COLLAPSIBLE IMPACT ENERGY ABSORBER OF MULTI TUBULAR STRUCTURE BY COMPUTATIONAL ANALYSIS

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DECLARATION

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS & NOMENCLATURE

FEA	Finite Element Analysis
FEM	Finite Element Method
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
EA	Energy Absorption
SEA	Specific Energy Absorption
CFE	Crush Force Efficiency
$\boldsymbol{\dot{\varepsilon}_0}$	Reference Strain Rate
$\boldsymbol{P}$	Density
Tm	Melting Temperature
Cp	Specific Heat
$\boldsymbol{\sigma_T}$	Dynamic Flow Stress
$\boldsymbol{\varepsilon^{\rho} e_{ff}}$	Effective Plastic Strain
$\boldsymbol{\dot{\varepsilon}^{\rho} eff}$	Effective Plastic Strain Rate
$\mathbf{T_o}$	Transition Temperature
Pm	Main crushing load
$\mathbf{d}\boldsymbol{\delta}$	Length Of Crushing
$\boldsymbol{\delta i}$	Original Crushing Specimen
$\boldsymbol{\delta b}$	Maximum Deformation

ABSTRAK

Analisis tentang keupayaan sesebuah struktur dalam melindungi penumpang ketika berlakunya pelanggaran telah menjadi perkara utama yang menarik ramai penyelidik baru-baru ini. Usaha untuk menyerap tenaga struktur yang lebih baik telah membawa penyelidik untuk menjalankan pelbagai prosedur analisis uji kaji juga simulasi. Tesis ini mengkaji perubahan bentuk dan tenaga penyerapan satu, dua dan pelbagai dinding struktur tiub bulat menggunakan dua bahan iaitu A36 keluli lembut dan AZ31 aloi magnesium. Tiub dimampatkan secara paksi pada kelajuan 15.6 m / s. Pemodelan dan simulasi berangka satu, dua dan pelbagai tiub konfigurasi dindingmenggunakan bahan-bahan diatas dibentangkan dalam parameter menggunakan perisian Abaqus . Kegunaannya adalah merubah bentuk, menyerap tenaga kemalangan, menghancurkan kecekapan tenaga, dan penyerapan tenaga tertentu. Keputusan menyifatkan menggunakan aloi magnesium dan keluli lembut sebagai ahli membujur tenaga yang digunakan dalam aplikasi kesesuaian kemalangan, aloi magnesium, bahan yang dipilih kerana lebih ringan berat badannya dan lebih disukai untuk digunakan dalam mengurangkan pencemaran dan bahan api konsumsi alam sekitar. Sebagai perbandingan, bahan keluli yang ringan telah digunakan beberapa dekad dalam pengangkutan dan industri automotif. Struktur tiub kedua-dua bahan menunjukkan mod ubah bentuk campur kerana kesan ketara perambatan gelombang tekanan tetapi hanya satu tiub aloi magnesium menunjukkan mod concertina . Akhir sekali, reka bentuk telah dipertingkatkan lagi untuk menangani kemalangan dengan lebih baik dengan menggunakan pelbagai dinding tiub kosong daripada aloi magnesium kerana ianya lebih tinggi dalam menyerap tenaga. Kajian ini akan membantu industri automotif untuk mereka bentuk komponen crashworthy unggul dengan struktur pelbagai tiub dan juga akan mengurangkan ujian eksperimen dengan menjalankan simulasi berangka.

ABSTRACT

Analysis of crashworthy structures has been a primary area of interest for many reseachers for quite a few years now . The quest for a better energy absorbing structure or a better crashworthy structure has led reseachers to carry out various analysis procedures experimentally also by simulating the characteristics. This thesis examines the deformation and energy absorption of single, double and multi-wall circular tube structure of two materials which are A36 mild steel and AZ31 magnesium alloy . The tubes are compressed axially at a speed of 15.6 m/s. Modeling and numerical simulation of these materials single , double and multi wall configuration tube is presented in ABAQUS .The performance parameters used are the deformation modes , absorbed crash energy, crush force efficiency, and specific energy absorption. The results described the using of magnesium alloy and mild steel as an energy longitudinal member used in crashworthiness applications. Magnesium alloy, material are chosen due to lighter in weight and is preferred to use to decrease the environmental pollution and fuel consumptions. In comparison , mild steel material have been used in decade in transport and automotive industry . It is observed that most of the tube structure of both materials shows mixed deformation modes due to the significant effect of stress wave propagation but only single tube magnesium alloy show concertina modes . Finally , the design was further enhanced for better crash performances by using multi-wall empty tube of magnesium alloy because of higher in energy absorbed . This study will help automotive industry to design superior crashworthy components with multi-tube structures and will reduce the experimental trials by conducting the numerical simulations.

CHAPTER 1

INTRODUCTION

1.1 Project Background

In the second half of the century many of impact engineering problems were investigate, especially we can see in the fields of the dynamic response of structures in the plastic range. This information contributes and important so that it can be able to build safer structure in the automotive industries. The public has aware of the safe design of components to minimize human suffering as well as the human burdens on society. Impacting events has been remind as tragedies like traffic accidents, natural collisions. In the last few decades ,many scientist and also engineers particularly to develop, research and investigate energy absorbers with the goal to reduce the force or effect of impact on people and structures including vehicle. [1]

1.2 Finite Element Analysis

Previously most studies on energy absorbing capabilities of metallic and non-metallic material has been done experimentally. Recently, the trend has shifted where many researchers trend to the computer simulation (finite element analysis-FEA) instead of doing experimental work. FEA (Finite Element Analysis) is being widely used in design and structural analysis in almost all branch of engineers as a form of computer simulation technique so that complex problem can be solve .

FEA has been known to be able and useful tools to understand the responses of the energy absorber tubes under impact loading and this technique is very popular [2]. The FEA simulations also mitigate the need to expensive prototypes being manufactured for improvement and comparison in physical testing of different concepts.[3]

1.3 Energy Absorber

An energy absorber can be define as a system that converts kinetic energy into different form like friction , plastic bending , fracture cyclic plastic deformation , crushing and cutting metal [4]. The energy that been converted is either reversible, such as pressure energy in compressible fluids and elastic strain energy in solids, if irreversible it is like plastic deformation energy.

The absorbing system is the energy dissipated in plastic deformation of metallic energy absorbers. The aims of designing a collapsible energy absorber is to absorb the majority of the kinetic energy of impact in an irreversible way within the device so that we can ensure the percentages of equipment damages and human injuries is not high .It is vital to investigate crushing energy absorption and need to be done for the safety design of passengers vehicles. This kind of structure like tubular structure play important role in the point of view of crashworthiness because of the ability to reduce the passenger injury in a collision .[2]

Figure 1.1 showing the structure of frontal longitudinal. To reduce the crash forces and energy transmitted to the vehicle, this structures remains deform so that it can mitigate the decelerations that happened to occupants.

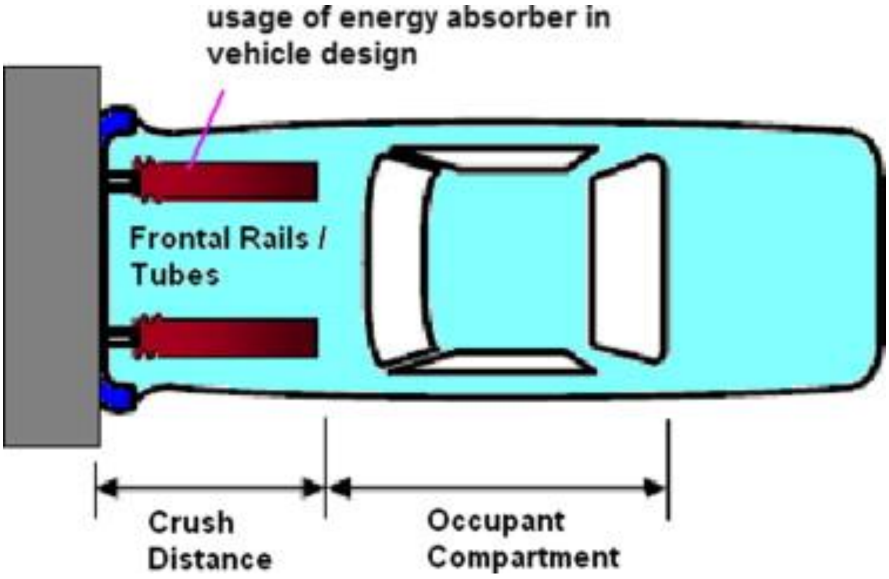


Figure 3.1: Energy absorber in vehicle design [3]

Since tubular structure have characteristic which are stiffness, high strength, low cost, high energy absorption capacity, and excellent loading-carrying efficiency, they are being used widely in engineering as structural elements. There are various shape of tubes. Common shapes include circular tubes, square tubes, frusta, struts, honeycombs, and sandwich plates. Common modes of deformation for circular tubes include axial crushing, lateral indentation, lateral flattening, inversion and splitting [2] Square or circular sectioned tubes are the shape that commonly being used as structural elements due to easy manufacturability. For example, for circular tubes it can dissipate elastic and inelastic energy through different modes of deformation ,and can be resulting in different responses of energy absorption [5] and because of its high stiffness and also strength , ease of manufacturing process and low weight which make it low cost [4] .

Energy absorbers have been used widely in the field of engineering like in the situations such as crashworthiness of vehicles like cars, lifts, aircraft and crash barrier design, collision damage to road bridges. It have been extensively used in all vehicles and also moving parts as road vehicle, aircraft, ships, lifts and machinery. The purpose of the absorbing devices is to protect these structures from damages and to minimize human injuries while collision is occurred in transportation systems.[4]. In several decades there only have single thin walled structures or tubes that being used in transportation industry. As a conclusion, this project is to investigate the collapsible impact energy absorber in multi tubular structures by computational analysis . Based on the result, we can see whether the multi tubular structures can reduce the impact then the single structure.

1.4 Problem Statement

Nowadays , due to advances in transport technology , the number of transportation vehicles in this society have increased .This have made the number of fatalities become greater because of impact collisions of one another [1]. Due to this, the safety of the passenger need to be put more attention and need to be concern so that we can reduce the case of vehicle crash. Dangerous have comes from the impact energy that transmit to the passengers. To avoid impact or crash the design of high energy absorption system need to be properly designed. It necessary to dissipate the energy comes from collision by absorbing the energy through deformation of car structure so that we can minimize the impact energy.

Hence, it is needed to find out the method to absorb impact energy as much as possible and allow an acceptable energy passes to the passenger. Through the background research there are many type of single tubular have been designed such as circular tubes, square tubes but it is hard to find for a multiple tubular structure. The energy absorbing characteristic of multi tubular structure could be improved by various method. This is the reason this project need to be done to achieve the objectives of this project.

1.5 Objectives

The objective of the work is mainly:

1) To simulate single, double and multi wall tubular structures of mild steel and magnesium alloy under impact loading.
2) To compare the characteristic and energy absorbing capabilities of mild steel and magnesium alloy of different tube arrangement.

1.6 Scope of the project

For this project, the modelling and numerical analysis of the tubular structure will be created using finite element analysis (FEA) which is ABAQUS. The arrangement is single, double, and multi tubular structured of circular cross-section. Two materials will be employed that is mild steels and magnesium alloy. The tubes is subjected to impact compression at a speed of 15.6 m/s.

1.7 Project outline

Overall, this thesis can be divided into five main chapters which are introduction, literature review, methodology, result and discussion, and conclusion. In chapter 1 , it is more about the introduction to the research background, problem statement, objectives and the scopes of the project.

Next, in chapter 2, some previous work which are closely related to the present study are reviewed based on journals, books and webpages as references. Detail explanations about this research are described in this chapter.

In Chapter 3, the methodologies in term of modelling works is briefly describe here. It covers from the early stage which is pre processing until post preocessing in Abaqus.

Chapter 4 generally discusses about the results obtained from the simulations conducted. The analysis of the project, and the results are presented in figures and tables accordingly in this chapter.

Last but not least, the conclusion of the project will be made in chapter 5. Some suggestions and recommendations are given for improvement in future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

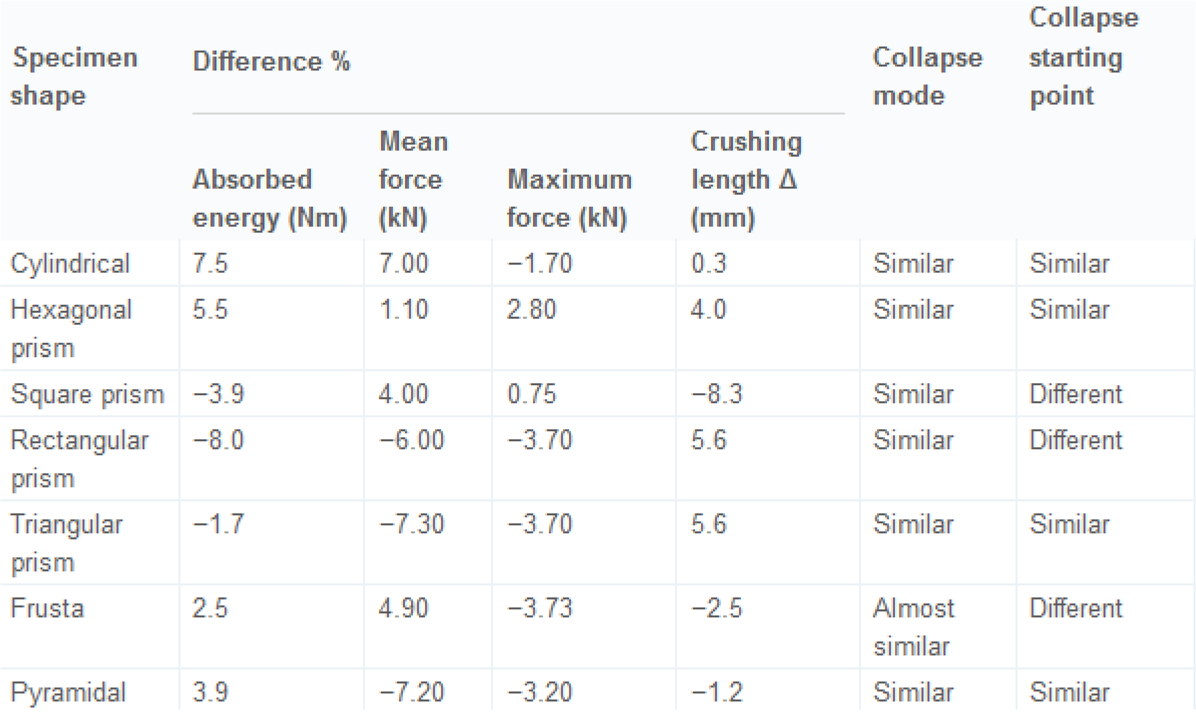
Until recently, many researchers have shown interest in the study of energy absorber. They have carried out numerous laboratory experiments and simulations regarding this field. Their findings and suggestions are reviewed here.This chapter will be reviewing their method, findings, and suggestions on the topic.

2.2 Analysis on energy absorption based on various cross sectional shape of single structures

In this literature, the authors [5] has investigated several different cross sectional shapes of thin walled structures under axial quasi static loading.These cross sectional profiles include square , rectangle , octagonal , circular , hexagonal and also triangular,pyramidal and conical profiles were designed . The tubular structure material that they used for all the models wasaluminum alloys, due to their light weights.For all the models ,the length and thickness of the tube were selected to be 100 mm and 1 and 1.5 mm respectively. The study of deformation modes and energy absorption capacity been done through experimentally and numerically. In experimental studied , the universal testing machine has been used . Meanwhile in numerically studied , they used LSDYNA 970 software. The relationship between and energy absorption has been investigated . The results shown in Table 2.1 and Table 2.2 are the comparison between simulations and experiment for both 1.5 mm and 1 mm thickness.

The maximum difference based on the Table 2.1 and Table 2.2 was 8.3% . Through the experiment and simulation , the energy absorption , the maximum force and average force was the same. Due to welding process that have effect on the samples, the load-displacement curves have some mismatches .

Table 2.1 : Comparison between results of simulations and experiment for 1.5 mm thickness [5]



Specimen shape	Difference %				Collapse mode	Collapse starting point
	Absorbed energy (Nm)	Mean force (kN)	Maximum force (kN)	Crushing length Δ (mm)		
Cylindrical	7.5	7.00	−1.70	0.3	Similar	Similar
Hexagonal prism	5.5	1.10	2.80	4.0	Similar	Similar
Square prism	−3.9	4.00	0.75	−8.3	Similar	Different
Rectangular prism	−8.0	−6.00	−3.70	5.6	Similar	Different
Triangular prism	−1.7	−7.30	−3.70	5.6	Similar	Similar
Frusta	2.5	4.90	−3.73	−2.5	Almost similar	Different
Pyramidal	3.9	−7.20	−3.20	−1.2	Similar	Similar

Table 2.2 : Comparison between results of simulations and experiment for 1 mm thickness [5]

Specimen shape	Difference %				Collapse mode	Collapse starting point
	Absorbed energy (Nm)	Mean force (kN)	Maximum force (kN)	Crushing length Δ (mm)		
Cylindrical	7.2	7.50	8.30	−0.7	Almost similar	Similar
Frusta	4.6	0.60	0.10	6.3	Similar	Similar
Square prism	−3.1	−0.78	−1.00	3.5	Almost similar	Similar
Pyramidal	4.0	6.20	1.40	0.3	Almost similar	Similar

Figure 2.1 show the folding and deformation mode of tube in experiment and simulation. It can be seen that the triangular cross section did not fold because of inherent incapable of folding modes .

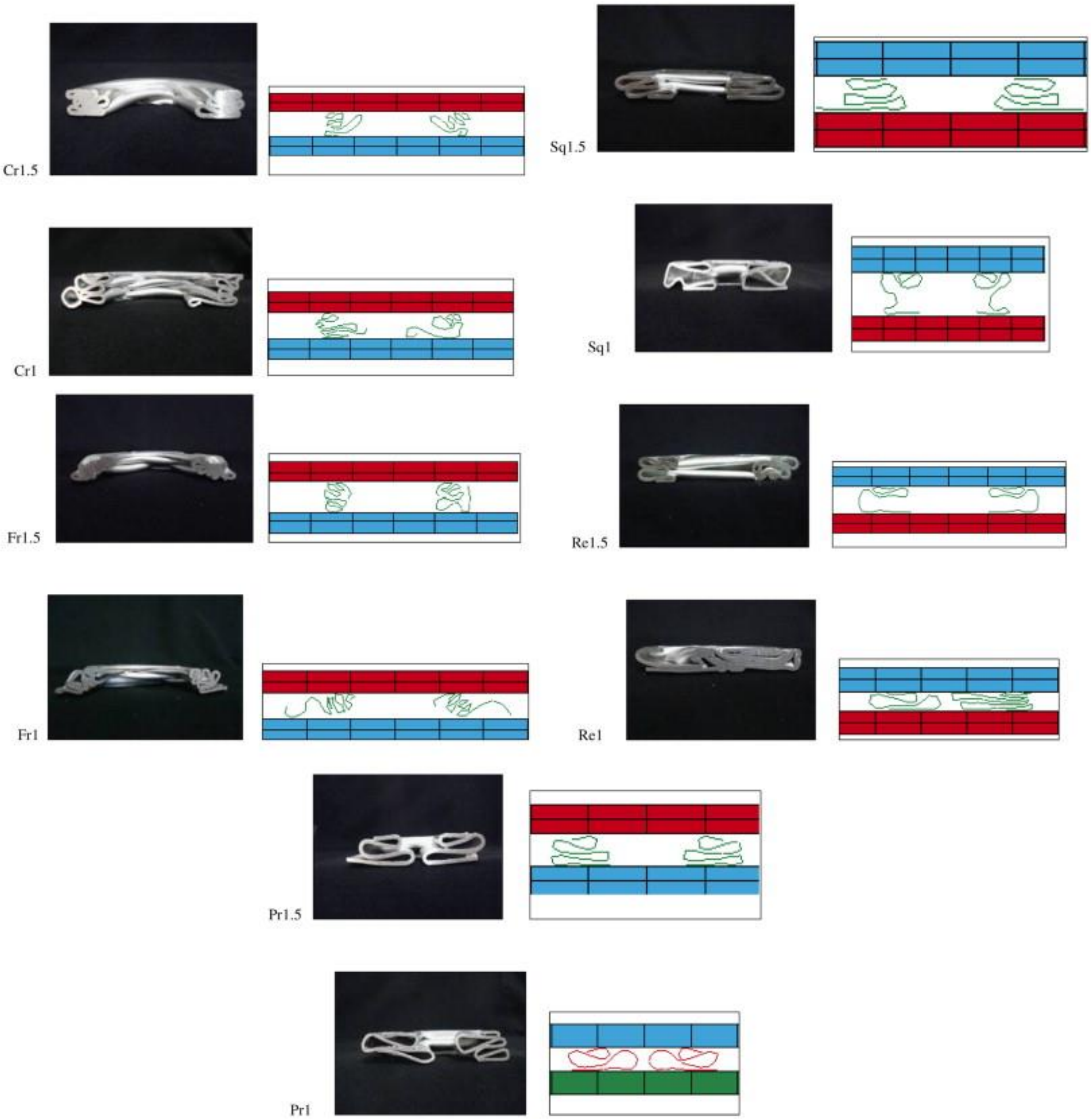


Figure 4.1 : Comparison between deformation modes of samples in experiment (left) and simulation (right) [5]

Figures 2.2 and 2.3 represents the relationship of different specimen shape with energy absorbed. It was reported that shown represent the result in the authors study which was the cylindrical tubes absorbed energy the most between the other specimen shape for both experiment and simulation and the thickness of tubes did not gave any affect to the energy absorption .

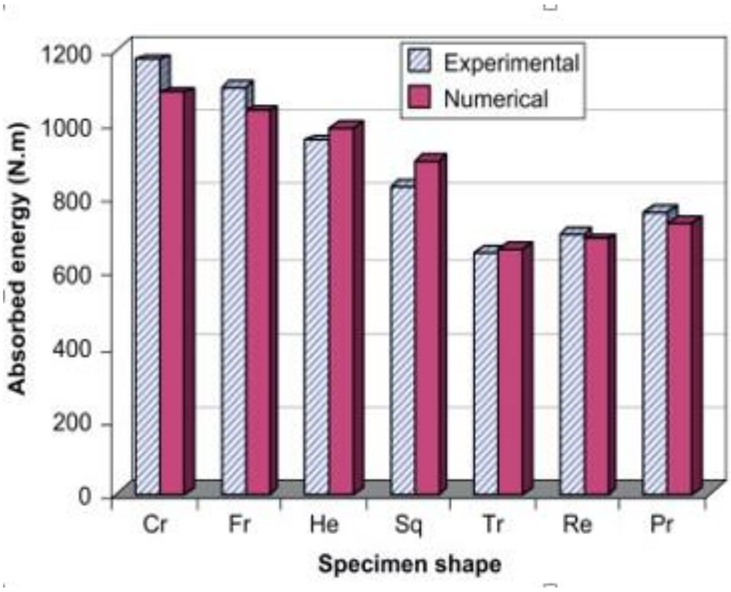


Figure 2.2 : The relationship between specimen shape and energy absorbed for 1.5 mm thickness [5]

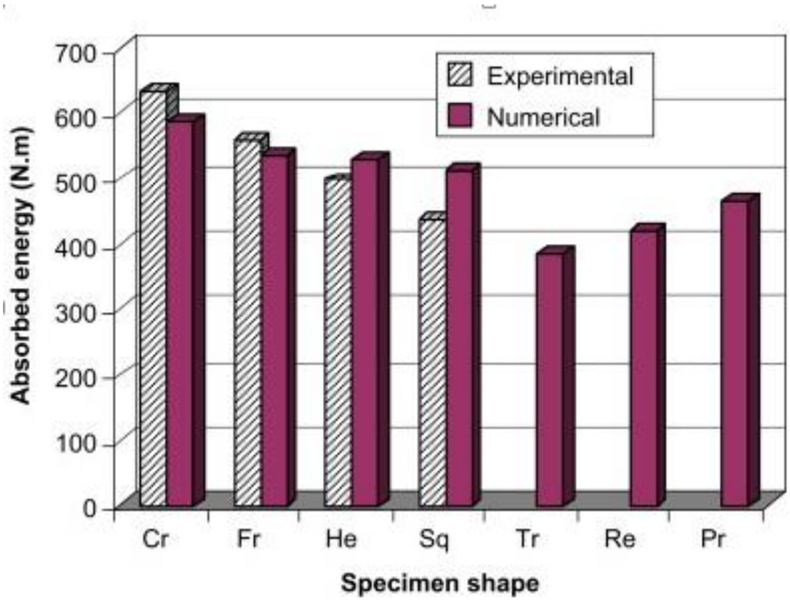


Figure 2.3 : The relationship between specimen shape and energy absorbed for 1 mm thickness [5]

2.3 Analysis study on energy absorption based on single and multi tubular structures with foam or empty tube

Manmohan Dass Goel [6] has studied energy absorption capacity with multiples of tube which were single , double and multi in square and circular shape structures . The author conducted FEM simulation and used aluminium tube and also aluminium foam as a material to the structures . Three square and three circular tube were modeled with aluminium foam or with empty tube for both shapes .

As shown in Figure 2.4, the size of square tube configuration was 50 mm × 50 mm with clearance of 5 mm . Meanwhile diameter circular configuration were 33.85 mm , 45.14 mm and 56.42 mm .

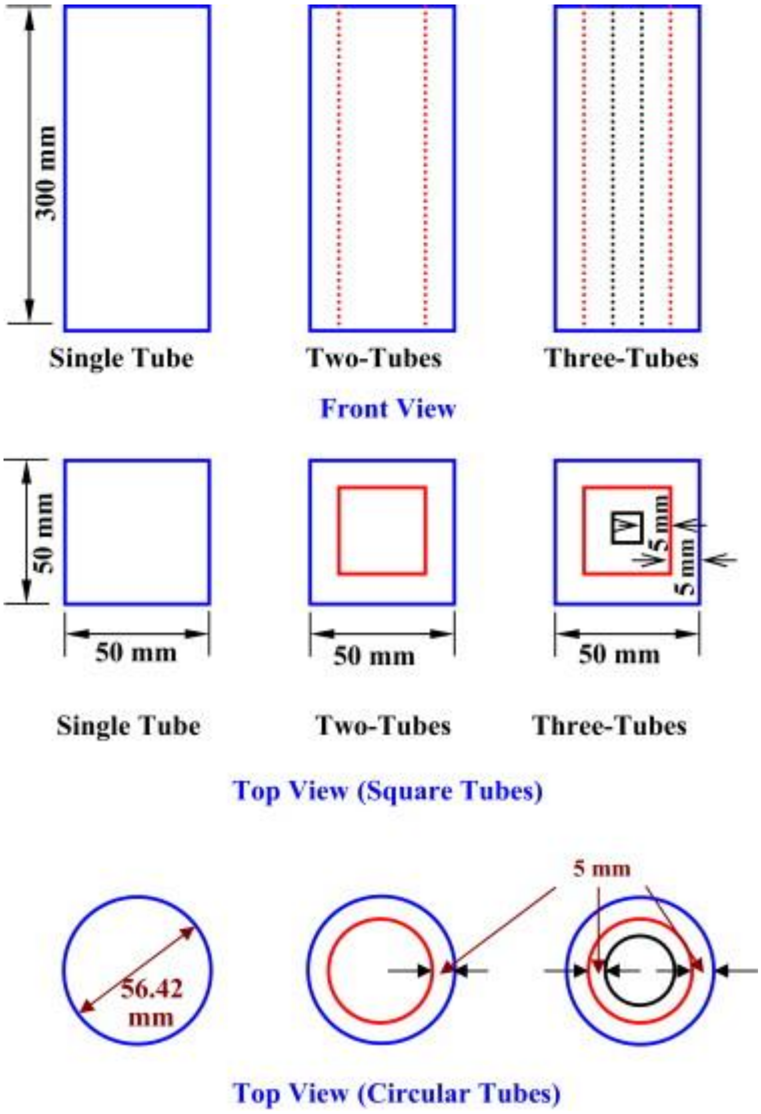


Figure 2.4 : Dimensions for square and circular tube [6]

As in Figure 2.5, the models were crushed axially where bottom plate as floor and the top plate as impactor with the vertical direction movement only . Investigation was carried out on the tubes by assigning 500 kg as a mass of upper plate with velocity of 15.6 m/s .

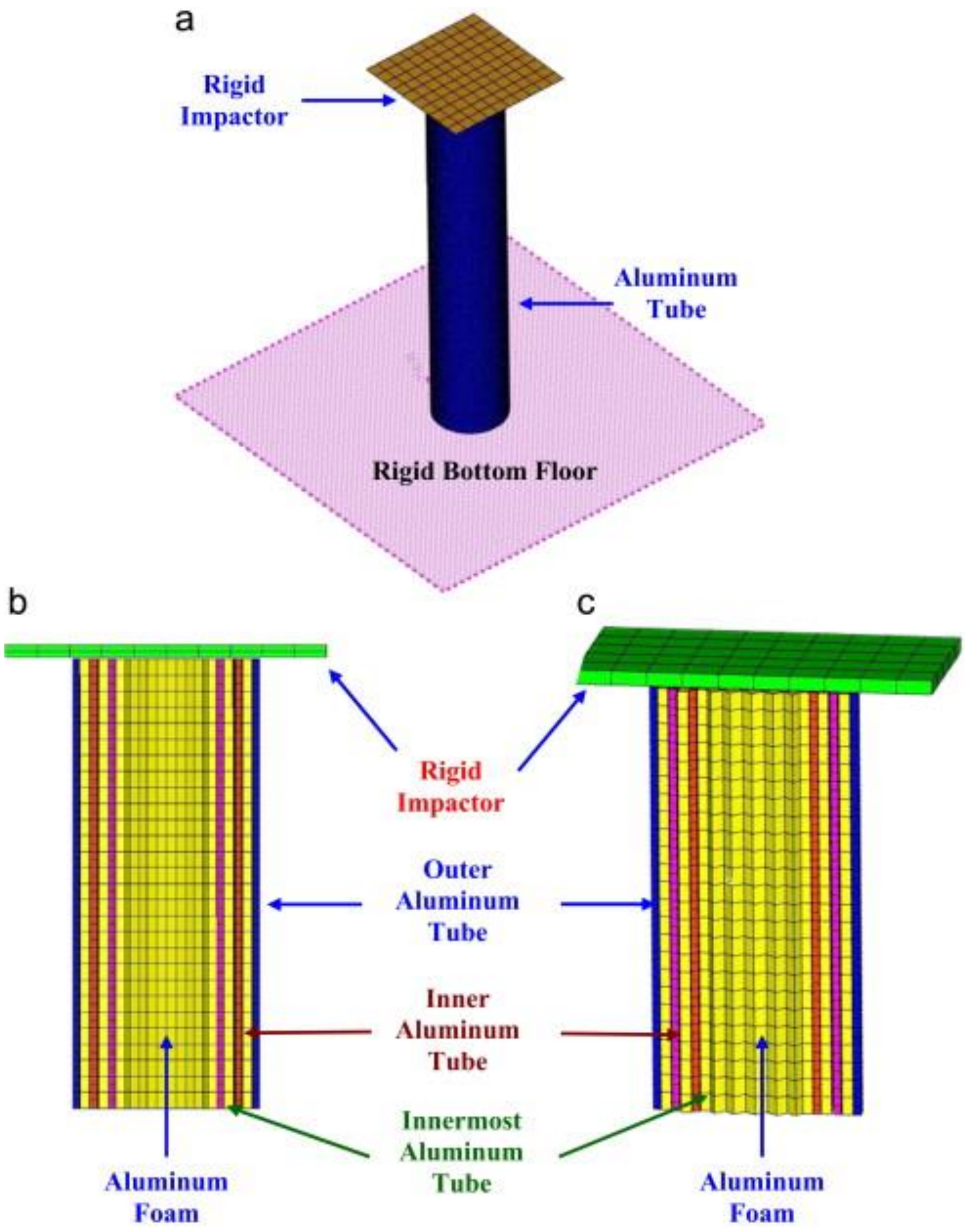


Figure 2.5 : (a) FE model that include the rigid floor and impactor (b) Multi tube with foam filled and (c) Cut section of multi tube with foam filled [6]

Based on the load-displacement relationship given in Figure 2.6 , Manmohan Dass Goel has found that in single tube , the comparison in energy absorption between foam filled or empty was the same. For the two tubes with empty foam the energy absorped was improved 93% and 110 % for multi empty tube . Meanwhile for two foam filled tube , the energy that absorbed was improved 95 % . However for three tubes , Manmohan did not obtained the result because of severe distortion of element that happened during numerical simulation . Through this investigation , the author conclude that energy absorption can be improved by filling the foam and with the used of tri- tubular structure and based on this paper , the shape in higher energy absorption was circular tube compared to the square tube in used of the same material for tubes and foam .

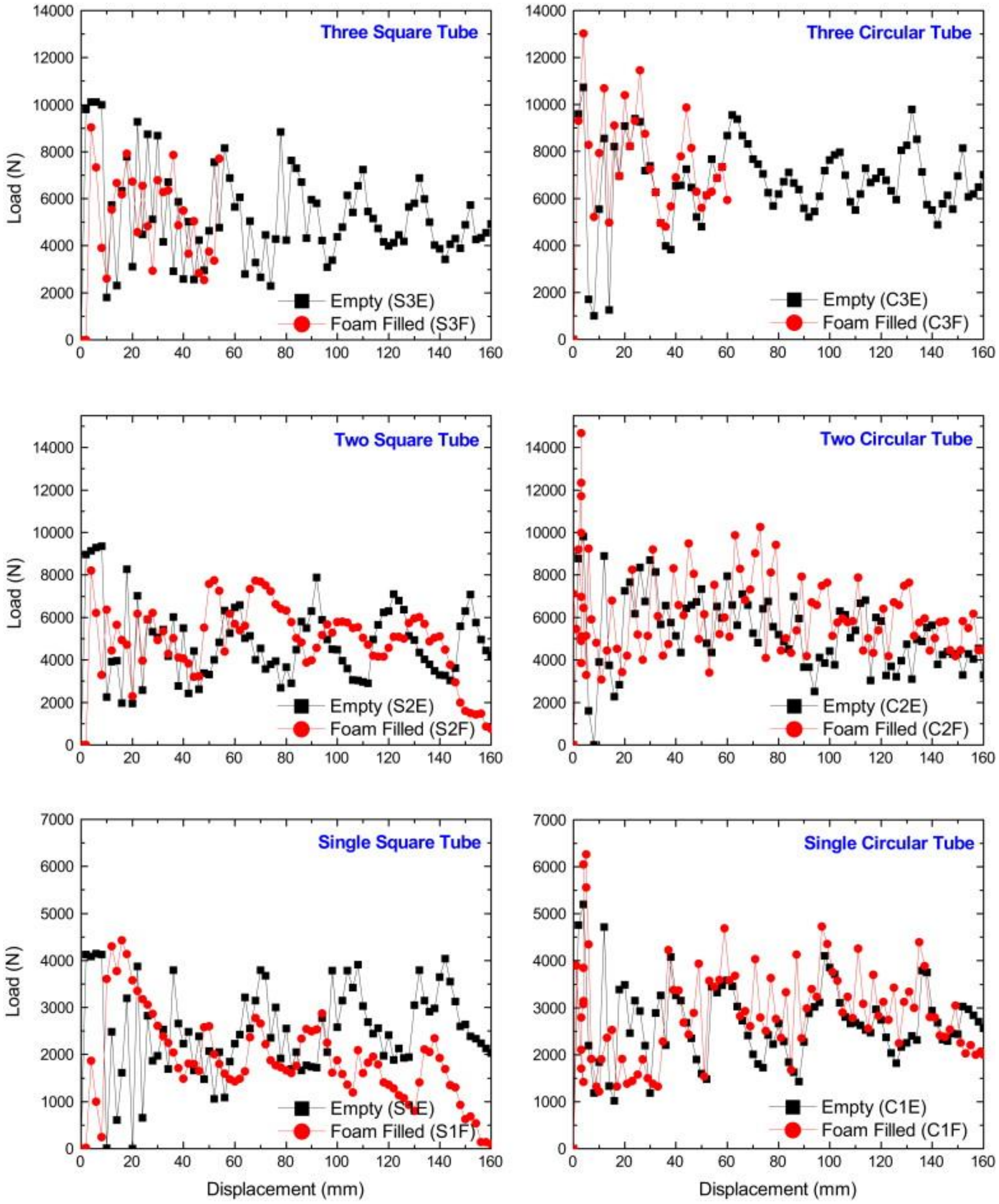


Figure 2.6 : The relationship load with displacement of empty and foam filled square and circular tube configurations [6]

2.4 Concluding remarks

From previous work , circular tube remains the best shape to be recommended and used in the present work . The present work have different tube arrangement and compared to magnesium alloy . The dimension of the tube limited to its availability and the speed of compression is 15.6 m/s based on the New Car Assessment Program (NCAP).

CHAPTER 3

METHODOLOGY

3.1 Introduction

One of the popular way of conducting research today is simulating the test conditions, investigate the performances and recording the results . These results are then compared with each other to see which one show the best performances and better choice.One of the popular techniques used by researchers is designing and analyzing test conditions using finite element modeling. Various software’s can be used to perform this type of task. Nowadays , the capability of simulating the characteristic of metals to absorb energy and deform plastically through folding of collapsing using finite element method. Such characteristics can be accurately modeled by the software’s being used today. The results obtained through these software’s are close to the actual test results.

In this chapter , it described the materials,geometry and dimensions, equations and also deals with the methods chosen to accomplish this thesis.

3.2 Model Formulation

The purpose to build these models is to simulate the impact test on tubular structure of single , double and multi tube and carry out the effect of every kind of working conditions to get the numerical results . The test structure modelling in this study was carried out using ABAQUS software.

3.3 Material properties and Geometry

This study was done to investigate the crash performance of different material and configuration . Six of thin walled tubular cross sectional structure were designed, namely circular that consist of single , double and multi tubular with two different material .The materials of tubular structure was modelled as AZ31 magnesium alloy and A36 steel (mild steel) . The properties of both materials are given in Tables 3.2

and 3.3. While modelling these structure ,the length and the thickness of the tubes, the perimeter of the cross section were made constant. For all the tubular structures models and material the condition is taken at room temperature of 293-297 °K.

Based on the average perimeter calculated from most sedan and compact cars found in the local market , the thickness and length have been chosen to be 2 mm and 350 mm respectively . 300 mm for the cross sectional perimeter for all tubular structures with 5 mm clearance in the case . Where for circular configuration has equivalent diameters of 91 mm , 80 mm , 69 mm for outermost, central and innermost tube, respectively . The tubes are subjected to impact loading by assigning a mass of 275 kg to the upper plate acting as impactor with a velocity of 15.6 m/s. More details are discussed further for why this values been chosen . The impactor is restrained in all direction except allowing the movement in vertical direction where the loading is applied. Details of the design are given in Table 3.1 and illustrates the view in Figure 3.1

Table 3.1 : Geometry and dimensions of tubes used for study

Profile	Perimeter (mm)	Length (mm)	Dimension(mm)	Thickness (mm)	Shape
Circular	300	350	Diameter outermost = 91 Diameter central = 80 Diameter Innermost = 69	2	

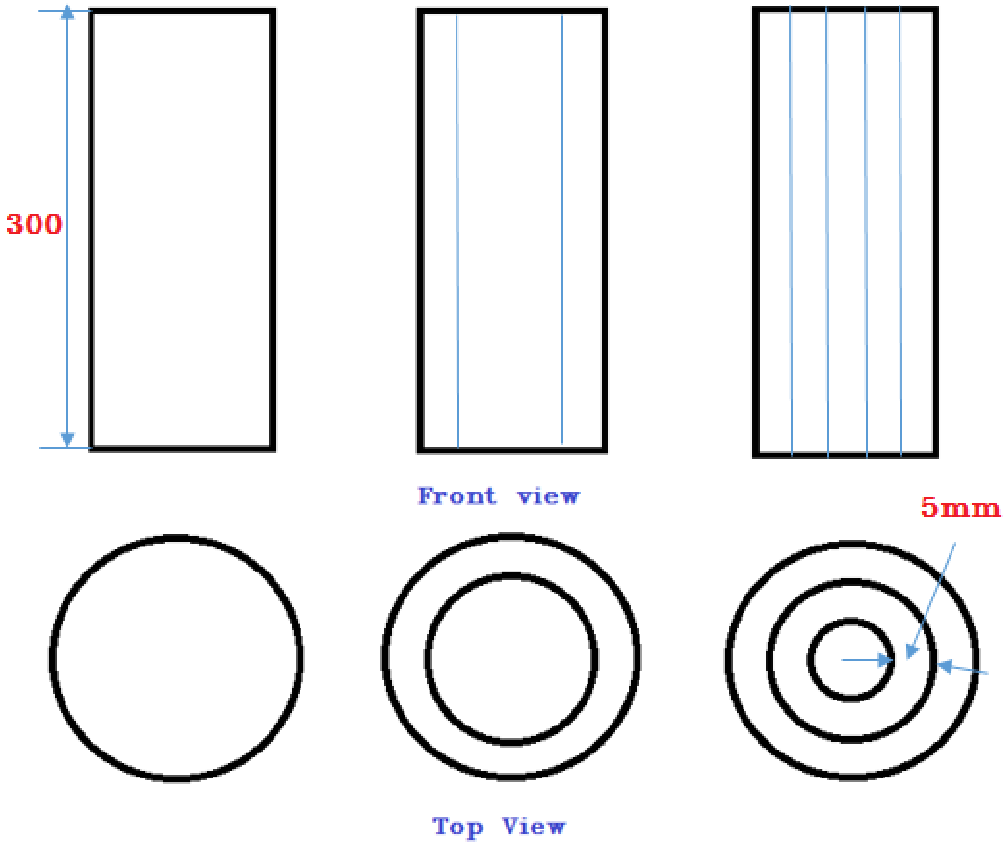


Figure 3.1: Front view and Top view of the single tube, two-tube and three-tube circular with the length and clearance .

3.4 Modelling of Tubular Structure

In Figure 3.2 shown finite element model (FE) model comprises principally of the thin wall structure under study, the striker, and the base. All other rotations and translational degree of freedom were fixed and the striker was modeled as a rigid body with only one allowable translational displacement. Only one direction movement, z direction, is allowed for the block to ensure this condition in the numerical model. In crash applications the model needs an impactor, this impactor is movable which has one axis motion (first degree of freedom) . Through the impactor, the velocity and mass have to be assigned. There may exist beyond one interface that can make the model run if combined different boundary conditions from the study that found [6]. Under the impact ,the interface "node to surface" is more reasonable than other's in this extrusion model. In order to let the upper end (impact end) deform stably between the extrusion and block, the coefficient of friction 0.2 be added. The boundary condition includes the initial velocity and constraints. The initial velocity is put into the every node of block. In order to simulate the projectile's movement, the constraint condition, restricting the rotation and movement in X and Y direction, is given to the block. While the bottom impactor assigned to be fixed (0 degree of freedom).

The idea of this crash test is to simulate a crash or accident when a car is hit axially (Head-on collision). There are two frontal longitudinals in the chassis of the vehicle which are responsible of absorbing the energy from the crash. In Figure 3.2, the tube represent the frontal portion of one of these longitudinal which has the cross section of 80x80 mm and the upper plate represent the other car's mass. Two longitudinal absorbs 50% or less of the kinetic energy of a car mass and that one longitudinal is designed to absorb almost 25% of the kinetic energy of the impacting car. An average sedan car that weighs about 1100 kg, both longitudinals will absorb 550 kg of its kinetic energy, thus one longitudinal will absorb 275 kg of kinetic energy so a lumped mass of 275 kg was chosen with the impact velocity of the striker on the tubes was modeled to be 15.6 m/s (56 km/h). The impact speed value was taken from the New Car Assessment Program (NCAP) by the National Highway Traffic Safety Administration (NHTSA) [3] .

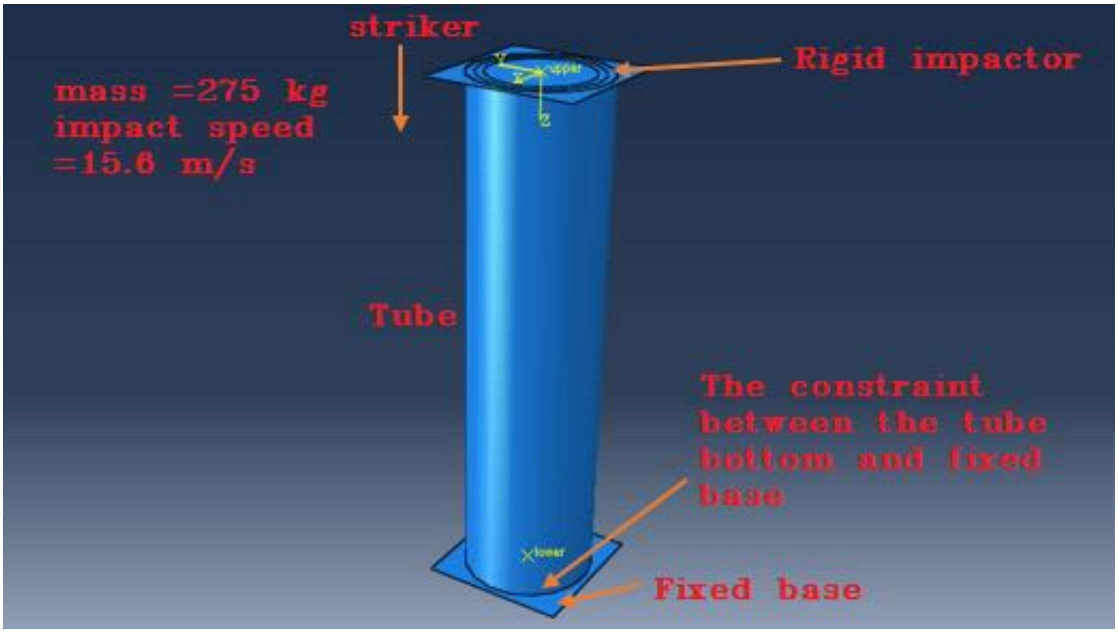


Figure 3.2 : Finite element model with rigid floor

In Figure 3.3 , the three-tubes parts have assigned and assembled together.. Based on a mesh convergence study,quadrateral mesh type with a 5 mm global mesh size has set for the tubes, small mesh size led to more number of nodes and produce more results accuracy. To ensure a sufficient mesh density to accurately capture the deformation process, a mesh convergence is important .

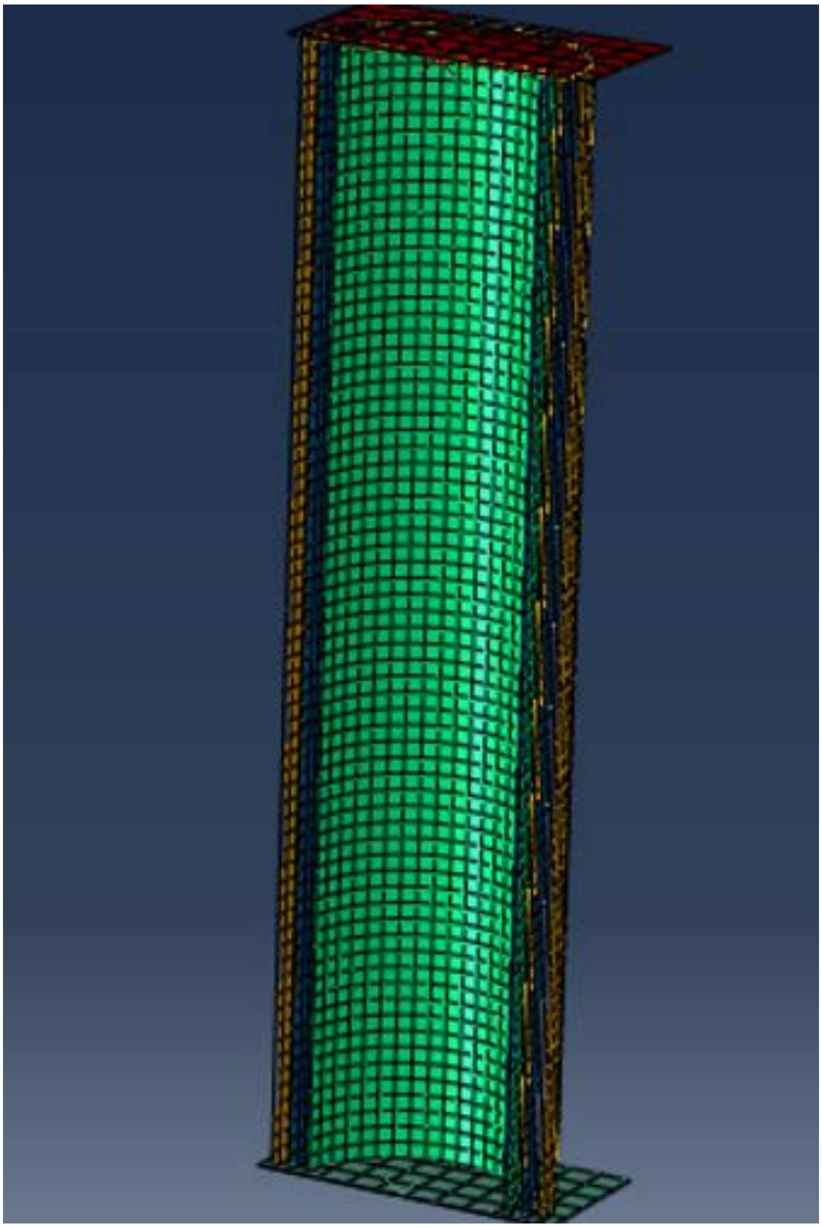


Figure 3.3 : Cut section multi empty tubes

In Figure 3.4 shown cut section of the assembled three-tubes that meshed with a 5mm global mesh size . From the figure , the yellow colour stand for outer tube , the blue colour for inner tube and the green colour for innermost tube .

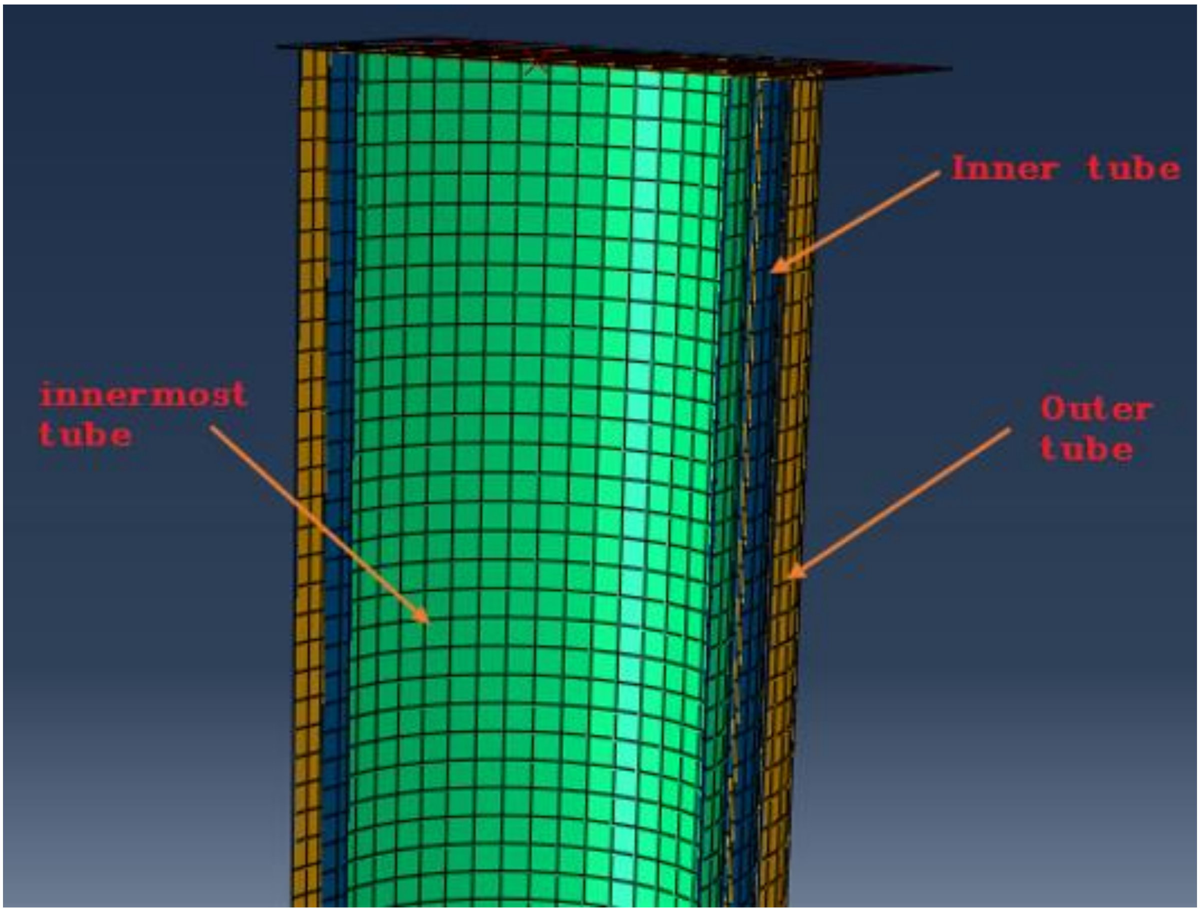


Figure 3.4 : Zoom in cut section multi empty tubes

Materials for the tubular structure were modeled as AZ31 magnesium alloy and A36 steel (mild steel). The summary of Johnson-cook parameters for AZ31 magnesium alloy are given in Table 3.2.

Magnesium alloy was set as material for the tubular structure because it has a durable structure for certain die cast components. Its contribute to lower fuel costs in vehicles, which has car manufacturers developing new technology to utilize magnesium’s unique properties. All magnesium alloys exhibit a high yield strength and tensile modulus of elasticity. Magnesium alloy as a light weight material and will take into consideration into this study . [7]

Table 3.2 : Summary of Johnson-cook parameter for AZ31 Magnesium alloy [7] .

Parameter	Value	Description
A	279.827 Mpa	Material parameter
B	159 Mpa	Material parameter
N	0.327	Strain power coefficient
C	0.013	Material parameter
M	1.573	Temperature power coefficient
$\dot{\varepsilon}_0$	1.0 sec^{-1}	Reference strain rate
ρ	1800 kg/m^3	Density
Tm	923 ° K	Melting Temperature
Cp	1.05 kJ/kg. K	Specific Heat

The summary of Johnson-cook parameters for A36 mild steel are given in Table 3.3.

A36 mild steel was set as material tubular structure because it is as the most commonly available one of the hot–rolled carbon steels . The material characterization of A36 was set as per johnson-cook constitutive isotropic hardening model .For problems where the strain rate varies over a large range and the temperature changes due to plastic deformation caused by thermal softening , it is suitable use this material . The strain hardening, strain rate effects and thermal softening takes into phenomenological model . [3]

Table 3.3 : Summary of Johnson-cook parameter for A26 mild steel [3]

Parameter	Value	Description
A	146.7 Mpa	Material parameter
B	896.9 Mpa	Material parameter
N	0.320	Strain power coefficient
C	0.033	Material parameter
M	0.323	Temperature power coefficient
$\dot{\varepsilon}_0$	1.0 sec^{-1}	Reference strain rate
ρ	7850 kg/m^3	Density
Tm	1773 ° K	Melting Temperature
Cp	0.486 kJ/kg. K	Specific Heat

These equation (3.1) below shows important material characteristic :

$$\sigma_T = [A + B(\varepsilon^{\rho} e_{ff})^N]\ (1 + Cln\ \frac{\dot{\varepsilon}^{\rho} eff}{\dot{\varepsilon}_0})[1 - (\frac{T - T_0}{T_{melt - T_0}}) \qquad (1)$$

σ_T is the dynamic flow stress, $\varepsilon^{\rho} e_{ff}$ is the effective plastic strain, $\dot{\varepsilon}^{\rho} eff$ is the effective plastic strain rate, $\dot{\varepsilon}_0$ is a reference strain rate, A, B, N, M and C are the material parameters and T_{melt} is the melting temperature whereas T_0 is the transition temperature.

It is usually taken as the room temperature of 293–297°K . The transition temperature is defined as the one at or below which there is no temperature dependence on the expression of the yield stress [3] .

3.5 Energy Absorption

The total energy absorbed (EA) is the area under the load/displacement curve, which is a function of the specimen cross-sectional area and the material density, and can be obtained numerically by integrating the load displacement load curve. [7]

As shown in Figure 3.5, the load-displacement curve shows how the energy absorption can be calculated. Energy absorption is denoted as an integration of a load-displacement curve.

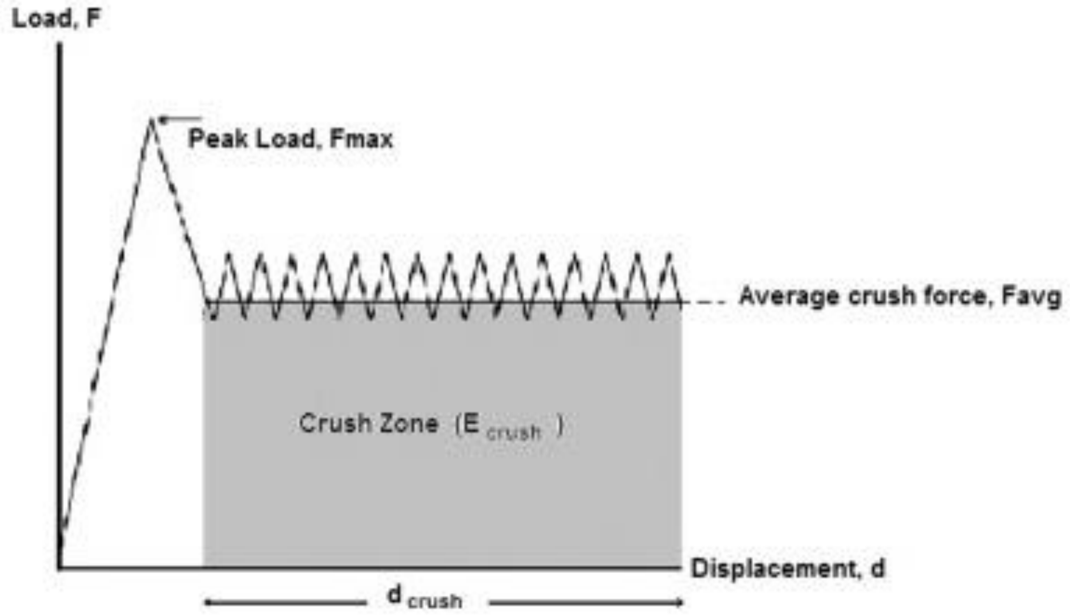


Figure 3.5 : Typical load vs. displacement crushing [8]

$$EA = \int_0^{\delta b} p.d\delta \tag{2}$$

When p is an instantaneous crushing load, dδ is the length of crushing the sample, like in equation (2)

$$EA = \int_0^{\delta b} p.d\delta = Pm\ (\delta b\ -\ \delta i\ ) \tag{3}$$

When Pm is the main crushing load , δi is the original of the crushing specimen and δb is the maximum deformation of the tube. The perfect energy absorption would preserve it persists for the whole length of the distortion and reach a supreme force .

The energy absorbed per unit mass of material as given is defined as the Specific energy absorption in the following equation

$$SEA = \frac{E_{total}}{M} \tag{4}$$

Where SEA is specific energy absorption , E total is total energy absorption and M is mass of the structure.

SEA is more specific to measure energy absorption capability of crash box per unit mass. Obviously, a higher SEA indicates a higher energy absorption capability [9] .

3.6 Crashworthiness Parameters

In general, several deformation modes can be obtained like in Figure 3.6 concertina, diamond, mixed (concertina and diamond) and Euler-type mode modes when the tubes are subjected to dynamic load. The amount of energy absorption depends on the type of deformation mode. More energy absorbed can be obtained in progressive mode than Euler-type.

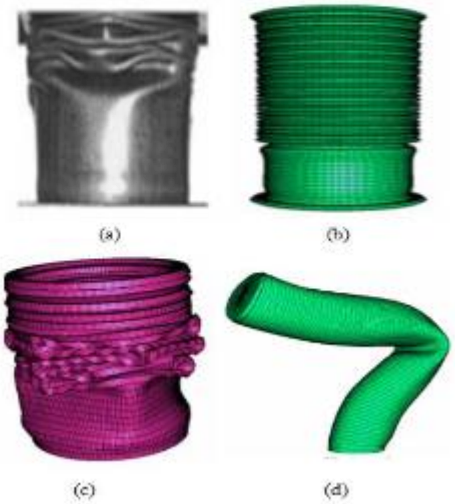


Figure 3.6 : Deformation mode (a) Diamond (b) Concertina mode (c) Mixed mode (diamond and concertina) and (d) Euler-type [7]