ADVANCED CRASH ABSORBERS STITCHED BY NATURAL FIBRES TO IMPROVE EFFECTIVE CRACK GROWTH RESISTANCE

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1. Introduction

In the present paper the effects of stitching on the energy absorption and crashworthy behaviour of composite box structures will be studied. The combination of unidirectional carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP) composite materials are used to laminate the composite boxes. Delamination study in Mode-I with the same lay-up was carried out to investigate the influence of stitching using natural flax fibres on the delamination failure, progressive crushing mechanisms and energy absorption capabilities of carbon fibre composite box absorbers under crushing load, using state-of-the-art techniques.

Most of previous researches have studied the effect of interlaminar fracture toughness on the crushing process of 2D composite materials. As discussed before, FRP composite structures are likely to experience delamination during their service life. It could be a proper motivation to investigate the response of stitched composite materials (3D) under crush loading.

Mouritz [1] published a comprehensive review into polymer composite laminates reinforced in the through-thickness direction with z-pins. Research into the manufacture, microstructure, delamination resistance, damage tolerance, joint strength and mechanical properties of z-pinned composites is described. Benefits of reinforcing composites with z-pins are assessed, including improvements to the delamination toughness, impact damage resistance, post-impact damage tolerance and through-thickness properties. Other experimental researches [2-6] have shown that z-pinning reduces the amount of delamination damage caused by impact events from low energy objects, ballistic projectiles and high-speed hailstones.
In this regard, the advanced manufacturing method is applied to stitch carbon-fibre composite testing specimens using sustainable natural flax fibres. The natural fibres running through the thickness of laminated composite structures will increase the resistance to crack propagation and consequently the energy absorption capability of composite absorbers. Natural flax fibres have the main advantage over the synthetic fibres (e.g. carbon and glass) of providing both resistance and progressive failure (effective crack growth resistance) in the wall of composite box absorbers (see Figure 1). Progressive failure can provide high energy absorption in a controllable behaviour which reduces the main injuries and death during a crash event.

The double cantilever beam (DCB) standard test method was chosen for delamination studies. For non-stitched and stitched composite boxes the lamina bending and brittle fracture crushing modes were observed. It was found that the stitched composite boxes which show higher fracture toughness in Mode-I delamination tests, are not necessarily able to absorb more crushing energy in comparison with non-stitched composite boxes. It was also observed that the position of stitched area can affect the crushing mode and consequently energy absorption capability of composite box structures. Transverse cracking of θ-oriented lamina at interface caused some fibre bridging for most of DCB tests as shown in Figures 2 and 3. The development of fibre bridging caused the force to continuously increase as the crack advanced resulting in a rising R-curve.
Fig. 2. Force-load line displacement from DCB and stitched-DCB tests for mid-plane interface of C90//G0.

For all non-stitched composite crush boxes the lamina bending crushing mode was observed. The lamina bending mode is shaped with long interlaminar, intralaminar, and parallel to fibre cracks. This mechanisms cause the formation of continuous fronds which spread inwards and outwards. Friction and inter/intra laminar fracture controls the energy absorption of lamina bending mode. This high energy absorption is caused by a larger crush area and therefore a higher potential to absorb energy by bending and frictional effects at the platen/specimen interface.

The brittle fracturing crushing mode which is a combination of transverse shearing and lamina bending which is called brittle fracture crushing mode was observed for all stitched composite boxes. In this mode the length of the interlaminar cracks are between 1 to 10 laminate thickness. In this case the main energy absorption mechanism is fracturing of lamina bundles. The highest energy absorption of composite tubes has been observed in brittle fracture and lamina bending crushing modes.

The comparison of force-crush distance behaviour of stitched-10mm and stitched-20mm composite boxes together with non-stitched ones from unidirectional GFRP and CFRP materials are compared in Figure 4.

Fig. 3. Transverse cracking in DCB specimen, (a) at crack tip and (b) typical pattern of crack propagation.

2. Stitched Composite Box Absorbers

The crush box specimens were made of the hybrid unidirectional carbon/epoxy and glass/epoxy by hand lay-up with fibre orientations in accordance to DCB tests. The composite boxes were stitched in two positions of 10mm (stitched-10mm) and 20mm (stitched-20mm) from top end of the specimen using natural Flax yarns. Each specimen was crushed at the rate of 2mm/min between two parallel platens for 50mm stroke using a Universal Testing Machine with 500 kN load cell. For each test configuration three specimens were tested [7].

3. Progressive Crushing Process of Non-stitched and Stitched Composite Crush Box
This comparison shows that stitched-10mm composite box has lower mean crushing force in comparison with non-stitched composite box. In this case, the amount of energy absorption is lower than the relevant capability in non-stitched composite box. It should be mentioned that, the weight of all composite boxes is the same i.e., 137 ± 2 gr. In stitched-10mm composite box, the main central crack initiates and propagates for 10mm until it reaches to natural fibres which prevent further crack propagation.

At this stage the load increases until the main central crack overcomes the natural fibres resistance and then continues its propagation under crushing load (see Figure 4a). The maximum load of stitched-10mm composite box was less than the similar load in non-stitched composite box. This phenomenon indicates that the crush force efficiency (CFE) of stitched-10mm composite box is more than the CFE of non-stitched composite box.

In the stitched-20mm composite box after elastic deformation, main central crack starts to propagate and at the same time load drops gradually. After crush distance of 20mm the main central crack reaches to the stitched area. Because of the resistance of natural fibres, the load starts to increase and this situation causes more energy absorption (see Figure 4b).

Comparing the mean force results of stitched boxes to non-stitched composite box shows that the mean force for non-stitched composite box made is \( F_m = 65 \) kN, while the mean force of stitched-10mm and stitched-20mm boxes are about 63 and 75 kN, respectively (see Table 1).

![Fig. 4. The comparison of force-crush distance in non-stitched, a) stitched-10mm and b) stitched-20mm composite crush box.](image)

![Table 1. Comparison of experimental maximum force, mean force and SEA.](image)
In non-stitched and stitched composite boxes the lamina bending and brittle fracture crushing modes were observed. In these crushing modes the main central interwall crack which is similar to Mode-I crack delamination starts to propagate at four sidewalls of each composite box (see Figure 5).

This situation causes to shape lamina bundles and resistance against the crushing load. In lamina bending mode, the main central crack causes to shape lamina bundles which has a significant role on absorbing the crushing energy. The crushing process of brittle fracture mode continues with some bundle fractures in internal and external bundles (see Figure 6).

<table>
<thead>
<tr>
<th>Laminate Lay-up</th>
<th>Cushing failure mode</th>
<th>$F_{\text{max}}$ kN</th>
<th>$F_m$ kN</th>
<th>CFE %</th>
<th>SEA kJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Stitched- $[C_{90}/G_0]$</td>
<td>LB</td>
<td>110</td>
<td>65</td>
<td>60</td>
<td>15.3</td>
</tr>
<tr>
<td>Natural-Stitched-10mm $[C_{90}/G_0]$</td>
<td>BF</td>
<td>90</td>
<td>63</td>
<td>70</td>
<td>13.8</td>
</tr>
<tr>
<td>Natural-Stitched-20mm $[C_{90}/G_0]$</td>
<td>BF</td>
<td>100</td>
<td>75</td>
<td>75</td>
<td>16.4</td>
</tr>
</tbody>
</table>

LB = Lamina bending and
BF= Brittle fracture

Fig. 5. Mode-I interlaminar crack propagation at the central inter-wall, a) lamina bending crushing mode for non-stitched, brittle fracture mode for b) stitched-10mm and c) stitched-20mm composite crush box.

Fig. 6. Plane view of crushed boxes, a) non-stitched (lamina bending), b) stitched-10mm (brittle fracture) and c) stitched-20mm (brittle fracture).
Earlier it was shown that stitching at the interface planes has a significant effect on Mode-I interlaminar fracture toughness. The $G_{IC}$ of initiation are more influential than the $G_{IC}$ of propagation in the energy absorption mechanism. It was found that the stitched composite boxes which showed higher fracture toughness in Mode-I delamination tests, are not necessarily able to absorb more crushing energy in comparison with non-stitched composite boxes. The main reason can be related to other mechanisms such as bending, friction and bundle fracture which significantly contribute to energy absorption. It was also observed that the position of stitched area can affect the crushing mode and consequently energy absorption capability of composite box structures.

4. Mechanisms Analysis

The composite boxes showed progressive crushing failure of lamina in bending and brittle fracture crushing modes. In the following analytical model which is based on an energy balance approach the mean crushing force, $F_m$, in axial crushing of square composite box is obtained.

The external work of crushing platen is dissipated by mechanisms of friction, bending, fracture and shear deformation.

The idealised crush zone for our analytical model is shown in Figure 7.

Fig. 7. Ideal crush zone, a) Lamina bending and b) brittle fracture crushing modes.

The applied external work by force $F$ during the crush distance $z$ is

$$ U_e = F \cdot z $$

where $z = \lambda - \lambda \cos \varphi$ is the crush distance as shown in Fig. 7 and $\lambda$ is the crush
The length of a single stroke. The maximum work done by external force happens when \( \varphi = \pi/2 \), \( z = \lambda \).

The energy dissipated by friction between crushing platen and the debris inside the internal and external fronds in brittle fracture and lamina bending crushing mode can be obtained from,

\[
U_f = \left( \mu_1 + \mu_2 \right) \frac{F}{2} \cdot x
\]

(2)

where, \( x = \lambda \sin \varphi \). The experimentally measured coefficient of friction is \( \mu_1 = 0.41 \) for CFRP and \( \mu_2 = 0.36 \) for GFRP.

The energy dissipated by frond bending was calculated by assuming that the whole cross section of the frond will reach to the flexural bending stiffness, \( \sigma_b \).

The flexural strength, \( \sigma_b \), for each lay-ups of hybrid GFRP/CFRP was measured \( \sigma_b = 440 \) MPa from 3PB experiment. The energy dissipated in bending for brittle fracture and lamina bending crushing mode at stationary hinge lines is

\[
U_b = \int_0^\pi \sigma_b (4b) t^2 d\varphi = \frac{\pi b t^2 \sigma_b}{8}
\]

(3)

The energy dissipated by interlaminar crack propagation in Mode-I is calculated from interlaminar fracture energies. In lamina bending and brittle fracture mode there is one interwall Mode-I crack at the centre of each side wall of the box as shown in Fig. 7. Therefore,

\[
U_d = 4b \lambda \left( G_{ic} \right)
\]

(4)

The Mode-I interlaminar fracture toughness was measured experimentally by DCB test as discussed earlier.

Dissipated energy by axial splitting at the four corners of the box for brittle fracture and lamina bending crushing mode is calculated based on the stress intensity factor.

At fibre splitting we assume \( \sigma = \sigma_u \). The crack assumed to propagate similar to a crack growth in a single edge notched (SEN) plate where \( Y = 1.12 \). Therefore, the dissipated energy in axial splitting for a fracture area of \( A = 4t \lambda \) is

\[
U_c = \frac{5\pi t \lambda^2 \sigma_u^2}{E_z}
\]

(5)

where \( E_z \) is Young’s modulus in axial direction of the crush box.
The energy dissipated in shear deformation of matrix during steady state progressive crushing was estimated in [8-9].

By assuming during the crushing process the shear stress will reach to its maximum shear strength value of the laminate, \( \tau = \tau_s \), the energy dissipated in shear deformation of laminate is

\[
U_s = \frac{1}{2} \int \tau^2 dV = \frac{2bt \lambda \tau_s^2}{G_{12}}
\]

(6)

Dissipated energy due to bundle fracture was obtained by replacing the crush distance, \( \lambda \) with the width of box, \( b/2 \).

\[
U_{bu.f} = \frac{1.25\pi t b^2 \sigma_u^2}{E}
\]

(7)

where, \( E = E_y \) Brittle fracture and \( E = E_z \) Lamina bending

The fracture area of \( A = 8 \left( \frac{t}{2} \right) \left( \frac{b}{2} \right) = 2bt \) was assumed for eight internal and external fronds with crack growth assumed to be half the width of the side wall as observed in the experiments and \( E_z \) and \( E_y \) are Young’s modulus in longitudinal and transverse direction of the crush box.

The energy balance for the brittle fracture crushing process during a single stroke crush distance is

\[
U_e - U_f = U_b + U_d + U_s + U_{bu.f}
\]

(8)

Substituting from Eqs. (1), (2), (3), (4), (5), (6) and (7) in Eq. (8), the energy dissipated by brittle fracture crushing mode, \( U_{BF} \), is

\[
U_{BF} = F \left( 1 - (\mu_1 + \mu_2) \right) \lambda = \frac{\pi bt^2 \sigma_b}{4} + 4b \lambda \left( G_{IC} \right) + \frac{5\pi t \lambda^2 \sigma_u^2}{E_z} + \frac{2bt \lambda \tau_s^2}{G_{12}} + \frac{1.25\pi tb^2 \sigma_u^2}{E_y}
\]

(9)

Therefore, the mean oscillatory crushing force in a stable brittle fracture progressive crush is:

\[
F = \frac{1}{\left( 1 - (\mu_1 + \mu_2) \right)} \left[ \frac{\pi bt^2 \sigma_b}{4\lambda} + 4b \left( G_{IC} \right) + \frac{5\pi t \lambda \sigma_u^2}{E_z} + \frac{2bt \lambda \tau_s^2}{G_{12}} + \frac{1.25\pi tb^2 \sigma_u^2}{E_y \lambda} \right]
\]

(10)

A single stroke crush distance for brittle fracture mode can be found from Eq. (10) by setting \( \partial F / \partial \lambda = 0 \)
\[ \lambda = \sqrt{\frac{bt\sigma_y E_z + 5b^2\sigma_u^2}{20\sigma_u^2}} \]

(11)

The energy balance for the lamina bending crushing process during a single stroke crush distance is

\[ U_e - U_f = U_b + U_d + U_c + U_s + U_{bu,f} \]

(12)

Substituting from Eqs. (1), (2), (3), (4), (5), (6) and (7) in Eq. (12), the energy dissipated by lamina bending crushing mode, \( U_{LB} \), is

\[ U_{LB} = F \left( 1 - (\mu_1 + \mu_2) \right) \lambda = \frac{\pi bt^2 \sigma_b}{4} + 4b\lambda (G_Kc) + \frac{5\pi t^2 \lambda \sigma_x^2}{E_z} + \frac{2bt\lambda\tau^2}{G_{12}} + \frac{1.25\pi b^2\sigma_y^2}{E_z} \]

(13)

Furthermore, the mean oscillatory crushing force in a stable lamina bending progressive crush is:

\[ F = \frac{1}{(1 - (\mu_1 + \mu_2))} \left[ \frac{\pi bt^2 \sigma_b}{4\lambda} + 4b(G_Kc) + \frac{5\pi t^2 \lambda \sigma_x^2}{E_z} + \frac{2bt\lambda\tau^2}{G_{12}} + \frac{1.25\pi b^2\sigma_y^2}{E_z\lambda} \right] \]

(14)

A single stroke crush distance for lamina bending mode can be found from Eq. (14) by setting \( \partial F / \partial \lambda = 0 \)

\[ \lambda = \sqrt{\frac{bt\sigma_y E_z + 5b^2\sigma_u^2}{20\sigma_u^2}} \]

(15)

The mean force during the progressive crushing can be found by calculating \( \lambda \) from Eqs. (10) and (14) substituting in Eqs. (11) and (15) (see Table 2).

<table>
<thead>
<tr>
<th>Laminate Lay-up</th>
<th>Crushing failure mode</th>
<th>( F_{m} ) (Exp.) (kN)</th>
<th>( F_{m} ) (Anal.) (kN)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-stitched-([C_{90}/G_{0}]_{2})</td>
<td>LB</td>
<td>65</td>
<td>60</td>
<td>7</td>
</tr>
<tr>
<td>Natural-Stitched- (20\text{mm-}[C_{90}/G_{0}]_{2})</td>
<td>BF</td>
<td>75</td>
<td>66.3</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 2. Comparison of experimental and analytical mean force results of each laminate design.

LB = Lamina bending and BF = Brittle fracture.

In previous works of authors [2-3] the combination of crushing modes of lamina bending/brittle fracture and transverse shearing/local buckling were analysed. In the current research stitching caused brittle fracture crushing mode while the lamina bending mode was observed for non-stitched composite box. The results were in good agreement with the relevant experimental results and the discrepancy between experimental and theoretical
results is less than 7% and 12% for lamina bending and brittle fracture crushing modes, respectively. As a result, delamination crack growth in Mode-I cannot far outweigh the bending, friction and bundle fracture mechanisms in energy absorption. Many other intralaminar fracture mechanisms such as fibre/matrix debonding, fibre breakage and matrix cracking are also contributing in dissipating the crushing energy. Finally, the stitched-20mm composite box showed higher mean crushing force and consequently higher energy absorption capability in comparison with non-stitched and stitched-10mm composite boxes. It is also concluded that stitching increases the interlaminar fracture toughness as well as energy absorption capability in the FRP composite structures.

5. Explicit Finite Element Modelling

The stitched composite box was modelled using finite element software LSDYNA. The size of outer cross section of the composite box was 80×80mm with a thickness of 3 mm. Trigger mechanism was modelled by reducing the thickness of the first row of shell elements at the top of each box.

The hybrid composite box model was based on Belytschko-Lin-Tsay quadrilateral shell elements. This shell element is based on a combined rotational and velocity strain. All surfaces of the model were meshed using quadratic shell element and the size of an element was 2.5×2.5mm. The striker was modelled as a rigid block using solid element.

The delamination failure mode needs three-dimensional representation of the constitutive equation and kinematics, and cannot be treated in thin shell theory. The delamination failure mode requires micro-mechanical modelling of the interface between layers and cannot be treated in thin shell theory that deals with stresses at macro levels. Thus, debonding and delamination are usually ignored when thin shell element are used to model failure in composite modelling. In this work the delamination behaviour in Mode-I was modelled with two layers of shell elements in the box wall. The thickness of each layer is equal to half of the total box wall thickness. The surface-to-surface tiebreak contact was used to model the bonding between the bundles of plies in the box walls. In this contact algorithm, the tiebreak works for nodes which are initially in contact. The failure of the bonding between these bundles takes place when the following failure criterion is fulfilled:

\[
\left(\frac{\sigma_n}{NFLS}\right)^2 + \left(\frac{\sigma_s}{SFLS}\right)^2 \geq 1
\]  

(16)
where $\sigma_n$ and $\sigma_s$ are normal and shear stress, respectively acting on the interface surface while NFLS and SFLS are the normal tensile and shear stresses at failure. The comparison between final element deformation from FE and relevant experimental results are presented in Figure 8.

Fig. 8. Comparison between a) FE and b) experimental results (in top view of crushed box).

6. Discussions and Conclusions

This paper investigated the new 3D (stitched) hybrid composite laminate which can significantly increase the interlaminar fracture toughness within the composite materials. This increase also causes the improvement of energy absorption capability and crush force efficiency (CFE) in the FRP composite absorbers.

In non-stitched composite box the lamina bending crushing mode was observed while the brittle fracture mode was observed for stitched-10mm and stitched-20mm composite boxes. In these crushing modes the main central interwall crack which is similar to Mode-I crack delamination starts to propagate at four sidewalls of each composite box. In lamina bending mode, the main central crack causes to shape lamina bundles which has a significant role on absorbing the crushing energy. It was found that the stitched composite boxes which showed higher fracture toughness in Mode-I delamination tests, are not necessarily able to absorb more crushing energy in comparison with non-stitched composite boxes. The main reason can be related to other mechanisms such as bending, friction and bundle fracture which significantly contribute to energy absorption process. The maximum load of stitched-10mm composite box was less than the similar load in non-stitched composite box. This phenomenon indicates that the crush force efficiency (CFE) of stitched-10mm composite box is more than the CFE of non-stitched composite box. The position of stitched area
can affect the crushing mode and consequently energy absorption capability of composite box structures. The stitched-20mm composite box showed higher mean crushing force and consequently higher energy absorption capability in comparison with non-stitched and stitched-10mm composite boxes. It can be generally concluded that stitching increases the interlaminar fracture toughness as well as energy absorption capability in FRP composite structures.

References


