QUASI-STATIC CRUSHING OF DIFFERENT CONFIGURATIONS OF METAL-COMPOSITES HYBRID TUBES UNDER AXIAL/LATERAL LOADING

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ABSTRACT

Metal-composites hybrid structures, which combine low-density composites with low-cost metallic materials, are gaining increasing attention for meeting higher and higher requirements of lightweighting and crashworthiness in automotive and aerospace engineering. This study explores the crushing characteristics involving energy absorption and damage behaviors of different configurations of hybrid aluminum/CFRP under quasi-static axial/lateral loading. For a comparative purpose, empty aluminum tube and CFRP tube were tested as well. Based on the experimental results, effects of different configurations on crashworthiness characteristics were studied; and it was found that the hybrid tube H-I (i.e. the aluminum tube internally filled with a CFRP tube) offers the best results for the axial loading. As for lateral loading condition, the better performance can be found in H-II hybrid tube (i.e. the CFRP internally filled with a aluminum tube tube).

1 INTRODUCTION

Over the past decades, thin-walled structures have been widely used as energy-absorbing devices to protect occupants from injury while collision occurs. The vehicle crash safety and environmental change due to exhausted gas emission have led to increasing interests in crashworthiness and lightweight. These concerns coupled with the desire to improve the vehicle energy efficiency continuously drive weight reduction in car manufacturers, making vehicles lighter and lighter. Thus, use of such lightweight materials as aluminum and composites to replace traditional steel has been increasingly seen in automobile engineering.

The crushing behaviors and crashworthiness characteristics of thin-walled metal structureshave been extensively studied under different loading conditions as axial crushing [1-3], oblique compression [4,5] and transverse crushing [6,7] by using experimental and numerical approaches. The collapse modes and energy absorption performance could be precisely predicted. As a promising class of lightweight materials, carbon fiber reinforced plastic (CFRP) composite materials have become more attractive for energy absorbing components thanks to their advantages in high specific strength, high specific stiffness, and tailorable mechanical properties in recent years.There have been substantial studies on crushing behaviors CFRP structures.

Notwithstanding the lightweight feature and advantages in specific energy-absorption (*SEA*) capacity, the CFRP materials are difficult to completely replace metallic components in entire structure. For this reason, the metal/composite hybrid structures are introduced by combining the low density and high strength of CFRP materials with low cost and high plasticity of metallic (e.g. aluminum) materials in crashing structures. Further, it has proven that catastrophic failure mode of CFRP structure can be changed to a progressive failure mode when the fracture process of the composites is guided by the plastic deformation of aluminum, thereby improving energy absorptions for the whole structures [8-11].

The crushing behaviors of metal/composite hybrid structures have been found to be affected by geometry, loading conditions, composite lay-up sequence, strain rate, etc.It is known that metal/composites hybrid structures provide a new structural configuration to meet increasing lightweight and crashworthiness requirements in automobile industry. However, there have been very limited studies available specifically addressing the effects of combination schemes on crashworthiness characteristics of the aluminum/CFRP hybrid tubes.The objective of this study is to investigate the crushing behavior of different aluminum/CFRP hybrid configurations under quasi-static axial load and transverse crushing test.

2 EXPERIMENTAL TESTING

Various failure modes for aluminium/CFRP hybrid and non-hybrid tube will appear when they are served as structure members. Here two types of experiments, namely transverse bending test and axial compression test are considered in this study. Additionally, several well-known indicators have been used to evaluate the crashworthiness of the tested components, including the energy absorption (*EA*), mean crushing force (F_{mean}), peak crushing force (*PCF*), crush force efficiency (*CFE*) and specific energy absorption (*SEA*).

2.1 Transverse bending test

All the specimensfor tests are shown in Fig. 1. The first aluminum tube, which has a 54.5 mm external diameter (D), 300 mm length (L) and 2.25 mm wall thickness (T), is named as AL_in. AL_out has a 65.5 mm external diameter, 300 mm length and 2.25 mm wall thickness. The CFRP tube, which has a 60.91 mm external diameter, 300 mm length and 1.9 mm wall thickness (9 layers), is named as CFRP. The aluminum tubes were made in commercial aluminum alloy (AA6061-O) and the CFRP tubes were fabricated in the bidirectional T300/epoxy prepreg produced by Toray industries through the bladder molding process. Fig. 2 showsthe schematic view of the three point bending test set-up.

Typical force-displacement curve, deformation mode and crashworthiness indicators are shown in Figs. 3-4 and Table 1.Through a comparative analysis of crashworthiness between different structural configurations, it can be found that that the hybrid tube H-II is of the best performance.

Fig. 1. Specimens for transverse crushing test.

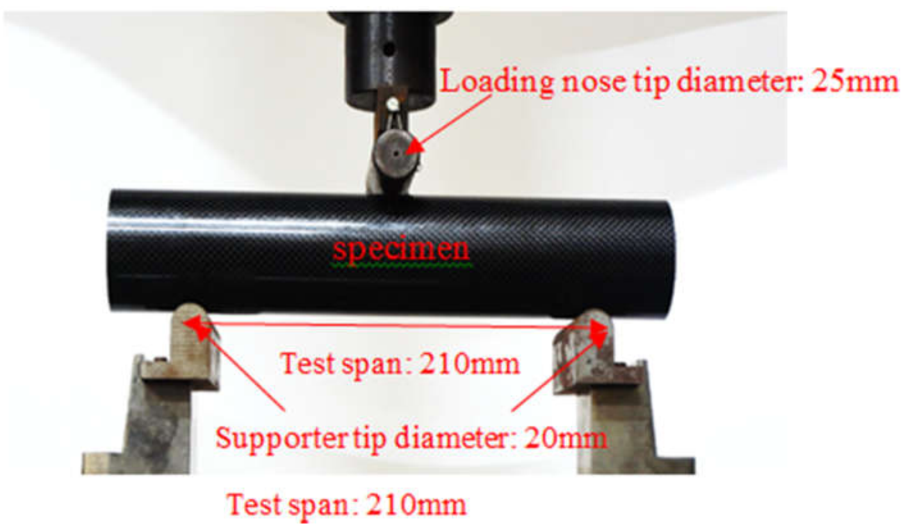


Fig. 2.Schematic view of the three point bending test set-up.

Al_out and Al_in

CFRP

CFRP+Al_in

CFRP+Al_out

Fig. 3.Deformed shape of specimens after testing.

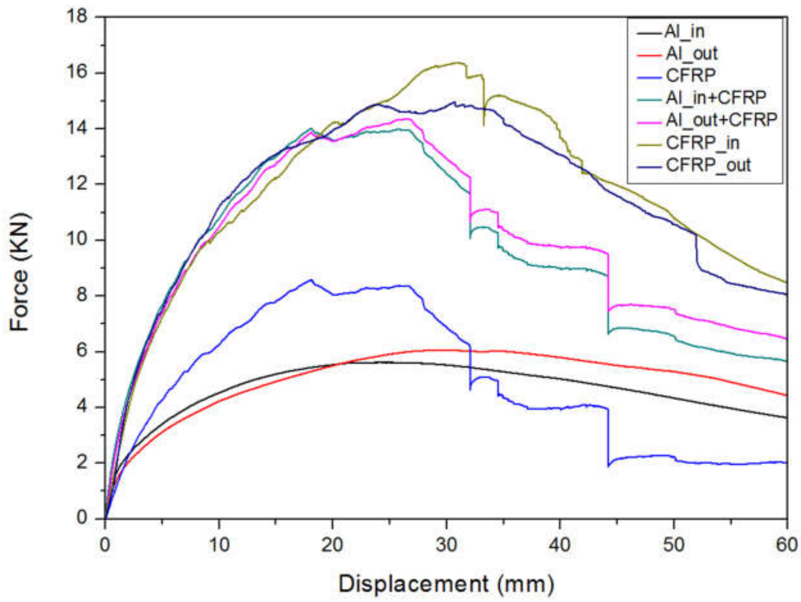


Fig. 4. Load-displacement curves for tests.

Specimens No.	*EA* (J)	*PCF* (N)	F_{mean} (N)	*CFE*	*SEA* (J/g)
Al_in	278.75	5620.03	4645.83	0.83	0.945
Al_out	300.68	6059.24	5011.33	0.83	0.845

CFRP	294.40	8574.37	4906.67	0.57	1.627
H-I	708.63	16382.72	11810.5	0.72	1.298
Sum(AL-out + CFRP)	595.08	14357.63	9918.23	0.69	/
H-II	691.22	14957.50	11520.33	0.77	1.388
Sum(CFRP+AL-in)	573.16	14014.50	9552.67	0.68	/

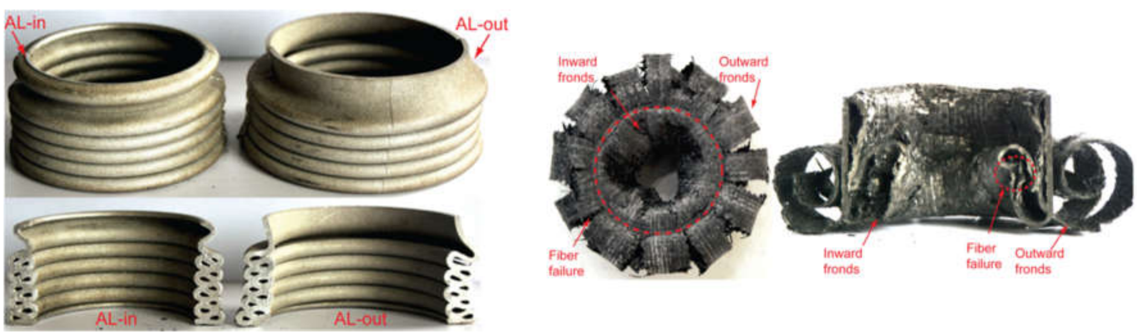
Table 1. The comparison of crashworthiness between different configurational specimens.

2.2 Axial crushing test

Axial crushing test had been undertaken for tubes with three combination schemes shown in Fig. 5. The materials of aluminium alloy and CFRP were kept the same as used in section 2.1. The first aluminum tube, which has a 57.1 mm external diameter (D), 120 mm length (L) and 1.7 mm wall thickness (T), is named as AL-in. AL-out has a 63.79 mm external diameter, 120 mm length and 1.7 mm wall thickness. The CFRP tube, which has a 60.91 mm external diameter, 120 mm length and 1.7 mm wall thickness (7 layers), is named as CFRP.

Typical force-displacement curve, deformation mode and crashworthiness indicators are shown in Fig. 6-7 and Table 2. Through a comparative analysis of on crashworthiness between different structural configurations, it can be found that that the hybrid tube H-I is the best. In particular, both the load carrying capacity and total energy absorption can be improved significantly.

Fig. 5.Force-displacement curve of specimen H-II.

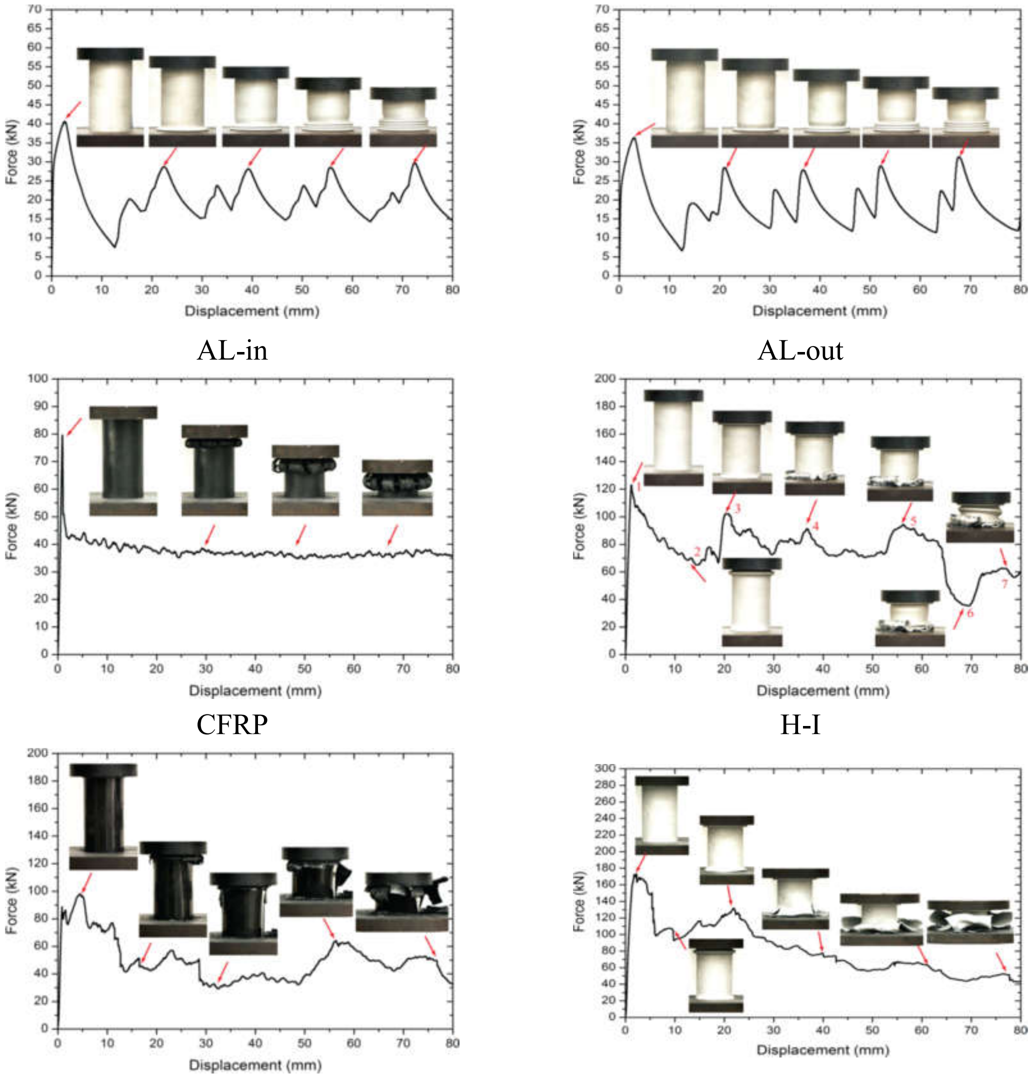


Al CFRP

H-I

H-II H-III

Fig. 6.Deformed shape of specimens after testing.



AL-in AL-out

CFRP H-I

H-II H-III

Fig. 7.Force-displacement curve of specimens.

Specimens No.	EA (kJ)	PCF (kN)	F_{mean} (kN)	CFE	SEA (kJ/kg)
AL-in	1.49	36.4	18.6	0.51	16.18
AL-out	1.67	40.5	20.7	0.51	15.80
CFRP	3.00	79.6	37.5	0.47	54.51
H-I	6.05	123.1	75.6	0.61	37.82
Sum(AL-out + CFRP)	4.67	120.1	58.2	0.48	/
H-II	3.98	98.2	49.7	0.51	26.87
Sum(CFRP+AL-in)	4.49	116	56.1	0.48	/
H-III	6.53	173.2	81.6	0.47	25.91
Sum(AL-out + CFRP+AL-in)	6.16	156.5	76.8	0.49	/

Table 2. The comparison of crashworthiness between different configurational specimens

3 CONCLUSIONS

This study investigated the collapse behaviors of different aluminum/CFRP hybrid tubes under quasi-static three point bending and axial compression condition by exploring the effects of different structural configurations on crashworthiness and comparing the results with the summation of each part's contribution separately. Conclusions can be drawn that under axial compression loading condition, the energy absorption of hybrid tube H-I increases by almost 30% when compared with the summation of CFRP tube and AL-out tube due to the complex ongoing interaction and the change of deformation modes. Further, under three point bending condition, the energy absorption of hybrid tube H-II increases by over 20% when compared with the summation of CFRP tube and AL_out tube.

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REFERENCES

[1] Andrews K R F, England G L, Ghani E. Classification of the axial collapse of cylindrical tubes under quasi-static loading. I*nternational Journal of Mechanical Sciences*, 1983, 25(9-10): 687-696.

[2] Guillow S R, Lu G, Grzebieta R H. Quasi-static axial compression of thin-walled circular aluminium tubes. *International Journal of Mechanical Sciences,* 2001, 43(9): 2103-2123.

[3] Hsu S S, Jones N. Quasi-static and dynamic axial crushing of thin-walled circular stainless steel, mild steel and aluminium alloy tubes. I*nternational Journal of Crashworthiness*, 2004, 9(2): 195-217.

[4]Greve L, Pickett A K, Payen F. Experimental testing and phenomenological modelling of the fragmentation process of braided carbon/epoxy composite tubes under axial and oblique impact. *Composites Part B: Engineering*, 2008, 39(7): 1221-1232.

[5] Zarei H R. Experimental and numerical crashworthiness investigation of hybrid composite aluminum tubes under dynamic axial and oblique loadings. 2015.

[6] Liu Q, Xing H, Ju Y, et al. Quasi-static axial crushing and transverse bending of double hat shaped CFRP tubes. *Composite Structures*, 2014, 117: 1-11.

[7] Kim H C, Shin D K, Lee J J. Characteristics of aluminum/CFRP short square hollow section beam under transverse quasi-static loading[J]. Composites Part B: Engineering, 2013, 51: 345-358.

[8] Kim H C, Shin D K, Lee J J. Characteristics of aluminum/CFRP short square hollow section beam under transverse quasi-static loading[J]. Composites Part B: Engineering, 2013, 51: 345-358.

[9] Zhao X L, Zhang L. State-of-the-art review on FRP strengthened steel structures[J]. Engineering Structures, 2007, 29(8): 1808-1823.

[10] Costas M, Díaz J, Romera L E, et al. Static and dynamic axial crushing analysis of car frontal impact hybrid absorbers[J]. International Journal of Impact Engineering, 2013, 62: 166-181.

[11] Costas M, Díaz J, Romera L, et al. A multi-objective surrogate-based optimization of the crashworthiness of a hybrid impact absorber[J]. International Journal of Mechanical Sciences, 2014, 88: 46-54.