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Effect of fiber orientation on the shear behavior of glass fiber/epoxy composites

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ABSTRACT

This paper deals with the study of the influence of the lay-up configuration on interlaminar and in-plane shear properties of glass fiber reinforced epoxy composites. The following laminates were produced by resin transfer molding with vacuum assistance for this study: $[0]_5$, $[90]_5$, [0/90/0/90/0] and randomly oriented (mat). The composites, with similar overall fiber volume fraction, were evaluated based on four tests: double-notched shear, short beam shear, V-notched rail and Iosipescu shear tests. Besides, the dynamic shear modulus was measured with non-destructive testing based on free vibration method. The $[0]_5$ laminate presented interlaminar shear strength almost twice that of $[90]_5$, whereas the mat samples presented higher in-plane shear strength in both tests used due to its random fiber orientation. The dynamic shear modulus was higher for the composites $[0]_5$, as expected due to the longitudinally oriented fibers. Among the shear test methods applied, double-notched and V-notched methods exhibited more auspicious features, possibly due to a more uniform shear stress state during testing.

1. Introduction

Owing to the ever-growing importance of polymer composite materials, new tests and methods for the determination of their engineering properties are continuously proposed. A particularly important area of continuous study is the shear behavior of composites, and many shear testing methods have been introduced over the years. Shear loadings are easily found in various types of structures, such as beams, bars, plates, bridges, wind blades, fuselage, among others [1,2]. For instance, in case of a beam under pure bending stress, apart from normal stresses in the axial direction of the beam, shear loading acting horizontally along the beam may also be significant. This situation is usually studied using short beam testing (also called interlaminar shear test – ILSS) [3–5].

It is important to differentiate between simple and pure shear. In case of small deformations, pure shear may be considered as simple shear followed by a rigid rotation [6]. Simple shear (two parallel faces sliding in opposite directions) can be defined by a linear transformation that converts a rectangular cross-section of a parallelepiped into a parallelogram. The surface tractions are sought, which produce such type of deformation [7]. Pure shear, in contrast to simple shear, is caused when under equi-biaxial tension and compression, being a three-dimensional constant-volume "homogeneous flattening" [8].

For a complete understanding of the shear behavior of composites, it is mandatory to evaluate in-plane and interlaminar properties. Up-to-date, no single shear test is widely accepted as more precise, more practical and with accepted failures for all composite configurations [9]. Other issues include: the need for a reasonable uniform shear stress state in the gage section [10] and, in some cases, the adequate measurement of only one property, shear strength or shear modulus [11].

There are several in-plane shear testing methods available, such as tensile test with fibers oriented at ±45° (ASTM: D3518-13), Iosipescu (ASTM: D5379-12) and two-rail shear (ASTM: D4255-07). The Iosipescu shear test is perhaps the most used, mainly due to its versatility and accuracy in obtaining the shear properties. But several studies for both isotropic and orthotropic materials, have mentioned a non-uniform shear stress distribution in the gage section (area between the notches) for some fiber orientations, for thin laminates or when the fiber bundle is too large, which demands a larger gage section to provide reliable results [12]. Adams et al. [13] developed a test called V-notched rail shear test (ASTM: D7078-12) for unidirectional, multidirectional, isotropic and for thin laminates. The specimen length was the same, but the width was increased considerably, from 20 mm to 31 mm. In addition, the two end regions on either side of V-notched specimen

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were shortened for face loading instead of edge loading. This fixture was designed to produce a uniform state of shear stress across the specimen gage section, allowing accuracy in determining the shear properties and providing acceptable failures in the gage section. In addition, the reduced cross-sectional area increases shear stresses in gage section [14].

A uniform stress state in Iosipescu test is over a small region and it is supposed to be only between the notches, but stresses beyond this area is sometimes observed, even though they may not cause premature failure of the specimen. The V-notched test allows a similarly uniform shear stress field but free of the edge effect, and the stress state is uniform in the gage area [15]. In the ±45° tensile test, a uniform stress field over a large area is expected in the free edges, which varies from layers to layer. However, there are transverse tensile stresses in each layer that are detrimental to the wanted stress state, and they increase with the increase in transverse/axial elastic modulus ratio.

Regarding interlaminar shear methods, short beam test (ASTM: D2344-13) is largely used for several types of composites. The fixture simplicity, easy specimen geometry, fast testing and low cost, combined with good testing efficiency in acceptable failures make it an excellent alternative to measure out-of plane shear strength (Adams and Busse [14], Silva et al. [16]). Selmy et al. [17], for instance, studied the interlaminar shear strength of glass/epoxy composite and concluded that unidirectional laminates display short beam strength (SBS) 50% higher than randomly oriented specimens. Nevertheless, this test presents drawbacks related to the lack of a uniform shear stress state and to the low span-to-thickness (s:t) ratio, which may cause failure by crushing (for s:t < 4:1) or due to vertical (for s:t > 6:1) cracks (typical of bending failures). Adams and Busse [14] and Silva et al. [16] realized a comprehensive study about the effect of s:t ratio on the SBS, and both reported an optimum s:t ratio of 6:1. Nevertheless, Markhan and Dawson [18] concluded that short beam test is not recommended for design purposes.

The double-notched shear (DNS) test was developed targeting unquestionable delamination failure to evaluate interlaminar shear strength of a composite. The failure must occur in the gage section (between notches) since the straight sides contain half-thickness and are flat-bottomed on opposing surfaces. Bauer et al. [19] employed this test to evaluate bond strength and interfacial adhesion as a function of the curing cycle applied to bisphenol-E cyanate ester used as matrix and they found a strong correlation of the shear values with results of the dynamic mechanical analysis. In short beam test, shear stresses are distributed following a parabolic law, with a maximum value at the neutral plane and zero at the upper and lower surfaces, whereas the interaction stresses are higher near the surfaces and zero at the neutral plane [20]. In DNS, the notches are staggered so that a shear plane between the notches is created when the axial tensile force is applied to the specimen [18].

There are just a few studies in the literature linking various shear tests. Adams and Lewis [21] assessed four shear test methods in different carbon/epoxy composite laminates and found that Iosipescu test presented strength values around 37% higher than that obtained via two-rail testing. Markhan and Dawson [18] compared shear strength of carbon fiber/epoxy and glass fiber/polyester composites, and the differences did not exceed 15%. The reported failures in double-notched test was typical delaminations, differently from short beam tests where crushing failure was described.

On this context, the aim of this paper is to study the influence of the lay-up configuration on interlaminar and in-plane shear properties of glass fiber reinforced epoxy composites. Different laminates were investigated ($[0]_5$, $[90]_5$, [0/90/0/90/0] and randomly oriented) under short beam, double-notched, V-notched and Iosipescu shear tests.

2. Experimental details

2.1. Composite manufacturing

The following materials were used: unidirectional glass fiber reinforcement (areal density of 300 g m^{-2}) and glass fiber mat reinforcement (areal density of 350 g m^{-2}) both supplied by Owens Corning; araldite LY1316 epoxy resin and Aradur 2969 hardener supplied by Aralsul Company.

The glass fiber reinforcements (five layers) were cut and placed inside the mold cavity (300 × 300 × 2.5 mm). The resin system (1:0.57 resin:hardener, in weight) was prepared using a mechanical stirrer with anchor type helix for 3 min, followed by 5 min in vacuum oven (at room temperature) for degassing. The resin was injected into the mold at room temperature and the pressure cycle consisted of initial positive injection pressure of 0.07 bar and vacuum (negative pressure) was kept constant in 0.1 bar, followed by 0.1 bar pressure variation every ≈200–250 s until a positive pressure of 0.5 bar and the negative pressure of 0.1 bar were reached. The [0/90/0/90/0] laminate was more difficult to infiltrate and, in this case, the positive pressure started at 1.0 bar and was continuously increased, reaching 2.0 bar. After infiltration, the resin was allowed to cure for 24 h at room temperature followed by post-curing for 10 h at 80 °C.

Four composites families were produced: (i) unidirectional at 0°; (ii) unidirectional at 90°; (iii) balanced and symmetrical laminate with a combination of 0° and 90° layers; and (iv) random. These families were called $[0]_5$, $[90]_5$, [0/90/0/90/0] and mat, respective. The fiber volume fraction (%V_f) in all composites was within 34–38%, being 38% the mat laminate, and 34% the others.

2.2. Characterization

The samples were cut from the molded plate and the edges were sanded in a polishing machine following the required geometry for testing. Iosipescu shear test (ASTM: D5379-12) was performed in a Shimadzu (AG-X model) testing machine with 50 kN load cell. The specimens had two centrally located V-notches. The V-notched rail shear test (ASTM: D7078-12) was performed in an Instron 3382 Universal machine (100 kN load cell). Fig. 1(a) and (b) shows specimen geometry and the apparatus. Eight specimens were prepared for each family and for both tests, and a minimum of five samples with acceptable failure modes were used in each case. To compare in-plane shear strength, an offset of 0.2 mm was used.

Interlaminar shear strength was measured using a jig anti-buckling support between compression plates in the same Instron machine. Specimen dimensions and the test apparatus are shown in Fig. 2(a) and (c). The double notched shear strength is obtained by maximum load/(width × length of the failed area), as recommended by ASTM: D3846-08 standard. Eight specimens were tested and five were validated. Short beam testing was performed according to ASTM: D2344-13 in the same Instron machine, using a span-to-depth ratio of 4:1. Twenty samples (length: 6 × thickness, width: 4 × thickness) were tested for each family and morphological analysis of the fractured specimens was carried out using an optical microscopy (Carl Zeiss model AX10). A summary of the four aforementioned shear tests is presented in Table 1.

Shear modulus was obtained through non-destructive testing. The technique employed is based on impulse excitation of vibration carried out in a Sonelastic® (ATCP Engenharia Física) equipment. The specimen under testing is subjected to a light mechanical tap to generate mechanical vibrations and the transducer captures the acoustic response allowing the reading of resonance frequencies.