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Energy Absorption Capacity of Empty and Foam-Filled Concentric Cylindrical Tubes

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Abstract

Axial folding of metal tubes has been renowned over ages as a superb energy-absorbing method. High-volume industrial items like automobiles, trains, and other sectors where energy must be absorbed in a controlled manner during a crush situation are using components based on this concept. From the perspective of passenger automobile safety design, it is crucial and anticipated to investigate crushing energy absorption.

These are thoroughly investigated experimentally and computationally how aluminium foam-filled sections behave when compressed axially. To represent quasi-static test circumstances, nonlinear dynamic finite element studies are conducted. It is discovered that the predicted crushing force and fold formation are rather similar to the experimental facts. The mean crushing force of the foam-filled sections is calculated using straightforward closed-form methods based on the computational models. It is shown that the increase in the mean crushing force of a full column increases linearly with the cross-sectional area and foam compressive resistance. The proposal, for a variety of column designs, materials, and foam strengths, has been within 8% of the experimental data.

Ultimately, the results highlight the advantages of using concentric cylindrical tubes to absorb impact energy in circumstances with axial loads. It only understands well how control the absorbed energy by using the geometrical features of such structures. The purpose of this study is to suggest design solutions on how to use concentric cylindrical tubes in energy absorption applications like crash-worthiness.

Keywords: *Nonlinear dynamic, quasi-static, closed-form solution, cylindrical tubes*

1.0 Introduction

Due to the significant growth of the automotive and transportation industries in recent years, the number of automobiles on the road has been steadily rising. The need for vehicles has risen as modern society depends more and more on transportation infrastructure. Vehicle crashes are becoming a significant threat to world health [5]. This is particularly true for vehicles used on roads, such as cars, trucks, vans, and heavy machinery [1].

Various accidents involving motor vehicles are possible, and each one may result in varying degrees of human harm. It is obvious that the cost of traffic accidents to society is high. Due to this major health concern, continual efforts are being undertaken to resolve it [4]. As a result of stronger safety rules, the energy absorption capability of vehicles and protective structures has gained significance. For instance, using energy absorber technology to lessen the impacts of an impact event has received a lot of attention. In order to safeguard the structure and its occupants after a collision, such devices are primarily designed to lessen impact energy [3]. Different types of energy absorbers have been employed in the building of vehicles, particularly cars, for years.

The better energy absorber must be capable of exerting the maximum force with a virtually constant pressure across the longest stroke. For a very long time, safety has been a serious issue in the field of design. Several different factors related to safety are taken into account while designing automobiles [6].

One of these qualities is the capacity to withstand impact without endangering the people within. By include crash-worthy structures in the vehicle's design, this trait can be achieved. The capacity of a structure to distribute impact energy and bring the passenger compartment to a halt while subjecting the occupants to with an extreme or rapid deceleration that might cause injuries, is referred to as crash worthiness. Some characteristics that might be employed to achieve crash-worthiness include controlled damage mechanisms and a steady decline in load profile [7].

In actuality, one of the most significant factors impacting energy dissipation systems is the energy absorbed during plastic deformation. The massive plastic behaviour of mechanical components such as plates, shells, tubes, and stiffeners under a variety of stresses has been the topic of several scientific studies. They are interested in learning more about the mechanisms of deformation, patterns of energy absorption, and failure during collapse. For a particular structure, the following criteria alone define this energy: the quantity, kind, and the method of applying loads, strain rates, patterns of deformation and material characteristics [10].

The plastic flow must be accurately assessed using experimental methods in order to completely comprehend the structural reaction during collapse. The mechanical properties of these materials during compression indicate, in combination to their mass efficiency, that they serve as good energy absorbers, with a clear peak of virtually constant force on the uniaxial compressive force displacement curve [14].

To satisfy the crash-worthiness requirements and subsequently safeguard the passengers and the vehicle's structure during an impact event, energy-absorbing systems made up of thin-walled square structures, such as crash boxes, are frequently utilised in automobiles in real-world applications [9].

Thin Walled Tubes: Thin-walled tubes of various forms and materials were employed in a range of structural applications as collapsible energy absorbers. These structures were guarded by these devices simply because they are intended to gradually collapse to absorb impact energy in a regulated manner and convert kinetic energy into plastic strain energy in impact scenarios (Lu and Yu 2003). In order to properly incorporate thin-walled tubes into energy absorption systems, academic institutions and individuals have worked hard to understand the reasons of structural collapse [11].

Circular tubes: An exceptionally effective way to absorb energy as square tubes is to crush thin-walled circular tubes axially. Circular tubes are favoured because it functions as good crash absorber under axial stress. Since it provides a largely steady operating load, axial compression of square and circular tubes is thought to be the most prevalent component in energy absorption systems. For a long time, most research has concentrated on examining the crush and energy absorption response of circular tubes. The static and dynamic crushing reactions of circular thin-walled tubes were the focus of several articles (Abramowicz and Jones 1984; Abramowicz and Jones 1986; Al Galib and Limam 2004; Guillow et al. 2001; Gupta 1998).

Square/rectangular tubes: Also in review articles, thin-walled tubes with square or rectangular cross sections are both thoroughly studied as energy absorption elements. There was a great of interest in the subject since a previous study regarding the crush and energy absorption properties of square tubes under axial and dynamic stress [13].

Other researchers have been investigating the reactivity of square tubes in order to understand more about how they perform with static and dynamic stresses (Reid et al. 1986). Whereas the load-deflection curves' essential features are similar, the deformation mode of square tubes differs dramatically from that of circular tubes. The impact of altering the initial length along a wide range in its deformation mechanism, energy-absorbing capacity, inertia impacts, and loading rate has been studied. Square or rectangular tubes, despite their high capacity for absorbing impact loads, must be appropriately handled in terms of geometrical characteristics such as initial length, width, thickness, and so on, because such tubes tend to shatter via a very unstable global bending collapse mode (Reid and Reddy 1986). As previously stated, global bending must be avoided in crash-worthiness applications because it might result in a considerable loss in energy absorption capacity.

2.0 Development and Analysis Using Finite Element model

2.1 Geometry and Finite Element Mesh

The foam was created utilising 8 noded solid pieces, the reduced integration approach, and hour-glass control. A structural rigidity hour-glass control is employed to reduce the amount of erroneous zero energy deformation modes, and lowered integration was employed to prevent volumetric locking (Figs.1&2).

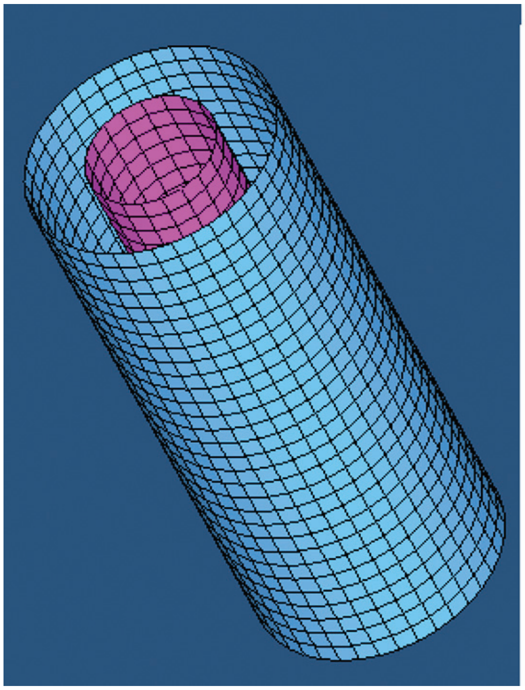

Figure 1: Meshed model - Empty cylindrical concentric tube

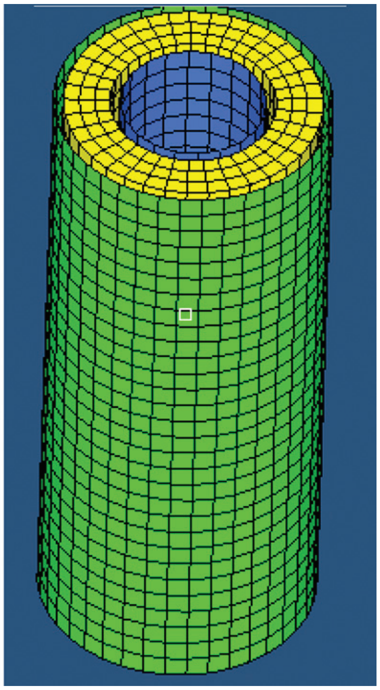

Figure 2: Meshed model - Foam filled cylindrical concentric tube

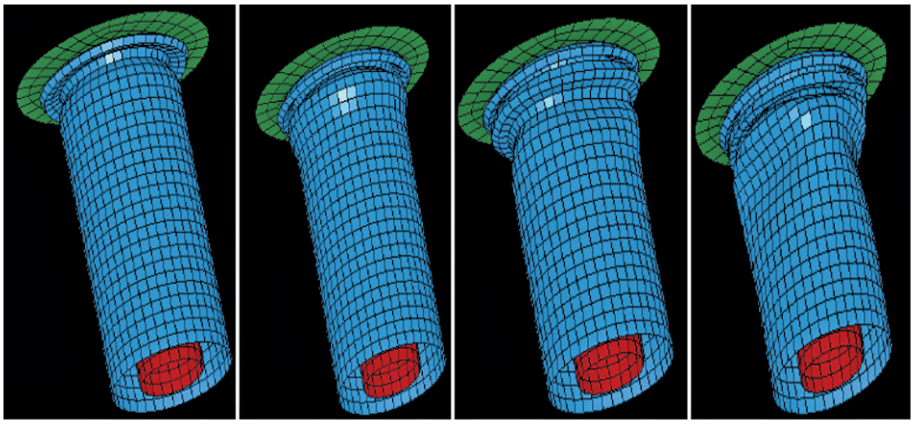

Figure 3: Numerical Simulation of Empty Cylindrical Concentric tube

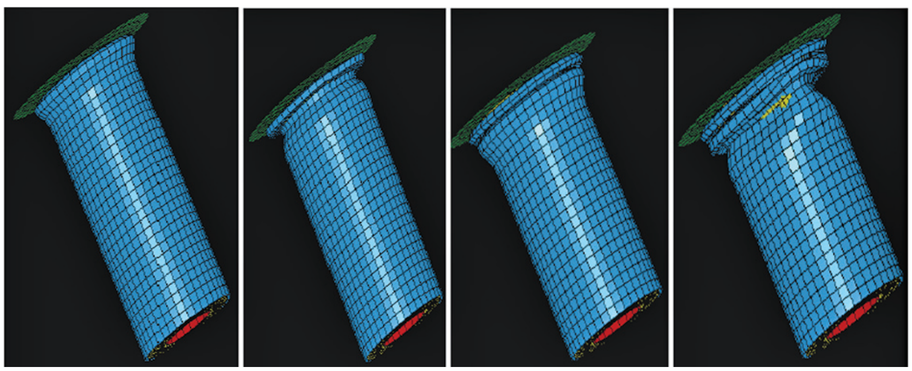

Figure 4: Numerical Simulation of Foam Filled concentric tube

2.2 Lobe Phenomenon Deformation-Induced Development in the Tube

As a result, when a compressive load is applied for the first time, the resistive force resisting the load increases dramatically. Then, as a result of local buckling at the most resistant spot, plastic folds form. As the specimen's compression loading mode transitions to the bending mode around the buckled area, stiffness decreases due to a loss in compression resistance force, and so longitudinal deformation occurs, culminating in the merging of both plastic folds. The compression-resistive force grows as the overall stiffness of the specimen increases, and the second plastic fold occurs. This procedure is repeated, resulting in a series of plastic bends.

Compressive deformation of extruded tube specimens and the potential for plastic fold development are also important variables in absorbed energy. The creation of such plastic folds provides the benefit of absorbing energy.

The load-displacement curve was obtained, and the peak was tabulated to measure the energy absorption of different configuration. Observation was made to see if the plastic fold or bending had formed during the axial compression of the specimens.

Compressive deformation of extruded tube specimens and the potential for plastic folds to form are important variables in absorbed energy. The creation of such plastic folds is a means of absorbing energy. The load-displacement curve was constructed in order to compute the peak of the curve and the energy absorbed by various configurations. Observation was performed to evaluate whether the plastic bending or folding had developed during the axial compression of the samples.

Table 1: Numerical results

(Numerical) FEM	Empty cylindrical Concentric tube	Foam filled cylindrical Concentric tube	% increase
Peak load (kN)	235	255	7.84
Mean load (kN)	153.27	168.78	9.18
Energy absorbed (J)	9039.782	9780.738	7.57
Weigh (Kg/m^3)	0.173748609	0.173750616	0.0011
Specific energy absorption	52027.939	56291.81	7.57

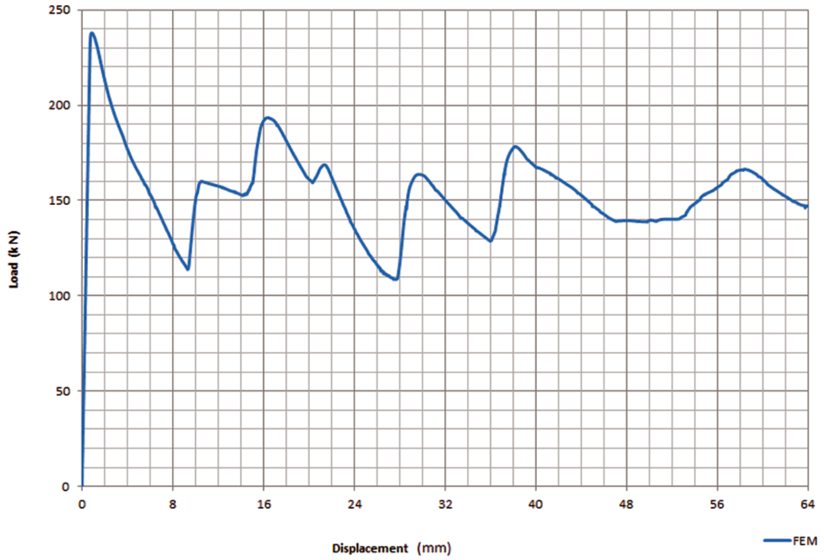

Figure 5: Numerical Load V/s Displacement Graph for Empty Cylindrical Concentric tube

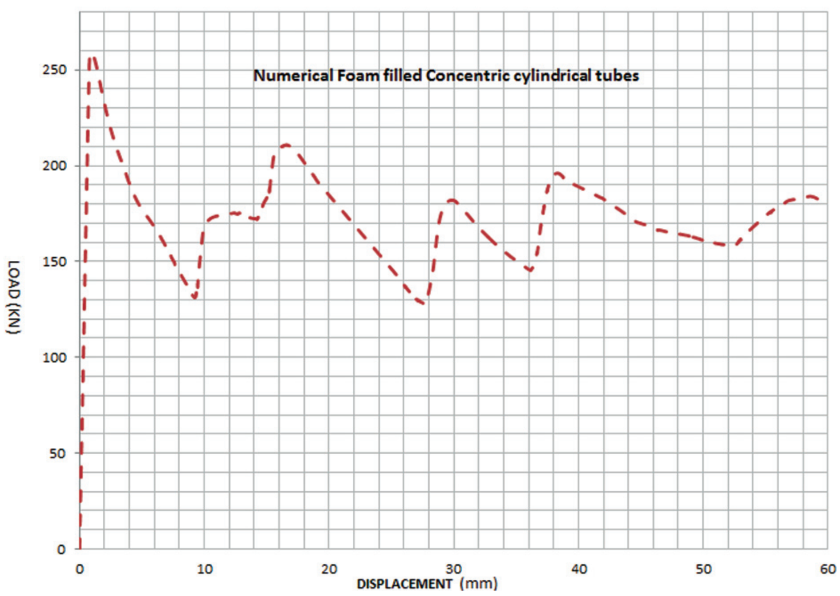

Figure 6: Numerical Load V/s Displacement Graph for foam filled Cylindrical Concentric tube

2.3 Load V/s Displacement Curve of FE Models

From the Hyper Graph, the relevant load displacement curve for each of the two models was generated. All the tubes were crushed to roughly 60mm, as was indicated in the part before it.

Thus, it was mathematically proven that foam-filled cylindrical concentric tubes were significantly more effective at absorbing energy than empty cylindrical concentric tubes.

3.0 Quasi-static Axial Loading Experimental Studies of Finite Element Models

3.1 Deformation Modes

Figures 7 and 8 illustrate the deformation modes of the specimens used to validate the FE findings. Quasistatic tests are important for investigating energy absorber response because they can constantly track load, displacement, and deformation mode. Furthermore, the load and deflection provide a numerical evaluation of the mean load. All of these discoveries are noteworthy since they are essential for the validation of the FE models.

A full explanation of the collapse process includes several stages. To put it differently, the first fold usually appears as compression begins, and it tends to develop outward from the two opposing sides of the tube and inward from the other two. The folds began with a load peak that increased fast above the preceding peaks before the tube sides

Figure 7: Deformation modes of Empty Cylindrical Concentric tube

Figure 8: Deformation modes of foam filled Cylindrical Concentric tube

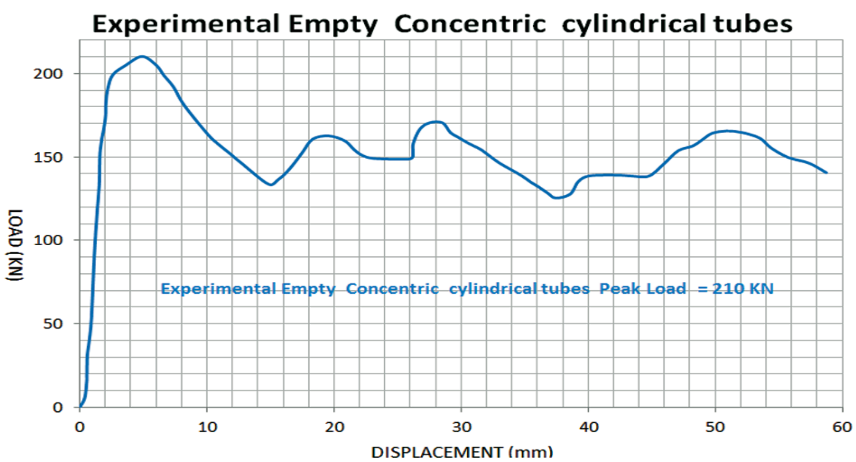

Figure 9: Experimental Load v/s displacement curve of empty cylindrical concentric tube

collapsed. The first outward and inward flattening folds were completely produced when the stress hit the initial local minimum. The load was rapidly lowered to that level. In other words, the walls of the tube started to collapse over one end.

After the initial folding of the walls was completed, the second increase in load was seen, indicating the start of wall contact and the development of the second folding of the neighbouring walls. The load then observed a second dip, indicating a second bending of the walls. As a result, when the walls made contact, the load increased and dropped when new folding occurred. This operation was continued until the tube entirely folded, illustrating how the crushed tube would act as a rigid body.

3.2 Load V/s Displacement Graph of Experimental Models

The experimental models' load v/s displacement graph is displayed as in Figs.9 and 10.

3.3 Results and Discussion

The experimental results of geometric models that are associated with one another are shown in Fig.11. The results of the experiment demonstrated that a cylindrical concentric tube filled with foam absorbed more force than a similar cylindrical concentric tube.

When contrasted to an empty cylindrical concentric tube, the load was absorbed by the foam-filled tube was 8.078% higher.

It is because the inner wall's intrusion into the outer wall, which allows for an extra compression force, delays the tube's sectional collapse. The more compressive would be necessary if this tube were filled with foam in between them, which would need deforming the specimen. This behaviour leads to a greater strain energy dissipation, which increases the columns' ability to withstand crushing. So it was discovered

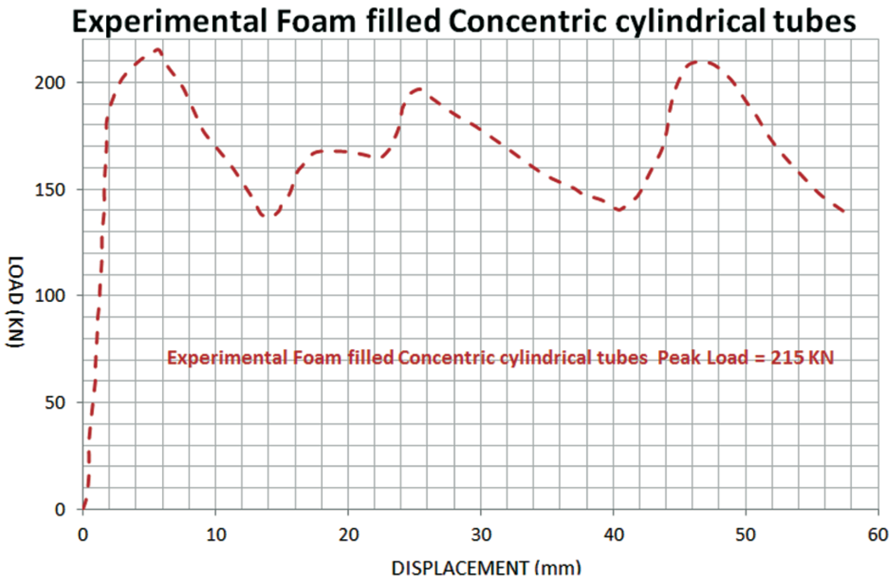

Figure 10: Experimental Load v/s Displacement curve of foam filled Cylindrical Concentric tube

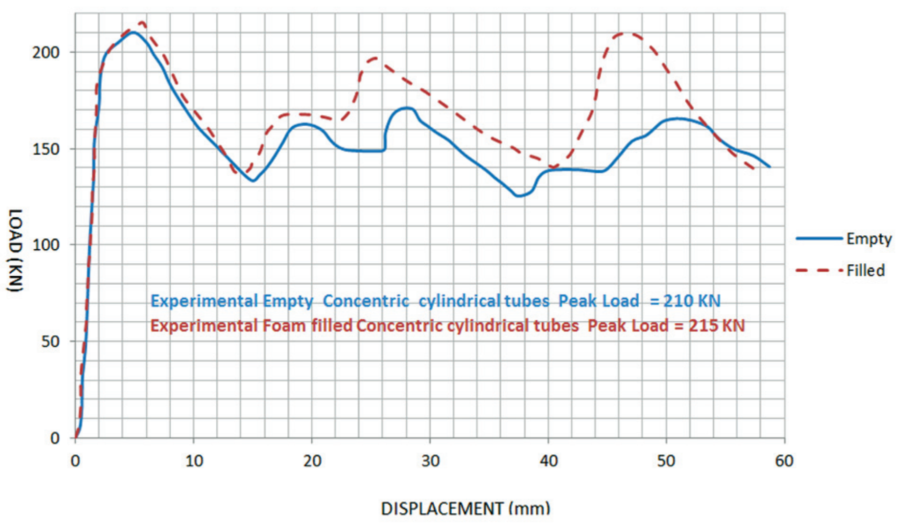

Figure 11: Experimental Correlated results of load v/s displacement of the two tubes

that filled cylindrical concentric tubes with foam are very energy-efficient than empty cylindrical concentric tubes.

The same method as in the previous section was utilized to compute the energy absorbed during deformation. Every specimen's peak load, mean load, weight, energy absorbed, and specific energy absorption are described in the Table 2.

As a result, it was determined that the foam-filled cylindrical concentric tube had a higher energy absorption capacity than the empty cylindrical concentric tube, and its peak load reading of 215 KN was sufficient when matched to the empty cylindrical concentric tube. It has been demonstrated that foam-filled cylinders with concentric walls will result in absorption structures that are more energy-efficient.

4.0 Conclusions

The main purpose of this study was to produce analysis results on the energy absorption behaviour of concentric tubes that were both empty and filled with foam in order to facilitate their use in energy absorption systems. While cylindrical concentric tubes were the subject of this study, the quantity of energy that concentric tubes would absorb could be examined using both empty and foam-filled cylindrical concentric tubes.

Table 2: Experimental Specific energy absorbed, Peak load, Weight, Mean load and Energy Absorbed by each specimen

Experimental	Empty cylindrical concentric tube	Foam filled cylindrical concentric tube	% increase
Peak load (kN)	210	215	2.32
Mean load (kN)	153.99	172.19	10.5
Energy absorbed (J)	8997.041	9787.856	8.07
Weigh (Kg/m^3)	0.173748609	0.173750616	0.0011
Specific energy absorption	51781.945	56332.7844	8.0785

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