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Plastic collapse and energy absorption of circular filled tubes under quasi-static loads by computational analysis †

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Abstract

This study presents the finite element analysis of plastic collapse and energy absorption of polyurethane-filled aluminium circular tubes under quasi-static transverse loading. Increasing focuses were given to impact damage of structures where energy absorbed during impact could be controlled to avoid total structure collapse of energy absorbers and devices designed to dissipate energy. ABAQUS finite element analysis application was utilized for modelling and simulating the polyurethane-filled aluminium tubes, different set of diameter-to-thickness ratios and span lengths, subjected to transverse three-point-bending load. Different sets of polyurethane-filled aluminium tubes subjected to the transverse loading were modelled and simulated. The failure modes and mechanisms of filled tubes and its capabilities as energy absorbers to further improve and strengthening of empty tube were also identified. The results showed that plastic deformation response was affected by the geometric constraints and parameters of the specimens. The diameter-to-thickness ratio and span lengths had shown to play crucial role in optimizing the PU-filled tube as energy absorber.

Keywords: Finite element analysis; Plastic collapse; Energy absorption; Polyurethane foam-filled aluminium tubes

1. Introduction

Tubular structures were significantly utilized as plastic energy absorbers to sustain dynamic loadings in off-shore, transportation, nuclear power plants and other critical industries. In recent times, thin-walled tubes had gained greater interest for dissipating impact energy and protecting structural concern. The ability of thin-walled tubes of various geometrical shapes to crush in a stable and progressive axial manner, had led to their use as energy absorbers in the automotive industry to attenuate detrimental crash effects [1]. The advantages of tubular structures in impact energy absorption application were attributed to their simplicity and high second moment of cross-sectional areas that produces resistance to flexural and torsional loadings, and so efficient energy absorption per unit weight of material used as compared to other types of deforming elements [2]. Circular tube being particularly weak in the transverse mode of impact loading. To predict structural collapse loads as energy absorbing structures, their collapse mechanism played an important aspect [3, 4].

Alghamdi [5], in his overview on collapsible impact energy absorbers, found that energy absorber as a system converts kinetic energy totally or partially, into another form of energy, either reversible or irreversible. In this particular research work, the interest focuses on the absorbing system to dissipate energy in plastic deformation of metallic circular pipes. The general trends and energy absorption capabilities of a component would provide the actual performance of a real structure. The quasi-static load-deflection curves was often utilized to characterize the energy absorption. Reid [3] showed that quasi-static load-deflection curves provide an expression and estimation of energy absorbing capacity and collapse load. The reason for the preference of quasi-static tests being simple and an effective measure of the collapse response, which also included the predominant geometrical effects [6].

Thin-walled tubes of various geometries and materials had preferably sought as collapsible energy absorbers for various structural applications. The energy absorbers were designed to undergo progressive collapse to absorb the impact in a controlled manner, besides converting kinetic energy to plastic strain energy under impact, thus protecting the structures [6]. Much effort had been made to understand the mechanisms of the thin-walled tube structural collapse to increase their efficiencies in absorbing energy. The energy absorption capacities of thin-walled tubes were also greatly influenced by the tube geometry and material properties [7].

Different thin-walled tubular sections had been studied, such as square, rectangular, circular, tapered, hat-section and conical tubes. Reid et al. [2] experimentally found that there

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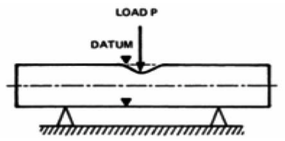
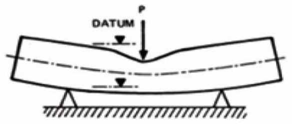
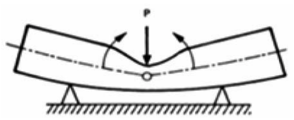


(a) Pure crumpling phase



(b) Bending and crumpling phase



(c) Structural collapse

Fig. 1. Modes of deformation of tubular under transverse load [3].

were three modes of deformation on aluminium tubes for a given fixed span were identified as one of the pure crumpling, combined crumpling and bending, and structural collapse.

1.1 Pure crumpling phase

In pure crumpling phase, initiation of localized crumpling at the top surface of the tube would take place. The load rose steeply during that period before the deflection of the bottom of the tube occurs between the supports. The load at which this occurred was denoted as PB, where maximum pure crumpling load, or also the load at which the pure crumpling phase changes to the crumpling and bending phase.

1.2 Bending and crumpling phase

As the deformation continues from Fig. 1(a) into the secondary phase, the tube crumpled further to combined with bending between the supports. During this period, Reid et al. observed that the slope of the load-deflection graph decreased slightly. The load then continued to increase till the maximum value, P_{max} was reached.

1.3 Structural collapse

When the load had achieved its maximum P_{max} value, the tube collapsed and the load decreases. Large rotations at the ends of the tube were observed during this collapse phase, known as the final phase of deformation.

Reinforced tubular consists of more than one type of material, such as foam-filled thin-walled tubes. This structure increases the energy absorption performance as compared to their counterparts without reinforcements. Structural and weigh efficiencies had also made them a preference for engineering applications. Reddy and Wall [8] utilized a low density polyurethane as the infill material for thin-walled circular metal tubes and studied on the energy absorption characteristics. They found that the tube absorption energy capacity was enhanced due to presence of filled polyurethane foam. This enhancement was not only due to the crush strength of the foam, but also the interaction of geometric constraints with the wall of tubes, which resulted in change of deformation mode. It was observed that deformation mode changes from an irregular diamond crumpling mode to concertina mode. The degree of compression was also greatly affected by the filler. Reid [3] also studied the effects of filling metal tubes with polyurethane. He found the polyurethane foam was able to stabilize and improve the performance of thin-walled tubes. He found axially compressed thin-walled square section metal tubes filled with polyurethane foam exhibits folding mechanisms similar to that of circular tubes. Progressive buckling occurred from one end of the specimen, where the folds were contiguous and this mode was described as compact. This was in contrast with non-compact behaviour leading to lower specific energy absorption capacities, besides causing global instability due to the formation of Euler-type failure mechanisms.

2. Theoretical background

For the bending collapse mechanism, the moment-angle relationship of thin-walled circular tube was derived by applying the global energy equilibrium method [9]. The derivation assumes that all work done by external forces were absorbed by the structure and transformed into internal energy. It was also assumed that the internal energy was well distributed. The relationship between the instantaneous impact force P and the instantaneous bending angle θ is be calculated as:

$$P = M_0 \left(\frac{1.08\left(\frac{R}{t}\right)^{1/4}\left(\frac{1}{\sqrt{\theta}}\right) + 1.93 + \ldots}{\sqrt{0.75R + 0.51t}\left(\frac{t^{1/4}}{R^{3/4}}\right)\left(\frac{1}{\theta}\right)} \right). \quad (1)$$

2.1 Moment-angle relation

Moment angle relation, Eq. (2), of tube had mean radius represented by *R,* while the thickness represented by *t.* From the Eq. (1), for a given thin-walled circular tube, the instantaneous impact force *P* had a factor of the bending angle θ during bending. The bending moment *M(θ)* caused by the instantaneous impact force *P* was then determined as:

$$M(\theta) = M_o \left[1.76\left(\frac{R^{5/4}}{t^{1/4}}\right)\left(\frac{1}{\sqrt{\theta}}\right) + 3.15 + \sqrt{2R + 1.36t}\,(Rt)^{1/4}\left(\frac{1}{\theta}\right) \right]. \quad (2)$$

The *M(θ)* was calculated as an instantaneous value, a function of the rotation angle θ for a given thin-walled tube model. The Eq. (2) allows the prediction of the bending behavior of circular tubes, even if small angle approximations were considered.

2.2 Effect of tube and foam-filler

Form-filled tubular increases the energy absorption capacity due to the interaction effect between the tube and the foam-filler. Studies had shown that the mean load and energy absorbing capacity of foam-filled structures were higher than empty tubes [10, 11]. Interaction effects were influenced by varying the geometry and material parameters of the foam and tubes. An empirical design formula for the average crushing load of foam-filled circular tubes, P_{mf} was developed by considering the interaction effects [10]. This was achieved by including the contributions of the mean crushing load of an empty tube, P_{mf}, foam plateau stress, σ_p and interaction effects, C_{avg} to yield as below:

$$P_{mf} = P_{me} + \sigma_p A_f + C_{avg} \sqrt{\sigma_p \sigma_y} A_o \tag{3}$$

where A_f and A_o were the cross-sectional area of the foam core and tube, respectively, and σ_y, the yield stress of the form filled tube.

3. Modelling and simulation

The 3D models of PU form-filled aluminium tubes were created using the ABAQUS to simulate the three-point bending, plastic collapse, and the energy absorption characteristics. Prior to running the simulations using ABAQUS, the program was divided into modules, where each module defines a logical process of the modelling. The modules include defining the geometry, defining material properties, and generating meshes. Moving from module to module throughout the process builds the model from which ABAQUS generates an input file to be submitted to the Abaqus / Standard or ABAQUS/ Explicit analysis product.

The materials used in this simulation were Aluminium 6061-T4 as the circular metallic tubes, polyurethane foam as the foam-filler, and cast alloy steel as the roller indenter. The specimens with different diameter-to-thickness ratios and span lengths were modelled accordingly. The indenter was set to move downward at a rate of 2 mm/min to create an indentation force at the middle of the specimen.

4. Experimental verification

The quasi-static three-point bend experiment was conducted on PU form-filled aluminium tubes of dimension similar to that modelled and simulated in ABAQUS for verification purposes. The three-point bend loading was carried out using the INSTRON universal testing machine – 8801, which had a 100 kN axial force capacity. Tests were carried out in accordance to the recommendation of ASTM E290 [12]. The Fig. 4 showed the set-up of the three-point bending test of PU-filled aluminium tubes as characterised in the Fig. 5.

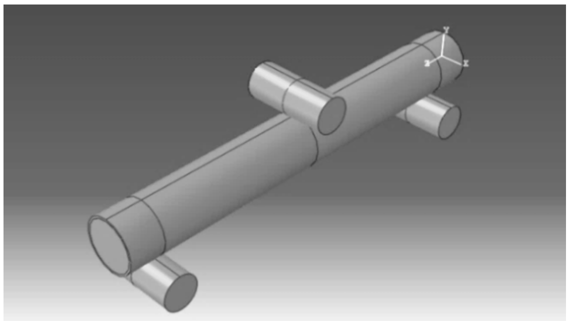


Fig. 2. Modelling three-point bending of polyurethane form-filled aluminium tubes in ABAQUS.

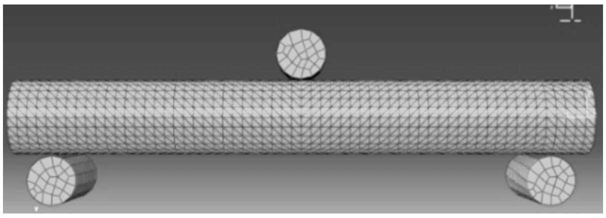


Fig. 3. Mesh generated on the model.

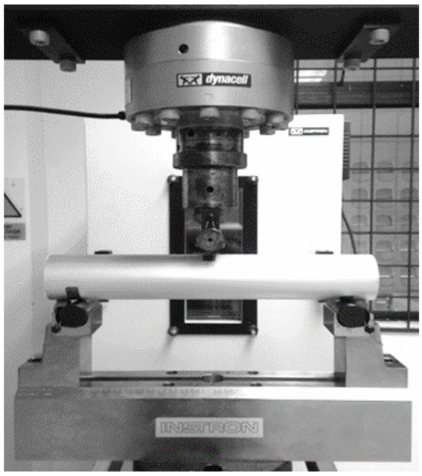


Fig. 4. PU-filled aluminium tube subjected to three-point bend loading on INSTRON machine.

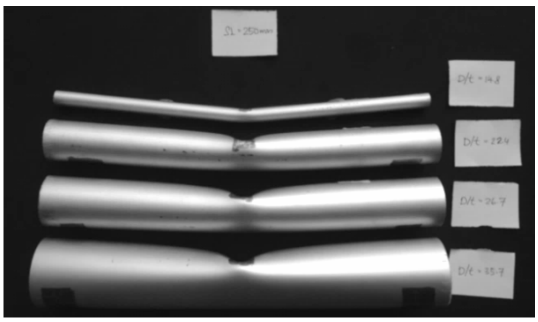
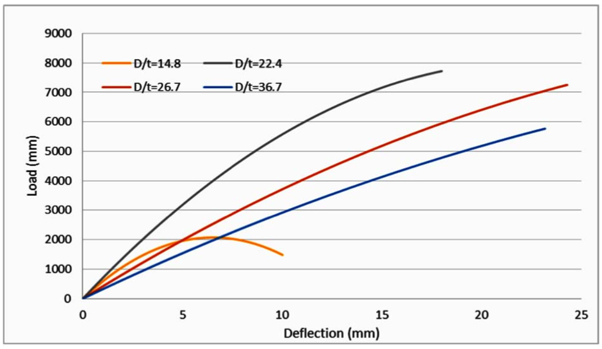
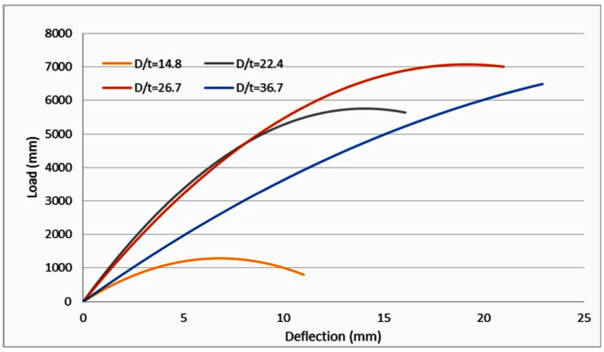


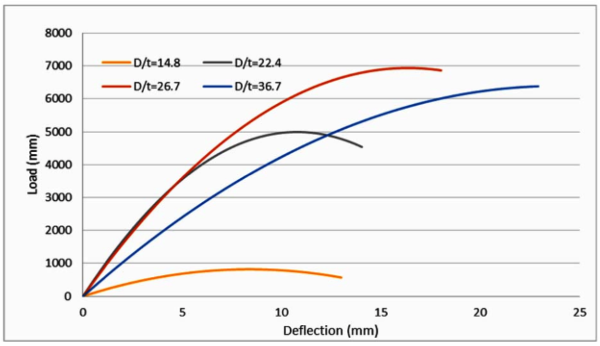
Fig. 5. Deformed PU-filled aluminium tubes of varying D/t ratio with fixed span length of 250 mm.



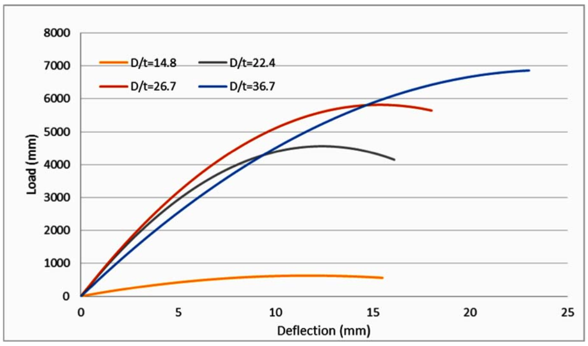
(a) Fixed span length of 100 mm



(b) Fixed span length of 150 mm



(c) Fixed span length of 200 mm



(d) Fixed span length of 250 mm

Fig. 6. Load-deflection curves for foam-filled tubes of different D/t ratios with fixed span lengths.

5. Deformation characteristics

The three-point bend loading test was simulated on the PU-filled tubes using the ABAQUS.

5.1 Load-deflection at constant span lengths

The Figs. 6(a)-(d) showed the load-deflection for different D/t ratios of foam-filled tubes of fixed span lengths of 100 mm, 150 mm, 200 mm and 250 mm, respectively. The result general trend of load-deflection subjected to D/t ratio increases for each fixed span lengths. However, at a much lower D/t value, highly exclusive trend were observed to achieve through a maximum load.

5.2 Load-deflection for constant D/t ratios

The Figs. 7(a)-(d) showed the computation simulation of load-deflection model using ABAQUS for different span-lengths of foam-filled tubes with fixed D/t ratios of 14.8, 22.4 mm, 26.7 mm and 35.7, respectively. The characteristic model trend showed gradual and consistent similarities, whereby the load-deflection trend gradually decreases as the span length increases, for each given fixed D/t ratios.

5.3 Deformation shape profile

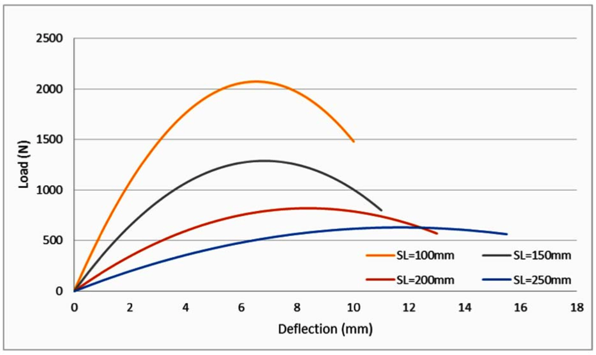
The deformation shape profiles of PU form-filled Aluminium tube subjected to three-point-bending transverse loading for various D/t ratio and span length by computational modelling were also developed. A complete set of visual deformation model of the PU-filled tubular provide a physical prediction on the response of the tubular by fixing span length while varying D/t ratios, and vice versa.

6. Results and discussion

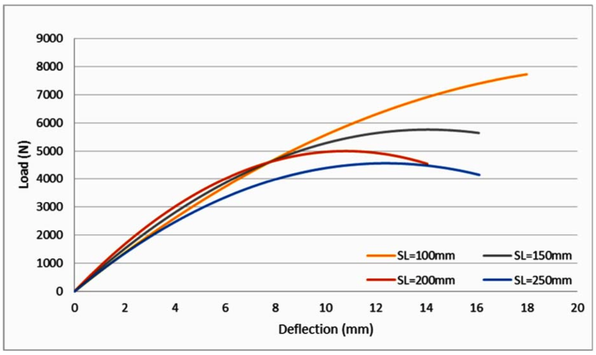
The results of the numerical or computation modelling and analysis on PU-filled circular tubes with varying span length and diameter-to-thickness ratio (D/t) are presented in the following sections.

6.1 Effect of diameter-to-thickness ratio

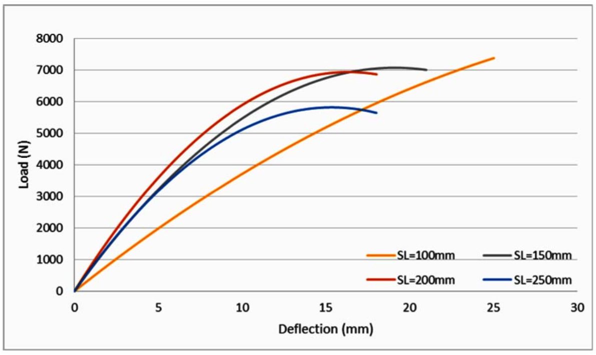
The Fig. 10 presented the results of strain energy absorbed with respect to the diameter-to-thickness ratio (D/t) for different span lengths of foam filled Aluminium tubes under three-point bend loading, obtained numerically. The characteristic trends showed that strain energy absorbed increases as the D/t ratio increases. This was associated with the modes of deformation the tubes had undergone. Tubes of the same given span length, but with higher values of D/t ratio were observed to undergo the crumpling phase over a longer period before entering into the second phase of deformation mode. These modes of deformation dictated the amount of strain energy absorbed during the crumpling phase for a given span length.



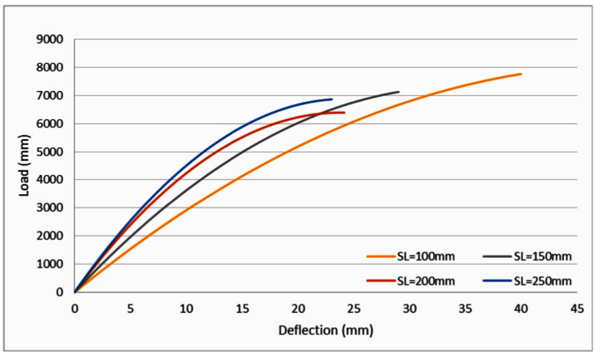
(a) Fixed D/t of 14.8



(b) Fixed D/t of 22.7



(c) Fixed D/t of 26.7



(d) Fixed D/t of 35.7

Fig. 7. Load-deflection curves for foam-filled tubes of different span lengths at fixed D/t ratios.

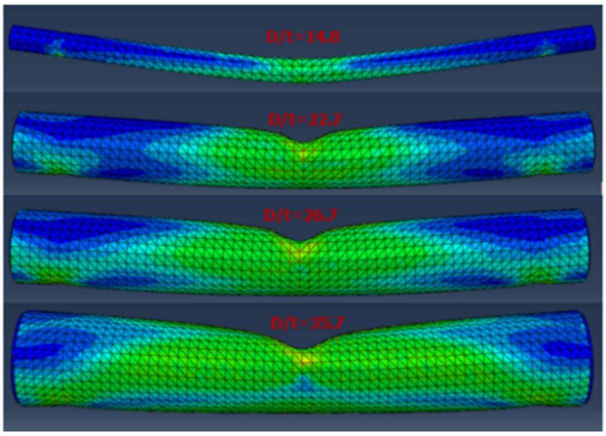


Fig. 8. Deformation model of filled-tubes with varying D/t ratios and fixed span length of 250 mm.

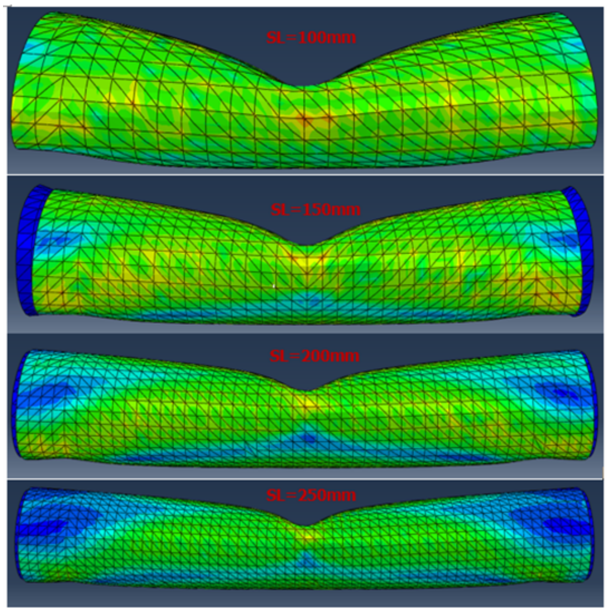


Fig. 9. Deformation model of filled-tubes with varying span lengths and fixed D/t ratio of 35.7.

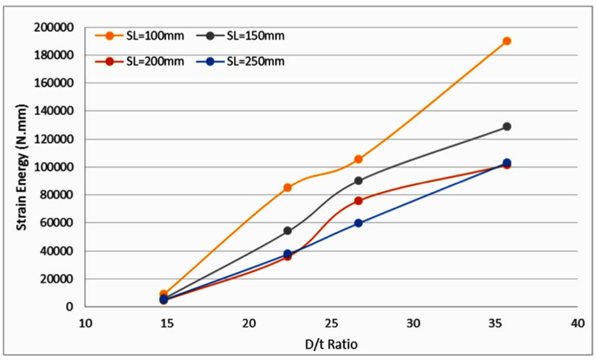


Fig. 10. Numerical strain energy vs D/t ratio for various span lengths of foam-filled Al-tubes by three-point bend loading.

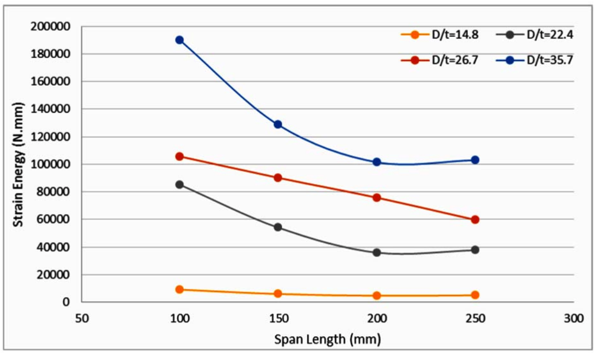


Fig. 11. Numerical strain energy vs span length for various D/t ratios of foam-filled Al-tubes by 3-point bend loading.

Tubes of constant span length with a lower D/t ratio was found to experience a faster transition into the crumpling and bending phase, thus contributed to a drop in the amount of strain energy absorbed.

6.2 Effect of span length

The Fig. 11 detailed the results of characteristic models of strain energy absorbed with respect to the span-lengths for different D/t ratios of foam-filled Aluminium tubes under 3-point bend loading, obtained numerically. From the characteristic trends in the figure, the amount of strain energy absorbed decreases as the span length increases. Again this can best be explained from the deformation mode change characteristics. Tubes of the same D/t ratio, but with longer span lengths were observed to undergo the crumpling phase at a shorter transition period before proceeding into the second phase of deformation mode. This behaviour explains the phenomena that the amount of strain energy absorbed during the crumpling phase as being less dominant.

The tubes were found to experience a faster transition into the second deformation phase, whereby longer tubes were found to undergo bending more than shorter tubes. Once in the second phase of the deformation mode, only a little further increase in the load was sufficient to cause the tube to start bending before achieving the maximum load. On the contrary, tubes of constant D/t ratio with a shorter span length experienced a slower transition into the crumpling and bending phase, thus increasing the amount of strain energy absorbed, whereby more load was needed to crumple the tubes.

6.3 Mesh dependency

Meshing steps was one critical and important process for computational analysis. The meshing quality greatly affects the simulation outcomes. A coarse meshing leads to a decrease in total number of elements, resulting to inaccurate outcome. On the contrary, a very fine mesh increases the total number of elements involved for the simulation, which lengthens the total computation time and in turn increased the cost without added values in the accuracy of the results. The Table 1 and Fig. 12 presented the effect outcomes of the simulation using different meshing qualities.

Table 1. Effect of mesh sizing.

Parameter	Properties	Fine	Medium	Coarse
Mesh characteristics	Nodes	117881	40428	25769
	Elements	48720	18114	11924
	Total time (sec)	42405	5884	3372
Energy absorption characteristics	Max. load (N)	6380	7045	9360
	Strain energy (N.mm)	67715	75789	97822

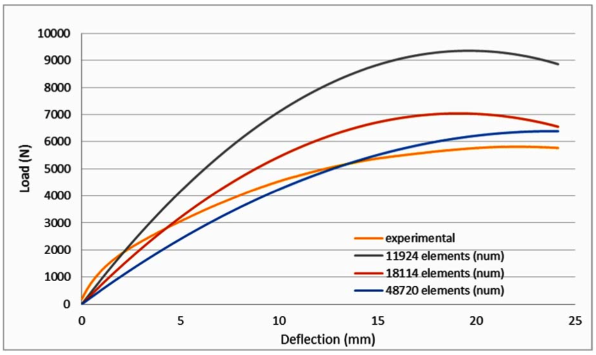


Fig. 12. Load-deflection of different mesh sizing and number of elements for foam-filled aluminium tubes (SL = 200 mm, D/t = 26.7) by 3-point bend loading.

A simple experimental 3-point bending as per similar boundary conditions and constraints of the computational analysis was conducted to verify the results obtained by the simulation. From the Fig. 12, the fine meshing (48720 elements) had shown the trend that closely predicts the experimental result. The FEA models with fine mesh had shown to yield a more accurate result, on the expense of the computing time. On the contrary, coarse meshing had shown to produce less accurate results. Smaller element size increases the FEA model complexity, as when a high accuracy result had been required. Larger element mesh size simplifies the FEA model, when a quick and rough estimation of design was required. Nevertheless, it was important to choose the appropriate mesh densities for the FEA to yield accurate results while saving computing time as much as possible.

7. Conclusion

The primary aim of this project was to investigate the behaviour of plastic collapse and energy absorption of polyurethane filled aluminium tubes under quasi-static transverse loading by utilizing the computational analysis. Experimental verification found that ABAQUS/CAE predicted closely the non-linearity deformation analysis of collapse of circular tubular structure. More accurate result was also found to achieve with more refine mesh density.

The energy absorption characteristic of circular tubes under transverse loading was found to influence by the span lengths and D/t ratios. It was observed that for specimens of constant span length, while varying the D/t ratio, the specimen with the largest D/t ratio was able to sustain a higher load and thus increased in the amount of energy absorbed. On the contrary, specimens of constant D/t ratio, while varying the span lengths, the shortest specimen had the highest tendency for energy absorption. Hence, these geometric parameters could be utilized to optimize a geometric dimension for an optimum energy absorber. Three modes of deformation were also identified in the numerical study. The first mode of deformation as the crumpling phase, followed by the crumpling and bending phase, before proceeding to a structural collapse phase.

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