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

José Humberto S. Almeida Jr. a,⇑, Clarissa C. Angrizani a, Edson C. Botelho b, Sandro C. Amico a

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
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 losipescu 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 similar uniformly 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 the resin system (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 losipescu 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]_{90}, [90]_{90}, [90/90/0/90/0] and randomly oriented) under short beam, double-notched, V-notched and losipescu 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 Aralsol 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 at 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 [0/90/90/0/90] 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]_{90}, [90]_{90}, [90/90/0/90/0] and mat, respective. The fiber volume fraction (%Vf) 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. Losipescu 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.
This procedure follows ASTM: E1876-09, and the shear modulus is obtained using Eq. (1):

\[ G = \frac{4Lmf_t^2}{wtR} \]  

where: \( m \), \( w \) and \( t \) are the mass, width and thickness of the sample; \( f_t \) is the fundamental resonance frequency in torsion mode and \( R \) is the correction factor for fundamental torsion mode.

3. Results and discussion

3.1. Interlaminar shear strength

Table 2 shows the results of short beam strength (SBS) and double-notched shear strength (DNS). The [0]\(^5\) composite presented the highest strength, around twice the value of the [90]\(^5\) specimen, whereas the balanced and symmetrical laminate [0/90/0/90/0] and the randomly oriented (mat) specimens presented similar strength. Considering the low deviation in the values, there is evidence of the orthotropy effect on shear strength. These results show the same trend observed by Selmy et al.\[17\], who reported that unidirectional glass/epoxy (%\(V_f\) = 35\%) composites achieved higher (c.a. 50\%) SBS than randomly oriented specimens.

![Fig. 1. Specimen dimensions (a) and apparatus assembled for V-notched test (b).](image)

![Fig. 2. Specimen geometry (a), exploded view of the apparatus (b), and JIG apparatus mounted (c) for double-notched test.](image)

<table>
<thead>
<tr>
<th>Test method</th>
<th>Test frame</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>Test speed (mm/min)</th>
<th>Load cell (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V-notched</td>
<td></td>
<td>76.0</td>
<td>56.0</td>
<td>2.5</td>
<td>2.0</td>
<td>100</td>
</tr>
<tr>
<td>Iosipescu</td>
<td></td>
<td>76.0</td>
<td>20.0</td>
<td>2.5</td>
<td>1.0</td>
<td>50</td>
</tr>
<tr>
<td>Double-notched</td>
<td></td>
<td>79.5</td>
<td>12.7</td>
<td>2.5</td>
<td>1.3</td>
<td>5</td>
</tr>
<tr>
<td>Short beam</td>
<td></td>
<td>15.0</td>
<td>5.0</td>
<td>2.5</td>
<td>1.3</td>
<td>5</td>
</tr>
</tbody>
</table>
In short beam testing, the shear response is strongly dependent on fiber orientation and it decreases from 0° (test direction) to 90° (transversely to the loading), and not so with the fiber content [22]. It implies that orthotropy characteristic of the laminates influences on the short beam strength. It is noticed that a simple shear state was generated on the short beam test, since the specimen’s parallel faces slid in opposite directions, generating horizontal cracks and delaminations (see Fig. 5(a)). Indeed, this test indicated absence of pure shear, since there was no rigid rotation.

The fixture used was designed to minimize tensile, compressive and bending influence, but the shear stress state is more complex than the pure shear stress predicted by the simple classical beam theory, which ignores the non-symmetric distribution of the transverse shear stress across the specimen [23]. Taken into account that a non-uniform shear stress state is not achieved in this test, simple shear is not achieved and non-uniform shear deformation is found.

Fig. 3 shows typical short beam load × displacement curves. All curves presented a nearly linear trend during the very early loading stage, followed by a higher slope region prior to achieving a maximum. The curve for the [0/90/0/90/0] specimen revealed a few steps after the maximum load, probably indicating that delamination occurred in a stepwise way. Since a plane of fracture along the mid-plan of the specimen is expected and there is a 0° layer there, this laminate yielded higher strength (but lower than the 0° laminate).

The abrupt drop noticed for the [90] specimen may be an indication that bending and compressive loads are relatively less important in this case, and the lack of fibers along the 0° promotes sudden failure. Indeed, the [0] laminate supported the highest load but did not display sudden failure. Thus SBS, similarly to other composites properties, gives a better response when the reinforcement is oriented along the loading direction.

In all fractured samples, interlaminar cracks were observed at the mid-plane, as expected for this test. Corroborating Fig. 3, the [0/90/0/90/0] sample presented several delamination planes, and these were less common in the unidirectional specimens. The mat specimens, who are considered in-plane isotropic, presented small cracks along the width, usually showing some evidence of crushing.

The double-notched shear test was originally designed for materials that do not yield acceptable data under short beam testing. In fact, a few authors reported unacceptable failures in short beam testing, such as crushing, due to the small span-to-depth ratio (i.e. 4:1) which may yield loading losses before maximum load that can be mistakenly seen as delaminations [22].

Fig. 4 shows typical load × displacement curves obtained for double-notched shear testing. The [0] specimen supported higher load than the other samples, which is a strong evidence of the effect of fiber alignment on this test. The [0/90/0/90/0] and mat specimens produced similar maximum load and curve profile, and the [90] specimen was the only one to display a clear shoulder after maximum load, with a less sudden drop. The visual aspect of all samples evidenced delamination at the gage section and, especially for the [90] samples, one main crack was found running along the length between the notches. It is important to add that identification of the crack length is needed for the suitable calculation of shear strength, for instance, the mat samples presented various small cracks horizontally distributed through the thickness, whereas the [90] sample showed a continuous crack throughout the gage area.

Fig. 5 shows the morphological aspect of the failed [90] sample after short-beam (Fig. 5a) and double-notch (Fig. 5b) testing. The SBS samples in general presented acceptable failure with a large number of cracks, and failure of the [90] specimen presented more than one main crack. The high number of horizontal cracks along the specimen width caused by the lack of a more restrict gage region. They may also suggest compressive and crushing mechanisms, caused by the small span-to-depth ratio recommended by the standard. Rosenshaft and Marom [3], Adams and Busse [14] and Silva et al. [16] recommended an increase in the s:t ratio for obtaining better overall failure. Nevertheless, there was no evidence of bending, characterized by vertical cracks at the lower center of the specimen. For the DNS fractures specimens (Fig. 5b), the failure mode was also acceptable, with horizontal cracks within the gage area (between notches). Typically, the fractured DNS samples presented one major horizontal crack at the middle of the thickness, characteristic of interlaminar shear. The micrographs also highlight some resin-rich regions.

### Table 2

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>Short beam strength (MPa)</th>
<th>Double-notched shear (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0]</td>
<td>34.4 ± 1.2</td>
<td>27.5 ± 0.6</td>
</tr>
<tr>
<td>[0/90/0/90/0]</td>
<td>23.0 ± 1.4</td>
<td>19.7 ± 0.7</td>
</tr>
<tr>
<td>[90]</td>
<td>17.9 ± 1.4</td>
<td>14.1 ± 0.9</td>
</tr>
<tr>
<td>Mat</td>
<td>22.9 ± 0.8</td>
<td>19.5 ± 0.9</td>
</tr>
</tbody>
</table>

Fig. 3. Typical load × displacement curves for SBS specimens.

Fig. 4. Typical load × displacement curves for DNS specimens.

### 3.2. In-plane shear strength

Fig. 6 shows typical load × displacement curves for the V-notched shear tests. The randomly oriented composite showed...
a clear peak, whereas in the others, stress just continuously increased, justifying the use of a strain offset to allow their comparison. It is also worth mentioning that the [0/90/0/90/0] laminate presented a shoulder near 1250 N, which may be associated to delamination.

The mat, considered in-plane isotropic, supported a load around three times that of the other samples, which were approximately similar. This behavior can be attributed to fibers bundles oriented at intermediate angles, including some near ±45°, which improve shear performance. Table 3 presents the mean values of in-plane shear strength of all composites. The mat presented shear strength of 70.4 MPa, around 206% higher than the [0]₅ and [0/90/0/90/0] composite configuration, which was slightly higher than [90]₅. These values are not being influenced by the area of each sample, which was nearly the same for all of them due to the high precision of the CNC composite cutting.

It is expected that the [0/90/0/90/0], [0]₅ and [90]₅ samples display similar in-plane shear strength when submitted to simple shear stress field. Although the [0/90/0/90/0] laminate is balanced and symmetrical, this material the number of 0° and 90° layers differs, which may lead to premature interlaminar failure (see Fig. 4) and to some degree of fiber twisting during testing [13].

![Fig. 5. Optical micrographs of the fractured specimens from short beam (a) and double-notch test (b).](image)

Fig. 5. Optical micrographs of the fractured specimens from short beam (a) and double-notch test (b).

![Fig. 6. Typical load × displacement curves for V-notched shear specimens.](image)

Fig. 6. Typical load × displacement curves for V-notched shear specimens.

Table 3

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>V-notched shear (MPa)</th>
<th>Iosipescu shear (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength Offset⁴</td>
<td>Strength Offset⁴</td>
</tr>
<tr>
<td>[0]₅</td>
<td>23.0 ± 1.3 7.5 ± 0.7</td>
<td>20.7 ± 1.3 4.6 ± 1.3</td>
</tr>
<tr>
<td>[0/90/0/90/0]</td>
<td>22.0 ± 0.3 7.6 ± 0.3</td>
<td>22.3 ± 0.9 3.0 ± 1.6</td>
</tr>
<tr>
<td>[90]₅</td>
<td>22.3 ± 0.6 6.1 ± 0.6</td>
<td>14.3 ± 1.9 4.2 ± 2.1</td>
</tr>
<tr>
<td>Mat</td>
<td>70.4 ± 0.8 17.3 ± 0.5</td>
<td>26.1 ± 1.1 5.1 ± 0.7</td>
</tr>
</tbody>
</table>

⁴ Offset at 0.2 mm.

Table 3 also presents the mean values of losipescu shear strength of the composites. The mat sample showed again the highest strength. However, the minimum strength was obtained for the [0/90/0/90/0], based on the offset reading, and for the 90° specimen, based on maximum stress. The [0/90/0/90/0] laminate showed again evidence of delamination, as shown in Fig. 8.

Broughton et al. [12] observed cracks initiating at the notch roots and propagating parallel to fiber alignment in the losipescu testing of unidirectional carbon fiber/epoxy composites. The stress concentration at the notches is primarily responsible for crack initiation, and crack growth in the principal stress plane is prevented by the aligned fibers, which justifies higher shear strength for the [0]₅ sample in comparison with the [90]₅ one. Furthermore, undesired bending moments, which induce transverse tensile stresses at the notch roots, have some influence on [0]₅ specimen since it produces axial stress, and this unidirectional composite is stronger in its axial direction [24].

As opposed to the results from the V-notched shear testing, the load × displacement curves of all samples tested following losipescu method presented a peak. The overall shape of these curves does not change significantly in these two in-plane shear tests, but it is worth mentioning the higher heterogeneity of the losipescu curves, especially at low loadings, which may be an influence of the shape of the gage section and the type of load applied for testing (compressive × tensile).

3.3. Shear modulus

Shear modulus of a composite material is usually measured using semi-static destructive tests. However, these methods require the use of strain gages, making the test costly and labor-intensive [24]. An alternative procedure is to use non-destructive
dynamic testing, such as one based on impulse excitation of vibration technique, even though these different approaches may give somewhat different results. Disregarding the contribution from cracks and other defects, internal damping of a composite is determined by the properties and relative content of constituents, dimensions of the inclusions, orientation of the reinforcement with respect to the loading axis, fiber surface treatment and voids [25,26]. Fig. 9 presents the dynamic shear modulus obtained using the cited technique, which varied in the following order: mat < [90]5 < [0/90/0/90/0] < [0]5.

Orientation of the layers yields different measurements in a simple shear strain field. For instance, for unidirectional laminates, in-plane shear modulus (G_{12}) is attained, and for biaxial symmetric laminate, G_{44} (±45°) is achieved. In addition, for orthotropic or transversely isotropic materials, there is influence of Poisson-type effect to consider in shear, once a contraction in j-direction was generated by applying a stress in the i-direction (v_{ij} ≠ v_{ji}) [27]. Also, the aligned composite in the axial direction should be stiffer than the transverse one, and even in bias (±45°) direction. In case of pure shear, the same panorama is found, once if a uniform stress state is achieved after a rigid rotation and the trend of the values should be similar.

4. Conclusions

This study focusing on evaluating shear strength of glass fiber reinforced epoxy composites using four different shear test methods. The 0° composite presented higher interlaminar shear strength and the opposite was observed for the 90° for both methods studied, short beam and double-notched. Short beam test is easier, more practical and cheaper, but experience undesired features during testing, like the influence of compressive forces and crushing. The double-notched shear test proved an excellent alternative to estimate interlaminar shear strength of the composite, and the halfway notches through the thickness yielded, under compressive loading, a shear stress in the specimen, easily observed by the delaminated gage area.

Regarding in-plane shear of the laminates and based on the load × displacement curves and the observed failure modes, the V-notched shear was found more suitable than losipescu, probably due to the larger gage section (with higher width and length between notches). The shear strength presented the same trend for both losipescu and V-notched, even though the level of shear stress was much higher for the V-notched. Nevertheless, for materials with low shear strength, such as the ones studied in this work, this is not so decisive.

The shear modulus was estimated by non-destructive testing based on impulse excitation of vibration. The results were in accordance with the theory and the literature, and the laminate with longitudinally aligned fibers presented higher modulus, as opposed to the transversely oriented one. Finally, all shear test methods used were considered successful in evaluating shear characteristics of the laminates.

Acknowledgements

The authors thank to FAPESP and CNPq for the financial support. Also, the first author thanks CAPES for his grant (funding process No. 9456-13-9).

References

