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# Evaluation for Energy Absorbing Capacity of Concentric Aluminium Tubes Filled With Foam of Different Density

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**Abstract: The energy absorption capacity of vehicles and protective structures has become more important due to ever stringent safety requirement. As an example, increasing focus has been paid to the use of energy absorbing devices in order to overcome the adverse effect of an impact load. Many devices have been designed to study impact energy absorption during a collision and hence protect the vehicle components and passengers. As decades passed on, various types of energy absorbers have been placed in vehicle structures, particularly cars as a significant number of road causalities have been caused by car crashes. Research shows that axial impacts account for approximately 35-40 % of all impacts on a vehicle. In response to this, a comprehensive study have been undertaken to experimentally & numerically investigate axial crushing responses, energy absorption performance of empty & foam filled aluminum concentric tubes with different density of foam. The study was extensively conducted using finite element techniques in conjunction with an experimental set-up& application of available theory.**

***Keywords:*** **Energy Absorption, Peak Load, Mean Load, Foam Filled Tube, Concentric Tube.**

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## I. INTRODUCTION

Number of vehicles on road has been rapidly increasing every year due to the continuous development of both automobile and transportation industry. There has been increasing demand for vehicles as modern society is more relying on transportation systems. Subsequently, vehicular accidents have now become major worldwide concern and continuous focus is on to address safety issues. This is especially in case for road vehicles such as cars, vans trucks and heavy vehicles.

A motor vehicle can be involved in a variety of crash events, each causing human injury of different severity. Road crashes obviously constitute a great economic lose to society. Thus, continuous effort has been implemented to overcoming this significant safety issue. The energy absorption capacity of vehicles and vehicle protective structures has become more important due to ever strict safety requirement. As an example, increasing focus has been paid to the use of energy absorber devices in order to overcome the adverse effect of an impact event. Such devices have predominantly been designed to simulate impact energy during a collision and hence protect the vehicle components and the passengers. For many decades, various types of energy absorbers have been placed in vehicle structures, particularly cars as a significant number of road causalities have caused by car crashes.

Research shows that axial impacts account for approximately 35-40 % of all impacts on a vehicle as shown in Fig 1.1. In response to this, a comprehensive study have been undertaken to experimentally & numerically investigate axial crushing responses, energy absorption performance of empty & foam filled aluminium concentric tubes with foam of different density. The study was extensively conducted using finite element techniques in conjunction with an experimental program & application of existing theories.

Analysis of crashworthy structures has been a primary area of interest for many researchers for quite a few years now. The quest for a better energy absorbing structure or a better crashworthy structure has led researchers to carry out various analysis procedures experimentally and also by simulating the characteristics.

The primary aim of this project is to investigate the crush behaviour of aluminium empty and foam filled concentric tube undergoing quasi static axial compressive loading condition. Also, the empty and foam filled concentric tube were examined and the result was compared with foam filled concentric tubes.

The comprehensive numerical study is performed and it is validated by experimental study to determine the crush behaviour of different tube sections namely empty concentric tube, foam filled concentric tube with foam of different density. Both numerical and experimental results are obtained regarding the main crushing characteristics, crash energy absorption and overall crushing response.

Fig 1.1 Percentageaxial load acting on vehicle due to frontal impact

## II. LITERATURE REVIEW

### *Introduction*

This chapter reviews the background literature to date which is pertinent to the research conducted in this study. All established studies and theories are identified to enhance understanding for undertaking this study. The study topic comprises several relevant research areas which will be addressed in turn, as follows.

(1) Energy absorbing structures

(2) Analysis of energy absorbers

Fundamentally, the load-displacement response of energy absorbing devices can primarily measure their energy absorption performance.

In general, a collapse load can be defined as the required load to cause a permanent deflection, and the deflection increases as the crush progresses. An ideal energy absorber can be represented with a constant crushing load, $P_{max}$from the onset of the crushing process up to the maximum deflection. Energy absorption capacity can then simply be calculated as the rectangular area of a load-deflection curve.

### *2.2.1 Specific energy absorption:*

The most important characteristic of energy absorbers is the specific energy absorption capacity, *SEA*. The specific energy absorption, *SEA* is defined by energy absorbed per unit mass where $E_{abs}$is the absorbed energy and *m* is the original undeformed mass.

$SEA=E_{abs}/ m$

The *SEA* is the most common performance parameter for energy absorbing components to assess the energy absorbing capacity particularly when weight reduction is vitally important. Moreover, the specific energy absorption is usually used as an indicator of the weight efficiency of an energy absorber. For a given absorbed energy, a higher *SEA* indicates a more efficient crash absorber in terms of its weight (Santosa et al. 2001; Zarei and Kroger 2006). However, it is important that weight-saving does not comprise safety or structural performance. In the case of foam-filled structures, the undeformed mass of a tube increases due to the foam filling. Thus, foam materials with a high strength to weight ratio must be used to obtain higher specific energy absorption.

### 2.2.2 Mean crush load:

The mean crush load is an indicator of energy absorbing capability of a structure when compared to the axial displacement required to absorb the energy. For the crush response of thin-walled tubes, the load in general fluctuates throughout the crushing process and the highest initial load point is defined as the initial peak load, $P_{peak.}$ Figure 2.2.2.1 shows the load-deflection curve for a metallic foam-filled circular tube as it crushes under axial loading. The maximum peak load gives an indication of the load required to initiate collapse and hence begin the energy absorption process.

For practical implications, the mean crush load and initial peak load are the predominant parameters in evaluating the energy absorption performance of energy absorbers.

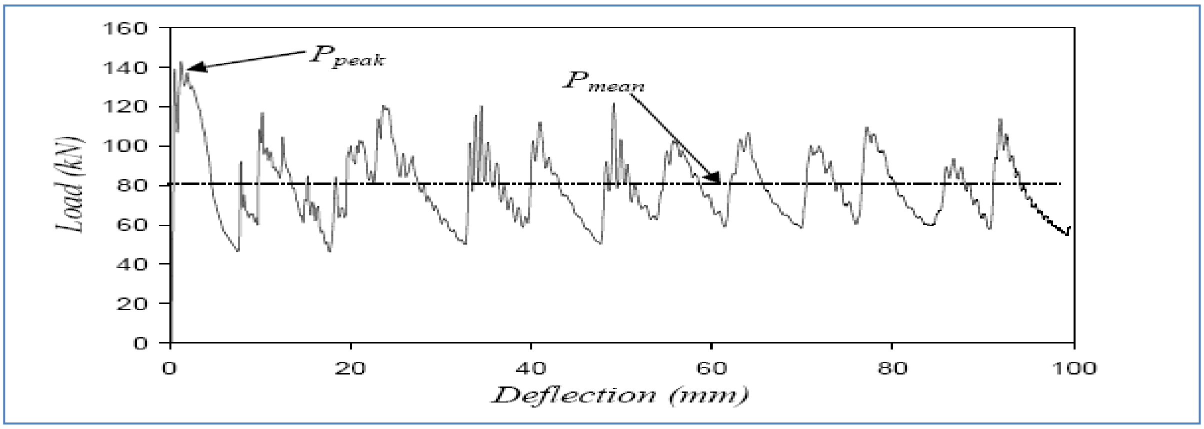


Fig 2.2.2.1 Load Deflection Curve under axial loading

The main reason behind this is experimental set up for quasi static loading is generally simpler than that for dynamic loading and enables easier observation of the detailed deformation history. This section presents limitedly a comprehensive review of existing thin-walled tubes found in the literature since they are more pertinent to this study.

### 2.3.1 Thin Walled Tubes:

The energy absorption capacity of thin-walled tubes is significantly influenced by the material properties and tube geometry (Huang and Lu 2003; Jensen et al. 2004; Thornton et al. 1983; Zhang et al. 2009). A variety of thin-walled tubular sections such as circular, square, rectangular, tapered, hat-section and conical tubes have been studied for many decades. This chapter mainly reviews the crush and energy absorption response of existing non-metallic thin-walled tubes under axial compression loading, which is pertinent to the research conducted in this study

### 2.4.1 Foam materials:

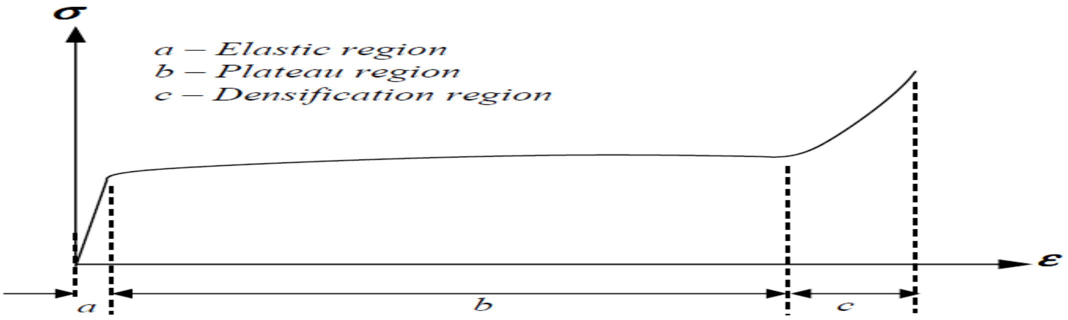


Fig 2.4.1 A typical nominal stress-strain curve for foam materials

Foams have a unique characteristic whereby they can progressively undergo a large strain deformation while maintaining a low stress level before the densification region (Gibson and Ashby 1997).A typical nominal (average) stress-strain curve of foam materials consists of an elastic region, a plateau region where the stress increases slowly as the cells deform plastically, and a densification region where the load increases rapidly as the cell edges progressively touch each other and the material attains bulk-like properties.

Fig 2.4.1 shows a typical nominal (average) stress strain curves for foam materials. owing to the above features, the use of foam material is widespread in vehicles as they require superior impact energy absorption with a significant reduction in the weight of components.

Another potential application of foam materials is to reinforce thin-walled tubes (foam filling), which is addressed in-depth in the next section. Foam filling can considerably increase the energy absorbing capability of a crash component without a significant increase in the mass. The plateau stress *is* predominantly used to characterize foam materials since this stress is a function of foam density.

To absorb energy effectively at a nearly constant load, foams must have a correct cell-wall material and relative density, if the relative density is too low, the cells will be crushed before sufficient energy can be absorbed. If the relative density is too high, the stress will exceed a critical value before sufficient energy can be absorbed. An obvious fact is that foams with a higher density as well as higher strength, have higher compression strength, however a reduction in the range of the plateau region occurs. In addition, the compaction strain decreases with an increase in the relative density. Indeed, the selection of suitable foams for energy absorption applications is crucial.

### *2.4.2 Polymeric foams*

Low-density polymeric (non-metallic) foams have been used in a wide range of engineering applications. This kind of foam, such as polyurethane and polystyrene foams, are prevalent in the energy absorption and impact applications due to their excellent energy absorbing capability. In the automobile industry, for instance, the new provisions in the Federal Motor Vehicle Safety Standards (FMVSS) require the use of polymeric foam materials inside motor vehicles to protect the occupants during accidents.

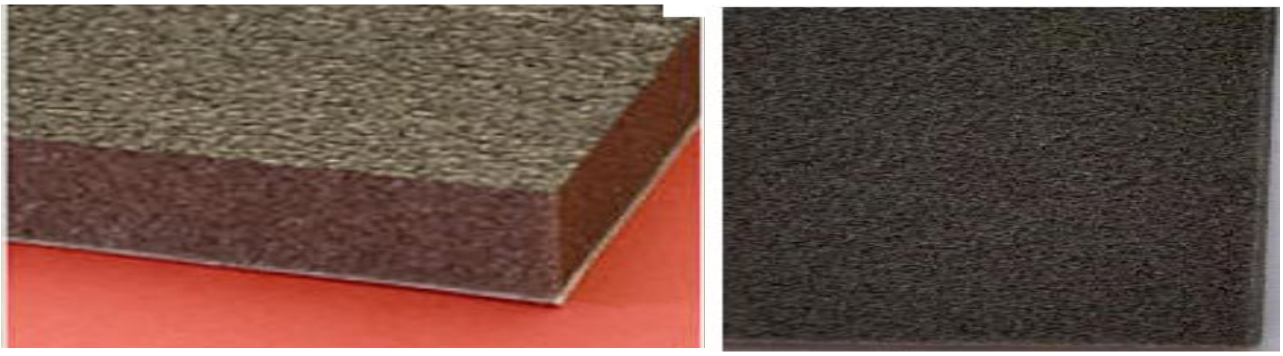


Fig 2.4.2.1 Polymeric Foams

Earlier research has found that both polystyrene and polyurethane foams are able to undergo large deformations without a large permanent set. During complete loading and unloading cycles, they are also capable of absorbing a large amount of energy due to their highly hysteretic nature. Perhaps the most important feature of polymeric foam is that the energy absorption performance is independent of loading direction.

Polyurethanes can be manufactured in an extremely wide range of grades, in densities from 6 to 1,220 kg/m3 and polymer stiffness from flexible elastomers to rigid, hard plastics.

Low-density flexible foams have densities in the range 10 to 80 kg/m3, made from a lightly cross-linked polymer with an open cell macro structure. Low-density rigid foams are highly cross-linked polymers with an essentially closed cell structure and a density range of 28 to 50 kg/m3. The individual cells in the foam are isolated from each other by thin polymer walls, which effectively stop the flow of gas through the foam. These materials offer good structural strength in relation to their weight, combined with excellent thermal insulation properties. High-density flexible foams are defined as those having densities above 100 kg/m3.

### *2.5.1Foam-filled thin-walled tubes:*

The gaps in the open literature are established by reviewing previous studies on foam-filled thin-walled tubes. The presence of foams as a reinforcement material in thin-walled tubes offers several potential benefits for energy absorption. It is apparent in the literature that there are numerous established studies on the crush and energy absorption response of foam-filled thin-walled tubes under axial loading. Examples include foam-filled square tubes (Aktay et al. 2006; Hanssen et al. 2000; Santosa et al. 2000; Seitzberger et al. 2000; Zarei and Kroger 2008), foam-filled circular tubes (Borvik et al. 2003; Kavi et al. 2006; Toksoy and Guden 2005; Yan et al. 2007), foam-filled hat sections (Chen 2001; Song et al. 2005), foam-filled tapered rectangular tubes (Mirfendereski et al. 2008; Reid et al. 1986)and foam-filled conical tubes (Gupta and Velmurugan 1999).

In general, the use of foam filler is to reinforce and stabilize the crush response of thin-walled tubes when subjected to impact loads. The effect of polyurethane foam-filling on the collapse of metallic thin-walled structures was first studied by Thornton (1980). By conducting extensive compression tests, the study concluded that polyurethane foam-filling is not weight effective, unless relatively thin sections made of high density low strength alloy are used. However, in the companion paper, Thornton et al found that it is more weight effective to increase the collapse load of the tube when using a foam density of below ~220kg/m.

In another study, it was also found that when the wall thickness of a section filled with polyurethane foam is reduced below a certain limit, weight effectiveness tends to be reduced which is of no practical use. Therefore, thickening the column wall is still more weight efficient than filling the tubes with polymer foams.

Contrary to the above findings, Santosa et al. (2000), Banhart (2001) and Reyes et al. (2004) found that filling metallic tubes with aluminium foam seems to save weight and be preferable to thickening the column wall, in terms of the energy absorption capacity. Moreover, Hanssen et al. (2001) found that the component length and volume of the tube can be reduced by approximately 32% and 68%, respectively using aluminium foam-filled tubes for absorbing impact energy. This is an important feature in today's concepts of energy absorbing system design. Broadly speaking, foam-filling is preferable than thickening the tube wall since the latter may change the characteristics of the load-deflection curve and cause large load fluctuations during the buckling process. Also, increasing the thickness inevitably increases the mass. Overall, foam-filling is more desirable when using metallic foam as the core, particularly aluminium foam.

It is well established that two major changes can typically be observed in the deformation response of thin-walled tubes when introducing foam filler. First, the number of lobes increases, and secondly the deformation mode shortens the fold length. In general, the number of lobes is an increasing function with foam density, as found in a previous study on the axial crushing of foam-filled circular tubes.

### *2.6Summary of literature review:*

This chapter has presented a literature review of the topics relevant to this study. The main topics discussed were structural crashworthiness, impact energy absorbing characteristic, energy absorbers and analysis of energy absorbers.

### *2.7 Main findings from the past research:*

The findings of the literature review show that there is a myriad of published research information on the energy absorption response of foam-filled thin-walled tubes, particularly for square and circular cross-sections. Moreover, much of this information relates to axial quasi static and dynamic impact loading, while FEA has in recent times become a common tool for studying the response of such structures. Numerous studies on foam-filled thin-walled tubes have focused on filled straight tubes (square tube, circular tube, etc.) rather than foam filled concentric tubes despite the superior performance of the latter, as enlightened in this chapter. More importantly, a concentric tube is capable of withstanding axial loads, and is less likely to fail via global bending compared with a single square tube. In the context of vehicle crashworthiness, an energy absorber is commonly subjected to axial loads, thus concentric tubes may prove advantageous in such applications.

Finally, the use of foam-filled concentric tubes in energy absorbing systems has not been investigated in the literature. Therefore, it was beneficial to study the effect of incorporating a foam-filled concentric tube as energy absorbers.

## III. EXPERIMENTAL STUDY OF FOAM FILLED ALUMINIUM TUBES FOR QUASI STATIC AXIAL LOADING

### *Introduction:*

All the experimental models have to be satisfactorily validated in order to ensure that reliable and accurate results will be obtained throughout this study & predict the mean loads, initial peak loads and collapse modes for the quasi static axial crushing of empty and foam-filled concentric tubes of different density foam.

### *3.1 Material Selection:*

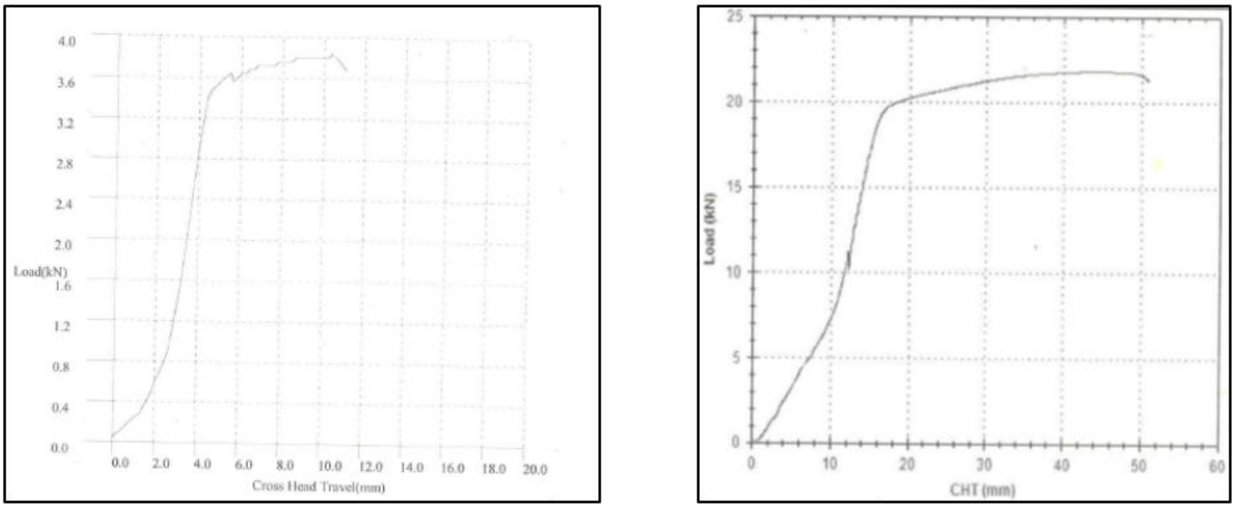
The model for the experiment was mainly consisted of 2 materials, Aluminium alloy 6063 T6 and Polyurethane foam for the tube material that form foam core respectively.

**Four specimen used for the experiment which are as below**:

Specimen 1: Empty Square and Cylindrical tube
Specimen 2: Square and Cylindrical tube filled with Foam of density 40kg/m3
Specimen 3: Square and Cylindrical tube filled with Foam of density 70kg/m3
Specimen 4: Square and Cylindrical tube filled with Foam of density 100kg/m3

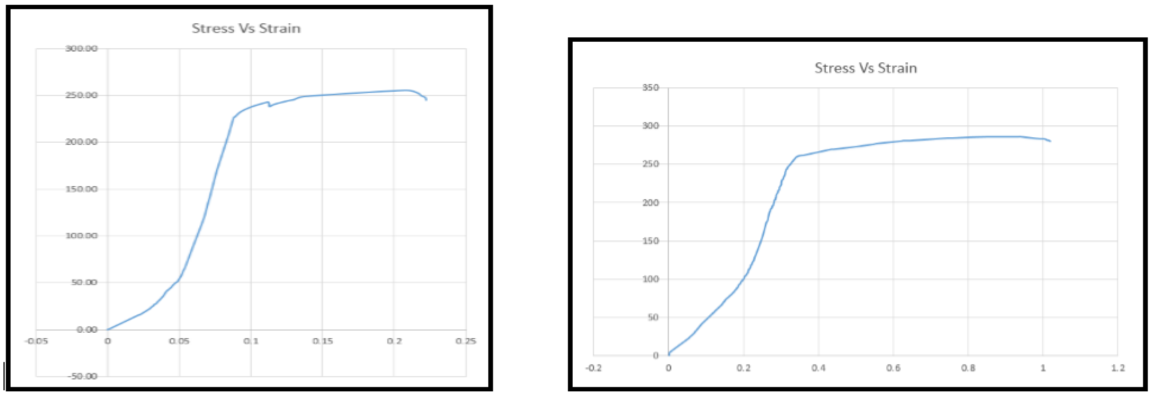
Fig 3.1.1 Experimental specimen of Empty and filledConcentric tubes

The tube material used for the experiment was Aluminium Alloy 63400(As per IS) or 6063T6 (As per ASTM) with the following mechanical properties: initial yield stress, $o_y$ =*226.3*MPa; Young's modulus, *E* = 72GPa for Outer tube and initial yield stress, $o_y$ =*256..06*MPa; Young's modulus, *E* = 70GPa for Inner tube;



Inner Tube Outer Tube

Fig 3.1.2 Load vs Deflection curve of Al Alloy

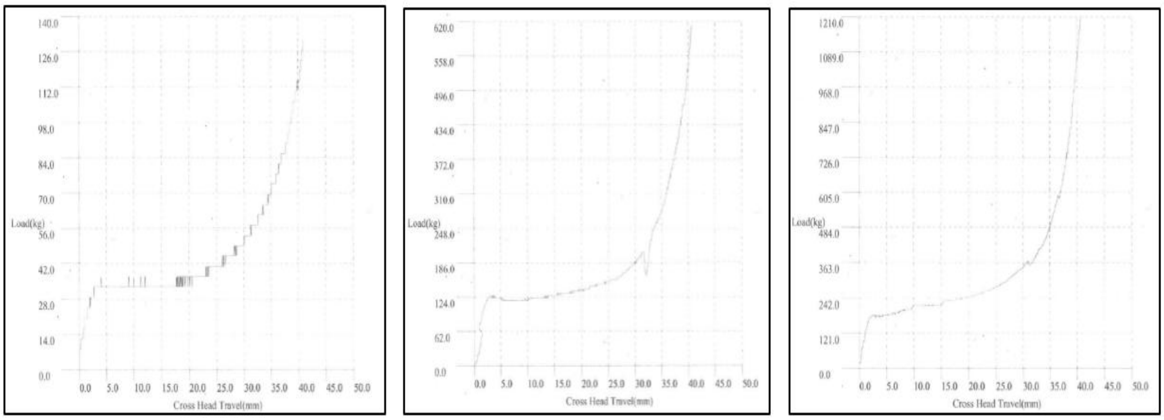


Outer Tube

Inner Tube

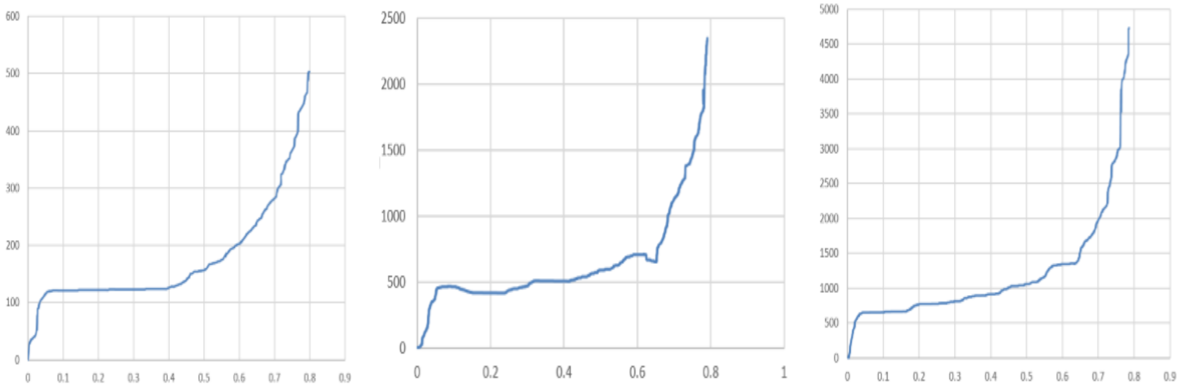
Fig 3.1.3 Engineering Stress-Strain curve of Al Alloy

The PU foam was prepared by reacting of an isocyanate compound such as diphenylmethanediisocyanate (MDI) and a polyhydroxyl-containing polymer, i.e., polyols, such as polyethylene glycol (PEG). To obtain the material properties of the PU foam, it was machined to 50mm*50mm as per ASTM standard ASTM E8M-11 and it was undergone compression test. The stress strain curve of the PU foam obtained is as shown in the Fig 3.1.4 and Fig 3.1.5 shows the Stress vs Strain Curve.



(a) (b) (c)

Fig 3.1.4 Load vs Deflection curve of PU Foam (a) Density 40kg/m$^3$ (b) Density 70kg/m$^3$ (c) Density 100kg/m$^3$



(a) (b) (c)

Fig 3.1.5 Stress vs Strain curve of PU Foam (a) Density 40kg/m$^3$ (b) Density 70kg/m$^3$ (c) Density 100kg/m$^3$

### *3.2 Quasi static experimental testing:*

There are no existing experimental data, theoretical relations or numerical results in the literature for the response of empty and foam-filled aluminium concentric tubes. Therefore, in a quasi-static analysis, the goal is to model the process in the shortest time period in which inertial forces remain insignificant. The FE model for the foam-filled concentric tube was therefore validated using results of experiments carried out by comparing the load - deflection curve, mean load-deflection response and mode of deformation. Fig 3.2.1 shows the test set-up for the axial quasi static testing.The dimensions were chosen based on the experimental constraints namely the maximum load capacity of the testing machine and the practical size of the test rig. The wall thickness, width and breadth of each specimen were measured prior to testing. In addition, each specimen was also weighed to obtain the actual mass of the specimen.The Experiments for the models were conducted using Universal Testing Machine of 80KN capacity was used for all quasi static tests at a crosshead speed of 6 mm/min as shown in. The load-deflection response of each specimen as it was crushed was obtained using load recordings from the testing machine, and by measuring the deflection of the cross-head using a Linear Variable Displacement Transducer (LVDT) with a data precision of ± 0.05 mm.

Fig 4.2.1 Quasi - Static test set up using Universal Testing Machine

The number of discrete data points can be manually or automatically recorded, and the curve response monitored for the entire collapse process, using the LAB TEC Notebook software package.

### *3.2.1 Deformation modes of Experimental Models:*

Fig 3.2.1.1 shows the deformation modes of specimens used to validate the FE result. Quasi static tests are convenient for analysing energy absorber response since they allow continuous monitoring of load, displacement and deformation mode. Moreover, the load and deflection provide a quantitative measure of the mean load. All these results are important since they are necessary for validation of the FE models.

As can be seen from Figure Fig 3.2.1.1, a complete description of the collapse process is involved in several stages. That is, when compression started, the first fold usually tended to form outwards from the 2 opposite sides of the tube and inwards from the other 2. The folds started with a load peak rise rapidly higher than the other peaks, until the tube sides collapsed. The load then decreased rapidly to the first local minimum, in which the first outward and inward flattening folds were fully developed. That is, folding of the walls started in the vicinity of one end of the tube. The second increase in the load could be observed after the first folding of the walls ended, i.e. contact of the walls started, leading to formation of the second folding of the adjacent walls. Then the second drop of the load occurred again, indicating the second folding of the walls. Thus, the load dropped when new folding started, and rose when the walls came in contact. This process was repeated until the folding of the tube was completed showing the behaviour of the crushed tube as a rigid body.

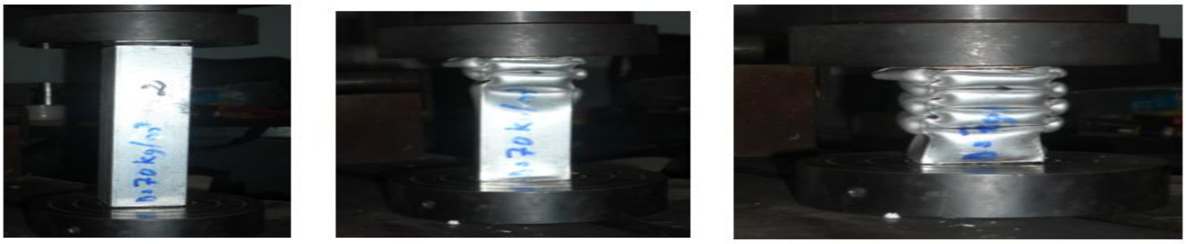


Fig 3.2.1.1 Deformation modes of foam filled (70kg/m3) Concentric tube

### *3.3Experimental Comparison of load v/s displacement curves of the four tubes.*

Fig 3.3.1 shows the Experimental Results of Geometric models which are correlated to each other. Experimental Result showed that foam filled concentric tube absorbed more load as compared to empty concentric tube.

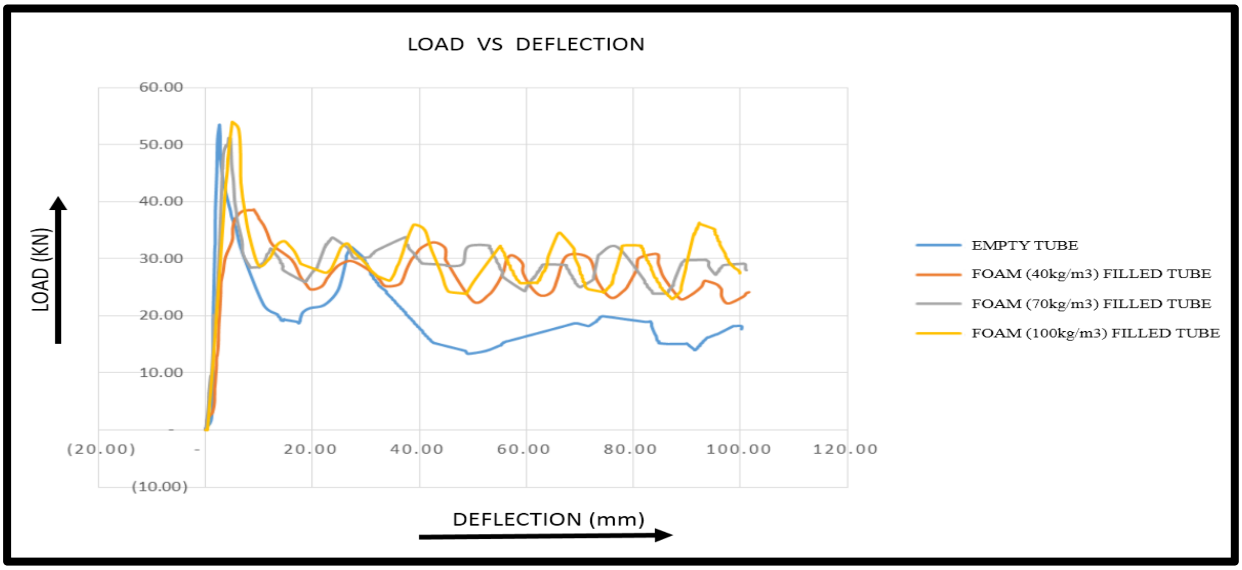


Fig 3.3.1 Experimental Correlated results of load v/s displacement of the four tubes.

This was because the encroachment of the inner wall inside the outer wall allows an additional compression load retards the sectional collapse of the tube. When this tube is filled with Foam between them, the more compressive would be require to deform the specimen. This behaviour results in the higher strain energy dissipation, which lead to the higher crushing resistance of the columns. Thus it was found that foam filled concentric tubes are more energy efficient when compared to Empty concentric tube.

Below Table 3.3.2 describes the Peak load, Mean load and Energy Absorbed by each specimen.

| Experimental | Empty Concentric tube | Foam filled Concentric tube 40kg/m3 | Foam filled Concentric tube 70kg/m3 | Foam filled Concentric tube 100kg/m3 |
|---|---|---|---|---|
| Peak Load (KN) | 53.5 | 38.64 | 51.14 | 53.97 |
| Mean Load (KN) | 21.25 | 24.92 | 28.63 | 28.7 |
| Energy absorbed (J) | 1116.6 | 1539.52 | 1546.39 | 1590.29 |

Table 3.3.2: Experimental Peak load, Mean load and Energy Absorbed by each specimen

Thus, it is evident that energy absorption of foam filled concentric tube was more than Empty concentric tube.

## IV. VALIDATION RESULTS

To verify the validity of the FE models, they were validated against experimental results which predict the mean loads, initial peak loads and collapse modes for the quasi static axial crushing of all specimens.

The FE models for all geometry was validated by comparing the load-deflection response, mean load, initial peak load and collapse modes with experimental results. The validation of the empty tube was carried out on the experimental model which was having same dimensions and material as used in numerical analysis.

### *4.1Validation of Numerical Simulation through Experimental Data:*

Simulation of FE models which was performed through LS-DYNA and is validated by comparing the experimental test data. Fig4.1 shows the comparison of both numerical and experimental models after deformation. In both cases, the column walls deform progressively by forming inward and outward folds in two connecting edges. This type of deformation is referred to as asymmetric (quasi-in extensional) folding mode. Approximately four lobes are formed due to plastic folding on both numerical simulation and the experiment.

From the direct comparison between plastic deformations obtained from the numerical simulation and actual experiments, it shows that a suitable finite element model has been used to simulate an actual physical problem of foam-filled sections. The choices of element types and sizes, material modelling, and boundary conditions in the finite element modelling have led to a deformation pattern which is in a good agreement with the actual experimental test.

Fig 4.1 shows the deformation modes of the Foam filled Concentric tube. It was observed that for the same deformation length, fold formation in the numerical model was same when compared with experimental model.

Fig 4.1 Deformation modes of Experimental and numerical simulation respectively

Similar deformation pattern was observed for empty and foam filled tube for other density of foam. The Figure 4.2 shows the load vs deformation comparison graphs and Table 4.3 shows the Experimental Peak load, Mean load, Energy Absorbed and Specific energy absorbed by each specimen which concludes that the foam filled of density 70kg/m3 and 100kg/m3 are good enough to support that are in conjunction with experimental data

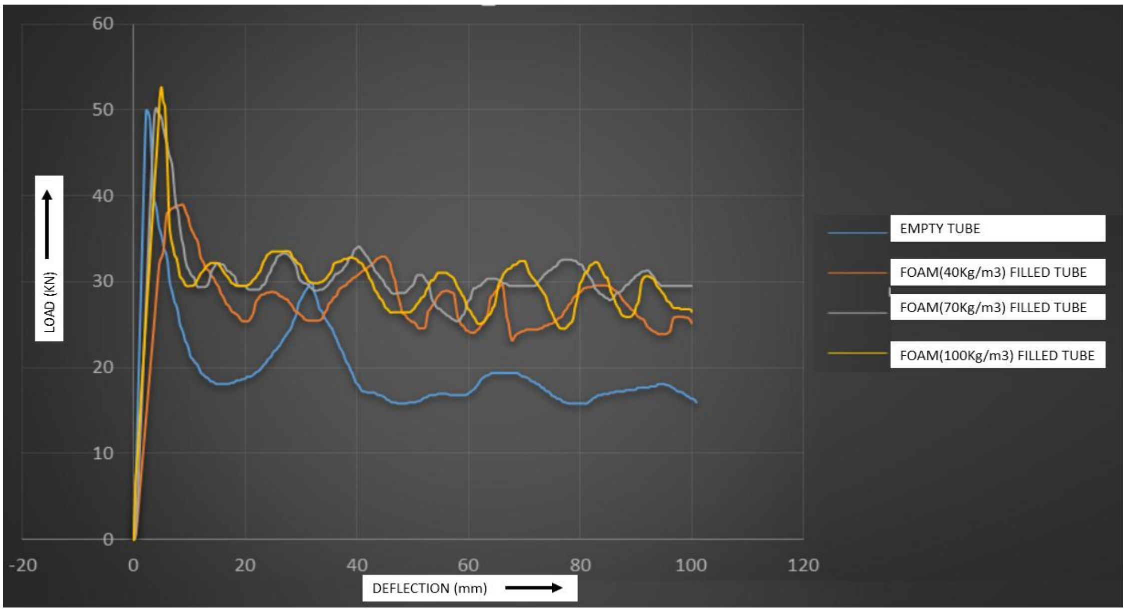


Fig 4.2 Graphical comparision of experimental and numerical result.

Table 4.3: Experimental Peak load, Mean load and Energy Absorbed by each specimen

| Numerical | Empty Concentric tube | Foam filled Concentric tube 40kg/m3 | Foam filled Concentric tube 70kg/m3 | Foam filled Concentric tube 100kg/m3 |
|---|---|---|---|---|
| Peak Load (KN) | 49.94 | 38.97 | 50.16 | 52.57 |
| Mean Load (KN) | 21.85 | 27.31 | 30.42 | 30.53 |
| Energy absorbed (J) | 1214.18 | 1486.26 | 1580.337 | 1654.976 |

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## V. CONCLUSION

### *Introduction:*

The main objective of this study was to investigate on the energy absorption behaviour of empty and foam-filled concentric tubes and to facilitate their application in energy absorbing systems. Though this study was limited to concentric tube, It made easier to compare the amount of energy which will be absorbed in empty concentric tube when compared to foam filled concentric tube with foam of different density in each specimen. In order to achieve the aim, this study has comprehensively examined the crush and energy absorption response of empty and foam-filled concentric tubes under axial loading. The geometry of the specimens, the tube wall thickness, length, cross-section dimension were made constant and foam density is varied. The loading parameters were kept constant through the study.

### *5.1 Innovations in this Investigation*

For the first time, this study, comprehensively investigated the crush and energy absorption response of empty and foam-filled concentric tubes under axial loading condition. This study has merit and is innovative as it generated new research information that can provide design recommendations for the use of foam-filled concentric tubes as energy absorber devices.

### *5.2 The special findings of this study are outlined below.*

The combination of a two tubes and foam material provides great enhancement of the energy absorption performance under axial loading and proves to be advantageous as an energy absorbing device. Such combination enhances the energy absorption capacity without a significant increase in the initial peak load, which is desirable for minimizing the impact loads transmitted to the protected structure.

### *5.3 Scope for future work*

From the results of this study, several recommendations for future work are discussed below where further research is recommended.

(1) The author recommends the use of metallic foam material such as aluminium and other polymeric foams such as polystyrene, polyethylene for further studies. The energy absorption response of these foam-filled concentric tubes may be further examined for a variety of tube sections and foam density for axial loading as such tubes may exhibit a different crush and energy absorption response. Further research will be required on this topic.

(2) The author recommends filling the tubes with a compound material by using foams of two different densities in one case. The density of foam will change the center of gravity of the structure, thereby, an elastic instabilities during the loading process.

(3) Further quasi-static experimental testing can be undertaken to build a larger database of results. These additional results can be added to strengthen the present research findings. Thus, further analysis can be done for a wide range of geometry, material and loading parameters.

## ACKNOWLEDGEMENT

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