STRUCTURAL ANALYSIS OF SANDWICH THIN-WALLED HOLLOW CYLINDRICAL TUBES WITH ALUMINUM FOAM FILLER SUBJECTED TO LOW VELOCITY AXIAL LOAD USING NUMERICAL SIMULATION

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Abstract

Impact safety and weight-saving are two important criteria for energy-absorbing structures in train, car and aircraft design. Innovations in light-weight material such as metallic cellular material, aluminum foam have developed significantly; it opens many researches to enhance capability of energy absorber. Research on structure of sandwich thin-walled cylindrical tubes with aluminum foam filler has been conducted much; however, the number of researches focusing on sandwich thin-walled hollow cylindrical tubes with aluminum foam filler is limited. This paper presents numerical analyses of sandwich thin-walled hollow cylindrical tubes with aluminum foam filler subjected to low velocity axial loading using a non-linear finite element method. The objective is to predict and compare the behavior of these structures in absorbing energy.

Keywords: Aluminum foam, Crashworthiness, Energy-absorbing, LS-DYNA

Introduction

Crashworthiness and weight reduction are two important design objectives for energy absorption structures in the automotive industry. The crashworthiness of automobile structures is characterized by the ability of energy absorption when subjected to crushing impact. One of methods increasing capability of energy absorption is usage of crash boxes. The ideal models describing a typical crash box are the prismatic structures with cross sections of a circle, a square and many other types of geometry.

Researches focusing on behavior of thin-walled structures have been conducted for many years [1]. In this topic, crushing phenomenon of aluminum tubes with foam filler was studied by Abramowicz et al. [2] and Hanssen et al. [3]. However, there have been very limited numbers of researches being carried out on sandwich structure of hollow cylindrical tubes with aluminum foam filler subjected to axial impact loading. Therefore, this paper concentrates on the cases of hollow cylindrical tubes, single-walled and double-walled cylindrical tubes inserted with foam material as well as changing their geometry so as to compare the energy absorption capability among them by using numerical simulation.

Theoretical Review

Energy Absorption Characteristics

Energy absorption, E_a is a crucial criterion when designing impact structures. To identify the precise value, E_a is calculated by integration of a load-displacement curve as follows:

$$E_a = \int_0^{\delta_{max}} P(\delta) d\delta \tag{1}$$

where $P(\delta)$ is an instantaneous crushing load, δ and δ_{max} are the present and maximum crushing displacement, respectively. The mean crushing load can be determined from Equation (1):

$$P_{mean} = \frac{1}{\delta} \int_0^{\delta} P(\delta) d\delta \tag{2}$$

For practical applications, the mean crushing load is employed as a measurement of energy absorbing capability of a structure corresponding to a specific axial displacement. In terms of thin-walled tubes, the pattern of load-deflection curve is similar to Figure 1. Generally, load fluctuates during the formation and proliferation of progressive crushing. The initial peak load, P_{peak} is determined by the highest initial load point as shown in Figure 1. Noting that the maximum peak load is also a sign of the load required to initiate collapse and begin the energy absorption process. In realistic contexts, the mean crushing and initial peak load are the pivotal parameters in assessing the energy absorption characteristics of energy absorbers.

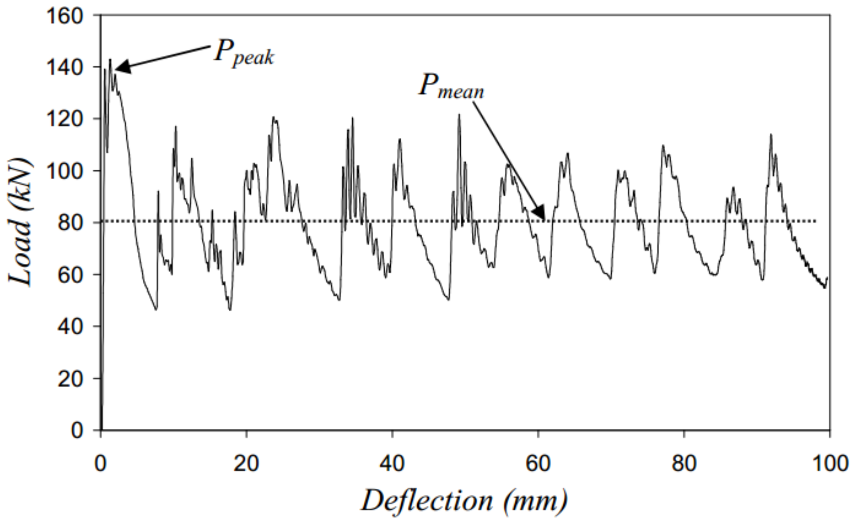


Figure 1. Load-deflection response of a metallic-filled cylindrical tube under axial loading [4]

Thin-Walled Cylindrical Tubes

The investigation of axial crushing behavior of thin-walled cylindrical tubes plays an important role in analysis of energy absorption performance. Among impact structures, cylindrical tubes are preferable and utilized prevalently given that they represents productive and light crash absorbers in case of axial loading.

Throughout the process of dynamic axial progressive buckling, it is witnessed that the collapse pattern of a cylindrical tube is effective and productive since the force-displacement relation is stable. In addition, deformation of circular tubes can be classified into 3 modes: axisymmetric ring (concertina mode), non-axisymmetric (diamond mode) and mixed mode, respectively. Figure 2 illustrates typical collapse modes of actual specimens subjected to axial loading.

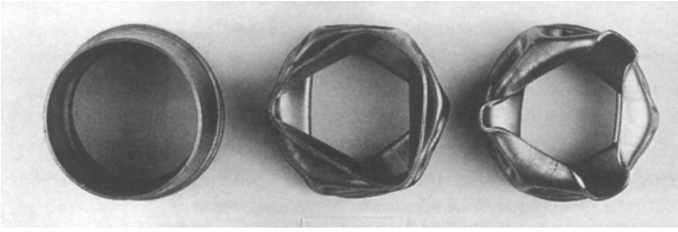


Figure 2. Typical collapse modes of cylindrical tubes under axial loading
Left: Concertina mode, Middle and Right: Diamond mode [2]

Metal Foam Material

In recent years, metal foam has gained currency in industry thanks to light weight and astonishing capability of energy absorption. Under the view of material engineering, composition of metal foam comprises two core components. The first one is a base metal which is generally aluminum and the other component is pores (air bubble) constituting approximately 75-95% volume of the material block.

A unique and salient characteristic of metal foam which makes it different from other materials is the ability to endure a large strain deformation while keeping a low stress level. This characteristic corresponds to plateau region in Figure 3. A conventional stress-strain relationship of metal foam materials includes 3 specific regions: an elastic region is small and similar to steel, a plateau region where the stress increases marginally in comparison to strain and a densification region where the load increases significantly as cellular structure of the foam is fully crushed, separate cells begin to contact with each other.

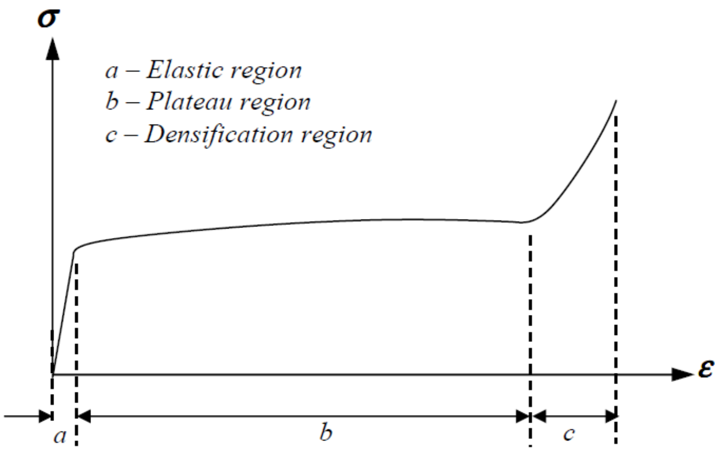


Figure 3. A typical nominal stress-strain curve for foam materials [4]

Beside the wide exploitation in means of transportation thanks to superior energy absorption capability along with light weight, another usage of metal foams is reinforcement of thin-walled tubes. In fact, foam filling can improve sharply the energy absorbing performance of crash components with just a minor rise in mass. The characteristic parameter of foam material is plateau stress, σ_p and a function of foam density [5]:

$$\sigma_p = C\left(\frac{\rho_f}{\rho_{f_0}}\right)^m \tag{3}$$

where ρ_f is the foam density, ρ_{f_0} is the density of the base material, C and m are material coefficients.

To identify the material parameters of aluminum foams namely the yield stressσ_y, a constitutive model is introduced based on the strain hardening rule [6]:

$$\sigma_y = \sigma_p + \gamma \frac{\hat{\varepsilon}}{\varepsilon_D} + \alpha_2 ln \left[\frac{1}{1 - \left(\frac{\hat{\varepsilon}}{\varepsilon_D} \right)^{\beta}} \right] \tag{4}$$

where α_2, β, γ are material parameters; $\hat{\varepsilon}$ is the equivalent strain; σ_p and ε_D are the plateau stress and densification strain.

Mean Axial Crushing Load of Cylindrical Tubes

In this paper, axisymmetric (concertina mode) crushing is concerned for circular tubes due to the prevalence and highly practical application of them. Abramowicz et al. [2] have developed equations predicting the mean axial crushing load:

$$\frac{\bar{P}_m{}^d}{M_0} = \left(\frac{20.79(2R/h)^{1/2} + 11.90}{0.86 - 0.568(h/2R)^{\frac{1}{2}}} \right) \left[1 + \left(\frac{0.25V}{6844R(0.86 - 0.568(h/2R)^{1/2})} \right)^{1/3.91} \right] \tag{5}$$

for symmetric crushing mode, with R is the tube radius, h is the thickness of the tube, V is the velocity of the impactor and

$$M_0 = \left(\frac{2\sigma_y}{\sqrt{3}} \right) \left(\frac{h^2}{4} \right) \tag{6}$$

Interaction Effect

After foam filling, the energy absorption capability of foam-filled tubes increases considerably and the rooted cause for this phenomenon is the interaction effect between cylindrical wall and aluminum foam filler. Interestingly, both mean crushing force and energy absorption capacity of aluminum foam-filled tubes are higher than when comparing to the sum of the mean crushing forces and energy absorption of aluminum foam and an empty tube separately. Interaction effect is affected and governed profoundly by geometrical and material parameters of both aluminum foam and cylindrical wall. To quantify the interaction effect, Hanssen et al. [3] basing on comprehensive experiments concluded an empirical formula for the mean crushing load of aluminum foam-filled cylindrical tubes, $\bar{P}_{mf}$ by dividing it into three parts: mean crushing load of the empty tube, $\bar{P}_m$; axial resistance from aluminum foam filled in the tubes, $\sigma_p A_f$ and interaction effect is represented by C_{avg}:

$$\bar{P}_{mf} = \bar{P}_m + \sigma_p A_f + C_{avg}\sqrt{\sigma_p \sigma_y} A_0 \tag{7}$$

where A_f and A_0 are the cross-sectional area of the foam core and tube, respectively and σ_y is the yield stress of the tube material.

Regarding to double-walled foam-filled cylindrical tubes, the mean axial crushing load is estimated by adding the mean axial crushing load of the inner tube:

$$\bar{P}^{d}_{mf2} = \bar{P}^{d}_{mf} + \bar{P}^{d}_{mt} \quad (8)$$

where $\bar{P}^{d}_{mf}$ is the mean crushing load for the case of single-walled foam-filled cylindrical tube, $\bar{P}^{d}_{mt}$ is the mean crushing force for the inner tube.

Finite Element Model

Model Geometry

Case 1: Hollow Cylindrical Tube

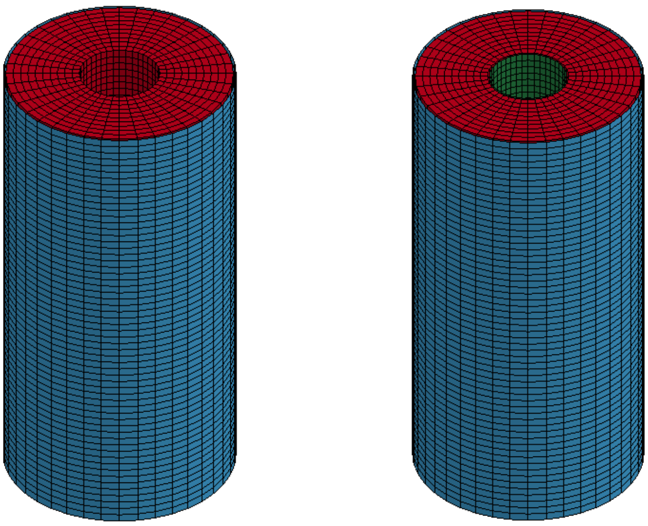
Geometric parameters: 3 types of tube with diameters D = 60 mm, D = 70 mm, D = 80 mm; length L = 120 mm; thickness h = 1.4 mm.

Case 2: Single-Walled Cylindrical Tube Filled with Foam

Geometric parameters: 3 types of tube with diameters D = 60 mm, D = 70 mm, D = 80 mm; length L = 120 mm; outer tube thickness h = 1.4 mm; inner radii of foam r = 5, 10, 15, 20 mm. Typical tube is shown in Figure 4(a).

Case 3: Double-Walled Cylindrical Tube Filled with Foam

Geometric parameters: 3 types of tube with diameters D = 60 mm, D = 70 mm, D = 80 mm; length L = 120 mm; outer tube thickness h = 1.4 mm; inner radii of foam r = 5, 10, 15, 20 mm; inner tube thickness ht = 0.5, 0.7, 1 mm. Typical tube is shown in Figure 4(b).



(a) (b)

Figure 4. Geometry of a cylindrical tube filled with foam:
(a) single-walled, (b) double-walled

Mesh Size

The thin walls of the tubes are simulated by the shell element. The number of elements along the length is 60 and the number of elements along the circumference is 40.

The foam block is simulated as the solid element. The number of elements along the length is 60 and the number of elements along the circumference is 40.

The impactor is described as the solid element with the Young's module E = 200 GPa and mass M = 65 kg.

Material Characteristic

The tubes are characterized as mild steel RSt37 with density ρ = 7830 kg/m^3, Young's module E = 200 GPa, Poisson coefficient ν = 0.3, yield stress σ_y = 215 MPa. Piece-wise linear plasticity is chosen in LS-DYNA.

The foam material (Deshpande–Fleck Foam model) used in this paper shown in Table 1.

Table 1. AluLight Aluminum Foam Parameters [7]

ρ_f (g/cm^3)	E (MPa)	α	γ (MPa)	ε_D	α_2 (MPa)	β	σ_p (MPa)
0.34	1516	2.12	3.92	2.07	60.2	4.39	5.76

Boundary Condition and Interface Contact Condition

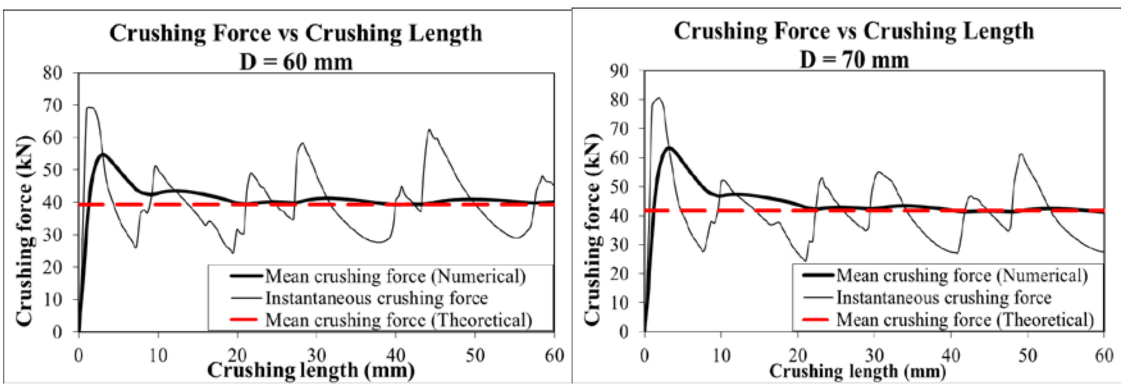
Clamped boundary conditions are applied at the bottom of the tube. The impactor has the initial velocity V = 10 m/s for all nodes.

Four different contact algorithms available in LS-DYNA are used. The contact between the impactor and the tubes is modelled with an automatic-node-to-surface contact. The contact between the impactor and the foam filler is modeled with an automatic-surface-to-surface contact. Automatic-single-surface contact is applied to the tubes to avoid interpenetration of folds generated during axial collapse. Tied-surface-to-surface-failure contact is used to represent the shearing contact between the tubes and the foam filler.

Results

Validation of Hollow Cylindrical Tubes

Response of hollow circular tubes described in Section 3.1.1 subjected to a 65 kg impactor dropped at 10 m/s velocity are plotted in Figure 5. The deformation of a typical cylindrical tube with D = 60 mm is shown in Figure 6. Mean crushing force obtained in numerical simulation has been matched very well with analytical results calculated from Equation (5). Therefore, simulation of hollow cylindrical tubes is validated.



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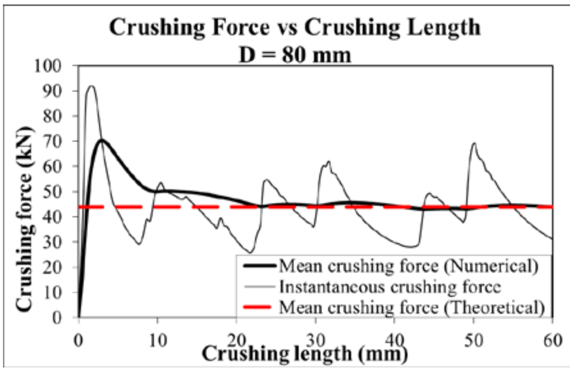


(c)

Figure 5. Crushing force response of hollow cylindrical tubes with 3 cases of tubes: (a) D = 60 mm, (b) D = 70 mm, (c) D = 80 mm

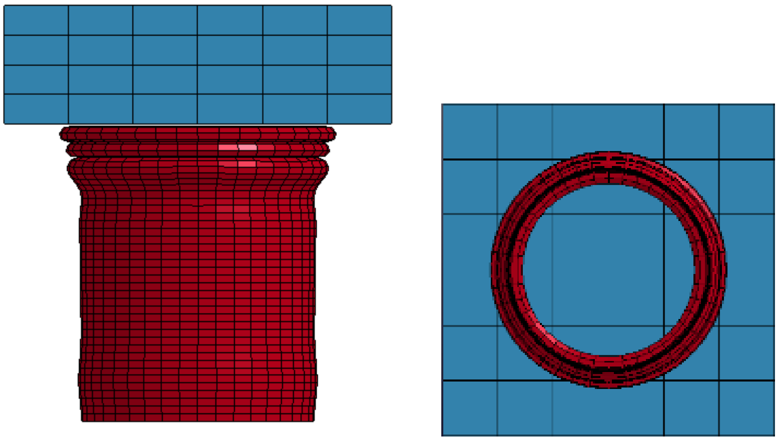
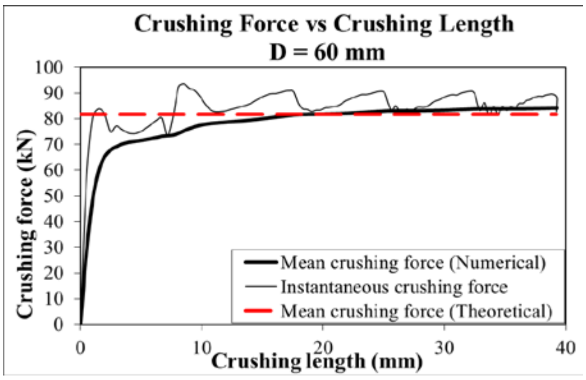


Figure 6. Deformation of hollow cylindrical tube with D = 60 mm

Validation of Sandwich Single-Walled Cylindrical Tubes Filled with Full Foam

Response of sandwich circular tubes described in Section 3.1.1 filled with full foam subjected to a 65 kg impactor dropped at 10 m/s velocity are plotted in Figure 7. The deformation of typical single-walled cylindrical tube D = 60 filled with foam is shown in Figure 8. Mean crushing force obtained in numerical simulation has been matched very well with analytical results calculated from Equation (7). Therefore, simulation of sandwich cylindrical tubes filled with full foam is validated.



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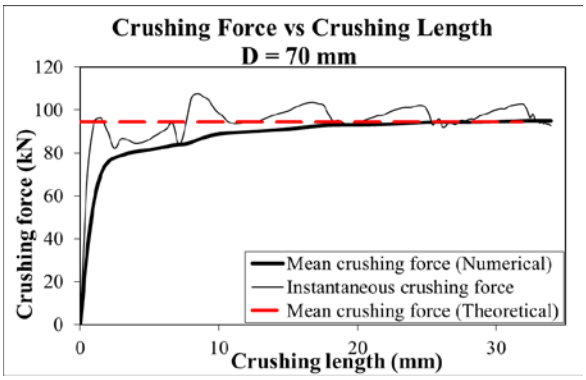

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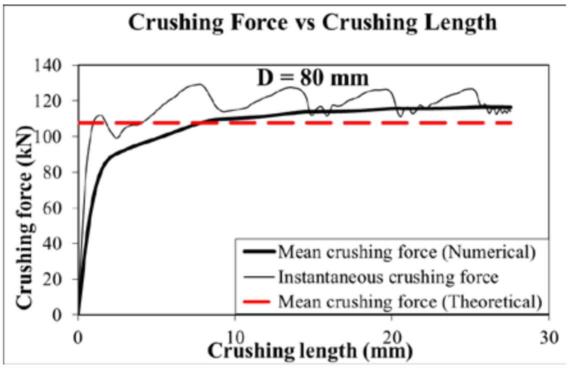

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Figure 7. Crushing force response of single-walled cylindrical tubes filled with full foam: (a) D = 60 mm, (b) D = 70 mm, (c) D = 80 mm

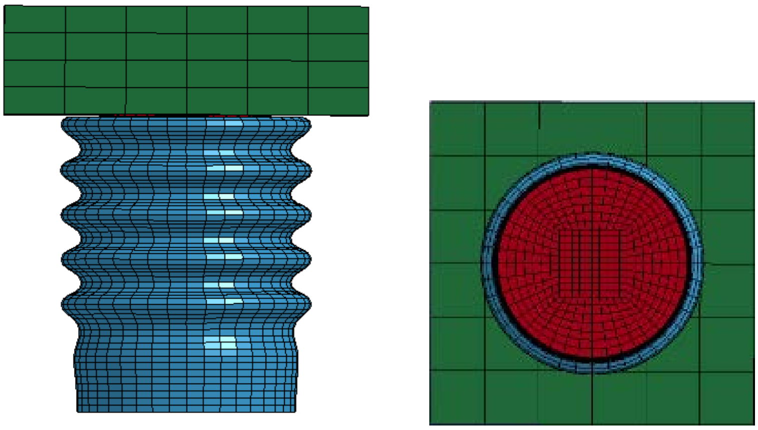
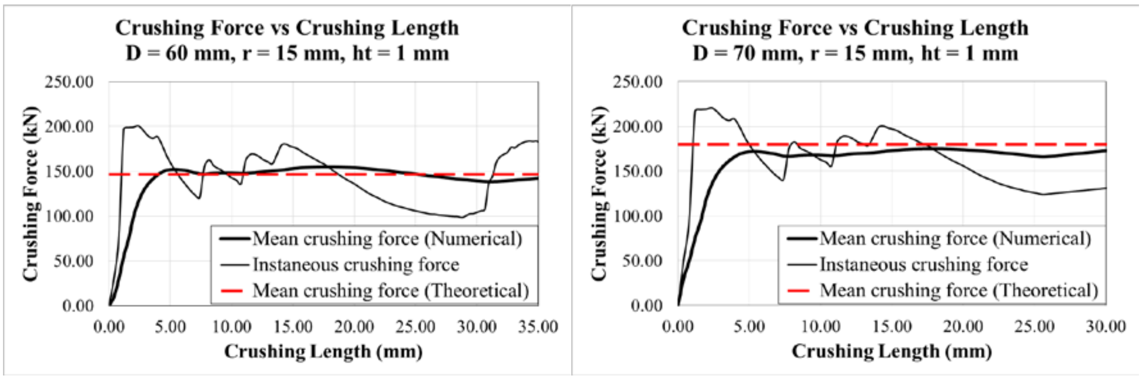


Figure 8. Deformation of single-walled cylindrical tube filled with full foam: D = 60 mm

Validation of Sandwich Double-Walled Cylindrical Tubes Filled with Foam

Response of several sandwich double-walled circular tubes described in Section 3.1.3 filled with foam subjected to a 65 kg impactor dropped at 10 m/s velocity are plotted in Figure 9. The deformation of a typical double-walled cylindrical tube D = 60, inner radius of foam r = 15 mm; inner tube thickness ht = 1 mm filled with foam is shown in Figure 10. Mean crushing force obtained in numerical simulation has been matched very well with analytical results calculated from Equation (8). Therefore, simulation of sandwich double-walled cylindrical tubes filled with foam is validated.



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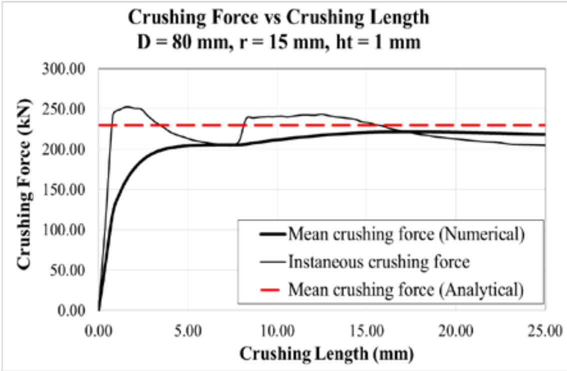


(c)

Figure 9. Crushing force response of double-walled cylindrical tubes filled with foam (r = 15mm, ht = 1 mm):
(a) D = 60 mm, (b) D = 70 mm, (c) D = 80 mm

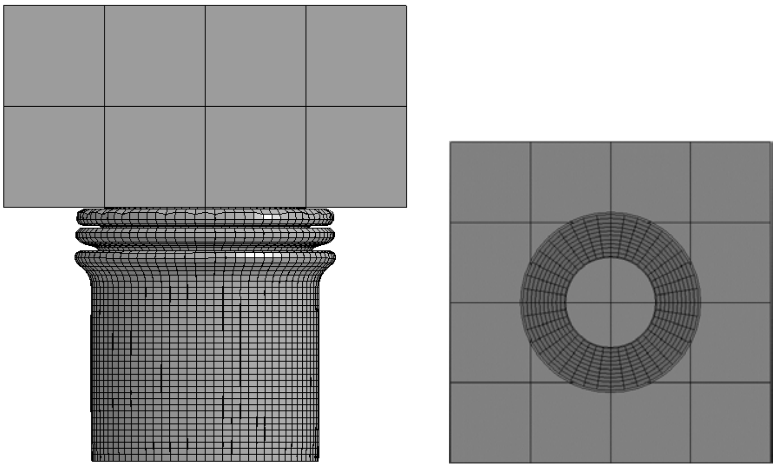
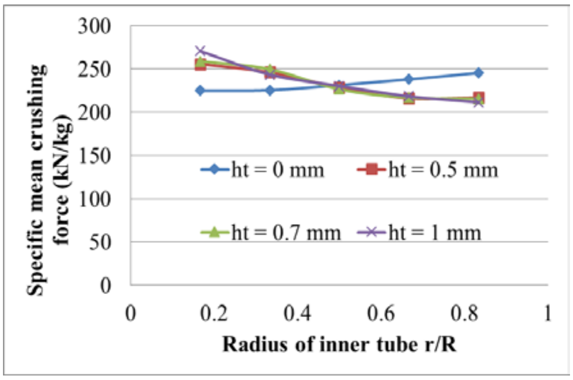


Figure 10. Deformation of double-walled cylindrical tube filled with foam: D = 60 mm

Energy Absorbing Capability

In order to compare the energy absorbing capability of structures, specific mean crushing force (SMCF) is defined as mean crushing force per unit mass of tube. SMCF distributions of single-walled and double-walled cylindrical tubes filled with foam are plotted in Figure 11. In here, the case of ht = 0 mm means single-walled structure and increase of r/R means decrease of foam core thickness.



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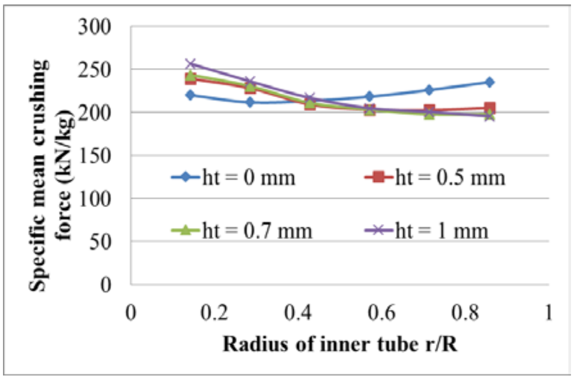

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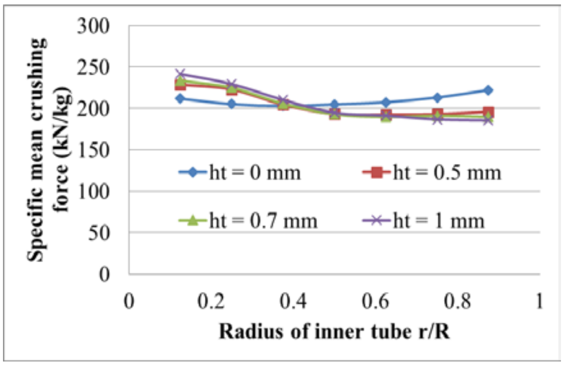
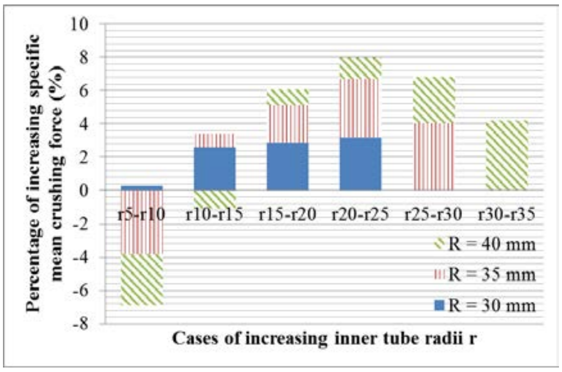


(c)

Figure 11. Specific mean crushing force: (a) R = 30 mm, (b) R = 35 mm, (c) R = 40 mm

It is observed in Figure 11 that SMCF in the case of single-walled foam-filled tubes has the tendency to rise when the inner radius of the tubes is increased. The amount of this increase is about 10%. Further comparison of SMCF for single-walled sandwich tubes which is different about 5 mm in radius of inner tube for each pair is described in Figure 12(a). It may be seen that the increase of SMCF is proportional with outer radius of the structure.

On the contrary, double-walled foam-filled tubes has the tendency to reduce SMCF when the inner radius of the tubes is increased. This SMCF decrease is taken about of 25% which is illustrated in Figure 12(b)-(d). However, this decrease is not significant if the ratio of r/R larger than 0.5. Furthermore, the amount of decrease SMCF is proportional with outer radius of the structure.



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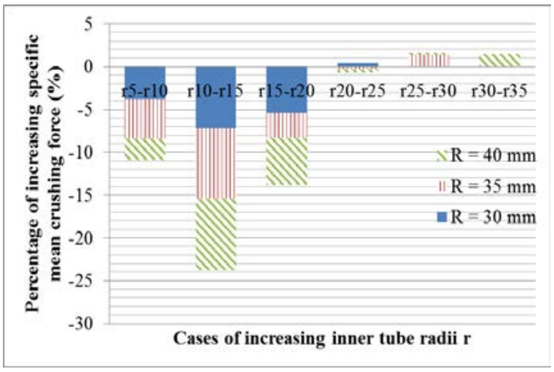

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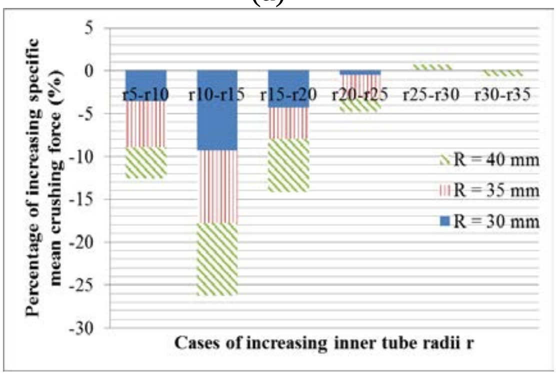

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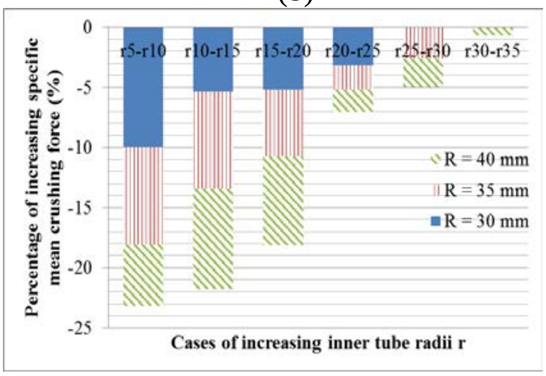

(d)

Figure 12. Comparison of SMCF for single-walled and double-walled foam-filled tubes:
(a) ht = 0 mm, (b) ht = 0.5 mm, (c) ht = 0.7 mm, (d) ht = 1 mm
(note: r5-r10: case of changing inner radii from r = 5 mm to 10 mm)

Conclusions

In this paper, the mean crushing force of sandwich thin-walled hollow cylindrical tubes has been predicted both analytically and numerically. The analytical predictions agreed well with numerical simulation results. Effect of changing the inner radius of the hollow tubes has been taken into account. The conclusions are summarized as follows:

- The SMCF in the case of single-walled foam-filled tubes has the tendency to rise when the inner radius of the tubes is increased. And it is also proportional with outer radius of the structure.
- Conversely, the SMCF in the case of double-walled foam-filled tubes decrease when the inner radius of the tubes increase. And the amount of decrease SMCF is proportional with outer radius of the structure.

The results of this study can be an important guideline for application of the sandwich thin-walled hollow cylindrical tubes with aluminum foam filler.

Acknowledgements

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