UNIVERSITI PUTRA MALAYSIA

CRUSHING BEHAVIOUR OF KENAF FIBRE-REINFORCED EPOXY COMPOSITE ELLIPTICAL TUBES

MOHAMED MOHAMED M ALKATEB

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By

MOHAMED MOHAMED M ALKATEB

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

September 2018

DEDICATION

This thesis is gratefully dedicated to:

My wife

My sons

My daughters

My supervisory committee

Thank you for your endless supports in this journey. For keeping your faith in me. For being there when I needed you.

Thank you for every thing.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Professor Mohd Sapuan Salit, PhD, PEng
Faculty : Engineering

Design selection is an important topic in the industry to manufacturing sustainable and competitive products. To meet the needs of strength and durability at component level, the shape can be used as a design tool during the early stages of the design process.The familiar range of tubular sections such as namely square, rectangular and circular hollow sections, this study attempts to addition a new hollow sections is elliptical tubes to tubular family. The new sections combine the elegance of circular hollow sections with the improved structural efficiency under crushing load conditions due to the differing flexural rigidities about the two principal axes. The purpose of this research is to study and analyzed crushing behaviour of composite elliptical tubes on the energy absorption. The main materials used in this project are unsaturated polymer resin, kenaf and wool fibers. A hand lay-up technique was used to fabricate the specimens of composite elliptical tubes. The specimens are tested for the quasi-static compressive testing. Four objectives were performed for crushing test. The first objective was to study the effect of vertex angles on crashworthiness parameters, energy absorption and failure mode; the vertex angles vary from 0° to 24° in 6° increments, the specific energy absorption for the composite elliptical cones showed a positive correlation, i.e., the vertex angle increased, the more energy was absorbed. In this regard, composite elliptical cone with the vertex angle is 24º exhibited the highest specific energy absorption capability equal to 441.473 kJ/kg. The objective two was devoted to study the effect of holes on crushing behaviour of composite elliptical tubes under axial load, four different elliptical tubes; three tubes with holes of (4, 6 and 8) and one without holes at same dimensions. Crushing behavior of kenaf composite elliptical tubes was affected by holes in their wall, results kenaf tubes without holes attributed to a lower initial peak load, (Pi) followed by a lower mean crush load compared with other tubes. It was clear from resulte that the average crush load increaes when holes increaes. Furthermore, On the other hand, it can be noticed that the kenaf tube with holes of 8 resulted the best specific energy (Es) of (486.207kJ/kg) as well as biggest value of average crushing load

equal to 21.043kN. Objective three involved fabrication and testing of four elliptical tubes, three supported by wooden sticks (four, six, and eight sticks) and unsupported to determine the effect of supported on crashworthiness parameters of natural kenaf fibre reinforced composite elliptical tubes. The supported can control the load distribution during the crushing period and can increase the carrying loads of the structure. The results revealed that all specimens have failed in longitudinal failure modes; the number of wooden sticks increases the more energy absorbed. In this regard, the tube with eight wooden sticks exhibited the highest specific energy absorption capability of 570.7329 kJ/kg and highest value of the average load of 12.401 kN. The last objective, was to study the effect of fibre content on the crashworthiness parameters, energy absorption and the failure modes of kenaf fibre-reinforced elliptical composite.tube. Various fibre contents were considered, including 30%, 35% and 40%. Reinforced fibers are strong and effective for improving the mechanical properties of composite materials. One the other hand, wool fibre used for reinforced elliptical composite tube to investigate the effect of fiber type on crashworthiness parameters and energy absorption. The main goal is to maximize the amount of impact energy absorbed, improve crashworthiness parameters in tube structure and at the same time minimize its weight. The methodology is based on comparison between kenaf and wool tube type with fiber content of 30%, 35% and 40%. It should be noted that an increase in the fiber content might not always necessarily improve the specific energy absorption capability. As the fiber volume fraction increases, the volume of the matrix between the fibers decreases. In this regard, the fiber content increases the specific energy absorption capability decreases. Overall, the wool tube with fiber content of 30% have the best value of specific energy absorption of 235.646kJ/kg. Above all, the experimental tests considered in this study results that the tube supporting by wooden sticks of 8 exhibited the highest specific energy absorption capability compared to all other tested samples. Furthermore, it was observed that tubes with wooden sticks of 8 displayed the specific energy absorption 570.7329 kJ/kg greater than those tubes with holes, vertex angle, fibre content respectively. The specific energy absorption by wool tube greater than that kenaf tube in the rate of 16%.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KELAKUAN PENGHANCURAN BAGI TIUB ELIPS KOMPOSIT EPOKSI DIPERKUAT GENTIAN KENAF

Oleh

MOHAMED MOHAMED M ALKATEB

September 2018

Pengerusi : Profesor Mohd Sapuan Salit, PhD, PEng
Fakulti : Kejuruteraan

Pemilihan reka bentuk adalah satu tajuk penting dalam industri bagi membuat produk yang lestari dan berdaya saing. Bagi memenuhi keperluan kekuatan dan tahan lama pada tahap komponen, bentuk boleh dijadikan satu perkakas reka bentuk semasa peringkat awal proses reka bentuk. Julat biasa bagi bahagian tiub seperti bahagian empat segi sama, empat segi tepat dan geronggang bulat, kajian ini cuba untuk menambah satu bahagian geronggang baharu ke dalam keluarga tiub iaitu tiub elips. Bahagian baharu ini menggabungkan keanggunan bahagian geronggang bulat dengan kecekapan struktur yang telah ditambah baik di bawah beban penghancuran disebabkan perbezaan ketegaran lenturan di atas dua paksi utama. Tujuan penyelidikan ini adalah untuk mengkaji dan menganalisis kelakuan penghancuran bagi tiub elips komposit ke atas penyerapan tenaga.Bahan utama yang digunakan dalam projek ini adalah damar poliester tak tepu, gentian kenaf dan bulu.Kaedah penyerakan tangan telah digunakan bagi membikin sampel tiub elips komposit. Sampel telah diuji bagi pengujian mampatan kuasi-statik. Kerja ini memfokuskan kelakuan penghancuran tiub elips komposit diperkuat gentian kenaf dengan perbagai kesan. Satu siri eksperimen telah dijalankan ke atas tiub elips komposit dengan pelbagai kesan bagi mengkaji kelakuan penghancuran tiub ini bila dikenakan beban mampatan kuasi-statik. Kaedah susunan tangan telah digunakan dalam pembikinan sampel tiub elips komposit. Empat tahap telah dijalankan bagi kelakuan penghancuran, ragam kegagalan dan parameter kebolehancuran bagi tiub elips komposit. Tahap pertama adalah mengkaji kesan sudut verteks ke atas parameter kebolehancuran, penyerapan tenaga dan ragam kegagalan; sudut verteks berubah dari 0 hingga 24° dalam penambahan 6°, penyerapan tenaga spesifik bagi tiub elips komposit menunjukkan korelasi positif, iaitu lebih bertambah sudut verteks, lebih banyak tenaga diserap. Ini adalah disebabkan "kawasan keratan rentas berkurangan dengan peningkatan sudut verteks" rupa lengkuk beban-ubah bentuk bagi setiap tiub komposit disebabkan sudut verteks. Dalam hubungan ini, kon elips komposit dengan sudut verteks 24º telah mempamerkan keupayaan penyerapan tenaga spesifik yang

tertinggi bersamaan 441.473 kJ/kg. Jadi, sudut verteks adalah satu faktor penting yang perlu diambil kira bagi mencapai nilai yang baik bagi penyerapan tenaga spesifik. Tahap kedua adalah berkaitan kajian, kesan lubang ke atas kelakuan penghancuran tiub elips komposit di bawah beban paksian, empat tiub elips berbeza; tiga tiub dengan lubang 4, 6 dan 8 pada dinding dan satu tanpa lubang pada dimensi yang sama. Kesan lubang pada dinding tiub telah memperbaiki parameter kebolehancuran. Kelakuan penghancuran tiub elips komposit kenaf telah dipengaruhi oleh lubang di dinding, keputusan bagi tiub kenaf tanpa lubang telah memberikan bebanan puncak permulaan yang lebih rendah (Pi) diikuti dengan beban penghancuran purata yang lebih rendah berbanding tiub yang lain. Adalah jelas daripada keputusan bahawa, beban penghancuran purata bertambah bila lubang ditambah. Sebagai tambahan, sebaliknya, boleh diperhatikan bahawa tenaga spesifik tiub kenaf tanpa lubang adalah lebih rendah berbanding tiub lain dengan lubang. Tiub kenaf dengan lubang 8 menghasilkan tenaga spesifik yang terbaik (Es) iaitu 486.207kJ/kg dan nilai terbesar bagi beban penghancuran purata bersamaan 21.043kN. Tahap ketiga melibatkan pembikinan dan pengujian empat tiub elips, tiga disokong dengan batang kayu (empat, enam dan lapan kayu) dan satu tidak disokong bagi menentukan kesan sokongan ke atas parameter kebolehancuran bagi tiub elips komposit diperkuat gentian kenaf. Batang kayu penyokong telah digunakan di dalam dinding tiub bagi memperbaiki tenaga yang terserap oleh tiub. Penyokong boleh mengawal agihan beban semasa tempoh penghancuran dan boleh menambah penanggungan beban bagi struktur. Keputusan menunjukkan bahawa semua sampel telah gagal dalam ragam kegagalan memanjang; bilangan batang kayu meningkatkan lebih banyak tenaga yang terserap. Dalam perkara ini, tiub dengan lapan batang kayu mempamerkan keupayaan penyerapan tenaga spesifik yang paling tinggi 570.7329 kJ/kg dan nilai tertinggi bagi bebanan purata iaitu 12.401 kN. Tahap terakhir adalah kajian kesan kandungan gentian ke atas parameter kebolehancuran, penyerapan tenaga dan ragam kegagalan bagi tiub komposit elips diperkuat gentian kenaf. Pelbagai kandungan gentian telah dipilih termasuk 30%, 35% dan 40%. Gentian diperkuat adalah kuat dan berkesan bagi meningkatkan sifat mekanikal bahan komposit. Sebaliknya, gentian bulu/kenaf digunakan bagi tiub komposit elips diperkuat bagi mengkaji kesan jenis gentian ke atas parameter kebolehancuran dan penyerapan tenaga. Matlamat utama adalah untuk memaksimumkan kandungan tenaga hentaman yang terserap, meningkatkan parameter kebolehancuran dalam struktur tiub dan pada waktu yang sama meminimumkan berat. Kaedah ini berasaskan perbandingan antara tiub jenis kenaf dan bulu dengan kandungan gentian 30%, 35% dan 40%. Perlu diingat bahawa penambahan dalam kandungan gentian mungkin tidak sentiasa memperbaiki keupayaan penyerapan tenaga spesifik. Apabila pecahan isipadu gentian meningkat, isipadu matriks antara gentian berkurangan. Dalam hubungan ini, kandungan gentian bertambah menyebabkan keupayaan menyerap tenaga spesifik berkurangan. Keseluruhannya, tiub bulu dengan kandungan gentian 30% mempunyai nilai terbaik bagi penyerapan tenaga spesifik iaitu 235.646kJ/kg. Sebagai tambahan, ujian eksperimen yang dipilih dalam keputusan kajian ini adalah tiub disokong oleh batang kayu sebanyak lapan 8 batang menunjukkan keupayaan menyerap tenaga yang tertinggi berbanding dengan sampel lain yang diuji. Seterusnya, dapat diperhatikan bahawa tiub disokong oleh batang kayu sebanyak lapan 8 batang menunjukkan penyerapan tenaga spesifik 570.7329 kJ/kg lebih besar daripada tiub lain yang ada lubang, sudut verteks dan kandungan gentian. Penyerapan tenaga spesifik oleh tiub bulu adalah lebih besar daripada tiub kenaf dalam kadar 16%.

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Mohamed Mohamed M. Alkateb

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Sapuan Salit, PhD, PEng
Professor, Ir
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Zulkifille bin Leman, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohammad Jawaid, PhD
Senior Fellow Researcher
Institute of Tropical Forestry and Forest Products
Universiti Putra Malaysia
(Member)

Mohamad Ridzwan Ishak, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

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Name and Matric No.: Mohamed Mohamed M Alkateb, GS41834

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

Signature: ____________________________
Name of Chairman of Supervisory Committee: Professor Ir Dr. Mohd Sapuan Salit

Signature: ____________________________
Name of Member of Supervisory Committee: Associate Professor Dr. Zulkifille bin Leman

Signature: ____________________________
Name of Member of Supervisory Committee: Dr. Mohammad Jawaid

Signature: ____________________________
Name of Member of Supervisory Committee: Dr. Mohamad Ridzwan Ishak

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A	Cross-sectional area (mm^2)
at, bt	Inner major and inner minor radii of the top end, respectively (mm)
h	Height of the tube (mm)
t	Thickness of the cone wall (mm)
B	Cone vertex angle (deg)
m	Mass density of the structure (kg)
Pi	First peak crush failure load (kN)
Pc_r	Critical crushing load (kN)
Pm	Average crush failure load (kN)
CFE	Crush force efficiency (kN)
IFIF	Initial failure indicator factor (kN)
CFMI	Catastrophic failure mode indicator (%)
σ	Crush stress(kN/mm^2)
Wt	Total work is done (kJ)
s	Instantaneous deformation(mm)
Es	Specific energy absorption (kJ/kg)
EN	Normalised specific energy absorbed
Ev	Volumetric energy absorbed
ε	Crush strain

CHAPTER 1

INTRODUCTION

Protecting the passengers from road accidents is a complex and comprehensive task. If critical transportation structures (automobiles, aeroplanes, etc.,) are suffered a sudden accident, to avoid the main concerns are with the optimal design and selection of suitable materials to meet the required purpose. The thin-walled tube is geometrically superior for energy absorption capacity. There are some of factors have direct effects on specific energy absorption such as shapes, triggering, fiber orientations, fiber types and material hybridization.

Crashworthiness in the present times is one of the important factors in the area of designing the transportation means such as automobiles, railroad vehicles and aeroplanes industries because it relates to vehicle structural ability to absorb the crashes energy resulted from collision/crushing as in the case of vehicles or airplanes components in the event of crash or collision. Frequently, the parameter of crashworthiness is expressed in term of Specific Energy Absorption (SEA) and defined as the energy absorbed per unit mass of the material. The automotive industry has started to focus on increasing energy saving, through different and/or more efficient on-drive systems, as well as the lightweight construction of vehicles. The composite materials have good advantages and suitable for the automotive industry .Composites materials have been proven to meet customer requirements for safe vehicles with low fuel consumption, low weight and are well suited to meet the design requirements of automotive manufacturers. Generally, composite materials are comprised of two type's materials or more. For example, fiber Reinforced Polymer (FRP) consist of polymer which is called matrix and the other material is called reinforcement. The fiber provides the strength and stiffness while the matrix acts as mediator and interface to transfer the load between the fibers. Usually, the fibers are developed from carbon / aramid or glass substances and the reinforcement are made of matrix. Despite that composite material demonstrated to be of excellent mechanical properties but them may cause environmental pollution due to non-degradability [1, 2]. As a consequence, more metals parts will be replaced by composite one for weight saving and increased reliability. However, the challenge is to find a suitable polymeric composite material with specific features for a suitable structural application.

The high efficiency of an impact energy absorber device may be defined as its ability to decelerate smoothly the occupant compartment to the rest within the allowable limit of 20g [3]. However, optimum energy absorbed management from practical collapsible energy absorber device is characterised by having a very small elastic energy and the area under its load-displacement curve is representing by rectangular with long sides (i.e. a constant load). It is evident for all practical collapsible energy absorber devices that initially their resistance response records very high load till reach its full capacity after which definitely different degrees of unstable response takes place [4]. Due to the design of energy absorber device suitable for vehicle protection, one can define the desirable energy absorber device as the one with suppressed energy absorption during the elastic or pre-initial crush failure stage not to exceed the safe allowable limits. Moreover, its post crush stage should have a very stable response during the post crush stage. In such design and for gross deformation, the overall stability of the energy absorber device is important as well as its energy absorbing capability and load carrying capacity. In order, to satisfy the crashworthiness design, a total system approach which includes a strong protective shell to protect the occupants from crushing as well as energy-absorbing components to minimize the severity of injuries. It is important to demonstrate that in replacing metals by composite materials in crashworthiness structures, the capability to absorb energy and to maintain post-crash integrity is not compromised. It is well known that any type of failure modes brings about euler buckling results in global instability which is an inefficient energy absorption mechanism and should be avoided in the design of energy absorption systems. Additionally, local buckling, bending failure and delamination modes play a vital role in energy absorption [5]. This instability is one of the more critical problems in using fibre composites for crash energy device and can be caused by many factors. Many researchers have studied the effect of crushing behaviour on energy absorption capability [6, 7]. Ataollahi et al [8] stated that the initial crush failure load was found to have a significant effect on the behaviour of specific energy absorption-deformation relationship during the entire post-crush process. They found that the peak load value is a nonlinear function of the thickness (t) of the inner diameter of the silk / epoxy composite square tubes. Results showed when the peak load decrease due the tube length increase. The energy absorption capability is reverse proportional to the high magnitude of initial crush failure load. In that manner, should be attention must be paid to the geometry, shape and materials used to avoid the euler-buckling failure mechanism, suppress the elastic energy and improve the crashworthiness parameters.

Approaches based on materials properties are categorised into two groups. The first is to fill the core of empty tubes with crushable medium (i.e. synthesised filler and natural filler). It has extensively been shown that filled tubes achieved high and stable load-displacement behaviour along the gross deformation with moderate specific energy absorption compared with the empty composite tubes [9, 10]. The second is to hybridise It has extensively been shown that hybridise tubes achieved high energy absorb ability and stable load-displacement behaviour. Ismail et al. [11], investigated of hybridized aluminium tubes with kenaf yarn composites and crushed quasi-statically. It is found that specific energy absorption performances increased when the numbers of layers are increased, but it is significantly not affected the energy absorption performances also the fiber orientations seemed not effect on the force ratios because the results showed force ratios are slightly decreased when the fiber orientations increased.

The use of composite circular tubes in structural and semi-structure applications is becoming more widespread throughout the automotive, aircraft and space vehicles. The simplest of all shell geometries is that of the circular shell. Elliptical tubes are circular tube with (a) and (b) radii a represents semi major radius along x-axis while b represents semi minor radius along y-axis. Elliptical shells are also belonging to shells of revolution with zero curvature these shells are developable. It can be development of the structural component by changing some parameters such as length, thickness and a/b ratio, etc. previous works which were found the first theoretical study on non-circular shells by Marguerre [12], Kempner, Chen and Feinstein et al. [13-15] investigated extensively the buckling and post buckling behaviour of oval cylindrical shells under compression. From these studies, can conclude that members with high a/b values (where a and b are the major and minor axis widths) are much less sensitive to imperfections and the ultimate load may even be greater than the buckling load, a sentence that was in sharp contrast with the significant imperfection sensitivity of circular cylindrical shells. Based on this inconsistency, Hutchinson et al. [16] investigated the buckling and post-buckling behaviour of oval cylindrical shells and concluded that these members are imperfection-sensitive like circular shells but the buckling phenomenon is not catastrophic like in circular shells.

On the above and not found previous experimental work has been made in the literature to study the crushing behaviour of composite elliptical tubes are used natural fibers in their composition. For this reason, this study focused on this shape of shells. The aim of this study is to examine the behaviour of the composite elliptical tubes with different effects which vertex angle, holes, wooden sticks and fibre content, in the absorbing energy of kenaf/epoxy elliptical tubes energy absorber.

1.1 Significance of Study

1. The findings from the current study are expected to enrich the knowledge in developing and improve the understanding of the behaviour of energy absorber devices.
2. This study could be considered as a first step in bridging the gap in the complicated geometry of elliptical tubes.
3. This study also proposes to use the wood sticks as supporting inside the tube wall.
4. Kenaf fibres was used as reinforcements to fabricate elliptical composite tubes. Due to its low cost and environmentally friendly, biodegradability, compared to the glass and carbon fibres problem statements.
5. In terms of waste, this study has explored a new potential application of wool wastes as novel reinforcement for polymer composite.
6. The successful development of natural fibres such as kenaf and wool would provide opportunities to improve the energy absorption capability.

1.2 Scope of Research

In this study, the kenaf fiber with the thickness of 3.5-4 mm were supplied by Tazdiq Enterprise, Malaysia. The kenaf originally comes in mat form and the used polymeric matrix is the epoxy resin, before the curing process, it was a viscous liquid material formed of two parts. The first part is the liquid epoxy resin D.E.R. ™ 331 ™ and the second one is the Joint Mine 950-3S as Hardener/curing. This work is limited to experimental study to potential of using kenaf (mat) fibre reinforced elliptical composite tubes in automobile industrial to improving the energy absorption capability and crushing behaviour. The wet winding process was used to fabricate the composite elliptical conical tubes by hand lay-up process using a hand-machine. A 30-70 % ratio of hardener to epoxy resin was used for the matrix in the present study. For the fabrication of the specimen's composites, a mandrels was prepared with the required dimension of the specimens composites and the kenaf fiber must be a processed to find the different tubes specimens. A total of fifty seven elliptical tube specimens including both forty eight specimens of kenaf and nine specimens of wool composite tubes are tested to investigate the axial compressive behaviour. Then, the axial crushing tests are carried out to these specimens' composites with some effects. In order to achieve the objective, the scopes was to make a feasibility study on considered for composite elliptical tubes. To considered properties of crashworthiness composite elliptical tubes in this work to peak load (Pi), average compressive load (Pm), initial failure indicator (IFI), crush force efficiency (CFE), and the absorbed crash energy (E), are presented. Briefly, this study limited to investigate the effect vertex angles, the effect wooden sticks, the effect fibre type and the effect fibre content on the crushing behaviour, failure modes and energy absorption.

1.3 Problem Statements

Protecting the passengers from road accidents is a complex and comprehensive task. If critical transportation structures (automobiles, aeroplanes, etc.,) are suffered a sudden accident, to avoid the main concerns are with the optimal design and selection of suitable materials to meet the required purpose. Many issues are related to the bodies of the car, such as the use of metal that leads to car body corrosion points, in order to get better design. Automobile and airplanes are designed to absorb energy for passenger safety.

This study is focused to investigating the effects of structural geometry of crushing behaviour, failure mode and energy absorption of composite elliptical tubes. These structural elements can offer greater structural efficiency than circular hollow sections when subjected to bending or combined loading, or when used as columns with intermediate restraint about the weaker axis, since they possess different major and minor axis flexural properties [17]. Price and Hull [18] performed an experimental study on the glass fibre–polyester (GFRP) composite cones. It was noticed that the composite cones with wall thickness more than 2 mm were failed by progressive crushing. They found that the specific energy absorption and absorbed energy of specimen increase with the increase in wall thickness and diameter of the composite specimens but decrease with the increase semi apical angle of the cone. It is concluded from experimental studies that the ratio of these composite elliptical tubes significantly affects energy absorption capability. Some researchers [19, 20] conducted experiments on energy absorption of composite tubes both circular and square cross sections. It was concluded that geometrical shape significantly influences the energy absorption capability of composite structures. Previous studies show that geometrical shape significantly influences the energy absorption capability of composite structures. Based on the mentioned works, it would appear that no previous investigation has been made in the literature to study the crushing behavior of thin-walled elliptical tubes. Studies on energy absorption capability as well as the load carrying capacity of thin-walled elliptical tubes and cones are however still scarce.

The current study used supporting wooden sticks inside elliptical tubes wall for the following reasons. The main purpose was to improve the energy absorbing. Also, the availability of materials is one of the necessary things for the continuity of production. In other word, researching on alternatives is important to find natural materials and available can be obtained continuously for the continuity of production. For this reason, this study focused to find a new material which is wool waste, not suitable for use in the carpet industry and fabric industry to possibility using in composite materials and to benefit from waste and environment protection.

1.4 Objectives of research

The principle aim of this study is to understand and addition a new hollow section is elliptical tubes to tubular family as energy absorber devices, also presents the quasi-static crushing performance for these tubes. Accordingly, the specific objectives this study can be summarized as follows:

1. To investigate the effect of cone vertex angles on the crushing behaviour of composite elliptical cones.
2. To examine the influence of holes on the perimeter on the energy absorption capability and load-carrying capacity of composite elliptical tubes.
3. To determine the effect of supporting wooden sticks on the crashworthiness parameters and crushing behaviour of composite elliptical tubes.
4. To find out the best value of fibre content with variable side fibre type that effect on the crashworthiness parameters and the failure modes of kenaf/wool reinforced elliptical composite tubes.

1.5 Thesis Outline

This thesis is divided into nine chapters. Following this chapter, Chapter 2 presents a review of literature that related to composite materials and energy absorption. Chapter 3 presents the methodology of this research. Publications are distributed in each chapter (4-7) separately following this chapters, results and discussed are presented in chapter 8 then conclusions and recommendations for further work are presented in cchapter 9.

Chapter 1

This chapter presents a background on the subject of this research, problem statements, scope of the study, thesis outline and the objectives of the research.

Chapter 2

Chapter 2 presents a review of literature that related to composite material, the achievements made so far in the area of natural fibres reinforced composites, mechanical properties, crushing process, crashworthiness properties, energy absorption and failure modes characteristics of the composite material.

Chapter 3

Chapter 3 dedicated to the methodology and the experimental work of this research.

Chapter 4

Chapter 4 entitled "Vertex angles effects in the Energy Absorption of Axially Crushed Kenaf Fibre-Epoxy Reinforced Composite Elliptical Tube". The work experimentally focused on the vertex angle's effects on energy absorption capability; the vertex angles vary from 0 to 24° in 6 increments.

Chapter 5

Chapter 5 entitled "Energy absorption capacities of kenaf fibre-reinforced epoxy composite elliptical tube with circumferential holes". A series of experiments carried out for composite elliptical tubes with the different circumferential perforations (0, 4, 6 and 8 holes). This range is good for obtaining the adjusted distance to achieve the second objective of the thesis. The crashworthiness of the tubes was evaluated by analysis of the specific energy absorption in quasi-static axial crushing.

Chapter 6

Chapter 6 entitled "Crushing behaviour of kenaf fibre/ wooden stick reinforced epoxy hybrid 'green' composite elliptical tubes". In this chapter of the research considered various wooden sticks number were considered experimentally work to study the effects of them on the energy absorption and load carrying capacity. For each of the tests, three samples were replicated.

Chapter 7

Chapter 7 entitled "Quasi-static Crushing Behaviour of Environmentally Friendly Kenaf/Wool Epoxy Composites Elliptical Tubes". Studies an experimentally the effect of the fibre content and fibre type on the crashworthiness parameters and the failure modes of non-woven kenaf fibre and woven wool fibre reinforced composite elliptical tubes. Various fibre contents were considered, including 30%, 35% and 40%.

Chapter 8

Chapter 8 dedicated to the results and discuses.

Chapter 9

Finally, the overall conclusions for various articles to this research and recommendations for further study are given in chapter 9.

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BIODATA OF STUDENT

Mohamed Mohamed Al-kateb, was born on 2nd February1963, Tajura, Libya. He received his degree in Industrial Technology from the Higher Institute for Industrial Technology (Department of Mechanical Engineering), Tripoli, Libya. He obtained his Master in 2004 from Mechanical and Manufacturing Engineering Department, Faculty of Engineering, Universiti Putra Malaysia. Alkateb was a Teaching Assistant in the Higher Institute for Industrial Technology (Department of Mechanical Engineering), Tripoli, Libya from 1995 to 2004. He was a lecturer from 2004 to 2014. He was appointed general supervisor for final projects from 2005 to 2007. He became the head of the specialized diploma department from 2008 to 2012. He also appointed as head of mechanical engineering department until 2014. Alkateb was supervisor for 16 final projects. He was an assistant supervisor more than 10 final projects. He has several international publication and conference regarding the Mechanical Engineering field.

LIST OF PUBLICATIONS

Mohamed Alkateb, S.M. Sapuan, Z. Leman, Mohammad Jawaid and M. R. Ishak. Postgraduate Symposium on Compsites Science and Technology and 5th Postgraduate Siminar on Natural Fibre Composites 2015, UPM Serdang.

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