FATIGUE LIFE ASSESSMENT FOR COMPOSITE MATERIALS

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1 Introduction

Manufacturing defects can severely deteriorate the matrix-dominated properties resulting in degraded strength and fatigue structural performance of composites. In particular, 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.

Although it might not be practical to eliminate all the defects in a composite part, it is possible to avoid assumptions of the worst-case scenario 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 recent advances in the technologies which enable accurate assessment of useful life for composite aircraft fatigue-critical, flight-critical components and structure.

Such technology advances include:
(1) Nondestructive subsurface measurement shift from just detection of manufacturing defects to accurate three-dimensional measurement of material structure including defect location and size;
(2) Ability of material characterization methods to generate 3D material allowables at minimum time and cost; and
(3) Fatigue structural analysis techniques ability to capture multiple damage modes and their interaction.

2 Fatigue Life Assessment Methodology

2.1 Nondestructive Subsurface Measurement

Viable techniques for accurate 3D characterization of manufacturing defects in fatigue-critical composite structures including thick composite spars and yokes are presented. In particular, micro-focus computed tomography (CT) is a proven non-destructive evaluation (NDE) technology enabling three-dimensional measurement of manufacturing defects including wrinkles and porosity/voids [1].

A recent feasibility assessment demonstrated the ability to detect wrinkles and porosity/voids in composites with a micro-focus CT system. North Star Imaging M5000CT industrial CT system with a 225 KV micro-focus X-ray tube and Varian 4030E series flat panel detector was utilized. Figure 1 shows examples of CT volume slices that show multiple manufacturing defects and structural damage in composite structure.

Figure 2 shows CT reconstruction results for a Glass/Epoxy laminate structural detail representative of a helicopter tail rotor flexbeam up to 1.5 inches thick.

Accuracy of volume detail reconstruction available in the CT scans shows a potential for automated interpretation of CT-based measurement of subsurface defects required for structural diagnostics. Defect measurements based on operator's experience often result in unacceptable measurement variation and affect the objectivity at making disposition decision of the affected part.

Figure 3 shows a sample slice of a CT scan volume data for the thick Carbon/Epoxy laminate composed of zero and ±45-degree plies with ply-waviness and porosity defects. The Figure shows the ability of the micro-focus CT evaluation to generate accurate subsurface geometry data for a composite structure with manufacturing defects.

2.2 Material Characterization

This section presents methods to develop accurate 3D stress-strain constitutive properties and fatigue failure criteria that are essential for understanding of complex deformation and failure mechanisms for materials with highly anisotropic mechanical properties. Large amount of different techniques and specimen types currently required to generate three-dimensional allowables for structural design may significantly decelerate material characterization. Also, some of the material constitutive properties are never measured due to prohibitive cost of the specimens needed.

Recently developed methods [2] based on a simple short-beam shear (SBS) test, Digital Image Correlation (DIC) full-field deformation measurement and finite element (FE) stress analysis show that the SBS test is well-suited for measurement of 3D constitutive properties for composite materials. These advancements can enable a major shift toward the accurate and affordable 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. Second, a counter-intuitive feasibility of closed-form stress and modulus models, normally 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. And third, the test method is viable for measurement of stress-strain relations at various load rates including static, fatigue [3, 4], and impact load conditions.

Figure 4 shows linear axial strain distribution for a unidirectional glass/epoxy coupon loaded in the 1-3 material plane. The strain distributions are measured using the Digital Image Correlation (DIC) technique. Accurate stress-strain curves, strength, and modulus data are generated for multiple glass/epoxy and carbon/epoxy materials [2, 5].

2.3 Fatigue Structural Analysis

Analysis methods able to capture multiple damage modes and their interaction in a structural model that accounts for model geometry and static and fatigue material properties are presented. Such methods can become a key to a successful fatigue analysis for composite structures.

This section presents structural analysis methodology based on 3D solid finite element models [6] that simulate the initiation and progression of structural damage to critical and/or detectable size. No a priori assumptions of the initial damage or the damage path are required. The methodology accounts for micromechanical damage through nonlinear stress-strain constitutive relations [5]. The fatigue damage progression algorithm [7] uses modified LaRC04 failure criteria [8] and damage simulation techniques [6] to predict the number of cycles to fatigue damage onset and subsequent progression to detectable size.

Fatigue damage progression algorithm starts by calculating the cycles to failure initiation in all elements in the FE model by substituting material fatigue (S-N) curves in the failure criterion [9]. Failed elements' stiffness is reduced to zero in the material directions consistent with the failure criterion [8]. The algorithm then combines failure initiations at the predicted cycles with the linear damage accumulation due to fatigue cycling. The stresses are recalculated to satisfy modified stiffness and the algorithm progresses to the next element failure.

Delamination failures are simulated by applying a failure criterion to the elements located in the thin layer between the laminate plies [4]. Delaminations are assumed to propagate in 1-3 material plane. The delamination layer is in three-dimensional stress state and all interlaminar stress components must be accounted for in the failure criterion.

Numerical methods that simulate damage by reducing material stiffness are known to be mesh-dependent [10]. To overcome crack dependence on mesh orientation the fiber-aligned mesh approach is introduced [6]. FE mesh for each ply is structured such that the mesh orientation is parallel to the fiber directions. Since the ply meshes are incompatible at their interfaces, mesh tie constraints are used to hold the mesh assembly together.

As shown in the following section, the fatigue progression algorithm was able to accurately capture ply cracking sequence, static and fatigue crack initiation and growth in the test specimens.

2.4 Simulations and Test Correlations

The methodology and models are supported by test evidence. A priori prediction and subsequent test correlation for glass/epoxy and carbon/epoxy technology verification fatigue test articles are presented.

Fatigue of Open-Hole Tensile Articles

Progressive crack propagation in open-hole tensile carbon/epoxy articles serves as validation example for the fatigue methodology.

The 16-ply quasi-isotropic IM7/8552 Carbon/Epoxy tape open-hole tensile (OHT) laminates were subject to constant amplitude load to 1,000,000 cycles at 10 Hz frequency, 22.2 kN (5,000 lbs) peak load and 0.1 load ratio. The laminate width is 38.1 mm (1.5 in), thickness is 2.64 mm (0.104 in), and the hole-diameter is 6.35 mm (0.25 in). Sub-modeling was used in FE simulations to allow sufficient mesh size for convergence of interlaminar stresses.

The progressive fatigue failure model predictions are compared with CT data for multiple OHT articles tested at various fatigue loads and cycles to the develop surface cracks of a target length. Table 1 shows the comparison for predicted crack lengths and delaminations.

Figure 5 shows the subsurface damage prediction and tensile fatigue test correlation. Excellent correlation of the locations and size of the major matrix cracks in the surface and sub-surface plies, and delaminations between the plies can be observed.

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.

Analysis of Articles with Manufacturing Defects

Test data show that porosity/voids at critical locations may significantly reduce strength and fatigue life of composite laminates. In particular, when lower curing pressure was used to reduce wrinkles in the thick IM7/8552 carbon/epoxy composite tensile test articles, they delaminated at much lower loads than theoretically predicted when porosity was ignored in the structural model.

The technical approach to account for the combinations of manufacturing defects in the failure models is based on the following workflow [11]:

(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.

A 104-ply 19.1 mm (0.752 in) thick IM7/8552 Carbon/epoxy tape laminate (0 and ±45-degree ply groups) with wrinkles and porosity is considered. The test data show failure initiation at 12.9 kN (2900 lbs) tensile load. The failure load prediction for the FE model without porosity is 34.7 kN (7800 lbs); and porosity included in the failure model as ellipsoidal surface voids reduces the failure load to 13.3 kN (3000 lbs). Figure 6 shows the results of defect detection algorithm, measured failure locations (on top of the 4^{th} wrinkle) and the simulated failure due to porosity (on top and below the 4^{th} wrinkle). Voids appear as black areas in ±45-degree plies.

As shown in Section 2.1, 3D material orientations and porosity defects could be measured based on CT volume data reconstruction.

3 Conclusions

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. Our 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 the inspected parts.

First-ply failures in composites typically do not affect their residual capability and useful life, and damage progression to significant (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 to successfully predict life of aircraft composite parts. Successful verification efforts started at laminate-level and element-level must be continued and expanded to full-scale parts.

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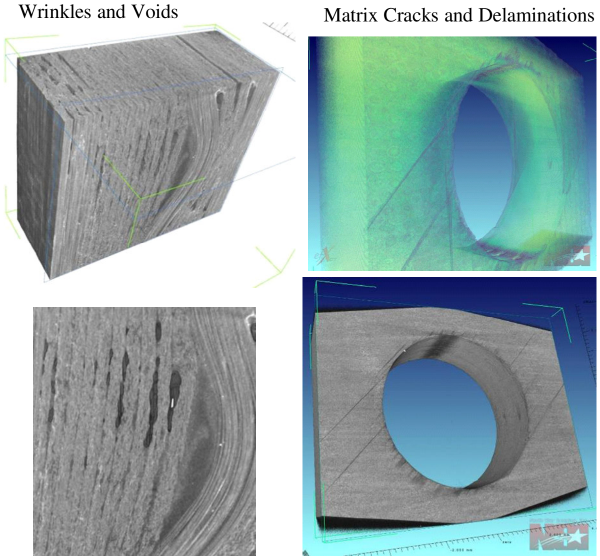

Fig. 1. Micro-focus CT images show the level of subsurface detail resolution including manufacturing defects, matrix cracks, and delaminations for glass/epoxy and carbon/epoxy composite articles.

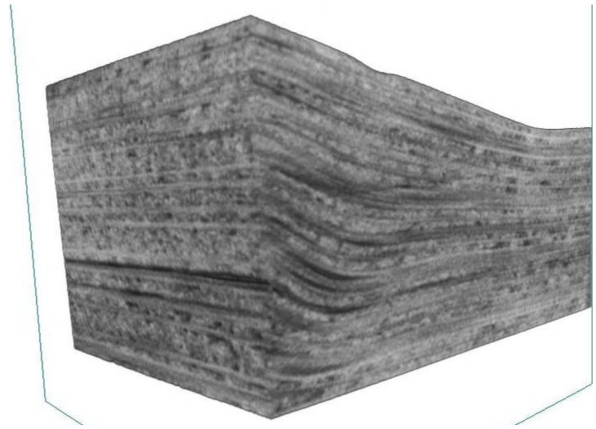

Fig. 2. A CT volume slice shows wrinkles and voids in a Glass/Epoxy laminate structural detail.

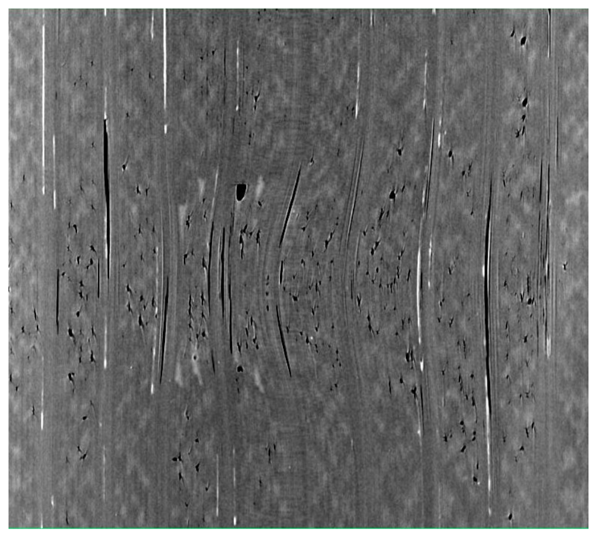

Fig. 3. Two-dimensional slice of a CT volume for a thick Carbon/Epoxy laminate with ply-waviness and porosity.

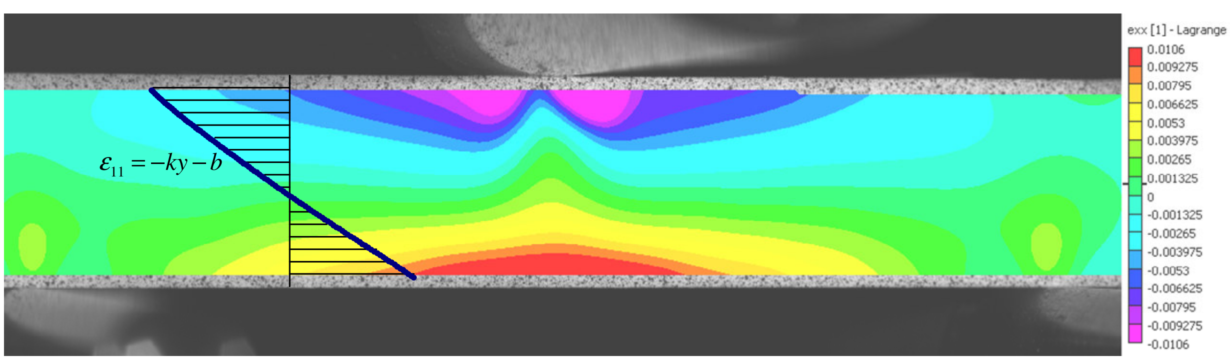

Fig. 4. A linear axial strain distribution through the specimen thickness enables simple stress and modulus approximations.

Peak load, kN	Cycles	Simulation		Test	
		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

Table 1. Comparison of largest crack lengths and delaminations for OHT articles at various loads and cycles. *Different quasi-isotropic layup.

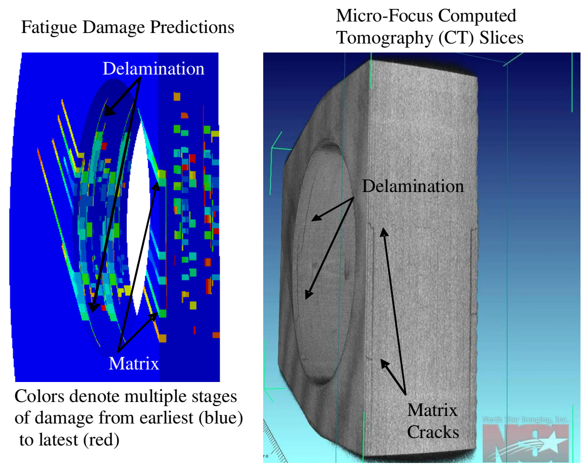

Fig. 5. Fatigue model predictions and test correlations for carbon/epoxy open-hole fatigue articles at 1,000,000 cycles (peak load about 70% static strength, R 0.1, 10 Hz)

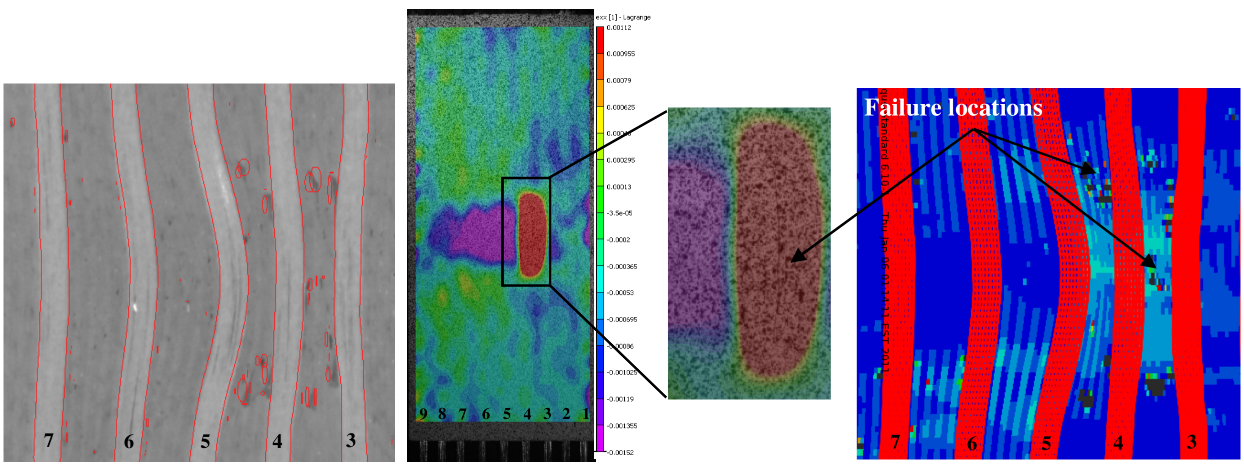

Fig. 6. Detected wrinkles and porosity (left), test data (center) and simulation results (right) show similar locations for delamination failure.