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FOAM FILLING EFFECTIVENESS OF CONICAL ALUMINIUM TUBES UNDER DYNAMIC AXIAL AND OBLIQUE LOADING

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ABSTRACT

This paper presents the behaviour of empty and foam-filled conical aluminium tubes under dynamic axial and oblique loading. The effect of foam filling on the energy absorption for variation in geometrical parameter and filler density was evaluated and discussed. This study employs a nonlinear finite element model which was validated against experiment data. The validated model was subsequently used to assess the beneficial of foam filling with respect to the variation of geometry and filler density. The identification of Critical Effective Point (CEP) with the approach taken in varying the semi apical angle and by keeping the bottom diameter constant are advantageous to enhance the Specific Energy Absorption (SEA) of foam-filled tube over that of empty tube. These approaches are however, apply to only particular combination of geometrical parameters and filler density thus highlights the importance of appropriate selection of these parameters in achieving efficient performance of energy absorber particularly under dynamic axial loading. The information established in this study will facilitate the future development of thin-walled tubes for impact applications.

Keywords: energy absorption, dynamic, conical tube.

INTRODUCTION

Tubular structures are widely used in engineering applications as energy absorbers to dissipate energy during the events of impact and to ensure the safety of the system under protection. In real-world impact event, an energy absorber is rarely subjected to axial or oblique alone but a combination of both loading conditions. The response of tubular structures under various loading conditions is still not well understood and therefore, further investigations are essential.

Geometrical parameters and loading conditions have shown significant effects on the energy absorption of tubular structures (Li, Yu, and Guo, 2012). In the matter of fact, tapered and conical tubes offer greater potential for energy absorption capacity under various loading conditions (Nagel and Thambiratnam, 2005). The energy absorption response of these tubes would be more stable under both static and dynamic loading (Mamalis, Manolakos, Ioannidis, and Kostazos, 2005) (Z. Ahmad and Thambiratnam, 2009a). Moreover, the use of cellular materials as fillers demonstrate significant increase in the energy absorption capacity of foam-filled tubes (Seitzberger, Rammerstorfer, Gradinger, and Degischer, 2000). However, it is found that foam-filled tube shows lower Specific Energy Absorption (SEA) compared to empty tube (Aktay, Toksoy, and Guden, 2006)(Ahmad and Thambiratnam, 2009a). Previous investigations on tapered and conical foam-filled tubes have shown that the semi apical angle is varied while the top diameter is kept constant (Reid, Reddy, and Gray, 1986) (Z. Ahmad and Thambiratnam, 2009b). In this manner, the mass of the tube increases as the semi apical increases hence reduces the SEA.

SEA is used to characterize the energy absorption response of a structure when mass reduction becomes the main concern. Higher value of SEA implies that the structure is more efficient in terms of lightness. In fact, the SEA can be observed at any point along the deformation length. Unsuitable point selection may affect the effectiveness evaluation of the structure. Furthermore, several investigations conducted on foam-filled tubes have found that there is a Critical Effective Point (CEP) at which the SEA of foam-filled tube is higher than that of empty one (Santosa and Wierzbicki, 1998) (Güden and Kavi, 2006). As such, the identification of CEP of foam-filled tube is vital to ensure that the SEA of foam-filled tube is only evaluated at appropriate point along the deformation length at which the foam filling becomes effective.

With the advancement in computational techniques, many literatures discussed up to this point have extensively employed Finite Element Method (FEM) in studying the response of thin-walled tubes subjected to quasi-static and dynamic loading conditions. Although importance progress has been made so far, still much works need to be done as reviewed by Qiao *et al*. (Qiao, Yang, and Bobaru, 2008). Furthermore, it is a formidable task in FE modelling to perform a precise simulation of foam-filled thin-walled tube as the designer need to deal with multiple stiffness of material. Moreover, the idealization of oblique dynamic loading to this structure brings further challenge to this task.

Concerning the above matters, this present study aims to investigate the dynamic response of foam-filled aluminium conical tube under axial and oblique loading by employing experimentally validated Finite Element (FE) model. In this study, the effect of foam filling on the energy absorption for variation in geometrical parameter and filler density is evaluated. A new approach is taken in varying the semi apical angle by keeping the bottom diameter constant and the correspond top diameter is varied. In this manner, the mass of foam-filled tube can be

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reduced as the semi apical increases and so the SEA. The identification of CEP along with the approach taken in varying the semi apical angle by keeping the bottom diameter constant are anticipated to substantially improve the SEA of foam-filled aluminium conical tube.

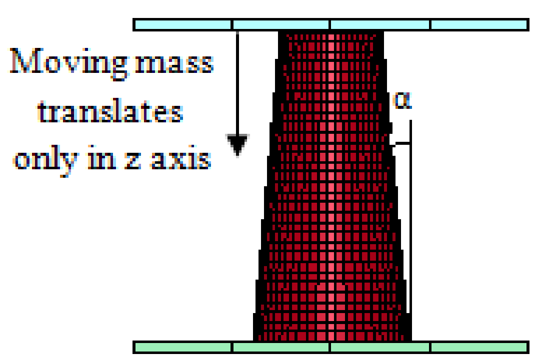
FINITE ELEMENT

Finite element (FE) model development

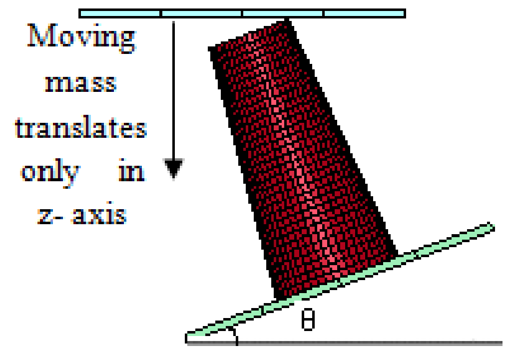
The geometric models of empty and foam-filled conical aluminium tubes were developed using the commercial explicit finite element code LS-DYNA (Hallquist, 2006). The Belytschko-Lin-Tsay shell element with five integration points through its thickness was selected to model the tubes. Eight-noded solid elements were employed to model the extruded polystyrene foam filler, moving mass and the stationary mass.

For simulating the axial (θ = 0 deg) dynamic loading, the moving mass, M subjected to initial velocity, V was allowed to move only in the load axis direction with a downward velocity due to free fall of the mass. Whereas, the tube and the stationary mass were positioned at θ = 20 deg to achieve oblique loading condition. The stationary mass (i.e. base plate) was constrained in all degrees of freedom in order to simulate the rigid plate upon which the specimen was placed during the oblique impact tests.

Figure-1 shows the models of conical tube with loading and boundary conditions arrangement under dynamic axial and oblique loading. The length of the tube is 160 mm and the bottom diameter of the aluminium conical tube remains unchanged at D_b=80 mm. The correspond tube diameter is varied with semi apical angle, α. In order to determine the appropriate minimum required mesh size for the tube and filler, a mesh convergence study (Ahmad, Ismail, and Mat, 2013) has been carried out. The study suggest that the maximum quadrilateral element sizes of 2.1 mm and 5.0 mm for tube and filler respectively provide sufficient accuracy within a reasonable amount of computational time. As pointed out by (Børvik, Hopperstad, Reyes, and Langseth, 2003), meshing size of foam filler is about double the size of shell element to sufficiently model the foam-filled tube.



(a)



(b)

Figure-1. FE model of empty and foam-filled conical tubes with defined loading and boundary conditions under dynamic (a) axial and (b) oblique loading.

A piecewise linear plasticity (MAT024) material model was selected to represent the aluminium tubes. The following material property values were applied: Young's modulus E = 68.9 GPa, density ρ = 2.70 g/cm^3, Poisson ratio's ν = 0.33 and yield stress σ_y = 276.0 MPa. In addition, the true stress-strain curve of aluminium obtained from a quasi-static tensile test as illustrated in Figure-2 was also employed to further characterise the material's response. Cowper–Symonds constitutive equation (Jones, 1989) was used to account for a possible strain rate effect. The values of material parameters D and q for AA6061-T6 are 6500 s^{-1} and 4, respectively (Gupta, Sheriff, and Velmurugan, 2008).

To model the aluminium foam and the extruded polystyrene, material models Deshpande Fleck (MAT154) and crushable foam (MAT063) were chosen. The material properties of aluminium foam as used by (Ahmad & Thambiratnam, 2009a) were adopted in this study. For extruded polystyrene, the following material property values were taken: Young's modulus E=14.9 MPa, density ρ=3.61x10^{-2} g/cm^3 and Poisson's ratio, ν=0.0. Further, the true stress-strain of the extruded polystyrene from a quasi-static compression test was used to establish the response behaviour of the filler as shown in Figure-3.

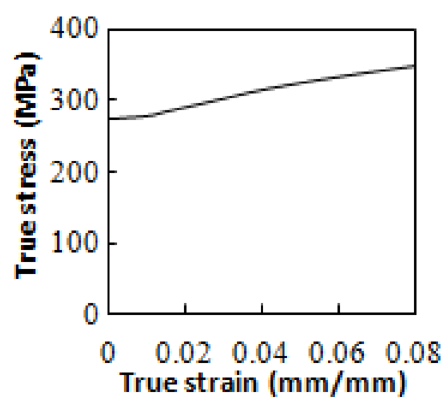


Figure-2. True stress strain curve for aluminium.

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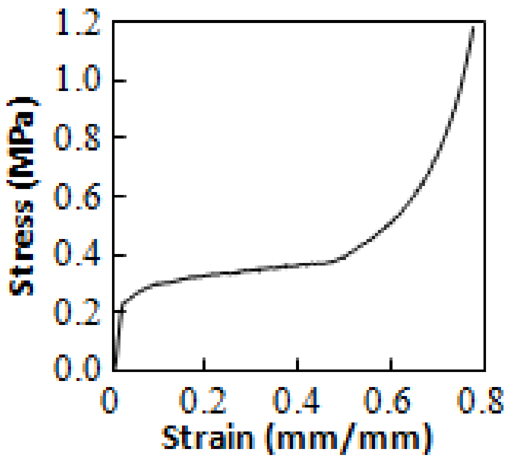

Figure-3. Stress strain curve for extruded polystyrene.

The results obtained from dynamic testing were used to validate the FE model of empty and foam-filled conical aluminium tubes. Only 5° aluminium tube of 69.3 bottom diameter and a single foam density of 0.0361 g/cm^3 extruded polystyrene were tested experimentally under dynamic axial and oblique loading whereas, no experimental testing was performed on aluminium foam. It is due to procurement and machining difficulties in forming the aluminium foam into conical shape. Similar approach of employing a polystyrene foam was adopted in (Ahmad and Thambiratnam, 2009a) in validating the FE results of foam-filled conical tubes. The validated FE model was used to treat the empty and foam-filled tubes with various geometrical parameters (semi apical angle and thickness) and filler densities in subsequent analyses.

Validation

Main trends in the experimental results are well captured by the FE results under dynamic axial and oblique loading. Nevertheless, the difference observed between experimental and FE results are as high as 29.3 % particularly for energy absorption as shown in Table-1. These differences may due to uneven thickness and in ability to constraint the movement of the tube at the fixed end (as per simulation).

Table-1. Absorbed energy of empty and foam-filled tubes subjected for dynamic axial and oblique.

Loading	Tube	Method of analysis	E (J)	Error(%)
AXIAL	Empty	Experiment	183.3	4.6
		Simulation	191.8	
	Foam-filled	Experiment	153.0	8.2
		Simulation	165.6	
OBLIQUE	Empty	Experiment	130.6	20.9
		Simulation	157.8	
	Foam-filled	Experiment	125.9	29.3
		Simulation	162.8	

RESULTS AND DISCUSSIONS

The influence of filler density on the response of conical tubes was investigated under dynamic axial and oblique loading as shown in Figure-4 and Figure-5, respectively. The tubes display the progressive collapse under axial loading. The initial peak force which signifies the initial phase of the force-deformation curve demonstrates the highest force level compared to the other subsequent peak force. However under oblique dynamic loading, the force reaches local maximum value as the deformed length increases and followed by abrupt decrease due to initiation of global buckling. Such a response is similar to that observed for the dynamic axial and oblique loading of multi-cell square aluminium tube (Fang, Gao, Sun, Qiu, and Li, 2015).

Nevertheless, foam-filled tubes exhibit higher dynamic force for both loading conditions compared to empty tubes thus lead to higher energy absorption. Although greater energy absorption can be achieved by employing higher density filler, this however leads to a smaller densification length as observed by (Kavi, Toksoy, and Guden, 2006).

On the other hand, the increase in semi apical angle successfully reduces the initial peak force of empty and foam-filled tubes when 10° conical tubes show lower initial peak force than that of 5° conical tubes. Such results have also been found for tapered rectangular tube (Nagel and Thambiratnam, 2005). The larger the semi apical angle, the lower the resistive force during collapse. Therefore, less energy is required to initiate the localized buckling of the tube wall.

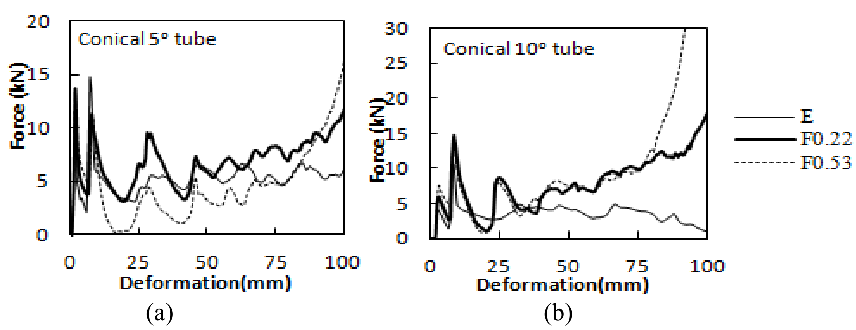

Figure-4. Force-deformation response of empty and foam-filled (a) 5° and (b) 10° conical tubes under dynamic axial loading.

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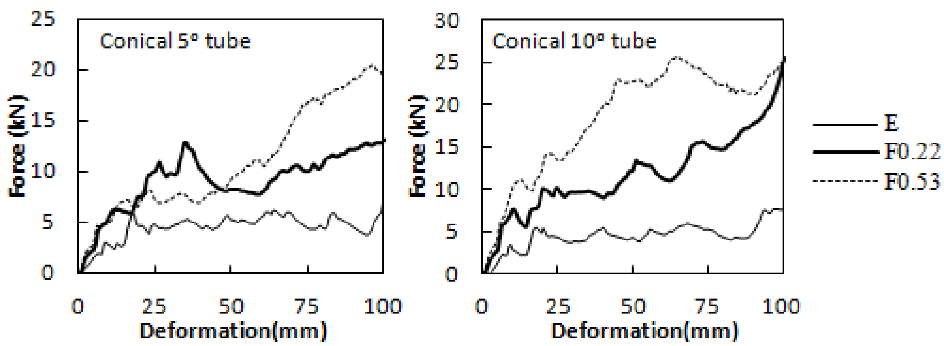


(a) (b)

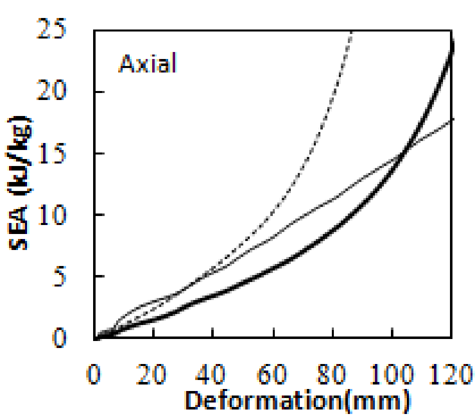
Figure-5. Force-deformation response of empty and foam-filled (a) 5° and (b) 10° conical tubes under dynamic oblique loading.

Critical effective point (CEP)

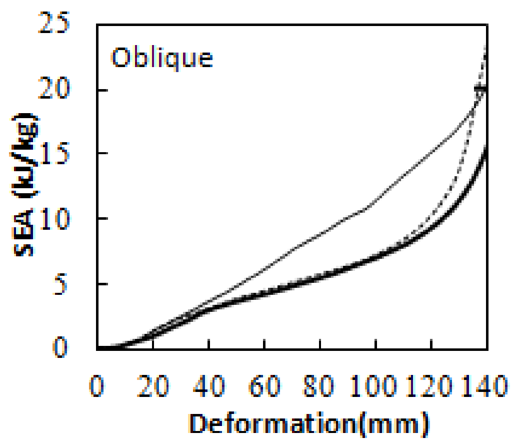
As shown in Figure-6, the effectiveness of foam-filled tubes ($\rho_f = 0.220$ g/cm^3 and 0.534 g/cm^3) can be segregated into two different regions which is defined by the coincidence point between empty and foam-filled tubes. This point is termed as a Critical Effective Point (CEP) which explains the critical total tube mass and critical filler density, as established by (Aktay *et al.*, 2006). The first region is dominated by empty tube as addressed by (Ghamarian, Zarei, and Abadi, 2011). In this region, the SEA value of the foam-filled tubes is lower than that of empty tube.

However, as the CEP is reached, the foam filling starts to become effective. The contribution of the filler on the strength of the foam-filled tube is significant as the SEA of foam-filled tube exceed that of the empty tube. Hence, indicated in the second region, the foam-filled tube is more effective than that of the empty tube. Here, the strength of the tube and filler has overcome the original undeformed mass of the foam-filled tube.

The dominance of higher density filler can be observed for foam-filled tubes with filler density of 0.534 g/cm^3 as the CEP occurs at shorter deformation length compared to lower density filler ($\rho_f = 0.220$ g/cm^3). These effects show that higher density filler is more effective than that of lower density filler.



(a)



(b)

Figure-6. Force-deformation response of empty and foam-filled conical tubes under dynamic (a) axial and (b) oblique loading.

On the other hand, the CEP under dynamic oblique loading relatively occurs at greater deformation length compared to dynamic axial loading. Such response therefore indicates that the nature of dynamic oblique loading possibly is one of the reasons that reduce the effectiveness of foam filling in foam-filled tubes.

Figure-7 summarizes the CEP of 5° and 10° conical tubes for various thicknesses and foam densities under axial and oblique dynamic loading. It is shown that higher density filler and larger thickness are more advantageous for SEA enhancement under axial loading. On the other hand, foam filling and thickness appear to be ineffective in enhancing the SEA over the empty tubes when subjected to oblique loading.

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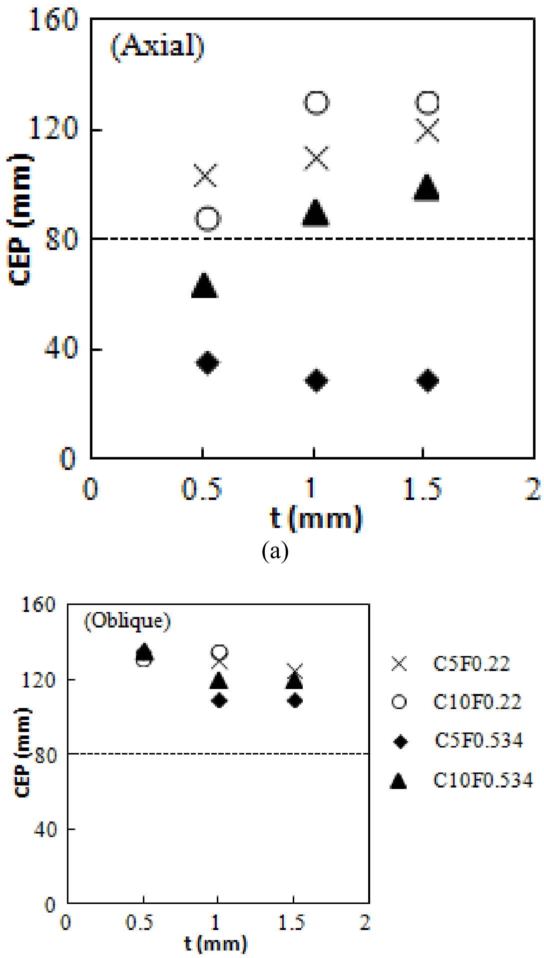

Figure-7. CEP of conical tubes subjected to dynamic (a) axial and (b) oblique loading. Dotted line (-----) refers to 80 mm of effective deformation length.

It is impractical to evaluate the SEA of all foam-filled tubes separately by considering their corresponding CEP. For crashworthiness, a common practice is to select any one point along the deformation length and this point is then used as a baseline. Therefore, the largest CEP must be selected. However, the use of maximum deformation length at which the CEP occur as a baseline could be unfeasible since some of the tube might have reached a densification phase at the largest CEP.

In densification region, the energy is absorbed inefficiently and may affect the effectiveness evaluation on the tubes studied (Zarei and Kroger, 2008). Therefore, in estimating the baseline, it is essential to make sure that the baseline selected is within the effective deformation length. By considering the effective deformation length, 80 mm is therefore considered as the baseline to evaluate the effectiveness of foam filling in foam-filled tubes for all geometry studied.

Based on 80 mm deformation length, the SEA is quantified for the given semi apical angle, thickness, filler density, diameter and length as shown in Figure-8. As expected, lower density filler is ineffective in enhancing the SEA of foam-filled tubes as it shows lower SEA than that of empty ones for both loading conditions for all thickness. Furthermore, foam filling is likely failed to improve the SEA of foam-filled tubes under oblique loading.

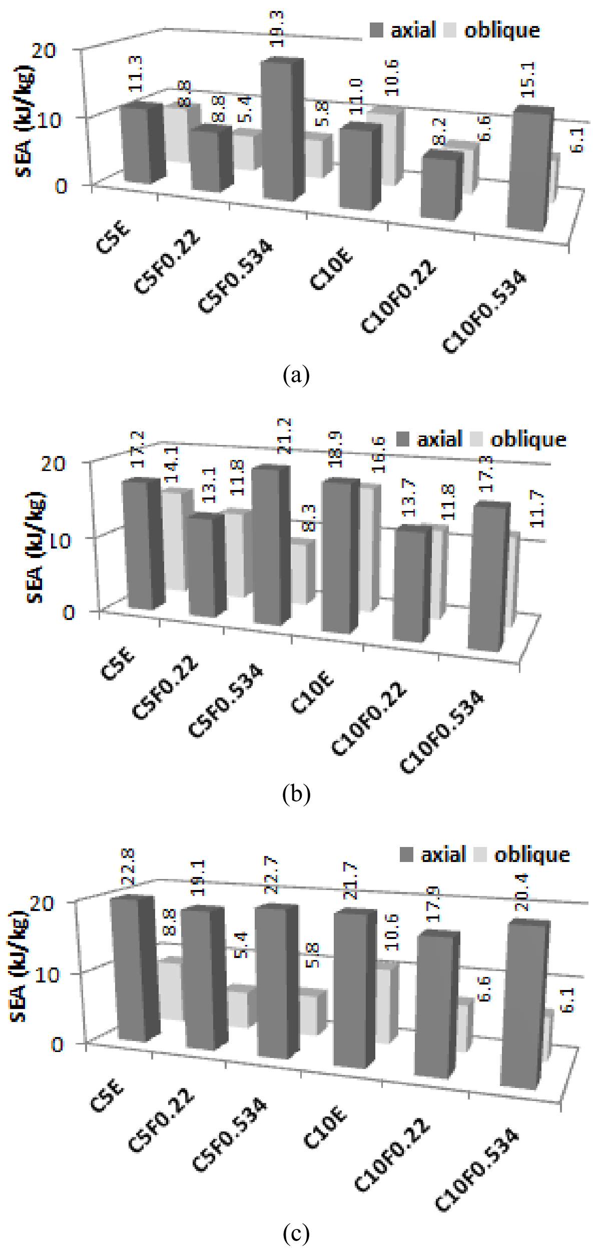

Figure-8. Effect of filler density on conical tubes for (a) t = 0.5 mm, (b) t = 1.0 mm and (c) t = 1.5 mm.

Compared to the empty tubes, foam filling with higher density filler demonstrates higher SEA. The SEA increases as high as 70.8% and 37.3% for 5° and 10° conical tubes compared to the empty tubes, respectively for t = 0.5 mm. Therefore, it can be considered that 5° has shown better effectiveness than 10° foam-filled conical tube as observed by (Zhang, Sun, Xu, Li, and Li, 2014). However, the SEA of foam-filled tubes with higher density filler is found relatively lower than empty tubes with increasing thickness particularly for 10° conical tubes. Such results are due to foam filling that is yet to be effective as the CEP occur beyond 80 mm deformation length which is considered as a baseline for SEA evaluation.

The aforementioned findings show that the SEA related to geometrical parameters and filler density as also been found by (Yang and Qi, 2013) on empty and foam-filled square tubes. For that reason, these parameters can be used as control parameters and hence the performance of the structure designed can be tailored to meet the desirable performance for different applications.

CONCLUSIONS

The response of foam-filled tubes under dynamic axial and oblique loading has been investigated using a non-linear finite element code, LS-DYNA. The identification of Critical Effective Point (CEP) along with the reduction of top diameter of the tube in varying the semi apical angle are successfully improved the SEA of foam-filled conical tubes over than that of empty tubes under dynamic axial loading. However, these approaches somehow apply to only particular combination of geometrical parameter. In spite of this, foam filling is found to be ineffective for enhancing the SEA of foam-filled tubes when subjected to oblique loading. Such response indicates the importance of selecting appropriate combination of geometrical parameters and filler density to achieve desirable performance of energy absorber for various impact applications.

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