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Evaluation of the fill yarns effect on the out-of-plane compressive fatigue behavior for an unidirectional glass fiber reinforced epoxy composite

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ABSTRACT

Understanding the out-of-plane mechanical behavior of composite materials is necessary to optimally design thick structures. In unidirectional laminates, the out-of-plane mechanical behavior is generally characterized by the in-plane data assuming transverse isotropy; nevertheless unidirectional woven contain a fraction of fill yarns that might change this property. To evaluate the fill yarns effect over the transverse isotropy, this work compares the in-plane mechanical performance to the out-of-plane behavior under a cyclic load for an epoxy glass fiber reinforced by a unidirectional weave.

First, the quasi-static tensile and compression strengths were determined for both planes. Fatigue tests were then performed at 95%, 90%, 80% and 70% of the compressive strength using stress ratios of $R = 2$, $R = 10$ (in compression–compression fatigue) and the critical stress ratio defined by the quotient between the compressive and tensile strengths. The results show that the quasi-static tensile strength depends on the plane, mainly due to the influence of the weave fill fibers. These fibers also influence the observed differences in compressive strength; however, the specimen geometry and boundary conditions also have an effect. Despite these differences, the fatigue strength detriment responds to the same causes and their magnitude in terms of the number of cycles is similar. An in-plane *S–N* curve of the compression–compression fatigue can be transformed into an out-of-plane curve using the compressive strength in both planes and vice versa.

1. Introduction

Designing thick structures requires understanding the full stress state required to optimize the structures. Currently, thick structural components on polymer fabric-reinforced composites, such as bearings (hemispherical [1] or spherical [2]), compressor blades [3], and pipes for oil, gas and cellulose [4], are being manufactured. Optimizing designs requires proper constitutive models that account for the anisotropic nature of the material. Knowing the material behavior under different loadings and boundary conditions is necessary before selecting a model. In general, despite significant progress in numerical analyses (for instance, the micro–macro approaches to simulation under complex loading conditions proposed by Totry et al. in [5]), experimental techniques are the most accepted and reliable method for understanding the macroscopic behavior of a material, validating a model and identifying material parameters.

Extensive knowledge exists for the in-plane mechanical behavior of polymer fiber-reinforced composites, while works handling the out-of-plane (or through-thickness) mechanical behavior are scarce. For instance, Park et al. establish in [6] that the stacking sequence influences the interlaminar stress field and thus the compressive strength; Kim et al. recommended in [7] using cylindrical specimens over cubic shapes for strength measurements despite the reported differences for unidirectional arrangements being negligible. Abot et al. developed a set of experiments in [8] to determine the out-of-plane properties. Gan et al. and DeTeresa et al. studied the effect that out-of-plane compression loads had on the in-plane shear properties in [9] and [10], respectively, and concluded that the out-of-plane compression significantly enhanced the interlaminar shear strength. In contrast, Gan et al. found that an out-of-plane compression decreased the in-plane tensile strength in [11]. Pettersson et al. proposed a modified shear test in [12] to study the out-of-plane shear behavior. Daniel et al. performed a series of out-of-plane tests in [13,14] to determine the failure envelopes. This review indicates that it is difficult to design and implement specimens and test conditions with

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homogeneous stress/strain fields to determine out-of-plane material parameters; furthermore, there is a lack of standards.

To determine material parameters for unidirectional arrangements, a single ply is generally assumed to exhibit a transversal isotropic behavior (see Puck and Schu [15], for instance). However, this approximation might have limitations for unidirectional woven arrangements with few fibers in the fill direction (used to preserve fibers aligned in the warp direction, especially useful for dry preforms for liquid transfer molding techniques) that interfere with the weave architecture according to the model of Adumitroaie and Barbero [16].

This work presents a comparative study on the fatigue behavior of an epoxy composite reinforced with unidirectional woven glass fibers. This study compares the results for in-plane and out-of-plane tests in order to evaluate the effect of the presence of fibers in the fill direction. Fig. 1 presents a diagram that defines the material directions, where the direction 1 is aligned to the warp direction, direction 2 is aligned to the fill direction and direction 3 is normal to the plane 1–2 (out-of-plane or through thickness). The following section describes the selected test conditions and protocols, and Section 3 describes the manufacturing and quality control. Section 4 discusses the results that establish the conclusions in Section 5.

2. Mechanical testing

2.1. Testing conditions

Fatigue tests are performed at 95%, 90%, 80% and 70% of the compressive strength in stress ratios of $R = 2$ and $R = 10$ (in compression–compression fatigue) and X, which is the critical stress ratio defined by the quotient between the compressive and tensile quasi-static strengths. All tests were performed at 5 Hz and room temperature in an Instron 8801 servo hydraulic testing machine with a 100 kN load cell.

The quasi-static tests were performed at 1 mm/min at room temperature in the same testing machine.

2.2. Specimen descriptions

In-plane test protocols are widely available. The specimen geometry in this work follows the ASTM D 4310 for in-plane compression testing and ASTM D 3039 for in-plane tensile testing (quasi-static and dynamic in both cases).

The out-of-plane compression specimens were selected from the work of Kim et al. [7] and consisted of a 10 mm × 10 mm × 10 mm cube. This specimen geometry is easily manufactured and does not significantly differ from a cylinder according to his results. Moreover, the strength measurements for unidirectional arrangements present low dispersions in terms of the specimen geometry and size. During the tests, the specimens were compressed between two lubricated steel plates without a self-alignment fixture because such a fixture increases the scatter during the strength measurements as reported by Park et al. [6].

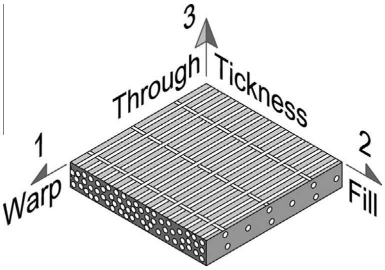

Fig. 1. Definition of the material directions.

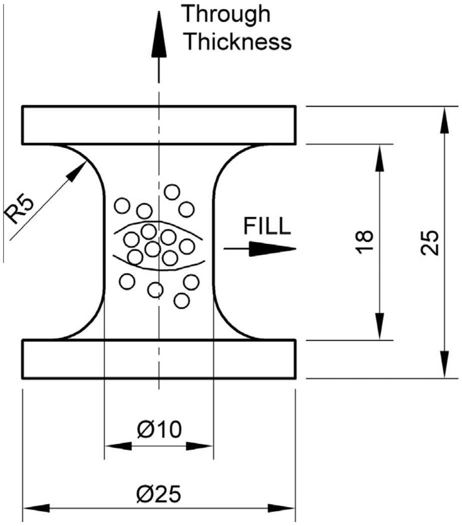

Fig. 2. Out-of-plane tensile specimen geometry, units in millimeter.

The specimen geometries for the out-of-plane tensile conditions were based on the ASTM D 7291 and complemented by the recommendations of Hara et al. in [17]. According to Hara's results, a spool specimen should be used over a cylindrical one. Spool specimens also exhibit a fracture at the specimen center and not the adhesive-composite interface. The specimen is fixed to the grips using a Plexus MA 310 adhesive. The specimen geometry is shown in Fig. 2.

The chosen tensile test specimen presumably exhibited a homogeneous stress/strain field over the gage zone (at least at the macroscopic level) during the deformation. This assumption is based on norms and originates from the slender geometries. In contrast, compressive specimens did not present a clear gage zone and exhibited different clamping mechanisms, geometries and shapes. Hence, the edge effects in the stress field influence the measured strength.

2.3. Data analysis

The fatigue strength (S) was measured from the absolute maximal load obtained for the machine's load cell and initial specimen cross section. The number of cycles (N) before the specimen fails was saved by the machine controller. This information was plotted with the strengths in absolute values as an S–N diagram for further analysis. These diagrams were constructed for four loading levels (95%, 90%, 80% and 70% of the strength) for two compressive stress ratios ($R = 2$ and $R = 10$) and the critical stress ratio, X, in two material directions (in-plane and out-of-plane). Each test was repeated five times, which resulted in 120 tests for the entire fatigue study.

The quasi-static analysis strength was the average of five tests per testing condition.

3. Specimen manufacturing

3.1. Materials

The matrix consists of the L20 epoxy resin with an EPH 161 hardener produced by Momentive, USA, and purchased from R&G composites, Germany. According to technical data from the manufacturer, this resin system is designed to resist heat up to 120 °C and for groutings approximately 10 mm thick. In addition, curing