



**UNIVERSITI PUTRA MALAYSIA**

**AXIAL AND LATERAL QUASI-STATIC CRUSHING BEHAVIOUR OF  
SEGMENTED AND NON-SEGMENTED COMPOSITE TUBES**

**AL-HADI A. SALEM ABOSBAIA**

**ITMA 2003 1**

**AXIAL AND LATERAL QUASI-STATIC CRUSHING BEHAVIOUR OF  
SEGMENTED AND NON-SEGMENTED COMPOSITE TUBES**

**By**

**AL-HADI A. SALEM ABOSBAIA**

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

**April 2003**



*Dedication*

*A Special Dedication To*

*My family*

*Hadi*

*Malaysia, 2003*

Abstract of thesis submitted to the Senate of Univeriti Putra Malaysia in partial fulfilment of the requirements for the degree of Master of Science

**AXIAL AND LATERAL QUASI-STATIC CRUSHING BEHAVIOUR OF SEGMENTED AND NON-SEGMENTED COMPOSITE MATERIAL TUBES**

**By**

**AL-HADI A. SALEM ABOSBAIA**

**April 2003**

**Chairman: Dr. Elsadig Mahdi Ahmed**

**Institute: Advanced Technology**

Considerable research interest has been directed towards the use of composite for crashworthiness applications, because they can be designed to provide impact energy absorption capabilities which are superior to those of metals when compared on weight basis. The use of composite circular tubes in structural applications is becoming more widespread throughout the automotives, aircraft industry.

This work examines the effect of segmentation on the crushing behaviour, energy absorption and failure mode of composite circular tubes. The segmented composite tube consists of more than one material, each with its own specific functions. Through out this study, segmented and non segmented composite tubes with different sequences were experimentally investigated under axial and lateral loading conditions. The effect of fibre reinforcement type and segments sequence on energy absorption and load carrying capacity were also presented and discussed.

Load-displacement curves and deformation histories of typical specimens are presented and discussed. The results showed that non-segmented composite tubes were found to be very brittle (i.e. tissue mat glass fibre/epoxy tubes), and show very low initial failure crush load value of 1.89kN, as well as low specific energy absorption value of 0.065kJ/kg under axial crushing. Whereas, the carbon fabric fibre reinforced plastic (CFRP) tubes showed highest load-carrying capacity among the tested specimens with initial failure crush load value of 18.85kN as well as specific energy absorption value of 19.27kJ/kg.

On the other hand, segmented composite tubes including the tissue mat glass fibres were found to suffer from low energy absorption and the catastrophic failure mechanism initiated at the part made of tissue mat glass fibre/epoxy. Segmented Composite tubes from carbon fabric fibre and cotton fabric fibres exhibited good specific energy absorption value of 13.53kJ/kg as well as stable load-carrying capacity under axial loading. A change in segmentation sequence affects the crush loads significantly just for double fibre segmented composite tubes under lateral loading.

The axial loaded segmented composite tubes have better load carrying capacity and energy absorption capability compared to the laterally loaded segmented composite tubes, and the failure modes were quite different.

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

**PENYIASATAN SECARA EXPERIMENTASI TERHADAP REMUKAN  
TIUB KOMPOSIT BERSEGMENT SECARA QUASI-STATIC AXIAL DAN  
LATERAL**

**Oleh**

**ALHADI A. SALEM ABOSBAIA**

**April 2003**

**Pengerusi: Dr. Elsadig Mahdi Ahmed**

**Institut: Teknologi Maju**

Banyak penyelidikan kini berarah kepada penggunaan komposit bagi aplikasi “crashworthiness” disebabkan ia dapat di reka bentuk untuk menyediakan keupayaan tenaga hentaman impak, dimana adalah lebih tinggi daripada logam-logam apabila hendak dibandingkan dengan ciri berat. Kegunaan komposit tiub berongga di dalam aplikasi struktur telah mendapat perhatian meluas hingga ke industri automotif, udara dan aeroangkasa.

Kerja penyelidikan yang dilakukan ini meliputi kesan segmentasi terhadap kelakuan remukan dan mod tenaga penyerapan bagi tiub komposit berongga. Tiub komposit bersegment mempunyai lebih dari satu bahan, setiap satu mempunyai ciri masing-masing. Kajian yang dibuat, segmen atau tidak bersegment dengan ciri-ciri yang berlainan telah disiasat dibawah bebanan axial dan lateral. Kesan daripada jenis gentian tetulang dan ciri-ciri segmen terhadap tenaga penyerapan dan kapasiti beban

bawaan juga telah dibincangkan. Lengkungan beban-anjakan dan sejarah deformasi bagi spesimen tipikal telah juga dibincangkan. Keputusan ujikaji telah menunjukkan bahawa tiub komposit tidak bersegmen adalah sangat rapuh (sebagai contoh: titik tisu gentian kaca/tiub epoksi). Atau mempunyai tenaga penyerapan yang rendah (sebagai contoh: fabrik gentian kapas/epoksi).

Komposit tiub bersegmen pula, termasuk tikar tisu gentian kaca telah didapati mengalami kadar penyerapan tenaga yang rendah dan mekanisma kegagalan teruk pada bahagian yang diperbuat daripada gentian/epoksi tersebut. Komposit tiub bersegmen menunjukkan kadar penyerapan yang baik dan juga kapasiti beban bawaan yang stabil dibawah bebanan axial. Perubahan ciri segmentasi tiub komposit akan mempengaruhi beban remukan (DF) dibawah bebanan lateral.

Beban axial tiub komposit bersegmen mempunyai kadar beban bawaan dan keupayaan kadar penyerapan tenaga keatas tiub komposit bersegmen yang dikenakan beban lateral tetapi pada sifat kegagalan yang berbeza.

## ACKNOWLEDGMENTS

بسم الله الرحمن الرحيم

أن من يستحق الشكر حقاً هو الله سبحانه وتعالى علي عظيم فضله وتوفيقه لي في إتمام هذا البحث المتواضع فله الحمد والشكر سبحانه وتعالى. كذلك شكر وتقدير ومحبه عظيمة الى أبي وأمي الأعتزاء لدعائهما لي بالتوفيق والنجاح فيدون تعبهما وسهرهما عليّ طوال سنوات العمر الماضية لما وصلت الى هذه الدرجة. ولا يفوتني أن أخص بالشكر الى زوجتي الفاضلة علي ما بذلته من جهد وتعب طوال فترة دراستي.

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

Furthermore, I would like to take this opportunity to express my deepest appreciation and gratitude to Associate Professor Dr. Abd El-Magid Salem Hamouda for his advice, valuable suggestion, and comments.

Also, I would like to thanks to Professor Dr. Barkawi Bin Sahari for his suggestions and constructive criticisms given at different stages of this study.

Finally, deep thanks to my best friend Ebrahim Alfegi for his support, and help during the fabrication of the experimental work.

Alhadi A. Absobaia



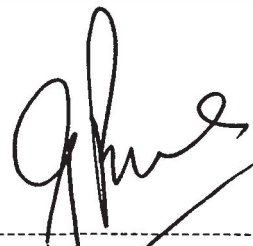
I certify that an Examination Committee met on 23<sup>th</sup> April 2003 to conduct the final examination of Alhadi A. Salem Abosbaia on his Master of Science thesis entitled “Axial and Lateral Quasi-Static Crushing Behaviour of Segmented and Non-Segmented Composite Tubes” in accordance with Universiti 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:

**Wang Shaw Voon, Ph.D**  
Mechanical Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Elsadig Mahdi Ahmed, Ph.D**  
Aerospace Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Abdel Magid Salem Hamuoda, Ph.D**  
Associate Professor,  
Mechanical Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Barkawi Bin Sahari, Ph.D.**  
Professor  
Mechanical Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)



---

**GULAM RUSUL RAHMAT ALI, Ph.D,**  
Professor/ Deputy Dean,  
School of Graduate Studies  
Universiti Putra Malaysia

Date: 16 JUN 2003

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

**Elsadig Mahdi Ahmed, Ph.D**

Aerospace Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Abdel Magid Salem Hamuoda, Ph.D**

Associate Professor,  
Mechanical Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Barkawi Bin Sahari, Ph.D.**

Professor  
Mechanical Department  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)



---

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

Date: 11 JUL 2003

## DECLARATION

I hereby declare that this 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 institution

  
AL-HADI A. ABOSBAIA

Date: 16.06.2003

## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	ii
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	v
<b>ACKNOWLEDGEMENTS</b>	vii
<b>APPROVAL</b>	viii
<b>DECLARATION</b>	x
<b>TABLE OF CONTENTS</b>	xi
<b>LIST OF TABLES</b>	xv
<b>LIST OF FIGURES</b>	xvi
<b>NOMENCLATURE</b>	xviii
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	1
1.1 Segmentation Concept	4
1.2 Objectives	4
1.3 Significance of the study	5
1.4 Organization of thesis	5
<b>2 LITRETURE REVIEW</b>	7
2.1 Composite Material	7
2.2 Fibre-Reinforced Composite Materials	8
2.2.1 Synthetic fibres	8
2.2.2 Natural Fjbre	10
2.2.3 Matrix Materials	11
2.3 Fabrication Methods of Composite Shells	12
2.3.1 Woven roving Wrapping	13
2.4 Composite Forms	13
2.4.1 Single Fibre System	13
2.4.2 Multi Material System	14
2.5 Failure Mechanism of composite materials	14
2.5.1 Matrix Crack	15
2.5.2 Fibre Breakage	15
2.5.3 Fibre Pullout	16
2.5.4 Fibre-Matrix Debonding	17
2.5.5 Delamination	17
2.6 Crushing Mode of Structure Composite Material	18
2.6.1 Transverse shearing crushing mode	19
2.6.2 Lamina bending crushing mode	20
2.6.3 Brittle fracturing crushing mode	21
2.6.4 Local buckling crushing mode	22
2.7 Crushing of metallic and composite circular tubes	23
2.7.1 Metallic Circular Tubes	24
2.7.2 Composite Circular Tubes	27
2.8 Crashworthiness Parameters	30



2.8.1	Crush Force Efficiency-Stroke Efficiency Relation	31
2.8.2	Energy Absorption Capability	32
2.8.3	Initial Failure Indicator	33
2.9	Conclusion	34
<b>3</b>	<b>METHODOLOGY</b>	<b>35</b>
3.1	Introduction	35
3.2	Preparation of mandrel	36
3.3	Fabrication of segmented and non- segmented composite tubes	37
3.3.1	Type of material and fibre	37
3.3.2	Specimen's specification	37
3.4	Test specimen's fabrication procedures	38
3.5	Crushing Process	39
3.5.1	Axial Crushing	39
3.5.2	Lateral Test	41
3.6	Discussion	41
<b>4</b>	<b>Results and Discussion</b>	<b>42</b>
4.1	Design Parameters	42
4.2	Repeatability and Accuracy of the Machine	42
4.3	Crashworthiness Parameters	43
4.3.1	Crush Force Efficiency-Stroke Efficiency Relation	44
4.3.2	Energy Absorption Capability	45
4.3.3	Initial Failure Indicator	46
4.4	Axial Crushing	47
4.4.1	Load-Deformation	47
4.4.1.1	Single Fibre (DF) Reinforced Segmented Composite Tube	47
4.4.1.1.1	(CT-CT-CT)FRP Tube	47
4.4.1.1.2	(C-C-C)FRP Tube	49
4.4.1.1.3	(GT-GT-GT)FRP Tube	50
4.4.1.2	Double Fibre (DF) Reinforced Segmented Composite Tube	51
4.4.1.2.1	(CT-CT-C)FRP Tube	51
4.4.1.2.2	(CT-CT-GT)FRP Tube	53
4.4.1.2.3	(GT-GT-C)FRP Tube	55
4.4.1.2.4	(GT-GT-CT)FRP Tube	56
4.4.1.3	Triple Fibre (TF) Reinforced Segmented Composite Tube	57
4.4.1.3.1	(CT- C-GT)FRP Tube	57
4.4.1.3.2	(C-CT-GT)FRP Tube	57
4.4.1.3.3	(CT -GT- C)FRP Tube	60
4.5	Failure Modes	61
4.5.1	Single Modes (SM)	61
4.5.1.1	SMI	61
4.5.1.2	SMII	62
4.5.2	Multi Modes (MM)	63
4.5.2.1	MMI	63
4.5.2.2	MMII	63

4.5.2.3	MMIII	64
4.5.2.4	MMIV	65
4.6	Discussion	66
4.6.1	Specific Energy Absorption (ES)	66
4.6.2	Effect of Fibre Reinforcement Type	69
4.6.3	Effect of Segmentation on Crashworthiness Parameters	70
4.7	Lateral Crushing	73
4.7.1	Failure Mode and Load-Deformation Curve	73
4.7.1.1	Tests on Single Fibre (SF) Tube	73
4.7.1.1.1	(CT-CT-CT)FRP Tube	73
4.7.1.1.2	(C-C-C)FRP Tube	74
4.7.1.1.3	(GT-GT-GT)FRP Tube	74
4.7.1.2	Tests on Double Fibre (DF) Tube	79
4.7.1.2.1	(CT-CT-C)FRP Tube	79
4.7.1.2.2	(CT-CT-GT)FRP Tube	79
4.7.1.2.3	(GT-GT-C)FRP and (GT-GT-CT)FRP Tubes	80
4.7.1.3	Triple Fibre (TF) Reinforced Segmented Composite Tube	85
4.8	Discussion	90
4.8.1	Specific Energy Absorption (ES)	90
4.8.2	Effect of Fibre Reinforcement Type and Segments Sequence	92
4.8.3	Effect of Segmentation on Crashworthiness Parameters	94
4.9	Recovery of Specimens	95
4.10	Conclusion	97
<b>5</b>	<b>ANALYTICAL SOLUTION</b>	<b>99</b>
5.1	Introduction	99
5.2	Assumptions	99
5.3	Orthotropic material	100
5.4	Plane stress	101
5.5	Reduced stiffness matrix	101
5.6	Laminate stiffness Matrix: (ABD Matrix)	102
5.7	Stress-strain relation	105
5.8	Failure criteria	106
5.8.1	Maximum stress	106
5.8.2	Tsai-Wu failure criteria	107
5.9	Numerical Example	108
5.9.1	Non-segmented composite tubes	108
5.9.2	Result	112
5.9.3	Discussion	112
5.9.4	Conclusion	113
5.10	Flow chart describe steps for a stress analysis for a composite laminate	114
<b>6</b>	<b>CONCLUSION</b>	<b>115</b>
6.1	Quasi-static Axial Crushing	115
6.2	Quasi-static Lateral Crushing	116

6.3	Recommendation and future suggestion work	117
	<b>REFERENCE</b>	119
	<b>APPENDIX (A)</b>	124
	<b>VITA</b>	126



## LIST OF TABLES

TABLE		Page
3.1	Constituent materials	37
3.2	Specification of test specimens	40
4.1	Characterization of failure mode	66
4.2	Crashworthiness parameters of segmented and non-segmented composite tubes under axial load	72
4.3	Crashworthiness parameters of segmented and non-segmented composite tubes under lateral load	97
5.1	Elastic engineering properties of the materials	109
5.2	Failure stresses of the materials	110
5.3	Comparison between the experimental and theoretical results for initial failure	112



## LIST OF FIGURES

Figure		Page
2.1	Unidirectional fibre-matrix reinforced composite material in a unidirectional form	8
2.2	Hybrid system	14
2.3	Matrix cracking failure	15
2.4	Fibre breaking failure	16
2.5	Fibre pull-out during crack failure	16
2.6	Fiber matrix debonding failure	17
2.7	Delamination crack failure	18
2.8	Crushing characteristics of transverse shearing crushing mode	20
2.9	Crushing characteristics of lamina bending crushing mode	21
2.10	Crushing characteristics of brittle fracture crushing mode	22
2.11	Crushing characteristics of local buckling crushing mode	23
3.1	Flow chart shows the procedure of methodology	34
3.2	Schematic fabrication process for segmented composite tube	35
3.3	Segmented composite tube under axial load	36
3.4	Segmented composite tube under lateral load	38
4.1	Repeatability of load-displacement curves for three specimens of (CT-CT-CT)FRP	43
4.2	Load-displacement curves and deformation histories of (CT-CT-CT)FRP segmented composite tubes under axial load	48
4.3	Load-displacement curves and deformation histories of (C-C-C)FRP segmented composite tubes under axial load	49
4.4	Load-displacement curves and deformation histories of (GT-GT-GT)FRP segmented composite tubes under axial load	51
4.5	Load-displacement curves and deformation histories of (CT-CT-C)FRP segmented composite tubes under axial load	52
4.6	Load-displacement curves and deformation histories of (CT-CT-GT)FRP segmented composite tubes under axial load	54
4.7	Load-displacement curves and deformation histories of (GT-GT-C)FRP segmented composite tubes under axial load	55
4.8	Load-displacement curves and deformation histories of (GT-GT-CT)FRP segmented composite tubes under axial load	57
4.9	Load-displacement curves and deformation histories of (CT-C-GT)FRP segmented composite tubes under axial load	58
4.10	Load-displacement curves and deformation histories of (C-CT-GT)FRP segmented composite tubes under axial load	59
4.11	Load-displacement curves and deformation histories of (CT-GT-C)FRP segmented composite tubes under axial load	60
4.12	Specific energy absorption-stroke efficiency curves of a single fibre (SF) reinforced segmented composite tubes under axial load	67
4.13	Specific energy absorption-stroke efficiency curves of double fibres (DF) reinforced segmented composite tubes under axial load	68

4.14	Specific energy absorption-stroke efficiency curves of triple fibres (TF) reinforced segmented composite tubes under axial load	68
4.15	Effect of fibre reinforcement types on crushing behaviour of axially loaded segmented composite tubes	69
4.16	Effect of segmentation types on crushing behaviour of axially loaded composite tubes	71
4.17	Load-displacement curves and deformation histories of (CT-CT-CT)FRP segmented composite tubes under lateral load	76
4.18	Load-displacement curves and deformation histories of (C-C-C)FRP segmented composite tubes under lateral load	77
4.19	Load-displacement curves and deformation histories of (GT-GT-GT)FRP segmented composite tubes under lateral load	78
4.20	Load-displacement curves and deformation histories of (CT-CT-C)FRP segmented composite tubes under lateral load	81
4.21	Load-displacement curves and deformation histories of (CT-CT-GT)FRP segmented composite tubes under lateral load	82
4.22	Load-displacement curves and deformation histories of (GT-GT-C)FRP segmented composite tubes under lateral load	83
4.23	Load-displacement curves and deformation histories of (GT-GT-CT)FRP segmented composite tubes under lateral load	84
4.24	Load-displacement curves and deformation histories of (CT-C-GT)FRP segmented composite tubes under lateral load	87
4.25	Load-displacement curves and deformation histories of (C-CT-GT)FRP segmented composite tubes under lateral load	88
4.26	Load-displacement curves and deformation histories of (CT-GT-C)FRP segmented composite tubes under lateral load	89
4.27	Specific energy absorption-stroke efficiency curves of a single fibre (SF) reinforced segmented composite tubes under lateral load	91
4.28	Specific energy absorption-stroke efficiency curves of double fibres (DF) reinforced segmented composite tubes under lateral load	91
4.29	Specific energy absorption-stroke efficiency curves of triple fibres (TF) reinforced segmented composite tubes under lateral load	92
4.30	Effect of fibre reinforcement types on crushing behaviour of laterally loaded segmented composite tubes	93
4.31	Effect of segmentation types on crushing behaviour of laterally loaded composite tubes	95
4.32	Recovery of specimens under quasi-static lateral condition	96
5.1	Uniaxial loading in x-direction	100
5.2	Symmetric laminate coordinates	103
5.3	Unidirectional reinforced lamina	105
5.4	Non-segmented composite tubes under axial compression	109
5.5	Tensile load-displacement curves for cotton fabric, carbon fabric, tissue mat fiber/epoxy	110
5.6	Flow chart describes steps for a stress analysis for a composite laminate	114
A.1	Straight-sided coupon	125

## NOMENCLATURE

A	Cross-section area
R	Radius of the tube
D	Diameters of the tube
H	Height of the tube
M	Weight of the tube
$P_m$	Average crush failure load
$P_i$	Initial crush failure load
$P_{1P}$	First peak crush failure load
$P_{pt}$	Highest first peak crush load
s	Instantaneous deformation
CFE	Crush force efficiency
SE	Stroke efficiency
$E_s$	Crushing energy absorbed per unit mass
MM	Multi failure modes
SM	Single failure modes
CT	Cotton fabric fibre
C	Carbon fabric fibre
GT	Tissue mat glass fibre
FRP	Fibre-reinforced plastic
SF	Single fibre
DF	Double fibre
TF	Triple fibre
IFI	Initial failure indicator
u	Crush distance
$E_{11}$	Young's modulus in 1 direction
$\nu_{12}$	Poisson's ratio in 1-2 direction
$G_{12}$	Shear modulus
$Q_y$	Reduced Stiffness
$A_{ij}$	Represents the extensional stiffness matrix
$B_{ij}$	Represents the coupling stiffness matrix
$D_{ij}$	Represents the bending stiffness matrix



$N_x, N_y$ , Normal forces in x-direction, y-direction resultants  
 $N_{xy}$ , Shear force resultants  
 $M_x, M_y$ , Bending moment resultants  
 $M_{xy}$  Twisting moment resultants  
 $k^0$  Curvature strain  
 $\sigma_1^t$  Tensile failure stress in the 1 direction  
 $\sigma_1^c$  Compressive failure stress in the 1 direction  
 $\sigma_2^t$  Tensile failure stress in the 2 direction  
 $\sigma_2^c$  Compressive failure stress in the 2 direction  
 $\tau_{12}^f$  Shear failure stress in the 1-2 plane

## CHAPTER ONE

### INTRODUCTION

Vehicle crashworthiness has been improved in recent years with attention mainly directed towards reducing the impact of the crash on the passengers. Efforts have been made in experimental research to establish safe theoretical design criteria for the mechanics of crumpling, providing the engineers with the ability to design vehicle structures so that the maximum amount of energy will dissipate while the material surrounding the passenger compartment is deformed, thus protecting the people inside.

During the last two decades, the attention given to crashworthiness and crash energy management has been centred on fibrous composite structures. The main advantages of fibre reinforced composite materials over conventional metals; however, are their high specific strength and stiffness, which can be achieved. It is also interesting to note that despite their relatively low strength and stiffness to weight ratio metal tubes are versatile construction components and are also efficient energy absorbing elements. In that manner, aluminium and paper honeycombs are rated as very efficient energy absorbers.

Moreover, with composites, the designer can vary the type of fibre, matrix and fibre orientation to produce composites with improved material properties. Besides the perspective of reduced weight, design flexibility and low fabrication costs of

composite materials offer a considerable potential for lightweight energy absorbing structures, these facts attract the attention of the automotive and aircraft industry owing to the increased use of composite materials in various applications, such as frame rails and the sub-floor of an aircraft, replacing the conventional materials used

Previous investigations indicated that composite shells deform in a manner different to similar structural components made of conventional materials, (i.e. metals/polymers) since micro failure modes, such as matrix cracking, delamination, fibre breakage etc, constitute the main failure modes of these collapsed structures. Therefore, this complex fracture mechanism renders difficulties to theoretically model the collapse behaviour of fibre-reinforced composite shells.

Extensive research work has focused primarily on axial loading and bending of simple thin-walled composite structures. The effect of specimen geometry on the energy absorption capability was investigated by varying the cross-sectional dimensions, wall thickness and length of the shell. The effect of the type of composite material, laminate sequence, loading conditions and strain rate on the crashworthy behaviour of the components were also studied. Environmental effects related to crash characteristics of composites have also been investigated.

However, the behaviour of crushable composite energy absorber devices is often unstable, with energy absorption rising and falling erratically. This instability is one of the more critical problems in using fibre composites for crash energy management. It is interesting to note that specific energy absorption capability of

composite devices is significantly influenced by the failure mechanism, which depends on many factors, such as material constituent, fibre architecture, fabrication process, geometry of elementary substructures and loading conditions.

It could be concluded from that axial crushing of non-trigger tubes (i.e. tube with constant thickness and straight wall) produces an unstable load-end shortening behaviour characterized by energy absorption rising and falling erratically. In previous work, the initial crush failure load was found to have a significant effect on the energy absorption during crush.

To achieve stable crush-deformation behaviour as well as to maximize the energy absorption capability of the composites structures, the sharpness and magnitude of the instability needs to be minimized or eliminated. Extensive experimental work concerning the axial collapse of thin-walled composite material tubes of various geometries and material under various loading conditions demonstrated a high energy absorbing capability of these materials.

The operating loads of laterally compressed tubes are for lower than those of axially compressed tubes and the energy absorbed by laterally loaded tube is about an order of magnitude less than what it can absorb under axial compression, however the energy absorbing capability of laterally compressed tubes can be increased by encouraging the tubes to deform in alternative modes which involve more plastic hinges. The stable crushing stage is generally more important because this is where much of the energy absorption takes place. Compliant material (i.e. cotton fabric

CTFRP) has used to achieve this stability, with low post crash stage. Whereas, when the stiff composite material is used (i.e. carbon fibre CFRP or tissue mat GFRP), it exhibited high post crash stage with unstable behaviour.

The inspiration of the current work is to study the crashworthiness performance of segmented woven roving laminated composite tubes in terms of energy absorption capability and load carrying capacity subjected to quasi-static axial and lateral crushing load.

### **1.1 Segmentation Concept**

Most of the existing data concerns with the failure mechanism and energy absorbing characteristics are obtained from the crushing investigation of composite circular tubes. Therefore, it was preferred to examine the effect of segmentation on their crushing behaviour. Tubes with same diameters were chosen to eliminate the influence of geometry so that the effect of segmentation remains.

### **1.2 Objectives**

The main objectives of this work are:

1. To study the effect of loading conditions on crushing behaviour of segmented composite tubes.



2. To study the crushing behaviour for different arrangements of axial segmentation composite tubes.
3. To examine the energy absorption capability of axially segmented composite tubes.

### **1.3 Significance of the Study**

It is interesting to study the effect of the segmentation on composite materials, and also to investigate the energy absorber devices using different materials as composite-composite materials. This study is important because of the following;

1. The present study is focused on introducing a new concept for collapsible energy absorber device.
2. This study may change the design philosophy of applying the hybrid energy absorber system.
3. The generated data from this study can be useful in the design of energy absorber elements made from composite materials.

### **1.4 Organization of Thesis**

The thesis is organised as follows: Chapter one is an introduction of thesis and the objectives. Chapter two reviews of the literature of the fibre reinforced composite materials and studies on their use as energy absorption structure devices. Methodology used in this study has explained in Chapter three. Experimental results