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Investigating the density of Polyurethane foam on crashworthiness and energy absorption parameters in foam filled tubes under axial quasi-static loading

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ABSTRACT

Thin-walled tubes can avoid the transition of injurious acceleration and excessive forces to the protected section and minimize the damage severity. They absorb energy under axial loading circumstances as crashworthiness structures. The present study deals with the investigation of the density effects of foam on the quasi-static loading response of foam filled and empty cylindrical tubes. To investigate energy absorption parameters by varying in foam density, two different densities of polyurethane foam were used to evaluate the efficacy of polyurethane foam density under axial quasi-static loading**.** According to the results, the use of foam as a filler also influences the tubes' deformation behavior in addition to the effects of thickness. It was revealed that by incrementing the thickness to 20%, the peak load increased by 25.2%. Two densities of foam were considered as 40 and 85kg/m3 to assess the effect of density of polyurethane foam as filler on the energy absorption behavior of tubes under axial loading. Result showed that when foam density increased by about two times, the peak load increased by 1%. According to the results, filling tube by foam also influences the tubes deformation behavior in addition to the effects of thickness

1. Introduction

Thin-walled tubes can absorb energy under the crash impact circumstances as crashworthiness structures. They can also avoid the transition of injurious acceleration and excessive forces to the protected section and minimize the damage severity [1]. Therefore, during the last 20 years, several studies have been performed on the tubes and the performance of tubes under axial impact because they absorb impact energy by deformation under axial compressive loads. Moreover, they are used for the crashworthiness and safety of the vehicles [2-5]. However, exposing the empty tubes to other types of loadings, the buckling mode as such as Euler-type buckling may be undesirable. Using lightweight materials like polymeric and metallic foam, tubular structures are filled to improve their crashworthiness [6-8]. The axially

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impacted structures specifically foam filled tubes are briefly explained in the following.

An experimental investigation was performed by Li et al. [9] on the crashworthiness of circular and square empty aluminum alloy and foam filled tubes under axial compression at quasi-static loading. They compared various parameters associated with their crashworthiness. They proposed the double and single circular Foam filled tube as crashworthy structures since they have energy-absorbing efficiency and higher crush force. In the experimental study of Hussein et al. [10], the axial crushing performance was investigated on the square hollow aluminum tubes, polyurethane foam filled aluminum tubes, honeycomb aluminum filled tubes, and aluminum tubes occupied with both aluminum honeycomb and polyurethane foam under quasi-static compressive loads. It was indicated that for square hollow aluminum tubes a progressive folding was the deformation mode. However, splitting mode was occurred for square tubes occupied with both aluminum honeycomb (ALH) and polyurethane foam. They revealed the most crashworthy combination as ALH and polyurethane foam filled aluminum tubes with square cross section compared to the hollow tubes. In these tubes, the maximum increase in energy absorption means crushing force. The mechanical features of foam filled auxetic tubes in axial compression were studied by Ren et al. [11]. Filling the rigid polyurethane (PU) foam into the hollow auxetic tube (FFAT), enhanced the energy absorption. They numerically assessed tubular types and the impacts of parameters such as ellipticity, and wall thickness FFATs. According to the results, the FFAT has higher overall absorbed energy than the summation of hollow auxetic tubes and single foams under compression. Padmaja et al. [12] experimentally studied empty and circular polyurethane foams-filled aluminum as well as light gauge square steel tubes at quasi-static axial compression tests. They experimentally examined the high-density polyurethane foam and empty tubes and Polyurethane foam filled tubes for quasi-static compression in axially loading. Through numerical simulation, they validated the findings. Based on the FEM and experimental results, the mean crushing loads were calculated for square steel tubes and polyurethane foam filled and hollow circular Aluminium. It was revealed that the resistance to buckling was significantly improved as a result of composite action between foam and tube, in comparison to empty tubes. Annamalai and Balaji [13] Investigated numerically the effect of physical parameters of honeycomb on crashworthiness on aluminum honeycomb filled high strength steel crash box. They showed thickness and cell size of honeycomb effect on energy absorption parameters under impact. Zarei and Nazari [14] investigated the crashworthiness of tubes filled with gradient foams. They studied experimentally and numerically behavior of filled square tubes by ALPORAS foam and empty same tube to investigate the energy absorption and demonstrated that the crashworthiness of the tubes modified by using gradient foam as filler. Raouf et al. [15] discussed the crashworthiness Parameters of Steel cylindrical shells filled with polyethylene under axial quasi-static compression and showed that the use of polyethylene filler in the filled samples causes a decreasing in the initial maximum crushing force values, an increasing in the average crushing force values and also a decreasing in energy absorption compared to the empty samples. Khalkhali et al. [16] presented a model for prediction crashworthiness parameters of composite cylinder tubes. By using data from FE modeling, they developed two meta-models which can be used to predict the energy absorbtion and the maximum crushing force with regards to the geometrical design variables. Raouf et al. [17] investigated effect of high density polyethylene filler on cylindrical tubes under high axial impact. They showed that the steel tubes filled by high density polyethylene have lower peak load and mean crushing force under high velocity impacts.

The present paper experimentally investigate the density effects of polyurethane foam on the energy absorption performance in the quasi-static loading of foam filled mild steel cylindrical tubes compared to the empty tubes. Two different densities of polyurethane foam were used to evaluate the effect of polyurethane

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foam density on crashworthiness parameters under quasi-static tests.

2. Material and samples

The material features and geometrical properties of specimens for foam filled and empty tubes and experimental setup are presented in this section.

2.1. Material features

2.1.1. Mild steel

Table 1 presents the chemical analysis of the mild steel used in the experimental investigation.

Table 1: Chemical composition of mild steel [17]

Chemical Elements	Percentage
Fe	98.6356
C	0.1880
Al	0.0762
S	0.0342
Mn	0.8375
Ni	0.0217
Cr	0.0213
Si	0.1855

Based on the ASTM E8, the static stress-strain curves of the utilized steel tubes were determined through STM machine (Figure 1). Figure 2 presents the steel specimens experimental stress-strain curves.

The yield stress, elastic modulus, density, and Poisson ratio are 225 MPa, 200 GPa, 7.864×10^{-6}kg/mm^3 and 0.30 respectively.

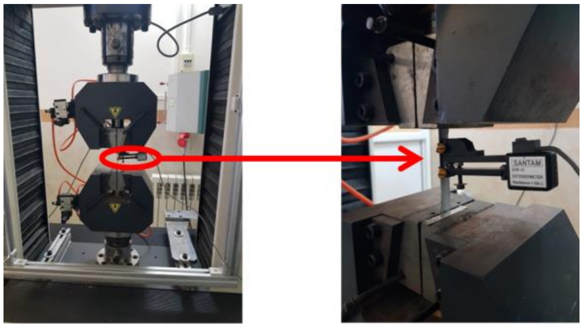

Figure 1: Tensile testing machine

2.1.2. Polyurethane foam

In the present work, Quasi-Static performance of rigid polyurethane foam with densities of 40 and 85 kg/m3 were calculated.

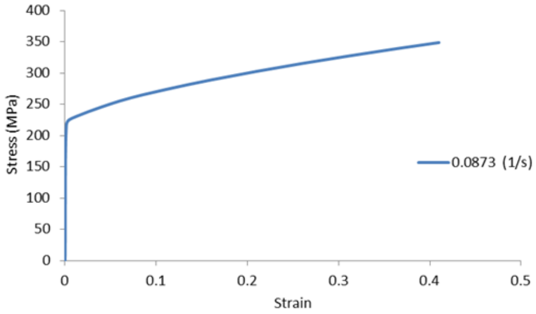

Figure 2: Quasi-static stress-strain curve

The cube foam specimen with a length of 40 mm in all directions prepared to acquire quasi-static behavior (Figure 3a). Polyurethane samples compressive experimentally according to the ASTM D1621 standard, at velocity of 1.2 mm/min (Figure 3b).

a b

Figure 3: (a) a polyurethane foam sample, (b) compression testing machine.

Figure 4 represents the stress vs. strain curves for polyurethane foam specimens at compression.

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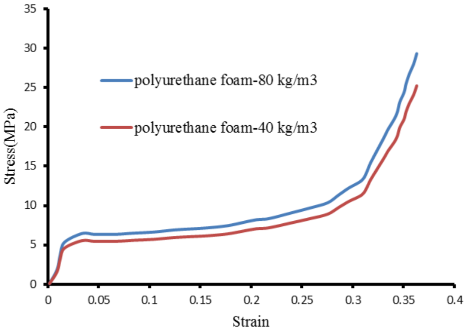


Figure 4: experimental the stress vs. strain curves for polyurethane foam at 40 and 85 kg/m^3 under quasi-static compression

The Poisson ratio and elastic modulus are 0.40 and 88 MPa respectively. The yield stress for polyurethane foam with densities of 40 and 85 kg/m3 are 4.9 Mpa and 5.2 Mpa respectively.

2.2. Preparation of test sample

The cylindrical tubes made of mild steel with mechanical properties found in section 2.1.1. Geometrical dimensions had the length of 60 mm, inner diameter 28 mm, and two thicknesses of 0.5, and 0.6 mm. The foams were prepared at two different mass densities: 40 and 85kg/m3 from polyurethane. The foam core with a diameter of 28 mm was prepared for steel tube (table.2).

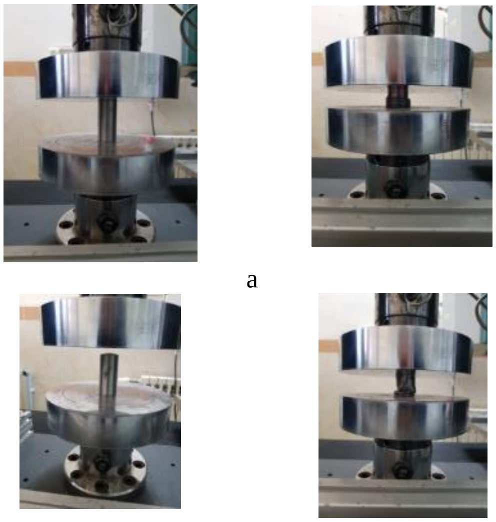
Table 2: Geometric characteristics of empty and foam cylindrical tubes

Model	Geometric characteristics					
	Material	Thickness (mm)	Inner Diameter (mm)	Length (mm)	Foam density (Kg/m^3)	Mass (gr)
Q5E	Steel	0.5	28	60	--	21.1
Q5F-40	Steel-foam filled	0.5	28	60	40	22.6
Q5F-85	Steel-foam filled	0.5	28	60	85	24.2
Q6E	Steel	0.6	28	60	--	25.4
Q6F-40	Steel-foam filled	0.6	28	60	40	26.9
Q6F-85	Steel-foam filled	0.6	28	60	85	28.6

As showed in table 2, all Q5E, Q6E, Q5F-40, Q5F-85, Q6F-40, and Q6F-85 samples have the same length and inner diameter of 60 mm and 28 mm, respectively and tubes thickness is 0.5 mm and 0.6 mm in Q5 and Q6, respectively. Two different densities of foam as 40 and 85kg/m^3 were utilized for filling the steel tubes to assess the effect of foam in deformation behavior.

3. Experimental setup

Foam filled and empty cylindrical tubes samples are exposed to the quasi-static axial loading using the universal test machine in the Islamic Azad University of Lashtenesha-Zibakenar branch. The samples were located aligned to the two jaws. A compressive load was applied by the moving jaw at a speed of 2 mm/min [18]. Some foam filled and empty cylindrical tubes samples before and after axial deformation in the universal test machine are presented in Figure 5.


a

b

Figure 5: specimens before and after quasi-static axial loading: (a) Empty cylindrical tube (b) Foam filled cylindrical tube

4. Results

4.1. Axial loading

Table 3 shows the experimental results of the quasi-static tests performed via the universal test machine. It also presents the experimental

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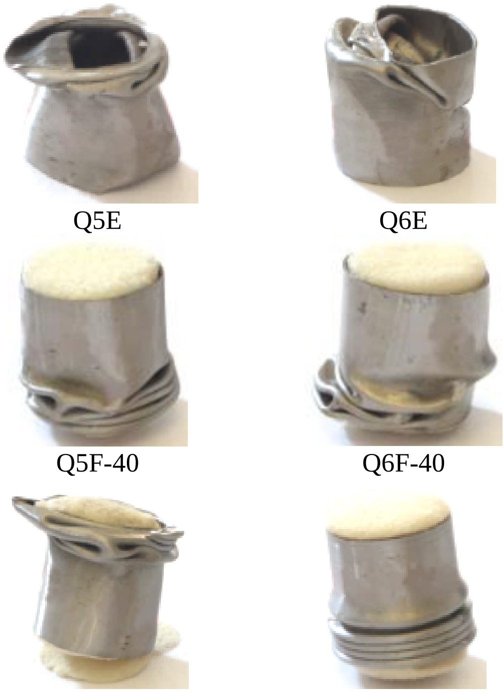
quantities of mean crushing force, peak load, and axial displacement at peak load. It should be mentioned that the axial displacement of the tube is equal to the upper jaw displacement in the universal test machine and mean crushing force is equal to the ratio of total energy absorption to the axial displacement.

Table 3: Experimental results of the quasi-static tests

Model	Axial Displacement (mm)	Peak Load (kN)	Mean Crushing Force (kN)
Q5E	1.30	20.39	7.1
Q5F-40	1.04	22.13	8.11
Q5F-85	1.04	22.19	9.32
Q6E	0.99	25.53	9.23
Q6F-40	1.30	25.89	12.11
Q6F-85	1.24	25.96	16.29

The experimental shapes of the foam filled and empty cylindrical tubes after axial compression in the universal test machine are presented in Figure. 6.



Q5E Q6E

Q5F-40 Q6F-40

Q5F-85 Q6F-85

Figure 6: The experimental shapes of specimens at quasi-static loading condition

As recognizable from the figure 6, by increasing the thickness of the tube as well as the use of foam as a filler and the increasing in the density of the foam causes the buckling mode to change from diamond to progressive buckling in the tubes under axial loading, which makes the energy absorption process more controllable. Figure 7 displays the experimental quasi-static force-displacement curves for Q5E, Q6E, Q5F-40, Q5F-85, Q6F-40, and Q6F-85 samples under axial compression.

4.2 Energy absorption and Crashworthiness parameters

In order to further look into the effect of foam and its density on the thin-walled tubes behavior under quasi static loading, the parameters of crashworthiness and energy absorption are investigated based on the definitions stated by Li and Xiang [9, 19]. The crashworthiness and energy absorption parameters of empty and foam filled tubes are shown in Figures. 8–11.

As observed from the curves, by adding foam as filler and also increasing the density of foam, the surface under the force-displacement diagram is increased and the mean crushing forces also are increase noticeably. In other words, the use of polyurethane foam as a filler in the cylandrical steel tube under axial loading is increased the amount of absorbed energy.

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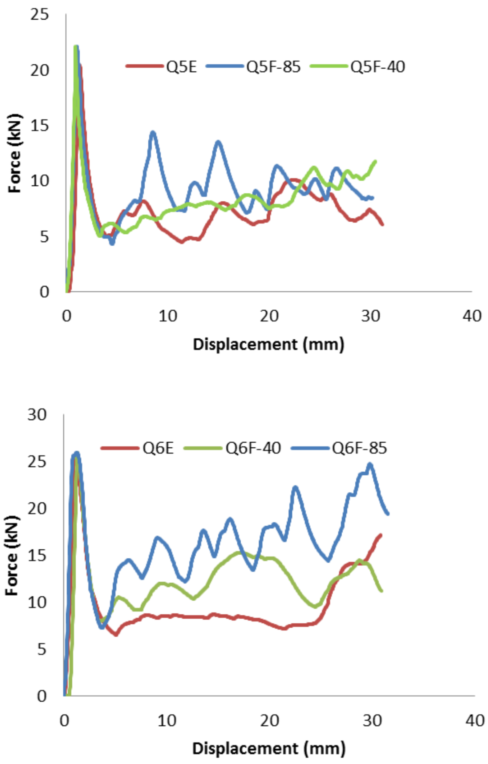

Figure 7: The experimental force versus displacement curves of specimens of table 2

4.2.1 EA (Energy Absorption) and SEA (Specific Energy Absorption)

EA (energy absorption) is defined as the area below the force versus displacement curve in the pressure test, which is shown in (1) [19]:

$$EA = \int_0^s F(s)ds \tag{1}$$

Where F is the axial force and s is the axial crushing distance.

SEA (specific energy absorption) is defined as the absorbed energy ratio to the total mass of the tube and is shown as follows [19]:

$$SEA = \frac{\int_0^s F(s)ds}{m_t} \tag{2}$$

Where, m_t is the mass of each specimen.

As determine from figure 8, by increasing tube thickness, the amount of EA and SEA increased, and also in foam filled tubes, an increase in the values of these two parameters is seen compared to the empty sample. The noteworthy point in this diagram is that in the foam filled tube which that the foam has a density of 85kg/m^3 and tube thickness is 0.5 mm, the amount of energy absorbed is close to the empty tube with a thickness of 0.6 mm and only 2.7% is less than it, while the specific energy absorption of the foam filled tube is 2.2% higher than it, due to the lower weight of the foam filled tube. This shows the importance of foam density affect in the energy absorption parameters of thin-walled tubes.

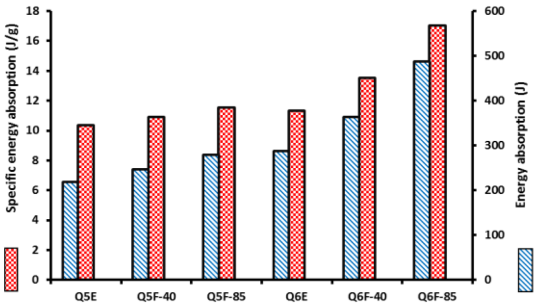

Figure 8: EA and SEA of foam filled and empty tubes

4.2.2 Peak load and mean crushing force

Peak load (F_{max}), is defined as the first maximum in the load–displacement curve. Mean crushing force (F_{ave}) is the total energy absorption (EA) ratio to the stroke between first increasing in force after peak load (s_a) and the end of compressing test (s) [9]:

$$F_{ave} = \frac{\int_{s_a}^{s} F(s)ds}{s - s_a} \tag{3}$$

Figure 9 shows the F_{ave} and F_{max} for the specimens in Table 2.

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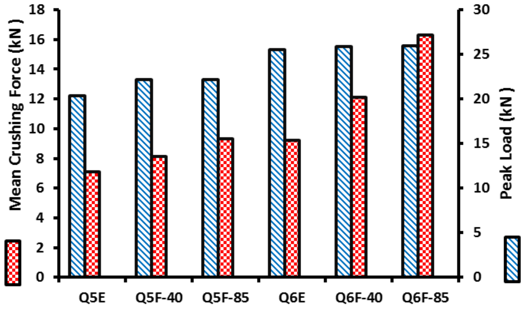

Figure 9: F_{ave} and F_{max} of foam filled and empty tubes

As shown in Figure 9, the peak load increases with increasing tube thickness, and this parameter is also greater in foam filled tubes than in empty tubes. Also, the effect of increasing the density of foam caused an increase in the F_{ave} parameter, which is more evident in thicker tubes. Although the maximum force in an empty tube with the thickness of 0.6 mm is higher than the foam filled tube with a density of 85kg/m^3 and tube thickness of 0.5 mm, their average force is approximately equal to each other because of the density of the foam.

4.2.3 ULC (Undulation of Load carrying Capacity) and CFE (Crushing force efficiency)

CFE (Crushing force efficiency) defined as the ratio of F_{ave} to F_{max} and the ratio between the work done by the deviation of the actual crushing force from the F_{ave} and the EA defined as ULC and it is shown as follows [19]:

$$ULC = \frac{\int_0^s |F(s) - F_{ave}| ds}{\int_0^s F(s) ds} \tag{4}$$

As shown in figure 10, crushing force efficiency (CFE) in foam filled tube is higher than an empty tube and this parameter also increased by increasing in the foam density. It should be noted that crushing force efficiency (CFE) is an important feature in the force-displacement diagram. Progressive buckling is characterized by higher values of crushing force efficiency (CFE) and this is due to the uniform distribution of load during the crushing process [9]. undulation of load-carrying capacity (ULC), Indicates the level of undulation of the crushing force around the mean crushing force, and the higher value of this parameter, shows instability in the deformation mode (figure 10).

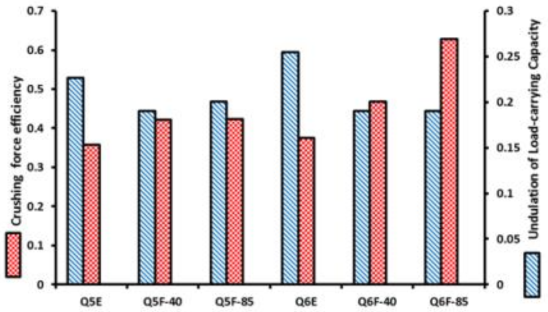

Figure 10: CFE and ULC of foam filled and empty tubes

4.2.4 NLC (Non-dimensional Load-carrying Capacity) and EEA (Effectiveness of Energy Absorption)

Effectiveness of energy absorption (EEA) defined as the Energy absorption (EA) ratio to the multiply of the yield stress of the material and length and pure cross section area of the tube [19]:

$$EEA = \frac{\int_0^s F(s) ds}{ALY} \tag{5}$$

Where L and A are the length and the pure cross section area of the tube respectively and Y is the yield stress. NLC is a ratio of mean crushing force to fully plastic bending moment per unit length [19]:

$$NLC = \frac{F_{ave}}{M_0} \tag{6}$$

Where M_0 defined as:

$$M_0 = \frac{2Yt^2}{4\sqrt{3}} \tag{7}$$

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Where t is the thickness of tube EEA and NLC of empty and foam filled cylindrical tubes have showed in figure 11.

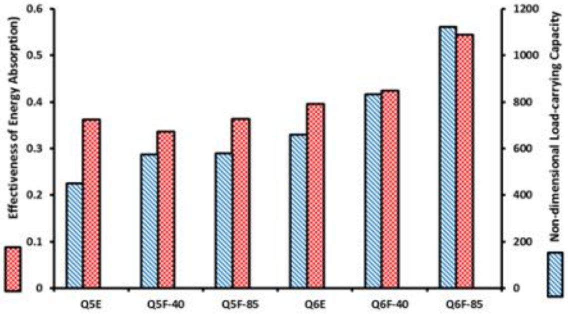

Figure 11: EEA and NLC of specimens

5. Conclusions

It was indicated that for specimens Q5E and Q6E in the empty cylindrical tubes under axial quasi-static loading, the quantity of peak load was incremented by rising the tube's thickness. Moreover, the average crushing force is also incremented as the crushing energy is divided by the tube shortening length. According to the experimental quasi-static force-displacement responses of the samples Q5F-40 and Q5F-85 that are axially compressed, the peak load amount of foam filled cylindrical tubes is more than of the empty tube (sample Q5E) (Figure 7). The reason is the effect of foam. Therefore, in the foam filled samples, the energy required for plastic deformation is more than the empty sample. The same results were found in the foam filled cylindrical tubes with other thicknesses. It is observed that increasing the foam density slightly affected the peak load. According to the results, the foam uses as a filler also influences the tubes' deformation behavior in addition to the effects of thickness. It was revealed that by incrementing the thickness to 20%, the peak load increased by 25.2%. Two densities of foam were considered as 40 and 85kg/m^3 to assess the effect of density of polyurethane foam as filler on the energy absorption behavior of tubes' quasi-static axial loading. It was revealed the peak load increased by 1.4% and 1.7%, respectively that in tubes at thickness of 0.6 mm filled with 40 and 85kg/m^3 density of foams, compared to the empty tubes. As observed, because of the thickness of the tube, the energy absorption parameters are less affected by the foam as the filler. Thus, the effect of foam as filler and its density was assessed by decreasing the thickness of the tube to 0.5 mm. It was observed that the peak load increased by 8.5% and 8.8%, respectively in tubes with the 0.5 mm of thickness filled with two mentioned densities of foams compared to the empty tubes. According to the experiments, the foam as filler is effective on the crashworthiness parameters of tubes made of mild steel under quasi-static axial loading.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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