Faculty of Mechanical Engineering

AN INVESTIGATION OF ENERGY ABSORPTION CHARACTERISTICS OF HONEYCOMB STRUCTURE UNDER LATERAL LOADING

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Master of Science in Mechanical Engineering

2018

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2018

DECLARATION

I declare that this thesis entitled "An Investigation of Energy Absorption Characteristics of Honeycomb Structure under Lateral Loading" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:………………....................
Name	: ABD JUMAIDI BIN CHULI
Date	:...

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering.

Signature	:………………......................
Supervisor Name	: DR. MOHD BASRI BIN ALI
Date	:..

DEDICATION

To my beloved parents-in-law and
To both my late parents whom their memories have been a source of inspiration to me

ABSTRACT

Nowadays, aluminium honeycomb has become well-known as a good energy absorbing cellular structure. Due to its lightweight and high stiffness properties, this structure has been more preferable metallic material compared to others in term of producing an energy absorbing structure. This study is concerned with the energy absorption characteristics of aluminium honeycomb structure. For the crashworthiness of a material research area, this study offers more understanding of the behaviour of aluminium honeycomb when subjected to quasi-static and dynamic lateral compression. Five different densities of honeycomb structure (empty and Oil Palm Trunk-filled with different densities) were introduced to study their deformation mode as well as the energy absorption characteristic. Since lateral compression is involved, all specimens were compressed in two directions; x_1-direction and x_2-direction. The results show that the honeycomb cores exhibit anisotropic response during the compression. Under quasi-static and dynamic loading, honeycomb compressed in the x_1-direction has higher energy absorption characteristics values such as collapse load, mean load, plateau load and energy absorption value compared to the honeycomb cores that were compressed in the x_2-direction. This is due to the cell wall arrangement of double thickness wall (2t) in the honeycomb core; the 2t cell wall aligned vertically when compressed in x_1-direction, and horizontally when compressed in the x_2-direction. The vertically arranged 2t cell wall caused the honeycomb structure to be stronger and has a higher stiffness value. In term of deforming modes, all honeycombs show a very different response from each other. Besides, the addition of filler element material (Oil Palm Trunk sawdust) into the honeycomb core caused the energy absorption values to increase by 83% in x_1-direction and 91% in the x_2-direction. Since the honeycomb is a man-made structure, the imperfections are randomly distributed in all parts of the structure. This caused the initiation point for the deforming mode of the honeycomb which occurred at the weakest point in the structure to be started in a random manner. All experimental results were compared by using finite element software, and a good agreement between them was shown for the compression of empty honeycomb. The main factors that caused the dissimilarity between the experimental and simulation results were found to be the imperfections of the honeycomb cores; the irregularities of the cell wall and the geometrical imperfections of the honeycomb that occurred during the manufacturing process.

ABSTRAK

Pada masa kini, struktur sarang lebah jenis aluminium semakin terkenal sebagai struktur penyerapan tenaga yang baik. Disebabkan oleh sifatnya yang ringan dan mempunyai nilai kekakuan yang tinggi, struktur ini adalah lebih diutamakan jika dibandingkan dengan jenis bahan besi yang lain bagi menghasilkan struktur penyerapan tenaga. Kajian ini berkenaan dengan ciri-ciri penyerapan tenaga yang dipunyai oleh struktur sarang lebah jenis aluminium. Dalam bidang kajian yang melibatkan kebolehtahanan kemalangan bagi sesuatu bahan, kajian ini menawarkan kefahaman yang lebih untuk sifat struktur sarang lebah jenis aluminium apabila menjalani mampatan sisian dalam keadaan kuasi-statik dan dinamik. Lima jenis ketumpatan bagi struktur sarang lebah telah diperkenalkan (yang kosong dan yang diisi dengan serbuk batang kelapa sawit dengan nilai kemampatan yang berbeza) untuk mengkaji mod ubahbentuk dan ciri-ciri serapan tenaga. Memandangkan mampatan jenis sisian telah digunakan, semua spesimen telah dimampatkan dari dua arah sisi iaitu arah x_1 dan arah x_2. Keputusan kajian menunjukkan bahawa struktur sarang lebah mempamerkan tindak balas yang anisotropik semasa proses mampatan. Dengan mapampatan di bawah keadaan kuasi-statik dan dinamik, struktur sarang lebah yang dimampatkan dari arah x_1 mempunyai ciri-ciri serapan tenaga yang tinggi seperti beban runtuh, beban purata, beban dataran kadar dan nilai serapan tenaga jika dibandingkan dengan struktur bahan yang dimampatkan dari arah x_2. Ini adalah kerana susunan dinding sel yang mempunyai ketebalan sekali ganda (2t) di dalam struktur sarang lebah. Dinding sel 2t disusun secara menegak semasa mapatan dari arah x_1, manakala disusun secara mendatar semasa mampatan dari arah x_2. Susunan dinding sel 2t secara menegak telah menyebabkan struktur bahan lebah menjadi lebih kuat dan mempunyai nilai kekakuan yang lebih tinggi. Dalam bahagian mod ubahbentuk pula, semua struktur sarang lebah menunjukkan tindak balas yang berbeza-beza antara satu dengan yang lain. Selain itu, penambahan bahan elemen pengisi (serbuk batang kelapa sawit) ke dalam struktur sarang lebah telah menyebabkan nilai serapan tenaga meningkat sebanyak 83% pada arah x_1 and 91% pada arah x_2. Memandangkan struktur sarang lebah adalah bahan buatan manusia, ketidaksempurnaan telah disebarkan secara rawak pada semua bahagain struktur sarang lebah. Hal ini menyebabkan mod ubahbentuk bagi struktur sarang lebah yang dimulakan pada titik paling lemah dalam struktur tersebut tersebar secara rawak. Semua keputusan eksperimen telah dibandingkan dengan menggunakan perisian unsur terhingga, dan keputusan diantara eksperimen dengan simulasi telah menunjukkan persetujuan yang baik di dalam mampatan struktrur sarang lebah yang kososng. Faktor utama yang menyebabkan perbezaan diantara keputusan eksperimen dengan simulasi adalah ketidaksempurnaan struktur sarang lebah iaitu dinding sel yang tidak sekata serta ketidaksempurnnan geometri bagi struktur sarang lebah yang telah wujud semasa proses pembuatan.

ACKNOWLEDGEMENTS

In the name of Allah, most gracious, most merciful, Alhamdulillah, thanks to the Almighty, Allah Azza Wajalla, for giving me the deen, health and strength in completing this research successfully. Without His Permission I am not able to reach this stage.

I would like to convey my honest appreciation to my supervisor, Professor Dr. Md Radzai bin Said, and my co-supervisor Dr. Mohd Basri Bin Ali for their valuable guidance, encouragement, patient, correlation, advice and suggestion that have greatly helped me in completing the research.

Next, I would like to acknowledge the Malaysian Government for giving me the opportunity to pursue my master study and providing the fund for the project under Fundamental Research Grant Scheme (FRGS/1/2014/TK01/FKM/01/F00206) as well as MyBrain15.

I am thankful to all the laboratory technical team for all their worthy assistance provided by them. Their attention, constructive ideas and contribution have been a great help to me in throughout my research. I am greatly thankful to all my colleagues for their meaningful togetherness in helping and giving opinions in the process of completing this research. I will never forget the joyful moment and their motivational encouragement that they have shared with me during my progress of my research.

Last but not least, my special devotion to my beloved family and wife for their unconditional love and prays standing beside me bearing the hardship together along the journey. Their loving support, cheerful moment, endless affection and prays continuously has inspired me a lot until the end of my research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

P_m	-	mean crushing strength
σ_0	-	yield stress
σ_{pl}^*	-	plastic collapse stress
σ_{ys}	-	yield stress
h	-	cell wall height
l	-	cell wall length
m	-	mass
t	-	thickness
v	-	velocity
γ	-	density gradient
δ	-	deformation
ρ	-	density

LIST OF PUBLICATIONS

Journal

1. Said, M.R., Chuli, A.J., Pokaad, A.Z., and Ghazali, N., 2017. Uniaxial and biaxial crushing characteristics of aluminium honeycomb. ARPN Journal of Engineering and Applied Sciences, 12 (14), pp. 4319-4323.

2. Said, M.R., and Chuli, A.J., 2016. Fabrication and Testing of the sheet metal tubes under quasi-static loading. ARPN Journal of Engineering and Applied Sciences, 11 (8), pp. 5418-5426

CHAPTER 1

INTRODUCTION

1.1 Overview

Transportation means such as cars, trains and aeroplane has been very demanded in the modern world, and the numbers kept increasing. In Malaysia alone, the accumulated number of registered vehicles has been recorded as 25101192 in 2014, according to MoTM (Ministry of Transportation Malaysia). Comparing the number of vehicles and the population for Malaysia in 2014 (30 million people), every ten persons had eight vehicles on average.

Technological advancements do not only increase the number of vehicles, but it leads to a higher speed and more production of massive vehicles such as aircrafts and trucks. These bigger structures can cause bigger and more serious effect to the people and environment if it involves in an accident. This motor vehicle related accidents proved to be a major health problem worldwide, as it creates economic loss to society and killed more people.

Generally, a motor vehicle accident can be explained as an impact in which two or more bodies (either stationary or moving) collides with each other in a brief time period. An average force F which predominate over time t and which arises at the impacting interfaces is produced by the need to change momentum (mass and velocity) mv; it is inversely proportional to t, $F = mv/t$. From the equation mentioned, it can be seen that a large value of force F can be generated if the time t taken is shorter. The large value of F may lead to more serious damage to the occupants and structures. For the occupants, the vehicle crash can cause them to be injured (or sometimes lead to death) in which pertains to the physical/

psychological injury and trauma. As for the structure, vehicle crash can cause damage to the structure; referring to the unintentional plastic deformation and fracture of the vehicle's structure and other subsequent parts resulting from the crash. Other than that, vehicle crash may also cause environmental damage, such as damage to the roadside object (road divider, trees poles, etc.).

As mentioned before, the occupant of the vehicle can be injured in the occurrence of a crash. According to (Carney III, 1993), the injury can be caused by the four following events; unacceptably high deceleration, crushing of the occupant compartment, impact with interior part of the vehicle, and ejection. All these events can cause injuries such as head injury, chest injury, and even thoracic injury. For many years, head injury (as well as brain injury) has been recognized as the most unbearable type of trauma experienced in accidents, due to the difficulties in treating them, and commonly result in long term dysfunction. They cause a great cost to the society, either because the cost of long span of treatment and loss of productivity, or because the losses due to an early death.

Due to these events, public has voiced their concern and demand a higher degree of protective devices/mechanisms either for personal or public usage. Therefore, the mechanical devices in the vehicle especially the energy-absorbing structures must be constantly upgraded in order to fulfil the public demand. However, the crashworthy performance of the vehicle proved to be very challenging in designing and testing of various types of vehicle. By definition, crashworthiness denotes the quality of response of a vehicle when it is involved in or undergoes impact. The crashworthiness value of a vehicle can be measured by analysing the effect of the impact to the structure's main body and its occupants. The more damage to the vehicle and/or to its occupants and contents after the given occasion, the lower the crashworthiness value of the vehicle and it signify the poor its crashworthy performance.

In the field of energy absorption, researchers are prone to explore the best Impact Energy Absorber (IEA) device; an expendable mechanical structural element when brought into collision. IEA device absorbed energy during impact and transfers minimum impact on the load and to the surrounding equipment. As the energy absorbed by the IEA device increase, lesser impact energy will be transferred to the main structures. There are two types of safety devices which are known as active and passive. An active safety device is where certain device will activate in response of abnormal event to avoid accident such as brakes and steering. Meanwhile, devices such as airbags, strong body structures and seatbelts are some examples of passive safety device which helps to minimize the effects of a collision. The significance of IEA device cannot be underestimated as it involved the safety of human being especially in automotive and aircraft industry.

There are some general principles in designing a good energy-absorption device made by previous researcher (Lu and Yu, 2003) and engineers. The principles are as follows:

- Irreversible energy conversion: The material/structure should be able to convert most of the input kinetic energy into inelastic energy by plastic deformation or other dissipation processes, rather than storing it elastically.
- Restricted and constant reactive force: The peak reaction force (also known as peak load) of an energy absorber must be kept lower than the threshold value; and should remain constant throughout the large deformation process of the structure.
- Long stroke: Since the energy absorption value of the structure is defined by the product of work done by the force and the total displacement experienced along the acting line of the force, the displacement stroke should be long in order to enable the structure to absorb more energy. The longer stroke and a constant reactive force (as mentioned above) will produce the best combination for the energy-absorbing structure.

- Stable and repeatable deformation mode: To ensure the reliability of the structure to deal with very unclear working loads, the deformation mode and energy-absorbing capacity of the designed structure should be stable and repeatable.
- Lightweight and high specific energy absorption capacity: The component of the energy-absorbing structure should be light itself and possess the high specific energy absorbing capacity (energy absorption capacity per unit weight) which is very important to carrier-vehicles especially trains and aircrafts.
- Low cost and easy installation: The manufacture, installation and maintenance of the energy-absorbing structure should be easy and cost effective, because they are usually one-shot item; one that must be discarded or replaced once deformed.

These principles are very important in helping engineers to design a good energy-absorbing structure since the designing and analysis of the energy-absorbing structure is very different to the conventional structure design (the structure only undergo a small elastic deformation). The energy-absorbing structures have to withstand forceful impact loads, so that their deformation and failure involve large geometry changes, strain-hardening effects, strain-rate effects, and various interactions between diverse deformation modes such as bending and stretching.

Cellular aluminium honeycomb is one of the popular materials that are being investigated in recent years. Known for its lightweight and high stiffness, there are many structures that used the honeycomb as its core material. In fact, sandwich panel which usually require the best stiffness to weight ratio also used the aluminium honeycomb as its core materials. The models of structures in which the sandwich panel are mostly seen are roofs, facades, floors and partition. In order to improve the energy absorbing capacity or the strength of metallic structures, filler elements such as foam and wood are used. Reticulated foams (open-cell-structured foam) and closed-cell- structured foams such as polyurethane, polyethylene and polystyrene are usually used when the structures prioritize the importance of surface area, low density and porosity. Many engineering applications used wood as its filler element due to the wood's properties; low density, high specific strength, low in thermal conductivity, low cost of production and most importantly, environmentally friendly. However, woods are also highly combustible and cannot be used in high temperature application.

By comparison to other countries, Malaysia is the second largest producer of oil palm in the world. Due to the import and export marketing, the importance of oil palm is highly regarded as it offers incomes for the country financially. However, the oil palm tree is usually produced only to extract the oil palm. The other parts of the tree such as trunk and leaf are usually scrapped as it cannot be used in other application, and this situation can be viewed as loss cost to the country. Oil palm trunk (OPT) has higher water content compared to the other kind of wood such as plywood, and thus offers lower strength to be used in the structural application. Though (OPT) cannot be used as main structures for houses alike, it can be processed to be charcoal and fuel.

Compression test is one of the most popular types of experiment in determining the behaviour and energy absorption capacities of certain specimens. There are many types of compression test condition such as static, quasi-static and dynamic loading. These three conditions are differed by their respective compression speed. As for the direction of compression, two most common direction of compression are known as axial loading (out-of-plane) and lateral loading (in-plane). The axial loading usually offers more strength and stiffness compared to lateral loading. In the axial compression of honeycomb, the collapse progression is started by initializing the linear-elastic deformation which involves substantial axial or shear distortions of the cell wall. The linear-elastic regime is shortened by buckling either elastic (for elastomer) or plastic (for metal or rigid polymer) and the final failure