Modelling of Energy-absorbing Behaviour of Metallic Tubes Reinforced Polymer Foams

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Abstract

This paper presents the findings of a research study investigating the energy-absorbing characteristics of polymer foams reinforced with steel and aluminium tubes. Initial attention focused on establishing the influence of tube diameter on the specific energy absorption (SEA) and the failure characteristics of the tubes. In the next stage of the investigation, the tubes were embedded in a range of polymer foams in order to establish the influence of foam density on the crush behaviour of these lightweight structures. The specimens were tested under quasi-static tests at a loading rate of 1mm/minute and the numerical analysis has been performed by using Abaqus software that was validated against the experimental results. The numerical metal tubes and foams were subjected to axial quasi-static loading similar to the experimental condition. The simulation results indicated that failure response of polymer foams reinforced by metallic tubes under quasi-static axial compression were in good agreement with the experimental results.

Keywords: Energy absorption, Numerical analysis, Quasi-static, Aluminium, Steel, Foams, Failure mechanisms.

Introduction

In recent years there has been an increased occurrence to develop high speed, energy-efficient transport systems. One of the important aspects to be improved in crashworthiness is the ability to absorb the impact energy during a crash. A considerable amount of research has thus been undertaken to develop effective impact energy absorption systems for use in high speed vehicles. The key approach of strengthening a structure is to dissipate the crush energy in order to prevent injuries and reduce damages. The metallic tube structures subject to buckling under axial loading are excellent for this purpose due to their low cost, easy fabrication, and high efficiency in absorbing energy. Extensive investigations previously carried out have revealed that various parameters, such as material properties, cross-sectional geometries, diameter to thickness ratio and the loading condition can affect the energy absorption capability of metallic tubes [Alexander (1960); Jones (2010) and McGregor et al. (1993)]. During the crush of metallic tubes, this energy is mainly absorbed due to the irreversible plastic deformation mechanisms that dominate the buckling process.

Several experiments on the impact of thin-walled tubes of circular and square cross section with different sizes have been performed by Jones [Jones (2010)]. Jones has observed that a circular shaped tube is the most efficient geometry in absorbing energy. Alexander developed theoretical study on the calculation of mean collapse load for circular tubes in concertina collapse mode [Alexander (1960)]. In another study on the effect of strain rate, McGregor et al. [McGregor et al. (1993)] found that strain rate effect on the mechanical properties is insignificant in the range of velocity 7–9 m/s. A number of recent researchers have investigated the axial crushing of circular aluminum tubes by conducting experimental and numerical modelling [Pled et al. (2012); Al Galib and Limam (2004) and Karagiozova et al. (2005)]. Pled et. al [Pled et al. (2012)] has reported that the boundary conditions will influence the crushing mode of circular aluminium tubes. Although a considerable amount of studies has been dedicated to study the crushing of thin walled tubes with different materials or geometries, little attention has been focused on the research of the using metallic tubes as reinforcement for foams in sandwich structures. This paper studies the numerical simulation of the axial crushing of metal circular tubes for use in lightweight energy-absorbing structures. The final section of this paper verifies the results between experimental data and numerical analysis.

Experimental Procedures

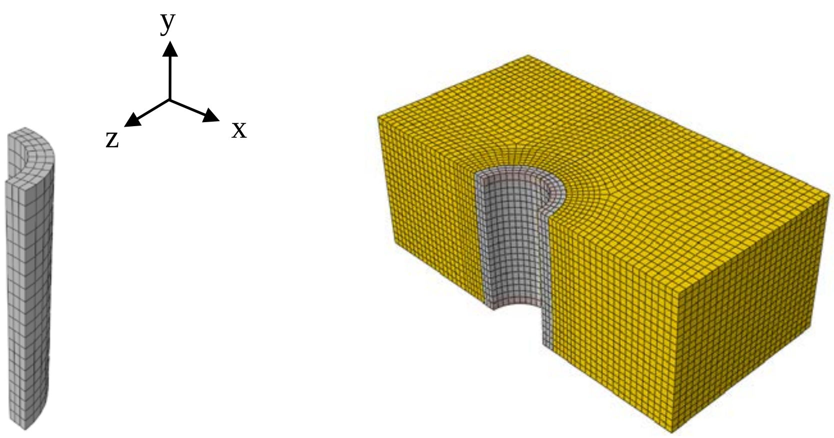
The primary aim of this research study was to investigate the energy-absorbing characteristics of tube-reinforced foams, similar to that shown in Fig. 1b. However, prior to testing the reinforced foams, attention focused on establishing the influence of the geometry of the individual metal tubes on their resulting energy-absorbing characteristics. The effect of varying the ratio of the inner diameter of the tube to its thickness, D/t, on energy absorption was then investigated by conducting compression tests on a range of aluminium and steel tubes, details of which are given in Table 2. Here, three different sizes of tubing were considered, with outer diameters ranging from approximately 12.6 mm to 25.4 mm. The values of D/t for the tubes ranged from 5.2 to 13.1 for the aluminium alloy tubes and 5.5 to 13.1 for the steel tubes. Prior to testing, the tubes were cut to a length of 20 mm and ground at both ends to ensure that they were parallel.

Crushing tests were conducted on individual tubes using an Instron 4505 universal test machine. Each test was undertaken at a crosshead displacement rate of 1 mm/minute and interrupted when the tube was fully crushed, i.e. to a point beyond which the force started to increase rapidly. The specific energy absorption (SEA) of the tubes was then determined by dividing the energy under the load-displacement trace up to densification (bottoming-out displacement) by the mass of the sample.

Individual tubes were then embedded into crosslinked PVC foams with densities ranging from 38.3 to 224 kg/m^3. Details of the tubes embedded into foams samples are given in Table 3. In preparation for these tests, a 12.6 mm diameter hole was drilled into a 50 mm square block of thickness 20 mm and either a steel or aluminium tube with an outer diameter of 12.6 mm and a length of 20 mm, was inserted into the hole. The tube/foam combinations were subsequently loaded in compression at a crosshead displacement rate of 1 mm/minute.

Finite Element Modelling

Finite Element models were developed using the commercial finite element Abaqus software package to simulate the crushing of metal tubes individually and embedded in foams. Here, quarter model of the structures were constructed as the structures are symmetrical in x-axis and z-axis as shown in Fig. 1a. A series of three aluminium and three steel circular tubes with diameters ranging from 12.62 mm to 25.40 mm and 20 mm height were simulated. The details of tubes are shown in Table 2. The tubes were modelled by using 8-node 3-D deformable solid and were extruded to a length of 20 mm in y-direction. Two square plates of 30 mm x 30 mm x 1mm were created to represent the upper and lower platen. The square plates were initially defined as 3-D discrete rigid and converted to shell elements. A reasonable mesh size of 1 mm and three elements through the thickness were defined for the tube models. In the latter stage of this research program, one metal tube of 12.62 mm was inserted into three foam materials with densities of 38.3, 90.4 and 224 kg/m^3. The foam materials were modelled as 8-node 3-D deformable solid and the mesh size used was the same as tubes which is 1 mm.



(a) (b)

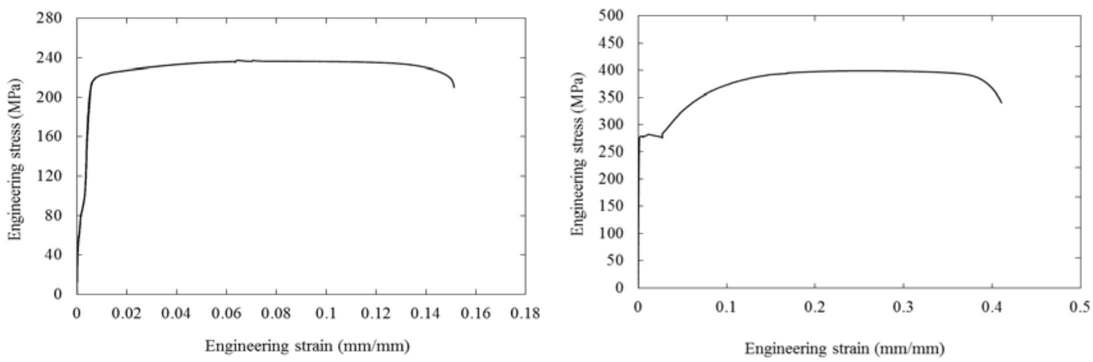
Figure 1. A quarter model of a tube and the cross-section view of a 12.62 mm metal tube in a foam block.

The isotropic elastic-plastic material model has been assumed as the mechanical properties of the metallic tubes. The mechanical properties of these metals are presented in Table 1 and their plastic stress-plastic strain diagrams are illustrated Fig. 2. The plastic yield stress and strain values were obtained from the true stress-true plastic strain curves of the metals. The foams were modelled by using crushable foam plasticity definition that was developed by Deshpande and Fleck (Deshpande and Fleck 2000). The mechanical material properties of foams were obtained from stress-strain curve of the foams. To yield accurate numerical results, it is important to define the required interactions of the structure to prevent interpenetration during the crushing process. Firstly, the top and bottom surfaces of the structure were selected to interact by Surface-to-surface definition. Next, the self-interaction between tube surfaces to itself was defined. This was done by selecting the General Contact option and allowing the outer tube surface to interact with itself.

For the next stage of simulation, a metal tube was embedded in foam, the interaction between tube and foam has to be considered. In the same General Contact option, the contact interaction of tube and foam surfaces was defined. The friction coefficient was set to 0.1 for all contact surfaces between tube and foam [Pled et al. (2012)]. In all simulations of axial crushing, the bottom plate was fixed to be stationary. The axial crushing of the structure was done by moving the top rigid platen in downward direction but constrained in all other degrees of freedom. The top and bottom end of the sample were set to be free to deform in all directions.

Table 1. Mechanical properties of metals.

Property	**Aluminium Alloy 6063-T6**	**Mild Steel**
Density, ρ [kg/m^3]	2543	7966
Young's modulus, E [GPa]	70.4	200
Yield stress, σ [MPa]	218	277
Tensile strength [MPa]	237	399
Poisson's Ratio, υ	0.33	0.33



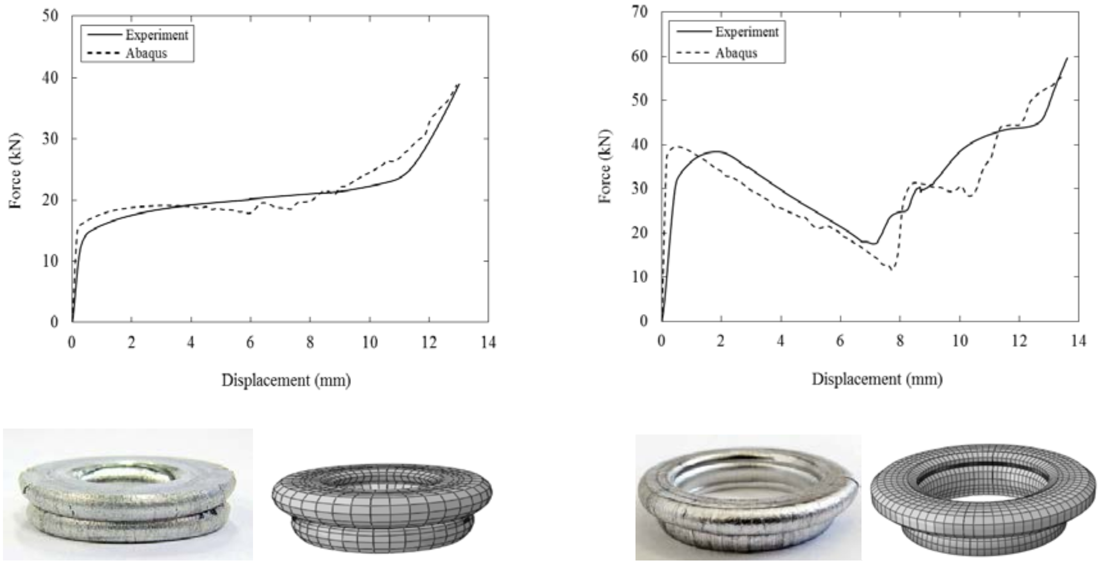
(a) (b)

Figure 2. Engineering stress-strain curve following a tensile test on (a) 12.62 mm diameter (D/t = 5.21) aluminium tube and (b) 12.62 mm diameter (D/t = 5.51) steel tube.

Results and Discussion

The initial part of this investigation focused on understanding the influence of tube diameter on the energy-absorbing characteristics of the individual metal tubes. The experimental axial crush of tubes results was compared to verify the presented finite element Abaqus modelling. Fig. 3 shows the typical experimental and Abaqus simulation load-displacement traces following compression tests on 20 mm long aluminium tubes having different D/t ratios. From the two graphs, it is clear that the simulation exhibits very close results of load-displacement to the experimental curves. It is evident from the compressed tubes in both experimental and simulation that the tubes deformed by forming two rings which is known as concertina failure mode. This asymmetric failure mode was also observed by Al Galib and Limam [Al Galib and Limam (2004)] for crushing of A6060 Aluminum tubes.

Table 2 shows the variation of SEA with the tube D/t ratio for both the aluminium and steel tubes. The energy-absorbing characteristics of the aluminium tubes have been shown to be superior to those of their steel counterparts. Here, it is also clear that the energy-absorbing capability of the tubes decreases rapidly with increasing D/t. The specific energy absorption obtained from Abaqus simulation results are very close to the experimental results with percentage of difference ranging between 1.2 to 9.7%.



(a) **(b)**

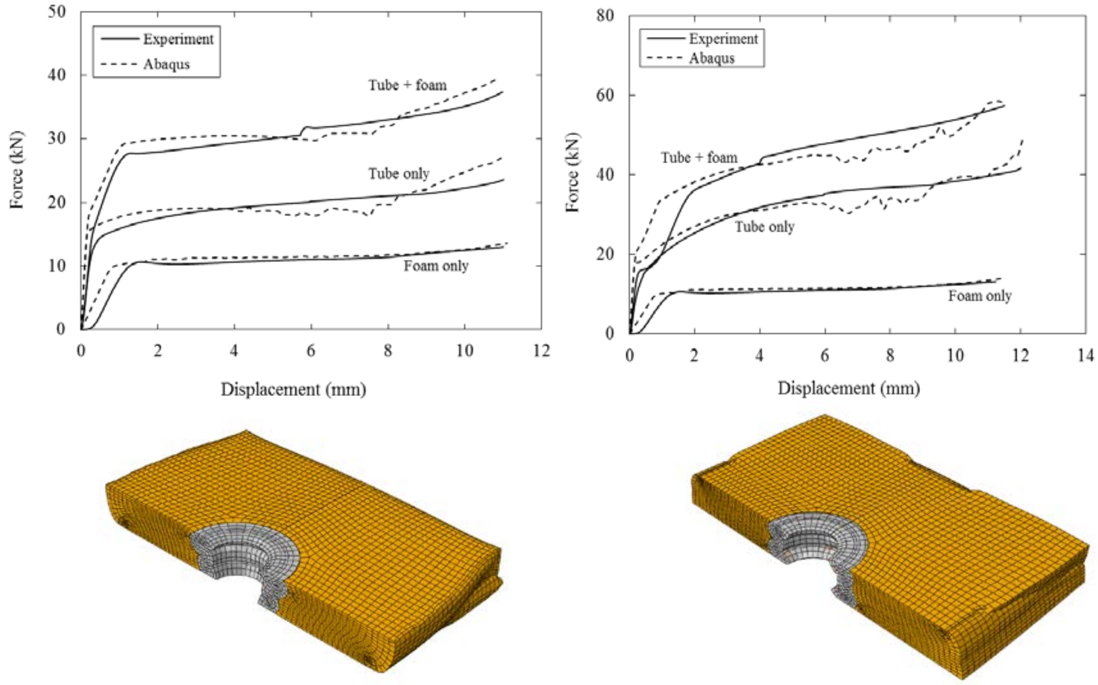
Figure 3. Load-displacement traces and the deformed aluminium tubes from experimental and Abaqus simulation results of (a) 12.62 mm diameter (D/t = 5.21) and (b) 25.40 mm diameter (D/t = 13.12).

Table 2. Summary of the geometrical and specific energy absorbing characteristics of the 20 mm long aluminium and steel tubes.

Specimen ID	Outer diameter, D_o (mm)	Inside diameter, D (mm)	Thickness, t (mm)	D/t	Experiment SEA (kJ/kg)	Abaqus SEA (kJ/kg)	Experiment to Abaqus (%)
Alu12	12.62	9.12	1.75	5.21	70.07	70.89	1.2
Alu16	16.00	12.36	1.82	6.79	63.47	57.96	8.7
Alu25	25.40	22.04	1.68	13.12	52.96	48.08	9.2
Ste12	12.62	9.26	1.68	5.51	41.46	40.75	1.7
Ste16	15.78	12.42	1.68	7.39	36.94	33.50	9.3
Ste25	25.40	22.04	1.68	13.12	24.12	21.78	9.7

The next stage of this study discusses the energy-absorbing characteristics of foams reinforced with relatively thick metal tubes tested at quasi-static loading. Tubes with low values of D/t (and therefore higher values of SEA) were embedded in a range of polymer foams with a view to developing lightweight energy-absorbing structures.

Fig. 4 shows the load-displacement traces and the compressed tubes embedded in PVC C70.200 foam for aluminium and steel tubes. As before, the aluminium-based systems offered superior properties to the steel-based materials. It has been shown that the foam does not modify the energy-absorbing capability of the embedded tubes. The traces from the Abaqus simulation agreed well with the experimental results. It shows that the load-displacement of tubes embedded in foams is resulted from a direct combination of forces from tubes and foams compressed individually.



(a) **(b)**

Figure 4. Load-displacement traces and the deformed 12.62 mm diameter tubes embedded in C70.200 foams from experimental and Abaqus simulation results for (a) aluminium and (b) steel.

Table 3. Summary of the SEA following tests on the 20 mm long (diameter = 12.62 mm) of aluminium and steel tubes with foam densities.

Specimen ID	**PVC Foam**	**Foam Density (kg/m^3)**	**Experiment SEA (kJ/kg)**	**Abaqus SEA (kJ/kg)**	**Experiment to Abaqus (%)**
Aluf40	C70.40	38.3	68.43	71.49	4.5
Aluf55	C70.55	56.0	68.56	70.74	3.2
Aluf200	C70.200	224.0	69.50	70.40	1.3
Stef40	C70.40	38.3	41.2	40.3	2.1
Stef55	C70.55	56.0	43.1	42.5	1.4
Stef200	C70.200	224.0	40.2	43.1	7.3

Conclusions

Finite element simulations of the crushing of individual metal tubes and metal tubes embedded into foam materials have been carried out. Initially, the influence of tube diameter (D/t) parameter on the specific energy absorption of empty tubes has been numerically investigated. Similar post-buckling deformation shapes to experimental observations have been successfully predicted by using Abaqus software. Abaqus simulation predictions were observed to be consistent with the experimental results. Given that the metal tubes absorb much greater levels of energy than the foams in which they are embedded, the density of the latter should be set as low as possible, ensuring that the metal reinforcements are held in place during the loading process. The experimental and numerical evidence suggests that it should be possible to predict the energy-absorbing capacity of multi-tube systems using a simple rule of mixtures approach based on the mass fractions of the tubes and the foam. The finite element simulations, once they are validated against experimental results, provide excellent tools to further study crushing characteristics of foams embedded with metal tubes.

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