Interlaminar Fracture Toughness of Stitched FRP Composites

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Abstract: - Delamination study in Mode-I was carried out to investigate the effect of stitching on delamination crack growth of stitched and non-stitched composite specimens. The double cantilever beam (DCB) standard test method was chosen for delamination studies. The combination of unidirectional carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP) composite materials are used to laminate the composite specimens. It is shown that stitching significantly improves the resistance force and interlamine toughness of composite materials.

Key-Words: Composite; Natural; Stitched; Delamination;

1 Introduction

The fibre-reinforced polymer (FRP) composite materials provide functional and economic benefits such as enhanced strength, durability, and stiffness to weight ratio. This could also result in a net environmental benefit in terms of lower fuel consumption and CO2 emission. Composites are the preferred materials in a variety of industrial applications. Although they are primarily used in aerospace structures, they are also the materials of choice in such diverse applications as the marine engineering, automotive structural parts, micro-electro-mechanical systems, wind turbine blades as well as stiffeners for civil structures. In this regard, it is important to investigate such advanced composite materials as 3D-FRP composites with a view to improving their mechanical and physical properties further compared to the 2D-FRP composites.

Although composites do not experience metal-like fatigue failure, laminated composites are, nevertheless, prone to failure by delamination. This not only can occur during the manufacturing process due to such factors as voids and trapped gas, contaminated reinforcing fibres, insufficient wetting of fibres and machining operations, but it could also occur during the service due to impact shocks or environmental degradation, particularly moisture intake. Furthermore, under transverse mechanical loading, interlaminar stresses are induced which, owing to the substantial difference between the resin and fibre moduli results in a correspondingly large straining of the resin. In the absence of any through-thickness reinforcement, this could lead to delamination. One of the most significant delamination failure modes is known as Mode-I opening force.

2 Determination of Mode-I interlaminar fracture toughness

The mechanical characteristics of unidirectional GFRP and CFRP were obtained in accordance with the relevant standards [1-3]. These tests were tensile, shear, fibre volume fraction, coefficient of friction, double-cantilever beam (DCB) (Figure 1), and quasi-static crush box.

Fig. 1. DCB specimen for Mode I delamination testing for Natural stitched-10mm DCB specimen (All dimensions in mm).

All specimens were manufactured from unidirectional GFRP and CFRP materials of density
1.8 g/cm³ and 1.6 g/cm³ with epoxy resin. For determining the Mode-I interlaminar fracture toughness GIC, BS ISO 15024 standard was followed together with the corrections developed elsewhere to take into account for the end-block, DCB arm bending and root rotation. The recommended specimen size is at least 125mm long and 20-25mm wide with an initial crack length (i.e. length of the insert from the load line) of 50mm. Loading was carried out at a constant crosshead displacement rate of 2 mm/min. The position of the crack tip was monitored through the travelling microscope as the crack advanced. When the crack first visibly propagated, the displacement of the crosshead was recorded. As the crack propagation past the subsequent marked lines, the crack length and crosshead displacement were recorded. For each test configuration four specimens were tested.

Many novel techniques such as z-pinning and stitching have been developed to reinforce laminated polymer composites in the through-thickness direction as a solution to problems of poor impact damage tolerance, low through-thickness mechanical properties, and weak strength of bonded joints. The most common through-thickness reinforcement techniques are 3D weaving, stitching and braiding. These techniques are effective at increasing the delamination resistance and impact damage tolerance. The manufacturing of stitched hybrid composite specimens in the current investigation is similar to the normal hybrid composite specimens except that subsequent to stitch the laminated composite with natural Flax yarn before curing process. Yarns of Flax (with diameter of 1.1mm) were stitched discretely onto the test specimens through the thickness using a needle. The Mode-I interlaminar fracture toughness $G_{IC}$, for each fibre orientation was calculated using the Corrected Beam Theory (CBT) method and the Modified Compliance Calibration (MCC) method. For CBT method, the cube root of compliance, $C^{1/3}$, was plotted as a function of crack length, $a$. The intercept with the x-axis was considered as the crack length correction, $\Delta$. The $G_{IC}$ value was then obtained from:

$$G_{IC} = \frac{3F^2\delta^2}{2Abt}$$  \hspace{1cm} (2)

The experimental $G_{IC}$ results obtained from CBT and MCC for different fibre orientation are shown in Table 1. The experimental force displacement and resistance curves (i.e. $G_{IC}$ versus crack length) are shown in Figures 2-4. Transverse cracking of $\theta$-oriented lamina at interface caused some fibre bridging for most of DCB tests as shown in Figures 5. The development of fibre bridging caused the force to continuously increase as the crack advanced resulting in a rising R-curve. Regarding the results and recommendations of other works on DCB-tests on multidirectional laminates, $G_{IC}$ values of initiation were considered as interlaminar fracture toughness.

Fig. 2. Force-load line displacement from DCB and stitched-DCB tests for mid-plane interface of C90/G0.
Three different methods to determine crack length for the initiation values from the precrack as the distance between the force-displacement and the precrack are considered. The first non-linearity (NL) method determines the point of deviation from linearity, by sketching a straight line from the origin. The second uses the visual observation (VIS) which is the first point at which the crack is observed to move from the tip of the Teflon insert. The last is the MAX/5 %, a point on the force-displacement curve at which the compliance has increased by 5% of its initial value. In this work the visual observation (VIS) was chosen to determine the initiation crack length. It was observed that fibre orientation in the layers adjacent to crack plane affects the $G_{IC}$.

Transverse cracking for interface plane of C90/G0 happened at the beginning of delamination growth. The results of Mode-I delamination fracture toughness, $G_{IC}$, using non-linearity (NL) for each interface, were presented in Table 1.

Table 1. Interlaminar fracture toughness obtained from DCB tests for various interface fibre orientations.

<table>
<thead>
<tr>
<th>Laminate lay-up</th>
<th>Fracture plane interface</th>
<th>$G_{IC}$ (MCC) $J/m^2$</th>
<th>$G_{IC}$ (CBT) $J/m^2$</th>
<th>$G_{prop.}$ (MCC) $J/m^2$</th>
<th>$G_{prop.}$ (CBT) $J/m^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Stitched [C90/G0]</td>
<td>C90//G0</td>
<td>570±15</td>
<td>610±15</td>
<td>830±15</td>
<td>830±15</td>
</tr>
<tr>
<td>Natural-Stitched [C90/G0]</td>
<td>C90//G0</td>
<td>760±15</td>
<td>800±15</td>
<td>950±15</td>
<td>950±15</td>
</tr>
</tbody>
</table>

MCC: Modified Compliance Calibration Method, CBT: Corrected Beam Theory
3 Conclusion

This paper investigated the new 3D (stitched) hybrid composite laminate system which can significantly increase the interlaminar fracture toughness within the composite materials. This increase also causes the improvement of energy absorption capability and damage tolerance in the FRP composite absorbers. It is worth mentioning that natural Flax yarns can benefit composite manufacturers to reduce the manufacturing cost and overcome recyclability issues in the new generation of composite components.

References: