

# UNIVERSITI PUTRA MALAYSIA

# DEVELOPMENT OF A NEW COMPOSITE ENERGY-ABSORBER SYSTEM FOR AIRCRAFT AND HELICOPTER SUB-FLOORS

SIAVASH TALEBI TAHER.

FK 2005 24



# DEVELOPMENT OF A NEW COMPOSITE ENERGY-ABSORBER SYSTEM FOR AIRCRAFT AND HELICOPTER SUB-FLOORS

By

## SIAVASH TALEBI TAHER

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

September 2005



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

## A NEW COMPOSITE ENERGY-ABSORBER SYSTEM FOR AIRCRAFT AND HELICOPTER SUB-FLOORS

By

## SIAVASH TALEBI TAHER

September 2005

Chairman: Elsadig Mahdi Ahmed, PhD

Faculty : Engineering

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 parts in structural and semi-structure applications is becoming more widespread throughout the automotives, aircraft and space vehicles.

In this study, an innovative lightweight composite energy-absorbing keel beam system has been developed to be retrofitted in aircraft and helicopter in order to improve their



crashworthiness performance. The developed system consists of everting stringer and keel beam. The sub floor seat rails were designed as everting stringer to guide and control the failure mechanisms at pre-crush and post crush failure stages of composite keel beam webs and core. Polyurethane foam was employed to fill the core of the beam to eliminate any hypothesis of global buckling. The numerical prediction was obtained using commercially available finite element analysis software. The experimental data are correlated with predictions from finite element model and analytical solution. An acceptable agreement between the experimental and computational results was obtained. For all structures considered classical axial collapse eigen values were computed.

The results showed that the crushing behaviour of the developed system is found to be sensitive to the change in keel beam core cross-section. Laminate sequence has a significant influence on the failure mode types, average crush loads and energy absorption capability of composite keel beam. The desired energy absorbing mechanism revealed that the innovated system can be used for aircraft and helicopter and meet the requirements, together with substantial weight saving.



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

## SISTEM KOMPOSIT PENYERAPAN TENAGA BARU UNTUK SUB-TAPAK KAPALTERBANG DAN HELIKOPTER

Oleh

## SIAVASH TALEBI TAHER

September 2005

Pengerusi: Elsadig Mahdi Ahmed, Ph.D.

Fakulti : Kejuruteraan

Banyak kajian telah dijalankan dalam penggunaan komposit untuk kajian 'crashworthiness' kerana komposit boleh direkabentuk untuk kebolehan penyerapan tenaga yang lebih tinggi jika dibandingkan dengan logam berasaskan berat. Penggunaan tiub bulat komposit dalam applikasi struktur dan semi-struktur semakin tersebar dalam industri automotif, pesawat dan kapal angkasa.

Dalam kajian ini, sistem penyerapan tenaga alur lunas ringan yang inovatif telah dihasilkan untuk pemasangan dalam pesawat dan helikopter bertujuan untuk



memperbaiki prestasi 'crashworthiness'. Gelegar, everting membentuk rel duduk sublantai bertujuan untuk membimbing dan mengawal mekanisma kegagalan pada web dan teras alur lunas komposit di tahap kegagalan pra-hancur dan selepas hancur. Polyurethane digunakan untuk membentuk teras alur tersebut agar lengkokan global dapat dihindarkan. Jangkaan numerikal diperolehi melalui perisian unsur terhingga komersil. Korelasi data eksperimen dengan data dari numerikal dan analitik dilakukan dan didapati ada persetujuan antara kedua-dua data eksperimen dan pengkomputeran. Nilai eigen runtuh sepaksi klasikal dikirakan untuk semua struktur yang dipertimbangkan.

Hasil menunjukkan bahawa kelakuan penghancuran sistem yang dibina adalah peka terhadap perubahan keratan rentas teras alur lunas. Susunan lamina memberi kesan terhadap jenis mod kegagalan, beban purata hancur dan kebolehan penyerapan tenaga alur lunas komposit. Mekanisma penyerapan tenaga terhasil membuktikan bahawa system inovatif ini boleh digunakan untuk pesawat dan helikopter serta memenuhi semua keperluan disamping menjimatkan berat.



### ACKNOWLEDGEMENTS

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

A particular note of thanks is also given to the Prof. Dr. Fakhrul-Razi Ahmedun for his suggestions and financial support and members of supervisory committee Dr. Ahmad Samsuri Mokhtar and Mrs. Dayang Laila Abg Abdol Majid for their suggestions and constructive criticisms given at different stages of this study.

Finally, I would like to express my indebtedness to my family for their moral and financial support.



# **TABLE OF CONTENTS**

ABS ABS ACK APPI DEC LIST LIST NOM	FRACT FRAK NOWL ROVAI LARAT OF TA OF FI IENCL	L L FION ABLES GURES ATURE	Page ii iv vi vii ix xiii xiv xxii
СНА	PTERS		
1	INTR	RODUCTION	1
	1.1	Research Objectives	2
	1.2	Significance of the Study	3
	1.3	Thesis Layout	4
2	LITE	CRATURE REVIEW	5
	2.1	Fabric Fibre Reinforced Composites	5
		2.1.1 Glass Fabric Fibre (2D Weaves)	6
		2.1.2 Epoxy Resin	8
		2.1.3 Fabrication Processes of Composite Beams	9
		2.1.4 Hand Lay-up Fabrication Process	9
	2.2	Energy Absorption Capability of Composite Materials	10
		2.2.1 Crashworthiness Parameters	10
		2.2.2 Crushing Behaviour of Composite Materials	14
	2.3	Aircraft Sub-structure as Energy Absorption Element	20
		2.3.1 Aircraft Crashworthiness	20
		2.3.2 Helicopters	22
	2.4	2.3.3 Large Airplanes	24
	2.4	Keel Beam	26
		2.4.1 Metallic Keel Beam	26
	25	2.4.2 Composite Keel Beam	28
	2.3	Discussion	33
3	EXPE	ERIMENTAL SET-UP	34
	3.1	Conceptual Design	36
		3.1.1 Keel Beam Components	34
	• -	3.1.2 Designed Energy absorption Mechanism of the Keel Beam	38
	3.2	Experimental Work	39
		3.2.1 Specimens Types	42
		3.2.2 Flange (Everting Stringer)	43



		3.2.3	Materials	45
		3.2.4	Test Procedure	45
	3.3	Discu	ssion	46
4	EXPI	ERIME	NTAL WORK	48
	4.1	Keel H	Beam Type A	49
		4.1.1	Load-Displacement Relations	49
		4.1.2	Energy-Displacement Relations	52
		4.1.3	Crushing History and Failure Modes	55
		4.1.4	Effect of the r/t Ratio on the Load Carrying Capacity	61
		4.1.5	Effect of the r/t Ratio on the Energy Absorption Capability	62
		4.1.6	Effect of r/t Ratio on the Specific Energy Absorption	63
	4.2	Keel E	Beam Type B	65
		4.2.1	Load-Displacement Relations	65
		4.2.2	Energy-Displacement Relations	68
		4.2.3	Crushing History and Failure Modes	72
		4.2.4	Effect of r/t Ratio on the Load Carrying Capacity	78
		4.2.5	Effect of the r/t Ratio on the Energy Absorption	79
			Capability	
		4.2.6	Effect of r/t Ratio on the Specific Energy	79
	4.3	Keel E	Beam Type C	82
		4.3.1	Load-Displacement Relations	82
		4.3.2	Energy-Displacement Relations	86
		4.3.3	Crushing History and Failure Modes	89
		4.3.4	Effect of r/t Ratio on the Load Carrying Capacity	95
		4.3.5	Effect of the r/t Ratio on the Energy Absorption Capability	96
		4.3.6	Effect of r/t Ratio on the Specific Energy	97
	4.4	Effect	of Everting Element on Keel Beam crushing	99
		Perfor	mance	
		4.4.1	Effect of Everting Element on Load-Displacement Relation	99
		4.4.2	Effect of Everting Element on Energy-Displacement Relation	100
	4.5	Effect	of Fibre Sequence on Keel Beam crushing Performance	101
		4.5.1	Effect of Fibre Sequence on Load-Displacement	10
			Relation	
		4.5.2	Effect of Fibre Sequence on Energy-Displacement Relation	104
	4.6	Failure	e Modes of Keel Beam Composite System	105
	4.7	Conch	usion	106
				100
5	ANAL	YTICA	L SOLUTION AND FINITE ELEMENT SIMULATION	107
	5.1	Analy	lical Solution	107

		5.1.1	Buckling of Laminated Plates	107
		5.1.2	Buckling of Simply Supported Laminated Plates under	111
			In-Plane Load	
		5.1.3	Analytical Results for Keel Beam	114
		5.1.4	Comparison of Experimental and Analytical Results	119
	5.2	Finite 1	Element work	121
		5.2.1	Modelling Composite Materials Using the ANSYS Finite	121
		Elemei	nt Software	
		5.2.2	Finite Element Model of Keel Beam Edge	124
		5.2.3	Comparison between Experimental and Finite Element	132
			Results	
	5.3	Conclu	ision	134
_				
6	CON	CLUSIC	ONS AND RECOMMENDATIONS	135
	6.1	Conclu	ision	135
	6.2	Recom	mendations for Future Work	137
REI	FRENCE	ES		139
API	PENDIC	ES		143
BIO	DATA (	OF THE	AUTHOR	159



# LIST OF TABLES

Table	Title	Page
4.1	Crashworthiness parameters for keel beams with foam ratio $FR=83\%$ .	64
4.2	Crashworthiness parameters for keel beams with foam ratio $FR=56\%$ .	81
4.3	Crashworthiness parameters for keel beams with foam ratio $FR=39\%$ .	98
5.1	Comparison of the experimental and theory eigenvalue analysis	119
5.2	Comparison between the experimental and FE buckling analyses	132
6.2	Knock-down factors for the FEM buckling analysis	134
B1	Test matrix for crush test of Keel beam	157



# **LIST OF FIGURES**

Figure	Title	Page
2.1	Commonly used 2D weave patterns	7
2.2	Schematic presentation of the load-displacement curve for a composite material under axial crush condition	11
2.3	Various failures at different scales	15
2.4	Transverse shearing crushing mode	18
2.5	Lamina bending crushing mode	19
2.6	Local Buckling crushing mode	20
2.7	Mechanism for energy absorption in a helicopter or aircraft. Occupant slowed down by total displacement of gear, sub-floor and seat.	22
2.8	Front view photos from a high-speed camera showing crash key events of the Sikorsky ACAP helicopter at NASA Langley Research Centre.	23
2.9	Crash tests of the large transport aircraft (a): Fuselage in drop test rig. (b): Fuselage after drop test. (c) A complete fuselage after crash test	25
2.10	Typical framework structure of aircraft sub-floor	26
2.11	Typical framework metallic structure of aircraft sub-floor. (a): Before crash test. (b): After crash test.	27
2.12	Sine-wave beam concept for energy absorption	29
2.13	Carbon/Aramid hybrid Energy absorption sine wave beam in Tiger helicopter (Euro copter Company). (a): Tiger internal structures.(b): EA si wave beam.	29 ne
2.14	Composite sub-floor and details of the lower forward fuselage. (a): Post test photograph of the sub-floor consisting of two horizontal C-channels, one above the other, with beaded (or waffle) web geometry. (b): Schematic of the lower forward fuselage.	31
2.15	Lear Fan full composite aircraft. (a): Lear Fan prototype in dynamic crash test rig. (b): keel beams in sub-floor. (c) Keel beam specimen after quasi static crushing test.	32



3.1	Schematic representation of the main steps used in the fabrication of the keel beams.	36
3.2	Beams are assembled in to a sub-floor.	37
3.3	Final assembling of keel beams in the fuselage	38
3.4	schematic representation of keel beam crushing mechanism	39
3.5	stages of keel beam web crushing	41
3.6	Flow chart describes the experimental work	42
3.7	General configurations of specimens with foam ratios 39%, 56% and 83%	44
3.8	Flanges and supports. (a): Plate and flanges assembly and positions of fixing everting flanges. (b): Plate part details. (c): Everting flange details.	46
3.9	Fabrication stages. (a): Cutting and sizing of composite laminates. (b): Bounding one side of foam. (c): Bounding another side of foam. (d): bounding the sandwich panel on a plywood base. (e): Some final specimens.	47
4.1	Load-displacement curves for three similar keel beam specimens with $r/t=12.5$	50
4.2	Load-displacement curves for three similar keel beam specimens with $r/t=8.33$	51
4.3	Load-displacement curves for three similar keel beam specimens with $r/t=6.25$	52
4.4	Energy-displacement curves for three similar keel beam specimens with $r/t=12.5$	53
4.5	Energy-displacement curves for three similar keel beam specimens with $r/t=8.33$	54
4.6	Energy-displacement curves for three similar keel beam specimens with r/t=6.25	55
4.7	The beginning of keel beam crushing.	56
4.8	Post-buckling failure of web edge immediately after first edge buckling	57
4.9	Load-displacement curve during pre-crush stage and decreasing the load	57

in beginning of post-crush stage

4.10	First and second buckling failures and a portion of web in threshold of buckling	58
4.11	Alternative stiffening and softening during buckling of composite web of keel beam	58
4.12	Buckling in left side web of beam. Crests and node of buckling wave are recognizable	59
4.13	Sequences of failure of keel beam on load-displacement curve	60
4.14	Post buckling failure in the both webs of the keel beam	60
4.15	Average crushing load as a function of r/t ratio for foam ratio of 83%	61
4.16	Energy per unit length absorbed as a function of $r/t$ ratio for foam ratio of 83%	62
4.17	Specific energy as a function of r/t ratio for foam ratio of 83%	63
4.18	Load-displacement curves for three similar keel beam specimens with $r/t=2.5$	66
4.19	Load-displacement curves for three similar keel beam specimens with $r/t=8.33$	67
4.20	Load-displacement curves for three similar keel beam specimens with $r/t= 6.25$	68
4.21	Energy-displacement curves for three similar keel beam specimens with r/t=12.5	69
4.22	Energy-displacement curves for three similar keel beam specimens with $r/t= 8.33$	70
4.23	Energy-displacement curves for three similar keel beam specimens with $r/t= 6.25$	71
4.24	Edge buckling and webs local buckling at the beginning of keel beam crushing.	72



4.25	Post buckling failure of edge and web immediately after pre-crush stage	73
4.26	Load-displacement curve during pre-crush stage and decreasing the load in beginning of post-crush stage	74
4.27	Alternative stiffening and softening during buckling of composite web of keel beam	75
4.28	Global buckling of keel beam after first edge buckling	76
4.29	Buckling in left side web of beam. Crests and node of buckling wave are recognizable	76
4.30	Post buckling failure in the both webs of the keel beam	77
4.31	Sequences of failure of keel beam on load-displacement curve	77
4.32	Average crushing load as a function of r/t ratio for foam ratio of 56%	78
4.33	Energy per unit length absorbed as a function of r/t ratio for foam ratio of 56%	80
4.34	energy as a function of r/t ratio for foam ratio of 56%.	80
4.35	Load-displacement curves for three similar keel beam specimens with $r/t= 12.5$	83
4.36	Load-displacement curves for three similar keel beam specimens with $r/t= 8.33$	84
4.37	Load-displacement curves for three similar keel beam specimens with $r/t=6.25$	85
4.38	Energy-displacement curves for three similar keel beam specimens with $r/t= 12.5$	87
4.39	Energy-displacement curves for three similar keel beam specimens with $r/t= 8.33$	88

4.40	Energy-displacement curves for three similar keel beam specimens with $r/t=6.25$	88
4.41	Edge buckling at the beginning of keel beam crushing. In pre-crush stage, edge of beam web, buckles inside the grove of stringer	89
4.42	Post buckling failure of edge and beginning second edge buckling after pre-crush stage	90
4.43	Load-displacement curve during first edge buckling (pre-crush stage) and second alternating buckling after pre-crush stage	91
4.44	Alternating load in post-crush stage includes a rising trend and a constant trend region	92
4.45	Global buckling of keel beam after first edge buckling	93
4.46	Buckling in left side web of beam. Crests and node of buckling wave are recognizable	94
4.47	Post buckling failure in the both webs of the keel beam	94
4.48	Sequences of failure of keel beam on load-displacement curve	95
4.49	Average crushing load as a function of the r/t ratio for foam ratio of 39%	96
4.50	Energy per unit length absorbed as a function of the r/t ratio for foam ratio of 39%	97
4.51	Specific energy as a function of the r/t ratio for foam ratio of 39%	98
4.52	Load-displacement curves for keel beam specimens with and without everting element	100
4.53	Energy-displacement curves for keel beam specimens with and without everting element	101



4.54	Load-displacement curves for keel beam specimens with two different lay up for keel beam web	103
4.55	Energy-displacement curves for keel beam specimens with and without everting element	104
5.1	Edge buckling of keel beam in pre-crush stage	108
5.2	Simply supported laminated rectangular plate under uniform uniaxial in-plane compression	112
5.3	Laminate nomenclature	115
5.4	Buckling loads for a rectangular orthotropic laminated plate in the sequence $[\pm 45]_s$ under uniform compression, $\overline{N}_x$	117
5.5 5.6	Buckling load as a function of the r/t ratio Experimental and analytical initial crushing load as a function of the r/t ratio	120
5.7	SHELL91 Nonlinear Layered Structural Shell	122
5.8	Flow chart describes the eigenvalue analysis using the ANSYS finite element program	123
5.9	Typical Mesh and nodes for keel beam edge composite web	124
5.10	An eight layer laminate lay-up of the keel beam web in a sequence $of[(\pm 45)_2(0/90)_2]$	125
5.11	General boundary condition for keel beam edge	126
5.12	Effect of number of mesh on finite element buckling load	127
5.13	Quadrilateral Shape	128
5.14	Triangular Shape	128
5.15	Effect of number of mesh on finite element buckling load	128
5.16	First four mode of buckling and displacement contour in meter	130
5.17	First mode shape buckling of finite element model and typical edge buckling of keel beam	131

5.18	The Finite element linear buckling loads for first mode as a function of r/t ratio.	131
5.19	Experimental and FEM initial crushing load as a function of r/t ratio	133
A1	Core is filled with 83% Polyurethane foam. (a): three view drawing. (b): Sample before test. (c): crushing during test	144
A2	Core is filled with 56% Polyurethane foam. (a): Top and side views drawing. (b): Sample before test. (c): crushing during test	145
A3	Core is filled with 39% Polyurethane foam. (a): Top and side views drawing. (b): Sample before test. (c): crushing during test	146
A4	Trapezoidal filled core with 55% Polyurethane foam. (a): three view drawing. (b): Sample before test. (c): crushing during test	147
A5	Triangular foam core keel beam. (a): three view drawing. (b): Specimen in test fixture. (c): crushing during test	148
A6	Multi row zigzag foam core keel beam. (a): three view drawing. (b): Specimen in test fixture. (c): crushing during test	149
A7	Single row zigzag foam core keel beam. (a): three view drawing. (b): Specimen before test. (c): crushing during test	150
A8	C channel composite sandwich ribs core keel beam. (a): Specimen before test. (b): crushing during test	151
A9	Simple corrugated composite ribs keel beam. (a): Specimen in test fixture. (b): crushing during test	152
A10	Saw edged corrugated composite ribs keel beam. (a): Specimen in test fixture. (b): crushing during test	153
A11	Traded edge corrugated composite ribs keel beam. (a): Specimen in test fixture. (b): crushing during test	154
A12	C-channel composite ribs with parallel cut outs keel beam. (a): Specimen in test fixture. (b): crushing during test	155
A13	Treaded core with 55% Polyurethane foam keel beam. (a): three view drawing. (b): Sample before test. (c): crushing during test.	156



## NOMENCLATURE

Parameter	Definition	Unit
a	Height of plate	mm
a/b	Plate aspect ratio	mm/mm
А	Cross-sectional area	$mm^2$
$A_{ij}$	Elements of extensional stiffness matrix $(ij=1, 2, 6)$	N/m
b	Width of plate	mm
$\mathbf{B}_{ij}$	Elements of coupling stiffness matrix $(ij=1, 2, 6)$	Ν
CFE	Crush force efficiency	N/N
С	Clamp support	
Cn	Clamp support on $n^{th}$ side of plate (n=14)	
c	Clamp support	
$D_{ij}$	Elements of bending stiffness matrix $(ij=1, 2, 6)$	N.m
δ <sub>p</sub>	Post crush displacement	mm
E	Young's Modulus	GPa
E <sub>T</sub>	Total energy absorbed	kJ
$E_{11}$	Longitudinal Young's Modulus (direction-1)	GPa
E <sub>22</sub>	Transverse Young's Modulus (direction-2)	GPa
Es	Specific energy absorbed	kJ/kg
$\varepsilon_x, \varepsilon_y, \varepsilon_z$	Strain in x, y and z directions respectively	mm/mm
FR	Foam ratio	$m^3/m^3$
Fx, Fy, Fz	Forces in x, y and z directions respectively	kN
G <sub>12</sub>	In-plane Shear Modulus (in the 1-2 Planes)	GPa
Н	Thickness of laminate	mm
$\mathbf{k}_{\mathbf{x},\mathbf{k}_{\mathbf{y},\mathbf{k}_{\mathbf{z}}}}$	Curvatures in x, y and z directions respectively	1/m
1	Length of the part	mm
Μ	Mass	kg
m	Number of buckle half wavelengths (in x-direction)	
$M_{x,} M_{y}, M_{z}$	Moments resultant in x, y and z directions respectively	N.m
M <sub>xy</sub>	Moment resultant in xy-plane	N.m
n 	Number of buckle half wavelengths (in y-direction)	
$N_x, N_y, N_z$	Stress resultant in x, y and z directions respectively	N/m
$ar{N}_{xy}$	Shear force resultant	N/m
Pi	Initial crushing load	kN
$\overline{\mathbf{P}}$	Average crushing load	kN
$Q_{ij}$	Elements of reduced stiffnesses matrix (ij=1, 2, 6)	GPa
$\overline{Q}_{ij}$	Elements of transformed reduced stiffness matrix (ij= 1, 2, 6)	GPa
r	Radius of everting groove	mm
S	Simple support	
SE	Stroke efficiency	
Sn	Simple support on $n^{th}$ side of plate (n=14)	
S	Simple support	

u	Displacement (in x-direction)	mm
V	Volume	m <sup>3</sup>
v	Displacement (in y-direction)	mm
$v_{12}$	Poisson's ratio (in the 1-2 Planes)	
$V_{f}$	Volume fraction of fibre	
Vr	Volume fraction of matrix	
W	Displacement (in z-direction)	mm
$W_{f}$	Weight of fibre	kg
Wm	Weight of matrix	kg
z <sub>k</sub>	Distance of k <sup>th</sup> layer of laminate from mid-plane	mm



#### **CHAPTER 1**

#### **INTRODUCTION**

Structural crashworthiness becomes an essential requirement in the design of automobiles, rail cars and aerospace application. The structural crashworthiness covers the energy absorbing capability of collapsible and non-collapsible elements. The later is designed to provide a protective shell around the occupants i.e. post crash structural integrity.

Traditionally, fuselages of fixed-wing transport aircrafts are made mostly of aluminium [1], a material with a considerable capacity for plastic deformation, hence, an inherent capability to absorb energy in crash situations. Since the last two decades, composite materials are used more extensively to build aircraft structures. However, the crashworthiness aspect related to composite structures has become a serious issue for many space organizations worldwide. For example, NASA Langley Research Center developed an innovative and cost-effective crashworthy fuselage concept for light aircraft and rotorcraft [1, 11].



### 1.1 Composite Keel Beam

As stated earlier, the primary design goal for crashworthiness is to limit the impact forces transmitted to the occupants. To meet this objective, aircraft or rotorcraft sub-floor elements must be designed for high-energy absorption to prevent structural collapse during a crash [10]. Yet, the sub-floor design must not be so stiff that transmits or amplifies high impact loads to the occupants. Ideally, the design should contain some crushable elements to control limit the loads transmitted to the occupant to survivable or non-injurious levels [2, 10 and 12]. In this case, many investigations have been carried out on sub-floor using crushable elements [4, 5, 13, 14, 15, 16 and 17]. A lightweight energy-absorbing keel beam concept was developed and retrofitted in a general aviation-type aircraft and helicopter to improve crashworthiness performance [4, 13]. For example, more recently in the year 2004 Airbus achieved a world premiere with the A340-600 model, which features the longest carbon fibre keel beam ever built for a civil airliner [18].

#### **1.2** Research Objectives

The primary objective of this current project is to develop a new composite keel beam to be used as main crush element in the aircraft sub floor. Accordingly the detailed objectives are:

1. To design and fabricate everting elements to control composite keel beam

