THE VARIABILITY CONTROL OF SOME CFRP MATERIALS BY NESTED METHOD

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ABSTRACT

This paper provides the implementation of the nested qualification method recommended by CMH-17-3G[1] in the variability control of some Carbon Fibre Reinforced Plastic(CFRP) materials. The nested qualification method classifies the variation sources by batches, process lots, test lots for the aerospace industry and this method is illustrated in this paper by presenting the engineering application of the strain-thickness relations, laminate fabrication variability, laminate batch-to-batch variability, test variability classified by small sample/ large sample/pooling statics with engineering judgments from the composite wing project. Based on the strain-thickness analysis for the tensile and compression coupon tests, the FHT and CAI are selected in determining the critical mechanical properties respectively because of their most preservative properties. The fabrication process remains a crucial problem from the large scattering range for compression and shear programs among the laminate and lamina data. However, the significant difference between maximum one and three-batch RTD laminate CVs presents insignificant batch-to-batch variability as a whole for tensile, compression and shear tests, except for very few programs. The nested qualification BKDF calculation method demonstrates more robust and reasonable test allowables by combining the pooling statistics and engineering judgment. The material equivalence tests are provided in a case to give the procedure of quantifying the similarity between the follow on materials and the original materials. Based on an testing data set, this paper accepts the tension and compression results in enlarging the standard databases while refuses the shearing data to enter the databases.

1 INTRODUCTION

The composite materials typically used in aircraft structures are composed of high strength fibers in a matrix. The purpose of matrix is to hold the structure's shape, protect the fibers from in-service effects such as impacts from tools dropping or hails. The primary stiffness and strength of the composite is in the fibers in specific directions which results in different responses in different directions. Although CFRP materials can demonstrate high strengths in specific directions, the large reliability knockdown due to uncertainty about the true variability substantially reduces the advantages of CFRP. The low value after the large knockdown is to ignore the effect of batch and to estimate the reliability based on the total numbers of coupons from all of the batches.

A new approach[2] of cross-ply laminate from [90/0]ns family via CLPT (Classical Laminate Plate Theory) has been found to be yielding higher mean strengths and lower variations, and stay robust under troublesome variations in specimen preparations and testing practice. The mechanical properties of composite materials will be affected differently by parallelism or flatness scattering, some are negligible (e.g. tensile) while some others are not (e.g. compression). In assumption of variability being mainly produced through independent layups and panels, the nested qualification approach is designed as two large [90/0]ns cross plied panels each representing an independent process lot. Each process lot is made from three qualification batches. Two subpanels were cut from each panel to present a test lot for each, and the test lot were machined into coupons properly conditioned and tested. Then the ambiguous batch-to-batch variability is partitioned into true batch variability, laminate fabrication, coupon test and residue variability. The nested experiment design was used to quantify these actual sources of variability for various mechanical and physical properties. During the allowable calculation, the process lots were treated as if they were batches, and creation of the multiple process lots from batches allows the development of more stable allowables.

The building-block approach of the composite wing-box project derive the design values from UT[3], UC[4], OHT[5], OHC[6], FHT[7], FHC[7], CAI[8], TAI[9], IPSV[10] tests on representative laminates in accordance with the airworthiness requirements of FAR 25.613 and ASTM standards. For the tensile programs as UT, OHT, FHT and TAI, the failure strains of the FHT program between 5mm and 6mm are conservative (the minimum level shown as the red line in Figure 1), so it is reasonable to select FHT to determine the critical tensile properties for the CFRP materials. Similarly, we choose CAI for the compression programs by the same philosophy (illustrated by the red line in Figure 2).

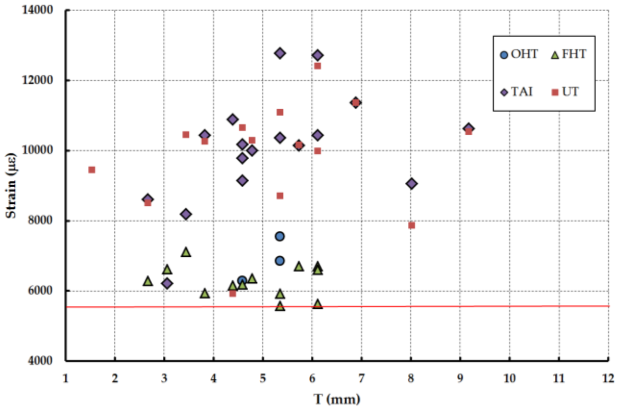

Figure 1: Strain- thickness relations for the tensile programs

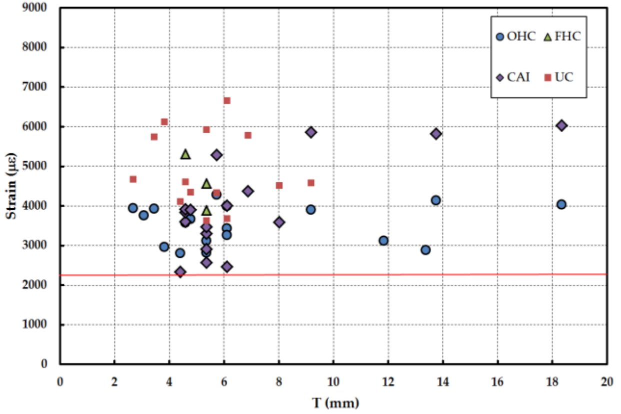

Figure 2: Strain- thickness relations for the compression programs

The CAI tests present more significant quality variability than other test programs, the failure stress generated by this test method are highly dependent upon several factors which include thickness, damage sizes, and fixtures.

A procedure of controlling the residue deviations is proposed in this paper. The methodology stems from the comparison between the small sampling, large sampling and pooling method in order to find the potentials of improving B-basis knock down factors (BKDF) by extending data regions for statistical analysis.

2 DATA VARIABILITY ANALYSIS

2.1 LAMINATE FABRICATION VARIABILITY

The specimens fabricated for test programs contain a minimum of 3 material batches to guarantee the statistical significance. The coefficients of the failure stress for the three representative ply sequences as A03 (25% 0 degrees, 50% +45/-45 degrees,25% 90 degrees), B03(44% 0 degrees, 44% +45/-45 degrees,12% 90 degrees) and C02 (57% 0 degrees, 29% +45/-45 degrees,14% 90 degrees) are listed in Table 1.

Table 1.
CV of failure stress for 9 test programs

	UT	OHT	FHT	TAI	UC	OHC	FHC	CAI	IPSV
A03	5.45%	3.86%	3.78%	11.89%	6.16%	3.57%	4.02%	8.91%	9.50%
B03	4.99%	2.05%	5.26%	3.97%	6.38%	3.45%	3.48%	8.49%	11.99%
C02	5.59%	3.11%	5.24%	6.22%	7.52%	4.08%	3.73%	8.74%	11.36%

Typical coefficients of variation (CV) for failure loads are in the range of 2% to 8%, while the typical CV's are in the range of 2 to 6% for modulus. The comparisons of CVs between the cross-ply coupon test and the 0 degree unidirectional thin lamina test are shown in Figure 3(Tensile), Figure 4(Compression) and Figure 5(Shear).

Most of the scatter points in the Figure 3 lie around the red dashed line of equal values, and the data variation effects from batch to batch, testing and fabrication is not apparent in the tensile programs as UT, OHT, FHT and TAI.

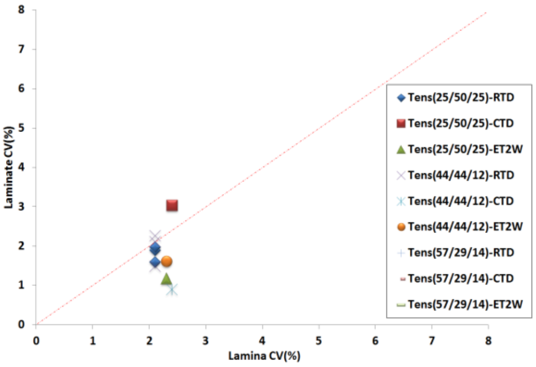

Figure 3: Comparison of CVs between Laminate/Lamina tensile tests for CFRP

The fragility of composite coupon under compression gives the different picture from Figure 3, where over 60% points in Figure 4 stay above the 45 degree line, and the remaining ones are inclined to prove the equivalence between Laminate and Lamina CVs. The difficulty in preparing thick laminates cannot avoid more voids, deficiencies, and probable delaminates on edges in machining. Hence, the quality variance of thick laminates is reasonably more apparent than the variance of thin lamina level.

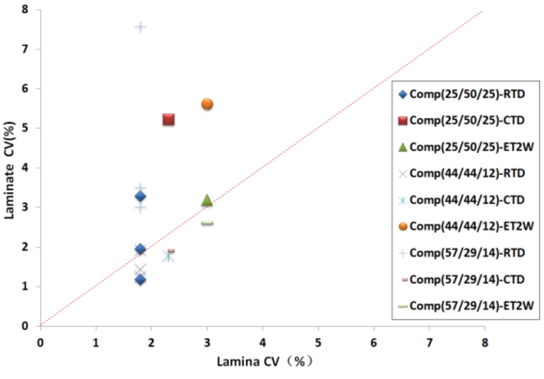

Figure 4: Comparison of CVs between Laminate/Lamina compression tests for CFRP

The large scattering range of test points in Figure 5 shows the difficulties of obtaining shear properties by test in accordance with ASTM D 7078. The unidirectional lamina test under RTD (Room Temperature Dry) condition is stable with small variations, and the coupling of shear properties in different ply angles of laminates complicates the general shear behavior, resulting large variations.

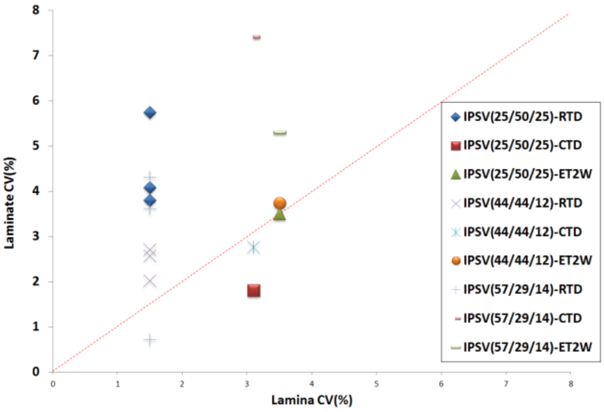

Figure 5: Comparison of CVs between Laminate/Lamina compression tests for CFRP

The data plots of tension, compression and shear in Figure 3 to Figure 5 demonstrate the significant effects of fabrication on variations.

2.2 LAMINATE BATCH-TO-BATCH VARIABILITY

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Variations for each batch within the three batch data set of RTD(23 ± 3^0C) is calculated in Fig.5, which compares the maximum of the one-batch CVs to the corresponding three-batch CVs.

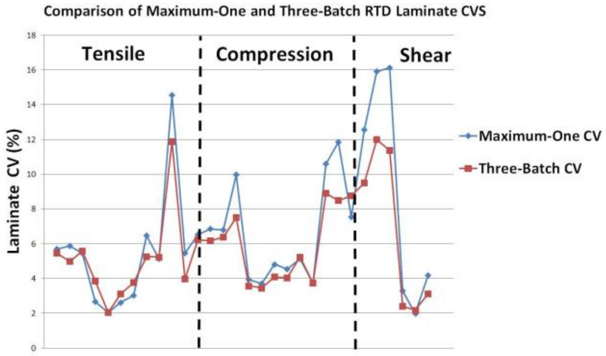

Figure 6: Comparison of Maximum One and Three-Batch RTD Laminate CVs

The Figure 6 presents insignificant batch-to-batch variability as a whole for tensile, compression and shear tests, except for very few programs. Therefore, as a special case of regression analysis, the pooling statistics considering the combined environmental effects has been recommend by FAA and CMH-17G programs. In parallel, the small sample and large sample methods are also provided.

2.3 TEST VARIABILITY

2.3.1 SMALL SAMPLE/LARGE SAMPLE STATISTICS

As thousands of coupon tests continue progressing through the composite wing box project life time, the economic reality will urge the engineering manager to consider the balance between enjoying lower costs by cutting the amount of the samples with unstable basis values and bearing higher costs by assuring confidence in conservative basis values. The LVM(Lamina variability method) is a first attempt recommended by DOT/FAA/AR-06/53[11] to solve this problem.

The small sample laminate B-basis value formula (1) (see DOT/FAA/AR-06/53[11], Equation (D-4)) to generate ratios of B-Basis for the individual batches. 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.

$$BKDF_S = \frac{(1-1.6CV)}{(1+2.33CV/\sqrt{N})} \tag{1}$$

In comparison with the small sample statistics, the large sample B-ratio formula (2) (see Table 8.5.10 in MIL-HDBK-17-1F[2] for kB values) are commonly accepted for a minimum of 18 specimens.

$$BKDF_L = 1 - k_B \bullet CV \tag{2}$$

However, the small sample and large sample analysis do not take the engineering judgment in consideration. The more advanced pooling process decomposes the calculation of BKDFs in many steps including engineering judgment which allows the user to select the best procedures.

2.3.2 ENGINEERING JUDGMENT

The main purpose of engineering judgment is to verify the assumption of identical batches of data and to check the possible outliers, otherwise, the ANOVA or linear regression models should be investigated to fit the structured data. For the unstructured data with identical groups, the normal distribution is considered in priority. If the data do not pass the normal test, the lognormal distribution can be subsequently selected, or the Weibull distribution remains the last choice for the most conservative basis values. The modified CV method shown as the equation (3) is provided for controlling overly small CVs. The CV value between 4% and 10% is typical of composite materials. Therefore, the CV values less than 0.04 can be regarded very rarely in the overly controlled conditions of a qualification not easily repeated for the follow-on tests, and the CVs less than 0.08 need to be adjusted accordingly.

$$\left(\mathrm{CV}^*\right) = \begin{cases} 0.06 & \mathrm{CV} < 0.04 \\ \dfrac{\mathrm{CV}}{2} + 0.04 & 0.04 \le \mathrm{CV} \le 0.08 \\ \mathrm{CV} & 0.08 \le \mathrm{CV} \end{cases} \tag{3}$$

2.3.3 POOLING STATISTICS

The chapter 8.3 of CMH-17-1G[12] provides explicit streamlines of the pooling analysis with engineering judgment in consideration. The BKDF calculated by pooling statistics under the jth environment is written in a form (4) of CVs.

$$BKDF_{j,P} = 1 - \left[1.28155\sqrt{\frac{N-r}{Q}} + \sqrt{\frac{1}{c_B n_j} + \left(\frac{b_B}{2c_B}\right)^2} - \frac{b_B}{2c_B}\right] \cdot \sqrt{\frac{\sum_{s=1}^{k} \frac{\bar{x}_s^2}{\bar{x}_j^2} (CV)_s^2}{(N-r)}} \tag{4}$$

The comparison of the small sample statistics (denoted by S1,S2,S3 for each batch), the large sample analysis(denoted by L) and the pooling analysis with engineering judgment (denoted by P) are provided in Table 2 and Figure 7(FHT as the critical tensile property), Table 3 and Figure 8 (CAI as the critical compression property), Table 4 and Figure 9(only IPSV for the shear property). The Room Temperature Dry is denoted by RTD, and the Elevated Temperature Wet, $82 \pm 3^0 C$, RH=85% environment is denoted by ET1W.

Table 2.

Small sample/Large sample/Pooled BKDFs for FHT test program

	A03-RTD	**A03-ET1W**	**B03-RTD**	**B03-ET1W**	**C02-RTD**	**C02-ET1W**
S1	0.87	0.87	0.84	0.87	0.87	0.87
S2	0.87	0.87	0.87	0.87	0.87	0.87
S3	0.87	0.87	0.87	0.87	0.87	0.87
L	0.93	0.96	0.90	0.91	0.90	0.90
P	0.87	0.87	0.87	0.87	0.87	0.87

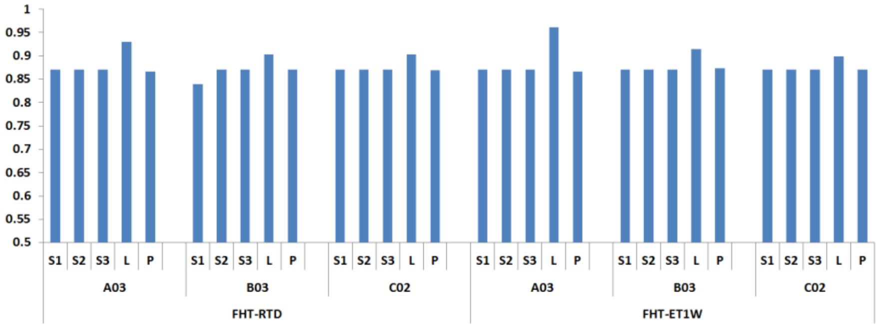

Figure 7: Column of Small sample/Large sample/Pooled BKDFs for FHT

The batch to batch variability is not obvious from the small sample analysis since S1 batch, S2 batch and S3 batch yield approximately the same BKDF. However, the CV of FHT program is too small (see the 4th column in Table 1), large sample statistics by equation (2) yields exceedingly higher BKDF than small sample ones. The pooling statistics for FHT considering the engineering judgment stay robust and more credible in comparison with large sample statistics.

Table 3.

Small sample/Large sample/Pooled BKDFs for CAI test program

	A03-RTD	**A03-ET1W**	**B03-RTD**	**B03-ET1W**	**C02-RTD**	**C02-ET1W**
S1	0.79	0.79	0.72	0.80	0.80	0.74
S2	0.75	0.80	0.80	0.80	0.80	0.77
S3	0.80	0.80	0.80	0.80	0.80	0.78
L	0.83	0.84	0.84	0.86	0.84	0.81
P	0.85	0.84	0.86	0.85	0.84	0.82

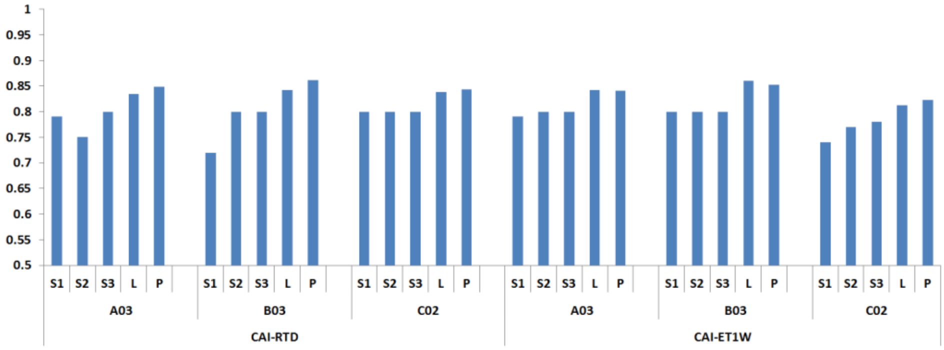

Figure 8: Column of Small sample/Large sample/Pooled BKDFs for CAI

Table 4.

Small sample/Large sample/Pooled BKDFs for IPSV test program

	A03-RTD	**A03-ET1W**	**B03-RTD**	**B03-ET1W**	**C02-RTD**	**C02-ET1W**
S1	0.80	0.80	0.80	0.79	0.80	0.80
S2	0.80	0.72	0.64	0.80	0.63	0.73
S3	0.70	0.80	0.80	0.79	0.80	0.75
L	0.82	0.84	0.78	0.87	0.79	0.82
P	0.85	0.82	0.82	0.79	0.83	0.78

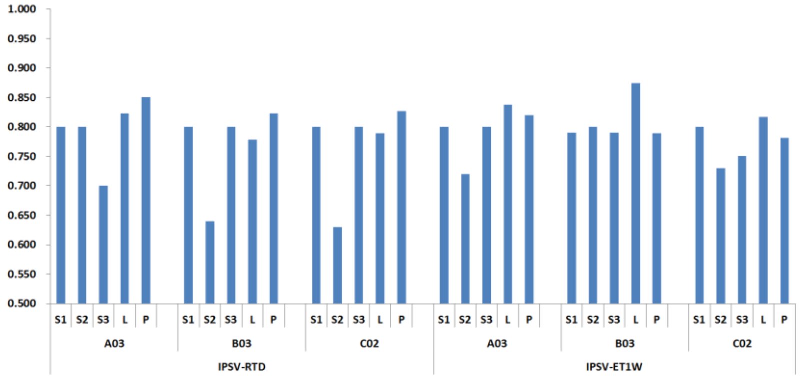

Figure 9: Column of Small sample/Large sample/Pooled BKDFs for IPSV

As for the CAI and IPSV programs, the pooling statistics with engineering judgment yield reasonably higher BKDFs in RTD condition than those in ET1W environment, since the property of composite materials is reduced by high temperature and moistures. The batch to batch variability is obvious by the difficulty in compression or shear tests, the BKDFs of pooled statistics remain stable.

3 MATERIAL EQUIVALENCE

The material equivalency programs are specified to ensure that a follow-on material or follow-on process will produce material equivalent to those of the original material databases. The criterion of acceptance is based on a statistical test. The test statistics are selected based on the material properties of interest. In assumption of the equal but unknown standard deviation, the test statistic is to calculate the formula (5) where subscripts 1 and 2 denote follow-on and original specimens.

$$t_0 = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\left(\overline{x}_1^{\,2} CV_1^2 + \overline{x}_2^{\,2} CV_2^2\right)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{5}$$

For determining material equivalency, it is recommended set the probability of rejecting a good property α=0.05 and set the critical threshold as t_{α,n_1+n_2-2} obtained from table 22 in DOT/FAA/AR-03/19[13]. The result $t_0 > t_{\alpha,n_1+n_2-2}$ is said to have failed the one-sided t test and mean of the follow-on property is significantly higher than that of the original one. We choose 12 specimens from individual test program as the follow-on materials and select the original materials from the standard database. The modulus property of the original and follow-on materials are listed in the following Table 5 and the one sided t-test in Table 6 has shown that the tensile and compression modulus are not significantly larger than the standard values while the shear modulus has failed the test. Therefore, the data obtained from tensile and compression programs can be accepted to enlarge the existing database.

Table 5.

Sample modulus property of the original and follow-on CFRP materials

		Number		Mean(GPa)		Std.(GPa)	
0 °Tensile-RTD	Original	48		168		5.1	
	Follow-on (GPa)	162	163	166	165	170	171
		169	162	164	161	165	167
0 °Tensile-ET1W		Number		Mean(GPa)		Std.(GPa)	
	Original	48		169		6.9	
	Follow-on (GPa)	170	170	169	181	169	171
		166	165	163	166	170	169
0 °Compression -RTD		Number		Mean(GPa)		Std.(GPa)	
	Original	30		163		3.0	
	Follow-on (GPa)	149	151	150	153	159	152
		151	151	149	154	141	138

0 °Compression -ET1W		Number		Mean(GPa)		Std.(GPa)	
	Original	30		161		6.2	
	Follow-on (GPa)	150	146	146	150	155	155
		149	151	147	137	149	133
Shear-RTD		Number		Mean(GPa)		Std.(GPa)	
	Original	30		4.14		0.10	
	Follow-on (GPa)	5.48	5.08	5.28	4.28	4.68	7.88
		6.68	6.91	6.40	5.37	5.88	5.88
Shear-ET1W		Number		Mean(GPa)		Std.(GPa)	
	Original	30		2.99		0.10	
	Follow-on (GPa)	5.68	6.26	5.28	6.28	4.88	5.28
		5.68	5.48	4.85	5.37	4.51	6.40

Table 6.
One sided t-test for CFRP material equivalence

TEST PROGRAM	t_0	t_{α,n_1+n_2-2}	EQUIVALENCE TEST
0 °Tensile-RTD	-1.68	1.67	PASS
0 °Tensile-ET1W	0.04	1.67	PASS
0 °Compression-RTD	-10.12	1.69	PASS
0 °Compression-ET1W	-5.9	1.69	PASS
Shear-RTD	8.68	1.69	FAILED
Shear-ET1W	23.43	1.69	FAILED

4 CONCLUSIONS

The study of nested qualification approach on the coupon test of CFRP materials was conducted in clarifying the variability sources from true batches, process lots and test lots. The strain-thickness relations of 9 representative test programs were selected to verify FHT and CAI as the most conservative program for tension and compression respectively in the introduction. The laminate-lamina scatter plots were presented to show the fabrication variability (true batch) was more obvious for compression and shear tests. The batch-to-batch variability was demonstrated insignificant from the comparison of coefficients of variants between the maximum and average value in three batches. The pooling statistics with engineering judgment in adjusting CVs were provided as a more robust and credible analysis in comparison with large sample or small sample analysis. The material equivalence result between the follow-on and original materials were given to accept the tension and compression result into the current database and leave the shear test data rejected for the future coupon experiment design.

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