Experimental study on the crashworthiness response of hybrid Al/GFRP crash-box structures under axial compression loading

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Abstract. In this research, the dynamic crushing behavior of crash boxes made of aluminum reinforced with Glass Fiber Reinforced Polymer (GFRP) with circular cross-section is presented. Energy absorption capacity and damage behavior for different composite wall thickness and fiber ply orientation were investigated. The result shows that adding composite layers to the aluminum column will improve the column's energy absorption capacity. Nevertheless, the Specific Energy Absorption (SEA) of the aluminum structures generally higher than the hybrid systems. However, the hybrid column has higher crushing resistance than a combination of separate aluminum and composite crash boxes with the same geometry. This shows that interaction between aluminum and composites enhance the crash behavior since a stable and progressive crushing mode were observed, resulting in greater energy absorption. Additional research should be carried out to investigate further.

1. Introduction

A crash box structure is designed to withstand and absorb kinetic energy due to axial impact. Until now, most crash box components are generally made of metal. Generally, different geometry was investigated to increase the energy absorption capacity without adding the weight of the structure such as multi-corner [1] [2] [3] and multi-cell [4] [5]. As an alternative, a hybrid crash box which combines metal and composite can also be used to increase the energy absorption capability by utilizing superior metal properties which can produce a stable, progressive buckling mechanism combined with composites that can be utilized to increase critical buckling load by preventing the out of plane deformation of the thin-walled metal column.

Research on the application of hybrid material to crash boxes was initiated by Mamalis et al. [6]. Energy absorption behavior of the bi-material crash box is a combination of aluminum-steel, polyvinyl chloride-steel, aluminum-copper, aluminum-polyvinyl chloride, steel-polyvinyl chloride, aluminum, steel, copper and polyvinyl chloride with analytical methods is studied. In the same year, Wang [7], through his dissertation, conducted experiments for multi-material structures, namely steel
metals and glass/resin composites, with circular and square cross-sections. Other research on hybrid crash boxes was also conducted for tapered rectangular cross-sections led by Ying [8]. The impact behavior is analytically evaluated and investigated the effect of orientation parameters on the fiber orientation and thickness of the coating on the ability of energy absorption. Research on the geometry of other hybrid crash boxes has also been carried out, such as circular geometry by W. Song [9], Bouchet et al. [10], Reuter [11], Hanefi [12], Praveen [13] and Babbage [14]; rectangular cross-section by Shin [15], Boria [16], and Bambach [17]; whereas hexagonal tapered cross-section by Nianfei [18].

This paper will discuss experimental works on cylindrical structures under compressive axial impact loads for several materials: aluminum, glass epoxy composite, and hybrid Al/Glass-epoxy materials. The results will be compared and analyzed. The glass-epoxy composites were manufactured using two different methods: hand lay-up and filament winding methods. The results of these different methods will also be examined.

2. Research Methodology

The dropped impact testing machine was built in Lightweight Structure Laboratory, Faculty of Mechanical and Aerospace Engineering, and is shown in Fig 1. Fig 1 shows the components of the drop impact test, such as a drop tower testing machine, load cell, impactor, and speed sensor. The maximum mass is 165 kg, and the maximum height is 1.75 m.
Table 1 shows the geometry of the specimens. It shows different specimen codes with different materials as well as the manufacturing methods, as shown in Figure 2. All specimens were subjected to the impact energy produced by the mass of 165 kg and a height of 1.75 m.

| Specimen codes | Massa (m) [gr] | Thickness (t) [mm] | Outer diameter ($D_{out}$) [mm] | Length (L) [mm] |
|----------------|---------------|--------------------|---------------------------------|----------------|
| **Aluminum specimens** | | | | |
| Al 1 | 31 | 1.21 | 32.11 | 100 |
| Al 2 | 31 | 1.24 | 32.13 | 100 |
| Al 3 | 62 | 1.30 | 33.10 | 200 |
| **Glass-fibre epoxy composite hand-layup (CGH) specimens** | | | | |
| CGH8_2 | 26 | 1.89 | 32.25 | 100.71 |
| CGH8_3 | 27 | 1.80 | 32.70 | 103.39 |
| CGH8_4 | 27 | 2.16 | 33.06 | 100.57 |
| CGH12_1 | 39 | 2.36 | 35.09 | 99.26 |
| CGH12_2 | 41 | 2.56 | 34.48 | 99.74 |
| **Glass-fibre composite filament winding (CGF) specimens** | | | | |
| CGF3_80_1 | 32.00 | 1.78 | 35.24 | 99.63 |
| CGF3_80_2 | 31.00 | 1.61 | 34.96 | 101.30 |
| CGF3_80_4 | 31.00 | 1.65 | 35.33 | 102.11 |
| CGF3_80_5 | 30.00 | 1.54 | 34.93 | 99.12 |
| CGF7_80_2 | 75.00 | 3.65 | 38.46 | 102.62 |
| CGF7_80_3 | 79.00 | 4.42 | 39.96 | 99.11 |
| CGF7_80_4 | 74.00 | 3.82 | 38.57 | 100.15 |
| **Hybrid Al/Glass-epoxy composite hand lay-up (HH) specimens** | | | | |
| HH3_1 | 41 | 1.9 | 33.04 | 101.48 |
| HH3_2 | 38 | 1.8 | 33.54 | 95.34 |
| HH3_3 | 40 | 2.03 | 29.97 | 99.03 |
| HH3_4 | 40 | 2.09 | 33.33 | 97.48 |
| HH5_1 | 45 | 2.44 | 34.63 | 96.60 |
| HH5_2 | 46 | 2.34 | 35.11 | 98.68 |
| HH5_3 | 44 | 2.10 | 34.12 | 97.55 |
| HH5_4 | 44 | 2.25 | 34.40 | 98.52 |
| HH7_1 | 53 | 2.70 | 35.06 | 102.44 |
| HH7_2 | 52 | 2.53 | 35.15 | 101.87 |
| HH7_3 | 53 | 2.51 | 35.48 | 104.00 |
| HH7_4 | 51 | 2.78 | 35.42 | 101.14 |
| **Hybrid Al/Glass-epoxy filament winding (HF) specimens** | | | | |
| HF1_80_1 | 47 | 2.14 | 33.42 | 100.73 |
| HF1_80_2 | 44 | 2.19 | 33.57 | 99.65 |
| HF1_80_3 | 43 | 2.13 | 33.50 | 100.41 |
| HF1_80_4 | 43 | 1.99 | 33.36 | 100.91 |
| HF1_27_2 | 102 | 4.62 | 39.20 | 102.00 |
| HF1_27_2 | 103 | 4.82 | 39.55 | 103.00 |
3. Results and Discussion

3.1. Aluminum

Fig 3 shows the experimental results for Aluminum 6063 specimens. The curve in the left-hand side in Fig 3 is the average curve for 3 specimens, while the right-hand side shows the failure characteristic of the Al tubular specimens due to impact loads. The curve and the failure mode are typical ductile tubular structures under impact loads, while Table 2 shows the summary of the experimental data.

![Figure 3](image.png)

**Figure 3. The experimental force-displacement curve for aluminum specimens.**

| Experimental results                         |
|---------------------------------------------|
| Peak force \((P_{peak})\) [kN]              |
| Mean crushing force \((P_m)\) [kN]          |
| Crushing force efficiency \((CFE)\)         |
| Energy absorption, \((EA)\) [kJ]            |
| 27.79                                       |
| 14.94                                       |
| 0.54                                        |
| 0.804                                       |

3.2. Composite Hand lay-up specimens

Figure 4(a) shows the force-displacement curve and failure mode of glass-epoxy composite tubular structures under axial impact loading. It shows the typical failure of composite tubular structures under impact loading. The failure modes were in the form of fiber splitting, where the composite specimens were unable to sustain the impact loads and failed in splitting.

Crash boxes composites absorb energy through the brittle fracture, delamination, and debonding mechanisms. In the 8-plies hand lay-up composite specimen, the failure mode that occurs is the fragmentation, as shown in figure 4(b), whereas 12-plies composite specimens absorb energy by the mechanism of fiber splitting/ splaying as shown in figure 4(c).

Fiber splitting/splaying failure characteristics are stable and progressive failures with a combination of delamination mode, lamina bending, and fracturing. Based on Sun [19], the splaying failure mode produces favorable energy absorption characteristics because it has a higher energy absorption value, as shown in Table 3.
Figure 4. (a) Force-displacement curve for composite hand-layup with 8 (CGH8) and 12 (CGH12) plies, (b) deformation modes of CGH8, (c) deformation modes of CGH12

3.3. Hybrid Al/Glass-epoxy hand lay-up

Fig 5 shows the experimental results for hybrid Al/glass-epoxy tubular structures made using hand lay-up methods. It shows that glass-epoxy composite system was used to strengthen the aluminum structures and to avoid collapse while the aluminum structures withhold the glass-epoxy from splitting.

Figure 5. Force-displacement curve of hybrid hand lay-up specimens with 5 plies (HH5)
Table 3 Summary of the experiment results

| Specimen codes | Peak Force ($P_{peak}$) [kN] | Mean Crushing Force ($P_m$) [kN] | Energy absorption (EA) [kJ] | Specific energy absorption (SEA) [J/Kg] | CFE ($P_m / P_{peak}$) |
|----------------|-------------------------------|----------------------------------|-----------------------------|----------------------------------------|------------------------|
|                | Specimen aluminum             |                                  |                             |                                        |                        |
| Al 1           | 27.79                         | 14.94                            | 0.8135                      | 48.21                                  | 0.54                   |
| Al 2           | 24.09                         | 14.81                            | 0.8586                      | 47.78                                  | 0.61                   |
| Al 3           | 27.43                         | 14.86                            | 0.8487                      | 47.92                                  | 0.54                   |
|                | Specimen composite glass fibre hand lay up (CGH) | |                             |                                        |                        |
| CGH8_2         | 23.41                         | 7.97                             | 0.6398                      | 28.68                                  | 0.34                   |
| CGH8_3         | 21.48                         | 9.86                             | 0.6996                      | 37.96                                  | 0.46                   |
| CGH8_4         | 16.95                         | 6.79                             | 0.5586                      | 25.27                                  | 0.40                   |
| CGH12_1        | 21.29                         | 16.96                            | 0.8763                      | 43.15                                  | 0.80                   |
| CGH12_2        | 21.59                         | 19.22                            | 0.8289                      | 43.58                                  | 0.89                   |
|                | Specimen hybrid aluminum glass fibre hand lay-up (HH) | |                             |                                        |                        |
| HH3_1          | 34.73                         | 18.04                            | 0.8138                      | 44.66                                  | 0.52                   |
| HH3_2          | 32.32                         | 17.06                            | 0.8166                      | 42.81                                  | 0.53                   |
| HH3_3          | 35.86                         | 17.92                            | 0.7951                      | 44.38                                  | 0.50                   |
| HH3_4          | 37.95                         | 17.78                            | 0.7899                      | 43.31                                  | 0.47                   |
| HH5_1          | 35.56                         | 20.07                            | 0.7250                      | 43.08                                  | 0.56                   |
| HH5_2          | 40.12                         | 19.39                            | 0.7912                      | 41.56                                  | 0.48                   |
| HH5_4          | 30.97                         | 18.82                            | 0.7092                      | 42.13                                  | 0.61                   |
| HH7_1          | 39.83                         | 22.59                            | 0.7558                      | 43.67                                  | 0.57                   |
| HH7_2          | 38.96                         | 21.27                            | 0.7035                      | 41.67                                  | 0.55                   |
| HH7_3          | 36.22                         | 20.42                            | 0.6895                      | 40.06                                  | 0.56                   |
| HH7_4          | 35.89                         | 21.43                            | 0.7292                      | 42.50                                  | 0.60                   |
|                | Specimen hybrid filament winding (HF) | |                             |                                        |                        |
| HF1_80_1       | 44.35                         | 15.85                            | 0.7655                      | 33.96                                  | 0.36                   |
| HF1_80_2       | 38.94                         | 20.87                            | 0.7517                      | 47.26                                  | 0.54                   |
| HF1_80_3       | 33.29                         | 16.52                            | 0.9188                      | 38.57                                  | 0.50                   |
| HF1_80_4       | 35.84                         | 17.43                            | 0.7956                      | 40.91                                  | 0.49                   |
| HF1_27_2       | 103.37                        | 40.41                            | 0.39                        | 39.89                                  | 0.39                   |
| HF1_27_2       | 114.06                        | 34.39                            | 0.30                        | 33.70                                  | 0.30                   |
|                | Specimen composite filament winding (CGF) | |                             |                                        |                        |
| CGF3_80_1      | 15.20                         | 8.88                             | 0.7033                      | 27.63                                  | 0.58                   |
| CGF3_80_2      | 10.35                         | 6.64                             | 0.3606                      | 21.71                                  | 0.64                   |
| CGF3_80_4      | 10.93                         | 7.80                             | 0.4008                      | 25.68                                  | 0.71                   |
| CGF3_80_5      | 8.74                          | 4.90                             | 0.3682                      | 16.20                                  | 0.56                   |
| CGF7_80_2      | 40.35                         | 21.56                            | 0.7131                      | 29.50                                  | 0.53                   |
| CGF3_80_3      | 42.61                         | 23.83                            | 0.8290                      | 29.89                                  | 0.56                   |
| CGF3_80_4      | 31.08                         | 23.47                            | 0.7928                      | 31.77                                  | 0.76                   |

3.4. Hybrid Al/glass-epoxy filament winding specimens

Fig 6 shows the experimental results of hybrid Al/glass-epoxy filament winding specimens. The failure mode is similar to hybrid Al/glass-epoxy hand lay-up specimens, as shown in Fig 5. The aluminum was able to protect the glass-epoxy materials, while the glass-epoxy materials withstand the aluminum structures from collapsing. The summary of the experimental results is given in Table 3.

Table 3 shows that, generally, the aluminum tubular structures are still superior to those of hybrid and composite structures in terms of Specific Energy Absorption (SEA). Therefore, the glass-epoxy materials failed to increase the SEA. It should be investigated further for further research.
4. Conclusion

Experimental studies have been carried out to investigate the behavior of hybrid Al/glass-epoxy tubular structures subjected to axial impact loads. The results were compared to pure Al and glass-epoxy tubular structures. The results showed that, in general, pure Aluminum tubular structures were still superior to those of hybrid structures, which were manufactured using hand lay-up and filament winding in terms of their Specific Energy Absorption (SEA). However, the maximum crushing loads of the hybrid Al/glass-epoxy hand lay-up specimens were higher compared to pure aluminum structures. These findings should be elaborated further for future research since glass-epoxy materials have a capacity to increase the SEA by protecting the aluminum structures from collapse. This research also found that the hand lay-up specimens produced higher SEA compared to filament winding. This is an important finding since hand lay-up manufacturing is cheaper and simpler compared to filament winding technology.

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