Fatigue damage evolution of unidirectional glass/epoxy composites

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Abstract

This study presents an experimental characterization of initial fiber breaks and evolution of the density of fiber breaks during the fatigue lifetime of unidirectional glass/epoxy materials. Uniaxial fatigue tests under tension-tension loading conditions and under different load levels are carried out. The damage evolution of the material is evaluated in terms of the probability of fiber breaks. The way that the probability of fiber breaks varies during the fatigue lifetime is found; however, further studies should be performed to define with greater certainty the factors that affect this response.

Introduction

Fatigue life estimation of composite materials has been a subject of significant interest in the last forty years since the application of these materials has been continuously increasing in many industrial applications, such as wind turbine blades. In these industrial applications, composite materials are mainly used as multidirectional laminates made of unidirectional (UD) plies. During the service life of these multidirectional laminates, the onset and propagation of matrix cracks in the off-axis plies are the first cause of their stiffness degradation. However, their structural load bearing capacity is governed by the 0° plies since they are more resistant to fatigue. Therefore, the final failure of the multidirectional laminate could be predicted if the development of the different fatigue damage mechanisms presented in the 0° plies and their final failure can be modeled. This study aims to understand how the different damage mechanisms presented in the 0° plies initiate and propagate, and how they interact with each other and are affected by material local conditions, in order to further identify and predict their final failure.

The fatigue behavior of the UD laminate under tension-tension loading conditions has been studied over many years [1, 2]. The different damage mechanisms involved in this type of material under these loading conditions, such as fiber breaks, fragmentation, fiber/matrix debonding (interface cracks) and coalescence of isolated fiber breaks, have been identified qualitatively through experiments in these studies. However, there is still not a direct quantitative link between them that allows predicting their development along the fatigue lifetime and therefore predicting the final failure of the material. Due to the complexity of the phenomenon, many studies have modeled one or two of these damage mechanisms in simple scenarios that normally involve one or few broken fibers under quasi-static loading conditions [3-5]. Moreover, few studies have considered the progression of these damage mechanisms under fatigue loading conditions [6] or under more complex scenarios (e.g. higher number of fiber) [7].

In this work, an investigation about the progression of the tension-tension fatigue damage in UD glass/epoxy material is shown. Uniaxial fatigue tests under different load levels were carried out, monitoring the initiation and propagation of the damage during the fatigue lifetime. The performance of the material was evaluated in terms of initial fiber breaks, evolution of the density of broken fibers and fragmentation evolution. A quantitative behavior of the density of broken fibers during the fatigue lifetime was determined.

Materials and Methods

UD composite laminates with stacking sequence $[0]_6$ were employed in the present study. Panels of 200 x 300 mm were fabricated by vacuum resin infusion (VARTM) using unidirectional glass fibres UT-E500 (by Gurit) and epoxy resin RIM-235 as reinforcement and matrix materials, respectively. From the infused panels, 7 specimens with 17 mm wide, 195 mm long and 1.8 mm of thickness were cut. Rectangular-shaped carbon-epoxy tabs with 30 mm length and thickness of 3 mm were bonded on the both ends of the specimens using epoxy adhesive. One surface of the specimens was polished starting with P180 sandpaper and ending with a 0.1 μm SiO_2 solution in order to be able monitoring the damage evolution, as described below.

Uniaxial tension-tension fatigue tests on the UD glass/epoxy specimens were carried out using a MTS 858 hydraulic machine. The tests were performed in load control with global tensile stresses $\sigma_{x,max}$of 200, 300, 320 and 340 MPa with a R-ratio (i.e. ratio between the minimum and maximum cyclic stress,$R = \sigma_{min}/\sigma_{max}$) of 0.05. The tests were repeated twice for each load level, except for$\sigma_{x,max} = 200MPa$ case.

The damage evolution in terms of fiber breaks was monitored during the test by taking pictures periodically on the polished surface of the specimen. Every certain number of applied cycles, the test was paused and the specimen was removed from the hydraulic machine to be scanned with an optical microscope. The first pause was made after the first cycle and the other ones after different number of cycles (i.e. 10, 100, 1000, etc. cycles). At each pause, approximately 150 pictures were taken, each corresponding to small areas located in the 20 mm long gage region of the specimen. Each small area had a size of 0.0415 mm^2, approximately. From the pictures, the number of initial fiber breaks, the evolution of the density of broken fibers and the fragmentation evolution was quantified along the test.

Results and Discussions

As described in [2], the fatigue damage in unidirectional glass-fiber composites initiates from fiber breaks, which occur even at low applied strains due to the statistical distribution of the fiber strength. Close to these fiber breaks, yielding of matrix or fiber/matrix debonding can develop due to high shear stresses in the interface region. These progressive mechanisms result in a redistribution of stresses in the area close to the fiber break, which causes further fiber breaks and, therefore, new yielding of matrix or new fiber/matrix debonding. This damage process continues until the final catastrophic failure of the composite takes place.

In this sense, it is clear that the density of fiber breaks ρ_{fb} and its evolution during the fatigue lifetime are significant parameters to be considered in future fatigue damage predictions of UD glass/epoxy composites.

According to [8], the normalized density of fiber breaks in UD composites can be defined as:

$$\rho_{fb} = N_{fb}\frac{r_f}{L_f} \tag{1}$$

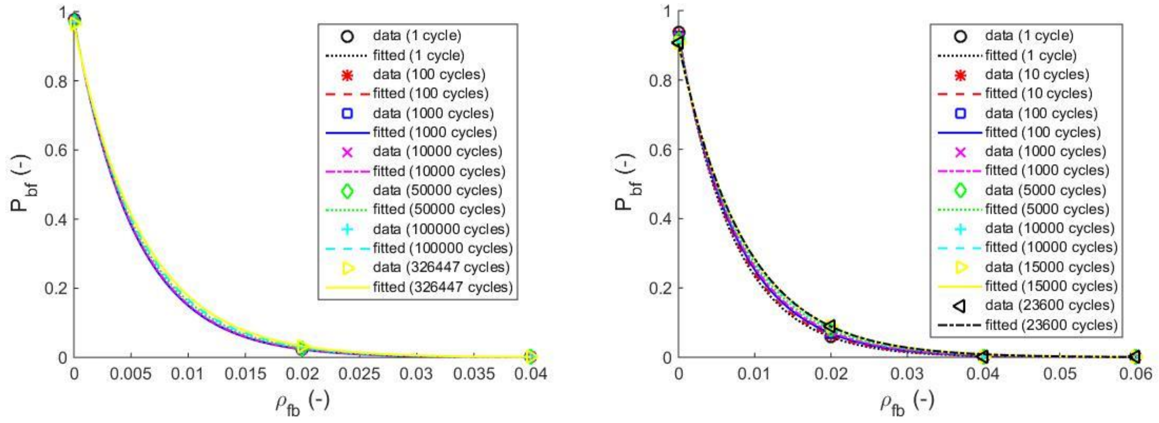
where N_{fb} is the number of breaks in a single fiber, r_f is the fiber ratio and L_f is the length of the observation area. In the present work, r_f is equal to 8.66 µm, and L_f can vary depending on the selected observation area.

Since the fiber strength follows a Weibull distribution function [9], it is reasonable to analyse the density of fiber breaks and its evolution during the fatigue lifetime from a probabilistic point of view. In this context, the probability of fiber breaks P_{fb} for a given ρ_{fb} can be defined as:

$$P_{fb} = \frac{N_{f,\rho_{fb}}}{N_{f,total}} \tag{2}$$

where $N_{f,\rho_{fb}}$ is the number of fibers with a given ρ_{fb} from a group of observed fibers and $N_{f,total}$ is the total number of observed fibers.

Based on the experiments carried out in the present work, the P_{fb} as a function of ρ_{fb} for each applied number of cycles N and for the different applied load levels could be obtained, see e.g. in Fig. 1. The P_{fb} per each specimen was estimated taking into account the total number of fibers in all observation areas of the specimen.



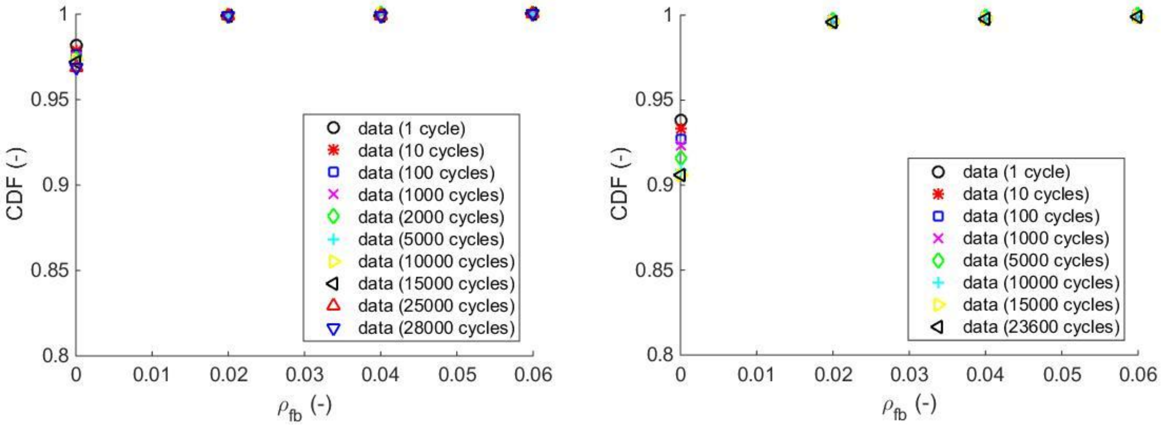
(a) $\sigma_{x,max} = 300\ MPa$ (b) $\sigma_{x,max} = 340MPa$

Figure 1. Probability of fiber breaks during the fatigue lifetime of specimens under (a) $300\ MPa$ and (b)$340\ MPa$

As shown in Fig. 1, the lower is the density of fiber breaks the higher is P_{bf} for each applied number of cycles, the maximum occurring when $\rho_{fb} = 0$ (i.e. when non fiber breaks occur). Fitting these experimental data with different functions, it was found that an exponential function with the following form provides the best fit for all cases:

$$P_{fb}(N, \sigma_{x,max}, \ldots) = C_1 e^{C_2 \rho_{fb}} \tag{3}$$

where C_1 and $C_2$are unknown functions that might depend at least on $N$and $\sigma_{x,max}$.



(a) Specimen No 1 (b) Specimen No 2

Figure 2. Cumulative distribution function of the density of fiber breaks of specimens under $340\ MPa$

Plotting the cumulative distribution function CDF of ρ_{fb} for all applied cycles (see e.g. in Fig. 2), it seems that C_1 and C_2 also depends on the number of surviving fibers after the first cycle. As shown in Fig. 2, under the same $\sigma_{x,max}$, the higher is the number of surviving fibers (i.e. $\rho_{fb} = 0$) after the first cycle, the lower is the number of new breaks during the fatigue lifetime. Even though this behaviour was found for all evaluated load levels, it is clear that a further micro-damage evolution study is needed to be sure about this finding and to define, therefore, the form of the C_1 and C_2 functions.

This micro-damage evolution study should also consider the behaviour of the fibers inside the materials, which can be observed, for example, by using 3D X-ray computed tomography (XCT) [10]. The scan of the UD composite specimens under fatigue loading condition by XCT is one of the further steps of the present work.

Conclusions

In this study, an experimental characterization of initial fiber breaks and evolution of the density of fiber breaks of UD glass/epoxy materials under tension-tension fatigue loading conditions was presented. It was found that the probability of fiber breaks in this type of materials follows an exponential function, which depends on the applied global tensile stress, the number of cycles and probably on the number of surviving fibers after the first cycle. A good way to confirm this is by analysing the response of the fibers inside the material by using 3D X-ray computed tomography. This will be done in the near future.

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