Experimental investigation of span length for flexural test of fiber reinforced polymer composite laminates

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ABSTRACT
Testing and evaluation of mechanical properties for FRP (Fiber Reinforced Polymer) composite parts play a significant role to qualify it for the end use. Among the mechanical properties, the flexural strength is significant and vital as it may vary with specimen depth, temperature and the test span length. The flexural strength varies for different materials with varying the test span length hence the current work aims to find an optimum span length to test flexural strength for the specimens made of Glass (7781, EC9756) and Carbon (HTA7, G801) prepreg materials. Experiments are conducted as per the ASTM Standard D 790 for flexural test by varying the span lengths to understand the behavior of the flexural strength and flexural modulus. The experimental data were compared with those obtained from the finite element program software Altair Hyper works 14.0. The results indicate that flexural modulus increases with the span length to a point and then it decreases. Thereby, an optimum span length can be obtained for testing flexural strength, which will be useful to the designers and the composite manufacturers to accomplish better standard testing procedures.

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1. Introduction

Flexural or bending test can be used to get a semi qualitative idea of the fiber/matrix interfacial strength of a composite. The flexural tests are conducted to determine the mechanical properties of resin and laminated fiber composite materials. These test methods are generally applicable to both rigid and semi rigid materials. However, flexural strength cannot be determined for those materials that do not break or that do not fail in the outer surface of the test specimen within the 5.0% strain limit. These test methods utilize either a three-point or four-point loading system to a simply supported beam. Park et al. [1] have carried few studies on the changes in flexural strength with the change in stacking sequence of aramid fiber composite laminates. They found that the flexural failure mechanism, which had an effect on the flexural strength, depends on the stacking sequence. Christiansen et al. [2] have investigated the effect of testing variables and the volume

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fraction of fibers on the three-point bend testing of glass fiber-reinforced composite laminates. They found that the flexural strength obeys a simple law of mixture relationship with fiber loading but the shear strengths were independent of fiber loading. Variation in the amount of overhang had no effect on the shear strength of the composites, but they have not evaluated the effect of variation in span length on flexural strength. Nunes et al. [3] have carried studies on polymeric matrix composite discs supported on three points subjected to a bending test to study their behavior in complex flexural loading situations. These authors [3] noticed that the flexural behavior of the composites varies on fiber orientation, laminate stacking and surface waviness. Grande et al. [4] have carried studies to evaluate whether the span/diameter ratio (L/D) would affect the mechanical properties of fiber reinforced composite posts. They noticed that the span diameter ratio is an important parameter for the interpretation of flexural strength and flexural modulus. Valarinho et al. [5] conducted experiments to study the flexural behavior of multi span composite beams made of annealed glass panes reinforced with GRFP. They mentioned that the ultimate load and the post-cracking performance of the multi span composite beams are affected by the type of the adhesive used to bond the GRFP to glass panes. Studies on the flexural fatigue behavior and enhancement of residual strength in 2D cross-ply carbon fiber reinforced carbon composites were done to show that the three-point bending fracture in both unfatigued and fatigued specimens is of delamination mode [6]. Few research has been done on short fiber reinforced composites to study the effect of flexural strength with different span lengths. It was found that as the span length reduces the flexural properties showed linear reduction [7]. Few studies have been reported earlier to analyze the effects of the specimen thickness and width on the flexural modulus in general for a composite laminate using Ansys [8]. However, the effect of the testing span length was not considered and the testing span length set for one class of material will not be the same for other types of laminates. Kumar et al. [9] conducted experiments to study the impact of the UTM testing speed on the inter-laminar shear stress and the flexural strength on fiber composites. Singh et al. [10] have carried experiments and found that with increasing in weight fraction of reinforcement, the tensile strength and flexural strength increased by 14.5% and 123.65% for 20% glass reinforced composites over pure epoxy. Haldar et al. [11] investigated the behavior of curved sandwich composite structures by performing flexural test for two different radii of curvature. Stiffness, strength and failure initiation were predicted using Finite Element Analysis (FEA) and the numerical simulations were verified with the experimental measurements. Alander et al. [12] have carried experiments to find flexural strength and flexural modulus of fiber-reinforced composite (FRC) specimens of rectangular and circular cross-sections with varying span length (L) to diameter (D) ratio. On the basis of their results, it was concluded that by increasing L/D ratio, the flexural strength and flexural modulus increased for shorter span length up to 20 mm. Hence the testing method, specimen dimensions and the process parameters play a significant role in the evaluation of flexural strength of any composite laminate. So, it is necessary to determine the effect of the testing span length on the flexural properties to find an optimum span length for a particular type of composite material. This paper solicits to find the optimum testing span length for flexural strength of four commercially used BD Carbon fiber G801, BD Glass fiber-7781, UD carbon fiber-HTA7 and UD Glass fiber-EC9756 materials. Bending moment in a three-point bending test increases from the support points of the beam to a maximum value at mid-point, i.e., maximum stress is reached along a line at the center of the beam, where the bending moment and the flexural stress is given by the following equations.

\[
M = \frac{P L}{2} = \frac{P L}{2}
\]

(1)

\[
\sigma_f = \frac{3PL}{2b_d^2}
\]

(2)

where P is the load, L is the length of support span, b is the width of test specimen and t is the thickness/depth of test specimen.

If support span-to-depth ratio greater than 16/1 are used such that deflections in excess of 10% of the support span occur, the stress in the outer surface of the specimen for a simple beam can be reasonably approximated with the following equation [13].

\[
\sigma_f = \frac{3PS}{2bd^2} \left[ 1 + \frac{D}{L} \left( \frac{d}{L} \right) \right]
\]

(3)

where D is the deflection of the center line of the specimen at the middle of the support span.

When large support span-to-depth ratios are used, significant end forces are developed at the support noses which will affect the moment in a simply supported beam. Eq. (3) includes additional terms that are an approximate correction factor for the influence of these end forces in large support span-to-depth ratio beams where relatively large deflections exist. Flexural modulus is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and is given by Eq. (4).

\[
E_f = \frac{L m}{4bd^3}
\]

(4)

where m is the slope of the tangent to the initial straight-line portion of the load-deflection curve.

1. Materials and method

Prepreg materials of Carbon UD (Hexply 913/35%/132/HTA7), Carbon BD (Hexply 913/40%/G 801), Glass UD (Hexply 913/28%/192/EC 9756) and Glass BD (Hexply 913/37%/7781) were used to manufacture the laminates. Hand-lay-up method was used to manufacture the laminates of size (150 mm × 150 mm) with [0/90]_s layer stacking sequence and were cured in autoclave. The cured laminates are tested for NDT tests like Ultrasonic C scan test to check the internal defects like voids and the compaction of the cured laminates and the C scan images of the four laminates were tested as shown in Figs. 1–4. The C scan profile indicates the absence of the voids and internal defects in the cured laminates. All four
laminates show the satisfactory attenuation levels and there is no indication of poor compaction.

The specimens were prepared from the cured laminates as per the ASTM D 790 standards in rectangular cross-section specimens (127 mm × 12.7 mm × 2 mm) as shown in Fig. 5.

Three-point bending test was performed on a Universal Testing Machine (UTM) manufactured by Star Testing System, Bombay with a maximum load cell of 50,000 N. The tests were carried at a crosshead speed of 2 mm/min and at four different span-to-depth ratio, i.e., 16 mm, 24 mm, 32 mm and 40 mm and depth of the specimen is taken as 2 mm for all the specimens. Five specimens of each material were tested and the load-deflection curves are plotted for different materials with varying span length to determine the flexural strength and flexural modulus.

3. Results and discussion

The flexural strength was calculated for specimens tested at different span lengths using the formulae given by Eqs. (2) (with correction factor) and (3) (without correction factor). From the characteristic graphs, it shows that the flexural strength increases with increase in span length for both carbon and glass BD (G801 & 7781) as shown in Figs. 6 and 7, while it decreases with increase in span length for carbon and glass UD laminates (HTA7 & EC 9756) as shown in Figs. 8 and 9, which signifies that the BD laminates are more stiffer and stronger than the UD laminates, as the maximum bending displacement is obtained in the BD laminates.

Flexural modulus was calculated using Eq. (4) to determine the optimum span length for the selected material laminates.

Numerical analysis was carried out using Altair HyperWorks 14.0 to evaluate the flexural behavior of Carbon UD-HTA7 and Carbon BD-G801 with span lengths of 24 mm, 32 mm, 48 mm, 64 mm, 80 mm and 96 mm. The comparison of values of reaction force and displacement obtained from numerical analysis results with the experimental analysis results is presented in Tables 1–4.

Flexural modulus values were obtained from numerical and experimental results of Carbon UD-HTA7 and Carbon BD-G801. Characteristic graphs are plotted between the flexural
modulus ($E_f$) and support span length ($L$) for all four materials as shown in Figs. 10–13.

To find the optimum span length, best fit curve approach is used. Apart from the span lengths 32 mm, 48 mm, 64 mm and 80 mm, the numerical analysis is done for two extra span lengths 24 mm and 96 mm. It is concluded that the polynomial of degree 3 provides best fit for the data points with minimum percentage error between numerical results and experimental results, due to which the data is extrapolated for other two materials using the equation of curve. The values of flexural
Analysis depicts that the flexural modulus initially increases and then decreases gradually with the increase in the span length for all four materials. The behavior of the flexural modulus shows the optimum span length is at the point where the maxima of flexural modulus vs span length curve occurs. The values of optimum span length obtained from the graphs on the modulus basis are the following. For CFRP-G801 was 80 mm, CFRP-7781 was 67 mm, CFRP-HTA7 was 48 mm and GFRP-EC 9756 was 42 mm.

Table 1 – Comparison (reaction force) of the numerical analysis results with the experimental analysis results for Carbon UD-HTA7 laminate.

<table>
<thead>
<tr>
<th>Span length (mm)</th>
<th>Numerical analysis</th>
<th>Experimental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>600</td>
<td>–</td>
</tr>
<tr>
<td>32</td>
<td>1691.02</td>
<td>1577.8</td>
</tr>
<tr>
<td>48</td>
<td>943.57</td>
<td>940.8</td>
</tr>
<tr>
<td>64</td>
<td>660.47</td>
<td>627.2</td>
</tr>
<tr>
<td>80</td>
<td>563.58</td>
<td>529.2</td>
</tr>
<tr>
<td>96</td>
<td>247</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2 – Comparison (displacement) of the numerical analysis results with the experimental analysis results for Carbon UD-HTA7 laminate.

<table>
<thead>
<tr>
<th>Span length (mm)</th>
<th>Numerical analysis</th>
<th>Experimental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>32</td>
<td>1.95</td>
<td>2.02</td>
</tr>
<tr>
<td>48</td>
<td>3.3</td>
<td>3.66</td>
</tr>
<tr>
<td>64</td>
<td>6.45</td>
<td>6.53</td>
</tr>
<tr>
<td>80</td>
<td>9.75</td>
<td>9.7</td>
</tr>
<tr>
<td>96</td>
<td>10</td>
<td>–</td>
</tr>
</tbody>
</table>
**Table 3** – Comparison (reaction force) of the numerical analysis results with the experimental analysis results for Carbon BD-G801 laminate.

<table>
<thead>
<tr>
<th>Span length (mm)</th>
<th>Numerical analysis</th>
<th>Experimental analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>1669</td>
<td>–</td>
</tr>
<tr>
<td>32</td>
<td>1079</td>
<td>941</td>
</tr>
<tr>
<td>48</td>
<td>820</td>
<td>617</td>
</tr>
<tr>
<td>64</td>
<td>595</td>
<td>480</td>
</tr>
<tr>
<td>80</td>
<td>449</td>
<td>405</td>
</tr>
<tr>
<td>96</td>
<td>285</td>
<td>–</td>
</tr>
</tbody>
</table>

**Table 4** – Comparison (Displacement) of the Numerical analysis results with the Experimental analysis results for Carbon BD-G801 laminate.

<table>
<thead>
<tr>
<th>Span length (mm)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Numerical analysis</td>
</tr>
<tr>
<td>24</td>
<td>1.5</td>
</tr>
<tr>
<td>32</td>
<td>1.65</td>
</tr>
<tr>
<td>48</td>
<td>4.2</td>
</tr>
<tr>
<td>64</td>
<td>6.5</td>
</tr>
<tr>
<td>80</td>
<td>9</td>
</tr>
<tr>
<td>96</td>
<td>12</td>
</tr>
</tbody>
</table>

**Fig. 10** – Flexural modulus behavior with the span length for Carbon BD G-801-laminate.

**Fig. 11** – Flexural modulus behavior with the span length for Carbon UD-HTA7 laminate.

**Fig. 12** – Flexural modulus behavior with the span length for Glass BD 7781 laminate.

**Fig. 13** – Flexural modulus behavior with the span length for Glass UD-EC9756 laminate.

**4. Conclusion**

The behavior of flexural strength and flexural modulus with the test span length was evaluated for four materials at four different test span lengths as per the ASTM standards. The results depict that the flexural strength increases with the test span length for the specimens made out of BD (Bi-Directional) prepreg layers. Similarly, the flexural strength decreases gradually with the increase in test span length for the specimens made out of UD (Uni-Directional) prepreg layers. However, the flexural modulus increases with the increase in the span length up to a point and then it gradually decreases for both UD and BD materials.

The experimental results and the numerical analysis proved a good agreement for all four materials as evident from the results obtained for the Carbon BD-G-801 and Carbon UD-HTA7.

**Conflicts of interest**

The authors declare no conflicts of interest.

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