UNIVERSITI PUTRA MALAYSIA

STUDY ON OPTIMIZATION OF COMPOSITE TUBULAR ENERGY ABSORPTION SYSTEM

HAKIM S. SULTAN ALJIBORI.

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By

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Thesis Submitted to the School of Graduate Studies, University Putra Malaysia in fulfilment of the Requirements for the Degree of Master of Science

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DEDICATION

I am happy to dedicate this work to my country “Iraq”. A country is great by the character of its people and not by its number. I adore my country because it is the land of civilizations from the time immemorial.

I would like to express my gratitude to all the people who have been supportive of my endeavor towards my M.Sc. study.

The support of my family has been encouraging me to pursue my M.Sc study. Without their support I could not have achieved thus far. To my mother, brothers and my wife I thank them for their supporting me for so many years. I wish to make both of them proud. I thank my wife for her support, understanding and love. You have been a constant source of strength throughout my M.Sc study whenever I need.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

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June 2004

Chairman: Elsadig Mahdi Ahmad, Ph.D.

Faculty : Engineering

A four-phase program to improve the specific energy absorbed by axially crushed composite collapsible tubular energy absorber devices was undertaken. In the first phase, the effects of trigged tube wall on the crushing behaviour were investigated. At this stage, triggered tubes were fabricated and crushed. The second phase is aimed at obtaining the best position for the triggered wall. The third phase focuses on the effects of material sizing in order to understand the influence of triggered wall length on the responses of composite circular tubes to the axial crushing load. The results from these three phases lead to the fourth phase. The objective of the 4^{th} phases was to optimise the shape geometry of the cross-section area to further improve tube energy absorption capability. The tubes were manufactured from woven roving glass/epoxy fabric and had the same lay-up providing a common laminate for comparison. The failure modes were observed and the specific sustained crushing loads were determined and compared against non-optimized

tubes of the same lay-up. The importance of differentiating between initiation energy and propagation energy is shown, and a new parameter (energy capability index (ECI)) is proposed, as a useful measure for comparing crush behaviour of composite structures. The experimental results demonstrated strong potential benefits of optimizing the material distribution. The sizing and shape optimization of composite collapsible tubes exhibited a pronounced effect on their capability to absorb high specific energy under axial compressive load.

For the effect of triggering it was that tubes (TN) observed to experience catastrophic failure mode during the post crush stage also displayed very poor energy absorption. Triggering a part of tube wall was very efficient in improving the energy absorption capacity of circular composite tubes. Accordingly tubes with triggered wall (T-tubes) exhibited highest energy absorption capacity compared with non-triggered tubes. They also experience stable post-crush region of load-displacement curves, which leads to high crashworthiness performance. It is also evident from the experimental results that change in the triggered wall aspect ratio significantly affected the energy absorption capability of tube with middle triggered wall (TM-tubes). Distinct differences were observed between the different aspect ratio, where TM tubes (i.e. tubes with triggered wall aspect ratio of 0.28) exhibited the highest energy absorption capacity. Different failure modes were observed for different triggered wall length ratios (L_{tr}/H). For the core tubes (TMC-), was observed that core presence markedly improved the energy absorption capacity of composite circular tubes. Among TMC- tubes, TMC3 tubes (i.e. tubes with core thickness of 3.35mm) displayed highest energy absorption capacity.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

KAJIAN MEGENAI PENGOPTIMUMAN SISTEM PENYERAPAN TENAGA TUBULAR KOMPOSIT

Oleh

HAKIM S. SULTAN ALJIBORI

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Suatu program empat fasa bagi meningkatkan tenaga tentu yang diserap oleh peranti penyerap tenaga bagi komposit boleh-musnah tiub yang dihancurkan secara menegak telah dijalankan. Dalam fasa pertama, kesan dinding tiub berpicu ke atas perlakuan hancur telah dikaji. Untuk ini, tiub berpicu dan tanpa-picu telah difabrikat dan dihancurkan. Fasa yang kedua bertujuan untuk mendapatkan posisi terbaik bagi dinding berpicu tersebut. Fasa ketiga memfokuskan kepada kesan pensaizan bahan, untuk memahami pengaruh panjang dinding berpicu ke atas tindakbalas tiub-tiub komposit membulat kepada beban paksi penghancuran. Keputusan yang dicapai oleh ketiga-tiga fasa ini menyumbang kepada fasa yang keempat, yang mana objektifnya adalah untuk mengoptimumkan bentuk geometri bagi luas keratan rentas tiub untuk lebih peningkatan dalam kebolehserapan tenaga oleh tiub. Tiub-tiub ini diperbuat daripada jalinan pintal kaca/fabrik epoksi dan mempunyai rekabentuk yang sama, ini menyediakan pelapik biasa untuk perbandingan.Mod-mod kegagalan diperhatikan,

dan beban penghancuran berterusan tertentu telah ditentukan dan dibandingkan dengan tiub-tiub tak-teroptimum yang sama rekabentuknya. Kepentingan untuk membezakan di antara tenaga inisiasi dan tenaga propagasi ditunjukkan, dan satu parameter baru (indeks kebolehan tenaga(ECI)) telah dicadangkan sebagai pengukuran yang berguna untuk membandingkan perlakuan hancur struktur-struktur komposit. Keputusan-keputusan eksperimen menunjukkan manfaat yang mungkin diperoleh dalam mengoptimumkan taburan bahan. Pensaizan dan pengoptimuman bentuk tiub komposit boleh-musnah menunjukkan kesan yang ketara dalam kebolehannya untuk menyerap tenaga tentu yang tinggi di bawah beban mampatan paksi .

Bagi kesan penambahan picu, adalah diperhatikan bahawa tiub-tiub dengan dinding tanpa-picu (TN) mengalami mod kegagalan katastrofik semasa tahap pasca-hancur, di samping menunjukkan kapasiti penyerapan tenaga yang amat rendah. Penambahan picu ke atas sebahagian daripada dinding tiub didapati amat berkesan dalam meningkatkan kapasiti penyerapan tenaga bagi tiub-tiub komposit membulat. Dengan itu, tiub-tiub dengan dinding yang berpicu (T-tubes) menunjukkan kapasiti penyerapan tenaga yang amat tinggi jika dibandingkan dengan tiub tanpa-picu. Ia juga mengalami rantau pasca-hancur yang stabil dalam lengkuk beban-peralihan, yang membawa kepada prestasi kebolehtahanan-musnah yang tinggi. Daripada eksperimen juga dapat dibuktikan bahawa pertukaran dalam nisbah aspek dinding berpicu memberi kesan langsung kepada kebolehan penyerapan tenaga bagi TM-tubes. Beberapa perbezaan ketara telah dikenalpasti di antara nisbah aspek yang berlainan, di amna tiub TM (iaitu tiub dengan nisbah aspek dinding berpicu sebanyak 0.28) menunjukkan kapasiti penyerapan tenaga yang tertinggi. Mod-mod kegagalan yang berlainan telah diperhatikan untuk nisbah L_{tr}/H yang berlainan. Bagi tiub-tiub teras (TMC-), adalah didapati bahawa kehadiran teras telah meningkatkan kapasiti penyerapan tenaga untuk tiub-tiub komposit membulat. Di antara tiub-tiub TMC-, tiub TMC3 (iaitu tiub yang mempunyai ketebalan teras sebanyak 3.35mm) menunjukkan kapasiti penyerapan tenaga yang amat tinggi.

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I certify that an Examination Committee met on 18th June 2004 to conduct the final examination of Hakim Samawi Sultan Aljibori on his Master of Science thesis entitled "Optimization of Composite Tubular Energy Absorption System" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis Submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree of Master of Science. The members of the Supervisory Committee are as follow:

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DECLARATION

I herby declare that the thesis is based on my original work except for quotation and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

HAKIM S. SULTAN ALJIBORI

Date: 27/08/2004

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

NOMENCLATURE

FRP	Fibre Reinforced Plastic
H	Total Height of Tube (mm)
L_{tr}	Triggered Wall Length (mm)
(L_{tr}/ H)	Triggered Wall Aspect Ratio
TN	Non-Triggered Tube
TI	Tube with Triggered Wall Placed at Inner Position
TO	Tube With Triggered Wall Placed at Outer Position
TM	Tube with Triggered Wall at Middle Position and (L_{tr}/ H) of 0.28
TM1	Tube with TM and (L_{tr}/ H) of 0.42
TM2	Tube with TM and (L_{tr}/ H) of 0.57
TM3	Tube with TM and (L_{tr}/ H) of 0.71
TMC	Tube with TM and Core
TMC1	Tube with TM and Core Thickness of 2.1mm
TMC2	Tube with TM and Core Thickness of 2.75mm
TMC3	Tube with TM and Core Thickness of 3.35mm
u	Crushed Distance (mm)
t	Thickness of the Triggered Wall (mm)
t_c	Thickness of the Core (mm)

D_m	Mean Top Diameter of Tube (mm)
M	Mass of the Tube (kg)
A	Cross-Sectional Area (m^2)
V_m	Volume of Material (m^3)
ρ	Mass Density of Structure (kg/m^3)
V_s	Volume of Structure (m^3)
A_1	Cross-Sectional Area of Material (m^2)
A_2	Cross-Sectional Area of Structure (m^2)
E_s	Specific Energy Absorption (kJ/kg)
E_v	Energy Absorption per Unit Volume (kJ/m^3)
Pi	Instant Crush Failure Load (kN)
W_p	The Total Work Done (kJ)
S	Instantaneous Displacement (mm)
P_m	Mean Crush Failure Load (kN)
P_{cr}	Critical Crush Failure Loads (kN)
P_1	First Peak Crush Failure Load (kN)
IFI	Initial Failure Indicator
CFE	Crush Force Efficiency
CS	Crushed Strain

CHAPTER 1

INTRODUCTION

In recent years there is an increasing demand in the use of composite materials for the automotive, aerospace and rail industry. The automotive and aerospace applications over the past quarter-century have been primarily in special areas such as energy absorber devices. As the automotive manufacturers have to take environmental issues into consideration, the composite space-frame concept has become more and more attractive in the design of vehicles. When using composite in the body structure of a vehicle, considerable weight reductions can be achieved compared to conventional isotropic structures, which leads to reduced fuel consumption and consequently lower carbon dioxide emissions.

The high efficiency of any energy absorber device may be defined as its ability to decelerate smoothly the occupant compartment to the rest within the allowable limit [1]. It is well-known that responses of axially crushed non-trigger tubes (i.e. tube with constant thickness and squared ends) are characterized by recording very high resistances till reach their full load carrying capacity after which definite different degrees of unstable behaviours take place [2]. Therefore, it is strongly believed that for core-less tubular energy absorber devices stable load-deformation curve could only be obtained by steering the failure initiation to occur in a designed region along the shell meridional direction. In that manner, two approaches based on material and geometry properties have been suggested to avoid the Euler-buckling failure mechanism or any mechanism leads to catastrophic failure. These approaches can be classified in two categories. The first Category based on material properties employs core thin-walled structures filled with crushable medium (i.e. synthesised or natural cellular materials filler). It has been extensively shown that tubes with filled cores achieved high and stable load carrying capacity along the gross deformation with very high total energy absorbed and very specific energy absorption compared with the core-less tubes [3]. This Category is being criticised because of apparent weight increasing, despite the specific filler density. More over researchers in composite structures introduces hybrid structures using different fibres types [4]. The hybridisation relatively improved the load-carrying capacity without a profound enhancement in the specific energy absorbed. A designed beneficial imperfection in the structure introduced by Hui [5] was introduced to enhance the energy absorption. This method resulted in a combination of instable and stable failure mode. The second Category based on geometry properties are also categorized in many groups. According to Farley [6] and Farley & Jones [7] reported that energy absorption capability is a non-linear function of inside diameter to wall thickness ratio (D/t) for tubular specimens. They stated that specific energy absorption was found to fall as D/t increased. Mamalis, et al [8] and Mahdi, et al. [9] reported that the crushing behaviour is dominated by increasing the cone vertex angle.

1.1 Problem Statement

The main objective to manufacturers and materials community is to produce vehicles with lightweight; therefore, using composite material for automotive and aerospace industry it is very attractive to be the main materials for many car components. One of these components is crash energy devices. Energy absorbs devices should be designed to meet the requirements and standards for the protections of the occupants or passengers in vehicles accident. However, behaviour of the composite energy absorber devices is often unstable in absorbing crash event and most probably leads to catastrophic failure mechanism. This instability is one of the more critical problems in using fibre composites for crash energy management. This is the main factor behind this present project. Accordingly this project introduces many aspects to improve the energy absorption capability of composite circular tubes under quasi-static axial compressive load.

1.2 Objectives

The purpose of this study is to optimise the structure of composite tubular energy absorber device in order to maximize its specific energy absorption capability. The only known quantities in this problem are the loading, support conditions and the structure domain. The detail objectives of this study can be summarised as follows:

1. To study the effect of triggering on the crushing behaviour of composite

circular tubes.

2. To examine the effect of the triggered wall position on the energy absorption of composite circular tubes.
3. To determine the effect of the triggered wall aspect ratio on the energy absorption of composite circular tubes.
4. To examine the effect of material distribution and shape optimisation on the energy absorption of composite circular tubes.

1.2 Significance of the Study

This work is important because of the following:

1. Any generic technology or structural system in the various engineering fields offers safety and provide enhanced levels of protection ought to be of considerable interest, that composite materials based structures is one such technology is not in doubt.
2. The efficient use of composite tubes as energy absorber depends on the understanding of their crushing behaviour.
3. The results of this study and the produced data can be helpful in the design stage of energy absorber elements made from composite material.