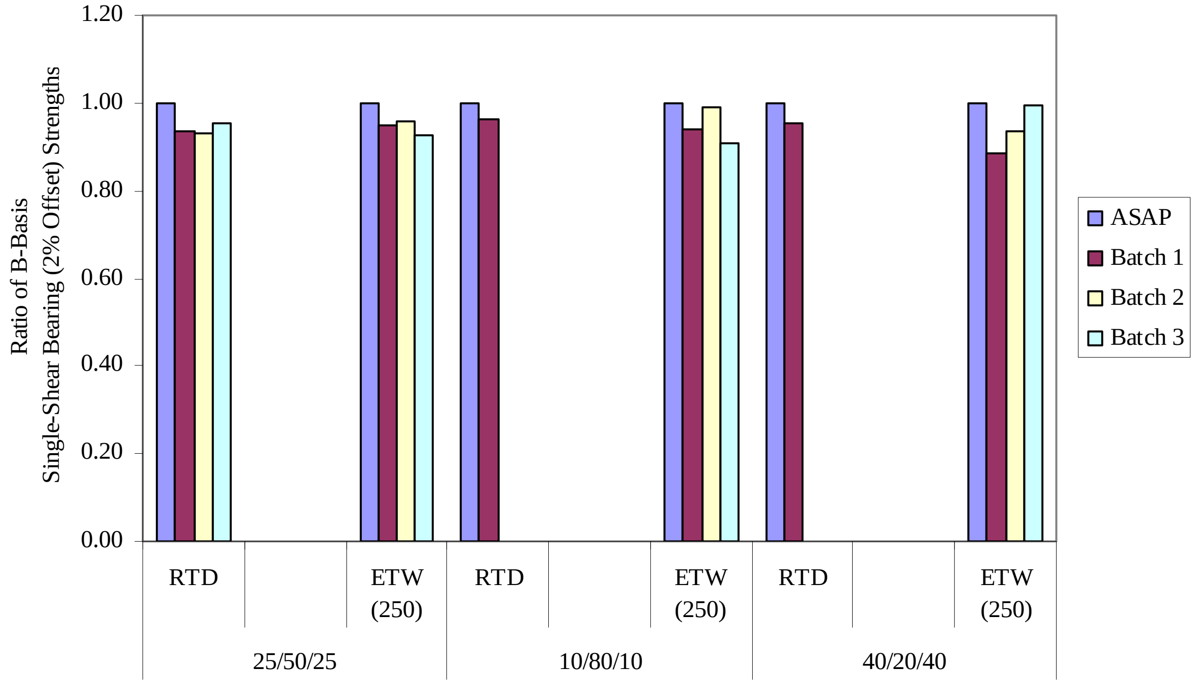

Figure B-28. Ratio of LVM to Laminate B-Basis for Single-Shear Bearing Strength of ACG 5HS

B.5 REFERENCES.

B-1. Ridgard, C. and Penn, D., "Design Allowable Property Data Acquisition and Test Plan for MTM45 Prepregs," FAA Special Project SP3505CPN, Advanced Composites Group, Inc., Oklahoma, July 2004.

APPENDIX C—BEARING-BYPASS INTERACTION CURVES

This appendix contains the bearing-bypass interaction curves for FiberCote unidirectional tape and plain weave (PW) fabric materials. In addition, hole-diameter and *w/D* ratio effects for these two material systems are included. The nomenclature used in figures C-1 through C-10 in this appendix is as follows:

5SH	Five-harness fabric
ACG	Advanced Composite Group
ASAP	AGATE Statistical Allowable Program
BB(50%)T	Single shear, two-fastener bearing (50% bypass) tension
BB(50%)C	Single-shear, two-fastener bearing (50% bypass) compression
CTD	Cold-dry tests
CV or CoV	Coefficient of variation
DSBT	Double-shear bearing tension
ETW	Hot-wet tests at 200° ±5°F
FHC	Filled-hole compression
FHT	Filled-hole tension
LVM	Lamina Variability Method
n	Number of test specimens
NHC	No-hole compression
NHT	No-hole tension
OHC	Open-hole compression
OHT	Open-hole tension
PB	Single-shear, single-fastener (with stabilizing fixture)
RTD	Ambient laboratory conditions
SSBT	Single-shear, single-fastener bearing tension
VNRS	V-notched rail shear

The OHT test results investigating the hole-size effects (*w/D* ratio) are compared to the predicted values using the classical finite width correction, as shown in the following equation:

$$OHT_{\mathrm{Predicted}} = OHT_{Baseline} \cdot \left(\frac{C_{wD-predict}}{C_{wD-baseline}}\right) \tag{C-1}$$

where

$$C_{wD} = \frac{3\cdot\left(1-\frac{D}{w}\right)}{2+\left(1-\frac{D}{w}\right)^{3}} \tag{C-2}$$

The baseline OHT values are defined as *w/D*=8 for unidirectional tape and *w/D*=6 for fabric material. Corresponding finite width correction values are calculated based on these *w/D* ratio values.

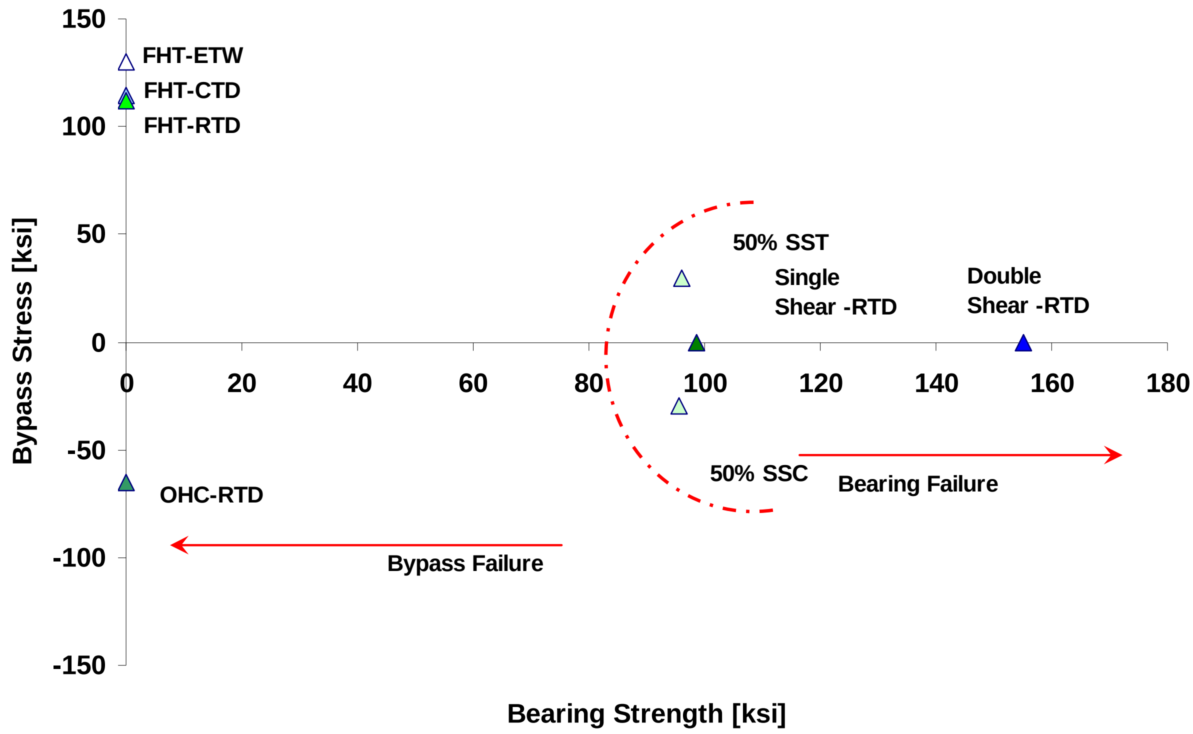

Figure C-1. Bearing-Bypass Interaction Curve for FiberCote 50/40/10 Tape

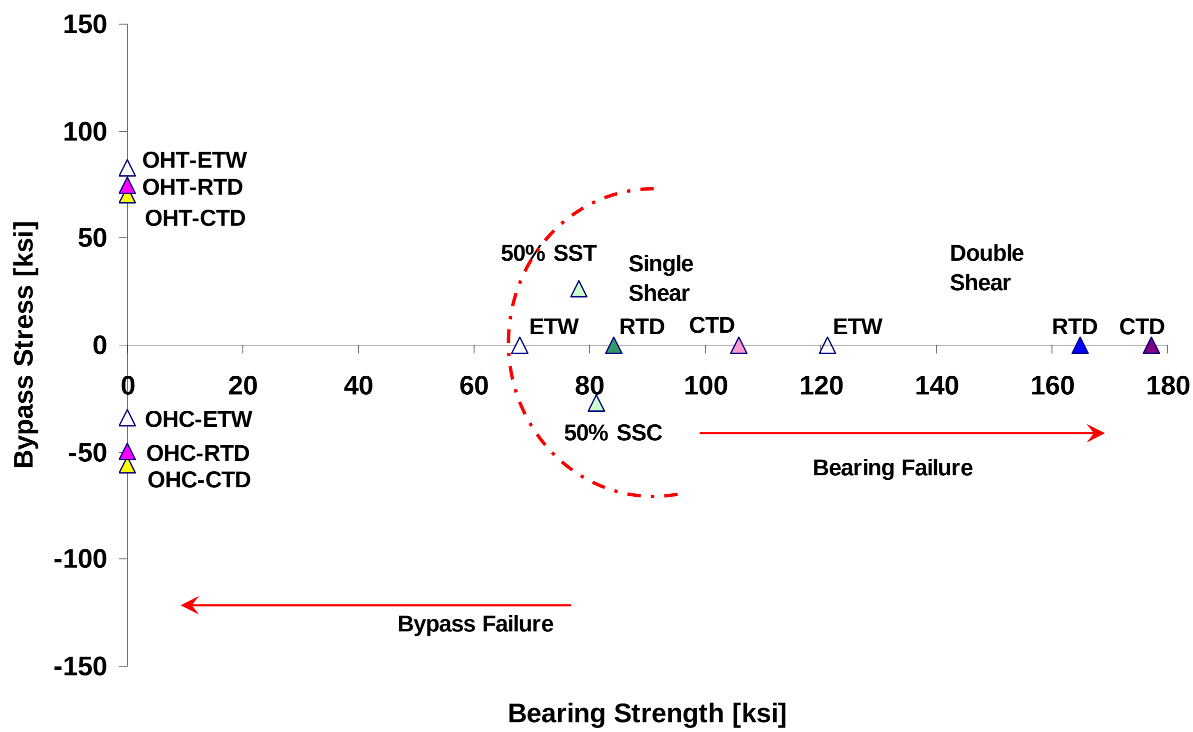

Figure C-2. Bearing-Bypass Interaction Curve for FiberCote 25/50/25 Tape

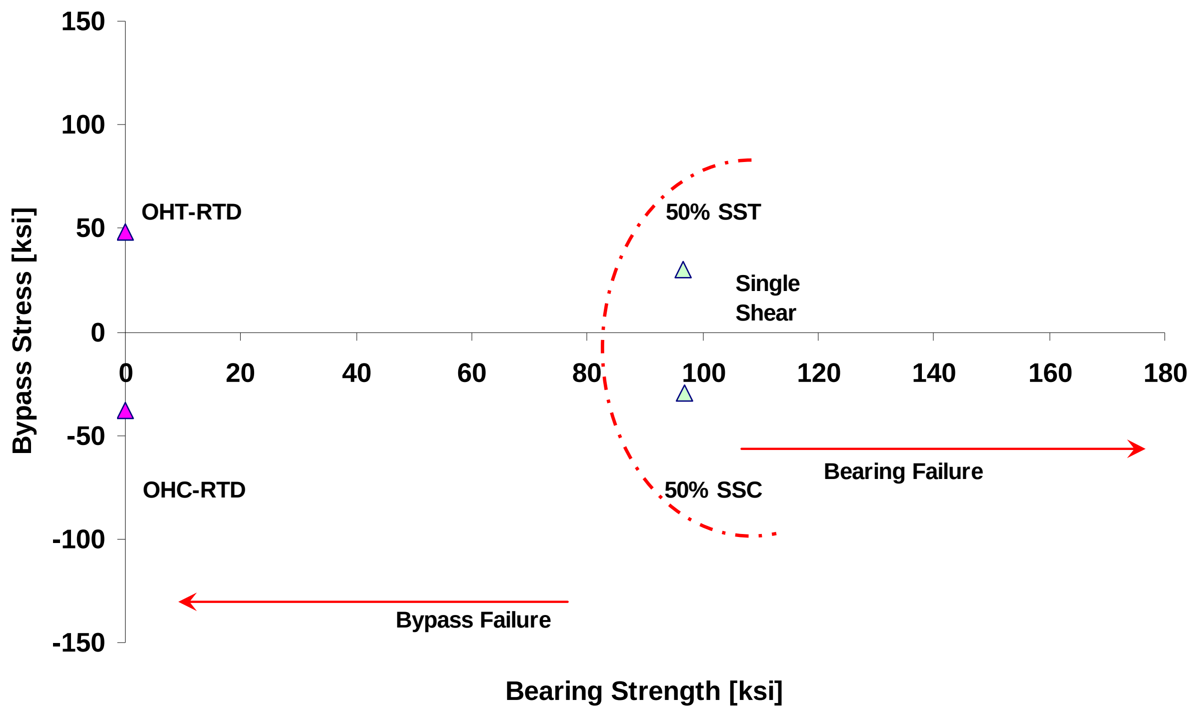

Figure C-3. Bearing-Bypass Interaction Curve for FiberCote 10/80/10 Tape

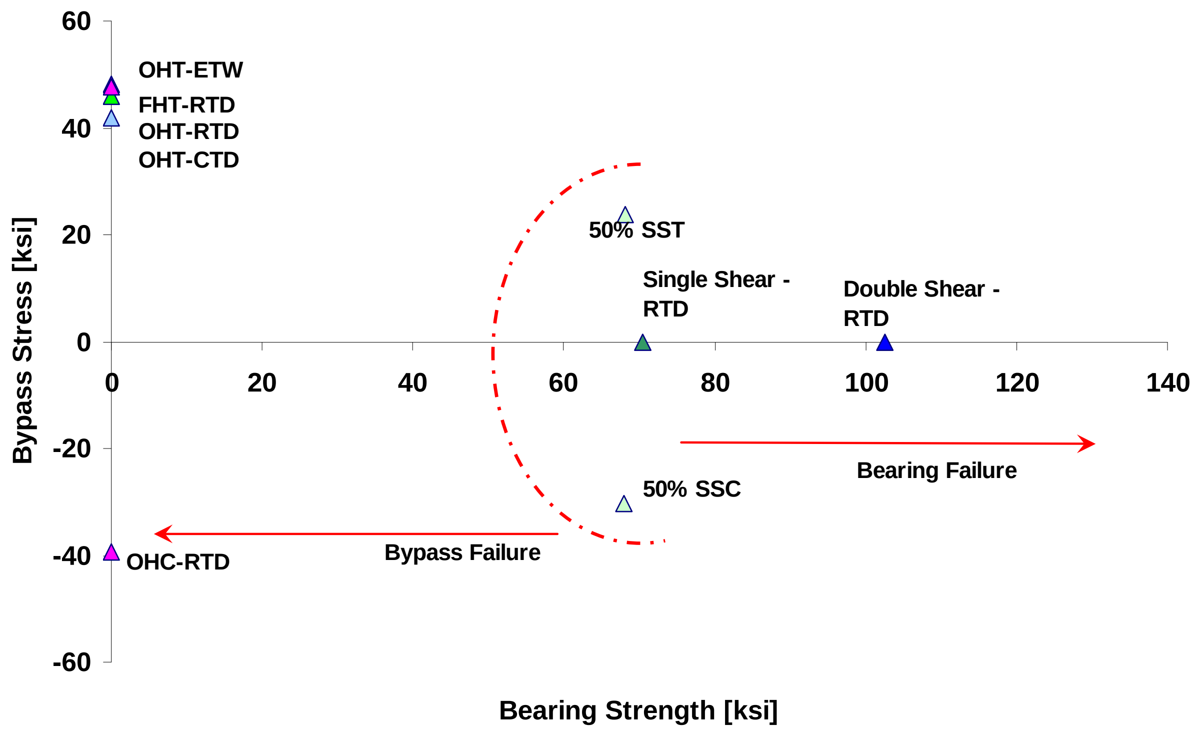

Figure C-4. Bearing-Bypass Interaction Curve for FiberCote 40/20/40 PW

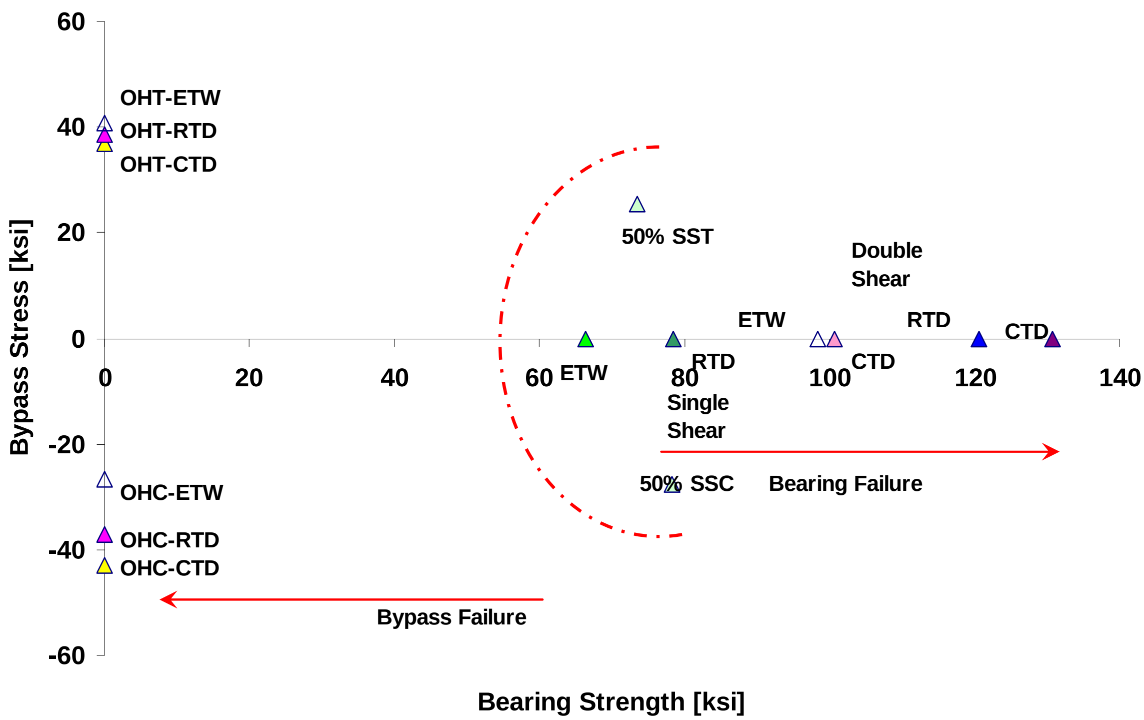

Figure C-5. Bearing-Bypass Interaction Curve for FiberCote 25/50/25 PW

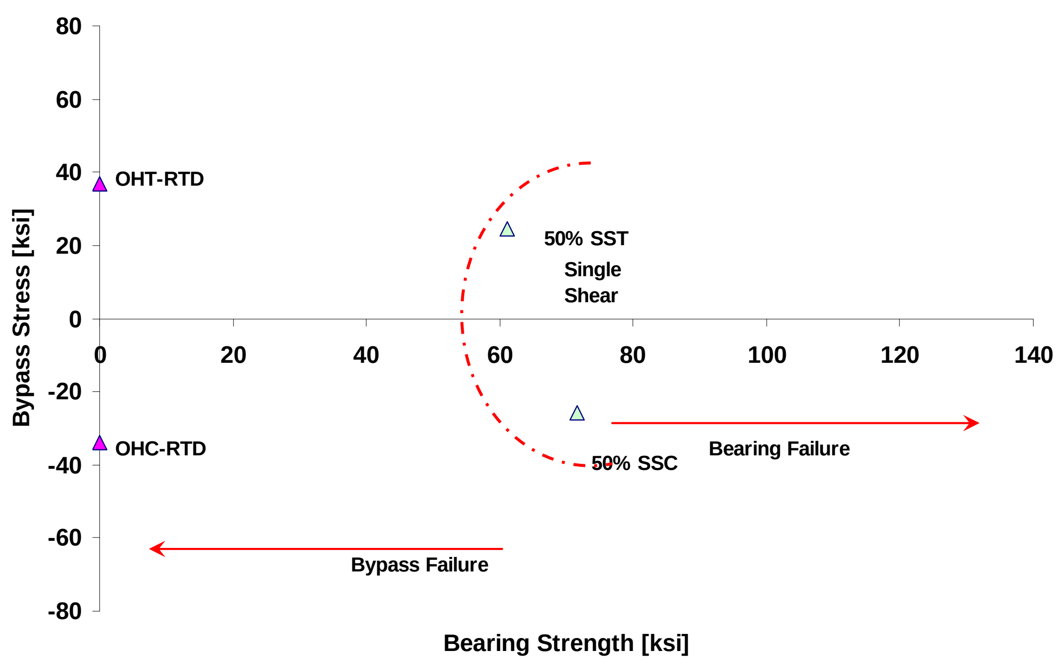

Figure C-6. Bearing-Bypass Interaction Curve for FiberCote 10/80/10 PW

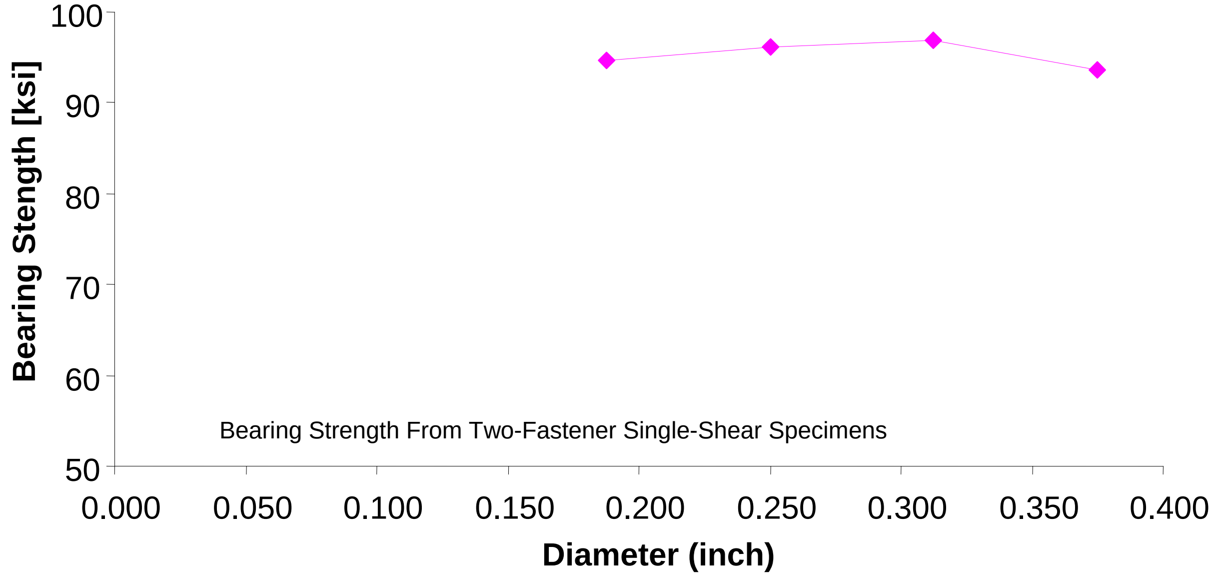

Figure C-7. Effects of Hole Diameter on FiberCote Tape 50/40/10 Bearing Strength

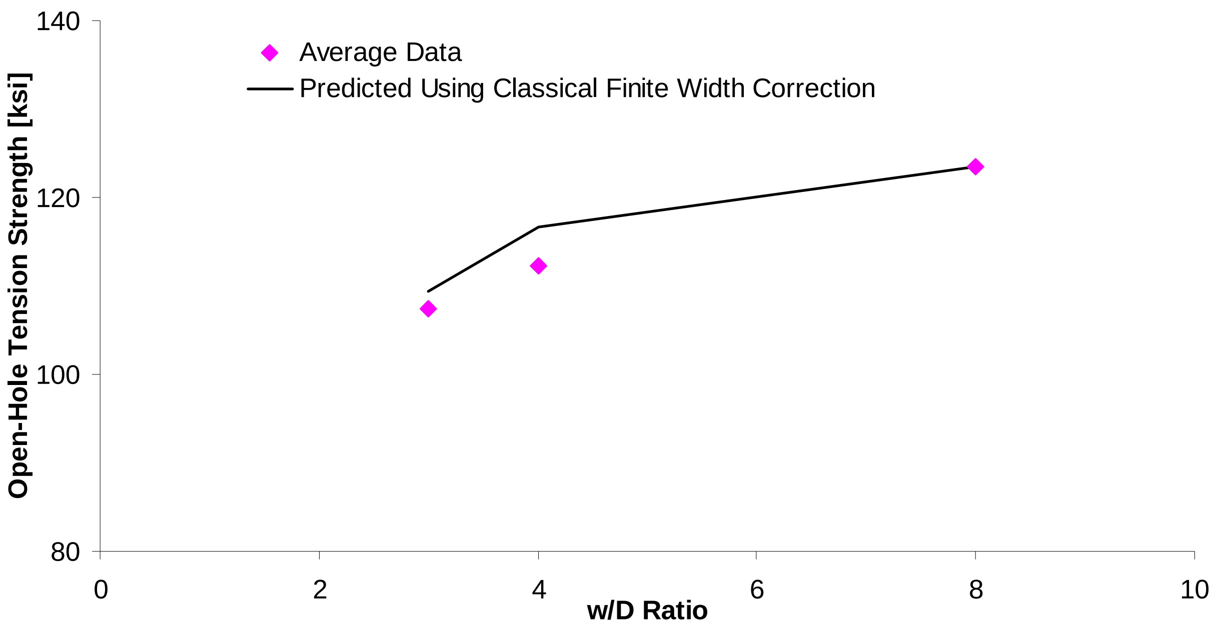

Figure C-8. Effects of *w/D* Ratio on FiberCote Tape 50/40/10 OHT Strength

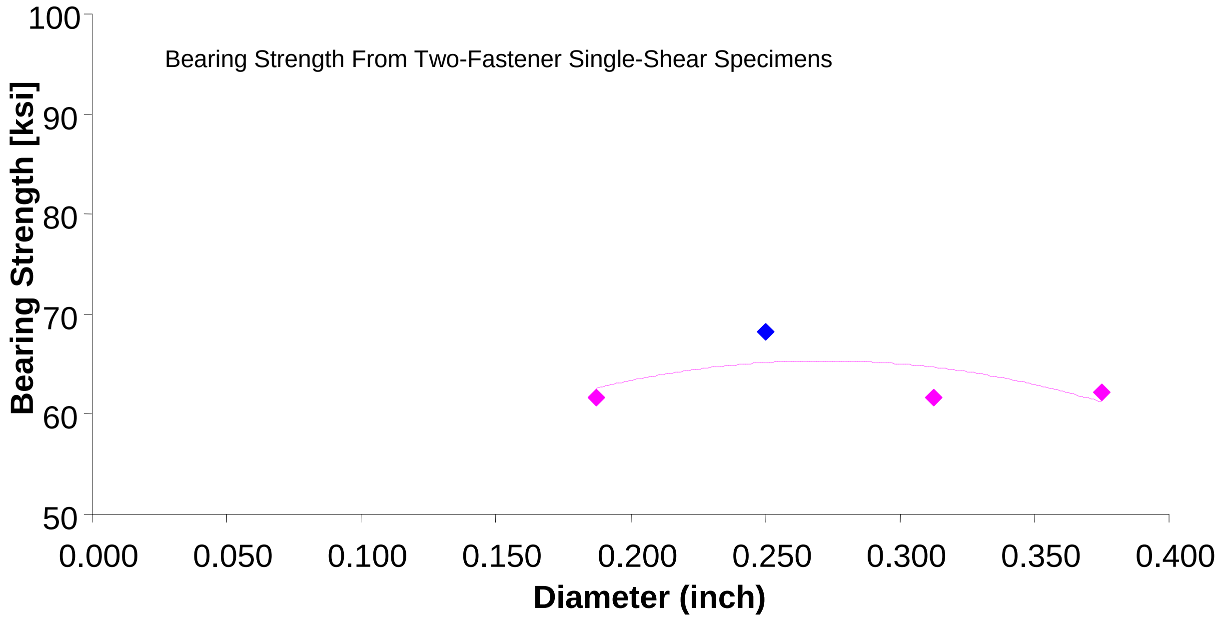

Figure C-9. Effects of Hole Diameter on FiberCote PW 40/20/40 Bearing Strength

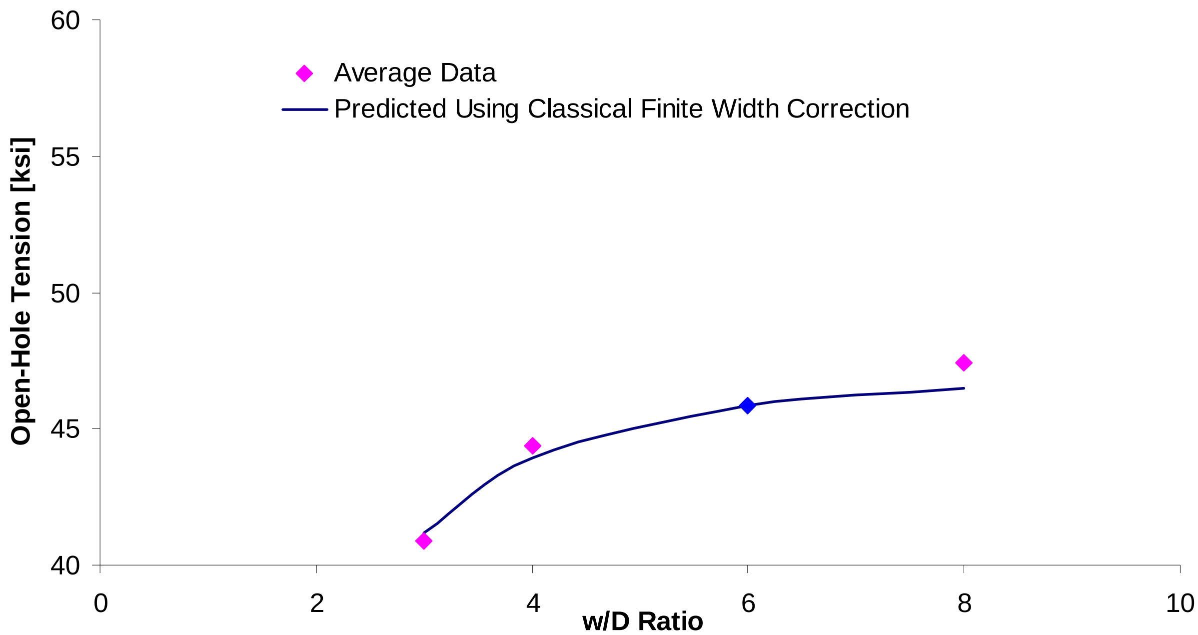

Figure C-10. Effects of *w/D* Ratio on Fibercote PW 40/20/40 OHT Strength

APPENDIX D—COMPARISON OF SMALL SAMPLE B-BASIS METHODS

This appendix includes data analysis conducted by Ward [D-1] on Toray unidirectional tape and plain weave (PW) laminate data. It contains B-basis values obtained from two additional small-sample statistical methods for Toray T700/#2510 material systems. Furthermore, B-basis allowables for the pooled data across environments using several different statistical procedures outlined in Military Handbook 17 (MIL-HDBK-17) are discussed.

BATCH NORMAL (WARD) METHOD.

This method for calculating a B-basis value from a small sample of laminate-level data will give conservative (but not excessively low) allowables, provided the laminate population coefficient of variation (CV) is not significantly higher than assumed. Extreme care should be taken in applying this method for high-temperature data, and for test methods, failure modes, and material types for which there is little experience. The derivation, assumptions, and equations follow. Variables are defined as follows:

μ = Unknown population mean
$\bar{x}$ = Sample mean
σ = Unknown population standard deviation
CV = Population coefficient of variation (assumed value)
N = Sample size
z_y = Normal distribution statistic for differences in the means
k_B = B-basis tolerance limit factor (see MIL-HDBK-17, Volume 1, Table 8.5.10)

The normal distribution statistic for a mean of N values is given by

$$z_\gamma = \frac{\bar{x}-\mu}{\sigma/\sqrt{N}} = \frac{\bar{x}-\mu}{\mu \cdot CV/\sqrt{N}} \tag{D-1}$$

Rearranging leads to

$$\frac{\bar{x}}{\mu} = 1 + z_y \cdot CV/\sqrt{N} \tag{D-2}$$

This equation is used to correct the sample mean that may be shifted from the true population mean. To produce basis values that are a conservative estimate of the population basis value, it must be assumed that the sample mean is on the high side of the population distribution, and an additional reduction is required to account for this situation. Combining the above equation with the standard B-basis value equation (see MIL-HDBK-17, Volume 1, Equation 8.3.4.2(e), written using the population mean) yields

$$B - basis = \mu(1 - k_B CV) = \bar{x}\frac{(1 - k_B CV)}{(1 + z_\gamma CV / \sqrt{N})} \tag{D-3}$$

Appropriate values for k_B and z_γ are required. To provide a sufficient level of conservatism, the following values are recommended:

z_γ = 2.33, which is based on allowing for 1% probability that the sample does not come from the population.

k_B = 1.6, which corresponds to a sample size of 63. This value was selected to produce a basis value factor of 0.80 with an assumed CV of 0.08 and N = 5, and the above value for z_γ. This basis value factor was judged to be appropriate based on experience with establishing basis values for large and small data sets for a wide range of composite materials.

With these values the equation for the small-sample laminate B-basis value (assuming no batch-to-batch variability) becomes

$$B - basis = \bar{x}\frac{(1 - 1.6CV)}{(1 + 2.33CV / \sqrt{N})} \tag{D-4}$$

Given a normally distributed population, a sample size of six, an assumed CV of 0.08 (8%), and assuming no batch-to-batch variation, it can be shown that there is only a 0.05% probability that a sample will give a higher B-basis value than the true population B-basis value. For a population mean of 100, the B-basis value is 89.7. Equation D-4 gives a reduction factor to the sample mean of 0.81, which means that the sample mean will have to be above 110.7 to result in a basis value above 89.7. The normal distribution statistic for this value (110.7) is 3.276, which corresponds to a 0.05% probability value. It also can be shown that if the true laminate population CV is 0.12, but an assumed CV of 0.08 is used, then there is only a 19% chance that the basis value will be greater than the true population basis value.

For the laminate sample, a minimum of six laminate specimens from two independently processed panels should be tested at each environment. A minimum of six specimens are recommended to give an acceptable estimate of the mean property. For cases where there is significant doubt about the laminate CV, this method for calculating a basis value should not be used.

In some cases, statistically significant batch-to-batch variations must be taken into account for the basis value calculation. For cases where there is only a small sample of laminate-level data, lamina-level multibatch data must be used either to verify that batch-to-batch variation is not significant or to provide the data to account for the batch-to-batch variation. The batch variability should be evaluated at the lamina level for the failure mode and environment that corresponds to the laminate sample. Corresponding refers to tests with the same basic type of failure mode; e.g., tension, compression, interlaminar. For laminate bearing tests, the use of lamina compression data is recommended. Two methods are given below to account for batch variation.

The first method assumes that batch effects are correlated between different tests with the same basic failure mode. This method requires lamina test data for the same batch as the corresponding laminate data at the same environment is needed; e.g., for calculating a basis value for open-hole tension (OHT) at 180°F/wet, lamina-tension data at 180°F/wet for the same material batch is required. The batch correction is obtained by taking the ratio of the average lamina test data for the laminate batch ($x_{\text{lamina, batch}}$) to the average lamina test data for all batches in the lamina database ($x_{\text{lamina, average}}$).

Using this approach, the equation for calculating the small-sample laminate B-basis value (with batch-to-batch variability) is

$$\mathrm{B-basis} = \bar{x}\,\frac{(1-1.6\mathrm{CV})}{(1+2.33\mathrm{CV}/\sqrt{\mathrm{N}})}\left(\frac{\bar{x}_{\text{lamina,batch}}}{\bar{x}_{\text{lamina,average}}}\right) \tag{D-5}$$

This method is most appropriate when there is a large number (>15) of batches in the lamina database. Also, ($x_{\text{lamina, batch}}/x_{\text{lamina, average}}$) ratios greater than 1.0 should not be used (rather, use a value of 1.0).

The second method can be used when lamina test data for the laminate data batch is not available, or when the number of lamina batches is small. This method assumes that the laminate sample comes from a high batch. This method requires batch variation statistics from lamina test data corresponding to the laminate sample. The ratio of the analysis of variance (ANOVA) basis value to the normal distribution basis value calculated for the corresponding lamina data is used to reduce the laminate basis value. Note that when there is high batch variability, the ANOVA value is low, while with no variability, the ANOVA and normal distribution methods give the same basis value. Thus, the ratio of the ANOVA to normal basis values gives an approximate measure of the batch variability.

Using this approach, the equation for the small-sample laminate B-basis value (with batch-to-batch variability) is

$$B-Basis = \bar{x}\,\frac{(1-1.6CV)}{(1+2.33CV/\sqrt{N})}\left(\frac{\text{Lamina ANOVA B - Basis value}}{\text{Lamina Normal B - Basis value}}\right) \tag{D-6}$$

This method is appropriate for a small number of batches (at least five) in the lamina database. Furthermore, to be conservative, the smaller of the two-batch variability factors can be used.

Preferably a minimum of five material batches of fiber and resin should be tested at the lamina level to adequately quantify batch variation. Batch variation should be checked again after the first 20 or more production material batches are produced.

This method recommends that, for carbon fiber/epoxy composite materials (or similar materials for which there is sufficient experience to validate these CV values), laminate basis values calculated using this method employ an estimated laminate population CV that is the greater of

- the corresponding lamina CV.
- the laminate sample CV.
- 8% for fiber tension or compression failure modes.
- 12% for bearing and interlaminar failure modes.
- 14% for test temperatures close to, or above, the material's wet glass transition temperature.

These recommended values assume that the CVs are either independent of the environment or represent the largest value over the typical range of environments.

MODIFIED N_1+N_2-2 METHOD.
The third method evaluated in this report was the Ward's modification of the Vangel N_1+N_2-2 method. The original method does not account for the possibility that the sample mean may be higher than the population mean. The method was modified to include the high mean correction used in the normal (Ward) method. The resulting basis value equation is

$$B-basis = X_1 \frac{(1-K*CV_2)}{(1+2.33CV_2/\sqrt{N})} \qquad \text{(D-7)}$$

where CV_2 is the coefficient of variation of the corresponding lamina data.

RECIPE REGRESSION ANALYSIS WITH BATCH EFFECTS.
The RECIPE (REgression Confidence Intervals on PErcentiles) code was developed by Vangel as a general-purpose code for determining one-sided tolerance limits (basis values) for arbitrary regression models with or without an additional random effect (e.g, batch variability) [D-2 through D-5]. RECIPE uses a normal probability model to determine the tolerance limits and assumes the variance (not the CV) is constant at each observation (e.g., test condition). This method results in basis values that are equal to the data average at each condition minus a constant value; this means that the ratio of the basis value to data average will be different at each condition (compared to the Advanced General Aviation Transport Experiments Statistical Allowable Program (ASAP) method where the ratio is constant). The code is written in Fortran and can be compiled to run on a personal computer under the Windows® operating system. Additional discussions of RECIPE and its use can be found in MIL-HDBK-17, Volume 1, Chapter 8.

Numerous composite data sets have shown that it is much more likely that CVs will be constant over layup and environmental conditions than for variances to be constant [D-1]. This means that the assumption of the environmental pooling method of constant CVs is more appropriate and more likely to be satisfied than the constant variance assumption used in RECIPE. However, putting this issue aside, RECIPE can be used to analyze a number of data situations:

1. Single test conditions with data from several material batches (i.e., ANOVA analysis; equivalent to MIL-HDBK-17 ANOVA method)

2. Several environments for a single-material batch, or batch effects not considered (i.e., ANOVA analysis with environment as a fixed variable; similar to ASAP pooling method)

3. Several environments with data from several material batches (i.e., ANOVA analysis with environmental as a fixed variable and batch effects as a random variable; pooling analysis with batch effects)

4. Several layups at a single environment for a single-material batch, or batch effects not considered (i.e., regression analysis with layup parameters as fixed variables)

5. Several layups at a single environment with data from several material batches (i.e., regression analysis with layup parameters as fixed variables combined with ANOVA analysis with environment as a fixed variable)

6. Several layups and environments with data from several material batches (regression analysis with layup parameters as fixed variables combined with ANOVA analysis with environment as a fixed variable and batch effects as a random variable)

In light of the above discussion of constant CVs versus constant variances, the environmental pooling method discussed in section 4.2 is preferred to using the RECIPE code described in 2 above.

In situations where regression models are desired for fitting the data and determining basis values over the regression parameters, either RECIPE or the regression method must be used since regression basis value methods, based on the constant CV assumption, have not been formulated. For 4 above, RECIPE will produce equivalent results. RECIPE is the only available option for 5 and 6.

COMPARISON OF LAMINATE DATA.

The laminate results compared in this section were analyzed using a number of methods. All methods were performed on data that was normalized to the nominal laminate thickness calculated using nominal per-ply thickness values, since nominal values are used for design purposes. For each data set consisting of 18 specimens (three batches, two panels per batch, three replicates per panel), the following were calculated:

- Average, standard deviation, CV for each batch and data set
- B-basis value using MIL-HDBK-17 normal distribution method (three batches pooled)
- B-basis value using 1-Batch N_1+N_2-2 (LVM) method for the batch with the highest average
- B-basis value using 1-Batch normal (Ward) method for the batch with the highest average
- B-basis value using modified 1-Batch N_1+N_2-2 method (high mean reduction) for the batch with the highest average

For the single-batch methods, basis values were calculated using the data from the batch with the highest average, because the purpose was to demonstrate whether the methods are sufficiently robust (conservative) for use with only a single batch of test data. For a one-batch, basis value method to be acceptable, it must produce basis values that conservatively estimate the population basis value, even when the sample data has an average value on the high end of the population distribution. This does not account for batch-to-batch variability, but simply the statistical distribution of sample means drawn from the same population.

In addition, for properties where tests were conducted at three environments, the ASAP pooling method was used to calculate B-basis values, and for cases where there was significant batch variability, B-basis values for the pooled environment data were calculated using two methods:

- ANOVA analysis of the pooled, normalized data from the ASAP analysis
- RECIPE code

Also, for properties where tests were conducted at three different layups, B-basis values for the pooled layup data were calculated using RECIPE. Comparisons of B-basis values obtained from different statistical methods, along with CVs for Toray tape and PW laminate data, are shown in figures D-1 through D-12 and D-13 through D-23, respectively.

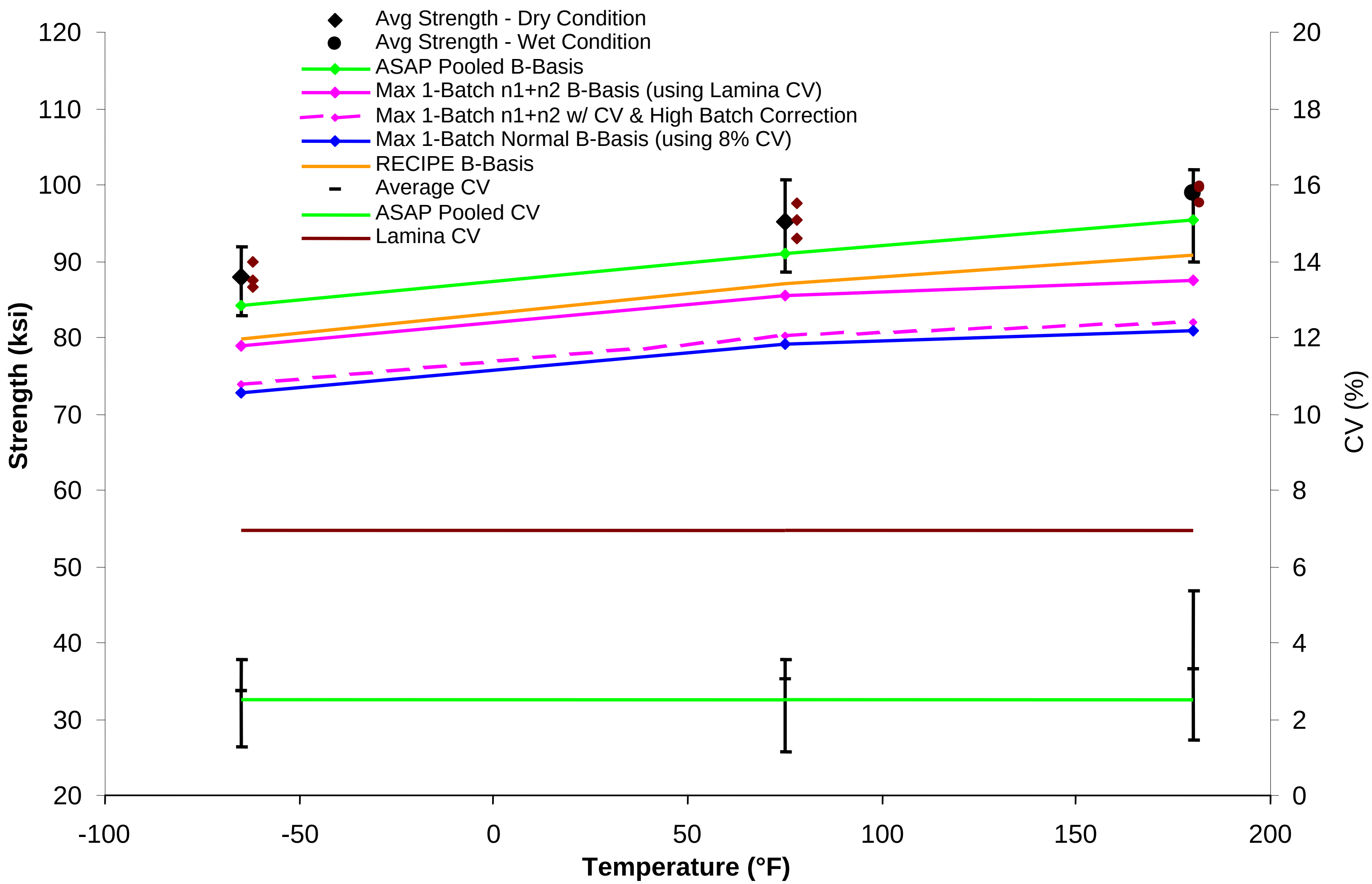

Figure D-1. The 25/50/25 Unnotched Tension (Normalized) Strength for Toray Tape

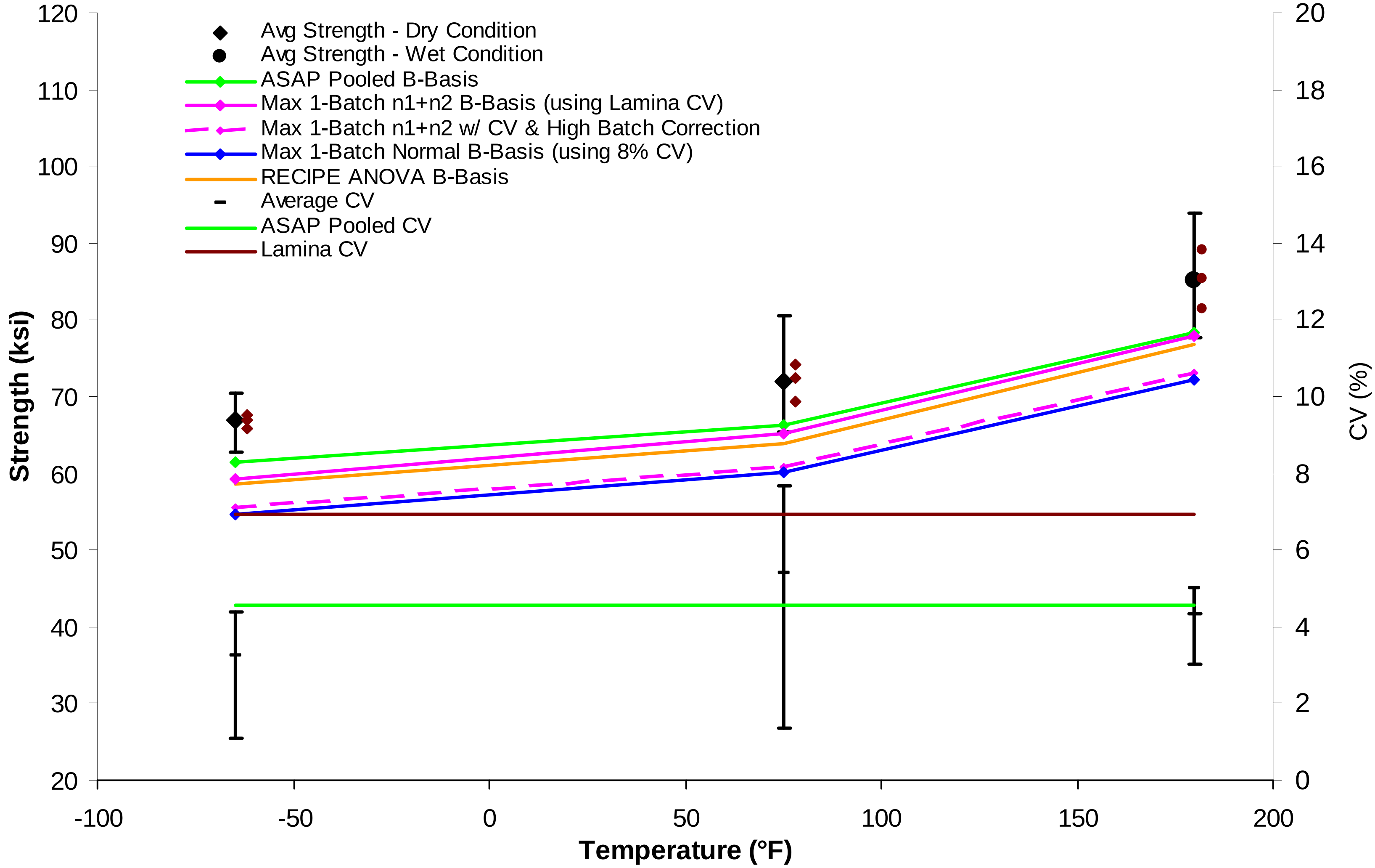

Figure D-2. The 25/50/25 Filled-Hole Tension (Normalized) Strength for Toray Tape

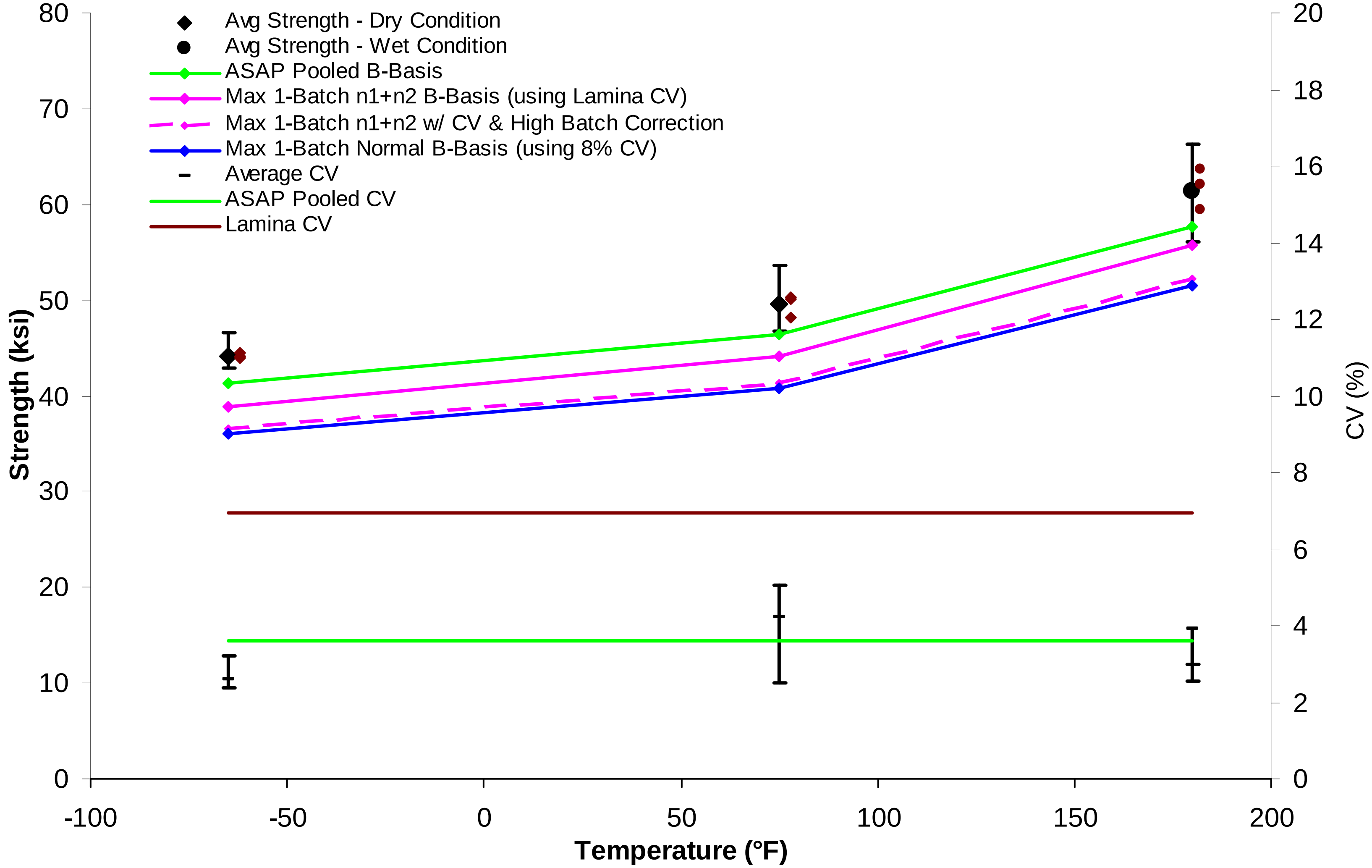

Figure D-3. The 25/50/25 OHT (Normalized) Strength for Toray Tape

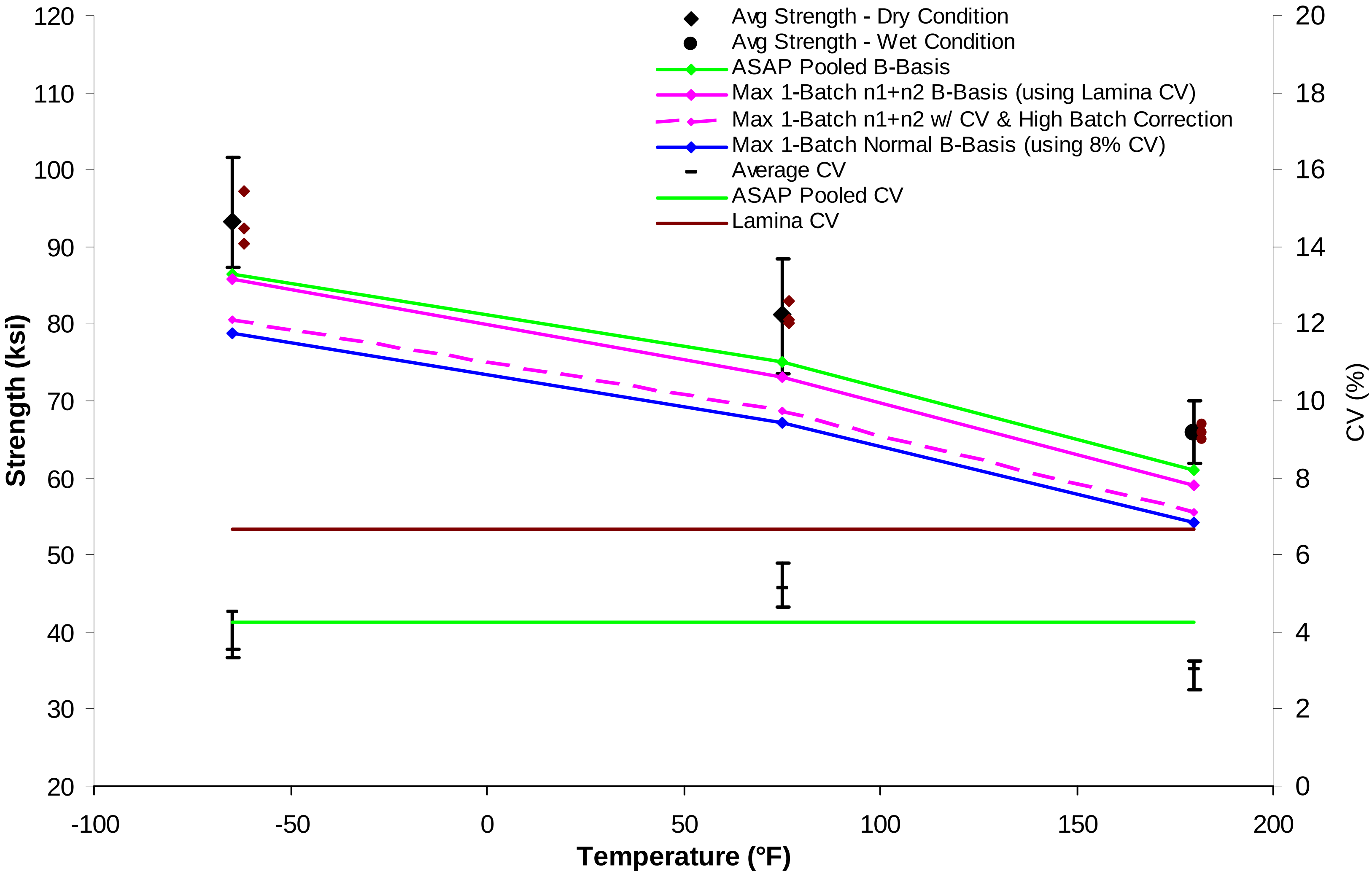

Figure D-4. The 25/50/25 Unnotched Compressive (Normalized) Strength for Toray Tape

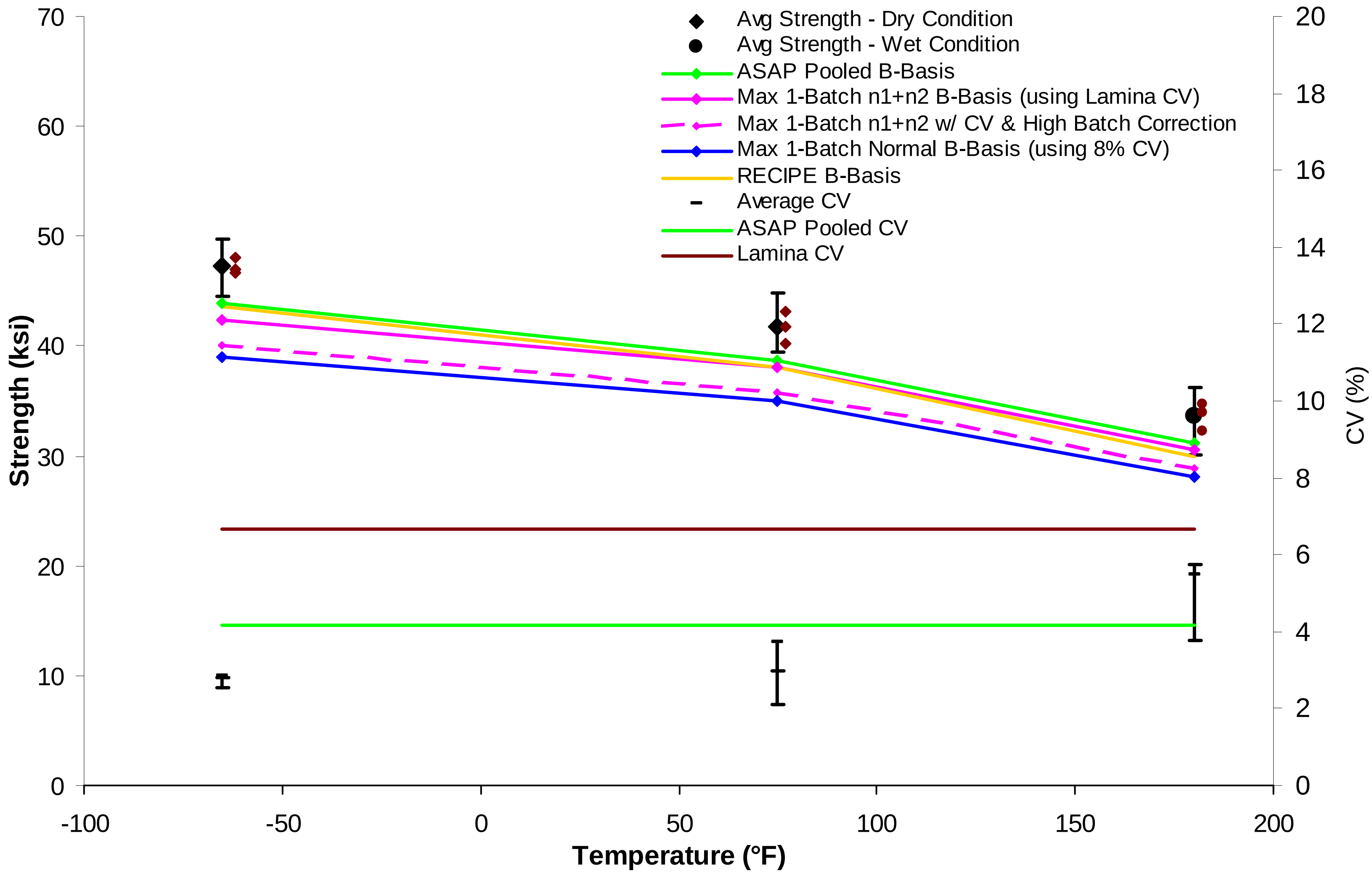

Figure D-5. The 25/50/25 OHC (Normalized) Strength for Toray Tape

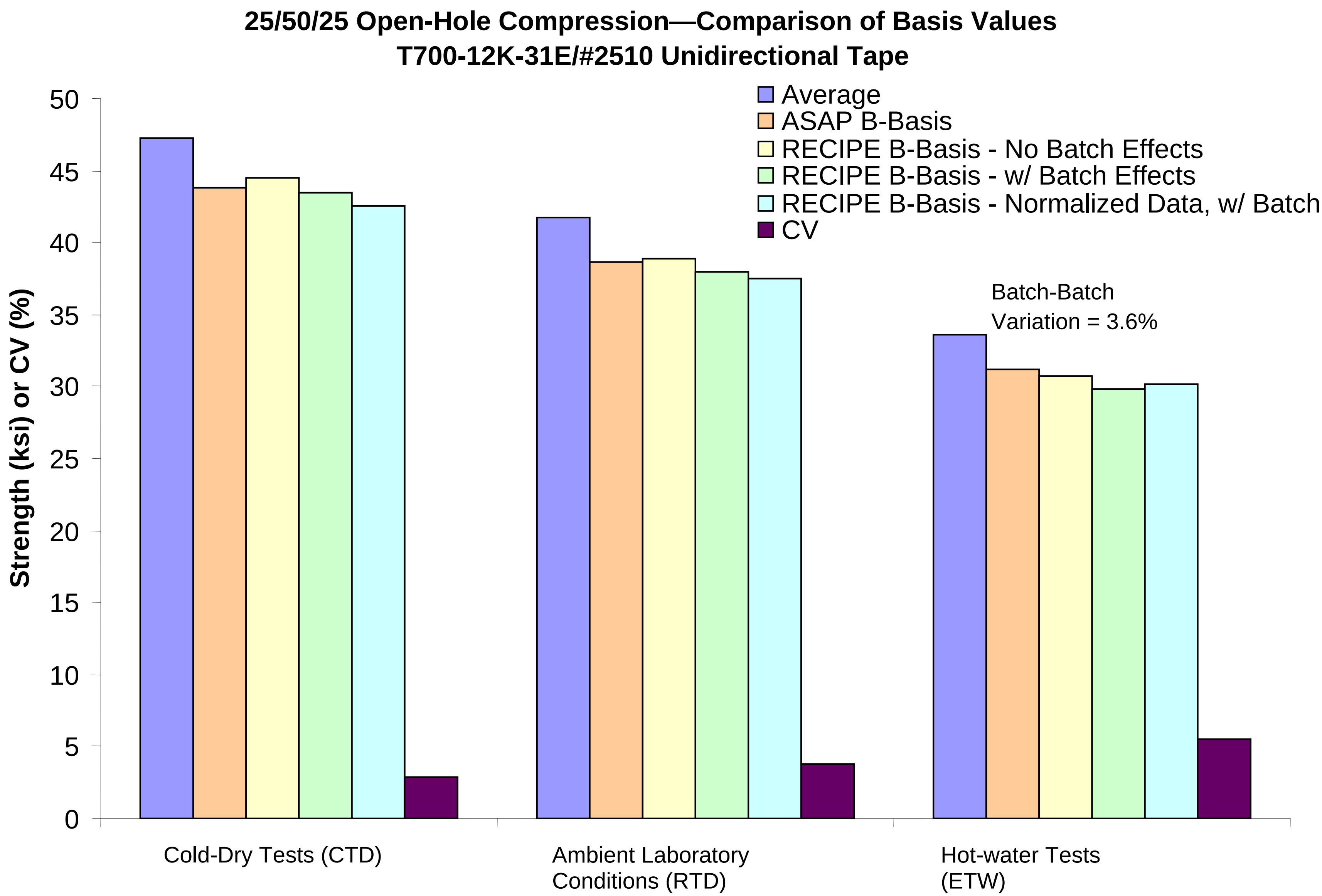

Figure D-6. Comparison of 25/50/25 OHT B-Basis Values for Toray Tape

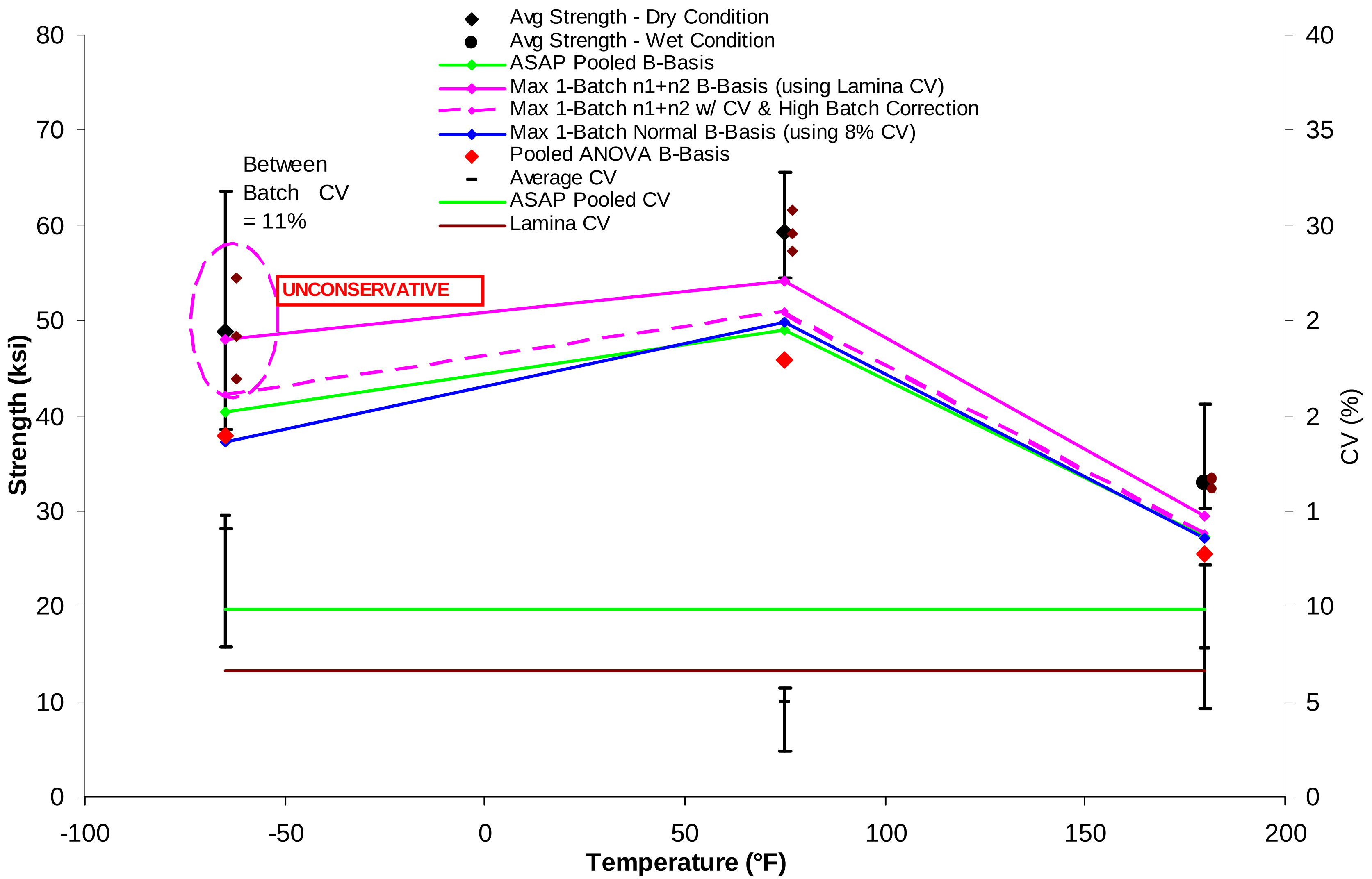

Figure D-7. The 10/80/10 In-Plane Shear (Normalized) Strength for Toray Tape

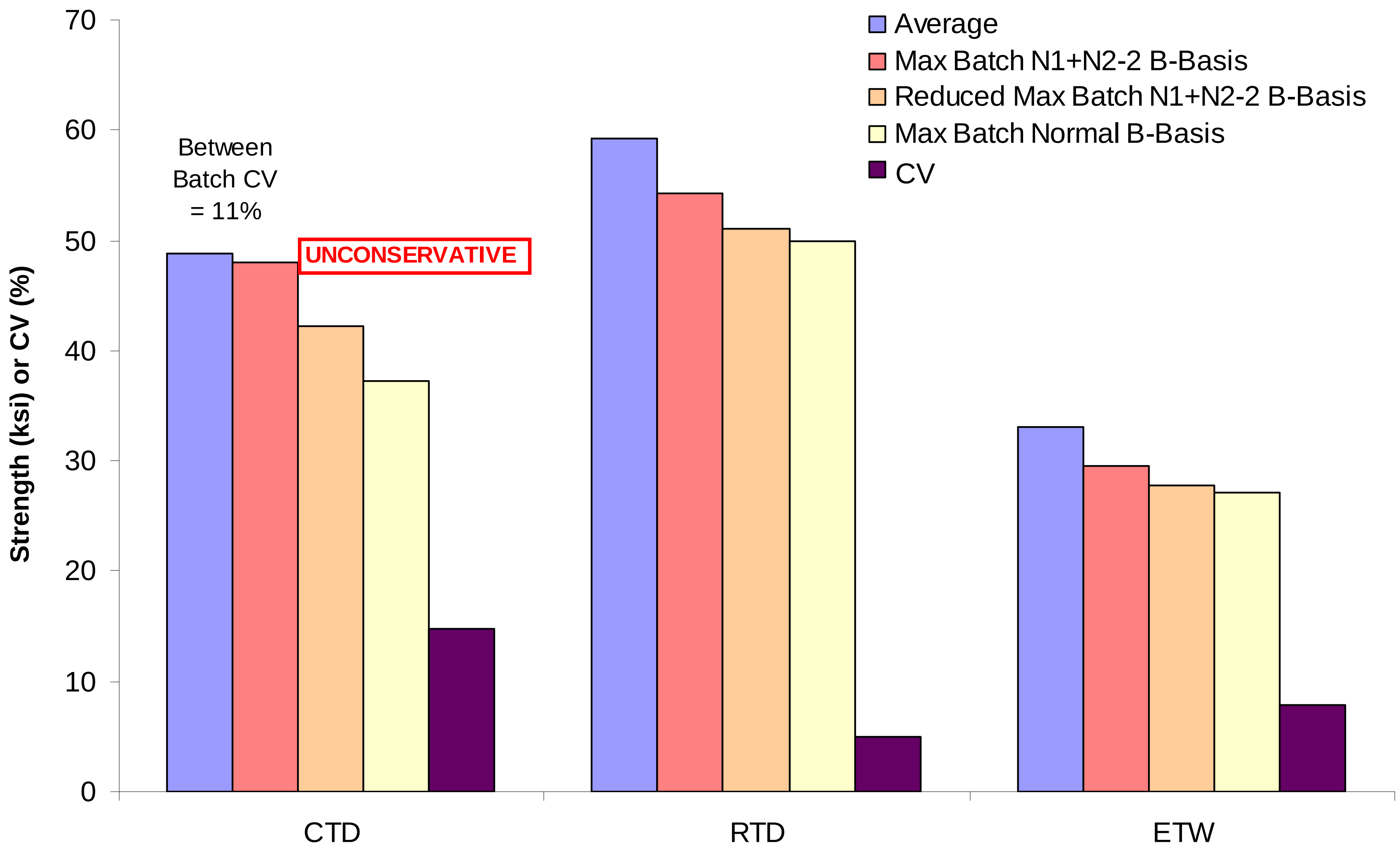

Figure D-8. Comparison 10/80/10 In-Plane Shear B-Basis Values for Toray Tape

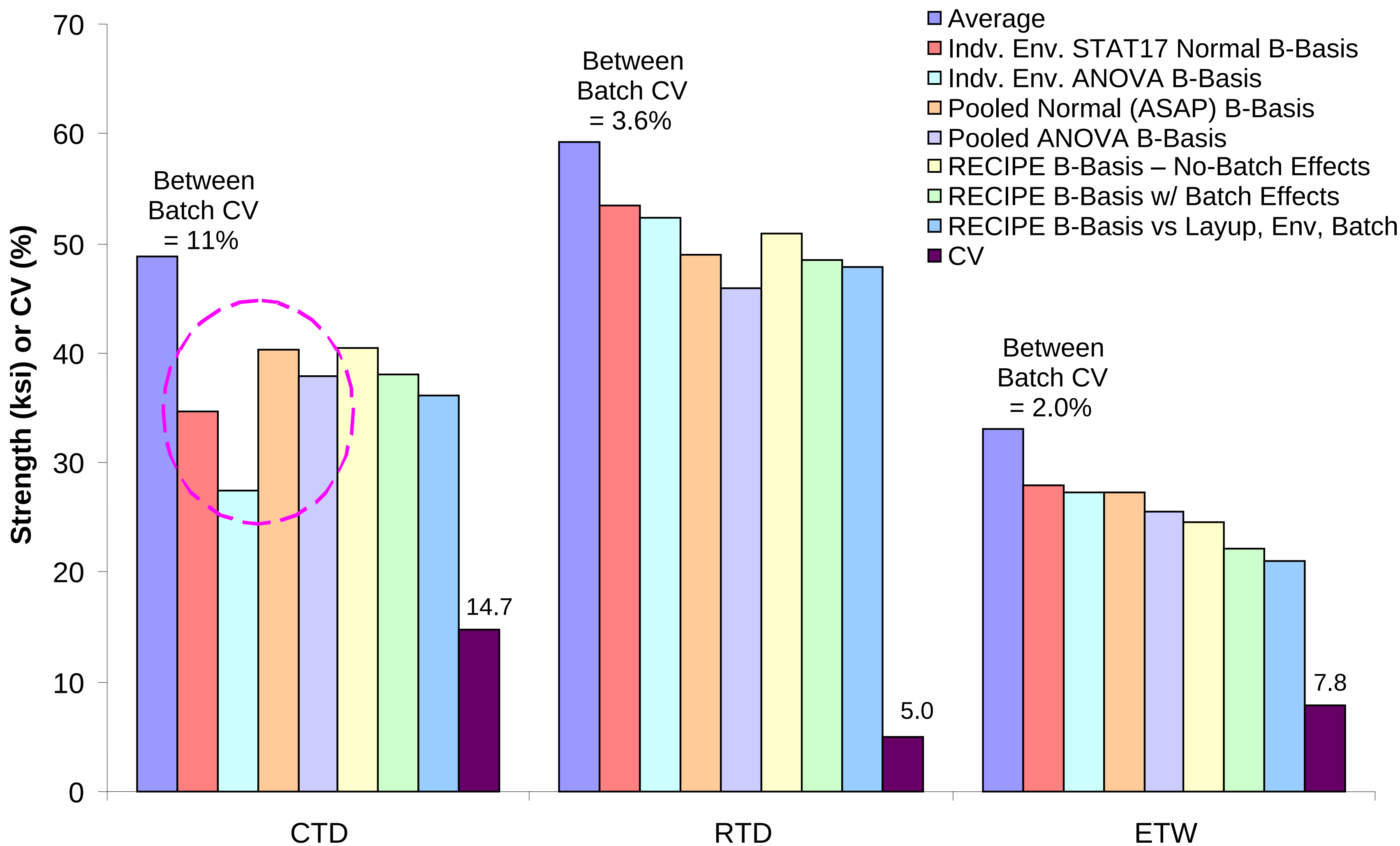

Figure D-9. The 10/80/10 In-Plane Shear B-Basis Values for Toray Tape (Single-Point and Pooled)

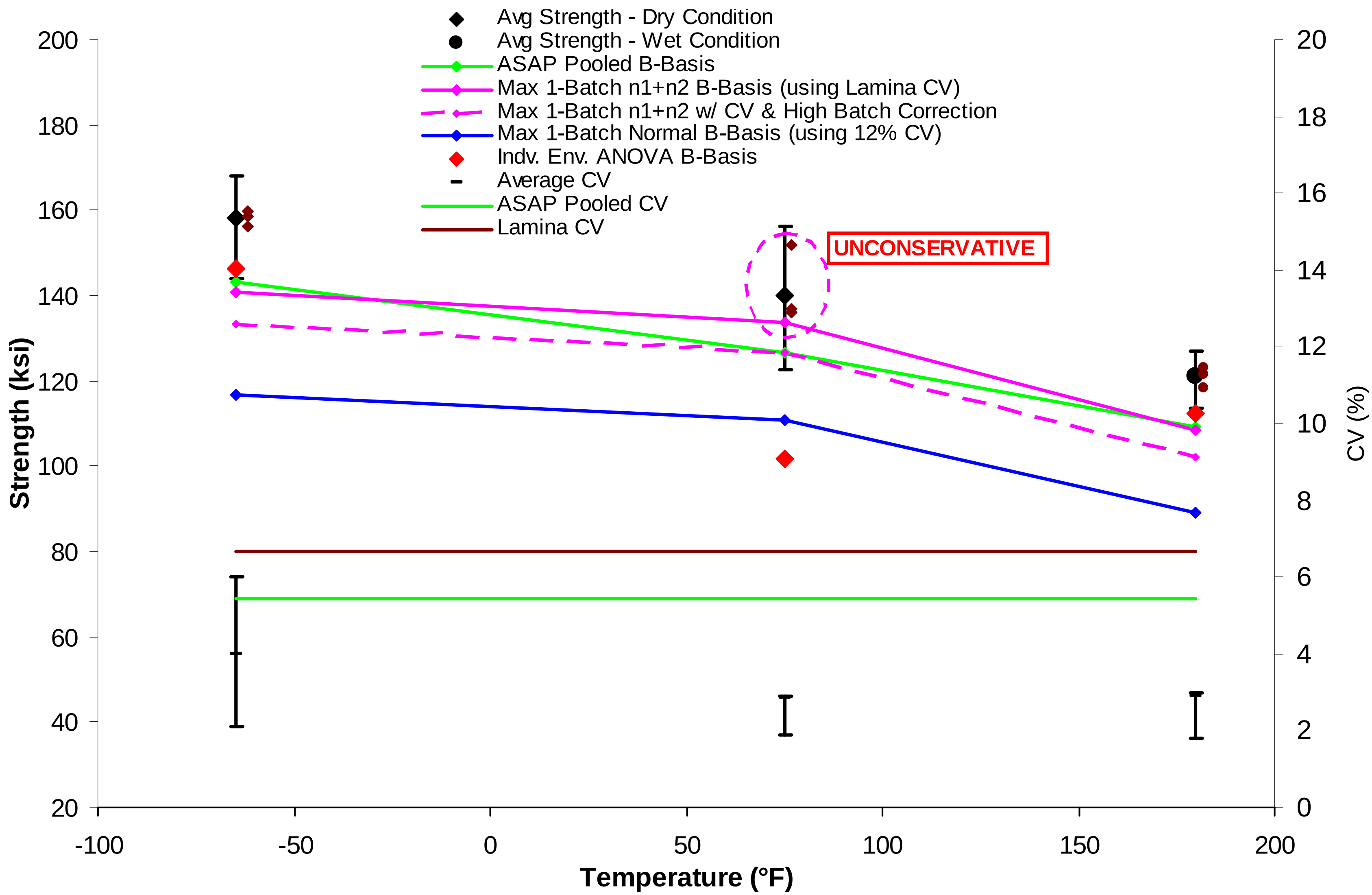

Figure D-10. The 25/50/25 Double-Shear Bearing (Normalized) Strength for Toray Tape

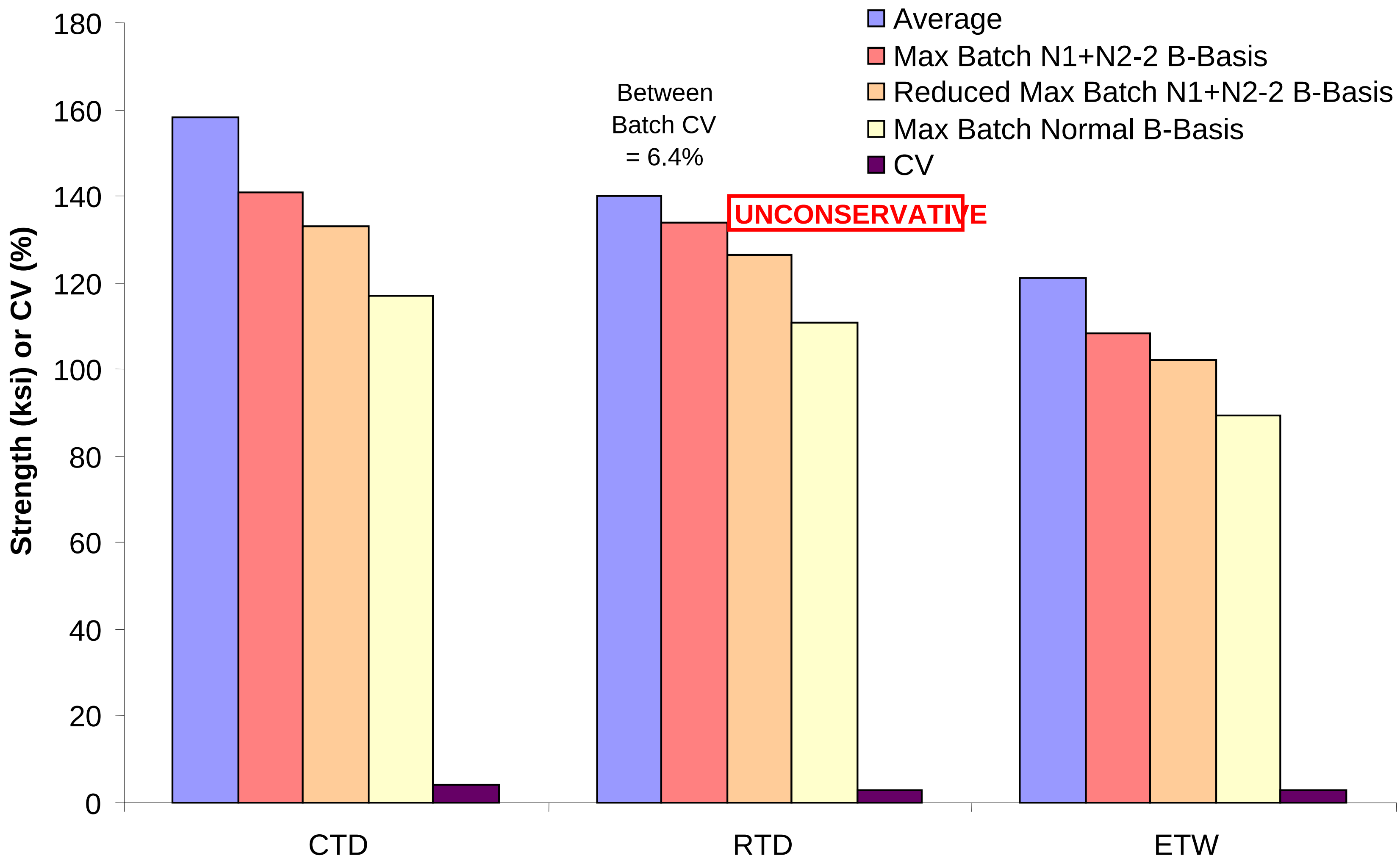

Figure D-11. Comparison of 25/50/25 Double-Shear Bearing Strength B-Basis Values for Toray Tape

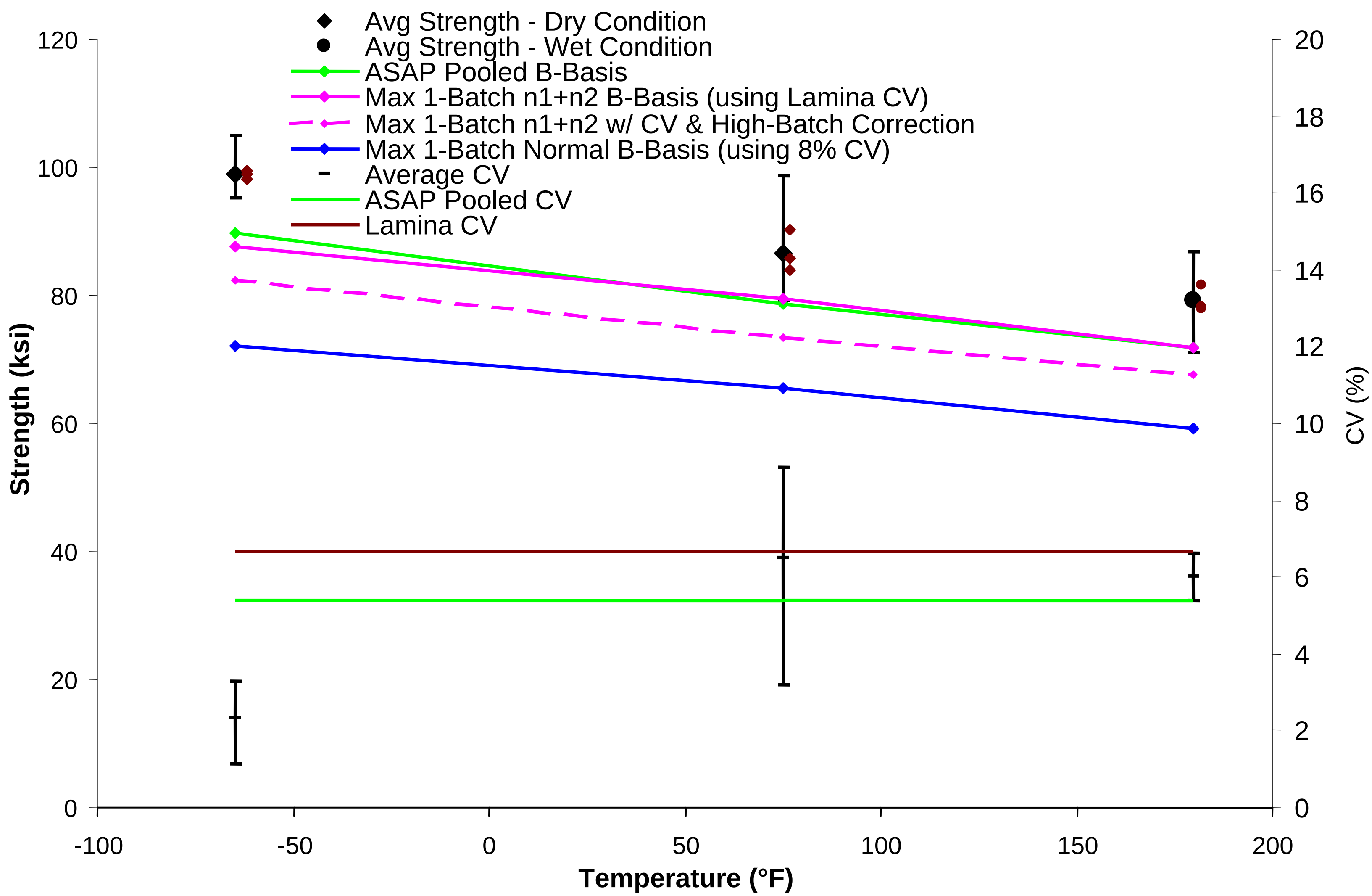

Figure D-12. The 25/50/25 Single-Shear Bearing (Normalized) Strength for Toray Tape

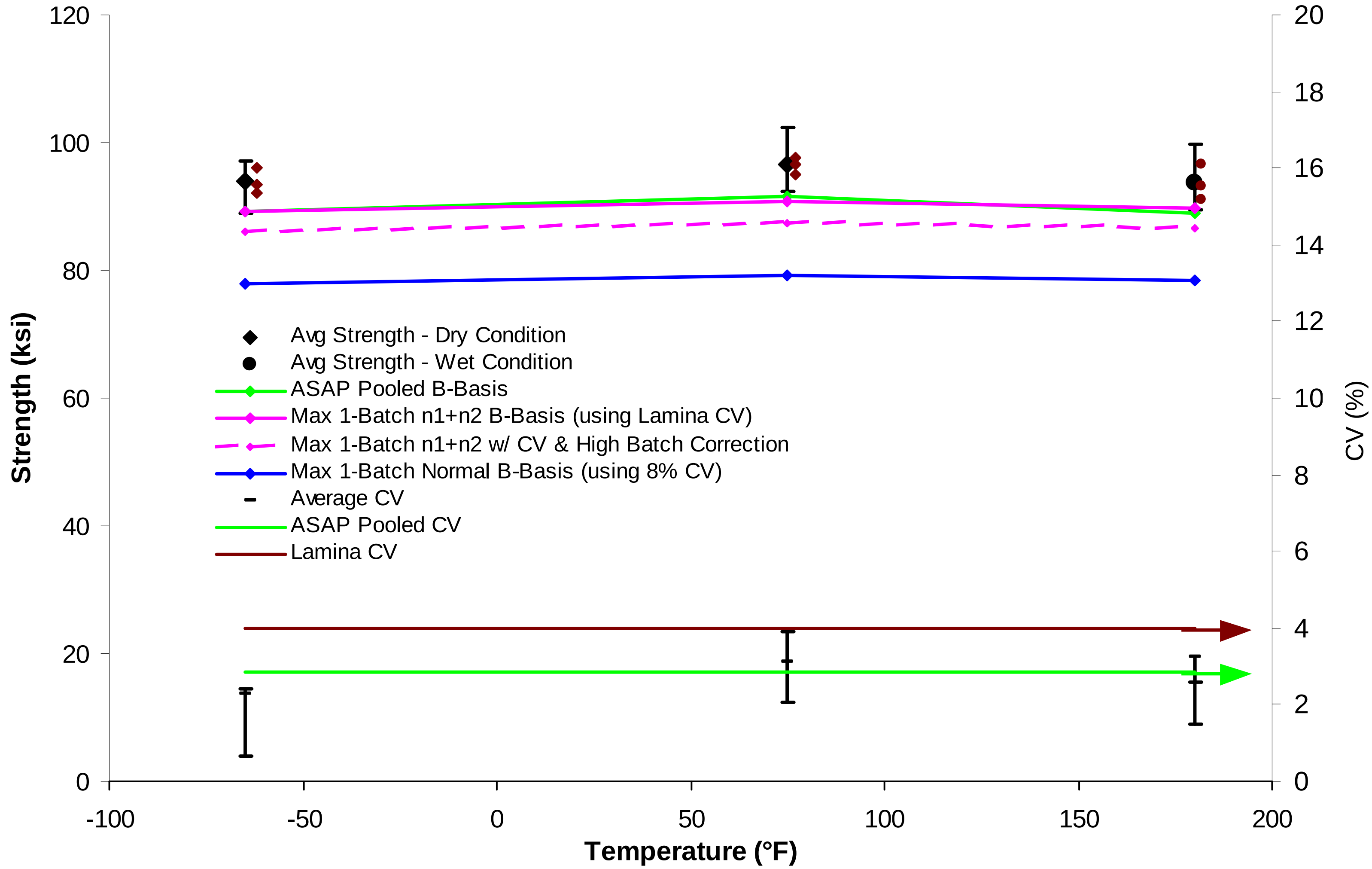

Figure D-13. The 25/50/25 Unnotched Tension (Normalized) Strength for Toray PW

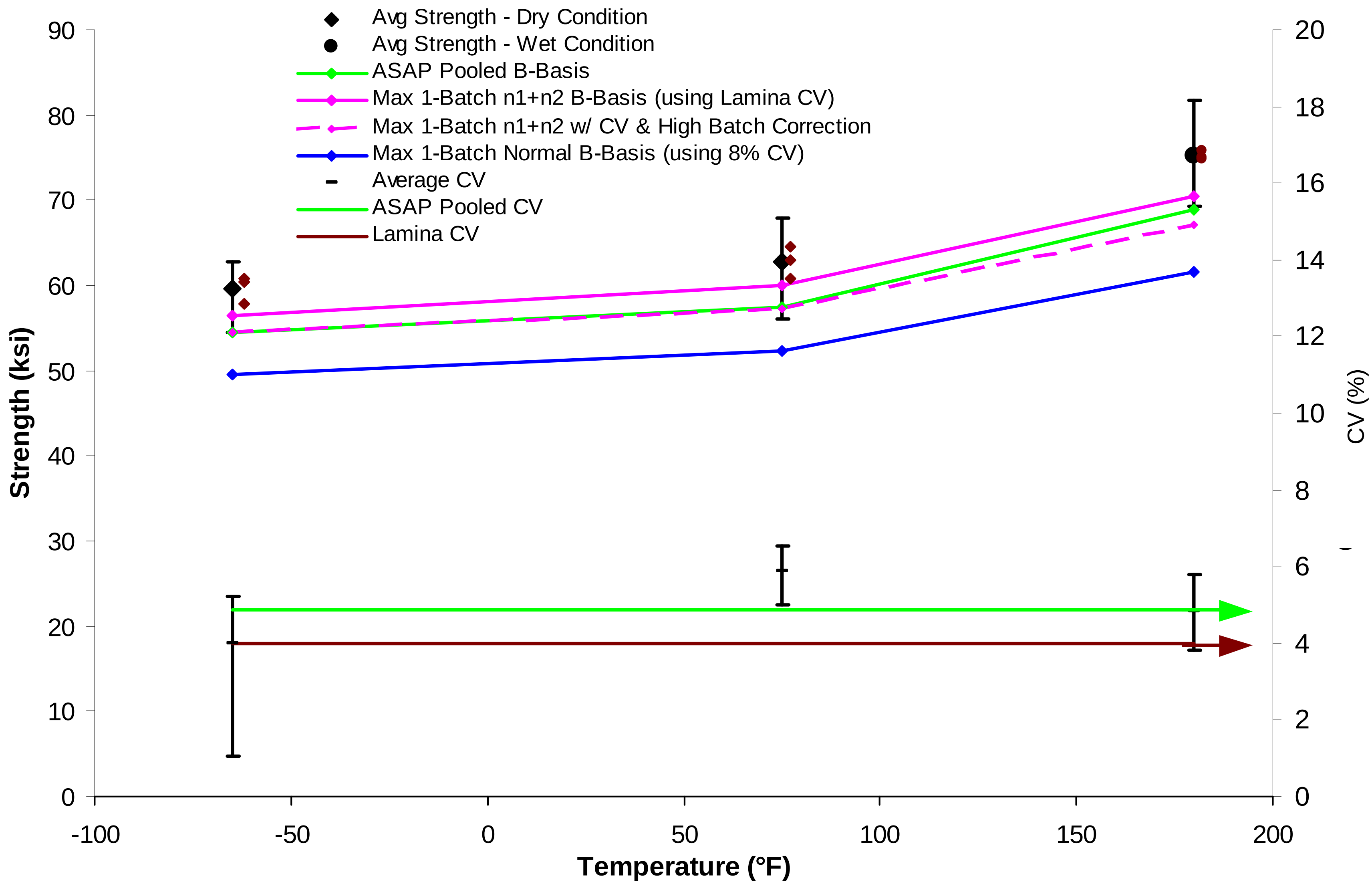

Figure D-14. The 40/20/40 Filled-Hole Tension (Normalized) Strength for Toray PW

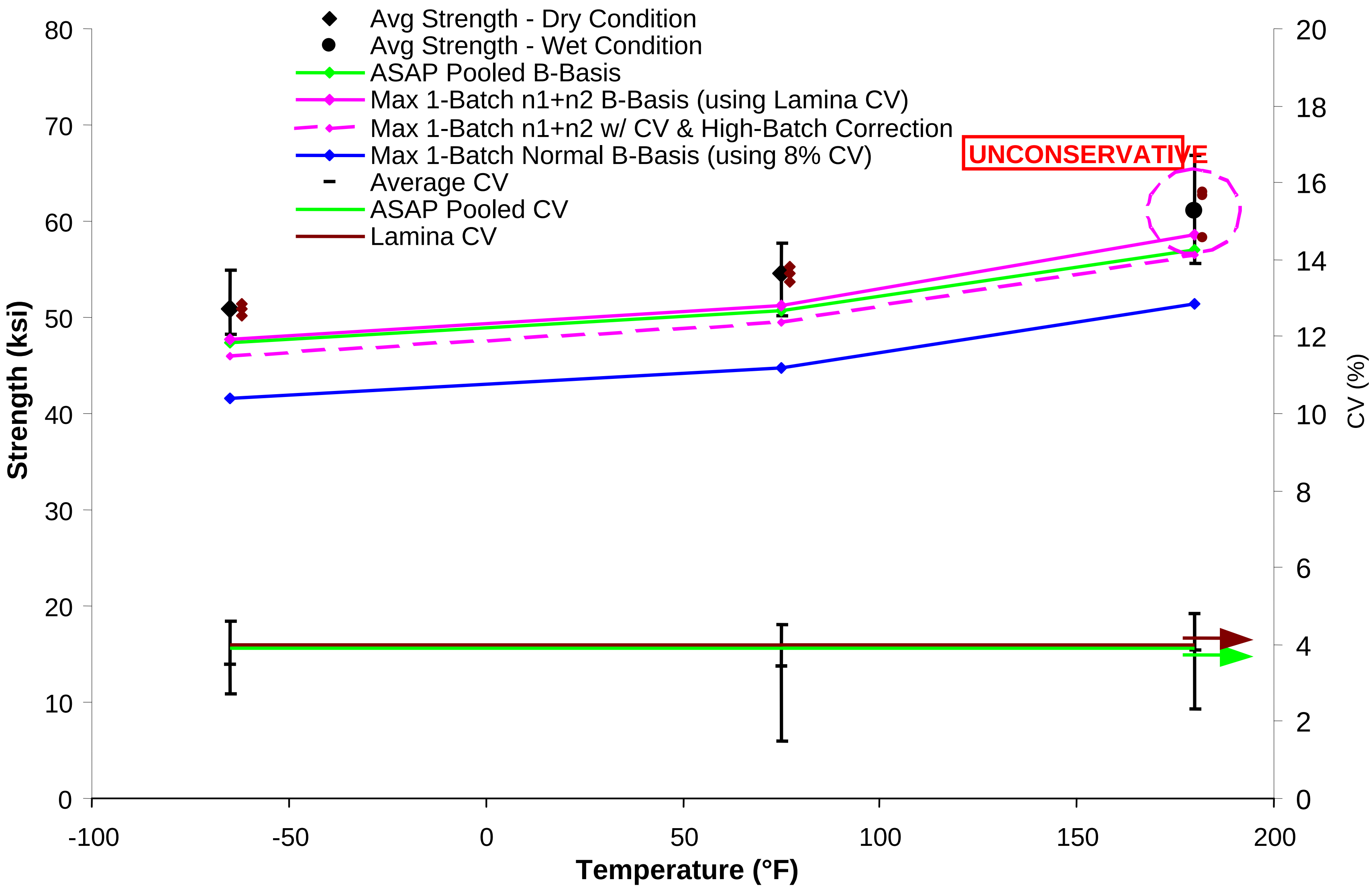

Figure D-15. The 25/50/25 OHT (Normalized) Strength for Toray PW

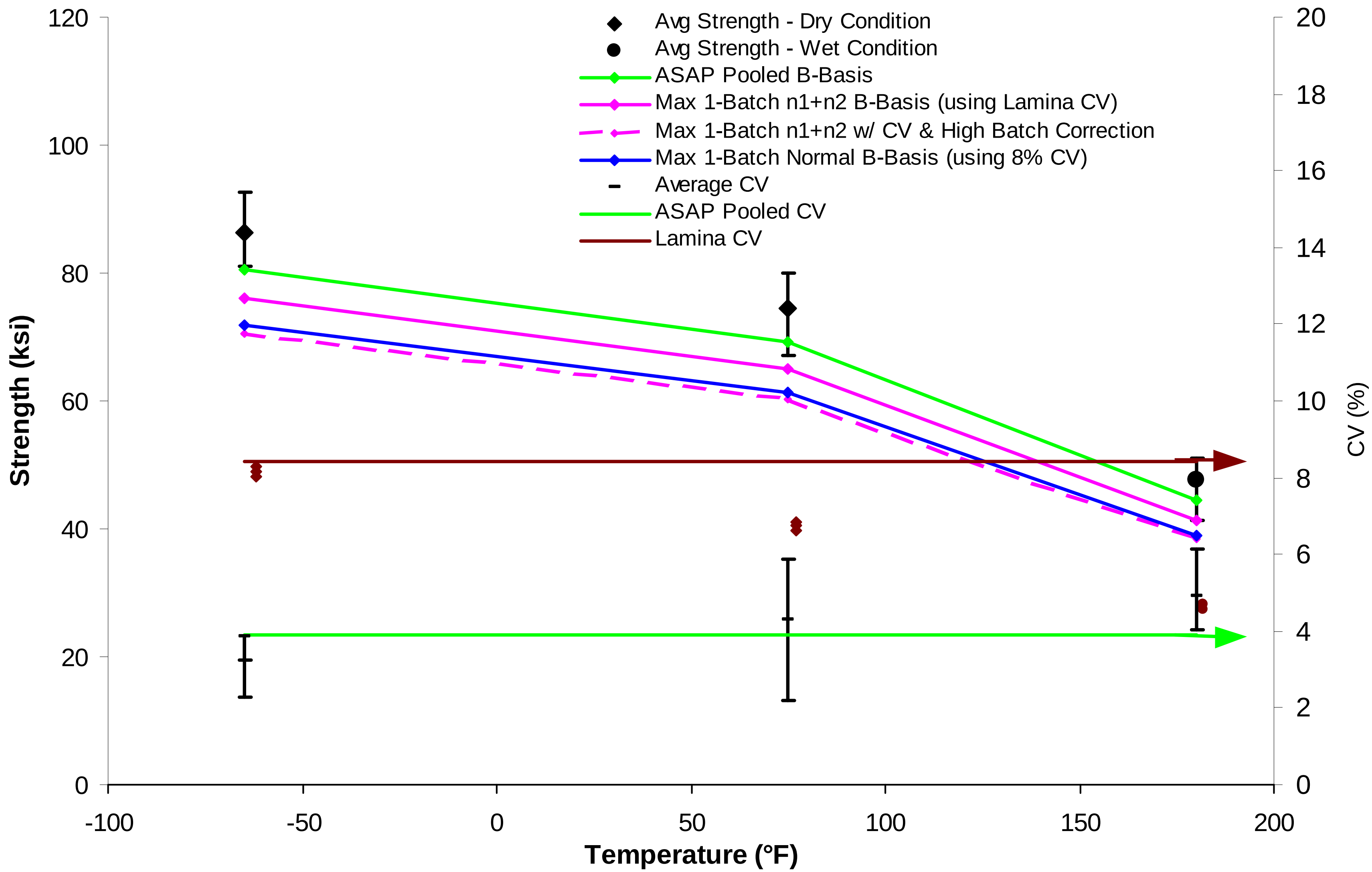

Figure D-16. The 25/50/25 Unnotched-Compressive (Normalized) Strength for Toray PW

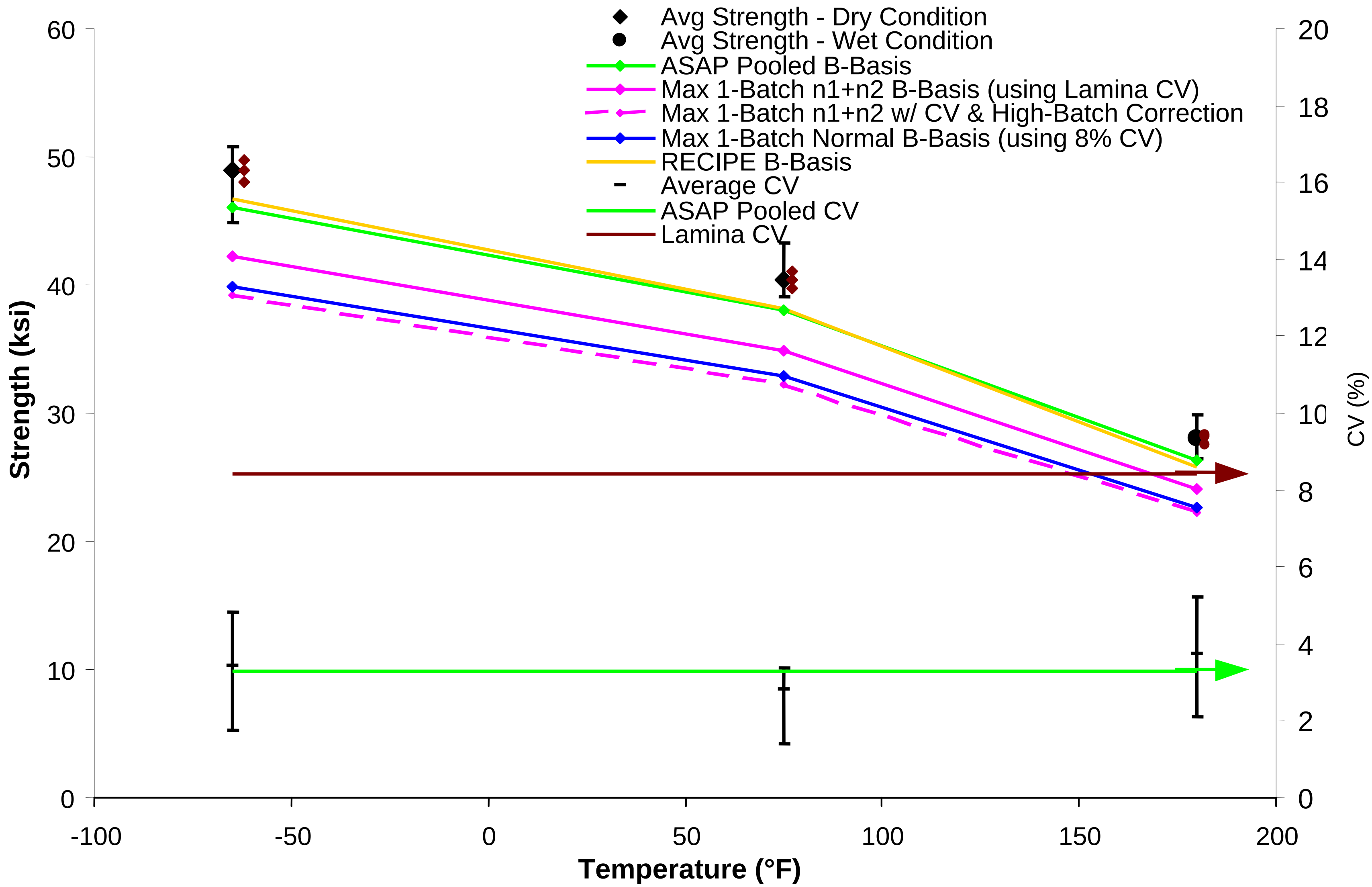

Figure D-17. The 25/50/25 OHC (Normalized) Strength for Toray PW

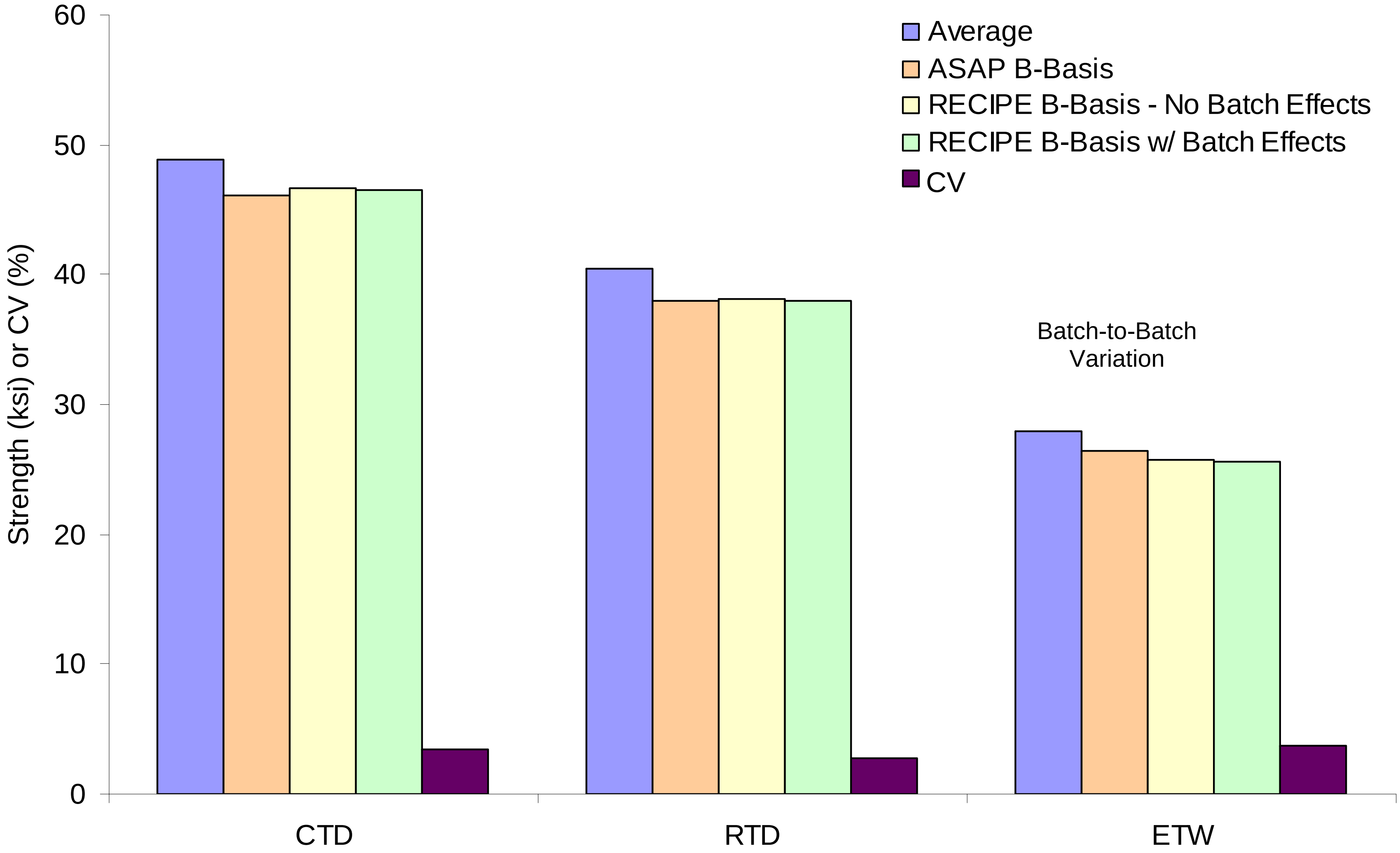

Figure D-18. Comparison of 25/50/25 OHC Strength B-Basis Values for Toray PW

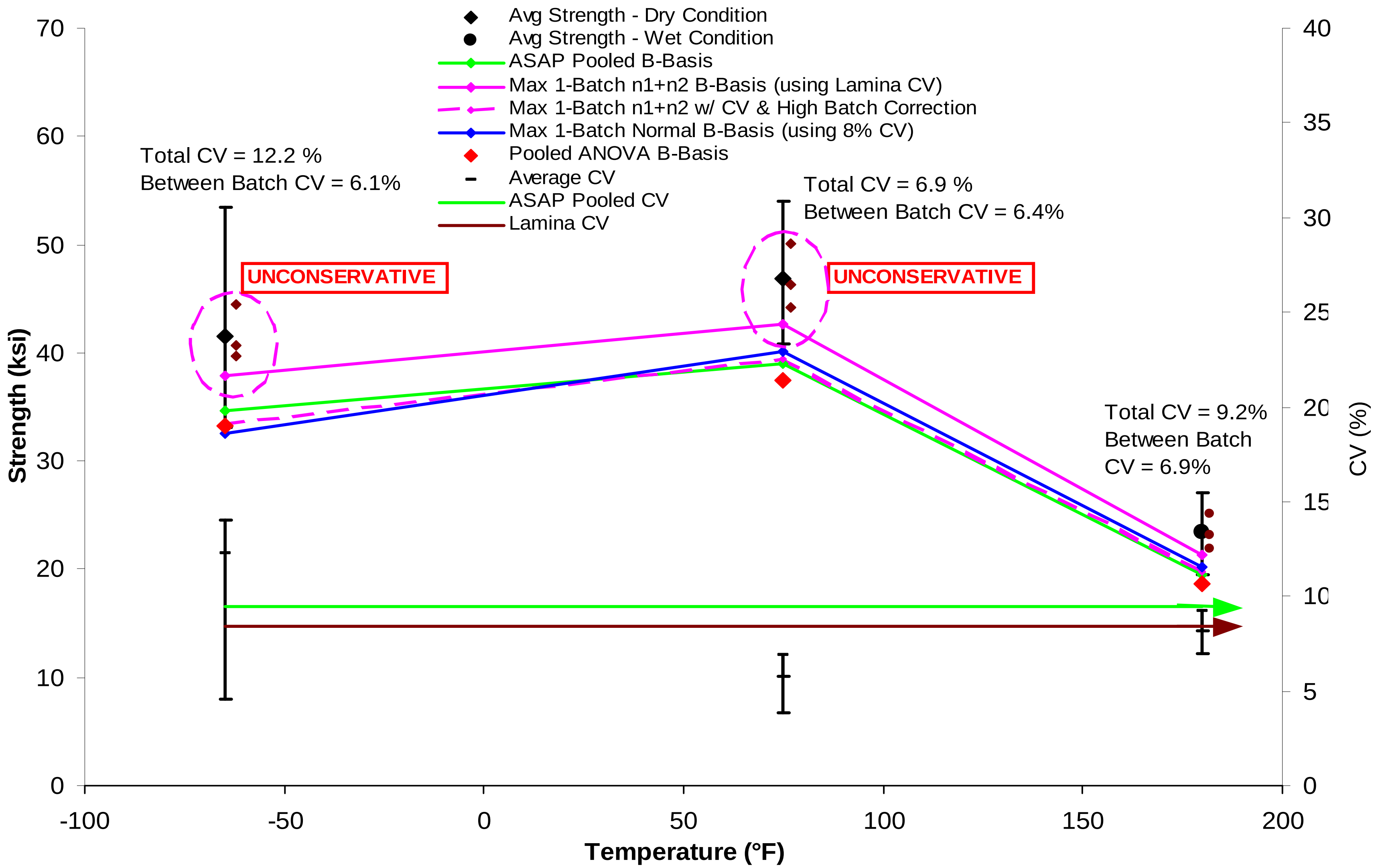

Figure D-19. The 10/80/10 In-Plane Shear (Normalized) Strength for Toray PW

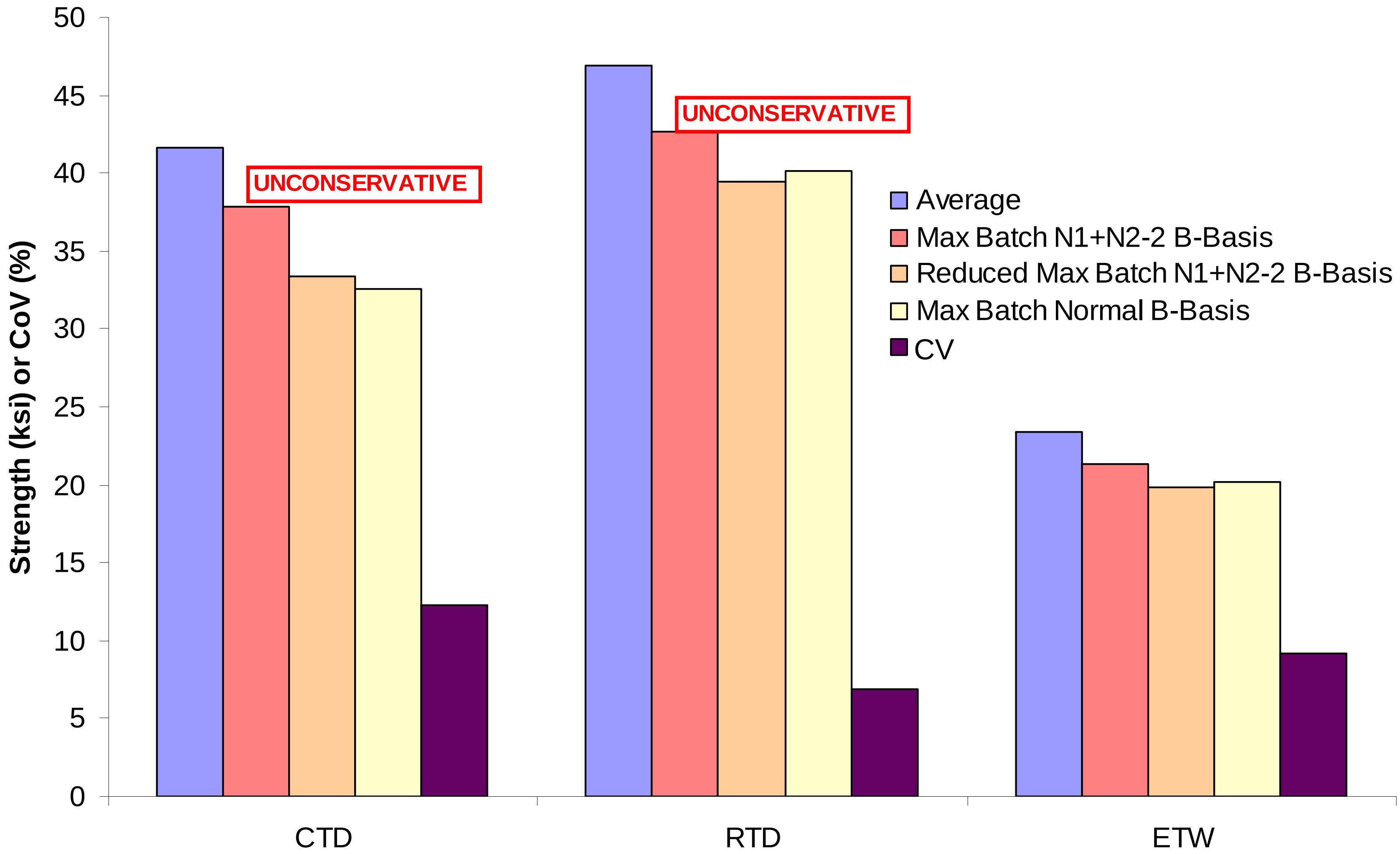

Figure D-20. Comparison of 10/80/10 In-Plane Shear Strength B-Basis Values for Toray PW

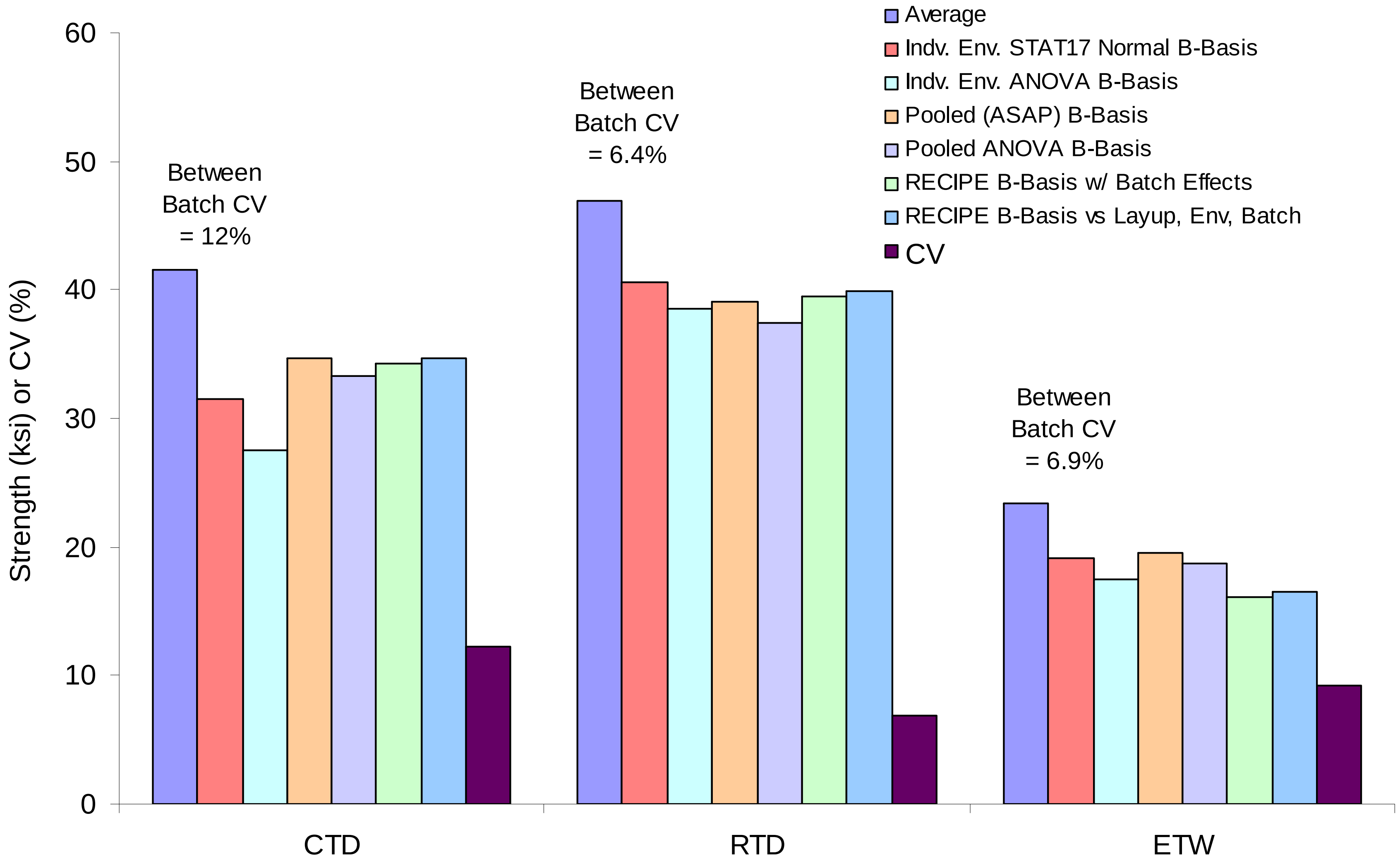

Figure D-21. The 10/80/10 In-Plane Shear (Normalized) Strength for Toray PW (Single Point and Pooled)

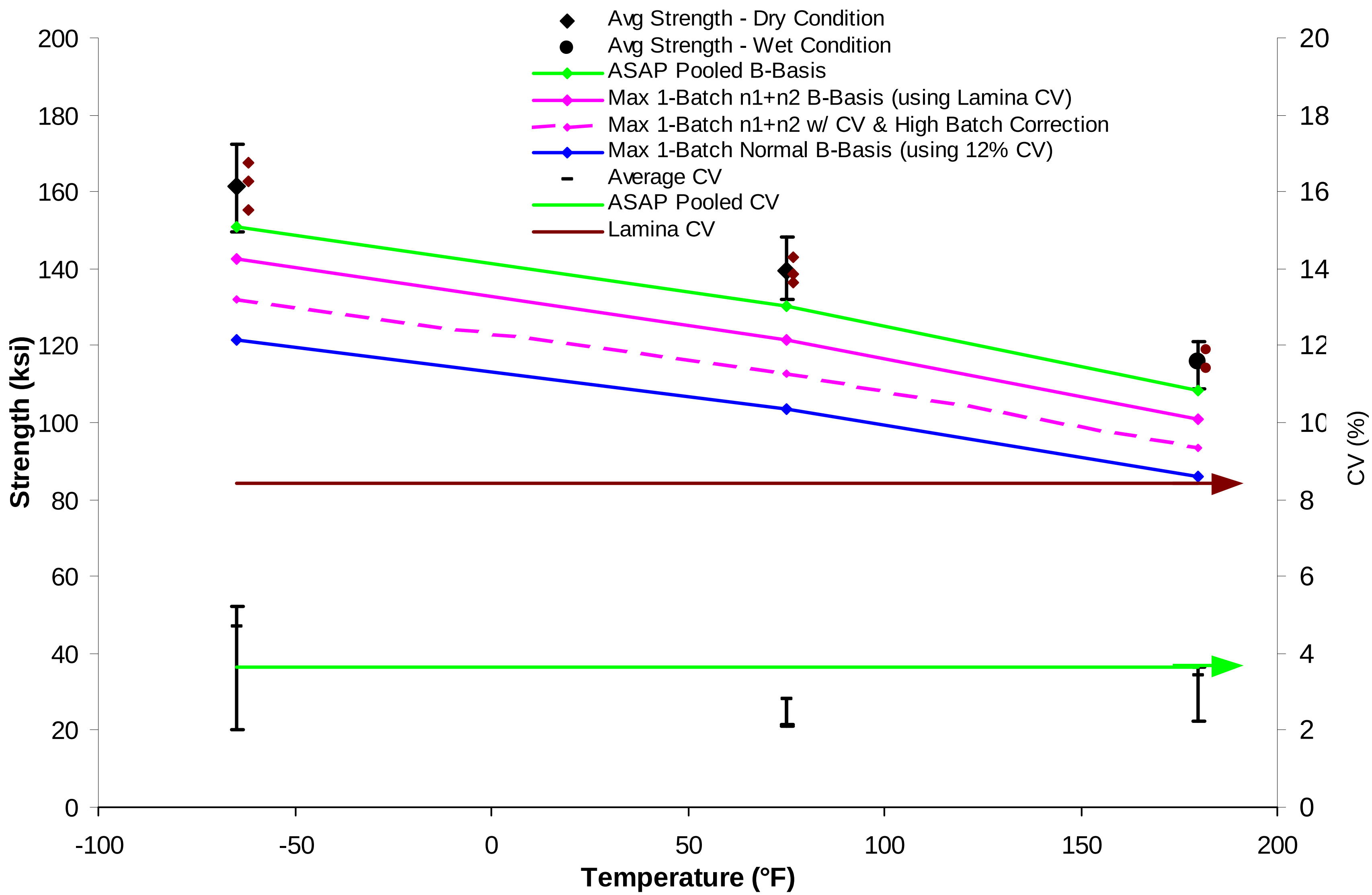

Figure D-22. The 25/50/25 Double-Shear Bearing (Normalized) Strength for Toray PW

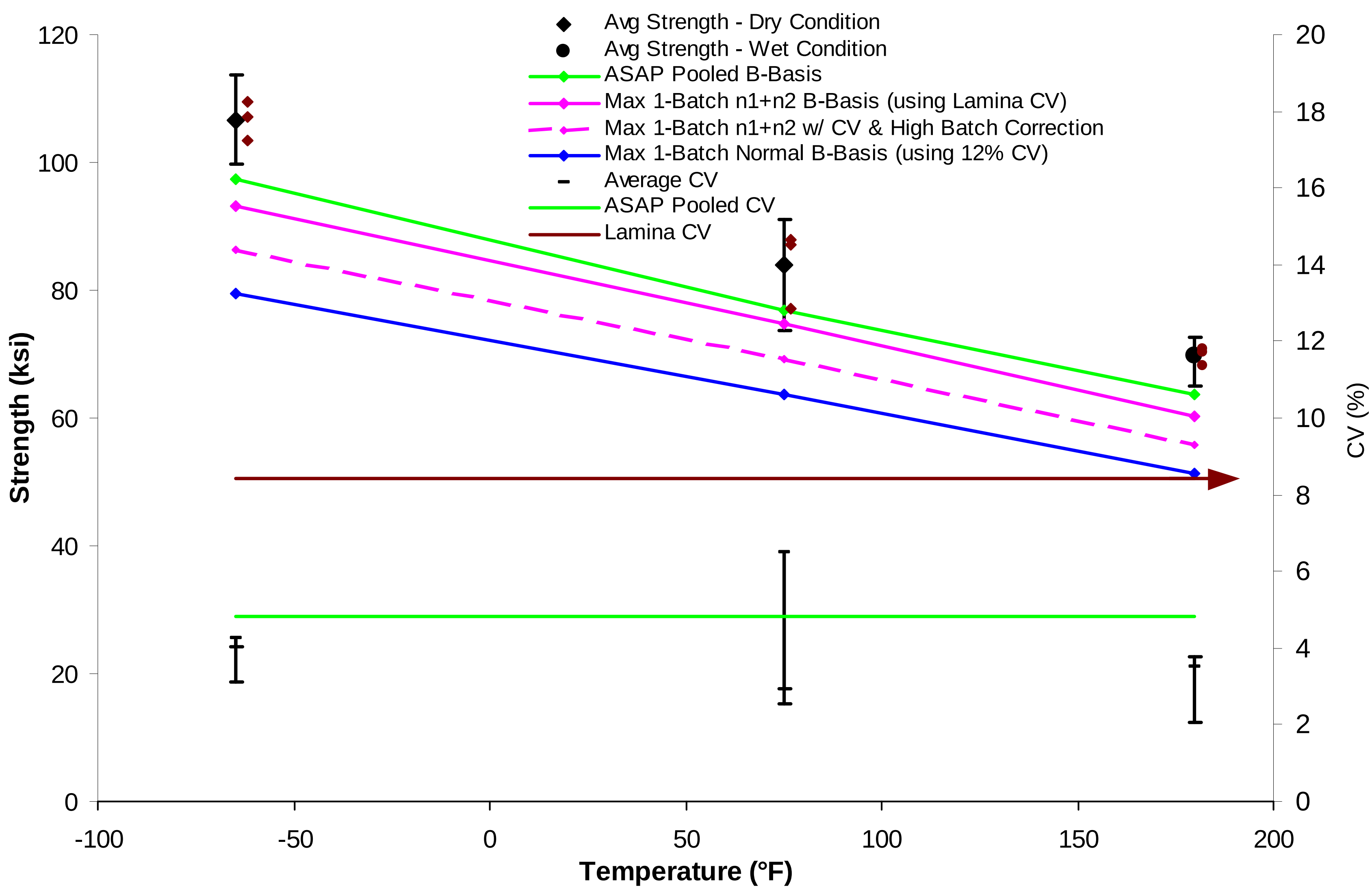

Figure D-23. The 25/50/25 Single-Shear Bearing (Normalized) Strength for Toray PW

D.7 REFERENCES.

D-1. Ward, S.H., "Development and Assessment of Procedures for Generating Statistical Allowables From Composite Laminate Test Data-Analysis of Toray T700/#2510 Uni Tape and PW Fabric Data," Report SWC-2005-01, SW Composites, Taos, NM, February 2005 (http://www.niar.twsu.edu/agate)

D-2. Adams, D.O., Moriarty, J.M., and Gallegos, A.M., "Development and Evaluation of a V-Notched Rail Shear Test," *34th International SAMPE Technical Conference*, Baltimore, MD, November 4-7, 2002.

D-3. Ridgard, C. and Penn, D., "Design Allowable Property Data Acquisition and Test Plan for MTM45 Prepregs," FAA Special Project SP3505CPN, Advanced Composites Group, Inc., Oklahoma, OK, July 2004.

D-4. "Material Qualification for Polymer Matrix Composite Material Systems-Advanced Composites Group MTM45/6K 5HS AS4C Graphite Fabric Prepreg," NIAR Report #2005-03, National Institute for Aviation Research, Wichita, KS, March 2005.

D-5. "Material Qualification for Polymer Matrix Composite Material Systems-Advanced Composites Group MTM45/AS4C 12K Unidirectional Prepreg," NIAR Report, National Institute for Aviation Research, Wichita, KS.

APPENDIX E—TORAY LAMINATE DATA SUMMARY

This section contains the summary sheets for Toray tape and plain weave (PW) materials using the format recommended in Military Handbook (MIL-HDBK)-17. The nomenclature used in figures is as follows:

5SH	Five-harness fabric
ACG	Advanced Composite Group
ASAP	AGATE Statistical Allowable Program
BB(50%)T	Single shear, double-fastener bearing (50% bypass) tension
BB(50%)C	Single-shear, double fastener bearing (50% bypass) compression
CV or CoV	Coefficient of variation
DSBT	Double-shear bearing tension
FHC	Filled-hole compression
FHT	Filled-hole tension
LVM	Lamina Variability Method
n	Number of test specimens
NHC	No-hole compression
NHT	No-hole tension
OHC	Open-hole compression
OHT	Open-hole tension
PB	Single-shear, single-fastener (with stabiling fixture)
SSBT	Single-shear, single-fastener bearing tension
VNRS	V-notched rail shear

No Hole Tension
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 33.287-37.671(%) **Comp. density: 1.513 - 1.625** g/cc

Fiber volume: 53.296-59.15 %(v)

Ply thickness: 0.0057-0.0062 inch

Test method: ASTM D5766-02a (modified) **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						**RTD (A)**						**ETW (F)**					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDJXX1B						DDJXX1A						DDJXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**
	Mean			88.009	88.220			159.534	160.263	95.227	94.870	53.107	53.002			98.958	99.158		
	Minimum			82.953	81.039			146.121	144.085	88.621	88.290	47.675	47.125			89.896	92.762		
	Maximum			91.896	92.614			175.142	179.454	100.650	101.071	57.950	58.891			102.078	106.179		
	C.V.(%)			2.713	3.248			5.157	5.597	3.020	3.533	5.852	6.849			3.291	3.453		
F^{NHT}	**B-value**			84.127	82.996			143.364	142.633	91.026	89.253	46.913	45.767			95.489	93.286		
(ksi)	**A-value**																		
	No. Specimens			18				19		18		18				18			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			6.764	6.780			10.453	10.501	6.729	6.703	4.357	4.346			6.662	6.683		
	Minimum			6.595	6.587			10.175	10.065	6.628	6.558	4.253	4.220			6.285	6.208		
	Maximum			6.897	7.012			11.098	11.217	6.916	6.918	4.453	4.482			7.085	7.008		
E^{NHT}	**C.V.(%)**			1.127	1.648			1.835	2.791	1.106	1.554	1.402	1.861			3.107	3.164		
(Msi)																			
	No. Specimens			18				19		18		18				19			
	No. Prepreg Lots			3				3		3		3				3			

NOTE: 2 outliers in 25/50/25 batch 3 normalized ETW data were removed for ASAP B-basis

Filled HoleTension Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 33.904-3.342 %(w) **Comp. density:** 1.517-1.541 g/cc

Fiber volume: 54.366-56.893 %(v)

Ply thickness: 0-0058-0.0063 inch

Test method: ASTM D6742-02 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDIXX1B						DDIXX1A						DDIXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean	66.826	67.545					71.991	72.394					85.050	85.424				
	Minimum	62.792	64.672					65.295	66.159					77.601	79.522				
	Maximum	70.424	72.199					80.538	83.411					93.865	91.749				
	C.V.(%)	3.251	3.383					5.375	6.002					5.011	3.917				
F^{FHT}	**B-value**	61.443	62.201					66.192	66.667					78.235	78.701				
(ksi)	**A-value**																		
	No. Specimens	18						18						19					
	No. Prepreg Lots	3						3						3					
	Mean	10.658	10.772					10.182	10.239					10.347	10.398				
	Minimum	10.293	10.417					9.972	9.725					10.105	10.148				
	Maximum	11.002	11.184					10.287	10.650					10.610	10.700				
E^{FHT}	**C.V.(%)**	1.708	1.861					0.847	2.409					1.233	1.689				
(Msi)																			
	No. Specimens	18						18						19					
	No. Prepreg Lots	3						3						3					

Open HoleTension [w/D = 3]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 31.576 - 34.363 %(w) **Comp. density: 1.521-1.545** g/cc

Fiber volume: 55-791-58.970 %(v)

Ply thickness: 0.0058-0.0062 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDXXX1B						DDXXX1A						DDXXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							70.229	70.304										
	Minimum							65.300	64.273										
	Maximum							76.956	78.537										
	C.V.(%)							4.588	5.352										
F^{OHT}	**B-value**							63.809	62.805										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							8.699	8.706										
	Minimum							8.577	8.438										
	Maximum							8.861	9.043										
E^{OHT} (Msi)	**C.V.(%)**							0.884	1.916										
	No. Specimens							18											
	No. Prepreg Lots							3											

Open HoleTension [w/D =4]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 34.519 - 36.218 %(w) **Comp. density:** 1.52 - 1.535 g/cc
Fiber volume: 54.166-56.179 %(v)
Ply thickness: 0.0059-0.0063 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDYXX1B						DDYXX1A						DDYXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							75.443	75.221										
	Minimum							67.730	69.161										
	Maximum							82.267	81.937										
	C.V.(%)							5.641	4.967										
F^{OHT}	**B-value**							66.961	67.775										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							9.596	9.573										
	Minimum							9.396	9.221										
	Maximum							9.699	9.859										
E^{OHT}	**C.V.(%)**							0.856	2.279										
(Msi)																			
	No. Specimens							18											
	No. Prepreg Lots							3											

Open HoleTension [w/D = 6]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 32.957-41.92 %(w) **Comp. density:** 1.519-1.547 g/cc
Fiber volume: 49.745-57.802 %(v)
Ply thickness: 0.0058-0.0074 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDHXX1B						DDHXX1A						DDHXX1F					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean			44.165	44.313					49.513	49.729	41.017	41.295			61.449	61.709		
	Minimum			42.881	41.386					46.701	46.525	39.317	39.443			56.107	56.837		
	Maximum			46.585	47.183					53.672	54.154	42.194	42.477			66.199	66.315		
	C.V.(%)			2.605	3.439					4.226	4.122	1.718	1.930			3.919	3.758		
F^{OHT}	**B-value**			41.362	41.411					46.370	46.473	39.613	39.707			57.606	57.728		
(ksi)	**A-value**																		
	No. Specimens			18						18		18				21			
	No. Prepreg Lots			3						3		3				3			
	Mean			6.625	6.647					6.586	6.616	4.326	4.355			6.444	6.472		
	Minimum			6.536	6.373					6.312	6.346	4.257	4.294			6.355	6.297		
	Maximum			6.732	6.883					6.757	6.774	4.409	4.415			6.535	6.631		
E^{OHT}	**C.V.(%)**			0.836	2.018					1.324	1.784	1.141	0.847			0.860	1.406		
(Msi)																			
	No. Specimens			18						18		18				21			
	No. Prepreg Lots			3						3		3				3			

Open HoleTension [w/D =8]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 34.332 - 35.653 %(w) **Comp. density: 1.524-1.546** g/cc
Fiber volume: 55.557-56.054 %(v)
Ply thickness: 0.0058-0.0062 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDZXX1B						DDZXX1A						DDZXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F^{OHT} (ksi)	**Mean**							80.413	80.696										
	Minimum							72.932	74.600										
	Maximum							85.483	86.468										
	C.V.(%)							3.672	4.048										
	B-value							74.610	74.276										
	A-value																		
	No. Specimens							19											
	No. Prepreg Lots							3											
E^{OHT} (Msi)	**Mean**							10.412	10.449										
	Minimum							10.311	10.219										
	Maximum							10.536	10.819										
	C.V.(%)							0.720	1.600										
	No. Specimens							19											
	No. Prepreg Lots							3											

No Hole Compression Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: N/A **Comp. density:** N/A

Fiber volume: N/A

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D6484-99 (modified **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDKXX1B						DDKXX1A						DDKXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean			93.328	93.908			116.424	117.210	81.121	81.704	52.398	52.429			65.930	66.302		
	Minimum			87.369	86.945			108.813	109.544	73.505	72.136	47.887	48.080			61.794	61.880		
	Maximum			101.583	104.572			124.179	126.123	88.320	90.681	56.168	56.466			69.939	71.033		
	C.V.(%)			4.507	5.794			3.239	3.395	5.152	6.269	4.310	4.670			3.011	3.368		
F^{NHC}	**B-value**			86.338	85.277			109.012	109.388	75.046	74.195	47.897	47.550			60.992	60.209		
(ksi)	**A-value**																		
	No. Specimens			18				19		18		18				18			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			6.430	6.468			9.765	9.829	6.421	6.463	4.260	4.262			6.120	6.147		
	Minimum			6.322	6.263			9.388	9.250	6.120	6.146	4.123	4.122			5.683	5.693		
	Maximum			6.541	6.803			10.452	10.535	6.688	6.910	4.410	4.438			6.435	6.500		
E^{NHC} (Msi)	**C.V.(%)**			1.125	2.618			2.705	3.354	2.230	3.176	1.626	2.011			3.101	3.430		
	No. Specimens			18				18		17		18				17			
	No. Prepreg Lots			3				3		3		3				3			

Open Hole Compression Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 35.688-38.074 %(w) **Comp. density: 1.533-1.549** g/cc

Fiber volume: 53.594-55.1125 %(v)

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D6484-99 (modified **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDLXX1B						DDLXX1A						DDLXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**
	Mean			47.254	47.400			55.991	56.329	41.692	42.024	35.424	35.615			33.547	33.734		
	Minimum			44.528	44.569			50.170	50.358	39.520	39.575	33.297	33.334			30.143	30.045		
	Maximum			49.693	51.131			61.301	62.155	44.842	46.439	36.990	37.290			36.263	37.344		
	C.V.(%)			2.864	4.011			5.082	5.331	3.741	5.090	2.879	3.256			5.476	5.439		
F^{OHC}	**B-value**			43.863	43.461			50.532	50.567	38.655	38.480	33.392	33.304			31.150	30.943		
(ksi)	**A-value**																		
	No. Specimens			21				21		18		18				22			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			6.109	6.126			9.201	9.255	6.045	6.093	4.076	4.098			6.061	6.095		
	Minimum			5.774	5.818			8.713	8.543	5.786	5.785	3.936	3.949			5.404	5.479		
	Maximum			6.775	6.798			9.662	9.797	6.257	6.503	4.244	4.264			6.544	6.730		
E^{OHC} (Msi)	**C.V.(%)**			3.556	3.800			3.085	3.118	2.140	3.548	1.621	1.999			4.470	4.530		
	No. Specimens			21				20		18		18				22			
	No. Prepreg Lots			3				3		3		3				3			

Double Shear Bearing-Tension
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 33.664-37.74 %(w) **Comp. density: 1.506-1.545** g/cc

Fiber volume: 52.764-57.148 %(v)

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

CTD (B)

Test Temperature [°F]	-65					
Moisture Conditioning	dry					
Equilibrium at T, RH	as fabricated					
Source code	DD1XX1B					
Laminate Layup [%, 0°/45°/90°]	**50/40/10**		**25/50/25**		**10/80/10**	
	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi) Mean			158.237	159.981		
Minimum			143.977	147.905		
Maximum			167.904	170.750		
C.V.(%)			3.978	3.915		
B-value			136.301	137.574		
A-value						
No. Specimens			22			
No. Prepreg Lots			3			
E_{br} (Msi) Mean			3.354	3.393		
Minimum			2.278	2.326		
Maximum			4.732	4.861		
C.V.(%)			19.398	19.802		
No. Specimens			22			
No. Prepreg Lots			3			

RTD (A)

Test Temperature [°F]	75					
Moisture Conditioning	dry					
Equilibrium at T, RH	as fabricated					
Source code	DD1XX1A					
Laminate Layup [%, 0°/45°/90°]	**50/40/10**		**25/50/25**		**10/80/10**	
	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi) Mean	147.801	149.544	135.276	136.325		
Minimum	141.013	142.857	91.218	90.824		
Maximum	156.289	160.194	156.148	156.671		
C.V.(%)	2.411	3.088	13.475	13.499		
B-value	140.882	140.579	116.264	116.967		
A-value						
No. Specimens	20		19			
No. Prepreg Lots	3		3			
E_{br} (Msi) Mean	4.120	4.171	3.548	3.580		
Minimum	2.861	2.876	2.645	2.621		
Maximum	6.591	6.715	5.466	5.488		
C.V.(%)	17.607	17.745	19.316	19.727		
No. Specimens	21		19			
No. Prepreg Lots	3		3			

ETW (F)

Test Temperature [°F]	180					
Moisture Conditioning	wet					
Equilibrium at T, RH	145°F, 85% RH					
Source code	DD1XX1F					
Laminate Layup [%, 0°/45°/90°]	**50/40/10**		**25/50/25**		**10/80/10**	
	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi) Mean			120.933	122.217		
Minimum			113.446	114.073		
Maximum			126.961	131.221		
C.V.(%)			2.866	3.565		
B-value			103.846	104.769		
A-value						
No. Specimens			18			
No. Prepreg Lots			3			
E_{br} (Msi) Mean			3.447	3.484		
Minimum			2.847	2.902		
Maximum			3.890	3.962		
C.V.(%)			8.576	8.964		
No. Specimens			18			
No. Prepreg Lots			3			

NOTE: 1 outlier in 50/40/10 batch 3 RTD data was removed for ASAP B-basis

Single Shear Bearing-Tension
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 34.378 - 39.202 %(w) **Comp. density:** 1.513-1.549 g/cc

Fiber volume: 52.196-56.662 %(v)

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)					
Test Temperature [°F]		-65					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DD2XX1B					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean			98.838	99.511		
	Minimum			95.379	96.484		
	Maximum			105.117	107.477		
	C.V.(%)			2.327	2.581		
	B-value			89.792	90.626		
	A-value						
	No. Specimens			18			
	No. Prepreg Lots			3			
E_{br} (Msi)	Mean			2.46	2.47		
	Minimum			2.17	2.14		
	Maximum			2.60	2.66		
	C.V.(%)			5.57	6.18		
	No. Specimens			18			
	No. Prepreg Lots			3			

		RTD (A)					
Test Temperature [°F]		75					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DD2XX1A					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean	94.043	94.638	86.699	87.198		
	Minimum	90.032	88.339	79.125	79.539		
	Maximum	97.766	100.252	98.565	98.952		
	C.V.(%)	2.216	3.564	6.475	6.265		
	B-value	89.946	88.009	78.765	79.412		
	A-value						
	No. Specimens	19		18			
	No. Prepreg Lots	3		3			
E_{br} (Msi)	Mean	3.00	3.02	2.41	2.43		
	Minimum	2.73	2.67	2.28	2.27		
	Maximum	3.87	3.82	2.74	2.81		
	C.V.(%)	7.83	7.67	4.51	18.00		
	No. Specimens	19		18			
	No. Prepreg Lots	3		3			

		ETW (F)					
Test Temperature [°F]		180					
Moisture Conditioning		wet					
Equilibrium at T, RH		145°F, 85% RH					
Source code		DD2XX1F					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean			79.198	79.392		
	Minimum			71.112	71.298		
	Maximum			86.728	87.114		
	C.V.(%)			6.015	5.795		
	B-value			71.950	72.303		
	A-value						
	No. Specimens			18			
	No. Prepreg Lots			3			
E_{br} (Msi)	Mean			2.39	2.40		
	Minimum			1.92	1.95		
	Maximum			3.86	3.92		
	C.V.(%)			18.29	18.58		
	No. Specimens			18			
	No. Prepreg Lots			3			

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 34.677-41.621 %(w) **Comp. density:** 1.494-1.545 g/cc
Fiber volume: 48.736-55.833%(v)
Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

Bearing-Bypass 50%, Tension
[t/D = 0.32]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDAXX1B						DDAXX1A						DDAXX1F					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							87.28	87.53										
	Minimum							79.92	79.65										
	Maximum							90.62	92.24										
	C.V.(%)							3.31	4.34										
F_{br}	B-value																		
(ksi)	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							29.17	29.25										
	Minimum							26.76	26.67										
	Maximum							30.22	30.80										
	C.V.(%)							3.28	4.31										
F_{br}^{gross}	B-value							27.26	26.74										
(ksi)	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							14.58	14.63										
	Minimum							13.38	13.34										
	Maximum							15.11	15.40										
	C.V.(%)							3.28	4.31										
F_{br}^{net}	B-value							13.63	13.37										
(ksi)	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							2.85	2.86										
	Minimum							2.53	2.54										
	Maximum							3.25	3.30										
E_{br}	C.V.(%)							5.47	6.10										
(Msi)																			
	No. Specimens							18											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Bearing-Bypass 50%, Tension
[t/D = 0.384]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 34.516-37.714 %(w) **Comp. density:** 1.519-1.537g/cc
Fiber volume: 52.882-56.247 %(v)
Ply thickness: 0.0058 - 0.0061 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDBXX1B						DDBXX1A						DDBXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							88.800	89.108										
	Minimum							84.294	82.650										
	Maximum							91.685	93.688										
	C.V.(%)							2.581	3.490										
F_{br}	**B-value**																		
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							29.728	29.831										
	Minimum							28.278	27.715										
	Maximum							30.692	31.386										
	C.V.(%)							2.562	3.476										
F_{br}^{gross}	**B-value**							28.152	27.764										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							14.864	14.915										
	Minimum							14.139	13.857										
	Maximum							15.346	15.693										
	C.V.(%)							2.562	3.476										
F_{br}^{net}	**B-value**																		
(ksi)	**A-value**							14.105	13.882										
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							2.709	2.718										
	Minimum							2.568	2.533										
	Maximum							2.953	2.982										
E_{br}	**C.V.(%)**							3.403	4.201										
(Msi)																			
	No. Specimens							18											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Bearing-Bypass 50%, Tension
[t/D = 0.48]
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 30.021-43.131 %(w) **Comp. density:** 1.507-1.555 g/cc

Fiber volume: 47.88-59.337 %(v)

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DD3XX1B						DD3XX1A						DD3XX1F					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean							90.72	91.25	82.02	82.76	88.70	88.88						
	Minimum							87.55	86.39	79.98	78.24	86.33	84.56						
	Maximum							93.57	96.19	84.24	85.76	91.46	92.82						
	C.V.(%)							1.89	2.73	1.48	2.53	1.68	2.77						
	B-value																		
	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
F_{br}^{gross} (ksi)	Mean							30.26	30.43	26.81	27.05	27.79	27.85						
	Minimum							29.15	28.81	25.05	25.75	26.69	26.15						
	Maximum							31.20	32.07	28.08	28.58	30.50	30.96						
	C.V.(%)							1.93	2.75	3.42	3.02	3.49	4.48						
	B-value							29.03	28.68	24.89	25.34	25.76	25.24						
	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
F_{br}^{net} (ksi)	Mean							15.13	15.22	13.41	13.52	13.90	13.93						
	Minimum							14.57	14.41	12.52	12.87	13.35	13.07						
	Maximum							15.60	16.04	14.04	14.29	15.25	15.48						
	C.V.(%)							1.93	2.75	3.42	3.02	3.49	4.48						
	B-value							14.52	14.34	12.44	12.67	12.88	12.62						
	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
E_{br} (Msi)	Mean							2.44	2.45	2.01	2.03	1.94	1.94						
	Minimum							2.33	2.27	1.92	1.90	1.84	1.82						
	Maximum							2.73	2.78	2.13	2.13	2.06	2.08						
	C.V.(%)							4.52	5.45	2.69	3.70	3.59	3.73						
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 35.252-43.43 %(w) **Comp. density:** 1.503-1.548 g/cc
Fiber volume: 47.5-56.005 %(v)
Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

Bearing-Bypass 50%, Tension
[t/D = 0.64]
Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDCXX1B						DDCXX1A						DDCXX1F					
Laminate Layup [%, 0°/45°/90°]		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10		50/40/10		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean							91.08	91.56										
	Minimum							85.84	85.29										
	Maximum							95.88	98.53										
	C.V.(%)							2.68	3.88										
	B-value																		
	A-value																		
	No. Specimens							17											
	No. Prepreg Lots							3											
F_{br}^{gross} (ksi)	Mean							30.68	30.84										
	Minimum							28.94	28.75										
	Maximum							32.32	33.21										
	C.V.(%)							2.67	3.97										
	B-value							29.02	28.37										
	A-value																		
	No. Specimens							17											
	No. Prepreg Lots							3											
F_{br}^{net} (ksi)	Mean							15.34	15.42										
	Minimum							14.47	14.38										
	Maximum							16.16	16.61										
	C.V.(%)							2.67	3.97										
	B-value							14.51	14.18										
	A-value																		
	No. Specimens							17											
	No. Prepreg Lots							3											
E_{br} (Msi)	Mean							2.25	2.27										
	Minimum							2.01	2.05										
	Maximum							2.61	2.69										
	C.V.(%)							6.32	7.45										
	No. Specimens							17											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: N/A **Comp. density:** N/A

Fiber volume: N/A

Ply thickness: 0.0058 - 0.0062 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

Bearing-Bypass 50%,Compression
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DD4XX1B						DD4XX1A						DD4XX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							91.04	91.36	83.89	84.43	90.51	91.37						
	Minimum							83.14	84.22	80.55	78.11	86.16	84.92						
	Maximum							96.42	100.04	86.91	89.23	93.90	95.11						
	C.V.(%)							3.05	3.80	1.97	3.44	2.40	2.75						
F_{br}	**B-value**																		
(ksi)	**A-value**																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							30.36	30.47	27.98	28.16	30.17	30.45						
	Minimum							27.72	28.08	26.91	26.09	28.73	28.32						
	Maximum							32.16	33.36	28.98	29.75	31.29	31.69						
	C.V.(%)							3.05	3.81	1.90	3.36	2.40	2.72						
F_{br}^{gross}	**B-value**							28.41	27.97	26.87	26.18	28.65	28.71						
(ksi)	**A-value**																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							30.36	30.47	27.98	28.16	30.17	30.45						
	Minimum							27.72	28.08	26.91	26.09	28.73	28.32						
	Maximum							32.16	33.36	28.98	29.75	31.29	31.69						
	C.V.(%)							3.05	3.81	1.90	3.36	2.40	2.72						
F_{br}^{net}	**B-value**							28.41	27.97	26.87	26.18	28.65	28.71						
(ksi)	**A-value**																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							3.16	3.18	2.59	2.61	2.59	2.61						
	Minimum							2.66	2.69	2.43	2.40	2.40	2.44						
	Maximum							3.41	3.50	2.76	2.81	2.73	2.74						
E_{br}	**C.V.(%)**							5.92	6.98	3.66	4.84	4.23	4.01						
(Msi)																			
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

V-Notched Rail Shear
Shear Strength & Modulus
Gr/ Ep
T700-12K-31E/#2510 Unidirectional Tape

Material: T700-12K-31E/#2510 Unidirectional Tape

Resin content: 35.539-38.643 %(w) **Comp. density:** 1.504-1.58 g/cc

Fiber volume: 53.040-55.123 %(v)

Ply thickness: 0.0059 - 0.0062 inch

Test method: ASTM D7078 * **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0060 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DDVXX1B						DDVXX1A						DDVXX1F					
Laminate Layup [%, 0°/45°/90°]		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**		**50/40/10**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							43.867	43.911										
	Minimum							41.456	41.543										
	Maximum							47.189	47.959										
	C.V.(%)							3.977	4.443										
$F_{12}^{0.2\% offse}$	**B-value**							34.363	34.626										
(ksi)	**A-value**																		
	No. Specimens							7											
	No. Prepreg Lots							3											
	Mean					48.884	48.826	44.094	44.226	30.974	31.066	59.303	59.249					32.534	32.559
	Minimum					38.521	39.067	38.792	38.352	25.496	24.963	54.526	54.709					30.367	30.504
	Maximum					63.637	63.163	53.296	53.074	37.595	38.697	65.562	65.331					35.292	34.972
F_{12}^{ult}	**C.V.(%)**					14.707	14.114	11.074	10.892	12.028	12.341	4.997	4.590					4.990	4.804
(ksi)																			
	B-value					40.834	41.138	34.363	34.626	23.549	23.425	49.537	49.920					27.146	27.403
	A-value					35.460	36.006					43.018	43.692					23.575	23.986
	No. Specimens					18		18		18		18						17	
	No. Prepreg Lots					3		3		3		3						3	
	Mean					3.618	3.616	2.087	2.094	2.489	2.496	3.663	3.660					3.542	3.546
	Minimum					3.451	3.448	2.022	1.986	2.442	2.367	3.583	3.582					3.207	3.253
	Maximum					3.856	3.883	2.143	2.147	2.554	2.592	3.788	3.787					3.671	3.668
G_{12}^{s}	**C.V.(%)**					3.407	3.205	1.526	1.873	1.361	2.424	1.525	1.265					3.247	2.900
(Msi)																			
	No. Specimens					18		18		18		18						18	
	No. Prepreg Lots					3		3		3		3						3	

NOTE: * - Standard was under development during the testing phase of this research
1 outlier in 10/80/10 batch 1 ETW data was removed for ASAP B-basis

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.081 - 48.73 %(w) **Comp. density:** 1.503-1.527 g/cc

Fiber volume: 43.634-50.977 %(v)

Ply thickness: 0.0082-0.0086 inch

Test method: ASTM D5766-02a (modifie **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

No Hole Tension
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGJXX1B						DGJXX1A						DGJXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**	**Normalized**	**Measured**
	Mean			93.917	95.877			124.688	127.966	96.476	99.013	56.866	57.818			93.661	95.332		
	Minimum			89.001	90.548			115.035	117.471	92.449	94.033	55.193	56.255			89.489	90.155		
	Maximum			97.088	99.420			130.755	137.050	102.428	105.567	58.817	60.134			99.651	100.978		
	C.V.(%)			2.302	2.483			3.938	4.507	3.099	3.521	2.223	1.962			3.260	3.568		
F^{NHT}	**B-value**			89.165	90.505			114.903	116.472	91.594	93.466	54.381	55.588			88.921	89.991		
(ksi)	**A-value**																		
	No. Specimens			18				18		18		19				18			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			5.904	6.027			7.351	7.544	5.760	5.911	3.773	3.837			5.709	5.810		
	Minimum			5.728	5.827			7.108	7.258	5.571	5.732	3.659	3.706			5.378	5.480		
	Maximum			6.048	6.202			7.568	7.829	5.943	6.116	3.849	3.928			5.976	6.277		
E^{NHT}	**C.V.(%)**			1.600	1.891			1.664	2.401	1.910	2.121	1.444	1.633			2.897	3.346		
(Msi)																			
	No. Specimens			18				18		18		19				18			
	No. Prepreg Lots			3				3		3		3				3			

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.02-48.074 %(w) **Comp. density:** 1.5-1.526 g/cc

Fiber volume: 44.539-51.368%(v)

Ply thickness: 0-0082-0.0086 inch

Test method: ASTM D6742-02 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

Filled Hole Tension Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGTXX1B **						DDIXX1A						DGTXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F^FHT (ksi)	**Mean**	59.583	60.630					62.854	64.185					75.250	76.448				
	Minimum	54.486	55.252					56.108	57.678					69.276	70.876				
	Maximum	62.668	64.266					67.942	70.051					81.693	83.168				
	C.V.(%)	3.984	4.383					5.871	5.946					4.824	4.418				
	B-value	54.495	55.428					57.486	56.684					68.789	69.854				
	A-value																		
	No. Specimens	19						19						18					
	No. Prepreg Lots	3						3						3					
E^FHT (Msi)	**Mean**	7.074	7.198					7.228	7.380					7.249	7.366				
	Minimum	6.925	6.960					7.060	7.116					6.956	7.015				
	Maximum	7.288	7.469					7.462	7.602					7.482	7.649				
	C.V.(%)	1.381	1.957					1.576	1.829					1.923	2.387				
	No. Specimens	19						18						18					
	No. Prepreg Lots	3						3						3					

**** Filled Hole case was the critical among RTD testing.**

Filled Hole Tension Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.02-48.074 %(w) **Comp. density:** 1.5-1.526 g/cc

Fiber volume: 44.539-51.368%(v)

Ply thickness: 0-0082-0.0086 inch

Test method: ASTM D6742-02 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGTXX1B **						DDIXX1A						DGTXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean	59.583	60.630					62.854	64.185					75.250	76.448				
	Minimum	54.486	55.252					56.108	57.678					69.276	70.876				
	Maximum	62.668	64.266					67.942	70.051					81.693	83.168				
	C.V.(%)	3.984	4.383					5.871	5.946					4.824	4.418				
F^{FHT}	**B-value**	54.495	55.428					57.486	56.684					68.789	69.854				
(ksi)	**A-value**																		
	No. Specimens	19						19						18					
	No. Prepreg Lots	3						3						3					
	Mean	7.074	7.198					7.228	7.380					7.249	7.366				
	Minimum	6.925	6.960					7.060	7.116					6.956	7.015				
	Maximum	7.288	7.469					7.462	7.602					7.482	7.649				
E^{FHT}	**C.V.(%)**	1.381	1.957					1.576	1.829					1.923	2.387				
(Msi)																			
	No. Specimens	19						18						18					
	No. Prepreg Lots	3						3						3					

**** Filled Hole case was the critical among RTD testing.**

Open HoleTension [w/D = 3]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 41.529-43.052 %(w) **Comp. density:** 1.518-1.521 g/cc

Fiber volume: 48.587-49.977 %(v)

Ply thickness: 0.0082-0.0086 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGXXX1B						DGXXX1A						DGXXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							59.638	60.953										
	Minimum							54.269	54.575										
	Maximum							66.327	69.057										
	C.V.(%)							5.903	6.662										
F^{OHT}	**B-value**							52.621	52.860										
(ksi)	**A-value**																		
	No. Specimens							20											
	No. Prepreg Lots							3											
	Mean							6.117	6.249										
	Minimum							5.989	6.089										
	Maximum							6.256	6.417										
E^{OHT}	**C.V.(%)**							1.227	1.718										
(Msi)																			
	No. Specimens							20											
	No. Prepreg Lots							3											

Open HoleTension [w/D = 4]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.018-41.633 %(w) **Comp. density:** 1.503-1.507 g/cc
Fiber volume: 49.3-50.806 %(v)
Ply thickness: 0.0083-0.0085 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGYXX1B						DGYXX1A						DGYXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							63.222	64.653										
	Minimum							58.658	59.326										
	Maximum							68.070	69.734										
	C.V.(%)							4.414	4.705										
F^{OHT}	**B-value**							57.660	58.591										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							6.675	6.825										
	Minimum							6.546	6.605										
	Maximum							6.834	7.057										
E^{OHT} (Msi)	**C.V.(%)**							1.266	1.786										
	No. Specimens							18											
	No. Prepreg Lots							3											

Open HoleTension [w/D = 6]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.509-44.274%(w) **Comp. density:** 1.503-1.535 g/cc
Fiber volume: 47.255-50.985 %(v)
Ply thickness: 0.0082-0.0086 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGHXX1B						DGHXX1A						DGHXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean			50.825	52.064			66.530	68.106	54.519	55.613	41.108	41.971			61.109	62.166		
	Minimum			48.228	49.175			61.825	63.417	50.125	51.716	38.669	38.557			55.606	56.246		
	Maximum			54.853	57.985			71.889	73.024	57.646	59.027	42.511	43.626			66.774	67.851		
	C.V.(%)			3.454	4.141			4.521	4.436	3.422	3.436	2.285	2.984			4.784	4.683		
F^{OHT}	**B-value**			47.315	48.322			60.692	62.242	50.754	51.615	39.236	39.475			56.950	57.764		
(ksi)	**A-value**																		
	No. Specimens			18				20		18		18				21			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			5.638	5.775			7.135	7.306	5.698	5.813	3.762	3.841			5.572	5.669		
	Minimum			5.340	5.465			7.006	7.076	5.554	5.636	3.660	3.649			5.385	5.447		
	Maximum			5.787	6.069			7.221	7.514	5.793	6.064	3.819	3.954			5.723	5.906		
E^{OHT}	**C.V.(%)**			1.774	2.523			0.890	1.887	1.018	1.779	1.119	1.822			1.711	2.035		
(Msi)																			
	No. Specimens			18				20		18		18				21			
	No. Prepreg Lots			3				3		3		3				3			

Open HoleTension [w/D = 8]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 39.947-41.247 %(w) **Comp. density:** 1.515-1.519 g/cc

Fiber volume: 50.03-51.276%(v)

Ply thickness: 0.0083-0.0085 inch

Test method: ASTM D5766-02a **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGZXX1B						DGZXX1A						DGZXX1F					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F^{OHT} (ksi)	Mean							69.266	70.572										
	Minimum							64.508	65.602										
	Maximum							76.242	77.366										
	C.V.(%)							4.386	4.601										
	B-value							63.212	64.101										
	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
E^{OHT} (Msi)	Mean							7.318	7.456										
	Minimum							7.198	7.289										
	Maximum							7.456	7.649										
	C.V.(%)							1.100	1.574										
	No. Specimens							18											
	No. Prepreg Lots							3											

No Hole Compression Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: N/A **Comp. density:** N/A

Fiber volume: N/A

Ply thickness: 0.0083 - 0.0086 inch

Test method: ASTM D6484-99 (modified **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

CTD (B)

Test Temperature [°F]		-65					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DGKXX1B					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F^{NHC} (ksi)	**Mean**			86.407	87.890		
	Minimum			80.983	82.288		
	Maximum			92.505	94.990		
	C.V.(%)			3.856	4.462		
	B-value			80.421	80.867		
	A-value						
	No. Specimens			18			
	No. Prepreg Lots			3			
E^{NHC} (Msi)	**Mean**			5.601	5.696		
	Minimum			5.359	5.503		
	Maximum			5.716	5.861		
	C.V.(%)			1.764	1.905		
	No. Specimens			18			
	No. Prepreg Lots			3			

RTD (A)

Test Temperature [°F]		75					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DGKXX1A					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F^{NHC} (ksi)	**Mean**	77.347	78.918	74.367	75.899	49.397	50.341
	Minimum	69.195	71.233	67.140	68.867	46.395	47.486
	Maximum	84.725	87.242	79.929	82.507	51.427	53.164
	C.V.(%)	5.727	5.836	4.316	4.450	3.287	3.416
	B-value	68.519	69.740	69.214	69.834	46.160	46.913
	A-value						
	No. Specimens	18		18		18	
	No. Prepreg Lots	3		3		3	
E^{NHC} (Msi)	**Mean**	6.814	6.953	5.508	5.622	3.704	3.775
	Minimum	6.612	6.688	5.376	5.420	3.577	3.639
	Maximum	7.001	7.153	5.665	5.796	3.806	3.865
	C.V.(%)	1.381	2.024	1.506	1.851	1.643	1.766
	No. Specimens	18		18		18	
	No. Prepreg Lots	3		3		3	

ETW (F)

Test Temperature [°F]		180					
Moisture Conditioning		wet					
Equilibrium at T, RH		145°F, 85% RH					
Source code		DGKXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F^{NHC} (ksi)	**Mean**			47.543	48.454		
	Minimum			41.220	42.349		
	Maximum			51.075	52.043		
	C.V.(%)			4.913	4.887		
	B-value			44.576	44.603		
	A-value						
	No. Specimens			19			
	No. Prepreg Lots			3			
E^{NHC} (Msi)	**Mean**			5.392	5.493		
	Minimum			5.245	5.327		
	Maximum			5.591	5.735		
	C.V.(%)			1.557	1.931		
	No. Specimens			18			
	No. Prepreg Lots			3			

NOTE: 1 outlier in 25/50/25 batch 3 normalized ETW data was removed for ASAP B-basis

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: N/A **Comp. density:** N/A

Fiber volume: N/A

Ply thickness: 0.0081 - 0.0086 inch

Test method: ASTM D6484-99 (modified **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

Open Hole Compression Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGLXX1B						DGLXX1A						DGLXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean			48.901	49.644			43.435	44.307	40.398	41.205	34.373	34.814			27.980	28.462		
	Minimum			44.906	44.961			40.843	41.344	39.103	39.302	32.432	32.933			26.455	26.523		
	Maximum			50.781	51.659			46.487	48.410	43.224	43.802	35.260	35.899			29.839	30.332		
	C.V.(%)			3.429	3.925			4.077	5.300	2.786	3.304	2.322	2.234			3.725	3.843		
F^{NHC}	**B-value**			46.073	46.472			39.954	39.691	38.050	38.558	32.783	33.264			26.377	26.660		
(ksi)	**A-value**																		
	No. Specimens			19				19		18		18				21			
	No. Prepreg Lots			3				3		3		3				3			
	Mean			5.694	5.781			6.674	6.800	5.433	5.541	3.675	3.722			5.281	5.371		
	Minimum			5.019	5.155			6.362	6.494	5.273	5.315	3.552	3.603			4.847	4.901		
	Maximum			6.474	6.561			7.160	7.272	5.735	5.783	3.789	3.844			5.655	5.671		
E^{NHC}	**C.V.(%)**			7.622	7.032			3.448	3.431	2.523	2.636	2.183	2.023			4.238	4.038		
(Msi)																			
	No. Specimens			17				18		18		18				21			
	No. Prepreg Lots			3				3		3		3				3			

Double Shear Bearing-Tension
Bearing Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.727-44.409 %(w) **Comp. density:** 1.502-1.258 g/cc

Fiber volume: 46.929-50.537 %(v)

Ply thickness: 0.0081 - 0.0086 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)					
Test Temperature [°F]		-65					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DG1XX1B					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	**Mean**			161.484	165.869		
	Minimum			149.710	152.114		
	Maximum			172.153	182.083		
	C.V.(%)			4.678	5.753		
	B-value			151.059	153.477		
	A-value						
	No. Specimens			17			
	No. Prepreg Lots			3			
E_{br} (Msi)	**Mean**			2.922	2.988		
	Minimum			2.136	2.150		
	Maximum			3.483	3.577		
	C.V.(%)			11.063	11.724		
	No. Specimens			18			
	No. Prepreg Lots			3			

		RTD (A)					
Test Temperature [°F]		75					
Moisture Conditioning		dry					
Equilibrium at T, RH		as fabricated					
Source code		DG1XX1A					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	**Mean**	109.745	112.570	139.411	143.091		
	Minimum	104.055	105.559	131.915	136.273		
	Maximum	116.174	118.324	148.296	152.822		
	C.V.(%)	2.502	2.654	2.794	3.033		
	B-value	104.848	107.243	130.461	132.401		
	A-value						
	No. Specimens	30		18			
	No. Prepreg Lots	3		3			
E_{br} (Msi)	**Mean**	2.631	2.699	2.838	2.914		
	Minimum	2.157	2.210	2.570	2.608		
	Maximum	3.663	3.823	3.138	3.284		
	C.V.(%)	12.965	13.121	6.240	6.628		
	No. Specimens	30		18			
	No. Prepreg Lots	3		3			

		ETW (F)					
Test Temperature [°F]		180					
Moisture Conditioning		wet					
Equilibrium at T, RH		145°F, 85% RH					
Source code		DG1XX1F					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	**Mean**			115.711	118.069		
	Minimum			108.710	111.048		
	Maximum			121.106	125.300		
	C.V.(%)			3.438	3.654		
	B-value			108.283	109.248		
	A-value						
	No. Specimens			18			
	No. Prepreg Lots			3			
E_{br} (Msi)	**Mean**			2.921	2.981		
	Minimum			2.396	2.419		
	Maximum			3.375	3.496		
	C.V.(%)			11.923	12.158		
	No. Specimens			18			
	No. Prepreg Lots			3			

Single Shear Bearing-Tension
Bearing Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 38.865-46.336 %(w) **Comp. density:** 1.493-1.531 g/cc

Fiber volume: 45.032-52.2 %(v)

Ply thickness: 0.0082 - 0.0086 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DG2XX1B						DG2XX1A						DG2XX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean			106.687	109.296			72.457	73.864	84.034	86.081					69.790	71.123		
	Minimum			99.717	100.392			69.099	70.056	73.788	73.936					64.998	65.516		
	Maximum			113.722	117.225			75.681	77.340	91.145	95.409					72.508	74.435		
	C.V.(%)			4.242	4.664			2.669	2.864	6.512	7.257					3.523	3.712		
F_{br}	**B-value**			97.487	99.017			63.697	65.577	76.829	77.985					63.806	64.434		
(ksi)	**A-value**																		
	No. Specimens			17				18		18						18			
	No. Prepreg Lots			3				3		3						3			
	Mean			2.334	2.388			1.875	1.912	1.985	2.036					1.887	1.923		
	Minimum			2.190	2.224			1.771	1.789	1.088	1.108					1.816	1.827		
	Maximum			2.597	2.625			2.004	2.012	2.647	2.771					1.957	2.005		
E_{br} (Msi)	**C.V.(%)**			4.835	4.555			3.257	3.326	30.740	31.259					2.050	2.794		
	No. Specimens			18				18		18						18			
	No. Prepreg Lots			3				3		3						3			

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.635-48.833%(w) **Comp. density:** 1.491-1.535g/cc
Fiber volume: 45.159-50.846 %(v)
Ply thickness: 0.0084 - 0.0086 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

Bearing-Bypass 50%, Tension
[t/D = 0.475]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGAXX1B						DGAXX1A						DGAXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							71.19	72.27										
	Minimum							66.54	67.47										
	Maximum							74.33	75.85										
	C.V.(%)							2.92	2.95										
F_{br}	**B-value**																		
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							23.80	24.16										
	Minimum							22.24	22.55										
	Maximum							24.90	25.33										
	C.V.(%)							2.95	2.98										
F_{br}^{gross}	**B-value**							22.40	22.73										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							11.90	12.08										
	Minimum							11.12	11.28										
	Maximum							12.45	12.67										
	C.V.(%)							2.95	2.98										
F_{br}^{net}	**B-value**							11.20	11.37										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							1.80	1.83										
	Minimum							1.56	1.58										
	Maximum							1.89	1.93										
E_{br}	**C.V.(%)**							4.02	4.06										
(Msi)																			
	No. Specimens							18											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Bearing-Bypass 50%, Tension
[t/D = 0.570]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 40.325-43.665 %(w) **Comp. density:** 1.505-1.523 g/cc
Fiber volume: 48.11-50.94 %(v)
Ply thickness: 0.0083 - 0.0085 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGBXX1B						DGBXX1A						DGBXX1F					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
F_{br} (ksi)	Mean							68.91	70.27										
	Minimum							64.74	65.36										
	Maximum							73.31	75.01										
	C.V.(%)							2.82	3.07										
	B-value																		
	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
F_{br}^{gross} (ksi)	Mean							23.10	23.56										
	Minimum							21.65	21.86										
	Maximum							24.59	25.16										
	C.V.(%)							2.84	3.09										
	B-value							21.80	22.11										
	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
F_{br}^{net} (ksi)	Mean							11.55	11.78										
	Minimum							10.83	10.93										
	Maximum							12.30	12.58										
	C.V.(%)							2.84	3.09										
	B-value							10.90	11.06										
	A-value																		
	No. Specimens							18											
	No. Prepreg Lots							3											
E_{br} (Msi)	Mean							0.69	0.70										
	Minimum							0.68	0.69										
	Maximum							0.71	0.73										
	C.V.(%)							1.13	1.36										
	No. Specimens							18											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Bearing-Bypass 50%, Tension
[t/D = 0.712]
Bearing-Bypass Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

Material: T700SC-12K-50C/#2510 -Plain Weave Fabric

Resin content: 39.134-43.7012 %(w) **Comp. density: 1.489-1.538** g/cc

Fiber volume: 47.421-52.615 %(v)

Ply thickness: 0.0083 - 0.0085 inch

Test method: ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in

Normalized by: 0.0086 in. ply thickness

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DD3XX1B						DD3XX1A						DD3XX1F					
Laminate Layup [%, 0°/45°/90°]		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10		40/20/40		25/50/25		10/80/10	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							69.481	71.109	83.116	85.099	72.914	74.289						
	Minimum							65.622	66.023	77.574	79.967	70.743	71.639						
	Maximum							71.810	74.467	86.320	88.730	74.847	76.607						
	C.V.(%)							2.667	3.287	2.640	2.853	1.815	2.197						
F_{br}	B-value																		
(ksi)	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							23.207	23.751	27.742	28.404	24.321	24.780						
	Minimum							21.861	21.995	25.875	26.674	23.652	23.951						
	Maximum							24.032	24.922	28.781	29.584	24.949	25.536						
	C.V.(%)							2.701	3.323	2.644	2.867	1.741	2.129						
F_{br}^{gross}	B-value							21.892	22.096	26.204	26.696	23.433	23.673						
(ksi)	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							11.603	11.875	13.871	14.202	12.161	12.390						
	Minimum							10.931	10.997	12.938	13.337	11.826	11.976						
	Maximum							12.016	12.461	14.390	14.792	12.475	12.768						
	C.V.(%)							2.701	3.323	2.644	2.867	1.741	2.129						
F_{br}^{net}	B-value							10.946	11.048	13.102	13.348	11.717	11.837						
(ksi)	A-value																		
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							
	Mean							1.531	1.567	1.917	1.963	1.597	1.627						
	Minimum							1.437	1.465	1.840	1.882	1.539	1.580						
	Maximum							1.584	1.656	2.005	2.044	1.683	1.694						
E_{br}	C.V.(%)							2.822	3.325	2.267	2.307	2.726	2.369						
(Msi)																			
	No. Specimens							15		15		15							
	No. Prepreg Lots							3		3		3							

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Material:	T700SC-12K-50C/#2510 -Plain Weave Fabric
Resin content:	39.904-43.974 %(w) **Comp. density:** 1.509-1.525 g/cc
Fiber volume:	47.527-51.501 %(v)
Ply thickness:	0.0082 - 0.0086 inch
Test method:	ASTM D5961-01 **Modulus calculation:** linear fit from 1000 to 6000 min/in
Normalized by:	0.0086 in. ply thickness

Bearing-Bypass 50%, Tension
[t/D = 0.949]
Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

		CTD (B)						RTD (A)						ETW (F)					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGCXX1B						DGCXX1A						DGCXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							64.945	66.503										
	Minimum							61.176	62.959										
	Maximum							70.219	72.106										
	C.V.(%)							3.251	3.413										
F_{br}	**B-value**																		
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							21.859	22.383										
	Minimum							20.655	21.224										
	Maximum							23.531	24.163										
	C.V.(%)							3.107	3.263										
F_{br}^{gross}	**B-value**							20.506	20.928										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							10.930	11.192										
	Minimum							10.327	10.612										
	Maximum							11.765	12.082										
	C.V.(%)							3.107	3.263										
F_{br}^{net}	**B-value**							10.253	10.464										
(ksi)	**A-value**																		
	No. Specimens							18											
	No. Prepreg Lots							3											
	Mean							1.424	1.459										
	Minimum							1.354	1.367										
	Maximum							1.521	1.563										
E_{br}	**C.V.(%)**							2.828	3.124										
(Msi)																			
	No. Specimens							18											
	No. Prepreg Lots							3											

NOTE: Bypass stresses were calculated based on the 2% offset bearing stress (bearing failure mode)

Material:	T700SC-12K-50C/#2510 -Plain Weave Fabric
Resin content:	39.996-42.04 %(w) **Comp. density: 1.505-1.522** g/cc
Fiber volume:	49.034-50.955 %(v)
Ply thickness:	0.0082 - 0.0086 inch
Test method:	ASTM D7078 **Modulus calculation:** linear fit from 1000 to 6000 min/in
Normalized by:	0.0086 in. ply thickness

V-Notched Rail Shear
Shear Strength & Modulus
Gr/ Ep
T700SC-12K-50C/#2510 -Plain Weave Fabric

		CTD (B)						**RTD (A)**						**ETW (F)**					
Test Temperature [°F]		-65						75						180					
Moisture Conditioning		dry						dry						wet					
Equilibrium at T, RH		as fabricated						as fabricated						145°F, 85% RH					
Source code		DGVXX1B						DGVXX1A						DGVXX1F					
Laminate Layup [%, 0°/45°/90°]		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**		**40/20/40**		**25/50/25**		**10/80/10**	
		Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured
	Mean							21.200	21.684	48.918	49.892								
	Minimum							20.175	20.527	46.289	47.180								
	Maximum							22.857	23.637	50.358	52.083								
	C.V.(%)							3.773	3.695	4.662	4.996								
$F_{12}^{0.2\% offse}$	**B-value**							19.606	20.087										
(ksi)	**A-value**																		
	No. Specimens							18		3									
	No. Prepreg Lots							3		3									
	Mean					41.587	42.374	30.184	30.873	46.084	47.013	46.859	47.608					23.401	23.826
	Minimum					33.165	34.005	28.956	29.440	38.892	39.853	40.786	41.534					19.531	19.494
	Maximum					53.445	54.734	31.313	32.053	52.913	53.727	54.063	54.427					27.066	27.352
F_{12}^{ult}	**C.V.(%)**					12.232	12.120	1.993	1.973	7.314	7.461	6.911	7.002					9.217	8.837
(ksi)																			
	B-value					34.627	35.386	28.985	29.659	39.367	40.023	39.058	39.798					19.485	19.897
	A-value																		
	No. Specimens					18		18		18		19						18	
	No. Prepreg Lots					3		3		3		3						3	
	Mean					3.072	3.130	1.201	1.229	2.226	2.271	3.080	3.130					2.869	2.922
	Minimum					2.856	2.904	1.148	1.147	2.144	2.166	2.797	2.832					2.372	2.413
	Maximum					3.287	3.359	1.266	1.348	2.308	2.352	3.224	3.258					3.371	3.467
G_{12}^{s}	**C.V.(%)**					4.532	4.434	2.744	3.807	2.314	2.706	3.299	3.338					9.611	9.359
(Msi)																			
	No. Specimens					18		18		18		19						18	
	No. Prepreg Lots					3		3		3		3						3	

NOTE: * - Standard was under development during the testing phase of this research

APPENDIX F—NATIONAL INSTITUTE FOR AVIATION RESEARCH/WICHITA STATE UNIVERSITY DOUBLE-SHEAR BEARING TEST FIXTURE DESIGN

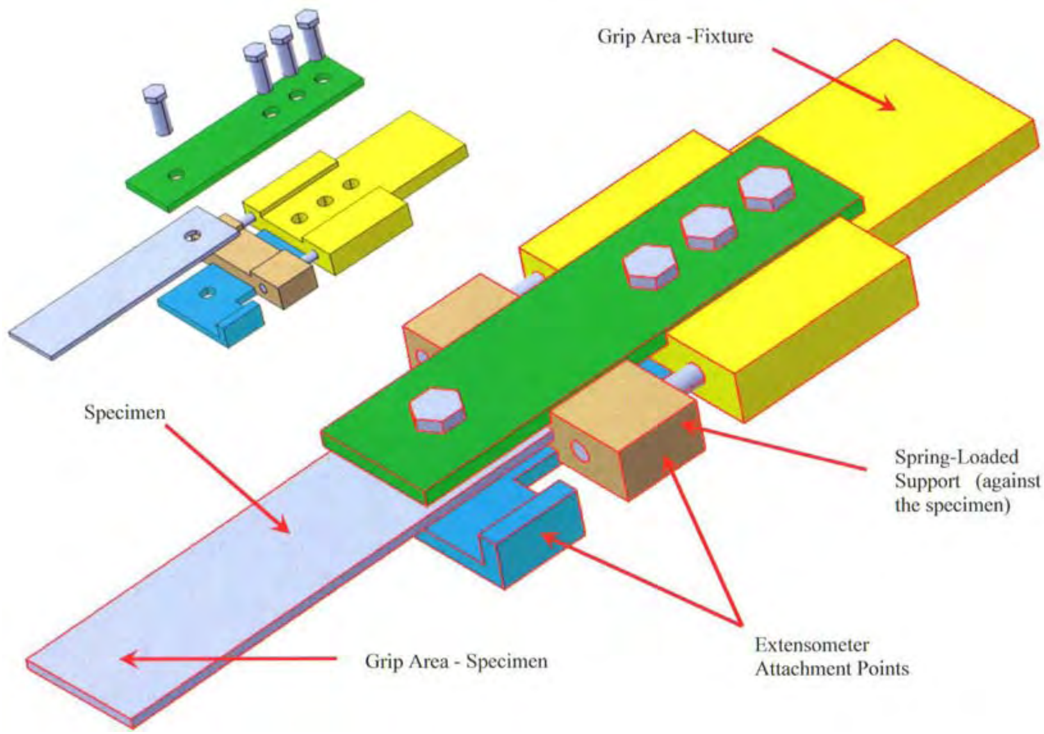

Figure F-1. Double-Shear Bearing Test Fixture Assembly