Geometrical Parameters and Foam Filling Effect of Aluminium Thin-Walled Tubes under Axial and Oblique Loading

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***Abstract*—This paper presents the behaviour of empty and foam-filled aluminium tubes under axial and oblique impact loading. The influence of filler density and geometrical parameters on the energy absorption response was investigated by employing a finite element (FE) code, LS-DYNA. Main trends in the experimental results are well reproduced by the FE results. The critical effective point for the foam-filled tubes has been identified. Significant influence of thickness, bottom diameter, filler density and load angle has been observed on the critical effective point and hence the specific energy absorption (SEA). These factors can be effectively used as controlled parameters in achieving lower critical effective point and hence higher SEA of foam-filled tubes. The information established in this study is envisaged to facilitate the future development of thin-walled tubes for impact applications.**

***Index Terms*—axial loading, oblique loading, finite element, sea, thin-walled tubes**

I. Introduction

Tubular structures are widely used in engineering applications as energy absorbers to absorb kinetic energy during the events of impact and dissipate it in other forms of energy [1]. During impact, the kinetic energy is converted into internal energy or strain energy through plastic deformation whilst at the same time preventing permanent deformations into the rest of the vehicle components. Hence protect the system under consideration. These energy-absorbing structures have been extensively studied since the 1960s [2] and their performance as energy absorbers are constantly being improved [3]. Nagel et al. [4] proved that introducing tapers to rectangular tubes improves the stability of the tubes under dynamic loading compared to straight tubes. Guler et al. [5] observed that conical tubes induce higher energy absorption than square and hexagonal tubes. Many researchers [6, 7, 8, 9, 10] have shown that the semi-apical angle improves the stability of the tubes, particularly under oblique loading.

The application of foam as filler in thin-walled tubes has attracted great interests among researchers. Foam-filled tubes absorb higher energy than empty tubes for the same length of deformation [6] due to the interaction effect that occurs between the filler and the tube wall. The strength of the filler itself also contributes to the stability of the structure during deformation [11, 12]. It has been proven that the use of high-density fillers increases the energy absorption of foam-filled tubes significantly [10, 13].

Despite the significant increase in energy absorption, foam filling is not preferable to empty tube in enhancing the energy absorption capacity in terms of mass. In other words, the specific energy absorption (SEA) of the foam-filled tube is lower compared to the empty tube, as also observed by Azarakhsh et al. [14]. In fact, investigations [13, 15, 16] on the performance of foam-filled tubes in terms of mass reduction, which is signified by the SEA value, have shown that there is a critical effective point at which the beneficial effects of foam filling are pronounced over those of the empty tubes. These findings, therefore, suggest that the critical effective point assessment is a crucial factor in ensuring the evaluation of the SEA of foam-filled tubes only when the foam filling becomes effective. Moreover, no attempt has been made so far to investigate the critical total tube mass and critical filler density of foam-filled tubes under dynamic loading.

Previous investigations [4, 7] performed on tapered and conical foam-filled tubes indicate that the semi apical angle is varied by keeping the top diameter constant. Thus, the mass of foam-filled tubes increases as the semi apical angle increases and hence reduces the SEA. In order to reduce the mass of foam-filled tubes, the semi apical angle should be varied by keeping the bottom diameter constant.

Therefore, in this study, the semi apical angle is varied by keeping the bottom diameter constant. The identification of the critical effective point along with the approach taken in varying the semi apical angle by keeping the bottom diameter constant are anticipated to substantially improve the effectiveness of foam filling in terms of SEA.

In this study, finite element (FE) models of empty and foam-filled tubes were developed using a nonlinear FE code, LS-DYNA, and validated with the experimental results. The validated FE models were then employed to study the dynamic responses of empty and foam-filled

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tubes subjected to axial and oblique impact loading. The influence of the filler density was assessed by employing aluminium foam (AlMg1Si) with various densities.

II. Experimental Studies And FE Model Validation

A. Experimental Studies

This section explains the experimental studies employed to validate the FE model under axial and oblique impact loading. Straight and conical AA6061-T6 tubes with a semi apical angle of 5° were manufactured from solid AA6061-T6 circular bars by a high precision machining process to minimise geometrical discontinuities that might have occurred. The straight and conical tubes were prepared with a bottom diameter of 69.3 mm and length of 50.0 mm as shown in Fig. 1. The following material properties were applied for AA6061-T6; E = 68.9 GPa, σ_y = 276.0 MPa, ν = 0.33 and ρ = 2.70 g/cm^3 where E, σ_y, ν and ρ is the Young's Modulus, yield stress, Poisson's ratio and foam density respectively.

(a) (b)

Figure 1. Empty and foam-filled (a) conical and (b) straight tubes.

Commercially available extruded polystyrene with a density of 3.61 x 10^{-2} g/cm^3 was used as the filler material due to the manufacturing difficulty in forming the aluminium foam into a conical shape. For extruded polystyrene, the following material property values were used: E = 14.9 MPa, ν = 0 and ρ = 3.61 x 10^{-2} g/cm^3. In order to investigate the effect of foam filling for various geometrical parameters and filler densities, these parameters are only varied in the FE analysis by employing the experimentally validated FE model. A similar approach of employing a polystyrene foam was adopted in [7] for validating the FE results of foam-filled conical tubes. For the filling process, the extruded polystyrene was cut to a slightly larger diameter than the inner diameter of the hollow tubes to ensure close-fit fillers into the tube.

The empty and foam-filled tubes were tested using a drop-weight impact hammer with a maximum capacity and drop height of 30.0 kg and 3.0 m, respectively. During the axial impact test, the specimen was placed on top of the base plate and hit by the falling carriage as shown in Fig. 2. On the other hand, a steel wedge with a 20° inclined plane and a steel ring were used to idealise the oblique impact loading as shown in Fig. 3. The specimen was fixed at its larger end to a 20° steel wedge via a steel ring. Four bolts were used to secure the ring in order to prevent any lateral movement during the test. The whole structure was then mounted on top of a piezoelectric load cell with a maximum capacity of 120 kN and impacted by a falling carriage, which was released from an adjustable drop height. Five specimens were tested, the geometrics were studied, and the average results were obtained.

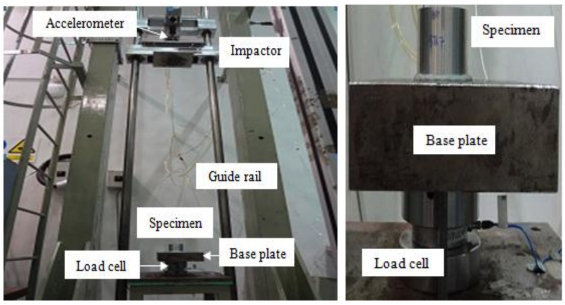
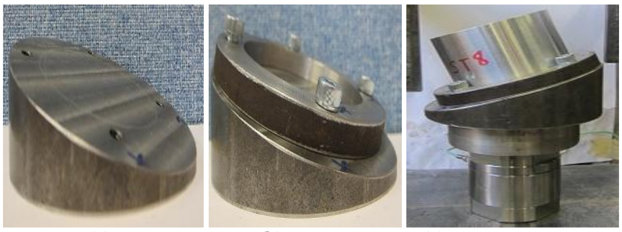


Figure 2. Drop-weight impact for axial impact test and the test setup prior testing.



(a) (b) (c)

Figure 3. Test setup for dynamic test; (a) 20° steel wedge, (b) steel ring secured to the wedge and (c) specimen secured to the 20° steel wedge via a steel ring and mounted on top of load cell.

B. FE Development

In the present study, the geometry of empty and foam-filled straight and conical AA6061-T6 tubes was modelled using a commercial explicit FE code, LS-DYNA [17]. Full models of empty and foam-filled tubes were created to obtain the experimental data under axial and oblique loading as shown in Figs. 4 and 5, respectively. As observed by Sheriff et al. [18], tube deformation is not always symmetrical. The Belytschko–Lin–Tsay shell element with five integration points through its thickness was selected to model the tubes. The extruded polystyrene foam filler was modelled using eight-node solid elements. The eight-node solid elements were also employed to model moving and stationary masses. Maximum quadrilateral element sizes of 2.1 mm and 5.0 mm were selected for modelling the tube and the filler, respectively, based on the results of a convergence study [19]. An auto-node-to-surface contact algorithm was defined for the contact between each rigid surface and the tube. On the other hand, an auto-surface-to-surface contact algorithm was employed for contacts between the foam and the tube, and between the foam and rigid bodies. An auto-single-surface contact algorithm was used to initiate fold formation during shell buckling.

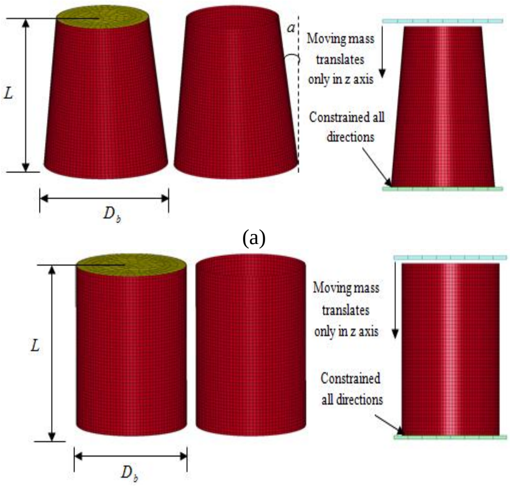


Figure 4. FE model of empty and foam-filled (a) conical (b) straight tubes with defined loading and boundary conditions under axial impact loading.

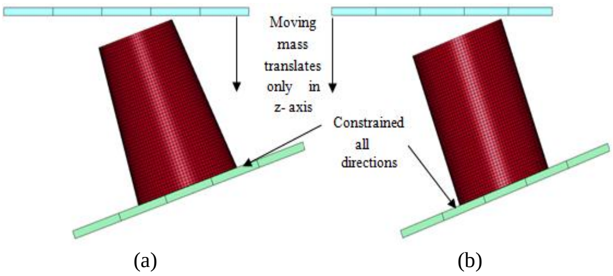


Figure 5. FE model of empty and foam-filled (a) conical (b) straight tubes with defined loading and boundary conditions under oblique impact loading.

A piecewise linear plasticity (MAT024) material model was selected to represent the tubes. The stress-strain curve obtained from a quasi-static tensile test using an Instron testing machine at a crosshead speed of 2.5 mm/min was also employed to further characterise the response of the material. In evaluating the response of various materials subjected to axial and oblique impact loading, the influence of the strain rate sensitivity of the materials must be considered. The Cowper–Symonds constitutive equation [20, 21] was used to account for a possible strain rate effect.

The values of D and q for AA6061-T6 are 6500 s-1 and 4, respectively [14, 15]. Deshpande Fleck (MAT154) and crushable foam (MAT063) material models were chosen for the modelling of aluminium foam and extruded polystyrene, respectively. The material model Deshpande Fleck [22] was incorporated into an LS-DYNA user subroutine by considering a simple fracture criterion. The properties of aluminium foam were obtained from Ahmad et al. [7]. Furthermore, the stress-strain curve of the extruded polystyrene obtained from a quasi-static compression test using an Instron testing machine at a crosshead speed of 2.5 mm/min was used to ensure an approximate representation of the actual behaviour of the filler material. The compression tests of the extruded polystyrene were conducted on 50 mm x 50 mm x 50 mm samples in accordance with ASTM D1621-10.

III. Validation of FE Model With Experiment

The FE models developed were validated using the experimental results by evaluating the force-deformation curves of empty and foam-filled straight and conical (5°) aluminium tubes as shown in Figs. 6 and 7 for axial and oblique impact loading, respectively.

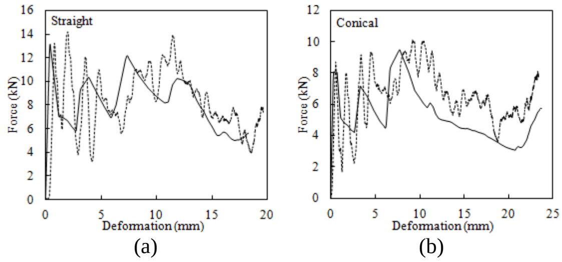


Figure 6. Experimental (---) and FE (-) analysis of foam-filled (a) straight and (b) conical aluminium tubes under axial impact loading.

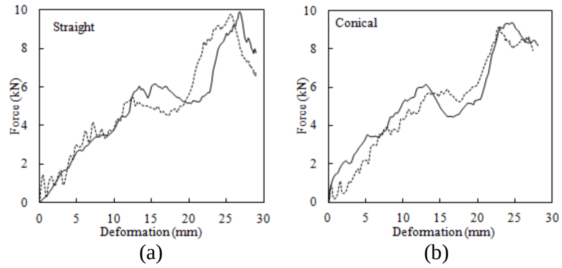


Figure 7. Experimental (---) and FE (-) analysis of foam-filled (a) straight and (b) conical aluminium tubes under oblique impact loading.

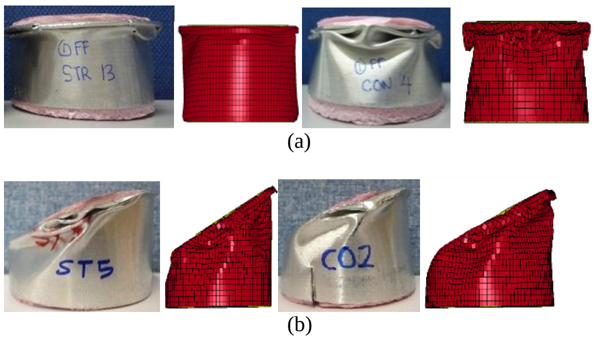


Figure 8. Deformation mode of experimental and FE results of straight and conical aluminium tubes for (a) axial and (b) oblique impact loading.

Close correlation between the FE and experimental results was achieved corresponding to the tube geometry and force orientation. These results can be further explained in terms of deformation modes of the tubes as shown in Fig. 8. It is seen that the folds are formed at the impacted end of the tubes under dynamic axial and oblique loading. A similar observation has been found in AlGalib and Limam [23] and Ahmad and Thambiratnam [24] for straight and conical foam-filled tubes respectively.

IV. Parametric Study

A. Introduction

The SEA is calculated as the energy absorbed divided by the mass of the undeformed structure. A high value of

SEA implies that the structure is more efficient in terms of mass reduction. In order to ensure that the evaluation of the SEA of foam-filled tubes is performed only when the foam filling becomes effective, an appropriate deformation length must be selected. As such, the identification of a critical effective point that explains the critical total tube mass and critical filler density, as established by Guden and Kavi [15], is vital and thus ensures that the effectiveness foam-filled tubes are evaluated only when the foam filling becomes effective. In fact, no attempt has been made so far to investigate the critical total tube mass and critical filler density of foam-filled tubes under dynamic loading, particularly the oblique loading condition.

The FE simulations were performed by employing the validated FE model. It is of interest to investigate the effect of foam filling under axial and oblique impact loading for varies of geometrical parameters. For that reason, the input parameters i.e. length, L, semi apical angle, a, bottom diameter, D_b, thickness, t and filler density ρ, were considered as tabulated in Table 1. The semi apical angle was increased from 0 ° to 10 ° whilst, the bottom diameter, D_b was varied from 80 mm to 240 mm.

TABLE I. DETAILS OF EMPTY AND FOAM-FILLED TUBES USED IN PARAMETRIC ANALYSIS

Geometry	Length L (mm)	Semi apical angle a (°)	Thickness t (mm)	Bottom diameter D_b (mm)
Empty	160	0, 5, 10	0.5, 1.0, 1.5	80, 160, 240
Filled	160	0, 5, 10	0.5, 1.0, 1.5	80, 160, 240

B. Identification of Critical Effective Point

As shown in Fig. 9, the SEA of foam-filled tubes under the axial and oblique impact loading can generally be segregated into two different regions defined by the point of intersection between the empty and foam-filled tubes. The intersection point is depicted as critical effective point that describes the critical total tube mass and critical foam density. At this point, the foam filling starts to become effective and beyond this point, the SEA of foam-filled tubes exceeds the SEA of the empty ones.

The first region is the point at which the empty tube exhibits higher SEA than that of the foam-filled one as previously observed by Ahmad et al. [7]. In this region, the effect of foam filling towards the effectiveness of tube-fillers is insignificant. Conversely, in the second region, significant effect of foam filling is observed as the strength of the tube, and the filler has overcome the original undeformed mass of the tube. Thereafter, the SEA of the foam-filled tube appears to exceed that of the empty tube. The critical effective point of the foam-filled tubes is marked by arrows and the numbering indicates the filler density; numbers 1 and 2 for 0.220 g/cm^3 and 0.534 g/cm^3, respectively.

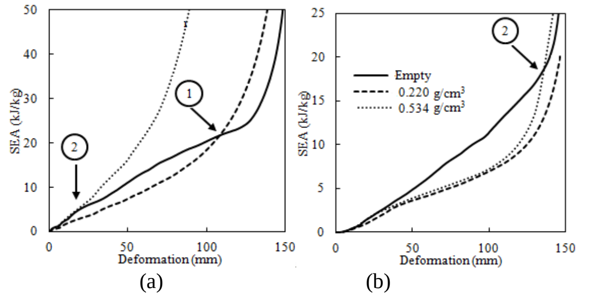
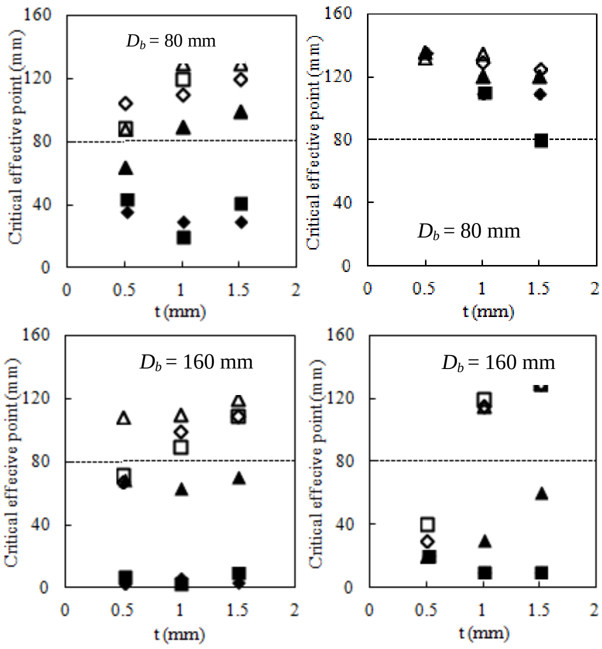


Figure 9. Effect of filler density on SEA-deformation curves of conical (5 °) aluminium tubes for (a) axial and (b) oblique loading (D_b = 80 mm, and t = 1.0 mm).

The dominance of high-density fillers can be observed in foam-filled tubes with a filler density of 0.534 g/cm^3 because the critical effective point occurs at a shorter deformation length compared to the low-density filler (ρ = 0.220 g/cm^3). On the other hand, the effect of foam filling appears at larger critical effective point, which is almost at the end of the tube length when subjected to oblique impact loading. Despite the uniqueness of the critical effective point found in each one of the tubes studied, it is still essential to select a point to appropriately assess the SEA of the tubes.

Therefore, 80 mm deformation length is then considered as the most appropriate point to calculate the SEA of each tube. The effects of geometrical parameters (semi apical angle, bottom diameter, thickness), filler density (ρ = 0.220 g/cm^3, 0.534 g/cm^3) and load angle (axial (0 °), oblique (10 °)) on critical effective point are further analysed for all tubes as shown in Fig. 10. Significant influence of bottom diameter, thickness, filler density and load angle are observed on the critical effectives points. Thus, indicates that these parameters have certain effects on the effectiveness of foam filling.



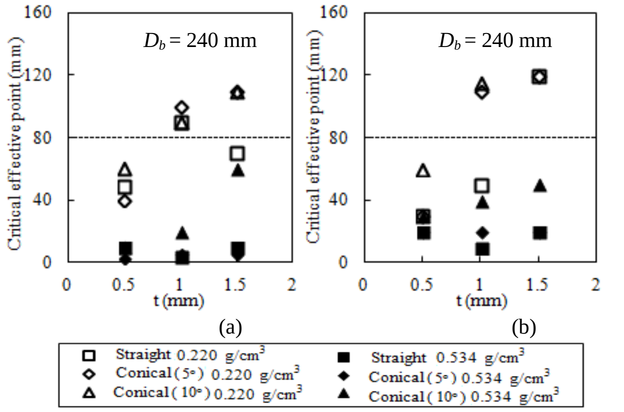


Figure 10. Effect of geometrical parameters, filler density and load angle on critical effective points of foam-filled tubes; (a) axial and (b) oblique impact loading. Dotted line (-----) refers to 80 mm effective deformation length.

C. Effects of Geometrical Parameters, Filler Density and Load Angle on SEA

Figs. 11 and 12 show the SEA results of empty and foam-filled tubes for various geometrical parameters (semi apical angle, bottom diameter, thickness), filler density (ρ = 0.220 g/cm^3, 0.534 g/cm^3) and load angle (axial (0°), oblique (10°)). These tubes are presented with the following identification system: straight (S), conical (C), empty (E) and foam-filled (F). 5° and 10° conical tubes are denoted as C5 and C10, whilst 0.22 and 0.534 after F are used to represent filler density of 0.220 g/cm^3 and 0.534 g/cm^3, respectively.

The results obtained provide a comparison between different combination of tube geometries, filler density and load angle to determine the better response of foam-filled tubes in terms of absorbed energy for a given tube mass.

Under axial loading, the highest SEA is achieved by all geometries with 1.5 mm thickness for every diameter studied, except for the 240 mm tube as shown in Fig.11. The highest SEA for 80 mm is 26.03 kJ/kg, which was achieved with an empty straight tube. Whilst, straight filled tubes with 0.534 g/cm^3 filler exhibit 21.07 kJ/kg for 160 mm. On the other hand, a 240 mm straight filled tube with 0.534 g/cm^3 filler having a thickness of 0.5 mm exhibits a SEA of 18.13 kJ/kg.

It is evident that the SEA of empty tubes increases significantly when the thickness increases from 0.5 mm to 1.5 mm as high as 184.48%, 125.38% and 159.78% for 80 mm, 160 mm and 240 mm, respectively. Surprisingly, the highest increase in SEA is observed in empty tubes with different geometry for different tube diameters. Similar observations were reported for empty corrugated tapered tubes [25]. The increase in thickness essentially increases the energy absorption capacity of the tubes since the amount of material available for plastic deformation increases as observed by Gupta [26]. Also, the thickness increase results in higher stiffness as the amount of material across the tube section increases; thus increasing the required crushing force to initiate localised buckling.

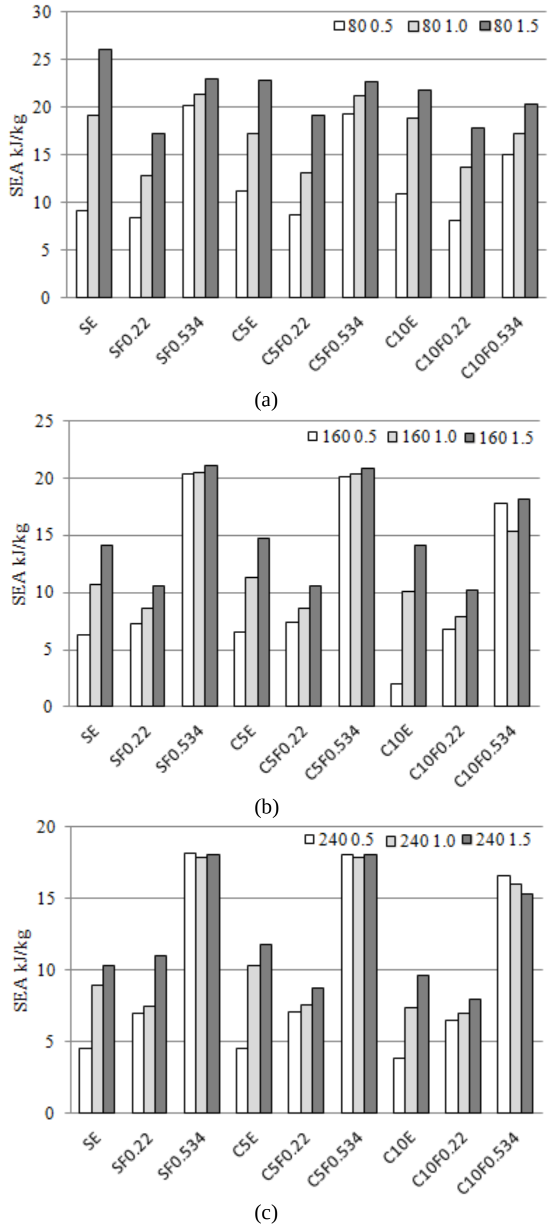
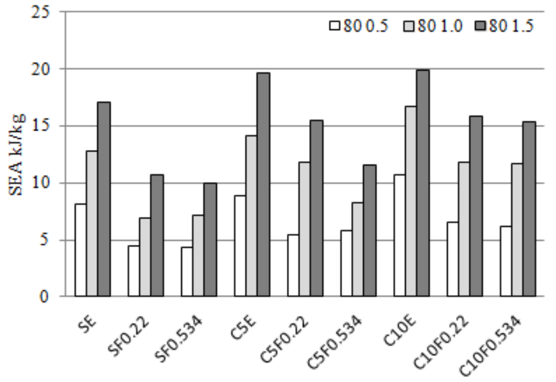


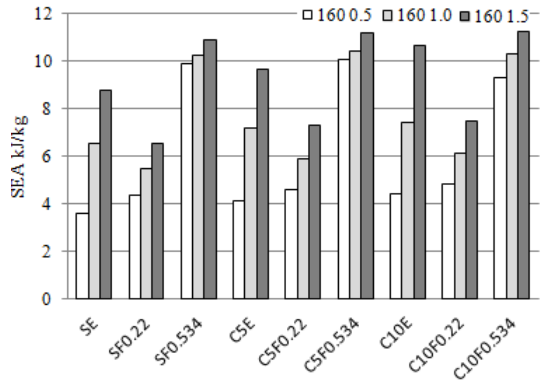
Figure 11. SEA response of (a) 80 mm, (b) 160 mm and (c) 240 mm bottom diameter for various semi apical angle, thickness and filler density under axial impact loading.

On the other hand, the SEA of all the tubes notably reduces as the bottom diameter increases. The highest reduction of SEA is as high as 61.16% found for the empty 10° conical tube when the bottom diameter increases from 80 mm to 240 mm. The increase in diameter increases energy absorbed yet reduces the SEA. The reason for the SEA reduction is the increase in the energy absorption has yet overcome the increase in the tube mass.

Fig. 12 shows the SEA response of tubes with respect to geometrical parameters (semi apical angle, bottom diameter, thickness) and filler density (ρ = 0.220 g/cm^3, 0.534 g/cm^3) under oblique impact loading. Under oblique loading, the highest SEA is achieved by conical tubes with 1.5 mm thickness for every diameter studied.



(a)



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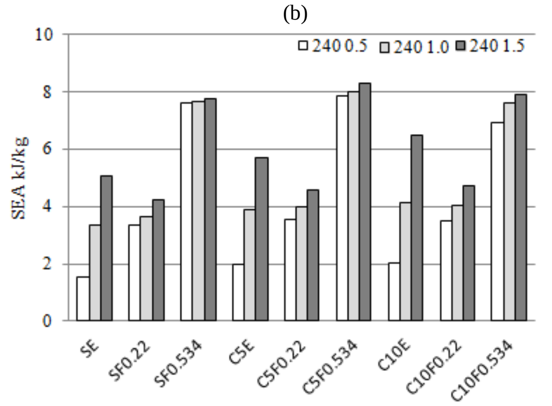

(c)

Figure 12. SEA response of (a) 80 mm, (b) 160 mm and (c) 240 mm bottom diameter for various semi apical angle, thickness and filler density under oblique impact loading.

The highest SEA for 80 mm is achieved by empty 5 ^{o} conical tube which is 19.65 kJ/kg. On the other hand, 10 ^{o} and 5 ^{o}conical tubes filled with 0.534 g/cm^3 filler exhibit 11.23 kJ/kg and 8.28 kJ/kg for 160 mm and 240 mm, respectively.

Significant increase in SEA percentage is noted when increasing the thickness of all the tubes from 0.5 mm to 1.5 mm thickness under oblique loading. The highest increase of SEA is found in empty straight of 80 mm tube at 233.55%. Following this, 5 ^{o} conical tube filled with 0.220 g/cm^3 filler and empty 10 ^{o}conical tube exhibit of 186.16 % and 140.09% increment, respectively.

As expected, the SEA of all the tubes generally reduces as the bottom diameter increases as previously observed under axial loading. Empty straight tube shows the highest reduction of SEA as high as 81.26% when the bottom diameter increases from 80 mm to 240 mm. Compared to axial loading, the reduction of SEA is higher when subjected to oblique loading. This observation implies that straight tubes are less preferable under oblique loading. In fact, Ahmad et al. [8] and Karbhari and Chaoling [27] have shown that conical tubes are more advantageous and exhibit excellent response under oblique loading compared to straight tubes. The introduction of semi apical angle in conical tube minimises the lateral deformation of the tube when subjected to oblique loading.

V. Conclusions

The response of the foam-filled tubes under axial and oblique impact loading has been investigated using a nonlinear FE code, LS-DYNA. The critical effective points and SEA were assessed. The main findings are summarised below:

1) The critical effective point for each tube is unique and demonstrates certain effect by the combination of geometrical parameters, filler density and load angle.
2) The appropriate point selection for SEA assessment may avoid any misleading conclusions from the findings, as the foam filling is yet to be effective. This indicates the importance in evaluating the critical effective point for each tube studied.
3) Low-density filler is inefficient in achieving better effectiveness of foam filling and induce lower SEA of foam-filled tubes.
4) The combined effects of geometrical parameters and filler density and load angle notably improve the effectiveness of foam filling and hence the SEA of foam-filled tubes.
5) Greater influence of thickness, bottom diameter and filler density and load angle on SEA response of the tubes is observed.
6) Under both axial and oblique loading condition, the SEA increases as the thickness and filler density increase. However, the increase in bottom diameter and load angle reduces the SEA of the tubes.
7) It is evident that conical tubes are more advantageous under oblique loading whilst straight tubes under axial loading condition in achieving better SEA.
8) A higher density of filler (0.534 g/cm^3) is more advantageous in achieving better SEA for larger bottom diameter (160 mm, 240 mm) under both axial and oblique loading conditions.

These findings can be employed to tailor the desired response of thin-walled tubes for various impact applications. This highlights the importance of the appropriate selection of the geometrical parameters and filler density under axial and oblique loading in achieving a more efficient energy absorber.

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