NASA Langley Research Center in Fatigue of Composites

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16. Abstract

This Technical Note describes the analysis effort by NASA Langley Research Center to predict fatigue behavior and life of composites and composite structures. The analysis was based on fatigue test results that were previously conducted using nondestructive evaluation methods to track damage due to repeated loads. The results of these tests are summarized in this Technical Note.

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LIST OF ACRONYMS

CT	Computed tomography
CZM	Cohesive zone model
FAA	Federal Aviation Administration
NDE	Nondestructive evaluation
VCCT	Virtual crack closure technique

EXECUTIVE SUMMARY

Over the past 5 years, the NASA Langley Research Center, as part of several NASA aeronautics projects (Aviation Safety, Rotary Wing, and Aerosciences) and in collaboration with the Center for Rotorcraft Innovation, conducted a series of composite sub-element structural fatigue tests using in situ nondestructive evaluation methods to track damage. The purpose of those tests was to generate a database for evaluating numerical models capable of predicting the fatigue life of composite structures. The results of those tests, which are summarized in this Technical Note, were used to undertake specific analysis activity that was funded by the Federal Aviation Administration (FAA). During the course of these studies, the FAA supplemented the funding for this activity to help accelerate advancements in state-of-the-art fatigue life prediction for composites.

APPROACH

The motivation for the 5-year study was to evaluate delamination onset and growth analysis methods in structural sub-element components that were generic by design but representative of rotorcraft components. Initially, delamination characterization data were generated under quasi-static and cyclic loading, and benchmarking was completed for commercially available virtual crack closure technique (VCCT) routines. Next, a validation building block approach was adopted, with increasing layup, geometry, and loading complexity at the higher levels of the building block. A significant number of fatigue tests at the lower level were completed during the course of these studies to identify some key issues for composite fatigue. These included a composite tube loaded in cyclic torsion (to simulate a first-level building block component relevant to a main rotor spar) and a single hat-stiffened panel loaded in cyclic compression (to simulate a tilt-rotor wing skin). As is commonly done for certification building block tests, Teflon™ films were implanted at anticipated critical locations to simulate initial manufacturing flaws in the components. A combination of nondestructive evaluation (NDE) methods was used during both tests, including:

1. Digital image correlation to measure surface displacements and strains.
2. Thermography to monitor damage formation and growth in real time during the cyclic loading.
3. In situ ultrasonics, achieved using an enclosed water column probe and scanning apparatus mounted on the test frame.
4. Post-test X-ray computed tomography (CT) to calibrate the accuracy of the damage documented from the other NDE methods.

TEST RESULTS

TUBE TORSION FATIGUE TESTS

Fatigue damage did not initiate at the embedded Teflon films. Instead, fatigue damage initiated in the form of matrix ply cracks emitting from built-in discontinuities in the structure, specifically at ply gaps and overlaps that vary part thickness. Several of these longitudinal discontinuities (gaps and overlaps) were located at different radial positions around the tube. Matrix cracks would quickly form at the longitudinal discontinuities and subsequently create small delaminations at the intersection of the discontinuities and the matrix cracks. However, after a finite number of matrix cracks formed at the first longitudinal discontinuity and small delamination formed and arrested, no further damage was observed. Instead, this same sequence of damage began at a second longitudinal discontinuity; the delamination would arrest and the sequence of damage would start again at a third longitudinal discontinuity. However, the damage did not arrest in the last event, and a complex pattern of delaminations bounded by matrix cracks. This third longitudinal discontinuity grew in size and ultimately failed the tube. A second nominally identical tube was also tested and showed remarkable repeatability in terms of location and sequence of damage formation. Cyclic loading was terminated in the second tube just prior to anticipated failure to document the damage state with X-ray CT.

SINGLE HAT-STIFFENED PANEL FATIGUE TESTS

Compression fatigue tests were performed on three nominally identical panels. No damage occurred under cyclic loading near the embedded Teflon film until the cyclic load exceeded the load necessary for skin buckling. Delamination growth occurred near the embedded Teflon film in only one of the three tests, indicating the strong sensitivity of material and thickness variations on compression-driven delamination formation and growth. However, matrix cracks and subsequent delaminations formed and grew in all three panels near the center of the panel length where the largest out-of-plane displacement occurred after the skin had buckled. These delaminations extended from the skin to underneath the flange of the hat stiffener. Repeated cyclic loading was accompanied by delamination growth in some interfaces and continued migration via matrix cracks to additional interfaces through the thickness. Ultrasonic scans just prior to failure indicated that fatigue failures occurred shortly after most of the interfaces at a single local location were delaminated.

CONCLUSIONS FROM BOTH TESTS

Documentation of the progression of damage in both types of tests resulted in the following conclusions:

1. Delamination onset and growth was a significant damage mode in the failure sequence. However, characterization and analysis of delamination alone would not be sufficient to capture the sequence of events and predict fatigue life.

2. Progressive damage analysis methods that incorporated the migration of delaminations through matrix cracks and discontinuities (ply drops/gaps/overlaps) need to be developed.

3. Fatigue failure occurs when a significant number of interfaces through the laminate thickness at a single location are delaminated, allowing the load-bearing plies to fail, either through a local tensile strain concentration or the loss of local stability in compression.

4. The final fatigue damage state is similar to what may be observed from a barely visible impact event, with interconnected matrix cracks and delaminations forming sublaminates. However, the damage was generated through fatigue loading and has none of the surface characteristics relating to an impact event.

FEDERAL AVIATION ADMINISTRATION FUNDED RESEARCH

As a first step in developing the necessary understanding of the migration phenomenon noted in conclusion 2, the following studies were undertaken.

A delamination migration characterization specimen was designed to isolate a single 2-D migration event that would allow for a better understanding of the underlying physics that control this phenomenon under both static and fatigue loading [1]. Existing (ABAQUS X-FEM) and newly developed (Floating Node Method, Regularized Rx-FEM) techniques were used to model the developed migration specimen. These analysis efforts were supported using Federal Aviation Administration funding. The following is a summary of the findings from these studies and the references of detailed reports of these findings.

In Chen et al. [2], the basis of the Floating Node Method was proposed. Reference [3] is a journal paper version of reference [2], providing further detail on the method, its formulation, and how it compares with other existing methods. In De Carvalho et al. [4], a combination of the method with the VCCT is exploited. A novel fracture mechanics-based migration criterion to model delamination migration (quasi-static) was proposed and evaluated against experimental evidence. Reference [5] uses recently developed benchmarks to assess XFEM as a commercially available tool to predict migration and highlights its potential and limitations. In De Carvalho et al. [6], the methodology presented in reference [4] was further improved and extended to predicting fatigue delamination growth and migration under fatigue loading, including a new migration criterion. In Pernice et al. [7], the delamination migration test was generalized and used with newly designed specimens to investigate delamination migration in multidirectional tape laminates.

Finally, in Iarve et al. [8], the regularized Rx-FEM methodology previously developed for static loading was extended to variable amplitude block cycling loading. Cycle-based and event-based fatigue simulation algorithms were considered. The Langley-developed static failure criterion, LaRC04, was extended to fatigue failure prediction as the crack insertion indicator. A material point history variable was introduced to track the loading history of each integration point. The Palmgren-Miner linear damage accumulation rule was used to update the history variable at each material point for each loading step. The history variable was continuously tracked through all material points and was then inherited by a cohesive zone model (CZM) as a mesh-independent crack through this material point. A consistent CZM formulation capable of initiation and propagation of cracking and delamination under fatigue loading, without any assumption regarding the size of initial damage, was proposed. The damage propagation stage was treated according to a process zone update method. The proposed CZM captured both the Paris law delamination propagation and the stress-based S-N curve. Overall, the proposed methodology is well positioned to solve complex fatigue loading problems in laminated composite materials.

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