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Compressive strength prediction for composite unmanned aerial vehicles

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Compressive Strength Prediction For Composite Unmanned Aerial Vehicles

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Thesis Submitted to the
College of Engineering And Mineral Resources
At West Virginia University
in Partial Fulfillment of the Requirements for the
Degree of

Master of Science
in
Aerospace Engineering

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Abstract

Compressive Strength Prediction for Composite

Unmanned Aerial Vehicles

Edward A. Wen

A rational methodology is presented to predict the compressive strength of carbon/epoxy compression specimens and prototype production parts using the model presented by Barbero in the Journal of Composite Materials, Vol. 32, No.5/1998. The experimental technique is an adaptation of the optical method first proposed by Yurgartis (1987) and can be directly applied to actual development, quality control or failure investigation programs. There is very good agreement between actual and predicted compressive strength at -125F and room temperature. At 180F, the predicted strength is conservative. Aurora Flight Sciences provided the prototype production parts and partial funding under the "Material Characterization Study for UAV Wing Development" contract. The results of the material characterization study of two carbon/epoxy prepregs presented to Aurora Flight Sciences are also shown here. An extension of the method presented by Barbero is also proposed for laminates with average global misalignment, α_G , in $[+\alpha_G]_n$ or $[-\alpha_G]_n$ stacking sequence.

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Nomenclature

$f()$	=	Probability density function, PDF
$F()$	=	Cumulative distribution function, CDF
FV	=	Fiber volume
F_{1C}	=	Longitudinal compressive strength
F_6	=	In-plane shear strength
G_{12}	=	In-plane shear modulus
W	=	Potential energy
α	=	Angle of local misalignment, or simply "misalignment"
α_G	=	Average angle of global misalignment
α_g	=	Angle of global misalignment
Ω	=	Standard deviation of local misalignment angle
σ	=	Compression stress
τ	=	Shear stress
γ	=	Shear strain
v_f	=	Volume fraction of fibers

Chapter 1: Introduction and Literature Review

1.1 Introduction

In the last 25 years, composite materials have proven themselves to be a cost effective alternative to metals. Starting from aerospace applications, designers are continually expanding their use into other industries such as marine, infrastructure, sports recreation and medical instruments. Despite extensive experience with composites, a large amount of testing is required (compared to metals) to have confidence in a particular design. In the next decade, composite manufacturers and engineers will be challenged to reduce the amount of testing required by improving manufacturing quality and analysis techniques.

While the tensile strength of composite materials is very well understood, the compressive strength of composites may still have significant variations from expected values [1]. The main factors affecting compression strength are:

- Matrix properties
- Local/Global misalignment of fibers
- Void content
- Moisture and other contamination

When the direction of a fiber is not the intended direction, the angle difference is called global misalignment. Local misalignment or just “misalignment”, is the angle at which individual fibers vary from the average fiber direction. In the case of a single ply of prepregged composite material, prepreg, misalignment is an inherent property of the

material and cannot be improved upon by the shop worker or tape laying machine. However when two or more plies are in a lay-up, the misalignment will either remain constant or get worse. Obviously, the shop worker or tape-laying machine will affect the amount of global misalignment when making a lay-up.

Because of the possible reductions to compressive strength caused by the items above, the aerospace industry uses a fixed ultimate compression strain allowable that provides a margin of safety for variations in the material. Depending on the design, extensive testing is required to validate the compression.

Ideally, compression strength could be measured from production parts without costly test fixtures and without destroying the part. This investigation strives to reach this ideal by showing that a compression strength model [2] and optical examination technique [3] can predict strength of unidirectional composites in a production setting. Fiber misalignment and matrix properties on compressive strength are measured and input into the theoretical model. Although they are not active parameters in this study, global misalignment and void content are measured and recorded. Moisture and contamination effects are minimized since the tests were done in ambient conditions and in a relatively clean workshop. Additionally, this study proposes an alternative method to predict the compressive strength of composites with average global misalignment α_G in a $[\alpha_G]_n$ or $[-\alpha_G]_n$ schedule. This method is an extension of the model proposed in [2].

Aurora Flight Sciences of West Virginia partly sponsored this research for the purpose of determining properties of two material systems under investigation, 949/M30GC and 948A1/M40J. These materials were being evaluated for possible use on

an Unmanned Aerial Vehicle (UAV). Two beams were constructed and tested at Aurora Flight Sciences were also used to determine the accuracy of this technique.

1.2 Literature Review

There is an enormous body of literature on the subject of prediction of compression strength of unidirectional, 0 degree composites from basic material properties in the time period 1965 to 1999. A brief review is shown here.

Rosen first proposed an analytical model to predict compressive strength laminates in 1965 [4]. Rosen modeled a composite with straight fibers and assumed linear material properties. Using energy methods in his derivation, he assumed that fiber buckling was the mode of failure and found that in the limit, compressive strength equals the elastic shear modulus. Microbuckling could be one of two types: In-phase (shear) mode or Out-of-phase (extensional) mode as shown in Figure 1.1. The shear mode required lower stress for failure but his predictions were two to three times higher than actual values. Only when the shear stiffness was linearly varied to account for inelastic behavior, did the results come closer to the actual values.

An important refinement of Rosen's model was made in 1978 by Wang [5] which included initial fiber misalignment, non-linear shear stiffness and non-linear analysis. The misalignment factor was determined by fitting predicted and experimental data and the non-linear shearing stiffness was modeled by piecewise linear segments. Using high and low temperature tests, Wang found good agreement between predicted and actual values.

In 1981, Maewal [6] modeled the buckling behavior using stability theory based on Koiter's theory of elastic stability. The results were very unexpected. When using linear material properties, such as shear stiffness, fiber buckling was found to be *insensitive* to initial misalignment and not expected to significantly reduce microbuckling stress. This contradicted the results found by [5].

In the same year, Martinez and Piggott [7] devised a modified pultrusion technique to study the effects of misaligned fibers in compression. By twisting tows of fibers before introducing them into the resin, the authors claim to have added an average misalignment angle of θ . Their data showed that up to $\theta = 10$ degrees misalignment, there was no significant effect on strength. More than likely, the "misalignment" induced by this technique was similar to the case of a balanced, symmetric lay-up with $[\pm\theta/\theta]_s$. The strength of this type lay-up is given by the stress transformation [8] and results in a cosine square term applied to F_{1c} . Thus at 10 degrees, the reduction in strength is only 3%. The authors also investigated the fiber matrix interface and concluded that poor adhesion between fibers and matrix also had a detrimental effect on strength. Separately, Piggott [9] concluded in 1981 that "in order to make a composite with good compressive properties, the fiber should be hard, as straight as possible and well bonded to the matrix. The matrix should have a high yield stress, tensile strength and compressive strength." This statement seems to contradict the earlier study since "straight" fibers imply low misalignment.

A different approach to predicting compression failure was introduced by Budiansky in 1983 [10]. Rather than microbuckling, Budiansky studied the mechanics of fiber kinking. By assuming straight fibers and linear material properties, he found that a

zero-degree kink angle could reproduce Rosen's results. As was well known, the kink band angle is usually 30-40 degrees and so Budiansky modified the approach to include non-linear material properties.

In 1987, Tang, Lee, and Springer [11] studied the effects of cure pressure on void content in a lay-up. By adjusting pressure during the cure cycle, they were able to change the void content, which they measured optically. In compression strength and interlaminar shear strength tests, they found that decreasing the void content helps these properties up to a point. Below 3-4% void content, the strengths do not improve significantly. One questionable area in this report is the high void content 10%, 6%, 5% reported for cure pressures 20, 55, 80 psig respectively. This may be due to calibration of the optical method used. Nevertheless, the authors did establish a relationship between compressive strength and other key parameters, such as void content.

In the same year, Yurgartis [3] developed an important optical technique to measure the initial fiber misalignment allowing it to be measured for the first time. This opened the way for researchers in the late 80's and early 90's to quantify and deepen the analysis of compression. Using the optical technique, Mrse and Piggott [12], Yurgartis and Sternstein [13], Barbero and Tomblin [14], Lagoudas and Saleh [15], Haberle [1] found that higher initial fiber misalignment did, in fact, *reduce* compression strength. Among these, [13], [16] added more evidence about the direct relationship between compressive strength and shear stiffness. Furthermore, Steif [17] proposed that the tangent hyperbolic function could be used to characterize shear stiffness because it successfully captured the antisymmetric nature of shear stiffness. Previously, piecewise

continuous linear segments or truncated polynomials were adequate but were very cumbersome when used in stability analysis.

Shuart [18] studied the effects of global misalignment on $[\pm\theta]_s$ laminates in a paper published in 1989. Shuart proposed three different failure mechanisms depending on θ . For $0 < \theta < 15$ degrees, interlaminar shear was the dominant failure mode. For $15 < \theta < 50$, it was in-plane matrix shearing and for $50 < \theta < 90$, matrix compression was the failure mode. His model included non-linear analysis and initial fiber waviness. The strength predictions were very good for $50 < \theta < 90$, but for $0 < \theta < 50$ they were generally conservative by a 0 to 30% margin.

In 1997, Tomblin, Godoy and Barbero [19] used stability theory to show that fiber buckling *was sensitive* to initial misalignment when non-linear shear stiffness (tangent hyperbolic) was used. When linear shear stiffness was used, fiber buckling was found to be *insensitive* to initial misalignment as [6] had proposed 15 years earlier. Later, [14] combined the continuous damage mechanics work of Kachanov [20] and a statistical approach to fiber misalignment to arrive at a numerical solution to the prediction of compressive strength. In 1998, Barbero [2] derived an explicit equation for compression strength which utilized the continuous damage mechanics and statistical approaches used in [14].

Despite the large body of work focused on correlating compressive strength with other basic material properties, the majority of studies use empirical parameters to correlate strength. Only a few studies base the prediction of compression specimen strength on actual measured properties of the specimen [1], [14], [21]. To date, there is

no known study that correlates compressive strength of *production parts* with basic material properties (shear stiffness and strength, but excluding compressive strength).

In industry, the compressive strength of production parts is predicted by finite element analysis using a database of material properties. Later, compressive strength and other design parameters are confirmed with a testing program. In the May 1999 ASTM Symposium on Composite Structures, [22] presented the “Building Block” structural qualification program for the RAH-66 Comanche Attack Helicopter as shown in Figure 2.2. As can be seen, structural qualification is composed of several levels of testing to gain confidence in the material allowables and analysis methods. Many times this is because the performance of a material as a laboratory specimen is better than as a production part. Lab specimens are fabricated under ideal conditions and tested in very controlled circumstances whereas production parts are open to the many variables in manufacturing and testing.

Because the full “Building Block” testing program is costly and time consuming, efforts are underway to use a “Modified Building Block” approach when possible [23] and reducing testing in the areas shown in Figure 1.2. In this process, the amount of testing is reduced to the minimum required based on previous testing experience and engineering judgement. The minimum required tests will usually involve one or more of the following: compressive strength, compressive strength after impact, shear strength and compression-shear interaction.

Industry has signaled a clear need to better predict the strength of composites to reduce development time and cost. At the same time, the literature shows that studies in the 90’s have made practical compressive strength prediction more and more a reality.

Figure 1.1 Modes of Fiber Buckling

Figure 1.2 Building Block Approach to Testing

Chapter 2: Theoretical Modeling

The theoretical model presented by Barbero in [2], [14] draws upon many of the references cited in the literature review. Fundamentally, it is a unique approach because it integrates a statistical representation of the composite with a continuum damage mechanics model to arrive at an explicit equation for compressive strength in terms of measured properties, shear modulus G_{12} , shear strength F_6 and the standard deviation of the fiber misalignment angle, Ω .

2.1 Composite Shear Response

The shear stress-strain relationship for polymer-matrix composites is not linear and can be represented as

$$\tau = F_6 \tanh\left(\frac{G_{12}}{F_6} \gamma\right) \quad (2.1)$$

or a quadratic polynomial such as

$$\tau = G_{12}\gamma - C_2\gamma^2. \quad (2.2)$$

The hyperbolic tangent function nicely represents the anti-symmetric nature of the shear response. The quadratic polynomial has the advantage of being easier to manipulate than the hyperbolic tangent expression but must be used where the fit is good. Consequently, the tangent hyperbolic was used when finding the exact but implicit solution that is solved by numerical methods in [14], and the quadratic polynomial was used when deriving an explicit solution in [2]. The derivation of the explicit solution is shown here.

The constant C_2 can be found solving the above two equations for C_2 and restricting γ to not exceed γ_{lim} .

$$\gamma_{\text{lim}} = 2 \frac{F_6}{G_{12}} \quad (2.3)$$

$$C_2 = -\frac{(G_{12})^2}{4F_6} \quad (2.4)$$

where γ_{lim} is an upper bound to the shear strain at which most composite materials, carbon-epoxy and glass-polyester, fail in compression. A comparison is shown in Figure 2.1 between the two equations and experimental results for 949/M30GC using the ASTM 5379 shear test.

Other micromechanical models that use in-situ properties, such as shear modulus of the matrix, G_m , were purposely avoided. This is because it would be very difficult to verify if the compression strength prediction was correct since the in-situ properties are very difficult to measure and could be different than properties in the bulk matrix.

2.2 Fiber Misalignment

Since the misalignment of fibers is very small, a microscope is used to measure this misalignment in the cross-section. The technique is described in detail in Chapter 4. Experimentally, the distribution of angles has been shown to be Gaussian or normal, hence the probability is given by

$$f(\alpha) = \frac{1}{\Omega\sqrt{2\pi}} e^{\left(\frac{-\alpha^2}{2\Omega^2}\right)} \quad -\infty < \alpha < \infty \quad (2.5)$$

where Ω is the standard deviation, α is the misalignment angle and $f(\alpha)$ is the probability density function. The probability of getting an angle between $-\alpha$ and α is given by the integral

$$F(a) = \int_{-a}^a f(a') da' \quad (2.6)$$

Changing to the normalized misalignment variable z , defined as

$$z = \frac{\alpha}{\Omega\sqrt{2}} \quad (2.7)$$

the cumulative distribution function can now be described as a “folded” function as below

$$F(z) = \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-z'^2) dz' \quad (2.8)$$

Since the integral of a transcendental equation is difficult to manipulate later, it is approximated by a quadratic polynomial,

$$F(z) = 1.179643858z - 0.3455580967z^2 \quad (2.9)$$

for the interval $0 < \alpha < 3\Omega$, which is sufficiently broad to model the problem at hand [2].

2.3 Imperfection Sensitivity Equation

The relationship between buckling stress and misalignment is called the imperfection sensitivity curve. Unlike equilibrium based models that compute shear strain only at the inflection points of the given fiber shape, the shear strain energy of the entire

Representative Volume Element, RVE, is modeled in the equation. This model assumes that all fibers are misaligned at the same angle as shown in Figure 2.2.

The model uses the principle of total potential energy and assumes axial effects can be neglected. In this one dimensional case, an expression can be written where only the shear energy is considered in the total potential energy

$$W = \int_0^l \int_A \int_0^\gamma F_6 d\gamma dA dx - P\Delta l \quad (2.10)$$

where P is the end load; Δl is the end shortening; τ and γ are the shear stress and strain; l and A are the length and area of the RVE. Using the shear stress as described in equation (2.2), equation (2.9) can be solved for the equilibrium stress as

$$\sigma(\alpha, \gamma) = \frac{\gamma G_{12}}{\gamma + \alpha} + \frac{8}{3} \frac{C_2 \gamma^2}{3(\gamma + \alpha)\pi} \quad (2.11)$$

This equilibrium equation produces a family of curves for 949/M30GC as in Figure 2.3. Thus for every angle α , there is a maximum value of compression strength before buckling occurs. The curve that joins all the maxima is

$$s(a) = \frac{4\sqrt{2}C_2 a (-8C_2 a + 3p G_{12})}{3p \sqrt{-C_2 a (-8C_2 a + 3p G_{12})}} - \frac{16C_2 a}{3p} + G_{12} \quad (2.12)$$

2.4 Continuum Damage Model

At any time during the loading of the specimen, the applied stress is equal to the effective stress in the composite times the area that remains unbuckled

$$\bar{\sigma} = \sigma(\alpha)[1 - \omega(\alpha)] \quad (2.13)$$

In this equation, $0 \leq \omega(\alpha) \leq 1$ is the area of the buckled fibers per unit of initial composite area. For any value of effective stress, all fibers having more than the corresponding value of misalignment given in Figure 2.4 have buckled. The area of the composite with buckled fibers $\omega(\alpha)$ is proportional to the area under the normal distribution located beyond the misalignment angle $\pm\alpha$. Therefore $\omega(\alpha)$ is given by:

$$\omega(\alpha) = 1 - \int_{-\alpha}^{\alpha} f(\alpha') d\alpha' = 2 \int_{\alpha}^{\infty} f(\alpha') d\alpha' \quad (2.14)$$

Substituting into equation (2.13) the compressive strength of a composite can be found as

$$F_{lc} = \max \left[S(\alpha) \int_{-\alpha}^{\alpha} f(\alpha') d\alpha' \right] \quad (2.15)$$

Graphically, F_{lc} can be seen as the maximum of the applied stress curve in Figure 2.5.

2.5 Explicit Equation

Substituting equation (2.9) for the integral in equation (2.15), the applied stress equation (2.13) becomes

$$\bar{\sigma}(z) = \sigma(z)F(z). \quad (2.16)$$

which simplifies subsequent derivations.

To find the maximum explicitly, equation (2.16) is expanded into a truncated polynomial about $\alpha = \Omega$ (or $z = (1/2)^{1/2}$), which is an adequate range for a broad class of materials [2]. The root of the derivative can then be found explicitly as

$$\begin{aligned}
F_{lc} = & \left[1019.011G_{12}C_2^2\Omega^3 - 375.3162C_2^3\Omega^4 - 845.7457G_{12}^2C_2\Omega^2 \right] \\
& + g(282.113G_{12}C_2\Omega^2 - 148.1863G_{12}^2\Omega - 132.6943C_2^2\Omega^3) \\
& \times \left[457.3229C_2^3\Omega^2 - 660.77G_{12}C_2^2\Omega^2 - 22.43143G_{12}^2C_2\Omega \right] \\
& + g(161.6881C_2^2\Omega^2 - 138.3753G_{12}C_2\Omega - 61.38939G_{12}^2) \Big],
\end{aligned} \tag{2.17}$$

where g is the following

$$g = \sqrt{C_2\Omega(8.0C_2\Omega - 9.424778G_{12})}. \tag{2.18}$$

Substituting C_2 and g , equation (2.4) and (2.18), into (2.17), the following expression can be written:

$$\begin{aligned}
\frac{F_{lc}}{G_{12}} = & \frac{c}{24p} \frac{C_3}{C_4} \\
C_3 = & -10979.6 - 8432.03c^2 - 19037.205c - 124.653c^4 - \frac{103961}{64}c^3 \\
& + (12191.07 + 1881.87c^2 + 176.286c^3 + 7979.978c) \sqrt{\frac{c^2}{2} + 2.356c} \\
C_4 = & (-7.146c^3 - 41.298c^2 + 5.608c) \sqrt{\frac{c^2}{2} + 2.356c} \\
& + (10.106c^2 + 34.594c - 61.389) \left(\frac{c^2}{2} + 2.356c \right) \\
c = & \frac{G_{12}\Omega}{F_6}
\end{aligned} \tag{2.19}$$

Taking into account that the dimensionless compression strength, F_{1c}/G_{12} , can be modeled in terms of a dimensionless number, χ , the following numerical approximation can be made of the ungainly equation (2.19) as follows:

$$\frac{F_{1c}}{G_{12}} = \left(\frac{c}{a} + 1 \right)^b \quad (2.20)$$

$$a = .21$$

$$b = -.69$$

Constants a and b are found by using a full factorial design within the range

$$0.5075 \text{ Msi} < G_{12} < 1.160 \text{ Msi}$$

$$5.8 \text{ ksi} < F_6 < 23.2 \text{ ksi}$$

$$1^\circ < \Omega < 3.5^\circ$$

This gives $n = 3^3 = 27$ points for which the dimensionless compression strength can be computed using equation (2.19) to find constants a and b.

2.6 Global Misalignment

When a lay-up has average global misalignment α_G and is balanced and symmetric $[\pm\alpha_G]_s$, the maximum compressive stresses can be found by stress transformation [8]. The compressive stress is given by $(F_{1c}) \times (\cos^2(\alpha_G))$. There is good agreement with the data for $0 < \alpha_G < 10$ degrees [18]. However, there exists no known method for estimating the strength of laminates with average global misalignment and $[\alpha_G]_n$ or $[-\alpha_G]_n$ stacking schedule.

When there is global misalignment, the representative volume element is as shown in Figure 2.6. The potential energy (2.9) and equilibrium (2.11) equations still apply but the distribution of fiber angles (2.5) and normalized misalignment variable (2.7) are shifted by the average angle, α_G .

$$f(a, a_G) = \frac{1}{\Omega\sqrt{2p}} e^{\left(\frac{-(a - a_G)^2}{2\Omega^2}\right)}, -\infty < a < \infty \quad (2.21)$$

$$z = \frac{\alpha - \alpha_G}{\Omega\sqrt{2}} \quad (2.22)$$

The probability density function from 0 to ∞ is no longer the probability density function (2.8) because there is no symmetry about zero. Therefore, the quadratic polynomial approximation (2.9) cannot be used. Instead, the function can be integrated numerically as shown in Figure 2.7 which is for the case of 0 degree average global misalignment and fixed value of $\Omega = 1.15$ degrees. Notice that there are slight differences between the previous quadratic polynomial approximation and the discrete numerical integration within the range of $0 < \alpha < 3\Omega$ for which equation (2.9) is valid. To illustrate the integration, Figure 2.8 shows the case of 1.0 degree average global misalignment. The function is folded about zero and the two distributions are added together. For comparison, the probability density function for 0 degree average global misalignment is shown too.

Using this technique, a family of probability density functions at various average global misalignment angles can be determined as shown in Figure 2.9. Figure 2.10 shows the integration of these curves (2.21) to obtain the cumulative distribution function at these angles of average global misalignment. When multiplied by the effective stress

(2.12), the resulting applied stress curves are shown in Figure 2.11. The maximum of each curve represents the compressive strength at the given average global misalignment angle with $\Omega = 1.15$ degrees. This technique is informally called the “Method of Shifted Distributions”.

Note that Figure 2.7 through 2.11 were for a fixed value of Ω . If Ω was taken at different values, it would produce a family of curves for F_{1c} as a function of Ω and α_G . Figure 2.12 shows the compressive strength F_{1c} as a function of α_G when the standard deviation of fiber misalignment is fixed at various values. An individual curve represents a part fabricated with a prepreg lay-up that has Ω and oriented with an average global misalignment of α_G with respect to the nominal direction.

Figure 2.1 Range of Shear Stiffness when using Quadratic Polynomial

Figure 2.2 Representative Volume Element

Figure 2.3 Equilibrium States for Various Values of Misalignment

Figure 2.4 Imperfection Sensitivity Plot

Figure 2.5 F1c at Maximum of Applied Stress

Figure 2.6 Representative Volume Element with Global Misalignment

Figure 2.7 Numerical Integration and Quadratic Polynomial Function

Figure 2.8 Probability Density Function at 0, 1.0 Ave. Global Misalignment

Figure 2.9 Probability Density Functions at Ave. Global Misalignments

Figure 2.10 Cumulative Distribution Functions

Figure 2.11 Applied Stress at Different Global Misalignments

Figure 2.12 949/M30GC F1c vs. Average Global Misalignment

Chapter 3: Material Characterization and Beam Testing

The matrix of tests requested by Aurora Flight Sciences to characterize the Cytech Fiberite 949 HYE/M30GC and the 948A1 HYE/M40J material systems at –125F, RTA, 180F is shown in Table 3.1. The first material, 949 HYE/M30GC, is a carbon/epoxy prepreg commonly used for golf club shafts and tennis rackets. The second material, 948A1 HYE/M40J, is also a carbon/epoxy prepreg that has an intermediate modulus fiber and a relatively stiffer matrix.

Phase I tests were arranged to study the effects of “debulking” on void sensitive properties. For example, to debulk a lay-up of 100 plys of prepreg, the lay-up is vacuum bagged every 10 plys to reduce voids or air pockets that occur in the process. This study looked at 5, 10 and 20 plys/debulk in the hope of finding the “knee” in the curve where increasing the number of plys/debulk had diminishing improvement in material properties. In Phase I, the compression tests were contracted to Touchstone Research Laboratories.

Phase II tests were intended to study the effects of temperature on mechanical properties. Phase II high and low temperature tests were contracted to Orange County Material Test Labs (OCM). All the results of the material characterization program are shown here but only the compression and shear tests are discussed in detail.

3.1 Compression/Shear Test Selection

Initially, the ASTM D3410 “IITRI” test was used for Phase I compression testing. It utilizes a shear loaded specimen as shown in Figure 3.1. Since the IITRI test gave low values of compression strength as in Table 3.2, the SACMA SRM-1R-94 procedure was selected for all subsequent compression tests (Figures 3.2, 3.3). Because of its end loaded specimen, this test typically provides compressive strengths 5% better than the D3410 “IITRI” method. The SACMA test also allowed easier comparison with manufacturer’s data because composite parts manufacturer’s and prepreg producers use it more often.

To measure shear strength and modulus, the D5379 “Iosipescu” method was selected (Figures 3.4 and 3.5). MicroMeasurements Shear Gages N2P-08-C032A-500 were used since they average the shear strain over the entire region between the notches of the specimen. Modulus data was taken between 1000-6000 microstrains from back-to-back shear gages and the results from each side were averaged together. A detailed description of the test methods can be found in Appendix A.

3.2 Compression/Shear Specimen Preparation

The prepregs were laid up by hand and cured in an oven at 275 deg F for 90 minutes with approximately 27 in. Hg vacuum bag pressure. A 7 ply [0 deg] panel was

made for the compression specimens and a 20 ply [0 deg] panel was used for the shear modulus and shear strength specimens. The 7 ply panel was cured with peel ply and caul plates on both sides of the panel so that the surface would have very little waviness and the thickness would be relatively uniform (Figure 3.6). To achieve low global misalignment, great care was taken to align the 7 plies of the prepreg to the manufactured edge of the tape. The 20 ply panel was cured without caul plates or peel ply because the variations in thickness were judged to be small when compared to the total thickness. Panel sizes were 12" X 18-24". The manufacturing history of each panel made in this study can be found in Appendix A.

The specimen tabs were bonded to the panels using technique similar to the one outlined in [1]. A room temperature cure paste adhesive, Magnabond 6380, was used to bond prefabricated glass/carbon tabs to a panel before cutting. A tile saw was used to rough cut the specimen panel to size. A surface grinder installed with a diamond blade was then used to make the final cuts. The surface grinder mounted with an 80 grit wheel was used to grind the surfaces square. A diamond bit on a milling machine ground the notches in the shear specimen.

3.3 Data Normalization

The panel thickness for the fiber driven property tests was very small – approximately 0.040 inches. Since local variations in thickness could cause big changes in the final results, the thicknesses were normalized to an average value. This method is consistent with MIL-HDBK-17-E practices.

$$\text{Normalized Value} = \text{Test Value} \times \frac{\text{Specimen Thickness}}{\text{Nominal Thickness}}$$

The nominal thickness was found by taking the average thickness of several specimens that were sanded with 50 strokes of 400 grit sandpaper in the gage section prior to bonding strain gages.

Since the panel thickness for the matrix driven properties was much larger, approximately 0.125 inches, local variations in thickness were not judged to cause a strong effect on the results. Therefore, the data reported was the raw data and was not normalized. In-plane shear strength, F6, was taken where there was a significant change in the slope of the load-displacement plot (Figure 3.7). In some cases, especially with the tougher resin 949, there was no significant change and so F6 was taken at the slight dip between the initial curved section and the linear section of the load-displacement plot (Figure 3.8).

At the customer's request, the material properties were reported at the fiber volumes (FV) in which they were tested and not normalized to a constant FV value (i.e. 60% FV). In order to predict strength with G12 and F6, these values are normalized to the FV of F1c for the compressive strength specimens as is shown in Chapter 4.

3.4. Difficulties in Obtaining F_{1c}

Compression is by far the most difficult of the tests shown in the test matrix because it requires a high level of precision in the specimen and very good test set-up.

Many attempts were made to get the final values reported in the previous tables. Highlights of the compression tests are shown in Table 3.3.

3.4.1 Sanding

Initially, the specimen panels were made without peel ply or caul plates because peel ply and caul plates they were used only selectively for fabrication of actual parts made at Aurora Flight Sciences. This produced a panel with a rough, wavy surface on the bag face and a smooth surface on the tool face (Figure 3.9).

The panels were sanded on the bag face to make a smooth surface for the tabs and to get a uniform thickness for measurement of thickness. Tests No. 1 and 2 in Table 3.3 showed that the sanding had reduced the strength from 170 to 140 ksi. Sanding had effectively removed one ply from the panel. However, even without sanding, the strength values were low compared to manufacturer's values and it would not be clear what thickness to use for comparison of strength.

3.4.2 Peel Ply & Caul Plates

In order to remove the waviness on the bag face and to straighten the fibers to increase the strength, peel ply and caul plates were used on both sides of the lay-up. These were used on the manufacturer's panel when they produced their specimen but again, were only selectively used in the shop at Aurora Flight Sciences. Tests No. 2,3 in

Table 3.3 showed that the peel ply/caul plates did improve strength, but still not to the level of the manufacturer.

3.4.3 Surface Ground/Solid Compression Head

Originally, the edges of the compression specimen were cut with a diamond saw blade mounted on a modified grinding table. This cut the edges smoothly but at a slight angle. To compensate for this angle, it was believed that a ball joint head would adjust the compression head to fit the exact angle of the end specimen. In truth, the adjustable head was most likely causing a premature failure of the specimen by concentrating the load in the area when the collapse first takes place (Figure 3.10).

To solve this problem, a surface grinder was purchased to grind accurate, square ends on the specimen after being cut by the diamond saw. The test fixture was modified from a ball joint head to a solid head. Tests No. 3,4 in Table 3.3 showed that these changes increased the compression strength significantly.

3.4.4 Bolt Torque

Bolt torque on the fixture made a significant difference on final strength as in Test No. 4, 5 in Table 3.3. The SACMA standard does call out a range of bolt torques but other similar standards such as the modified D695 call for hand tight bolts. After discovering this fact, bolts were held to a constant torque on the WVU tests to approximately 5 in-lbs.

3.4.5 Bond Tabs at High Temperature

There was a concern that because the two testing labs used film adhesives cured at 250 F, it would cause a post-cure to this material system (which is cured at 275F). This would artificially increase their strength values. WVU used a room temperature cure adhesive throughout the program but Tests No. 6,7 in Table 3.3 showed that there was no noticeable improvement in strength from the post-cure of WVU's own specimens. If there was an effect, it was small compared to other aspects of the testing.

3.5 Experimental Results

The test results summary from Phase I is shown on Table 3.2. The details of Phase I results are in Appendix B. The effects of debulking were not clear from the Phase I results. It is expected that voids increase with increasing plys/debulk and therefore mechanical properties (excluding density) decrease with increasing plys/debulk. Indeed in the "Delta" column of the table, many of the properties show a small decrease in properties. However, the two most important properties, Longitudinal Compressive Strength and In-Plane Shear Strength, are increasing with increasing plys/debulk. This brings into question the validity of the entire Phase of this study.

More than likely, the panels (1 foot by 2 foot) made were too small to show any effect of voids and larger panels, e.g. 20 feet long, would show a meaningful difference. As shown in Figure 3.11, the void content at the center of a 20 ply panel with 5 plys/debulk is 1.066%. On the same size panel but with 20 plys/debulk, the void content

is 1.736%. This is a 63% increase in void content but the absolute value is still below 2%, which is considered to be low. Thus, the differences in material properties were probably hidden by the variations in test specimen preparation, test set-up, etc.

Fortunately, the effect of temperature on mechanical properties is clear in the Phase II results. Higher temperatures are expected to lower the material properties and the Tables 3.4, 3.5, 3.6 confirm these expectations. The details of Phase II results are in Appendix C. Graphs of these trends are shown in Figures 3.12 through 3.17. It is important to note there is a sharp decrease in shear modulus when going from RTA to 180 F (Figure 3.15).

3.6 Beam Preparation

Two C-section beams were made at Aurora Flight Sciences of West Virginia. These beams were made of the 949 HYE/M30GC and were relatively thick hand lay-ups cured at 275F with 27 in Hg vacuum pressure (Figure 3.18). The beam caps were much thicker towards the ends and thinner in the test section in the center. In Beam 1, the test section caps consisted of 60 plies of 0 deg and ± 45 deg on top and bottom. In Beam 2, the test section had 56 plies with one ± 45 deg ply every 8 plies of 0 deg. The shear web at the test section was made of a honeycomb core with ± 45 deg plies for shear stiffness and 90 deg plies for transverse stiffness. Twenty eight total strain gages were placed on the beam with twelve gages on the test section as shown in Figure 3.19.

3.7 Beam Testing

Two C-section beams were tested in four point bending at Aurora Flight Sciences (Figure 3.20). These beams were restrained at their ends and pulled at two points roughly $\frac{1}{4}$ of the length from the ends. Teflon pieces were used to separate the loading fixture from the beam table to allow it to displace in the transverse direction. Roller pins allowed the loading fixture to move along the table (Figure 3.21).

3.8 Beam Test Results

The strain gage data shown in Figure 3.22 and 3.23 show that the highest compressive strain experienced on Beam 1 was 7500 microstrains and on Beam 2 was 7772 microstrains. From visual inspection, it was confirmed that compression (and not shear) was the most likely mode of failure because of the presence of kink bands at the damaged area. There was also a significant void content tested in Beam 1. Figure 3.24 shows the increase in voids from 2.679% at the end of the beam, to 4.636% close to the middle. Nevertheless, the ultimate strain capability of the beams were very close to the 8043 microstrains ultimate capability of the 949/M30GC compression specimens.

Test	Property	Temp [F]	Phase I				Phase II	
			949/M30GC				949/M30GC	948A1/M40J
			Ply/ Debulk				Ply/ Debulk	Ply/ Debulk
			5	7	10	20	7 or 20	7 or 20
Compression SRM-1R-94 (SACMA) & D3410-95 (IITRI)	Longitudinal Compressive Modulus & Ultimate Strength: E_{1C} , F_{1C}	+180	-	-	-	-	5	10
		RTA	3	(5) ^a	4	3	-	(20)
		-125	-	-	-	-	5	5
	Transverse Compressive Modulus & Ultimate Strength: E_{2C} , F_{2C}	+180	-	-	-	-	-	-
		RTA	5	-	5	-	-	(6)
		-125	-	-	-	-	-	-
Shear D 5379-93 (Iosipescu)	Shear Modulus & Ultimate Shear Strength: G_{12} , F_{12}	+180	-	-	-	-	5	5
		RTA	(5)	-	(5)	(5)	-	(5)
		-125	-	-	-	-	5	5
Tension D 3039-95a	Longitudinal Tensile Modulus, Ultimate Strength & Longitudinal Poisson's Ratio: E_{1T} , F_{1T} , ν_{12}	+180	-	-	-	-	-	5
		RTA	-	-	-	-	(6)	(6)
		-125	-	-	-	-	-	5
	Trans. Tensile Modulus, Ult. Strength & Transverse Poisson's Ratio: E_{2T} , F_{2T} , ν_{21}	+180	-	-	-	-	-	-
		RTA	(5)	-	(5)	(5)	-	(5)
		-125	-	-	-	-	-	-
Density D 792-91	Bulk Density w/Pycnometer	RTA	(10)	-	(5)	(10)	(20)	(5)
Void Content	Theor.&Bulk Density w/Pycno.	RTA	(10)	-	(5)	(10)	(20)	(5)
Glass Transition D 3418-97	T _g w/DSC	@ T _g	-	-	-	-	(2)	(2)
Long/Trans CTE E831-93	Long./Trans. α_T w/DTA	-125 to +180	-	-	-	-	3	3

Note a: "()" denotes number of tests done by WVU. If # of strength tests differ from # of modulus tests, the # of strength tests are shown here.

Touchstone Research Labs performed all tests in Phase I not done by WVU.

Orange County Materials Test Labs performed all tests in Phase II not done by WVU.

Table 3.1 Aurora Flight Sciences Test Matrix

Property	Notation	Units	Average Values			Delta	Retest	Fiberite Values
			5 plys/debulk	10 plys/debulk	20 plys/debulk	5 to 20 ply [%]	7 plys/debulk	
1. Long. Compressive Strength	F _{1C}	[ksi]	112.0 ¹	130.5 ¹	135.2 ¹	20.7%	185.0 ²	195.8 ^{2,3}
2. Long. Compressive Modulus	E _{1C}	[Msi]	18.18 ⁴	17.97 ⁴	17.96 ⁴	-1.21%	23.0 ⁵	low 20's ⁶
3. Trans. Compressive Strength	F _{2C}	[ksi]	24.9	24.6	-	-1.20%	-	-
4. Trans. Compressive Modulus	E _{2C}	[Msi]	1.070	1.028	-	-3.93%	-	-
5. In-Plane Shear Strength	F ₁₂	[ksi]	9.80	10.04	10.06	2.61%	-	9.72 ^{7,8}
6. In-Plane Shear Modulus	G ₁₂	[Msi]	0.576 ⁹	0.541 ⁹	0.537 ⁹	-6.77%	-	-
7. Trans. Tensile Strength	F _{2T}	[ksi]	4.68	4.69	4.76	1.71%	-	-
8. Trans. Tensile Modulus	E _{2T}	[Msi]	1.059	1.040	1.008	-4.82%	-	-
Minor Poisson's Ratio	v ₂₁	-	0.00903	0.00894	0.00762	-15.61%	-	-
9. Apparent (Bulk) Density	rho _a	[gm/cc]	1.4848	1.4833	1.4788	-0.40%	-	-
Void Content: Near Edge ¹⁰	Void	[%]	1.857	1.781	2.092	12.65%	-	-
Void Content: Near Center ¹⁰	Void	[%]	1.066	-	1.736	62.85%	-	-

Notes:

1. IITRI D3410-95, fiber volume 54.13%.
2. SACMA SRM-1R-94, fiber volume 61.45%.
3. Fiberite fiber volume adjusted to 61.45%.
4. Fiber volume 54.13%, using SACMA SRM-1R-94.
5. Fiber volume 61.45%, using SACMA SRM-1R-94.
6. Fiberite said reasonable to get low 20's [Msi].
7. Fiberite fiber volume adjusted to 54.13%.

8. Inter-laminar Shear Strength used, no In-Plane Strength provided.
9. Revised with correct usage of shear gage data.
10. Panel length 22", width 12", thickness .120".

Table 3.2 Phase I Test Results

No.	Panel NTP-	Sanded	Unsanded	Peel Ply & Caul Plate	Surface Ground	w/ 250 F Post Cure	Ball Joint Head	Solid Head	Bolts Hand Tight	Bolts Tight	948A1/M40J [ksi]	949/M30GC [ksi]
1.	8,7	Y					Y		Y		140 ¹	139
2.	8		Y				Y		Y		170 ¹	----
3.	11,15		Y	Y			Y		Y		182	143
4.	17,15		Y	Y	Y			Y	Y		194	185
5.	17		Y	Y	Y			Y		Y	216	----
6.	16		Y	Y	Y	Y		Y	Y		204	----
7.	16		Y	Y	Y			Y	Y		219	----

Average of Dashed Box Values 208

Notes: 1. Used .039" sanded thickness for stress calculation.

Table 3.3 Highlights of Compression Testing

				948A1 HYE/M40J			949 HYE/M30GC		
Property	Notation	Units	Temp	Mean	FV%	Cv	Mean	FV%	Cv
1. Longitudinal Compressive Strength	F _{1C}	[ksi]	180 F	194	59	9.83	149	61	2.92
			RTA	208	59	5.83	185	61	9.34
			-125 F	223	59	6.76	226	61	4.13
2. Longitudinal Compressive Modulus	E _{1C}	[Msi]	180 F	24.8	59	4.00	21.0	61	0.83
			RTA	28.8	59	4.34	23.0	61	0.92
			-125 F	41.7	59	5.13	41.8	61	8.48
3. Transverse Compressive Strength	F _{2C}	[ksi]	RTA	27.2	52	5.06	24.9	54	3.29
4. Transverse Compressive Modulus	E _{2C}	[Msi]	RTA	1.15	52	7.63	1.07	54	3.49
5. In-Plane Shear Strength	F ₁₂	[ksi]	180 F	8.93	52	1.12	6.07	54	5.40
			RTA	11.35	52	1.59	9.80	54	5.07
			-125 F	14.28	52	5.72	16.01	54	4.58
6. In-Plane Shear Modulus	G ₁₂	[Msi]	180 F	0.439	52	6.23	0.365	54	5.64
			RTA	0.625	52	1.56	0.576	54	3.67
			-125 F	0.676	52	4.65	0.627	54	2.51
7. Longitudinal Tensile Strength	F _{1T}	[ksi]	180 F	368	59	2.03	----	61	----
			RTA	336	59	5.99	451	61	5.55
			-125 F	290	59	11.27	----	61	----
8. Longitudinal Tensile Modulus	E _{1T}	[Msi]	180 F	33.0	59	6.44	----	61	----
			RTA	32.5	59	1.74	24.7	61	1.65
			-125 F	31.7	59	2.42	----	61	----

Table 3.4 Phase II Test Results, Page 1

				948A1 HYE/M40J			949 HYE/M30GC		
Property	Notation	Units	Temp	Mean	FV%	Cv	Mean	FV%	Cv
9. Major Poisson Ratio	ν_{12}	[]	180 F	0.310	59	9.96	----	61	----
			RTA	0.288	59	11.31	0.275	61	11.05
			-125 F	0.277	59	13.26	----	61	----
10. Minor Poisson Ratio	ν_{21}	[]	RTA	0.01024	52	47.43	0.00903	54	11.54
11. Transverse Tensile Strength	F_{2T}	[ksi]	RTA	5.47	52	6.81	4.68	54	7.28
12. Transverse Tensile Modulus	E_{2T}	[Msi]	RTA	1.00	52	2.93	1.06	54	4.40
13. Panel Apparent Density: Edge, t = ~.125"	ρ	[gm/cc]	RTA	1.5043	52	0.02	1.4788	54	0.03
14. Panel Void Content A: Edge, t = ~.125"	Void	[%]	RTA	2.019	52	n/a	2.092	54	n/a
Panel Void Content B: Center, t = ~.125"	Void	[%]	RTA	----	---	n/a	1.736	54	n/a
Panel Void Content C: Center, t = ~.041"	Void	[%]	RTA	----	---	n/a	1.468	61	n/a
15. Beam Void Content A: End, Near Web	Void	[%]	RTA	----	---	n/a	2.679	---	n/a
Beam Void Content B: Center, Near Web	Void	[%]	RTA	----	---	n/a	4.267	---	n/a
Beam Void Content C: Center, Near Edge	Void	[%]	RTA	----	---	n/a	4.636	---	n/a
16. Glass Transition Temperature	T_g	[F]	n/a	303	59	n/a	254	61	n/a
17. Long. Coeff. of Thermal Expansion	α_{Lm}	[$^{\mu}in/inF$]	n/a	-0.80	52	27.43	-1.10	54	81.24
18. Trans. Coeff. of Thermal Expansion	α_{Tm}	[$^{\mu}in/inF$]	n/a	20.0	52	2.26	18.6	54	4.41

"----": Not Scheduled for Testing

"n/a": Not Applicable

Table 3.5 Phase II Test Results, Page 2

				948A1 HYE/M40J			949 HYE/M30GC		
Property	Notation	Units	Temp	Mean	FV%	Cv	Mean	FV%	Cv
19. Longitudinal Compressive Ult. Strain	ϵ_{1C}	[$\mu\text{in/in}$]	180 F	7823	59	n/a	7095	61	n/a
			RTA	7222	59	n/a	8043	61	n/a
			-125 F	5348	59	n/a	5407	61	n/a
20. Longitudinal Tensile Ult. Strain	ϵ_{1T}	[$\mu\text{in/in}$]	180 F	10578	59	n/a	----	61	n/a
			RTA	9821	59	n/a	16854	61	n/a
			-125 F	8736	59	n/a	----	61	n/a

"----": Not Scheduled for Testing

"n/a": Not Applicable

Table 3.6 Phase II Test Results, Page 3

Figure 3.1 IITRI Test Set-Up

Figure 3.2 Compression Specimen Dimensions

Figure 3.3 SACMA Compression Test Set-Up

- Notes:
1. All dimensions in inches
 2. Tolerance as follows

0.X	0.XX	0.XXX
+/- 0.1	+/- 0.03	+/- 0.01
 3. All angles have atolerance of +/- 0.5 degree.
 4. Ply orientation +/-0.5 degree.

Figure 3.4 Shear Specimen Dimensions

Figure 3.5 Shear Test Set-Up

Figure 3.6 Lay-Up Sequence

Figure 3.7 Significant Change in Slope at Max. Shear Load

Figure 3.8 No Significant Change in Slope at Max. Shear Load

Figure 3.9 Bag Face vs. Tool Face

Figure 3.10 Effects of Ball Joint Head

Figure 3.11 Void Content Increase with Ply/Debulk Increase.

Figure 3.12 Longitudinal Compressive Strength vs. Temperature

Figure 3.13 Longitudinal Compressive Modulus vs. Temperature

Figure 3.14 In-Plane Shear Strength vs. Temperature

Figure 3.15 In-Plane Shear Modulus vs. Temperature

Figure 3.16 Longitudinal Tensile Strength vs. Temperature

Figure 3.17 Longitudinal Tensile Modulus vs. Temperature

Figure 3.18 C-Beam Dimensions

Figure 3.19 C-Beam Cross Sectional Views

Figure 3.20 Four Point Bending Test

Figure 3.21 Teflon Spacers to Allow Deflection

Figure 3.22 Beam 1 Test Results

Figure 3.23 Beam 2 Test Results

Figure 3.24 Beam Void Content Increase with Location

Chapter 4: Prediction of Compression Strength

With the material characterization and beam compression tests complete, the work turned to predicting the compression strengths. Two of the three parameters required, shear strength and modulus, were already captured in the experimental portion of the program. The only remaining parameter was the standard deviation of the fiber misalignment, Ω .

4.1 Optical Technique

An optical technique first proposed by Yurgartis [3] can be used to measure the misalignment angle of each fiber in the cross section. The technique consist of cutting the composite at a known angle and measuring under microscope the major axis of the ellipse formed by the intersection of a cylindrical fiber with the cutting plane. The misalignment angle is computed from the major axis length, l , the fiber diameter, d , and the angle of the cutting plane ϕ , as shown in Figure 4.1.

This technique assumes that (1) fibers are straight over short sections and that (2) fibers have equal diameters. The first assumption has been shown to be reasonable in [1], [3]. The fiber diameters were roughly equal and were averaged for each material system. The fiber diameters for both materials were found to be lower than those reported by the manufacturer, Toray. Approximately forty points of data were taken on each specimen and the coefficient of variation is about 10% as shown in the Table 4.1. As in [1], [21], the effect of fiber diameter variation was not included in the study.

The angle of the sectioning plane should be chosen so that most of the misaligned fibers can be captured. At the same time, the angle should not be set such that the ellipse formed at the plane of intersection is very long since the assumption of straight segments is less likely to be fulfilled. Practically speaking, a low viewing magnification would be required to measure long ellipses. This would reduce accuracy when taking measurements manually. The angle to cut the composite was chosen at 5 deg since [1], [3] obtained good results with carbon/epoxy at this angle. Later, the results would show it was a good choice.

When laying down the unidirectional prepreg at 0 degrees, it was assumed that the global misalignment tolerance was ± 0.25 degrees for the compression specimen panels and ± 0.5 degree for the prototype production beams. A ± 0.25 degree tolerance was assumed when cutting and polishing the specimens and beam samples. Summing the tolerances, a ± 0.50 degree total tolerance was expected on the angles produced from the compression specimen samples and a ± 0.75 degree total tolerance was expected on the beam samples.

It is reasonable to expect a symmetric distribution of fiber angles but this technique typically shows a distribution of angles that is skewed as shown in Figure 4.2. This shows more fibers counted with positive angles. Statistically, skew can be quantified as,

$$skewness = \frac{n}{(n-1)(n-2)} \sum_{j=1}^n \left(\frac{x_j - \bar{x}}{s} \right)^3 \quad (4.1)$$

where

n = number of data points

s = sample standard deviation

$\bar{x}$ = sample average

x_j = j th sampled data point.

Positive skewness indicates a distribution with an asymmetric tail extending toward more positive values. Negative skewness indicates a distribution with an asymmetric tail extending toward more negative values [24].

One explanation of why there is a skew is that fibers that have angles less than -5 degrees get “flipped” back into the distribution [1], [21]. For example, if $\alpha = -6$ deg, it would be recorded as $\alpha = -4$ deg, $\alpha = -7$ deg as $\alpha = -3$ deg, etc. However, this does not explain the phenomenon that was observed in this study. The technique had a tendency to show more frequency on the side of the distribution where the fiber lengths are shorter. Also, it seems unlikely that fibers with angles greater than -5 degrees are getting “flipped” back into the distribution because most of the fibers never went beyond -4 degrees. One would have expected more frequency leading up to -5 degrees in order to believe significant frequency beyond -5 degrees.

4.2 Modifications to Optical Technique

Because there is inherent skew in this technique, researchers have proposed different methods of adjusting the curve to make it a normal or Gaussian distribution. In [21], the negative side of the curve was discarded and assumed to be a mirror image of the positive side. In [1], the values were first shifted to make the mean equal 0 degrees,

and then the positive values were added to the negative values to get a “folded” distribution.

In this investigation, another method is proposed with the intent of changing the original data as little as possible. Data was taken on a +5 and –5 degree cut surface so that two oppositely skewed distributions would be obtained. If the average angles of the distributions were within the tolerances caused by cutting/polishing and global misalignment, then it was judged to be reasonable to shift the distributions to have an average of zero degrees. The distributions were then added to get a single distribution with skewness closer to zero (Figure 4.3).

4.3 Preparation

After the compression specimens were broken, the two halves of the specimens were carefully ground to regain parallel edges. This is possible since the damage from the compression failure is around the gage section and the end of the specimen can still be used to establish a reference surface. A 5 degree cut was made on each of the compression specimen halves so that one side would have +5 degree cut and the other side would have a –5 degree cut as shown in Figure 4.4. Each side was cut into three pieces so that they could be potted in small circular acrylic cylinders with the ± 5 degree surfaces on top. These cylinders were installed in a carousel that could handle 3 or 6 cylinders at one time and the carousel was installed in the Buehler Ecomet 2 polishing machine. These surfaces were then polished at 240, 400, 600, 800 grit sandpaper and with 1 micron alumina polishing compound.

In the case of the beams, a piece was cut from the compression caps as near as possible to the location of the failure as shown in Figure 4.5. A piece cut in this manner had two faces that were against the tool and therefore could be taken as reference surfaces when performing the subsequent grinding to square up the specimen. Again, the pieces were sectioned into thirds and then potted in acrylic

To quantify fiber misalignment, the major and minor axes of the fiber ellipse were measured with a conventional microscope and a graphics software program, OPTIMAS. The major axis was measured at 200X magnification for 1512 fibers on each specimen and the minor axis of the fiber was measured at 500X magnification for 40 points on each specimen.

As pointed out in [1], [3], there is a tendency to pick the fibers with a major axis of smaller length and neglect the fibers with a longer length. To make the selection as random as possible, a line was drawn on the screen as shown in Figure 4.6 and all fibers crossing the line were measured. The line was kept so that it started from the top of the specimen and ended at the bottom. Additional lines of data were taken until the required number of points had been achieved.

4.4 Data Reduction and Interpretation

Tables 4.2, 4.3, 4.4, 4.5 show the average angle before shifting to zero and the skew for all the specimens. (Note the “Left Side” was cut at -5 degrees and the “Right Side” was cut at $+5$ degrees.) The average angle is very small - less than ± 0.5 deg with only a few exceptions. As mentioned before, this is caused by cutting, polishing and

global misalignment errors. Hence, it is reasonable to disregard these average angles and shift to zero degrees in each case. As expected, the combined skew is reduced by adding the “Left Side” and “Right Side” angles.

4.5 Fiber Volume Correction

As noted in Chapter 3.3, the material properties were reported at the fiber volumes in which they were tested and not normalized as in Table 4.6 and 4.7. In order to make the compressive strength comparisons, the data for F6 and G12 was normalized to the same fiber volume fraction of F1c by the following equations.

$$G_{12} \cong \frac{v_f \bar{G}_{12}}{\bar{v}_f} \quad (4.2)$$

$$F_6 \cong \frac{v_f \bar{F}_6}{\bar{v}_f} \quad (4.3)$$

For the 949/M30GC material, G12 and F6 were reported at 54.13% and F1c at 61.45%. For the 948A1/M40J material, G12 and F6 were reported at 52.02% and F1c at 59.41%. Therefore the correction factor was 1.135 for 949/M30GC and 1.142 for 948A1/M40J.

It should be noted that these are approximate equations and the relationships could be more refined. From the inverse rule of mixtures, G12 does not have a linear relationship with fiber volume. However, in the range of fiber volumes of this study, 52% to 61%, the relationship is essentially linear and can be written as above.

$$G_{12} = \bar{G}_{12} \left(\frac{1 - \bar{v}_f}{1 - v_f} \right) \cong \frac{v_f \bar{G}_{12}}{\bar{v}_f} \quad (4.3)$$

4.6 Confidence Intervals on Measured Data

The confidence interval on the mean of a normal distribution with the population variance unknown, is given by [25],

$$\bar{x} - \frac{t_{a/2, n-1} s}{\sqrt{n}} \leq m \leq \bar{x} + \frac{t_{a/2, n-1} s}{\sqrt{n}} \quad (4.5)$$

where

m = population mean for G_{12} , F_6 , F_{1c}

$\bar{x}$ = sample mean

s = sample standard deviation

a = probability

n = number of data points

$t_{a/2, n-1}$ = t distribution at $a/2$, $n-1$.

Thus, there is a $100(1 - \alpha)$ percent confidence that the population mean, μ , lies between the above two values, which form the confidence interval. This equation was used for F_6 , G_{12} , and the experimental values of F_{1c} . The confidence intervals are shown in Table 4.6 and 4.7.

The confidence interval on the standard deviation of a normal distribution with the population variance unknown, is given by [25],

$$\sqrt{\frac{(n-1)s^2}{C_{a/2, n-1}^2}} \leq \Omega \leq \sqrt{\frac{(n-1)s^2}{C_{1-a/2, n-1}^2}} \quad (4.6)$$

where

Ω = population standard deviation
 s = sample standard deviation
 s^2 = sample variance
 a = probability
 n = number of data points
 $C^2_{a/2, n-1}$ = χ^2 distribution at $a/2$, $n-1$
 $C^2_{1-a/2, n-1}$ = χ^2 distribution at $1-a/2$, $n-1$.

The results of the confidence interval on Ω are shown in the “chi-squared” column of Table 4.8 and 4.9 with $\alpha = 0.05$, or a 95% confidence level. Since 1512 fibers per sample were measured ($n=1512$), the confidence intervals were very narrow. However, as can be seen for the samples with identification NTP-15-XX, the confidence intervals of the four samples *do not overlap*. The same is true of the other three types of samples. This means that Ω changes from point to point in the same panel (i.e. NTP-11-XX) or from panel to panel. Because of this, the values of Ω were treated as point estimates, or *samplings*, of the standard deviation of the misalignment angle at different locations in the panels instead representing the *population* standard deviation of the misalignment angle. The standard deviation was then calculated as

$$\Omega = \sqrt{\frac{s_1^2 + s_2^2 + s_3^2 + \dots + s_n^2}{n}} \quad (4.7)$$

where

Ω = population standard deviation
 s = sample standard deviation
 s^2 = sample variance
 n = number of data points = 4.

The confidence interval was calculated as

$$\sqrt{V - \frac{t_{a/2, n-1} SV}{\sqrt{n}}} \leq \Omega \leq \sqrt{V + \frac{t_{a/2, n-1} SV}{\sqrt{n}}} \quad (4.8)$$

where

Ω = population standard deviation

V = sample variance

SV = standard deviation of sample variance

a = probability

n = number of data points

$t_{a/2, n-1}$ = t distribution at $a/2$, $n-1$.

The values of Ω and the confidence intervals are shown in the “t-dist.” column of Tables 4.8 and 4.9.

4.7 Confidence Intervals on Predicted Data

Because the three terms in the compression formula (2.20) all have their own confidence interval, the predicted compression strength will have its associated confidence interval. Using a binomial expansion for the terms in compression formula, it shows that the highest value of F_{1c} occurs when G_{12} and F_6 are at their highest value and Ω is at its lowest. The lowest values of F_{1c} occur when the values take the opposite extremes, which is consistent with intuition.

$$F_{1c} = G_{12} \left(\frac{c}{a} + 1 \right)^b \left(1 + \frac{\pm \frac{c}{a} \frac{\Delta F_6}{F_6} \pm \frac{1}{a F_6} (\Omega \Delta G_{12} \pm G_{12} \Delta \Omega)}{\frac{c}{a} + 1} \right) \quad (4.8)$$

	949/M30GC Fiber Diameter [microns]	948A1/M40J Fiber Diameter [microns]
Average	5.02	4.85
Standard Dev.	0.41	0.52
Cv	8.16	10.67
No. of pts n	238	320

Table 4.1 Fiber Diameters

Left Side			Right Side		Combined	
949/M30GC Specimen	α^1 [deg]	Skew []	α^1 [deg]	Skew []	α^1 [deg]	Skew []
NTP-15-1	-1.22	0.424	-0.12	-0.168	-0.67	-0.022
NTP-15-84	-0.47	-0.167	-0.02	-0.064	-0.24	-0.113
NTP-15-86	-0.36	0.413	0.02	-0.328	-0.17	-0.010
NTP-15-21	0.26	-0.118	0.10	-0.173	0.18	-0.145
Average	-0.45	0.138	0.00	-0.183	-0.23	-0.072
Standard Dev.	0.61	0.32	0.09	0.11	0.35	0.07

Note 1: Angles before shifting to zero.

Table 4.2 Average Angle and Skew, 949/M30GC compression specimens

Left Side			Right Side		Combined	
948A1/M40J Specimen	α^1 [deg]	Skew []	α^1 [deg]	Skew []	α^1 [deg]	Skew []
NTP-11-1	-0.14	0.328	0.18	-0.100	0.02	0.105
NTP-17-7	0.35	0.405	-0.41	-0.193	-0.03	0.099
NTP-16-5	0.78	0.750	-0.50	-0.259	0.14	0.221
NTP-11-21	0.37	-0.064	0.26	-0.332	0.32	-0.218
Average	0.34	0.355	-0.12	-0.221	0.11	0.052
Standard Dev.	0.38	0.33	0.39	0.10	0.15	0.19

Note 1: Angles before shifting to zero.

Table 4.3 Average Angle and Skew , 948A1/M40J compression specimens

Left Side			Right Side		Combined	
949/M30GC Beam 1 Sample	α^1 [deg]	Skew []	α^1 [deg]	Skew []	α^1 [deg]	Skew []
B1-1	0.31	0.346	0.14	-0.133	0.23	0.035
B1-L1R1	-0.02	0.176	-0.12	-0.470	-0.07	-0.207
B1-L2R2	-0.38	0.429	-0.28	-0.264	-0.33	0.113
B1-L3R3	-0.01	-0.086	-0.13	-0.017	-0.07	-0.046
Average	-0.03	0.216	-0.10	-0.221	-0.06	-0.026
Standard Dev.	0.28	0.23	0.17	0.19	0.23	0.14

Note 1: Angles before shifting to zero.

Table 4.4 Average Angle and Skew, 949/M30GC Beam 1 Samples

Left Side			Right Side		Combined	
949/M30GC Beam 2 Sample	α^1 [deg]	Skew []	α^1 [deg]	Skew []	α^1 [deg]	Skew []
B2-1	0.30	0.082	-0.07	-0.585	0.12	-0.260
B2-L1R1	0.30	0.082	-0.01	-0.728	0.15	-0.310
B2-L2R2	-0.38	0.388	-0.29	-0.253	-0.34	-0.022
B2-L3R3	0.25	0.835	-0.95	-0.325	-0.35	0.306
Average	0.12	0.347	-0.33	-0.473	-0.11	-0.072
Standard Dev.	0.33	0.36	0.43	0.22	0.27	0.28

Note 1: Angles before shifting to zero.

Table 4.5 Average Angle and Skew, 949/M30GC Beam 2 Samples

Material	Temp.	G12 (Fib. Vol. 54.13%)	95% Confidence Interval (t-dist.)	F6 (Fib. Vol. 54.13%)	95% Confidence Interval (t-dist.)	F1c (Fib. Vol. 61.45%)	95% Confidence Interval (t-dist.)
		[F]	[Msi]		[ksi]		[ksi]
949/M30GC	180	0.365	+ .026 - .026	6.07	+ .410 - .410	149	+ 5.41 - 5.41
	RTA	0.576	+ .026 - .026	9.80	+ .621 - .621	185	+ 21.4 - 21.4
	-125	0.627	+ .020 - .020	16.01	+ .906 - .906	226	+ 11.6 - 11.6

Table 4.6 G₁₂, F₆, F_{1c} Confidence Intervals, 949/M30GC

Material	Temp.	G12 (Fib. Vol. 52.02%)	95% Confidence Interval (t-dist.)	F6 (Fib. Vol. 52.02%)	95% Confidence Interval (t-dist.)	F1c (Fib. Vol. 59.41%)	95% Confidence Interval (t-dist.)
		[F] [Msi]	[Msi]	[ksi] [ksi]	[ksi]	[ksi] [ksi]	[ksi]
948A1/M40J	180	0.439	+ .034 - .034	8.93	+ .124 - .124	194	+ 13.6 - 13.6
	RTA	0.625	+ .012 - .012	11.40	+ .223 - .223	208	+ 5.68 - 5.68
	-125	0.676	+ .039 - .039	14.30	+ 1.02 - 1.02	223	+ 18.6 - 18.6

Table 4.7 G₁₂, F₆, F_{1c} Confidence Intervals, 948A1/M40J

Type of Sample	I.D.	Standard Deviation	95% Confidence Interval	Modified Standard Deviation Ω	95% Confidence Interval
		n=1512	(Chi ² dist.)	n=4	(t - dist.)
		[deg]	[deg]	[deg]	[deg]
948A1/M40J SACMA Compression Specimen	NTP-11-1	1.129	+ .040 - .039	1.205	+ .157 - .181
	NTP-17-7	1.164	+ .041 - .040		
	NTP-16-5	1.163	+ .041 - .040		
	NTP-11-21	1.352	+ .048 - .047		

Table 4.8 Standard Deviation of Misalignment Angle Confidence Intervals, 948A1/M40J

Type of Sample	I.D.	Standard Deviation	95% Confidence Interval	Modified Standard Deviation	95% Confidence Interval
		n=1512	(Chi ² dist.)	Ω n=4	(t - dist.)
		[deg]	[deg]	[deg]	[deg]
949/M30GC SACMA Compression Specimen	NTP-15-1	1.236	+ .046 - .043	1.150	+ .091 - .099
	NTP-15-84	1.123	+ .042 - .039		
	NTP-15-86	1.129	+ .042 - .039		
	NTP-15-21	1.109	+ .041 - .038		
949/M30GC Beam 1	B1-1	1.342	+ .0500 - .046	1.313	+ .091 - .097
	B1-L1R1	1.328	+ .049 - .046		
	B1-L2R2	1.223	+ .045 - .042		
	B1-L3R3	1.355	+ .050 - .047		
949/M30GC Beam 2	B2-1	1.158	+ .043 - .040	1.125	+ .055 - .058
	B2-L1R1	1.134	+ .042 - .039		
	B2-L2R2	1.074	+ .040 - .370		
	B2-L3R3	1.133	+ .042 - .039		

Table 4.9 Standard Deviation of Misalignment Angle Confidence Intervals, 949/M30GC

Figure 4.1 Calculation of Fiber Angle

Figure 4.2 Specimen Skew Example

Figure 4.3 Reducing Skew by Combination of Distributions

Figure 4.4 Specimen Polishing Procedure

Figure 4.5 Beam Sample Polishing Procedure

Figure 4.6 Measurement of Ellipses That Intersect Selection Line

Chapter 5: Prediction Results

5.1 Normal Distribution

The plots of cumulative distribution show that they are very close to a normal cumulative distribution. The lowest and highest skew for all the specimens was in 949/M30GC samples and is shown in Figures 5.1 and 5.2. Figure 5.3 shows a typical one-sided skew for the 948A1M40J material. These figures compare the analytical normal cumulative distribution function (CDF) with the experimental CDF. Hence, it was reasonable to use the normal distribution in the derivation of the compressive strength.

5.2 Predicted Strength

Actual vs. predicted compressive strengths of the SACMA specimens and four-point beam bending specimens are shown in Figure 5.4 for the 949/M30GC, Figure 5.5 for the 948/M40J and Figure 5.6 for the 949/M30GC Beam 1 and 2. For a full breakdown of the data, see Table 5.1. The formula predicted the compressive strength of the RTA and -125 F compression specimens very well. The averages are within 8%. However, the 180 F specimen strength predictions were low even when using the full extent of the confidence interval. The predictions at this temperature are conservative by a 25% margin. The discrepancy is believed to be due in part to the large changes in shear modulus that occur at high temperature. One can see from Figure 3.11 and Figure 3.12, shear strength is almost linear in the -125F to 180F temperature range while shear

modulus has a large decrease between RTA and 180F. Residual stresses from curing the part in manufacturing may also play a role in the discrepancy.

Actual vs. predicted strengths on the beam data was also very good as can be seen in Figure 5.6. On beam 2, the value was within a percentage point of the experimental values. Plotted against other data from the literature [1], [21] in Figure 5.7, the experimental data falls along the line of predicted values vs. the non-dimensional parameter, χ .

The sensitivity plot for 949/M30GC at room temperature in Figure 5.8 confirms the trends expected by intuition. Increases in G12 and F6 increase compressive strength F1c, and increases in Ω decrease F1c. On a percentage basis, F6 is most powerful in reducing F1c and Ω is the most powerful in increasing F1c.

In Figure 5.9, the combined buckling/misalignment plot for 949/M30GC at room temperature shows the maximum strength of 177 ksi at the point of zero slope on the σ applied curve. This point corresponds to a misalignment of approximately 1.75 degrees which means that fibers with angles greater than 1.75 degrees have already buckled by the time compression failure occurs. The percentage of fibers that had not buckled before compression failure was approximately 87%. A normalized version of this data in Figure 5.10, shows that the failure occurs at only 27% of the theoretical maximum ($F1c = G12$) and at 1.5 times the standard deviation, Ω . Interestingly, other than the different absolute values of compressive strength, similar values were obtained in the normalized version for 948A1/M40J as shown in Figure 5.11, 5.12.

The strength values for global misalignment of 949/M30C and 948A1/M40J at room temperature are shown in Figures 5.13 and 5.14 using the method of shifted

distributions described in section 2.6. As can be seen, this method shows that the drop in strength caused by global misalignment occurs much faster than the stress transformation factor of cosine squared α_G . “Carpet plots” of compressive strength vs. Ω and average global misalignment, α_G , are shown on Figures 5.15 and 5.16. According to this, composites with high misalignment Ω (i.e. fiberglass $\Omega = 3-4$ degrees), are quite insensitive to global misalignment.

Type of Sample	Temperature	Predicted Compressive Strength F1c [ksi]	95% Confidence Interval [ksi]	Actual Compressive Strength F1c [ksi]	95% Confidence Interval (t-dist.) [ksi]	% Diff. (Actual Base) [%]
949/M30GC SACMA Compression Specimens	180	111	+ 14 - 12	149	+ 5 - 5	-26%
	RTA	177	+ 20 - 17	185	+ 21 - 21	-4%
	-125	243	+ 24 - 21	226	+ 12 - 12	8%
949/M30GC Beam 1	RTA	160	+ 17 - 15	169	N/A	-5%
949/M30GC Beam 2	RTA	176	+ 16 - 14	175	N/A	1%
948A1/M40J SACMA Compression Specimens	180	147	+ 21 - 16	194	+ 14 - 14	-24%
	RTA	196	+ 23 - 17	208	+ 6 - 6	-6%
	-125	231	+ 39 - 30	223	+ 19 - 19	4%

Table 5.1 Actual vs. Predicted Compressive Strength

Figure 5.1 Cumulative Distribution Function for Specimen with lowest skew.

Figure 5.2 Cumulative Distribution for Specimen with highest skew.

Figure 5.3 Cumulative Distribution Function of 948A1/M40J specimen.

Figure 5.4 949/M30GC Actual vs. Predicted Compressive Strength

Figure 5.5 948A1/M40J Actual vs. Predicted Compressive Strength

Figure 5.6 949/M30GC Beam 1&2 Actual vs. Compressive Strength

Figure 5.7 Formula vs. Experimental, Literature Data

Figure 5.8 949/M30GC RTA Sensitivity to Ω , G12, F6

Figure 5.9 949/M30GC RTA Maximum Compressive Strength

Figure 5.10 949/M30GC RTA Normalized Maximum Compressive Strength

Figure 5.11 948A1/M40J RTA Maximum Compressive Strength

Figure 5.12 948A1/M40J Normalized RTA Maximum Compressive Strength

Figure 5.13 949/M30GC RTA Compressive Strength vs. Ave. Global Misalignment

Figure 5.14 948/M40J RTA Compressive Strength vs. Ave. Global Misalignment

Figure 5.15 949/M30GC RTA F1c vs. Ave. Global Misalignment, Ω

Figure 5.16 948A1/M40J RTA F1c vs. Ave. Global Misalignment, Ω

Chapter 6: Summary and Conclusions

This study has shown very good agreement between actual and predicted values of compressive strength in compression specimens. At the higher temperatures, the prediction method is conservative which suggests that there are other effects that may not have been considered. These include errors in reading the shear stiffness and strength in the shear test because of the significant increase in temperatures.

The prototype-beam actual strengths were also very close to the predicted. Interestingly, the misalignment Ω of beam 1 was the highest and beam 2 the lowest of all samples tested. While it is expected that production parts would have higher misalignment Ω than test specimens, beam 2 shows that Aurora Flight Sciences can make production parts with very low misalignment and, when doing so, will gain a benefit in ultimate compressive strength capability.

Void content was very low on the specimen panels (1-2%) and thus did not effect material properties in Phase I. The void content on the beams was considerably higher (2-4%) but did not seem to be a factor affecting compressive strength since the predictions were very close. This agrees with the results from [11].

Despite some conservatism, the technique outlined here could be practical in some production environments. Already there are some production parts that are made slightly longer so that the excess can be cut for density and void content tests. Likewise, if a segment of the compression portion of the part could be lengthened, it too could be cut and polished to take fiber misalignment data. The measurement of fiber

misalignment does not have to be done manually. Commercial equipment is available that automate the polishing and the acquisition of the fiber data [26]. This would greatly reduce the time required for this process.

Undoubtedly, this technique has application to “post-mortem” investigation. For example, a part that failed (i.e. wing spar) could be examined to find the fiber misalignment Ω and, with shear properties, a compressive strength capability could be determined. The investigators could then deduce if the reason for failure was lower than expected strength capability. The alternative is much more difficult. Cutting the damaged part to get a specimen for compression tests causes micro-defects in the material that greatly reduce strength.

Lastly, the technique proposed to predict the compression strength of composites with average global misalignment in a $[\alpha_G]_n$ or $[-\alpha_G]_n$ stacking schedule also holds promise. Test fixtures will need to be devised to stabilize this type of laminate up to compressive failure stress in order to confirm the predictions.

Chapter 7: Recommendations

Due to the time and budget restraints of this study, there are some areas that could not be explored and would be excellent candidates for future investigations.

- Determine the mechanism that allows compressive strength to be higher than predicted at 180F and incorporate into explicit equation.
- Test commercially available software [26] that measures fiber misalignment in an actual case to predict compressive strength of a production part.
- Determine the minimum number of data points necessary to get Ω on a production part by checking variation in Ω at different points in the production part.
- Generalize the explicit equation by incorporating effects of global misalignment and void content.
- Demonstrate effectiveness of this technique on an actual Quality Control and “Post-Mortem” studies.

References

1. Haberle, J.G. 1991. "Strength and Failure Mechanisms of Unidirectional Carbon Fibre-Reinforced Plastics Under Axial Compression," Ph.D. Thesis, Imperial College, London, U.K.
2. Barbero, E.J. 1998."Prediction of Compression Strength Of Unidirectional Polymer Matrix Composites," *Journal of Composite Materials*, 32(5):483-502.
3. Yurgartis, S.W. 1987. "Measurement of Small Angle Fiber Misalignment In Continuous Fiber Composites," *Composite Science and Technology*, 30:279-293.
4. Rosen, B.W. 1965. Chapter 3 in "Fiber Composite Materials," Metals Park, OH: American Society for Metals.
5. Wang, A.S.D. 1978. "A Non-Linear Microbuckling Model Predicting the Compressive Strength of Unidirectional Composites," ASME Winter Annual Meeting. ASME Paper 78-WA/Aero-I.
6. Maewal, A. 1981. "Post Buckling Behavior of a Periodically Laminated Medium in Compression," *International Journal of Solids and Structures*. 17:335-344.
7. Martinez, G.M., M.R. Piggott, D.M.R. Bainbridge and B. Harris. 1981. "The Compression Strength of Composites with Kinked, Misaligned and Poorly Adhering Fibres," *Journal of Materials Science*. 16: 2831-2836.
8. Barbero, E.J. 1999. "Introduction to Composite Materials Design," Taylor and Francis, Philadelphia, PA.
9. Piggot, M.R. 1981. "A theoretical framework for the compressive properties of aligned fibre composite," *Journal of Materials Science*. 16: 2837-2845.
10. Budiansky, B. 1983. "Micromechanics," *Computers and Structures*. 16: 3-12.
11. Tang, J.M., W.I. Lee and G.S. Springer. 1987. "Effects of Cure Pressure on Resin Flow, Voids, and Mechanical Properties," *Journal of Composite Materials*. 21:421-440.
12. Mrse, A. and Piggott. 1990. "Relation between Fibre Divagation and Compressive Properties of Fibre Composites," 35th International SAMPE Symposium, April 2-5, pp. 2236-2244.
13. Yurgartis, S. W. and S.S. Sternstein. 1992. "Experiments to reveal the role of matrix properties and Composite Microstructure in Longitudinal Compression Strength,"

- ASTM Symposium on Compression Response of Composite Structures. November 16-17.
14. Barbero, E.J. and J.S. Tomblin, 1996. "A Damage Mechanics Model for Compression Strength of Composites," *Int. J. Solid Structures*. 33(29):4379-4393.
 15. Lagoudas, D.C. and A.M. Saleh. 1993. "Compressive Failure Due to Kinking of Fibrous Composites," *Journal of Composite Materials*, 27:83-106.
 16. Crasto, A.S. and R.Y. Kim, 1992. "The Effects of Constituent Properties on the Compression Strength of Advanced Composites," *ASTM Symposium on Compression Response of Composite Structures*. November 16-17.
 17. Steif, P.S. 1990. "A Model for Kinking in Fiber Composites-Part I Fiber Breakage via Micro-buckling," 26:549-561, and "II Kink Band Formation," *Int. J. Solid Structures*. 26:563-569.
 18. Shuart, M.J. 1989. "Failure of Compression-Loaded Multidirectional Composite Laminates," *AIAA Journal*. 27:1274-1279.
 19. Tomblin, J.S., L.A. Godoy, and E.J. Barbero. 1997. "Imperfection Sensitivity of Fiber Micro-buckling in Elastic-Nonlinear Polymer Matrix Composites," *Int. J. Solid Structures*. 34(13):1667-1679.
 20. Kachanov, L.M. 1990. "Introduction to Continuum Damage Mechanics," Kluwer Academic Publishers, Hingham, MA.
 21. Tomblin, J.S. 1994. "Compressive Strength Models for Pultruded Glass Fiber Reinforced Composites," Ph.D. Thesis, West Virginia University, Morgantown, WV.
 22. Dobyns, A., B. Barr, and J. Adelmann. 1999. "RAH-66 Comanche Building Block Structural Qualification Program," *ASTM Symposium on Composite Structures: Theory And Practice*, May 17-18.
 23. Anderson, T.C. 1999. "The Interaction Between CAI and BVID as It Applies to the Development of a Thermoplastic Tailboom," *ASTM Symposium on Composite Structures: Theory And Practice*, May 17-18.
 24. Sachs, L. 1982. "Applied Statistics: A Handbook of Techniques," Springer-Verlag, New York, New York.
 25. Montgomery, D.C. and G.C. Runger. 1994. "Applied Statistics and Probability for Engineers," John Wiley and Sons, New York, New York.
 26. Buehler Enterprises. 41 Waukegan Rd, Lake Bluff, IL.

Appendix A:

Testing Methods/Panel History

Property: Longitudinal Compressive Strength

Tested by: Touchstone Research Laboratories
Test Specification: ASTM D3410-95
Method: Procedure B, "IITRI", with tabs
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE948A1/M40J
Length: 6.0 in
Width: 0.5 in
Depth: .110-.115 in
Tab Material: E-glass, plain weave
Tab Depth: .062 in
Adhesive: 275 deg F, 90 min. cure
Rate of Cross-head: ~1.5mm/min
Strain Measurement: none
Test Humidity: Ambient
Test Environment: Lab Air
Test Temperature: ~65 deg F

Notes: 1. Tabs protruded .1" from end of grips.
2. 3-4 samples tested of each material type.

Property: Longitudinal Compressive Strength
Longitudinal Compressive Modulus
Transverse Compressive Strength
Transverse Compressive Modulus

Tested by: Touchstone Research Laboratories, WVU, OCM
Test Specification: SACMA SRM 1R-94
Method: Standard
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE948A1/M40J
Length: 3.18 in
Width: 0.5 in
Depth: .037-.044 and .110-.115
Tab Material: Alternating carbon/E-glass panel, McMaster-Carr
Tab Depth: .090 in
Adhesive: AF163, 250 deg F, 60 min. cure, Magnabond 6380
Rate of Cross-head: ~1.0 mm/min
Strain Measurement: extensometer, EA-06-125AC-350,-120 strain gages
Test Humidity: Ambient
Test Environment: Lab Air
Test Temperature: ~65 deg F

Notes: 1. Touchstone used extensometer and found modulus in 1000-3000 microstrain range.
2. WVU used strain gages and found modulus in 0-1000 microstrain range. This was because specimens buckled 1500 microstrain and above.
3. WVU used surface grinder to square off four of six faces of specimens.

Property: In-Plane Shear Strength
In-Plane Shear Modulus

Property: Longitudinal Tensile Strength
Longitudinal Tensile Modulus
Transverse Tensile Strength
Transverse Tensile Modulus

Tested by: WVU, OCM
Test Specification: ASTM D5379-93
Method: With tabs
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE948A1/M40J
Length: 3.0 in
Width: .75 in
Depth: .110-.115 in
Tab Material: Alternating carbon/E-glass panel, McMaster-Carr
Tab Depth: .062 in
Adhesive: DP460, EPI 1559A/B, Magnabond 6380, OCM film ad
Rate of Cross-head: .05 in/min
Strain Measurement: MicroMeasurements Shear Gages
Test Humidity: 50% Relative Humidity
Test Environment: Lab Air
Test Temperature: 23 deg C

Notes: 1. Back-to-back shear gages used.
2. Over 3% twist occurred in some tests, cause unknown, values are averaged from both gages
3. Shear Chord Modulus taken over 1000-6000 microstrains.

Tested by: WVU
Test Specification: ASTM D3039-95a
Method: With tabs
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE948A1/M40J
Length: 10.0 in., 7.0 in
Width: 0.5 in., 1.0 in
Depth: .041 in, .110-.115 in
Tab Material: Alternating carbon/E-glass panel, McMaster-Carr
Tab Depth: .062 in
Adhesive: DP460, EPIBOND 1559A/B, Magnabond 6380
Rate of Cross-head: .05 in/min
Strain Measurement: EA-06-125TM-120 strain gages
Test Humidity: 45% Relative Humidity
Test Environment: Lab Air
Test Temperature: 24 deg C

Notes: 1. Transverse Chord Modulus taken over 1000-2500 microstrains. Longitudinal Chord Modulus taken over 1000-3000 microstrains.
2. MTS 810 material system used for modulus tests.
3. Instron 1000 with manually tightened, self-aligning grips, used for Transverse strength testing.
4. Transverse strength specimens taken from modulus specimens with tabs removed. Specimen length = 5.0 in.
5. Emery cloth used at grips.

Property: Apparent Density

Tested by: WVU
Test Specification: ASTM D 792-91, Helium Pycnometer Method
Method: Method B for D792-91
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE 948A1/M40J
Length: 38 mm
Width: 11 mm
Depth: .110-.115 in
Tab Material: none
Tab Depth: none
Adhesive: none
Rate of Cross-head: none
Strain Measurement: none
Test Humidity: 50% Relative Humidity
Test Environment: Lab Air
Test Temperature: 20 deg C

Notes:

1. Both liquid displacement and helium pycnometer used for tests.
2. 4 samples for each material type used with D 792-91.
3. 5 samples used for each material type with pycnometer.

Property: Theoretical Density
Void Content

Tested by: WVU
Test Specification: Procedure from Micromeritics
Method: Micromeritics Accu Pyc 1330 Standard
Specimen Material: Cytech Fiberite Carbon Tape, Intermediate Modulus
Product Code: HYE 949/M30GC, HYE 948A1/M40J
Length: 2.75-5.25 cc, ground to pass 30 mesh sieve
Width: 2.75-5.25 cc, ground to pass 30 mesh sieve
Depth: 2.75-5.25 cc, ground to pass 30 mesh sieve
Tab Material: none
Tab Depth: none
Adhesive: none
Rate of Cross-head: none
Strain Measurement: none
Test Humidity: 45% Relative Humidity
Test Environment: Lab Air
Test Temperature: 20 deg C

Notes:

1. Differences in theoretical density most likely caused by variations in grinding.

Property: Glass Transition Temperature

Tested by: WVU
Test Specification: Cytech Fiberite Test Method T16
Method: Max Value of $\tan(\delta)$
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC, HYE 948/M40J
Length: 5.5 mm
Width: 1.1 mm
Depth: .042"-.043"
Tab Material: none
Tab Depth: none
Adhesive: none
Rate of Cross-head: none
Strain Measurement: none
Test Humidity: 50% Relative Humidity
Test Environment: Lab Air
Test Temperature: 20 deg C

Notes:

Property: Longitudinal Coefficient of Thermal Expansion
Transverse Coefficient of Thermal Expansion

Tested by: OCM
Test Specification: ASTM E-831
Method: TMA
Specimen Material: Cytech Fiberite Carbon Tape
Product Code: HYE 949/M30GC
Length: .25"
Width: .25"
Depth: .120"-.127"
Tab Material: none
Tab Depth: none
Adhesive: none
Rate of Cross-head: none
Strain Measurement: none
Test Humidity: 45% Relative Humidity
Test Environment: Lab Air
Test Temperature: 20 deg C

Notes: 1. Tested in temperature range -125 F to 180 F.

Panel ID NTP-	Material	Len [in]	Wid [in]	Approx Thick Unsanded [in]	# Plys	Plys/ Debulk	Manufacturing Method				Notes
							Caul Plates	Peel Ply	Perf. Ply	Bleeder/ Breather	
1	949/M30GC	22	12	0.120	20	5	---	---	P7	Yes	Cured to 240F,post cured to 275F.
2	949/M30GC	22	12	0.120	20	10	---	---	P7	Yes	Cured to 240F,post cured to 275F.
3	949/M30GC	22	12	0.120	20	20	---	---	P7	Yes	Cured to 240F,post cured to 275F.
4	949/M30GC	22	12	0.124	20	5	---	---	CT	Yes	
5	949/M30GC	20	4	CT	20	5	---	---	CT	Yes	
6	949/M30GC	20	4	CT	20	10	---	---	P3	Yes	
7	949/M30GC	12	24	0.046	7	7	---	---	P7	Yes	
8	948A1/M40J	12	24	0.046	7	7	---	---	P7	Yes	
9	948A1/M40J	18	12	0.124	20	20	---	---	P7	Yes	Cracked when removed from tool.
10	948A1/M40J	23.5	12	0.042	7	7	.5" Alum	Yes	---	---	Discarded,suspected lint contamination
11	948A1/M40J	23.5	12	0.042	7	7	.5" Alum	Yes	---	---	
12	948A1/M40J	22	12	0.127	20	20	---	---	P7	Yes	Discarded, creases caused by rel. film.
13	Not Used										
14	948A1/M40J	22	12	0.124	20	20	---	---	P7	Yes	
15	949/M30GC	23.5	12	0.041	7	7	.5" Alum	Yes	---	---	
16	948A1/M40J	23.5	12	0.042	7	7	.5" Alum	Yes	---	---	
17	948A1/M40J	23.5	12	0.042	7	7	.5" Alum	Yes	---	---	

Notes: "CT": Cannot Trace this information.

Appendix B:

Phase I Test Results

Touchstone Tests:

1. Longitudinal Compressive Strength

5 ply/debulk

Specimen	Ult. Load [lb]	Jlt. Stress [ksi]
NTP-4-26	6860	123.6
NTP-4-30	5905	106.4
NTP-4-25	5883	106.0
Ave	6216	112.0
St Dev	558	10.05
Cv	8.97	8.97

Ave + StD	6774	122.0
Ave - StD	5658	102.0

10 ply/debulk

Specimen	Ult. Load [lb]	Jlt. Stress [ksi]
NTP-6-3	7309	131.7
NTP-6-5	6699	120.7
NTP-6-4	7526	135.6
NTP-6-6	7426	133.8
Ave	7240	130.5
St Dev	371	6.69
Cv	5.13	5.13

Ave + StD	7611	137.1
Ave - StD	6869	123.8

20 ply/debulk

Specimen	Ult. Load [lb]	Jlt. Stress [ksi]
NTP-3-28	6693	120.6
NTP-3-26	7670	138.2
NTP-3-22	8147	146.8
Ave	7504	135.2
St Dev	741	13.36
Cv	9.88	9.88

Ave + StD	8245	148.6
Ave - StD	6762	121.8

2. Longitudinal Compressive Modulus

5 plys/debulk

Specimen	Modulus [Msi]
1L-2S	18.46
1L-3S	18.71
1L-4S	17.86
1L-5S	17.50
1L-XS	18.35
Ave	18.18
St Dev	0.488
Cv	2.69

Ave + StD	18.66
Ave - StD	17.69

10 plys/debulk

Specimen	Modulus [Msi]
2L-2S	18.23
2L-3S	17.78
2L-4S	17.87
2L-5S	18.63
2L-XS	17.36
Ave	17.97
St Dev	0.482
Cv	2.68

Ave + StD	18.46
Ave - StD	17.49

20 plys/debulk

Specimen	Modulus [Msi]
3L-1M	17.47
3L-2M	17.75
3L-3M	17.80
3L-4M	18.04
3L-5M	18.75
Ave	17.96
St Dev	0.487
Cv	2.71

Ave + StD	18.45
Ave - StD	17.48

3. Transverse Compressive Strength

5 ply/debulk

Specimen	Ult. Load [lb]	Jlt. Stress [ksi]
1T-4M	1464	24.6
1T-5M	1494	25.3
1T-6M	1535	23.6
1T-7M	1520	25.4
1T-9M	1520	25.6
Ave	1507	24.9
St Dev	28.0	0.819
Cv	1.86	3.29

Ave + StC	1535	25.7
Ave - StD	1479	24.1

10 ply/debulk

Specimen	Ult. Load [lb]	Jlt. Stress [ksi]
2T-4M	1498	25.4
2T-5M	1493	25.3
2T-6M	1458	24.4
2T-7M	1400	23.7
2T-8M	1423	24.4
Ave	1454	24.6
St Dev	42.9	0.709
Cv	2.95	2.88

Ave + StC	1497	25.3
Ave - StD	1412	23.9

4. Transverse Compressive Modulus

5 ply/debulk

Specimen	Modulus [Msi]
1T-6S	1.083
1T-7S	1.030
1T-8S	1.047
1T-9S	1.064
1T-XS	1.127
Ave	1.070
St Dev	0.0374
Cv	3.49

Ave + StC	1.108
Ave - StD	1.033

10 ply/debulk

Specimen	Modulus [Msi]
2T-4S	1.045
2T-5S	1.058
2T-6S	1.034
2T-7S	1.013
2T-8S	0.992
Ave	1.028
St Dev	0.0262
Cv	2.55

Ave + StC	1.055
Ave - StD	1.002

WVU Tests

1. Longitudinal Compression Strength

7 ply/debulk

Specimen	Ult. Load [lb]	Ult. Stress [ksi]
NTP-15-82	3426	184
NTP-15-83	3941	211
NTP-15-84	3510	187
NTP-15-85	3057	164
NTP-15-86	3276	177
Ave	3442	185
St Dev	328	17
Cv	9.52	9.32
Ave + StD	3770	202
Ave - StD	3114	167

2. Longitudinal Compressive Modulus

7 plys/debulk

Specimen	Mod 1 [Msi]	Mod 2 [Msi]	Ave. Mod. [Msi]
NTP-15-52	23.2	23.1	23.2
NTP-15-53	21.3	24.7	23.0
NTP-15-54	21.9	24.0	22.9
NTP-15-55	23.6	21.8	22.7
NTP-15-56	21.8	24.6	23.2
Average	22.3	23.6	23.0
St Dev	0.99	1.22	0.21
Cv	4.44	5.14	0.92
Ave + StD	23.3	24.8	23.2
Ave - StD	21.3	22.4	22.8

5. In-Plane Shear Strength

5 Ply/Debulk			10 Ply/Debulk			20 Ply/Debulk		
Specimen	Ult. Load	Ult Stress	Specimen	Ult. Load	Ult Stress	Specimen	Ult. Load	Ult Stress
	[lb]	[psi]		[lb]	[psi]		[lb]	[psi]
NTP-4-9	513	9950	NTP-2-9	518	10380	NTP-3-9	498	9770
NTP-4-10	552	10590	NTP-2-11	515	10360	NTP-3-11	513	10060
NTP-4-11	488	9440	NTP-2-15	491	9940	NTP-3-12	513	10040
NTP-4-14	483	9360	NTP-2-16	474	9680	NTP-3-14	527	10300
NTP-4-16	493	9680	NTP-2-17	483	9830	NTP-3-17	510	10120
Ave	506	9804	Ave	496	10038	Ave	512	10058
St Dev	28	496	St Dev	20	317	St Dev	10	191
Cv	5.58	5.06	Cv	3.93	3.16	Cv	2.02	1.90
Ave + StD	534	10300	Ave + StD	516	10355	Ave + StD	523	10249
Ave - StD	478	9308	Ave - StD	477	9721	Ave - StD	502	9867

6. In-Plane Shear Modulus

5 Ply/Debulk			10 Ply/Debulk			20 Ply/Debulk		
Specimen		[Msi]	Specimen		[Msi]	Specimen		[Msi]
NTP-4-9	Mod 1	0.492	NTP-2-9	Mod 1	0.543	NTP-3-9	Mod 1	0.5174
	Mod 2	0.601		Mod 2	0.47		Mod 2	0.5895
	Ave Mod	0.5465		Ave Mod	0.5065		Ave Mod	0.55345
	Twist	9.97%		Twist	7.21%		Twist	6.51%
NTP-4-10		[Msi]	NTP-2-11		[Msi]	NTP-3-11		[Msi]
	Mod 1	0.604		Mod 1	0.498		Mod 1	0.498
	Mod 2	0.584		Mod 2	0.586		Mod 2	0.570
	Ave Mod	0.594		Ave Mod	0.542		Ave Mod	0.534
NTP-4-11		[Msi]	NTP-2-15		[Msi]	NTP-3-12		[Msi]
	Mod 1	0.504		Mod 1	0.564		Mod 1	0.414
	Mod 2	0.622		Mod 2	Not Avail.		Mod 2	0.598
	Ave Mod	0.563		Ave Mod	0.564		Ave Mod	0.506
		[Msi]			[Msi]			[Msi]
	Twist	10.48%		Twist	Not Avail.		Twist	18.12%

5 Ply/Debulk			10 Ply/Debulk			20 Ply/Debulk		
Specimen		[Msi]	Specimen		[Msi]	Specimen		[Msi]
NTP-4-14	Mod 1	0.557	NTP-2-16	Mod 1	0.554	NTP-3-14	Mod 1	0.548
	Mod 2	0.634		Mod 2	0.564		Mod 2	0.549
	Ave Mod	0.596		Ave Mod	0.559		Ave Mod	0.549
	Twist	6.47%		Twist	0.90%		Twist	0.09%
NTP-4-16	Mod 1	0.531	NTP-2-17	Mod 1	0.478	NTP-3-17	Mod 1	0.508
	Mod 2	0.634		Mod 2	0.593		Mod 2	0.579
	Ave Mod	0.583		Ave Mod	0.535		Ave Mod	0.543
	Twist	8.84%		Twist	10.78%		Twist	6.54%
	Ave Mod	0.576		Ave Mod	0.541		Ave Mod	0.537
	St Dev	0.021		St Dev	0.023		St Dev	0.019
	Cv	3.67		Cv	4.19		Cv	3.49
	Ave + StD	0.597		Ave + StD	0.564		Ave + StD	0.556
	Ave - StD	0.555		Ave - StD	0.519		Ave - StD	0.518
	Ave Twist	7.49%		Ave Twist	6.75%		Ave Twist	7.59%

7. Transverse Tensile Strength

5 Ply/Debulk			10 Ply/Debulk			20 Ply/Debulk		
Specimen	Ult. Load	Ult Stress	Specimen	Ult. Load	Ult Stress	Specimen	Ult. Load	Ult Stress
	[lb]	[psi]		[lb]	[psi]		[lb]	[psi]
NTP-4-1	561	4963	NTP-2-1	496	4510	NTP-3-2	532	4668
NTP-4-2	486	4303	NTP-2-2	493	4445	NTP-3-3	517	4571
NTP-4-3	534	4726	NTP-2-6	508	4615	NTP-3-4	562	4929
NTP-4-6	496	4354	NTP-2-7	569	5176	NTP-3-5	556	4920
NTP-4-8	560	5045	NTP-2-8	526	4696	NTP-3-6	535	4696
Mean	527	4678	Mean	518	4688	Mean	540	4757
St Dev	35	340	St Dev	31	289	St Dev	19	160
Cv	6.62	7.28	Cv	6.02	6.17	Cv	3.43	3.37
Mean+StD	562	5019	Mean+StD	550	4978	Mean+StD	559	4917
Mean-StD	493	4338	Mean-StD	487	4399	Mean-StD	522	4596

8. Transverse Tensile Modulus and Minor Poisson's Ratio

5 Ply/Debulk Specimen	E_2 [Msi]	ν_{21}	10 Ply/Debulk Specimen	E_2 [Msi]	ν_{21}	20 Ply/Debulk Specimen	E_2 [Msi]	ν_{21}
NTP-4-1	1.069	0.00965	NTP-2-1	1.084	0.00540	NTP-3-1	1.008	0.00880
NTP-4-2	1.026	0.00795	NTP-2-2	1.058	0.00882	NTP-3-2	0.978	0.00594
NTP-4-6	1.131	0.00980	NTP-2-6	1.025	0.01475	NTP-3-6	1.020	0.00774
NTP-4-7	1.011	0.00990	NTP-2-7	1.049	0.00590	NTP-3-7	1.029	0.00975
NTP-4-8	1.058	0.00783	NTP-2-8	0.983	0.00984	NTP-3-8	1.004	0.00585
Mean	1.059	0.00903	Mean	1.040	0.00894	Mean	1.008	0.00762
St Dev	0.047	0.00104	St Dev	0.038	0.00375	St Dev	0.019	0.00172
Cv	4.40	11.54	Cv	3.67	41.98	Cv	1.92	22.65
Mean+StD	1.106	0.01007	Mean+StD	1.078	0.01270	Mean+StD	1.027	0.00934
Mean-StD	1.012	0.00798	Mean-StD	1.002	0.00519	Mean-StD	0.988	0.00589

9. Density and Void Content at Location A

Density¹: Helium Pycnometer, apparent density

Density²: Liquid Displacement Method, liquid - isopropanol, apparent density

Density³: Helium Pycnometer, sample ground to 30 mesh sieve, theoretical density

Location A: 4" from end of panel 12"x22"

5 Plys/Debulk

Apparent Density ¹ [gm/cc]	Apparent Density ² [gm/cc]	Theoretical Density ³ [gm/cc]
1.4848	1.4866	1.5129
		↓
Void Content [volume %]		1.857%

10 Plys/Debulk

Apparent Density ¹ [gm/cc]	Apparent Density ² [gm/cc]	Theoretical Density ³ [gm/cc]
1.4833	1.4833	1.5102
		↓
Void Content [volume %]		1.781%

20 Plys/Debulk

Apparent Density ¹ [gm/cc]	Apparent Density ² [gm/cc]	Theoretical Density ³ [gm/cc]
1.4788	1.4787	1.5104
		↓
Void Content [volume %]		2.092%

9. Density and Void Content at Location B

Density¹: Helium Pycnometer, apparent density

Density⁵: Helium Pycnometer, sample ground to 30 mesh sieve, theoretical density

Location B: At center of panel 12"x22"

5 Plys/Debulk

Apparent Density ¹ [gm/cc]	Theoretical Density ⁵ [gm/cc]
1.4846	1.5006

Void Content [volume %]	
1.066%	

20 Plys/Debulk

Apparent Density ¹ [gm/cc]	Theoretical Density ⁵ [gm/cc]
1.4776	1.5037

Void Content [volume %]	
1.736%	

Appendix C:

Phase II Test Results

180 F Longitudinal Compressive Strength

Material: 948A1

Tested by: OCM
 Temp: 180
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate .5" Aluminum
 Peel Ply: Both sides
 Modulus: 24.8 ([Msi] Adjusted OCM data)
 22.6 ([Msi] Original OCM data)

Specimen	Width [in.]	Thick use [in]	Load [lbs]	Strength Adj [ksi]	Thick [in]	Adj Str [ksi]
NTP-11-1	0.501	0.040	4167	208	0.038	219
NTP-11-2	0.502	0.040	4011	200	0.038	210
NTP-11-3	0.500	0.040	4077	204	0.038	215
NTP-11-4	0.500	0.038	3759	198	0.038	198
NTP-11-5	0.498	0.040	3926	197	0.038	207
NTP-16-21	0.500	0.040	3074	154	0.038	162
NTP-16-22	0.501	0.040	3460	173	0.038	182
NTP-16-23	0.501	0.041	3283	160	0.038	172
NTP-16-24	0.501	0.040	3492	174	0.038	183
NTP-16-25	0.501	0.041	3648	178	0.038	192
Average	0.501	0.040	3690	184	0.038	194
St Dev	0.001	0.001	362	19	0.000	19
Cv	0.22	2.04	9.81	10.45	0.00	9.83
Ave + StD	0.502	0.041	4052	204	0.038	213
Ave - StD	0.499	0.039	3328	165	0.038	175

Ult Strain
[ue]
8180

Adj Ult Strain
[ue]
7823

Material: 949

Tested by: OCM
 Temp: 180
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate .5" Aluminum
 Peel Ply: Both sides
 Modulus: 21.0 ([Msi] Adjusted OCM data)
 19.4 ([Msi] Original OCM data)

Specimen	Width [in.]	Thick use [in]	Load [lbs]	Strength Adj [ksi]	Thick [in]	Adj Str [ksi]
NTP-15-1	0.502	0.038	2710	142	0.037	146
NTP-15-2	0.503	0.037	2807	151	0.037	151
NTP-15-3	0.500	0.037	2779	150	0.037	150
NTP-15-4	0.501	0.039	2683	137	0.037	145
NTP-15-5	0.500	0.038	2880	152	0.037	156
Average	0.501	0.038	2772	146	0.037	149
St Dev	0.001	0.001	79	6	0.000	4.360
Cv	0.26	2.21	2.84	4.35	0.00	2.92
Ave + StD	0.503	0.039	2850	153	0.037	154
Ave - StD	0.500	0.037	2693	140	0.037	145

Ult Strain
[ue]
7531

Adj Ult Strain
[ue]
7095

RTA Longitudinal Compressive Strength

Material: 948A1

Tested by: WVU
Temp: RTA
of Plys: 7
Sanding: Yes, for strain gage only
Bleeder: No
Caul Plate: .5" Aluminum
Peel Ply: Both sides
Modulus: 28.8 ([Msi] WVU data)

Material: 949

Tested by: WVU
Temp: RTA
of Plys: 7
Sanding: Yes, for strain gage only
Bleeder: No
Caul Plate .5" Aluminum
Peel Ply: Both sides
Modulus: 23.0 ([Msi] WVU data)

Specimen	Width [in.]	Thick usec [in]	Load [lbs]	Strength [ksi]	Adj Thick [in]	Adj Str [ksi]
NTP-16-1	0.485	0.040	3588	185	0.038	195
NTP-16-2	0.488	0.041	3812	191	0.038	206
NTP-16-3	0.479	0.040	3636	190	0.038	200
NTP-16-4	0.486	0.0405	3998	203	0.038	216
NTP-16-5	0.49	0.041	3810	190	0.038	205
NTP-16-6	0.490	0.041	4332	216	0.038	233
NTP-16-7	0.492	0.041	4116	204	0.038	220
NTP-16-8	0.498	0.041	3860	189	0.038	204
NTP-16-9	0.498	0.041	4072	199	0.038	215
NTP-16-10	0.495	0.0415	4162	203	0.038	221
NTP-17-1	0.502	0.040	3545	177	0.038	186
NTP-17-2	0.504	0.040	3721	185	0.038	194
NTP-17-3	0.508	0.040	4170	205	0.038	216
NTP-17-4	0.509	0.041	4218	202	0.038	218
NTP-17-5	0.505	0.041	4134	200	0.038	215
NTP-17-6	0.506	0.041	4100	198	0.038	213
NTP-17-7	0.509	0.041	4244	204	0.038	220
NTP-17-8	0.506	0.040	3792	187	0.038	197
NTP-17-9	0.472	0.041	3535	183	0.038	197
NTP-17-10	0.425	0.042	3148	176	0.038	195
Average	0.492	0.041	3900	194	0.038	208
St Dev	0.019	0.001	306	10.55	0.000	12.14
Cv	3.86	1.41	7.85	5.43	0.00	5.83
Ave + StD	0.511	0.041	4206	205	0.038	220
Ave - StD	0.473	0.040	3593	184	0.038	196

Adj Ult Strain [ue] 7222

Specimen	Width [in.]	Thick usec [in]	Load [lbs]	Strength [ksi]	Adj Thick [in]	Adj Str [ksi]
NTP-15-8:	0.503	0.038	3426	179	0.037	184
NTP-15-8:	0.504	0.039	3941	200	0.037	211
NTP-15-8:	0.506	0.039	3510	180	0.037	187
NTP-15-8:	0.503	0.038	3057	160	0.037	164
NTP-15-8:	0.501	0.038	3276	172	0.037	177
Average	0.503	0.038	3442	178	0.037	185
St Dev	0.002	0.000	328	14.73	0.000	17.26
Cv	0.38	1.17	9.52	8.25	0.00	9.34
Ave + StD	0.505	0.039	3769	193	0.037	202
Ave - StD	0.501	0.038	3114	164	0.037	168

Adj Ult Strain [ue] 8043

-125 F Longitudinal Compressive Strength

Material: 948A1

Tested by: OCM
 Temp: -125
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: .042-.043 unsanded
 0.038 sanded
 Modulus: 41.7 ([Msi] Adjusted OCM data)
 36.9 ([Msi] Original OCM data)

Specimen	Width [in.]	Thick [in.]	Load [lbs]	Strength [ksi]	Adj Thick [in.]	Adj Str [ksi]
NTP-11-2	0.501	0.040	4448	222	0.038	234
NTP-11-2	0.496	0.039	3812	197	0.038	202
NTP-11-2	0.501	0.040	4135	206	0.038	217
NTP-11-2	0.499	0.039	4565	235	0.038	241
NTP-11-2	0.501	0.040	4176	208	0.038	219
Average	0.500	0.040	4227	214	0.038	223
St Dev	0.002	0.001	294	15	0.000	15
Cv	0.44	1.38	7	6.87	0.00	6.76
Ave + StD	0.502	0.040	4521	228	0.038	238
Ave - StD	0.497	0.039	3933	199	0.038	208

Ult Strain
[ue]
5790

Adj Ult Strain
[ue]
5348

Material: 949

Tested by: OCM
 Temp: -125
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: .041-.042 unsanded
 0.037 sanded
 Modulus: 41.8 ([Msi] Adjusted OCM data)
 38.4 ([Msi] Original OCM data)

Specimen	Width [in.]	Thick [in.]	Load [lbs]	Strength [ksi]	Adj Thick [in.]	Adj Str [ksi]
NTP-15-21	0.498	0.038	4377	231	0.037	238
NTP-15-22	0.500	0.037	3997	216	0.037	216
NTP-15-23	0.500	0.039	4334	222	0.037	234
NTP-15-24	0.501	0.036	4107	228	0.037	222
NTP-15-25	0.501	0.039	4091	209	0.037	221
Average	0.500	0.038	4181	221	0.037	226
St Dev	0.001	0.001	165	9	0.000	9
Cv	0.24	3.45	4	3.99	0.00	4.13
Ave + StD	0.501	0.039	4346	230	0.037	235
Ave - StD	0.499	0.036	4016	213	0.037	217

Ult Strain
[ue]
5764

Adj Ult Strain
[ue]
5407

180 F Longitudinal Compressive Modulus

Material: 948A1

Tested by: OCM
 Temp 180
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.042-.043 unsanded
 0.038 sanded

Specimen	Thick used [in]	Modulus [Msi]	Thick to use [in]	Adj. Mod. [Msi]
NTP-11-11	0.042	22.70	0.038	25.1
NTP-11-12	0.042	22.84	0.038	25.2
NTP-11-13	0.042	20.93	0.038	23.1
NTP-11-14	0.041	23.85	0.038	25.7
NTP-11-15	0.042	22.45	0.038	24.8
Average	0.042	22.6	0.038	24.8
St Dev	0.000	1.05	0.00	0.99
Cv	1.07	4.67	0.00	4.00
Ave + StD	0.042	23.6	0.038	25.8
Ave - StD	0.041	21.5	0.038	23.8

Material: 949

Tested by: OCM
 Temp 180
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.041-.042 unsanded
 0.037 sanded

Specimen	Thick used [in]	Modulus [Msi]	Thick to use [in]	Adj. Mod. [Msi]
NTP-15-11	0.040	19.60	0.037	21.2
NTP-15-12	0.040	19.27	0.037	20.8
NTP-15-13	0.039	20.02	0.037	21.1
NTP-15-14	0.041	18.78	0.037	20.8
NTP-15-15	0.040	19.52	0.037	21.1
Average	0.040	19.4	0.037	21.0
St Dev	0.001	0.46	0.00	0.17
Cv	1.77	2.35	0.00	0.83
Ave + StD	0.041	19.9	0.037	21.2
Ave - StD	0.039	19.0	0.037	20.8

RTA Longitudinal Compressive Modulus

Material: 948A1

Tested By: WVU
 Temp RTA
 # of Plys: 7
 Sanding: Yes, for strain gage only
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.042-.044 unsanded
 0.038 sanded
 Strain Range 0 to 1000 ue

Specimen	Thick used [in]	Mod 1 [Msi]	Mod 2 Ave. Mod. [Msi]	Mod. [Msi]
NTP-11-71	0.038	26.64	26.69	26.67
NTP-11-72	0.038	27.68	29.81	28.75
NTP-11-73	0.038	29.17	29.18	29.18
NTP-11-74	0.038	29.51	29.95	29.73
NTP-11-75	0.038	32.14	27.10	29.62
Average	0.038	29.0	28.5	28.8
St Dev	0.000	2.09	1.54	1.25
Cv	0.00	7.20	5.40	4.34
Ave + StD	0.038	31.1	30.1	30.0
Ave - StD	0.038	26.9	27.0	27.5

Material: 949

Tested By: WVU
 Temp RTA
 # of Plys: 7
 Sanding: Yes, for strain gage only
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.041-.042 unsanded
 0.037 sanded
 Strain Range: 0 to 1000 ue

Specimen	Thick used [in]	Mod 1 [Msi]	Mod 2 Ave. Mod. [Msi]	Mod. [Msi]
NTP-15-52	0.037	23.23	23.09	23.16
NTP-15-53	0.037	21.30	24.65	22.98
NTP-15-54	0.037	21.85	24.00	22.93
NTP-15-55	0.037	23.56	21.77	22.67
NTP-15-56	0.037	21.76	24.62	23.19
Average	0.037	22.3	23.6	23.0
St Dev	0.000	0.99	1.22	0.21
Cv	0.00	4.44	5.14	0.92
Ave + StD	0.037	23.3	24.8	23.2
Ave - StD	0.037	21.3	22.4	22.8

-125 F Longitudinal Compressive Modulus

Material: 948A1

Tested By: OCM
 Temp -125
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.042-.044 unsanded
 0.038 sanded

Specimen	Thick used [in]	Modulus [Msi]	Thick to use [in]	Adj. Mod. [Msi]
NTP-11-31	0.043	39.36	0.038	44.5
NTP-11-32	0.044	34.28	0.038	39.7
NTP-11-33	0.043	38.20	0.038	43.2
NTP-11-34	0.043	36.49	0.038	41.3
NTP-11-35	0.042	35.98	0.038	39.8
Average	0.043	36.9	0.038	41.7
St Dev	0.001	1.98	0.00	2.14
Cv	1.64	5.36	0.00	5.13
Ave + StD	0.044	38.8	0.038	43.8
Ave - StD	0.042	34.9	0.038	39.6

Material: 949

Tested By: OCM
 Temp -125
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.041-.04 unsanded
 0.037 sanded

Specimen	Thick used [in]	Modulus [Msi]	Thick to use [in]	Adj. Mod. [Msi]
NTP-15-31	0.041	39.36	0.037	43.6
NTP-15-32	0.040	34.27	0.037	37.0
NTP-15-33	0.039	42.45	0.037	44.7
NTP-15-34	0.041	40.15	0.037	44.5
NTP-15-35	0.040	35.99	0.037	38.9
Average	0.040	38.4	0.037	41.8
St Dev	0.001	3.29	0.00	3.54
Cv	2.08	8.55	0.00	8.48
Ave + StD	0.041	41.7	0.037	45.3
Ave - StD	0.039	35.2	0.037	38.2

RTA Transverse Compressive Strength

Material: 948A1

Tested By: WVU
 Temp RTA
 # of Plys: 20
 Sanding: 220 grit, lightly sanded
 Bleeder: Yes
 Caul Plate: no
 Peel Ply: no
 Strain Range: 1000 to 3000 ue

Specimen	Width [in]	Thick used [in]	Load [lb]	Stress [ksi]
NTP-14-31	0.510	0.120	1665	27.2
NTP-14-32	0.505	0.120	1745	28.8
NTP-14-33	0.498	0.119	1671	28.2
NTP-14-34	0.499	0.119	1478	24.9
NTP-14-35	0.500	0.119	1577	26.5
NTP-14-37	0.497	0.119	1619	27.4
Average	0.501	0.119	1625	27.2
St Dev	0.005	0.001	92	1.37
Cv	1.01	0.43	5.65	5.06
Ave + StD	0.507	0.120	1717	28.5
Ave - StD	0.496	0.119	1534	25.8

Material: 949

Tested By: Touchstone
 Temp RTA
 # of Plys: 20
 Sanding: No
 Bleeder: Yes
 Caul Plate: no
 Peel Ply: no
 Strain Range: 1000 to 3000 ue

Specimen	Width [in]	Thick used [in]	Load [lb]	Stress [ksi]
1T-4M	0.499	0.119	1464	24.6
1T-5M	0.494	0.119	1494	25.3
1T-6M	0.499	0.130	1535	23.6
1T-7M	0.498	0.120	1520	25.4
1T-9M	0.497	0.120	1520	25.6
Average	0.497	0.122	1507	24.9
St Dev	0.002	0.005	28	0.819
Cv	0.42	3.88	1.86	3.29
Ave + StD	0.499	0.126	1535	25.7
Ave - StD	0.495	0.117	1479	24.1

RTA Transverse Compressive Modulus

Material: 948A1

Tested By: WVU
Temp RTA
of Plys: 20
Sanding: 220 grit, lightly sanded
Bleeder: Yes
Caul Plate: no
Peel Ply: no
Strain Range 1000 to 3000 ue

Specimen	Width [in]	Thick [in]	Mod 1 [Msi]	Mod 2 [Msi]	Ave. Mod. [Msi]
NTP-14-41	0.487	0.123	1.31	1.09	1.20
NTP-14-42	0.47	0.126	1.12	1.07	1.09
NTP-14-43	0.502	0.127	1.04	1.05	1.04
NTP-14-44	0.522	0.121	1.08	1.20	1.14
NTP-14-45	0.501	0.126	1.10	1.43	1.27
Average	0.496	0.125	1.13	1.17	1.15
St Dev	0.019	0.003	0.10	0.16	0.09
Cv	3.89	2.01	9.29	13.56	7.63
Ave + StD	0.516	0.127	1.23	1.33	1.24
Ave - StD	0.477	0.122	1.02	1.01	1.06

Material: 949

Tested By: Touchstone
Temp RTA
of Plys: 20
Sanding: No
Bleeder: Yes
Caul Plate: no
Peel Ply: no
Strain Range 1000 to 3000 ue

Specimen	Width [in]	Thick [in]	Mod 1 [Msi]
1T-6S	0.503	0.119	1.08
1T-7S	0.504	0.119	1.03
1T-8S	0.502	0.119	1.05
1T-9S	0.498	0.120	1.06
1T-10S	0.500	0.118	1.13
Average	0.501	0.119	1.07
St Dev	0.002	0.001	0.04
Cv	0.48	0.59	3.49
Ave + StD	0.504	0.120	1.11
Ave - StD	0.499	0.118	1.03

180 F In-Plane Shear Properties

Material: 948A1

Tested by: OCM
Temp: 180 F
of Plys: 20
Sanding: 220 grit, very lightly
Bleeder: No
Caul Plate: No
Peel Ply: No

Specimen	Width [in]	Thick [in]	Ult. Load [lbs]	Strength [ksi]	Modulus [Msi]
NTP-14-1	0.445	0.125	499	8.97	0.426
NTP-14-2	0.447	0.124	492	8.88	0.404
NTP-14-3	0.444	0.124	495	8.99	0.433
NTP-14-4	0.446	0.123	496	9.04	0.467
NTP-14-5	0.445	0.124	485	8.79	0.467
Average	0.445	0.124	493	8.93	0.439
St Dev	0.001	0.001	5	0.10	0.027
Cv	0.26	0.57	1.08	1.12	6.23
Ave+StD				9.03	0.467
Ave-StD				8.83	0.412

Material: 949

Tested by: OCM
Temp: 180 F
of Plys: 20
Sanding: 220 grit, very lightly
Bleeder: No
Caul Plate: No
Peel Ply: No

Specimen	Width [in]	Thick [in]	Ult. Load [lbs]	Strength [ksi]	Modulus [Msi]
NTP-4-19-1	0.443	0.123	315	5.78	0.351
NTP-4-19-2	0.444	0.124	334	6.07	0.398
NTP-4-19-3	0.443	0.125	319	5.76	0.348
NTP-4-19-4	0.445	0.123	339	6.19	0.356
NTP-4-19-5	0.438	0.124	356	6.55	0.371
Average	0.443	0.124	333	6.07	0.365
St Dev	0.003	0.001	16	0.33	0.021
Cv	0.61	0.68	4.95	5.40	5.64
Ave+StD				6.40	0.385
Ave-StD				5.74	0.344

RTA In-Plane Shear Properties

Material: 948A1

Tested by: WVU
Temp: RTA
of Plys: 20
Sanding: 220 grit, very lightly
Bleeder: No
Caul Plate: No
Peel Ply: No

Specimen	Thick [in]	Mod 1 [Msi]	Mod 2 [Msi]	Twist [%]	Ave Mod [Msi]	Strength [ksi]
NTP-14-21	0.124	0.6117	0.6695	4.51%	0.6406	11.33
NTP-14-25	0.122	0.6514	0.6023	3.92%	0.6269	11.31
NTP-14-26	0.122	0.6357	0.6094	2.11%	0.6226	11.53
NTP-14-27	0.122	0.5889	0.6473	4.72%	0.6181	11.49
NTP-14-28	0.122	0.5269	0.7055	#####	0.6162	11.07
Average	0.122	0.6029	0.6468	5.95%	0.625	11.35
St Dev	0.001	0.0487	0.043	4.88%	0.010	0.18
Cv	0.731	8.07	6.62	82.06	1.56	1.59
Ave+StD					0.635	11.53
Ave-StD					0.615	11.16

Material: 949

Tested by: WVU
Temp: RTA
of Plys: 20
Sanding: 40/80/150 grit
Bleeder: No
Caul Plate: No
Peel Ply: No

Specimen	Thick [in]	Mod 1 [Msi]	Mod 2 [Msi]	Twist [%]	Ave Mod [Msi]	Strength [ksi]
NTP-4-9	0.112	0.4919	0.6012	10.00%	0.5466	9.95
NTP-4-10	0.113	0.6040	0.5842	1.67%	0.5941	10.59
NTP-4-11	0.112	0.5042	0.6216	10.43%	0.5629	9.44
NTP-4-14	0.112	0.5569	0.6341	6.48%	0.5955	9.36
NTP-4-16	0.111	0.5307	0.6342	8.88%	0.5825	9.68
Average	0.112	0.5375	0.6151	7.49%	0.576	9.80
St Dev	0.001	0.0448	0.022	3.60%	0.021	0.50
Cv	0.631	8.34	3.56	48.03	3.67	5.07
Ave+StD					0.597	10.30
Ave-StD					0.555	9.31

-125 F In-Plane Shear Properties

Material: 948A1

Tested by: OCM
 Temp: -125 F
 # of Plys: 20
 Sanding: 220 grit, lightly
 Bleeder: No
 Caul Plate: No
 Peel Ply: No

Specimen	Width [in]	Thick [in]	Ult. Load [lbs]	Strength [ksi]	Modulus [Msi]
NTP-14-11	0.445	0.125	761	13.68	0.660
NTP-14-12	0.446	0.124	784	14.18	0.635
NTP-14-13	0.446	0.126	847	15.07	0.672
NTP-14-14	0.445	0.124	735	13.32	0.711
NTP-14-15	0.446	0.123	831	15.15	0.704
Average	0.446	0.124	792	14.28	0.676
St Dev	0.001	0.001	47	0.82	0.031
Cv	0.12	0.92	5.93	5.72	4.65
Ave+StD				15.10	0.708
Ave-StD				13.46	0.645

Material: 949

Tested by: OCM
 Temp: -125 F
 # of Plys: 20
 Sanding: 220 grit, lightly
 Bleeder: No
 Caul Plate: No
 Peel Ply: No

Specimen	Width [in]	Thick [in]	Ult. Load [lbs]	Strength [ksi]	Modulus [Msi]
NTP-4-19-11	0.443	0.126	947	16.97	0.646
NTP-4-19-12	0.445	0.126	900	16.05	0.623
NTP-4-19-13	0.445	0.127	930	16.46	0.631
NTP-4-19-14	0.442	0.129	870	15.26	0.603
NTP-4-19-15	0.444	0.128	871	15.33	0.632
Average	0.444	0.127	904	16.01	0.627
St Dev	0.001	0.001	35	0.73	0.016
Cv	0.29	1.03	3.83	4.58	2.51
Ave+StD				16.74	0.643
Ave-StD				15.28	0.611

180 F Longitudinal Tensile Properties

Material: 948A1

Tested By: OCM
 Temp: 180 F
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.042-.044 unsanded
 0.038 sanded

specimen	thick used [in]	Strength [ksi]	Modulus [Msi]	Poisson []	Ult Strain [ue]	thick to use [in]	Adj Strength [ksi]	Adj. Modulus [Msi]
NTP-11-41	0.040	340.92	29.60	0.317	11070	0.038	358.86	31.2
NTP-11-42	0.040	345.25	30.60	0.334	10880	0.038	363.42	32.2
NTP-11-43	0.041	346.63	30.50	0.283	10820	0.038	374.00	32.9
NTP-11-44	0.041	339.07	29.90	0.343	10860	0.038	365.84	32.3
NTP-11-45	0.041	349.30	34.00	0.273	9260	0.038	376.88	36.7
Average	0.041	344.23	30.92	0.310	10578.00	0.038	368	33.0
St Dev	0.001	4.19	1.77	0.031	743.05		7.48	2.13
Cv	1.35	1.22	5.73	9.96	7.02		2.03	6.44
Ave+StD					11321.05		375	35.2
Ave-StD					9834.95		360	30.9

RTA Longitudinal Tensile Properties

Material: 948A1

Tested by: WVU
 Temp: RTA
 # of Plys: 7
 Sanding: Yes, for strain gage only
 Bleeder: No
 Caul Plate: .5" aluminum
 Peel Ply: both sides
 Thick: 042-.043 unsanded
 0.038 sanded

Specimen	Width [in.]	Thick [in]	Load [lbs]	Strength [ksi]	Mod [Msi]	Poisson []	Ult. Strain [uin/in]
NTP-11-81	0.479	0.038	5418	298	32.3	0.277	8777
NTP-11-82	0.486	0.038	6278	340	32.2	0.302	10059
NTP-11-83	0.459	0.038	6008	344	32.2	0.270	10046
NTP-11-84	0.490	0.038	6294	338	33.3	0.265	9717
NTP-11-85	0.471	0.038	6026	337	33.2	0.348	9729
NTP-11-86	0.494	0.038	6710	357	32.0	0.265	10596
Average	0.480	0.038	6122	336	32.5	0.288	9821
St Dev	0.013	0.000	428	20	0.6	0.033	603
Cv	2.72	0.00	7.00	5.99	1.74	11.31	6.14
Ave+StD				356	33.1	0.320	10424
Ave-StD				316	32.0	0.255	9218

Material: 949

Tested by: WVU
 Temp: RTA
 # of Plys: 7
 Sanding: Yes, for strain gage only
 Bleeder: No
 Caul Plate: .5" aluminum
 Peel Ply: both sides
 Thick: 041-.042 unsanded
 0.037 sanded

Specimen	Width [in.]	Thick [in]	Load [lbs]	Strength [ksi]	Mod [Msi]	Poisson []	Ult. Strain [uin/in]
NTP-15-61	0.468	0.037	7764	448	24.5	0.238	16895
NTP-15-62	0.448	0.037	7868	475	25.0	0.296	17114
NTP-15-63	0.455	0.037	7304	434	24.9	0.262	16577
NTP-15-64	0.467	0.037	7250	420	24.0	0.290	16052
NTP-15-65	0.455	0.037	8172	485	24.8	0.248	18054
NTP-15-66	0.468	0.037	7642	441	25.1	0.316	16430
Average	0.460	0.037	7667	451	24.7	0.275	16854
St Dev	0.009	0.000	350	25	0.4	0.030	694
Cv	1.87	0.00	4.56	5.55	1.65	11.05	4.12
Ave+StD				476	25.1	0.305	17548
Ave-StD				426	24.3	0.245	16160

-125 F Longitudinal Tensile Properties

Material: 948A1

Tested By: OCM
 Temp: -125 F
 # of Plys: 7
 Sanding: No
 Bleeder: No
 Caul Plate: .5" Aluminum
 Peel Ply: Both sides
 Thick.: 0.042-.043 unsanded
 0.038 sanded

specimen	thick used [in]	Strength [ksi]	Modulus [Msi]	Poisson []	Ult Strain [ue]	thick to use [in]	Adj Strength [ksi]	Adj. Modulus [Msi]
NTP-11-51	0.041	266.59	29.80	0.279	8330	0.038	287.64	32.2
NTP-11-52	0.041	286.24	29.70	0.305	9370	0.038	308.84	32.0
NTP-11-53	0.041	281.63	29.70	0.299	8990	0.038	303.86	32.0
NTP-11-54	0.041	217.13	29.40	0.214	7370	0.038	234.27	31.7
NTP-11-55	0.041	291.66	28.10	0.290	9620	0.038	314.69	30.3
Average	0.041	268.65	29.34	0.277	8736.00	0.038	290	31.7
St Dev	0.000	30.27	0.71	0.037	905.36		33	0.8
Cv	0.00	11.27	2.42	13.26	10.36		11.27	2.42

RTA Transverse Tensile Properties

Material: 948A1

Tested by: WVU
 Temp: RTA
 # of Plys: 20
 Sanding: 220 grit, lightly sanded
 Bleeder: Yes
 Caul Plate: No
 Peel Ply: No

Material: 949

Tested by: WVU
 Temp: RTA
 # of Plys: 20
 Sanding: 40/80/150 grit
 Bleeder: Yes
 Caul Plate: No
 Peel Ply: No

Specimen	Width [in.]	Thick [in]	Load [lbs]	Strength [ksi]	Mod [Msi]	Minor Poisson []
NTP-14-51	0.983	0.123	613	5.070	0.9573	0.00292
NTP-14-52	0.995	0.122	736	6.063	----	----
NTP-14-53	1.006	0.126	689	5.436	1.0310	0.01650
NTP-14-54	0.999	0.127	----	----	1.0168	0.01068
NTP-14-55	0.993	0.126	691	5.523	0.9872	0.00975
NTP-14-56	1.000	0.126	664	5.270	1.0146	0.01136
Average	0.996	0.125	679	5.47	1.00	0.01024
St Dev	0.008	0.002	45	0.37	0.03	0.00486
Cv	0.78	1.60	6.62	6.81	2.93	47.43

Specimen	Width [in.]	Thick [in]	Load [lb]	Strength [ksi]	Mod [Msi]	Minor Poisson []
NTP-4-1	1.000	0.113	561	4.963	1.069	0.00965
NTP-4-2	1.000	0.113	486	4.303	1.026	0.00795
NTP-4-3	1.000	0.113	534	4.726	----	----
NTP-4-6	1.000	0.114	496	4.354	1.131	0.00980
NTP-4-7	1.000	0.116	----	----	1.011	0.00990
NTP-4-8	1.000	0.111	560	5.045	1.058	0.00783
Average	1.000	0.113	527	4.68	1.06	0.00903
St Dev	0.000	0.002	35	0.34	0.05	0.00104
Cv	0.00	1.44	6.62	7.28	4.40	11.54

Apparent Density and Void Content

Material	# Plys	Plys/Debulk	Location	Apparent Density [gm/cc]	Theoretical Density [gm/cc]	Void Content [%vol]
949	20	5	panel, edge	1.4848	1.5129	1.857%
949	20	10	panel, edge	1.4833	1.5102	1.781%
949	20	20	panel, edge	1.4788	1.5104	2.092%
949	20	5	panel, center	1.4846	1.5006	1.066%
949	20	20	panel, center	1.4776	1.5037	1.736%
949	7	7	panel, center	1.5172	1.5398	1.468%
949	~89	10	beam, near end,web	1.4931	1.5342	2.679%
949	~65	10	beam: near center,web	1.4649	1.5302	4.267%
949	~65	10	beam, near center,edge	1.4583	1.5292	4.636%

Material	# Plys	Plys/Debulk	Location	Apparent Density [gm/cc]	Theoretical Density [gm/cc]	Void Content [%vol]
948	20	20	panel, edge	1.5043	1.5353	2.019%

Apparent Density and Void Content Continued

Apparent Density: Helium Pycnometer

Theoretical Density: Helium Pycnometer, sample ground to pass through 30 mesh sieve

Panel Locations

Location A: 4" from edge on 12" x 22" x .125" panel

Location B: Center of 12" x 22" x 0.125" panel

Location C: Center of 12" x 22" x 0.042" panel

Beam Locations

Location A: Near Beam End, Near Web

Location B: Near Beam Center (about 42" from end), Near Web

Location C: Near Beam Center (about 42" from end), Near Flange Edge

Glass Transition Temperature and Coefficient of Thermal

Glass Transition Temperature

Material: 948A1 HYE/M40J

Specimen	Maximum Temperature Value Tan(δ)	[F]
NTP-11-91	0.322	302
NTP-11-92	0.275	303

Average 303

Material: 949 HYE/M30GC

Specimen	Maximum Temperature Value Tan(δ)	[F]
NTP-15-71	0.358	249
NTP-15-72	0.516	258

Average 254

Longitudinal/Transverse Coefficient of Thermal Expansion

Material: 948A1 HYE/M40J

Specimen	Longitudinal α_{Lm} [$\mu\text{in/in F}$]	Specimen	Transverse α_{Tm} [$\mu\text{in/in F}$]
NTP-14-71	-0.63	NTP-14-81	19.8
NTP-14-72	-0.71	NTP-14-82	20.5
NTP-14-73	-1.04	NTP-14-83	19.7

Average -0.80

St Dev 0.22

Cv 27.43

Average 20.0

St Dev 0.5

Cv 2.26

Material: 949 HYE/M30GC

Specimen	Longitudinal α_{Lm} [$\mu\text{in/in F}$]	Specimen	Transverse α_{Tm} [$\mu\text{in/in F}$]
NTP-2-21	-0.55	NTP-2-31	18.1
NTP-2-22	-2.13	NTP-2-32	19.5
NTP-2-23	-0.62	NTP-2-33	18.1

Average -1.10

St Dev 0.89

Cv 81.24

Average 18.6

St Dev 0.8

Cv 4.41