Mechanics of Advanced Composite Structures 6 (2019) 57–64

Semnan University

Mechanics of Advanced Composite Structures

journal homepage: http://MACS.journals.semnan.ac.ir

Numerical Crashworthiness Analysis of Graded Layered Foam-Filled Tubes Under Axial Loading

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PAPER INFO

Paper history:
Received 2018-10-15
Received in revised form 2018-11-27
Accepted 2019-04-25

Keywords:
Energy absorption
thin-walled tube
graded layered foam
Crashworthiness
Polyurthane

ABSTRACT

In this article, the results of a study on energy absorption characteristics of foam-filled thin-walled structures with finite element analysis have been presented. Four specimens of thin walled structures have been filled with uniform foam and three specimens have been filled with linear four-layered foam. Also, eight layers HLH (High-Low-High) and eight layers LHL (Low-High-Low) have been simulated. The total weight of all layered specimens is the same and main difference is just the arrangement of the layers. In order to study the energy absorption behavior of the specimens, they have been subjected to quasi-static crushing load. The results indicated that by utilizing the filler foam in the thin-walled energy absorbers, the energy absorption capacity of the foam filled specimens in comparison with hollow specimens, significantly promotes; however, the initial peak force for hollow specimens is lower than the foam-filled specimens. Consequently, from the layered specimens, LHL showed higher specific energy absorption and less initial peak force compared with other specimens, in which the LHL specimen shows 16% more initial peak force and 114% more specific energy absorption than the hollow specimen.

1. Introduction

Crashworthiness is the capacity of a structure and its components to protect occupants in collision. Indeed, this criterion is the ability of the vehicle structure to have plastic folding and also maintain enough space to survive the occupants during the crash. Thin-walled structures are widely used as energy absorbers in various industries such as automobiles and aerospace, for protecting the occupants from severe injuries.

The first studies on the capability of the energy absorption of thin-walled structures were done by Alexander [1]. He presented a theoretical expression for the force in the circular sections. This expression was later verified by Wierzbicky and Abramowicz and is generalized for square sections [2]. They provided a simplified formula for predicting the energy absorption response in thin-walled sections. Since then, numerous empirical and numerical studies have been done to predict the energy absorption behavior of thin-walled structures. In the 80s and 90s, empirical studies were carried out which confirmed the quality of the obtained theory relations [3, 4]. To date, many studies are conducted to improve the performance of thin-walled structures. Shojaeefard et al. performed a quasi-static experimental and nonlinear finite element analysis to compare the energy absorption and initial peak load of combined circular and square sections with those of regular circular and square sections [5, 6]. The results showed that the hybrid model has the advantage of square sections that is low initial peak force and having a circular section with high energy absorption.

Due to high energy absorption capacity under high compressive loading, light-weight foams are

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DOI: 10.22075/macs.2019.16180.1168

considered as fillers in thin-walled structures. The first studies on the use of the foams in energy absorber structures were conducted by Reid et al. in the 80's in which they used polyurethane foam as filler [7]. The results showed that the filling of tubes with foam, increases the energy absorption of collision. More comprehensive studies were carried out later by Hanssen et al. [8, 9]. Aluminum tubes with circular and square sections filled with aluminum foam were investigated experimentally. They established a relationship for the design of such structures. Seitzberger et al. studied the crashworthiness of steel tubes filled with high density foams [10]. The overall result of this study was that absorbed energy can be increased by using filler foams, but the increase in overall weight will reduce the efficiency of filled tubes compared to hollow tubes. The behavior of hollow and foam-filled thin-walled aluminum tubes under oblique load was studied by Reyes et al. [11]. Their study showed that the use of high-density aluminum foam as a filler significantly increases the energy absorption, but the Specific Energy Absorption (SEA) is lower compared to the hollow tube. Aktay et al. numerically and experimentally studied thin-walled aluminum tubes filled with polystyrene foam [12]. The results showed that the absorbed energy from the foam-filled structure is more than the sum of the energy absorbed from the hollow tube (alone) and the foam filler (alone). Also, Rafea Dakhil Hussein et al. experimentally investigated the energy absorption characteristics of square hollow aluminum tubes, aluminum honeycomb-filled tubes, polyurethane foam-filled tubes and aluminum tubes filled with both polyurethane foam and aluminum honeycomb under quasi static compressive load with different velocities [13].

The studies on the foam-filled thin-walled structures are mainly focused on the foams with uniform densities. In order to further investigation on the energy absorption capacity of foam-filled thin-film structures, a new concept of foams, called Functionally Graded Foams (FGFs), is investigated. In these materials, the foam core density varies in axial or transverse directions under different functions in the thin-walled structure. Gupta fabricated a gradient structure for microballoon filled syntactic foams which is capable of withstanding compression for 60–75% strain without any significant loss in strength [14]. Liang Cui et al. proposed a model of FGF that the characteristics of foam (for example, density) have been changed through the thickness according to various gradient functions [15]. They showed that the FG foams could exhibit better energy absorption properties compared to uniform foams under low energy impact. Atiia et al. investigated the crushing behavior of FG foam-filled thin-walled columns and evaluated the effect of density distribution on total and specific energy absorption [16]. Yin et al. examined the energy absorption performance of multi-cell structures filled with FGF [17]. Fang et al. investigated the energy absorption characteristics functionally graded foam-filled tubes in longitudinal and transverse directions under lateral load using finite element analysis [18]. In their study, for both transverse and axial models, the variations are considered as separate layers, where each layer has a uniform density. Kohbor and Kidane proposed an optimal design to study the effect of density variation on load bearing and energy absorption characteristics [19]. Mohammadiha and Ghariblu evaluated the crush behavior of different arrangements of multi-tubes filled by functionally graded foams [20].

Foam injection into a hollow structure for the automakers is much easier than changing the overall structure of energy absorber. It is recommended to use foam filler in such structures. Hence, in this article, the properties of polyurethane foam are extracted for four different densities. The obtained data are utilized as input for the finite element software ABAQUS/Explicit™. Hollow and uniform density foam-filled and layered foam-filled specimens are simulated and the results are extracted and compared with each other. The novelty of this work is the study of crashworthiness charactristics on two new design energy absorber structures. HLH specimen in which the density varies from its lowest value in the middle of the tube to highest value at the two ends and LHL specimen is reversed to the HLH one.

2. Materials and Methods

2.1. Crashworthiness criterions

In order to investigate the energy absorption characteristics of thin-walled energy absorber structures, it is necessary to define indicators for energy absorption [21]. There are many characteristics to evaluate the energy absorption capacity of different structures. Among these indicators, special energy absorption (SEA) is very useful to estimate the absorption capacity of different structures with various materials and weights. The SEA for an energy absorption structure is calculated as:

$$SEA = \frac{EA}{M} \tag{1}$$

where M represents the total mass of the thin-walled structure and EA is the total energy absorbed during crushing, defined by:

$$EA = \int_0^l f(x)dx \tag{2}$$

In Eq. (2), F indicates the collision force in the axial direction and l is the crash distance. It is obvious that high SEA values indicate higher energy absorption.

Another very important characteristic for determining the absorption capacity of the structure is the initial peak force of the collision. This criterion represents the acceleration of the occupants when it comes to severe impact. High values of initial peak force often results in a high negative acceleration, which can cause severe injuries or even death of passengers.

2.2. foam-filler material

The closed-cell polyurethane foams with various densities (under the commercial name FR-6700) are considered in this study as filler. The obtained date set from the compression test for the foam specimens with densities of 160, 240, 320 and 400 Kg/m^3 that carried out in ref. [19] was used as input data in finite element analysis. The stress-strain curves obtained from the compression test performed in ref. [19] are given in Fig. 1.

The data obtained from the empirical test are confirmed with a non-linear phenomenological constitutive model, provided by Liu and Subhash [22], with a general form:

$$\sigma = A\frac{e^{\alpha\varepsilon}-1}{B+e^{\beta\varepsilon}} + e^{c}(e^{\gamma\varepsilon}-1) \quad (3)$$

In Eq. (3), σ and ε indicate compressive stress in MPa and strain in percent respectively. In this study, parameters B, α and β were assumed to be constants for simplification, while A, C and γ are determined as a function of density. The mathematical expression for the parameters of the constitutive model is given in Table 1.

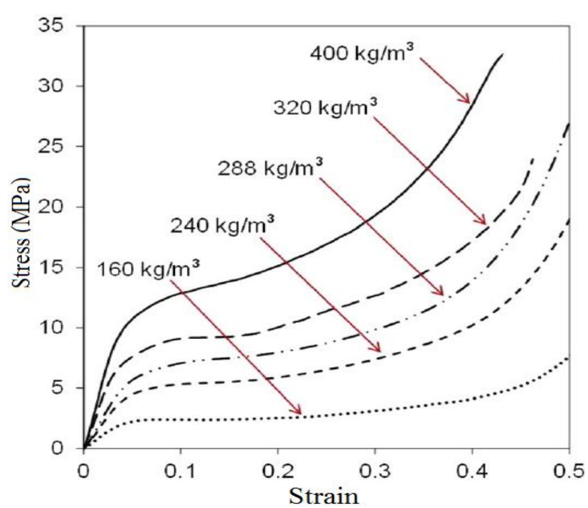

Fig. 1. Experimental true stress-strain curves for foam specimens with various nominal densities [16].

Table1. Mathematical expressions and values of the model parameters as a function of nominal Density [19]

parameter	values
A	$3.378\times10^{-5}+2.351\times10^{-2}\rho-7.105$
C	$-1.675\times10^{-5}\rho^2+2.351\times10^{-2}-7.105$
γ	$-1.248\times10^{-4}\rho+0.130$
B	1
α	0.5
β	0.5

2.3. Finite Element Simulation

The simulated tubes in this paper are composed of a thin-walled tube that is filled with polyurethane foam with different densities and configurations. The dimensions of the thin-walled tube are given in Table 2. In order to apply boundary conditions on the specimens, two rigid plates are placed at the two ends of the tube by using tie constraint. Fixed boundary condition is applied at one rigid plate and 0.5 m/s velocity is applied at another one. Load cases and boundary conditions are exerted in the same way for all specimens.

With the aim of avoiding noisy and inaccurate solutions due to stress wave propagation, a typical smooth loading curve is utilized (Fig. 2). According to Fig. 2, by setting the initial velocity and initial acceleration equal to zero, inessential dynamic effects would be avoided.

If the analysis is quasi-static, the material velocity in that test is very small. This means that inertial force can be neglected [5]. Hence, internal energy is equal to the work exerted by the external force, while the kinetic energy is very small and does not exceed a small fraction of the internal energy.

Table 2. Thin-walled tube dimensions used in the numerical simulation.

Dimensions	Measures (mm)
Cross section	90×90
Thin-walled tube length	400
Thin-walled tube thickness	2
Foam core	$90\times90\times400$

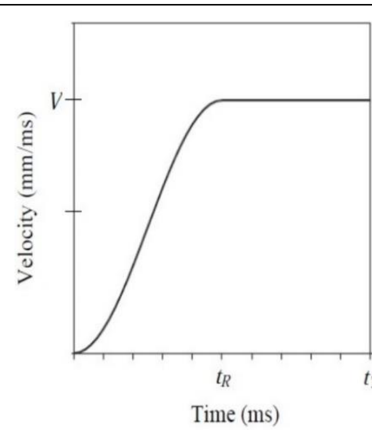

Fig. 2. Typical smooth loading curve [5]

There are three types of contact considered between the thin-walled tube and foam with the rigid plates, the foam core and the thin-walled tube, and adjoining folds on the thin-walled tube. General contact interaction is also utilized in this study. The thin-walled tube is made of steel which the mechanical properties of it are given in Table 3.

First-order square shell elements with four nodes and reduced integral property (S4R) are applied in order to discrete the thin-walled tube. The foam core is meshed using the first-order brick element with eight nodes and one point reduced integration (C3D8R). The reduced integration first-order element suffers from its own numerical difficulty called hourglassing, since it tends to be excessively flexible [23]. In order to overcome this problem, both types of elements are capable of controlling the hourglass phenomenon. After mesh dependency studies, the element size of 5 mm was used.

In this article, a hollow tube, four tubes filled with uniform foam with densities of 160, 240, 320 and 400 (kg/m^3) and three tubes filled with layered foam are simulated. For layered specimens, the foam core in the first specimen is divided into four and in the second and third samples are divided into eight equal layers respectively. In the second layered specimen, in the vicinity of the rigid plates, the density has the highest value, which reaches the lowest value by approaching the middle of the tube. This specimen is briefly named HLH. In the third layered specimen, the variation of the density is reversed, as the maximum density is highest in the middle of the tube, and by approaching the rigid plates, its value decreases and reaches its lowest amount. The third specimen is briefly named LHL. Each layer has a density and mechanical properties corresponding to the density extracted from Eq. (3). The total density is the same for all layered specimens, and the difference is only in the configuration of foam layers. The layered specimens simulated in this study are schematically shown in Fig. 3.

3. Results and discussion

In this study, a square hollow tube is simulated according to the conditions presented in the work of Shojaeefard et al. [5]. The numerical results obtained from the finite element analysis are confirmed with those of the experimental works of the mentioned study (Fig. 4).

Four foam-filled tubes with uniform foam of densities 160, 240, 320 and 400 (kg/m^3) are simulated and the force-displacement and energy-displacement curves are extracted and compared with each other. Moreover, layered specimens which are a combination of different densities are simulated. The force-displacement and energy-displacement curves are obtained for these specimens as well. In all specimens, the total weight of the structure is the same, and the purpose of this study is to find the proper layout for foam layers with respect to the energy absorption and initial peak force. In Fig. 5, the final deformation for the specimens under investigation is presented after applying a quasi-static load. As it can be seen, there is no buckling in the layered specimens and the deformation is started from lower density regions as expected.

Table 3. Mechanical properties of the thin-walled tube [5].

Mechanical properties	measures
Density (kg/m^3)	7800
Young modulus (GPa)	205
Yield stress (MPa)	233.5
Ultimate stress (MPa)	383.5

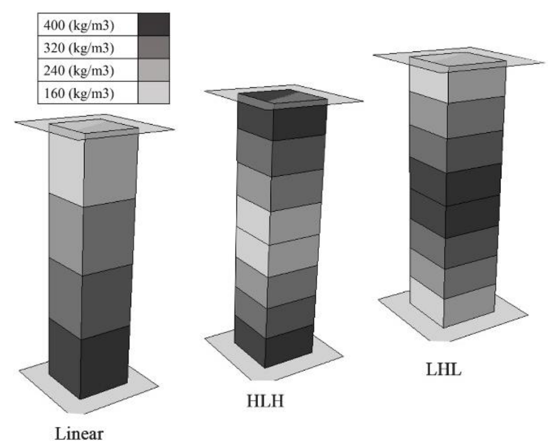

Fig. 3. Schematic of layered foam-filled specimens with different densities.

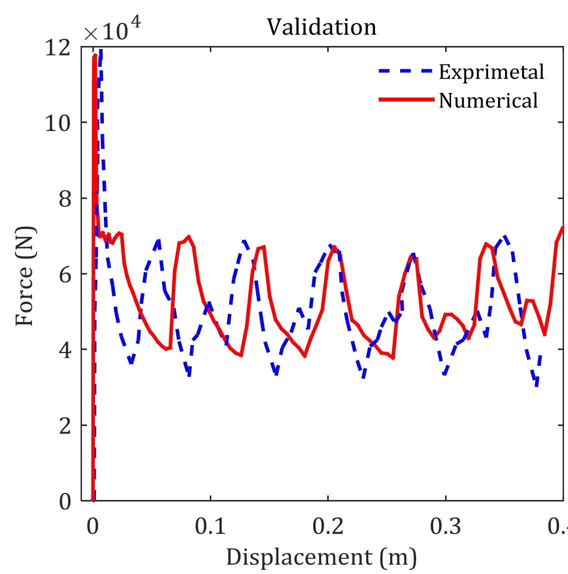

Fig. 4. Comparison of experimental Force- Displacement curves with numerical results [5].

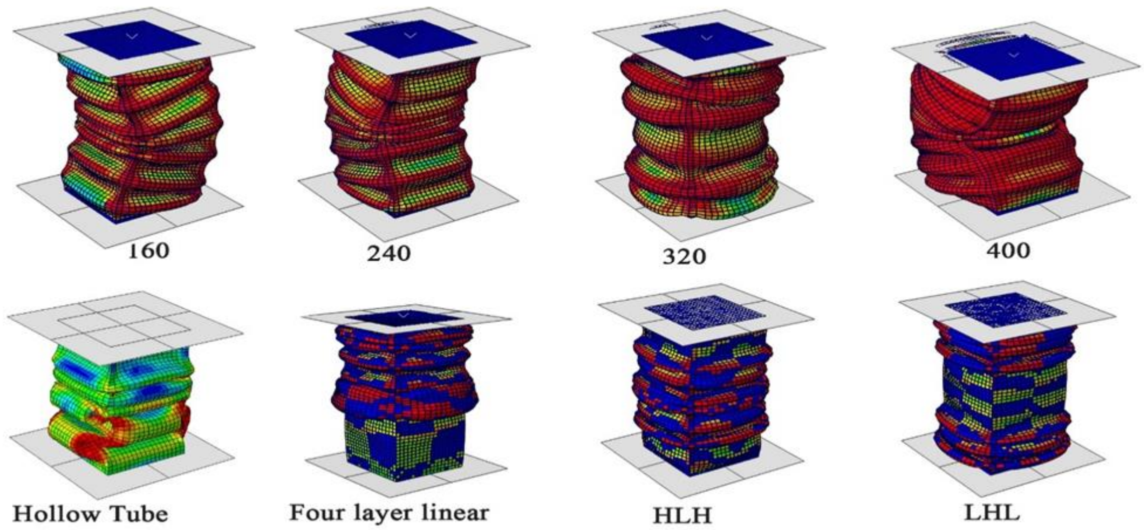

Fig. 5. Final deformed shape of specimens

In Figs. 6 and 7, energy-displacement curves are provided for uniform density foam-filled and layered foam-filled samples respectively, and compared with hollow tube. According to Figs. 6 and 7, it is depicted that the energy absorption in foam-filled thin-walled structures is much higher than that of a hollow tube, and the energy absorption is strongly dependent on the density of the foam. In the layered specimens, since the total mass of energy absorber is the same, the energy absorptions are very close to each other. The insignificant difference observed in the absorbed energy of the layered specimens is due to the different configuration of the layers. Among the layered samples, the LHL one has more energy absorption than other specimens. Compared to the hollow tube, the energy absorption for the LHL sample increased about 114%.

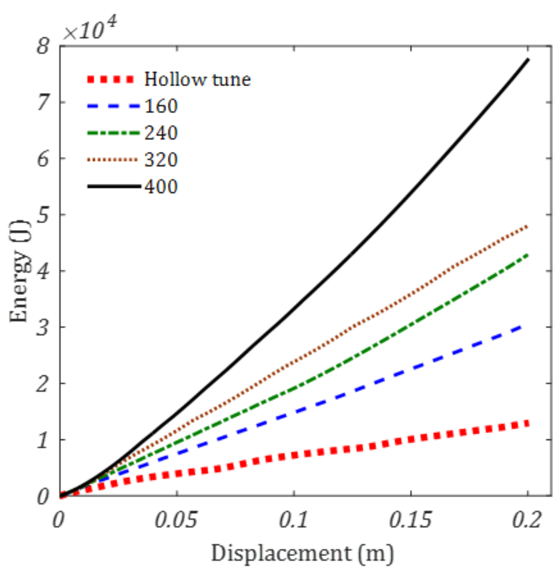

Fig. 6. Energy- displacement curves of uniform density foam-filled specimens compared to the empty tube.

In Figs. 8 and 9, the force-displacement curves are presented for samples filled with uniform foam and layered foam, respectively. The area below the force-displacement curve represents the exerted external work. Since the test is quasi-static and the kinetic energy is very low compared to the internal energy, it can be assumed that the entire external work converted to the internal energy.

Fig. 8 shows that the use of foam, although increases the energy absorption, would lead to an increase in the initial peak force. In foam-filled energy absorbers, there is a direct correlation between the density of foam and the absorbed energy and initial peak force. Fig. 9 indicates that the energy absorption in the hollow tube is far less than that of the layered specimens, while the initial peak force is lower.

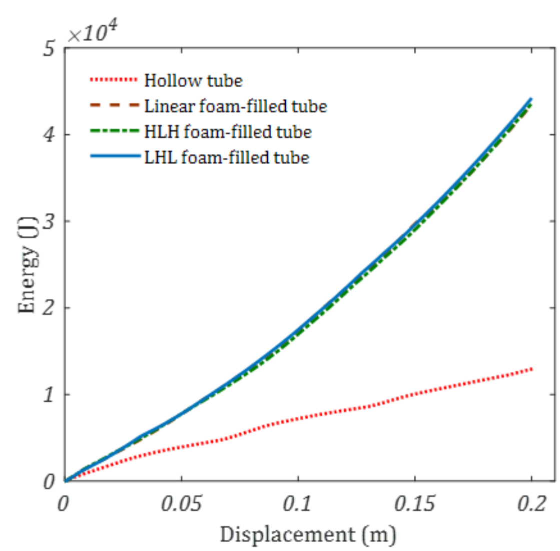

Fig. 7. Energy- displacement Curves of layered Foam-filled specimens compared to the empty tube.

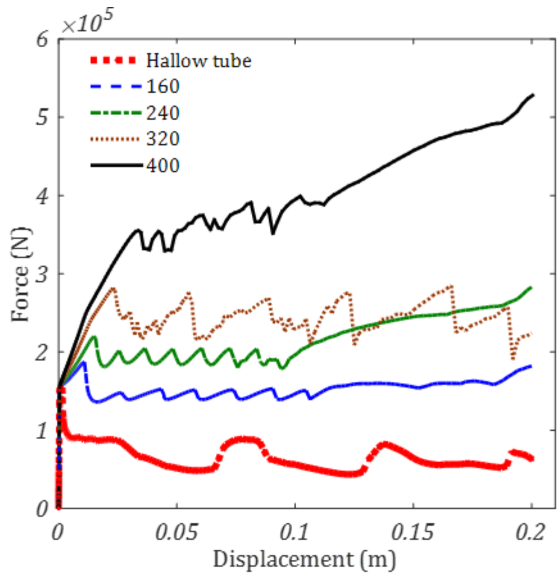

Fig. 8. Load- displacement Curves of Uniform Foam-filled specimens compared to the empty tube.

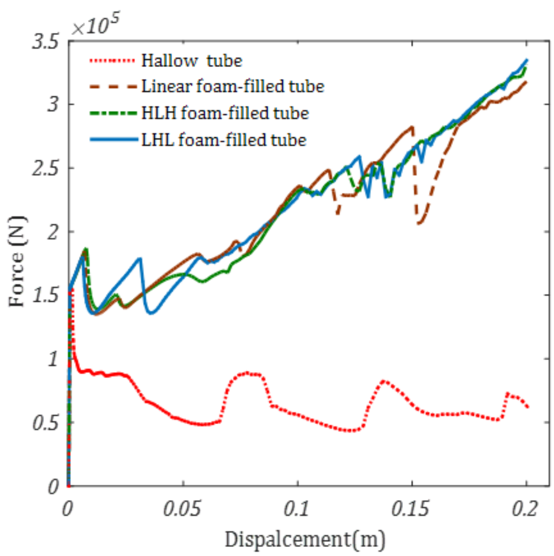

Fig. 9. Load- displacement Curves of Uniform Foam-filled specimens compared to the empty tube.

In Tables 4 and 5, the energy absorption characteristics, such as the initial peak force, the maximum energy absorption, the total mass and the specific energy absorption, are presented for uniform foam-filled and layered specimens, respectively and are compared with hollow tube.

Table 4 shows that the foam has a great influence on increasing the energy absorption. The use of 400 (kg/m^3) foam has increased 332% in energy absorption compared to the hollow tube. As mentioned, the density of foam filler has a direct correlation with the initial peak force. The foam filler with a density of 400 (kg/m^3) increases the initial peak force by 130% compared to the hollow tube.

The use of layered foam in thin-walled energy absorbers has caused a significant reduction in initial peak force. Table 5 shows that the initial peak force for all layered samples is approximately equal to the initial peak force associated with uniform foam with a density of 160 (kg/m^3). As a result, the initial peak force for a layered energy absorber is very close to the initial peak force for the layer with the lowest density. Among the layered specimens, the LHL has a lower initial peak force, which is 16% higher than the hollow tube. Layered foam-fillers also absorb more energy than the hollow tube, which is approximately equal to the energy absorption for the layer with the highest density. The LHL also has a higher specific energy absorption compared to other specimens and an increase of 114% compared with the hollow tube.

4. Conclusion

In this article, energy absorption characteristics such as initial peak force and specific energy absorption for hollow and uniform foam-filled and layered foam-filled specimens under quasi-static loading are numerically investigated. Polyurethane foam with different densities is used as filler in a thin-walled structure. Layered samples are simulated in linear form, LHL and HLH.

Table 4 Energy absorption characteristics of uniform specimens.

Specimens (Density)	Initial Peak Force (kN)	Max. Energy Absorption (kJ)	Mass (kg)	SEA (kJ/kg)
Hollow tube	154.8	14.76	2.246	6.572
160	187.17	30.57	2.756	11.057
240	219.76	42.9	3.024	14.188
320	281.52	48.02	3.283	14.625
400	355.19	100.62	3.542	28.403

Table 5. Energy absorption characteristics of layered specimens.

Specimens (Density)	Initial Peak Force (kN)	Max. Energy Absorption (kJ)	Mass (kg)	SEA (kJ/kg)
Hollow tube	154.8	14.76	2.246	6.572
Four layers	184.77	43.479	3.146	13.82
HLH	186.99	43.605	3.146	13.86
LHL	179.46	44.212	3.146	14.052

According to the results, the use of polyurethane foam, although increases the internal energy, it has increased the initial peak force. The energy absorption and initial peak force have been influenced by foam density. For layered specimens, the initial peak force is approximately equal to the initial peak force associated with the specimen filled with low density foam and energy absorption is approximately equal to the energy absorption of the specimen filled with low density foam. Among the layered specimens, the LHL sample has better crashworthiness characteristics than other specimens. In comparison with the hollow sample, the initial peak force and the specific energy absorption have increased about 16% and 114%, respectively.

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