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Experimental Study on Double-Walled Copper and Carbon/Epoxy Composite Tubes under the Axial Loading

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ABSTRACT

This paper investigates axial compression process of multi-layered tubes with circular cross-section under the axial loading in the quasi-static condition using experimental method. Some specimens are prepared in seven different groups, namely; empty carbon/epoxy composite tubes, solid carbon/epoxy composite rods, empty copper tubes, composite tubes with silicon sealant filler, concentrically solid carbon/epoxy composite rod and copper tube with silicon sealant-filler between them, double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them, and double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them and into the inner tube. For each test, diagrams of axial load-displacement and absorbed energy-displacement are sketched and also, specific absorbed energy by each specimen is measured. The experiments show that filling the copper tube with the composite tubes and also, filling the carbon/epoxy composite tubes with the silicon sealant increase instantaneous axial load and consequently, increase energy absorption capability of the structure. Then, comparing the experimental measurements in viewpoint of energy absorption capacity and specific absorbed energy, an optimum sample is introduced. Furthermore, the effects of geometrical characteristics of composite and copper tubes such as tube diameter and different filling conditions are investigated, based on the axial compression tests. The experiments show that absorbed energy of the circular copper tubes that are filled with the carbon/epoxy composite tubes is higher than sole copper tubes. Also, it is found that copper tubes have less absorbed energy per unit of mass, compared to the empty carbon/epoxy composite tubes and also, the filled composite tubes by the silicon sealant.

1. Introduction

Nowadays, vehicles are used extensively and a large number of horrible accidents related to them occurs everyday. Increasing the safety for passengers is a valuable aim and a lot of investigations are carried out in this region. Using energy absorbers is an appropriate option for this purpose [1].

Briefly, only the most important works on theoretical and experimental studies of axial and lateral crushing of thin-walled tubes are introduced here. Gupta et al. [2] performed experimental and computational investigations of deformation and energy absorbing behaviour of rectangular and square tubes made of aluminium and mild steel under lateral compression. Results show that between square and rectangular tubes of the same cross-sectional area, square tube absorbs more energy than the rectangular one. Niknejad et al. [3] investigated theoretical and experimental analyses on rectangular and square metal columns during the flattening process

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subjected to lateral compression load; based on the energy method, some theoretical formulas were derived to predict instantaneous lateral load, absorbed energy and specific absorbed energy by the columns as the functions of lateral displacement, geometrical characteristics, and material properties of the columns. Experiments show that lateral load and absorbed energy by a rectangular column that is compressed along the shorter edge are more than the corresponding quantities of the same column that is flattened along the longer edge. Also, Niknejad and M. Rahmani [4] introduced a new theoretical model of deformation and some new theoretical relations were derived to estimate instantaneous and lateral load mean of hexagonal columns during the flattening process in two different conditions, namely; empty and polyurethane foam-filled. Then, the effects of column length, edge length, column wall thickness and plateau stress of polyurethane foam were investigated on the flattening process of hexagonal columns. Hall et al. [5] investigated Al-foam filled and empty tubes of aluminium, brass and titanium under lateral compression test. Nemat-Alla [6] introduced a simple technique to identify stress–strain behaviour in the hoop direction for tubular material, based on experimental data obtained from the lateral compression test. Karamanos and Eleftheriadis [7] examined collapse of tubular members under lateral loads in the presence of pressure. Their work emphasized the effects of external pressure on ultimate load and energy absorption capacity. Morris et al. [8] investigated the quasi-static lateral compression of nested systems with vertical and inclined side constraints using numerical and experimental methods. Different variations of external constraints were used to increase energy absorption capacity of the nested systems. Numerical results were found to be well behaved and quite satisfactory in comparison with those of experiments. Fan et al. [9] studied deformation behaviour of sandwich tubes under quasi-static lateral crushing experimentally. Three major collapse patterns were clearly observed such as simultaneous collapse pattern, simultaneous collapse pattern with fracture of foam core, and sequential collapse pattern. White et al. [10] developed a theoretical analysis based on rigid-plastic assumption to describe collapse behaviour of top-hat and double-hat structures under the quasi-static axial loading conditions. In experimental and analytical studies of Schneider and Jones [11] on axial progressive collapse of spot-welded top-hat sections, no consistent reliability was obtained for predicting crush parameters for different geometries and materials with an analytical approach. Alavi Nia and Hamedani [12] investigated numerical and experimental deformations and energy absorption capacity of thin-walled tubes with various sectional shapes (circular, square, rectangular, hexagonal, triangular, pyramidal, and conical). The tubes had the same volume, height, average section area, thickness and material, and were subjected to axial quasi-static loading. The results of simulations were in good agreement with the experimental data and showed that the section geometry had considerable effect on their energy absorption. Niknejad et al. [13] presented a theoretical formula to predict instantaneous folding force of a polyurethane foam-filled square column as a single unit of square honeycombs under axial loading. Comparison of the results obtained from theoretical predictions with experiments shows that introduced theoretical relation predicts maximum value of crushing force in polyurethane foam-filled square columns with a good accuracy. Origami patterns were introduced to thin-walled tubes to minimize initial peak and subsequent fluctuations by Song et al. [14]. Tubes of square, hexagonal and octagonal cross-sections with origami patterns were investigated using finite element analysis. Abedi et al. [15] derived some theoretical relations to predict diagrams of absorbed energy and axial force versus axial displacement during the folding process in square and rectangular columns. Hong et al. [16] evaluated energy dissipation characteristics of multi-cell lattice tubes using experiments and theoretical analysis. According to their research, lattice tubes had a higher crushing force mean about 60-103%, compared with single-cell tubes; and lattice tubes had better energy absorbing capacity. Axial crushing behaviour of empty and aluminium close-cell foam-filled single aluminium tubes and aluminium multi-tube designs (hexagonal and square) were investigated through quasi-static compression testing by Guden and Kavi [17]. Effects of foam-filling on deformation mode and average crushing load of single tubes and multi-tube designs were determined. Salehghaffari et al. [18] experimentally investigated two new design methods to improve energy absorption characteristics of cylindrical metal tubes. They show that the developed design methods are efficient in improving crashworthiness characteristics of cylindrical metal tubes such as sensitivity to external parameters like loading uniformity and direction, crushing stability, crush force efficiency and collapse mode while subjecting to the axial compression. Palanivelu et al. [19] studied crushing behaviour and corresponding energy absorption capabilities of small-scale composite tubes. Nine different geometrical shapes with two different triggering mechanisms were considered for their study. Furthermore, effects of dimension on each geometrical shape were captured with two different thicknesses.

The objective of the present work is to investigate axial compression process of multi-layered tubes with circular cross-section under the axial loading in the quasi-static condition using the experimental method. During the investigation, the effects of geometrical characteristics of composite and copper tubes such as tube diameter as well as different filling conditions are investigated. The present article as a novelty investigates the effects of silicon sealant as the filler on copper tubes, composite tubes, and double-walled copper and composite tubes in viewpoint of energy absorption. Furthermore, solid carbon/epoxy composite rod is used as central core into copper tubes and carbon/epoxy composite tubes and influences of this core are studied on crashworthiness of the structure as a novelty of the present article.

2. Experiment

Seven different groups of specimens with different amounts of silicone sealant-filling were tested in quasi-static loading condition. To prepare the specimens, circular copper and carbon/epoxy tubes of different diameters and same thicknesses were used. The specimens were prepared in seven different categories, namely; empty carbon/epoxy composite tubes, solid carbon/epoxy composite rod, empty copper tubes, composite tubes with silicon sealant-filler, concentrically solid carbon/epoxy composite rod and copper tube with silicon sealant-filler between them, double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them, and double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them and into the inner tube. All the specimens of the present study were prepared in the same length. Table 1 gives geometrical characteristics of the specimens and Table 2 reports schematic top view of empty and silicone sealant-filled conditions of the specimens. All the axial tests were performed using a DMG machine, model 7166 at a constant cross head speed of 5 mm/min in the quasi-static condition.

Figure 1. (a) The specimen C.C-15 before and after axial test, (b) The specimen C-01 before and after axial test

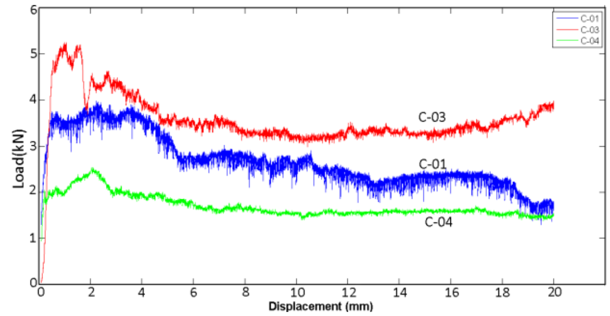


Figure 2. Comparison of load–displacement diagrams of empty carbon/epoxy composite tubes with different diameters

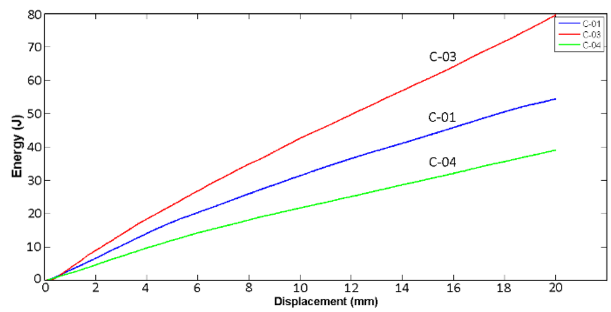


Figure 3. Comparison of energy–displacement diagrams of empty carbon/epoxy composite tubes with different diameters

3. Results and Discussion

In this section, effects of geometrical parameters such as diameter of copper and carbon/epoxy composite tubes and several filling conditions of the specimens by silicone sealant and their effects on energy absorption behaviour of the structure are investigated.

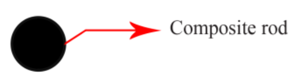
3.1. Effects of Carbon/Epoxy Composite Tube Diameter

Fig. 2 indicates load-displacement diagrams of three empty carbon/epoxy composite tubes with the same length and thickness and different diameters. Diameters of the specimens C-01, C-03 and C-04 are 10, 12 and 5 mm, respectively. According to Fig. 2, the specimen with the largest diameter has the highest instantaneous peak load in comparison with the others. Energy-displacement diagrams of these three specimens are shown in Fig. 3. Based on Fig. 3, it is found that when composite tube diameter increases absorbed energy increases too. It means that in empty carbon/epoxy composite tubes, by increasing tube diameter, total absorbed energy by the structure increases. For investigating silicon sealant-filled condition of carbon/epoxy composite tubes, Fig. 4 illustrates axial load-displacement diagram of the specimens C.F-05, C.F-06 and C.F-07

Table 1. Geometrical characteristics of the specimen

Specimens code	Composite tube diameter (mm)	Copper tube diameter (mm)	Specimens type	m (gr)	L (mm)
C-01	10	-	A	1.78	40
C.R-02	10	-	B	4.77	40
C-03	12	-	A	1.98	40
C-04	5	-	A	0.76	40
C.F-05	12	-	C	4.91	40
C.F-06	10	-	C	3.55	40
C.F-07	5	-	C	1.02	40
CP-08	-	19	D	17.09	40
CP-09	-	16	D	10.60	40
C.C-10	12	19	G	26.25	40
C.C-11	10	19	G	25.85	40
C.C-12	5	19	G	25.30	40
C.C-13	12	16	G	17.86	40
C.C-14	10	16	G	16.73	40
C.C-15	5	16	G	17.21	40
C.C.E-16	12	16	F	14.81	40
C.C.E-17	10	16	F	15.82	40
C.C.R-18	10	16	E	18.81	40
C.C.R-19	10	19	E	27.30	40

Table 2. Schematic top view of different specimens and their filling conditions

Specimen Type	Schematic Top View
A	
B	
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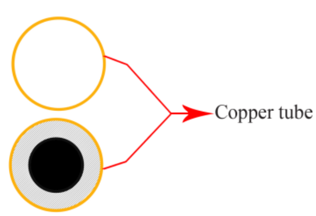
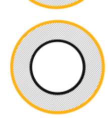
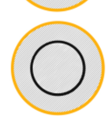
D E	
F	
G	

All the mentioned samples have the same initial length, tube wall thickness and filling conditions; but, their diameters are different. Fig. 5 shows diagram of axial compression load versus displacement of the specimens C-01 and C.R-02 with the same external diameter, in which, the specimen C-01 is a carbon/epoxy composite tube with wall thickness of 1 mm and the specimen C.R-02 is a solid carbon/epoxy composite rod. The figure indicates that by increasing tube diameter in the silicon sealant-filled condition of composite tubes, axial compression load enhances. As shown in Fig. 5, initial peak load of the specimen C.R-02 is almost three times bigger than the initial maximum load of the specimen C-01.

Experimental observations show that fracture occurs during the axial compression test on the solid composite tube and so, a sudden decrement is considered in axial load of the specimen C.R-02 in the graph. Also, Fig. 5 shows that energy absorption by the carbon/epoxy composite rod is more than the corresponding empty carbon/epoxy composite tube.

Specific Absorbed Energy (SAE) is a very important parameter in design of energy absorbers. Fig. 6 compares SAE of carbon/epoxy composite tubes with empty and silicon sealant-filled conditions as well as, a solid carbon/epoxy composite rod. The specimens C-01, 03 and 04 are empty carbon/epoxy composite tubes with the same initial length and tube wall thickness and with different diameters. Also, the specimens C.F-05, 06 and 07 are filled carbon/epoxy composite tubes with silicon sealant having different tube diameters and the same characteristics. The figure shows that in silicon sealant-filled condition of carbon/epoxy composite tubes, when tube diameter decreases, SAE by the structure increases, but, in empty composite tubes, there is an optimum diameter for tubes and an empty tube with optimum diameter has the highest performance, in viewpoint of the ratio of absorbed energy/mass. On the other hand, in the filled composite tubes, specimens with smaller diameters are better energy absorbers; but, in the empty ones, by increasing tube diameter, SAE of some cases decreases and SAE of some other cases increases.

The specimens C-04 and C.F-07 are the same tubes with different filling conditions of empty and silicon sealant-filled, respectively. There is a similar order between the empty and filled specimens C-01 and C.F-06 and also, between the specimens C-03 and C.F-05. The figures shows that in all the cases, when carbon/epoxy composite tube is filled with silicon sealant-filler, SAE of the structure decreases in comparison with the corresponding empty one. It means that in viewpoint of crashworthiness, an empty carbon/epoxy composite tube is preferred to the corresponding silicon sealant-filled composite tube. In other words, filling carbon/epoxy composite tubes with silicone sealant is not a suitable method to increase specific absorbed energy by the structure.

Also, Fig. 6 illustrates that specific absorbed energy by the solid carbon/epoxy composite rod C.R-02 is less than the corresponding values of most of the cases. It means that carbon/epoxy composite cylinder with hollow profile is preferred to the corresponding solid structure.

3.2. Effects of Copper Tube Diameter

Fig. 7 depicts load-displacement curves of the specimens CP-08 and CP-09. Both of the samples are made of copper with the same wall thickness and length, while having different diameters. Based on the fact that the area under the load-displacement curve indicates energy absorption of the specimen, the figure shows that copper tube with larger diameter has more energy absorption compared to the other one. Fig. 8 shows SAE of the two above mentioned specimens. According to the figure, it is found that in the studied cases, SAE increases by decreasing the copper tube diameter.

3.3. Copper Tubes Reinforced with Carbon/Epoxy Composite Tubes

The effects of tube diameter and different filling

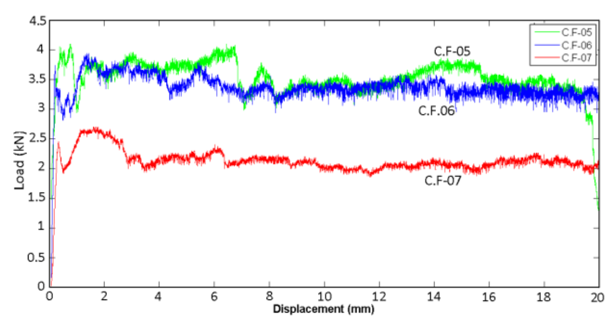


Figure 4. Comparison of load–displacement diagrams of silicone sealant-filled carbon/epoxy composite tubes with different diameters

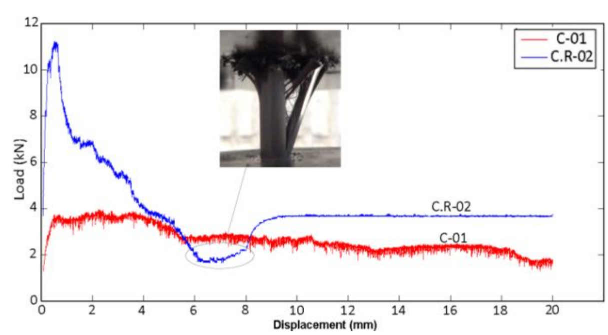


Figure 5. Comparison of load–displacement diagrams of an empty carbon/epoxy composite tubes and a carbon/epoxy composite rod

conditions on energy absorption behavior of the specimens are investigated.

3.3.1. Effects of Carbon/Epoxy Composite Tube Diameter

In the specimens C.C-10, C.C-11 and C.C-12, carbon/epoxy composite tubes with different diameters Are positioned concentrically into copper tube of 19 mm diameter and then both of them are filled with silicone sealant (type G in Table 2). Fig. 9 and Fig. 10 show load-displacement and energy-displacement diagrams of three above mentioned specimens, respectively. Comparison of the curves in Fig. 9 indicates that when diameter of composite tube reduces, axial load of double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them and into the inner tube increases. Also, Fig. 10 shows that absorbed energy by the specimens C.C-10, C.C-11 and C.C-12 are equal to 338.2, 268.5 and 222.6 J, respectively. It means that by increasing diameter of carbon/epoxy composite tube, energy absorption of the structure increases. On the other hand, when total absorbed energy is the main parameter in design of an energy absorber, smaller diameter of composite tubes into the cupper ones is suggested.

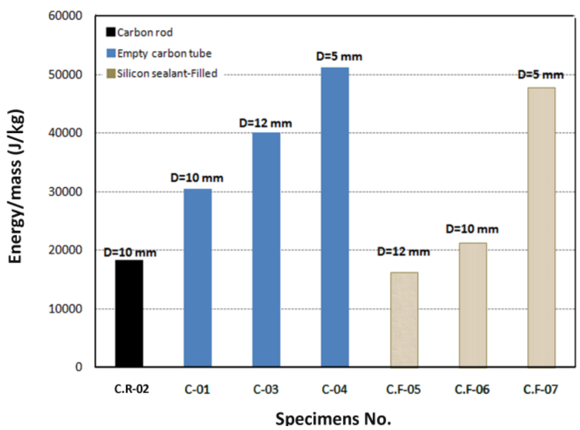


Figure 6. Comparison of SAE of empty and silicon sealant-filled carbon/epoxy composite tubes and also, carbon/epoxy composite rod

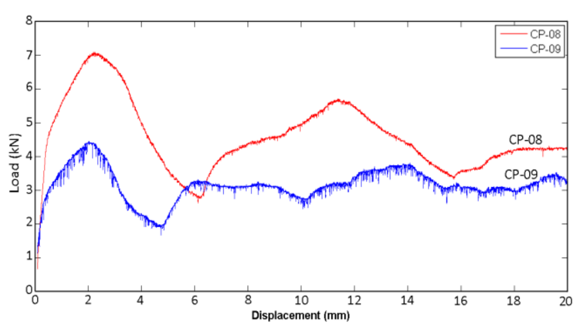


Figure 7. Comparison of load–displacement diagrams of empty copper tubes with different diameters

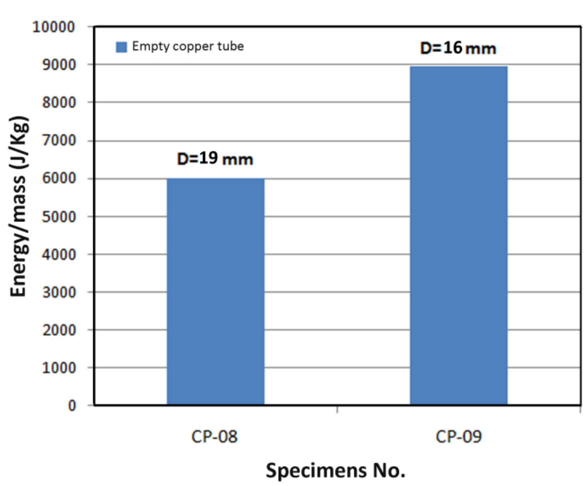


Figure 8. Comparison of SAE by the empty copper tubes with different diameters

3.3.2. Effects of Copper Tube Diameter

Load-displacement and energy-displacement diagrams of the specimens C.C-12 and C.C-15 are shown in Fig. 11 and Fig. 12, respectively. The figures indicate that in double-walled copper and carbon/epoxy composite tubes with silicon sealant-filler between them and into the inner tube (type G in Table 2), by enhancing copper tube diameter, axial load and energy absorption of specimens increase due to the higher volumes of silicon sealant-filler and copper tube material in the specimen C.C-12. Furthermore, Fig. 13 depicts an experimental comparison with SAE of the above mentioned specimens. As shown in the figure, it is found that when diameter of carbon/epoxy composite diameter reduces in the filled double-walled tubes with the same copper tube diameter, SAE decreases. Also, by decreasing copper tube diameter in the specimens with the same diameter of carbon/epoxy composite tube, SAE increases.

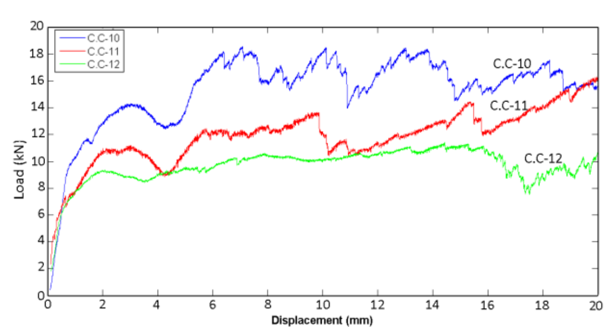


Figure 9. Comparison of load–displacement diagrams of copper tubes reinforced by carbon/epoxy composite tubes with different diameters

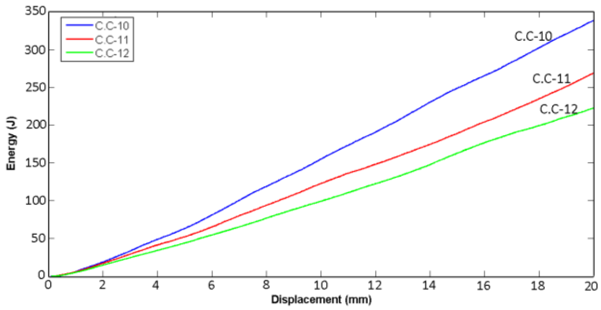


Figure 10. Comparison of energy–displacement diagrams of copper tubes reinforced by carbon/epoxy composite tubes with different diameters

It means that according to the ratio of absorbed energy/mass, filled double-walled structures with smaller diameter of copper tube and larger diameter of composite tube are suggested.

3.3.3. Effects of Filling Conditions

Load-displacement curves of the specimens C.C-13 and C.C.E-16 with the same geometrical characteristics are depicted in Fig. 14. The only difference between these specimens lies in filling condition, so that the specimen C.C-13 is filled by silicone sealant completely (type G in Table 2), but in the specimen C.C.E-16, the gap between the tubes is only filled by silicone sealant (type F in Table 2). By comparing the results in Fig. 14, it can be concluded that energy absorption of the specimen which is completely filled is more than the other one due to higher volume of silicon sealant-filler. SAE of double-walled copper and carbon/epoxy composite tubes with different filling conditions is shown in Fig. 15. The figure shows that in the specimens with the same copper and carbon/epoxy tube diameters, filling condition G (table 2) has more energy absorption than the filling condition F. On the other hand, in double-walled copper and carbon/epoxy composite tubes, when silicon sealant is used as the filler between the tubes and also, into the inner tube, a better energy absorber structure is obtained, compared to using silicon sealant-filler just between the tubes. Also, in Fig.15, two specimens C.C.R-18 and C.C.R-19 are compared. In both of the specimens, a solid carbon/epoxy composite rod of 10 mm diameter is used instead of carbon/epoxy composite tube. Diameter of copper tube in the specimen C.C.R-19 is larger than the copper tube in the specimen C.C.R-18. Comparison shows that, decreasing the copper tube diameter in concentrically solid carbon/epoxy composite rod and copper tube with silicon sealant-filler between them, leads to an increase in SAE of the structure.

Palanivelu et al. [19] perform some valuable experiments on nine different geometrical shapes of composite tubes in viewpoint of their quasi-static crushing performance to understand effects of geometry, dimension and triggering mechanism on progressive deformations of small-scale composite tubes. They manufacture different geometrical shapes of composite tubes by hand lay-up technique using unidirectional E-glass fabric (with single and double plies) and polyester resin. 144 quasi-static tests are conducted for all nine geometrical shapes with different thickness/diameter ratios (t/D) and two triggering profiles: 45^{o} chamfering and tulip pattern with an included angle of 90^{o}. Their experimental results [19] show that in composite samples with wall thickness of 1 mm, specific absorbed energies by all different geometrical shapes of composite tubes with two different triggering profiles except for a type of conical circular tube are in the range of 3630-17300 J/kg. Comparing the recently reported results by Palanivelu et al. [19] and numerical results of the present article in Fig. 15, it is found that specific absorbed energy by the specimen C.C.R-18 that is a concentrically solid carbon/epoxy composite rod and copper tube with silicon sealant-filler between them is almost 21000 J/kg and it is higher than specific absorbed energies by all eight types of different geometrical shapes of composite tubes with two different triggering profiles. It novelty of the present article in introducing solid carbon/epoxy composite rods as a central core into copper tubes, comparing with the previous published work by Palanivelu et al. [19].

Abedi et al. [15] investigate folding process of square and rectangular metal columns under the quasi-static axial loading and study effects of polyurethane foam-filler on energy absorption behavior of the columns. For this purpose, they introduce a new theoretical deformation model for column and the foam-filler and derive some equations for predicting instantaneous axial force versus displacement through the process, based on the energy method. Furthermore, they prepare some metal specimens with rectangular and square cross-sections and use them in the folding test between two rigid platens. Their experimental results show that during the axial compression of aluminium and brazen columns, energy absorption capability by metal columns increases through the folding progress due to the polyurethane foam-filler; but, at the commencement of the process, compression axial load increases from zero and when the load reaches a peak value, decremental trend starts. On the other hand, during the axial compression of metal columns, axial load has intensive variations through the process, and in viewpoint of energy absorption, it is an undesirable trend. But, the sketched curves in Fig. 4 show that silicone sealant-filler into the carbon/epoxy compo-

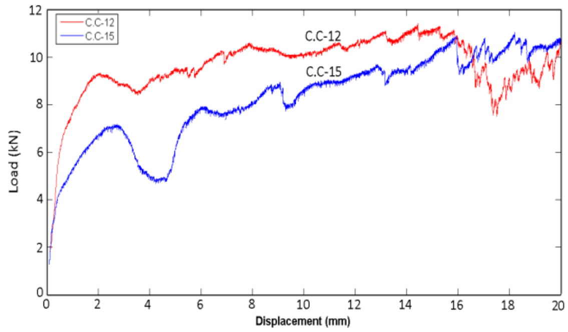


Figure 11. Comparison of load–displacement diagrams of copper tubes with different diameters reinforced by carbon/epoxy composite tubes with the same diameter

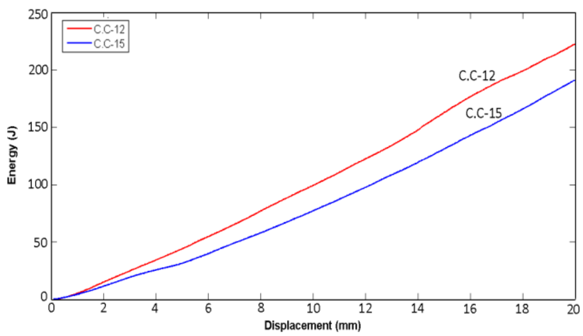


Figure 12. Comparison of energy–displacement diagrams of copper tubes with different diameters reinforced by carbon/epoxy composite tubes with the same diameter

site tubes causes an approximate constant load through the process. Constant load during plastic deformations is a valuable advantage of energy absorbers and the present work introduces the new filler of silicone sealant into the carbon/epoxy composite tubes with this valuable advantage during the axial compression between two rigid platens in the quasi-static condition.

4. Conclusion

Circular copper tubes reinforced with carbon/epoxy composite tubes were tested in the axial compression condition and their energy absorption capabilities were measured. Load–displacement and energy–displacement diagrams of the specimens were sketched and energy absorption was calculated per unit of mass.. The effects of different geometrical characteristics such as carbon/epoxy composite tube diameter, copper tube diameter and the effects of filling conditions were studied. The experiments showed that absorbed energy of circular copper tubes that were filled with carbon/epoxy composite tubes was higher than a sole copper tube.

Also, it is found that copper tubes have less absorbed energy per unit of mass, compared to corresponding empty carbon/epoxy composite tube and also, a filled composite tube by the silicone sealant. The present research suggests filled double-walled structures with smaller diameter of copper tube and larger diameter of composite tube by considering the ratio of absorbed energy/mass. Also, the experiments show that when silicon sealant is used as the filler between the tubes and also, into the inner tube in double-walled copper and carbon/epoxy composite tubes, a better energy absorber structure is obtained, compared to using silicon sealant-filler just between the tubes.

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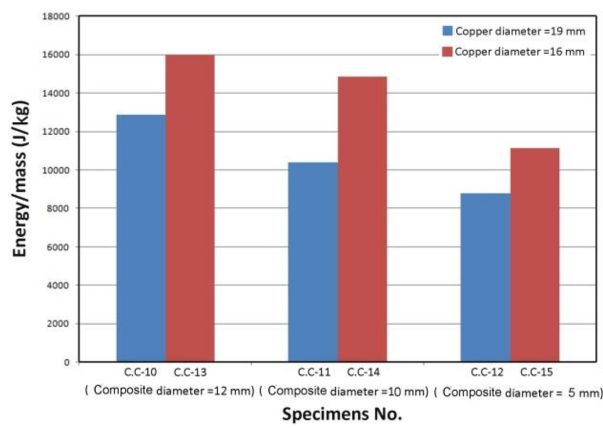

Figure 13. Comparison of SAE of reinforced copper tubes with carbon/epoxy composite tubes (type G in Table 2)

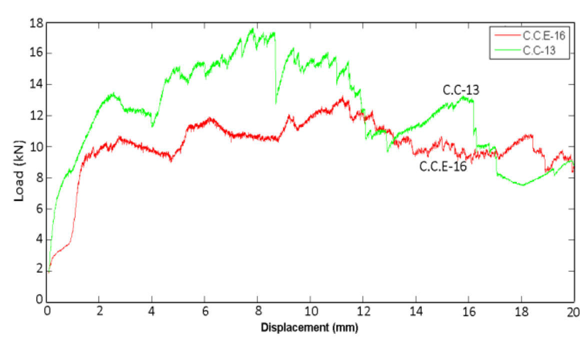

Figure 14. Load-displacement curves of specimens with the same geometrical characteristics and different filling conditions

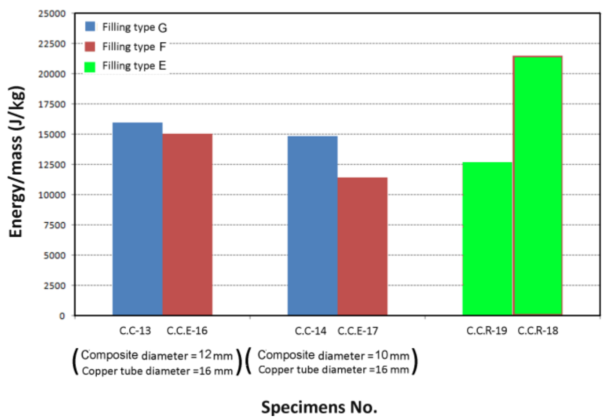

Figure 15. SAE of copper tubes reinforced with carbon/epoxy composite tubes by different filling conditions

References

[1] Mahdi E, Hamouda AMS. Energy absorption capability of composite hexagonal ring systems. Mater Des 2012; 34: 201–210.

[2] Gupta NK, Sekhon GS, Gupta PK. A study of lateral collapse of square and rectangular metallic tubes. Thin-Walled Struct 2012; 39: 745–772.

[3] Niknejad A, Elahi SM, Elahi SA ,Elahi SA. Theoretical and experimentalstudy on the flattening deformation of the rectangular brazenand aluminum columns. Archives Civil Mech Eng 2013; 13: 449–464.

[4] Niknejad A, M. Rahmani D. Experimental and theoretical study of the lateral compression process on the empty and foam-filled hexagonal columns. Mater Des 2014; 53: 250–261.

[5] Hall IW, Guden M, Claar TD. Transverse and longitudinal crushing of aluminum-foam filled tubes. Script Mater 2002; 46: 513–518.

[6] Nemat-Alla M. Reproducing hoop stress–strain behaviour for tubular material using lateral compression test. Int J Mech Sci 2003; 45: 605–621.

[7] Karamanos S, Eleftheriadis C. Collapse of pressurized elastoplastic tubular members under lateral loads. Int J Mech Sci 2004; 46: 35–56.

[8] Morris E, Olabi AG. Analysis of nested tube type energy absorbers with different indenters and exterior constraints. Thin-Walled Struct 2006; 44: 872–885.

[9] Fan Z, Shen J, Lu G. Investigation of lateral crushing of sandwich tubes. Procedia Eng 2011; 14: 442–449.

[10] White MD, Jones N, Abramowicz W. A theoretical analysis for the quasi-static axial crushing of top-hat and double-hat thin-walled sections. Int J Mech Sci 1999; 41: 209–233.

[11] Schneider F, Jones N. Observations on the design and modelling of some joined thin-walled structural sections. Thin-Walled Struct 2008; 46: 887–897.

[12] Alavi Nia A, Hamedani JH. Comparative analysis of energy absorption and deformations of thin-walled tubes with various section geometries. Thin-Walled Struct 2010; 48:946–954.

[13] Niknejad A, Liaghat GH, Moslemi Naeini H, Behravesh AH. Theoretical and experimental studies of the instantaneous folding force of the polyurethane foam-filled square honeycombs. Mater Des 2011; 32: 69–75.

[14] Song J, Chen Y, Lu G. Axial crushing of thin-walled structures with origami patterns. Thin-Walled Struct 2012; 54: 65–71.

[15] Abedi, MM, Niknejad A, Liaghat GH, Zamani Nejad M. Theoretical and experimental study on empty and foam-filled columns with square and rectangular cross section under axial compression. Int J Mech Sci 2012; 65: 134–146.

[16] Hong, W, Fan H, Xia Z, Jin F, Zhou Q. Axial crushing behaviours of multi-cell tubes with triangular lattices. Int J Imp Eng 2014; 63: 106–117.

[17] Guden M, Kavi H. Quasi-static axial compression behaviour of constraint hexagonal andsquare-packed empty and aluminum foam-filled aluminum multi-tubes. Thin-Walled Struct 2006; 44: 739–750.

[18] Salehghaffari S, Tajdari M, Panahi M, Mokhtarnezhad F. Attempts to improve energy absorption characteristics of circular metal tubes subjected to axial loading. Thin-Walled Struct 2010; 48: 379–390.

[19] Palanivelu, S, Paepegem WV, Degrieck J, Vantomme J, Kakogiannis V. Crushing and energy absorption performance of different geometrical shapes of small-scale glass/polyester composite tubes under quasi-static loading conditions. Composite Struct 2011; 93: 992–1007.