# PLASTIC COLLAPSE AND ENERGY ABSORPTION OF FILLED TUBES UNDER QUASI-STATIC LOADS BY COMPUTATIONAL ANALYSIS

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**FACULTY OF ENGINEERING**
**UNIVERSITI MALAYSIA SABAH**

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**THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF BACHELOR OF MECHANICAL ENGINEERING**

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# DECLARATION

I hereby declare that this thesis, submitted to Universiti Malaysia Sabah as partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering, has not been submitted to any other university for any degree. I also certify that the work described herein is entirely my own, except for quotations and summaries sources of which have been duly acknowledged.

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12 JUNE 2015

WOO WEN TZENG

**CERTIFIED BY**

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**SUPERVISOR**

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# ABSTRACT

Over the past decades, increasing focus has been given to the impact of structures where energy needs to be absorbed during the impact in a controlled manner. This demand has led to considerable researches being carried out on studying the behaviours of energy absorbers, devices designed to dissipate energy during impact. Energy absorbers are widely used in various applications, such as aircraft, constructions, highway barriers, and vehicles. Various authors have conducted researches on the different energy absorbers and modes of deformation. The deformation of tubular structures subjected to transverse loading has received relatively limited attention in the open literature. The aim of this thesis was to study the plastic collapse and energy absorption of filled tubes under quasi-static transverse loads by means of computational analysis. Detailed finite element models, validated using experiments, were conducted to assess the plastic collapse behaviour and energy absorption characteristics of aluminium tubes filled with polyurethane foam. Overall, the results show that foam-filled tubes were able to increase the performance in the energy absorption capacity. The results show that the energy absorption response was affected by the geometry parameters of the specimens. The diameter-to-thickness ratio and span lengths can be used as parameters to control the amount of energy absorbed.

# ABSTRAK

*Semenjak beberapa dekad yang lalu, banyak tumpuan telah diberikan kepada kapasiti penyerapan tenaga struktur di mana penyerapan tenaga diperlukan dalam keadaan yang terkawal. Tumpuan ini telah membawa kepada banyak penyelidikan yang dijalankan oleh para penyelidik untik mengkaji tingkah laku penyerap tenaga. Penyerap tenaga digunakan secara meluas dalam pelbagai aplikasi, seperti pesawat, pembinaan, halangan lebuh raya, dan kenderaan. Para-para penyelidik telah menjalankan kajian mengenai penyerap tenaga yang berlain jenis dan mod ubah bentuk. Ubah bentuk struktur berbentuk tiub yang tertakluk kepada bebanan melintang kurang diberikan perhatian. Tujuan projek ini adalah untuk mengkaji ciri-ciri penyerapan tenaga plastic untuk tiub yang berisi dan tertakluk kepada beban melintang kuasi-statik dengan penggunaan analisis komputer. Model unsur terhingga terperinci, disahkan dengan eksperimen, telah dijalankan untuk menilai tingkah laku dan ciri-ciri penyerapan tenaga plastik tiub aluminium yang diisikan dengan busa polyurethane. Secara keseluruhan, keputusan menunjukkan bahawa aluminium tiub yang dipenuhi dengan busa polyurethane dapat meningkatkan prestasi dalam kapasiti penyerapan tenaga. Keputusan menunjukkan bahawa tindak balas penyerapan tenaga telah dipengaruhi oleh parameter geometri spesimen. Nisbah dan jangka panjang diameter ke ketebalan boleh digunakan sebagai parameter untuk mengawal jumlah tenaga yang diserap.*

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# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Tubular structures are significantly being utilized as plastic energy absorbers to sustain dynamic loadings in off-shore, transportation, nuclear power plants and other critical industries (Alghamdi, 2001). Various critical structures and components are designed without considering the plastic collapse behaviour that could result in serious structural damages and hazard to the user. In recent times, thin-walled tubes has gained great interest in dissipating impact energy, and hence protecting the structure in consideration. The ability of thin-walled tubes of various geometrical shapes to crush in a stable and progressive axial manner, has led to their use as energy absorbers in the automotive industry to attenuate detrimental crash effects (Abramowicz, 2003)

The advantage of tubular structures in impact energy absorption application are attributed to their simplicity and high second moment of cross-sectional areas that produces resistance to flexural and torsional loadings, and so efficient energy absorption per unit weight of material used as compared to other types of deforming elements (Reid et. al, 1976). Wherever the tubular structures are utilized as the dynamic load barriers, the structure is designed with the capability of handling the designed maximum load, high energy absorption and containable modes of structure deformation. To predict the structures' collapse loads when they are being used as energy absorbing structures, their collapse mechanism is one important aspect to be investigated and focused on. Various earlier authors have also carried out similar investigation (Reid, 1993 ; Wierzbicki & Abramowicz, 1983)

Research work into large plastic deformation of tubes (Reid, 1993) has on the whole provided useful possibilities for either designing or incorporating or both more effective energy absorbing devices into the pipe-on-pipe impact systems. A characteristic of the deformation process is the continuous formation of plastic hinges. It is well known that when a ductile material is stretched or compressed plastically, energy will be transformed into a non-recoverable plastic deformation. However, deformation behaviour could always be a combination of stretching, compression, and rotation, in the forming of plastic hinges as the structure collapse.

This research project aims to investigate the plastic deformation and energy absorption of filled tubes under quasi-static loads. The failure modes and failure mechanisms of the filled tubes and its capabilities as energy absorbers to further improve and strengthen an empty tube has much to be studied. The performance of filled tubes being able to operate at its optimum calls for a need to evaluate the characteristic behaviours of the geometric parameters of span length and diameter to thickness ratio under plastic collapse loading.

## 1.2 Problem Statement

Tubular structures have been widely used as plastic energy absorbers in various fields throughout the decades. The study of failure mechanism for the tubular structure is important as its usage as energy absorbers increases. In order to design a strengthened tubular structure, which can withstand dreadful impacts; structural dynamics knowledge and the understanding of properties and deformation of the materials are required. Although much attention has been given into studying tubular structures as energy absorbers, not much work has been carried out to investigate the behaviour of filled tubes loaded transversely in close proximity to each other. Moreover, structures subjected to transverse load experience the weakest mode of failure mechanism among other modes of loading. Hence, it is essential that sufficient knowledge and data are generated concerning the plastic collapse and energy absorption of the filled tubular structures under transverse load.

## 1.3 Research Objectives

The general objective of this project is to investigate and study the plastic collapse and energy absorption of polyurethane filled circular tubes under quasi-static transverse loading by utilizing the computational analysis. Thus, the specific objectives to be achieved shall include the following parts: -

i. To develop a finite element model and simulation of plastic collapse of polyurethane filled circular metallic tubes (Al alloy) simply supported on three-point bends subjected to quasi-static transverse loading.

ii. To carry out experimental standard test method by three-point bend for the actual verification of load deformation characteristics for the varying span length and diameter to thickness ratio of polyurethane filled circular metallic tubes as per similar conditions in (i)

iii. To establish the computational model for the optimization of deflection, load, and energy absorption behaviour with respect to the geometric parameters of span length and diameter to thickness ratio of plastic collapse of polyurethane filled circular tubes subjected to transverse loading.

## 1.4 Scope of Work

The scope of this study was to investigate and study the plastic collapse and energy absorption of polyurethane filled circular tubes subjected to quasi-static loading by utilizing the computational analysis through modelling and simulation work. The scope of work on how the three specific objectives can be carried out is deliberated in the following paragraphs.

Firstly, the computational tool, ABAQUS, was utilized to develop a finite element model for simulation studies. Aluminium tubes of different span length and diameter to thickness ratio filled with polyurethane foam were modelled, constraints, loading of a three-point bending, and initial boundary conditions were implemented for modelling and simulated using the ABAQUS. The results from the finite element analysis provided a prediction on the deformation characteristics and energy absorption for each type of the modelled specimens.

Experimental standard test by three point-bending is utilized to carry out tests on the filled aluminium tubes of varying span lengths and D/t ratios for verification of the numerical results. Empty aluminium tubes are filled with polyurethane foam of a fixed density according to industrial practice. Specimens are then prepared and assemble on the Instron Universal Testing Machine for the three-point-bend tests. The experimental deformation characteristic and plastic collapse behaviour of the polyurethane filled circular tube are recorded and observed.

Lastly, the results from both the numerical and experimental tests could be studied, investigated and compared for verification purposes. Optimization of the obtained results with respect to the D/t ratios and span lengths are then organized and correlated to interpret and explain the foundation of plastic collapse and energy absorption of the polyurethane foam-filled Aluminium tubes. The findings could then be recorded in the thesis.

## 1.5 Project Methodology

The project methodology is elaborated in the form of a thesis organization for the completion of studies and investigation of plastic collapse and energy absorption of polyurethane filled tubes under quasi-static transverse loading by computational analysis consists of 8 chapters. Chapter 1 provided an overview of the project topic, problem statement, project objectives, scope of work and the methodology.

Chapter 2 is a literature chapter, which reviewed and cited the previous and current works of various authors related to this project study. The works of various authors on deformation and energy absorption of tubular structures have been reviewed to understand the concept and findings of the topic. Theoretical and computational foundation from the authors are also investigated and compared.

Chapter 3 presents the theoretical considerations of the study on the plastic deformation and energy absorption of polyurethane filled circular tubes. Basic concepts and fundamentals on the tubes subjected to transverse three-point-bend loading were included in this chapter for the interpretation of plastic collapse.

Chapter 4 consists of the computational framework. The finite element analysis framework of a computational tool, in this study, ABAQUS, for modelling and simulation are deliberated. The framework on how the computational tool deals with elements and meshing, loadings, constraints, and the basic fundamentals of the computational analysis were included in this chapter. Modelling and simulation of plastic collapse of polyurethane filled circular tube subjected to transverse loading under a simply supported three point-bend test are presented here.



Chapter 5 describes the experimental methods and procedure carried out for the development of plastic collapse of polyurethane filled circular tube under the three point-bend test standard utilizing the Instron Universal Testing Machine. Experimental tests were conducted to obtain physical results for verification of the finite element analysis modelling and simulation. The preparation of specimens and tests were carried out in accordance to ASTM standards.

Chapter 6 presents the description on the characterization of plastic collapse of polyurethane filled circular tube subjected to transverse loading using the three point-bend method, with respect to span length and diameter to thickness ratio. Trends, behaviours and modes of deformation and plastic collapse are describe in this chapter, which consist of the load-deflection of varying span lengths and D/t ratios, and numerical and experimental results.

Chapter 7 consists of the results and discussion chapter, which correlated the behaviour, findings and comparison on the finite element model and the experimental method. Optimization with respect to D/t ratios and span lengths were correlated between the numerical and experimental results to explain the rational and mechanisms in the deformation and energy absorption of the filled tubes.

Chapter 8 concluded the findings of the plastic collapse of polyurethane filled circular tubes under three point-bend tests. Conclusive statement is drawn with respect to each of the objectives laid out in the project work. In addition, suggested future works for further develop of this project are also provided.

## 1.6 Research Benefit

The main objective of this study was to investigate and study the plastic collapse and energy absorption of polyurethane filled circular tubes under quasi-static transverse loading by utilizing the computational analysis. It is expected that at the end of this project, the plastic deformation characteristics and energy absorption of the foam-filled Aluminium tubes could be developed and modelled using the finite element computational analysis. At the same time, experimental data obtained, optimization of D/t ratios and span lengths could be developed for further future modelling and simulation works of optimum energy absorption of filled tubular structures. Prior to the main benefit of this project, a strong understanding and command in computational modelling and simulation is also hope to be achieved.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Overview

In this chapter, journals, reference books, and researches that contain and provide related and relevant information on the theories, concepts and results for the development of this research topic is reviewed. Details of tubular structures, material properties of the tubular structures, infill materials and their properties for the tubular pipes, various tests on the plastic deformation, and energy absorption of the tubular pipes are reviewed. Numerical computation, ABAQUS software, using finite element analysis is also reviewed. Including past researches conducted by various authors, which are relevant to this project are also reviewed and studied

## 2.2 Energy Absorbers

Protection of structures subjected to impact loading often requires the need for energy absorbing systems. In general, an energy absorbing system should be cost-effective, effort has been made to understand the mechanisms of the thin-walled tubes' structural collapse to increase their efficiencies in absorbing energy. The energy absorption capacity of thin-walled tubes is greatly influenced by the tube geometry and material properties (Jensen et. al, 2004). For many decades, different thin-walled tubular section have been studied, such as square, rectangular, circular, tapered, hat-section and conical tubes.

(a) Tubes

Circular tubes has the most widespread use as energy absorbers, due to their high occurrence and easy manufacturability. The details of tubes acting as energy absorbers is the main focus of this paper and will be discussed in later sections.

(b) Frusta

Truncated circular cones, or also known as frusta, have a wide range of applications. The occurrence of frusta as structural members has drawn some attention, due to their stable plastic behaviour when crushed axially. Postlethwaite and Mills (1970) first studied the frustrum. Alexander's method (extensible collapse analysis) was used for rigid perfectly plastic material cones. They reported the mean crushing force ($P_{av}$) for external collapse as:

$$P_{av} = 6Yt^{3/2}\sqrt{d + 2x\sin(\varphi)} + 5.69Yt^2\tan(\varphi) \qquad (2.1)$$

Where Y is the yield strength, $t$ is the frustrum thickness, $x$ is the deformation, $d$ is the small diameter of the frustum and $\varphi$ is the semi-apical angle of the frustum.

Mamalis and Johnson (1983) investigated the quasi-static crumpling of aluminium tubes and frusta under quasi-static compression experimentally. It was observed that the frusta have load-deflection curves that were more regular than those of cylinders. It was also noticed that the post-buckling load increases in a parabolic manner with an increase in wall thickness, while an increase in semi-apical angle decreases the post-buckling load. The authors observed that thin frusta deformed into a diamond shape, while thick ones deformed into axisymmetric rings.

(c) Multicorner Colums

The crushing of thin-walled multicorner structures made from plate elements was analyzed by Wierzbicki and Abramowicz (1983), by considering stationary plastic hinges and narrow toroidal regions of circumferential stretching and bending which travel through the structure.

(d) Sandwich plates

Sandwich plates are widely used in various applications, where they are very common in transport vehicles such as aircraft, trains, cars and boats. A sandwich structure, constructed from a core with a skin attached to each side, is analogous to an I beam. There is a considerable flexibility in sandwich plates as there is a wide range of materials that can be considered for the skin and core. The impact and energy absorption of sandwich structures has drawn interest of many researchers. Gilkie and Sundaraj (1971) investigated the effect of laminate thickness, core thickness, facing thickness and support span on the impact strength of the sandwich. It was reported that sandwich panels have higher resistance to impact failure than simple laminates.

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