Analysis Methods Improving Confidence in Material Qualification for Laminated Composites

Andrew Makeev, Guillaume Seon, Yuri Nikishkov
University of Texas Arlington, Arlington, Texas, United States

Dean Nguyen
Sikorsky Aircraft Corporation – A Lockheed Martin Company, Stratford, Connecticut, United States

Peter Mathews, Mark Robeson
U.S. Army Aviation Development Directorate, Fort Eustis, Virginia, United States

ABSTRACT
Fiber-reinforced composite materials are increasingly used in rotorcraft structures to reduce weight and improve efficiency. A major challenge, delaying the implementation of recently developed higher-performance materials that offer improved mechanical strength and stiffness at a lower weight, is the lack of efficient common material qualification. The current standard practices are too costly and time-consuming. Due to low confidence in material allowables, the entire material qualification process, including numerous test methods and large test matrices, must be repeated for every seemingly minute change in the composite system. This work presents initial results of research activities under the National Rotorcraft Technology Center, focused on utilizing recent advances in understanding complex deformation and failure mechanisms of polymer-matrix composites towards the development of consolidated common analysis processes. These common processes will enable reduced material qualification test matrices potentially accommodating substitution of resin types and other modifications of the material systems. In particular, analysis methods, developed at the University of Texas Arlington Advanced Materials and Structures Lab, are verified on carbon-fiber reinforced / untoughened and toughened polymer-matrix composite material systems. Due to well-recognized susceptibility of polymeric composites to matrix-dominated failures, thorough verification of the analysis methods using a range of the matrix types is required for improving confidence in the analysis-based material allowables accelerating material qualification.

INTRODUCTION
The US Department of Defense (DoD) and Rotorcraft Industry are facing the Future Vertical Lift (FVL) aviation challenge to replace more than 6,300 military vertical lift aircraft over the next 25-50 years. Accurate analysis and prediction methods reduce development and procurement risk to FVL. In particular, advanced polymeric composites are playing a major role in designing high-performance and lightweight vertical lift structures. However, uncertain residual strength and remaining useful life of the composite rotor and airframe structures due to complexity of failure mechanisms and susceptibility to manufacturing irregularities which may be precursors to structural damage impose risks that cannot be mitigated exclusively by time-consuming and costly experimental iterations. Validated analysis techniques accelerating design, certification, and qualification of composite structures are needed.

Over the last five years, Advanced Materials and Structures Lab (AMSL) at the University of Texas at Arlington laid the groundwork for developing such techniques. We improved understanding of complex deformation and failure mechanisms in composites and advanced our ability to predict material behavior. We developed methodologies based on greatly reduced lamina testing that enable accurate measurement of all key lamina stiffness/strength/fatigue properties in 3D, including out-of-plane characteristics (Refs. 1-6); and demonstrated that these properties can be successfully used in Finite Element Method (FEM)-based structural analysis for strength and fatigue predictions in multi-directional laminates. Verification articles included small coupons currently used in material qualification and simple elements (Refs. 7-10). Our computational models captured initiation and progression of the multiple failure modes including cracks and delaminations to detectable sizes (Refs. 7-10).

However, the analysis methods developed at AMSL have been verified only on a Hexcel IM7 carbon-fiber / 8552 toughened-epoxy matrix 350° F curing composite material
Due to well-recognized susceptibility of polymeric composites to matrix-dominated failures, a more comprehensive verification of the analysis methods using a broad range of the matrix types is required for improving confidence in the analysis methods. At the minimum, an untoughened polymer-matrix must be included in the verification to improve our confidence that our methods would work on any composite system. In this work, we will employ an untoughened IM7/PMT-F7 low-viscosity 350º F curing composite material system developed by Patz Materials and Technologies (PMT) as a basis for nanosilica reinforcement of the epoxy matrix throughout the composite material designed for improving fiber-direction compression and interlaminar strength and fatigue material performance compared to the legacy systems such as IM7/8552 (Ref. 12). Manufacturability has been an important role in engineering the PMT-F7 epoxy resin. Even at 40% nanosilica weight content in the matrix, the resin processing and handling qualities including tack and working life are comparable to 8552; and the resin viscosity remains lower compared to 8552 (Ref. 12). It is worth noting that currently, several rotor system applications use 250º F curing resins due to the relatively high viscosity of 350º F curing toughened epoxy systems such as 8552.

Intermediate-modulus (IM7) carbon/epoxy and glass/epoxy composites with 40% nanosilica weight content in the PMT matrix demonstrated as high as 45% increase in compressive strength; 20% improvement in interlaminar strength; and 25% higher endurance limit or more than a factor of 10 increase in fatigue lifetimes compared to the legacy material systems (Ref. 12). Functionalized nanosilica particles are cost-effective and well integrated in the PMT resin. Small diameter (100 nm) of the nanosilica particles, compared to the fibers, enables uniform dispersion in the composite. On the other hand, micrometer-scale length of carbon nanotubes and in-plane dimensions of graphene platelets cause filtration of such fillers by the fibers and result in poor interlaminar performance of prepreg composite material systems (Ref. 12).

A major challenge, delaying the implementation of recently developed higher-performance materials that offer improved mechanical strength and stiffness at a lower weight, is the lack of efficient common material qualification. The current standard practices are too costly and time-consuming. Due to low confidence in material allows, the entire material qualification process, including numerous test methods and large test matrices, must be repeated for every seemingly minute change in the composite system. This work presents initial results of research activities under the National Rotorcraft Technology Center, focused on utilizing recent advances in understanding complex deformation and failure mechanisms of polymer-matrix composites towards the development of consolidated common analysis processes, leading to reduced material qualification test matrices potentially accommodating substitution of resin types and other modifications of the material systems.

**LAMINA TESTING AND DATA-DRIVEN MODELING IMPROVING CONFIDENCE IN MATERIAL PROPERTIES**

Accurate non-contact full-field deformation techniques, such as digital image correlation (DIC) allowing for assessment of all surface strain components on the entire test specimen surface, enable simple test specimen configurations for more efficient and accurate measurement of multiple lamina material properties in a single experiment. In Ref. 18, we proposed a method utilizing a simple short-beam shear (SBS) specimen and DIC-based strain measurement for assessment of tensile and compressive modulus, Poisson’s ratio, nonlinear shear stress-strain curve and shear strength in the plane of loading for glass and carbon/epoxy composites in a single experiment. Figure 1 shows the test setup, SBS specimen configurations; and an example of DIC-based strain assessment. It is worth noting that at least three different ASTM standard test methods would be required otherwise, e.g. ASTM D3039 (Ref. 19) for measuring tensile modulus and Poisson’s ratio; ASTM D6641 (Ref. 20) or SACMA SRM 1R-94 for compressive modulus; and ASTM D5379 (Ref. 21) for measuring shear stress-strain curves and shear strength. Moreover, multiple failure modes, including in-plane and 1-3 interlaminar shear, 90º-transverse and interlaminar tension, and fiber-direction compression, are achievable by varying specimen dimensions, attachment sizes, and material orientation. Therefore, most of the stress-strain relations and strength material properties key to structural analysis could be characterized. The same method is applicable to static, fatigue, and impact loads (Ref. 13).

**Figure 1. A short-beam method to measure multiple stress-strain properties of composites in a single experiment: a) test setup, b) specimen configurations, and c) measured strains (DIC). N/L denotes nonlinear material behavior.**
As shown in Fig. 1, SBS specimens can be machined in the fiber direction (1), 90°-transverse direction (2), and interlaminar or through-the-thickness direction (3) from a single unidirectional panel and loaded in the principal material planes to characterize most of the 3D constitutive relations for composite material systems (the corresponding specimen configurations are color-coded in Fig. 1). It is worth noting that due to low 90°-transverse and interlaminar tensile (ILT) strength of polymer-matrix composites, SBS specimens machined in the corresponding directions (2 and 3) fail in tension before exhibiting nonlinear shear stress-strain behavior. References 3 and 22 showed that such SBS coupons loaded in the 2-3 interlaminar material plane exhibit linear through-the-thickness axial strain distribution; and a closed-form approximation of the normal stress distribution could be derived for accurately assessing 90°-transverse and interlaminar tensile and compressive moduli (Ref. 22). Results and their verification are listed in Refs. 3 and 22 for a legacy IM7-carbon/8552-epoxy tape material system.

It is worth noting that our SBS and SPT methods use elaborate experimental setups combined with advanced measurement techniques as well as data-driven analysis methods to verify simplifying assumptions and increase confidence in material allowables. In particular, Ref. 18 shows that when a material system exhibits significant shear non-linearity at high strain levels, maximum shear stresses can be significantly over-estimated by the closed-form approximation in the ASTM D2344. A 15% to 20% FEM based strength correction calculated using the DIC data-driven iterative nonlinear FE stress analysis has been required for IM7/8552 (Ref. 18). Data-driven modeling is also required in the SPT method for assessing the shear stress-strain curves in 3D, since there is no closed-form solution for evaluation of surface stresses due to complexity of deformation exhibited by the SPT specimens (Refs. 1, 2). Details on the SPT methodology, including utilization of the full-field measurement capability of DIC combined with an iterative FE model updating procedure for simultaneous assessment of non-linear shear stress-strain curves in all three principal material planes, can be found in Ref. 2. An interesting result obtained in Refs. 1-2 for IM7/8552 tape was that the shear modulus in the 2-3 material plane verified the assumption of transverse isotropy; and the material properties characterizing the non-linear shear behavior in the 1-3 material plane could also be used for accurate approximation of the 2-3 plane nonlinear ILS behavior.

In Refs. 3-5, the value of data-driven modeling is also demonstrated for characterization of ILT strength and fatigue properties. ILT properties have been among the most difficult basic material properties to characterize, due to their extreme sensitivity to manufacturing defects, including porosity. ASTM D6415 (Ref. 23), which is based on a curved-beam specimen subject to 4-point bending, is commonly used in the composite community for assessment of the ILT strength (ILTS). However, as indicated in Ref. 23, ASTM D6415 test “results may reflect manufacturing quality as much as material properties”, due to sensitivity of the curved-beam test method to void content. In Refs. 3-5,
Computed Tomography (CT) based measurements of porosity defects present in curved-beam test specimens were integrated into FE stress analysis to capture the effects of defects on the ILT behavior. Once the effects of defects were captured through transfer of the CT measurements into a three-dimensional FE model, the scatter in the curved-beam test data was reduced; and reliable material ILT properties could be determined. In particular, results presented in Ref. 3 for IM7/8552 showed a reduction of the coefficient of variation (COV) in ILT test results from 28.2% using ASTM D6415 based closed-form stress approximation ignoring porosity to less than 3% COV using CT data-driven stress modeling. Similarly, Ref. 5 shows that the scatter in the least-squares approximation of test data for generating the ILT S-N fatigue curve for IM7/8552 could be reduced from $R' = 0.34$ using the ASTM D6415 ILT stress approximation, to $R' = 0.92$ using CT data-driven FE stress modeling.

Table 1 lists the IM7/8552 and IM7/PMT-F7 lamina material properties measured using SBS and SPT methods as the input to multidirectional laminate analysis models summarized in the following sections. It is worth noting that these values were validated by the laminate analysis as they were essential for accurately predicting failure initiation and progression in multidirectional laminate coupons and elements subject to quasi-static and fatigue loading. And it is noteworthy that standard methods also reproduce some of these properties, e.g. Hexcel data (Ref. 11) list $E_{11T} = 23.8$ Msi tensile modulus and $E_{11C} = 21.7$ Msi compressive modulus in the fiber direction, matching SBS results. However, certain material properties could not be captured using existing standards, e.g. Ref. 11 lists $S_{13} = 17.4$ ksi ASTM D2344 1-3 ILS strength approximation for IM7/8552 that is much higher than true ILS strength. In addition, similar average values of some measured material properties for IM7/8552 in different material directions resulted in their simplified approximation for laminate analysis. However, such simplified approximation has not been appropriate for the IM7/PMT-F7 laminate analysis accomplished in this work for the following reason.

Table 1 shows significant differences between the in-plane shear and ILS material properties of IM7/PMT-F7 including shear moduli and parameters governing nonlinear behavior. Such difference has been attributed to in-plane fiber-waviness observed in all IM7/PMT-F7 coupons also including the multidirectional laminate panels used in this work. Figure 3 illustrates the waviness.

Figure 3. In-plane fiber waviness observed in the IM7/PMT-F7 coupons.

<table>
<thead>
<tr>
<th>Property</th>
<th>IM7/8552</th>
<th>IM7/PMT-F7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial modulus, $E_{11} = (E_{11T} + E_{11C})/2$</td>
<td>22.8 Msi</td>
<td>22.2 Msi</td>
</tr>
<tr>
<td>Axial modulus, $E_{22} = E_{33}$</td>
<td>1.3 Msi</td>
<td>1.2 Msi</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu_{12} = \nu_{13}$</td>
<td>0.32</td>
<td>0.254</td>
</tr>
<tr>
<td>Poisson’s ratio, $\nu_{23}$</td>
<td>0.5</td>
<td>0.506</td>
</tr>
<tr>
<td>Shear modulus, $G_{12}$</td>
<td>737 ksf$^{(1)}$</td>
<td>636 ksi</td>
</tr>
<tr>
<td>Shear modulus, $G_{13}$</td>
<td>737 ksi</td>
<td>584 ksi</td>
</tr>
<tr>
<td>Shear modulus, $G_{23}$</td>
<td>433 ksi</td>
<td>418 ksi</td>
</tr>
<tr>
<td>Shear secant-intercept modulus, $K_{12}$</td>
<td>36.1 ksf$^{(1)}$</td>
<td>31.7 ksi</td>
</tr>
<tr>
<td>Shear secant-intercept modulus, $K_{13}$</td>
<td>36.1 ksi$^{(1)}$</td>
<td>35.2 ksi</td>
</tr>
<tr>
<td>Shear secant-intercept modulus, $K_{23}$</td>
<td>36.1 ksi$^{(1)}$</td>
<td>35.2 ksi</td>
</tr>
<tr>
<td>Shear exponent, $n_{12}$</td>
<td>0.248$^{(1)}$</td>
<td>0.276</td>
</tr>
<tr>
<td>Shear exponent, $n_{13}$</td>
<td>0.248</td>
<td>0.307</td>
</tr>
<tr>
<td>Shear exponent, $n_{23}$</td>
<td>0.248$^{(1)}$</td>
<td>0.311</td>
</tr>
<tr>
<td>In-plane tensile strength, $S_{22}$</td>
<td>14.3 ksf$^{(2)}$</td>
<td>14.6 ksi</td>
</tr>
<tr>
<td>Interlaminar tensile (ILT)</td>
<td>16.8 ksi</td>
<td>14.6 ksi</td>
</tr>
<tr>
<td>strength, $S_{13}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-plane shear strength, $S_{12}$</td>
<td>13.9 ksf$^{(1)}$</td>
<td>14.3 ksf$^{(4)}$</td>
</tr>
<tr>
<td>1-3 plane ILS strength, $S_{13}$</td>
<td>13.9 ksi</td>
<td>12.2 ksi</td>
</tr>
<tr>
<td>2-3 plane ILS strength$^{(3)}$, $S_{23}$</td>
<td>12.5 ksi</td>
<td>11.6 ksi</td>
</tr>
<tr>
<td>Fiber-direction compressive strength, $S_{11C}$</td>
<td>174 ksf$^{(2)}$</td>
<td>175 ksi</td>
</tr>
<tr>
<td>Fracture toughness ratio, $g = G_{IC}/G_{IC}$</td>
<td>0.35</td>
<td>0.4</td>
</tr>
<tr>
<td>Interlaminar and 90°-transverse tensile S-N curves $\sigma = a S_{ij,\text{stat}}(\log N)^b$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a = 1.575$</td>
<td>$a = 0.973$</td>
<td></td>
</tr>
<tr>
<td>$b = -0.733$</td>
<td>$b = -0.256$</td>
<td></td>
</tr>
<tr>
<td>Shear S-N curves $\tau_{ij} = a S_{ij,\text{stat}}(\log N)^b$</td>
<td>$a = 1.284$</td>
<td>$a = 1.223$</td>
</tr>
<tr>
<td>$b = -0.341$</td>
<td>$b = -0.345$</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Approximated as equal to 1-3 value for laminate analysis
2. Reference 24
3. $S_{ij}$ value is calculated using SPT measured shear stress-strain response in 2-3 plane and assuming the same approximately 4% ultimate shear strain as for 1-2 and 1-3 planes
4. In-plane fiber waviness increased the 1-2 ultimate shear strain to 7.6% and the corresponding 1-2 shear strength to 14.3 ksi

Challenges in Measuring Material Shear Properties

The first essential step increasing confidence in material allowables was to demonstrate that, as a subset, DIC-based SBS and SPT methods reproduce the lamina basic material properties which can be generated with the current standard tests (SBS and SPT methods also generate material properties which cannot be generated with standard methods and such material properties may be key to laminate analysis). This has been confirmed so far by the initial test results. We tested multiple sizes of IM7/PMT-F7 SBS and SPT specimens to verify consistency of the measured material properties. We also applied DIC strain assessment to some of the standard test methods currently used in lamina characterization.
For example, Fig. 4 compares average (AVG) 1-2 shear stress-strain curves measured using SPT (Twist) and ASTM D5379 V-notched test methods. Three different sizes, 1 x 0.15 x 0.15 in, 1.5 x 0.25 x 0.25 in, and 2.5 x 0.25 x 0.25 in were utilized. Seven coupon batches were used in each test configuration. In the past we compared DIC and resistance strain gage measurements and were able to accurately reproduce the strain gage data by DIC (Ref. 32). Figure 5 shows two virtual gage areas simulated by DIC in a V-notched specimen. Figure 4 illustrates that V-notched specimens exhibit nonuniform strain concentrating near the notch radius and hence a strong sensitivity to the gage area.

The initial set of IM7/PMT-F3GHT panels/coupons designated for lamina characterization came with excessive taper increasing scatter in test data and prompting the refabrication and retest extra efforts. Figure 6 shows example of the unusually high scatter in the 1-3 ILS stress-strain response exhibited by SBS coupons. For reference, COV of shear stress-strain curve parameters has been below 5% in the previous effort.

The large scatter has been initially assumed to result only from test specimen taper in the thickness direction. However, high-fidelity FEM based stress analysis including the specimen taper did not eliminate the scatter. The technical challenges prompted additional investigation into measurement accuracy and robustness of our techniques, revealing some unexpected shortfalls not to be discovered otherwise and which had to be corrected in order to increase confidence in resulting material properties.

In particular, a redundant DIC system has been utilized for simultaneously measuring strain at front and back lateral surfaces of untapered SBS specimens. To our surprise, the two DIC systems measured up to 50% difference in strain values between front and back at low strain levels as symmetric strain responses were expected. Figure 7 shows such difference in maximum strain.

In fact, we found that the ASTM D2344 Wyoming Test Fixture has a flaw which may cause different loading of the specimen front and back surfaces and hence different strain distributions. Figure 8 shows that such a test fixture has two centrally located alignment columns – a configuration which is inherently unstable across the fixture resulting in perturbations of the loading angle. Further FEM based assessment confirmed that less than a 0.5 degree misalignment angle may cause 50% difference between the front and back surface strains. Only a 2 mil/in misalignment which is unavoidable due to the alignment ball bearings
susceptibility to very small pivoting movement as shown in Fig. 8 may result in more than 10% different strains.

In order to improve loading symmetry, we redesigned the SBS test fixture by replacing the two central columns with a more stable four alignment column configuration. Figure 9 shows our temporary redesign which is subject to further improvement.

The scatter in the SBS test data has been reduced to our satisfaction. Figure 10 shows 1-3 ILS stress-strain response measured on the left and the right sides of the front and the back surfaces of another batch of seven SBS test specimens.

Comparison of data in Figs. 6 and 10 shows that the improved test fixture reduces scatter.

**ILT Strength and Fatigue**

Going back to the details of data listed in Table 1, static and fatigue ILT characteristics for IM7/PMT-F7 were verified using ASTM D6415 test coupons (Ref. 23) in conjunction with CT-FEM analysis of voids and confirmed by the ILT SBS tests. References 3-5 list the analysis methodology. In particular, it is known that ILT strength and ILT fatigue performance are strongly affected by voids in the curved areas (Ref. 23); and Refs. 3, 5 present the methodology to detect, transfer to FE model and determine critical stress values developing near voids. X-ray CT scans were performed before and after testing the curved beam specimens to automatically transfer the defect geometry to local FE analysis models and to confirm the critical voids. Figure 11 shows an example of a critical void in IM7/PMT-F7 curved beam specimen in pre-test and post-test CT scans confirming the responsibility for delamination.
Figure 11. Critical void and interlaminar failure in IM7/PMT-F7 curved beam specimens.

A corrected strength value was found as an ILT stress at the critical distance corresponding to the smallest coefficient of variation between different specimens (Ref. 3). This led to almost 3x correction of strength: 14.6 ksi by the Point Stress method; as compared to the 5.6 ksi ILT strength obtained by the ASTM D6415 method that does not include the effect of voids. The same corrections based on the void geometry were performed for the specimens failed in fatigue: stress concentration at the void at maximum cyclic load defined the peak fatigue stress level. The peak fatigue stresses obtained by four different methods and normalized by the respective ILTS are plotted versus cycles to failure in Fig. 12. Both void-corrected method and ILT SBS method result in close agreement of fatigue curves as they represent the true ILT material properties and not the effects of defects.

Figure 12. ILT fatigue S-N curves obtained by different methods for IM7/PMT-F7.

Fracture Toughness

Unidirectional 6-ply 0.5 in-wide Open-Hole Tension (OHT) specimens with 0.25 in-diameter hole were selected for finding the critical values of strain energy release rates for the subcritical intralaminar crack development in notched laminates. Micro-focus CT measurement of the subsurface crack front geometry were used to build FE models that capture topology of crack propagation based on mesh morphing; and calculate energy release rates using Virtual Crack Closure Technique. This methodology was presented in Refs. 25-26, where the fracture toughness properties were obtained for the IM7/8552 Carbon/Epoxy tape composite. The goal of these tests was to compare the critical values of strain energy release rates measured for short cracks in notched laminates with the critical values obtained in standard tests.

In these tests cracking started from a pristine undamaged state as mixed Mode I and II; continued in dominant Mode II after reaching hole radius size; and eventually became mixed Mode II / III. The cracks with the dominant Mode II values are used to determine the dependence of Mode II fracture toughness upon the crack length. Critical values for dominant Mode II cases for IM7/PMT-F7 were found between 3 and 12 lb-in/in² compared to 1.4–5.9 range found for IM7/8552 (Ref. 26). Figure 13 shows much stronger dependency of Mode II fracture toughness upon the crack length developing from the notch for the IM7/PMT-F7 Carbon/Epoxy composite compared to IM7/8552 (Ref. 26). This strong dependency may be explained by the effects of in-plane fiber waviness present in the IM7/PMT-F7 coupons used in this work.

Figure 13. Mode II resistance curve for IM7/PMT-F7.

LAMINATE ANALYSIS AND VERIFICATION

This section presents initial results of the second step increasing confidence in material qualification. In particular, we will utilize the lamina basic material properties generated based on our custom testing and use the analysis to predict multidirectional laminate strength and fatigue behavior. Accurate analysis capability not only further increases our confidence in the material allowables but also has a potential for tremendous reduction in testing to qualify material systems and for expanding the material composition and layup design space. We plan to cover various loading conditions including tensile, compressive and bearing loading under a limited budget hence working
with the established ASTM standard test configurations trying to capture the deformation, damage patterns, failure loads and cycles to failure based on the analysis. ASTM standard laminate test specimens are also appealing as the specimen sizes and load magnitudes are within capacity of the AMSL micro-focus CT system with the integrated load frame which is well suited for proof and verification of the analysis techniques.

In this section we will review the progress of laminate analysis and verification testing including IM7/PMT-F7 laminate OHT strength tests based on ASTM D5766; OHT fatigue; open-hole compression (OHC) strength tests based on ASTM D6484; OHC fatigue; and double-shear bearing (DSB) strength tests based on ASTM D5961 (Refs. 27-29). Figure 14 shows the OHT, OHC, and DSB test setups and examples of DIC images used to verify the deformation and the load-displacement response calculations.

**Figure 14. OHT, OHC and DSB test setups.**

**OHT**

References 30, 8, and 10 demonstrated the analysis methodology and showed accurate predictions of damage initiation and progression in notched specimens under static and fatigue loading conditions for IM7/8552 OHT multidirectional laminates. These works demonstrated excellent correlation of multilayer damage patterns, including the locations and sizes of matrix cracks and delaminations, which were verified by the X-ray CT scans. FEM-based computational models have used the key lamina characteristics for capturing the initiation and progression of multiple failure modes to detectable sizes in multidirectional laminates. In addition to the coupon-level testing, IM7/8552 material allowables generated using our methods were further verified at a larger, element scale (Refs. 7, 15).

In this work, OHT laminate verification testing was accomplished for IM7/PMT-F7 using a 16-ply [45/90/-45/0]_2s layup and specimen dimensions defined in ASTM D5766. In-situ CT scans were accomplished at various load increments to verify the damage patterns in three dimensions. The scans were accomplished after each load or cycle increment, holding constant displacement at approximately 90% of the peak loads. The X-Ray CT technique included 60 kV tube voltage, 416 μA target current, scan speed of 1.3 frames/sec and approximately 14.6X magnification which resulted in 8.7 μm voxel resolution.

Predictions of damage initiation and progression in OHT specimens under static and fatigue loading conditions were completed using continuum damage mechanics (CDM) methodology developed in Refs. 30 and 8. This analysis method uses modified LaRC04 failure criteria to capture shear non-linearity and to capture delamination failure based on implementing a transverse shear term as described in Ref. 8. Element stiffness degradation has been accomplished at a half step of the load increments for static loading or a half step of the fatigue cycle increments to simulate a brittle failure. The local FE model uses a mesh of elements oriented along the fiber directions of each ply. Delamination predictions were accomplished using a stiffness degradation method (Ref. 8) and a cohesive element method. Fatigue damage progression algorithm from Ref. 8 was used to simulate damage growth in fatigue tests. All material constitutive properties (including non-linear shear stress-strain relations) and strength properties were obtained from lamina SBS and SPT methods.

Figures 15-17 provide examples of model verification based on the ply-by-ply assessment of damage detected by a CT scan for a specimen tested at 8,050 lbs tension. The CT scan reconstruction data are compared to the damage predictions. Figure 15 shows good agreement for most of the matrix cracks in the first 45° ply (location and size) and over-predicted delamination sizes at the first subsurface 45°/90° ply-interface, using the CDM method for both matrix cracking and delamination predictions. On the other hand, using CDM for matrix cracking while employing cohesive elements for delamination prediction (CDM + Cohesive) leads to excellent agreement with CT for delamination size and the interaction with matrix cracks in the adjacent plies, but underpredicting the leading matrix crack length.

Figure 16 shows that CDM is able to capture complex interactions of matrix cracks between adjacent 90° and 45° plies; but delamination at the 90°/-45° ply-interface are again somewhat over-predicted. And cohesive element based simulation results in a better agreement with CT for delamination while 90°-ply matrix crack lengths are overpredicted and the cracking density is less representative of the measured crack pattern. Figure 17 again confirms accurate matrix crack lengths and locations in 0° ply as well as accurate location of delamination at the adjacent 0°/45° ply-interface, predicted by CDM. However, CDM overpredicts the delamination size while CDM + Cohesive simulation agrees with CT for delamination prediction but underpredicts the adjacent matrix cracking.
Figure 15. Comparison of matrix cracks and delaminations in the 1st 45° ply (top images) and at the 1st 45°/90° ply-interface (bottom images).

Figure 16. Comparison of matrix cracks and delaminations in 90° ply (top images) and at 90°/-45° ply-interface (bottom images).

Figure 17. Comparison of matrix cracks and delaminations in 0° ply (top images) and at 0°/45° ply-interface (bottom images).

Figure 18. Ply-by-ply comparison of matrix cracks and delaminations in OHT fatigue specimens.

OHC

We previously completed OHC analysis and verification testing for a 24-ply [45/90/-45/0]_3S IM7/8552 laminate configuration (Ref. 31) revealing excellent correlation of the damage patterns between in-situ X-ray CT scan and CDM predictions. Figure 19 compares the FE based predictions of the matrix cracking and delamination damage patterns with CT data under tensile load after static OHC testing at 10,000 lbs. A close agreement has been established for the crack sizes as well as locations of matrix and fiber failures in each ply group of the laminate.

In this work, OHC analysis and testing was completed for another 24-ply [45/90/-45/0]_3S IM7/PMT-F7 laminate manufactured per ASTM D6484 specifications. Figure 15 shows the OHC test setup. Slightly-clamped steel support plates were used according to ASTM D6484 to prevent specimen buckling. In situ CT scans under a 4,000 lbs tensile load were accomplished after compressive load and load/cycle increments specified for the OHC specimens. The X-ray CT technique included a 60kV tube voltage, 416 μA target current, scan speed of 1.2 frames/sec, and approximately 12.5X magnification resulting in about 10 μm voxel resolution of the scan.

OHC strength and fatigue predictions were accomplished using the CDM methodology from Ref. 8 extended with a more complete set of the modified LaRC04 failure criteria in order to allow for matrix compression as well as fiber kinking failures. In particular, stiffness degradation in shear simulates matrix compression and fiber kinking failures while keeping compressive stiffness of the failing elements for physical consistency.
Figure 19. Comparison of FE predictions and CT data under load for IM7/8552 OHC specimens (Ref. 31).

Figure 20 compares damage in different plies between the CDM-based FE predictions and the in-situ CT scans. The comparison shows a good correlation for matrix crack sizes; and for initiation of fiber failure but not their interaction with delaminations at the adjacent ply-interfaces that are apparent in CT scans. Also, consistent with the OHT, CDM over-predicts delamination.

The OHC fatigue analysis and verification testing were accomplished at 600 lbs to 6,000 lbs constant-amplitude compression loading. In-situ CT scans under 4000 lbs tensile load were completed after 50K, 200K, 500K and 1M cycles. The following CT scan based observations are worth noting: a) matrix tension cracking initiation in the mid-plane 0°-ply at 50K cycles; b) surface matrix cracking and corresponding delamination at 200K cycles; c) similar but larger size damage at 500K cycles; and d) fiber damage in 0° ply and matrix cracks in most plies at 1M cycles.

Our fatigue damage progression algorithm (Ref. 8) was used to simulate damage growth in the OHC fatigue tests. Figure 21 compares the OHC fatigue damage predictions and in-situ CT scan results after 1 million cycles. The model captured the matrix-cracking patterns. However, delamination and fiber damage predictions are more challenging similar to static simulation.

**DSB**

We accomplished analysis and verification testing for a 24-ply [45/90/-45/0]$_3$ IM7/PMT-F7 DSB laminate following ASTM D5961 DSB strength requirements. Approximately 2,400 lbs ultimate strength was confirmed. CT scans were accomplished after five DSB specimens were subject to quasi-static loads (0.05 in/min loading rate) ranging from 1,600 lbs to 2,400 lbs. The ASTM D5961 steel fixture prevented in-situ CT scanning.
DSB simulation introduced additional challenges compared to the OH simulations. High-fidelity FE-modeling of complex contact boundary conditions was required for enabling accurate predictions. In addition to the composite specimen, the FE model had to include the complete test fixture and the pin with a measured 0.43 mm clearance between the pin and the fixture as shown in Fig. 22. As the load was applied, the pin and the fixture were bending resulting in load redistribution at the contact surfaces affecting the model predictions.

Figure 21. Comparison of fatigue damage prediction and X-ray CT results for IM7/PMT-F7 OHC specimens.

Figure 22. FE model of the DSB test.

Figure 23 compares damage predictions and results of CT reconstruction for a DSB specimens loaded to 2,200 lbs. Multiple failure modes are observed in the CT scans: matrix cracks, fiber failure, and delaminations. FE model predictions capture the extent of the most significant damage modes including the matrix compression failure and delamination. Also, matrix tensile failure in the 45° plies demonstrates good agreement with tests. Overall, the DSB specimen predictions show excellent correlations of the damage progression for different loads.

1st 45° ply and 45°/90° ply-interface

4th 0° ply and 0°/45° ply-interface

Figure 23. Comparison of damage predictions and X-ray CT results for IM7/PMT-F7 DSB specimens after 2,200 lbs loading. Legend: MT – matrix tensile failure; MC – matrix compressive (shear) failure; FC – fiber compressive failure; MD – delamination.

STRUCTURAL ANALYSIS PERSPECTIVES

Accurate structural strength and fatigue predictions for larger and more complex composite structures are by far not a straightforward extension of laminate analysis techniques. Major technical barriers include manufacturing complexity limitations of the current techniques. In order to enable accurate structural strength and fatigue predictions for larger and more complex composite structures up to components we must capture their manufacturing complexity and variability.

An ultimate goal of composite aircraft manufacturers is the ability to design and build a composite part to specifications the first time (Ref. 13). Major challenges to achieving such goal include the susceptibility of composite parts to variations in the manufacturing processes, and unknown manufacturing irregularities as well as their implications. Currently, yields of greater than 90% remain a “hit-and-miss” target even at the production stage (Ref. 14). Once adequate structural diagnostics technologies integrated with the comprehensive structural analysis tools for predicting strength and life of large composite structures are available to the designers, such enabling technologies will
facilitate better design and improved manufacturing through a shift from relying on the traditional time-consuming trial and error experimentation loops and empiricism in design, to efficient diagnostics and prognosis methods.

AMSL has been successful in developing and verifying abilities to predict strength and fatigue performance of composites, including the effects of defects. Our methods integrate nondestructive structural diagnostics capturing the critical defects with automated transition to structural FEM (Refs. 7, 9, 13); accurate material characterization methods capturing 3D mechanical properties (Refs. 1-6); and comprehensive structural strength/fatigue prognosis methods able to capture multiple damage modes and their interaction (Refs. 7, 8, 13). We have been increasing complexity and size of structural verification articles, the most recent published examples included about 2 foot long and 0.5 in. thick IM7/8552 carbon/epoxy flapping elements with a lay-up representative of a yoke structure (Ref. 7); and 2.5 foot long IM7/8552 skin and hat-section stiffener elements (Ref. 15). Fig. 24 schematically shows the integration of material characterization, structural diagnostics, and prognostics using an example of the flapping elements (Ref. 13).

As reported in Ref. 7, our integrated structural analysis methods demonstrated remarkable 95% accurate strength and 80% accurate fatigue life predictions for the composite flapping elements with manufacturing defects.

It is worth noting that the fidelity of the nondestructive inspection (NDI) needed to quantify the smallest defects that would impact structural performance is key to structural diagnostics of aircraft composite parts. However, the fidelity of NDI required to understanding manufacturing of production composite parts is not yet adequate. Current work on smaller structural details is useful in identifying technology gaps and motivating the development of the higher-resolution NDI technology appropriate for large structures (Refs. 13, 14). In particular, recent improvement in computing power and advances in X-ray CT reconstruction make it possible to develop high-resolution limited-angle CT technology breaking through the object size limits of X-ray CT in order to develop high-fidelity NDI of large composite aircraft structures at the factory. A focused R&D effort, starting with the development and demonstration of the algorithms and software required for enabling high-resolution partial CT capability to handle large composite structures, has a strong potential for enabling much needed efficient and accurate NDI products, and better understanding of the manufacturing processes and failure mechanisms (Refs. 13, 16, 17).

![Figure 24. Integration of material characterization, nondestructive structural diagnostics, and prognostics has been essential for accurate strength and fatigue predictions for composite flapping elements.](image-url)
CONCLUSIONS

This work has been taking essential steps towards improving confidence in material qualification for laminated composites. The first step started with our reduced lamina test methods, SBS and SPT based on DIC measuring as a subset the standard material properties; and in addition, key properties that cannot be currently measured using any standard test methods. Advanced measurement techniques and analysis methods were required to verify simplifying assumptions and increase our confidence in material allowables. We listed the values of the SBS and SPT measured lamina properties for IM7/8552 and IM7/PMT-F7 materials and were able to validate such properties by a subsequent multidirectional laminate strength and fatigue analysis. We also identified standing challenges in lamina characterization, including inconsistencies of certain ASTM test fixtures and analysis methods preventing accurate measurement of lamina characteristics key to laminate analysis.

The laminate analysis has been the second step increasing confidence in material qualification. We were able to utilize the basic lamina material properties generated based on our custom testing and use the analysis to predict multidirectional laminate strength and fatigue behavior. This second step not only further increases our confidence in the material allowables but also has a strong potential to tremendously reduce qualification testing and expand the material composition and layup design space. We were able to cover various loading conditions including tensile, compressive, and bearing within the limited budget hence working with the established ASTM standard laminate test configurations trying to capture the deformation, damage patterns, failure loads and cycles to failure based on analysis. ASTM standard laminate test specimens are appealing as the specimen sizes and load magnitudes are within capacity of the AMSL micro-focus CT system with the integrated load frame which is well suited for proof and verification of the analysis techniques.

At this stage, the knowledge accumulated based on the laminate analysis and verification testing completed in this work consistently agrees with our previous results obtained from a different composite system. The following preliminary conclusions can be drawn. The IM7/PMT-F7 laminate analysis and verification testing confirms that strength and fatigue prognosis methods relying on three-dimensional finite element analysis with built in material models, failure criteria, meshing techniques, and damage progression algorithms developed at AMSL agree with test data including ASTM D5766 OHT strength, OHT fatigue, ASTM D6484 OHC strength, OHC fatigue, and ASTM D5961 DSB Strength ASTM D5961 tests. In particular, our models seem to accurately capture location of the multiple failure modes including matrix cracks and delaminations as well as their interaction in laminates. Our models predict accurate matrix crack sizes but sometimes overpredict delamination sizes. Furthermore, predicting fiber failure in compression and bearing has been the most challenging and requiring further development of the analysis methods as well as their thorough verification. Although we believe that are on the right path to success, further development of laminate analysis methods is essential for capturing fiber-direction compressive failure modes and the associated strength and fatigue performance characteristics.

Corresponding Author: Andrew Makeev, makeev@uta.edu

ACKNOWLEDGMENTS

This work is partially funded by the National Rotorcraft Technology Center, U.S. Army Aviation and Missile Research, Development and Engineering Center under Agreement No. W15QKN-10-9-0003. This support is gratefully acknowledged. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the U.S. Government. The authors are also grateful to Mr. Brian Shonkwiler, Research Scientist; and Dr. Julia Cline, Mr. Bastiaan Van Der Vossen, and Ms. Sarvenaz Ghaffari, Ph.D students at the University of Texas Arlington, for their assistance with material characterization tests.

REFERENCES


