LOW AND HIGH SPEED IMPACTS ON BRAIDED HYBRID TWILL COMPOSITES

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Abstract

Composite impact behaviour can be significantly improved by replacing part of the high strength fibres with more ductile fibres such as glass or synthetic fibres. Yielding a composite with improved ultimate strengths and strains and, therefore, better impact withstanding. These composites are called hybrid composites and can be divided in several types. This study concentrated only on hybrid textile composites with the tow phases composed of carbon and glass organised in separated tows/yarns and braided together in a twill textile. Low and high speed impact tests highlighted two different failure mechanisms dominated, respectively, by quasi-static and wave phenomena. The damage severity was estimated only in term of damage area (C-scan) and absorbed energy. In addition, the hybrid composite damage severity was compared against experimental data retrieved from literature. This comparison highlighted that the hybrid composite solution investigated offered the best compromise in terms of reduced damage area for high level of absorbed energy.

1. Introduction

The use of composite materials has boomed in the last couple of decades due to a unique capability to accurately respond to design requirements, without the compromises usually associated with metal alloys. In addition, composites offer a series of attractive benefits including good corrosion resistance, excellent strength and stiffness to weight ratio. On the other hand, composite materials are susceptible to impact damage caused by the brittle nature of the reinforcing fibres; limited interlaminar shear strengths; and a lack of reinforcement in the thickness direction [1]. Impact damage tends to be located internally in the form of delamination areas, and matrix cracks showing very small imprints in the surface, causing compressive strength reduction with potentially catastrophic consequences.

In general, impact damage consists of two phases: (1) dynamic compaction of the material, which ends in the fibre breakage in front of the foreign object; and (2) delamination around the impact site [2]. More specifically, the exact nature of damage may depend on the composite internal geometry, impact test geometry, and set up conditions [1]. However, for low speed impacts, damage can be roughly classified in impact and distal surfaces bending damages and an approximately circular internal delamination, followed by fibre splitting and perforation or shear failure at high incident energies [3]. Moreover, the impact damage tends to initiate in the bottom layers for thin
samples, and in the top layers for thick specimens [4]. For high speed impacts, wave propagation effects need to be considered as different local fibre orientation and, so, different local stiffness trigger different failure mechanisms [5].

Impact damage determines a reduction of the composite compressive strength mainly due to delamination [1]. This occurs in the interlaminar (resin rich) regions where the extensional and bending stiffness differs due to mainly different fibre orientation between the layers or, in some cases, different materials [5-6]. Further investigations have suggested that delamination is initiated by matrix cracks in both opening mode I and II [7-8].

The adoption of through thickness fibre reinforcements and tougher resins (thermoplastic) are two of several solutions employed to increase the delamination toughness and, so, improving the composite impact behaviour. The first act as crack stoppers by altering the fracture paths from intra-tow mode to inter-ply mode and approximately doubling the fracture toughness [9]. On the other hand, with tougher matrices and stronger interfaces, larger impact energies are required to initiate delamination [10].

An alternative way to reduce the impact damage is to tackle the excessive brittle nature of high strength fibres, and their low ultimate strains by replacing part of the carbon fibres with more ductile fibres. This will result in a trade off from part of the composite mechanical properties with larger ultimate strains and strengths [12], and so larger compliances and potentially smaller damages and larger dissipated energies [11]. These composites are called hybrid composites and can be classified as: hybrid lay up (one material per ply); hybrid textile (one material per tow/yarn); and commingled composites (hybrid tow/yarn).

In this paper, the results of low and high speed impacts on a hybrid textile (hybrid ply/layer composites) were presented and compared with experimental data found elsewhere in literature. At first, the hybrid composite was introduced, and the experimental impact procedure explained. Then, experimental data were analysed, (C-scan damage area; absorbed (dissipated) energy; contact force; and sample surface micrographs), in order to understand the failure mechanisms triggered by impact. To conclude, the efficiency and efficacy of the hybrid ply was estimated in comparison with experimental data in literature.

2. Materials

The material under investigation was a hybrid textile with an overall fibre volume fraction of 51%, of which 75% was high strength carbon fibres and, the remaining 25%, glass fibres. The carbon and glass fibres were braided from separated tows in 2×2 twill dry preforms (Figure 1).
These were laid up over four layers with epoxy resin injected by resin transfer moulding, and cured in 40×40 cm plates with a nominal thickness of 4.5 mm. Finally, in order to investigate possible size effects on impact generated damages, square plates of two sizes 20×20 cm and 13×13 cm were cut out using a diamond saw. The impact mass and speed effects were addressed by impacting plates with different masses and speeds as described in Table 1.

<table>
<thead>
<tr>
<th>Test N</th>
<th>Plate size [cm]</th>
<th>Mass [g]</th>
<th>Device</th>
<th>Impact Energy [J]</th>
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<td>13×13</td>
<td>754</td>
<td>Drop Tower</td>
<td>10, 17.5</td>
</tr>
<tr>
<td>5</td>
<td>13×13</td>
<td>12.5</td>
<td>Gas Gun</td>
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<td>Gas Gun</td>
<td>25, 50</td>
</tr>
<tr>
<td>4</td>
<td>13×13</td>
<td>21.5</td>
<td>Gas Gun</td>
<td>25, 32.5, 40, 50</td>
</tr>
</tbody>
</table>

Table 1 – Table of experiments.

Low speed impacts were carried out using the Cambridge Drop Tower (DT, Figure 2) fitted with an impactor of 0.754 kg mass. The impactor had 12.5 mm hemispherical head made of steel, which falling speed was estimated at the end of the drop tower pipe by infrared cells, while a force transducer was employed to measure the contact force and a high speed camera estimated the impact rebound speed.
High speed impacts were carried out using a Gas Gun (GG, Figure 3) with two 12.5 mm hemispherical projectiles (12.5 g – Light Projectile, LP – and 21.5g – Heavy Projectile, HP) mode of steel. The projectile impact speed was estimated by infrared cells located before the end of the gas gun barrel. Contact force and rebound speed were monitored using a high speed camera.

For both the drop tower and the gas gun, the infrared cells predicted speed was underestimated because the projectile kept on accelerating after breaking the infrared beams. Therefore, these speed estimates were used just for calibration purposes, while a high speed camera was employed to evaluate more accurate impact and rebound speeds of the impactors. A maximum error of 5% in the predicted speed by the infrared cells was observed.

The procedure used, for the impact experiments, was as follows:

1. Pre-impact NDT tests: woodpecker; C-scan; and non linear elastic wave spectroscopy.
2. Sample clamping: bolts tied with torque force of 20Nm.
3. Impact.
4. Post impact NDT tests: woodpecker; C-scan; non linear elastic wave spectroscopy, pulse thermography and thermo-acoustics.
6. Surface micrography of impacted samples.

3. Results

Impact data post processing led to the evaluation of contact force, absorbed energy and C-scan damage area trends against impact energy. These trends were then analysed against impact and distal surface micrographs in order to have a more comprehensive insight of the failure mechanisms involved in low and high speed impacts of hybrid composites.

3.1 Contact force

Contact force was estimated as product of the projectile displacement second derivative and the projectile mass. Projectile displacement was evaluated using the high speed camera with accuracy that depended by the camera resolution (256×256 pixels) and camera view width. Therefore, for the high speed camera set up, the projectile displacements was predicted within an error of 1.2mm for the gas gun and 0.6mm for the drop tower, while the speed and the accelerations were given by the displacement error divided by, respectively, the camera sample time (18kHz for gas gun, 4.5kHz for the drop tower) and its square. This led to errors in the speed estimates of 21m/sec and 3m/sec, respectively, for high speed and low speed impacts. However, the adoption of appropriate data filtering with cut off frequency of two fifth of the camera sampling frequency, in order to allow a sufficient number of data point during the plate impactor contact time, reduced the speed errors to 8 m/sec for the gas gun and to 1m/sec for the drop tower. Concluding the maximum error in the estimate of the contact force was about 1kN.

In light of this error, the contact force maxima plotted against the impact energy (Figure 4) showed that the drop tower (circle marker) had larger values than light (12.5g) and heavy projectile (21.4g) impacts. On the other hand, considering large data scatter associated with contact force maxima (see red square and cyan triangles) and the contact force estimate error, the difference associated between low and high speed impact data reduces consistently. Concluding contact force maximum tends to increase with the impact energy and seemed to be independent by the projectile mass and plate size.
3.2 Absorbed energy and damage severity

As mentioned in the previous section the speed error depended on the projectile displacement error, high speed camera sampling frequency and the cut off frequency. Therefore, in order to increase the accuracy of the impact and rebound speed values, the cut off frequency was made to be one tenth than the high speed camera. As result the speed error for the drop tower was of 0.3 m/sec and for the gas gun of 2m/sec. This allowed estimating the absorbed energy with errors within 10%.

As showed in Figure 5 – Absorbed Energy. For legend see Figure 4. Figure 5, the absorbed energy behaved almost linearly against the impact energy. In addition, low speed impact absorbed energy (black circle marker) was about 40% smaller than high speed (red square marker) dissipated energy. For high speed impacts, light (red square marker) projectile impacts showed level of absorbed energy always larger than the heavy projectile (cyan triangle marker). However, the data scatter and the absorbed energy accuracy might lead to conclude that high speed projectile mass effect is not significant.
However, a similar behaviour to that recorded by the absorbed energy was observed by plotting the C-scan damage area against impact energy (Figure 6). Drop tower damage was observed to be smaller 20-30% than the high speed damage area. While, the light projectile yielded to larger damages than heavy projectile impacts. For both light and heavy projectile, the second data point for the LP and the last data point for the HP were observed to drop out from the trend outlined by the remaining data. An explanation for this discrepancy was given in the next subsection.

In terms of size effects, the large plate damage area (blue diamond marker) showed values compatible with those of the small plates (cyan triangle marker) for the same projectile mass (HP).
3.3 Surface micrography

At the aim to identify the failure mechanisms involved in low and high speed impacts and establish correlations between global experimental data (contact force maxima, absorbed energy and damage area) impact sample surface micrographs were analysed.

In the previous section absorbed energy and damage area highlighted differences between low and high speed impacts. This behaviour was confirmed by sample surface micrographs (Figure 8-Figure 10). In particular, the drop tower impact samples presented a clearly identifiable dent with tow splitting and fibre breakage cracks departing from its rim. On the other hand no dent was observed for the high speed impact for the same level of impact energy.

This is due to the different failure mechanisms triggered by low and high speed impacts, respectively, quasi-static and wave effect phenomena. Further insight of the damage evolution during impact for low speed impacts can be seen by analysing the contact force time history (Figure 7). This show that the dent and delamination initiation can be associated with the first drop of the contact force (see first critical load – contact force drop – in Figure 7) as subsequent rise followed a more gentle slop, confirming the damage occurrence. This occurred when the level of compressive stresses, underneath the contact area, and shear stresses, propagating along the rim of the projectile/sample contact area through the plate thickness according to a diverging cone, have reached the ultimate compressive and shear strengths of the matrix. A further increase of contact force resulted in the increase of delamination damage and compressive stress around the dent rim leading to tow failures in the form of tow and fibre splitting (see other critical loads in Figure 7). These failure mechanisms are associated with a sharper drop of contact force and a larger decrease of the contact force rising slope due to the large amount of energy dissipated (released) by the tow collapse [13]. An analogue behaviour of the contact force was observed in low speed impact experiments on E-glass epoxy laminates [14].

![Contact force time history](image.png)
Moreover, plane weave carbon epoxy laminates (10 layer, 1.9mm thick, identical experimental set up to twill plates) showed similar failure mechanisms for low speed impacts as shown in Figure 11. Therefore, this failure mechanism seems to be independent by the composite internal geometry and associate to the low impact speeds and assimilated as quasi-static phenomenon [1-4].

Figure 8 – Impact surface micrographs: (a) drop tower (13.5J, 6m/sec); (b) gas gun (12J, 43m/sec).

Figure 9 – Distal surface micrographs: (a) drop tower (13.5J, 6m/sec); (b) gas gun (12J, 43m/sec).
Figure 10 – Impact sample micrographs: Impact surface (a) drop tower (22J, 7m/sec); (b) gas gun (25J, 60m/sec); Distal surface (c) drop tower (22J, 7m/sec); (d) gas gun (25J, 60m/sec)

Figure 11 – Plane weave textile composite impact surface micrograph (5J – 3.5 m/sec).
As previously observed, the dent area could not be observable for high speed impact damages (see Figure 8, the circle identifies the impact centre) and cracks do not depart anymore from its rim. Moreover, on the distal surface (Figure 9) a bulge could be observed with inter tow and tow and fibre splitting cracks. In contrast, the low speed impact presented no apparent cracking but fibre glass debonding. With the increase of the impact energy, a dent started forming on the impact surface, though, less deep than that observed for the drop tower samples. Cracks were clearly propagating according a preferential direction +/- 45 deg (tow direction). This means that wave effects are important at these speed levels, as stress/strain rates are too high to be redistributed in a quasi-static manner. Thus, stress propagates under form of stress waves along the tow direction determining local stress concentration leading to tow and inter-tow failures with large energy dissipation. Hence, less energy is dissipated in the dent formation.

This failure mechanism is more harmful that the quasi-static one, since in the initial stages of the impact only a small portion of the plate reacts. Therefore, less impact energy is stored as elastic energy and more is dissipated by crack initiation and propagation, as it can be observed by the absorbed energy plot versus impact energy (Figure 5). Where, the drop tower impact samples absorbed on average 25% less energy than gas gun samples. This was further confirmed by the C-scan damaged area (Figure 6), which was about 25-35% larger for the gas gun specimens than the drop tower samples.

As observed before, the damage tends to propagate along tow directions (+/-45deg). However, from a close analysis of the impact surface, the propagation did not occur in even way along both +/-45 deg direction, (Figure 10-b, Figure 12-Figure 15). A preferential damage propagation direction can be identified along the closest glass fibre tow to the impact centre. In other words, as glass fibre tows are loaded, the load (stress) is transferred to neighbour carbon tows proportionally to the carbon/glass fibre stiffness ratio (240GPa/80GPa). Therefore, the carbon tow stretch till their breaking elongation 1.7-1.8% against the 4.5% of the glass fibre tows. Effects of this failure mechanism can be seen on the ellipticity of the delamination paths (Figure 12-Figure 15) with the ellipse major axis along the preferential damage propagation direction. Although, this failure mechanism ensures large amount of energy dissipation (carbon tow failures) has a detrimental effect on the extension of the delamination area. In fact, when the glass fibre tow fails has result of a direct hit from the impacting projectile, the chain effect is broken and the delamination area drops with respect to the trend as it can be observed from the damage area plot (Figure 6), in the case of the second data point of the light projectile tests (squares, see also Figure 9-b) and the last point of the heavy projectile tests (triangles, see also Figure 14).
Figure 12 – Light projectile impact (39J, 79m/sec): a) Impact surface micrograph; b) C-scan.

(a) (b)

Figure 13 – Heavy projectile impact (33J, 56m/sec): a) Impact surface micrograph; b) C-scan.

(a) (b)

Figure 14 – Heavy projectile impact (52J, 69m/sec): a) Impact surface micrograph; b) C-scan.

(a) (b)
As mentioned before, absorbed energy and damage area plots (Figure 5-Figure 6) against impact energy highlighted a gap between the light (square markers) and the heavy (triangle markers) projectile impact data trends (HP/LP mass ratio =1.7). This behaviour has to be related to the different masses, since LP data always upper bounded the HP one. This was corroborated by the lack of differences in the damage propagation paths between HP and LP tests. Moreover, strain rate effects associated with the glass fibre should not be very important as the speed between the two projectiles at the same level of impact energy changes only of the 30% (HP max speed 70m/sec). In addition, according to literature [12], significant increases in stiffness and strength at intermediate and impact strain rate were observed only for plane weave glass fibre composites while for other textile geometry the increase was not considered significant.

Overall, the absorbed energy and the damage area plots show that the impact energy can be considered the main factor characterizing the impact phenomenon

4. Discussion

In order to draw some conclusion on the efficiency of the hybrid composite investigated, experimental data relative to different kind of composites hybrid and not were retrieved from literature and compared. As shown in Table 2, a broad spectrum of materials (2D and 3D textile, stitched bonded mats) with different sample sizes have been considered for comparison to the textile composite investigated in this study (see x in Table 2).
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<th>Fibres</th>
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<th>Resin type</th>
<th>Material</th>
<th>Clamp Free area [mm]</th>
<th>Sample Thickness [mm]</th>
<th>Impactor Diameter [mm]</th>
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<td>76 76 2.39</td>
<td>0.4% γ-MPS – 20 plies – Drop tower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[20]</td>
<td>Stitch bonded mats</td>
<td>E glass</td>
<td>58</td>
<td>Vinyl Epoxy</td>
<td>○</td>
<td>76 76 2.34</td>
<td>0.4% γ-MPS – 20 plies – Drop tower</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Literature data.
As mentioned before, impact energy in first approximation is the most important parameter influencing the impact dynamics, however, the dissimilar test conditions, in terms of clamping, plate sizes, projectile size and mass, cause a large data dispersion, (Figure 16). The main cause for this large data scatter can be associated with the different plate slenderness ratios a/h (side length/thickness). A plate with a larger slenderness ratio tends to be more compliant and capable of deflecting more under impact load, storing more energy under elastic form, as it was proven next.

IE during impact is converted in elastic energy (EE) plus dissipated energy (AE):

\[
IE = EE + AE
\]  

(1)

Considering the plate compliance that in static analytical solutions for isotropic materials is proportional to [22]:

\[
\frac{a^2}{D} D = \frac{Eh^3}{12(1-\nu^2)}
\]  

(2)

where a is either the plate longest side (rectangular/square clamping) or its radius (circular clamping) and E is the elastic modulus.

Unfortunately, not all the composite materials under investigation behave isotropically at macroscopic level, so, eq. 2 could not be used. However, this highlighted a direct dependency of the compliance from the slenderness ratio (a/h). Consequently, in view of eq. 1 the elastic energy can be written as:

\[
EE = \frac{1}{2} K x_{max}^2 \iff EE = \frac{1}{2} K \left( \frac{P}{K} \right)^2 \iff EE = \frac{1}{2} \frac{P(EI)}{K}
\]  

\[
EE = \frac{1}{2} S \cdot P(EI)^2 \propto \frac{a}{h} P(EI)^2
\]  

(3)

where \(x_{max}\) is the maximum displacement, K the plate stiffness, P contact force and, S plate compliance.

Considering eq. 1 and 3, for constant impact energy, an increase of the slenderness ratio causes a decrease of the absorbed energy. Consequently, the absorbed energy is inversely proportional to the slenderness ratio.

Therefore, the larger compliance (slenderness ratio) the larger the plate deflection and the elastic energy storable, consequently, the smaller the plate damage.

By comparing the C-scan damage area (Figure 16) and the C-scan damage area divided by h/a plots (Figure 17 – trends lines have been use to improve the plot clarity) vs the impact energy, a reduction of the data scatter was obtained as the data points of the chopped glass fibres ( chù ) and stitched bonded mats ( chù , chù ) shifted leftwards and blended in the main data point stream.
Therefore, in terms of damage area per “stiffness unit”, carbon fibre composites independently of their deployment within the layers (stitched bonded mats - ▼, ▲ - and crowfoot weave - ▼, ▲, ◆, ◆) have steeper slopes compared to glass fibre composites except for the quadriaxial warp knitted composites (▼, ◆). This could be due to pre-existing damage of fibres introduced by stitching [21]. Moreover, by analysing crowfoot
weave composites, a consistent reduction of the delamination (damage area) was observed as projectile hemispherical head diameter increases from 12.7mm (●, ▲) to 42mm (●, ▼). In addition, a reduction of delamination area was observed for different lay ups e.g. twill carbon textile composites (from ●[45,0,45,0],s to ●[0,45,0,45],s) and stitched bonded mats (from ▲ [+/-45],s to ▲ [0,90,+/45],s).

For glass fibre composites, the thickness did not affect the slope of the normalised damage area as it can be seen for plane weave textiles (◊ marker). In addition, glass fibre treatment strongly improves the delamination toughness of the plane weave composites as the damage area detected decreases with the change of surface treatment from γ-GPS (■) to 0.01%γ-MPS ( ) 0.4%γ-MPS ( ). A similar delamination toughness to the best plane weave (0.4%γ-MPS) was achieved by the chopped glass fibre (50mm long) composites (▲), and hybrid twill textile composite investigated in this paper (☆ markers). Together, these three types of composites had the lowest damage area per stiffness unit between all the material analysed. This means that twill hybrid composites offer the best compromise in terms of damage area and mechanical characteristics, since have similar damage levels of glass fibre composites and larger elastic modules and ultimate strengths due to the carbon fibres. In addition, the solution of having hybrid plies in the investigated composites showed to be more successful than that adopting hybrid lay ups (△ markers) as shown in Figure 17. Moreover, the hybrid lay up solution did not always sort an improved behaviour in term of damage with respect to non hybrid composites. In fact, for identical impact conditions, the smallest damage area was observed on the plane weave glass fibre composite (▲), while the only hybrid lay up performing better than the twill carbon fibre composite (▲) was [C₄/G₄],s lay up (▲, C = carbon fibre twill layers, G = glass fibre plane weave layers). This lay up configuration exploits the carbon fibre mechanical properties, being stronger and stiffer than glass fibre, by laying their plies on the plate surfaces. This solution enables the carbon fibres to withstand the high stress located on the sample surface due to impact deflections. As matter of fact, both the remaining two hybrid lay up studied, [G₄/C₄],s (▲) and [G/C]₄s (▲) had glass fibre layers on surface, with the second having the largest damage.

The later, unexpectedly, did not dissipate the most energy (Figure 18), since the most dissipating was also the least damaged hybrid lay up [C₄/G₄],s, with the pure carbon lay up being second, while the worst performing was the pure glass fibre lay up. This discrepancy could be explained by the presence of extended fibre breakage on the samples having carbon fibres on the surface [12].
In line with the previous literature findings in terms of absolute absorbed energy, the hybrid composite investigated dissipated energy levels compatible with those observed on hybrid lay up. Moreover, all the sample data points seemed to fall along the same path when plotted against the impact energy confirming once more that this is the main driving factor in impacts.

However, by dividing the absorbed energy with the “plate stiffness”, a more correct interpretation of the experimental results is possible (Figure 19). For each different material, the absorbed energy per “plate stiffness unit” tends to increase along parallel lines to then deviate from it at high level of impact energy. This deviation is likely to be caused by extended fibre breakages. Moreover, thin plates (aphael) tended to absorb more than thick plates (raphael).
In addition, stitched bond mat composites absorbed the least energy (○ markers), while 3D orthogonal weave (■) dissipated energy was close to that of hybrid lay up and hybrid layer composites. Overall, the twill hybrid composite studied showed normalised absorbed energy levels inferior to thin plates but compatible with those of thick plates.

Furthermore, by dividing the absorbed energy with the damage area (strain energy release rate) Figure 20, it becomes clear that the hybrid layer solution offers the best compromise between the designer need to have as much as possible dissipated energy (in order to stop the projectile) with the least possible damage. In fact, though, the hybrid layer solution presents similar values for the absorbed energy and damage area ratio to a thin glass fibre plane weave composite, its mechanical properties are by far superior.
Figure 20 – Absorbed energy damage area (m²) ratio vs impact energy. For legend see Table 2.

In addition, plane weave data points (diamonds markers) showed an initial plateau with low level of impact energy to then deviate from it at high level of energy. This might be index of a change of the most important failure mode. Likely, for low impact energies, delamination failure is the most important ($G_I=0.6\,kJ/m^2$ and $G_{II}=6\,kJ/m^2$), while for high level of impact energy fibre breakage becomes predominant.

5. Conclusions

In this study, the experimental evidences of low and high speed impacts carried out on braided hybrid textile composites were presented.

Low and high speed impacts highlighted two different failure mechanisms dominated, respectively, by quasi-static and wave effect phenomena.

Low speed impacts were observed to be not significantly affected by the textile composite geometry, complying with literature observations. On the contrary, high speed impact presented a rather unique damage evolution, dominated by the textile geometry and its hybrid nature. As the damage was observed to propagate along a preferential direction dictated by neighbour glass tows.

Impact energy was observed being the main factor dominating impact phenomena for both low and high speed impacts. Therefore, the incident energy normalised with the plate slenderness ratio was used to compare the braided hybrid textile composite experimental data against literature data, in terms of damage area and absorbed energy.

Results pointed out that the hybrid ply solution investigated in this study offered the best compromise in terms of absorbed energy and damage area.
References


