UNIVERSITI PUTRA MALAYSIA

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By

MUNIR FARAJ ALMABROUK ALKBIR

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

June 2016

DEDICATION

This thesis is gratefully dedicated to:

My beloved Mother and Father for unlimited supports and encouragements throughout my life

The soul of my sister (Halema)

My wife for her patience and understanding

My supervision committee for their support

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

CRUSHING BEHAVIOR AND FAILURE MODES OF KENAF FIBRE-REINFORCED COMPOSITE HEXAGONAL TUBES

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

This research focused on the crashworthiness characteristics of kenaf fibre reinforced composite hexagonal tubes with a variety of configurations. A series of experiments were carried out for composite hexagonal tubes with a different dimension. A hand lay-up technique was used to fabricate the specimens of composite hexagonal tubes Four phases were performed for crushing behaviour, failure mode and crashworthiness parameters of hexagonal composite tubes.The first phase was to study the effect of fibre content on the crashworthiness parameters (i.e, energy absorption and stroke efficiency) and the failure modes of a non-woven kenaf (mat) fibre-reinforced hexagonal composite tube. Various fibre contents were considered, including 25%, 30%, 35% and 40%. A fibre content of 25% to 30% (mass percent) demonstrated the best crashworthiness parameters. A high percentage of fibre loading 40% and more, due to poor bonding between the fibre and matrix, was not capable of transferring load to another, and hence stress was accumulated at certain points of the composite, which led to lower energy absorption mechanical properties. The reinforcing fibers are strong, stiff and effective for improving the mechanical properties of composite materials. However, reinforcing fibres are often brittle and abrasive, lack toughness, and can degrade chemically when exposed to the environment. A few distinct failure modes were identified during the experiments, including the progressive failure mode, in which failure begins at the top end of the tube, and the transverse crack failure mode, which is associated with the buckling failure mode. Phase two was devoted to study the static crushing behaviour of composite hexagonal tubes under uniform axial load. Three lengths of hexagonal composite tubes were tested 50, 100, and 150 mm with same hexagonal angle 45°. Results showed that tube with length 50 mm exhibits a high specific energy absorption as well as higher average crushing load. Phase three involved fabrication and testing of five different hexagonal tubes of reinforced natural kenaf (mat) with different angles from a range of 40^{o} to 60^{o} and in 5^{o} increments of the angle, to determine the effect of geometry on crashworthiness parameters of natural kenaf fibre reinforced composite hexagonal tubes. Results obtained in this phase show that the structures failed in a few distinct failure modes such as progressive failure mode and

fragmentation failure associated with longitudinal cracks. The composite tube with β= 60º exhibited a local buckling failure mode and displayed the highest specific energy absorption capability equal to 9.2 kJ/Kg. On the other hand, the new crashworthiness parameter was introduced as a catastrophic failure mode indicator (CFMI),the last phase was when the specimens were subjected to a lateral quasi-static compressive load. In this phase, the supporting plate was used inside the tube for the following reasons. The main purpose was to improve the energy absorbed by the tubes. The improvements, including the use of energy absorbing materials and structures in the plate inside the tubes, ensure more favourable decelerations during a crash/accident, resulting in fewer injuries to the car occupants. Furthermore, using a supporting plate inside the hexagonal tubes can control the load distribution during the crushing period and can diminish the structure weight. Three configurations of β=40º, β=50º and β=60º of natural non-woven kenaf (mat)/epoxy were laminated. The effects of the hexagonal angles, supporting plate inside the tubes, and failure modes were studied by a lateral compression test. The crashworthiness of the tubes was evaluated by an analysis of the specific energy absorption in quasi-static lateral compression. Specific energy absorption was obtained from the load-displacement curve during testing. The failure mode of the tubes was analysed from high resolution photographs. Overall, the tube with β=40º had the best crashworthiness among the tubes. Above all, the results showed that the tubes with supporting plates showed better specific energy absorption (SEA) for all tested specimens and exhibited approximately 69% better crashworthiness than the non-supporting ones. The results also demonstrated that all specimens failed by the longitudinal failure mode.

Abstrack tesis yang dikemukakan kepada senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazh Doktor Falsafah

KELAKUAN PENGHANCURAN DAN MOD KEGAGALAN BAGI TIUB KOMPOSIT HEKSAGON DIPERKUAT GENTIAN KENAF

Oleh

MUNIR FARAJ ALMABROUK ALKBIR

Jun 2016

Pengerusi : Mohd Sapuan Salit, PhD, PEng
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Penyelidikan ini memfokuskan kepada ciri-ciri pelindungan laga bagi tiub heksagon komposit diperkuat gentian kenaf dengan pelbagai konfigurasi. Satu siri eksperimen telah dijalankan bagi tiub heksagon komposit dengan dimensi yang berbeza. Kaedah bengkalai tangan telah digunakan untuk membikin specimen tiub heksagon komposit. Empat fasa telah dilaksanakan bagi kelakuan penghancuran, mod kegagalan dan parameter pelindungan laga bagi tiub komposit heksagon.Fasa pertama adalah mengkaji kesan kandungan gentian terhadap parameter pelindungan laga (iaitu penyerapan tenaga dan keberkesanan lejang) dan mod kegagalan bagi tiub komposit heksagon diperkuat gentian kenaf tidak tertenun (tikar). Pelbagai kandungan gentian telah dikaji, termasuk 25%, 30%, 35% dan 40%. Kandungan gentian sebanyak 25% ke 30% (peratus jisim) menunjukkan parameter pelindungan laga yang terbaik. Peratusan yang tinggi bagi bebanan gentian 40% atau lebih, disebabkan ikatan yang lemah antara gentian dan matriks, tidak mampu untuk memindahkan beban ke bahagian lain, dan seterusnya tegasan telah terkumpul pada tempat yang tertentu pada komposit, yang menjurus kepada sifat mekanikal penyerapan tenaga yang lebih rendah.Gentian penguat adalah kuat, kukuh dan efektif bagi meningkatkan sifat mekanikal bahan komposit. Walau bagaimana pun, gentian penguat selalunya rapuh dan berlelas, kurang liat, dan boleh merosot secara kimia bila didedahkan kepada persekitaran.Beberapa mod kegagalan berlainan telah dikenal pasti semasa eksperimen, termasuk mod kegagalan progresif, di mana kegagalan bermula pada bahagian hujung atas tiub, dan mod kegagalan rekahan melintang, iaitu yang berkaitan dengan mod kegagalan melengkok. Fasa kedua diuntukkan bagi mengkaji kelakuan penghancuran static bagi tiub komposit heksagon di bawah beban paksian seragam. Tiga kepanjangan bagi tiub komposit heksagon telah diuji 50, 100 dan 150 mm dengan sudut heksagon yang sama 45°. Keputusan menunjukkan bahawa tiub dengan kepanjangan 50 mm menunjukkan penyerapan tenaga spesifik yang tinggi dan juga purata beban penghancuran yang lebih tinggi.Fasa ketiga melibatkan pembikinan dan pengujian bagi lima tiub heksagon yang berbeza bagi gentian kenaf (tikar) dengan sudut yang berbeza daripada julat 40^o ke 60^o dan dalam 5^o kenaikan sudut, bagi menentukan kesan geometri ke atas parameter pelindungan laga bagi tiub heksagon

komposit diperkuat gentian kenaf. Keputusan yang diperolehi dalam fasa ini menunjukkan bahawa struktur gagal dalam beberapa mod kegagalan yang berlainan seperti mod kegagalan progresif dan kegagalan pencebisan yang berkaitan dengan rekahan membujur. Tiub komposit dengan $\beta = 60^o$ mempamerkan mod kegagalan melengkok setempat dan mempamerkan keupayaan penyerapan tenaga spesifik yang tertinggi bersamaan 9.2 kJ/kg. Sebaliknya, parameter pelindungan lagi yang baharu telah diperkenalkan sebagai penunjuk mod kegagalan bencana.Fasa terakhir adalah apabila spesimen dibebankan dengan beban mampatan kuasi-statik sisi. Dalam fasa ini, plat penyokongan telah digunakan di dalam tiub atas alasan berikut. Tujuan utama adalah bagi meningkatkan tenaga yang diserap oleh tiub. Peningkatan termasuk penggunaan bahan penyerapan tenaga dalam bahan dan struktur pada plat di dalam tiub bagi memastikan nyahpecutan yang lebih diingini ketika pelanggaran/kemalangan, menghasil lebih sedikit kecederaan kepada penumpang dan pemandu kereta. Tambahan pula, menggunakan plat di dalam tiub heksagon boleh mengawal agihan beban sewaktu penghancuran dan boleh mengurangkan berat struktur. Tiga tatarajah $\beta=40^o$, $\beta=50^o$ dan $\beta=60^o$ bagi epoksi/kenaf tidak tertenun telah telah dilaminat. Kesan sudut heksagon, plat penyokonan di dalam tiub, dan mod kegagalan telah dikaji menggunakan ujian mampatan sisi. Pelindungan laga tiub telah dinilai menggunakan analysis penyerapan tenaga spesifik dalam mampatan sisi kuasi-statik. Penyerapan tenaga specifik telah diperolehi daripada lengkok beban-sesaran ketika pengujian. Mod kegagalan bagi tiub telah dianalisis menggunakan fotograf resolusi tinggi. Secara keseluruhan, tiub dengan $\beta=40^o$ menunjukkan pelindungan laga yang terbaik antara semua tuib. Pada umumnya, keputusan menunjukkan bahawa tiub dengan plat penyokongan menunjukkan penyerapan tenaga spesifik yang lebih baik bagi kesemua specimen yang diuji dan mempamerkan kira-kira 69% pelindungan laga yang lebih baik daripada suatu yang tanpa penyokongan. Keputusan juga menunjukkan bahawa semua specimen gagal dengan mod kegagalan membujur.

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I certify that a Thesis Examination Committee has met on 9 June 2016 to conduct the final examination of Munir Faraj Almabrauk on his thesis entitled "Crushing Behavior and Failure Modes of Kenaf Fibre-Reinforced Composite Hexagonal Tubes" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of 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:

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Declaration by graduate student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- The research conducted and the writing of this thesis was under our supervision;
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LIST OF ABBREVIATIONS

β	Hexagonal angle (°)
SEA	Specific energy absorption (J/Kg)
S.H.T.β	Hexagonal tube with a supporting plate
E.H.T.β	An empty hexagonal tube
Pi	Peak load kN
TRI	Tube resistant indicator
$\boldsymbol{m}$	The specimen mass kg
S and Si	Crushing distances (mm)
CFE	Crush Force Efficiency (–)
E_S	Specific energy absorption (J/g)
IFI	Initial failure indicator
M	Weight of the specimens (kg)
CFMI	Catastrophic failure mode indictor (%)
P_{cr}	Critical crushing load (kN)
NFR	Natural fiber reinforcement
Pm	Mean crash load kN
(E_t):	Total energy absorbed kJ
S_E	Stroke efficiency %

CHAPTER 1

INTRODUCTION

1.1 Background

Fibre reinforced polymers (FRP) are composite materials comprised of a polymer matrix combined with high-strength fibres such as glass, aramid and carbon. Although these composite materials exhibit excellent mechanical properties, they also give rise to environmental pollution due to their non-degradability [1, 2]. Currently, traditional reinforcement materials such as glass and carbon fibres are increasingly being replaced by advanced composite materials, e.g, natural fibre-reinforced polymers (NFRP). It is expected that use of fibre/polymer composites will expand in the near future due to the many advantages offered by these materials such as high strength, low weight and corrosion resistance [3].

Several natural fibres such as hemp, flax, sisal, kenaf, and jute have been used in different industrial applications. Recently, natural fibres have drawn the interest of researchers, engineers and scientists as substitute reinforcements for fibre reinforced polymer (FRP) composites tubes. Due to their fairly good mechanical properties, low cost, high specific strength, environmentally-friendly and bio-degradability, ease of fabrication, and good structural rigidity, these materials can be used in an extensive range of applications, including aerospace and the automotive industry. Previous studies focused on how to introduce the natural fibres into industrial applications and the replacement of synthetic fibres with natural fibre materials. The tensile properties of natural fibre reinforce polymers are mainly influenced by Mechanical properties such as tensile properties, flexural properties, and impact strength is strongly affected by fiber content.

In particular, crashworthiness has attracted much attention, especially for the evaluation of crushing behavior and the energy absorbing capability of various composite shapes. In automotive engineering, crashworthiness is defined as the capability of a vehicle to protect its occupants and passengers from serious injury and harm or death in case of accidents or sudden impacts of a specified magnitude. Crashworthiness is related to energy absorption through controlled failure modes that enable the maintenance of a gradual decay in the load profile during energy absorption [4, 5].

Studies of natural fibre-reinforced plastic (NFRP) have been carried out for special geometric shapes of composite tubes that are mainly intended for automobile crashworthy applications due to their favourable strength, weight and corrosion resistance [6-9].Several researchers reported that a well-designed NFRP composite can exhibit better energy absorption than metals; natural composite materials such as kenaf, silk and hemp fibre-reinforced composite tubes subjected to axial crushing will undergo a fracture to obtain energy absorption rather than the fibre deformation exhibited in metal

tubing [10-12]. As reported previously [13], delamination, local buckling, and bending failure modes make the largest contributions to energy absorption.

In recent eras, most studies globally wide were concerned with the difference methods of incorporating natural fibres, such as hemp, flax, kenaf or bagasse into various types of polymer compositions, in order to modify their properties and to decrease their costs and increasing environmental concern and requirement for developing sustainable materials in engineering application [14-17]. Commonly, the method of processing produce the composite structure for both of fibres were Filament winding process, Hand Lay-up Process followed by curing stage to gain the final product to be ready for test [18-20]. The synthetic fibre used as a fibre part not only for increased tensile strength, the flexural rigidity and crashworthiness properties of the final product, however additionally, helped to ligament the natural fibres together and aided to mold for desired final shape [21, 22].

1.2 Significance of study

1. Several reasons, including weight saving, low density, corrosion resistance, availability, being renewable, environmentally friendly and ease of handling make natural fibers superiors to syntheses fibers in the automobile manufacturing sector.
2. Kenaf fibre was used as reinforcement due to fabricate hexagonal campsite tubes. Due to its low cost, high specific strength, environmentally-friendly and bio-degradability, ease of fabrication, and good structural rigidity, these materials can be used in an extensive range of applications, including aerospace and the automotive industry.
3. Kenaf Natural fibre composites-epoxy, are particularly attractive in automotive applications because of lower cost and lower density. Compared to the Glass fibres and carbon fibres Problem Statements
4. Catastrophic failure modes in composite structure cause less energy absorption capability and instability in failure.
5. The successful development of natural fibres such as kenaf (mat) and yarn would provide opportunities to improve the energy absorption capability and crushing behavior of automobile accidents.
6. The findings from the current study are expected to enhance the knowledge in developing high performance of the industrial sector.

1.3 Scope of study

In this work, The kenaf yarn and (mat) fibres were supplied by (IPSB) Innovative Pultrusion Sdn.Bhd., Seremban, Malaysia. The kenaf (mat) originally comes in a mat

form. This research is limited to experiments to study the potential of using kenaf natural fibres reinforced hexagonal composite tubes. In the industrial application.

In this study, the fabrication process involved The wet wrapping process by hand lay-up was used to fabricate the specimens of non-woven kenaf fibre/epoxy composite hexagonal tubes.

Before fabricate the specimens composite, the kenaf fibre must be processed first to find the different size of kenaf fibre. Then, the axial and lateral tests are carried out on this composite. The microstructure of this composite will be observed by using the Scanning Electron Microscope (SEM). In order to achieve the objective, the scope of research was to make a feasibility study on fibre contents for fibre reinforced hexagonal composite tube, fibre loading is used with value of 20% to 40% to get the best composition for the composite. To considered properties of crashworthiness hexagonal composite tubes in this study to Initial peak Load (Pi), Mean-Crushing Load (Pm), Crush Force Efficiency (CFE), Initial Failure Indictor (IFI) and Specific Energy Absorption (Es).At this stage, two new parameters of crashworthiness were introduced from compression test the first one is indicated for the catastrophic failure mode. It presents a criterion for determining withers the tubes crash in catastrophic or otherwise and Tube resistant indicator (TRI), The tube resistant indicator can be defined as the peak load value per average load value. To protect passengers from shock loads, the tube resistant indicator should be kept in unity. Finally, This work limited to investigate few effects of crushing behavioer and failure modes of composite hexagonal tubes such as, the effect of fibre content, effect of length, The effect of geometry, effect of the fibre reinforcement type.

1.4 Problem Statements

Many issues are associated with car bodies, such as using a metal, which leads to a corrosion point in the car body, to obtain better design. Roads and airplanes are designed to absorb crushing energy for passenger safety. This research is allocated to investigate the effect of structural geometry of crushing behavior, failure mechanism, and failure mode and energy absorption capability.

Failure of a structure component defined as the. Inability of the component to carry load. Generally, failure occurs when a component of the structure has no more ability to carry the load, in other words, when the component is no longer capable of satisfactory fulfilling its service function either because of fractures, excessive deformation, deterioration, or any other mechanisms of failure. When failure occurs, it causes a permanent deformation, load redistribution within the structure, and may cause large reductions in laminate stiffness and strength and any of these or all together cause the damage to grow. Some studies have used a filler tube to absorb the energy, but the weight of such tubes is too high. Natural and synthetic fibers are known for its low density, easier fabrication than metallic, and their structural rigidity are high, and can be used for wide applications, such as. Aerospace applications and automotive industry sector. Owing to this, in depth studies had been conducted to evaluate its failure modes and

process of fabrication for axial and lateral crushing behavior to replace metallic materials. In this thesis, Failure modes and geometrical designs such as shapes, triggering, geometry and effect have been studied where these factors affected on crashworthiness parameters

Furthermore, the current work used a supporting plate inside hexagonal tubes for the following reasons. The main purpose was to improve of the energy absorbed by tubes. The improvements, including the use on energy absorbing materials and structures in the plate inside the tubes, ensure more favorable decelerations during a crash/accident, resulting in fewer injuries for the car occupants. Furthermore, using the supporting plate inside hexagonal tubes can control the load distribution during the crushing period and can diminish the structure weight.

1.5 Objectives

The objective of this research work to

- To find out the best value of fibre content that effect on the crashworthiness parameters and the failure modes of non-woven kenaf fibre (mat) reinforced hexagonal composite tubes.
- To examine the influence of response of hexagonal light to quasi-static axial compressive load of non-woven kenaf fibre/epoxy hexagonal composite tubes.
- To investigate the effect of geometry on energy absorption capability and load-carrying capacity of natural kenaf fibre reinforced composite hexagonal tubes.
- To determine the effect of supporting plates inside the hexagonal tubes with variable side hexagonal angles in terms of the improvement of crashworthiness.
- To investigate experimentally the effect of hexagonal angles on the failure modes and specific energy absorption capability of hexagonal composite tubes.

To achieve these objectives, the following tools were either designed, fabricated or conducted:

1. Design and fabrication of novel mandrels with different Hexagonal angles.
2. Renovate a filament winding machine.
3. Fabrication of hexagonal composite specimens with different tube lengths and differenthexagonal angles.
4. Conduct quasi static (axial and lateral) crushing tests.
5. Conduct microscopic investigation to characterize the failure modes.

1.6 Thesis Outline

The layout of this thesis is in accordance with Universiti Putra Malaysia alternative thesis format based on publications, in which each research chapter (3 – 9) represent a separate

study that has its own introduction, Materials and methods, Results and discussion, and Conclusion. The details of the thesis structure are presented beneath.

Chapter 1

The problems and the research objectives were clearly highlighted in this chapter. In addition, the significant contribution and scope of this study were also elucidated within the chapter1.

Chapter 2

Literature review,which presents an overview of the developments made in the area of natural fibres reinforced composites, in terms of their physical and mechanical properties, and crashworthiness properties and Failure modes.

Chapter 3

The methodologies by which the current work was approached are in the details in this chapter . Uncertainties affecting the experimental results such as, Void content, Calibration of the testing machine, Reading error and Maxing up the mixture and adhesion between layers were discussed in this chapter.

Chapter 4

This chapter presents the article entitled. The effect of fibre content on the crashworthiness parameters of natural kenaf fibre-reinforced hexagonal composite tubes.Studies an experimentally the effect of the fibre content on the crashworthiness parameters and the failure modes of non-woven kenaf fibre (mat) reinforced hexagonal composite tubes. Various fibre contents were considered, including 25%, 30%, 35% and 40%.

Chapter 5

Presents the behavior of composite hexagonal tubes under constant axial load, article two entitled Experimental quasi – static axial crushing of non-woven kenaf fibre/epoxy hexagonal composite tubes .Three lengths of hexagonal composite tubes were tested 50, 100, and 150 mm. It also addresses experimentally the effect of length on energy absorption capability and load - carrying capacity of non-woven kenaf /epoxy wrapped hexagonal composite tubes under quasi-static axial compressive load.

Chapter 6

This chapter presents the third objective with article four entitled. Effect of geometry on crashworthiness parameters of natural fibre reinforced hexagonal tubes The Inclusive experimental work implements to study the response of non-woven kenaf fibre/epoxy composite hexagonal tubes to quasi-static axial compressive load. A series of experiments carried out for composite hexagonal tubes with different angles from a range of 40°– 60° in 5° steps. This range is suitable for obtaining a regular hexagonal shape.

Chapter 7 and 8

In this chapter, two articles entitled.Lateral crushing properties of non-woven kenaf (mat) –reinforced epoxy composite hexagonal tubes and Quasi-static lateral crushing of non-wovn kenaf fibre reinfored composite Hexagonal tube .

Three configurations of $\beta=40^{o}$, $\beta=50^{o}$ and $\beta=60^{o}$ of natural non-woven kenaf (mat) /epoxy laminate. The effects of hexagonal angles, supporting plate inside the tubes, and failure modes, were studied by a lateral compression test. The crashworthiness of the tubes was evaluated by analysis of the specific energy absorption in quasi-static lateral compression. Specific energy absorption was obtained from the load–displacement curve during testing. The failure mode of the tubes was analyzed from high resolution photographs.

Chapter 9

Finally, the overall conclusions of the various research articles as well as relevant suggestions for future research were presented in this chapter.

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2.10 Conclusion

From the previous literature review, the following can be concluded:

- Many research works are administrated on thin walled synthetic composite shells and only a few studies carried out on natural fibre reinforced composite tubes as well as. Most of them have focused on investigation the effect of different parameters the geometry cross section area, loading conditions, length, thickness, diameter, etc, fibre orientation, composite constituents, laminate sequence, etc. on crushing behavior, crashworthiness parameters , and failure modes.
- Most of these studies and investigations are experimentally carried out where the Effect factors were studied by developing, creating a relation between load applied -displacement were done under axial and lateral compression test.
- The failure modes and crushing behavior in composite tubes depend on the type of material reinforced composite tubes and structure.

The manners in which composite materials absorb energy are a lot of complicated and wildly differ from the same conventional material structures. From a crashworthiness point of view, the problem with failure mode of structure is that when the failure happens the main of the load-carrying capacity is lost, resulting in catastrophic non-crashworthy failure, the instability behavior of composite structures under crushing load and their uncontrolled failure mode are some problems that need more attention. The instability should be avoided to maximize the energy absorption capability and load carrying capacity.

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4.10 Conclusion

In this study, the effects of different fibre contents on crashing modes and the energy absorbed by nonwoven kenaf (mat) composite hexagonal tubes were investigated under axial compression loads. It was shown that the resin outflow from a composite usually leads to an undesirable void content during the fabrication process, an irregular arrangement of fibres and uneven resin distribution. Various fibre contents, including 25%, 30%, 35% and 40% by mass, were axially compression tested using an the Instron 3382 system at a fixed speed of 15 m/min. Based on the test data, the following conclusions are possible :

1. The total amount of energy absorbed decreases as the fibre content increases. This is also the case for the stroke efficiency.
2. Axial crashing results in decreasing stroke efficiency, crash efficiency, tensile strain and mean crashing load as the fibre content increases.
3. A few distinct failure modes were identified during the experimental tests of the hexagonal composite tubes:
   - A progressive failure mode in which the failure starts at the top of the tube.
   - A transverse crack failure mode is associated with the buckling failure mode.
   - After the crash, the top or bottom end of the hexagonal tubes starts to break and is fragmented into small pieces.
4. Kenaf fibre content of 25% to 30% results in optimum values of the crashworthiness parameters.

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8.6 Conclusion

This work is a sequel to a series of previous works which published in material & design journal 2014 [3]. In demand to investigate experimentally the effect of hexagonal angles on the failure modes and specific energy absorption capability of the hexagonal composite tubes. The variety of hexagonal tubes with different angles were subjected to quasi-static lateral compression test load upon the results gained, the main conclusion are listed as follows:

1. The hexagonal tubes for lateral compression load have exhibited a slight difference of SEA

2. The formation of the fracture longitudinal failure mode was observed for all causes.

3. Composite hexagonal tube with β 40^{o} exhibited high energy absorption capability under in the lateral crushing.

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LIST OF PUBLICATIONS

As an outcome of this study several publication were published in peer reviewed journals and confereces/ Seminar as fllows

M.F.M. Alkbir, S. M. Sapuan, Nuraini A.A. And M. R. Ishak Quasi-Static lateral crushing of Non-Woven Kenaf fibre reinforced composite hexagonal tubes , Advanced material research – volume 1119 March 2015 , Scopus

M.F.M. Alkbir, S.M. Sapuan, A.A. Nuraini, M.R. Ishak, Effect of geometry on crashworthiness parameters of natural kenaf fibre reinforced composite hexagonal tubes, Materials & Design, vol. 60, pp. 85-93, August 2014 (Impact factor = 3.171) (Q1).

M.F.M. Alkbir, S. M. Sapuan, Nuraini A.A. And M. R. Ishak Quasi-Static lateral crushing of Non-Woven Kenaf fibre reinforced composite hexagonal tubes, Advanced material research – volume 1119 March 2015, Scopus.

M.F.M. Alkbir, S. M. Sapuan, Nuraini A.A. And M. R. Ishak Lateral Crushing Properties of Non –woven kenaf (mat) Reinforced Epoxy Composite Hexagonal tubes International Journal of Precision Engineering and Manufacturing, July 2016, Volume 17, Issue 7, pp 965–972 (Impact Factor 1.205) (Q 2)

M.F.M. Alkbir, S.M. Sapuan, A.A. Nuraini, M.R. Ishak The Effect of Fiber Content on the Crashworthiness Parameters of Natural Kenaf Fiber-Reinforced Hexagonal Composite Tubes, Journal of Engineered Fibers and Fabrics. Volume 11, Issue 1 – 2016) (Impact Factor 0.986) (Q 2).

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M.F.M. Alkbir, S.M. Sapuan, A.A. Nuraini, M.R. Ishak, Comparative Investigation on the Failure Modes of Natural Kenaf/Epoxy Reinforced Composite Hexagonal Tube Key Engineering Materials (Volume 709), September 2016 Page 7-10 (Impact factor = 0.39 (Q4)

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