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Procedia Manufacturing 7 (2017) 225 – 233

Procedia
MANUFACTURING

International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2017, 23-25 January 2017, Kruger National Park

Energy Absorption of Foam Filled Aluminum Tubes under Dynamic Bending

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Abstract

In this article, energy absorption of foam filled and empty aluminum alloy tube under dynamic bending were investigated numerically and experimentally. The material model for aluminum foam was based on the implementation of crushable foam with isotropic hardening combined with strain rate dependence in ABAQUS. Model parameters were determined from quasi-static ($\dot{\varepsilon}$=1x10-3 s^{-1}) and dynamic compression tests on closed cell aluminum foam. The Johnson cook material model was used for tubes. Energy absorption capacity of foam filled aluminum alloy AA7075 tubes was higher than the empty tubes. The peak loads and energy absorption values between experimental results and simulation were found to be in good agreement. At high strain rates, an increase in the energy absorption capacity was observed, which is useful for crashworthy applications.

Peer-review under responsibility of the organizing committee of SMPM 2017

Keywords: Aluminum alloy, Energy absorption, Crashworthiness, Crushable foam

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1. Introduction

In passenger cars, Side Impact Beam (SIB) is used as crashworthy structure which strengthens the door of the vehicle and protects passengers from side collisions [1]. Aluminum alloys tubes are mostly used as side impact beam because of their improved strength-to-weight ratios which is a key factor for fuel economy. Mostly metallic circular cylindrical aluminum alloy tubes are used as energy absorbers because of low weight and ease of manufacturing process. The severity of the side collision in the passenger cars can be reduced by increasing the load carrying capacity and energy absorption characteristics of the aluminum alloy tube [2]. In recent days aluminum foams have shown

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Peer-review under responsibility of the organizing committee of SMPM 2017
doi:10.1016/j.promfg.2016.12.054

interesting properties for shock absorption and crashworthiness applications in aviation and automotive sectors. The load carrying capacity, energy absorption characteristics of a SIB tube can be tested by dynamic three-point bending test method (Federal Motor Vehicles Safety Standard No. 214).

In the present work, a finite element (FE) model is developed for simulating the effect of filling closed cell aluminum core inside AA7075 tube subjected to impact bending test. CATIA modeling is used as a modeling tool and ABAQUS (ABAQUS User's Manual) is used as a finite element solver. For verifying the suitability of FE model, the results obtained are compared with experimental testing.

Nomenclature

SIB	Side Impact Beam
E_a	Energy absorption
ρ^*	Density of foam
ρ_s	Density of aluminium
σ_{pl}	Plateau stress
ε_D	Densification strain

2. Experimental testing

2.1. Quasi static compression test on closed cell aluminum foam:

Relative density (ρ^*/ρ_s) of the closed cell aluminum foam filler has been measured in six specimens and the average was estimated around 0.16. To determine the quasi-static ($\dot{\varepsilon} = 1\times10^{-3}\ \mathrm{s}^{-1}$) response of the foam, four compression test specimens were cut into regular square prisms of size $20\times20\times40$ mm using wire cutting machine and then uniaxial compression at a crosshead speed of 1 mm/min.

2.2. Dynamic compression test on closed cell aluminum foam:

Impact compression tests of foam at higher strain rates ranging from 400 to 1000 s^{-1} were performed using modified Split Hopkinson pressure bar setup. A total of 18 tests were conducted at targeting pressures of 1.5 kg/cm^3, 2 kg/cm^3, 4 kg/cm^3 in order to determine strain rate sensitivity of foam specimen.

2.3. Drop weight impact test on empty and foam filled tube:

Drop weight impact tests were performed on empty and foam filled circular AA7075 tubes of length 150 mm, outer and inner diameter of 24 mm and 19 mm respectively as shown in Figure 1 (Fractovis plus, Ceast). Impactor having 3.56 kg weight with a nose of 20.0 mm diameter was impacted at a velocity of 2.0 m/s at the center of the specimen. The force displacement of sample and energy absorbed by the sample was recorded directly from the data acquisition system.

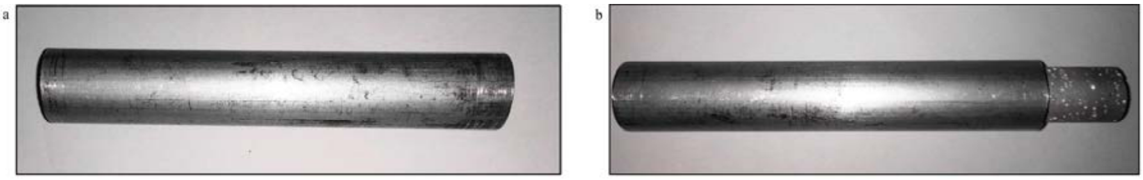

Figure 1. (a) Photographs of empty AA7075 tube b) AA7075 tube with foam core

3. Finite element modeling:

The tube, loading device and supports are modeled by using CATIA. Figure 2 shows the meshed model. In order to reduce the computation time, the tube is modeled as deformable bodies while the loading device and supports are considered as rigid bodies. The tube is supported by the rollers as shown in Figure 2. The loading device is placed at the center of the tube and it is pressed at different velocities. By taking shell elements for both the foam & tube the contact interaction between them is numerical difficulty because of this reason 4-node solid elements are taken for foam & tube. Initially, the exactness of the developed FE model is verified by comparing the force-displacement curve obtained with the experimental and the same FE model is used to carry out simulation at higher velocities.

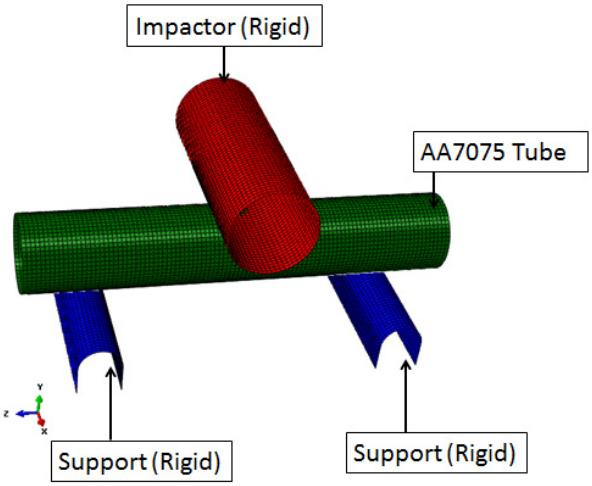

Figure 2: Meshed Model

4. Material models and properties

4.1. Material model of closed cell aluminum foam core

Closed cell aluminum foam was modeled by the means of the implementation of an isotropic hardening model contained in the FEA code ABAQUS, which was originally proposed by Deshpande and Fleck [3].The model assumes the usual decomposition of the total strain rate into its elastic (ε_{ij}^{e}) and plastic part (ε_{ij}^{p}).

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \tag{1}$$

The elastic part is given by the linear constitutive equation

$$\sigma_{ij} = C_{ijkl} \bullet \varepsilon_{lk}^{e} \tag{2}$$

Where C_{ijkl} is the elasticity tensor. The plastic strain rate is given by

$$\varepsilon_{ij}^{p} = \dot{\lambda}\frac{\partial G}{\partial \sigma_{ij}} \tag{3}$$

Where $\dot{\lambda}$ ˙is the non-negative plastic flow multiplier. The flow potential is defined as

$$G = \sqrt{q^2 + \beta^2 p^2} \tag{4}$$

Where q q is the Mises stress, p is the pressure stress and β represents the shape of the flow potential envelope. β is related to the plastic Poisson's ratio υ_p according to

$$\beta = \frac{3}{\sqrt{2}}\sqrt{\frac{1-2\upsilon_p}{1+\upsilon_p}} \tag{5}$$

For aluminum foam the plastic Poisson's ratio υ_p nearly zero, which corresponds to value of β~2.12. The remaining input parameter of the model was extracted from quasi static compression test of the foam. Material properties of quasi-static compression test were used in the constitutive model to be implemented for the foam in the computational code. The mechanical properties of foam were obtained from the stress-strain curve shown in Figure 3. These properties are the Young's modulus (E), the yield stress at 0.2 % of the total strain (σ_y), the compressive strength (σ_c), the plateau stress (σ_{pl}) and the densification strain (ε_D) (see Table 1.)

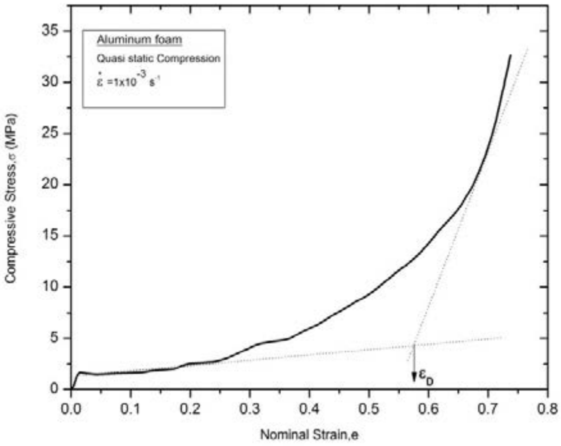

Figure 3: Compressive stress vs nominal strain curve of foam core

Table 1: Mechanical properties of aluminum foam under quasi static compression.

Foam Density, ρ* (g/cm^3)	Relative Density, ρ*/ρ$_s$	Young's Modulus, E (GPa)	Plateau stress, σ_{pl}(MPa)	Densification strain, ε_D
0.4191	0.16	0.7	2.5	0.57

4.2. Rate dependence of closed cell aluminum foam core

At higher strain rate, aluminum foam shows an increase in the yield stress. Cowper-Symonds overstress power law [4] was implemented to define strain rate dependence. Based on power law the dynamic flow stress is expressed as

$$\bar{\sigma}^{c}_{dyn} = \bar{\sigma}^{c}_{sta}\left[1+\left(\frac{\bar{\varepsilon}^{p}}{d}\right)^{\frac{1}{n}}\right] \tag{6}$$

Where $\bar{\sigma}^{c}_{sta}$ is the static uniaxial compression yield stress, $\bar{\sigma}^{c}_{dyn}$ is the yield stress at a non-zero strain rate and $\bar{\varepsilon}^{p}$ is the equivalent plastic strain rate. Strain rate sensitivity n=1.285, d=2319 1/sec calculated from dynamic compression test was used in simulation.

4.3. Material model of AA7075 tube

The material model for AA7075 tube was modeled by means of Johnson-cook material model contained in the FEA code ABAQUS.

$$\sigma = \left[\mathrm{A} + \mathrm{B}\varepsilon_p^n\right]\left[1 + \mathrm{C}\ln\dot{\varepsilon}^*\right]\left[1 - \mathrm{T}^*\right] \tag{7}$$

Where $\dot{\varepsilon}^* = \bar{\varepsilon}_p / \dot{\varepsilon}_D$ and $T^* = \left(T - T_r\right)/\left(T_m - T_r\right)$.

Table 2: J-C material model parameters for AA7075-T6 [5]

Constant	A (MPa)	B (MPa)	n	C	m
AA7075-T6	546	678	0.71	0.024	1.56

5. Results and discussion

5.1. Validation of material models of empty and foam filled AA7075 tube:

For the purpose of the verification of our FE model and material models, the impact bending of empty tube and the foam filled AA7075 tubes were first simulated with dimensions of tube inner and outer diameter of tube are 19 mm & 24 mm, which are identical to the dimensions of the experimental sample. Figure 4 to Figure 6 shows the deformed shape and force displacement curve of an empty tube and foam filled tube impacted at a velocity of 2 m/s, compared with the experimental observation.

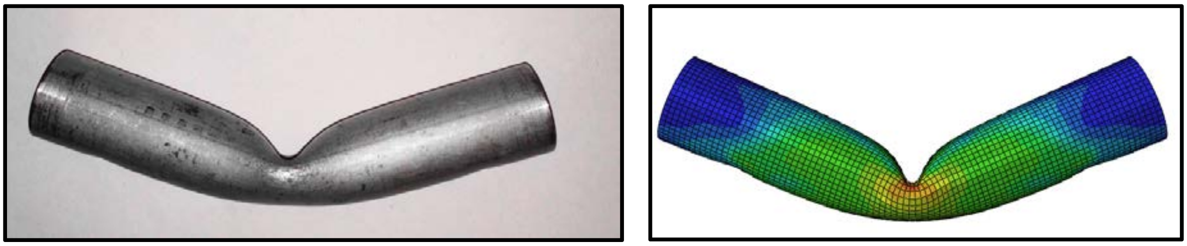

Figure 4: Comparison of the deformed shape between experimental and numerical results of empty AA7075 tube

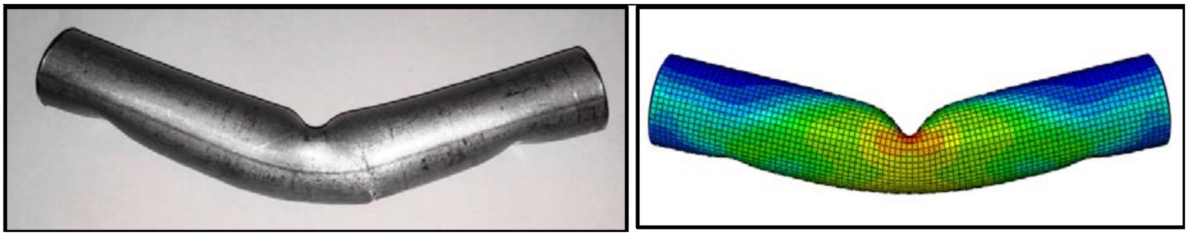

Figure 1: Comparison of the deformed shape between experimental and numerical results of foam filled AA7075 tube

The load increases against the displacement until elastic deformation. Once the plastic deformation starts the load will be approximately constant against the displacement and then there will be a drop in the load-displacement curve due to buckling. In both experimental and simulation studies, the drop in the load-stroke curve is approximately at a stroke of 80 mm.

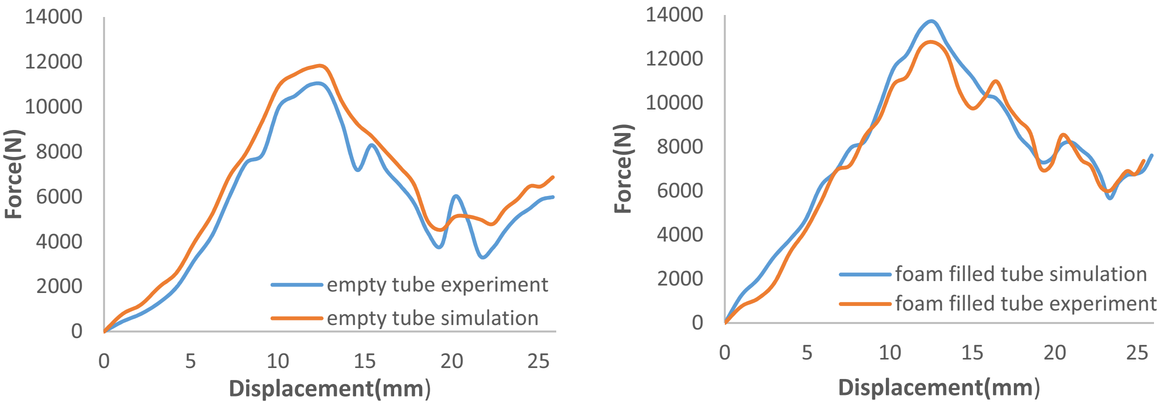

Figure 6: Comparisons of force displacement curves between experimental and numerical simulations

The numerical curve successfully produced the dynamic bending behavior of empty and foam filled tube. Considering the complexity of the cell structures in the foam, the comparison indicates that the simplified material model can simulate the bending of the foam reasonably well. From the above sections we verified that chosen material models for AA7075 Tube & foam are in good agreement with the experimental data. In the sections below, we were simulating the empty & foam filled AA7075 tubes at higher velocities i.e. 6 m/s, 12 m/s and 20 m/s.

5.2. Simulation of empty and foam filled Tubes

Both tube and foam were modeled using three dimensional solid 8-node linear brick elements with hourglass control and reduced integration (C3D8R in ABAQUS library). The accuracy of the finite element simulation highly depends on the number of element or element size. The mesh independence was verified by using convergence study. The final deformed specimens and load displacement curve of empty and foam filled AA7075 tube subjected to different impact velocities is shown in Figure 7 to Figure 10.

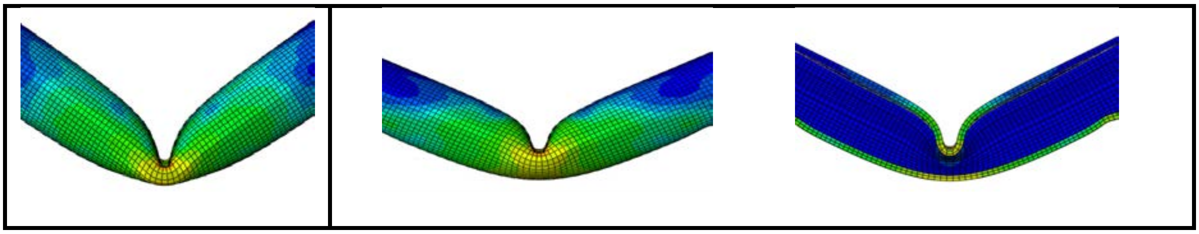

Figure 7: Deformed shape of empty and foam filled tubes after impact velocity of 6 m/s.

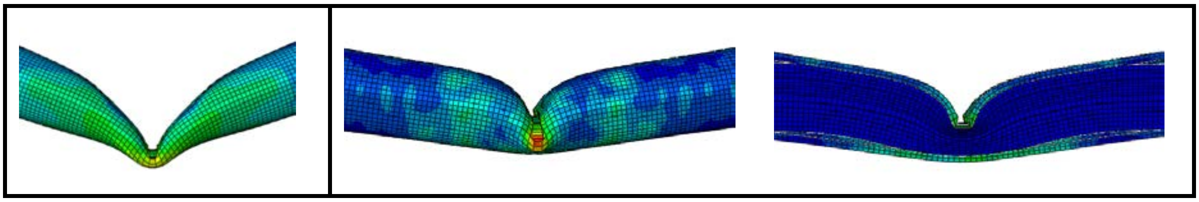

Figure 8: Deformed shape of empty and foam filled tubes after impact velocity of 12 m/s.

In order to evaluate the crash performance of energy-absorbing structures, it is necessary to define the crashworthiness parameter. The energy absorption can be used to evaluate the efficiency of structures.

Energy absorption is calculated as:

$$E_a = \int_0^{\delta} F d\delta \tag{8}$$

Where F is the crushing force with the function of the displacement δ, δ is the displacement and mass is the total mass of tube and foam.

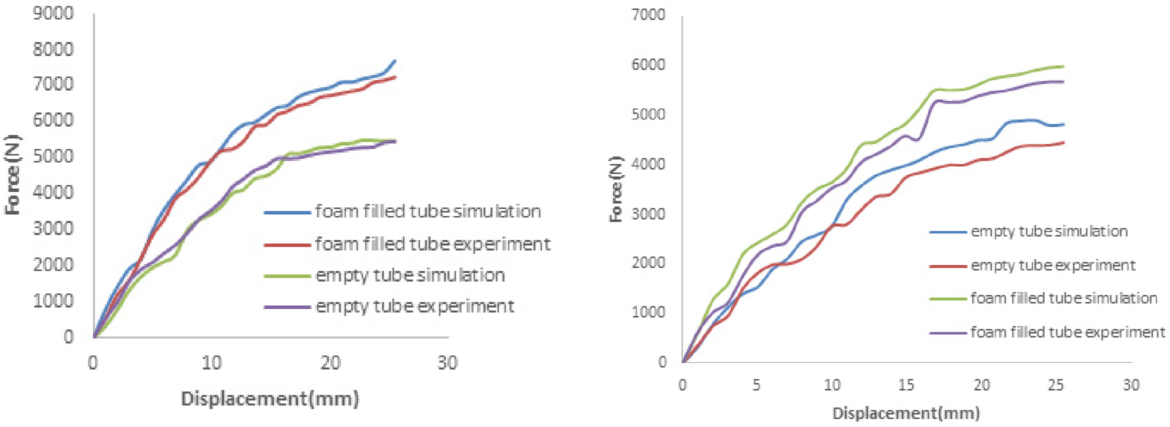

Figure 9: Force displacement curves a) Impact velocity of 12 m/s b) Impact velocity of 6 m/s

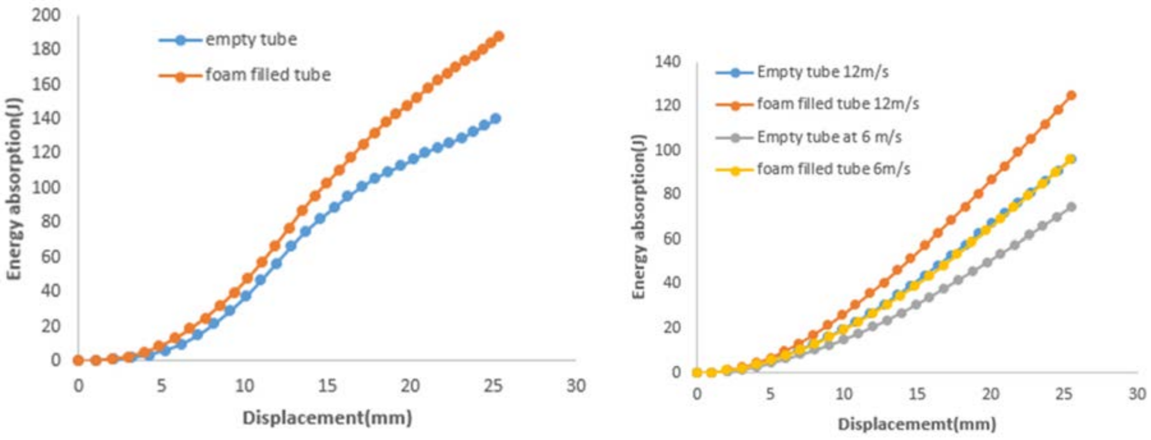

Figure 10: Energy absorption curves a) impact velocity of 2 m/s b) impact velocity of 6 m/s and 12 m/s

6. Conclusion

This work gives an idea about the effect of filling foam core on the load carrying capacity and energy absorption characteristics of the AA7075 tube. The following conclusion can be drawn from the present work:

- Energy absorption capacity of foam filled AA7075 tube is higher than the empty tube under dynamic bending.
- At higher impact velocities, increases in energy absorption were observed which is due to strain rate sensitive behavior of closed cell aluminum foam filler.
- Filling closed cell aluminum core inside the AA7075 tube results in more force and energy required to bend the tube.

Therefore, foam filled tubes are strongly recommended as crashworthy side impacts application of passenger cars.

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