**LOW-VELOCITY IMPACT PERFORMANCE OF CARBON FIBRE RE-INFORCED THERMOPLASTIC COMPOSITES FOR AUTOMOTIVE APPLICATIONS**

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**ABSTRACT**

The damage response of rectangular plates of three different composite systems; two carbon/thermoplastic (T700/polyamide 6.6 and T700/polyphenylene sulphide) and one carbon/thermoset (T700/MTM57), at three distinct energy levels (40, 100 and 160 J) has been characterised. The varying energy levels were determined to correspond to the several degrees of penetrability; no penetration (at 40 J), partial-penetration (at 100 J) and full-penetration (at 160 J). Each plate was subjected to an out-of-plane, localised impact using an INSTRON® drop-weight tower with a hemispherical impactor measuring 16mm in diameter. Following the test results and data reduction, the low-velocity impact (LVI) performance of the different composite systems was ranked from best to worst (based on the amount of impact energy absorption per areal weight) as follows; (i) T700/PPS, (ii) T700/MTM57 and (iii) T700/PA6.6. Post-mortem analysis techniques such as C-scan and X-ray were used to investigate the extent of damage of each sample; it was concluded that the T700/PA6.6 and T700/MTM57 experienced comparable levels of localised penetration whereas the best-performing T700/PPS exhibited no penetration (even at the highest energy level) but instead, demonstrated relatively significant degree of delamination in comparison to other two.

1 INTRODUCTION

Laminated composite structures used in aerospace and automotive applications are always susceptible to damage and failure due to in-plane loading conditions such as tension and compression and out-of-plane contact such as impact with foreign objects [1]. For example, the exterior components of a vehicle such as bumper, fender and bonnet are constantly prone to impact, particularly low-velocity transverse impact. Impact damages as such could result in matrix cracking, fibre fracture and delamination [2–4], all of which leads to deterioration in the mechanical properties of the material. Likewise, such damages could also be very difficult to be identified by the naked eyes.

Recently, the automotive industry has shown a significant interest in understanding the mechanical behaviour of thermoplastic (TP) composites [5,6] due to their out-of-autoclave (OOA) manufacturability and recyclability, which are not currently achievable with typical thermosetting (TS) systems. Therefore, the characterisation of TP composites’ impact response, would allow for better prediction of their performance under structural automotive applications. Likewise, this research aims to contribute invaluable information to the ever-growing composite materials database.

The non-crimp fabric (NCF) composite material systems selected include two carbon/TP (T700/PA6.6 and T700/PPS) and one carbon/TS (T700/MTM57). The fibre-volume-fraction (FVF) of each system has been quantified using thermogravimetric analysis (TGA) to be 50% (with a coefficient of variance of 2%).

2 LOW-VELOCITY IMPACT (LVI) TEST

The LVI test allows for the determination of the damage resistance of a laminated composite subjected to a drop-weight impact event. The test was conducted partially in accordance to the standardised
The dimensions of the drop-weight impact test panel and impact location were as described in Figure 1. The test method was designed to characterise materials for damage resistance and tolerance. The impact performance of a laminated composite material is largely governed by several common factors, such as specimen geometry, layup quality, impactor mass, force and energy, and boundary conditions. Hence, the results gathered from specifically from this test is not necessarily scalable to other configurations.

At present, the published information with regards to the LVI performance of carbon fibre reinforced thermoplastic (CFRTP) is scarce, unlike TS composites [1,8–10]. And since the automotive industry has been continually interested in finding the alternatives of OOA manufacturing, this study aims to provide invaluable information with respect to the impact resistance of TP composites and how do they compare to their TS counterparts.

3 EXPERIMENTAL METHOD AND DATA REDUCTION

The drop-weight impact test was conducted using a balanced, symmetrical laminated composite plate (or panel). The damage was induced out-of-plane, concentrated on the centre on the plate using a hemispherical impactor with a diameter of 16mm from an INSTRON® drop tower machine (Figure 2). The impact response or damage resistance was measured in terms of the damage, type and size on the panel.

Three energy levels were chosen (40, 100 and 160J) to achieve three different degrees of penetrability; no penetration, partial-penetration and full-penetration. The impact velocity, impactor displacement and applied contact force against time history were recorded.

The impact energy absorption was calculated by partially integrating the area under the force-displacement graph. Nonetheless, the energy absorption was only calculated for when the damage starts to occur, which refers to only two energy levels, 100 and 160J. The calculated values reported in Table 1 specifically represents the initiation impact energy. Hence, the area under the curve of interest consists of the beginning of impact, where the force starts to increase to the point where it starts to decrease.

![Figure 1. Drop-weight impact test specimen according to the ASTM D7136/D7136M [7]](image-url)
4 RESULTS

The laminated composite panels post impact are shown in Figure 3. This figure highlights the different types and degrees of damage, which include typical damage characteristics, such as delamination, matrix cracking and fibre breakage. Following the drop-weight impact test, each panel was placed in a water bath where an ultrasonic NDE was conducted (Figure 4). The images obtained from the NDE scan is shown in Figure 5. The NDE scans of the representative panels were also complemented by the X-ray images are shown in Figure 6 to further visualise the extent of damage of the materials.

The NDE scans of each specimen representing the varying impact loading conditions exhibited relatively predictable level of damage, where lowest to greatest correspond to lowest to highest impact energy i.e. 40 to 160 J. Likewise, the X-ray images revealed the same.

Figure 7, 8 and 9 depict the time histories (force-time, deformation-time and velocity-time) and force-displacement graph of the three different material systems under varying impact conditions.

The C-scan images (Figure 5) clearly indicate that the size of damage increases as the energy level increases. At 40J, all the specimens indicate minor extent of damage. With regards to the T700/PA6.6 samples, the damage was found to be most localised as the extent of damage was the smallest, particularly at 100 and 160 J. However, significant petaling of the rear surface was observed. The T700/MTM57 on the other hand exhibited larger extent of damage. Although the petaling effect at the rear of the samples of the T700/MTM57 was similar to that of the T700/PA6.6, the C-scan images of the former suggest higher degree of delamination. Conversely, Figure 5 also shows that the T700/PPS specimens suffered severe delamination albeit without any penetration.
Figure 3. The laminated composite specimens post impact

Figure 4. The specimens submerged in a water bath for non-destructive evaluation (NDE) via ultrasonic scan
The X-ray images provide similar information to that of the C-scan images. The petaling of the rear surfaces of the T700/PA6.6 and T700/MTM57 at 100 and 160 J is clearly shown in Figure 6. Nonetheless, the more severe delamination of the T700/MTM57 is not indicated in the X-ray images at those higher energy levels.
Figure 6. X-ray images of the specimens after impact

Figure 7. Time histories and force-displacement plot of the three different composite systems under impact energy of 40J
Figure 7 indicates that all the time histories, including the force-displacement plot for all materials follow similar trends under the impact energy of 40J. However, at 100J (Figure 8) and 160J (Figure 9), the time histories and the force-displacement plot of each material demonstrated a distinct behaviour and response.

At 100J, the representative T700/PA6.6 specimen appears to experience the highest magnitude of impact force, followed by the T700/MTM57 and T700/PPS samples (Figure 8). With respect to deformation, the T700/MTM57 specimen seems to suffer the largest deformation, followed by the T700/PPS and T700/PA6.6 systems.

With regards to the time histories and force-deformation curve at 160J (Figure 9), once again, the T700/PA6.6 panel indicates the largest impact force, while the T700/PPS and T700/MTM57 incurred comparable magnitude of impact force. In relation to the degree of deformation, the force-displacement curve obtained in Figure 9 suggests that the T700/MTM57 sample shows the greatest level of deformation, followed by the T700/PA6.6 and T700/PPS specimens.

Since the thicknesses of the impact panels vary slightly across the different material systems, the calculated values of energy absorption i.e. the conforming area under the force-displacement curve were normalised to the respective areal weight of each system. Table 1 summarises the LVI performance of the different materials and with respect to their accompanying densities and areal weight. Table 2 reports the summary of the mechanical properties gathered from standardised in-plane and out-of-plane tests of the three materials previously conducted by Mohsin et al. [11,12].
Figure 9. Time histories and force-displacement plot of the three different composite systems under impact energy of 160J

Based on Table 1, at 100J, the T700/PA6.6 absorbed 11.77 $kJ,m^2/kg$ of impact energy per areal weight and performed 8.3% worse than that of its TS counterpart, the T700/MTM57 (which absorbed 12.83 $kJ,m^2/kg$ of energy). Conversely, the T700/PPS showed 5.3% better performance compared to the TS system, absorbing 13.51 $kJ,m^2/kg$ of energy per areal weight.

Under the highest impact loading condition (160J), the T700/PPS achieved much higher (+10.5%) energy absorption per areal weight (23.08 $kJ,m^2/kg$) than the corresponding TS system (20.88 $kJ,m^2/kg$). The T700/PA6.6 on the other hand, was still inferior to T700/MTM57, albeit at a lower margin of –2.4% with 20.37 $kJ,m^2/kg$ of energy absorption per areal weight.

Table 1. Summary of the LVI performance of the different composite systems relative to the T700/MTM57 system

<table>
<thead>
<tr>
<th>Impact Energy (J)</th>
<th>Material</th>
<th>Density (kg/m$^3$)</th>
<th>Areal Weight (kg/m$^2$)</th>
<th>Energy Absorption per Areal Weight (kJ.m$^2$/kg)</th>
<th>Percentage difference to T700/MTM57 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>T700/PA6.6</td>
<td>1485</td>
<td>8.158</td>
<td>11.77</td>
<td>-8.3</td>
</tr>
<tr>
<td></td>
<td>T700/PPS</td>
<td>1553</td>
<td>6.807</td>
<td>13.51</td>
<td>+5.3</td>
</tr>
<tr>
<td></td>
<td>T700/MTM57</td>
<td>1534</td>
<td>5.800</td>
<td>12.83</td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>T700/PA6.6</td>
<td>1485</td>
<td>8.158</td>
<td>20.37</td>
<td>-2.4</td>
</tr>
<tr>
<td></td>
<td>T700/PPS</td>
<td>1553</td>
<td>6.807</td>
<td>23.08</td>
<td>+10.5</td>
</tr>
<tr>
<td></td>
<td>T700/MTM57</td>
<td>1534</td>
<td>5.800</td>
<td>20.88</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. Summary of the basic mechanical properties of the materials tested [11,12]

<table>
<thead>
<tr>
<th>Material</th>
<th>Tensile Modulus (GPa)</th>
<th>In-plane shear Strength (MPa)</th>
<th>Compression Strength (MPa)</th>
<th>Interlaminar Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>T700/PA6.6</td>
<td>65</td>
<td>3.2</td>
<td>74</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T700/PPS</td>
<td>870</td>
<td>73</td>
<td>265</td>
<td>34</td>
</tr>
<tr>
<td>T700/MTM57</td>
<td>1147</td>
<td>53</td>
<td>520</td>
<td>32</td>
</tr>
</tbody>
</table>

\(^1\)Interlaminar shear (ILS) strength values obtained from short-beam shear test [13]

5 DISCUSSIONS

Typically, an impact damage exhibits a form of matrix cracking, fibre-matrix debonding, delamination and fibre fracture. Delamination occurs due to the low interlaminar shear (ILS) strength, which leads to critical reduction in the material’s performance after impact. Laminated composite structures are normally designed to absorb LVIs in most applications. When a laminated structure is subjected to barely visible impact damage (BVID), categorically, micro-damage is incurred. This led to a significant deterioration in the laminate’s strength and durability [10,14,15].

At the lowest impact energy (40\textit{J}), all systems showed comparable response as expected (Figure 3). This is because at 40\textit{J}, only BVID was observed, as depicted in the C-scans (Figure 5) and X-ray images (Figure 6). Similarly, the time histories and force-displacement plots reported analogous trends.

Under the intermediate impact energy of 100\textit{J}, it was initially predicted that the samples would all suffer partial-penetration. Nevertheless, two of the systems, namely the T700/PA6.6 and T700/MTM57 experienced full-penetration, with petaling effect on the rear surface. On the contrary, the T700/PPS system showed a large degree of delamination without any penetration. The extent of damage in the T700/PA6.6 sample at 100\textit{J} indicated by the C-scan images (Figure 5) was found to be the smallest and most localised, with minor delamination. The T700/MTM57 showed greater extent of damage and degree of delamination. The extent of damage and delamination in the T700/PPS sample was the largest.

At 160\textit{J}, the extent of damage and delamination seen at 100\textit{J} were simply amplified. Both specimens, the T700/PA6.6 and T700/MTM57 showed greater extent of damage whereas the T700/PPS sustained more severe delamination. This was clearly pictured in both the C-scans and X-ray images (Figure 5 and 6). The delamination areas of all materials relative to the T700/PA6.6 were quantified and tabulated in Table 3. The relative delamination areas of the T700/MTM57 and T700/PPS were calculated to be 1.9 and 3.1 at 100\textit{J} and 2.9 and 3.8 at 160\textit{J} respectively.

The delamination of a laminated composite is largely governed by the interlaminar shear stresses. Likewise, delamination is one of the main energy absorption of polymer composite materials. Hence, the results obtained from this study is indicative of the interlaminar shear strength gathered reported by Mohsin et al. [11] (Table 2), where the weakest T700/PPS suffered the greatest level of delamination while absorbing the highest amount of energy. It is also postulated that the delamination which was seen in the T700/PPS system under both impact energies of 100 and 160\textit{J} could have been contributed by the relatively tougher Kevlar® stitching in the NCF. The stitching may have also resulted in a pull-in effect seen on the post-impact panels. However, as of now, the reason behind the impenetrability of the T700/PPS is still inconclusive and could only be determined by fractographic analysis using a scanning electron microscope (SEM), which is unfortunately not covered by this study.
Table 3. Summary of delamination areas relative to the T700/PA6.6 system

<table>
<thead>
<tr>
<th>Impact Energy (J)</th>
<th>Material</th>
<th>Relative Delamination Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>T700/PA6.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>T700/PPS</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>T700/MTM57</td>
<td>1.9</td>
</tr>
<tr>
<td>160</td>
<td>T700/PA6.6</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>T700/PPS</td>
<td>3.8</td>
</tr>
<tr>
<td></td>
<td>T700/MTM57</td>
<td>2.9</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

In this paper, the LVI test on three different NCF composite materials; (i) T700/PA6.6, (ii) T700/PPS and (iii) T700/MTM57 was successfully conducted at three different drop-weight impact energy levels; 40, 100 and 160 J using a 16mm diameter impactor. The impact performance of both TP and TS laminated composite material systems has investigated and compared.

The amount of impact energy absorption per areal weight of T700/PA6.6, T700/PPS and T700/MTM57 are 11.77, 13.51 and 12.83 kJ.m²/kg at 100 J and 20.37, 23.08 and 20.88 kJ.m²/kg at 160 J respectively. Thus, the best performing laminated composite system in terms of energy absorption investigated in this study was the carbon/TS T700/PPS (up to +10.5% better), followed by the carbon/TS T700/MTM57 and carbon/TP T700/PA6.6 (with a combined average difference of −5.3%).

In relation to the extent of damage and delamination however, the T700/PPS performed the worst (with relative delamination areas of 3.1 at 100 J and 3.8 at 160 J), largely due to its relatively low interlaminar shear strength. This is followed by the T700/MTM57 system, with relative delamination areas of 1.9 at 100 J and 2.9 at 160 J. The T700/PA6.6 exhibited the most localised penetration with comparatively small extent of damage and low level of delamination. The results obtained were indicative of the interlaminar shear strength of the different systems and the influence of NCF stitching.

Although the T700/PA6.6 exhibited marginally inferior energy absorption capabilities when compared to the TS system (T700/MTM57), it must be noted that the such a TP composite system would still offer superior OOA manufacturability and recyclability. Hence, it can be concluded that TP composites promote a more sustainable and economical alternative solution for structural automotive applications than the outgoing TS composite systems.

ACKNOWLEDGEMENTS

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REFERENCES


