ENERGY ABSORPTION CAPABILITY OF MULTI-CELL THIN-WALLED TUBE UNDER LATERAL LOADING

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Energy absorption performance of a structure is a vital aspect in modern transportation design to minimize human injuries during collision. To minimize impact energy, it is necessary to dissipate the energy generated from the collision by absorbing it through deformation of crashworthy structure. Thin-walled structures are widely used as energy absorbing systems due to their capability to efficiently absorb kinetic energy through plastic deformation. However, there are several accidents reported that involve collision between vehicles with toll booths, utility poles and flyover pillar that are lack of protective device. Most of the crashworthiness studies emphasized on the multi-cell structure with load applied axially. Therefore, the investigation on the multi-cell circular thin-walled tubes under lateral loading still gained less attention among the researchers. The primary objective of this thesis is to evaluate the crush response and energy absorption performance of multi-cell thin-walled tubes under quasi-static lateral loading. The compression test was performed under quasi-static lateral loading to evaluate the energy absorption performance of circular thin-walled tubes. Finite element models were developed and validated by comparing the crushing profile and load-displacement curve response of. A multi-cell configuration study was performed to identify the most optimal multi-cell configuration. Furthermore, the response surface method (RSM) for the design of experiment (DOE) was employed to identify the correlation between the geometrical variables parameters and the energy absorption responses. In addition, an investigation of geometrical factor of multi-cell structure was conducted by employing the multi-objective optimization design approach in order to establish the design guidelines of optimal geometrical configuration. Compression test result shows that a multi-cell thin-walled tube has superior energy absorption performance compared to a single thin-walled circular tube under lateral loading. It is evident that the specific energy absorption (SEA) of multi-cell thin-walled tube produces 28% and 76% greater than the single thin-walled circular tubes, SC-small and SC-large configurations, respectively. The outcomes of the study show that the energy absorption performance of multi-cell structure is significantly dependent on the number of tube cells and contact joint of the tube. Based on the multi-objective optimization study, it is evident that the optimal configuration of multi-cell thin-walled tube can be achieved with a smaller diameter and thicker circular tube. The main contribution of this thesis is the development of design guideline for the most optimal geometrical parameter of multi-cell thin-walled tube under lateral loading.

ABSTRAK

Prestasi penyerapan tenaga struktur adalah aspek penting dalam mereka bentuk struktur pengangkutan moden, bagi mengurangkan kecederaan semasa perlanggaran. Untuk mengurangkan tenaga impak, adalah perlu untuk melesapkan tenaga yang dihasilkan dari perlanggaran dengan menyerap tenaga melalui perubahan bentuk struktur yang kekal. Struktur berdinding nipis digunakan secara meluas sebagai sistem menyerap tenaga kerana keupayaannya untuk menyerap tenaga kinetik melalui perubahan bentuk plastik. Walau bagaimanapun, terdapat beberapa laporan tentang kemalangan yang melibatkan kenderaan dengan struktur yang kurang perlindungan seperti plaza tol, tiang jalan raya dan juga tiang jejambat. Kebanyakan daripada kajian keupayaan perlanggaran menekankan kepada struktur berbilang sel dengan beban paksi. Oleh itu, penyiasatan ke atas tiub dinding nipis bulat berbilang sel di bawah beban sisi masih kurang mendapat perhatian di kalangan penyelidik. Objektif utama tesis ini adalah untuk menilai tindak balas penghancuran dan prestasi penyerapan tenaga tiub berdinding nipis berbilang sel di bawah beban sisi kuasi-statik. Ujian mampatan dilakukan di bawah beban sisi kuasi-statik untuk menilai prestasi penyerapan tenaga tiub berdinding nipis bulat. Selain itu, model unsur terhingga telah dibangunkan dan disahkan dengan melakukan perbandingan profil penghancuran dan lengkung tindak balas beban ujian mampatan. Malahan, kajian konfigurasi berbilang sel telah dilakukan untuk mengenal pasti konfigurasi berbilang sel yang paling optimum. Kaedah permukaan tindak balas (RSM) untuk reka bentuk eksperimen (DOE) telah digunakan bagi mengenal pasti hubungan di antara parameter pemboleh ubah geometri dan tindak balas penyerapan tenaga. Di samping itu, penyelidikan mengenai struktur geometri struktur pelbagai sel telah dijalankan dengan menggunakan pendekatan reka bentuk pengoptimuman multi-objektif bagi menghasilkan garis panduan reka bentuk konfigurasi geometri yang optimum. Hasil ujian mampatan menunjukkan bahawa, tiub berdinding nipis berbilang sel di bawah ujian bebanan sisi mempunyai prestasi penyerapan tenaga yang lebih baik berbanding dengan satu tiub berdinding nipis. Adalah jelas bahawa tiub berdinding nipis pelbagai sel mampu menghasilkan penyerapan tenaga tertentu (SEA) masing-masing sebanyak 28% dan 76% lebih besar daripada konfigurasi tiub berdinding nipis tunggal, SC-kecil dan SC-besar. Kesimpulan utama dari kajian konfigurasi berbilang sel menunjukkan prestasi penyerapan tenaga struktur berbilang sel bergantung kepada bilangan tiub sel dan juga gabungan sentuhan di antara tiub. Berdasarkan kajian pengoptimuman multi-objektif, ianya dapat dibuktikan bahawa konfigurasi optimum tiub berdinding nipis berbilang sel boleh dicapai dengan diameter yang lebih kecil dan tiub yang lebih tebal. Sumbangan utama tesis ini adalah pembangunan satu garis panduan reka bentuk untuk memperolehi parameter geometri yang paling optimum bagi tiub berdinding nipis berbilang sel di bawah beban sisi.

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LIST OF ABBREVIATIONS

ASTM	-	American Standard for Testing and Material
DOE	-	Design of Experiment
FE	-	Finite Element
OVAT	-	One Variable at A Time
ROPS	-	Rollover Protective Structure
RSM	-	Response Surface Methodology
RS	-	Response Surface
TIG	-	Tungsten Inert Gas
WEDM	-	Wire Cut Electrical Discharge Machine

LIST OF SYMBOLS

a	-	Total Length of Specimen
b_{ij}	-	Coefficient value
c	-	Width of Grip Section
CLE	-	Crush Length Efficiency
d	-	Displacement
D	-	Diameter
D/t	-	Ratio of Diameter to Thickness
E	-	Energy
e_E	-	Energy Absorption Efficiency
F	-	Maximum Load
F_{mean}	-	Mean Crushing Load
F_{peak}	-	Initial Peak Load
$F(y)$	-	Response of Model
L_{cr}	-	Critical Tube Length
L/D	-	Ratio of Length to Diameter
m	-	Total Mass of Energy Absorber
Mx	-	Rotation on x-axis
My	-	Rotation on y-axis
Mz	-	Rotation on z-axis
r	-	Radius
SEA	-	Specific Energy Absorption
t	-	Thickness
t_f		Time
TEA	-	Total Energy Absorption
Ux	-	Translation on x-axis
Uy	-	Translation on y-axis
Uz	-	Translation on z-axis
v	-	Velocity
w	-	Width
X_1	-	First Factor

X_2	-	Second Factor
X_3	-	Third Factor
x^l	-	Lower Design Variable
x^u	-	Upper Design Variable

CHAPTER 1

INTRODUCTION

1.1 Research Background

The demand for various types of vehicles in society is increasing year by year due to the development of new technology and features in automobile and transportation industries. Vehicles have become an important part of modern society life that are used almost every day for transportation. Unfortunately, road accidents are somewhat inevitable that have been increasing and becoming a major worldwide hazard problem. Subsequently, any vehicular accident will either cause loss of life, severe injuries, or property losses. Annually, automobile accidents result in critical wounds or fatality of up to thousands of individuals globally. It shows that the worldwide phenomenon of transportation vehicles proliferation is an indirect consequence to the increase in vehicle accidents. In Malaysia, the rate of road accidents is increasing on par with increasing the number of road users. Statistics show that the rate of accidents in year of 2017 increased by 30 % compared to year of 2008 as tabulated in Table 1.1.

Therefore, it is obvious that a major action in safety of vehicles structures needs to be taken to reduce the serious effect of vehicle accident on human lives and health. Thus, over the past few decades plenty of efforts have been made by engineers and researchers to develop reliable energy absorber components and systems that can dissipate the impact energy during a collision. An energy absorber is a vital component in modern transportation design structure to reduce human death or injuries during collision. However, energy absorption systems are not capable of preventing any of road accidents from occurring owing to most of accidents happening caused by human errors.

Table 1.1 Statistics of vehicles and road accident in Malaysia (source of Traffic Investigation and Enforcement Department, Polis Diraja Malaysia)

Year	Total number of accidents	Death	Serious injuries
2008	373,071	6,527	8,868
2009	397,330	6,745	8,849
2010	414,421	6,872	7,781
2011	449,040	6,877	6,328
2012	462,423	6,917	5,868
2013	477,204	6,915	4,597
2014	476,196	6,674	4,432
2015	489,606	6,706	4,120
2016	521,466	7,152	4,506
2017	533,875	6,740	3,310

Meanwhile, the crashworthiness is defined as the quality or condition of the vehicles or energy absorber structures under impact collision [1]. The energy absorbers have good crashworthiness performance when the protected structure or passengers sustaining less damage after collision. In order to diminish likelihood of injuries and wounds, it is imperative to disperse energy directing towards the passengers onto the vehicle structure via energy absorber deformation during a crash. The crashworthiness performance of energy absorber is evaluated based on several energy absorption indicators. Hence, numerous studies have been performed to comprehend the behaviour of energy absorption response with several of crashworthiness structures.

Thin-walled tubes have extensively been utilized in crashworthiness application as energy absorber structures [2]. This structure has inclusively been utilized in crashworthiness applications for its capability to efficiently absorb kinetic energy through plastic deformation, thus improving energy dissipation and crashworthiness performances. Several reasons govern the predominant application of energy absorbers that are thin-walled tubes. One of the reasons is thin-walled tubes are easy to be fabricated and still maintain great energy absorption performance. Furthermore, thin-walled tubes made from various ductile materials have been used as crashworthy structure due to its abilities to convert kinetic energy into inelastic energy by permanent plastic deformation during the impact event. In addition, thin-walled tubes can be produced in several geometrical shapes and different configurations with minimum manufacturing cost. Depending on the material used, thin-walled tube is a lightweight structure that can be utilized in vehicles such as airplane and cars in reducing weight of vehicles.

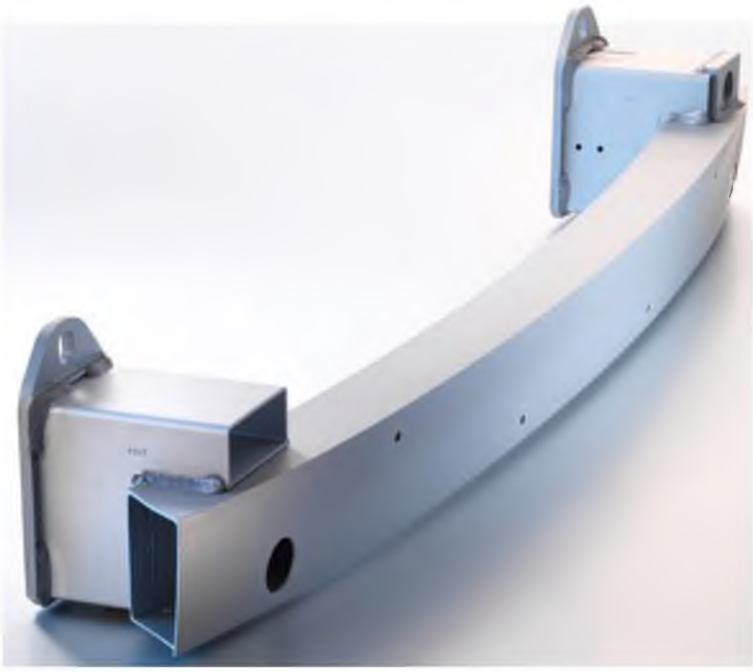

Figure 1.1 Aluminium crash boxes of BMW 5 series (Aluminium Automotive Manual, European Aluminium Association)

The most noticeable application of thin-walled structure as an energy absorber is as crash boxes of vehicles as shown in Figure 1.1. During the frontal collision of vehicles, the crash boxes undergo plastic deformation before the impact load transferred to other vehicles components. Thus, the crash boxes minimize the load transmitting to other parts of protected structure or components. This energy absorber system will reduce the risk of injuries or death to passenger as well cost of damage repair. Moreover, thin-walled tube also has been widely utilised in other crashworthiness applications such as aircraft subfloor structures and Roll over Protective Structures (ROPS) of heavy vehicles, such as bulldozers and tractors [3-5].

Over past few decades, researchers carried out continuing efforts to enhance the energy absorption of structures through analytical, experimental and numerical methods [2]. In the selection of energy absorption structures, single cell structures are outperformed by multi-cell structures by their better energy absorption capacity. Generally, a multi-cell structure is a structural member created from combination of different angle and cells numbers with thin-walled tubes. Additional number of cell structure will contribute in strengthening of the energy absorber, thus enhancing the energy absorption capacity.

In addition, the concepts of multi-cell thin-walled tube structure are practical as an energy absorber for crash barrier system as shown in Figure 1.2. There are several accidents reported that involve collision between vehicles with toll booths, utility poles and flyover pillar that are lack of protective device on these structures [6]. The idea of this system is to retrofit a crash barrier, thus to prevent force from transmitting to the protected structure. Consequently, this barrier will minimize the damage level and cost as it will reduce risk of injury or death.

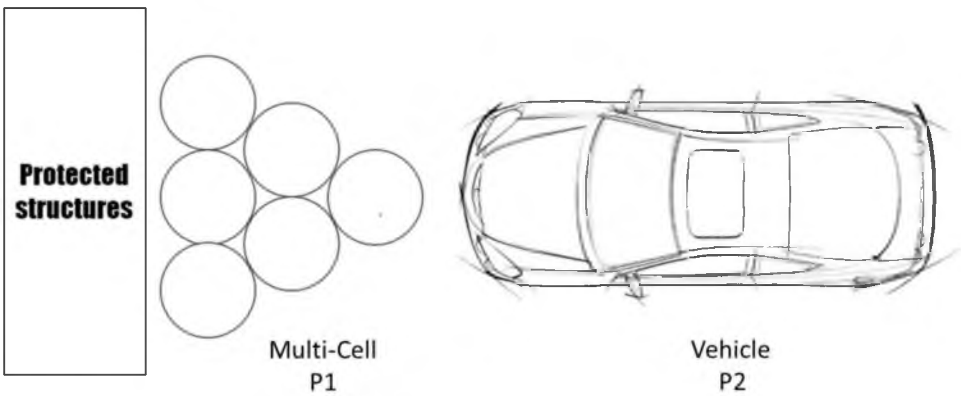

Figure 1.2 A crash barrier protection system consisting of multi-cell thin-walled tube structures

1.2 Problem Background

The safety of road users has always been the priority that needs the most attention. Road accidents involving collision between two or more vehicles are common throughout the year. Such tragic accident obviously contributes a great economic loss to society. Furthermore, road accident also can involve collision of vehicles with other structure such as toll booths, utility poles and flyover pillar. Due to lack of protection against the structure, it will cause serious injuries or fatality.

Owing to the advantages of thin-walled tubes in energy absorption application, numerous studies of thin-walled tubes had been carried out to identify their energy absorption performance based on several factors. Most of the crashworthiness studies emphasized on the multi-cell structure with load applied axially. Therefore, the investigation on the multi-cell circular thin-walled tubes under lateral loading still gained less attention among the researchers.

1.3 Research Objectives

The thesis consists of two main objectives which are listed as follows.

(a) To evaluate the crush response and energy absorption performance of multi-cell thin-walled tubes under quasi-static lateral loading.

(b) To evaluate the geometrical factor of multi-cell structures by employing the multi-objective optimization design approach.

1.4 Research Scopes

This research is concentrated on crush response and energy absorption of multi-cell thin-walled circular tubes under lateral loading. In order to achieve the aims, the finite element model of multi-cell thin-wall circular tubes was developed to identify the energy absorption performance. Both experimental and numerical studies are performed in this research. The scope of the work is highlighted as follows:

i. Develop preliminary finite element (FE) models of the thin-walled circular tubes using finite element nonlinear code LS-DYNA to comprehend the crushing behaviour of these structures under quasi-static lateral loading.
ii. Conducting standard tests to identify the material properties of circular tubes.
iii. Conducting a series of quasi-static compression tests on the multi-cell and single thin-walled circular tubes and perform the energy absorption performance comparison between each thin-walled structure in order to examine the advantages of multi-cell structure.
iv. Develop detailed finite element models of multi-cell and single thin-walled circular tubes for examining the impact characteristics and energy absorption performance.
v. Validate the numerical models by comparing the crushing profile and load-displacement responses.
vi. Perform an investigation on various multi-cell configuration structures based on validated FE model in order to identify the optimal multi-cell configuration.
vii. Develop Response Surface (RS) models of multi-cell thin-walled tubes by using statistical software, Design-expert v6.
viii. Perform a series of parametric study to identify the influence of geometrical parameter on the energy absorption performance.
ix. Conduct multi-objective optimization algorithm to identify the optimum performance of multi-cell thin-walled circular tubes.

1.5 Significance of Study

The present study provides comprehensive research information on the energy absorption performance of multi-cell and single thin-walled circular tubes when subjected to quasi-static lateral loading condition. At the moment, there are limited information on multi-cell circular tubes structure subjected to the crushing load laterally. Hence, this study may indispensably contribute as design information and provide the advantages of multi-cell tubes structures as an energy absorber for crashworthiness applications. In addition to this, the multi-cell configuration study can assist in understanding the influence of multi-cell configuration on energy absorption responses. It has also established the effect of multi-cell structure's geometrical factor on energy absorption responses. Moreover, the primary outcome of this study is to generate a new optimal design for multi-cell structure. Therefore, the results can be utilized for developing a new design guidelines of multi-cell tubes to enhance the crashworthiness performance.

1.6 Thesis Outline

This thesis is divided into 6 chapters. Chapter 1 presents the overview of this study. This chapter highlights the discussion on the background study of research where detailed explanation on energy absorption structures and applications involved are described. A problem statement is clearly defined based on the current problem in crashworthiness application. In addition, the main objectives, scope of work and significance study are also treated in this study.

Subsequently, Chapter 2 provides a critical review on the recent works that are related to the objectives and scopes of this research. This chapter begins with the fundamental of energy absorption characteristics. Then the literature review continues with explanation of general principles in designing energy absorbers. Further discussions based on previous conducted research on types of loading with various energy absorber structures are also presented in this chapter. In addition, the advantages of multi-cell structure in crashworthiness applications are also explicitly explained. Finally, the finite element analysis and multi-objective optimization study of energy absorption systems are described.

In Chapter 3, the important methods and approaches used in this research are presented. This chapter focuses on four parts: experimental technique, finite element (FE) model, multi-objective optimization and parametric study. The experimental part discusses the techniques that are involved in performing tensile and compression tests, while FE model is briefly described the methods required in finite element modelling of circular thin-walled tubes structures. The next section deals with the design of experiment and multi-objective optimisation approach by using design expert software. Finally, this chapter discusses the parametric study that consists of geometrical and multi-cell configuration study. 3

Chapter 4 discusses the results of thin-walled structures obtained from quasi-static compression test. The energy absorption behaviour of each thin-walled tube was investigated to allow more understanding these thin-walled structures under lateral loading condition. In addition, the comparison between the energy absorption responses of each thin-walled structures was also discussed in this chapter. The validation of FE models of thin-walled structures also was described in this chapter where the developed FE models were validated by comparing the numerical results with experiment results. The validation is required to ensure the accuracy of the numerical model and FE models.

Chapter 5 introduces the multi-cell tubes with different configurations where energy absorption responses of each multi-cell configuration was analysed. Thus, first section of this chapter will provide the optimal multi-cell configuration as a design guideline for utilizing in crashworthiness application. The next section describes the Response Surface Methodology (RSM) for Design of Experiment (DOE) constructed along with finite element approach. The parametric study based on RS models was performed in order to investigate the relationship between various geometries parameters with specified energy absorption and initial peak load responses. Moreover, multi-objective optimization method of multi-cell thin-walled structures was employed to identify the optimum geometrical factor of the energy absorber.

Chapter 6 is a final chapter where a clear and concise summary of the thesis is presented. In addition, this final chapter also provides recommendation for future works for refining the research in this field.

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LIST OF PUBLICATIONS

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