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On the axial crush performance of PVC foam-filled aluminum/CFRP hybrid circular tube

Muhammet Muaz Yalçın[1], Kenan Genel[*2]

Abstract

In this study, an experimental investigation was carried out to improve the energy absorption capability of the circular aluminum tubes. For this purpose, different specimen configurations such as polyvinylchloride (PVC) foam-filled, empty hybrid (strengthened with CFRP) and PVC foam-filled hybrid tubes were prepared and tested under axial compression. It is noted from the experiments that the contribution of foam filling maximized when it was used with CFRP together. The results revealed that energy absorption capacity (EAC) of the foam-filled hybrid tube was 2.7 times of the base tube. Moreover, the specific energy absorption (SEA) value enhanced almost 70% compared to that of the base tube and reached 34.9 J/gr.

Keywords: carbon fiber reinforced polymer (CFRP), hybrid composite, interaction effect, aluminum tube

1. INTRODUCTION

There is an ever-increasing interest in the development and utilization of a lightweight structure. In this respect, tubular structures are preferable due to their high strength with low weight, excellent ability to dissipate crash energy by a progressive deformation under the axial compression [1-5]. This interest has resulted in extensive researches on the tubular structures. Pugsley and Macaulay [1] presented an analytical study on the quasi-static axial crushing of circular tubes for axisymmetric and diamond deformation modes. Since then, the axial compressive behavior of different sectioned tubular structures was studied extensively over the last decade [2–4] and has been overviewed by Alghamdi [5].

The ratio of the energy absorption value of the tube to the mass is identified as the specific energy absorption which is often used as a significant measure in most of the studies. As a result, different kind of polymeric foams such as polyurethane (PU) [6], PVC [7], polystyrene (PS) [8] generally used as a filler material. Foams offer high stiffness and strength even with low density. In addition, foams can be fully compressed with almost the same force before the densification. Unlike foam filling tubes, Alia et al.

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experimentally investigated the tube reinforced PVC foam under different compressive conditions [9]. They reported that the foam filling offers superior properties for aluminum tubes compare to that of steel ones. It is reported for the embedded tube that the foam filling doesn't have any contribution to the energy absorption capability of the tubes. Using fibers for reinforcing the tubes is another way to enhance the crashworthiness of the tubular structure. Therefore different fiber types such as carbon [10–12] and glass [13,14] were used to wrap the tubes in a series of studies. It can be pointed out from the studies that the fiber reinforcing has a significant contribution to the tube wall stability even they increasing embrittlement in tubes. Bambach and Elchalakani [15] experimentally and analytically investigated the effect of CFRP strengthening on deformation process of tubes. They reported that empirical expressions for the plastic collapse were carried out and mean forces are compared well with the result of experiments.

The interaction between the strengthening materials and the tube is another important issue that most of the studies mentioned. It is revealed from the literature that the strengthened tube has higher absorbed energy compare to the summation of the values of the base tube and the strengthening material, separately. This situation is defined as the interaction effect and can be attributed to the contribution to the tube wall stability [16,17]. There are lots of studies on crashworthiness of the strengthened tubular structures and some of them referred briefly to the interaction effect [16,18–21].

The present study aims to improve the energy absorption capability of the aluminum tubes. For this purpose, aluminum tubes were filled with PVC foam and strengthened with CFRP. Different specimen configurations as foam-filled tubes, empty hybrid tubes (CFRP strengthened aluminum tube) and foam-filled hybrid tubes were conducted to axial compression test to evaluate energy absorption performance with respect to SEA.

2. EXPERIMENTAL STUDY

2.1. Material Properties

A6063-T5 aluminum alloy tubes were used for experiments of the present study. In order to determine the mechanical properties of the aluminum tube, the tensile test was carried out according to ASTM-E8/E8M-09 standard for pipes with a diameter higher than 25 mm. The mechanical properties of the aluminum tube are given in Table 1.

Table 1. Mechanical properties of the 6063-T5 aluminium tube

Yield strength (MPa)	Ultimate stress (MPa)	Young's modulus (GPa)	Poisson's ratio
188	212	69	0.33

80 kg/m^3 density of closed-cell PVC foam was used as a foam filler material. Cylindrical PVC foams with the diameter of 56 mm were machined by using CNC to accurate geometrical size. The axial compressive test was conducted to the cylindrical foam and the test result is given in Figure 1. Moreover, the scanning electron microscopy (SEM) examination was carried out to show the cellular structure of the foam. An extra sharp knife was used to cut and prepare PVC foams for SEM analysis. The machined cylindrical foams and SEM image of the foam are given in Figure 2. The approximate cell size of the PVC foam was calculated as 440 μm.

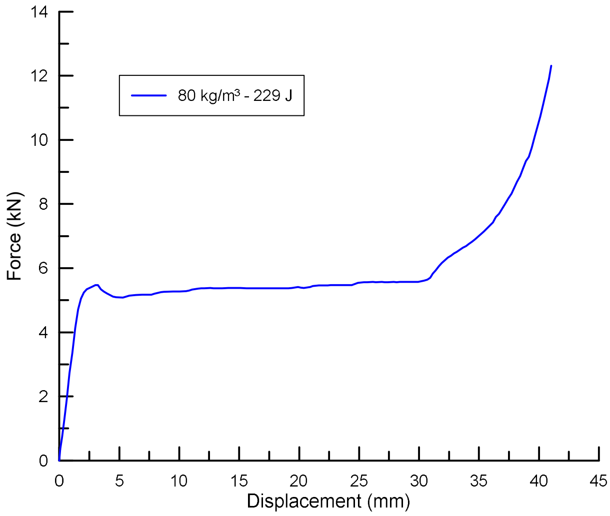

Figure 1. The force-displacement curve of the PVC foam

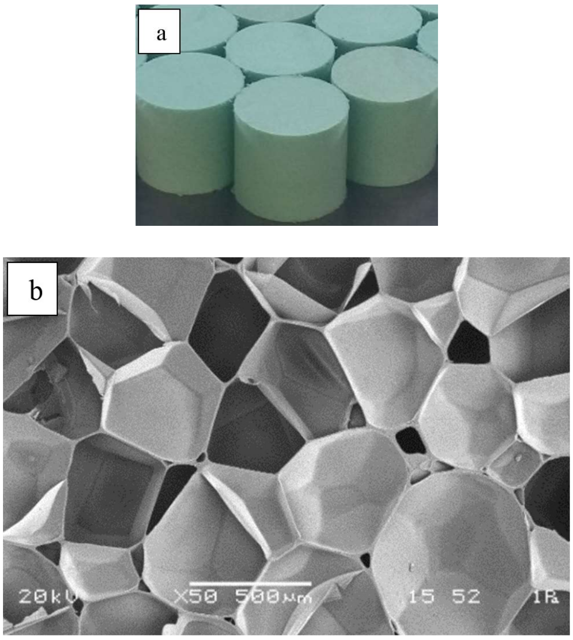

Figure 2. (a) Cylindrical PVC foam and (b) SEM image of the PVC foam

Carbon fiber fabric with a density of 200 g/m^2 was applied to the outside of the aluminum tubes with epoxy. The CFRP has nominally 340 MPa ultimate tensile strength and 42 GPa elasticity modulus. The thickness of the fabric is nominally 0.176 mm.

2.2. Specimen Preparation

The tubes were used in the experimental study have the following geometric properties diameter of 58.5 mm, the wall thickness of 1.25 mm and length of 50 mm. The hardness of all aluminum tubes was measured in the range of 70-72 HV. The commercial aluminum tubes have some imperfections in terms of tube wall thickness along the cross-section which may cause incompatibility of test results. Because of that aluminum tubes were machined both sides of inner and outer to eliminate the inhomogeneity of the wall thickness in cross-section (Figure 3).

Figure 3. Machining process of aluminum tubes

All CFRP reinforced aluminum were cured at least 6 hours at 60°C according to the manufacturer's instructions. Due to the importance of that the aluminum tube and the CFRP should be in contact with the loading platens at the same time, the ends of the hybrid tubes were minimally handed ground. Specimen configuration views of the base, PVC foam-filled, empty hybrid and PVC foam-filled hybrid composite tubes are represented in Figure 4.

Figure 4. Specimen configurations

The tests were performed on a compressive testing machine which has a capacity of 250 kN and 60 mm/min of crosshead speed and the force-displacement data pairs were recorded automatically. Moreover, all of the tests were recorded by a video camera. It is also important that at least three specimens were tested for each specimen combinations.

3. DEFORMATION MODES OF CIRCULAR TUBES

In general, a circular tube starts to deform from one of the ends and the deformation progressively proceeds. There are three different deformation modes for a circular tube namely, i) axisymmetric, ii) diamond and iii) mixed mode. Deformed tube images after axial loading in different modes are given in Figure 5.

Figure 5. Axisymmetric, diamond and mixed deformation modes of tubes (respectively from left)

Andrews et al. [23] and Guillow [18] examined the relation between tube geometry and collapse mode in an extensive range of L/D and D/t. It is deduced from their studies that the deformation would be in axisymmetric mode when D/t and L/D are lower than 50 and 2 respectively. The mix-mode would occur especially for the higher values of L/D. The mix-mode, starting in axisymmetric mode and turning into the diamond mode during the progressive deformation, is generally related to the geometrical imperfections of the tube [3].

A similar test program was carried out for aluminum tubes with different tube geometry to obtain the relationship between geometrical properties and deformation mode. In addition to the previous work, the hardness values of the tubes were also considered. Figure 6 shows a classification chart. It is seen from the chart that the changes in deformation modes with respect to D/t and L/D ratios. It is possible to say that there is a line at the value of L/D=2 which divide the chart into two regions. The axisymmetric mode was observed under this critical ratio. It is pointed out that the hardness has a significant effect on deformation, the tubes were fractured for the higher hardness values [3,18]. It is seen in Figure 7 that the aluminum tube with a hardness value of 75 HV was deformed without folding because of the higher hardness.

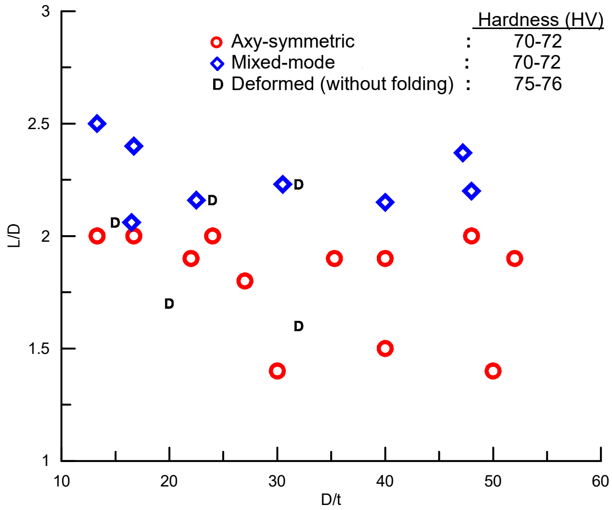

Figure 6. Deformation mode chart of aluminum tubes with different size

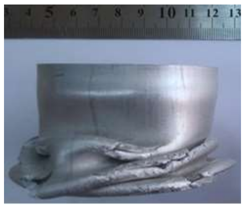

Figure 7. Fractured tube

4. RESULTS AND DISCUSSION

At least three experiments were performed for each specimen configurations. The force-displacement curve of the base tube, deformed in axisymmetric mode, is given in Figure 8. It is seen that the curve has a form that oscillates between high and low peak force values. These peak forces are directly related to the inwardly and outwardly movement of the tube wall and each upper peak forces (A-F) were associated with the formation of one fold. Soon after from application of the axial loading, an outward buckle, sometimes two buckles, was seen close to the top or/and bottom ends of the tube. Just before this buckles occurring, the force reached its highest value at point A. All of the other peak forces were lower than A which is because of that the tube was free of all deformations during the first fold formation. Soon after the first fold was completed, the formation of the second fold was already initiated by a local bending produced by the first fold.

Because of that, the other peak forces are lower than that of the peak force at point A.

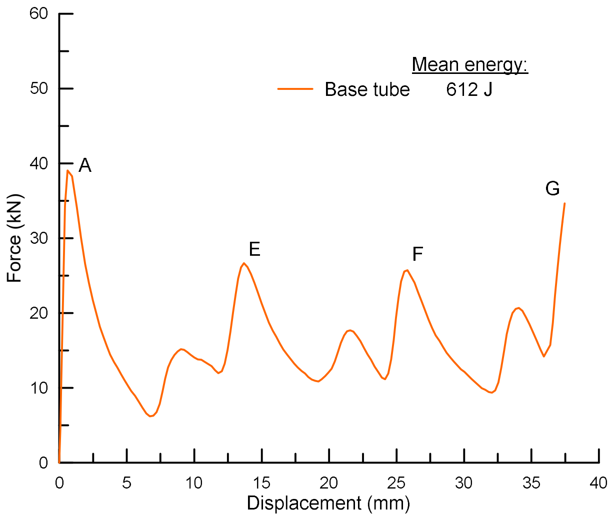

Figure 8 Force-displacement curve of the base tube (t=1.25)

The force-displacement curves of PVC foam-filled specimens are given in Figure 9 shows. It is deduced that foam filling has a decisive role in forces. All upper and lower peak forces were shifted up by foam filling and the specimens almost have the same oscillation form as that of the base tube. Although foam filling was caused an increase in the first peak forces about 6 kN compare to the base tube, the difference reached almost 10 kN for other upper and lower forces. This possibly a result of that the contribution of the foam material is limited at the beginning of the test. During the folding process, the severity of the interaction effect was increased (which is because of the inward movement of the tube wall) and as a result, it was enhanced the other peak forces. The mean absorbed energy value of foam-filled specimens was calculated as 951 J which is almost 55% higher than the base tube.

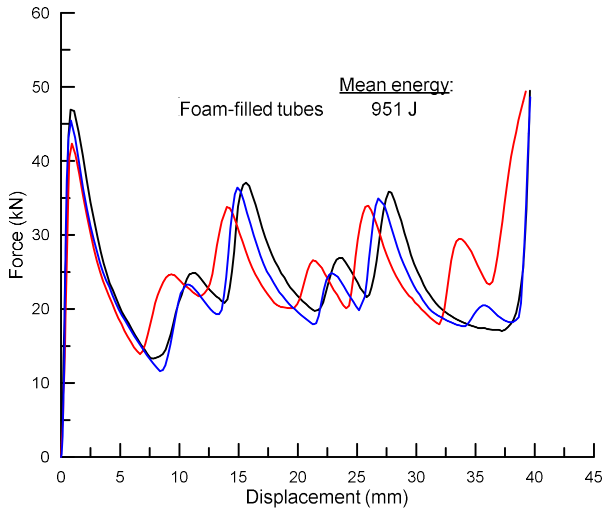

Figure 9 Force-displacement curve of foam-filled tubes

The force-displacement curves of empty hybrid tubes which were produced by reinforcing the aluminum tubes with CFRP are given in Figure 10. It is easily concluded that the CFRP reinforcement changed the oscillation form of the base tube. It is seen that the force-displacement curve, except the start and end parts, has a plateau-like behavior. The first peak force was increased by CFRP reinforcement almost 80% compared to the first peak force of the base tube. It is revealed that the CFRP reinforcement has a more significant effect on the first peak in contrast to foam filling. The absorbed energy of these specimens is almost twice of the base tube and 30% higher than that of the PVC foam-filled specimen.

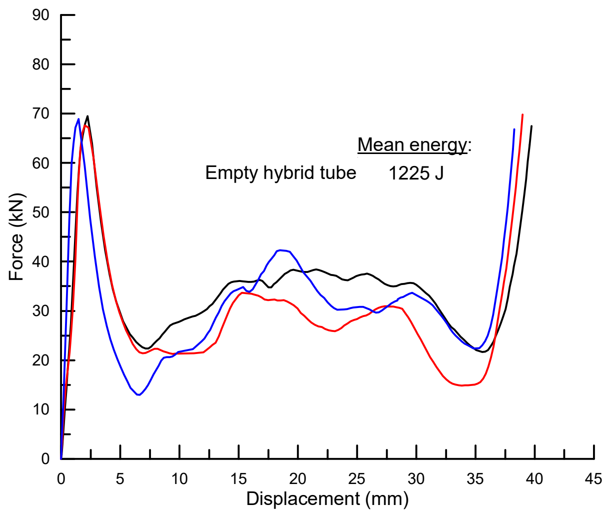

Figure 10 Force-displacement curve of empty hybrid composite tubes

The test results of the PVC foam-filled hybrid specimens under axial loading are represented in Figure 11. When the force-displacement curves are examined, though the characteristic form of the curve is quite similar there is an increase as 10 kN in the first peak force compared to that of empty hybrid tubes. As a result, it can be revealed that the contribution of foam filling was increased when it was used with CFRP reinforcement. When the absorbed energy values of the empty and foam-filled hybrid tubes are compared, it is obvious that the contribution of the foam has a remarkable effect on the energy absorption capability, as well. Foam filling enhanced the energy absorption capacity by almost 34%.

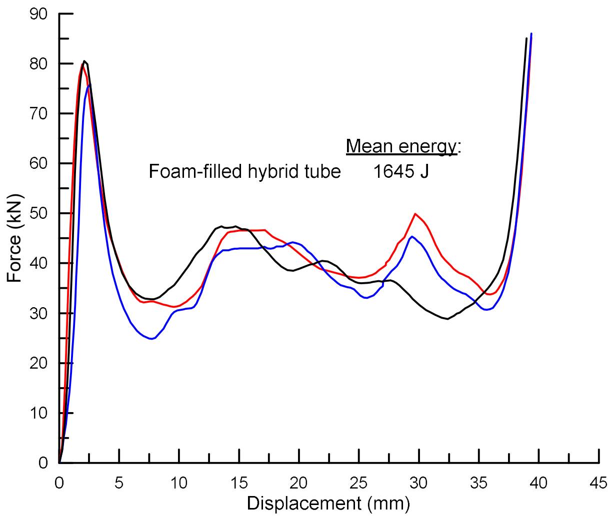

Figure 11. Force-displacement curves of foam-filled hybrid composite tubes

Deformed base tubes and other specimen configurations are given in Figure 12. It is clearly seen that the base tubes were deformed in axisymmetric mode and the mode was the same after foam filling. It can be pointed out that the deformation mode of the empty hybrid tube was changed into diamond mode from axisymmetric by CFRP reinforcement. This could be a result of the restriction of the outward movement of the tube which caused the tube wall tends to move inwardly and diamond mode occurs. The deformation mode was turned into axisymmetric mode again in foam-filled hybrid tubes by foam filling (Figure 13) [2].

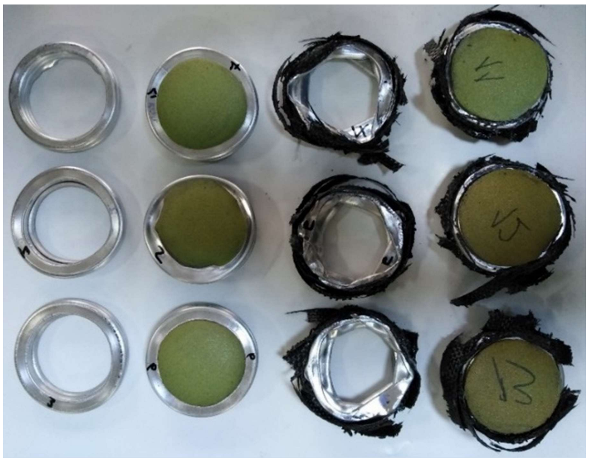

Figure 12. Specimen views after test

Figure 13. Changes in deformation modes with different reinforcement materials

4.1. The Interaction Effect

The interaction effect between the tube wall and the foam filler is examined in this section. It is known from the literature that the energy value of the foam-filled tube is higher than the sum of energy values of the base tube and the foam individually. To clarify how the foam filling contributes to the absorbed energy, a graph is given in Figure 14. The difference in absorbed energy is a result of the complex interactions between the tube wall and the foam filler. It is pointed out from the literature that, the wall stability is directly related to these interactions and efficiency of interactions depends on especially the density and type (metallic, polymeric) of the foam [23,24].

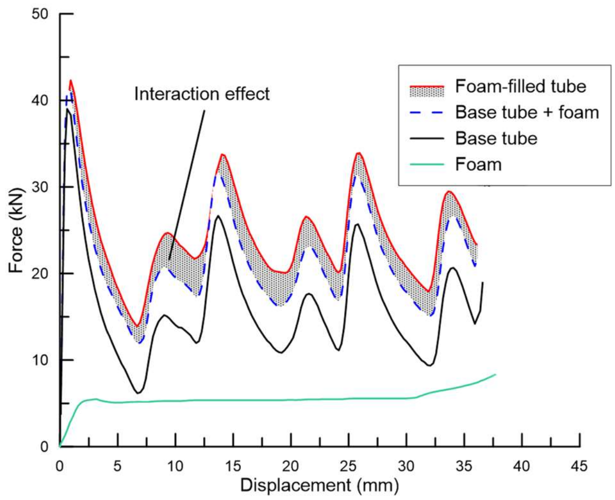

Figure 14. The interaction effect between foam filler and tube by means of absorbed energy

The detailed contributions provided by different strengthening materials such as PVC foam and CFRP is given in Figure 15. It is possible to say that the CFRP strengthening is more effective on absorbed energy than that of foam filling even though it changes the folding mode of the base tube. It is also seen that the contribution of the foam is higher in hybrid specimens compare to that of the base tube. It is because of that the outward movement of the tube wall is restricted in the hybrid tubes which, unlike the base tube. As a result, the tube wall tends to penetrate to the foam filler more than that of the tube without any restriction.

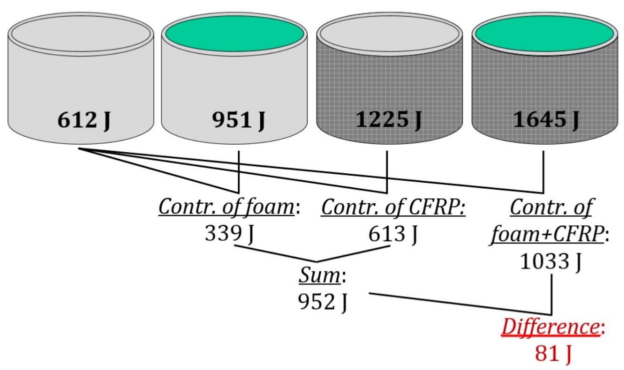

Figure 15. The contributions of reinforcement materials to the absorbed energy

The SEA capabilities for all specimen configurations were calculated. The SEA values were calculated by dividing the energy to the mass and given in Table 2. The results indicate that the foam-filled hybrid structure offers the most effective strengthening model. The SEA of the foam-filled hybrid composite tube was increased by 70% compared to that of the base tube. It is also possible to say that the SEA would obtain higher by using longer tubes.

Table 2. The SEA values of different specimen configurations

Specimen configuration	Energy (J)	Mass (gr)	SEA (J/gr)
Base tube	612	29.9	20.47
Foam-filled	951	40.5	23.48
Empty hybrid	1225	36.7	33.20
Foam-filled hybrid	1645	47.1	34.93

5. CONCLUSIONS

In this study, the EAC and deformation behaviors of the PVC foam-filled aluminum (6063-T5) and hybrid tubes were investigated. For the base tube, the absorbed energy was calculated as 612 J in the axisymmetric mode which was as the same for the foam-filled specimen. Although the hybrid tubes changed the deformation mode from axisymmetric to diamond, it had a significant effect on EAC value. It was also another important point that the improvement in EAC was obtained with lower mass increase compare to that of foam-filled tubes for the hybrid tubes. As a result, the empty hybrid tubes (33.2 J/gr) offered higher SEA values than the foam-filled ones (23.5 J/gr). It is expected that the longer foam-filled hybrid tubes would offer higher EAC and SEA values and they could be used as effective energy absorber devices.

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