Filler strengthening of foam-filled energy absorption devices using CFRP beams

T.A. Sebaey 1,⇑, E. Mahdi

Mechanical and Industrial Engineering Department, College of Engineering, Qatar University, 2713 Doha, Qatar

ARTICLE INFO

Article history:
Received 9 September 2016
Revised 16 October 2016
Accepted 17 October 2016
Available online 18 October 2016

Keywords:
CFRP
Foam-filled
Crushing
Energy absorption

ABSTRACT

The crashworthiness of fiber reinforced plastics (FRP) is attracting more interest as they are currently contributing to several industries. In the present study, internally strengthened foam-filled rectangular carbon fiber reinforced plastics (CFRP) composites are presented for energy absorption applications. Commercially available carbon/epoxy beams/tubes were employed. After arranging the internal strengthening, each structure was filled with foam for better structural integrity. The structures were subjected to lateral compression and their crashworthiness was assessed using the peak load, the mean crushing load, the stability during post-crushing, the energy absorption, and the specific energy absorption. Up to 100% improvement was observed in both the energy absorbed and the load carrying capacity (referring to the peak load and the mean crushing load). Moreover, the stability in the post-crushing stage did not show significant dependency on the strengthening arrangement. Since it is highly dependent on the specimen weight, which is different from one specimen to another, the specific energy absorption showed different responses compared to the scalar value of the energy. For some configurations, internal strengthening had a negative effect on the specific energy. In contrast, an improvement of up to 22.5% was achieved for the other specimen configurations.

1. Introduction

Crashworthiness involves the absorption of energy through controlled failure mechanisms and modes that enable the sustainability of a stable load-time profile during the post-crushing stage. The ability to tailor composites’ properties, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance, and corrosion resistance, makes them extremely attractive in crashworthiness applications. The challenge is to use specific features of geometry and materials to enable greater safety while simultaneously decreasing weight without negatively affecting the overall economics of fabrication and production. However, the effective design of these energy absorbers is a complex undertaking due to the complexity of the multiple concurrent failure modes and their interactions [1–6].

Assessment of the crushing response of composites requires detailed information about the load-displacement history. In general, composite structures show linear and then almost linear load-displacement profiles. This profile is maintained until a certain limit, at which point the load carrying capacity of the structure suddenly drops. The load at which the first peak appears on the load-displacement plot is defined as the peak load ($P_i$). After the first peak, the plot fluctuates to peaks and valleys before reaching the final densification. The average load reading between the first drop and the final densification represents the mean crushing load ($P_m$). A smaller difference between the peak and the mean crushing forces reflects greater safety and comfort for the passenger (assuming an emergency case in transportation) and a smoother damage process. The ratio between the mean crushing load and the peak load defines the crush force efficiency ($CFE = P_m/P_i$), and the desired value of the $CFE$ is unity. To assess the difference in the two load values and the fluctuations during the post-crushing stage, the crush load stability is used ($CLS = CFE(1 – COV)$, where COV is the coefficient of variation of the load readings with respect to its mean crushing load).

Several factors contribute to the crashworthiness characteristics of laminated composites structures [7]. Among these factors, the geometry of the energy absorption devices plays an important role [8,9]. Palanivelu et al. [10] studied the response of glass fiber-reinforced polyester composite tubes with different geometries. Foam-filled structures were examined by the same authors in [11]. The results of their work showed that the load capacity, crush...
force efficiency, and energy absorption are highly affected by the specimen geometry and filler.

The improvements obtained by radially stiffening composite tubes were introduced in [12]; the results showed that reinforcing circular tubes with radial GFRP webs improved the load carrying capacity, specific energy absorption, and stability during the post-crushing stage. In addition, the use of hexagonal and octagonal CFRP tubes inside the energy absorption device was introduced for both unfilled and foam-filled rectangular carbon/epoxy [13] and aramid/epoxy [14] composite tubes. Configurations with closed cells are advantageous in terms of the peak and average crushing load, as well as energy absorption, whereas open cells are of great interest when comparing the stability of the crushing load in the post-crushing stage. At the same geometry, the fiber material and orientation highly affects the crashworthiness properties. These effects can be seen in the results obtained by Esnaola et al. [15] for the semi-hexagonal cross-section with glass and basalt fibers. The effect of the fiber orientation on the energy can also be shown in the work done by Hu et al. [16] under the quasi-static and the impact tests. The Energy absorbed in quasi-static crushing was similar to the once obtained by impact crushing. This validates the conclusions resulted by quasi-static tests. Xu et al. [17] also compared the energy absorption of composites specimens under quasi-static and the dynamic crushing tests. The results showed that the difference between them is 15%, which also supported using the quasi-static test. In the same study, the authors presented a comparison between the hybridization scheme of carbon, glass and aramid fibers. The composite specimens, mostly, failed in a brittle fracture mode under crushing, independent of the test condition or the fiber orientation, as it was observed by Wang et al. [18]. The results of that paper showed that, unlike the fracture mode, the energy absorption capability could be improved by selecting proper fiber orientation and wall thickness.

As energy absorbers, rectangular sections are extensively used in automotive structures. In the current paper, commercially available carbon/epoxy tubes are used. Rectangle tubes of 1 × 2 cross-sections, I beams and hat sections were arranged in different configuration to fill in the rectangle tube 2 × 4. All of the configurations were then filled with foam. The materials adopted for all of the cross-sections were CFRP composites. The specimens were tested under quasi-static lateral crushing up to final densification.

2. Sample preparation

The material used in this study was commercially available sections of epoxy-reinforced carbon fiber delivered by Dragon Plate\textsuperscript{TM} (Elbridge, New York, USA). Two grades of carbon fiber were used, as follows: plain weave (σ\textsubscript{f} = 3500 MPa and E = 230 GPa) and unidirectional (σ\textsubscript{f} = 4400 MPa and E = 235 GPa). Four different cross-sections were used to form our energy absorption devices. The dimensional properties of each cross-section are shown in Fig. 1.

The stacking sequence of each cross-section is summarized in Table 1. For all of the cross-sections, the carbon fiber volume fraction was 50%. The composites were delivered in the form of beam/tube of 1.5 m in length. To generate our proposed system, parts of 25 mm long were cut from the original tubes/beams and used to form the proposed energy absorption device.

All of the designed configurations used the 2 × 4 rectangle as the structure’s outer skin. Seven configurations were designed using the outer skin and different configurations of the other cross-sections shown in Fig. 1. Three specimens were tested for each configuration. Configuration A was composed only of the outer skin of the CFRP composite tube filled with polypropylene foam (Fig. 2). Each specimen of configurations B and E was formed of four hat cross-sections in different arrangements in addition to the outer skin. Each of the specimens in configuration C had two I-beams and a 1 × 2 rectangle tube in addition to the housing. In group D, the 1 × 2 rectangle tube was replaced by two hat beams. The specimens of configuration F were composed of an outer rectangle tube of 2 × 4 and four rectangle tubes of 1 × 2 (two with vertical arrangements and the other two arranged horizontally). Configuration G, representing the last group of specimens, was fabricated using a single rectangular 1 × 2 tube and two hat beams.

The specimens were fabricated in-home by cutting all of the beams/tubes of the same length and arranging the internal strengthening cross-sections in the desired configuration. No gaps were generated in the structure as the internal structure height was as nearly the same height as the rectangle 2 × 4 tube. When they were in the correct position, the different parts of the specimens were glued from the edge, forming the shapes shown in Fig. 2. Following this, the polyurethane foam (of 25 kg/m\textsuperscript{3} and 0.23 MPa compressive strength) was applied as a filler. The foam was introduced into the specimens using the procedure introduced in [13]. Filling the energy absorption device (either with polymeric [19] or metallic [20] filler) resulted in a high impact on the energy absorption, the load carrying capacity, and the stability of the damage propagation process [21].

The polyurethane foam was delivered as a two-part system (the foam and its own hardener). After joining all of the sections together, the device was closed from one side using plastic film. Then, the two parts of the foam were mixed in a 1:1 ratio and poured into the device. The foam reached its full strength after 20 min. Finally, the plastic film was removed and the excess parts of the foam were cut off using a handsaw. After obtaining the desired configurations, the specimens’ mass properties were measured; these are listed in Table 2.

Foam is important for this study to improve the structural stability of the whole structures. In the initial stage of the current study, the authors tried to do the same experiments with the same configurations without applying foam. The tests failed due to separation of the parts of the internal strengthening at an early stage of the loading followed by testing un-strengthened tubes. On the other hand, the effect of the foam filling was also studied. The comparison showed improvements of 17%, 37%, and 13% in the peak load, the mean crushing load and the energy absorbed. These results are in agreement with that in [19–21].

3. Crushing test protocol

Crushing tests were performed laterally in the 105.9 mm direction (vertically), Fig. 1. Two highly machined steel plates were initially attached to the machine acting as the upper and lower loading platforms. The tests were performed using an Instron 8500 digital-testing machine with a full-scale load range of 250 kN. The behavior of each tube under compression loading was recorded using a Canon XS150iS with a resolution of 14.1 megapixels. The acquisition system of the universal testing machine recorded the load-displacement data at a constant cross-head speed of 15 mm/min. The recording rate was 20 readings per second.

During a structural crash, energy absorption is required across the complete spectrum of passenger transportation [22]. The absorbed energy \( E \) during the lateral crushing of the proposed device equals the area under the load-displacement curve. The information in Table 2 reveals that there was a difference between the mass of the specimens filled with pure foam and those filled with foam and CFRP beams/tubes. In such a case, the data related to the absorbed energy are sufficient to assess each individual configuration. For comparison, the more realistic component is the
specific energy absorption \( (E_s) \), defined as the energy per unit mass of the specimen.

4. Results and discussion

4.1. Load-displacement and damage profile

Fig. 3 shows the load-displacement profile for the damage sequence of the specimens in configuration A. An initial longitudinal crack propagated inside the filler with the buckling of the vertical members of the rectangular tube. At the peak load, the vertical edges of the rectangular tubes started to fracture at mid-length, forming a hexagonal shape. The deformation continued, with foam compression, up to the final densification. The load histories and damage profile of configurations B and E are shown in Fig. 4. Both configurations were strengthened by four hat sections in different arrangements. The regular hexagonal deformed shape is also shown for the two configurations. All of the hat parts showed distortion at the same time and failed in random sequence. It is worth remarking that the specimens in configuration E had a higher peak load than those in B.

Specimens from configurations C and D each had two I-beams for strengthening with other sections. The loading scenario and damage are shown in Fig. 5. Specimens in C started to break via vertical cracks in the foam and buckling of the vertical walls, which led to twisting of the internal strengthening structure. In configuration C, the damage started from the I-beams, which were weaker than the rectangular tubes. In contrast, the specimens in configuration D started to fail at the hat sections, as these represented the weakest point in the structure, followed by the I-beams. This justifies the peak shown before the final densification of the structure in configuration D.

The load-displacement profile and damage sequence of F and G are shown in Fig. 6. For configuration F, the damage was different than that observed in the other groups, as it started with separation of the outer surface from the foam. This occurred on both sides for each of the three specimens. Following this, the core (composed of four small rectangles and foam) started to fail, causing the second peak in the load-displacement profile. The load displacement pro-
file and damage of configuration G specimens were extremely similar to those in configurations C and D (Fig. 5).

In general, strengthening of the foam filling the energy absorption device with CFRP beams/tubes shows improvement in the load carrying capacity. This improvement varies depending on the specimen type, as discussed in Section 4.2. An insignificant effect was recorded for the stability during the post-crushing process. The outer skin (2 × 4 rectangle) showed the same failure mode for all specimens, and the vertical walls of the skin were damaged at almost the mid-point to form a nearly regular hexagonal shape.

4.2. Crashworthiness assessment

The average peak and mean crushing loads and their tolerances are shown in Fig. 7. Generally, the peak load was higher with CFRP sections added to the filler. The improvement in the peak load ranged from 13% for configuration D to 75% for configuration E. For the other four configurations, the peak load was almost the same, with an improvement of 46±1%. Although they were extremely similar, specimens in configurations E and B exhibited different peak load values. This difference illustrates the importance of experimental optimization studies like the present one.

The average crushing load values showed much higher improvements ranging from 56% for configuration C to 100% for configuration F as compared to the baseline configuration A. The other four configurations showed nearly equal values in the mean load. The improvement in these configurations was 66±2%. Although they were extremely similar, specimens in configurations E and B exhibited different peak load values. This difference illustrates the importance of experimental optimization studies like the present one.

The average crushing load values showed much higher improvements ranging from 56% for configuration C to 100% for configuration F as compared to the baseline configuration A. The other four configurations showed nearly equal values in the mean load. The improvement in these configurations was 66±2%. Although they were extremely similar, specimens in configurations E and B exhibited different peak load values. This difference illustrates the importance of experimental optimization studies like the present one.

The efficiency of the energy absorption device is usually measured by the degree of safety and comfort throughout the whole crushing process. The crush force efficiency measures the difference between the mean load and the peak load. In our experiments, the maximum crush force efficacy was recorded for the specimens in configuration D followed by those in configuration F (Fig. 8). For more practical information on the post-crushing stage, the crush load stability was also measured for all specimens. The differences in the crush force stability were extremely limited.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>44.46</td>
<td>70.40</td>
<td>74.58</td>
<td>74.77</td>
<td>71.60</td>
<td>114.19</td>
<td>69.59</td>
</tr>
<tr>
<td>Standard deviation (g)</td>
<td>0.60</td>
<td>4.69</td>
<td>1.55</td>
<td>1.69</td>
<td>0.57</td>
<td>3.21</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Fig. 3. Load-displacement and damage sequence of configuration A.

Fig. 4. Load-displacement and damage sequence of configurations B and E.
This means that although there were differences in the mean value, the actual readings fluctuated highly around the mean, which justifies the relatively small value of the crush force stability. The similarity of this value for all specimen types (B–F) revealed that the scatter in the reading had a greater effect than the mean value of the load during the post-crushing.

The energy absorption, measured from the load-displacement plot, is shown in Fig. 9. Specimens from configuration F showed the highest values compared to the other configurations; however, the weight of this configuration was higher than that of the other configurations (Table 2). Specimens in configurations D, E, and G showed values that were close to the average energy absorption. Configurations D and E exhibited 100% improvement compared to the baseline configuration (A). For configuration G, the improvement was 86%. For the other two configurations, the levels of improvement were 55% and 60% for B and C, respectively.

Data on scalar energy absorption can be of great interest for applications with no weight constraints. However, more realistic information on the energy absorption can be drawn from the specific energy absorption (Fig. 10).

The data shown in Fig. 10 illustrate that the benefits of the internal strengthening of the tubes depends on the arrangement of the internal structure. As a result of their higher weights, configurations B, C, and F did not show any improvement is the specific energy absorbed. In contrast, they all had smaller or at most the same value of specific energy compared to the baseline configuration A. However, configurations D, E, and G returned higher specific energy values compared to the baseline. The improvement in the specific energy for configurations D, E, and G was $22.5\pm1.5\%$. 

---

Fig. 5. Load-displacement and damage sequence of configurations C and D.

Fig. 6. Load-displacement and damage sequence of configurations F and G.

Fig. 7. Peak and mean crushing load for the test campaign.
Although the specimens in these groups were all made from the same cross-sections, the arrangement of the internal structure beams showed a significant effect on the specific energy absorption.

For the automotive industry, rectangular cross-sections are frequently used in the bumper; these can either be filled with foam (metallic and polymeric) or left empty. The primary function of these cross-sections is energy absorption during any emergency event. The internal strengthening presented in this study showed an improvement in both the load carrying capacity and the energy absorption of the structure. The proposed methodology is economically friendly, as all of the materials and structures that were used are commercially available. Although we did not discuss this in our study, the same improvement can also be obtained for metallic bumpers.

5. Conclusions

An experimental optimization study was implemented in this research to investigate the effect of internal strengthening of foam-filled 2 × 4 rectangular tubes made of CFRP. Six different strengthening schemes were adopted in addition to the original baseline configuration. The internal strengthening was carried out by fabricating different cross-sections using 1 × 2 rectangles, hats, and I-beams made of CFRP. The manufacturing sequence started with arranging and gluing the strengthening inside the 2 × 4 rectangular tubes and then pouring in the two-part foam system. The proposed configurations were subjected to compression loading up to final densification at a test speed of 15 mm/min.

The results showed that any strengthening with the proposed methodology advantageous to the load carrying capacity. A minimum improvement of 13% was achieved for configuration D (with two hats and two I-beams) in the peak load. An improvement of up to 100% was observed for configuration E (four hat beams) in the peak load. Similarly, the improvement in the mean crushing load reached 100% for configuration F specimens. The stability of the crushing process, as measured by the CFE and CLS, did not show a clear improvement, as the load-displacement plot did not exhibit stable crushing. The energy absorption (E) showed significant improvement (up to 100%) for some strengthening arrangements. All of the proposed arrangements resulted in improvement in the quantity of the energy absorbed. For the normalized energy $E_n$, some of the configurations showed improvements of 22.5%. In contrast, for configurations B, C, and F, there were no recorded improvements in the specific energy absorbed, which reveals that the improvement in the energy ($E$) was due to the increase in the specimen weight.

Acknowledgements

This paper was made possible by NPRP Grant # NPRP05-1298-2-560 from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the authors.

References


