Initiation of damage in composite plates under transverse central static loading

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Abstract
Experimental and analytical studies have been carried out on transverse static central load threshold for damage initiation. Experiments have been carried out on a typical plain weave E-glass/epoxy laminated plate. A good correlation is observed between the experimental results and finite element analysis predictions. Further, analytical studies have been carried out on the effect of reinforcement architecture on the load threshold for damage initiation. It is observed that transverse static central load threshold for damage initiation is higher for woven fabric composites compared to those of cross-ply laminates made of unidirectional layers and unidirectional composites.

Keywords: Damage initiation; Transverse static loading; Experimental results; Prediction; Woven fabric composites

1. Introduction
Polymer matrix composite materials are finding increasing use in high performance applications because of their high inplane specific stiffness and specific strength. For effective use of composite structures, they should be able to withstand multidirectional loading also. Composite structures under transverse static loading are one of the important design requirements. For laminated composites made of unidirectional (UD) layers different failure modes are: matrix cracking/ lamina splitting, fibre debonding, delamination and fibre breakage. Normally, the macro damage initiation takes place in the form of matrix cracking/lamina splitting and delamination.

Stress analysis of laminated composite plates subjected to transverse loading has received considerable attention of researchers, and many articles are available [1–8]. The objective of the present work is to look into the initiation of damage in composite plates under transverse central static loading. Experimental studies have been carried out on a typical plain weave E-glass/epoxy laminate. The damage initiation has also been predicted using the inhouse finite element analysis code. Further, a parametric study has been carried out on damage initiation with different reinforcement architectures. Specifically, the studies have been carried out on balanced symmetric cross-ply laminates made of UD layers, woven fabric (WF) composites and three-dimensional (3D) composites.

2. Stress and damage analysis
A three-dimensional linear elastic finite element analysis has been used to predict the initiation of damage in composite plates. A 3D eight-noded brick element was used in the analysis, with three degrees of freedom at each node \((u, v, w)\). The aspect ratio considered in the present analysis is inbetween 1 and 2. By taking symmetry into consideration, quarter plate analysis was used for the present study. Convergence study was carried out for the mesh size. Based on this study, a mesh size of \(32 \times 32 \times 5\) was chosen for the quarter plate. The co-ordinate system for the composite plate is shown in Fig. 1. The boundary conditions for quarter plate are as given below:
(a) Simply supported boundary conditions:
At \(X = 0\), \(u \neq 0, v = 0, w = 0\),
At \(X = L_X/2\), \(u = 0, v \neq 0, w \neq 0\),
At \(Y = 0\), \(u = 0, v \neq 0, w = 0\),
At \(Y = L_Y/2\), \(u \neq 0, v = 0, w \neq 0\).
3. Damage evolution during transverse central quasi-static loading

The damage initiation in laminated composite plates subjected to transverse loading can be in the form of matrix cracking/lamina splitting, debonding and initiation of delamination. Upon further loading, the major damage propagation mode can be the delamination growth, and the cracking of the adjacent layers, finally leading to fibre breakage and fibre pull out. Matrix micro-cracking and the debonding are the micro-failure mechanisms, and can take place at very early stages. For UD-laminated composites the first macro damage occurs in the form of lamina splitting on the tensile side of the laminates during transverse loading because of the inplane stresses [11]. This is because of the lower transverse tensile strength properties of the UD lamina.

Lammerant and Verpoest [11] carried out transverse quasi-static loading experiments on cross-ply laminate [90/0]/s made of toughened carbon/epoxy prepreg HTA/6376. In the experiments, they used plate-like composite specimens clamped in a square fixture and loaded at a speed of 0.01 mm/sec with a hemispherical tup at a central loading point. The laminates could still slide in the fixture because of the flat polished surface of the fixture. So, at the edges the fixture only prevented the plate from translating in the loading direction or rotating. The unsupported area of the composite plate was 80 mm × 80 mm and the thickness 1.8 mm. Using the acoustic emission technique and ultrasonic testing, they monitored initiation and propagation of damage. They observed that the first damage in the laminate was matrix cracking/lamina splitting in the bottom layer right under the loading point at a displacement of 1 mm. They experimentally observed that the first matrix crack initiated only a small delamination in the centre of the plate at the lower interface.

The WF composites are characterised by balanced inplane properties. Hence, inplane elastic and strength properties are equal along both warp and fill directions. Hence, early lamina splitting may not take place. It was observed that the failure initiates in the top layer for WF laminates because of inplane stresses [12]. This is because of lower inplane compressive strength of the WF laminate compared to its inplane tensile strength. The damage can also initiate in the form of delamination at different interfaces because of interlaminar stresses for WF composites.

4. Experimental studies: transverse quasi-static loading

Composite plates of dimension 150 mm × 150 mm × 5 mm made of a typical plain weave E-glass/epoxy laminate GLE-12 were used for the experimental studies under transverse quasi-static loading. Loading was
performed on the clamped specimen at the rate of 0.2 mm/min. The unsupported area of the plate was 128 mm × 128 mm. Loading was continued till the damage initiated. Tests were planned at loads at which the damage just initiated and at loads at which substantial damage occurred. Experimental load–displacement behaviour is presented in Fig. 2.

In the first test, loading was continued till a substantial damage was visible on the top and bottom surfaces of the specimen. The maximum load in this case was 5.12 kN. In the second test, loading of the specimen was continued until damage was clearly visible on the top surface. The corresponding load was 4.06 kN. C-scans also showed damage at this load. The other two tests were carried out at comparatively lesser loads of 2.3 and 2.56 kN. No clear damage was visible on any of the surfaces. However when viewed against a strong source of light, these specimens showed a dense region below the point of contact. The C-scans did not show any damage. It can be taken that the point damage initiated at a load below 2.3 kN. Typical C-scans are shown in Fig. 3.

4.1. Validation

Using the inhouse finite element analysis code [13,14], the central point displacement and the inplane failure function have been evaluated in the present study for the composite plate used in [11]. It was observed that, the failure had just initiated in the form of matrix cracking/ laminate splitting in the bottommost layer as in the case of Lammerant and Verpoest experimental observations. Lammerant and Verpoest considered quasi-static load-

Material: Plain weave E-glass/epoxy laminate, GLE-12, Lz = 5 mm.
Plate dimension: 150 mm x 150 mm.

Fig. 3. Damage shapes and sizes under transverse quasi-static central loading: C-scan results.

As seen earlier, the boundary condition was not simply supported or clamped realistically for the experimental studies of Lammerant and Verpoest [11]. Hence, the displacement predicted should be in between the limiting case of 1.221 mm for simply supported case and 0.57 mm for the clamped case at I_1 = 1.04.

Realistically, the transverse central loading can be treated as a small patch load rather than a point load. Hence the transverse load was distributed over a central patch for the predictions. The patch area considered was 0.097% of the plate area.

Further, the experimental and predicted results have been compared for plain weave E-glass/epoxy laminate GLE-12. The prediction was carried out with mechani-
Table 1
Elastic properties of composites: E-glass/epoxy

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{11}$ (GPa)</th>
<th>$E_{22}$ (GPa)</th>
<th>$E_{13}$ (GPa)</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{13}$ (GPa)</th>
<th>$G_{23}$ (GPa)</th>
<th>$v_{12}$</th>
<th>$v_{11}$</th>
<th>$v_{23}$</th>
<th>$V^o_{I}$</th>
<th>$\rho$ (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD</td>
<td>48.0</td>
<td>15.3</td>
<td>15.3</td>
<td>5.1</td>
<td>5.1</td>
<td>5.8</td>
<td>0.32</td>
<td>0.32</td>
<td>0.33</td>
<td>0.33</td>
<td>0.65</td>
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<td>UD</td>
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<td>8.3</td>
<td>2.8</td>
<td>2.8</td>
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<td>0.33</td>
<td>0.33</td>
<td>0.40</td>
<td>0.40</td>
<td>1750</td>
</tr>
<tr>
<td>GLE-12</td>
<td>20.8</td>
<td>20.8</td>
<td>8.7</td>
<td>3.92</td>
<td>4.2</td>
<td>4.2</td>
<td>0.17</td>
<td>0.28</td>
<td>0.28</td>
<td>0.44</td>
<td>1808</td>
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<tr>
<td>WG02G</td>
<td>20.8</td>
<td>20.8</td>
<td>8.7</td>
<td>3.92</td>
<td>4.2</td>
<td>4.2</td>
<td>0.17</td>
<td>0.28</td>
<td>0.28</td>
<td>0.40</td>
<td>1750</td>
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<tr>
<td>3D-O</td>
<td>20.1</td>
<td>19.9</td>
<td>14.0</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
<td>0.20</td>
<td>0.29</td>
<td>0.30</td>
<td>0.40</td>
<td>1750</td>
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<tr>
<td>3D-OO</td>
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<td>19.5</td>
<td>11.7</td>
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<td>3.9</td>
<td>3.9</td>
<td>0.19</td>
<td>0.36</td>
<td>0.36</td>
<td>0.40</td>
<td>1750</td>
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Toughened carbon/epoxy HTA/6376

<table>
<thead>
<tr>
<th>Material</th>
<th>$X_I$ (MPa)</th>
<th>$Y_I$ (MPa)</th>
<th>$Z_I$ (MPa)</th>
<th>$S_{12}$ (MPa)</th>
<th>$S_{13}$ (MPa)</th>
<th>$S_{23}$ (MPa)</th>
<th>$X_C$ (MPa)</th>
<th>$Y_C$ (MPa)</th>
<th>$Z_C$ (MPa)</th>
<th>$V_{I}^o$</th>
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<tbody>
<tr>
<td>UD</td>
<td>1297</td>
<td>27.8</td>
<td>27.8</td>
<td>39.2</td>
<td>39.2</td>
<td>38</td>
<td>820</td>
<td>150</td>
<td>150</td>
<td>0.65</td>
</tr>
<tr>
<td>UD</td>
<td>798</td>
<td>27.1</td>
<td>27.1</td>
<td>36.8</td>
<td>36.8</td>
<td>36</td>
<td>480</td>
<td>140</td>
<td>140</td>
<td>0.40</td>
</tr>
<tr>
<td>GLE-12</td>
<td>360</td>
<td>360</td>
<td>32.0</td>
<td>28.0</td>
<td>28.0</td>
<td>28</td>
<td>225</td>
<td>225</td>
<td>445</td>
<td>0.44</td>
</tr>
<tr>
<td>WG02G</td>
<td>250</td>
<td>250</td>
<td>27.1</td>
<td>28.0</td>
<td>28.0</td>
<td>28</td>
<td>183</td>
<td>183</td>
<td>140</td>
<td>0.40</td>
</tr>
<tr>
<td>3D-O</td>
<td>359</td>
<td>340</td>
<td>83.0</td>
<td>36.8</td>
<td>36.8</td>
<td>36</td>
<td>215</td>
<td>204</td>
<td>170</td>
<td>0.40</td>
</tr>
<tr>
<td>3D-OO</td>
<td>253</td>
<td>333</td>
<td>22.0</td>
<td>36.8</td>
<td>36.8</td>
<td>36</td>
<td>152</td>
<td>200</td>
<td>170</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Toughened carbon/epoxy HTA/6376

For static loading, the predictions showed that the point damage initiates at a transverse central patch loading of 2 kN. The experimental study also showed that the point damage would initiate at about 2 kN load. The corresponding central deflection, $\delta$ was 1.7 mm. The prediction shows $\delta = 1.0$ mm for clamped boundary condition and $\delta = 2.28$ mm for simply supported boundary condition. It was observed during experimentation that the composite plate could still slide even though clamped boundary condition was adopted. At the edges the clamping fixture only prevented the composite plate from translating in the loading direction or rotating. Hence, during experimentation, the boundary condition was not exactly clamped. The prediction of central deflection is based on clamped boundary condition. Hence, the central deflection predicted should be in between the limiting cases of 1.0 mm for clamped case and 2.28 mm for simply supported case.

5. Parametric studies

A parametric study has been carried out on the effect of reinforcement architecture on transverse static central load for damage initiation. Studies have been carried
Table 3
Stress and failure behaviour of composites under transverse central static loading

<table>
<thead>
<tr>
<th>Material</th>
<th>Load, P (kN)</th>
<th>Central displacement, ( \delta_m ) (mm)</th>
<th>( \sigma_x ) (MPa)</th>
<th>( \sigma_y ) (MPa)</th>
<th>( \sigma_z ) (MPa)</th>
<th>Failure function 11</th>
<th>Failure function 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD1</td>
<td>0.49</td>
<td>0.172</td>
<td>51.2</td>
<td>27.6</td>
<td>(−)16.3</td>
<td>0.99</td>
<td>−</td>
</tr>
<tr>
<td>UD2</td>
<td>0.51</td>
<td>0.301</td>
<td>55.8</td>
<td>27.5</td>
<td>(−)1.8</td>
<td>1.03</td>
<td>−</td>
</tr>
<tr>
<td>CP1</td>
<td>0.55</td>
<td>0.189</td>
<td>56.8</td>
<td>27.8</td>
<td>(−)2.3</td>
<td>1.00</td>
<td>−</td>
</tr>
<tr>
<td>CP2</td>
<td>0.58</td>
<td>0.334</td>
<td>62.5</td>
<td>27.4</td>
<td>(−)2.5</td>
<td>1.03</td>
<td>−</td>
</tr>
<tr>
<td>GL-E12</td>
<td>2.00</td>
<td>1.006</td>
<td>(−)22.7</td>
<td>(−)22.7</td>
<td>(−)139.0</td>
<td>−</td>
<td>1.02</td>
</tr>
<tr>
<td>WGO2G</td>
<td>1.60</td>
<td>0.805</td>
<td>(−)182.0</td>
<td>(−)182.0</td>
<td>(−)112.0</td>
<td>−</td>
<td>0.99</td>
</tr>
<tr>
<td>3D-O</td>
<td>1.85</td>
<td>0.938</td>
<td>(−)206.0</td>
<td>(−)204.0</td>
<td>(−)136.0</td>
<td>−</td>
<td>1.00</td>
</tr>
<tr>
<td>3D-OO</td>
<td>1.40</td>
<td>0.767</td>
<td>(−)154.0</td>
<td>(−)165.0</td>
<td>(−)102.0</td>
<td>−</td>
<td>1.01</td>
</tr>
</tbody>
</table>

*Plate dimensions: \( L_x = 128 \) mm, \( L_y = 128 \) mm, \( L_z = 5 \) mm, clamped.

1. \( J_{0}^{\phi} = 0.65 \).
2. \( J_{0}^{\phi} = 0.40 \).

Fig. 4. Transverse static central load threshold for damage initiation for E-glass/epoxy composites – clamped.

out on E-glass/epoxy composites clamped on all four sides using the inhouse finite element analysis code [13,14]. The plate dimension: 128 mm × 128 mm × 5 mm. The central patch area is 0.097% of the plate area.

Studies have been carried out on balanced symmetric cross-ply laminate (CP) made of UD layers and UD composites with fibre volume fraction, \( J_{0}^{\phi} = 0.65 \) and 0.4. Studies have also been carried out on two types of plain weave E-glass/epoxy composites (GL-E12 and WGO2G) and two types of 3D orthogonal through-the-thickness interlock woven composites (3D-O and 3D-OO). The mechanical properties are given in Tables 1 and 2 [12,15].

Transverse static central load threshold for damage initiation (P), central displacement (\( \delta_m \)) and peak stress values (\( \sigma_x \), \( \sigma_y \) and \( \sigma_z \)) are given in Table 3 and Fig. 4. It may be noted that the corresponding failure function values are equal to one. Damage initiates at the bottom surface (Fig. 1, point b) for CP and UD composites. This is because of lower transverse tensile strength of the unidirectional composites. On the other hand, failure initiates at the top surface (Fig. 1, point a) for WF and 3D composites. This is because of lower inplane compressive strength of WF and 3D composites compared to the corresponding tensile strength. It may be noted that through-the-thickness stress \( \sigma_z \) does not lead to initiation of delamination.

From Table 3 and Fig. 4 it can be seen that transverse static central load threshold for damage initiation is higher for WF and 3D composites compared to those of CP laminates made of UD layers and UD composites. This is because of balanced inplane properties of WF and 3D composites.

6. Conclusions

Experimental studies have been carried out on a typical plain weave E-glass/epoxy composite, and the transverse quasi-static central load threshold for damage initiation has been determined. The damage initiation has been predicted using the inhouse finite element analysis code. A good correlation is observed between the experimental and predicted results.

The transverse static central load threshold for damage initiation is higher for WF and 3D composites compared to those of CP laminates made of UD layers and UD composites.

Acknowledgements

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References