EXPERIMENTAL STUDY OF COMPOSITE STRUCTURES IN AUTOMOTIVE APPLICATIONS

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ABSTRACT

The fuel efficiency and emission gas regulation of passenger cars are two important issues nowadays. The best way to increase fuel efficiency without sacrificing safety is to employ fibre-reinforced composite materials in the body of cars because fibre-reinforced composite materials have higher specific strengths than those of steel. This was one of the motivating factors behind this paper. A two-phase program to improve the specific energy absorbed by axially crushed composite collapsible tubular energy absorber devices was undertaken. In the first phase, examining of the crushing behaviour of non-triggered tubes (NTT). The second phase is aimed at obtaining the best position for the triggered wall and effect of triggered wall position of composite circular tubes to the axial crushing load. The experimental results demonstrated the strong potential benefits of optimizing the material distribution.

Keywords: Triggered wall, Shape; Composite; Energy Absorber

NOTATIONS

H Total height of tube
r Radius of the tube
L_t Triggered wall length
(L_t/H) Triggered wall aspect ratio
u Crushed distance
t Thickness of the triggered wall
E_s Specific energy absorption
E_{NS} Normalised specific energy absorption
E_E Energy absorption per unit volume
W_p The total work done
S Instantaneous displacement
P_m Mean crush failure load
P_c Critical crush failure load
P_1 First peak crush failure load
CFE Crush force efficiency= P_m/ P_{mp}
CS Crushed strain=u/H
NIT Non-Triggered tube
ITT Inner triggered tube
OT Outtriggered tube
MTT Middle triggered tube (L_t/H) of 0.28

1 INTRODUCTION

Using the right geometrical shape and wise material distribution could give great payoffs such as lower weight, designed higher stiffness areas and stable energy absorption process. A two-phase program to improve the specific energy absorbed was undertaken. In the first phase, examining of the crushing behaviour of non-triggered tubes (NTT). The second phase is aimed at obtaining the best position for the triggered wall and effect of triggered wall position of composite circular tubes to the axial crushing load. Three sets of triggered tubes were fabricated and placed in inner triggered tube (ITT) position, outer triggered tube position (OTT) and middle triggered tube position (MTT). The crushing behaviour of circular composite tubes under axial compression has been extensively studies, experimentally and numerically [1-4]. Approaches aimed to improve the energy absorption capability of collapsible structures often leads to some penalties and can be classified in two approaches. The approach based on material properties employs core thin-walled structures filled with crushable medium [5-7]. This approach is being criticised because of apparent weight increasing, despite the specific filler density. Other researchers introduced hybrid [8] and segmented [9] structures using different fibres types in a single matrix system. A designed beneficial imperfection in the structure was also introduced to enhance the energy absorption of crush elements [10]. The usual practice in this approach is to take an existing material and utilize it in the best possible way by varying structural geometry. The primary purpose of this research is to study the effect of triggering on the crushing behaviour of composite circular tubes and to examine the effect of the triggered wall position on the energy absorption of composite circular tubes in order to maximize its specific energy absorption capability.

In this work a material distribution was considered. The position of a wall with less material was also optimised. The latter is being considered to optimize the compliances matrix in order to suppress the elastic energy absorbed during the initial crush failure stage which results in avoiding instantaneous high deceleration.
of the payload. While, the main purpose of implementing shape optimization is to further improve the specific energy absorbed while maintaining the weight of size optimized tube.

2. CRASHWORTHINESS PARAMETERS

Before the details and discussion of the results, the variables used are defined and some remarks with respect to these values are given. When evaluating the crashworthiness performance of energy absorber devices, attention should be directed to the instantaneous crush behavior such as crush force efficiency (CFE), crushed strain (CS), failure modes in different stages of the crushing process and energy absorption capabilities [11]. Since the crashworthiness parameters are dimensionless, they have been used to as a consequential comparative study of the crushing behavior of the structural elements that is the result of the interaction between the different structural geometry.

Crush Force Efficiency-Crush Strain Relation

It is well known that the crush force efficiency-crush strain relation allows a homogeneous comparison of the structural response independently from the material elastic properties. The crush force efficiency (CFE) is defined as:

$$ CFE = \frac{P_m}{P_{cr}} $$  \hspace{1cm} (1)

In which $P_m$ and $P_{cr}$ represent the mean crush failure load and critical crush failure loads, respectively. The mean crush failure load obtained by averaging the crushing load over the crush displacements through the stable load displacement. The desired value of the CFE parameter is equal to 1.0. If the instantaneous CFE is greater than 1.0 the tube is initially crushed by matrix failure, otherwise if CFE is far less than 1.0 the tube crushed in an ultimate catastrophic failure mode. On the other hand the desired energy absorber device has a crushable structure, which can be defined as the crushed strain (CS). The CS can be obtained by:

$$ CS = \frac{u}{H} $$  \hspace{1cm} (2)

Where, $u$ and $H$ represent the crushing distance and the total height of the structure, respectively. It is clear that the higher the value of the CS parameter, the higher the magnitude of energy absorbed by the structure, the more optimum the design of the structure.

Initial Failure Indicator

Alkoles [11] introduced a new crashworthiness parameter to study the nature of failure modes at pre-crush stage. From the load-displacement response of composite specimens using the data of tests can be calculate the initial failure indicator (IFI) as

$$ IFI = \frac{P_1}{P_{cr}} $$  \hspace{1cm} (3)

Where, $P_1$ and $P_{cr}$ represent the first peak and highest peak crush failure loads respectively.

As far as the initial peak value of the force coincide with the highest peak force value, the desired value of the IFI parameter is equal to 1.0 if the IFI is greater than 1.0, the tube is initially crushed by matrix failure, otherwise if IFI is far less than 1.0 the tube crushed in an ultimate catastrophic failure mode [11].

Energy Absorption Capability

Energy absorption capability during the structural crash is a requirement across the complete spectrum of passenger transportation. Therefore, the instantaneous specific energy absorption capability of composite tubes was computed. The total work done (Wp) during the axial crushing of the tubes, which is equal to the area under the load-displacement curve is given by:

$$ W_p = \int_{s_p}^{s} P_i ds $$  \hspace{1cm} (4)

The post-crush stage is generally more important due to its strong influence on the crashworthiness parameters. Therefore, the work done at post crush stage ($W_p$) can be calculated as;

$$ W_p = \int_{s_p}^{s} P_i ds \Rightarrow \int_{s_p}^{s} P_{cr} (s - s_p) $$  \hspace{1cm} (5)

One can also write the energy absorbed per unit mass (i.e. specific energy absorption) as

$$ E_s = \frac{W_p}{M} $$  \hspace{1cm} (6)

The volumetric energy absorption capability (per unit volume) is also important parameter for energy absorption system design, where the space is a restraint. The energy absorption per unit volume ($E_v$) can be calculated via

$$ E_v = \frac{E_s \times M}{V_s} $$  \hspace{1cm} (7)

Where, the volume of structure $V_s = A_s \times H$ and $A_s$ is the cross-section area of structure given by $A_s = \pi r^2$.

3. EXPERIMENTAL WORK

3.1 Preparation of mandrel

Bulk wood was used to fabricate the mandrel. Lathe machine was used to provide the cylindrical shape with dimensions, 10 cm diameter and 30 cm length. The
mandrel was segmented axially into three parts, which can be separated for the ease of extracting the circular tubes. A plastic wrapper was used to rejoin the three parts before winding process. The geometry chosen was circular for some reason. It should be noted that many research done previously concerning composite tubes was in circular shape. This allows comparative study between previous studies and this study. The schematic diagrams are shown in Figure 1.

![Figure 1 Schematic diagrams of mandrel with (a) non-triggered (NTT) and inner (ITT), (b) outer (OTT) and middle (MTT)](image)

### Composite Constituents

The fibre reinforcement used in this study was woven roving glass. The matrix materials were the epoxy resin and the hardener. The ratio of hardener to epoxy resin is 17 parts to 100 parts, respectively. This ratio follows the manufacturer’s recommendation. The industrial types of these materials

### 3.2 Fabrication Process of the Specimens

In fabrication process was used woven roving fibre glass is under-run resin bath causing saturation, one hundred parts by volume of epoxy resin was mixed with 17 parts by volume of epoxy hardener from Leco Corporation USA was used for the matrix, then passed the wet fibre across tension devices to the circular sold wooden mandrel. The type of fibre reinforcement was woven roving E-glass, which chosen based on its enhanced impact resistance and because it is the most common reinforcement used through the composite industry. The woven roving E-glass is relatively cheap; possess good strength and resistance of water degradation. The process is shown schematically in Figure 2. The composite tube curried out at room temperature 32 C° and leaved behind for 24 hours to provide optimum blend. The winding parameters (e.g. winding tension, winding speed, and resin content, resin mixing time and winding time between layers) were maintained at constant level during the fabricated period. The cured woven roving cylindrical composite shells were then extracted from the mandrel. Figures 3 and 4 show the fabricated tubes.

![Figure 2 Schematic diagrams for woven roving winding process](image)

![Figure 3 Triggered wall distribution of tubes, (a) NTT, (b) ITT, (c) OTT and (d) MTT](image)

![Figure 4 Typical Photographic of Tubes](image)

### 3.3 Crushing Process

Fifteen specimens were examined under quasi-static axial crushing test as shown in Figure 5. Quasi-static axial crushing tests were carried out using an Instron 8500...
digital-testing machine with maximum loading capacity of 250kN. Load platens were set parallel to each other prior to initiation of the test. The entire specimens were compressed and loaded by displacement at speed of 15mm/min. Load and displacements were recorded by an automatic data acquisition system. The test was designed in order to be highly precise. Therefore, the results are presented from the average of the five tests under same testing condition. Table 1 listed the dimension of the test specimens.

![Composite tubes under axial crushing](image)

Figure 5 Composite tubes under axial crushing

Table 1 Characteristics of tubes dimensions

<table>
<thead>
<tr>
<th>Specimen (ID)</th>
<th>( t ) (mm)</th>
<th>( D_m ) (mm)</th>
<th>( A ) (m²)</th>
<th>( V_s ) (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTT</td>
<td>6.30</td>
<td>106.30</td>
<td>0.002103</td>
<td>0.00134</td>
</tr>
<tr>
<td>Triggered Wall Position</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITT</td>
<td>3.35</td>
<td>103.35</td>
<td>0.00108</td>
<td>0.00129</td>
</tr>
<tr>
<td>MTT</td>
<td>3.35</td>
<td>106.70</td>
<td>0.00113</td>
<td>0.00131</td>
</tr>
<tr>
<td>OTT</td>
<td>3.35</td>
<td>110.05</td>
<td>0.00115</td>
<td>0.00134</td>
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</table>

4 RESULTS AND DISCUSSION

To investigate the effect of non-triggered and triggered wall position on the crushing behaviour of axially crushed composite tubes, specimens in different positions were fabricated and crushed. Tubes of non-triggered and three sets of triggered were fabricated. These are tubes with non-triggered (NTT) and triggered wall placed in inner (ITT), middle (MTT) and outer (OTT) positions. Representative results will be presented and discussed in the following section. The load-displacement curves with crushing history for axially loaded composite tubes at different positions are shown in Figures 6-9.

4.1 Load-Displacement Relationship

The load-displacement relationship of energy absorption devices is one of the keys factors in measuring their crashworthiness performance. Generally, the curves histories can be divided into three distinct stages, a stage of crushing initiation, a stage of crushing propagation and stage of material densification. As the load increases during crushing initiation stage, elastic strain energy is accumulated in the specimen and no gross failure takes place; but local failure mechanisms on a micro scale-for example, micro buckling of the fibres on the compression side or debonding at the fibre-matrix interface—are most probably dominated the failure mechanism during the pre-crush stage. This type of failure mode is investigated using optical microscope. When a critical load is reached at the end of the initiation phase, the specimen would failed by many scenarios depending on the positions of triggered wall as well as the shape of cross sectional area. At this point the fracture propagates either in a catastrophic "Euler buckling" manner or in a progressive manner continuing to absorb energy at desirable crush loads.

4.1.1 Non-Triggered Tubes (NTT)

Figure 6 shows the deformation history and corresponding load-end shortening paths for non-triggered circular composite tube. It is shown that the load increased nonlinearly prior to the onset of matrix micro cracking initiated at ends of the tube, when first peak is developed with 41.75kN (point 1).

![Typical load-displacement curve and deformation histories of NTT-tubes](image)

Figure 6 Typical load-displacement curve and deformation histories of NTT-tubes

After achieving the first peak, a non-linear region appears again in the load-end shortening path, where, the load-end shortening path presents increased in tube resistance to reach its highest peak load value of 41.06kN at 17.97mm deformation (point 2) corresponds to the progressive matrix cracking and fibre debonding. Following the highest peak, a transverse shear cracking at the bottom end of the tube led to steep drop in tube load
carrying capacity and the curve reached its lowest value of 13.9kN at 70mm displacement (point3). It is evident from Figure 6 that the tube exhibited an unstable behaviour. Final lock-up region follows the sharp drop and the load increases linearly as shown in Figure 6. Typical load-displacement curve and deformation histories of non-triggered wall tube shows in figure 6; the mean crush load \( P_m \) value is 21.47kN.

### 4.1.2 Inner Triggered Tubes (ITT)

Figure 7 shows the deformation history and load-displacement curve for (ITT). The load increased non-linearly prior to the onset of matrix micro cracking initiated at ends of the tube, when first peak is developed with 15.40kN at 2.01mm (Point 1). This leads to increase in the overall displacement with an almost constant applied crush load. After the first peak, a non-linear region appears again in the load-displacement curve where, the load presents a steep increase in tube resistance to reach its highest peak load value of 36.7kN at 38mm (Point 4). A tiny drop in load carrying capacity was recorded. Load-displacement curve in this stage corresponds to the progressive matrix cracking and fibre debonding. Then the load-displacement curve rises and fluctuates non-linearly. Final lock-up region follows the sharp drop and the load increases non-linearly as shown in Figure 7, the mean crush load \( P_m \) value is 28.6kN.

### 4.1.3 Outer Triggered Tubes (OTT)

Figure 8 presents the typical load-displacement curve for OTT tube. It can be noticed that the crushing load at pre-initial crush failure stage increased non-linearly and reached its first peak value of 28.73kN at 1.54 mm displacement (point 1). Following the first peak value, matrix cracking associated by fibre debonding failure mode was observed. This type of failure leads to material degradation at crushed zone, which resulted in considerable drop in the magnitudes of tubes resistance to reach its lowest value of 23.95kN load at 2.29mm(point 2). Then after, the load fluctuates about a constant load value of 26kN in the displacement range between 3mm and 18mm (point 2- 3). The tube resistance was recovered and the load reaches its second peak value of 58kN at 40 mm (point 4). Following the second peak the load rises gradually to record its highest peak value of 63kN at 46mm. At this instant the gross deformation of the tube was observed to equal the length of the triggered wall. The crush zones were characterized by debris splitting the tube wall into internal and external fronds. This is repeating till the starting of material densification phase, where the specimen behaved as rigid body.

### 4.1.4 Middle Triggered Tubes (MTT)

Figure 9 shows the deformation process and corresponding load-end shortening paths for specimen with MTT composite tube. In this regime the curve increases non-linearly until the first peak value of 28.58kN at 1.26mm displacement (point 1), In this stage matrix cracking initiated at the top end of the structure and the audible matrix cracking and crack propagation. Subsequently the Load-displacement curve was dropped from 28.53kN at 1.26mm to 23.64kN at 3.01mm (point 2) this occurs because of matrix cracking and crack propagation. Then the load rises and reaches to 25.78kN at 4.5mm. Thereafter, stable load –displacement curve behaviour was achieved and it is fluctuating about 26.5kN between 4.5mm to 12.25mm displacement (point 3). With the crushing process progresses it is shown that the tube resistance increased and load carrying capacity increased and the load reach to highest peak load \( P_{HP} \) of 65.8kN at 49.5mm (point 4). Following the \( P_{HP} \), a gradual drop in the tube load-carrying capacity was observed and found to be due to the development of interlaminar and intralaminar micro cracks propagating between the layers in crushed zone at the top end of the
tube forming lamina bundles. Following the highest peak the tube resistance dropped slightly and audible matrix cracking at both ends of the tube accompanied this drop and the load-displacement curve reach to about 60kN at 90mm (point 5). In the last stage of crushing the tube behaves as rigid body results in load lockup to occur. The typical load-displacement curve and deformation histories of middle tube triggered wall show in figure 9; the mean crush load (Pm) value is 51.2kN.

4.2 Energy Absorption Capabilities

Figure 10 shows the energy-displacement curve for T-tubes. Table 2 summarizes the results of the energy absorption capabilities for T-tubes. The energy-displacement curves were calculated by numerical integration of load-displacement relations. Figure 9 shows that the total energy increased with increased in the displacement. It is obvious from the figure that all the tubes have a non-linear energy-displacement relation as well as it is obviously that the TM tube has superior energy absorption capability along the displacement of crushing.

Table 2 Summarized results of the energy absorption capabilities for tubes

<table>
<thead>
<tr>
<th>Tube ID</th>
<th>E (kJ)</th>
<th>Eₘₘ (kJ/kg)</th>
<th>Eₘₜ (kJ/kg.m²)</th>
<th>Eₖ (kJ/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTT</td>
<td>2.49</td>
<td>7.56</td>
<td>3596.7</td>
<td>1858.21</td>
</tr>
<tr>
<td>ITT</td>
<td>3.9</td>
<td>14.4</td>
<td>13300.0</td>
<td>3023.0</td>
</tr>
<tr>
<td>MTT</td>
<td>5.12</td>
<td>18.3</td>
<td>16195.0</td>
<td>3910.0</td>
</tr>
<tr>
<td>OTT</td>
<td>4.7</td>
<td>15.3</td>
<td>13304.0</td>
<td>3544.0</td>
</tr>
</tbody>
</table>

The energy-absorption capability trend is different for ITT, OTT, and MTT tubes as plotted in Figure 10. It is interesting to note that MTT specimens exhibit more flexibility behaviour and high compressive strength than the ITT and OTT specimens. Higher compressive strength means more resistance to advancing crushing platen, while reasonable flexibility means more stable deformation as well as structural integrity. This resulting in higher energy absorption compared with other specimens. One more important observation is that most of the energy absorption process occurs in the post crush stage. As clearly shown from Figures 6 to 9, post-crush stage (i.e. stage after Pₘₘ) for MTT specimens is more stable than that for the TN, TI and TO specimens. Further more, MTT exhibited highest crush force efficiency (CFE) as well as highest load carrying capacity. The normalized energy absorbed by NTT, ITT, OTT and MTT tubes are 3596.7kJ/kg.m², 13300kJ/kg.m², 13304kJ/kg.m² and 16195kJ/kg.m², respectively.

Figure 9 Load-displacement curve and deformation histories of MTT tube.

Figure 10 Energy-displacement relations of tubes

Figure 11 shows the energy absorption per unit mass, normalized specific energy absorption and energy absorption per unit volume as a function of triggered wall position (r/t). The energy-absorption capability trend is similar for ITT, OTT, and MTT tubes as plotted in Figure 11. It is interesting to note that MTT specimens (r/t=15.93) exhibit more flexibility behaviour and high compressive strength than ITT and OTT specimens. Higher compressive strength means more resistance to advance crushing platen, while reasonable flexibility means more stable deformation as well as structural integrity. This resulting in higher energy absorption compared with other specimens. One more important observation is that most of the energy absorption process occurred in the post crush stage. As clearly shown from Figures 6-9 that the post-crush stage (i.e. stage after Pₘₘ) for TM specimens is more stable than that for TI and TO specimens and during this stage TM exhibited highest crush force efficiency (CFE) as well as highest crush
resisting force. The specific energy absorbed by ITT, OTT and MTT specimens are 14.4kJ/kg, 15.3kJ/kg and 18.3kJ/kg, respectively.

However, the normalized specific energy should be obtained to eliminate the effect of cross-sectional area of material. Also from Table 2, the normalised specific energy absorption of MTT tubes is quite high compared with others tubes. The volumetric energy absorbed by T-tubes is 1858.2kJ/m$^3$, 3023kJ/m$^3$, 3544kJ/m$^3$ and 3910kJ/m$^3$, respectively. It may observe that the triggered wall position significantly affected the crashworthiness parameters of the tubes. Crush failure initiation and propagation at all specimens was influenced by triggered wall failure mechanism, which is strongly affected by triggered wall position. The middle position of triggered wall in MTT tubes allows the tubes to resist crush loads in membrane manner, while the other positions lead to bending mechanism for OTT and ITT tubes. The presence of this membrane resistance mechanism in MTT specimens increases their crashworthiness parameters. From the energy absorption capabilities point of view one can deduce that MTT tubes have superior energy compared to the other tubes. MTT tubes will be considered for further crushing test to study effect of sizing and material optimisation techniques on the energy absorption capabilities.

4.3 Failure Modes

The crushing failure modes of the tubes are investigated in two scale levels; macro scale using photographs taken during the crushing test. Distinct failure modes were observed to dominate failure mechanisms could be identified and classified as follows:

Mode I

Mode-I is a progressive failure mode in which the failure starts at the top end of the structure. This mode is associated with crush mechanism that involves extensive matrix deformation and matrix fragmentation. Fibre micro fracture in small zones that moves progressively through the structure was also observed in this mode. In this failure mode the structure remains intact without debris splitting after being crushed. The load-displacement behaviour of this type of failure was shown to be stable along the post crush stage. This mode is observed to dominate the crushing process of MTT tubes as shown in Figure 9.

Mode II

Multi failure mode is a combination of progressive failure mode with transverse shear cracking at the top end of the OTT and ITT tubes. In the pre-crush stage, most of the composite tubes failed after matrix cracking, while after the peak load a progressive failure mode developed, and when closed from the end of triggered wall the resistance tube is increasing therefore, matrix cracking again it is also observed, Then a progressive failure mode developed from both ends and consisting of fragmentation accompanied by transverse shearing.

4.4 Crush Failure Loads

The variation of the crush failure loads were plotted as function of aspect ratio (r/t). Variations in initial and mean and critical failure loads as shown in Figure 12.

![Figure 11 Energy absorption as a function of triggered wall aspect ratio r/t](image)

![Figure 12 Crushing loads as a function of aspect ratio r/t](image)
51.2kN, 45.2kN 28.6kN for MTT, OTT and ITT tubes, respectively.

4.4 Crushing Force Efficiency (CFE) and Crushed Strain (CS)

Table 3 lists the crush force efficiency (CFE), initial failure indicator (IFI) and crushed strain (CS). As expected from the appearance of load-displacement curves in Figure 9, MTT tubes are displayed the highest crush force efficiency value of 0.79. This result also illustrated the excellent structural integrity of this tube. On the other hand, the crushed strain CS that provides an indication of the crushability of the structure. The high value (0.76) for MTT indicates a rather stable and crushable structure, which corroborated by the IFI factor. This was again apparently attributed to a difference in failure modes along the post crushing process.

CONCLUSION

In this paper, the effect of non-triggered and triggered wall position on the energy absorption, crush failure loads as well as the failure modes were examined. Results of the tubes were presented, it was found that in designing an improved energy absorber, due consideration has to be given to the influence of triggered wall distribution, shape optimization on the composite based energy absorber device. Middle triggered tube (MTT Triggered tubes) recorded significantly higher energy absorption than all triggered wall distribution specimens.

REFERENCES