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Laminate Repair of Solvay (Formerly Cytec) 5320-1 T650 3k-PW fabric with 36% RC Qualification and Equivalency Statistical Analysis Report

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1. Introduction

1.1 Scope

This report analyzes the test results for 3-batch qualification and a single batch equivalency of the laminate repair of Solvay 5320-1 T650 3k plain weave fabric prepreg using Solvay FM®300-2M Adhesive Film 0.06psf. The NCAMP Test Plan NTP 5325QR1 was used for this 3-batch qualification and a single batch equivalency of laminate repair program.

The laminate material property data have been generated with NCAMP oversight in accordance with NSP 100 NCAMP Standard Operating Procedures; the test panels and test specimens have been inspected by NCAMP Authorized Inspection Representatives (AIR) and the testing has been witnessed by NCAMP Authorized Engineering Representatives (AER). However, the data may not fulfill all the needs of any specific company's program; specific properties, environments, laminate architecture, and loading situations may require additional testing.

The use of NCAMP material and process specifications do not guarantee material or structural performance. Material users should be actively involved in evaluating material performecm א D p ve N ꞥ p.

The material property data acquisition process is designed to generate basic material property data with sufficient pedigree for submission to Complete Documentation sections of the Composite Materials Handbook (CMH-17-1G).

Part fabricators that wish to utilize the material property data, allowables and specifications may be able to do so by demonstrating the capability to reproduce the original material properties; a process known as equivalency. More information about the equivalency process including the test statistics and its limitations can be found in section 6 of DOT/FAA/AR-03/19 and Section 8.4.1 of CMH-17-1G. The applicability of the equivalency process must be evaluated on a program-by-program basis by the applicant and certifying agency. The applicant and certifying agency must agree that the equivalency test plan, along with the equivalency process described in section 6 of DOT/FAA/AR-03/19 and Section 8.4.1 of CMH-17-1G, are adequate for the given program.

Aircraft companies should not use the data published in this report without specifying NCAMP Material Specification NMS 532/6 (Solvay 5320-1 T650 3k-PW) and NMS 300/1 (FM300-2M

Environmental Condition	Abbreviation	Temperature

2. Background

Statistical computations are performed with CMH17 STATS. Pooling across environments will be used whenever it is permissible according to CMH-17-1G guidelines. If pooling is not permissible, the results of a single point analysis provided by CMH17 STATS is included instead. If the data does not meet CMH-17-1G requirements for a single point analysis, estimates are created by a variety of methods depending on which is most appropriate for the dataset available. Specific procedures used are presented in the individual sections where the data is presented.

2.1 CMH17 STATS Statistical Formulas and Computations

This section contains the details of the specific formulas CMH17 STATS uses in its computations.

2.1.1 Basic Descriptive Statistics

The basic descriptive statistics shown are computed according to the usual formulas, which are shown below:

Mean: $$\bar{X} = \sum_{i=1}^{n} \frac{X_i}{n}$$ **Equation 1**

Std. Dev.: $$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}$$ **Equation 2**

% Co. Variation: $$\frac{S}{\bar{X}} \times 100$$ **Equation 3**

Where n refers to the number of specimens in the sample and X_i refers to the individual specimen measurements.

2.1.2 Statistics for Pooled Data

Prior to computing statistics for the pooled dataset, the data is normalized to a mean of one by dividing each value by the mean of all the data for that condition. This transformation does not affect the coefficients of variation for the individual conditions.

2.1.2.1 Pooled Standard Deviation

The formula to compute a pooled standard deviation is given below:

Pooled Std. Dev.: $$S_p = \sqrt{\frac{\sum_{i=1}^{k}(n_i - 1)S_i^2}{\sum_{i=1}^{k}(n_i - 1)}}$$ **Equation 4**

Where k refers to the number of batches, S_i indicates the standard deviation of i^{th} sample, and n_i refers to the number of specimens in the i^{th} sample.

2.1.2.2 Pooled Coefficient of Variation

Since the mean for the normalized data is 1.0 for each condition, the pooled normalized data also has a mean of one. The coefficient of variation for the pooled normalized data is the pooled standard deviation divided by the pooled mean, as in equation 3. Since the mean for the pooled normalized data is one, the pooled coefficient of variation is equal to the pooled standard deviation of the normalized data.

Pooled Coefficient of Variation $$\frac{S_p}{1} = S_p$$ **Equation 5**

2.1.3 Basis Value Computations

Basis values are computed using the mean and standard deviation for that environment, as follows: The mean is always the mean for the environment, but if the data meets all requirements for pooling, S_p can be used in place of the standard deviation for the environment, S.

Basis Values: $$A\text{-basis} = \overline{X} - K_a S$$ $$B\text{-basis} = \overline{X} - K_b S$$ **Equation 6**

2.1.3.1 K-factor computations

K_a and K_b are computed according to the methodology documented in section 8.3.5 of CMH-17-1G. The approximation formulas are given below:

$$K_a = \frac{2.3263}{\sqrt{q(f)}} + \sqrt{\frac{1}{c_A(f)\cdot \tilde{n}_j} + \left(\frac{b_A(f)}{2c_A(f)}\right)^2} - \frac{b_A(f)}{2c_A(f)}$$ **Equation 7**

$$K_b = \frac{1.2816}{\sqrt{q(f)}} + \sqrt{\frac{1}{c_B(f)\cdot \tilde{n}_j} + \left(\frac{b_B(f)}{2c_B(f)}\right)^2} - \frac{b_B(f)}{2c_B(f)}$$ **Equation 8**

2.1.4.1 Transformation of data based on Modified CV

In order to determine if the data would pass the diagnostic tests under the assumption of the modified CV, the data must be transformed such that the batch means remain the same while the standard deviation of transformed data (all batches) matches the modified standard deviation.

To accomplish this requires a transformation in two steps:

$$\text{MNR} \quad \frac{\max\limits_{\text{all } i} \left| X_i \quad \bar{X} \right|}{S}, \ i \quad 1 \quad n$$ **Equation 23**

$$\frac{n \quad 1}{\sqrt{\ }}\sqrt{\frac{t^2}{2 \qquad ^2}}$$

$$\sigma_n^2 = VAR(ADK) = \frac{an^3 + bn^2 + cn + d}{(n-1)(n-2)(n-3)(k-1)^2} \quad \textbf{Equation 27}$$

With

$$a = (4g-6)(k-1) + (10-6g)S$$

$$b = (2g-4)k^2 + 8Tk + (2g-14T-4)S - 8T + 4g - 6$$

$$c = (6T+2g-2)k^2 + (4T-4g+6)k + (2T-6)S + 4T$$

$$d = (2T+6)k^2 - 4Tk$$

$$S = \sum_{i=1}^{k} \frac{1}{n_i}$$

$$T = \sum_{i=1}^{n-1} \frac{1}{i}$$

$$g = \sum_{i=1}^{n-2} \sum_{j=i+1}^{n-1} \frac{1}{(n-i)j}$$

The data is considered to have failed this test (i.e. the batches are not from the same population) when the test statistic is greater than the critical value. For more information on this procedure, see reference 3.

2.1.7 The Anderson Darling Test for Normality

Normal Distribution: A two parameter (μ, σ) family of probability distributions for which the probability that an observation will fall between a and b is given by the area under the curve between a and b:

$$F(x) = \int_a^b \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad \textbf{Equation 28}$$

A normal distribution with parameters (μ, σ) has population mean μ and variance σ^2.

The normal distribution is considered by comparing the cumulative normal distribution function that best fits the data with the cumulative distribution function of the data. Let

$$z_{(i)} = \frac{x_{(i)} - \bar{x}}{s}, \quad \text{for } i = 1, \ldots, n \quad \textbf{Equation 29}$$

where $x_{(i)}$ is the smallest sample observation, $\bar{x}$ is the sample average, and s is the sample standard deviation.

The Anderson Darling test statistic (AD) is:

$$AD = \sum_{i=1}^{n} \frac{1-2i}{n} \left\{ \ln\left[F_0(z_{(i)})\right] + \ln\left[1 - F_0(z_{(n+1-i)})\right] \right\} - n \quad \textbf{Equation 30}$$

If the normal distribution has an OSL greater than 0.05, then the data is assumed to be from a population with a normal distribution. If not, then if either the Weibull or lognormal distributions has an OSL greater than 0.05, then one of those c

2.1.9.3.1 Estimating Weibull Parameters

This section describes the maximum likelihood method for estimating the parameters of the two-

2.1.9.4.1 Goodness-of-fit test for the Lognormal distribution

In order to test the goodness-of-fit of the lognormal distribution, take the logarithm of the data and perform the Anderson-Darling test for normality from Section 2.1.7. Using the natural

$$r_A \quad \frac{n}{100} \quad 1.645\sqrt{\frac{99n}{10,000}} \quad 0.29 \quad \frac{19.1}{n}$$ **Equation 49**

The formula for the A-basis values should be rounded to the nearest integer. This approximation is exact for most values and for a small percentage of values (less than 0.2%), the approximation errs by one rank on the conservative side.

The B-basis value is the r_Bth lowest observation in the data set, while the A-basis value is the r_Ath

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Table 2-3: A-Basis Hanson-Koopmans Table

2.1.11 Analysis of Variance (ANOVA) Basis Values

ANOVA is used to compute basis values when the batch to batch variability of the data does not pass the ADK test. Since ANOVA makes the assumption that the different batches have equal variances, the data is checked to make sure the assumption is valid. Levene's test for equality of variance is used (see section 2.1.8). If the dataset fails Lev ex x x x x m x l Mmake

2.1.11.1 Calculation of basis values using ANOVA

Two k-factors are computed using the methodology of section 8.3.5 of CMH-17-1G using a sample size of n (denoted k_0) and a sample size of k (denoted k_1). Whether this value is an A- or B-basis value depends only on whether k_0 and k_1 are computed for A or B-basis values.

Denote the ratio of mean squares by

$$u = \frac{MSB}{MSE} \qquad \textbf{Equation 59}$$

If u is less than one, it is set equal to one. The tolerance limit factor is

$$T = \frac{k_0 - \frac{k_1}{\sqrt{n'}} + (k_1 - k_0)\sqrt{\frac{u}{u + n' - 1}}}{1 - \frac{1}{\sqrt{n'}}} \qquad \textbf{Equation 60}$$

The basis value is $\bar{x} - TS$.

The ANOVA method can produce extremely conservative basis values when a small number of batches are available. Therefore, when less than five (5) batches are available and the ANOVA method is used, the basis values produced will be listed as estimates.

2.2 Equivalence Tests

Equivalence tests are performed in accordance with section 8.4.1 of CMH-17-1G and section 6.1 of DOT/FAA/AR-03/19, "Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure."

2.2.1 Results Codes

Pass indicates that the test results are equivalent for that environment under both computational methods.
Fail indicates that the test results are NOT equivalent under both computational methods.
Pass with Mod CV indicates the test results are equivalent under the assumption of the modified CV method that the coefficient of variation is at least 6 but the test results fail without the use of the modified CV method.

2.2.2 Equivalency Computations

Equivalency tests are performed to determine if the differences between test results can be reasonably explained as due to the expected random varia the material and testing processes. If so, we can conclude the two sets of tests are from 'equivalent' materials.

2.2.2.1 Hypothesis

This comparison is performed using the statistical methodology of hypothesis testing. Two mutually exclusive hypotheses are set up, termed the null (H_0) and the alternative (H_1). The null hypothesis is assumed true and must contain the equality. For equivalency testing, they are set up as follows, with M

2.2.2.3 Cumulative Error Probability

Each characteristic (such as Longitudinal Tension strength or In-Plane Shear modulus) is tested separately. While the probability of a Type I error is the same for all tests, since many different tests are performed on a single material, each with a 5% probability of a type I error, the probability of having one or more failures in a series of tests can be much higher.

If we assume the two materials are identical, with two tests the probability of a type I error for the two tests combined is $1 - .95^2 = .0975$. For four tests, it rises to $1 - .95^4 = 0.1855$. For 25 tests, the probability of a type I error on 1 or more tests is $1 - .95^{25} = 0.7226$. With a high probability of one or more equivalence test failures due to random chance alone, a few failed tests should be allowed and equivalence may still be presumed provided that the failures are not severe.

2.2.2.4 Strength and Modulus Tests

For strength test values, we are primarily concerned only if the equivalence sample shows lower strength values than the original qualification material. This is referred to as a ‘one-sided’ hypothesis test. Higher values are not considered a problem, though they may indicate a difference between the two materials. The equivalence sample mean and sample minimum values are compared against the minimum expected values for those statistics, which are computed from the qualification test result.

The expected values are computed using the values listed in Table 2-4 and Table 2-5 according to the following formulas:

> The mean must exceed $\bar{X} - k_n \cdot S$ where $\bar{X}$ and S are, respectively, the mean and the standard deviation of the qualification sample and k_n comes from Table 2-4.
>
> The sample minimum must exceed $\bar{X} - k_n \cdot S$ where $\bar{X}$ and S are, respectively, the mean and the standard deviation of the qualification sample and k_n comes fromnTable 2-5.

If either the mean or the minimum falls below the expected minimum, the sample is considered to have failed equivalency for that characteristic and the null hypothesis is rejected. The

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2QH VLGHG WROHUDQFH IDFWRUV IRU OLPLWV RQ VDPSOH PLQLPXP									
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	0.25	0.1	0.05	0.025	0.01	0.005	0.0025	0.001	0.0005
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Table 2-5: One-sided tolerance factors for limits on sample minimum values

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CV^* is used to compute a modified standard deviation S^*.

$$S^* = CV^* \cdot \bar{X} \qquad \textbf{Equation 62}$$

To compute the pooled standard deviation based on the modified CV:

$$S_p^* = \sqrt{\frac{\sum_{i=1}^{k} (n_i - 1)\left(CV_i^* \cdot \bar{X}_i\right)^2}{\sum_{i=1}^{k} (n_i - 1)}} \qquad \textbf{Equation 63}$$

The A-basis and B-basis values under the assumption of the modified CV method are computed by replacing S with S^*.

When the basis values have been set using the modified CV method, we can use the modified CV to compute the equivalency test results.

3. Summary of Results

The basis values for all tests are summarized in the following tables. The NCAMP recommended B-basis values meet all requirements of CMH-17-1G. However, not all test data meets those requirements. The summary tables provide a complete listing of all computed basis values and estimates of basis values. Data that does not meet the requirements of CMH-17-1G are shown in shaded boxes and labeled as estimates. Basis values computed with the modified coefficient of variation (CV) are presented whenever possible. Basis values and estimates computed without that modification are presented for all tests.

3.1 NCAMP Recommended B-basis Values

The following rules are used in determining what B-basis value, if any, is included in tables Table 3-1 of recommended values.

1. Recommended values are NEVER estimates. Only B-basis values that meet all requirements of CMH-17-1G are recommended.
2. Modified CV basis values are preferred. Recommended values will be the modified CV basis value when available. The CV provided with the recommended basis value will be the one used in the computation of the basis value.
3. Only normalized basis values are given for properties that are normalized.
4. ANOVA B-basis values are not recommended since only three batches of material are available and CMH-17-1G recommends that no less than five batches be used when computing basis values with the ANOVA method.
5. Basis values of 90% or more of the mean value imply that the CV is unusually low and may not be conservative. Caution is recommended with B-Basis values calculated from CMH-17 STATS when the B-basis value is 90% or more of the average value. Such values will be indicated.
6. If the data appear questionable (e.g. when the CTD-RTD-ETW trend of the basis values is not consistent with the CTD-RTD-ETW trend of the average val

Laminate Strength and Ultimate Joint Running Force per Repair Ply

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Prepreg Material: 6ROYD\ 7 N 3: IDEULF ZLWK 5&
Material Specification: 106 6ROYD\ 7 N 3:
106)0 0 SVI
Process Specification: 136 %DVHOLQH &XUH &\FOH 3DUHQW
136 5 %DVHOLQH &XUH &\FOH 5HSDLU
Fabric: 7 N 3: **Resin:** &\FRP

	Tg(dry):	Tg(wet):
	ƒ)	ƒ)
Tg METHOD:	'0$ $670 '	

	Tg(dry):	Tg(wet):
Parent Section:	ƒ)	ƒ)
Repair Section:	ƒ)	ƒ)
Scarf Section, Adhesive:	ƒ)	ƒ)
Scarf Section, Laminate:	ƒ)	ƒ)

	Tg(dry):	Tg(wet):
Parent Section:	ƒ)	ƒ)
Repair Section:	ƒ)	ƒ)
Scarf Section, Adhesive:	ƒ)	ƒ)
Scarf Section, Laminate:	ƒ)	ƒ)

Test Type	Scarf Ratio	Property	Normalization	% %DVLV 0RGLILHG &9 % EDVLV 0HDQ	% %DVLV 0RGLILHG &9 % EDVLV 0HDQ	% %DVLV 0RGLILHG &9 % EDVLV 0HDQ
[redacted]						

4. Individual Test Summaries, Statistics, Basis Values and Graphs

Test data for fiber dominated properties was normalized according to nominal cured ply thickness. Test failures, outliers and explanations regarding computational choices were noted in the accompanying text for each test.

All individual specimen results are graphed for each test by batch and environmental condition with a line indicating the recommended basis values for each environmental condition. The data is jittered (moved slightly to the left or right) in order for all specimen values to be clearly visible. The strength values are always graphed on the vertical axis with the scale adjusted to include all data values and their corresponding basis values. The vertical axis may not include zero. The horizontal axis values will vary depending on the data and how much overlapping there was of the data within and between batches. When there was little variation, the batches were graphed from left to right. The environmental conditions were identified by the shape and color of the symbol used to plot the data. Otherwise, the environmental conditions were graphed from left to right and the batches were identified by the shape and color of the symbol.

When a dataset fails the Anderson-Darling k-sample (ADK) test for batch-to-batch variation, an ANOVA analysis is required. In order for B-basis values to be computed using the ANOVA method, data from five batches are required. Since this qualification dataset has only three batches, the basis values computed using ANOVA are considered estimates only. However, the

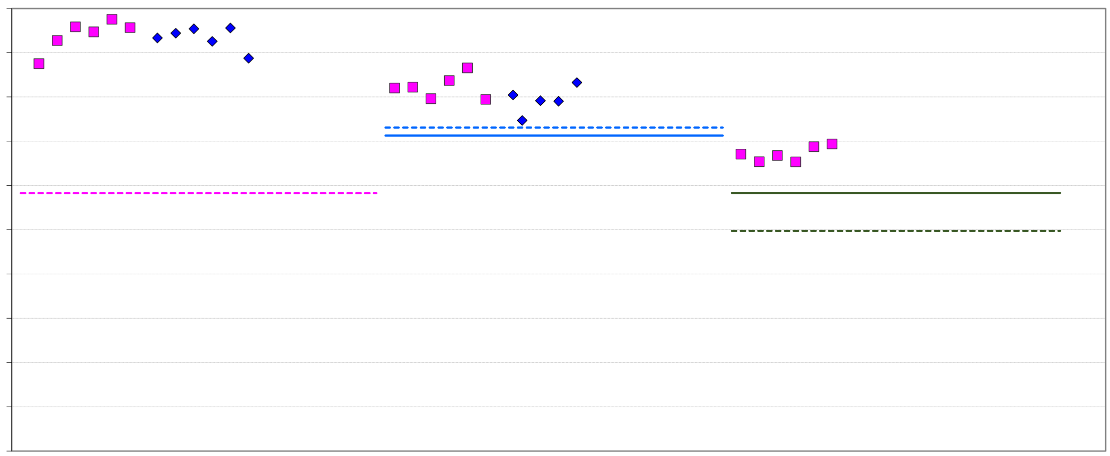
4.1 Un-Notched Compression Baseline (UNC1)

The UNC1 data is normalized. Data is available only for strength. Test results are available from three environmental conditions, CTD, RTD and ETW2. These tests provide a baseline for equivalency comparison to the UNCR50 and UNCR30 test data presented in the next section.

The CTD and ETW2 conditions failed the Anderson Darling k-sample test (ADK test) for batch to batch variability, which means that pooling across environments was not acceptable and CMH-17-1G guidelines required using the ANOVA analysis. With fewer than five batches, these are considered estimates. The CTD datasets, both normalized and as-measured, and the as-measured ETW2 dataset did not pass the ADK test after they were transformed according to the assumptions of the modified CV method, so modified CV basis values could not be provided for those datasets. The normalized ETW2 dataset did pass the ADK test after applying the modified CV transformation and the RTD and ETW2 normalized datasets met all requirements for pooling to compute the modified CV basis values.

There were no statistical outliers.

Statistics, estimates and basis values are given for the UNC1 strength data in Table 4-1. The normalized specimen strength data, B-estimates and B-basis values are shown graphically in Figure 4-1.



Un-Notched Compression (UNC1) Strength Basis Values and Statistics [ksi]						
	Normalized			As-measured		
Env	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)
Mean	90.59	79.76	66.80	90.26	79.81	66.57
Stdev	5.394	3.391	3.511	6.006	3.719	4.086
CV	5.954	4.252	5.257	6.654	4.660	6.138
Mod CV	6.977	6.126	6.628	7.327	6.330	7.069
Min	79.66	72.46	57.96	78.02	71.14	56.62
Max	97.52	86.57	71.19	97.39	86.39	71.82
No. Batches	3	3	3	3	3	3
No. Spec.	18	18	18	18	18	18
Basis Values and Estimates						
B-Basis Value		73.06			72.46	
B-Estimate	58.29		49.76	53.76		44.52
A-Estimate	35.24	68.32	37.61	27.72	67.26	28.79
Method	ANOVA	Normal	ANOVA	ANOVA	Normal	ANOVA
Modified CV Basis Values and Estimates						
B-Basis Value	NA	71.26	58.30	NA	69.83	NA
A-Estimate		65.49	52.53		62.78	
Method		pooled	pooled		Normal	

4.2 Un-Notched Compression Repair with scarf ratio of 50:1 (UNCR50)

The UNCR50 data was normalized with parent material CPT. Data is available for the Ultimate Joint Running Force per Repair Ply (as-measured only) and Strength both normalized and as-measured. Test results are available for three environmental conditions, CTD, RTD and ETW2. Basis values and estimates are computed for each condition. Equivalency tests were made comparing the UNCR50 data to the UNC1 data presented in the previous section.

The as-measured RTD and ETW2 conditions for Strength properties failed the Anderson Darling k-sample test (ADK test) for batch to batch variability, which means that pooling across environments was not acceptable and CMH-17-1G guidelines required using the ANOVA analysis. With fewer than five batches, these are considered estimates. Both datasets passed the ADK test after they were transformed according to the assumptions of the modified CV method, so modified CV basis values could be provided. The normal distribution could be used for the as-measured CTA dataset and for all th-o

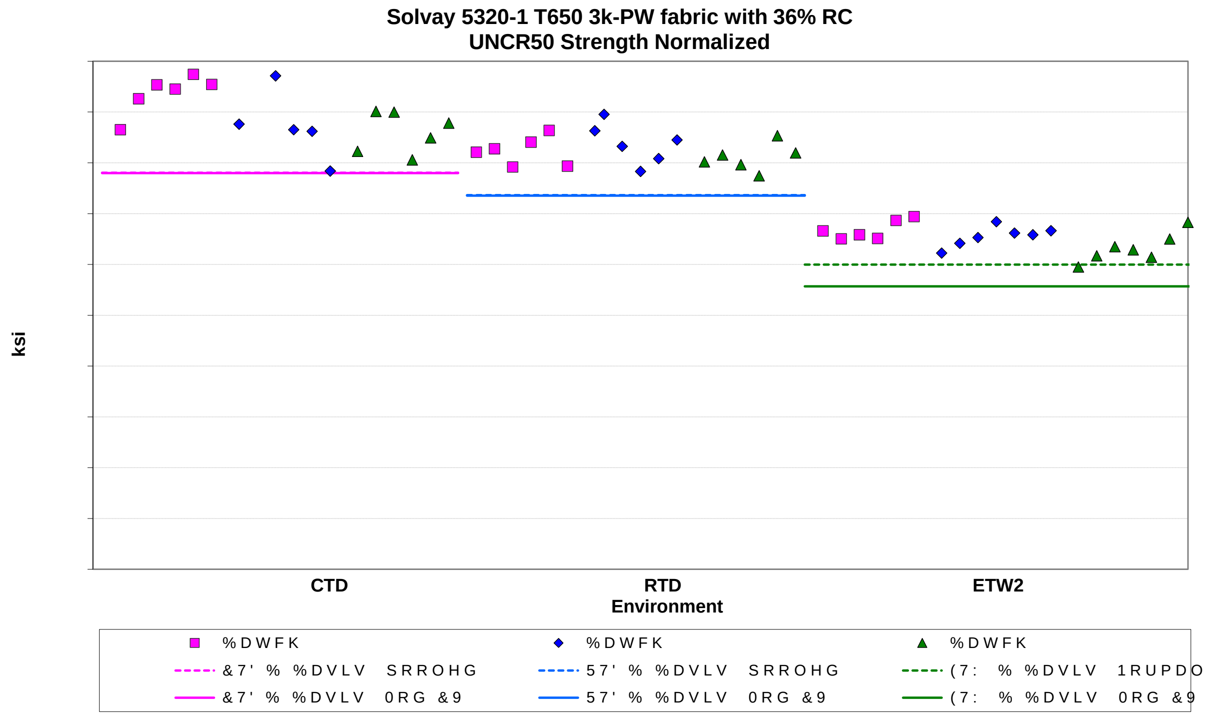


Figure 4-2: Batch Plot for UNCR50 Strength Normalized

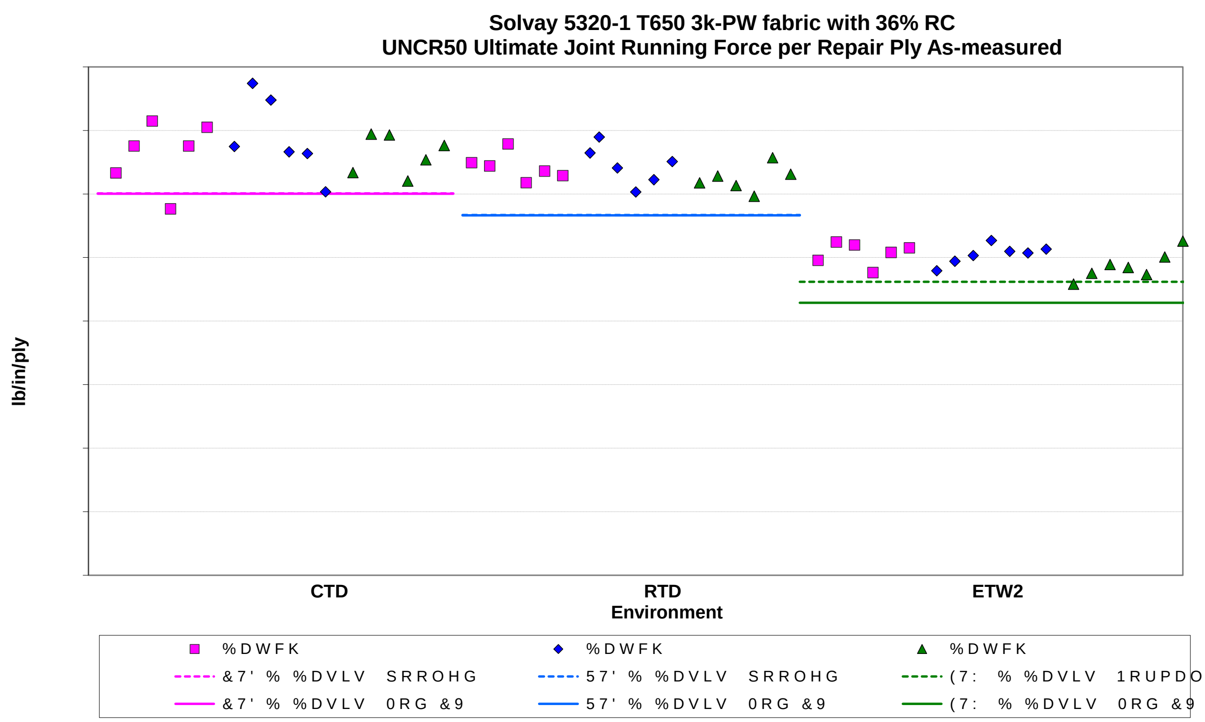


Figure 4-3: Batch Plot for UNCR50 Ultimate Joint Running Force per Repair Ply As-measured

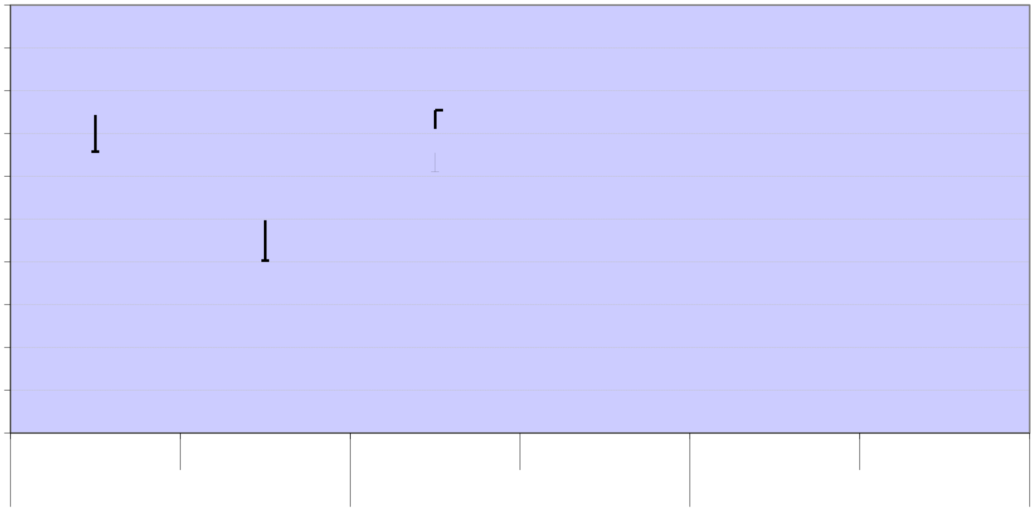
Un-Notched Compression Repair (UNCR50) Ultimate Joint Running Force per Repair Ply Basis Values and Statistics [lb/in/ply]			
Env	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)
Mean	671.1	637.1	498.6
Stdev	48.45	24.93	19.37
CV	7.220	3.913	3.885
Mod CV	7.610	6.000	6.000
Min	576.4	596.4	458.2
Max	773.9	689.4	526.7
No. Batches	3	3	3
No. Spec.	18	18	21
Basis Values and Estimates			
B-Basis Value	600.9	566.9	461.7
A-Estimate	553.2	519.2	435.4
Method	pooled	pooled	Normal
Modified CV Basis Values and Estimates			
B-Basis Value	600.2	566.2	428.8
A-Estimate	553.0	519.1	381.4
Method	pooled	pooled	pooled

4.3 Un-Notched Compression Repair with scarf ratio of 30:1 (UNCR30)

The UNCR30 data was normalized with parent material CPT. Data is available for the Ultimate Joint Running Force per Repair Ply (as-measured only) and Strength (normalized and as-measured). Test results are available from three environmental conditions,f

	UNCR50	UNCR30	UNCR50	UNCR30	UNCR50	UNCR30
Mean (lb/in/ply)	671.1	693.3	637.1	635.2	498.6	450.2
Standard Deviation	48.45	43.03	24.93	42.44	19.37	11.06
Coefficient of Variation %	7.220	6.207	3.913	6.681	3.885	2.456
Minimum	576.4	638.7	596.4	579.1	458.2	434.4
Maximum	773.9	759.9	689.4	694.9	526.7	463.3
Number of Specimens	18	8	18	8	21	8
RESULTS						
Minimum Acceptable Equiv. Sample Mean						
Minimum Acceptable Equiv. Sample Min						
MOD CV RESULTS						

Figure 4-6 illustrates the Un-Notched Compression strength means and minimum values for the UNCR50 sample and the UNCR30 sample. Figure 4-7 illustrates the Un-Notched Compression Ultimate Joint Running Force per Repair Ply means and minimum values for the UNCR50 sample and the UNCR30 sample. The limits for equivalency are shown as error bars with the UNCR50 data. The longer, lighter colored error bars are for the modified CV computations.



4.4 Tension Repair with Scarf Ratio of 50:1 (TR50)

The TR50 data was normalized with parent material CPT. Data is available for Strength at Parent Laminate (normalized and as-measured), Strength at Repair Laminate (normalized and as-measured), Ultimate Joint Running Force per Repair Ply (as-measured only), Modulus I (normalized and as-measured) and Modulus II (normalized and as-measured). Test results are available from three environmental conditions, CTD, RTD and ETW2. Basis values and estimates are computed for each condition for the strength and force properties but not for the modulus. Equivalency tests comparing the TR50 data to the TR30 data are presented in the next section.

The ETW2 condition datasets all failed the Anderson Darling k-sample test (ADK test) for batch to batch variability, which means that pooling across environments was not acceptable and CMH-17-1G guidelines required using the ANOVA analysis. With fewer than five batches, these would be considered estimates, but for these datasets, there were no computed basis values above zero. None of the ETW2 datasets passed the ADK test after the datasets were transformed according to the assumptions of the modified CV method, so modified CV basis values could not be provided.

The Strength at Parent Laminate CTD and RTD datasets, both normalized and as-measured, and the normalized Strength at Repair Laminate met all requirements for pooling. The Strength at Repair Laminate as-measured datasets failed the normality test and Levene's test for pooling, but passed them after the datasets were transformed according to the assumptions of the modified CV method, so pooling was acceptable for computing the modified CV basis values. The Ultimate Joint Running Force per Repair Ply failed the normality test for pooling, but passed after the datasets were transformed according to the assumptions of the modified CV method, so pooling was acceptable fosis vf M Š d as-mthptable ʿ l
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Tension Repair (TR50) Strength at Parent Laminate Basis Values and Statistics [ksi]

	Normalized			As-measured		
Env	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)
Mean	76.83	92.19	74.35	72.03	85.10	68.57
Stdev	4.115	3.136	19.53	3.962	2.383	17.61
CV	5.356	3.402	26.27	5.501	2.800	25.68
Mod CV	6.678	6.000	26.27	6.750	6.000	25.68
Min	65.70	86.64	45.88	61.32	80.61	42.82
Max	83.67	97.99	105.3	78.64	88.82	95.50
No. Batches	3	3	3	3	3	3
No. Spec.	18	18	22	18	18	22
Basis Values and Estimates						
B-Basis Value	70.16	85.53	NA	66.07	79.14	NA
A-Estimate	65.63	81.00		62.02	75.09	
Method	pooled	pooled		pooled	pooled	
Modified CV Basis Values and Estimates						
B-Basis Value	67.11	82.48	NA	62.94	76.02	NA
A-Estimate	60.50	75.87		56.77	69.84	
Method	pooled	pooled		pooled	pooled	

#

[redacted]

Tension Repair (TR50) Modulus II Statistics [Msi]						
	Normalized			As-measured		
Env	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)	CTD (−65˚F)	RTD (70˚F)	ETW2 (180˚F)
Mean	7.382	7.295	7.184	6.921	6.733	6.634
Stdev	0.1077	0.1805	0.1463	0.1306	0.1745	0.1005
CV	1.458	2.474	2.036	1.888	2.592	1.514
Mod CV	6.000	6.000	6.000	6.000	6.000	6.000
Min	7.158	7.009	6.924	6.680	6.499	6.443
Max	7.540	7.574	7.456	7.192	7.051	6.805
No. Batches	3	3	3	3	3	3
No. Spec.	18	17	22	18	17	22

Table 4-12: Statistics from TR50 Modulus II Data

4.5 Tension Repair with Scarf Ratio of 30:1 (TR30)

The TR30 data was normalized with parent material CPT. Data is available for Strength at Parent Laminate (normalized and as-measured), Strength at Repair Laminate (normalized and as-measured), Ultimate Joint Running Force per Repair Ply (as-measured only), Modulus I (normalized and as-measured) and Modulus II (normalized and as-measured). Test results are available from three environmental conditions, CTD, RTD and ETW2. Equivalency tests were made comparing the TR30 data to the TR50 data for all five properties.

The three strength and force properties failed equivalency tests for the ETW2 condition, but passed for the CTD and RTD conditions. There is no modified CV computation for the ETW2 condition because the CV for that condition was above 8%, so no modification is made. The Modulus I CTD and the Modulus II CTD and RTD properties required the use of the modified CV method to pass equivalency.

The equivalency test results for the TR30 results compared with

Tension Repair Strength at Repair Laminate	CTD (−65˚F)		RTD (70˚F)		ETW2 (180˚F)	
	TR50	TR30	TR50	TR30	TR50	TR30
Data normalized with Parent Material CPT 0.0077						
Mean Strength (ksi)	75.15	73.64	89.83	89.11	72.41	59.18
Standard Deviation	4.313	5.077	2.358	2.857	18.87	7.408
Coefficient of Variation %	5.740	6.895	2.625	3.206	26.06	12.52
Minimum	64.04	66.11	85.35	84.69	44.46	50.32
Maximum	83.23	81.62	93.79	92.66	101.02	71.38
Number of Specimens	18	8	18	8	22	10
RESULTS	**PASS**		**PASS**		**FLAG**	
Minimum Acceptable Equiv. Sample Mean	72.22		88.23		60.92	
Minimum Acceptable Equiv. Sample Min	63.50		83.46		20.00	
MOD CV RESULTS	**PASS with MOD CV**		**PASS with MOD CV**		**NA**	
Modified CV %	6.870		6.000			
Minimum Acceptable Equiv. Sample Mean	71.64		86.17			
Minimum Acceptable Equiv. Sample Min	61.21		75.28			

	TR50	TR30	TR50	TR30	TR50	TR30
Data normalized with Parent Material CPT 0.0077						
Mean Modulus (Msi)	7.422	7.224	7.261	7.254	7.122	7.169
Standard Deviation	0.167	0.178	0.192	0.162	0.127	0.105
Coefficient of Variation %	2.247	2.461	2.645	2.232	1.783	1.463
Minimum	7.190	7.019	6.781	7.041	6.963	6.979
Maximum	7.625	7.487	7.597	7.565	7.358	7.286
Number of Specimens	18	8	18	8	22	10
RESULTS						
Passing Range for Modulus Mean	7.273 to 7.571		7.099 to 7.422		7.028 to 7.216	
Student's t-statistic						
p-value of Student's t-statistic						

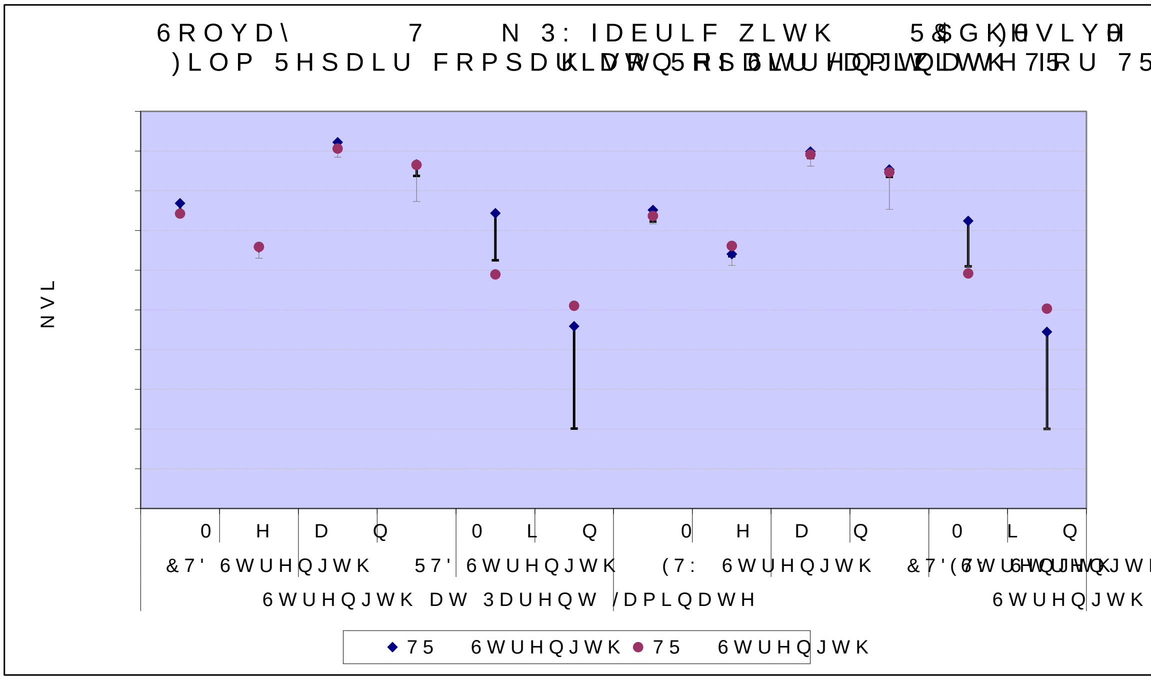


Figure 4-10: TR30 with TR50 normalized Strength at Parent and Repair Laminate means, minimums and Equivalence limits

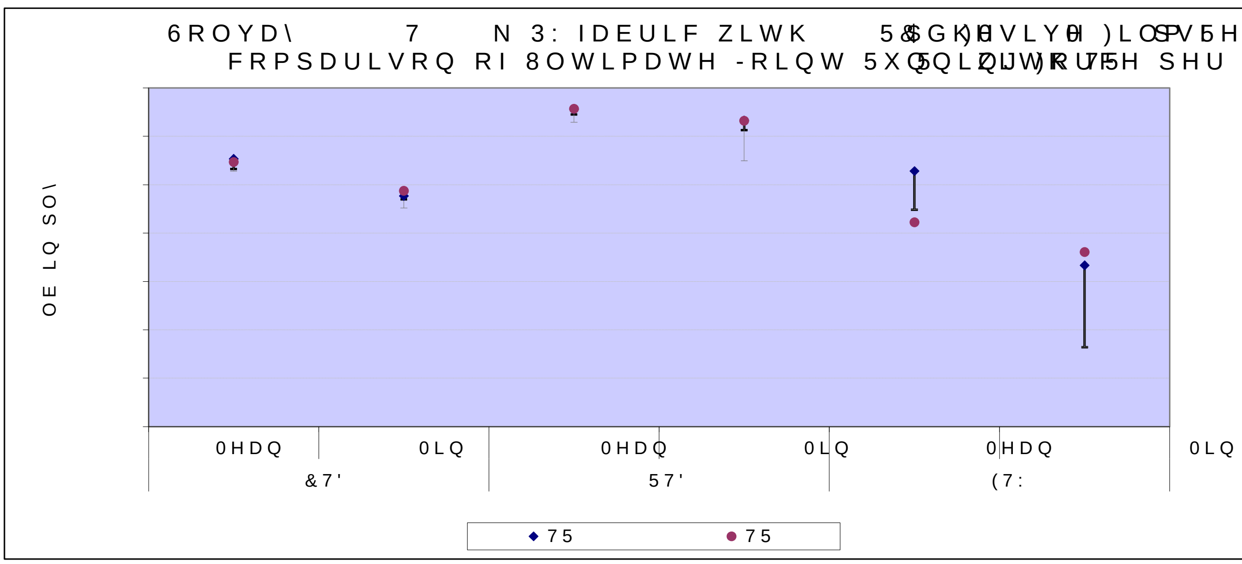
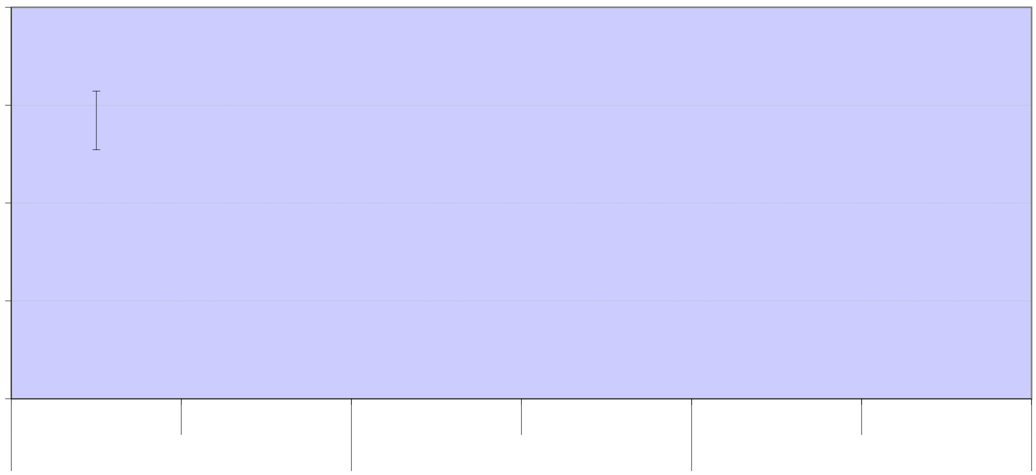
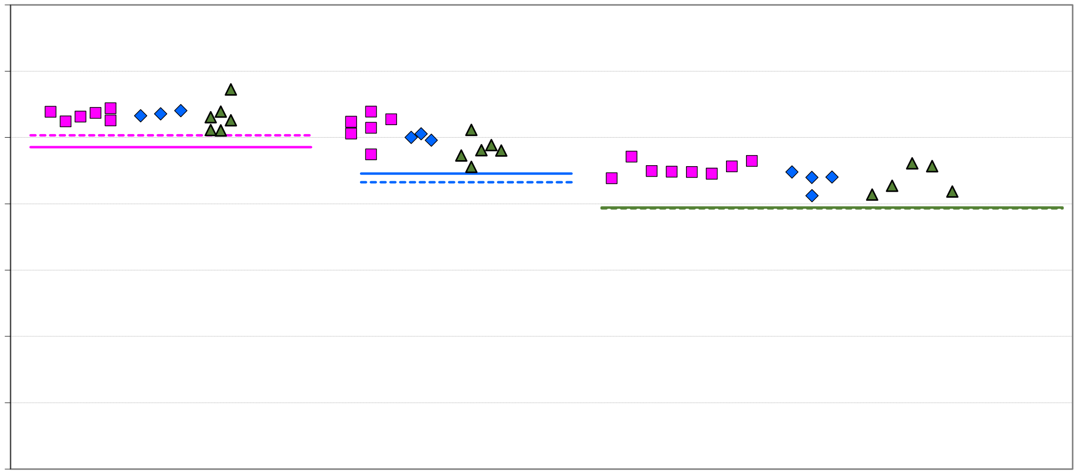


Figure 4-11: TR30 with TR50 Joint Running Force as-measured per Repair Ply means, minimums and Equivalence limits



4.6 Compression After Impact Repair with Scarf Ratio of 50:1 (CAI150)



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5.

Scarf Ratio	Test Type	Data	Property	CTD (-65°F)	RTD (70°F)	ETW2 (180°F)
			F_p^{tu} [ksi]	Pass	Pass	Failed by 5.66%
			F_r^{tu} [ksi]	Pass	Pass	Failed by 2.86%
			Modulus I [Msi]			

5.2 Failures

The FAA Laminate Repair Study material has sufficient test results for comparison on a total of 21 different test types and conditions.

Using the modified CV method, there were five failures.

1. Strength at Parent Laminate Tensile Repair (TR30) compared with Tensile Repair (TR50) for the ETW2 condition failed by 5.66%
2. Strength at Repair Laminate Tensile Repair (TR30) compared with Tensile Repair (TR50) for the ETW2 condition failed by 2.86%
3. Ultimate Joint Running Force per Repair Ply Tensile Repair (TR30) compared with Tensile Repair (TR50) for the ETW2 condition failed by 5.86%
4. Un-Notched Compression Strength Repair (UNCR30) compared with Un-Notched Compression Strength Repair (UNCR50) for the ETW2 condition failed by 5.87%
5. Un-Notched Compression Ultimate Joint Running Force per Repair Ply (UNCR30) compared with Un-Notched Compression Ultimate Joint Running Force per Repair Ply (UNCR50) for the ETW2 condition failed by 5.87%

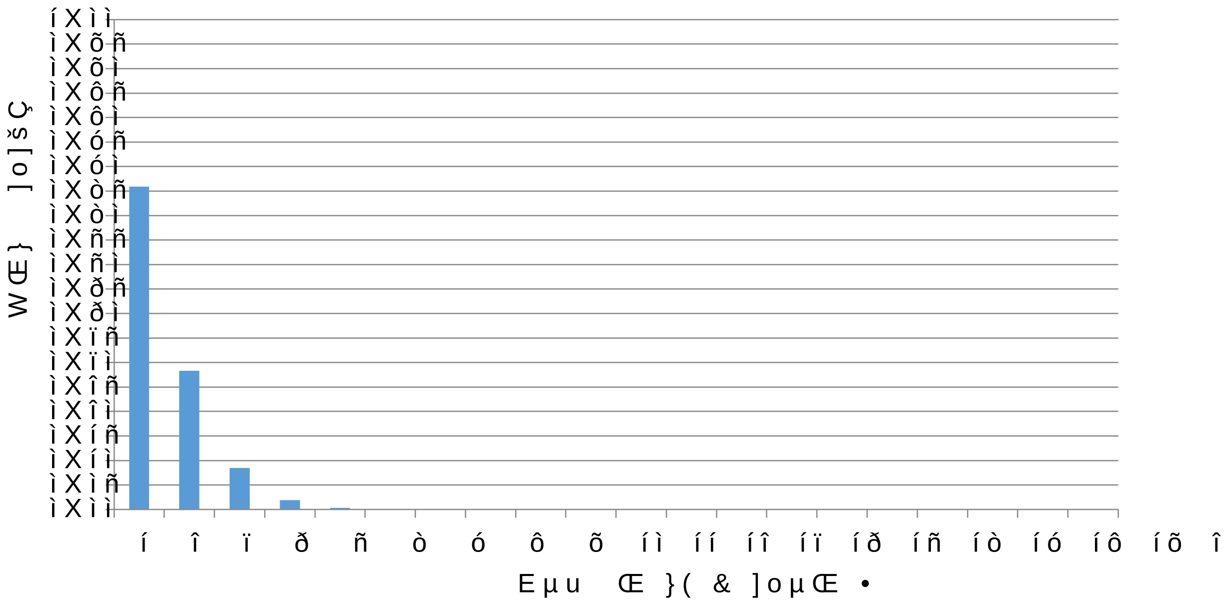
Those properties that did not pass equivalency tests should be evaluated regarding the needs of the application to determine if the test results for this equivalency sample will be sufficient for their design/build purposes.

5.3 Pass Rate

Five failures out of 21 tests and conditions gives the equivalency panels for the FAA Laminate Repair Study a pass rate of 76.19% for these tests. If the equivalency sample came from a material identical to the original qualification material and all tests were independent of all other tests, the expected pass rate would be 95%. This equates to 1.05 failures.

5.4 Probability of Failures

If the equivalency sample came from a material with characteristics identical to the original qualification material and all tests were independent of all other tests, the chance of having five or more failures is 0.32%. Figure 5-1 illustrates the probability of getting one or more failures, two or more failures, etc. for a set of 21 independent tests. If the two materials were equivalent, the probability of getting four or more failures is less than 5%. This means that the material



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7. References

1. Snedecor, G.W. and Cochran, W.G., *Statistical Methods*, 7th ed., The Iowa State University Press, 1980, pp. 252-253.
2. Stefansky, W., "Rejecting Outliers in Factorial Designs," *Technometrics*, Vol. 14, 1972, pp. 469-479.
3. Scholz, F.W. and Stephens, M.A., "K-Sample Anderson-Darling Tests of Fit," *Journal of the American Statistical Association*, Vol. 82, 1987, pp. 918-924.
4. Lehmann, E.L., *Testing Statistical Hypotheses*, John Wiley & Sons, 1959, pp. 274-275.
5. Levene, H., "Robust Tests for Equality of Variances," in *Contributions to Probability and Statistics*, ed. I. Olkin, Palo, Alto, CA: Stanford University Press, 1960.
6. Lawless, J.F., *Statistical Models and Methods for Lifetime Data*, John Wiley & Sons, 1982, pp. 150, 452-460.
7. *Metallic Materials and Elements for Aerospace Vehicle Structures*, MIL-HDBK-5E, Naval Publications and Forms Center, Philadelphia, Pennsylvania, 1 June 1987, pp. 9-166,9-167.
8. Hanson, D.L. and Koopmans, L.H., "Tolerance Limits for the Class of Distribution with Increasing Hazard Rates," *Annals of Math. Stat.*, Vol 35, 1964, pp. 1561-1570.
9. Vangel, M.G., "One-Sided Nonparametric Tolerance Limits," *Communications in Statistics: Simulation and Computation*, Vol. 23, 1994, p. 1137.
10. Vangel, M.G., "New Methods for One-Sided Tolerance Limits for a One-Way Balanced Random Effects ANOVA Model," *Technometrics*, Vol 34, 1992, pp. 176-185.
11. Odeh, R.E. and Owen, D.B., *Tables of Normal Tolerance Limits, Sampling Plans and Screening*, Marcel Dekker, 1980.
12. Tomblin, John and Seneviratne, Waruna, *Laminate Statistical Allowable Generation for Fiber-Reinforced Composites Material: Lamina Variability Method*, U.S. Department of Transportation, Federal Aviation Administration, May 2006.
13. Tomblin, John, Ng, Yeow and Raju, K. Suresh, *Material Qualification and Equivalency for Polymer Matrix Composite Material Systems: Updated Procedure*, U.S. Department of Transportation, Federal Aviation Administration, September 2003.
14. CMH-17 Rev G, Volume 1, 2012. SAE International, 400 Commonwealth Drive, Warrendale, PA 15096
15. Vangel, Mark, "Lot Acceptance and Compliance Testing Using the Sample Mean and an Extremum", Technometrics, Vol 44, NO. 3, August 2002, pp. 242-249