Crush Response of Stacked Square Toroidal Tubes with A Central Tube

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ABSTRACT

An extensive study was carried out to determine the impact response of various impact attenuator designs. This study was important in order to develop and improve the energy absorption system and crashworthiness of impact attenuators. In the event of collision, vehicles are subjected to very high initial force. This phenomenon contributes severity of human injuries and damage to protected goods. New configuration in the form square of stacked toroidal tubes with a central tube was proposed. The aim of this study was to determine the performances and the characteristics of energy absorption of design configuration when subjected to axial static and impact loading. Finite element analyses were carried out using ABAQUS software. Aluminium Alloy AA6063-T5 of square tube was cut and welded into specific configuration for experiment purpose. The simulation results were verified by experiment before embarking into the simulation study. Results showed that the stacked toroidal tube had commendable impact energy absorbing capability. Stacked toroidal tube showed improvement in energy absorption and studied well as discussed in objectives.

Keywords: *Crush Response, Impact Energy Absorption, Toroidal Tube, Stacked Structure, Axial Static Loading*

Introduction

Energy absorption has been extensively studied for the past few decades due to the increasing investment in the transportation sector including other fields such as nuclear reactor, oil-rigs and oil tankers, crash barriers for road-side and air-drop cargo [1]. Recently, automotive manufacturers are facing a very high pressure in terms of fulfilling the demands and needs of users to reduce or

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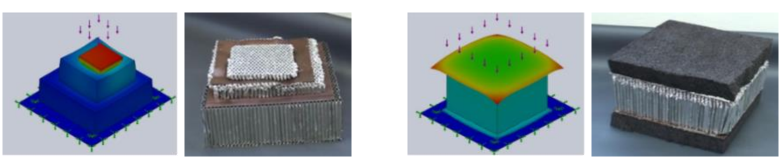
minimize human injuries and serious damage to the vehicles or any structures that need full protection upon impact. To avoid that matter, passive protections are taken such as seat belt, air bags and crashworthy vehicle which are important to diminish accidents that may happen in the future.

The National Highway Traffic Safety Administration (NHTSA) upgraded the side impact protection requirement in Federal Motor Vehicle Safety Standard (FMVSS) No. 214 and added dynamic requirements to reduce the likelihood of thoracic injuries in side crashes [2]. Therefore, many researchers studied the types of structures and materials involved to develop and explore the crashworthiness and safety in automotive as in other applications which protect goods. Crashworthiness is a quality response of vehicle when involved or undergoing impact.

Thin walled structures must be compiled with the criteria for better energy absorption effect. Large amount of energy dissipated during plastic deformation, slit and fractures of collision. This phenomenon absorbs kinetic energy during impact by various mechanisms [3]. Five types of deformation had been studied; inversion, splitting, axial crushing, lateral indentation, and lateral flattening [4].

Worcester Polytechnic Institute (WPI's) FSAE race car requires an impact attenuator that can protect the driver and frame when mounted on the front bulkhead of the vehicle [5]. Two designs of impact attenuator design have been proposed. The two designs developed for modeling and testing were the Honeycomb Pyramid and the Foam-Honeycomb-Foam design. These were further analyzed and designed using solid modeling software. The test data showed that the Foam-Honeycomb-Foam design was the best in this application. It produced both a lower peak and average deceleration over the period of impact.



(a) (b)

Figure 1: WPI FSAE race car impact attenuator result after impact; (a) Honeycomb Pyramid simulation and experiment results, (b) Honeycomb Foam simulation and experiment results [5]

Belingardi and Obradović analyzed the crash analysis of composite sacrificial structure for racing car [6]. They introduced composite attenuator which was tested by comparing the result from the aluminium attenuator. Numerical simulation of crash-test for a formula SAE car was studied by Boria and Forasassi [7]. In the figure, a sheet at the top of the attenuator was represented. It avoided the structure, subjected to a non-frontal impact, and behaved as a hinged parallelogram. It was attached directly to the sandwiches and transferred the impact load on both the panels in case of off-axis collision with an obstacle.

The highest energy-absorbing geometrical section of thin-walled steel tubes was the objective of this study [8]. Energy absorption in square, circular, pentagonal and hexagonal steel tubes were evaluated by finite element analysis. The experimental results of load displacement with square steel tube showed good agreement with finite element method. The study suggested that a pentagonal structure of crush box would avoid higher impact and hence minimized damage to the automotive structure.

A. Ghani et al. proposed a novel design of impact attenuator for FSAE “Eco Challenge Car” of toroidal tube with central tube [9]. The design was introduced to design an impact attenuator that complied with requirements of FSAE competition. The team introduced the design that had yet to be optimized and no further study was done. Results of the design showed that rate of acceleration decreased with time, which was below 20g that complied with the requirement. An inner tube was added at the central to improve the energy absorption as predicted.

For ring compressed between two plates, there are two common modes of collapse during compression. Energy absorption can be maximized by arranging the tubes into laterally constrained. Compared to unconstrained tube, there was less plastic hinges formed during deformation. Lu and Yu studied the deformation of stacked under end impact with and without plate inserts. The study of rings crushed between two plates showed they were almost flat of force-displacement which was in perfect requirement for energy absorber. Wrap-around and plastic wave phenomenon were shown in the free platen at final deformation compared to plated system which was more regular [10].

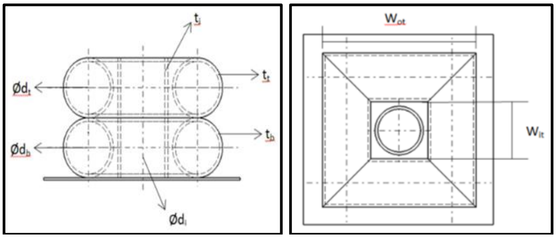
The comparison of stacked single and stacked square accesses the best performance of energy absorption. By comparing, the best performance of double-walled column in the study of Gunawan et al. showed higher mean crushing force and larger energy absorption than single-walled column [11]. The simulations result showed good agreement with the experiments.

There were other several designs proposed in order to study the crashworthiness for various practical applications. They included varying the amount of tubes corners [3], bi-structures design [12], window patterned [13], buckling initiator [14], single and double walls structures [15], corrugated tubes [16], and pattern tube [17].

Stacked Square Toroidal Tube with Central Tube

The proposed impact attenuator was made from standard Aluminium 6063 circular tubes, cut and welded into specific configurations; for example, stacked toroidal tubes with a central axial tube compressed between two plates. The Finite Element Analysis (FEA) software ABAQUS was used to determine the impact response for energy absorption and initial peak force. Simulation data were validated by experiments before embarking on parametric study via simulation. Parameters of interest were tube thickness, diameter and number of stack. It is hoped that this new configuration will exhibit high energy absorption with low initial peak force and uniform crushing force. The characteristics of impact response were determined from the proposed configuration.

The objective was also to find the optimum configuration for impact protection by evaluating the parametric study. The configuration was divided into two; single toroid tube and stacked toroidal tube, which were tested in simulation and verified in experiment. Each design was tested on axial static and impact loading through simulations and few by experiments. A velocity of 6 m/s was used in impact testing which was compatible with the maximum machine load of 26 kg. Because of the machine limitation, only axial static loading was verified in this paper. Figure 2 and Table 2 show the dimensions of proposed structures for each case.



(a) (b)

Figure 2: Stacked of Square Toroidal Tube with Central Tube (S1); (a) Front View, (b) Top View, (mm)

Table 1: Dimension of each specimen of square toroids

SPECIMEN							
DIMENSION	**SQUARE TOROID, S_a (mm)**						
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Top Diameter, $Ød_t$	25.50	25.50	25.50	25.50	25.50	25.50	25.50
Below Diameter, $Ød_b$	25.50	25.50	25.50	25.50	25.50	25.50	25.50
Top Thickness, t_b	0.50	1.00	1.50	2.00	0.50	0.50	0.50
Below Thickness, t_t	0.50	1.00	1.50	2.00	1.00	1.50	2.00
Inner tube diameter, $Ød_{ti}$	25.50	25.50	25.50	25.50	25.50	25.50	25.50

Inner tube thickness, t_i	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Inner Width, W_{it}	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Outer Width, W_{ot}	81.00	81.00	81.00	81.00	81.00	81.00	81.00

Finite Element Analysis

Finite element analyses were carried out by using ABAQUS software. This software helps to analyze the finite element of the proposed configuration. The characteristics of impact response of the new configuration are determined and compared to the experimental result. The top plate and bottom plate were discrete rigid bodies while the circular tube was a 3D deformable shell. The top plate represented the impactor while the bottom plate represented the platen. Both top and bottom plate had 9 nodes and 4 quadrilateral explicit shells element. Table 2 shows the number of nodes and element of configured design in finite element analysis. According to Table 3, the material properties used are Aluminium Alloy AA6063-T5.

Table 2: Designs configuration with number of nodes and element

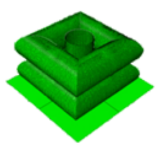
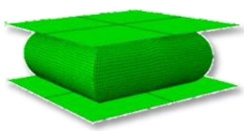
Design	Stacked toroid	Single toroid
Square Shape	 Number of nodes: 29884 Number of linear quadrilateral element: 29275	 Number of nodes:12836 Number of linear quadrilateral element: 12572

Table 3: Properties of Aluminium Alloy AA6063-T5

Density	2700 kg/m^3
Ultimate tensile strength (UTS)	220 MPa
Yield strength	180 MPa
Young's Modulus	65 GPa
Poisson's Ratio	0.3
Plastic strain at UTS	0.1

The simulation was run by using the Abaqus/Explicit. The type of general interaction property with type contact automatic surface detection and the tangential behavior was selected as the contact properties. The friction formulation used penalty and the friction coefficient used in this simulation was 0.25.

There were two types of simulation which were static analysis and impact analysis. In static analysis, the top plate was moved 18 mm downwards to ensure maximum effective crushing. In impact analysis, the mass of top plate was 34 kg for stacked and 23 kg for single toroid with impact speed of 6 m/s. The time duration to ensure sufficient time for crushing the tube was 0.045 s. Before proceeding for further analysis, the test began with compressive testing for single and stacked square toroids. The analyses were validated by experiments. Table 4 below shows the configuration list for parametric studies of impact testing analysis.

Table 4: Toroid configuration for impact tests

Design Configuration	**Specimen**	
	Same thickness at top and bottom tube	**Different thickness at top and bottom tube**
Square Toroids, S_a	S1 S2 S3 S4	S5 S6 S7

Specimen Fabrication and Experimental Set Up

Single toroidal tube

Single toroidal tubes consisted of 4 tubes to be assembled into a square shape. Each tube had a length of 81 mm with a diameter of 25.5 mm. By using the adjustable metal cutter, it allowed the tube to be cut inclined at 45 degree for each edge. After the cutting process, each edge went through finishing process for the purpose of effective welding. Before the welding process, the angle of the tubes was measured by using L-square to ensure that the shape was exactly square. Tungsten Inert Gas (TIG) welding was used to weld all tubes into a square shape. TIG welding was suitable to weld the aluminium alloy.

(a) (b)

Figure 3: Samples of configuration upon compression axial loading; (a) single toroidal tube, (b) stacked toroidal tube

Stacked toroidal tubes with central tube

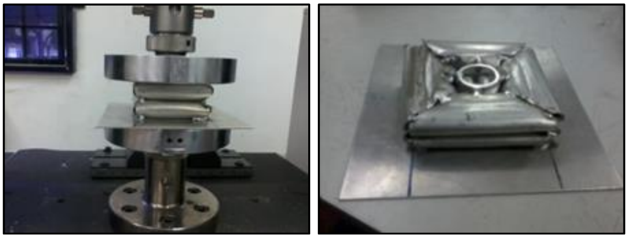
This configuration consisted of two layers of the single toroid; one piece of plate at the bottom, and one vertical tube at the middle of the stacked toroidal tubes. Height of vertical tube was 51mm with a diameter of 25.5mm. Vertical tube was cut using turning process in order to get a smooth and flat surface. Flatness of the vertical tube was measured by the bubble balancer. Fabrication was started by welding the tube on the middle of bottom plate. Then it was followed by welding the stacked toroidal tubes and assembling all parts on the bottom plate by using TIG welding.

Experiment

Compressive test or axial compression testing was carried out in order to verify the result of simulation. Axial compression testing was a useful procedure for measuring the plastic behavior and ductile fracture limits of a material. Measuring the plastic behavior requires frictionless (homogenous compression) test conditions, while measuring ductile fracture limits and takes advantage of the barrel formation and controlled stress and strain conditions at the equator of the barreled surface when compression is carried out with friction. In this experiment, single toroid was compressed from 25.5 mm into 18 mm, while for stacked toroidal tubes, the height of 51 mm was compressed into 30mm. This project focused on the axial crushing either in static or dynamic mode. In static experiment, the velocity to compress was small. Experimental quasi static test was performed on square toroidal tube. For the static experiment, the Instron 3382 Universal Testing Machine was used.

(a) (b)

Figure 4: Deformation of single toroidal tube upon compression axial loading; (a) Before, (b) After



(a) (b)

Figure 5: Deformation of stacked toroidal tube upon compression axial loading; (a) Before, (b) After

Results and Discussion

Validation results

Figures 6(a) and 6(b) are the comparison of experimental and simulation test results for single and stacked square toroid respectively. With the height of 25.5 mm, single square was compressed into 18 mm. The curve was shown in Figure 6(a) which showed that simulation had higher force compared to the experiment. Simulation showed an ideal deformation which was perfectly joined compared to the experiment. The joint between tubes was not fully welded during fabrication for experiment. The way of joining the tubes was different in simulation and experiment; so the result showed some large differences occurred in the curve of Figure 6(a). Besides that, the design with fully welded joint (simulation) was stiffer compared to design with only four dots or spot of TIG (Tungsten Inert Gas) welding in experiment. A design with stiffer structure was needed for more compression force, so the reason of not fully welded in experiment made the force much lower than in simulation.

Figure 6(b) is the comparison of stacked square toroid. The combination of two layers of square toroid with central tube was tested in simulation and experiment. The results showed the experiment agreed well in simulation. However, a little bit of difference occurred between the curve of simulation and experiment due to the way of joint in the tubes. Besides the reason on the way of the joints, the difference between them was due to manufacturing material inconsistency such as exposed to compression during fabrication. For compression of stacked square toroids, the original height was 51 mm. The height of the stacked square then turned into 30 mm after compression.

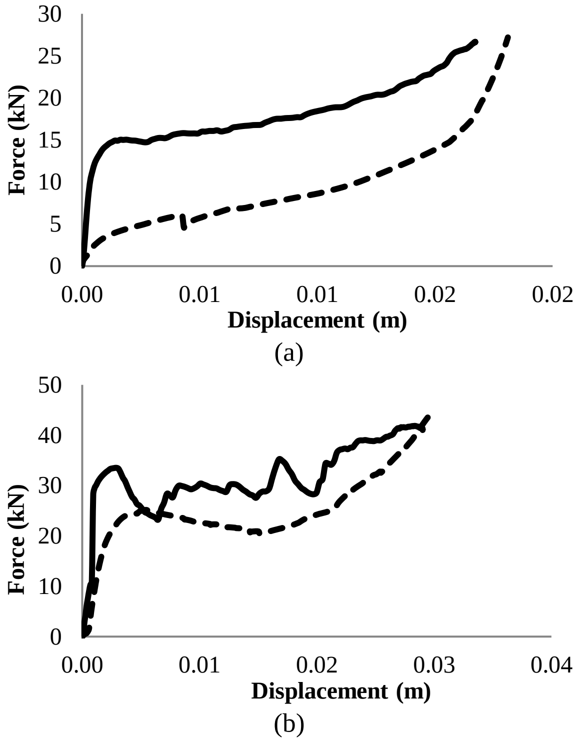
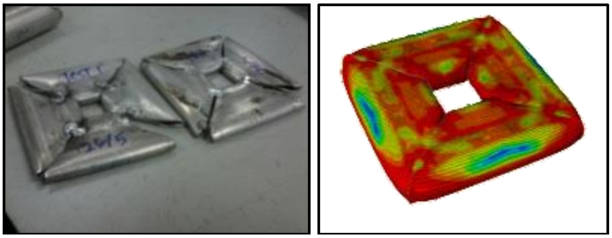


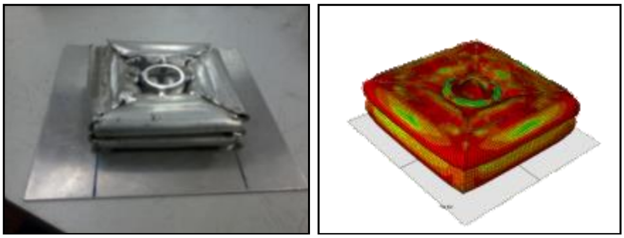
Figure 6: Force-Displacement curve upon compression axial testing; dashed line represents the experiment and smooth line as simulation (a): Single toroidal tube, (b): Stacked toroidal tube

Figure 7 and Figure 8 show the deformation between two conditions of single and stacked square toroids respectively. The figure of specimen after experiment was compared to the final visual of simulation. As in Figure 7(a), the condition of the specimen almost tore apart at every edge. This was because of the method of assembling the tubes by using TIG welding. Compared to the simulation at visualization result in Figure 7(b), the specimen was perfectly compressed without any defects. Deformation of single square was the same with the stacked square in Figure 8, but the existence of central tube made the deformation more compact compared to single square. Though each edge was torn apart for stacked square, it had less defect unlike single square. By observing the comparison between the specimens, the differences between experiment and simulation can be figured out more easily.



(a) (b)

Figure 7: Comparison of single square toroid after deformation; a) Experimental and b) Simulation under axial static loading



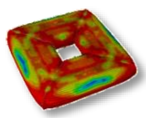
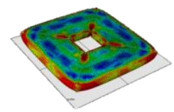
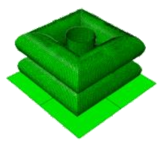
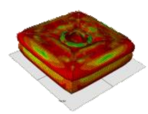
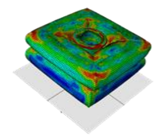
(a) (b)

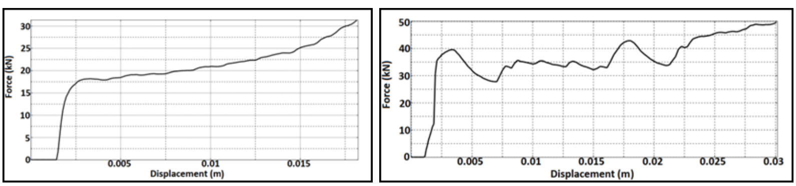
Figure 8: Comparison of stacked square toroid after deformation; a) experimental and b) simulation under axial static loading

Single and stacked square toroid subjected to static and impact loading by simulation

The final deformation of single and stacked of square toroid for static and impact analysis is shown in Table 5 respectively. Machine limitation was the reason for running only on static analysis of validation process. Figure 9 and Figure 10 both represent the curve of Force-Displacement under static and impact axial loading respectively. Both curves in static and impact for single and stacked toroids showed great energy absorption with existence of flat curves. For single square, it was a little bit higher at the end of the deformation. This was because the platen and impactor had touched each other since the specimen was completely compressed. Stacked square showed few fluctuations compared to static loading in terms of the impact. This was because compression happened through the layers of stacked toroid. It also showed good energy absorption which maintained high force.

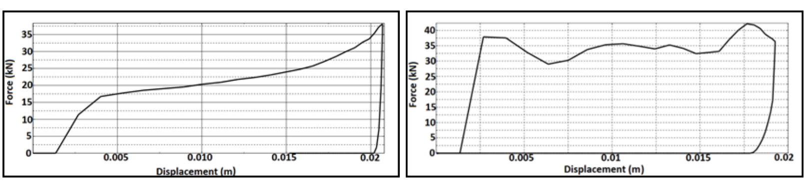
Table 5: Deformation of single and stacked square toroidal tube under axial static and impact loading

Design	Before Deformation	After Deformation	
		Static	Impact
Single			
Stacked			



(a) (b)

Figure 9: Graph of force vs displacement upon axial static loading; (a) Single square toroid, (b) Stacked square toroids



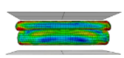
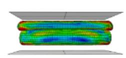
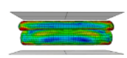
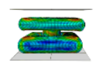
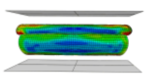
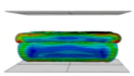
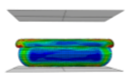
(a) (b)

Figure 10: Graph of force vs displacement under axial impact loading; (a) Single square toroid, (b) Stacked square toroid

Parametric studies

Table 6 are the final deformation of two different cases of parametric study. The first was to study the deformation of stacked square with the same thickness of top and bottom toroids. Table 6(a) shows regular deformations. The deformation started from the top toroid and propagated to the bottom toroid. Different deformation occurred in the second case (b). Top and bottom were designed with different thicknesses. Top thickness was constant and the bottom was varied. As predicted, the top layer wrapped around the phenomenon as mentioned before. The most apparent was S7 since it had 0.5 m and 2.0 mm thickness for top and bottom respectively. Material was stiffer at the bottom layer and made the deformation greater in energy absorption.

Table 6: Deformation of stacked circular and square toroids; (a) Same thickness of top and bottom under axial impact loading, (b) Different top and bottom thickness under axial impact loading

Before Deformation	Square toroids			
(a) After deformation (with same thickness of top and bottom)	S1 	S2 	S3 	S4 
(b) After deformation (with different type of thicknesses, mm)	S5 	S6 	S7 	

Conclusion

All results obtained in this project showed that the proposed configuration was suitable to be used in automotive industry, manufacturing or any materials' protections. In terms of energy absorbed, stacked square was more compatible to achieve a good performance in terms of specific energy absorption. Since the simulation was verified from experiments as well, the configuration proved that the design on impact response of energy absorption can be further studied. Further analysis of this study should show more ideas that could be explored from the stacked toroidal tubes. Material imperfection was neglected in the simulation study. This issue is important to be considered in further study. Different size and shape of stacked toroidal tube design can also be explored further.

Acknowledgement

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