EFFECTS OF WINDING ANGLE ON QUASI-STATIC AXIAL AND LATERAL CRUSHING BEHAVIOUR OF CARBON FIBRE-REINFORCED PLASTIC (CFRP) - FILAMENT WINDING HEXAGONAL TUBES

MOHD SUPIAN BIN ABU BAKAR

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ABSTRACT

This thesis presents the results of a quasi-static experiment of crushing behaviour for Carbon Fibre-Reinforced Polymer (CFRP) hexagonal tubes in axial and lateral compression loads, whereby the fabrication in a wet-filament winding technique provided a high geometrical accuracy, constant fabrication quality, and relatively high fibre volume fractions. Moreover, in order to improvise the crushing behaviour of energy absorption tube, the filament winding technique of fabrication was applied to provide the final progressive crushing that had withstand the collapsible tubes in one piece and was still intact at the final crushing phase without breaking apart into debris or fragments, which would increase the energy absorption value and the crushing performance of CFRP energy absorbing tube.

The behaviour of energy absorbing CFRP tube destruction was examined through experimental quasi-static axial and lateral compression loads to obtain the collapse and crushing modes for CFRP tube. Three hexagonal CFRP tubes from the winding orientation angles of 30°, 45°, and 80° were fabricated from the wet-filament winding technique to determine the local failure effects, which were also able to assess the pattern of destruction for CFRP hexagonal tube at every change of compression load value. Energy absorbed by CFRP hexagonal tube was recorded, while static image at each effect of compression loads reflected the behaviour of energy absorber tubes. There were three main phases in the experiment of quasi-static compression load:

1) The pre-crush phase where the tube was compressed below 30% of the original height of the tube, followed by a maximum compression load at a local peak load point;

2) The third phase was a post-crush phase, defined as compression at the height of the tube under 50%; and

3) The final phase was a compression load at the maximum displacement of 80% from the height of the tube.

The results of the experimental data showed the differences in behaviour of CFRP tubes in three winding orientations and the total amount of energy absorption at each orientation and collapse mode which occurred in quasi-static compression loads had been slightly similar for the three winding orientation tubes. The collapsible mode in the final crushing phase showed that the crushing tubes were still intact in their original forms without breaking into small or large fragments. Overall, the winding tube of 45° orientation for energy absorber tubes showed the best failure mode in the folding mechanism produced high values of energy absorbing in axial and lateral compression loads. Besides, the experimental test data obtained from this study were also expected to be used as references in advanced research related to such structures like honeycomb sandwich panels or energy-absorbing structures in the fields of automotive, aerospace, and many others.

ABSTRAK

Tesis ini membentangkan hasil eksperimen kuasi-statik dalam kelakuan kehancuran bagi tiub heksagon *Carbon Fiber-Reinforced Polymer* (CFRP) secara mampatan paksi dan sisi yang mana teknik fabrikasi iaitu *wet-filament winding* akan menyumbang kepada kejituan geometri yang lebih baik, mutu fabrikasi dan juga pecahan isipadu (*fiber volume fractions*) yang tinggi. Untuk menambah baik tingkah laku bagi menghancurkan tiub penyerap tenaga, teknik fabrikasi *filament winding* untuk tiub heksagon CFRP adalah bertujuan untuk menyediakan sifat dan kelakuan bagi tiub penyerapan tenaga yang akan dihancurkan secara progresif dan akan menjadi satu struktur yang renyuk dan utuh tanpa terpecah menjadi serpihan kecil dan besar seperti mana tiub penyerap tenaga FRP yang lain. Teknik fabrikasi yang sesuai juga akan mempengaruhi peningkatkan nilai penyerapan tenaga dan juga meningkatkan prestasi kehancuran bagi stuktur tiub penyerap tenaga FRP.

Kajian tingkah laku kehancuran tiub CFRP, dengan ekperimen kuasi-statik mampatan paksi dan sisi telah dijalankan untuk mendapatkan tindakbalas keruntuhan dan mod kehancuran bagi tiub CFRP. Tiga tiub hexagon CFRP yang dihasilkan dari sudut orientasi penggulungan iaitu 30°, 45° dan 80° adalah hasil daripada teknik fabrikasi *wet-filament winding* untuk mendapatkan kesan kegagalan setempat yang juga dapat menilai pola penghancuran tiub heksagon CFRP pada setiap perubahan anjakan tiub heksagon apabila tiub mengalami mampatan pada keadaan tertentu. Kapasiti tenaga yang telah diserap oleh tiub heksagon CFRP pula

akan direkod dan perubahan bagi setiap spesimen tiub dirakam dalam imej statik untuk menilai kesan daripada hasil mampatan ke atas tiub penyerap tenaga heksagon. Terdapat tiga fasa utama dalam ujikaji kuasi-statik iaitu

1) Fasa Pra-Kehancuran di mana tiub akan mampat di bawah 30% daripada jumlah ketinggian asal tiub, dan diikuti bersama dengan beban mampatan maksimum pada titik beban tertinggi;

2) Fasa Pasca-Kehancuran yang ditakrifkan di bawah 50% daripada ketinggian tiub; dan

3) Fasa akhir mampatan iaitu pada anjakan maksimum pada 80% daripada ketinggian tiub.

Hasil data eksperimen yang diperoleh telah menunjukkan perbezaan tingkah laku bagi tiub CFRP dalam tiga orientasi penggulungan yang menunjukkan jumlah nilai tenaga penyerapan oleh tiub heksagon CFRP yang berbeza bagi setiap orientasi dan keruntuhan tiub yang berlaku secara mampatan paksi adalah dalam mod lipatan secara keseluruhannya dan utuh dalam satu bentuk tanpa pecahan kepada serpihan kecil atau besar. Manakala hasil bagi mampatan sisi pada tiub heksagon CFRP telah menunjukkan sifat keruntuhan maksimum dalam keadaan renyuk dan juga utuh tanpa pecahan serpihan sepertimana yang berlaku pada tiub penyerap tenaga yang lain. Secara keseluruhan, penggulungan tiub orientasi 45° bagi tiub penyerap tenaga telah menunjukkan mod kegagalan secara lipatan dan mekanisme lipatan ini menghasilkan jumlah nilai tenaga menyerap yang tinggi dalam mampatan paksi dan keruntuhan sisi. Data ujian eksperimen yang diperoleh daripada kajian ini juga dijangka akan menjadi rujukan dalam kajian lanjutan yang berkaitan struktur

Honeycomb Sandwich sebagai panel ataupun struktur penyerap tenaga dalam aplikasi automotif, aero angkasa dan lain-lain.

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APPROVAL

This thesis is submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfillment of the requirements for the degree of Master of Science (Mechanical Engineering). The members of the Supervisory Committee were as follows.

Dato' Dr Ahmad Mujahid Bin Ahmad Zaidi, PhD
Professor
Faculty of Mechanical Engineering
National Defence University of Malaysia (NDUM)
(Supervisor)

Gunasilan s/o Manar
Lecturer
Faculty of Mechanical Engineering
National Defence University of Malaysia (NDUM)
(Co-Supervisor)

UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

DECLARATION OF THESIS

Author's full name : **MOHD SUPIAN BIN ABU BAKAR**

Date of birth : **7 JULY 1979**

Title : **EFFECTS OF WINDING ANGLE ON QUASI-STATIC AXIAL AND LATERAL CRUSHING BEHAVIOUR OF CFRP - FILAMENT WINDING HEXAGONAL TUBES**

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LIST OF ABBREVATIONS AND SYMBOLS

ABS	Anti-Lock Braking System
CAD	Computer Aided Design
CFE	Crush Force Efficiency
CFRP	Carbon Fibre-Reinforced Plastic
EA	Energy Absorption
FRP	Fibre-Reinforced Plastic
F1	Formula One
GFRP	Glass Fibre-Reinforced Plastic
PEEK	Polyetheretherkotone
PTFE	Polytetrafluoroethylene
PAS	Polyarysulfone
PET	Polyethermide
PI	Polyimide
RTM	Resin Transfer Moulding
SEA	Specific Energy Absorption
UTM	Universal Testing Machine
UD	Uni-Directional
WHO	World Health Organisation
A	Area Under The Curve
C	Width
E_{abs}	Absorption Energy
F	Force
H	Thickness
L	Height
l_o	Initial Height
M	Mass
P	Compressive Load
P_{max}	Peak Load

$\bar{P}$	Average Load
P_i	Initial Crush Load
P_m	Mean Crushing Load
S	Crush Displacement
S_b	Final Displacement
S_i	Initial Displacement
S_{max}	Maximum Displacement
W	Work / Energy Absorbed
θ	Winding Angle
δ	Displacement

CHAPTER 1

INTRODUCTION

1.1 Overview

The design of safety devices is widely merging at various applications such as automotive, aerospace and many others. For example, the global automotive industry has designed the seat belt, bumper, airbag and anti-lock braking system (ABS) as safety devices equipment to protect and minimise fatalities of occupant during actual vehicle crash. Furthermore, composite industries have introduced many designs and components that contribute widely to the safety of vehicle components and body structures. Thus, the capability of materials in properties is the most crucial phase in the development of safety requirement in industry. Subsequently more extensive research in composite materials is needed in the areas of cost and weight reduction. Moreover, the modern fabrication of Fibre-Reinforced Plastic (FRP) structures allows for improve capability in strength, which are now used in major parts and structures in automotive, airlines, aerospace and many others.

Meanwhile, the research regarding composite structural geometries and fabrication techniques is continuous to provide lightweight and high performance energy absorption components. This has improved the structures and led to crashworthiness characteristics of the structures themselves. Therefore, a combination of modern fabrication techniques and variation of properties in composites materials will result in a higher value of energy absorption for the structures. A higher energy absorption reduces the impacts of collision and thus minimises the casualty of occupants in transportation or airlines industries. As such examples of crashworthiness structures are predominantly used in monocoques in Formula One racing cars as survival cells and road crash barriers.

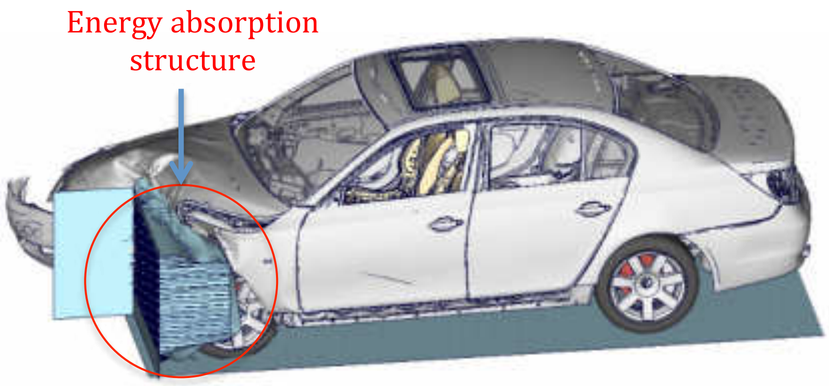

Figure 1.1: Survivability in simulation crash [57].

Figure 1.2: Formula one (F1) actual impact structures incident [56].

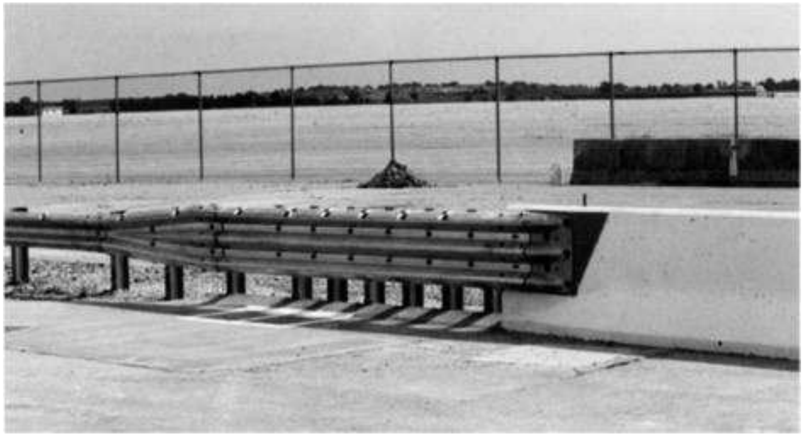

Figure 1.3: Energy absorber as road crash barrier [58].

In this study, Carbon Fibre-Reinforced Plastic (CFRP) material was used to test the characteristic of deformation and value of energy absorbing tube structure. The function of energy absorbing tube is to deform progressively, and at the same time absorbs the most of energy from the impacts or sudden forces with energy dissipation. Instead of energy absorbing function, the CFRP tube also can be used as a honeycomb core in a sandwich structure, which will offer excellent rigidity with a minimal weight. Previously, the sandwich structure concept has been used as a panel and slab in the construction of buildings. Therefore, the advantage of this sandwich structure concept has translated into the sandwich panel in the body of vehicles, trains, shipping containers, motor sports and many others. The main components in the sandwich structure consist of the sandwich core, face sheets and adhesive layers. Today, the fabrication of sandwich honeycomb structures has included the used of a wide variety of materials such as Glass Fibre-Reinforce Plastic (GFRP), Carbon Fibre-Reinforced Plastic (CFRP), Nomex and perhaps, most of the sandwich cores are made from metal.

Indeed, there is a huge demand on composite materials especially in the transportation industry. The need for lightweight and yet increase in strength has led to continuous research in manufacturing techniques of composite materials that focus on weight-to-strength ratio. The attraction of FRP goes beyond its metal capacity; its capability to absorb energy is more critical where it is able to exhibit brittles and fractures that can be manipulated by modern techniques of fabrication and properties of composite materials.

The main part of this study is to evaluate the capability of crashworthiness in a manufacturing technique, where in practice of manufacturing the energy absorption tube, generally a manual process is used as it is cost and time effective. Furthermore, the consistency of mixture between fibre and matrix is not suitable for an application study. Therefore, an important in the filament winding technique allows more energy absorption into the hexagonal tubes.

1.2 The problem statement

Statistics from the world transportation department shows that accidents have contribute more to human fatalities. According to the global status report on road safety 2013 by World Health Organization (WHO), more than six thousand people were killed by road traffic injuries in Malaysia [59]. It is argued that this number may increase as the number of vehicles, vessels and high-speed trains and aircrafts also increases. Predominantly, motor vehicle accident is the highest number of worldwide fatality and causes a great loss to society. Because of that, most of occupant safety structures in ground vehicles are developed following the regulations of transportation industries and within road safety system rules to prevent severe injuries and fatalities during vehicle crash. In line with the evolution in composite materials and fabrication technology, the use of composite is widely applied as sacrificial structure parts in energy absorber devices. The composite structures have a supreme performance that contributes to crashworthiness behaviour. Moreover composite materials exhibit a significantly higher energy absorption compared with other materials.

Despite the advantages of various types of composite materials as energy absorber tubes, there are still many limitations in their application that need to be improved such as the level of crashworthiness and value of energy absorbed. Therefore, this study will contribute to the understanding of the collapsible characteristics of CFRP as an energy absorber tube and how CFRP functions as a high value compressive load tube with a progressive stable post-crush during the crushing phase. In an attempt to improve energy absorber in crashworthiness studies, researchers have been developing structural tube crashworthiness with