

Evaluation of the Performance of Initiator on Energy Absorption of Foam-Filled Rectangular Tubes: Experimental and Numerical Assessment

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Abstract In this paper, the effect of initiator on axial crushing response of partially foam-filled and foam-filled rectangular tubes was investigated. For this purpose, an initiator was placed at the top of the filling rectangular tube with rigid polyurethane foam to prevent a suddenly applied force to the main part of the structure when the accident occurs. In this new idea, the process of axial crushing was carried out in two steps. In the first step, the initiator crushed the foam core as much as the initiator length, and, the second step, the initiator simultaneously crushed the thin-walled rectangular tube and the foam core. In this research, a number of numerical simulations were performed to study the dissipated energy of the rectangular tubes with initiator. To verify these numerical findings, some quasi-static experimental tests were conducted to explain energy absorption, initial peak load and crush force efficiency. Moreover, load-displacement curves and deformation mechanism of this shock absorber with different length of initiators were described. The results showed that, in the considered material and geometry, the design with an initiator on partially foam-filled and foam filled rectangular tube have superior performance rather than the specimen without an initiator. In addition, selecting the appropriate length of initiator for the specimens of partially foam-filled and foam-filled resulted in an increase in the energy absorption. Besides, the results showed that the increase in the absorbed energy in the

foam-filled specimen was more than that of the partially foam-filled specimens. Therefore, by applying the initiator on the top of the tube, it would be help to reduce the occupant injury and main structure in a collision.

Keywords Initiator · Energy absorption · Maximum crushing load · Rectangular tube

Introduction

Thin-walled tubes as energy absorbers have been commonly used in a wide range of applications, notably behind car bumpers and train buffers, and at the base of lift shafts. Nowadays, these tubes are one of the most efficient energy absorption systems because of their good crashworthiness characteristics. Such tubes permanently (or plastically) deform to mitigate the impact energy and loads transmitted to the vehicle. Furthermore, these tubes act “sacrificially” by deforming in preference to other components of the vehicle structure, thus reducing repair costs and maintaining the integrity of the passenger compartment.

Extensive studies have been done on square or rectangular cross section to gain an in-depth understanding of the crushing behaviour of such tubes both numerically and experimentally. In general, the deformation mode of rectangular tubes is very different from other tubes, though the general characteristics of the load-displacement curves are similar. Despite the great potential of square or rectangular tubes for sustaining impact loading, their crushing response must be carefully controlled in terms of geometrical parameters such as initial length, width and thickness, as such tubes tend to fail via a global bending collapse mode which is relatively unstable [1]. In crashworthiness applications, global bending must be avoided since it

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can cause a significant reduction in the energy absorption capacity. Studies have experimentally examined the effect of changing the initial length within a wide range to evaluate deformation mode, energy absorption capacity, inertia effects and loading rate (Jensen et al. 2004). Recently, thin-walled structures have been filled with foams. Foams are potentially effective materials which are used in the automotive industry, due to their energy absorption capability and help to stability of crushing process of tubes [2]. A comprehensive experimental study was carried out on the thin-walled columns filled with aluminum foam by Hanssen et al. [3, 4]. They investigated the crushing behavior of the foam-filled aluminum square tubes under quasi-static axial loading. They found that significant increases of crushing force were obtained from the direct compressive strength of the foam and from the interaction between the foam and wall column.

Although thin-walled tubes have many advantages as energy absorbers, one of their major shortcomings is a distinctly high initial peak load under axial impact. According to the injury criteria (for example, Head Injury Criterion), this high initial peak load might cause death or pose severe injuries to the passengers [5]. Decreasing the initial peak load is desirable for minimizing the impact loads transmitted to the protected structures [6]. Therefore, in order to reduce the initial peak load, various methods have been presented such as creating dents or grooves [7, 8], and using corrugated tubes [9, 10]. Although these methods could reduce the initial peak load, they could also reduce the stiffness of the structure under usual working conditions. Thus, it is desired to have a device which can enhance energy absorption characteristics without having any effect on the performance of the structure in the normal use. The effect of cracks on energy absorption characteristics of square and cylindrical tubes was studied by Alavi Nia et al. [11]. They made these cracks in different situations and various angles and showed that the initial peak load decreases in crack angles from 0 to 45° and increases for angles between 45° and 60°. Bodlani et al. [12] performed dynamic and quasi-static axial crush tests on mild steel tubes of various hole configurations. Their results showed that the insertion of hole discontinuities decreased the initial peak load. The deformation modes and energy absorption of aluminum tubes with circular discontinuities were investigated for square tubes both experimentally and numerically by Arnold and Altenhof [13, 14]. They found that geometric discontinuities increased the absorbed energy up to 22%. The study of energy absorption and collapse modes was carried out for square aluminum tubes with geometric triggers [15]. The triggers led to decrease the maximum load, increase energy absorption capacity, and crush force efficiency of the tubes. The effect of cuttings on the tube corners as initiators has investigated both experimentally and numerically on energy absorption characteristics of square tubes [16]. Results showed that the initiators changed the deformation mode

from general buckling to progressive buckling and decreased the maximum crushing load; therefore, increased crush force efficiency. Ghani and Hassan [17] studied the effect of external tapered plunger as a trigger mechanism on crush performance of square columns. They found that by increasing the plunger angle reduced the initial peak load and increased the crush force efficiency.

The effect of added initiator was studied for square and circular empty tubes [5, 18]. Those results indicated that by adding a buckling initiator at the end of the tube, the initial peak load of a circular and square tube effectively reduced about 30%; however, this result was associated with a decrease in energy absorption capacity. Recently, an idea of utilizing the initiator on the foam-filled thin-walled circular tubes with stiffened annular rings has been performed to increase the energy absorption and to prevent the sudden force applied to the main part of the automotive and its occupants [19].

The aim of this study is to design a new shock absorber under axial compression. Up until now, no model has been proposed for the axial crushing of foam-filled rectangular tubes with an initiator. This method allows preventing a suddenly applied load to the main part of the structure when the accident occurs. This present study develops the effectiveness of installing an initiator at the top of the foam-filled and the partially foam-filled rectangular tubes. In this innovative idea, numerical simulations were conducted using an explicit ABAQUS finite element code to study the energy absorption of foam-filled rectangular tubes with the initiator. To verify numerical simulations of this type of shock absorber, some experimental tests were carried out to investigate the effects of (i) filling tubes by rigid polyurethane foam with different lengths of foam and (ii) adding initiator with different lengths in the top of the foam-filled tubes; on crashworthiness characteristics of thin-walled rectangular tubes under axial compression.

Material Properties

Aluminum Rectangular Tubes

The present work investigates the effect of the initiator on crushing response of the rectangular tubes filled with polyurethane foam. To do so, the test specimens were fabricated using the aluminium alloy 6063. Furthermore, the tensile stress-strain curve was obtained following the ASTM B557M standard test, which has shown in Fig. 1. The elastic modulus of this material is $E = 69 \text{ GPa}$, the density is $\rho = 2700 \text{ kg/m}^3$ and the Poisson ratio is $\nu = 0.35$. Also, the yield stress and ultimate stress for this alloy are equal to $\sigma_y = 175 \text{ MPa}$ and $\sigma_u = 214 \text{ MPa}$, respectively.

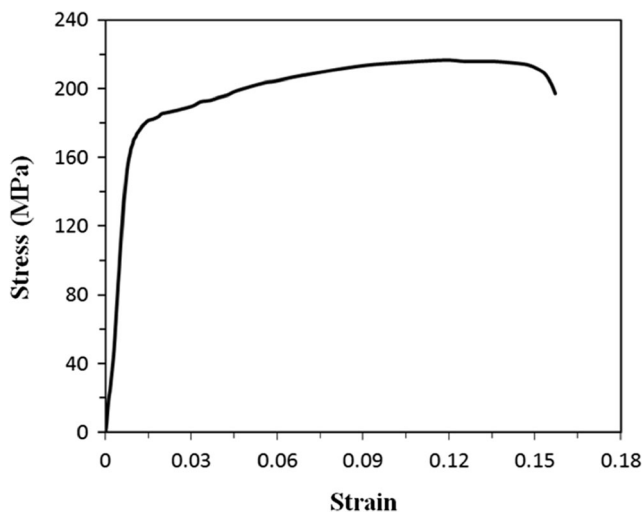


Fig. 1 Typical tensile stress–strain curve for 6063 aluminum

Polymeric Foam

In this study, rigid polyurethane (PU) foam has been prepared with 3 M brand Scotchcast™, via mixing an appropriate weight ratio of two liquid chemical compositions; Polyol and Isocyanate. The basic chemistry of rigid polyurethane foam is fairly simple. Its driving force is the high reactivity of the Isocyanate (NCO) group. Typically, an NCO group can react with a hydroxyl (OH) group from an alcohol or Polyol to form a urethane species, which is the primary reaction for polyurethane foam formation. For efficient foam formation, this reaction is physically promoted by mixing the Isocyanate (18.31 g) and the Polyol (13.92 g) using steel twister rotating at a high speed up to 2000 rpm. After mixing the foam liquids (Polyol and Isocyanate) components, the liquid mixtures were poured into rectangular tubes. Then, both ends of tubes were closed tightly by the fixture and held at room temperature for more than 2 h. Therefore, the density of the foam 126 kg/m^3 was calculated from this process. Figure 2 shows the stress–strain curve of foam prepared according to the ASTM D1621–94 standard by compressing a cubic specimen quasi-statically. As can be seen from the figure, the compression curve has three distinct regions: elastic phase, plateau stage and densification stage.

Experimental Procedure

To ascertain the effects of initiator length and the foam-filled length on the crashworthiness of specimens, several foam-filled rectangular tubes with a thickness of 2 mm and a length of 120 mm were manufactured. Next, these tubes with cross-sections of $55 \times 35 \text{ mm}$ were studied to understand the effect of initiator on the collapse mode and the energy absorption. The initiators used in these tests were made from aluminium. The dimensions of initiators were chosen less than the inner

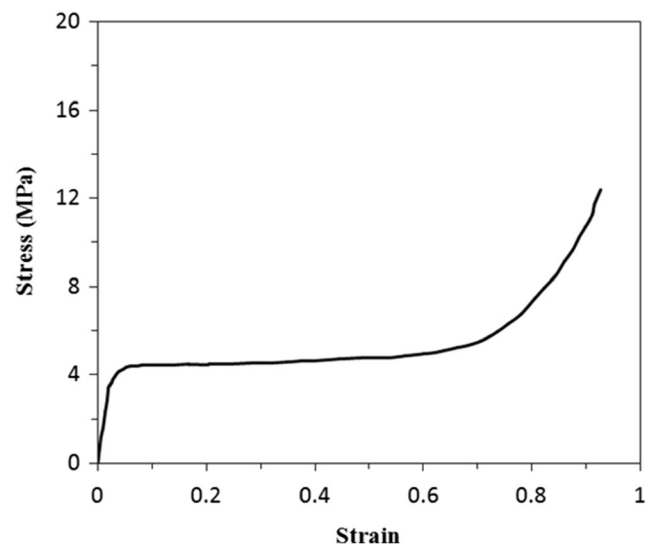


Fig. 2 Stress-strain curves of polyurethane foam for $\rho=126 \text{ kg/m}^3$

surface of tube. Therefore, any contact occur between the inner surfaces of tube and the initiator. So, the initiator only plays a role of pressing the foam.

In this study, quasi-static axial compression tests were carried out using the Universal Testing Machine. Also, the tests for each sample were repeated three times to ensure the repeatability of the obtained results. The crosshead went down to compress the initiator top of the rectangular tube with the constant strain rate of 1.42×10^{-3} (equal to 10 mm/min). As can be seen from Fig. 3, the specimen with initiator was placed between the plates of test machine without any additional fixing.

In the present work, different lengths of the initiator were studied (Fig. 3). The details and dimensions of the manufactured specimens and initiators are given in Table 1. Also, to show the effects of the initiator and rigid polyurethane foam, an empty specimen was compressed axially which load–displacement curve and collapse mode are shown in Fig. 4. Pictures of the crushing test for partially foam-filled and foam-

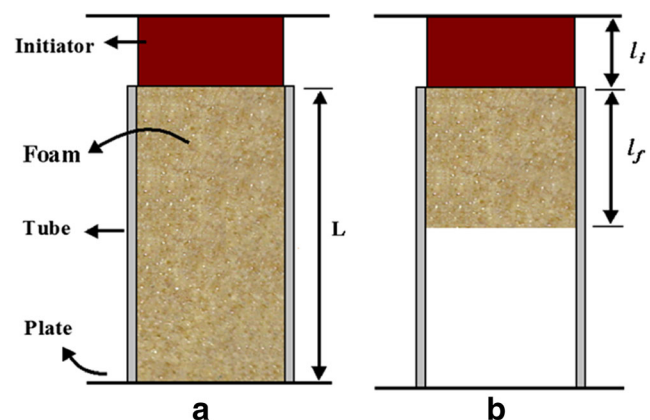


Fig. 3 A schematic of two groups of the thin-walled rectangular tubes with the aluminum initiator: (a) foam-filled; (b) partially foam-filled

Table 1 Specimen's dimension and initiator

Specimen	$L(mm)$	$l_f(mm)$	$t(mm)$	$l_i(mm)$
S-E	120	-	2	-
S60-0I	120	60	2	-
S60-20I	120	60	2	20
S60-30I	120	60	2	30
S120-0I	120	120	2	-
S120-10I	120	120	2	10

filled specimens with and without initiator are shown in Fig. 5. Furthermore, the load-displacement curves, resulting from experimental tests, are plotted in Fig. 6.

Energy Absorber Criteria

Desired parameters in this research which are used for comparison and could be obtained from load–displacement curve are as follows [20]:

Energy Absorption

Energy absorption is calculated from integration of area under the load-displacement curve as beneath:

$$E_{abs} = \int Pd\delta \quad (1)$$

Where P and δ are the crushing force and crushing distance, respectively.

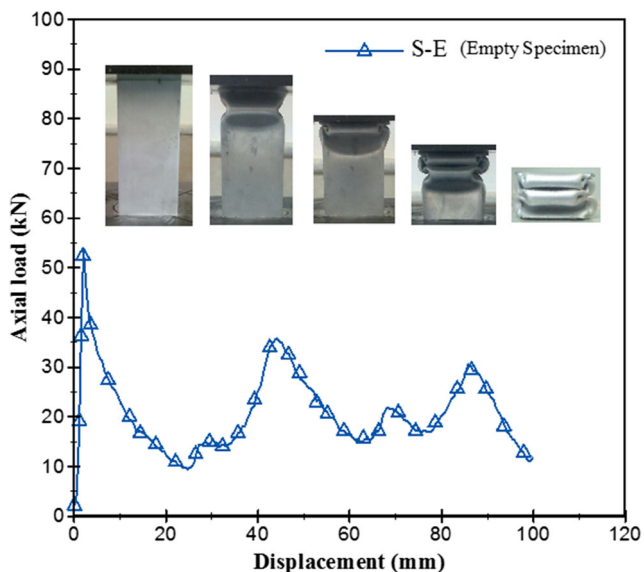


Fig. 4 Load-displacement curve and crushing mode for empty rectangular tube

Mean Crush Load

The mean crushing load is defined as the absorbed energy E_{abs} per total deformation of a specimen δ and calculated as following:

$$P_m = \frac{E_{abs}}{\delta} \quad (2)$$

Crush Force Efficiency

The crush force efficiency (CFE) which is an important criterion for comparing energy absorber capabilities, is defined as:

$$CFE = \frac{P_m}{P_{max}} \quad (3)$$

Where P_m and P_{max} are the mean crush load and initial peak load, respectively. For an ideal energy absorber this parameter should be as close to 100% as possible.

Energy Absorbed Per Unit Mass

The energy absorbed per unit mass, is referred to as the specific energy absorption, and denote by SEA (kJ/kg). This value is obtained by the following equation:

$$SEA = \frac{E_{abs}}{m} \quad (4)$$

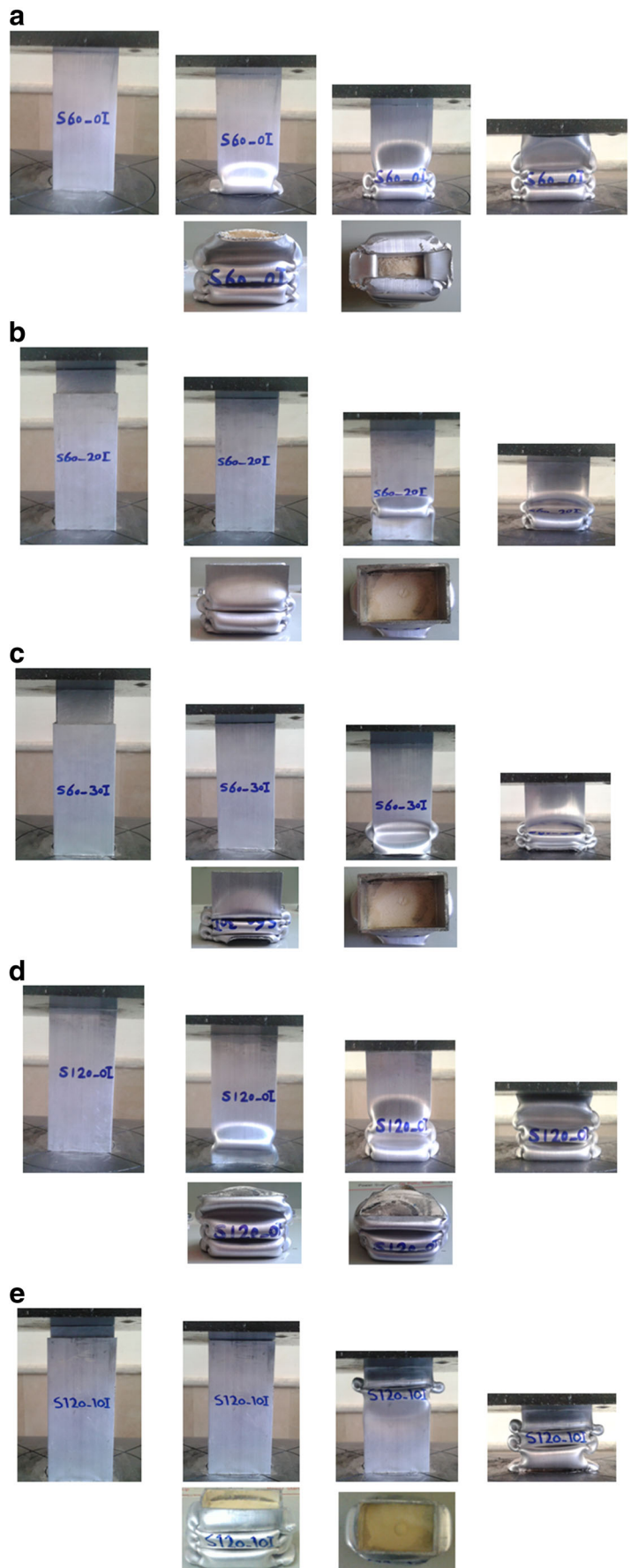
Where E_{abs} (kJ) is the total energy absorbed, and m (kg) is the total mass of the undeformed of the specimen.

FE Simulation

In the present paper, the finite element models (FEM) of the foam-filled rectangular tubes with initiator were modeled using explicit FE code ABAQUS/CAE version 6.5 and the basic 3D geometry of the model was created in part module. As shown in Fig. 7, two rigid plates are placed on the top and on the bottom of the tube. The element type of rigid plates is R3D4 (A 4-node 3-D bilinear rigid quadrilateral). The bottom rigid plate is constrained in all degrees of freedom, while the top plate is free to move only along the vertical axis with a constant velocity. Therefore, under this loading condition, no inertial effect on forming mechanism is likely to occur and no dynamics effect in the deformation mechanics is necessary to be considered indeed.

The aluminium rectangular tubes were modelled with shell elements (S4R) and three dimensional reduced integration, eight-node linear solid element (C3D8R) was used for the foam material and initiator. After convergence of solution, the optimum element size of 1.5 mm for the rectangular tubes

Fig. 5 Different stages of crushing for partially foam-filled and foam-filled specimens with and without initiator: (a) S60-0I, (b) S60-20I, (c) S60-30I, (d) S120-0I, (e) S120-10I



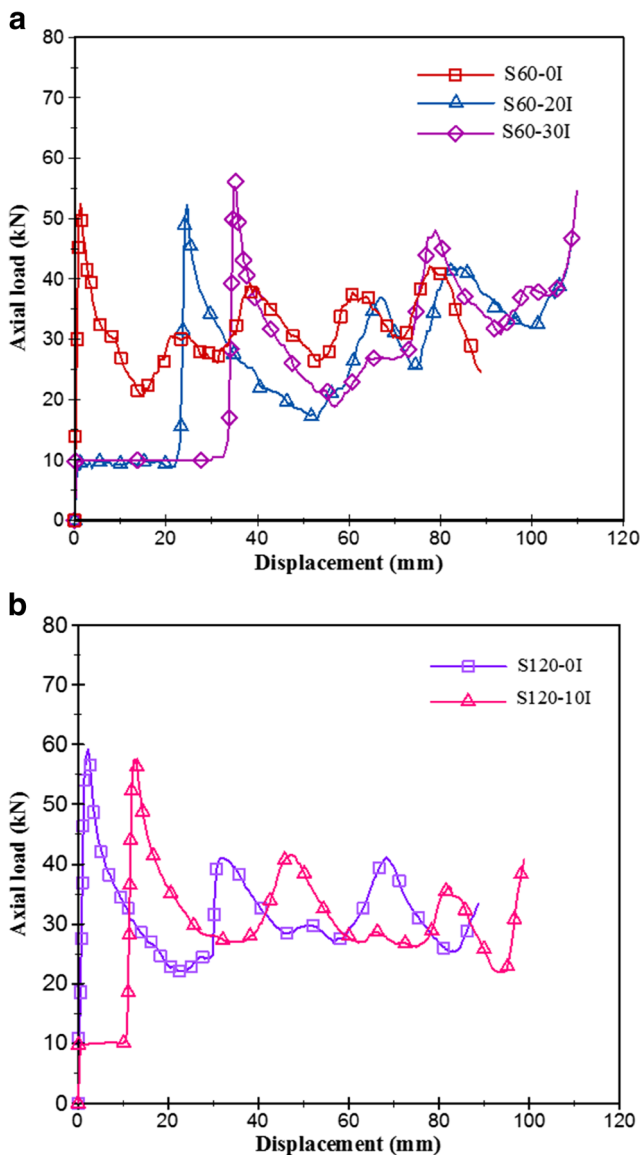


Fig. 6 Load–displacement curves obtained from experiment test for specimens with different length of initiator: (a) Partially foam-filled; (b) foam-filled

and 3 mm for the foam filler were selected to produce acceptable results. The material properties of the aluminum tubes were defined as linear elastic and non-linear work hardening in the plastic region. The isotropic plasticity and crushable foam material models were used to model the rectangular tube and foam filler respectively. The true stress-strain curves for both filler and aluminium materials were used to introduce the approximated true stress-plastic strain data points in numerical simulations. Table 2 shows the material parameters for polyurethane foam based on the crushable foam model.

In these models, a self-contact interface was selected to prevent interpenetration between each structure surface with itself. To define contact between the movable rigid plates, the fixed rigid plate, the foam and the tube, “surface to surface”

contacts were introduced. Since simulation of the crushing tubes with test conditions in FE software takes a long time extremely, we should find an economical solution for solving the problem. With knowledge of natural frequency, we can detect a down limit of time to consider the situation quasi-static. For choosing the load rating in the quasi-static situation, we start with the largest load rating which time is equal to the period of natural frequency. Then, by comparing the internal energy and kinetic energy, we detect the best load rating scale. In this paper, the actual crushing velocity of 10 mm/min was scaled up to 600 mm/min. Fig. 8 reveals the total kinetic and the internal energy through the deformation process of the foam-filled rectangular tube under quasi-static loading. Such approaches have a negligible error under the crushing load. Hence, as shown in Fig. 9, the FE model predicts the load-displacement curve observed in experimental results with a reasonable accuracy.

The numerical simulations of collapsed shapes after axial crushing are illustrated in Fig. 10. Also, the values of energy absorption and mean crushing load were summarized in Table 3. The results show that there is an acceptable agreement between FE analysis and experimental tests.

Results and Discussion

Crush Mode

The collapse shapes of the rectangular tubes obtained from numerical simulation were given in Fig. 10. Comparing the collapse shapes of the numerical simulation and the experimental tests, it is demonstrated that the presented FE model can simulate the crushed shape of the shock absorber with sufficient accuracy.

As shown in Fig. 11, the column walls deform progressively by forming inward and outward folds in two connecting edges. This type of deformation is referred to as an asymmetric folding mode. However, a different number of lobes were formed in the specimens due to plastic folding and no substantial change was observed in the crushing mode. Therefore, except the S60-30I and the S120-0I specimens, all the other specimens have four folds. As can be seen from Figs. 5 and 10, the length of initiator up to 20 mm on the top of the partially foam-filled rectangular tube does not lead to a change in the number of folds. In comparison, the number of folds decreases using the initiator with length of 30 mm. Also, by adding the initiator on the top of the foam-filled rectangular tube, the number of folds decreases.

The Load-Displacement Curve

The crashworthiness parameters are calculated by the load-displacement curve. Figure 12 shows a schematic diagram

Fig. 7 Finite element mesh and 3D model for partially foam-filled rectangular tube with initiator

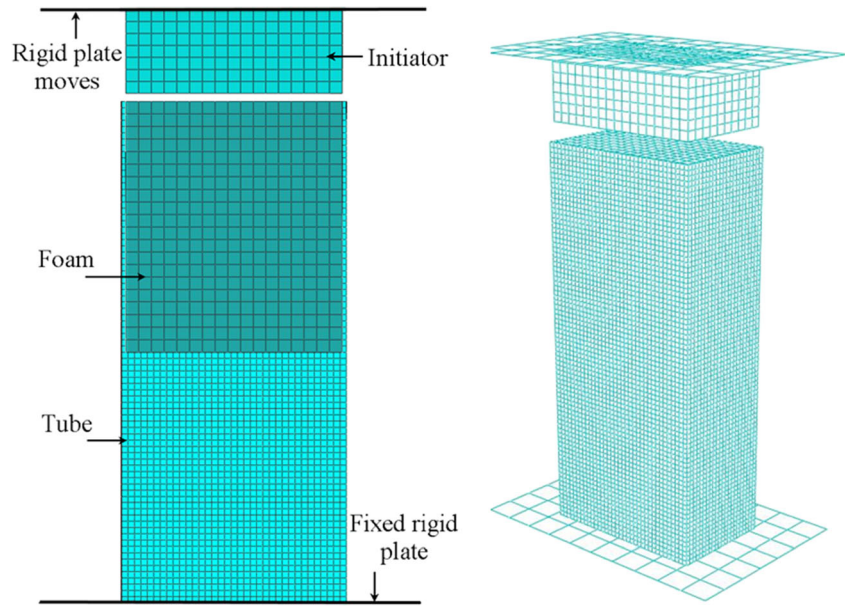


Table 2 Material parameters of crushable foam model considered for polyurethane foam

Density $\rho^f(kg/m^3)$	Elastic parameters		Plastic parameters	
	$E^f(Mpa)$	ν^f	k^f	ν_p^f
126	21.5	0	1	0

of the axial crushing of the foam-filled tube with the initiator. As observed in this figure, axial crushing has occurred in two steps. In the first step, the initiator will crush the foam core as much as the initiator length. Thereby, the load-displacement curve consists of a linear elastic region and a plateau region. In the second step, the initiator will simultaneously crush the

thin-walled rectangular tube and the foam core. In this step, it can be observed that after an initial elastic deformation, load increases during the plastic deformation due to the strain hardening process and declines dramatically while a plastic fold shapes completely. By further increasing the crushing force, second fold is created and the procedure is repeated until the specimen is completely crumpled.

In this study to illustrate the effect of initiator, the foam-filled and the partially foam-filled specimens without an initiator were crushed under axial compression. The load-displacement curves of these specimens were shown in Fig. 6. As observed from the figure, the behavior of the crushing is completely different between the specimens with and without an initiator. For example, the first fold for the specimen

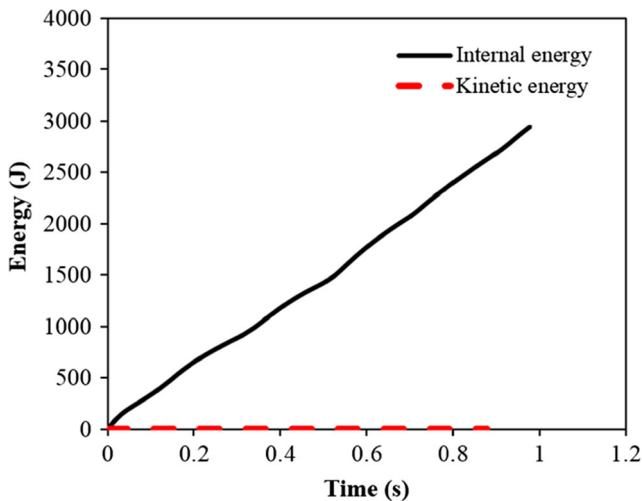


Fig. 8 Kinetic and internal energy for S120-0I specimen under quasi-static loading

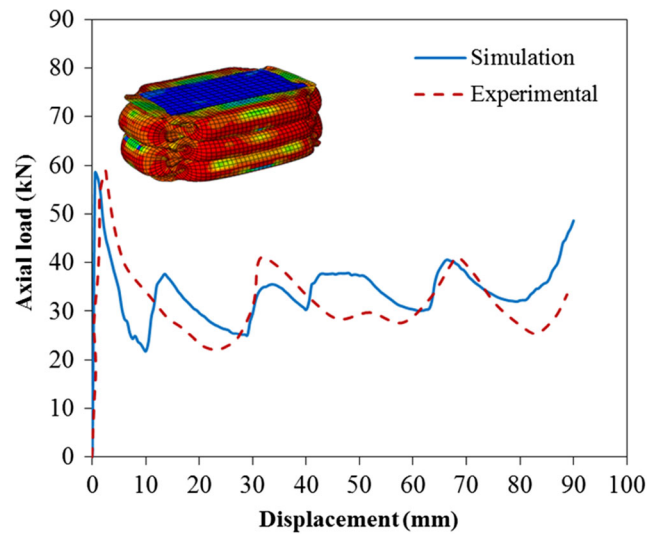
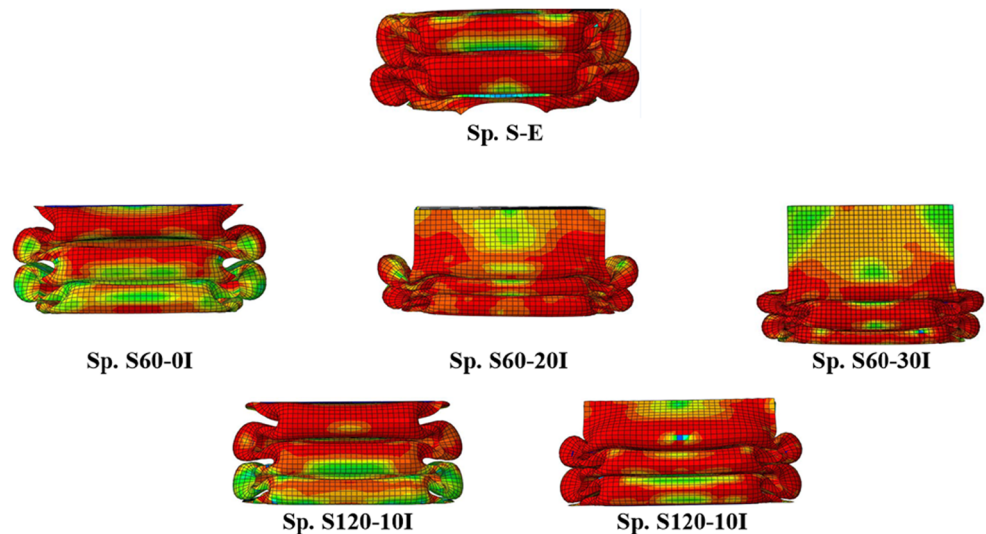


Fig. 9 Comparison between load–displacement curves obtained from experimental test and numerical simulation for S120-0I specimen

Fig. 10 Crushed shapes of partially foam-filled and foam-filled rectangular specimens derived from numerical simulation



without initiator, S60-0I, was formed immediately after starting of crushing load. In comparison, the first fold for the specimen with an initiator, S60-20I, was created after crushing of the foam core as much as the initiator length. Also, in the S60-20I specimen, the total crushing length was about 110 mm, while for the S60-0I specimen, the total crushing length was 90 mm. Therefore, using the initiator on the top of the rectangular tube, the total deformation (δ) increases.

The Effect of the Initiator

In this study, to show the effect of initiator on the crashworthiness parameters, three groups of the specimens, empty, partially foam-filled and foam-filled rectangular tube were crushed under axial compression. The load-displacement curves of these groups were plotted in Figs. 4 and 6. As can be seen from those figures, the behavior of the crushing load is totally different in the specimens with and without an initiator, as it was explained in before section. Figure 13 presents a comparison of the initial peak load, crush force efficiency, and the mean crushing load for the specimens of partially foam-filled and foam-filled. Initial peak load refers to initial maximum load during loading after which the first folding of the tube occurs. Because of the

importance of this parameter in the design of energy absorbers, many attempts have been made to reduce its value with respect to residual energy absorption capacity. The initial peak load for the specimens without initiator S60-0I and S120-0I is 54.20 kN and 59.39 kN respectively, which occurred immediately after starting of crushing load. Using the initiator, the initial peak load for specimens S60-20I, S60-30I, and S120-10I is 54.81 kN, 57.74 kN, and 58.19 kN, respectively, which created after crushing of the foam core as much as initiator length. As shown in Fig. 13, there is no substantial change in the initial peak load for the specimens with and without an initiator. According to Fig. 13, by adding the initiator on the top of the rectangular tube, the crush force efficiency for specimens of S60-20I and S60-30I decreased 17% and 22%, respectively, with respect to the specimen of without initiator (S60-0I). This is due to the fact that, by using the initiator, the total deformation (δ) increases, and it leads to a decrease in the mean crushing load. However, in the foam-filled specimen with an initiator (S120-10I), the crush force efficiency and mean crushing load are greater than the partially foam-filled ones. In this regard, the higher values of CFE means that the shock absorber has a large energy absorption potential associated with low initial peak load, making it the best criterion for comparing

Table 3 Experimental and numerical results after axial crushing

Material	Sample	Simulation				Experimental			
		$E(J)$	$P_{\max}(kN)$	$P_m(kN)$	$CFE(\%)$	$E(J)$	$P_{\max}(kN)$	$P_m(kN)$	$CFE(\%)$
Empty	S-E	1852.41	54.44	20.56	38	1911.49	53.51	21.22	40
Partially filled	S60-0I	2845.00	52.26	32.00	61	2836.37	54.20	31.97	58
	S60-20I	2779.22	54.78	25.56	50	2870.81	54.81	26.40	48
	S60-30I	2887.87	54.93	26.31	46.80	2855.56	57.74	26.02	45
Filled	S120-0I	3014.00	58.47	33.97	50.00	2804.65	59.39	31.61	53
	S120-10I	2890.64	58.01	29.22	51	2899.24	58.19	29.31	50

Fig. 11 Different stages of the collapse for partially foam-filled with length of initiator $l_i = 20\text{mm}$ (S60-20I specimen)

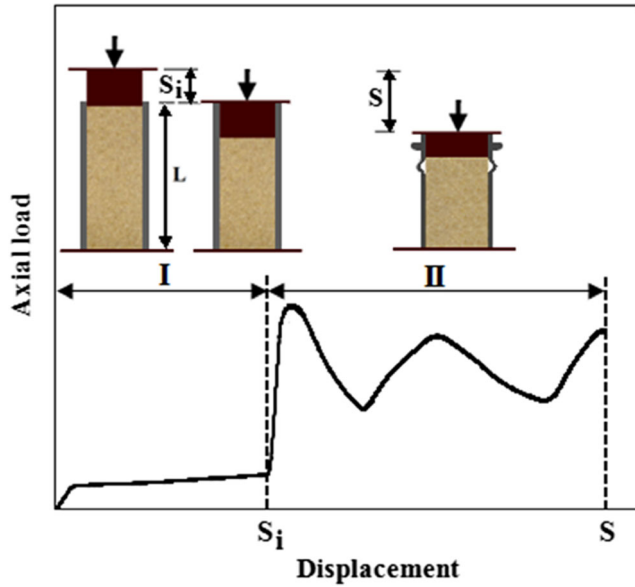
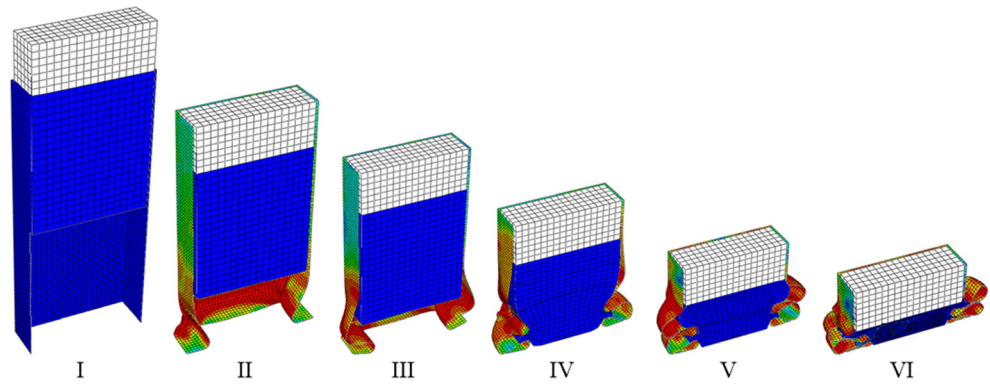


Fig. 12 Schematic representation of different stage of axial crushing of the foam-filled rectangular tube with initiator

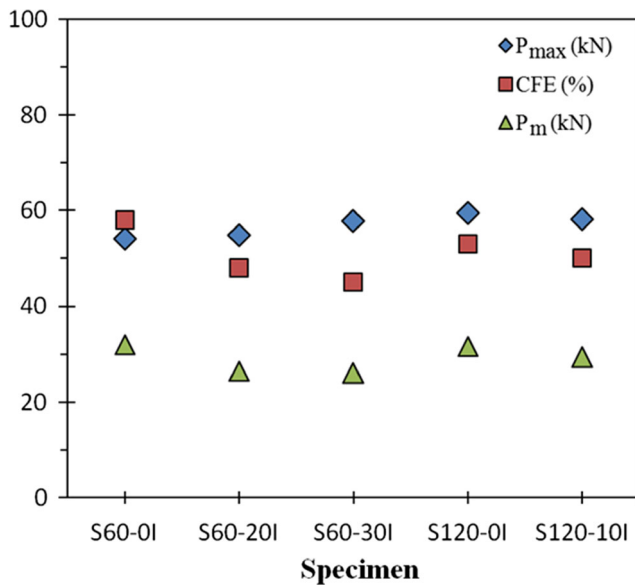


Fig. 13 Comparison of the initial peak load, crush force efficiency and the mean crushing load for specimens of partially foam-filled and foam-filled

them. Therefore, it can be concluded that CFE is a very important parameter in energy absorbers design.

Energy absorption characteristics of different types of specimens are shown in Fig. 14. A remarkable reduction in the energy absorption is evident between the tubes without initiator (S60-0I and S120-0I specimens). As can be observed from the figure, the energy absorption for specimen of S60-0I is 2836.37 J . Also, the energy absorption for the specimens of S60-20I and S60-30I is 2870.81 J and 2855.56 J , respectively. In the design of an energy absorber from the partially foam-filled specimens, the initiator length must be selected 20 mm to gain a high energy absorption capacity. In the specimens of foam-filled, the largest and lowest values of the energy absorption are respectively 2899.24 J and 2804.65 J , which belong to specimens of S120-10I and S120-0I. Figure 14 shows that the increase in the absorbed energy in the foam-filled specimen with initiator is more than the partially foam-filled ones. Thus, it can be concluded that by installing the initiator at the end of foam-filled rectangular tubes, an increase in the energy absorption of foam-filled rectangular tubes and a decrease in the sudden intense force would be occur.

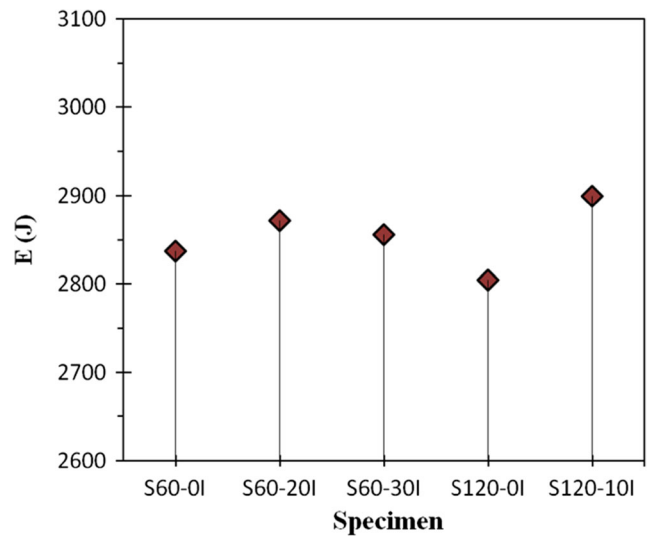
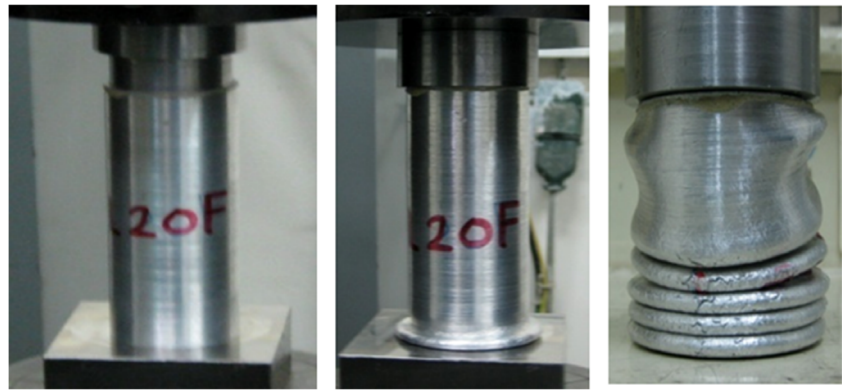


Fig. 14 Comparison of the energy absorption for specimens of partially foam-filled and foam-filled

Fig. 15 Different stages of crushing for foam-filled circular tube with initiator [19]



Comparison Between Rectangular and Circular Tube with Initiator

In this section, to determine the relative performance of initiator in the foam-filled rectangular tube, the crashworthiness characteristics is compared with a foam-filled circular tube from a previous study [19]. Therefore, the foam-filled aluminum circular tube with the length of initiator 20 mm (specimen of C-0R-1I) is compared with the S120-10I specimen. The circular specimen with density $\rho=217 \text{ kg/m}^3$, thickness $t_0=1.5 \text{ mm}$, length $L=120 \text{ mm}$, and inner diameter $D_0=42 \text{ mm}$ was tested in quasi-static axial compression. The final shape of the specimen after the compression test is shown in Fig. 15. Comparison of crushing mode between circular and rectangular tubes, reveals the less stability of circular tube design.

In Table 4, the absorbed energy, maximum crushing load, mean crushing load, specific energy absorption and crush force efficiency for circular tube are compared with a rectangular one. As can be seen from Table 4, however, the foam density in the circular tube is higher than that of the rectangular one, there is no substantial change in the maximum crushing load, mean crushing load, specific energy absorption, and the crush force efficiency for two structures. The foam-filled rectangular tube, thus, is preferred because of its higher energy absorption capacity and higher stability in comparison with the circular tube. Therefore, the results from this study would be useful for the automotive industry to design crashworthy components based on the foam-filled rectangular tubes with the initiator.

Conclusions

In this paper, the effect of initiator on the crushing response of the partially foam-filled and foam-filled thin-walled rectangular aluminum tubes was studied. In this new idea, to decrease the intensity of the applied load on the main structure, the initiator was added on the top of the foam-filled rectangular tube. Quasi-static numerical simulations were performed to investigate the crashworthiness characteristics of tubes with different lengths of the initiator. To verify the numerical simulations, experimental tests were conducted to measure the absorbed energy. Furthermore, the load-displacement curves and the deformation mechanism of the specimens under axial compression were described. The main conclusions are outlined as follows:

- The behavior of the crushing load was totally different for the specimens with and without initiator. The process of axial crushing was carried out in two steps. In the first step, the initiator crushed the foam core as much as the initiator length, and, the second step, the initiator simultaneously crushed the thin-walled rectangular tube and the foam core.
- By applying the initiator, no substantial change was observed in the initial peak load. Also, the crush force efficiency and the mean crushing load decreased for partially foam-filled. Whereas, by selecting the length of initiator $l_i=20 \text{ mm}$, the crush force efficiency and the mean crushing load increased for the foam-filled specimen.,
- In the design of an energy absorber from the partially foam-filled specimens, the initiator length must be selected 20 mm to gain a high energy absorption capacity.

Table 4 Comparison of experimental results between the circular and rectangular tubes

Specimen	$E(J)$	$P_{\max}(kN)$	$P_m(kN)$	$SEA \text{ (kJ/kg)}$	$CFE \text{ (\%)}$	Number of folds
C-0R-1I [19]	2228.51	59.50	31.82	23.71	53	5
S120-10I	2899.24	58.19	29.31	22.47	50	4

- The energy absorption increased by installing the initiator at the top of the partially foam-filled and the foam-filled rectangular tubes. The increase in the absorbed energy in the foam-filled specimen was more than the partially foam-filled specimens.
- By installing the initiator at the top of the partially foam-filled and the foam-filled rectangular tubes, a decrease in the sudden intense force occurred.
- The foam-filled rectangular tube with initiator was preferred because of its higher energy absorption capacity and higher more stability in comparison with the circular tube.

Therefore, the idea of adding the initiator in the foam-filled rectangular tubes as energy absorber can be used in automotive industries.

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