UNIVERSITI PUTRA MALAYSIA

CRUSHING BEHAVIOUR OF WOVEN ROVING GLASS FIBRE/EPOXY LAMINATED COMPOSITE RECTANGULAR TUBES SUBJECTED TO 'QUASI-STATIC COMPRESSIVE LOAD

FAYIZ Y. M. ABU KHADRA

ITMA 2002 1

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirement for the Degree of Master of Science

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Abstract of thesis presented to the senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

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Chairman: Associate Professor Abdel Magid Salem Hamouda, Ph.D.

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The automotive industry is exploring to adapting more fibre reinforced composite materials due to their stiffness to weight ratio. The amount of energy that a vehicle absorbs during a collision is a matter of concern to ensure safer and more reliable vehicle. The efficient use of composite material in the field of crashworthiness depends on the understanding of how a composite member absorbs and dissipates energy during the event of an impact.

An experimental and finite element investigation of the woven roving glass fibre/epoxy laminated composite rectangular tubes subjected to compressive loading were carried out under compressive loading. Through out this investigation, rectangular tubes with different cross-sectional aspect ratio varying (a/b) from 1 to 2 with 0.25 increment were investigated under axial and lateral loading conditions applied independently. The effects of increasing the cross-sectional aspect ratio on the load carrying capacity and the energy absorption capability were also presented and discussed. Finite element models to predict the load carrying capacity, failure

mechanism and stress contours at pre-crush stage of the rectangular tubes under axial and lateral loading conditions have been developed.

Experimental results show that the cross-sectional aspect ratio significantly affects the load carrying capacity and the energy absorption capability of the tubes. The axially loaded rectangular tubes have better load carrying capacity and energy absorption capability compared to the laterally loaded rectangular tubes. The buckling failure mode has been identified for the rectangular tubes under the different loading conditions.

The developed finite element models approximately predict the initial failure load and the deformed shapes. The discrepancy between the finite element prediction and the experimental results is due to the assumption made in the finite element models and not considering the imperfection of the real tubes in the finite element models. From the experimental and finite element results 'knockdown' factors have been proposed to be used in the design phase of energy absorption elements to predict the initial failure load.

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

PENYIASATAN KEATAS RECTANGULAR KAPAS/EPOKSI YANG DIBAWAH BEBAN MAMPTAN PAKSI

Oleh

FAYIZ Y. M. ABU KHADRA

November 2002

Pengerusi: **Profesor Madya Abdel Magid Hamouda, Ph.D.**

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Disebakan oleh nisbah stiffnes teradap berat, industri automotif kini mencari dan mengadaptasikan kegunaan bahan komposit bergentian. Jumlah tenaga yang diserap ketika perlanggaran adalah perkara yang dititikberatkan bagi menentukan tahap keselamatan di dalam bidang ini bergantung kepada permahaman bagaimana member komposit tersebut menyerap dan menyelerakan tenaga impak.

Pada penyiasatan ini, didapati rectangular tubes dengan nisban aspek keratan rentas meliputi dari julat 1 hinnga 2 dengan 0.25 increment telah diselidiki dibawah bebanan axial dan lateral. Kesan daripada kenaikan nisbah aspek keratan rentas tersebut ialan pada kapasiti beban bawaan dan keupayaan penyerapan tenaga. Model elemen tidak terhingga digunakan untuk menganggar kapasti beban bawaan. Mekanisma kegagalan dan kontour stress didapati pada keadaan remukan rectangular tubes model.

Elemen tidak terhingga yang telah di bentuk secara tepat telah mengunakan initial failure load dan kecacatan bentuk. Ketidak seragaman diantara elemen tidak terhingga dan keputsan ujikaji adalah disebarkan dan andaian yang dibuat adalah pada model elemen tidak terhingga dan tidak mengambil kira ketidak sempurnaan of the real tubes dalan model tersebut.

Daripada keputusan dan permodelan ini 'knockdown' faktor telan dicadangkan untuk kegunaan fasa rekabentuk keupayaan penyerapan elemen untuk menganggar kegagalan beban permulaan.

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Finally, I would like to express my indebtedness to my family. My thank you goes especially to my father and my brother, Fawwaz, for their moral and financial support.

I certify that an Examination Committee met on 12th November 2002 to conduct the final examination of Fayiz Y. M. Abu Khadra on his Master of Science thesis entitled "Crushing Behaviour of Woven Roving Glass Fibre/Epoxy Laminated Composite Rectangular Tubes Subjected to Quasi-static Compressive Load" in accordance with Unversiti 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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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations 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.

Fayiz Y. M. Abu Khadra

Date: 27/12/2002

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NOMENCLATURE

A	Cross-sectional area
a/b	Cross-sectional aspect ratio
E	Young's Modulus
E_1	Longitudinal Young's Modulus (direction-1)
E_2	Transverse Young's Modulus (direction-2)
E_3	Transverse Young's Modulus (direction-3)
G12	In-plane Shear Modulus(in the 1-2 Planes)
M	mass
L	length
P_1	Initial crushing load
$\overline{P}$	Average crushing load
Q_{ij}	Reduced stiffnesses (i,j=1,2,6)
$\overline{Q}_{ij}$	Transformed reduced stiffnesses (i,j=1,2,6)
S_{ij}	Reduced compliances (i,j=1,2,6)
$\overline{S}_{ij}$	Transformed reduced compliances (i,j=1,2,6)
N_x	Stress resultant in x-direction
N_y	Stress resultant in y-direction
N_{xy}	Shear force
M_x	Moment resultant in x-direction
M_y	Moment resultant in y-direction
Mxy	Moment resultant in xy-plane
A_{ij}	Elements of the A Matrix
B_{ij}	Elements of the B Matrix
D_{ij}	Elements of the D matrix
E	Total energy absorbed
E_s	Specific energy absorbed
CEF	Crush force efficiency
SE	Stroke efficiency
AX	Axial loading condtions
LTA	Lateral loading condition on the 'A' side
LTB	Lateral loading condition on the 'B' side
t	Thickness of the tube
V_f	Volume fraction of fibre
W_f	Weight of fibre
W_m	Weight of matrix
ρ	Density
ρ_f	Density of fibre
ρ_m	Density of matrix
V	Volume

CHAPTER 1

INTRODUCTION

Structural crashworthiness is now an essential requirement in the design of automobiles, rail cars and aerospace application. The structural crashworthiness covers the energy absorbing capability of crushing structural part as well as the demand to provide a protective shell around the occupants i.e. post crash structural integrity.

An energy absorber device is designed such that in the event of crash it absorbs impact energy in a controlled manner, such that the net deceleration of the occupants of a car is less than the net deceleration above which irreversible brain damage occurs.

Composite materials are found to have an energy absorption capability, structural weight reduction, and improved vehicle safety by higher or at least equivalent crash resistance compared to metallic structure. Therefore, the increasing use of composite material in aerospace and in automobile industries has resulted in many economical and technical advantages. The efficient use of energy absorbing devices made from composite material depends on the full understanding of the crushing behaviour of tubular structures. The only possible way to fully understand the crushing behaviour is in performing crushing tests to understand how the various variables influence the crushing behaviour. In a later stage the generated data can be very useful in deriving mathematical models which can describe the crushing behaviour and predict the energy absorbed from a tubular structure, because the development and validation of reliable analytical and simulation tools for the crashworthiness studies is an important means of reducing development cost and tests for certifications to meet safety and crashworthiness requirements.

The current research work focuses in studying the effect of the various variables, which influence the energy absorption capability of composite materials. Much of the experimental work on composite material has been carried out using axi-symmetric cylindrical tubes mainly because they are easy to fabricate and their geometry has proven to be one of the most favourable shapes for energy absorption. This geometry is self-stabilising and allows testing of relatively thin-section laminates. The lack of edges along its length reduces the complexity of the boundary conditions and provides consistency throughout the cross section. Also composite cones show high-energy absorption performance with the advantage of a self-triggering capability.

Limited work is available on the flat plates. A test fixture for crushing flat plate specimens is needed. The plate is stabilised by steel rod that provide a simply-supported boundary condition on the sides of the specimens. Some researchers suggest by testing flat plate the complexity of the geometry reduced and the response may be more easily studied. Furthermore, the manufacturing cost of flat specimens is less than that of tube specimens. Using such specimens, the influence of the various variables on failure modes and the energy absorption performance can be studied.

Tubes of square and rectangular cross-sections tubes made of metal are frequently used as energy absorbing structural elements, the S-rail of an automobile is an example. Studies on the crushing behaviour of these tubes have been frequently conducted, although the use of square and rectangular tubes made of composite materials as an energy absorbing structural element can result in many technical and economical advantages. Studies on the performance of square and rectangular tubes made of composite material under compressive load are very scarce. Therefore, the main aim of the present work is to explore the response of square and rectangular tubes to axial and lateral compressive load. In this project the load-displacement response, the specific energy absorption capability, and failure mode of rectangular tubes will be investigated when the cross-sectional aspect ratio increases from 1 to 2 in 0.25 increment.

1.1 Research Objectives

The aims of this study can be summarised as follows:

- To study the performance of the woven roving glass/epoxy composite material under quasi-static compressive load.
- To explore the behavior of the rectangular tubes under quasi-static compressive load.
- To investigate the effect of the cross-sectional aspect ratio on the crushing behaviour of the tubes under quasi-static compressive load.
- To study the effect of loading conditions on the crushing behaviour of the rectangular tubes.

1.2 Significance of the Study

This study is important because of the following:

- Tubes of square and rectangular cross-sections made of metal are frequently used as energy absorber elements, the use of composite tubes instead of metal tubes can result in much technical and economical advantage.
- The efficient use of composite tubes as energy absorber depends on the understanding of their crushing behaviour.
- The generated data from this study can be useful in the design phase of energy absorber elements made from composite materials.

The remainder of this thesis is organised as follows: Chapter 2 reviews the literature of the fibre reinforced composite materials and studies on their use as energy absorption structural element. The methodology used in this study is explained in chapter 3. In chapter 4, the experimental results will be presented and discussed. In chapter 5 finite element results will be presented and discussed. Overall discussion is presented in chapter 6. Finally, the conclusion from the work and the proposal for future studies are listed in chapter 7.