Bending, compression, and shear behavior of woven glass fiber–epoxy composites

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Received 20 May 1999; accepted 25 August 1999

Abstract

The mechanical properties and failure mechanisms of through-the-thickness stitched plain weave glass fabric–epoxy composites were studied. Unstitched plain weave and biaxial non-crimp fabrics were used for comparison. Composite panels were fabricated using Resin Transfer Molding. Z-directional stitching increased the delamination resistance and lowered the bending strength of the composites. Composites made from through-the-thickness stitched fabrics demonstrated improved compression after impact behavior as compared to the unstitched fabrics. The results presented in this investigation should be useful in tailoring textile composites to achieve specific property goals. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Bending

1. Introduction

Textile technologies such as weaving, stitching, braiding, knitting are being employed to fabricate advanced composites with conformability, quality and integrated mechanical properties [1\textendash}10]. One of the objectives of using textile reinforcement is to take advantage of through-the-thickness arrangement of fibers to enhance interlaminar strength and toughness, compressive strength, as well as compression-after-impact (CAI) strength [11\textendash}13]. Reinforcing fibers in the thickness direction also contribute to stiffness and strength in that direction.

Research efforts to improve interlaminar fracture behavior have generally focused in the following areas: (i) the reinforcement material, for example, the development of three-dimensional (3D) preforms; (ii) the use of tough matrix material such as PEEK [14]; (iii) the addition of microfiber [15]; and (iv) developing good fiber\textendash matrix interface with the use of improved coupling agents for controlled interfacial properties. The improved interlaminar shear property in the thickness direction gives much improved fracture and impact resistance over the conventional laminates.

The compressive response of fiber-reinforced composites has been the subject of continued investigation [9,16\textendash}18]. Many factors influence the compressive response of composite materials. These include the compressive properties of the fiber [19] and the matrix [20] as well as the fiber\textendash matrix interface. The presence of local inhomogeneities and defects, which are often difficult to characterize and model, also influence the failure in compression. On a macrostructure level, laminate orientation, specimen geometry, method of loading and stress concentrations are some of the factors that play a role in determining the compression failure mode.

Conventional laminate composites are sensitive to out-of-plane loading, as they are weaker in the through-the-thickness direction than in the plane of lamination. Therefore, to improve interlaminar properties, multi-layer continuous glass fiber textile preforms have been stitched using Kevlar yarn. Epoxy has been used as the matrix material. The objective of this research is to study the relationship among textile preform architecture, mechanical properties, and the resulting failure modes. Significant attention was focused on the compressive response of the textile composites.

2. Materials and sample preparation

The following E-glass reinforcements were used in this study: (1) non-crimp biaxial laminate (LM) with glass fiber...
in the 0 and 90° direction; (2) plain weave fabric (PW); and (3) through-the-thickness biaxial (BS) or uniaxial stitched (US) plain weave fabrics. The non-crimp biaxial laminate fabric, containing 1% polyester yarn and 99% E-glass, was obtained from Tech Textiles USA. The polyester yarn (usually 70 or 150 denier) was used to stitch bond the glass fiber layers. The plain weave fabric of E-glass was obtained from PPG. The ratio of warp to filling yarn was approximately 1.3:1. Woven fabric structures result in inherent fiber waviness. A 156 denier Kelvar™ yarn was used for stitching the plain weave fabric layers in the thickness direction (denier is the weight of 9000 m length of yarn in grams). Three and six layers of plain weave fabrics were stitched. The stitching lines were 2, 5, 10, 15, and 20 mm apart. In all cases, both uniaxial and biaxial stitching modes were used. Kelvar™ stitching yarn accounted for less than 3% of the total woven fabric weight. Various samples tested are listed in Table 1.

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Sample description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM</td>
<td>Non-crimp laminate</td>
</tr>
<tr>
<td>PW</td>
<td>Plain Weave</td>
</tr>
<tr>
<td>US2</td>
<td>Uniaxial stitching 2 mm apart</td>
</tr>
<tr>
<td>US5</td>
<td>Uniaxial stitching 5 mm apart</td>
</tr>
<tr>
<td>US10</td>
<td>Uniaxial stitching 10 mm apart</td>
</tr>
<tr>
<td>US20</td>
<td>Uniaxial stitching 20 mm apart</td>
</tr>
<tr>
<td>BS2</td>
<td>Biaxial stitching 2 mm apart</td>
</tr>
<tr>
<td>BS5</td>
<td>Biaxial stitching 5 mm apart</td>
</tr>
<tr>
<td>BS10</td>
<td>Biaxial stitching 10 mm apart</td>
</tr>
<tr>
<td>BS20</td>
<td>Biaxial stitching 20 mm apart</td>
</tr>
</tbody>
</table>

The glass preform containing three, six, or 12 layers was placed in the steel mold. The mold dimension was 25.4 × 30.5 × z cm³. The sample thickness varied between 0.18 and 0.63 mm. Two different molds and an aluminum plate were used for varying sample thickness. There were two nozzles in the mold, one for resin injection and the other one for vacuum line to remove air bubbles. Some of the excess resin was also removed through the vacuum nozzle. The mold was impregnated with the epoxy resin (EPON 862 and the curing agent W in the weight ratio 100:26). Both components of the epoxy were obtained from Shell Chemical Co. Before injecting in the mold, the epoxy resin was heated to approximately 45°C. The equipment used was a VRM 2.5 Resin Transfer Molding machine from Liquid Control Corporation. The system was totally enclosed and the mixing of resin and curing agent only took place at the final stage with the mixing chamber at the point of dispensing in the mold. After resin transfer, the specimen was cured at 125°C for 6 h.

Density was measured by weighing the composite samples in air and in water. Fiber volume fraction was determined using the following equation:

\[ \rho_c = \rho_f V_f + \rho_m V_m \]

where \( \rho \) is the density and \( V \) the volume fraction. The presence of voids was not accounted for. Subscripts c, f, and m refer to composite, fiber and matrix, respectively. The density of the fiber and matrix were taken to be 2.58 and 1.2 g cm³, respectively. For the stitched and unstitched woven samples, three, six, and 12 fabric layers were used for the bending, compression, and grooved shear tests, respectively. To achieve comparable thickness, for the non-crimped laminate samples, six and 12 plies were used for the bending and compression tests, respectively.

3. Mechanical testing

The following test methods were used to determine the interlaminar shear strength: (i) short beam shear test (ASTM D2355); and (ii) tensile testing of grooved coupons (ASTM D2677). The length-to-depth (l/d) ratio in the short beam shear test was approximately 5. The thickness of the grooved coupon was 7.2 mm, groove depth was 3.5 mm and the distance between the grooves was 20 mm.

Low-velocity impact was applied to the specimen using a small pendulum apparatus. The diameter of the hemispherical impactor was 10 mm. The impact energy ranged from 0 to 8.7 J, and this corresponds to 0–2.5 J mm⁻¹ of the sample thickness. Impact loading produced near-circular damage areas. These samples were subsequently used for compression after impact and bending after impact testing.

Bending strength was measured according to the ASTM 790-91 test method. The three-point loading scheme was selected, and the test was performed using Instron 5500 universal testing machine. The length to depth ratio was 40:1. Compressive strength was determined using the IITRI method (ASTM D3410). The sample dimensions were 120 × 40 × z cm³, and the gauge length was 25 mm.

4. Results and discussion

4.1. Interlaminar shear strength

Initially attempt was made to determine the interlaminar shear strength using the short beam shear test. However, it was observed that the short-beam shear specimens of the unstitched fabric composites did not develop shear cracking in the mid-plane of the specimens as required in the ASTM test. Apparent shear strength of 47 MPa was calculated for this composite, however, both the upper and lower surfaces underwent extensive damage. Damage in the upper surface of the beam is from compressive failure; damage in the lower surface is from tensile failure. There was no indication of shear failure or crack initiation in the mid-plane. Furthermore, fiber unevenness deterred fabric plane slippage, and additional through-the-thickness stitching practically eliminated the possibility of inter-plane slippage. Thus, interlaminar failure was not observed. Based on these observations, it was concluded that the short-beam shear test
Shear testing was therefore done using the grooved coupon test. In comparison to the short beam shear test, the grooved coupon test is purely in a state of Mode II loading. In the grooved coupon specimens, shear cracking initiates around the notch and propagated between the fabric layers. The failed samples were characterized by the full-length delamination along the plane between the grooves.

Table 2 lists the data on interlaminar shear strength of 2D woven and through-the-thickness stitched woven composites measured using the grooved test. Two factors affect grooved coupon test results: (i) shear stress concentration predominantly develops around the grooves; and (ii) shear strength measured by the grooved coupon test also varies depending on the precision of the cut of the grooves. Some tearing in the composite takes place during the testing of undercut specimens. Bending and peeling also occurs especially for the overcut specimen. Z-directional kevlar yarn used in stitching fiber appears to resist shear crack development. Table 2 shows that increasing density of Z-directional stitching yarn moderately increases the delamination resistance of the composite. The crack surface was clear and smooth for the plane weave fabric composite as seen in Fig. 1, which represents poor adhesion between fiber and the matrix.

### 4.2. Bending strength

Bending and bending-after-impact strength data is presented in Table 3. In general, stitching adversely affect the bending behavior. Higher stitching density lowers the bending strength. Three-point bending load versus displacement curves for the unstitched samples were characterized by “knee” effect and non-linearity. Similar load–displacement behavior is also reported for this sample in tensile test [21]. The non-linearity is caused primarily by a structural change in the fabric during deformation. “Knee” effect occurs, when layers, whose filament axes are perpendicular to the loading direction, crack or break. Bending curve for uniaxial and biaxial stitched composites in general are different from those of the unstitched plain weave composites. Densely stitched samples did not exhibit “knee” effect. Bending test showed that the outer layer fracture along the beam axis led to the final failure. A closer observation of the specimen showed that there was some visible damage on the compressive side. As loading progressed, cracking first developed in outer ply on the tensile side. Microcracking initiated when the stress exceeded the local matrix pocket strength.

### 4.3. Impact damage analysis

The impact damage zone is generally complex in nature and consequently not easy to characterize [22]. Due to the lack of existing standards or the established test techniques for impact damage of composite materials, direct comparison of data for various material systems reported in the literature are often misleading. We have determined impact damage using a pendulum tester, which generated approximately round-shape damaged areas. Three energy levels, i.e. 0, 1.65, 2.5 J mm\(^{-2}\), were used in the present study. Damage area increased with the increasing impact energy. At the impact point on the surface of the specimen, the damage consisted primarily of crushed material with some delamination between plies at the interface. A cone of damage was formed beneath the point of impact. The amount of crushed material decreased with increasing depth whereas the interlaminar delamination increased. In specimen without through-the-thickness reinforcement, the damage cone angle was much smaller and damage area did not increase with the depth. An analysis suggests a number of damage
mechanisms. These include delamination, fiber–matrix debonding, and interlaminar matrix cracking.

The energy absorbing capability of composites depends on the properties of the constituents, and is reflected in the damage area. Table 4 lists relative damage areas for various stitching density samples. It was clear that stitching reduces damage area and dense stitching is more effective in the damage area reduction. Significantly higher damage area was observed in the laminate composites than the composites made from the plain weave fabric.

An interesting phenomenon is that increasing the thickness of the specimen resulted in an increase in the delamination area as can be seen from the results of three and six layer samples reported in Table 4. This increase in damage area may result from the reduction in energy absorbing capability as proposed by Dorey [23]. It was suggested that the number of likely delamination sites increase with fabric thickness. More manufacturing defects and voids may be present in the thick samples.

4.4. Compressive strength

Compression test results are given in Table 5 and compressive stress–strain curves are shown in Fig. 2. The results indicate that the 0/90° non-crimp laminate has higher compressive strength as compared to the woven samples, a result of fiber waviness in the woven samples. The influence of waviness parameters, such as wavelength and amplitude, on the compressive behavior has not been studied extensively. This study only describes some experimental observations and shows qualitatively that the compressive strength decreases with the increasing fiber misalignment or waviness.

The different compressive response can also be reflected in the failure mode. Fig. 3a shows the IITRI compression failure of the 0/90° non-crimp laminate. Compressive loading resulted in the formation of a shear band. There was no relative displacement of the fibers across the failure zone, i.e. transverse movement across the failure band. Post-failure examination showed that shear band was at 45° angle to

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Fiber volume (%)</th>
<th>Composite thickness (mm)</th>
<th>Bending strength (MPa)</th>
<th>Bending strength after impact (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW</td>
<td>1.76</td>
<td>43</td>
<td>2.35</td>
<td>370 ± 13</td>
</tr>
<tr>
<td>BS 5</td>
<td>1.71</td>
<td>40</td>
<td>2.50</td>
<td>220 ± 10</td>
</tr>
<tr>
<td>BS 2</td>
<td>1.71</td>
<td>40</td>
<td>2.51</td>
<td>233 ± 9</td>
</tr>
<tr>
<td>US 20</td>
<td>1.72</td>
<td>41</td>
<td>2.53</td>
<td>326 ± 9</td>
</tr>
<tr>
<td>US 5</td>
<td>1.71</td>
<td>40</td>
<td>2.52</td>
<td>198 ± 3</td>
</tr>
<tr>
<td>US 2</td>
<td>1.7</td>
<td>39</td>
<td>2.50</td>
<td>177 ± 6</td>
</tr>
</tbody>
</table>

* Bending strength after impact (energy level 2.5 J mm⁻¹).

<table>
<thead>
<tr>
<th>Sample code</th>
<th>Damage area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three layer composite</td>
<td>Six layer composite</td>
</tr>
<tr>
<td>PW</td>
<td>100 (283 mm²)</td>
</tr>
<tr>
<td>BS 20</td>
<td>87</td>
</tr>
<tr>
<td>US 20</td>
<td>87</td>
</tr>
<tr>
<td>BS 10</td>
<td>43</td>
</tr>
<tr>
<td>US 10</td>
<td>–</td>
</tr>
<tr>
<td>BS 5</td>
<td>28</td>
</tr>
<tr>
<td>US 5</td>
<td>33</td>
</tr>
<tr>
<td>US 2</td>
<td>22</td>
</tr>
</tbody>
</table>

Fig. 2. Compressive stress–strain curves for glass fiber–epoxy composites: (a) non-crimp 0/90° laminate (LM) composite; (bi) plain weave (PW) unstitched composite; (bii) uniaxially (US5) stitched composite; and (biii) biaxially stitched (BS5) composite.
the loading direction. Samples failing in this mode yielded high compressive strength values.

Fig. 3b shows the IITRI compression failure in the plain weave fabric composite. The damage appears to be initiated by interlaminar stress, generated by the waviness of fiber. These interlaminar stresses appear to cause local delamination in the sample, thereby reducing the local transverse support for the fibers. The fibers in adjacent region of low waviness were thus likely to be overloaded. Finally, global microbuckling can be observed in these composites. Delamination and global buckling are in fact a bending failure due to interlaminar stresses. Composites failing in this mode yielded relatively low compressive strength.

The compressive failure in the composites made from loosely stitched woven fabrics was comparable to that of the unstitched fabric composites. However, the dense stitching appeared to have different failure mode. Fig. 3c shows typical failure mechanism for the densely stitched biaxial woven composite. Localized failure in the form of a kink band can be seen in the crack initiation. Argon [24] suggested that the regions in a composite in which fibers are not aligned with the compression axis would form a failure nucleus that undergoes kink band formation.

4.5. Compression-after-impact strength

As discussed previously, impact damage area is a function of impact energy. The CAI strength is very much dependent on the impact energy. Compression-after-impact data at two energy levels (1.65 and 2.5 J mm$^{-1}$) are reported in Table 5. It is seen that compressive strength of undamaged laminate is 15% higher than that of the composite from woven fabric. However, after being subjected to impact energy of 2.5 J mm$^{-1}$, CAI strength of woven fabric composite was up to 37% higher than that of the laminate. CAI of 5 mm spacing biaxial stitched woven specimen was over 60% higher as compared to the laminate composites. This dramatic reversal in the structural performance of the glass–epoxy composite materials is consistent with published results for graphite–epoxy composites [25]. The specimens with stitched through-the-thickness reinforcement exhibited higher CAI strength than the unstitched woven fabrics did. Loose stitching was not much effective in improving the CAI strength.

The macroscopic failure modes of CAI samples are different from the compression behavior of undamaged samples. Fig. 4a shows interlaminar splitting mode in a

![Fig. 3. Compressive failure in: (a) non-crimp laminate composite; (b) unstitched woven composite; and (c) biaxial stitched (stitching lines 5 mm apart) woven composite.](image-url)
laminate composite. Interlaminar crack is caused due to the delamination in the impact damaged region. For unstitched woven and loosely stitched sample, the CAI fracture is mix-mode as shown in Fig. 4b. Crack was caused by the buckling–bending close to the damaged region, followed by debonding. Loose stitching has played no obvious role in moderating failure propagation. Fig. 4c shows kink failure for densely stitched sample. The kink band in the damage sample propagated through the sample thickness at an angle of 37° rather than the 45° angle in the undamaged composite.

5. Conclusions

There is no clear evidence of cracking in the mid-plane of woven glass fiber–epoxy composites during the short beam shear (SBS test). The grooved coupon test for interlaminar shear strength shows that increasing density of Z-directional stitching fibers will moderately increase the delamination resistance of the composites. Composites of stitched 2D woven samples exhibited lower bending strength as compared to the unstitched samples. Z-directional stitching is effective in reducing the impact damage.

The compressive strength of the non-crimp laminate samples is about 15% higher than that for the woven fabric composite, a result of waviness in the woven fabric composites. At high stitching density, CAI has been significantly improved. Compression failure modes for the variety of fiber arrangements are different. The experimentally observed shear failure of fiber across the specimen thickness was the failure mechanism of laminate composites. Delamination, followed by microbuckling and global buckling is the failure observed in woven fabric composites. The densely stitched composites appear to fail via kinking followed by fiber buckling.

CAI samples display different fracture mechanisms. Interlaminar splitting is the dominant mode of fracture in unstitched woven fabrics and laminate composites. Densely stitched samples showed shear failure via kinking.

Acknowledgements

This work was supported by the US Department of Commerce through the National Textile Center (Grant no. 99-27-07400).

References


