CRUSH BEHAVIOR OF ALUMINUM/COMPOSITE HYBRID TUBES UNDER QUASI-STATIC LOADING

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Abstract

This paper presents a review of the crush behavior of aluminum/composite hybrid tubes which are produced by wrapping one or more composite layers on aluminum tubes. It also provides new experimental data on the effect of crush initiators on the crush behavior of aluminum/composite hybrid tubes. It is shown that the crush initiator can influence both the failure mode as well as the energy absorption of all three types of tubes.

Keywords: *Crush behavior, crush energy, crush initiator, aluminum/composite hybrid tubes*

Introduction

The most important design requirement for crashworthy structures in automotive and aerospace vehicles is that they must absorb impact energy in a controlled manner as they collapse so that the occupants are protected from serious injuries. Many of these structures use tubular constructions of lightweight materials, such as aluminum alloys and fiber reinforced composites. The crush behavior of aluminum and composite tubes has been studied by many investigators [1-7]. Additionally, crush behavior of aluminum/composite hybrid tubes has also been of interest, since such a combination has the possibility of either increasing the energy absorption, improving the collapse mechanism or both. This paper presents a review of the crush behavior of aluminum/composite hybrid tubes along with related information on the crush behavior of aluminum and composite tubes.

Crush Parameters

The ideal crush behavior of a crashworthy tubular structure is represented in Fig.1. It shows the load-displacement diagram of a ductile metal tube tested under quasi-static axial compressive loading. The crush is initiated at or below the maximum load; afterward, crushing or collapse of the tube continues with repeated fold formation, and the load fluctuates in an up-and-down manner with small peaks and valleys as the folds are formed one after another. In a metal tube, local plastic buckling is the cause for fold formation, which is the principal mechanism for energy absorption. Depending on the material and effective diameter-to-thickness ratio, the folding can be of either axisymmetric (concertina) or asymmetric (diamond) type. In a composite tube, crushing may not occur with fold formation; instead, transverse shear failure, delamination and lamina bending are the primary energy absorbing mechanisms [8], and since they occur in a progressive manner, the load-displacement diagram may show characteristics similar to that shown in Fig.1. Similar crush behavior is also desirable under dynamic or impact condition; however, it is possible that different failure mechanisms may be activated at high impact velocities and the energy absorption value may be affected due to strain rate effects.

There are several crush parameters that can be obtained from the load-displacement diagram shown in Fig.1. The first parameter is the maximum load, which is the load at which controlled crushing is ensued. In both metal and composite tubes, crush initiators or triggers are often included at one or both ends of the tube to initiate controlled crushing and keep the maximum load within a safe limit. In some cases, several smaller peaks are observed before the maximum load is reached. The first load drop from the maximum load is also an important parameter since it indicates the load effect on the occupant and, in general, should be as small as possible. In addition to these three parameters that can be directly obtained from the load-deflection diagram, there are three other parameters that are calculated from the load-deflection diagram. They are (a) mean load during controlled crushing, (b) energy absorbed, calculated from the area under the load-deflection plot and (c) specific energy, which is the ratio of energy absorbed and mass of the tube.

Crush Behavior of Aluminum/Composite Hybrid Tubes

The concept of combining metal and composite tubes to increase crush energy absorption appeared in a paper in 1996 authored by Hanefi and Wierzbicki [9]. The experiments conducted in their study involved 0.5 to 1 mm thick steel tubes and 0.5 to 1.5 mm thick hoop wound E-glass-epoxy overwraps and showed that the steel/composite hybrid tubes produced a significantly higher mean load and specific energy absorption than the steel tubes.

Ragalyi and Mallick [10] reported that hybrid tubes containing aluminum and filament-wound E-glass fiber-reinforced epoxy overwrap had higher energy absorption than either the composite tubes or the aluminum tubes. Three different wind angles (with respect to the tube axis) were considered, namely ±45, ±60 and ±75. For the round tubes, the highest energy absorption was obtained with ±45 overwrap, whereas for the square tubes, the highest energy absorption was obtained with ±75 overwrap. The energy absorption by the round hybrid tube with ±45 overwrap was 15% higher than the round aluminum tube. The energy absorption by the square hybrid tube with ±75 overwrap was 245% higher than the square aluminum tube. Since the increase in energy absorption by the round hybrid tube was relatively small, its specific energy absorption was lower than that of the round aluminum tube. However, in the case of square hybrid tube, the specific energy absorption was 36% higher than that of the square aluminum tube. Another result of this study was that both maximum load and mean load were significantly higher for hybrid tubes than the composite tubes and either equal to or higher than the aluminum tubes.

Babbage and Mallick [11] further explored the crush behavior of aluminum/composite hybrid tubes using ±45 E- glass/epoxy overwrap on round and square aluminum tubes. In this study, the number of overwrap layers was varied. The load-displacement diagrams (Figs.2 and 3) show the up-and-down load fluctuation associated with regular asymmetric (diamond) folding pattern observed in these tubes (Figs.4 and 5). The maximum load, mean load, and energy absorption increased with increasing overwrap thickness. The specific energy absorption of the round hybrid tubes was the same as that of the round aluminum tube, whereas the specific energy absorption of the square hybrid tubes was 16 to 19% higher than that of the square aluminum tube.

There were several other studies reported in the literature on the crush performance of hybrid aluminum/composite tubes. Song et al. [12] performed quasi-static and impact tests on E-glass/epoxy wrapped circular aluminum tubes. The fiber orientations were [±15], [±45] and [90]. They observed that the specific energy absorption of the hybrid tubes was higher than that of the base aluminum tubes and increased with increasing fiber orientation. The failure modes of the hybrid tubes were either asymmetric folding, fragmentation/axial splitting, delamination or catastrophic failure, depending on the fiber orientation in the overwrap and inner metal tube material (ductile or brittle).

Shin et al. [13] performed quasi-static axial crush and bending collapse tests on hybrid tubes produced by wrapping E-glass fiber/epoxy prepregs around 45 mm x 45 mm x 1.2 mm (thickness) square aluminum tubes. The ply orientations were [0], [90], [0/90] and [±45] with respect to the tube axis and the overwrap thickness was either 1, 2 or 3 mm. They observed that the [0] overwrap was completely ineffective, since it failed by splitting at the corners and separated easily from the aluminum tube. Hybrid tubes with the [90] overwrap showed stable local buckling and fold formation, whereas the other two tubes showed mixed mode of crushing. In axial crushing experiments, hybrid tubes with the [90] overwrap exhibited the highest energy absorption.

Bouchet et al. [14] conducted dynamic compression tests on circular aluminum-composite hybrid tubes in which the composite was a carbon fiber reinforced epoxy prepreg wrapped in the hoop direction. The aluminum tube with 1 mm wall thickness showed asymmetric (diamond) folding, whereas the aluminum tube with 2 mm wall thickness showed axisymmetric (concertina) folding. The thicker aluminum tube showed twice the specific energy absorption as the thinner tube (42.7 kJ/kg and 22 kJ/kg, respectively). On the other hand, hybrid tubes with both 1-mm and 2-mm thick aluminum inner tubes failed by asymmetric (diamond) folding and both showed similar specific energy absorption (26 kJ/kg and 21 kJ/kg, respectively). They also observed that the specific energy absorption was 33-38% higher if the aluminum tube surface was anodized before making the hybrid tube.

Bambach and his co-workers [15-17] published a number of articles on axial crushing of thin-walled square cross-sectioned hollow metal tubes externally reinforced with 0/90 layers of carbon fiber reinforced epoxy (CFRP).

The 0° layers were in the axial direction and the 90° layers were in the transverse direction. The metal tubes were made of low carbon steel, stainless steel and aluminum. In all cases, significant increase in mean load, maximum load and specific energy was observed. For example, when 65-mm x 65-mm x 2.4-mm (thickness) aluminum tube was externally reinforced with one 0° layer and one 90° layer of CFRP, the mean load increased by 42% and specific energy increased by 14% in comparison to aluminum tubes [17]. With two 0° layers and two 90° layers of CFRP, the increases in mean load and specific energy were 87% and 14%, respectively. All of the tubes crushed in axi-symmetric collapse mode and the CFRP layers folded along with the aluminum tube with no delamination observed between them.

Effect of Crash Initiators

Crash initiators are often needed to trigger controlled crushing of the tube under axial loading and reduce the crush initiation load. In aluminum tubes, the common crush initiators are chamfers or holes drilled at one of the tube. Similar crush initiators have also been used with composite tubes. In the study reported here, four different crush initiators were used: (1) plug with sharp corner, (2) plug with a 45° chamfer, (3) plug with a 6-mm radius rounded corner, and (4) a triangular hole pattern drilled at one end of the tube (Figs.6 and 7). Each end of the tube was fitted with a plug to support the specimen during quasi-static axial crushing. One of these plugs had a sharp corner, while the plug at the other end either had a sharp corner or was modified to include either a 45° chamfer or a 6-mm radius rounded corner. The hole pattern was drilled with a 5 mm drill and arranged in a triangular fashion repeated four times around the circumference of the tube. A summary of the test results is shown in Table-1. As can be seen in this table, composite tubes had lower maximum load as well as specific lower energy absorption than either the aluminum or the hybrid tubes. It is also evident that both failure mode and crush parameters were influenced by the crush initiator.

Conclusion

This paper gives a brief review of the published experimental work on the axial crush behavior of aluminum/composite hybrid tubes. In general, composite tubes by themselves have lower energy absorption than aluminum tubes, and depending on the fiber type, fiber arrangement, etc. can exhibit a variety of crush failure modes. Aluminum tubes, on the other hand, fail by regular folding caused by local plastic deformation. The published data show that, in general, aluminum/composite hybrid tubes fail by regular folding much like the inner aluminum tube and the specific energy absorption is similar to that of aluminum tubes. The crush initiator can influence both the failure mode as well as the energy absorption of all three types of tubes. Further work is needed to optimize the

Table-1 : Crush Performance of Aluminum, Composite and Hybrid Tubes

Material	Wall Thickness	Initiator	Crush Initiation Load (kN)	Max. Load (kN)	Mean Load (kN)	Energy Absorbed (J)	Specific Energy (kJ/kg)	Failure Mode
6061-T6 Aluminum	0.84 mm	Flat	40	40	17.5	704	25.5	Folds
		Chamfered	9.4	30.2	18.2	1042	37.2	Folds or Tulip
		Radiused	8.3	22.4	13.9	645	29	Tulip
		Holes	18	19.7	13	610	22	Folds
[±45] Filament Wound E-glass/Epoxy	2 mm	Flat	19.9	19.9	5.23	290.6	8.1	Buckle
		Chamfered	3.6	14.7	10.5	516.3	14.3	Tulip
		Radiused	7.6	9.2	7.9	384.4	10.7	Tulip
		Holes	8.1	18.6	12.5	599	16.9	Folds
Al/Composite Hybrid		Chamfered	10	36.5	22.68	1228	24.6	Folds
		Radiused	12	34.8	24.87	1231	24.6	Folds
		Holes	14	28	21.29	1024	20.4	Folds

hybrid tube construction so that hybridization can produce higher specific energy absorption than the aluminum tubes.

References

1. Guillow, S.R., Lu, G. and Grzebieta, R.H., "Quasi-static Axial Compression of Thin-walled Circular Aluminium Tubes", Int. J. Mechanical Sciences, 43, 2001, pp.2103-2123.

2. Gupta, N. K., "Some Aspects of Axial Collapse of Cylindrical Thin-walled Tubes", Thin-Walled Structures, 32, 1998, pp.111-126.

3. Meadows, D.J., Seeds, A.D., McGregor, I.J. and Kenyon, M., "Aluminum Crash Members in Axial and Bending Collapse", SAE Paper No. 922113, Society of Automotive Engineers, 1992.

4. Langseth, M. and Hopperstad, O.S., "Static and Dynamic Axial Crushing of Square Thin-walled Aluminium Extrusions", Int. J. of Impact Engineering, 18, 1996, pp.949-968.

5. Farley, G.L., "Energy Absorption of Composite Materials", J. Composite Materials, 17, 1983, pp.267-279.

6. Mamalis, A.G., Robinson, M., Manolakos, D.E., Demosthenous, G.A., Ioannidis, M.B. and Carruthers, J., "Crashworthy Capability of Composite Materials Structures", Composite Structures, 37, 1997, pp.109-133.

7. Jacob, G.C., Fellers, J.F., Simunovic, S. and Starbuck, J.M., "Energy Absorption in Polymer Matrix Composite Materials for Automotive Crashworthiness", J. Composite Materials, 36 (7), 2002, pp.813-850.

8. Farley, G.L. and Jones, R.M., "Crushing Characteristics of Continuous Fiber-reinforced Composite Tubes", J.Composite Materials, 26 (1), 1992, pp.37-50.

9. Hanefi, E. H. and Wierzbicki, T., "Axial Crush Resistance and Energy Absorption of Externally Reinforced Metal Tubes", Composites: Part B, 27B, 1996, pp.387-394.

10. Ragalyi, A. and Mallick, P. K., "Crashworthiness of Aluminum-composite Hybrid Crush Tubes Containing Filament-wound Over-wraps", Proc. SAMPE-ACCE-DOE-SPE Midwest Advanced Materials and Processing Conferences, Dearborn, MI, 2000, pp.420-426.

11. Babbage, J. M. and Mallick, P.K., "Static Axial Crush Performance of Unfilled and Foam-filled Aluminum-composite Hybrid Tubes", Composite Structures, 70, 2005, pp.177-184.

12. Song, H.W., Wan, Z.M., Xie, Z.M. and Du XW., "Axial Impact Behavior and Energy Absorption Efficiency of Composite Wrapped Metal Tubes", Intl. J. of Impact Engineering, 24, 2000, pp.385-401.

13. Shin, K.C., Lee, J.J., Kim, K.H., Song, M.C. and Huh, J.S., "Axial Crush and Bending Collapse of an Aluminum/GFRP Hybrid Square Tube and its Energy Absorption Capability", Composite Structures, 57, 2002, pp.279-287.

14. Bouchet, J., Jacquelin, E. and Hamelin, P., "Dynamic Axial Crushing of Combined Composite Aluminium Tube: The Role of Both Reinforcement and Surface Treatments", Composite Structures, 56, 2002, pp.87-96.

15. Bambach, M.R., Jama, H.H. and Elchalakani, M., "Axial Capacity and Design of Thin-walled Steel SHS Strengthened with CFRP", Thin-Walled Structures, 47, 2009, pp.1112-1121.

16. Bambach, M.R., Jama, H.H. and Elchalakani, M., "Static and Dynamic Axial Crushing of Spot-welded Thin-walled Composite Steel-CFRP Square Tubes", International Journal of Impact Engineering, 36, 2009, pp.1083-1094.

17. Bambach, M.R., "Axial Capacity and Crushing Behavior of Metal-fiber Square Tubes Steel, Stainless Steel and Aluminum with CFRP", Composites: Part B, 41, 2010, pp.550-559.

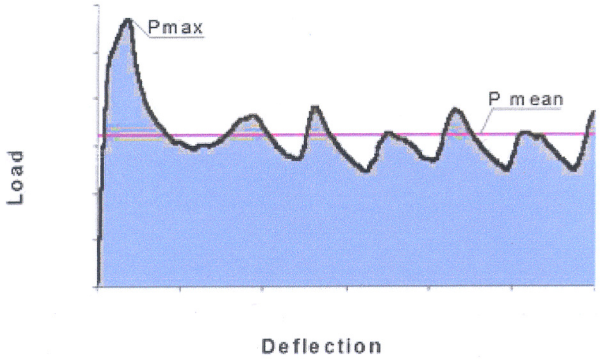

Fig.1 Schematic Load-deflection Diagram of Crush Resistant Tubes Under Axial Compressive Loading

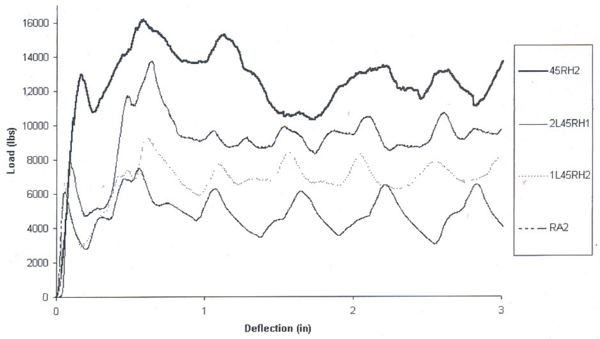

Fig.2 Static Axial Load-displacement Diagrams of Round aluminum (RA) Tube and Round Hybrid (RH) Tubes with ±45° Overwrap. In the figure above, RA2 is a round aluminum tube and 1L45RH2, 2L45RH1 and 45RH are round hybrid tubes with 1 layer, 2 layers and 3.5 layers of overwrap, respectively. (from Ref.11) (Note : 1 lb = 4.444 N and 1 in = 25.4 mm)

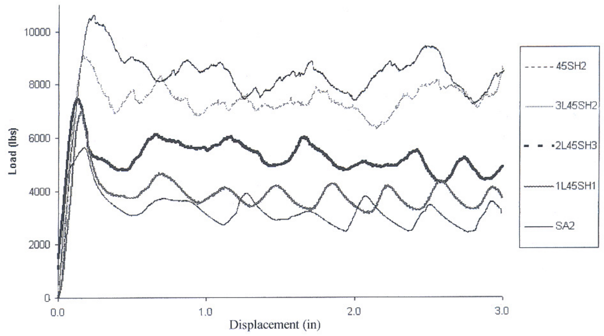

Fig.3 Static Axial Load-displacement Diagrams of Square aluminum (SA) Tube and Square Hybrid (SH) Tubes with ±45° Overwrap. In the figure above, SA2 is a square aluminum tube, and 1L45SH1, 2L45SH3, 3L45SH2 and 45SH2 are square hybrid tubes with 1 layer, 2 layers, 3 layers and 3.5 layers of overwrap, respectively. (from Ref.11) (Note : 1 lb = 4.444 N and 1 in = 25.4 mm)

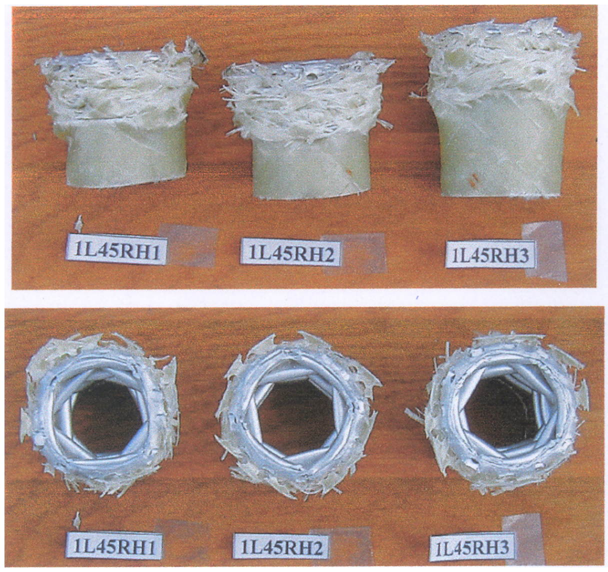

Fig.4 Folding pattern of round hybrid tubes with one layer of ±45° E-glass/epoxy overwrap on a 50-mm diameter, 1.24 mm thick round aluminum (6061-T6) tube (from Ref.11)

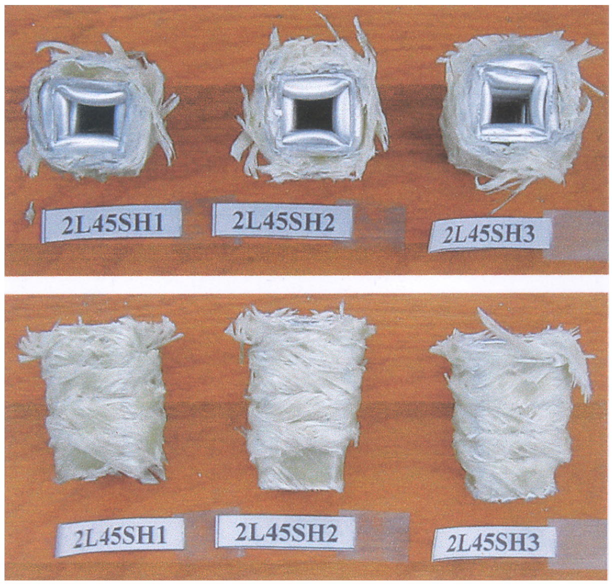

Fig.5 Folding pattern of square hybrid tubes with two layers of ±45° E-glass/epoxy overwrap on a 25mm x 25 mm x 1.6 mm square aluminum (6063-T52) tube (from Ref.11)

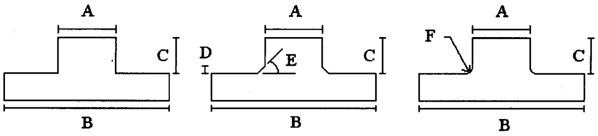

Fig.6 Plug configurations : (Left) with sharp corner, (Middle) with a 45° chamfer and (right) with a 6-mm radius (A = 47.5 mm, B = 100 mm, C = 25 mm, D = 2 mm, E = 45°, F (radius) = 6 mm)

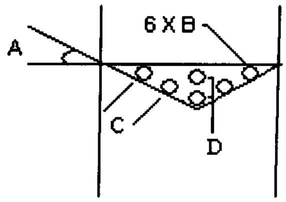

Fig.7 Triangular Hole Pattern Used as Crush Initiator (A = 35°, B = 5 mm, C = 9 mm, D = 7 mm