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# Crashworthiness Characteristics of Multi-Cell Tubular Structures Subjected To Axial Impact

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***Abstract**: To mitigate the impact forces in crash events, thin-walled tubular elements are employed as an energy absorbing attenuators in frontal part of the automotive vehicles. To develop more progressive deformation modes, at the initial period, and to absorb more impact energy at the final period of crash, it is significant to enhance the crashworthiness performance of the tube by modifying its geometrical parameters. Multi-cell tubular structures have recognized to own superior impact energy absorbing ability and lightweight effect in the modern automotive vehicles. This research article examines the deformation behaviour of thin walled aluminum alloy multi-cell tube with different stiffeners exposed to axial impact loading using numerical simulation. Nonlinear impact simulations were performed on multi-cell tubes using finite element ABAQUS/CAE explicit code. From the overall results obtained, the deformation behaviour of multi-cell tubes was compared. Furthermore, hexagonal tubes with stiffeners were retained as most prominent for better energy dissipation. This type of tube was found to be most efficient type to enhance the crashworthiness performance during axial impact.*

***Keywords:** Axial impact, ABAQUS/CAE, Crashworthiness, Multi-cell, Stiffeners*

## I. INTRODUCTION

Amongst the various types of energy absorbing devices, thin-walled tubular elements have been extensively employed in crashworthiness applications to protect occupants from fatalities and major injuries [1]. These tubes are commonly utilized in frontal parts of automobiles owing to their light-weight, less cost, progressive stable deformation and better energy absorption performance [2]. Numerous research studies have been conducted earlier to examine several single-cell structures like conical, cylindrical, square and polygonal shaped tubes exposed to quasi-static and impact loads [3, 4]. Sawairi et al. [5] performed a comparative study of single-cell tubes with various cross-sectional configurations. The results obtained revealed that the cylindrical tubes could absorb more impact energy than the square section.Multi-cell tubular elements have been investigated by numerous scientists and researchers owing to their superior Energy Absorption Capability (EAC) than that of traditional single-cell tubes. Rohani et al. [6] investigated the square profile tubes with number of cells, number of corners, and related their variations in EAC. Marzdashti et al. [7] performed a comparative study on the deformation performance of multi-cell tubes comprise of two flat plates associated together by various ribs. Shojaeefard et al. [8] examined the crushing characteristics of conical multi-cell tubes both analytically and numerically. The results revealed that the number of cells in the configuration and increase in the taper angle would enhance the EAC of the tube. Sun et al. [9] studied the influence of the number of cells and variations in shapes of multi-cell tubes on their EAC characteristics.Though the crashworthiness performance of multi-cell tubular structures are gaining importance in recent years, still only cylindrical configurations under quasi-static loading is examined [10, 11]. In the current study, multi-cell tubular structures research is further stretched for determining the deformation and EAC characteristics of such structures having stiffeners under axial impact. In this regard, the proposed multi-cell tubular structures are defined and deformed numerically for determining the deformation profiles and crashworthiness characteristics such as Mean Crushing Force (MCF), Crush Length (CL) and EAC and the results are compared with the conventional single cell tubes.

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## II. MATERIALS AND TUBE CONFIGURATION

In this article, multi cell tubes were made of aluminium alloy and this material was chosen owing to its common utilization in automotive structures. Mechanical properties of the aluminum were determined from standard tensile test of samples pierced from tubes. The strain rate effect was not incorporated in the numerical simulation, owing to the insensitivity of aluminum alloy in impact loading. For aluminum tubes, material properties of the model could be modeled as elasto-plastic materials using isotropic elasticity, and von mises yield criterion, The yield stress and plastic strain values were of the aluminum material are presented in Table 1.

**Table 1: Plastic properties of aluminum AA6061 alloy**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Yield stress (MPa)** | 68 | 78 | 125 | 148 | 155 | 159 | 165 | 170 |
| **Plastic strain** | 0 | 0.019 | 0.03 | 0.06 | 0.08 | 0.1 | 0.16 | 0.19 |

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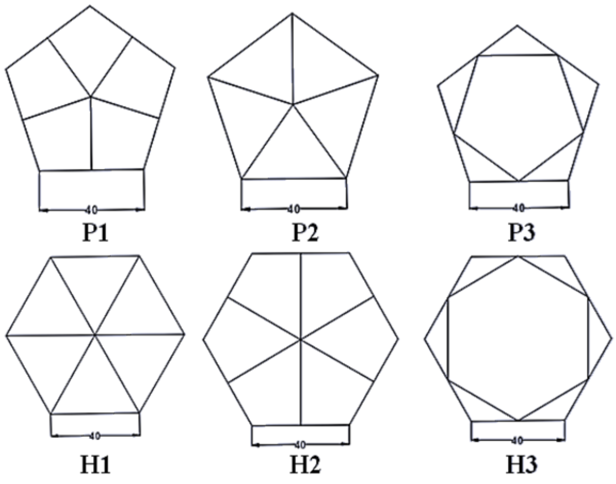


**Fig.1 Geometry of proposed multi cell tubes**

The dimensions of the proposed multi-cell tubes tested under axial impact loading is shown in Figure 1. The tube samples are specified using codes for better understanding, identification and comparison. These codes comprise one alphabet and one number. The first letter represents the section and the subsequent number indicates the type of specimen. In multi cellular tubes three different types of stiffener positions were employed. P1- pentagon tube of type one, P2- pentagon tube of type two, P3- pentagon tube of type three, H1- hexagon tube of type one, H2- hexagon tube of type two, H3- hexagon tube of type three.

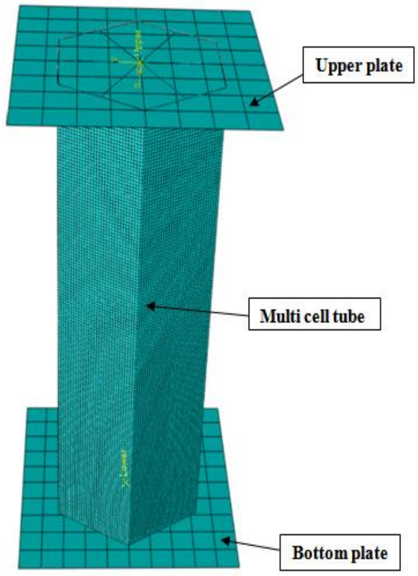


**Fig.2 Boundary conditions applied to tube**

**Table 2: Crashworthiness indicators of multi cell tubes**

| Specimen geometry | Thickness (mm) | Velocity (m/s) | CL (mm) | IPF (kN) | MCF (kN) | EAC (Joules) |
|---|---|---|---|---|---|---|
| **P1** | 2 | 10 | 113 | 74.11 | 51.38 | 5791.43 |
| **P2** | 2 | 10 | 113 | 80.86 | 57.10 | 6433.85 |
| **P3** | 2 | 10 | 98 | 113.55 | 71.90 | 7066.19 |
| **H1** | 2 | 10 | 115 | 96.54 | 62.20 | 7170.71 |
| **H2** | 2 | 10 | 89 | 111.55 | 80.59 | 7176.02 |
| **H3** | 2 | 10 | 111 | 85.06 | 64.67 | 7198.20 |

## III. FINITE ELEMENT SIMULATION

Numerical models were developed using the finite element ABAQUS code to numerically simulate the axial crushing of multi cellular tubes. The boundary conditions applied to the multi cell tube simulated subjected to axial impact load is presented in Figure 2. For axial impact simulation, a multi cell tube is placed between upper plate and bottom plate, the bottom plate is stationary and the upper plate will translate in the axial direction. A mass of 100 kg and an impact velocity is defined for the upper plate. The element size of 1 mm is applied for multi cell tube which is obtained after performing the mesh sensitivity study. The contact between the upper plate and the multi cell tube is a node-to-surface contact with friction coefficient of 0.2. Four noded shell elements are used in the tube model and the plates are modeled with a four-noded rigid element. Table 2 displays the comparative results of crashworthiness indicators of multi cell tubes under axial impact load.

## IV. RESULTS AND DISCUSSION

The axial impact crashworthiness analysis of multicell tubular structures was investigated numerically using ABAQUS/CAE code. The typical progressive deformation of multi cell tubes at four different deformation values (for every 25mm) of axial impact is shown in Figure 3. When the stiffened pentagonal tube is loaded axially, the deformation was started by developing a progressive folding from loading end. The deformation sustained with the development of the successive symmetric folds till the ultimate crush length of 113 mm. On the other hand, in case of stiffened hexagonal tubes, crushing started from the impactor end and developed continuously with axisymmetric folds till the final deformation of 111 mm. Both the proposed multicell tubular structures with various stiffeners showed progressive deformation and bette r deformation characteristics.

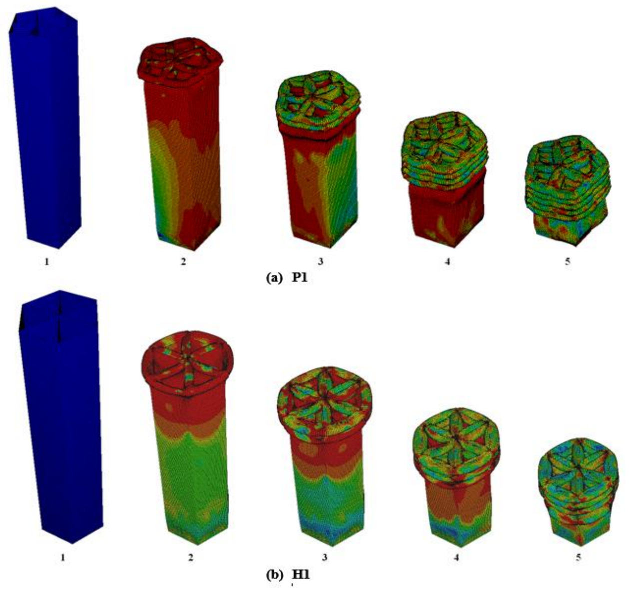


**Fig.3 Progressive deformation of multi cell tubes**

Thin walled polygonal tubes exhibit mostly symmetric deformation patterns under impact force when loaded without inclusion of stiffeners. The buckling profile change significantly when the tubes with stiffeners are deformed axially. The comparison of final deformation patterns of multi cell tubes in three different views subjected to axial impact force is shown in Figure 4. It is perceived from the figure that the pentagonal tube of first type (P1) deformed with five uniform folds till the crush length of 113 mm. On the contrary, the pentagonal tube of second and third type (P2 and P3) deformed with big size uniform folds but deforms completely for the total length of the tube. Moreover the hexagonal tube of first and second type (H1 and H2) deformed from loading end and it continues till the crush length of 115 mm. In contrast, the third type buckled from both the loading and fixed ends with axisymmetric folds with the crush length of 111 mm.

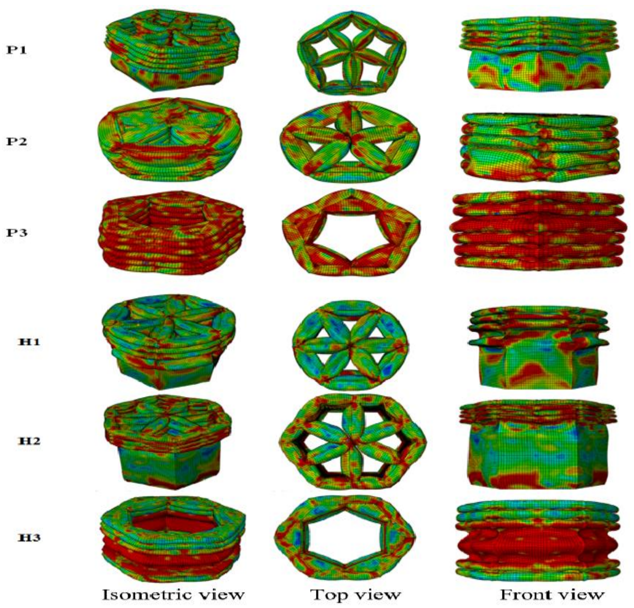


**Fig.4 Comparison of axial deformation patterns of multi cell tubes**

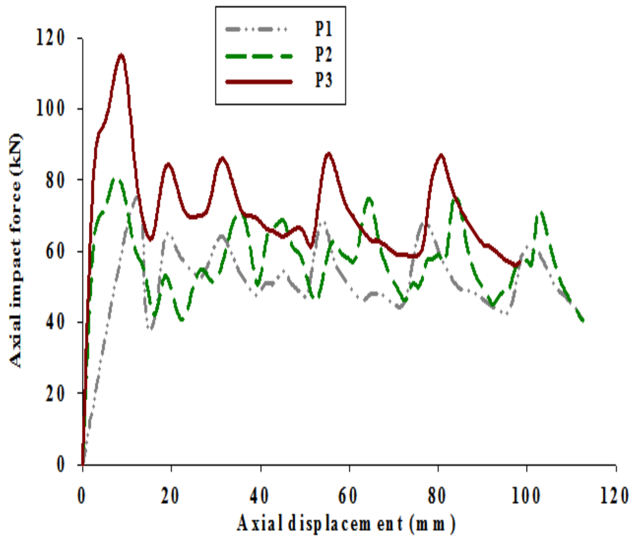


**Fig.5 Deformation response of pentagon tubes with various stiffeners**

The comparison of deformation curves of pentagon tubes with various stiffeners exposed to same impact loading is shown in Figure 5. Devoid of using the triggers in the pentagonal tubes increased the IPF but decreased the MCF and EAC, the proposed tubes with stiffeners displays remarkably smoothed deformation curves under axial impact force. After the initial peak force, the curve suddenly dropped, then after the crushing force value exhibited a smaller amount of difference in the MCF value till the completion of the deformation process. All the proposed three pentagonal tube configurations showed reasonably smooth impact force-axial deformation curves with an almost constant MCF. The pentagonal tube of third type displays moderately high crushing force deviance during the fold development with less number of folds. The pentagonal tube of third type exhibited the highest IPF with prior densification.

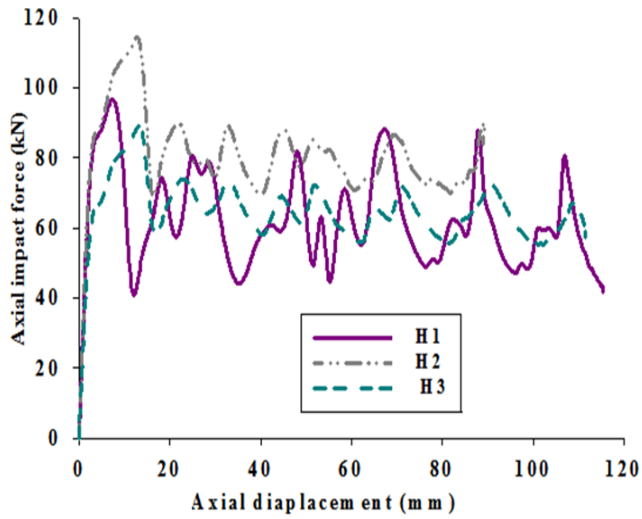


**Fig.6 Deformation response of hexagon tubes with stiffeners**

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Figure 6 shows the comparison of deformation response of hexagon tubes with stiffeners exposed to same impact loading. It is observed that the impact force-axial displacement curve is effected by the dstiffener configurations as the IPF value is fluctuating from 85 kN to 111 kN displaying that the position of stiffeners could affect the deformation pattern and EAC of the tubular structure. The variation of stiffeners in hexagonal tube displays a significant reduction in IPF values with quite stable deformation in H1 and H2 tube configurations. The crushing length of the H2 tube is shortest and longest in H1 tube configuration. All the three proposed configuration displays a significant deformation behaviour in terms of MCF, and EAC.The comparative plot of EAC characteristics of multi cell tubes with various stiffener configurations is shown in Figure7. It is observed that the hexagonal tube with stiffeners shows the highest EAC values than the stiffened pentagonal tubes. The lowest EAC characteristics was revealed by P1 tube, exhibiting the least effective structure. All the proposed pentagonal and hexagonal tubes with stiffeners exhibited superior crashworthiness characteristics and EAC performance than the conventional simple geometry tubes without stiffeners. The position of stiffeners influenced the deformation behaviour and EAC. The determined EAC values of all the hexagonal tubes are almost similar and ranges about 7200 joules.

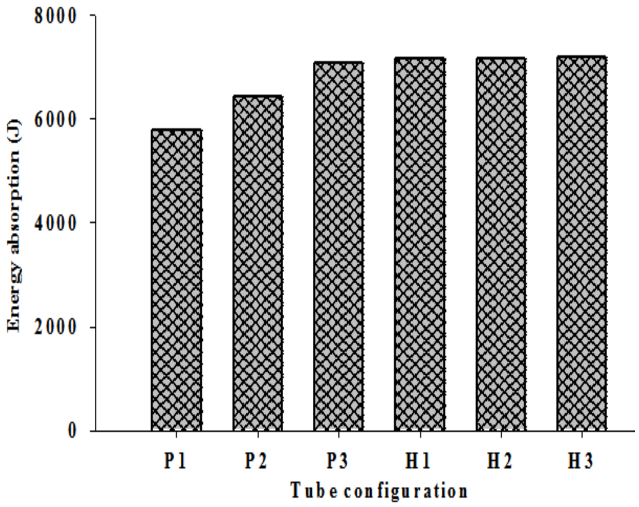


**Fig.7 Comparison of EAC characteristics**

## V. CONCLUSION

The crash performance analysis of multicell tubular structures were analyzed by Finite Element methods. The crushing patterns and deformation response were determined from numerical simulations. The EAC of the various tube configuration was determined with deformation response curves. Both the proposed pentagonal and hexagonal tubes with stiffeners show similar trends in an impact force-axial displacement curve, but the proposed tubes have a higher MCF and EAC than the simple geometry tubes. All the three proposed configuration indicates a stable behaviour in terms of MCF, and EAC. Overall results revealed that the stiffened multi cell tubes might be utilized as energy absorbing elements in modern cars.

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