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ENERGY ABSORPTION CAPABILITY OF ALUMINIUM TUBE PARTIALLY WRAPPED WITH GLASS/EPOXY SUBJECTED TO QUASI-STATIC LOADING

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ABSTRACT

Thin-walled hybrid tubes developed by a combination of metal and composite merge the benefits of metal and composite that is a high axial load carrying capacity, stable collapse modes, which result in maximum total energy absorption (TEA), specific energy absorption (SEA), and crush force efficiency (CFE). The improvement in energy absorption competency of round aluminium tube, having applications in transportation vehicles as well as aircraft, is meted out throughout this examination. Impact properties for partially wrapped tube are not well addressed in all previous studies. In order to improve energy absorption features, partial wrapping and full wrapping of the circular aluminium tube with glass/epoxy by applying 90° fiber angle and 6 numbers of layers of composite is performed, using filament winding process. Moreover, impact properties of partially wrapped tube and fully wrapped tubes are determined by applying quasi-static loading. In addition to this, TEA, SEA, axial load carrying capacity (P_{max}) and CFE are analyzed to achieve improvement in energy absorption capability of partially wrapped aluminium tube with glass/epoxy. The result revealed that SEA of partially wrapped aluminium tube is 49.09% and 14.84% more as compared with partially wrapped steel and fully wrapped aluminium tube respectively.

Keywords: thin-walled hybrid circular tube, aluminium, composite, crashworthiness, energy absorption.

INTRODUCTION

Thin-walled tubes broadly utilized in applications required absorption of energy, and these tubes very often exist in square or circular cross-section [1]. An extensive use of these tubes for absorption of impact energy is in the automobile and aerospace vehicles. These tubes transmitted the impact to vehicle after plastically or forever misshape, accordingly decreasing the deceleration accomplished by the passengers. Moreover, such type of tubes also play safeguard role by disfiguring in inclination to other parts of the vehicle construction, in this manner decreasing overhaul expenses and keeping the unwavering quality of the traveller box [1].Circular tubes having thin-walled are needed as an energy absorber because they are lower in cost, versatile and efficient in energy absorption [2]. Circular tube as compared with square tube is more ideal for energy absorption subjected to axial loading [3, 4]. Sides of square tubes lead them to fast splitting because of stress concentration, resulting in low energy absorption [5]. The materials frequently used for tubes in applications that need absorption of impact energy are aluminium, steel and fiber reinforced plastic (FRP). In addition to, these materials a combination of metal and composite (hybrid) is also used. Hybrid tube normally developed by wrapping the fiber material with resin (a binder) on metal tube. The most frequently used fiber materials are carbon, kevlar and glass. Energy absorption capability of thin-walled hybrid aluminium tube is more as compared with aluminium or composite tube. Hybrid tubes absorb energy through plastic deterioration of inner aluminium tube and brittle fracture of external composite [6]. As compared with other cross-sectional shapes (square and rectangular), thin-walled circular tubes have identical and stable deformation mode when subjected to quasi-static and dynamic compression (specifically impact having low velocity) [7]. Due to this these tubes demonstrate better energy absorption characteristics.

LITERATURE REVIEW

Mamalis *et al.* [8] was pioneer to study the energy dissipation ability of bimaterial thin-walled tube. Numerous factors take part to the crushing performance and energy absorption proficiency of hybrid tube. For example, metal and composite thickness, material used for the tube (e.g. aluminium, steel, carbon, kevlar and glass fiber composites), different construction parameters (e.g. number of layers, orientation angle etc.), the geometry of the tube (e.g., square, circular, rectangle) and wall thickness ratio of metal to composite (tm/tc).

K.C Shin *et al.* [9] performed studied on aluminium/glass fiber reinforced polymer (GFRP) hybrid square tubes to analyze energy absorption capability under axial crush . He developed hybrid tube by full wrapping of square aluminium tube with glass/epoxy, with three different angles 0°, 90° and ± 45° of prepreg sheets on tube, using dry filament winding process. Similarly, same process was performed to develop composite tube. He evaluated energy absorption features; mean crushing load and mechanisms of failure for hybrid tube as well as composite tube and aluminium tube without composite under quasi-static loading. He found that 90° is best for energy absorption. Furthermore, aluminium tube wrapped by glass/epoxy is better in energy absorption as compared with aluminium tube without composite and tube prepared by only composite material.

M. Bambach and M. Elchalakani [10] conducted research on hollow steel tube having square cross-section, fully wrapped for 0° and 90° with carbon fiber reinforced

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polymer (CFRP), using prepreg sheet winding process. He determined that by increasing number of layers of composite material, axial load carrying capacity of tubes increases under quasi-static loading. Bambach [11] also worked on hollow square steel tubes wrapped with CFRP under axial impact loading. Two different matrix orientation that is 0° and 90° of the CFRP were examined. The result revealed that the hybrid tube with 90° orientation is good at carrying out larger axial load. Kalhor [12] studied the effect of fiber-reinforced plastics (FRP) thickness on energy absorption. He developed hybrid tube by full wrapping of FRP on square steel tube. He evaluated the effect of thickness of composite on hybrid tube subjected to axial compressive loading. He analysed that energy absorption of tube increases when the thickness of fiber-reinforced plastics (FRP increased. Moreover, load carrying capacity of hybrid tube was greater than tube without composite wrapping.

Song *et al.* [13] studied collapse modes and properties of circular steel hybrid tube. He developed hybrid tube by applying three different angles 15°, 45° and 90° of glass/epoxy with wet filament winding process. He analyzed energy absorption competence for example, strain rate, wall thickness of composite material, fiber orientation, and mechanical properties related to metals and composite under quasi-static and impact loading condition. He also found that by increasing the wall thickness of composite material specific energy absorption (SEA) increases. Furthermore, by increasing the winding angle SEA also increases.

Babbage and Mallick [14] performed an experimental examination on round and square cross-section aluminium–glass/epoxy hybrid tubes. He developed hybrid aluminium tubes by full wrapping with-glass/epoxy using wet filament winding process. The fiber layup angles in were ± 45° and ± 75° to the tube axis. Few tubes were filled with epoxy foam for further analysis. These tubs were evaluated under impact loading. Experimental results revealed that circular tubes are better than square tubes to carry out more axial load as well as in absorption of energy.

Lima *et al.* [15] studied the behaviour of circular tube made by steel and partially wrapped with glass fiber reinforced polymer, subjected to axial quasi static loading. He developed the tube by using fiber layup angles ± 45°and ± 75º. Furthermore, 4, 6, and 8 composite layers were applied to tube axis, using wet filament winding process. Experimental results indicated that 90º is better in energy absorption for partially wrapped steel tube with glass fiber reinforced polymer.

From the literature review, it is clear that there is no study available for partial wrapping of aluminium tube. Due to light weight and good energy absorption features aluminium tube is selected. Furthermore, to improve energy absorption features partial wrapping of aluminium tube with glass/epoxy is performed. The reason for selection of glass/epoxy is that glass/epoxy is inexpensive as compared with carbon/epoxy. Moreover, energy absorbed by glass/epoxy rise with increase of orientation angle [16] as illustrated in Figure-1 .

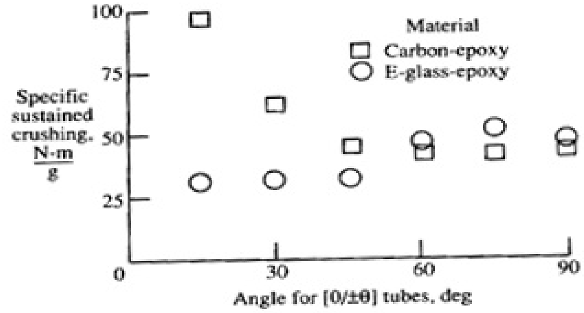

Figure-1. Energy absorption capability of tubes [16].

MATERIALS AND METHODS

In this research, for appropriate collapse mode the length of internal aluminium tube was chosen to be 200 mm. Complete specifications of selected tube is shown in Figure-2.

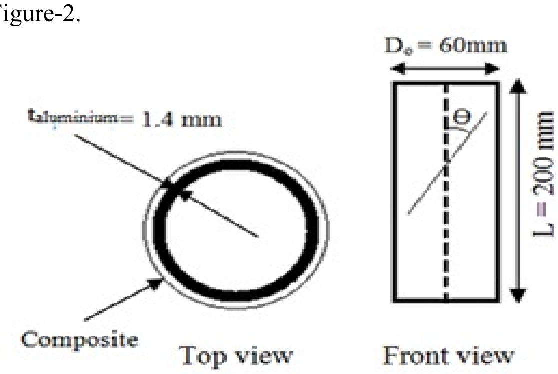

Figure-2. Dimensions of selected aluminium tube.

The aluminium tube samples were fully and partially wrapped (Figure-3) with 90° fiber angle and six layers of glass fiber using wet filament process. Area covered by partial wrapping is shown in Table-1. For six layers of glass/epoxy, composite thickness was measured 3mm . Quasi-static tests were executed using zwick roell universal testing machine at speed of 0.08 mm/sec (5mm/min) to avoid strain rate effect. Load-displacement (L-D) curves obtained from axial compression of aluminium tube samples, fully wrapped and partially wrapped were used to evaluate parameters of crashworthiness.

(a) (b) (c)

Figure-3. Different samples (a) without wrapping (b) partially wrapped (c) fully wrapped.

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Table-1. Area covred by partailly wrapped tube.

Numbers of layers	Fiber orientation 90° (mm^2)	% covered area by composite
6	18849.6	50 %

RESULTS AND DISCUSSIONS

Failure mechanism and behavior of aluminium hybrid tubes were analyzed. Moreover, the parameters for crashworthiness; TEA, SEA, CFE, P_{max} and P_{mean} were also calculated from L-D curves obtained under quasi-static tests of hybrid aluminium tubes.

Load displacement curves and modes of failure

Aluminium tube samples subjected to quasi-static load portrayed axisymmetric folding as shown in Figure-4. Figure-5 demonstrated the outside and inside portions of tube bends by alternate peaks of load (maximum and minimum). The equilibrium wave in load-displacement graph approaches to higher level of load, without any change in the axisymmetric mode of failure. Upon reaching at this point, continuous increase in load application one of the buckles confine and the wall of the specimens starts to fold outside and there is a sharp decrease in force to form the first complete fold. The force approaches to its lower value, and then rise up to its higher value again. In the failure area the wall tries to fold inside, resulting in another peak of force, at this moment internal buckling appears. Due to the inside folding of the wall, there is fall in force. After the minor folding of the wall towards inside, the value of force again increases, resulting in recurrence of this pattern.

(a) (b)

Figure-4. Axisymmetric folding of aluminium tube (a) front view (b) top view.

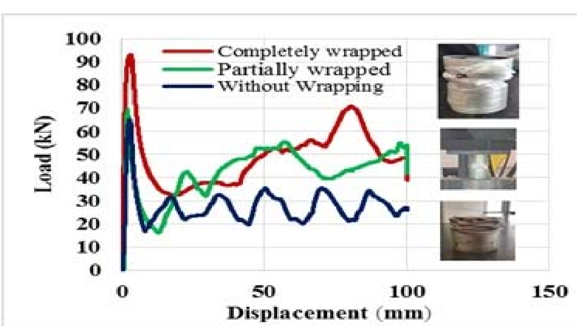

Figure-5. Load-displacement curves for completely wrapped, partially wrapped and without wrapping of tubes.

For partially and completely wrapped tube mode of failure reformed and tubes were failed in global buckling. Moreover, partially wrapped tube failure (Figure-6) started at area of tube without wrapping then multiple inside folds started to develop along with wrapped area. This phenomenon can be the reason for increse in SEA of partially wrapped tube as compared with fully wrapped. Because in fully wrapped tube failure occurred in middle (Figure-7) and during post-buckling condition due to delamination and debonding, fiber did not contribute in absorption of energy.

(a) (b)

Figure-6. Folding pattern of partially wrapped aluminium tube (a) front view (b) top view.

(a) (b)

Figure-7. Folding pattern of fully wrapped aluminium tube (a) front view (b) top view.

Energy absorption parameters

The TEA can be calculated using the following

$$TEA = \int P_{mean}\, Ds = P_{mean}\,(Df - Di) \quad (1)$$

Where P_{mean} denotes the mean load and Df and Di represents the final and initial crushing displacement respectively. From above equation 1 we can also get P_{mean} value as shown in Equation. (2).

$$Pmean = TEA\ /\ (Df - Di) \quad (2)$$

Energy absorbed divided by unit mass is called specific energy and can be calculated from Equation. (3) [17].

$$SEA = TEA\ /\ m \quad (3)$$

Where m is the mass of original unshaped sample. When it is important to reduce weight of vehicle, SEA parameter is essential to evaluate in terms of absorbing of energy. Furthermore, for light weight energy absorber greater value of SEA interpret that it is better in absorbing impact energy [18, 19].

To measure the smoothness of compressive load CFE is necessary to evaluate, it can be calculated using Equation. (4) [17] where P_{max} is maximum load.

$$CFE = P_{mean} / P_{max} \tag{4}$$

Parameters for energy absorption are calculated and presented in Table-2 for fully wrapped, partially wrapped and without wrapping of aluminium tubes with fiber. It is obvious in Table-2 that parameters for absorption of energy enhanced, for fully wrapped and partially wrapped aluminium tubes.

Table-2. Parameters for absorption of energy for aluminium tube.

Aluminium Tube	No.of composite layers	TEA (kJ)	SEA (kJ/kg)	P_{max} (kN)	P_{mean} (kN)	CFE
Without wrapping	....	2.67	22.25	65	26.79	41
Partially wrapped	6	4.23	26.46	69.5	42.35	60
Fully wrapped	6	4.84	23.04	93	48.40	52

Furthermore, it is clear that values of SEA and CFE of partially wrapped tube are better as compared with fully wrapped and without wrapped aluminium tube. So, partially wrapped tube energy absorption capability is better. This is because of mix fragmentation failure mode of partially wrapped tube, which result in fiber kinking and composite fragmentation. Table-3 is showing the percentage of improvement for parameters of energy absorption. It is obvious all parameters have been improved after wrapping with glass and epoxy. Furthermore, partially wrapped aluminium tube has also 31.66 % higher value of CFE as compared to without wrapped aluminium tube. In addition to this fully wrapped aluminium tube has also 26.8 % higher value of CFE and 3.55 % higher value of SEA as compared with without wrapped aluminium tube. Furthermore, partially wrapped aluminium tube has also 6.92 % higher value of P_{max} as compared to without wrapped aluminium tube.

Table-3. Comparison of parameters for absorption of energy for aluminium tube.

Parameters of crashworthiness	Aluminium tube	Improvement with partial wrapping (%)	Improvement with full wrapping (%)
TEA (kJ)	2.67	58.42	81.27
SEA (kJ/kg)	22.25	18.92	3.55
P_{max} (kN)	65	6.92	43.07
P_{mean} (kN)	26.79	58.08	80.66
CFE	41	31.66	26.8

Moreover, the comparison between partially wrapped aluminium and partially wrapped steel tube has been conducted to show that aluminium tube is more efficient in terms of SEA and CFE. Parameters of energy absoption for steel tube [15] are shown in Table-4 and comparison among partially wrapped aluminium tube, partially wrapped steel tube and fully wrapped aluminium tube has been carried out in Table-5 and Table-6 alongwith Figure-8. It can been seen energy absorption capability of partially wrapped aluminium tube is 49.09 % and 14.84 % more than partially wrapped steel and fully wrapped aluminium tube.

Table-4. Parameters for absorption of energy for steel tube [15].

Steel Tube	No.of composite layers	TEA (kJ)	SEA (kJ/kg)	P_{max} (kN)	P_{mean} (kN)	CFE
Without wrapping	....	3.93	9.77	87.72	39.35	44.81
Partially wrapped	6	9.31	15.77	155.55	93.11	59.85

Table-5. Comparison of parameters for SEA partially wrapped aluminium and steel tube.

Parameters of crashworthiness	Partially wrapped steel tube	Partially wrapped aluminium tube	Improvement (%)
SEA (kJ/kg)	15.77	26.46	41.09

Table-6. Comparison of SEA for partially and fully wrapped aluminium tube.

Parameters of crashworthiness	Fully wrapped aluminium tube	Partially wrapped aluminium tube	Improvement (%)
SEA (kJ/kg)	23.04	26.46	14.84

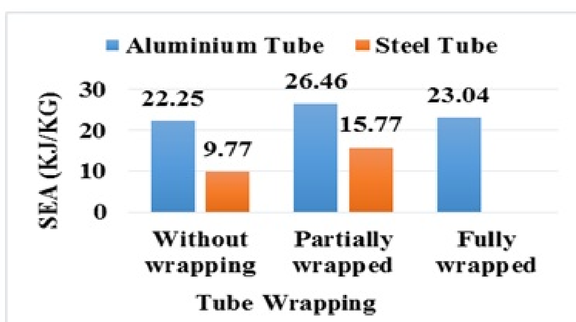

Figure-8. Energy absorption capability comparison among partially wrapped aluminium tube, partially wrapped steel tube and fully wrapped aluminium tube.

CONCLUSIONS

In this research, the failure modes of aluminium tubes without wrapped, partially wrapped and fully wrapped with glass and epoxy were investigated. Wrapping of aluminium tubes was performed to enhance energy absorption features. Furthermore, partial wrapping was done to achieve improvement in parameters of energy absorption. The results depicted that SEA for partially wrapped aluminium tube has 49.09% and 14.84% higher value as compared with partially wrapped steel and fully wrapped aluminium tube which will result in designing of light weight structures for energy absorption application in automobile as well as in aircraft. Moreover, quasi-static results revealed that parameters of energy absorption enhanced for partially wrapped and fully wrapped aluminium tubes as compared with aluminium tube without wrapping by composite. In addition to this, partially wrapped aluminium tube is more efficient in SEA and CFE as compared with partially wrapped steel fully wrapped aluminium tube owing to compound fragmentaion mode of failure. For future work parameters of energy absorption can be studied by applying low velocity impact and gap variation between composite layers.

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