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Energy absorption and failure behavior of Al/CFRP/GFRP hybrid tubes under quasi-static axial loading

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Abstract Fiber metal laminate (FML) is gaining increased interest among researchers in designing thin-walled tubes as an efficient energy absorber. The combination of aluminum tube and fiber-reinforced polymer (FRP) as an FML hybrid tube has successfully demonstrated enhanced crashworthiness performance of structures. Previous studies reported FML hybrid tubes employing a single type of FRP composite material as the laminate material. Investigations on the effect of stacking sequences of multiple types of FRP composite as laminate materials are limited and mostly focused on sandwich structures. This study aims to investigate the effect of reinforcement material as a laminate layer and stacking sequences on the crashworthiness characteristics of aluminum-FRP hybrid tubes under quasi-static axial compression loading. The crashworthiness characteristics and the failure behavior of aluminum monolithic tube, aluminum-single FRP material, and aluminum-multi FRP material hybrid tubes are tested and compared. Glass FRP (GFRP) demonstrates great potential as a laminate material for aluminum tube compared with carbon FRP (CFRP). Aluminum-GFRP and aluminum-GFRP-CFRP hybrid tubes exhibit a 26.4 % and 66.9 % increase in energy absorbed, respectively, compared with the monolithic aluminum tube. The specific energy absorption and crushing force efficiency of the aluminum-GFRP-CFRP hybrid tube show minimal reductions of 4.9 % and 6.2 %, respectively. GFRP is the better choice of laminate material for aluminum tubes compared with CFRP. Multiple FRP laminates show a larger crashworthiness enhancement of FRP hybrid tubes in achieving better crashworthiness performance of the energy absorber. These findings imply that the selection and stacking sequences of laminate material are vital in tailoring the performance of the hybrid tubes toward efficient energy absorbers.

1. Introduction

Crashworthiness is one of the most important criteria to be considered in vehicle design. A good crashworthiness structure should deform progressively in a stable crushing response to effectively mitigate the kinetic energy during impact and protect the vehicle and passengers. An efficient energy absorber must demonstrate high energy absorption with mass reduction through the largest possible deformation length. These structures must demonstrate high specific energy absorption (*SEA*) to achieve mass reduction. Various materials, such as thin-walled tubes [1], cellular materials [2], composite [3], and sandwich structures [4, 5], have been investigated in designing an energy absorber.

Combining multiple material types is gaining interest in developing an effective energy absorber. A combination of metallic materials and composites has shown benefits in achieving higher energy absorption with mass reduction. The advantages of each material are combined while minimizing or eliminating the drawbacks of the constituent material. Fiber metal laminate (FML) is a combination of metallic material and fiber-reinforced polymer (FRP). Carbon FRP (CFRP) and glass FRP (GFRP) are FRP materials that are mostly used and investigated to develop FML hybrid structures because they exhibit outstanding mechanical characteristics and are easy to process.

Most studies on FML focus on sandwich structures [6-8], and further development in FML shows the introduction of natural fiber composites as a substitute for FRP materials [9, 10]. The effects of laminate materials [11], material's orientations [12, 13], and number of laminate layers [14] on the energy absorption response and failure deformation of FML sandwich structures under quasi-static and dynamic loading have been investigated. A similar approach is then adopted in thin-walled tube structures, where metallic thin-walled tubes are wrapped with FRP materials as laminate to form an FML hybrid tube.

Thin-walled tubes offer high energy absorption with a stable crushing response when the tube undergoes progressive collapse during plastic deformation. The benefits of thin-walled tubes are achieved by manipulating their geometrical parameters [15] and material types [16]. Thin-walled tubes are available at a reasonable cost and easy to manufacture. FRP composites demonstrate excellent energy absorption capability with mass reduction compared with conventional materials [17]. Despite their advantage in achieving mass reduction, FRP composites are brittle and exhibit anisotropic material properties. An abrupt failure may occur due to delamination or breakage of the fiber at a certain extent of the deformation length [18]. Thus, a rapid drop occurs in the energy absorption capacity of the composite material.

The combination of metallic tubes and FRP materials has successfully enhanced the energy absorption of the hybrid FML tube, as observed in Abada et al.'s work [19]. Compared with the aluminum single-cell tube, the aluminum-CFRP hybrid quadruple-cell tube has shown as 116 % higher energy absorption. The energy absorption of the aluminum-CFRP and aluminum-GFRP hybrid tubes exhibit lower energy absorption compared with bare materials as observed in Ref. [11]. The aluminum-CFRP hybrid tube shows higher energy absorption compared with the aluminum-GFRP hybrid tube. The enhancement of the FML structures' performance is investigated by employing a cross-ply layer of FRP composite [7, 20]. Compared with the composite GFRP, the aluminum-GFRP-aluminum hybrid shows higher energy absorption due to delamination of the metal/GFRP interface and shear and metal plastic deformation. The energy absorption of the FML hybrid tube is enhanced by increasing the number of laminate layers. Shen et al. [21] employs 2, 3, and 4 layers of CFRP materials as laminate layers for aluminum T6063-T6 square tubes. The number of collapse lobes increases with the increasing number of laminate layers, and the energy absorption increases.

Single and double tube cells of aluminum-CFRP hybrid tubes exhibit lower specific energy absorption (*SEA*) than that of the monolithic single cell aluminum tube [19]. Only the hybrid quadruple cell aluminum-CFRP hybrid tube surpassed the *SEA* of the monolithic single cell aluminum tube. By contrast, the work done by Yang et al. [11] shows that the aluminum-CFRP hybrid tube demonstrates a 54.3 % and 40.4 % increase in *SEA* and *CFE*, respectively, for tubes with 40 mm inner diameter compared with the monolithic aluminum tube. The aluminum-CFRP hybrid tube displays better *SEA* than that of the aluminum-GFRP hybrid tube. These findings have shown that laminate materials and geometrical parameters play important roles in the energy absorption and *SEA* enhancement of hybrid tubes.

Although these findings have shown further insight into FML hybrid tubes, the focus is on a single FRP material type as a laminate. Its advantages can be further explored by manipulating the stacking sequence of the multiple types of laminate layers. However, studies on the effects of the stacking sequence of laminate layers of FML hybrid tubes are limited in the open literature. The outcome of this investigation is envisaged to achieve enhanced performance of FML hybrid tubes by tailoring the desired response of hybrid tubes toward lightweight and high energy absorption in impact applications. To date, few studies have investigated the stacking sequence effects of laminate layers of hybrid tubes. Mirzamohammadi et al. [22] studied the stacking sequence effect of laminate materials under flexural and shear loadings. However, the work is performed on the sandwich structures of aluminum-jute-basalt with carbon nanotubes. Another work investigated the stacking effect on aluminum-CFRP/GFRP-aluminum and aluminum-CFRP/GFRP-GFRP/CFRP-CFRP/GFRP-aluminum sandwich structures on the fatigue stress cycle. Aluminum-CFRP-aluminum exhibited the highest fatigue life, followed by aluminum-CFRP/GFRP-GFRP/CFRP-CFRP/GFRP-aluminum tubes, and the least is aluminum-GFRP-aluminum [17]. Wiedemann et al. [23] quantified the in situ induced strains of steel-CFRP hybrid sandwich structures. The structures are prepared by stacking the steel and CFRP materials repeatedly. However, the work only employed a single type of laminate material. The use of multiple materials as laminate is observed in Yang et al.'s work [24], where the stacking sequence effect of polyurethane, aluminum, and CFRP is evaluated.

This work aims to enhance the crashworthiness performance of the hybrid thin-walled tube by laminating the aluminum empty tube with multiple types of FRP materials. The stacking sequence of different laminate materials is expected to provide a remarkable effect on the crashworthiness performance of hybrid tubes with enhanced energy absorption and mass reduction. The energy absorption performance and failure deformation are investigated.

2. Crashworthiness parameters

Key indicators are used to assess the crashworthiness of the studied structures and achieve the desired performance of an energy absorber. On the basis of the force-displacement curves obtained during the axial compression test, energy absorption (*E*), mean force (*Pm*), *SEA*, and *CFE* are retrieved. These key indicators are defined as follows.

Energy absorption (*E*) represents the capacity of energy absorbed during the axial compression test. *E* is the area under the force-displacement curve and can be obtained by integrating the equation below.

$$E = \int_{\delta_i}^{\delta_{i+1}} F dx , \tag{1}$$

where δ is the crushing distance. The variation of the crushing force from δ_i to δ_{i+1} can be characterized by the mean force (P_m).

$$P_m = \frac{1}{\delta_{i+1} - \delta_i} \int_{\delta_i}^{\delta_{i+1}} F dx . \tag{2}$$

SEA signifies the lightness of the structure, which is defined by dividing the energy absorbed with the mass of the tube.

$$SEA = \frac{P_m dx}{m} , \tag{3}$$

where *m* is the mass of the tube. The higher the *SEA*, the better the energy absorption efficiency of the structure. *CFE* is calculated as the ratio of the mean crushing force to the initial crushing force of the structure (P_{peak}).

$$CFE = \frac{P_m}{P_{peak}} . \tag{4}$$

3. Specimens and methods

3.1 Specimen preparation

Aluminum tubes and FRP materials were purchased from a local supplier. The plain woven CFRP and GFRP were received in the form of mats (300 mm×300 mm per ply) with 0°/90° fiber orientation angle. The aluminum tube is made of aluminum alloy 6063 with a 63.5 mm outer diameter and 3.0 mm thickness. Each specimen was cut into 100 mm lengths. Unsaturated polyester and methyl ethyl ketone peroxide, used as the hardener, were mixed at a ratio of 100: 1 [25] to produce the pure resin used to fabricate the specimen. The properties of the aluminum and FRP materials are tabulated in Table 1. The Al-GFRP and Al-CFRP were fabricated by manually wrapping the outer aluminum tube with 10 plies of plain woven FRP layers to form the hybrid tubes. For the Al-GFRP-CFRP and Al-CFRP-GFRP tubes, the outer side of the aluminum tube was wrapped with 5 layers of GFRP and 5 layers of CFRP. The average diameter (D_{outer}+D_{inner}/2 = D) of Al-GFRP and Al-CFRP tubes is 59.6 and 61.9 mm, respectively. The Al-GFRP-CFRP and aluminum-CFRP-GFRP tubes have an average diameter of 62.5 mm. The specimen was weighed prior to testing for *SEA* calculation. The dimensions and mass of the monolithic aluminum and the hybrid tubes are tabulated in Table 2.

A polyvinyl chloride (PVC) pipe tightened with cable ties was used to cover the outer layer of the hybrid tube for minimizing entrapped air and ensuring better bonding between the aluminum tube and FRP layers. A normal plastic sheet was wrapped at the outer layer of the hybrid tubes to prevent the binding between the tubes and the PVC pipe. The tubes were left overnight at room temperatures for curing purposes.

Table 1. Material properties of aluminum tube, resin, and FRP laminates.

Properties	Materials			
	Al 6063	CFRP	GFRP	Polyester
Density (g/cm^3)	2.7	2.5	2.5	1.22
Strength (MPa)	162 or 192	2000	2000-3000	12.1
Modulus (GPa)	70	70	70	1.4
Elongation at break (%)	-	2.5	2.5	-
Refs.	[26]	[27]	[28]	[29]

Table 2. Dimensions of the tested tubes.

Specimen	No. of layup	Diameter (mm)	Thickness (mm)	Height (mm)	Mass (g)
Aluminum	0	60.3	3.39	81.76	128.14
Al+GFRP	10	59.6	5.34	85.66	201.07
Al+CFRP	10	61.9	5.34	97.63	216.76
Al+CFRP+GFRP	5/5	62.5	6.05	94.55	226.59
Al+GFRP+CFRP	5/5	62.5	5.61	93.30	224.47

3.2 Quasi-static test

A quasi-static axial compression test was performed by using an INSTRON universal testing machine (UTM). The upper platen of the machine moved downward at a constant crosshead speed of 5 mm/min with a 150 kN load cell. The tube specimen was positioned on top of the fixed bottom platen. Axial compression force was progressively applied to the tubes up to 50.0 mm deformation length. Force-displacement curves were recorded for each of the tested specimens to assess the crashworthiness characteristics of the tubes. The tests were performed three times to ensure repeatability.

4. Results and discussion

4.1 Effect of reinforcement material on crashworthiness characteristics

The effect of reinforcement material on crashworthiness characteristics was studied experimentally under quasi-static loading of monolithic aluminum and hybrid tubes made of aluminum-CFRP and aluminum GFRP. The results of the work are presented in this section.

4.1.1 Crashworthiness response

Fig. 1 shows the force-displacement curves of the tested specimens when subjected to axial compression up to 50.0 mm length. During the test, the kinetic energy is converted into plastic deformation as the tube is subjected to a compression load. The tubes start to deform as the crushing force sharply increases to the highest value, which is called the initial peak crushing force, and then followed by a drop. This condition is when the buckling of the tube occurs, indicating the first collapse of the tube walls. The initial peak crushing force exhibits the highest crushing force as higher crushing force is needed to overcome the stiffness of the tube walls. The crushing force continues to rise and fall to form a complete fold, and the process is repeated throughout the length of deformation. In this case the crushing force fluctuates up to a length of 50.0 mm. Therefore, the initial crushing force is the maximum crushing force observed throughout the deformation length of the tube.

The maximum crushing force of hybrid aluminum-GFRP and aluminum-CFRP tubes is 141.5 and 139.9 kN, respectively, and that of aluminum monolithic tube is 97.14 kN. The maximum crushing force of the hybrid tubes is notably higher than that of the monolithic aluminum tube. This effect is attributed to the interlayer bonding between the lamination layer and the aluminum layer of the tube, causing higher circumferential stiffness. Hence, a higher crushing force is required to initiate the localized buckling at the first fold of the hybrid tubes compared with the aluminum monolithic tube. The significant enhancement of the maximum crushing force in the hybrid tubes shows that the wrapping of the aluminum tube with composite laminate promotes a higher energy absorption capacity of the tubes.

Similar conditions were observed in Zhang et al.'s work, where the composite wrapped metal tube shows a higher crushing force compared with the monolithic tube [18]. This finding clearly demonstrates the benefit of composite lamination, as the aluminum-CFRP and aluminum-GFRP tubes showed remarkable enhancement of the crushing force with considerable crushing force amplification.

Compared with the first cycle, the crushing force of all tubes fluctuates lower in the second cycle. This condition is because less force is required to develop the successive folds compared with the first fold. During the first fold formation, the crushing force is transmitted to the remaining undeformed length of the tube and develops a partial buckling in the subsequent fold. Therefore, a lower crushing force is required to develop the latter fold. In the second cycle, the crushing force of the monolithic aluminum and aluminum-GFRP hybrid tubes is found to be higher than that of the aluminum-CFRP hybrid tube. This scenario can be further explained in terms of crashworthiness characteristics, such as energy absorbed (*E*), mean force (*Pm*), *SEA*, and *CFE*, which are extracted and calculated from the force-displacement curve obtained during the test. These characteristics are tabulated in Table 3 and Fig. 2.

As shown in Fig. 2(a), the aluminum-GFRP tube absorbed 3962.8 J followed by the monolithic aluminum and the aluminum-CFRP tubes. The hybrid tube with GFRP shows a distinct enhancement with 26.4 % of energy absorbed (E) compared with the aluminum monolithic tube. Wrapping an aluminum tube with CFRP reduced the energy absorption performance of the hybrid tube. The aluminum-CFRP tube exhibited a 5 % reduction in the energy absorbed compared with the monolithic aluminum tube. The reduction in energy absorption is consistent with the force-displacement behavior in Fig. 1, as the crushing force shows a gradual decrease from the beginning of the second crushing cycle onward. The crushing force of the CFRP-aluminum tube is even lower than that of the monolithic aluminum tube. This finding can be explained by the lower value of *E* of the aluminum-CFRP tube compared with the aluminum-GFRP and monolithic aluminum tubes.

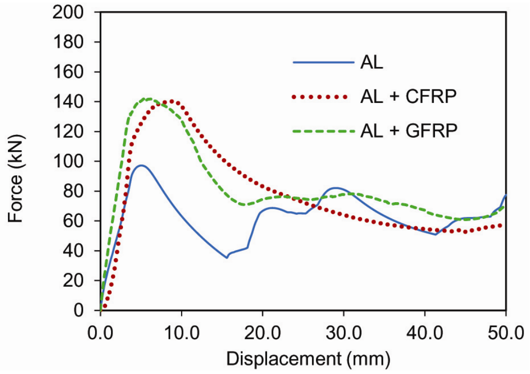


Fig. 1. Force-displacement curves of aluminum and hybrid tubes.

The energy absorbed, *E*, can be further corroborated with the calculated mean force, *Pm*, as tabulated in Fig. 2(b). As expected, the aluminum-GFRP tube shows the highest *Pm*, reaching 79255.5 N, whereas the aluminum-CFRP tube demonstrates the lowest mean force of 59554.8 N. By contrast, the *SEA* and *CFE* of the aluminum-GFRP and the aluminum-CFRP are relatively lower than that of the monolithic aluminum tube, as shown in Figs. 2(c) and (d). A 19.6 % and 42.5 % *SEA* reduction is observed for the aluminum-GFRP and the aluminum-CFRP, respectively, compared with the aluminum monolithic tube. In terms of *CFE*, the aluminum-GFRP and the aluminum-CFRP exhibit 0.56 and 0.42, respectively. Lower E, *SEA*, and *CFE* of FRP hybrid tubes were also found in Ref. [11]. However, an aluminum-GFRP hybrid tube with a 40 mm diameter exhibits outstanding performance compared with the other diameters. This finding can suggest that to enhance the crashworthiness performance of the hybrid tube, the laminate material is not the sole factor, but it is achievable with appropriate geometrical parameters.

Concerning the *SEA* and *CFE*, the aluminum-GFRP has better crashworthiness performance compared with the aluminum-CFRP tube. These findings conclude that the selection of material as the laminate material has an important contribution to the energy absorption mechanism. The enhancement of the hybrid tube's crashworthiness performance is due to the interface bonding and interaction of the layers in the hybrid tubes. Hence, this enhancement leads to higher *SEA* and *CFE* of GFRP-aluminum compared with CFRP-aluminum tube.

4.1.2 Failure mode of deformation

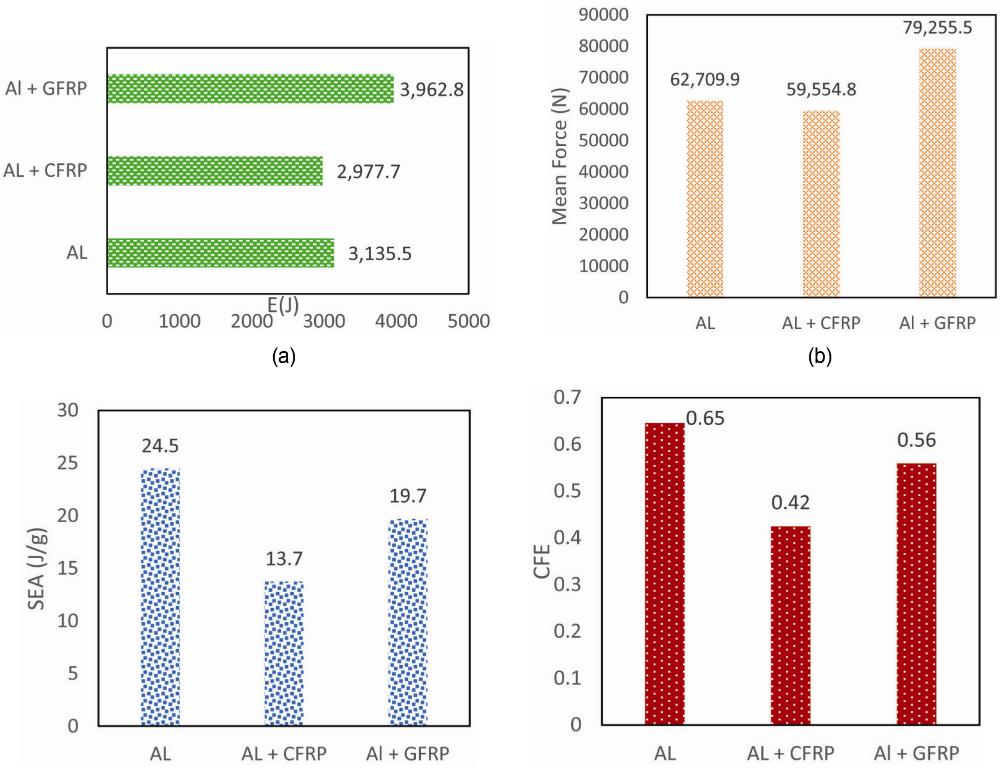
The failure deformation mode of the aluminum monolithic and the hybrid tubes subjected to quasi-static loading is shown in Fig. 3. The aluminum monolithic tube progressively deforms into two completed concertina modes of deformation, initiated at the impacted end. A similar mode of deformation is observed by Altin et al. [30] for the aluminum alloy 6063-T52 of 100 mm length, diameter of 75 mm, and 1.35 mm thickness when subjected to a quasi-static compression test. Metallic circular tubes deform either in a diamond or concertina mode of deformation depending on the type of loading, material, and geometrical parameters, as found in Refs. [31, 32].

FRP-aluminum hybrid tubes and the aluminum monolithic tubes start to deform at the impacted end, as reported in Ref. [21]. When subjected to quasi static axial loading, remarkable deviation can be observed in the deformation mode of the tubes compared with the aluminum monolithic tube. Specifically, aluminum-GFRP and aluminum-CFRP tubes deform into a diamond mode of deformation. These findings are in good agreement with those obtained in Ref. [33]. One completed diamond mode of deformation is when the tube wall progressively collapses, with two sides folding inward and the other two sides folding outward. The GFRP-aluminum tube deforms into one completed diamond mode and progresses into the next fold. The CFRP-aluminum tube progresses into a diamond mode of deformation but has not completed a fold. No cracking or breakage was observed on the aluminum-CFRP hybrid tube. However, a massive drop of the aluminum-CFRP crushing force was found in the second cycle, which continued to drop gradually and was lower than that of the monolithic aluminum tube. The crushing force and energy absorbed by the aluminum-CFRP tube were lower than those of the aluminum-GFRP tube.

On the basis of the number of folds developed, the aluminum-GFRP tube notably demonstrates the highest energy absorption capability among all the tubes for the same length of deformation. The hybrid tubes show higher energy absorption compared with their counterparts due to the lamination effect. These results confirm that the energy absorption performance of the hybrid tubes is successfully promoted by wrapping the metallic thin-walled tubes with a composite layer. This finding is consistent with the crushing force pattern obtained in Fig. 1. The result also shows that better interlayer bonding is achieved between aluminum-GFRP compared with aluminum-CFRP, thereby implying that the lamination type of materials plays a vital role in enhancing the energy absorption capacity of the aluminum tube. Therefore, GFRP is suggested as the better choice of laminate for aluminum tube compared with CFRP in achieving better crashworthiness performance of the energy absorber.

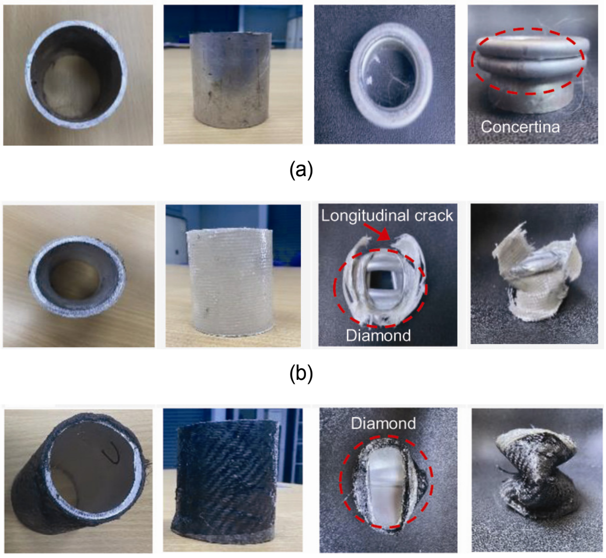
Table 3. Crashworthiness characteristics for aluminum tubes with different laminated composite materials at 50 mm deformation.

Material	*E* (J)	*Pm* (kN)	*SEA* (J/g)	*CFE*
Aluminium	3135.49	62 709.9	24.5	0.65
Aluminium+CFRP	2977.74	59 554.8	13.7	0.42
Aluminium+GFRP	3962.77	79 255.5	19.7	0.56



(a) (b) (c) (d)

Fig. 2. Absorbed energy, mean force, *SEA*, and *CFE* of aluminum monolithic and aluminum hybrid tubes.



(a)

(b)

(c)

Fig. 3. Before and after deformation of (a) aluminum monolithic; (b) aluminum-GFRP; (c) aluminum-CFRP tubes.

This trend is also observed in Ref. [34], where the energy absorption of an aluminum-GFRP conical hybrid tube with chopped, woven, and unidirectional GFRP laminates is enhanced compared with the monolithic conical aluminum tube. Oppositely, the aluminum-GFRP hybrid tube in Yang et al.'s work shows lower energy absorption compared with the aluminum monolithic tube [11]. This condition can be due to the different geometries of the tubes because geometrical parameters are shown to remarkably affect the performance of the tubes. Another reason is the fabrication methods used, as Yang employs filament winding, whereas hand lay-up is used in Ref. [34] and the current work.

As the aluminium-GFRP tube progresses into the second cycle, the interlayer bonding of aluminum-composite tubes begins to degrade, causing failure as the tubes cannot sustain the subjected load. The composite layer cracks and propagates in a longitudinal direction due to shear and bending forces, causing the laminate layer to break away from the aluminum layer [11].

4.2 Effect of laminate stacking sequence on crashworthiness characteristics

The effect of the stacking sequence of the laminate material on the crashworthiness characteristics of the hybrid tubes was experimentally studied under quasi-static loading. The results of the aluminum-CFRP-GFRP and aluminum-GFRP-CFRP hybrid tubes are presented in this section.

4.2.1 Crashworthiness response

The crashworthiness characteristics, namely, energy absorption (*E*), mean force (*Pm*), *SEA*, and *CFE*, are calculated for a 50 mm length of deformation and tabulated in Table 4. The force-displacement curves of the tested specimens when subjected to quasi-static loading are shown in Fig. 4.

Table 4. Crashworthiness characteristics for aluminum tubes with different laminated composite materials at 50 mm deformation.

Material	*E* (J)	*Pm* (kN)	*SEA* (J/g)	*CFE*
Aluminum	3135.49	62 709.9	24.5	0.65
Aluminum+CFRP+GFRP	3919.76	78 395.2	17.3	0.52
Aluminum+GFRP+CFRP	5232.57	104 651.4	23.3	0.61

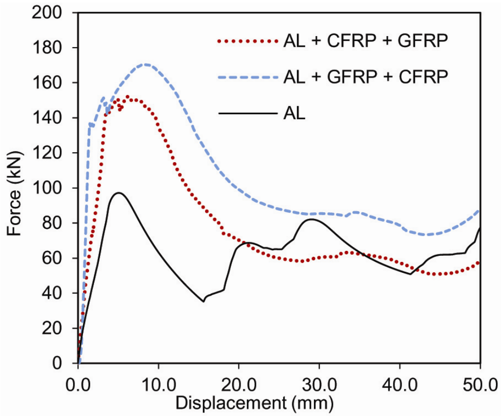


Fig. 4. Force displacement curve of multiple lamination hybrid tubes.

Referring to Fig. 4, the force-displacement curves of the aluminum monolithic tube, hybrid tubes of aluminum-GFRP-CFRP, and aluminum-CFRP-GFRP are compared. The maximum crushing force of the aluminum-GFRP-CFRP and the aluminum-CFRP-GFRP hybrid tubes is 169.3 and 157.3 kN, respectively. Compared with the monolithic aluminum tube, the maximum crushing force is 95.2 kN. A 77.8 % and 65.2 % increase is observed in the initial crushing force for the aluminum-GFRP-CFRP and the aluminum-CFRP-GFRP tubes, respectively, compared with the aluminum monolithic tube. The crushing force of the hybrid tubes is notably higher than that of the aluminum monolithic tube, particularly in the first crushing cycle. The interlayer bonding between aluminum, CFRP, and GFRP develops higher circumferential stiffness. Thus, a higher crushing force is required to form the first fold of the hybrid tube.

From the second crushing cycle onward, the highest crushing force is obtained by the aluminum-GFRP-CFRP and surprisingly, the aluminum-CFRP-GFRP tube exhibits the lowest crushing force. The aluminum monolithic tube exhibits a higher crushing force than that of the aluminum-CFRP-GFRP tube. Here, a major influence of the laminate stacking sequence is observed. The stacking sequence of aluminum-GFRP-CFRP develops better interlayer bonding compared with aluminum-CFRP-GFRP, resulting in a higher stiffness of the tube wall. Consequently, a higher crushing force is needed to initiate the localized buckling of the aluminum-GFRP-CFRP than that of the aluminum-CFRP-GFRP tube, as a higher stiffness is achieved by the aluminum-GFRP-CFRP hybrid tube wall.

The force-displacement response of the tubes is further detailed by the variations presented in terms of *E*, *Pm*, *SEA*, and *CFE* of aluminum monolithic, aluminum-CFRP-GFRP, and aluminum-GFRP-CFRP tubes in Table 4. The aluminum-CFRP-GFRP and the aluminum-GFRP-CFRP tubes absorb 3919.8 and 5232.6 J, respectively. Compared with the monolithic aluminum tube, the aluminum-GFRP-CFRP tube absorbs 66.9 % more energy. The aluminum-GFRP-CFRP tube absorbs 33.5 % more energy than that of the aluminum-GFRP-CFRP tube. The results are consistent with the calculated *Pm* because it is obtained by dividing the energy absorbed with the deflection length. Similar findings have been observed in Ref. [35] as the higher crashworthiness performance is shown by the hybrid conical than that of the monolithic aluminum tubes.

Despite having higher *E* and *Pm*, the hybrid tubes of the aluminum-CFRP-GFRP and the aluminum-GFRP-CFRP exhibit lower *SEA* and *CFE* compared with the aluminum monolithic tube, as shown in Fig. 5. The aluminum-GFRP-CFRP tube exhibits 23.3 J/g of *SEA* and 0.61 of *CFE*, respectively.

Despite having lower *SEA* and *CFE*, the aluminum-GFRP-CFRP tube exhibits a 4.9 % and 6.2 % difference in *SEA* and *CFE*, respectively, compared with the aluminum monolithic tube. The aluminum-GFRP-CFRP hybrid tube demonstrates 34.7 % and 17.3 % higher *SEA* and *CFE*, respectively, compared with the aluminum-CFRP-GFRP hybrid tubes.

From the perspective of crashworthiness design, the higher the energy absorbed, *E*, *SEA*, and *CFE*, the better the crashworthiness of the structure. This finding suggests that the aluminum-GFRP-CFRP is comparatively better than the aluminum-CFRP-GFRP because the tube demonstrates the least reduction in *SEA* and *CFE*. The use of GFRP and CFRP as the first and second laminate layers, respectively, is beneficial in improving the crashworthiness performance of the hybrid tube. This observation implies that the stacking sequence and the selection of laminate materials are crucial in achieving an optimum energy absorber.

The use of CFRP as the first layer of lamination causes a remarkable drop in the energy absorption performance of the hybrid tube. The higher energy absorption characteristics are observed when the CFRP becomes the second layer of the hybrid tube. These results imply that the use of CFRP as the second laminate layer of aluminum outer tubes offers high energy absorption performance, thereby leading to greater deceleration to the passenger in the vehicle compartment. These findings confirm that laminate selection and stacking sequence are vital in tailoring the performance of the hybrid tubes toward efficient energy absorbers.

4.2.2 Failure mode of deformation

Fig. 6 presents the deformation mode of the aluminum-CFRP-GFRP and aluminum-GFRP-CFRP hybrid tubes after quasi-static loading. These tubes exhibit a diamond mode of deformation, similar to what was observed for the aluminum-GFRP and aluminum-CFRP tubes in Sec. 4.1. This observation deduces that the lamination effect is responsible for the diamond mode of deformation in the hybrid tubes.

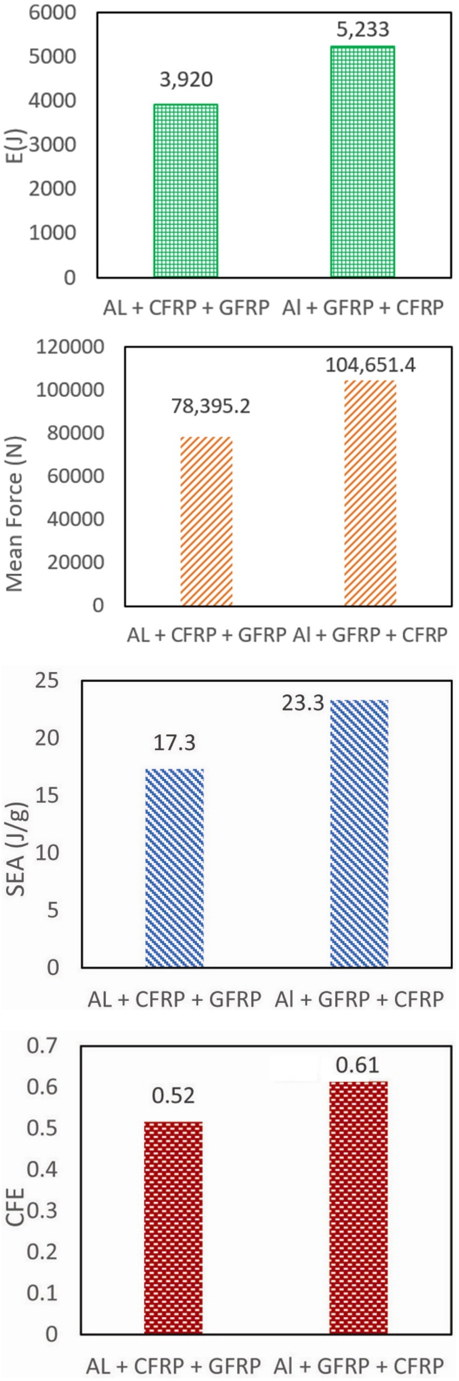


Fig. 5. Crashworthiness response of aluminum-CFRP-GFRP and aluminum-CFRP-GFRP tubes.

The aluminum-GFRP tube demonstrates higher *E*, *Pm*, *SEA*, and *CFE* compared with the aluminum-CFRP tube, with less reduction of *SEA* and *CFE*. For the aluminum-CFRP-GFRP and aluminum-GFRP-CFRP tubes, the stacking sequence of the laminate layer has a remarkable effect on the crashworthiness performance of the tubes despite having similar deformation mode. The use of GFRP as the first outer layer in aluminum-GFRP-CFRP tubes results in higher *E*, *Pm*, *SEA*, and

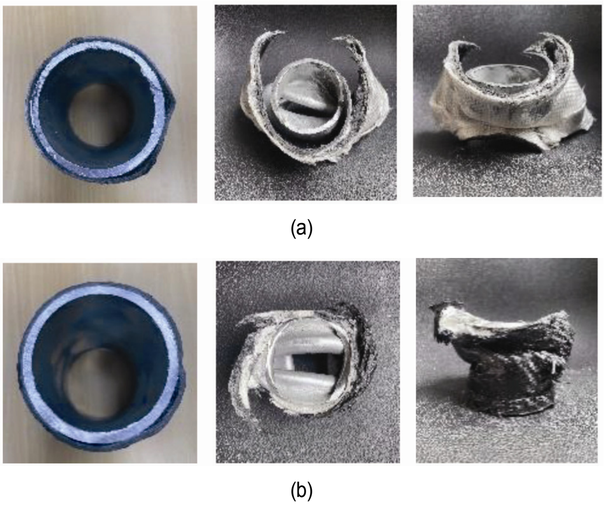


Fig. 6. Before and after deformation of (a) Al-CFRP-GFRP; (b) Al-GFRP-CFRP.

CFE compared with aluminum-CFRP-GFRP when GFRP is used as the second outer layer of the tube.

The aluminum-CFRP-GFRP shows the breakage of the laminate layer and later detaches abruptly from the aluminum layer from the top end to the bottom of the tube, thereby leading to tube failure. This scenario shows that lamination of GFRP as the second outer layer may induce weaker interlayer bonding between the aluminum tube, CFRP, and GFRP laminates. By contrast, better bonding is demonstrated between the aluminum, CFRP, and GFRP in the aluminum-GFRP-CFRP tubes, resulting in higher crashworthiness performance than its counterparts in the aluminum-GFRP-CFRP tubes. Consequently, the aluminum-GFRP-CFRP tubes gain higher energy dissipation through 1) the collapse and fold formation of the aluminum tube wall; 2) the progression of crack, breakage, and delamination of the laminate layer; 3) the interlayer interaction and friction during deformation. Compared with the observation in Yang's work [13], the hybrid tubes exhibit a splaying deformation mode. A breakage of the aluminum-GFRP-CFRP is observed only at the top of the impacted layer, indicating better interlayer bonding between the aluminum-GFRP-CFRP hybrid tube than the aluminum-CFRP-GFRP hybrid tube. This finding reveals that GFRP is a better choice of laminate for the aluminum tube than CFRP in achieving better crashworthiness performance of an energy absorber.

5. Conclusions

The energy absorption capacity of aluminum monolithic and hybrid aluminum-FRP tubes are investigated experimentally under axial quasi-static loading. The effect of the reinforcement material as a laminate layer on the crashworthiness characteristics of aluminum-GFRP and aluminum-CFRP hybrid tubes is studied.

The observations are made on the force-displacement curves obtained during the experiments. The maximum crushing force of the aluminum-GFRP tube is higher than that of the aluminum-CFRP tubes. This effect is due to the interlayer bonding of the hybrid tubes between the lamination layer and the aluminum layer of the tube, which results in higher circumferential stiffness. Thus, a higher crushing force is required to initiate the localized buckling at the first fold. The remarkable enhancement of the maximum crushing force in the hybrid tubes shows that the wrapping of the aluminum tube with composite laminate promotes higher energy absorption capacity of the tubes.

The crashworthiness characteristics are analyzed and calculated on the basis of the force-displacement curves. Wrapping the aluminum tube with the FRP composite remarkably enhances the energy absorption of the hybrid tubes compared with the aluminum monolithic tube. The energy absorbed, *E*, and mean force, *Pm*, of the aluminum-GFRP tube is higher than that of the aluminum monolithic tube. However, the *SEA* and *CFE* are lower compared with the aluminum monolithic tube. The use of GFRP to wrap the outer aluminum tube results in higher energy absorption despite lower *SEA* and *CFE*. Wrapping the aluminum tube with CFRP reduces the energy absorption, *Pm*, *SEA*, and *CFE* of the hybrid tube.

The aluminum monolithic tube progressively deforms into two completed concertina modes of deformation initiated at the impacted end. For the aluminum-CFRP tube, neither cracking nor breakage is observed. The crushing force of the aluminum-CFRP tube fluctuates lower than that of monolithic aluminum tube. This finding shows that better interlayer bonding is achieved between aluminum-GFRP compared with aluminum-CFRP, thereby revealing that GFRP is the better choice of laminate for aluminum tubes compared with CFRP in achieving better interface bonding and interaction of the layers in the hybrid tubes. Consequently, the better crashworthiness performance of the aluminum-GFRP is obtained than that of the aluminum-CFRP hybrid tubes.

The use of multiple FRP materials further improves the energy absorption of the hybrid tubes. Further enhancement in the crashworthiness characteristics is achieved by wrapping the aluminum tube with multiple FRP composite materials. The higher energy absorption characteristics are observed when the GFRP becomes the first layer of the aluminum outer tube. The aluminum-GFRP-CFRP tube demonstrates further increase in absorbed energy and mean force compared with the aluminum-GFRP-CFRP hybrid and aluminum monolithic tubes. The aluminum-GFRP-CFRP tube exhibits the least reduction of *SEA* and *CFE*, with differences of 4.9 % and 6.2 %, respectively, compared with the aluminum monolithic tube. By contrast, the use of CFRP as the first laminate layer of the aluminum tube reduces the crashworthiness characteristics of the hybrid tubes. These results suggest that the use of GFRP as the first laminate layer of the aluminum outer tubes offers high energy absorption performance, thereby leading to greater deceleration for the passenger in the vehicle compartment. The findings confirm that the laminate sequence is vital in tailoring the performance of the hybrid tubes.

The aluminum-CFRP-GFRP shows the breakage of the laminate layer and later detaches abruptly from the aluminum layer from the top end to the bottom of the tube, leading to the failure of the tube. The breakage is observed only at the top of the impacted layer, showing that better interlayer bonding is achieved between aluminum-GFRP-CFRP compared with aluminum-CFRP-GFRP. This finding reveals that GFRP is a better choice of laminate for aluminum tubes compared with CFRP in achieving better crashworthiness performance of the energy absorber. The aluminum-GFRP-CFRP tubes offer higher energy dissipation due to 1) the collapse and fold formation of the aluminum tube wall; 2) the progression of crack, breakage, and delamination of the laminate layer; 3) the interlayer interaction and friction during the deformation. The findings from this study will facilitate the design of thin-walled tubes as energy absorbers in impact applications. Further improvement can be made to the fabrication aspects of the FML hybrid tube itself. The interlayer bonding between the multiple laminate materials can be enhanced by employing other techniques, such as a vacuum bagging, resin transfer molding, and autoclaves. Focus should be extended toward treating FML hybrid tubes for hazard mitigation applications, such as fire retardancy.

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Nomenclature

FML : Fiber metal laminate
FRP : Fiber-reinforced polymer
CFRP : Carbon-reinforced polymer
GFRP : Glass-reinforced polymer
E : Energy
SEA : Specific energy absorption
CFE : Crushing force efficiency
Pm : Mean force
δ_i : Initial displacement
δ_{i+1} : Subsequent displacement
RTM : Resin transfer molding

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