Low Velocity Impact Behavior of Carbon Nanotubes Reinforced Aluminum Foams

Y. M. Chordiya and M. D. Goel

1 Introduction

From the previous reports on road accident in India, it is observed that there has been a tremendous amount of increase in number of accidents over the past years [1]. Hence, a lot of research is being done in this area, i.e., to increase the crashworthiness of the vehicles because vehicular occupant safety is the prime concern while designing the vehicles. The crash boxes are the devices which are filled in with different materials and are impact tested to get energy absorption response of the different materials. One of the best suitable materials to be used as energy absorber is foams, and it is because of their lightweight structure and their impressive compressive properties. The reason can be attributed to the fact that internal structure of the foam has pores present within them, so when they are subjected to impact it leads to cellular rearrangement of the foam which ultimately leads to energy absorption. Also, the stress–strain curve of the foam (Fig. 1) has a plateau region present which is the region in which maximum energy absorption of the foam takes place [2]. Further, foams find their use in a wide range of applications like packaging, automobiles, safety guards, packaging, safety guards, blast lining materials, and helmets [3–7]. Hence, the material used for in this investigation is carbon nanotubes reinforced aluminum foam either.

There are many tests available for impact testing but the most widely used test is drop weight impact hammer machine test. It is used by many researchers in the past for testing different materials like foams, graphite-fiber-reinforced composite, hybrid fiber engineered cementitious composite, concrete [8–12]. Further, many variations in these tests had been suggested by earlier researchers [13–17]. Considering its simplicity and application, drop weight impact hammer test is test simulated in

Y. M. Chordiya · M. D. Goel (✉)
Visvesvaraya National Institute of Technology (VNIT), Nagpur 440 010, India
e-mail: mdgoel@apm.vnit.ac.in

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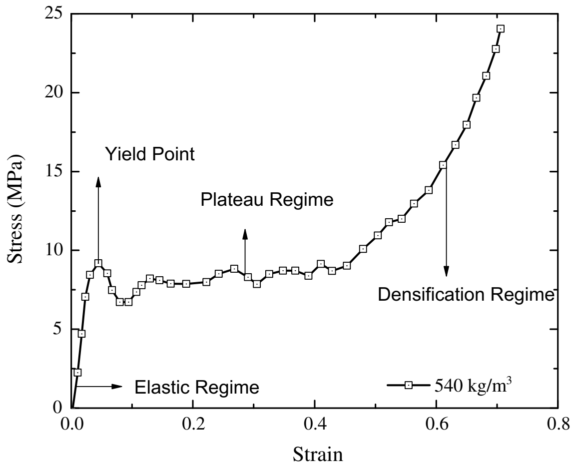
Fig. 1 A Quasi-static stress–strain curve for carbon nanotubes reinforced aluminum foams for density of 540 kg/m^3 [2]



the present investigation. The commonly used foams include aluminum cenosphere syntactic foam, polymeric foams, closed-cell aluminum foam, and polymeric foams [18–23]. However, in this study, carbon nanotubes (CNTs) reinforced aluminum foam is used. In this foam, CNTs are added to the molten aluminum matrix using the liquid metallurgy method, and it is observed that CNTs addition improves the strength of the foam composite [18].

Drop weight impact hammer is an optimum option for conducting impact testing but it requires a lot of manpower, and it is also evident from the literature review that use of numerical simulation is very scarce. Hence, numerical model is prepared in LS-DYNA® for numerical simulation of drop weight impact hammer test. Herein, the hammer is modeled using bilinear material model and foam is modeled using crushable foam material model. In this study, in addition to the effect of drop height and effect of density of foam, the effect of skin is also investigated. Moreover, a comparative study is done based on the parameters such as reaction force–time history, displacement–time history, and energy absorption for all the models developed in this study.

2 Finite Element Modeling and Material Properties

Numerical simulation of drop weight impact hammer test is done by preparing a model in LS-DYNA®, wherein the dimensions of the hammer are 720.2 mm length and 155 mm diameter and the dimensions of foam are 100 mm length and 80 mm diameter. The FE model is said to be validated from Fig. 2a and for further details about validation the author's earlier investigation can be referred [20, 24]. In this study, hammer and skin around the foam are modeled using MAT_003 (MAT_ PLASTIC_KINEMATIC) material model of LS-DYNA® material library

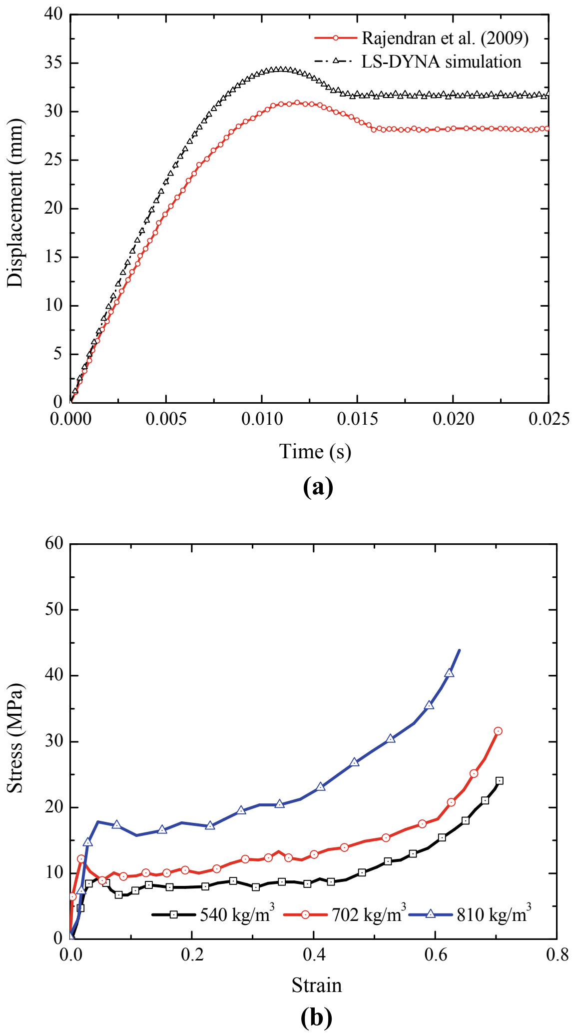


Fig. 2 **a** Variation of displacement–time history of foam in comparison with results reported by Rajendran et al. [7] and **b** Quasi-static stress–strain curve for carbon nanotubes reinforced aluminum foams for three densities [2]

[25]. Hammer is modeled using the eight noded hexahedral solid elements, whereas skin is modeled using shell element. The MAT_003 material model card requires density (ρ), modulus of elasticity (E), Poisson's ratio (μ), yield stress (σ_y), and tangent modulus (E_t) to simulate the behavior of material. The corresponding values for hammer are 7800 kg/m^3, 210 GPa, 0.3, 230 MPa, 800 MPa, respectively, and for the skin, these are 2700 kg/m^3, 70 GPa, 0.3, 364 MPa, 700 MPa, respectively. Foam is modeled using MAT_063 (MAT_ CRUSHABLE_ FOAM) material model and eight noded hexahedral solid elements of LS-DYNA® material library [25]. The properties of the foam for all the three densities are reported in Table 1, and stress–strain curve of the foam is reported in Fig. 2b. The mesh size chosen for hammer

Table 1 Material properties of carbon nanotubes reinforced aluminum foams [2]

Property	Values		
Young's Modulus, E (MPa)	250	900	520
Poisson's ratio, υ	0.3	0.3	0.3
Damping co-efficient	0.3	0.3	0.3
Tension cutoff, p_t	2	2	2
Density, ρ (kg/m^3)	540	702	810

is 20 mm, whereas the mesh size chosen for foam and skin is chosen as 10 mm considering the mesh convergence criteria. The nodes between foam and skin are merged together because separation between foam and skin is not desirable during the analysis. The impact velocities for this investigation are 6.26, 7.67, and 8.85 m/s and these correspond to drop height of 2 m, 3 m, and 4 m, respectively, and can be derived from Eq. 1.

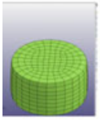
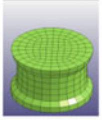
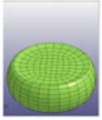
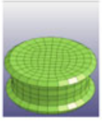
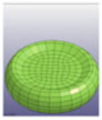
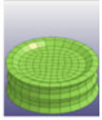
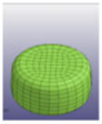
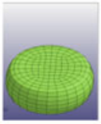
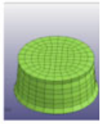
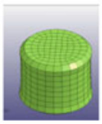
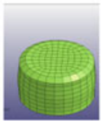
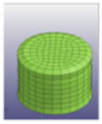
$$v = \sqrt{2gh} \tag{1}$$

The time chosen for analysis is 0.025 s, and the results are extracted at a time interval (Δt) of 0.00125 s. This time interval is chosen such that it satisfies the relation $\Delta t < l/C_L$. Here, l is the length of smallest division of sample and C_L is speed of longitudinal wave which travels through the material. In the present simulation, automatic surface to surface contact criteria is defined between top surface of foam and bottom surface of hammer and clamped boundary condition is given at the bottom of foam.

3 Results and Discussions

In this study, a finite element model is prepared in LS-DYNA® and parameters considered herein are drop height, density of foam, and effect of skin. This study comprises a total of eighteen models and the comparison is done on the basis of parameters such as reaction force–time history and displacement–time history. The deformed shape of the foam at a time 0.015 s is reported in Table 2 for all the models considered herein. It can be observed from the deformed shape of foam that increase in drop velocity leads to increase in deformation in the foam and increase in density leads to reduction in the deformation in the foam. The effect of skin is observed for foam of all the densities and it leads to reduction in deformation of the foam. It can also be observed that deformed patterns of the foams for models without skin follow a buckling type of deformation. Whereas, for model with skin, concertina mode of deformation is observed for foam with density 540 and 702 kg/m^3, but for foam with density 810 kg/m^3 only the top and bottom layer of the foam folds, whereas the other part bulges out. So, for this foam density model, hammer is imparted a velocity of 12 m/s and the deformation pattern is observed to be concertina, but it is observed

Table 2 Deformed shape of foam at time t = 0.015 s for different densities

Density (kg/m^3)	Deformed Shape					
	Velocity = 6.26 m/s		Velocity = 7.67 m/s		Velocity = 8.85 m/s	
	Without Skin	With Skin	Without Skin	With Skin	Without Skin	With Skin
540						
702						
810						

that the model with skin and without skin model gave comparable results, i.e., if the strain rate is increased then the effect of skin does not matter much. The peak stress values of model with skin and without skin are compared, and it is observed that presence of skin reduces stress on foam by 4–30%.

Figure 3a depicts the displacement–time history, and it can be observed that increase in drop height leads to increase in displacement and increase in density leads to reduction in displacement. The effect of skin reduces the deformation of foam and this reduction can be observed for foam of all three densities considered herein. The peak displacement comparison is done for model with skin and without skin for velocity of 7.67 m/s, and it is observed that model with skin results in 22.26, 27.71, 16.05% lower peak displacement response in comparison with model without skin for density 540 kg/m^3, 702 kg/m^3, and 810 kg/m^3, respectively.

Figure 3b depicts the reaction force–time history, and it can be observed that increase in drop height and density leads to increase in reaction force. The presence of skin leads to significant amount of increase in the reaction force for all the three densities of foam considered in this investigation. Eventually, up to time duration of 0.01 s, the model with skin gives higher reaction force in comparison with model without skin. Whereas, in some cases model without skin showed more reaction force in comparison with model with skin with all other parameters being same.

The peak reaction force comparison is done for model with skin and without skin for velocity of 7.67 m/s, and it is observed that model with skin results in 7.65, 17.3, 13.04% higher peak reaction force response in comparison with model without skin for density 540 kg/m^3, 702 kg/m^3, and 810 kg/m^3, respectively. It is interesting

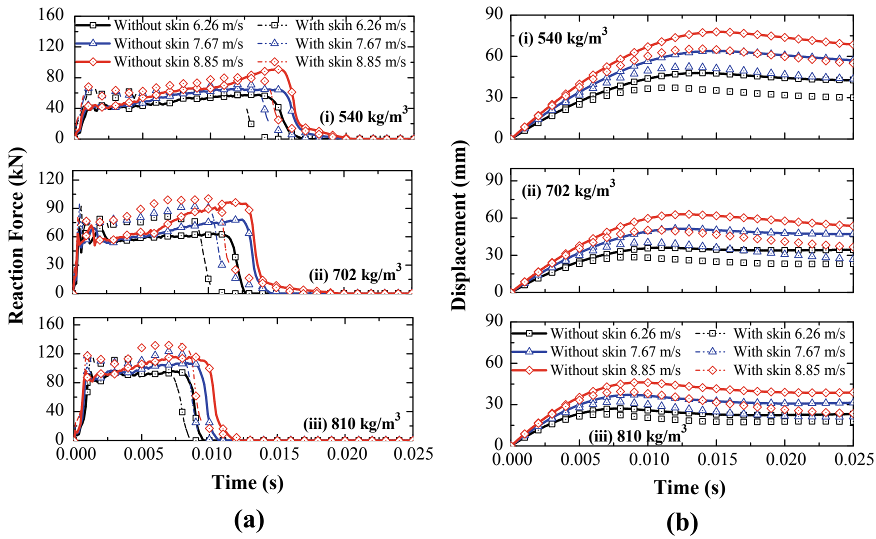


Fig. 3 **a** Reaction force–time history under different drop velocities for foam with density (i) 540 kg/m^3 (ii) 702 kg/m^3 (iii) 810 kg/m^3 and **b** Displacement–time history under different drop velocities for foam with density (i) 540 kg/m^3 (ii) 702 kg/m^3 (iii) 810 kg/m^3

to note that there is a plateau region present in almost all the reaction force–time histories and the displacement corresponding for that particular time duration goes on increasing. This means that in this region there is almost constant force for an increase in displacement which is the basic principle of energy absorption. Hence, these foams are good energy absorbers.

The area under the force–displacement curve gives us the energy absorbed by the foam and it is calculated by Eq. 2.

$$E = \int_0^u F du \tag{2}$$

Figure 4 shows force–displacement variation for foam of all the densities considered herein, and it observed that the curve increases up to a certain point and then it retraces back. For a particular foam density and the skin configuration the trajectory followed is same. Based on Eq. 2, energy absorption is calculated and reported in Table 3. It can be observed from the table that increase in drop velocity leads to increased energy absorption, increase in density leads to increase in energy absorption and presence of skin accounts an appreciable increase in energy absorption for foam models with skin in comparison with model without skin. The comparison for energy absorption is done for model with skin and without skin for velocity of 7.67 m/s, and it is observed that model with skin results in 14.57, 13.42 17.97% more energy

Fig. 4 Variation of force with displacement under different drop velocities for foam with density (i) 540 kg/m^3 (ii) 702 kg/m^3 (iii) 810 kg/m^3

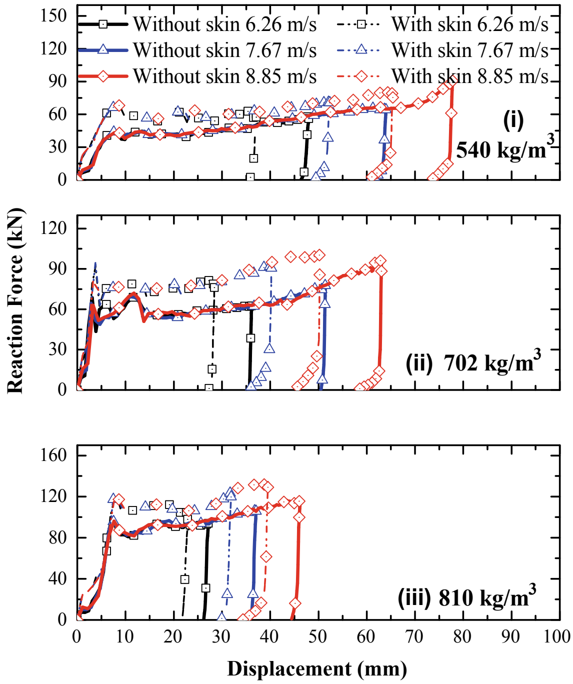


Table 3 Energy absorbed by foam of different densities under different impact velocities

Properties	Energy absorption (J)			
Density (kg/m^3)	Provision of skin	Velocity = 6.26 m/s	Velocity = 7.67 m/s	Velocity = 8.85 m/s
540	No	2006.24	3023.84	4013.79
	Yes	2651.83	3464.58	4785.43
702	No	2050.64	3104.62	4150.07
	Yes	2706.4	3521.35	4826.84
810	No	2080.81	3150.6	4218.62
	Yes	2807.4	3176.8	5000.45

absorption in comparison with model without skin for density 540 kg/m^3, 702 kg/m^3, and 810 kg/m^3, respectively.

4 Conclusions

The basic aim of this study was to investigate the effect of drop height, density of foam, and effect of skin on energy absorption characteristics of foam. The material chosen for testing here is carbon nanotubes reinforced aluminum foams. For this, a FE model is prepared in LS-DYNA®, wherein bilinear material model is used to model the hammer, skin, and crushable foam material model is used to model the foam. Based on the study following conclusions can be deduced

1. Increase in drop height leads to increase in the reaction force, displacement, and energy absorption for all the models considered in the present investigation.
2. Increase in density leads to increase in reaction force and increase in energy absorption but it leads to decrease in displacement.
3. Presence of skin leads to decrease in displacement but leads to increase in reaction force and energy absorption. Also, it leads to reduction in stress on foam from 4 to 30%.
4. If the velocity imparted to hammer exceeds a certain value then the presence of skin does not matter much.

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