

Study on Fatigue Behaviors of Porous T300/924 Carbon Fiber Reinforced Polymer Unidirectional Laminates

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ABSTRACT

Morphological features of voids were characterized for T300/924 12-ply and 16-ply composite laminates at different porosity levels through the implementation of a digital microscopy (DM) image analysis technique. The composite laminates were fabricated through compression molding. Compression pressures of 0.1MPa, 0.3MPa, and 0.5MPa were selected to obtain composite plaques at different porosity levels. Tension-tension fatigue tests at load ratio $R=0.1$ for composite laminates at different void levels were conducted, and the dynamic stiffness degradation during the tests was monitored. Fatigue mechanisms were then discussed based on scanning electron microscope (SEM) images of the fatigue fracture surfaces. The test results showed that the presence of voids in the matrix has detrimental effects on the fatigue resistance of the material, depending on the applied load level. A fatigue model was also established in this paper by introducing the void content into the conventional residual stiffness approach. The residual stiffness model can evaluate the void effects on the fatigue behaviors of CFRP unidirectional laminates. The dynamic stiffness degradation of composite laminates at different porosity levels and different load levels was predicted in this study. The prediction results show a good correlation with the test data.

Keywords: CFRP composite, void effects, fatigue model, fatigue mechanism

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INTRODUCTION

Light weighting, as one of the most urgent targets for vehicle and airplane manufacturing industries in meeting customer demands and government regulations for energy efficiency, can be achieved by the implementation of new materials with relatively low density as well as high stiffness and strength. Carbon fiber reinforced polymer (CFRP) composites, which can offer some unique advantages in terms of their high strength-to-density ratio compared to traditional materials, have become a promising material for future application.

Although CFRP composites have shown excellent fatigue resistance in previous applications, the fatigue failure of composite components can be very crucial. As some of the structural components (e.g., turbine blades) require good durability when subjected to complex loading conditions, which is detrimental to the components, fatigue life evaluation must be done during the components' design process.

Different from fatigue failure of metal, fatigue failure of CFRP composites is not dominated by a single main crack and its propagation, but is rather a combination of a variety of failure modes (e.g., fiber breakage, matrix micro-cracks, delamination, and fiber/matrix interfacial debonding) that act synergistically and simultaneously to cause damage to accumulate in the material [1].

Much research has been dedicated to the study of the fatigue behavior of CFRP composites, and some factors have proved to have impacts on the fatigue behavior: (1) mechanical properties of the material components, such as fiber, matrix, and fiber/matrix interface [2]; (2) fiber orientation and fiber volume fraction [3,4]; (3) loading conditions, including load frequency and load ratio [5, 6, 7]; (4) manufacturing defects and aging effect of the material, such as fiber defects [8] and voids in matrix [9, 10, 11] or mechanical degradation due to hygrothermal aging [12] or ultraviolet radiation [13].

Porosity is one of the most common defects in CFRP composites and is inevitable in fabrication of the material. Many efforts have been made to study the voids' effects on the mechanical properties of CFRP composites, the results of these studies show that many mechanical properties, including transverse tension/compression stiffness and strength, bending strength, interlaminar shear strength, and fatigue resistance, will degrade with voids present in the matrix [14, 15, 16]. Sanjay Sisodia investigated the effects of voids on CFRP laminates under tension-tension cyclic loading and quasi-static tensile loading, and the results showed that the fatigue life of composites is more sensitive to the void content in comparison with the static properties, including stiffness and strength; besides, the sensitivity to voids was found to be more significant for transverse cracking in the 90° plies under cyclic loading [10]. Based on the test results, Sisodia suggested that quasi-static testing of the composites alone is not adequate for quality control of composite materials that may be used under cyclic loading. Despite all of these efforts, the understanding of voids' effects on fatigue of CFRP composites is still insufficient; the degradation of fatigue resistance of the material with voids present needs to be evaluated by an appropriate model in components design.

For the purpose of getting a better understanding of the voids' effects on the fatigue properties of CFRP unidirectional laminates, experimental research was carried out in this study by conducting tension-tension fatigue tests for unidirectional T300/924 CFRP laminates at different void levels under load control. The 12-ply and 16-ply 0° unidirectional laminates with void content at 0.8%, 2.2%, and 4% were fabricated by applying different compression pressures during the compression molding procedure. Dynamic stiffness degradations of the materials in the loading direction due to cyclic loading were also obtained by monitoring the axial displacement changes with respect to the number of cycles. For the assessment of the void content, a digital microscopy (DM) image analysis technique was implemented. On top of that, a scanning electron microscope (SEM) was also utilized to identify the underlying failure mechanisms. In an attempt to evaluate the voids' effects on fatigue behaviors of CFRP composite laminates as well as to predict the fatigue life, a residual stiffness model for porous composite laminates was presented by introducing the void content v_v as a variable into the model of H. Mao. This model is able to reflect the voids' effects on the stiffness degradation of CFRP laminates and can be used to predict the fatigue life for composites at different porosity levels. The prediction results showed a good correlation with the test data.

Experimental

Materials

The composite laminate plaques were fabricated by the compression molding approach. The reinforcement was T300 carbon fiber produced by Toray, and the matrix was HexPly 924 provided by Hexcel. For the purpose of obtaining plaques at different levels of porosity, 0.5MPa, 0.3MPa, and 0.1MPa were selected as the

compression pressures during the compression molding procedure. The unidirectional laminate plaques have a size of 500mm × 600mm with lay-up $[0^\circ]_{12}$ and $[0^\circ]_{16}$. The resulting void contents were determined with the implementation of a digital microscopy (DM) image analysis technique. The fiber volume content of the laminates ranged from 47.9% to 49.5%, which were also obtained by the aforementioned DM approach. Details of the geometric and manufacturing parameters can be found in Table 1.

Table 1. Manufacturing parameters of the CFRP plaques.

Types	Lay-up	Thickness /mm	Compression pressure /MPa
UD laminates	$[0^\circ]_{12}$	1.53	0.1/0.3
	$[0^\circ]_{16}$	2.03	0.5

Porosity Characterization

The samples for porosity characterization were cut by water jet from the laminate plaques with dimensions of 10mm × 10mm. Before DM analysis, the samples were first embedded into epoxy resin and cured for 24 hours; the cross sections were then prepared with #400, #600, #1200, and #2000 abrasive papers, and the final polishing was completed by using a synthetic diamond compound of 0.5um, 0.3um, and 0.1um. To accomplish the porosity characterization, a PC-based optical microscope with a CMOS camera was used in this study to capture micro-images of the cross-sectional area, with 100X and 200X magnification selected to provide adequate resolution of the fibers/matrix as well as a large enough representative area. For the purpose of providing a statistically representative data set, 5 samples for each plaque were prepared and 3 images per sample were examined. The captured images were analyzed by a software module based on MATLAB's image toolbox to obtain the morphological parameters of the voids in the composites, such as the voids' area content, denoted as v_v ; aspect ratio; and equivalent size of the micro-voids. Some typical micro-images of the samples cured at different compression pressures are shown in Figure 1.

Quasi-Static Tensile Test

The quasi-static tensile tests were carried out first on an MTS 647 hydraulic servo dynamic material test machine. The tests were performed under displacement control using a displacement rate of 1mm/min at room temperature (22±0.5°C). For strain measurements, a 2-inch MTS E 634.31F-24 extensometer was used with its blade glued to the sample surface to avoid unexpected gliding during the monotonic loading procedure. Rectangular samples equipped with aluminum/glass fiber reinforced polymer (GFRP) composite tabs were used according to ASTM D3039/3039M to provide a reduced cross-sectional testing area as well as to protect the gripping section. In the tensile tests, 5 samples were tested for each laminate of the same porosity level. The designs of the specimens are shown in Figure 2.

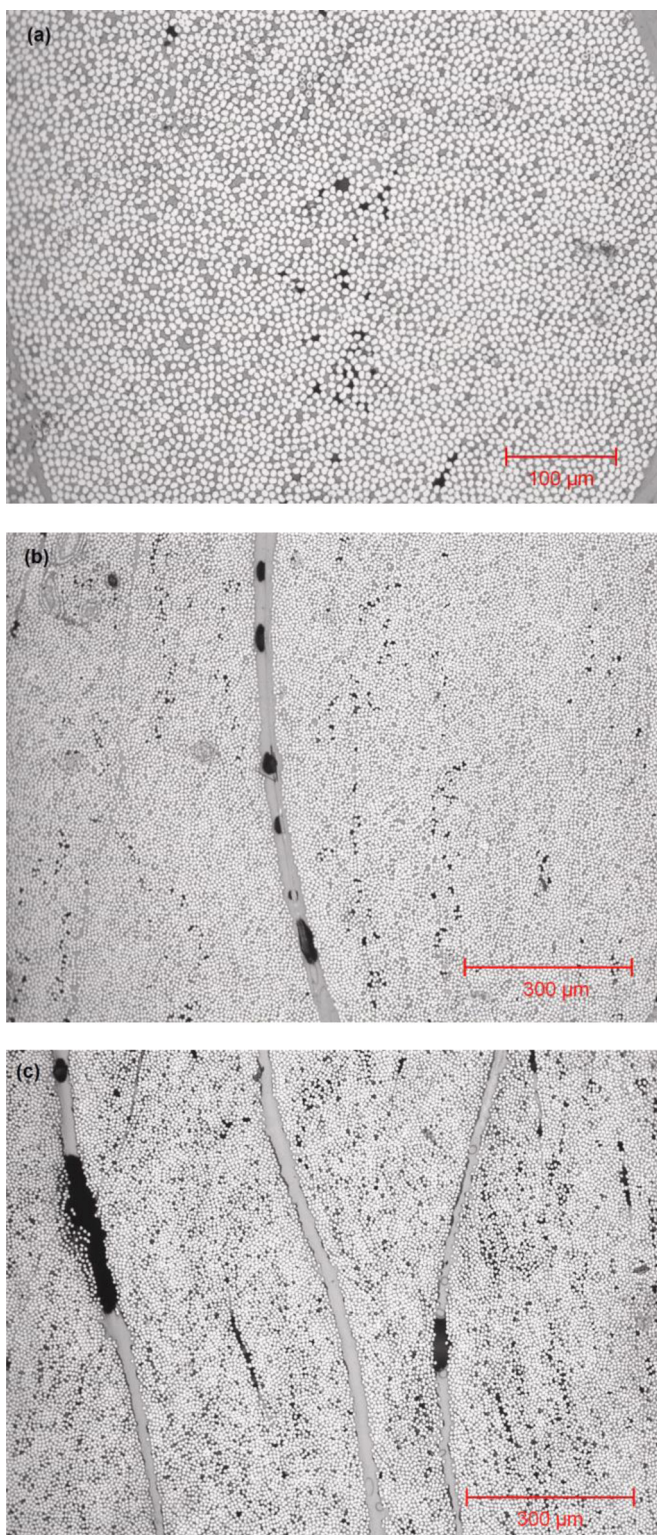


Figure 1. Cross-sectional images of unidirectional laminates (a) cured at 0.5MPa, (b) cured at 0.3MPa, and (c) cured at 0.1MPa.

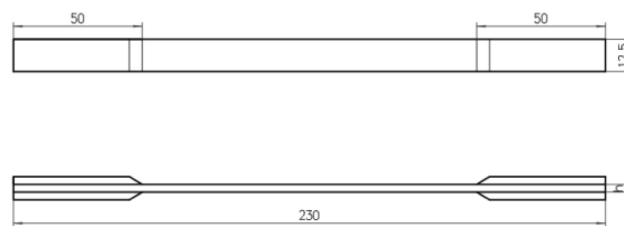


Figure 2. Geometric parameters of specimens for longitudinal quasi-static tensile tests and fatigue tests.

Fatigue Test

The fatigue tests were also conducted on the MTS 647 hydraulic servo dynamic material test machine. The specimens were subjected to cyclic loading at a frequency of 7Hz at room temperature. The tests were performed under load control with the load ratio $R = 0.1$. Specimens with the same geometry as in the tensile tests were used according to ASTM D3479. Specimens remaining intact after application of 1,000,000 cycles were treated as run-outs in this study, and the S-N curves for unidirectional laminates at different void levels in the longitudinal direction were then obtained by plotting the maximum stress and fatigue life in a semi-logarithmic diagram. The dynamic stiffness degradation of composite laminates due to fatigue loading were also analyzed by monitoring the maximum/minimum displacements for each cycle; the residual Young's modulus for samples after the application of a certain number of load cycles can then be calculated based on the difference between the maximum and minimum stress/strain.

SEM Image Analysis

Quasi-static/fatigue fractography observation was also done in this study using a scanning electron microscope (SEM) to get a better understanding of the underlying failure mechanisms. A Denton vacuum coating machine was used before observation, given the poor electrical conductivity of the epoxy matrix. By using a carbon coating technique, a nanoscale carbon coat was formed on the fracture surfaces, thereby allowing electrical charge phenomena to be avoided in SEM observation. The fracture surfaces of samples for longitudinal tensile testing and longitudinal fatigue testing were compared, and the differences between the failure mechanisms were determined.

Results and Discussions

Void Characterization

Samples from plaques cured at different compression pressures were analyzed in this section to determine the void content. Fifteen samples cut from 16-ply plaque cured at 0.5MPa and 12-ply plaque cured at 0.3MPa and 0.1MPa (denoted as plaques A, B, and C, respectively) were mounted and polished for observation by the optical microscope; three images per sample were examined in this study. The results from the void content measurement (Figure 3 (a)) show that the samples cured at lower compression pressure have obvious high void content. For the laminates cured at 0.1MPa, the void content is determined as 4.0%, whereas the laminates cured at 0.5MPa have a void content of only 0.8%. By plotting the aspect ratio and equivalent diameter of each void in a diagram (Figure 3 (b)), the relationship between size and shape of voids can be investigated. As can be seen in the figure, most