

**QUASI-STATIC AXIAL CRUSHING BEHAVIOUR OF
COMPOSITE HEMI-SPHERICAL SHELLS**

MHFUD AHMED MASOUD SALEH

**MASTER OF SCIENCE
UNIVERSITI PUTRA MALAYSIA**

2004

**QUASI-STATIC AXIAL CRUSHING BEHAVIOUR OF COMPOSITE
HEMI-SPHERICAL SHELLS**

By

MHFUD AHMED MASOUD SALEH

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfilment of the Requirements for the Degree of Master of
Science**

March 2004

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

**QUASI-STATIC AXIAL CRUSHING BEHAVIOUR OF COMPOSITE
HEMI-SPHERICAL SHELLS**

By

MHFUD AHMED MASOUD SALEH

March- 2004

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

Faculty: Engineering

Experimental investigations were carried out to investigate the energy absorption capability and load-carrying capacity of hemi-spherical composite shells subjected to quasi-static axial compressive load. The hemi-spherical shell specimens were fabricated by hand lay-up fabrication process in which the fibre was mixed with the matrix. Two types of resins were explored (polyester and epoxy) two types of fibre were also studied (woven glass fibre and woven carbon fibre). Four different R/t ratios of hemi-spherical composite shells were investigated as well as four different shells cross section area (A) were studied. A description of typical crushing modes and mechanisms of energy absorption for hemi-spherical composite shells is presented. Results showed that epoxy resin has higher value of load-caring capacity and energy-absorption capability than polyester resin. The results also show that the carbon fibre has higher value of load-carrying capacity and energy-absorption capability than glass fibre. The results of R/t ratio and area

(A) of shells also show that the specific energy absorption capability of hemispherical shells increases with reducing both of the geometry values.

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

**KELAKUAN PENGHANCURAN PAKSIAN MIRIPSTATKIK BAGI
KELOMPANG KOMPOSIT HEMISFERA**

Oleh

MHFUD A. M. SALEH

March 2004

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

Fakulti: Kejuruteraan

Pakaian eksperimentasi yang telah dijalankan untuk mengkaji keupayaan tenaga penyerapan dan keupayaan membawa beban komposit hemisfera dipawah beban quasi static paksian. Specimenkelompok” ini dibikin dengan menggunakan proses “be ngkalai tangant” di mana gentian telah dicampurkan dengan matriks. Dua jenis resin telah digunakan (polyester dan epoksi) dan gentian jenis jalinan juga telah dikaji (gentian kaca dan karbon teranyam). Empat nisbah R/t bagi “kelompok” komposit hemi-spherical telah disiasat dan empat luas keratan rentas “kelompok” juga telah dikaji. Satu penerangan mengenai ragam penghancuran tipikal dan mekanisma tenaga penyerapan bagi kelompok komposit hemisfera kelompok telah dilaporkan. Kelakuan “kelompok” hemisfera tersebut telah diuji dan dilaporkan mengenai keupayaan membawa beban dan juga kapabiliti tenaga penyerapan yang mendadak. Keputusan menunjukkan bahawa damar epoksi mempunyai nilai keupayaan membawa beban dan tenaga penyerapan yang tinggi berbanding dengan poliester, tetapi keputusan juga menunjukkan gentian karbon mempunyai nilai keupayaan membawa beban dan keupayaannya

penyerapan yang tinggi berbanding gentian kaca. Keputusan nisbah R/t dan luas (A) “kelompang” juga menunjukkan bahawa keupayaan penyerapan tenaga spesifik bagi “kelompang” hemisfera meningkat dengan penguangan kedua-dua nilai geometri kelompang tersebut.

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to Associate Professor Dr. Abdel Magid Salem Hamouda for his encouragement, valuable advice, and guidance through my years as a master student. It is a pleasure and an honour to be his student.

I would like also to express my sincere gratitude and deep thanks to my committee member, Dr. Elsadig Mahdi Ahmed for his kind assistance, advice, encouragement, and suggestions throughout this work and during the preparation of this thesis.

I would like to thanks to my committee member, Associate Professor Dr. Yousif Abdullah Khalid for his suggestions at different stage of this study. Also, I would like to express my regards to my external and internal examiners for their valuable comments and suggestions.

I would like to acknowledge the Libyan community members in Malaysia, for their inspiration throughout this study.

I would like to thank all staff at Universiti Putra Malaysia for their helpful and support.

Mhfud A. M. Saleh

I certify that an Examination Committee met on 5th March 2004 to conduct the final examination of Mhfud Ahmed Saleh on his master of science thesis entitled “Quasi-Static Axial Crushing Behaviour of Composite Hemi-Spherical Shells” 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:

Ir Mohd Sapuan Salit Ph.D.

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Megat Mohamad Hamdan Megat Ahmad Ph.D.

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hassan Yudie Sastra Ph.D.

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Che Hassan Che Haron Ph.D.

Associate Professor
Faculty of Engineering
Universiti Kebangsaan Malaysia
(Independent Examiner)

GULAM RUSUL RAHMAT ALI,Ph.D.

Professor/ Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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

Abdel Magid Salem Hamouda Ph.D.

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Elsadig Mahdi Ahmed Ph.D.

Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Yousif Abdullah Khalid Ph.D.

Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

AINI IDERIS, Ph. D.
Professor / Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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.

MHFUD A. M. SALEH

Date:

TABLE OF CONTENTS

	Page
ABSTRACT	iii
ABSTRAK	v
ACKNOWLEDGMENTS	vii
APPROVAL	viii
DECLARATION	x
LIST OF TABLES	xiv
LIST OF FIGURES	xv
NOMENCLATURE	xviii
 CHAPTER	
I INTRODUCTION	1
Problem Statement	4
Objectives	4
Importance of the Study	5
Thesis Layout	5
 II LITERATURE REVIEW	 6
Energy Absorbers	6
Energy Absorbers Systems	7
Thin Walled Tubes	7
Composite Cones	10
Sandwich Plates	11
Honeycomb Panels	13
Spherical Shells	14
Compound System	28
Parameters Effects on Energy Absorption Capability of Composite-Material	30
The Effect of Reinforcing Fibre	30
The Effect of the Matrix	32
The Effect of Fibre	33
The Effect of Fibre Volume	34
Test Methods	36
Quasi-static Testing	36
Impact Testing	37
Failure Modes and Mechanisms	37
Catastrophic Failure Modes	37
Progressive Failure Modes	38
Characteristic Types of Progressive Crushing Modes	39
Transverse Shearing or Fragmentation Mode	39
Lamina Bending or Splaying Mode	39
Brittle Fracturing	41

Local Buckling or Progressive Folding	42
Crashworthiness Parameters	44
Crush Force Efficiency-Stroke Efficiency	44
Specific Energy Absorption Capability	45
Conclusions	48
III Methodology and experimental work	49
Fabrication Process	50
Hemispherical Shells	50
Plates for Tensile Test Specimens	52
Testing Procedures	53
Quasi-static Axial Crushing Process	53
Tensile Test	53
Summary	55
IV RESULTS AND DISCUSSION	56
Tensile Testes Results	56
Effect of Materials Selection	59
Matrix Type Effects	60
Matrix Type Effect on Load-Deformation	60
Matrix Types Effect on Specific energy-Deformation	61
Failure Mode of Glass/Epoxy	62
Failure Mode of Glass /Polyester	63
Effect of Fibre Types	66
Fibre Type Effect on Load-Deformation	66
Fibre Type Effect on Specific Energy-Deformation	66
Failure Mode of Glass Polyester	67
Failure Mode of Carbon Polyester	67
Effect of Geometry	71
Effect of R/t Ratio	71
Effect of R/t Ratio on Load-Deformation	71
Effect of R/t Ratio on Specific Energy-Deformation	72
Failure Modes of Different R/t Ratio	72
Effect of shell Cross Suction Area	78
Effect of Shell Cross Suction Area on Load-Deformation	78
Effect of Shell Cross Suction Area on Specific Energy-Deformation	78
Effect of Cross Suction Area on Failure Modes	79
Multi Failure modes	83
Energy Dissipation Mechanisms	86
Microscopic Investigation	86
V CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORKS	92
Conclusions	92
Suggestions for Future Work	93
REFERENCES	94
BIODATA OF THE AUTHOR	99

LIST OF TABLES

Table	Page
3.1 Specimen geometry of matrix effect	51
3.2 Specimen geometry of fibre effect	51
3.3 Specimen geometry of R/t ratio effect	51
3.4 Specimen geometry of shell area effect	51
3.5 Geometry of tensile specimens	54
4.1 Mechanical property of materials used	57
4.2 Crashworthiness parameters for axially loaded hemi-spherical shells with different matrix types	65
4.3 Crashworthiness parameters for axially loaded hemi-spherical shells with different fibre types	71
4.4 Crash worthiness parameters of axially loaded hemi-spherical shells with different R/t ratio	77
4.5 Crash worthiness parameters of axially loaded hemi-spherical shells with different area	80

LIST OF FIGURES

Figure	Page
2.1 Direct inward inversion of frusta	11
2.2 Honeycomb configurations	14
2.3 Typical load-deformation curves	15
2.4 Comparison of experimental and computed results(a)Load deformation curves(b)Energy compression	16
2.5 Load-deformation curves of shells (a)Different radii and constant thickness(b)Different thicknesses and constant radius	17
2.6 Experimental and computed load-deformation curves of spherical shell of shallow depth	18
2.7 Experimental load-deformation curve of spherical shell and one computed by assuming constant meridional thickness	18
2.8 Variation of mean collapse load with R/t values of the spherical shells(a)different radii and constant thickness(b)different thicknesses and constant radius	19
2.9 Energy-compression curves of shells(a)different radii and constant thickness (b)different thicknesses and constant radius	20
2.10 (a)Bottom view of specimens collapsed (b) tope view of specimens collapsed	21
2.11 (a)Experimental and computed load-deformation curves (b) Experimental and computed energy-compression curves	24
2.12 Fragmentation mode of collapse observed in quasi-static (S) and impact (D) tests (specimens G3) (a) top view, (b) bottom view	25
2.13 Progressive splaying mode of collapse observed in quasi-static (S) and impact(D) tests (a) top view, (b) bottom view	25
2.14 Energy-compression curves of shells; (a) same thickness and different radii, (b) same radius and different thicknesses	26
2.15 Specific energy-compression curves of the shells of; (a) same thickness and different radii, (b) same radius and different thicknesses	27

2.16 Mean collapse loads from quasi-static and impact tests, and computed results for composite shells	28
2.17 Notation used for FWL complete and semi-circular curved compound systems	29
2.18 Transverse crushing mode	40
2.19 Lamina bending crushing mode	41
2.20 Brittle Fracturing Mode	42
2.21 Local buckling crushing mode	43
2.22 Schematic representation of a typical force versus indentation curve for a thin-walled structure subject to crushing loads	43
2.23 Typical Load Displacement Curve for a Progressively Crushed composite hemi-spherical shell	46
2.24 Diagram of the hemispherical shell	48
3.1 Flow chart for the design parameters	49
3.2 Fabrication process	52
3.3 Hemi-spherical shells with different geometry	53
3.4 Hemi-spherical composite shell under axial compressive load	54
3.5 Tensile test specimen geometry	54
4.1 Stress –strain curve for carbon fabric/polyester	58
4.2 Stress –strain curve for glass fabric/epoxy	58
4.3 Stress –strain curve for glass fabric/polyester	59
4.4 Effect of matrix types on load-deformation	61
4.5 Effect of matrix type on specific energy-deformation	62
4.6 Crashing history of the hemi-spherical shell (glass/epoxy)	63
4.7 Crashing history of the hemi-spherical shell (glass/polyester)	64
4.8 Effect of fibre type on Load-deformation relation	68
4.9 Effect of fibre type on specific energy-deformation relations	69

4.10 Failure mode of glass polyester (effect of fibre study)	69
4.11 Failure mode of carbon polyester (effect of fibre study)	70
4.12 Effect of R/t ratio on Load-deformation relation	73
4.13 Effect of R/t ratio on specific energy-deformation relations	74
4.14 Failure mode of glass polyester (effect of R/t ratio R/t= 60)	74
4.15 Failure mode of glass polyester (effect of R/t ratio R/t= 45)	75
4.16 Failure mode of glass polyester (effect of R/t ratio R/t= 35)	75
4.17 Failure mode of glass polyester (effect of R/t ratio R/t= 25)	76
4.18 Identical extensions laminates	77
4.19 Effect of shell area on Load-deformation	80
4.20 Effect of shell area on specific energy-deformation relations	81
4.21 Failure mode of glass epoxy (effect of area $A= 0.045\text{m}^2$)	81
4.22 Failure mode of glass epoxy (effect of area $A= 0.050\text{m}^2$)	82
4.23 Failure mode of glass epoxy (effect of area $A= 0.055\text{m}^2$)	82
4.24 Failure mode of glass epoxy (effect of area $A= 0.060\text{m}^2$)	83
4.25 Failure stages of composite hemi-spherical shell	84
4.26 Final crushed shape of axially crushed composite hemispherical shells: top view	85
4.27 Final crushed shape of axially crushed composite hemispherical shell: bottom view	85
4.28 Microscopic photo of glass/epoxy specimen	89
4.39 Microscopic photo of glass/ polyester specimen	90
4.30 Microscopic photo of carbon/polyester specimen	91

NOMENCLATURE

t	Average thickness of the shell
Z	Depth of the shells
D	Inner minor radius
L	Span of the spherical shell
R	Mean radius of the spherical shell
A	Cross-section area of the spherical shell
ρ	Density of the composite material
E_{11}	Longitudinal modulus
E_{22}	Transverse modulus
G_{11}	In plane shear modulus
σ_{11}	Longitudinal stress
ε_{11}	Failure strains
ν_{12}	Poisson's ratio
P_i	Initial crush failure load
P_m	Mean crush failure load
P_h	Highest load
E_s	Specific energy absorbed
E_{NS}	Normalised Energy Absorption
CFE	Crush force efficiency
SE	Stroke efficiency
IFI	Initial failure indicator

$[D]$ Laminate bending stiffness

$[\bar{Q}]^k$ Kth-layer reduced stiffness matrix

CHAPTER- I

INTRODUCTION

The increasing deployment of composite structures in engineering applications, many of which are being designed as the primary load-carrying parts in hostile environments, has given greater attention to the long-term behaviour of composite components. Accordingly, there is an urgent need in the engineering community for a predictive tool of the durability, reliability, energy absorber, and safety of composite systems. In the design of modern structures, the damage tolerance of a structure needs to be quantified.

Composite structures are well suited for design with emphasis on damage tolerance due to the ability of continuous fibre composites to arrest cracks and prevent self-similar crack propagation. However, a number of design parameters such as fibre orientation patterns, choices of constituent material combinations, ply drops and hybridization, and render a multiplicity of design options for composite structures. Only by a priori quantification of progressive damage in a composite structure and its fracture characteristics, it is feasible to achieve a damage tolerant design. Compared with homogeneous materials, damage initiation and progression characteristics of fibre composites are much more complicated.

Energy absorber device is used to absorb impact energy in the event of a crash to reduce the net deceleration of the vehicle which might cause serious damage to the occupants. Materials such as carbon fibre/epoxy are inherently brittle and usually

exhibit a linear elastic response up to failure with little or no plasticity. Thus composite structures are vulnerable to impact damage and have to satisfy certification procedures for high velocity impact from the sudden accidents. Conventional metallic structures absorb impact and crash energy through plastic deformation and folding. Modern explicit FE codes are able to model these effects and are being successfully applied to simulate the collapse of metallic aircraft and automotive structures.

High-energy absorbency per unit mass is possible with composite materials if proper failure mechanisms are initiated and maintained during the crash event. Whereas metals absorb energy primarily through plastic deformation, composite materials absorb energy through a variety of failure mechanisms. For example, Kevlar reinforced composites absorb energy through a buckling failure mechanism similar to the accordion buckling modes of metal structures. Carbon fibre and glass fibre-reinforced composites absorb energy through successive failures involving delamination, intraply cracking, and fibre fracture. Because energy absorbency of a composite structure is directly dependent on the failure mode that occurs and the failure mode is a function of the laminate stacking sequence, the loading history and environment, proper characterization ought to include off-axis crush tests.

As well known an initial geometry used by researchers to study the energy absorption capabilities of composite materials was the tube. This geometry is self-stabilizing and allows testing of relatively thin-section laminates. However, the lack of edges along its length reduces the complexity of the boundary conditions and provides consistency throughout the cross section.

In passenger vehicles, the ability to absorb impact energy and be survivable for the occupant is called the “crashworthiness” of the structure. This absorption of energy is through controlled failure mechanisms and modes that enable the maintenance of a gradual decay in the load profile. The crashworthiness of a material is expressed in terms of its specific energy absorption that is characteristic to that particular material. It is defined as the energy absorbed per unit mass of material. In the crashworthiness of automotive structures, the primary issues to the automotive industry are the overall mechanisms, e.g., fibre fracture, matrix crazing and cracking, fibre-matrix debonding, delamination, and inter-ply separation, and sequence of damage are highly dependent on lamina orientation, crush speed, triggers and geometry of the structure. Much of the experimental work to study the effects of fibre type, matrix type, and fibre architecture and specimen geometry on the energy absorption of composite materials has been carried out on axisymmetric tubes. Tube structures are relatively easy to fabricate and close to the geometry of the actual crashworthy structures. These tubes were designed to absorb impact energy in a controlled manner by providing a trigger to initiate progressive crushing. A trigger is a stress concentrator that causes failure to initiate at a specific location within a structure and propagate through the body in a controlled predictable manner. The most widely used method of triggering is chamfering one end of the tube. The brittle fibre reinforced composite tubes crushed in the fragmentation and splaying modes while progressive folding was exhibited by ductile fibre reinforced composite tubes. Both material and structural damage processes need to be well understood to accurately model and design crashworthy automotive composite structures. In the progressive crushing of composite tubes, many different failure mechanisms contribute to the overall energy absorption of

the structure. To isolate the damage mechanisms and quantify the energy absorption contributed by the splaying mode.

Problem Statement

To ensure passengers safety or at least to alleviate severe impact during collision, a highly reliable system is required. In such design and for gross deformation, the overall stability of the energy absorber device is important. However, the tubular composite energy absorber devices crush behaviour is often unstable, with energy absorption rising and falling erratically. The instabilities are one of the more critical problems in using composites tubular devices for crash energy management. To overcome this instability behaviour was the main reason behind this study. Therefore, the primary aim of this study is to explore the ability of composite hemispherical shells as collapsible energy absorber devices.

1.2 Objectives

The overall aim of the present project is to introduce the hemispherical shells to the field of collapsible energy absorber devices. The main specific objectives are as following:

1. To investigate the materials type (matrix& fibre reinforced) effect on the energy absorber capability, failure modes and load carrying capacity of hemi spherical composite shells
2. To examine the effect of the hemi spherical shells aspect ratio (R/t) on the energy absorber capability and failure modes.

3. To examine the relationship between the cross-section area and the energy absorber capability and failure modes of hemi spherical composite shells.

1.3 Importance of the Study

Composite hemispherical shells can be used in many applications such as energy absorber devices in aeroplanes, spacecraft and automotive vehicles, packaging and cushion goods, closure of compressed natural gas and submarines. This study could be useful in a manner to introduce the spherical geometry to the field of energy absorber devices.

1.4 Thesis Layout

Following this introduction chapter, Chapter 2 presents the literature reviews of the energy absorber capability of composite materials, energy shapes and the parameters that affects the energy absorption capability of composite structures. The overall methodology of the current study is presented in Chapter 3. The details of experimental work as well as fabrication and testing procedure are given in Chapter 4. Chapter 5 presents the result and discussion. Finally, in Chapter 6 includes the conclusion drawn from this study as well as the future recommendations are giving.

CHAPTER- II

LITERATURE REVIEW

In this chapter, literatures related to energy absorbers of composite structure, concentrating on hemi-spherical composite shells are reviewed. Factors that affect the energy absorption capability of composite structures are also discussed. In addition, the test methods, crushing modes and mechanisms of composite structure are explained.

2.1 Energy Absorbers

During the last part of the last century, a number of impact engineering problems were studied, especially in the field of the dynamic response of structures in the plastic range. This contributed towards a better understanding of the modes of failure and the energy dissipation patterns during impact in such structures. Such information is important in order to be able to design safer structures and also in evaluating existing ones for specific uses, therefore reducing losses in human and material resources. Application of this field of engineering is now available for use in a wide variety of situations, which include such aspects as crashworthiness of vehicles (cars, lifts, aircraft, ships, etc) [1,2], crash barrier design [3], safety of nuclear reactors [4], collision damage to road bridges [5] and offshore structures and oil tankers [6].

2.2 Energy absorbers Systems

An energy absorber is a system that converts, totally or partially, kinetic energy into another form of energy. Energy converted is either reversible, like pressure