Material Characterization and Failure Prediction for Composites

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ABSTRACT

This work presents some of the most recent advances in the technologies that enable accurate structural diagnostics and assessment of useful life for composite aircraft fatigue-critical, flight-critical components. Such advances include: nondestructive subsurface measurement shift from defect detection to accurate three-dimensional measurement of defect location and size; material characterization methods ability to generate three-dimensional material allowables at minimum time and cost; and fatigue structural analysis techniques ability to capture multiple damage modes and their interaction.

INTRODUCTION

Composite parts are inherently susceptible to variations in manufacturing processes. In addition to material variation in the resin content, bulk factor and fiber alignment, and part fabrication process variations are common causes that contribute to variation in part quality. The effects of inadequate design method and manufacturing process used to produce carbon/epoxy and glass/epoxy composite aircraft fatigue-critical, flight-critical components manifest themselves as defects such as wrinkles and porosity/voids, and such defects impact the performance and the service life of these components. Consequently, the increased sensitivity of composite part quality to material and process variations lowers production yields. In order to increase production yields, heavy burden is placed on composite manufacturing communities to understand and control their processes.

Manufacturing defects can severely deteriorate matrix-dominated properties resulting in degraded strength and fatigue structural performance of composites. Although it might not be practical to eliminate all the defects in a composite part, it is necessary to avoid worst-case assumptions and address improved part durability and damage tolerance once the defects and their effects are captured. Advanced structural methods that account for manufacturing defects in composite parts are needed to enable accurate assessment of their capability and useful life and enhance current design and maintenance practices.

This work presents some of the most recent advances in the technologies that enable accurate structural diagnostics and assessment of useful life for composite aircraft fatigue-critical, flight-critical components. Such advances include: nondestructive subsurface measurement shift from defect detection to accurate three-dimensional measurement of defect location and size; material characterization methods ability to generate three-dimensional material allowables at minimum time and cost; and fatigue structural analysis techniques ability to capture multiple damage modes and their interaction. The authors summarize their recent results in all three subjects.

SUBSURFACE MEASUREMENT

Computed tomography (CT) is a proven nondestructive evaluation (NDE) technology that enables three-dimensional measurement of various subsurface flaws including manufacturing defects such as wrinkles and voids [1].

Figure 1 shows the operation basics for a modern industrial CT system. The system uses three major components: an x-ray tube, x-ray detectors, and a rotational stage. New generation micro-focus x-ray tubes and amorphous silicon flat panel area detectors offer micron-scale resolution, which cannot be matched by the other available NDE methods.

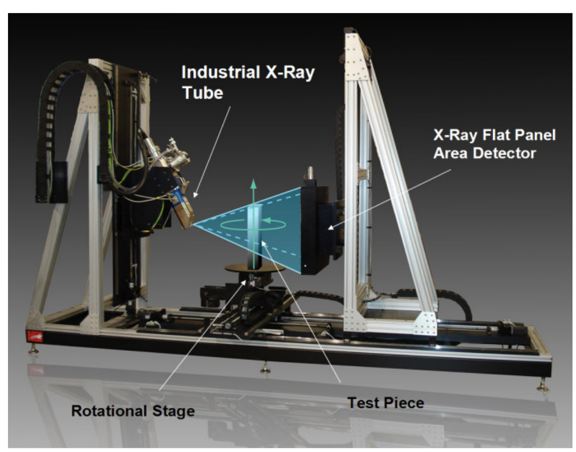

Figure 1. Major components and operation principle for a modern industrial CT system.

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A CT scan includes series of x-ray images of the object rotating 360 degrees (full rotation) or at least 180 degrees if full rotation is not possible due to object size. CT systems acquire between 120 and 3600 digital images with the image size of 3 to 10 megapixels depending on the desired resolution. CT reconstruction algorithms are then used to generate the volumetric information. Due to recent advancement in the fast CT reconstruction software and computer hardware, the reconstruction process can be accelerated ranging from a few minutes to a few hours for most challenging specimens. After the reconstruction is completed, one can manipulate the volume in real time, slice anywhere inside the object, and separate object features of different density.

A recent feasibility assessment demonstrated the ability to detect wrinkles and voids in composites with a Micro-CT system, such as M5000CT industrial CT system with a 225 KV Microfocus X-ray tube and Varian 4030E series Flat Panel detector provided by North Star Imaging, Inc. Figure 2 shows CT volumes and slices that demonstrate examples of detecting manufacturing defects and structural damage in glass/epoxy and carbon/epoxy tape composite laminates.

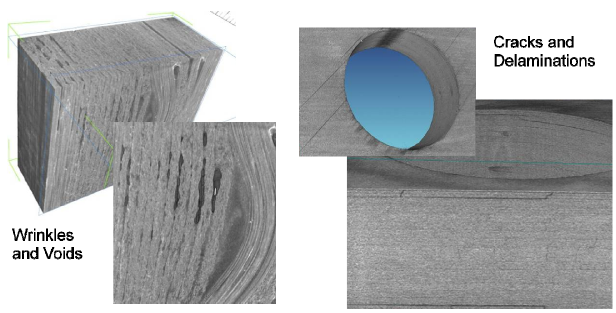

Figure 2. Wrinkles and voids in 30-ply thick glass/epoxy tape laminate; and matrix cracks and delaminations in 16-ply thick carbon/epoxy tape laminate obtained from micro-focus CT.

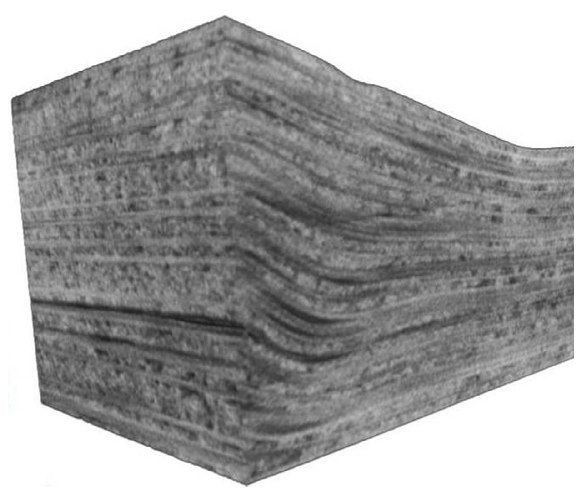

Figure 3. Wrinkles and voids in a Glass/Epoxy laminate structural detail representative of a helicopter tail rotor tapered flexbeam section.

Figure 3 shows the CT volume of a Glass/Epoxy laminate structural detail representative of a helicopter tail rotor flexbeam up to 1.5 inches thick.

Figure 4 shows a Glass/Epoxy main rotor blade spar section near the root end. Although the wrinkles are located at the surface, wrinkle measurement conducted by visual inspection that uses a ruler or a caliper could result in unacceptable measurement variation and affect the objectivity at making disposition decision of the affected part. The Figure shows that the CT scan can provide images with high enough spatial resolution and clarity that is sufficient to make repeatable and reproducible in-plane and out-of-plane characterization possible [1].

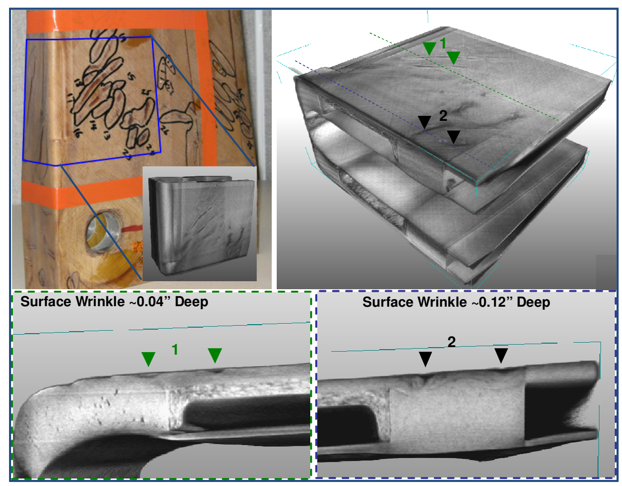

Figure 4. CT images show the material structure and surface wrinkles for a fiberglass main rotor spar root section.

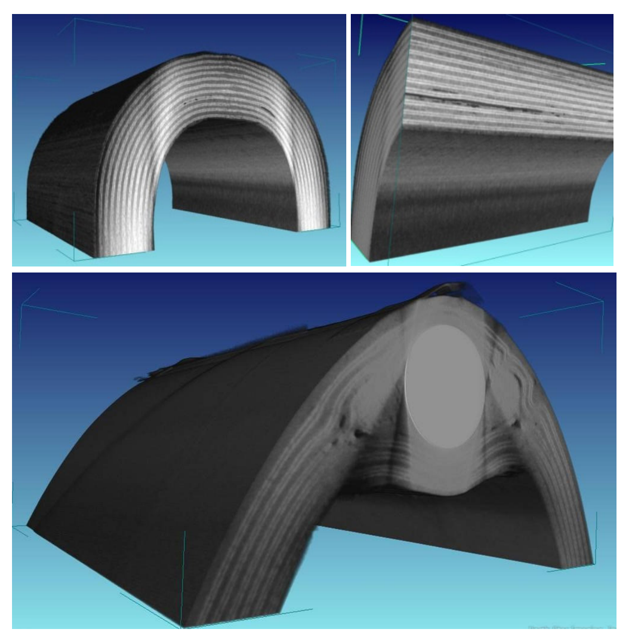

Figure 5. Wrinkles and voids in main rotor blade spar structure including imperfections around a molded-in metallic section.

Figure 5 illustrates CT reconstruction results for composite laminate main rotor blade spar structure with a molded-in metallic section. Wrinkles and voids are clearly shown although large difference in the densities between the metal and the composite causes scattering artifact during the reconstruction.

Currently available system configuration is not suitable for inspection of long composite parts such as wing spars, rotor blades, yokes, flexbeams, etc. Manipulating parts in the CT scanner is impractical due to potential part deformations; the parts must be stationary and the x-ray tube and detectors must move around the parts - an arrangement similar to the medical CT systems. A successful CT system for efficient and accurate measurement of manufacturing defects in large and thick composite parts must combine the industrial micro-CT resolution ability and the medical CT ability to scan large objects.

CT can become a powerful diagnostic tool and enable the ability to predict part capability and remaining useful life. The defect measurement conversion to finite element-based failure models can allow the assessment of the effects of manufacturing imperfections on structural performance. Coupling accurate measurements and rigorous failure models will improve overly conservative part rejection criteria and enable lower scrap rates in the flight-critical, fatigue-critical composite parts.

Measurement and characterization of defects must be fully-automated for the impartial part characterization. The quality of micro-focus CT detail reconstruction allows for the ability to automate the defect interpretation. The automated recognition of the defects is essential for using detected defect data in the durability and damage tolerance models based on accurate three-dimensional geometric characterization.

MATERIAL CHARACTERIZATION

Accurate three-dimensional stress-strain constitutive properties are essential for understanding complex deformation and failure mechanisms for materials with highly anisotropic mechanical properties. Among such materials, glass-fiber and carbon-fiber reinforced polymer-matrix composites play a critical role in advanced structural designs [2]. A large number of different methods and specimen types currently required to generate three-dimensional allowables for structural design slow down the material characterization [3]. Also, some of the material properties are never measured due to prohibitive cost of the specimens used for the material characterization.

Recent work [4, 5] shows that a simple short-beam shear (SBS) test, coupled with the Digital Image Correlation (DIC) full-field deformation measurement and simple stress analysis, is well-suited for measurement of 3D constitutive properties for composite materials, and that can enable a major shift toward accurate 3D material characterization. The SBS test methodology introduced three fundamental contributions to the experimental mechanics:

First, tensile, compressive, and shear stress-strain relations in the plane of loading are measured in a single experiment. Figure 6 shows multiple standard methods that can be reduced to a single test and specimen configuration. It is simple to machine short-beam coupons in the 0-deg. and 90-deg. material directions; and load in the 1-2 (in-plane), 1-3 (interlaminar), and 2-3 material planes and measure 3D constitutive properties.

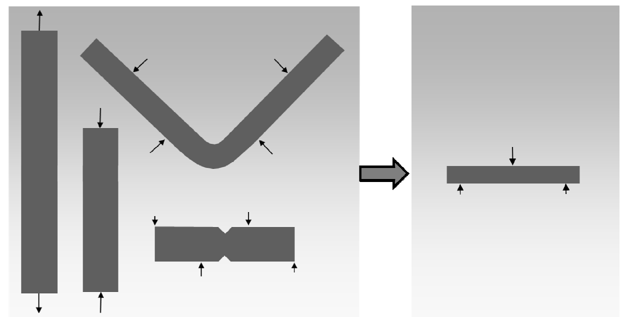

Figure 6. A single method to generate 3D material constitutive properties for composites enables affordable material characterization.

Second, a feasibility of closed-form stress and modulus models applicable to long beams, is demonstrated for short-beam coupons. Linear axial strain distributions through the specimen thickness observed in the coupons enable simple stress/modulus approximations. The strain distributions measured using the DIC technique resulted in accurate stress-strain curves, strength, and modulus data generated for multiple glass/epoxy and carbon/epoxy materials [4-6].

And third, the SBS test method can be used for measurement of stress-strain relations including static, fatigue [7-9], and impact load conditions. Figure 7 shows a high-strain rate test setup.

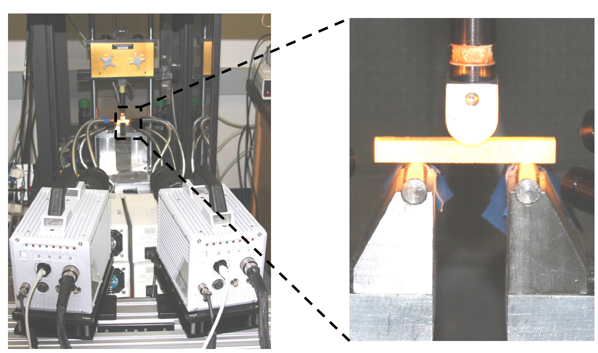

Figure 7. SBS test setup for impact load rates: Instron Dynatup load frame and Photron SA1 high-speed (up to 200,000 frames/sec) camera system.

The most recent results obtained using this test setup verified the SBS test ability to provide constitutive property approximations at impact load rates. It is worth noting that even low-speed impact load rates significantly affect the interlaminar material properties. For example, a 4 m/s load rate (10^2 strain rate) increased the interlaminar shear strength value for a Glass/Epoxy composite in the 1-3 plane from the static 10.4 ksi to 15.2 ksi (46% increase); and the modulus value from the static 0.604 msi to 0.746 msi (24% increase).

STRUCTURAL ANALYSIS

This section presents selected results of recently developed fatigue structural analysis methodology able to predict initiation and progression of matrix cracks and delaminations in composites. The structural analysis is based on three-dimensional solid finite element (FE) analysis combined with stress-based failure initiation criteria and damage propagation technique. Application of these analysis methods to high fidelity FE models allows to capture multiple damage modes and their interaction including effects of defects. The following simulation results are demonstrated and correlated with tests: delamination of thick tensile composite articles with ply-waviness defects under fatigue loading, analysis of porosity defects, and updated results of the fatigue damage analysis in open-hole tensile articles.

Fatigue Analysis of Thick Composite Articles with Ply-Waviness (Wrinkles)

A 88-ply $[(\pm45_3/0_2)_3/\pm45_4/0_2/\pm45_4/0_2]_S$ IM7/8552 Carbon/Epoxy tape laminate with wavy plies subject to tensile fatigue load is considered as the first example. Three articles illustrated in Figure 8 were loaded at constant amplitude 0.1 load ratio and at 10 Hz frequency, to delamination onset. The defect geometry allowed to obtain accurate ply-waviness geometry from digital images of the coupon surface.

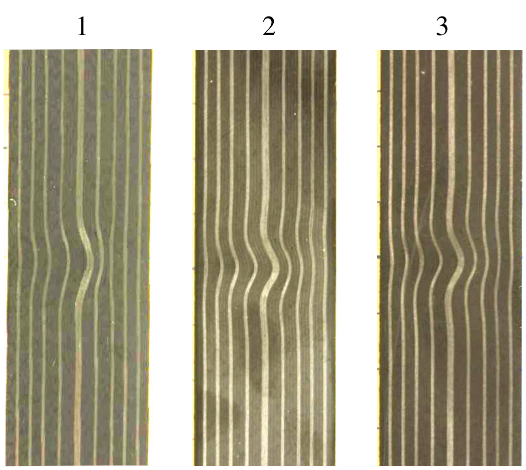

Figure 8. Articles with ply-waviness defects. Zero-degree plies look lighter in the digital images.

Nonlinear in-ply and interlaminar stress-strain relations that account for micromechanical damage, and stress-based failure criteria that include allowables adjusted according to fatigue S-N curves, were used to predict failure initiation [9, 10]. Table 1 lists peak loads and compares cycles to delamination onset predicted using the Hashin failure criterion [10] and a modified LaRC04 fracture-toughness-based failure criterion [11], and test measurements.

Table 1. Predicted and measured cycles to failure for articles with ply-waviness.

Test	Peak Load, N	Hashin cycles	Fracture cycles	Test Data cycles
1	9875	3,800,000	710,000	750,000
2	8674	700	600	$\leq$1,000
3	6894	225,000	93,000	100,000

The DIC technique was used to monitor peak strains at 500-cycle intervals during fatigue loading. Progressive damage simulation was necessary to compare rapid development of the delamination crack after initiation. Figure 9 shows measured and predicted fatigue delamination patterns for article 1 at 750,000 cycles. Explicit modeling of ply-terminations present in the ±45-degree ply-groups at the failure-critical locations was required to capture the ply-interface damage locations [8].

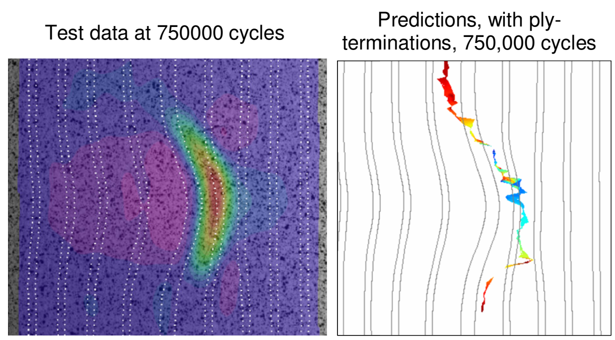

Figure 9. Fatigue delamination progression in test article (left) and simulation (right).

Analysis of Structure with Porosity Defects

Tests show that porosity at critical locations may significantly reduce strength and fatigue life of composite structures. For example, when lower curing pressure is used to reduce wrinkles in the thick IM7/8552 carbon/epoxy composite tensile test articles, the articles delaminate at much lower loads than predicted by models with porosity ignored.

Although porosity defects can be accurately detected by nondestructive evaluation methods shown in the Subsurface Measurement Section, precise account of all defects in structural models seems impractical. This work proposes the following technical approach for the efficient analysis of the porosity/voids and the combinations of manufacturing defects in failure models:

1. Measure ply-orientation defects (wrinkles);
2. Detect porosity/voids shapes and locations;
3. Calculate local stress fields and the stress concentrations associated with the porosity geometric shapes;

4. Build a FE mesh that accounts for the wrinkles;
5. Combine local stress field due to the porosity geometric shapes and the stresses in the model with the ply-orientation defects;
6. Use static/fatigue failure criteria to predict the load/cycles to structural damage.

The second example demonstrates modeling of wrinkle and porosity defects in a 104-ply $[(\pm45_3/0_4)_3/\pm45_4/0_4/\pm45_4/0_2]_S$ IM7/8552 Carbon/epoxy tape laminate. The model was built as follows: material orientations of wavy plies were defined in the FE models using edge detection analysis of the digital images of the coupon surfaces and by further interpolation of the wrinkle curves tangent orientations; porosity locations and sizes were found by edge detection analysis; and local stress field due to porosity was added to failure criteria in the post-processing. Porosity was modeled as ellipsoidal surface voids for the purpose of local stress analysis. Figure 10 shows the results of defect detection algorithm.

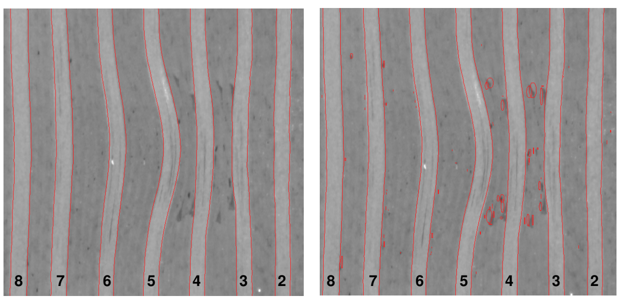

Figure 10. Imperfection detection results for wrinkles (left) and porosity (right).

The test shows a 12.9 kN (2900 lbs) failure initiation. The failure load prediction for the FE model of the laminate with wrinkles and no porosity predicts is 34.7 kN (7800 lbs); and the porosity included in the failure model reduces the failure load to 13.3 kN (3000 lbs).

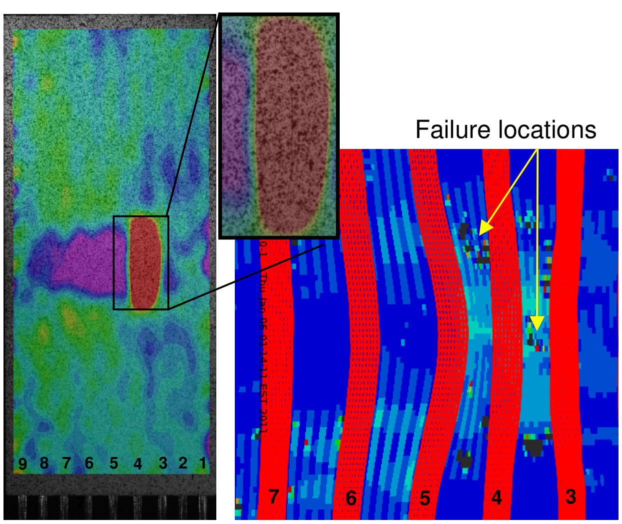

Figure 11. Comparison of delamination failure locations in test data (left) and simulation (right).

Figure 11 demonstrates measured failure locations (on top of the 4th wrinkle) and simulation results with stress concentration due to porosity (on top and below the 4th wrinkle). Voids included in the simulation model are shown as black areas in ±45-degree plies.

Fatigue Analysis of Open Hole Tensile Coupons

The third example presents update of the fatigue failure model predictions and test correlations for open-hole tensile articles subject to cyclic loads**.** Ref. [7] presented some initial results of fatigue damage progression of matrix cracks and delaminations and their interaction in three dimensions. This work provides additional test correlations for model simulations under various maximum loads and cycles tested.

The 16-ply quasi-isotropic IM7/8552 Carbon/Epoxy tape open-hole tensile (OHT) laminates were subject to constant amplitude loads at 10 Hz frequency and 0.1 load ratio. The laminate dimensions were 38.1 × 190.5 × 2.642 mm (1.5 × 7.5 × 0.104 in); and the hole-diameter was 6.35 mm (0.25 in).

The fatigue structural analysis methodology and models, including FE mesh and fatigue simulation algorithm, is described in detail in Ref. [12]. Sub-modeling is used to allow sufficient mesh size for convergence of interlaminar stresses. The sub-model is assembled from the regular meshes representing laminate plies. The meshes for each ply are aligned with the ply material directions and connected using mesh constraints. Delamination is simulated by matrix failure of thin (10% ply thickness) solid element layers between the plies. A modified three-dimensional fracture toughness-based criterion [7, 11] accounts for the interlaminar tensile and shear failure modes in both 1-3 and 2-3 material planes; and damage progression algorithm simulates further propagation of matrix cracks and delaminations.

Ref. [7] compared predictions of matrix cracks and delaminations, and the CT data of the specimen obtained at 22.2 kN (5000 lbs) maximum load and 1,000,000 cycles of fatigue loading. Excellent correlation of the locations of the major matrix cracks in the surface and sub-surface plies and delaminations between plies was demonstrated. The fatigue damage progression algorithm that included multiple damage modes was able to conservatively predict largest crack lengths and delaminations within crack measurement tolerance. The simulations that included only a single failure mode were not able to obtain the conservative predictions.

To further verify the methodology, the progressive fatigue failure model predictions are compared with CT data for multiple OHT articles tested at various fatigue loads and cycles. The appropriate cycle values were determined during simulations to achieve the same major surface crack lengths in different specimens. Table 2 shows the comparison of predicted crack lengths and delamination sizes with tests. Figures 12-14 show typical comparison of the simulations with the CT data of the OHT article subjected to 24 kN (5400 lbs) maximum load and tested to 200,000 cycles.

Table 2. Comparison of largest crack lengths and delaminations for OHT articles at various loads and cycles.

		Simulation		Test	
Peak load, kN	**Cycles**	Max crack mm	Max delam mm	Max crack mm	Max delam mm
21.4	3,000,000	6.3	2.0	8.1	1.0
22.2*	1,000,000	5.6	2.5	5.3	2.5
23.1	400,000	6.3	1.8	7.4	1.5
24.0	200,000	6.3	1.8	6.9	1.3
24.9	100,000	6.3	1.8	6.6	0.8

*Different quasi-isotropic layup.

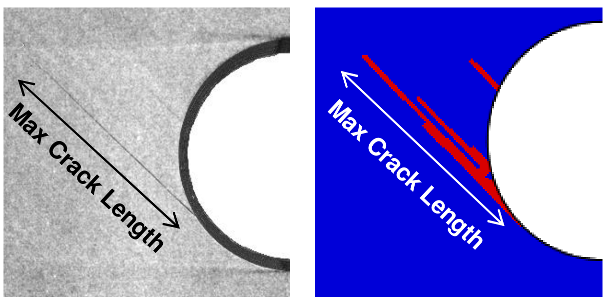

Figure 12. Matrix cracks in the surface -45° layer.

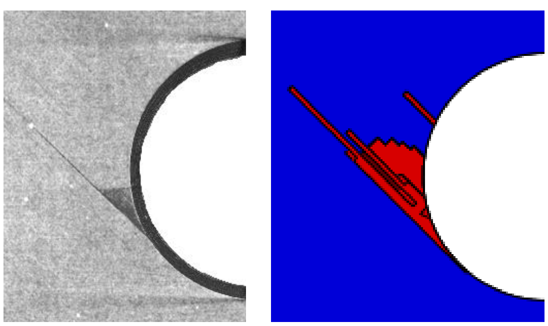

Figure 13. Delamination at the 1st subsurface 45°/90° interface and matrix cracks in the surface 45° layer.

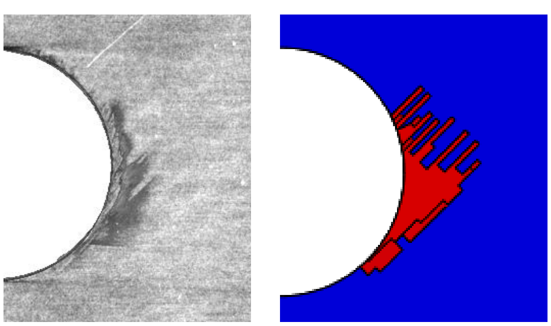

Figure 14. Delamination at the 3rd subsurface 45°/0° interface and matrix cracks in the 3rd subsurface 45° layer.

The FE simulations show good qualitative and quantitative agreement with the tests. The simulations were able to predict locations and sizes of matrix cracks and delaminations in the multiple laminate layers. Simulation of crack development and failure mode interaction was essential for obtaining good test correlations for various maximum loads and fatigue cycles.

CONCLUSIONS

The main objective of this work is to inform the aerospace engineering community about advanced structural methods and prognostics that could account for manufacturing issues in the fatigue-critical, flight-critical composite parts and enable accurate assessment of their capability and useful life.

Composite aircraft structures must undergo a fundamental shift from fleet statistics to accurate assessment of condition for individual parts in order to enable both safe and economical usage and maintenance. Technologies to measure defects and understand their effects on fatigue performance could potentially enable that shift. The goal is to make such technologies the industry standard practice for structural diagnostics in the existing aircrafts and the emerging composite aircraft platforms. It is critical to enable: (a) accurate three-dimensional nondestructive measurement of manufacturing defects location and size; and (b) defect characterization based on fatigue structural models that automatically take the subsurface measurement data and account for multiple failure modes and their interaction to predict remaining useful life for inspected parts.

A close relation among the technology elements presented in this work is essential for success. For example, the SBS test methodology could minimize the number of test methods required for material characterization; and the structural analysis techniques applied at the coupon-level could enable a heavy reliance on analysis (virtual tests) to capture laminate-scale strength and fatigue behavior. Such relation could reduce costly experimental iterations to qualify every new composite material, which delay insertion of advanced materials that address performance and operations efficiency requirements for aircraft structural designs, and limit the design space of material configurations.

First-ply failures in composites typically do not affect their residual capability and useful life, and damage progression to detectable size is required for life assessment. A comprehensive fatigue structural analysis methodology that captures multi-stage failure modes and their interaction in composites, and predicts initiation and progression of structural damage to detectable size without a priori assumptions of the initial damage or the damage path is required. The structural analysis methodology being developed by the authors attempts to satisfy these requirements by employing three-dimensional solid finite element analysis that simulates the initiation and progression of structural damage to detectable size. No a priori assumptions of the initial damage or the damage path are required; the models account for micromechanical damage through nonlinear interlaminar stress-strain constitutive relations. Stress-based and fracture mechanics-based failure criteria are used to predict initiation of ply-cracks and delaminations, and fatigue damage progression algorithm predicts their progression to detectable size.

The failure models must be supported by tests. Successful verification efforts started at laminate-level and element-level must be continued and expanded to full-scale parts.

ACKNOWLEDGMENTS

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