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Interlaminar shear fatigue behavior of glass/epoxy and carbon/epoxy composites

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ABSTRACT

This work addresses a strong need in accurate fatigue properties of glass- and carbon-fiber reinforced polymer–matrix composites. In particular, interlaminar shear fatigue properties of glass/epoxy and carbon/epoxy composite tape material systems used in aircraft fatigue-critical applications are needed. The interlaminar shear fatigue material properties, essential for the development of the analysis methods able to capture fatigue delamination failure onset in composite structures, are presented in this work. *S–N* curves are generated based on custom short-beam shear (SBS) fatigue tests. The custom SBS test configurations ensure a consistent interlaminar shear failure mode. This work extends the recently developed methodology, published in Composites Science and Technology to characterize nonlinear shear properties of composite materials using digital image correlation (DIC) and finite element analysis, to fatigue loading. Test data sets used to develop the fatigue properties, include approximately 20 glass/epoxy and 30 carbon/epoxy SBS coupons. All tests were run in load control at 0.1 load ratio. To better understand material behavior under cyclic loading, surface shear strain was monitored using the DIC technique. Accurate shear stress approximation resulted in similar *S–N* curve shapes for the glass-fiber and the carbon-fiber composites.

1. Introduction

The ability to predict failure of composite structures under cyclic loads is one of the major challenges in the aerospace engineering community for both fixed-wing and rotary-wing aircraft applications. In particular, helicopter rotor systems are subject to extreme fatigue environments. Fatigue capability is a limiting factor for high-cycle components found in the helicopter dynamic systems [1].

Glass-fiber and carbon-fiber reinforced epoxy-matrix tape composites are frequently used in the design of helicopter rotor systems. Typical examples of the fatigue-critical primary composite structures include main rotor blade spars and yokes in commercial and military helicopters [2]. Primary failure mechanism for such structures is delamination. A major barrier to accurate fatigue life prediction for composites has been the lack of material properties that could be used as a basis for the development of the failure criteria [3–5]. As fatigue tests are expensive and time-consuming, companies which own such data often keep them proprietary, and there is a significant lack of quality data on this subject available in the open literature. To accelerate the development of rigorous fatigue life prediction methods for composite structures, accurate characterization of the material fatigue failure behavior is required in the public domain. As composite materials could exhibit complex failure phenomena including multiple failure modes and their interactions, appropriate consistent failure modes in the fatigue test configurations are critical for measurement of specific basic material properties. And test results must reflect true material characteristics and not just coupon behavior.

Following numerous requests from the engineering community, to expand the methodology for characterization of nonlinear shear properties for composite materials using digital image correlation and finite element analysis, recently published in Composites Science and Technology [6], this work develops interlaminar shear fatigue properties representative of glass/epoxy and carbon/epoxy tape material systems. In particular, Cytec E-Glass/5216-Epoxy and Hexcel IM7-Carbon/8552-Epoxy prepreg tape composites [7,8] used in rotorcraft applications, are studied. Interlaminar shear *S–N* curves [1] for such materials are generated based on custom short-beam shear (SBS) fatigue tests. The custom test configurations [6,9,10] ensure consistent interlaminar shear failure mode in the unidirectional SBS coupons. To better understand material behavior under cyclic loading, surface shear strain was monitored using the Digital Image Correlation (DIC) technique. Periodic images taken throughout the fatigue history also ensured accurate number of cycles to failure in the SBS tests. The failure was defined as the onset of visually detectable delamination.

Test data presented in this work are essential for the development of the analysis methods able to capture fatigue delamination

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failure phenomena in composite aircraft structures. In particular, References [3,5] presented a comprehensive structural analysis methodology to capture matrix-dominated failure modes and their interaction in composites, and predict initiation and progression of structural damage under cyclic loads, without a priori assumptions of the initial damage or the damage path. The methodology is based on 3D solid finite element models (FEMs) that simulate the initiation and progression of structural damage to detectable size. Stress-based and fracture-based criteria are used to predict initiation of ply-cracks and delaminations as well as their progression [3,5]. The failure criteria relied upon matrix-dominated shear and tensile *S*–*N* curves to predict the onset of the fatigue damage growth [3,5] in composite structures.

This work expands results of Ref. [6] which developed a SBS based method for assessment of interlaminar shear material properties for composites under quasi-static loads, to fatigue loading. The Digital Image Correlation (DIC) technique for full-field measurement of surface deformation was successfully coupled with three-dimensional finite element stress analysis to develop the nonlinear interlaminar shear stress–strain curve for a 350°F cured IM7-Carbon/8552-Epoxy tape composite.

DIC was also utilized in Refs. [9,10] to generate the nonlinear interlaminar shear stress–strain relations based on SBS tests of 250°F cured glass/epoxy tape composites. Full-field deformation measurements overcame the conventional strain gage limitations in the SBS tests and proved the validity of simple stress models to characterize the shear stress–strain curves. While a finite element-based shear stress model was used to generate accurate nonlinear portion of the shear stress/strain curve for the carbon/epoxy composite up to the material failure [6], a simple closed-form stress approximation was acceptable for the glass/epoxy material systems [9,10].

It is worth noting that before Ref. [9], use of the SBS test method for the development of design allowables for structural design criteria for composites was discouraged in the literature due to complexity of stress distribution not being reflected in the simple beam equation for peak shear stress. According to Ref. [11], instrumentation of SBS test coupons was not practical; therefore shear modulus and stress–strain data could not be obtained using conventional strain gages. Indeed, a conventional strain gage suitable for a SBS test must be very narrow to minimize the effect of the strong gradient of the strain in the coupon thickness direction. Also, the strain gage must be perfectly placed along the neutral axis corresponding to the maximum absolute value of the shear strain throughout the coupon thickness. However, the location of the neutral axis might be unknown prior to the test. One reason for a shift of the neutral axis could be the difference in the axial tensile and compressive moduli, which is the case for unidirectional carbon/epoxy tape systems [10]. Another deficiency of the strain gages is their inability to capture the effect of the out-of-plane displacement on the in-plane strain tensor components during finite deformation. Three-dimensional deformation measurement would be required to account for such effect.

SBS specimens are prismatic coupons with uniform rectangular cross-sections and subject to three-point bending. The American Society for Testing and Materials (ASTM) standard [11] guidelines for geometry of polymer–matrix composite SBS specimens include the width W twice the thickness T, and the support length L 4 times the thickness. Consistent with DIC surface strain assessment, the surface strain must represent the strain distribution throughout the specimen width away from support locations. Based on three-dimensional finite element analysis, the width of the SBS coupons has been reduced from the ASTM recommended 200% to a 100% of the specimen thickness (square cross-section) for more uniform strain distribution through the specimen width [6,10]. It is worth noting that the author initially used $W = 0.8T$ [9] but found that $W \sim T$ was also acceptable. The square cross-section is convenient as the SBS test coupons could be machined in the 0° and 90° directions from a single unidirectional panel and loaded in the 1–2 (in-ply), 1–3 (interlaminar) and 2–3 principal material planes to characterize 3D constitutive relations for composite materials [10]. The fiber direction is denoted as 1 (0°); the in-ply transverse direction as 2 (90°); and the laminate thickness direction as 3 (interlaminar material direction.)

Guidance to assessment of fatigue properties for composite materials, available in public domain, is limited [1,12]. As listed in Ref. [1]: fatigue testing is performed by cyclic loading of a test specimen below static failure load to determine time or number of cycles to failure. The loading is often characterized by the ratio of the minimum to maximum load, for example, $R = 0.1$. A series of tests are usually conducted at a loading frequency chosen to be low enough to avoid heating of the specimen. This heating can lead to thermally-induced failure. Load is cycled between selected values until failure, and maximum load or some other indication of load intensity is plotted against the log of the number of cycles to failure. Multiple tests are performed and the plot of the results of these tests is referred to as an *S*–*N* curve.

It is also worth noting that Ref. [13] evaluated the ASTM standard [11] SBS test configuration to generate interlaminar shear *S*–*N* curves for carbon/epoxy. Consistent with Ref. [10], Ref. [13] also reported matrix cracks in unidirectional carbon/epoxy tape coupons under the ASTM standard 0.25-in diameter loading nose [11], causing the subsequent delamination shift from shear to mixed-mode failure closer to the loading nose. Therefore, the author believes the ASTM standard SBS test setup is not adequate for the development of appropriate interlaminar shear fatigue properties for carbon-fiber material systems. In this work, the loading nose diameter in the unidirectional IM7-Carbon/8552-Epoxy tape SBS tests was increased compared to the ASTM standard [11] to eliminate compressive damage under the loading nose before shear delamination failure. Fig. 1 shows an example of the modified ASTM standard SBS test fixture with a 2-in diameter loading nose. However, no increase of the ASTM standard loading nose diameter was required for more compliant unidirectional E-Glass/5216-Epoxy SBS coupons to exhibit shear delamination.

2. Stress approximation

In the development of techniques to measure accurate stress–strain curves in composite materials with strong anisotropy and complexity of the stress–strain constitutive relations, the ability to eliminate the need in *ad hoc* assumptions regarding formulation of the nonlinear constitutive models is desired. If stress calculation is independent of the deformation measurement, such *ad hoc* assumptions are not needed.

The stress state in a unidirectional SBS specimen is complex. Stress concentrations exist at the loading nose and support

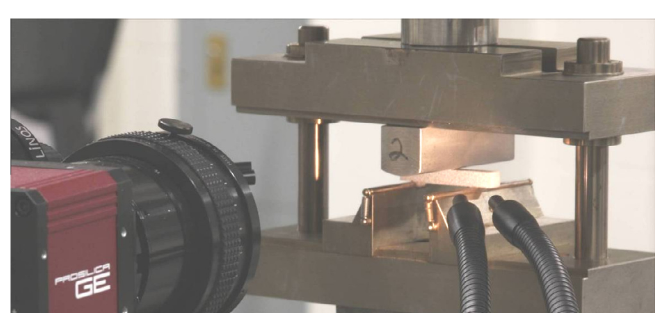

Fig. 1. A custom SBS test with 2-inch diameter loading nose.