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Effect of Fiber Orientation and Stacking Sequence of AL/GFRP Hybrid Tube under Axial Impact

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***Abstract*—This research was aimed to study the effect fiber orientation and stacking sequence on the energy absorption capacity of hybrid tube subjected to axial impact. The specimens were composite cylindrical AL/GFRP tubes. They were manufactured using circular aluminum tubes and wrapped with 2 and 4 layers of E-glass/polyester. The orientations of E-glass/polyester layers were $[0_2]$, $[90_2]$ and [0/90], [90/0] for 2 layers and $[0_4]$, $[90_4]$, $[0_2/90_2]$, $[90_2/0_2]$ for 4 layers. They were tested under free fall impact using Vertical Impact Testing Machine with a speed of 6.67 m/s. The results implied that hybrid tube with $[0_2/90_2]$ of GFRP can resist highest impact load while the $[0_4]$ tube absorbed highest impact energy. The mode of collapse of each tube was also discussed in this paper.**

***Index Terms*— energy absorption, hybrid tube, axial impact, composite tube.**

I. INTRODUCTION

Composite material is a high potential alternative materials. It is widely used in many industries such as spacecraft and automobile. This is because the strength per weight of composite material is high which is very useful for transportation. In addition, the property of composite material can be improved corresponding to direction of load. Therefore, composite material is selectively used in frontal section of automobile.

The automobile cockpit is generally made of metal, because metal is prominent in absorbing impact. However, metal is low strength per weight, fatigue and corrosive. Therefore, composite can be alternative for metals and attack intentions of researchers.

S. Solaimurugan et al. [1] studied the energy absorption of cylindrical composite tube subjected to impact. The specimens were composed of 4 and 6 layers of fiber glass. The fiber glass is woven roving (WRM) with 610 g/m^2 density and unidirection (UD) with density of 750 g/m^2. Isophthalic resin is used as binder. The specimens were manufactured by hand layup technique in a sequence of $[WRM/(UD)_m/WRM]$ for 4 and 6 layers. The D/t ratio of specimens are 15 and 25. The end angle of each was cut to be 30 degree. The specimens were tested with a speed of 2 mm/min. The results revealed that the energy absorption capacity of tube is increasing as the number of layer increased. P. Feraboli et al. [2] studied on the crashworthiness of rectangular composite tubes subjected to impact. The specimens were 5 different sections but thickness, composition, manufacturing process and testing method were similar. The material used for making specimens were T700 / 2510 carbon fiber/epoxy prepreg, fabricated in $[0/90]_{4s}$ by vacuum technique. They were tested with a speed of 50.8 mm/min. The results revealed that tubes with higher number of angle offer higher energy absorption capacity. M. M. Shokrieh et al. [3] investigated the effect of manufacturing process of glass/polyester tubes focusing on vacuum and non-vacuum process. The result suggested that the vacuum process provides tube with twice in energy absorption compare to the non-vacuum process. In addition, the circular tube can absorption higher energy than square tube. H. C. Kim et al. [4] investigated the characteristics of hybrid aluminum tube subjected to quasi-static load. The specimens were Al 6063-T5 wrapped with CFRP. Three patterns of fiber orientation were $[0]_4$, $[90]_4$, $[0/90]_2$, $[45/-45]_2$, [0/45/90/-45] / $[0]_8$, $[90]_8$, $[0/90]_4$, $[45/-45]_4$, $[0/45/90/-45]_2$ and $[0]_{12}$, $[90]_{12}$, $[0/90]_6$, $[45/-45]_6$, $[0/45/90/-45]_3$. It found that the tube with $[0/45/90/-45]_3$ is the most efficient in term of energy absorption. M. Costas et al. [5] conducted a study on crashworthiness parameters of hybrid tubes under impact and quasi-static load. Five different types of specimens were used i.e. empty tube, hybrid tube with fiber glass, hybrid tube with CFRP, tube filled with polyethylene foam, tube filled with cork. The quasi-static experiment was carried out with speed of 1 mm/s while the impact was conducted by free falling of 350 kg weight from 2.5 m tower. The result suggested that hybrid tube with fiber glass absorbed higher energy than others. M. Y. Huang et al. [6] conducted a numerical study on energy absorption capacity of hybrid tube under quasi-static and impact test. The specimens were steel tubes wrapped with carbon fiber and focused parameters are thickness, type of load and ply angle. Those ply angles were $[+0/-0]_3$, $[+15/-15]_3$, $[+30/-30]_3$, $[+45/-45]_3$, $[+60/-60]_3$, $[+75/-75]_3$ and $[+90/-90]_3$. It was found that the energy absorption of hybrid tube is improved compared to empty one. M. Mizaei et al. [7] also studied on aluminum tube hybrid with GFRP under quasi-static axial load. The thickness and sequence of ply angle were investigated. Diamond mode of collapse was normally found and specimens of [60/-45/0/90] was excellent in energy absorption. M. Kathiresan et al. [8] investigated the behavior of aluminum cone wrapped with fiber glass under impact using FEA. The study suggested that cones with low angle offer higher energy absorption. In addition, the cones with

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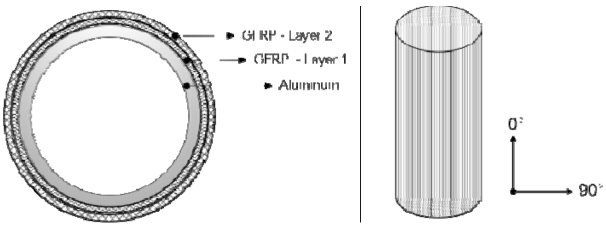
fiber glass were higher in energy absorption by about 15% compared to empty cone. Effect of apex angle and impact velocity were also discussed. R. Kalhor et al. [9] investigated square 304 stainless tube wrapped with S glass / Heuply Prepreg steels. The effect of ply angle and thickness were studied. The specimen was tested at a speed of 6 mm/min using MTS 810 testing machine. The result showed that hybrid tube can change collapse mode from split mode to be axisymmetric mode or mix mode and absorb higher energy. In addition, the fluctuation of load was also reduced throughout the collapse process.

This study is aimed to investigate the crush characteristic of AL/GFRP hybrid tube under axial impact. The study is focused on the effect of ply angle and stacking sequence of GFRP layers on crashworthiness of tube. Modes of collapse and energy absorption are discussed.

II. EXPERIMENT

A. Specimen

The specimens were made from aluminum tube wrapped with E glass unidirectional mat and Isophthalic polyester resin. Orientation angle and number of layers were $[0]_2$, $[90]_2$, [0/90], [90/0], $[0]_4$, $[90]_4$, $[0_2/90_2]$ และ $[90_2/0_2]$. The specimens were manufactured using vacuum process in order to reduce to effect of bubble. The specimens were 44.4 mm diameter, 1.2 mm thickness and 100 mm long. Figure 1 (a) illustrates the stacking sequence of aluminum tube and AL/GFRP. Figure 1 (b) shows direction of ply angle, 0 degree is measured along tube axial while 90 degree is tangent to the tube surface.



(a) (b)

Fig. 1. (a) Stacking sequence AL/GFRP (b) direction of GFRP

B. Specimens fabrication

Aluminum tube of 44.4 mm diameter and 500 mm long was prepared. The E glass unidirectional mat was cut in an assigned angle to have 450 mm width and 500 mm long. The aluminum tube was cleaned with acetone solution and wrapped with E glass mats to have designed orientations and layers. The specimen was contained in a sealed vacuum bag. The vacuum pump was used to evacuate air from bag. Polyester resin was mixed with hardener, put in the container and let it flow all over the specimens. The specimen was left for 24 hours, took the mold off and cut in a desired size. Figure 2 shows equipments and setting up in the specimen manufacturing process.

Fig. 2. Vacuum process setting up

III. IMPACT TEST

The impact testing was carried out using Vertical Impact Testing Machine, as showed in Figure 3. The machine is a 3 m height tower and consists of a 20-60 kg hammer which can be free fallen to impact to target specimen. The bottom of machine is an anvil with load cell embedded. The load cell is connected to data logger to record reaction force. The load and time of impact were then process for analysis. In this study, 45 kg hammer was dropped from 2.33 m and impact speed was 6.67 m/s. High speed camera was also used to record the collapse development throughout the process.

Fig. 3. Vertical impact testing machine

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IV. COLLAPSE BEHAVIOR OF SPECIMENS

A. *Characteristic of load displacement curve*

As the specimen was impacted, it failed in a certain form of collapse modes. In the collapse process, the reaction force and displacement of structure were formed corresponding to the collapse mode. Therefore, the collapse mode and load-displacement curve are worth to be investigated. Figure 4-6 show some examples of failure history of specimens. Figures 7 and 8 illustrate load history curves, which total displacement and duration of impact can be observed.

The collapse process of aluminum tube is showed in Figure 4. It is observed that the specimen is failed from the top end and progressed to the bottom in a series of lobes. The total displacement is 61 mm and impact time was 0.024 sec.

Figure 5 shows the collapse process of AL/GFRP-[0_2] tube, which is collapsed for 69 mm within 0.025 sec. The collapse process of AL/GFRP-[0_4] tube is showed in Figure 6, the total displacement is 76 mm and impact time is 0.026 sec.

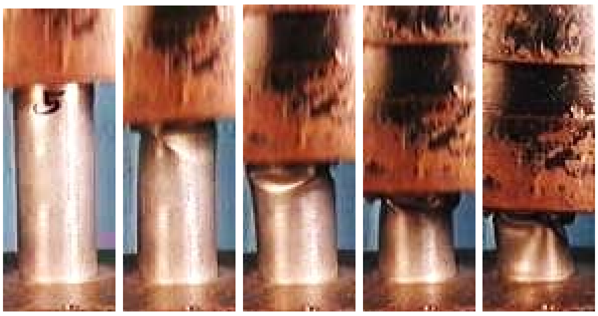

Fig. 4. Progressive collapse of naked aluminum

Fig. 5. Progressive collapse of AL/GFRP - 2 Layers and [0_2]

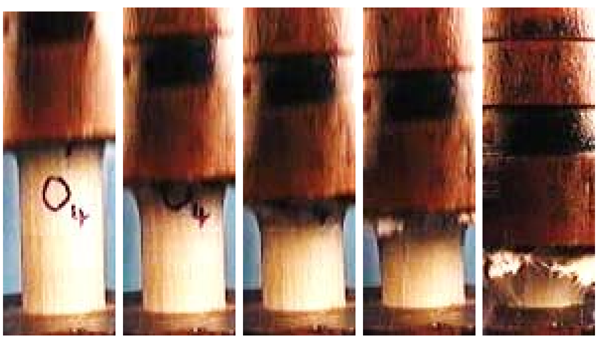

Fig. 6. Progressive collapse of AL/GFRP - 4 Layers and [0_4]

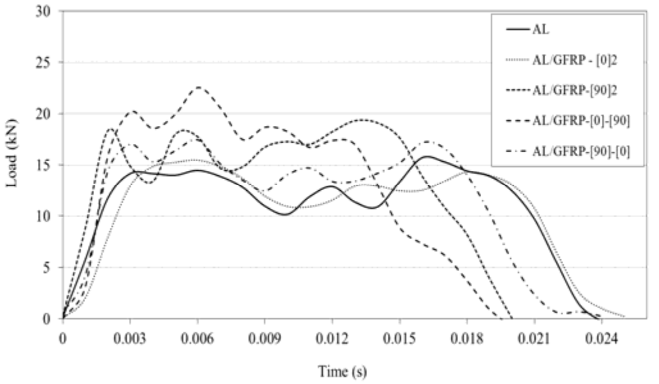

Fig. 7. Load-time curve of AL and AL/GFRP-2 layer tubes

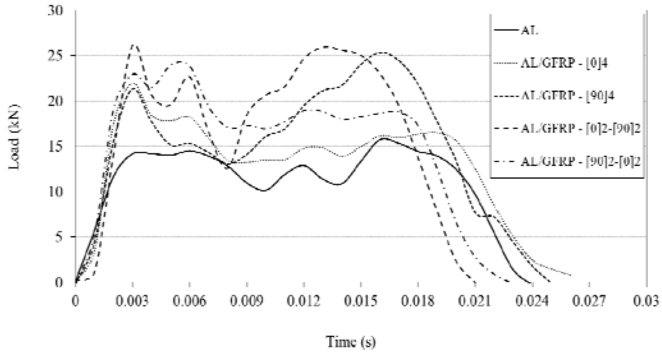

Fig. 8. Load-time curve of AL and AL/GFRP-4 layer tube

B. *Mode of collapse*

This study found that AL and AL/GFRP tubes fail in 5 modes, which are Diamond mode, Lamina bucking, Fiber breaking, Local bucking and Laminar bending. The details of these modes are discussed as followed.

Figure 9 is the collapse mode of AL tube which is called diamond mode. This mode consists of a number of lobes stacking on each other.

Figure 10 (a) shows the collapse mode of AL/GFRP- [0_2] tube. It is observed that the AL tube is failed in diamond mode while the GFRP which is oriented in 0 degree for 2 layers, is failed by bending in horizontal direction. This is called Lamina bucking mode. In this mode, the GFRP sheet is buckling and spring out of the AL tube. The final mode is showed in Figure 12 (a).

The final collapse of AL/GFRP- [90_2] is showed in Figure 10 (b). The aluminum tube is also failed in diamond mode while the GFRP is failed in Fiber breaking. This mode, the fiber is broken and inserted in between two adjacent lobes of aluminum wall.

Figure 10 (c) is the collapse mode of AL/GFRP- [0/90] tube, the AL tube is also failed in diamond mode, while the 1^{st} layer of fiber, lied in 0 degree, is failed in Local bucking. The 2^{nd} layer, lied in 90 degree, is failed in Fiber breaking and helps maintaining the 1^{st} layer in position, as showed in Figure 12 (c).

Figure 10 (d) is the final mode of AL/GFRP- [90/0] tube. Again, the aluminum tube is failed in diamond mode while the 1^{st} layer of fiber, 90 degree orientation, is failed in Fiber breaking. The 2^{nd} layers of fiber, 0 degree orientation, is failed in Laminar bending as showed in Figure 12 (d).

Figure 11 (a) shows final collapse of AL/GFRP- [0_4]. The aluminum tube is failed in diamond mode. The fiber, 0 degree orientation for 4 layers, is failed in Lamina bucking mode as showed in Figure 13 (a).

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Figure 11 (b) is the collapse mode of AL/GFRP- [90_4] tube. Aluminum tube is also failed in diamond mode while the fiber layers are failed in Fiber breaking and inserted between two lobes as showed in Figure 13 (b).

Figure 11 (c) shows the failure mode of AL/GFRP- [$0_2/90_2$] tube. It is found that the AL tube is failed in diamond mode. The first two layers of fiber, 0 degree orientation, are buckling in Local bucking mode and inserted into lobes of aluminum tube. The 3rd and 4th layers of fiber which are 90 degree orientation, failed in Fiber breaking. The fibers are broken, some are inserted between lobes while some are spring out off aluminum tube, as showed in Figure 13 (c).

The collapse mode of AL/GFRP- [$90_2/0_2$] is showed in Figure 11 (c). Aluminum tube is failed in diamond mode, while the 1st and 2nd layers of fiber, lied in 90 degree, are failed in Fiber breaking and inserted between the wall of collapse tube. The 3rd and 4th layers of fiber, 0 degree orientation, are failed in Laminar bending and spring out of the aluminum tube. Figure 13 (d) illustrates the failure mode of this case.


Fig. 9. Final mode of AL tube.


(a) (b) (c) (d)
Fig. 10. Mode of collapse of AL/GFRP tubes (a) [0_2], (b) [90_2], (c) [0/90] and (d) [90/0].


(a) (b) (c) (d)
Fig. 11. Mode of collapse of AL/GFRP tubes (a) [0_4], (b) [90_4], (c) [$0_2/90_2$] and (d) [$90_2/0_2$].


(a) (b) (c) (d)
Fig. 12. Sectioned of collapsed wall of AL/GFRP tubes (a) [0_2], (b) [90_2], (c) [0/90] and (d) [90/0].

TABLE I
ENERGY ABSORPTION OF IMPACT TEST

Specimen	Maximum load (kN)	Average load (kN)	Energy absorption (kN.m)
AL	15.719	10.819	17.991
Al-GFRP 2 PLY			
[0_2]	15.470	10.740	14.040
[90_2]	19.327	13.493	9.121
[0/90]	22.538	12.643	7.291
[90/0]	17.476	11.162	12.569
Al-GFRP 4 PLY			
[0_4]	21.992	12.439	13.258
[90_4]	25.286	14.341	12.690
[$0_2/90_2$]	26.060	16.423	9.430
[$90_2/0_2$]	23.895	14.814	11.468


(a) (b) (c) (d)
Fig. 13. Sectioned of collapsed wall of AL/GFRP tubes (a) [0_4], (b) [90_4], (c) [$0_2/90_2$] and (d) [$90_2/0_2$]

V. ENERGY ABSORPTION BEHAVIOR

A. *Maximum and Average Load*

The maximum load, average load and energy absorption of specimens under impact are showed in table 1. From table 1, considering on AL tubes with 2 layers GFRP, the maximum loads of [0/90], [90_2], [90/0], AL and [0_2] are 22.53, 19.32, 17.47 15.71 and 15.47 kN respectively. Considering on the average load, it is found that the hybrid tube of AL/GFRP- [90_2] gives 13.49 kN while the hybrid tubes of [0/90], [90/0], AL and [0_2] give 12.64, 11.16, 10.81 and 10.74 kN of average load respectively. The comparison between AL tube and AL/GFRP tubes suggests that the hybrid tube with [0_2], [90_2], [0/90] and [90/0] give different of average load as -0.65, +19.86, +14.47 and +3.13 % respectively.

In case of the AL tube and hybrid AL/GFRP tube of 4 layers, the result revealed that the maximum load of tube with AL/GFRP-[$0_2/90_2$], [90_4], [$90_2/0_2$], [0_4] and naked AL are 26.06, 25.28, 23.89, 21.99 and 15.71 kN, respectively. In addition, it is found that the AL/GFRP tube with [$0_2/90_2$], [$90_2/0_2$], [90_4], [0_4] and AL tube give the average loads of 16.42, 14.81, 14.34, 12.43 and 10.81 kN, respectively. The comparative result between AL and AL/GFRP tube, it is found that the hybrid tube with [0_4], [90_4], [$0_2/90_2$] and [$90_2/0_2$] give higher average value than AL tube by 13.03, 24.61, 34.16 and 27.00 %, respectively. It is obviously seen that hybrid tubes with orientation of [0/90] and [$0_2/90_2$] give highest value of maximum load. This is because the 0 degree fiber is inserted into the collapsed lobes of aluminum tube and enhances the load resistance capacity of tube.

B. *Energy absorption*

The energy absorptions of specimens are showed in Table 1. It is found that AL tube absorbs energy of 17.99 kN.m. The hybrid AL/GFRP tube of 2 layers with [0_2] absorbs 14.04 kN.m, while the hybrid tubes of [90/0], [90_2] and [0/90]

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absorb 12.56, 9.12 and 7.29 kN.m of impact energy, respectively. This is implied that hybrid tubes with [0_2] absorb higher energy than that of [90/0], [90_2] and [0/90] by 11.701, 53.94 and 92.59 % respectively.

Considering hybrid AL/GFRP tube of 4 fiber layers, it reveals that tube with [0_4] absorbs highest impact energy at 13.25 kN.m. This is higher than that of hybrid tube with [90_4], [$90_2/0_2$] and [$0_2/90_2$] by 4.41, 16.22 and 40.50 %, respectively. In addition, the hybrid tube with $[0]_4$ absorbs highest energy compared to other orientations.

VI. Conclusion

This study investigates the influence of ply angle and stacking sequence of GFRP wrapped on aluminum tube, focusing on its energy absorption capacity. The crashworthiness and mode of collapse are observed and discussed. It is found that the aluminum tube was normally failed in diamond mode. Considering the fiber layer, in case of [$0_2/90_2$], the 0 degree orientation fiber is buckled and inserted into the gabs between folds of aluminum tube. In addition, it is also found that the 90 degree orientation fiber ties up the [0_2] in the position.

The mean loads achieved from hybrid AL with 2 GFRP layers compared to naked aluminum tube are -0.65, +19.86, +14.47 and +3.13% for [0_2], [90_2], [0/90] and [90/0], respectively. In case of hybrid AL with 4 GFRP layers, the mean load are increasing by 13.03, 24.61, 34.16, and 27.00% for fiber orientation of [0_4], [90_4], [$0_2/90_2$] and [$90_2/0_2$], respectively.

The study also is found that hybrid tubes of 2 layers with [0_2] absorb higher energy than [90/0], [90_2] and [0/90] tube by 11.701, 53.94 and 92.59%. In case of [0_4], it absorbs more energy than [90_4], [$90_2/0_2$] and [$0_2/90_2$] hybrid tubes by 4.41, 16.22 and 40.50%, respectively.

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