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Bending fatigue failure mechanisms of twill fabric E-Glass/Epoxy composite

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ABSTRACT

Composite materials exhibit very complex failure mechanisms because of their heterogeneous property leads the formation of different stress levels within the material and results various combinations of damage. The objective of this research is a contribution to physical understanding of composite failure mechanism under bending fatigue loading, as a physical understanding of composite failure mechanism is crucial step for developing both theoretical and numerical models. To investigate the fatigue damaging mechanism and the resulting material strength deterioration of a particular composite material, four-point flexural quasi-static and displacement-controlled fatigue tests have been performed. The analysis methodology relies on interrupted flexural fatigue tests. The damage formation and propagation was continuously monitored through the decrement of bending moment during cycling. This leads to a characteristic history curve that can be subdivided into three stage, namely initial, intermediate and final. Each of them has specific trend in stiffness degradation. Through microscope and SEM image analysis of the pre-cycled specimens, four different subsequent failure modes and mechanisms of the targeted material are identified at different stages of component life. A correlation between the trend of the bending moment time history and the sequence of the different failure modes is established.

1. Introduction

Fatigue is a process in which damage accumulates in a component due to repeated cycling load that may lead a component to fails much below the ultimate strength of the material and often even below the yield strength. Such failure mode is most common for dynamic loaded components and contributes up to 90% of all mechanical service failures [1–4]. Fatigue failure is usually considered dangerous due to the fact that they occur suddenly or without warning. The failure begins with a minute crack that is too small to detect with any non-destructive inspection techniques. The crack may get initiated by internal cracks in the component or irregularities in manufacturing. Once a crack has formed, it propagates rapidly under the effect of stress concentration until the stress resisting area decreases so much that it leads to a sudden failure.

Metals have been the main structural material for many years; therefore, their fatigue failure mechanism has been intensively studied for more than one century. Design data have been accumulated for every conceivable engineering metal and alloy, and engineers have access to a comprehensive set of rules, some empirical and some based on scientific understanding, with which to deal with any given design requirements [5]. Whereas, an intensive use of composite material for main structural application is not as old as metal and the accumulated mechanical information are not sufficient.

Composite materials are mainly characterized by high specific strength, both in static and impact loading conditions, and high specific stiffness, besides being heterogeneous and anisotropic (having properties based on direction) makes them suitable candidate material for many structural application. However, the anisotropic characteristic in their strength and stiffness also yields very complex failure mechanisms under static and fatigue loading. Unlike with isotropic materials, such as metals, where failures result mainly from predominant single crack in both dynamic and static loading, cyclic loading causes extensive damage throughout the composite volume that leads to general material degradation, therefore, fatigue failure in composite results from volume material degradation instead of predominant single crack [6,7]. The accumulated damage may include matrix cracking, matrix–fiber debonding, fiber breakage, delamination, etc. Those different failure modes combined with the inherent anisotropy, complex stress fields, and overall non-linear behavior of

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composites severely limit the understanding of true nature of fatigue failure mechanism of composite material and to set a general rule that works for all material architecture, structure and loading.

Researchers used different techniques to monitor the damage accumulation for entire component service life and understand the fatigue failure mechanism of the material by consider particular cases i.e. a particular material architecture and loading case to give a contribution on the subject. To investigate the effect of material defects such as fiber waviness and ply drops on the fatigue performance of composite structures, Wang et al. [8] used 15 Hz video camera. Fiber waviness and ply drops were intentionally created in both longitudinal and transverse direction during laminate manufacturing. Through performing compression fatigue test, failure behavior of the selected material were continuously monitored in situ through a series of the snapped video images at an interval of N cycles.

The fatigue life and failure mechanism study of a fiber-reinforced titanium-matrix composite (TMC) has been conducted by Steyer et al. [9] and provides the Goodman diagram of the targeted material for a wide range of loading conditions, $R = 0–0.8$. They have identified four types of failure mechanism as (i) damage-intolerant, with fracture controlled by crack initiation; (ii) damage-tolerant, associated with the formation of multiple matrix cracks and followed, eventually, by fiber bundle fracture; (iii) damage-tolerant, without fiber bundle fracture, thus yielding a fracture threshold; and (iv) undamaged indefinitely. The fracture threshold is governed by the fiber bundle strength, which degrades somewhat during cycling. This degradation appears to be due to the formation of new surface flaws upon repeated fiber–matrix sliding.

Damage development in open-hole composite specimens in fatigue were investigated by Nixon-Pearson et al. [10], interrupted fatigue tests were carried out with peak amplitude at 60% of the ultimate static load (60% severity) in order to determine the 3D sequence of damage events using X-ray Computer Tomography (CT). Matrix cracking at the surface ply and initiation of matrix cracks in the subsequent plies lead to delaminations that progress through the thickness, and ultimately to the propagation of delamination at the 45/0 interface all the way back towards the end tabs. In a double logarithmic scale diagram, the number of cycles to failure decreased linearly as the maximum fatigue stress level increased.

Van Paepegem and Degrieck [11,12] conducted experimental and simulation study on bending fatigue of plain glass/epoxy composite material and identified the three stages of stiffness degradation. Belingardi et al. [13] used stiffness degradation as a measure of damage monitoring to study bending fatigue property of intraply hybrid composite that consists of distinct layers of biaxial glass-fiber-reinforced composite and biaxial carbon fiber- reinforced composites as well as biaxial layers of bundles of carbon and glass fibers mixed within a single layer. They observed that the rate of stiffness reduction was a function of the magnitude of applied fatigue loading.

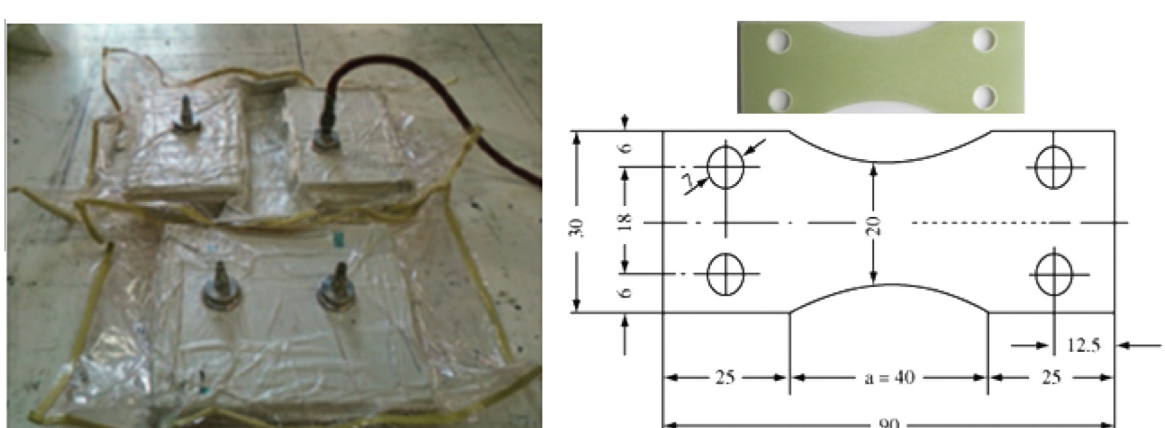
In the current study, to investigate the fatigue damaging mechanism and the resulting material strength deterioration of a particular composite material, four-point flexural quasi-static and an interrupted displacement-controlled four-point flexural fatigue tests were conducted on standard specimens and the damage formation and propagation in the composite was continuously monitored through the decrement of bending moment during cycling. Stiffness degradation was evaluated by measuring the reduction during fatigue cycling in relative bending moment (RBM). The RBM parameter is defined as the ratio between the bending moment applied at first cycle and the bending moment applied at the Nth cycle. Through characterization and SEM analysis of the pre-cycled specimens, the failure modes and mechanisms of the targeted material are identified at different portion of component life.

2. Manufacturing process of specimens and material data

The material under investigation is a prepreg (twill 2 × 2 type) E-Glass/Epoxy composite with a mass of 250 g/m^2 and resin mass content of 36.5%. The mechanical property and detail material characterization and failure analysis are documented in [7,14,15]. A summary of basic material mechanical properties are presented in Table 1, while the vacuum bagging technique used for plate manufacture and the final specimen geometry are presented in Fig. 1.

Table 1
Material properties, standard deviations are reported in brackets.

Composite type	0/90 E-Glass/Epoxy
Weave	2 × 2 Twill
Fiber fraction (wt %)	63.4
Tensile strength (MPa)	496.62 ± 4.98
E_x (GPa)	25.49 (0.17)
G_{xy} (GPa)	3.543 (0.059)
υ_{xy}	0.126 (0.009)



a b

Fig. 1. Laminate production: (a) vacuum bagging; (b) specimen geometry.