Cost Effective Computational Approach for Generation of Polymeric Composite Material Allowables for Reduced Testing

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1. Introduction

The objective of this work is to provide the aerospace community with a robust computational capability to determine composite material strength allowables. The technical approach presented in this document serves two purposes: (1) reduce laminate level testing for determination of allowables; and (2) estimate allowables with some level of reliability when such data are difficult to obtain. A- and B-basis strength values are essential for reducing risk in aircraft structural components made from fiber reinforced polymer composite materials. Risk reduction is achieved by lowering the probability of failure of critical aircraft structures through the use of A- and B-basis design values. Generating strength allowables solely by means of testing is costly and time consuming as large number of composite coupons must be tested under various environments: cold, ambient and elevated temperatures (with and without moisture). The aerospace community is challenged by the following: (1) tests must be conducted on many types of coupons to determine allowables for in-plane and out-of-plane properties (un-notched and notched); and (2) new composite materials are introduced to the market at a rapid rate amplifying the need for timely cost effective approach. The tests must be carried out in accordance to standards set by ASTM (American Society for Testing and Materials).

Current practices for determining allowables follow procedures recommended by FAA and working draft of the composite materials handbook CMH-17 Rev G (formerly military handbook Mil-HDBK-17-1F) [1&2]. Table 1 lists the robust and reduced test sampling requirements set forth by CMH-17. Determination of A-basis values requires more test samples than those needed to determine B-basis values as A-basis strength are applied to single members within an assembly whose failure would result in loss of structural integrity. For A-basis, at least 99% of the population of material strength values is expected to equal or exceed this tolerance bound with 95% confidence. B-basis values are applied to redundant structures where failure would result in safe load redistribution. For B-basis, 90% of the population of material strength values is expected to equal or exceed that strength value with 95% confidence. Figure 1 illustrates the statistical definition of 0.01 and 0.10 probabilistic
strength for A-basis and B-basis, respectively. The physical definition of A- and B-basis is presented in Figure 2. A-basis strength value [2] is traditionally calculated using equation \((\bar{x} - (K_A) \cdot S)\); similarly B-basis strength value is computed using equation \((\bar{x} - (K_B) \cdot S)\); where \(\bar{x}\) is the mean strength of the test samples, \(S\) is sample standard deviation, and \(K_A\) and \(K_B\) are tolerance factors. The higher the tolerance factor, the lower the allowable; the higher the number of test replicates the more stable the allowable. CMH-17 provides tables of tolerance factors for various distributions as function of the sample size. The same procedures and standards require checking for outliers, distribution types if non-normality is observed, and batch variability. Details on numerical and test procedures for standard practice for determination of allowables can be found in [1 & 2].

| Category              | # of Batches | # of Samples | Category              | # of Batches | # of Samples |
|-----------------------|--------------|--------------|-----------------------|--------------|--------------|
| A-basis – Robust Sampling | 10           | 75           | B-basis – Robust Sampling | 10           | 55           |
| A-basis – Reduced Sampling | 5            | 55           | B-basis – Reduced Sampling | 3            | 18           |

Table 1. FAA Guidelines for Robust and Reduced Sampling

The proposed approach for determination of strength allowables builds on existing accepted standards and practices [1 & 2]. It uses statistics from lamina level testing to reverse engineer uncertainties in fiber and matrix material properties and manufacturing variables. These uncertainties are subsequently used in generating virtual test samples for laminated notched and un-notched specimens. The virtual samples are then used in lieu of actual test samples with resulting savings in cost and time. The methodology combines probabilistic methods with advanced multi-scale multi-physics progressive failure analysis (MS-PFA) [4] to reduce the number of tests needed for determination of A- and B-basis strength values. Details of the technical approach are provided next and the viability of the approach is demonstrated through application to four composite materials.

![Fig. 1. Statistical Definition of A-and B-basis Strength [3]](image-url)
## 2. Nomenclature

| Symbol | Description |
|--------|-------------|
| $E_{11}$ | Lamina extensional modulus in fiber direction |
| $E_{22}$ | Lamina extensional modulus perpendicular to fiber direction |
| $E_{f11}$ | Fiber extensional modulus in fiber direction |
| $E_{f22}$ | Fiber extensional modulus perpendicular to fiber direction |
| $E_m$ | Matrix extensional modulus |
| $\varepsilon_{11C}$ | Lamina compressive strain limit parallel to fiber |
| $\varepsilon_{11T}$ | Lamina tensile strain limit parallel to fiber |
| $\varepsilon_{22S}$ | Lamina in-plane strain limit |
| $\varepsilon_{22C}$ | Lamina compressive strain limit perpendicular to fiber |
| $\varepsilon_{22T}$ | Lamina tensile strain limit perpendicular to fiber |
| FVR | Fiber volume ratio |
| VVR | Void volume ratio |
| MVR | Matrix volume ratio |
| $G_{12}$ | Lamina in-plane shear modulus |
| $G_{f12}$ | Fiber shear modulus – In-plane |
| $G_{f23}$ | Fiber shear modulus – Out-of-plane |
| GUI | Graphical user interface |
| IPS | In-plane shear |
| LC | Longitudinal compression |
| LT | Longitudinal tension |
| $S_{11C}$ | Lamina compressive strength in fiber direction |
| $S_{11T}$ | Lamina tensile strength in fiber direction |
| $S_{12S}$ | Lamina in-plane shear strength |
| $S_{22C}$ | Lamina compressive strength perpendicular to fiber direction |
| $S_{22T}$ | Lamina tensile strength perpendicular to fiber direction |
| $S_{f11}$ | Fiber compressive strength |
| $S_{f11T}$ | Fiber tensile strength |
| $S_{mC}$ | Matrix compressive strength |
| $S_{mS}$ | Matrix shear strength |

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Fig. 2. Physical Definition of A-and B-Basis Strength
3. Description of technical approach

Methodology and computational procedure is described as an integrated MS-PFA and probabilistic analysis capability. It is comprised of the following:

- determination of scatter and sensitivity of in-situ material properties and fabrication parameters (e.g., fiber tensile strength, and fiber volume ratio);
- reproducing the test measured scatter/distribution in lamina using MS-PFA, and probabilistic analysis;
- generate random samples using lamina level uncertainties;
- update scatter from simulation to match lamina CDF and PDF curves using Bayesian statistics followed by determination of allowables with the desired confidence levels;

Scatter in strength data obtained from unidirectional lamina testing is used in predicting allowables for notched and un-notched laminates. The variability is generally caused by: (1) scatter in micro-scale mechanical properties of the fiber, matrix, and interface; (2) variability in composite manufacturing parameters; and (3) manufacturing defects such as void, waviness, and gaps. Lamina level testing is carried out to determine ply in-plane and out-of-plane mechanical properties. Table 2 lists the measured ply properties obtained from in-plane testing of composite specimens made from unidirectional laminates. The same table also lists the physical parameters influencing the measured ply response. For example, variation in ply longitudinal strength collected from test is a function of scatter of fiber strength and fiber content. MS-PFA \[4\] is used in conjunction with probabilistic methods \[5\] to reproduce scatter in strength obtained from lamina level testing. Figure 3 shows the lamina level testing performed per ASTM standards to generate in-plane ply properties. Figure 4 shows the process for reproducing the scatter from lamina level testing. Micro-scale random variables consisting of fiber and matrix mechanical properties combined with fabrication parameters are perturbed to reproduce the scatter from lamina level testing. This process results in a unique set of coefficient of variations for various random variables that can be used in random sampling of test specimens for higher order ASTM tests (laminate level).

The use of lamina level uncertainties to predict allowables for laminate level building block tests is the added value of the work presented in this paper. The work reported in \[6\] confirms that lamina uncertainties are adequate for use in generation of scatter in laminate level response. The uncertainties causing scatter in strength of a composite laminate are: (1) variability in fiber and matrix properties and composite fabrication parameters; (2) manufacturing defects (“as designed” versus “as built” and “as is”); and (3) human error encountered during testing. A flow chart of the technical approach for determination of A- and B-basis allowables is presented in Figure 5. The basis for the computation is the reproduction of scatter in ply strength caused by variability of constituent material properties and manufacturing defects. The approach was validated by comparing its A- and B-basis predictions with values obtained from standard methods \[1&2\] using test data from robust or reduced sampling.
| Measured Ply Property                          | Physical Variables Influencing Measured Property                                                                 |
|----------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| Longitudinal tension strength (S11T)         | Fiber tensile strength (Sf11T) and fiber volume ratio (FVR)                                                 |
| Longitudinal tension modulus (E11T)          | Fiber longitudinal tensile stiffness (Ef11) and fiber volume ratio (FVR)                                      |
| Longitudinal compression strength (S11C)      | Fiber compressive strength (Sf11C) and fiber volume ratio (FVR), fiber micro-buckling                        |
| Longitudinal compression modulus (E11C)       | Fiber longitudinal compressive stiffness (Ef11) and fiber volume ratio (FVR)                                  |
| Transverse tension strength (S22T)           | Matrix tensile strength (SmT) and matrix volume ratio (MVR)                                                  |
| Transverse tension modulus (E22T)            | Matrix modulus (Em), fiber transverse modulus and matrix volume ratio (MVR)                                  |
| Transverse compression strength (S22C)        | Matrix compressive strength (SmC) and matrix volume ratio (MVR)                                               |
| Transverse compression modulus (E22C)         | Matrix modulus (Em) and matrix volume ratio (MVR)                                                             |
| In-Plane shear strength at 0.2% Offset (IPS)  | Matrix shear strength (SmS) and matrix volume ratio (MVR)                                                     |
| In-Plane shear strength at 5% Strain (IPS)    | Matrix shear strength (SmS) and matrix volume ratio (MVR) and nonlinear properties of the matrix               |
| In plane shear modulus (G12)                  | Matrix modulus (Em), matrix Poisson's ratio, Fiber Shear Modulus (Gf12) and matrix volume ratio (MVR)        |

Table 2. Stiffness and Strength Properties Obtained by Physical Testing of Composite Specimens (in-plane loading)

Fig. 3. Five Basic ASTM Tests are Needed at the Lamina Level to Characterize Fiber and Matrix Constituent Material Properties
4. Validation of technical approach

The computational capability described herein is validated for polymer composite materials typically used in aerospace applications. Data for MTM45-1 145 AS4, IM7/MTM45 graphite/epoxy and T300/PPS material are used to demonstrate the effectiveness of the methodology. Additionally, the capability of obtaining A-basis starting from B-basis is demonstrated.

Strength Allowables for MTM45-1 145 AS4 (Lamina Level)

Ply properties from lamina level testing at room temperature dry condition, obtained from [7], are used to characterize the MTM45-1 145 AS4 tape composite material. This is achieved by deriving its in-situ fiber and matrix properties. Table 3 lists the AS4 fiber in-situ
mechanical properties while Table 4 lists similar properties for the MTM45 matrix. The derived constituent properties combined with ply manufacturing parameters of 61% fiber volume fraction and 2% void volume fraction reproduced accurately the average ply properties reported from test in [7]. A comparison of calculated ply properties by MS-PFA simulation and test is presented in Table 5. With accurate determination of average ply properties starting from in-situ fiber matrix properties, random variables statistics for micro-scale mechanical properties are obtained directly from lamina level testing published in [7]. Table 6 lists the derived random variables statistics for use in determination of strength allowables for MTM45-1 145 AS4. The COVs of strength and stiffness properties were obtained from lamina level tests published in reference [7] while the COVs of other random variables were iterated on to ensure proper simulation of lamina level scatter. The considered random variables included fiber and matrix stiffness and strength and fiber and

Table 3. AS4 Fiber In-Situ Properties

| Fiber (1) | AS4-  |
|-----------|-------|
| Description: | Calibrated from Input Ply Properties: |
| FVR=0.6065; VVR=0.02 |
| Mechanical | |
| Modulus | |
| $E_{11} = 3.139E+07$ lbf/(in^2) |
| $E_{22} = 3.611E+06$ lbf/(in^2) |
| $G_{12} = 5.318E+06$ lbf/(in^2) |
| $G_{23} = 1.234E+06$ lbf/(in^2) |
| Poisson Ratio | |
| $N_{12} = 2.895E-01$ |
| $N_{23} = 4.832E-01$ |
| Strength | |
| $S_{11T} = 4.500E+05$ lbf/(in^2) |
| $S_{11C} = 3.120E+05$ lbf/(in^2) |

Table 4. MTM45 Matrix In-Situ Properties

| Matrix (1) | MT45  |
|-----------|-------|
| Description: | Calibrated from Input Ply Properties: |
| FVR=0.6065; VVR=0.02 |
| Mechanical | |
| Modulus | |
| $E = 3.495E+05$ lbf/(in^2) |
| Poisson Ratio | |
| $N = 3.400E-01$ |
| Strength | |
| $S_T = 1.075E+04$ lbf/(in^2) |
| $S_C = 4.000E+04$ lbf/(in^2) |
| $S_S = 1.400E+04$ lbf/(in^2) |
Table 5. Comparison of Average Ply Properties Obtained from Test to those from Simulation for MTM45-1 145 AS4

| Property                  | Mean Value | COV  | Standard Deviation | Distribution Type |
|---------------------------|------------|------|--------------------|-------------------|
| Fiber Ef11 – Longitudinal modulus (msi) | 31.39      | 3.0% | 0.9417             | Normal            |
| Fiber Sf11T – Longitudinal tension strength (ksi) | 450        | 5.5% | 24.75              | Normal            |
| Fiber S11C – Longitudinal compression strength (ksi) | 312        | 5.0% | 15.6               | Normal            |
| Matrix Em – Normal modulus (msi) | 0.3495     | 3.1% | 0.018345           | Normal            |
| Matrix SmT – Matrix tension strength (ksi) | 10.75      | 17.5%| 1.881              | Normal            |
| Matrix SmC – Matrix compression strength (ksi) | 40         | 5.0% | 2                  | Normal            |
| Matrix SmS – Matrix shear strength (ksi) | 14         | 4.0% | 0.56               | Normal            |

Table 6. Random Variables Statistics for Use in Determining Allowables for MTM45-1 145 AS4 Composite

void contents. The COVs for the mechanical properties were obtained from lamina level testing published in reference [7] using the correlation between measured ply property and micro-scale properties of Table 2. The COVs for the manufacturing variables were obtained by iterating on the scatter produced by combined MS-PFA and probabilistic analysis to match the one from lamina level testing of the five in-plane ASTM tests of Figure 3.
Figure 6 shows the lamina level cumulative distribution functions (CDFs) for the 5 in-plane ASTM tests LT, LC, TT, TC, and IPS generated from virtual test data using MS-PFA simulation and from actual test. The data from test and simulation are fitted to a normal distribution in the plots (a) through (e) for the various ASTM tests. The amount of data reported in reference [7] for each ASTM type varied. For example, for the LT test, 19 samples were reported while for LC a total of 24 samples were reported. The CDF from simulation was generated for each test using the random variables statistics listed in Table 6. A total of 55 samples were randomly generated with MS-PFA considering simultaneous uncertainties in material and manufacturing random variables. That means MS-PFA was run 55 times for each ASTM test to predict failure stress for each sample. All variables listed in Table 6 took on random values for each analysis sample by MS-PFA. As illustrated in Figures 6-a through 6-c, the distribution (scatter) and mean strength generated by the simulation matched perfectly the ones from test for LC, LT, and TT tests.

The data generated for TC and IPS are shown in Figures 6-d and 6-e. The CDFs from simulation are updated for TC and IPS per the procedure outlined in Figure 5 for fine tuning the COV variables. Initial predictions for mean strength from simulation were 5.5% and 6.3% lower than average from test for TC and IPS. The updates, although not necessary, are done to ensure that the mean strength from simulation matches exactly the mean from test. This process allows the analyst to correlate data from test with simulation and update the simulation results with test data regardless how limited the data is. The difference between mean predicted and test strengths for TC and IPS specimens could be have been reduced to a negligible value by adjusting the calibrated in-situ properties. However, the authors intended to illustrate that the difference in mean strength between simulation and test depicts a realistic situation.

![Graph](image-url) (a) MS-PFA Samples Compared to Test for MTM45-1 145 AS4 Longitudinal Tension (LT)
(b) MS-PFA Samples Compared to Test for MTM45-1 145 AS4 Longitudinal Compression (LC)

(c) MS-PFA Samples Compared to Test for MTM45-1 145 AS4 Transverse Tension (TT)
Based on accurate reproduction of strength scatter with MS-PFA from test, one concludes that the uncertainties defined are valid for use in laminate level simulation of notched or un-notched specimens. If the scatter produced from simulation is not accurate, other physical random variables can be included in the analysis while iterating on the COV to match the scatter at the lamina level.

The virtual test samples data produced by MS-PFA are run with STAT-17 [2] to determine A- and B-basis values. Table 7 compares the A- and B-basis values from the 55 samples generated.
by MS-PFA to those reported in reference [7]. The samples generated virtually by MS-PFA are analyzed using STAT-17 to determine A- and B-basis values. The results obtained from STAT-17 for MS-PFA samples met the normality criterion. Note that the allowables reported in [7] for TT and IPS tests were obtained using ANOVA method (a very conservative criterion). The advantage of simulation lies in its capability of providing alternate approach to avoid unreasonable allowable strength values when CMH-17 criteria are not met.

| Lamina Test | Test Mean | MS-PFA Mean | Test Report [7] | MS-PFA* | % Diff |
|-------------|-----------|-------------|-----------------|---------|--------|
|             | Strength (ksi) | Strength (ksi) | A-Basis (ksi) | A-Basis (ksi) | w.r. [7] |
| LT          | 274.78     | 275.18      | 234.76         | 224.01   | -4.58% |
| LC          | 203.53     | 203.38      | 168.23         | 172.55   | 2.57%  |
| TT          | 6.92       | 7.05        | 0.48**         | 3.68     | N/A    |
| TC          | 26.81      | 25.36       | 21.61          | 21.71    | 0.46%  |
| IPS         | 9.36       | 8.76        | 4.97**         | 7.61     | N/A    |

| Lamina Test | Test Report [7] | MS-PFA | % Diff |
|-------------|-----------------|--------|--------|
|             | B-Basis (ksi)   | B-Basis (ksi) | w.r. [7] |
| LT          | 250.71          | 245.80 | -1.96% |
| LC          | 182.47          | 185.68 | 1.76%  |
| TT          | 0**             | 5.12   | N/A    |
| TC          | 24.26           | 23.27  | -4.08% |
| IPS         | 6.8**           | 8.10   | N/A    |

* Randomly generated with MS-PFA then used as input to STAT-17 (Normal)
**Reference [7] used ANOVA method to report allowables

Table 7. Validation of MTM45-1 145 AS4 Lamina Level Allowables Obtained Using Virtual Test Samples by MS-PFA (Simulated Samples are Inputed to STAT-17)

Table 8 lists lamina level allowables obtained from simulated CDF at 0.01 probability for A-basis and at 0.10 probability for B-basis are compared to those reported in reference [7]. Overall, generating samples randomly with MS-PFA and processed with STAT-17 produce similar allowables to those obtained from a CDF for the given ASTM test. However, the CDF curve would depict more stable allowables as it is not dependent on tolerance factors. Next, results obtained for laminate level allowables are presented and discussed.

| Lamina Test | Test Mean | MS-PFA Mean | Test [7] | MS-PFA* | Difference |
|-------------|-----------|-------------|----------|---------|------------|
|             | Strength (ksi) | Strength (ksi) | A-Basis (ksi) | A-Basis (ksi) | w.r.t [7] |
| LT          | 274.78     | 275.18      | 234.76   | 229.91  | -2.07%     |
| LC          | 203.53     | 203.38      | 168.23   | 175.17  | 4.13%      |
| TT          | 6.92       | 7.05        | 0.48**   | 4.04    | N/A        |
| TC          | 26.81      | 25.36       | 21.61    | 22.32   | 3.29%      |
| IPS         | 9.36       | 8.76        | 4.97**   | 7.93    | N/A        |

| Lamina Test | Test [7] | MS-PFA | Difference |
|-------------|----------|--------|------------|
|             | B-Basis (ksi) | B-Basis (ksi) | w.r.t [7] |
| LT          | 250.71   | 249.91 | -0.32%     |
| LC          | 182.47   | 187.11 | 2.54%      |
| TT          | 0**      | 5.12   | N/A        |
| TC          | 24.26    | 23.27  | -4.08%     |
| IPS         | 6.8**    | 8.29   | N/A        |

* Obtained from CDF of Probabilistic Strength (A-basis at 0.10 Probability; B-basis at 0.1 Probability)
**Reference [7] reported use of ANOVA for this prediction

Table 8. Validation of MTM45-1 145 AS4 Lamina Level Allowables Obtained Using Virtual Test Samples by MS-PFA (A- and B-Basis Values are Obtained from CDF Curve at 0.01 and 0.1 Probabilities)
Strength Allowables for MTM45-1 145 AS4 (Laminate Level without use of Test Data)

A major contribution of the work presented here is the ability to use lamina level uncertainties to predict uncertainties for any laminate. Micro-scale uncertainties are infused to higher level structures of the FAA building block of Figure 7. The uncertainties derived in Table 6 are used to determine A- and B-basis allowables for un-notched laminate specimens for two layups: [0/90], and quasi-isotropic (25% 0° plies, 50% ±45° plies, and 25% 90° plies). The allowables were obtained with MS-PFA for tension and for compression loading conditions. Figure 8 shows plots of the CDF of strength determined using the same uncertainties used in the lamina level simulation. Table 9 lists the values for A- and B-basis obtained from MS-PFA simulation and from reference [7] using standard methods.

Fig. 7. FAA Building Block Validation with Generic and Non-Generic Specimens Depicting Multi-Scale and Multi-Level Integration of Structural Parts

In Figure 8, strengths from physical testing are plotted alongside the strengths generated with MS-PFA. This is done to illustrate the degree of fitness of simulated data compared to test. The allowables values listed in Table 9 are obtained from simulation using the uncertainties of Table 6 and assuming data from physical testing are not available. Figure 9 shows the probabilistic sensitivities of random variables for the quasi-isotropic laminate. The sensitivity analysis ranks the random variables by order of influence on the laminate strength response. This is done by identifying the “root cause” for composite damage and failure. Controlling variability in the influential random variables reduces scatter in laminate strength response. As can be concluded from Figure 9, the transverse tensile strain EPS22T is the most predominant uncertainty followed by fiber volume ratio, FVR. Note that for laminate level specimens, a strain failure criteria is used for ply failure analysis in MS-PFA while for lamina level specimens, strength based criteria were used. The random variable statistics remain unchanged as the evaluation moved from lamina level to laminate level. Strain limits used as fracture criteria for laminate analysis are derived from lamina analysis and the reverse engineering process of fiber and matrix properties discussed earlier (Table 3 and Table 4).
(a) MS-PFA Samples Compared to Test for 0/90 MTM45-1 145 AS4 Un-notched Tension

(b) MS-PFA Samples Compared to Test for 0/90 MTM45-1 145 AS4 Un-notched Compression
(c) MS-PFA Samples Compared to Test for MTM45-1 145 AS4 Quasi Isotropic Un-notched Tension

(d) MS-PFA Samples Compared to Test for MTM45-1 145 AS4 Quasi Isotropic Un-notched Compression

Fig. 8. Scatter in Laminate Level Failure Stress for MTM45-1 145 AS4 0/90 and Quasi Un-notched Specimens Generated by MS-PFA Simulation Compared to Test Data [7]
Table 9. Validation of MTM45-1 145 AS4 Laminate Level Allowables Obtained Using Virtual Test Samples by MS-PFA (Simulated Samples are Input to STAT-17)

The effect of sample size on A- and B-basis predictions is presented in Figure 10 for the quasi-isotropic laminate under tension loading. MS-PFA was used to generate 55, 100 and 1000 samples. The predictions improved with the use of increased number of samples as compared to the 21 physical tests reported in reference [7]. The A and B- basis values for different random sample size are listed in Table 10. The randomly generated samples were fitted to normal distribution. Evaluating these virtual samples with STAT-17 yielded the A- and B-basis values presented in Table 10. As more virtual samples were generated, the mean value approached the real mean from the 21 physical tests. Data presented in Table 10 establishes confidence in the computational approach, especially to the stability of data obtained from virtual simulation. Next, validation of allowables for IM7/MTM45-1 with reduced testing is presented and discussed.

![Random Variables](www.intechopen.com)
Fig. 10. Effect of Number of Virtual Samples on Strength of MTM45-1 145 AS4 Quasi Un-notched Laminate (Tension Loading)

| Test Type          | Mean | A-Basis | B-Basis |
|--------------------|------|---------|---------|
| Un-Notched         |      |         |         |
| 21 Test Samples    | 108.82 | 95.34  | 100.83  |
| 55 Virtual Samples | 110.62 | 99.80  | 104.41  |
| 100 Virtual Samples | 110.09 | 98.85  | 103.66  |
| 1000 Virtual Samples | 109.15 | 96.90  | 102.32  |
| Difference w.r.t. tests [6] | 1.65% | 4.68% | 3.55% |
| 55 Virtual Samples | 1.16% | 3.68% | 2.81% |
| 1000 Virtual Samples | 0.31% | 1.64% | 1.48% |

Table 10. Effect of Number of Virtual Samples on Determination of A- and B-Basis for MTM45-1 145 AS4 Quasi Un-Notched Laminate (Tension Loading)

B-Basis Strength Allowables for IM7/MTM45-1 (Sealed Envelope Prediction)

To further affirm the validity of the approach for generating allowables with reduced testing, Northrop Grumman Corporation (NGC) provided data for IM7/MTM45 composite for use in a “sealed envelope” process [8]. Using statistics provided by NGC for lamina level testing, B-basis values were calculated for notched and un-notched laminates using the approach proposed in this document to reduce laminate level testing. NGC provided one third of the laminate level test data usually used in the generation of allowables. Independent of full test results, predictions were made and handed to NGC for comparison against a “sealed envelope” of real test data. B-basis tensile strength values for un-notched and notched IM7/MTM45-1 coupons were predicted (using a reduced number of test replicates) and provided to NGC. Predicted results were compared to those obtained using standard military specification practices and the standard number of test replicates. The
difference in the B-basis results obtained from prediction and those from current practices ranged from -5.31% and 5.34%. Figure 11 shows the steps followed to compute B-basis values for the various coupons starting with a reduced number of test replicates. The number of replicates varied from 3 to 6 as listed in Table 11. The same table compares MS-PFA B-basis predictions to those obtained using traditional methods and all available replicates [9-10]. The B-basis values from the references were not made available until after computational allowables were derived. The B-basis predictions were obtained with MS-PFA using a unique set of prescribed uncertainties of the following random variables: fiber tensile strength, matrix tensile strength, matrix shear strength, fiber volume ratio, and void volume ratio. The uncertainties were derived from the lamina level testing for IM7/MTM45 Open hole tension (OHT) coupon simulations showed errors in predicted mean tensile strength ranging from -12.7% to 8.88% compared to true average from test. The difference

| Coupon Type | Lamina Proportions | MS-PFA B-basis (ksi) | CMH17 [2] B-basis (ksi) | w.r.t. [2] Difference |
|-------------|--------------------|----------------------|-------------------------|---------------------|
| Un-Notched Tension RTD | [50-0-50] | 156.22 | 158.54 | -1.46% |
| | [25-50-25] | 112.98 | 119.32 | -5.31% |
| | [10-80-10] | 69.09 | 65.59 | 5.34% |
| Un-Notched Compression RTD | [50-40-10] | 173.41 | 178.4 | -2.80% |
| | [25-50-25] | 59.4 | 62.15 | -4.42% |
| | [10-80-10] | 41.59 | 41.67 | -0.19% |
| | [50-40-10] | 98.13 | 100.63 | -2.48% |

Table 11. Un-Notched and Notched B-Basis Strength Predictions for IM7/MTM45 (Tension Loading)
between simulation and test averages were addressed using Bayesian statistics update where CDF from simulation was corrected with the 6 few tests that were available. Animation of damage at the initiation stage and progression up to ultimate failure for the quasi open hole coupon under tension loading is presented in Figure 12. MS-PFA [4] identified critical damage evolution events isolating plies and elements contributing to the failure.

**A- and B-Basis Validation for Open Hole Tension (OHT) T300/PPS Thermoplastic**

To further demonstrate the validity of the MS-PFA approach for determination of allowables with reduced testing, A- and B-basis predictions were made for an open hole specimen under tension loading [11,12]. The specimen was fabricated from T300 carbon PPS thermoplastic composite material in a woven configuration with [±45/(0/90)]3S layup. First, MS-PFA was used to reverse engineer the constituent properties from lamina level LT, LC, TT, TC and IPS tests. Second, uncertainties in fiber and matrix properties and fabrication parameters were assumed since lamina level statistics for the T300/PPS material were not available. Unknown COV’s can be obtained from existing databases of comparable or similar materials or from experience based on anticipated scatter. Table 12 lists the

| Test # | Failure Load | Test # | Failure Load |
|--------|--------------|--------|--------------|
| 1      | 0.9218       | 16     | 1.0008       |
| 2      | 0.9507       | 17     | 1.0027       |
| 3      | 0.9593       | 18     | 1.0027       |
| 4      | 0.9690       | 19     | 1.0065       |
| 5      | 0.9709       | 20     | 1.0065       |
| 6      | 0.9728       | 21     | 1.0065       |
| 7      | 0.9853       | 22     | 1.0143       |
| 8      | 0.9853       | 23     | 1.0143       |
| 9      | 0.9892       | 24     | 1.0266       |
| 10     | 0.9950       | 25     | 1.0287       |
| 11     | 0.9950       | 26     | 1.0335       |
| 12     | 0.9960       | 27     | 1.0335       |
| 13     | 0.9979       | 28     | 1.0393       |
| 14     | 0.9979       | 29     | 1.0470       |
| 15     | 0.9998       | 30     | 1.0510       |

Table 12. Normalized Tensile Failure Load for T300/PPS Open Hole Composite Coupon
Table 13. Random Variables Used in Predicting A- and B-Basis Allowables for T300/PPS normalized failure load from the test for the OHT case. The range of the failure load varied from 0.9218 to 1.051 with a standard deviation of 0.028. **Table 13** lists the assumed random variables for use in the prediction of allowables. Initial COV of 5% was assumed for all random variables.

MS-PFA was used in conjunction with probabilistic analysis to replicate the scatter in the failure strength for the OHT coupon. The random variables were selectively perturbed by the analysis engine to populate enough data to predict the cumulative distribution of the failure stress. As indicated in **Figure 13**, the scatter from simulation did not agree with that from test when a coefficient of 5% was applied uniformly to all random variables. However, reducing the coefficient of variation to 1% for the fiber and matrix stiffness and strength and the fabrication variables, yielded an excellent agreement with test (**Figure 14**). If test data did not exist to calibrate the COV’s of the constituent properties and fabrication parameters, one can assume a 5% value as a starting point. Sensitivity analysis can also be used to reduce the list of random variables to include those that are very influential (those with sensitivity higher than 10%).

![Graph](https://www.intechopen.com)
Fig. 14. Comparison of Scatter from Simulation and Test for T300/PPS OHT Strength With a Coefficient of Variation of 1%

Processing the 30 test data through STAT17 resulted in an A-basis value of 0.92 and a B-basis value of 0.9486 with respect to a mean normalized strength of 1.0. The CDF obtained from MS-PFA resulted in A-basis value of 0.9104 and a B-basis value of 0.959 when the strengths were retrieved at the 1/100 and 1/10 probabilities. The maximum error from the prediction with respect to test was 1.1% as shown in Table 14.

| Test (Mil-HDBK) | Analysis | % Error |
|-----------------|----------|---------|
| A-Basis | 0.92 | 0.9104 | 1.04% |
| B-Basis | 0.9486 | 0.959 | -1.10% |

Table 14. Open Hole Tension Case Comparison of A- and B-Basis Values from Test and Analysis

**Determination of A-Basis Values from B-Basis**

As discussed earlier, accepted standards for determination of A-basis require physical testing of 55 specimens from 10 batches (as a minimum). Reference [13] listed strength data from testing of 145 specimens for 90° tension laminate made from T700 fibers and 2510 epoxy matrix. The MS-PFA approach was used to generate random samples to determine A-basis for the transverse tension laminate assuming only 18 test samples existed. Note that the 18 specimens is the minimum accepted standard [1,2] for B-basis determination. The 18 test specimens were obtained from a total 3 batches from [13], the data extracted were the first 18 test points reported in reference [13]. MS-PFA was then used to simulate the scatter for the 18 specimens and used to generate additional samples (55 and 145 random samples). The virtual test samples generated by MS-PFA used the statistics listed in Table 15.

Figure 15 shows a plot of the 18 test samples, 145 test samples, and 55 and 145 MS-PFA virtually generated test samples. The MS-PFA virtual samples fitted the 145 samples from physical test with great accuracy. The technical approach in MS-PFA can be used to generate virtual test samples not available thru physical testing. This is evident by the goodness of fit between simulated and test data and with the accurate calculation of A-basis as presented in Table 16.
Table 15. Random Variable Statistics for Determining A-Basis Strength from B-Basis for T700/2510 90° Tension Laminate

| Property | Mean  | COV   | Distribution |
|----------|-------|-------|--------------|
| E11 (ksi)| 34.80 | 5.00% | Normal       |
| Sf11T (ksi)| 604.50 | 7.56% | Normal       |
| Sf11C (ksi)| 366.90 | 6.15% | Normal       |
| Em (msi)   | 0.53  | 5.00% | Normal       |
| SmT (ksi)  | 11.62 | 8.39% | Normal       |
| SmC (ksi)  | 46.00 | 4.73% | Normal       |
| SmS (ksi)  | 37.82 | 2.82% | Normal       |
| FVR       | 0.53  | 2.50% | Normal       |
| VVR       | 0.03  | 2.50% | Normal       |

Fig. 15. Comparison of 18 and 145 tests to 55 and 145 MS-PFA Virtual Samples Used in Determining A-Basis Strength from B-Basis for T700/2510 90° Tension Laminate

Table 16. Determining A-Basis Strength from B-Basis for T700/2510 90° Tension Laminate

| Test Type       | Mean Strength (ksi) | A-Basis Strength (ksi) | B-Basis Strength (ksi) |
|-----------------|---------------------|------------------------|------------------------|
| Un-Notched 90 Deg Tension |                     |                        |                        |
| 18 Test Samples [12]   | 7341 | 4610 | 5741 |
| 145 Test Samples [12]  | 7083 | 5523 | 6200 |
| 55 Virtual Samples    | 7302 | 5603 | 6326 |
| 145 Virtual Samples   | 7121 | 5684 | 6258 |
| Difference w.r.t. 145 Test Samples [13] | 3.09% | 1.45% | 2.03% |
| 55 Virtual Samples    | 0.53% | 2.92% | 0.94% |

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The referenced table lists A- and B-basis calculations obtained using the data from test and simulation after running STAT-17 with the generated virtual test samples. For each random sample generated, MS-PFA is executed to determine sample failure stress. Table 16 also lists the mean strength from test and simulation. The mean strength value from 145 MS-PFA simulations was within about 0.5% of that from 145 physical test samples. The accuracy in predicting mean strength and A-basis values demonstrates the effectiveness of the devised methodology for determination of allowables with reduced testing.

5. Summary

A computational method has been presented for determining A and B-basis composite strength allowables with a significant reduction in testing over standard FAA and CMH-17 methods. The method combines multi-scale multi-physics progressive failure analysis (MS-PFA) with probabilistic methods and Bayesian updates. It was demonstrated for typical aerospace composite materials such as MTM45-1 145 AS4, IM7/MTM45-1, T300/PPS and T700/2510. Starting from lamina level coupon test data, root cause fiber and matrix properties, fabrication variables, and associated uncertainties are reverse engineered with MS-PFA for use in generation of strength allowables. MS-PFA is then used to virtually generate random laminate level test samples. In turn, the virtual test data are used to calculate allowable values for notched and un-notched composite laminate specimens.

The methodology is robust and can be easily inserted into material characterization and qualification programs to yield a significant reduction in the number of physical tests at the laminate level. Additionally, the approach can be relied on to generate allowables for configurations (layups) that were not initially included in a test plan as long as the simulation results are verified with few tests that are representative of the overall design envelope. Very importantly, the methodology was validated for typical aerospace composite laminates and calculated A and B-basis values compared very well with test.

6. References

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By adopting the principles of sustainable design and cleaner production, this important book opens a new challenge in the world of composite materials and explores the achieved advancements of specialists in their respective areas of research and innovation. Contributions coming from both spaces of academia and industry were so diversified that the 28 chapters composing the book have been grouped into the following main parts: sustainable materials and ecodesign aspects, composite materials and curing processes, modelling and testing, strength of adhesive joints, characterization and thermal behaviour, all of which provides an invaluable overview of this fascinating subject area. Results achieved from theoretical, numerical and experimental investigations can help designers, manufacturers and suppliers involved with high-tech composite materials to boost competitiveness and innovation productivity.

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