Numerical Crashworthiness Improvements of Thin Walled Structures

Sharifah Shazzana Bt Wan Taha, Haidar F. Al-Qrimli, and Omar Dhari Hussein

***Abstract*—The aim of the present paper is to achieve an improved understanding of the crushing behavior of thin-walled structures under axial impact. Maintaining the material, length and thickness of the specimens, the crushing behavior of innovative profiles namely Hexagon, Octagon and 12-sided profile, is investigated. In the study, the entire crushing process, including the initial stage of collapse, its localization and the subsequent progressive folding will be analyzed by using Finite Element Analysis (FEA). The relation between the localized plastic deformation and the corresponding crushing force is done by comparing the cross sections of the specimens and their load-displacement curves, maximum crushing force, mean crushing force, crushing force efficiency, total energy absorption and most importantly, the specific energy absorption. These data would provide substantial insight of the collapse mechanism of thin-walled tube structures, in order to find the most suitable specimen for an energy absorber which is an essential parameter in the oil and gas application. The results showed that the 12-sided Cross profile performed most efficiently under dynamic impact absorbing more than 80% higher energy compared to the 6-sided Hexagonal tube and the 8-sided Octagonal tube.**

***Index Terms*—Component, thin-walled structures, crashworthiness, energy absorption.**

I. Introduction

Highlight a The growing number in population leads to an increasing number of vehicles on the road and this causes multiple traffic problems such as road congestions due to growing traffic intensity, noise and air pollution and most importantly, road accidents refinery applications. This rapid increase in vehicles is due to the advanced development of automobile and transportation industry and of course, the increasing demand of today's society who rely heavily on transportation systems and depend on the oil and gas industry, be it personal or public transportations. Consequently, the number of road accidents has dramatically increased as well, making road traffic crashes rank as the 9th leading cause of death worldwide [1]. Thin walled structures are able to dissipate a vast amount of kinetic energy through plastic deformation, slit and fracture upon impact [2]. Galib and Limam [3] conducted a comprehensive experimental and numerical study on the crash behavior of circular aluminum tubes undergoing axial compressive loading. The numerical analysis predicted the crushing force and fold formation of the tubes was matching with the experimental tests.

The two most important parameters when it comes to crashworthiness analysis are material properties and geometry. Yousefsani, Rezaeepazhand and Maghami [4] conducted a numerical study on the axial crushing of metallic and hybrid energy absorbing thin-walled tubes with polygonal cross sections where they investigated the combined effects of varying the geometry and material properties on the specific energy absorption, SEA, mean and the maximum crush forces. Their results showed that these metallic and hybrid tubes with non-circular cross-section shapes have better SEA capabilities than circular ones during the impact. Yamazaki and Han studied the crushing energy absorption cylindrical shells where they conducted an experimental test on a series of aluminum cylindrical tubes under axial impact condition. It was observed that the optimum tubes possessed specific dimensions in order to achieve the allowable limit of the mean axial impact force and then to have the most number of symmetric progressive wrinkles until column buckling occurred [5]. The energy absorption efficiency of a thin walled structure is affected by various factors such as material properties, wall thickness, cross-sectional geometries and boundary conditions. Cross-sectional geometry is the focal investigation in most cases. A vast amount of researches have been done theoretically, numerically and experimentally in metal structures with several cross sections such as circular and polygonal cross-sections [6], [7].

The most common observation in these previous studies is that major deformation occurs near the corners of the structure and the membrane deformation or folding dissipates the impact energy, especially in the corner zone. Hence, it is safe to say that the number of corners or edges of a structure greatly influences the energy absorption efficiency [8]-[10].

Performance, fuel consumption, and engine power are the governing factors in automotive design, and hence, these factors influence the materials selection. It is now a trend to use lightweight metals and their alloys, particularly in automotive bodies. Over the past decades, the research in vehicle's crashworthiness revolved around investigating the crash behavior of various thin-walled structures with different cross-sectional geometries and wall materials.

One of the essential points of interest for aluminum is its accessibility in different semi-finished forms, such as shape castings, extrusions and sheet and all these are suitable for mass manufacturing and innovative solutions. That is the reason aluminum alloys emerge as an appealing material for

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automotive bodies as they weigh around 33% lighter than steel and also having comparable strength to weight proportion as steel [11]. Fyllingen *et al.* conducted an experimental study on the transition of progressive buckling to global bending collapse of tubes. They observed that the transition from a progressive mode to a mixed mode appeared over a large range of lengths, concluding the fact that the length of the tube does affect its collapse mode [12]. Then Tasdemirci [13] carried out an investigation of the effect of tube end constraining on the axial crushing behavior aluminum tubes. The experimental and simulation result, both showed similar behavior under impact [13]. Due to the demands and needs for lightweight vehicles and in order to improve fuel efficiency and reduce pollutions, Aluminum alloy has been the preference in material selection. Its ability to be easily extruded makes it an important factor in vehicle parts especially the frontal longitudinal members. For an energy absorber to be ideal, the initial peak force should be low while its average crushing force should be high. Thin-walled structures are lightweight yet they possess excellent crash energy absorption that produces controlled progressive collapse upon impact. Showing promising and successful collapse mechanisms for energy absorption in the previous studies, thin-walled structures have made it to the center of attention in automobile industries.

II. Methodology

To investigate the crashworthiness of the energy absorbing structures, the crashworthiness parameters must firstly be defined. The commonly used parameters of crashworthiness optimization design for thin walled structures are indicated by the; energy absorption (EA), specific energy absorption (SEA), mean crushing force (MCF) and crash load efficiency (CLE). The structure's crashworthiness can be proficiently evaluated using these parameters. The boundary condition is identical for all the crashing conditions as can be seen in Fig. 1.

The energy absorption is governed by the following equation:

$$EA(d) = \int_0^d F(x)dx \quad (1)$$

where d is the crushing distance in meters (m) and F is the crushing force in Newton (N).

The specific energy absorption (SEA) is the energy absorbed per unite mass for the structure, hence the equation is written as follows:

$$SEA(d) = (EA(d))/M \quad (2)$$

where M is mass of the structure in kilograms (kg).

The crash force efficiency (CFE) is governed by the following equation,

$$CFE = MCF / PCF \times 100\% \quad (3)$$

where PCF stands for peak crushing force.

The material of the profiles in this research is aluminum extrusion AA6060 T4 with Young's Modulus, $E = 68.21$ GPa, density $\rho = 2700$ kg/m^3, Poisson's Ratio $v = 0.3$, yield strength, $\sigma y = 80$ MPa, ultimate strength, $\sigma u = 173$ MPa and ultimate elongation $\varepsilon u = 17.4\%$. [10]

Table I shows three different multi-cornered tubes studied; 6-sided Hexagonal tube, 8-sided Octagonal tube and 12-sided Cross tube. The specimens have the same length of $L = 230$ mm and thickness of $t = 2.5$ mm.

TABLE I: Geometries of Test Specimens

Hexagonal	Octagonal	Cross
6 sided profile	8 sided profile	12 sided profile
		
$C_1 = 56$ mm	$C_2 = 42$ mm	$C_3 = 39.2$ mm $C_4 = 33$ mm

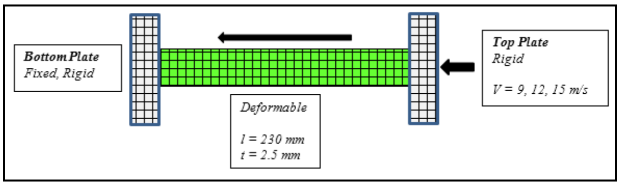


Fig. 1. Boundary conditions of the dynamic crushing.

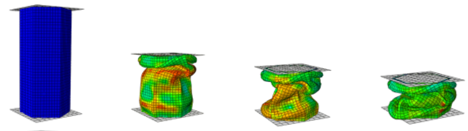
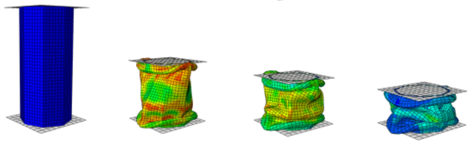
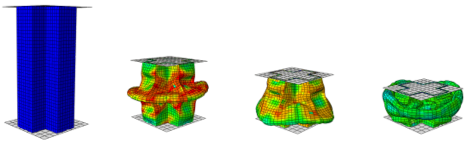
A mesh refinement study has been carried out when the crashed tube is analyzed by using five different mesh densities namely; 2, 4, 6, 8 and 10 mm. The goal here is to obtain accurate results while economizing time and computing power. It was observed that the deformation modes are almost similar for mesh densities 4 – 8 mm which is known as the asymmetrical mode whereas their maximum force, total energy absorbed and simulation time are within close range. Hence a mesh size of 6×6 mm was used for this simulation as it lies within a consistent range of data.

III. Results and Discussions

A. Collapse Mode

The different cross sections of the tubes with its collapse mode and behavior can be seen in Table II. The Hexagonal and Octagonal tubes collapsed in a repeatable pattern of forming 2 lobes, whereas the Cross tube formed 1 lobe. The Hexagonal and Octagonal tube have a circular inner cross section with a radius of 95mm. Since it is circular, the collapse behavior tends to follow the same pattern as the extensional mode and mixed mode. On the other hand, the collapse mode of the Cross tube varied significantly as the speed increases. The Cross tube tends to follow the pattern of a diamond mode and the asymmetrical mode. The difference in the collapse modes between these tubes is due to the number of the edges that each tube possess. The higher the number of the edges, the more stress points are present, which in turn cause different types of deformation.

TABLE II: DEFORMATION MODES OF THE TUBES

Tube	0 (m/s)	9 (m/s)	12 (m/s)	15 (m/s)
Hexagonal				
Octagonal				
Cross				

B. Load-Displacement Curves

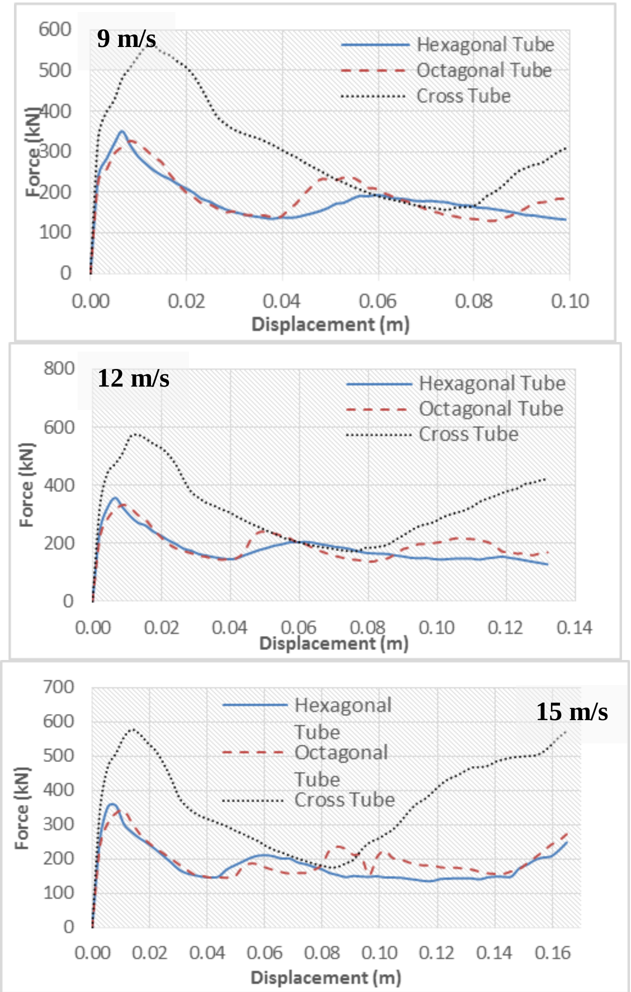


Fig. 2. Comparison between the Load-Displacement Curves for Hexagonal, Octagonal and Cross Tube under 9 m/s, 12 m/s and 15 m/s.

The initial peak force for the Hexagonal tube has range of between 350 kN – 357 kN. As for the Octagonal tube, its initial peak force under all three velocities lie between 320 kN -345kN whereas for the Cross tube, the values lie within the range of 560 kN -570 kN as seen in Fig. 2. The number of vertices on the specimens have affected the load-displacement curve of each specimens greatly. The higher number of vertices, the higher energy is absorbed. The Cross tube is evidently a more efficient energy absorber as compared to the Hexagonal and Octagonal tube. It has absorbed the highest amount of energy under all three speeds.

C. Crashworthiness Parameters

1) Total Energy Absorption (TEA)

A comparison of the FEA simulation results for each specimen, under all three velocities have been done and can be seen in Table III. It can be seen that there is not much difference between the TEA trends of Hexagonal and Octagonal tubes. Generally, the Hexagonal tube has been found to have the lowest values of TEA, ranging between 17.59 kJ – 29.35 kJ. The values of TEA for the Octagonal tube lie within the range of 18.37 kJ – 31.55 kJ. Subsequently, the TEA values for the Cross tube has been found to be much higher compared to the previous specimens, ranging between 29.13 kJ – 58.93 kJ. At this point, the Cross tube has absorbed more than 80% higher energy compared to both of the tubes. As the number of edges increase, more dissipation occurs amongst the edges, allowing the specimens to absorb more energy. That is why the Cross tube, is found to have the highest TEA amongst the specimens. The Cross tube has more edges and corners to absorb more energy.

2) Mean Crushing Force (MCF)

The MCF comparison results obtained from each specimen when crushed under each velocity is shown in Table III. With the highest number of edges, the Cross profile can most definitely be seen leading the other profiles with the MCF ranging from 177.88 kN to 356.99 kN. Followed by the Octagonal tube which has its MCF ranging from 185.61 kN to 191.24 kN whereas the Hexagonal tube was found to have the lowest values of MCF, 177.64 kN to 177.88 kN. The MCF of the Cross tube is more than 80% higher compared to the other specimens. This means that the Cross profile is a more efficient energy absorber compared to the Octagonal and the Hexagonal profiles. The high number of edges allows more energy to be absorbed, as there is more energy dissipation amongst the edges and the corners, amongst its folds.

3) Peak Crushing Force (PCF)

The PCF for the Hexagonal tube is 356.22 kN under the velocity of 15 m/s, whereas the PCF for the Octagonal tube is 342.34 kN under the same velocity. Leading the other tubes, the PCF for the Cross tube is found to be 577.93 kN under the velocity of 15 m/s The PCF value for the Cross tube is more than 68% higher than the other tubes. The Cross profile is the least suitable as it has the highest PCF, under all three velocities. This means that it required a much higher energy to form the first lobe of deformation as compared to the other specimens. This is due to the fact that the Cross tube has a much higher resistance due to the 900 corners and the higher number of edges made it much harder to collapse compared to the Hexagonal and Octagonal tubes as shown in Table III.

4) Crushing Force Efficiency (CFE)

The CFE of the Hexagonal tube are 50.7%, 49.6% and 49.9% under each speed respectively. On the other hand, the CFE of the Octagonal tube is found to be higher than the

Hexagonal tube with the values of 56.8%, 57.0% and 55.9% under each speed respectively. Interestingly, the Cross tube has a lower CFE than the Octagonal tube under the speeds of 9 m/s and 12 m/s, with the values of 52.3% and 54.2% accordingly. However, at 15 m/s, its CFE has increased to 61.8% which is higher than the CFE of the Octagonal at the same speed. Under 15 m/s, the Cross tube has a much higher CFE compared to the other specimens. This means that the Cross tube performed much better under high speeds, making it more ideal as an energy absorber as most car crashes happen because of fast speeds. (see Table III).

5) *Specific Energy Absorption (SEA)*

The comparison between the SEA of each specimen under the velocities of 9 m/s, 12 m/s and 15 m/s is shown in Fig. 3. Similar to the trends shown in the previous sections, the Cross tube has yet again been found to have higher results compared to the other specimens. Under the highest velocity, the SEA for Cross tube, Octagonal tube and the Hexagonal tube is 112.89 kJ/kg, 91.92 kJ/kg and 87.49 kJ/kg respectively. At 15 m/s, the SEA of the Cross tube is found to be around 22% higher than the other tubes, possessing the highest SEA under all three velocities. This shows the geometry of the tubes affect the SEA significantly, clearly proving the fact that a specimen with the higher number of edges has the higher potential of being a more suitable and efficient energy absorber.

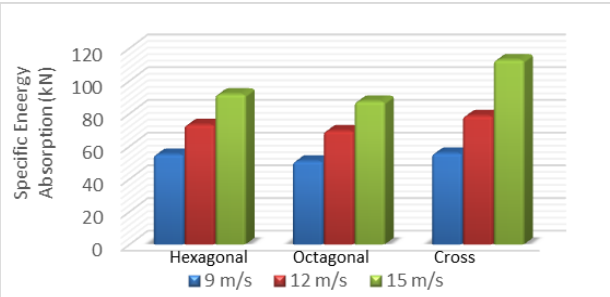


Fig. 3. Comparison of the SEA by each specimen under various speeds.

TABLE III: DEFORMATION MODES OF THE TUBES

Tube	Velocity (m/s)	Parameters				
		TEA (kJ)	MCF (kN)	PCF (kN)	CFE (kN)	SEA (kJ/kg)
Hexagonal	9	17.59	177.64	350.58	50.67	55.09
	12	23.37	177.09	357.02	49.60	73.21
	15	29.35	177.88	356.22	49.94	91.92
Octagonal	9	18.37	185.61	326.40	56.86	50.93
	12	25.05	189.72	332.74	57.02	69.47
	15	31.55	191.24	342.34	55.86	87.49
Cross	9	29.13	294.03	561.86	52.33	55.81
	12	41.07	310.87	573.65	54.19	78.68
	15	58.93	356.99	577.93	61.77	112.89

IV. CONCLUSION

Aluminum alloy is just as good as steel in energy absorption by comparing the findings with the previous literature review done. Despite being much lighter that steel, the aluminum alloy material was able to absorb a substantially high amount of energy while obtaining a high value of SEA.

Under dynamic loading, all three specimens behaved very differently based on its collapse modes. The Hexagonal tube has a mixed deformation modes of a diamond and symmetrical. It can also be seen that the fold and the deformation is focused at the top of the tube. The Octagonal tube shows a mixed extensional fold where the tube deformed at the top and at the bottom of the tube. As for the Cross tube, the deformation is centered on the middle of the tube where this fold is known as the asymmetrical tube. As the speed increases, the deformation of the tubes increases.

The 12-sided Cross profile has the highest SEA of 112.89 kN under the velocity of 15 m/s. This is then followed by the 6-sided Hexagonal tube that achieved an SEA of 91.92 kN under the same velocity, As for the 8-side Octagonal tube, its SEA under 15 m/s is found to be 87.49 kN. Based on these values, it can be deduced the SEA is affected by the geometry of the profiles. The 12-sided Cross tube has the highest number of edges, therefore making it very effective as an energy absorber as it was able to achieve the highest value of SEA.

In a nutshell, the objectives of this research study are met and it is safe to deduce that the number of edges of the profiles do have an effect on the crashworthiness parameters. The higher number of edges, the better the energy absorption efficiency, which is effective to be used in refinery applications.

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