

DESIGN AND DEVELOPMENT OF 3D WOVEN SPACER FABRICS FOR STRUCTURAL COMPOSITES

GHANSHYAM SURYAKANT NEJE



**DEPARTMENT OF TEXTILE TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2018**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2018

DESIGN AND DEVELOPMENT OF 3D WOVEN SPACER FABRICS FOR STRUCTURAL COMPOSITES

by

GHANSHYAM SURYAKANT NEJE

Department of Textile Technology

Submitted

in fulfillment of the requirement of the degree of Doctor of Philosophy

to the



**DEPARTMENT OF TEXTILE TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY DELHI
OCTOBER 2018**

**Dedicated
To
My Parents**

CERTIFICATE

This is to certify that the thesis entitled “**Design and development of 3D woven spacer fabrics for structural composites**” being submitted by **Mr. Ghanshyam Suryakant Neje** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a record of bona fide research work carried out by him. Mr. Ghanshyam Suryakant Neje has worked under my guidance and supervision and fulfilled the requirements for submission of the thesis. The results contained in thesis have not been submitted, in part or full, to any other university for the award of any degree or diploma.

Prof. B. K. Behera

Department of Textile Technology

Indian Institute of Technology Delhi,

New Delhi- 110016.

ACKNOWLEDGEMENTS

Words of appreciation and gratitude fall short to acknowledge the inspiring guidance, valuable suggestions, constant encouragement and liberty provided by Prof. B. K. Behera at every stage of this research. I enjoyed working under him throughout my Ph.D.

I gratefully acknowledge the help and suggestions by my SRC members Prof. R. Alagirusamy, Prof. Samrat Mukhopadhyay, Prof. S. P. Singh (Department of Mechanical Engineering), and other faculty members of the department. I also wish to thank ex-Heads of the Department, Prof. Kushal Sen and Prof. R. Chattopadhyay for their encouragement and support.

I gratefully acknowledge the help and support of Dr. Elif Ozden Yenigun, Dr. Hulya Cebeci, and Mr. Firat Turgut from Istanbul Technical University, Turkey.

I acknowledge the help & cooperation of the lab staff members especially Mr. M. Kundu, Mr. M. Singh, Mr. B. Biswal, and Mr. Vikas Khatkar.

I am thankful to Mr. Jeevan Pandey and Mr. T. H. Ansari for their help and support.

I am thankful to all my friends especially Mr. Rahul Gadkari, Mr. Vijay Goud, Ms. Sanchi Arora, Ms. Swati Sharma, Mr. Zunjar Kambale, Mr. Ashwini Dash, and Mr. Manjunath for their help, support and encouragement.

I thank all my M.Tech batch mates for their help and support.

I wish thank to my parents, brother and sisters for their help, support and understanding.

Date:

Ghanshyam Suryakant Neje

Place:

Abstract

The demand for lightweight materials has increased the quest for new structures to be used in various fields like automobiles, aviation, marine, railways, etc. The textile reinforced light-weight composite structures mainly utilize hollow fibrous preforms made from various textile manufacturing processes. Out of various textile manufacturing processes, weaving is the most commonly used method for the manufacturing of reinforcement fabrics. The weaving process is capable of producing 3D structures that can have different fibre architectures, fabric structures, and geometrical shapes. The type of 3D fabric to be used as reinforcement is decided based on the end use requirement. For the production of light-weight sandwich structures, 3D woven spacer structures woven from high-performance fibres are used as reinforcements. This thesis focuses on the manufacturing of lightweight sandwich structures from 3D woven spacer structures connected with woven cross-links and having hollow tunnels of simple geometrical shapes formed along the weft direction and comparison of the mechanical properties of composites manufactured from them having different geometrical configurations.

The manufacturing of 3D woven spacer structures requires specially designed weaving machine. Therefore, a customized weaving machine with a linear type of take-up system and a negative let-off system capable of handling eight beams were designed and fabricated. These systems were then attached to a manual rapier weaving machine equipped with 16 shafts electronically controlled shedding device.

The next step in the production of spacer fabric structures is the weave design creation. Generalized mathematical relationships for cell geometrical parameters and the cross-sectional representations were used to create weave design for each of the spacer structures with specific cell geometrical shape and parameters, and the corresponding structures were woven on the

fabricated weaving machine. A 600 tex multifilament E-glass fibre tow was used to produce all the spacer structures, and the spacer fabrics had hollow tunnels of trapezoidal, triangular and rectangular shapes aligned in weft direction. The different fabric structures developed in this research consisted of trapezoidal structures with different cell wall opening angles (between 45° to 65°), triangular structures with different cell wall opening angles (between 35° to 47°), rectangular spacer structures with different cell widths (varying from 33 mm to 63 mm) at almost constant height and with different cell heights (varying from 21 mm to 47.5 mm) at almost constant width, trapezoidal double level structures with varying cell wall opening angles (between 45° to 65°), and one structure each for rectangular, trapezoidal and triangular structures with thickened face sheets. Additionally, one spacer structure connected with core piles was also produced for the comparison of its mechanical properties with other structures.

The produced fabrics were then converted to their composites using vacuum assisted resin transfer moulding. Wooden blocks of appropriate size and shape were used to keep the fabric in its 3D shape during resin impregnation and curing stages. These composite structures were then characterized for their compressive properties and flexural properties. Rectangular spacer structure with double layer wall construction (RECTDL) sustained higher specific compressive load than spacer structure connected with core piles (SPY), while the absorbed energy/volume in compression for these two structures was almost the same. In case of structures with single layer wall constructions, the specific compressive load and the absorbed energy/volume in compression were in the order of rectangular > triangular > trapezoidal structure. The SPY structure had lowest flexural stress compared to spacer structures with any cell geometry and wall constructions.

The comparison of performance of spacer composites with different cell geometrical parameters revealed that the rectangular spacer structures with the smallest cell width (among the different width samples) found to have the highest specific compressive load, absorbed energy/volume in compression, the highest specific bending load, and flexural stress. These properties decreased with an increase in the cell width of the rectangular structures. Similar trend was observed in case of rectangular spacer structures with different cell heights, i.e., rectangular spacer structures with the smallest cell height (among different height samples) had the highest specific compressive load and absorbed energy/volume in compression, the highest specific bending load, and flexural stress. These properties decreased with an increase in the cell height of the rectangular structures. The compressive load, specific compressive load, the absorbed energy/volume in compression, specific bending load and flexural stress increased with increase in the cell wall opening angles for trapezoidal spacer structures. The compressive load, specific compressive load, specific bending load and flexural stress of triangular structures increased with the increase in cell wall opening angle. But, the absorbed energy/volume in compression was observed to be the highest for the triangular structure with 42.5° cell wall opening angle than the other triangular structures.

The effect of face sheet thickening increased the bending load for these structures, but the specific bending load decreased due to increased mass of the specimen due to the additional face sheets. The absorbed energy/volume in compression and the flexural stress were observed to be lower for thickened face sheet structures compared to their corresponding single layer face sheets structures. The comparison of single level and double level trapezoidal spacer structures demonstrated that the compressive load and specific compressive loads decreased

for double level trapezoidal structures compared to their single level counterparts, whereas the bending load and specific bending load were observed to be higher for double level structures.

The possibility of growing aligned carbon nanotubes (CNTs) on selected 3D preforms made from glass fibres, with the use of chemical vapour deposition (CVD) process was explored. The radially aligned CNTs were successfully grown on the glass tows but when the same procedure was followed for 3D preforms the alignment of CNTs was observed to be random. Still, the treatment of CNTs increased the electrical conductivity of the treated glass tows, 3D preforms (I beam) and their composites compared to their neat counterparts.

To conclude, it may be stated that the mechanical performance of the spacer sandwich composites depends on the load-bearing cell wall thickness, the angle between the wall and loading axis, and the configuration in which the walls are integrating with face sheets (at a line as in TR or with some space as in TPZ structure). The findings of this study can help in designing the light-weight sandwich composites, as it encompasses the detailed investigation on the effect of different cell geometrical shapes and cell geometrical parameters of the spacer architecture on the mechanical properties of their composites.

सार

हल्के पदार्थों की मांग ने ऑटोमोबाइल, विमानन, समुद्री, रेलवे इत्यादि जैसे विभिन्न क्षेत्रों में नई संरचनाओं के खोज में वृद्धि की है। कपड़ा प्रबलित हल्के वजन की कम्पोजिट संरचनाएं मुख्य रूप से विभिन्न वस्त्र निर्माण प्रक्रियाओं से बने खोखले फाइबरस प्रीफॉर्म का उपयोग करती हैं। विभिन्न वस्त्र निर्माण प्रक्रियाओं में से, बुनाई (विब्रिंग) सुदृढीकरण के कपड़े के निर्माण के लिए सबसे अधिक उपयोग की जाने वाली विधि है। बुनाई प्रक्रिया श्रीडी संरचनाओं का उत्पादन करने में सक्षम है जिसमें विभिन्न फाइबर आर्किटेक्चर, कपड़े संरचनाएं, और ज्यामितीय आकार हो सकते हैं। सुदृढीकरण के रूप में उपयोग किए जाने वाले श्रीडी कपड़े का प्रकार अंतिम उपयोग व आवश्यकता के आधार पर तय किया जाता है। हल्के वजन वाले सैंडविच संरचनाओं के उत्पादन के लिए, उच्च प्रदर्शन वाले रेशे से बुने हुए श्रीडी बुने हुए स्पेसर संरचनाओं को मजबूती के रूप में उपयोग किया जाता है। यह शोध प्रबंध बुने हुए क्रॉस-लिंक से जुड़े श्रीडी बुने हुए स्पेसर संरचनाओं से हल्के सैंडविच संरचनाओं के निर्माण पर केंद्रित है और विभिन्न ज्यामितीय आकृतियों और विन्यासों के खोखले सुरंगों के साथ निर्मित कम्पोजिट के यांत्रिक गुणों की तुलना में केंद्रित है।

श्रीडी बुने हुए स्पेसर संरचनाओं के निर्माण के लिए विशेष रूप से डिजाइन की गई बुनाई मशीन की आवश्यकता होती है। इसके लिए, रैखिक प्रकार की टेक-अप प्रणाली और आठ बीमों को संभालने में सक्षम लेट-ऑफ सिस्टम वाली मशीन डिजाइन की और बनाई। इन प्रणालियों को १६ शाफ्ट इलेक्ट्रॉनिक नियंत्रित शेडिंग डिवाइस से सुसज्जित मैनुअल रैपिडर बुनाई (विब्रिंग) मशीन से जोड़ा गया था।

स्पेसर कपड़े संरचनाओं के उत्पादन में अगला कदम बुनाई डिजाइन का निर्माण है। सेल ज्यामितीय पैरामीटर के लिए सामान्यीकृत गणितीय संबंध, और क्रॉस-सेक्शनल प्रस्तुतियों का उपयोग विशिष्ट सेल ज्यामितीय आकार और पैरामीटर के साथ प्रत्येक स्पेसर संरचनाओं के लिए बुनाई डिजाइन बनाने के लिए किया गया था, और संबंधित संरचनाएं डिजाइन किए गये बुनाई मशीन पर बुने गए थे। सभी स्पेसर संरचनाओं के उत्पादन के लिए ६०० टेक्स मल्टीफिलामेंट ई-ग्लास फाइबर टॉव का उपयोग किया गया है, और स्पेसर कपड़ों में समलम्बाकार, त्रिकोणीय और आयताकार आकार के खोखले सुरंग वेफ्ट की दिशा में होते थे। समलम्बाकार, त्रिकोणीय आकार के खोखले सुरंग वाले कपड़े विभिन्न क्रॉसलिंक कोण ($45^\circ - 65^\circ$) के साथ बनाए गए थे। आयताकार स्पेसर कपड़े विभिन्न सेल ऊंचाइयों (२१ मिमी से ४७.५ मिमी) के साथ लगभग स्थिर चौड़ाई पर और विभिन्न सेल चौड़ाई (३३ मिमी से ६३ मिमी) के साथ लगभग स्थिर ऊंचाई रखकर बनाए गए थे। एक संरचना प्रत्येक आयताकार, समलम्बाकार और त्रिकोणीय संरचनाओं के लिए मोटे फेसशीट के साथ बनाए गए थे। इसके अतिरिक्त, पाइल धागे के साथ बना हुआ एक स्पेसर कपड़ा अन्य संरचनाओं के साथ तुलना के लिए बनाया गया था।

उत्पादित कपड़ों को वैक्यूम सहायक रेजिन स्थानांतरण मोल्डिंग का उपयोग करके कंपोजिट में परिवर्तित कर दिए गए। उचित आकार के लकड़ी के ब्लॉक का उपयोग रेजिन संसेचन और जमने के दौरान कपड़े को अपने शीडी आकार में रखने के लिए किया जाता था। बनाए गए कंपोजिट संरचनाओं का उनके कम्प्रेसन और फ्लेक्सुरल गुणों के लिए परीक्षण किया गया।

दोहरी क्रॉसलिक वाले आयताकार संरचना वाले कंपोजिट का विशिष्ट कम्प्रेसन भार पाइल धागो वाले स्पेसर कपड़े से अधिक था, जबकि इन दो संरचनाओं के लिए कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन लगभग समान थी। एकल क्रॉसलिक के साथ संरचनाओं के मामले में विशिष्ट कम्प्रेसन भार और कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन आयताकार > त्रिभुज > समलम्बाकार संरचना के क्रमानुसार था। किसी भी सेल ज्यामिति और क्रॉसलिक के साथ स्पेसर संरचनाओं की तुलना में पाइल धागो वाली स्पेसर संरचना का फ्लेक्सुरल स्ट्रेस सबसे कम था।

विभिन्न सेल ज्यामितीय पैरामीटर के साथ बने स्पेसर कंपोजिट्स के प्रदर्शन की तुलना से पता चला कि छोटे सेल चौड़ाई के आयताकार स्पेसर संरचनाओं में उच्चतम विशिष्ट कम्प्रेसन भार, कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन, उच्चतम विशिष्ट बेन्डिंग भार, और फ्लेक्सुरल स्ट्रेस पाए गए। उपरोक्त गुण आयताकार संरचनाओं के सेल चौड़ाई में वृद्धि के साथ कम होते हैं। इसी तरह की प्रवृत्ति विभिन्न सेल ऊंचाइयों वाले आयताकार स्पेसर संरचनाओं में देखी गई थी, जैसे की, आयताकार स्पेसर संरचनाओं को छोटी सेल ऊंचाई के साथ उच्चतम विशिष्ट कम्प्रेसन भार, कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन, उच्चतम विशिष्ट बेन्डिंग भार, और फ्लेक्सुरल स्ट्रेस पाए गए। उपरोक्त गुण आयताकार संरचनाओं के सेल चौड़ाई में वृद्धि के साथ कम पाए गए। कम्प्रेसन भार, विशिष्ट कम्प्रेसन भार, कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन, विशिष्ट बेन्डिंग भार, और फ्लेक्सुरल स्ट्रेस समलम्बाकार स्पेसर संरचनाओं के लिए क्रॉसलिक कोण में वृद्धि के साथ बढ़ गये हैं। कम्प्रेसन भार, विशिष्ट कम्प्रेसन भार, विशिष्ट बेन्डिंग भार, और फ्लेक्सुरल स्ट्रेस त्रिभुज संरचनाओं में क्रॉसलिक कोण में वृद्धि के साथ बढ़ गये। लेकिन, कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन क्रॉसलिक कोण 42.5° त्रिकोणीय संरचना के साथ उच्चतम पाया गया।

फेसशीट के मोटाई के प्रभाव ने इन संरचनाओं के बेन्डिंग भार में वृद्धि हुई, लेकिन फेसशीट की मोटाई के कारण संरचना के बढ़ते द्रव्यमान के कारण विशिष्ट बेन्डिंग भार घट गया। मोटी फेसशीट की संरचनाओं में कम्प्रेसन में अवशोषित ऊर्जा प्रति इकाई आयतन और फ्लेक्सुरल स्ट्रेस उनके समान एकल फेसशीट की संरचनाओं की तुलना में कम पाया गया। सिंगल लेवल और डबल लेवल समलम्बाकार स्पेसर संरचना की तुलना ने दर्शाया कि कम्प्रेसन भार और विशिष्ट कम्प्रेसन भार उनके एकल स्तर के समकक्षों की तुलना में डबल लेवल समलम्बाकार संरचनाओं के लिए कम हो गया, जबकि बेन्डिंग भार और विशिष्ट बेन्डिंग भार डबल लेवल संरचनाओं के लिए उच्च पाया गया।

रासायनिक वाष्प जमावट (सीवीडी) प्रक्रिया के उपयोग के साथ, ग्लास फाइबर से बने चयनित थ्रीडी प्रीफॉर्म पर कार्बन नैनोट्यूब (सीएनटी) उगाने की संभावना का पता लगाया गया। मूल रूप से सीएनटी ग्लास टॉक्स पर सफलतापूर्वक उगाए गए थे, लेकिन जब थ्रीडी प्रीफॉर्म के लिए उसी प्रक्रिया का पालन किया गया तो सीएनटी का सरेखण यादृच्छिक पाया गया। फिर भी, सीएनटी की ग्लास टॉक्स पर जमावट से, थ्रीडी प्रीफॉर्म (आई बीएम) और उनके कंपोजिट की विद्युत चालकता में साफ समकक्षों की तुलना में वृद्धि पायी गयी।

उपरोक्त अध्ययन से यह कहा जा सकता है की स्पेसर सैंडविच कंपोजिट्स का यांत्रिक प्रदर्शन क्रॉसलिक की मोटाई, क्रॉसलिक और लोडिंग अक्ष के बीच के कोण, और किस तरह से क्रॉसलिक्स फेस शीट्स के साथ एकीकृत होती हैं इस पर निर्भर करता है। इस अध्ययन के निष्कर्ष, हल्के वजन वाले सैंडविच कंपोजिट्स को डिजाइन करने में मदद कर सकते हैं, क्योंकि इसमें विभिन्न ज्यामितीय आकारों और स्पेसर आर्किटेक्चर के विभिन्न सेल ज्यामितीय पैरामीटर के साथ बने हुए कंपोजिट्स के यांत्रिक गुणों पर विस्तृत जांच व विवरण शामिल हैं।

Contents

	Page No.
Certificate	i
Acknowledgements	ii
Abstract	iii
Table of Contents	xi
List of Figures	xix
List of Tables	xxxi
Abbreviations	xxxiii
Chapter 1: Introduction	1
Chapter 2: Objectives	9
Chapter 3: Literature Review	11
3.1 3D fabrics	11
3.1.1 Classification of 3D fabrics	11
3.2 3D spacer fabrics	12
3.3 Knitted spacer fabrics	13
3.3.1 Spacer fabrics production on warp knitting machines	13
3.3.2 Spacer fabrics production on weft knitting machine	14
3.3.2.1 Spacer fabrics production on double jersey circular knitting machines	15
3.3.2.2 Spacer fabrics production on V-bed flat knitting machines	15
3.4 Stitched fabrics preforms	16
3.5 3D nonwoven structures (STRUTO)	18
3.6 Woven spacer fabric	18
3.6.1 Spacer structures connected with core piles	19
3.6.2 Spacer structures connected with woven cross-links	20
3.6.2.1 Production of spacer on conventional shuttle loom	20
3.6.2.2 Spacer fabrics production on specially designed weaving machines	33

3.6.2.2.1 Spacer fabrics production on Multi-rapier looms	33
3.6.2.2.2 Spacer fabrics production on modified loom	34
3.7 Textile composites and Textile structural composites	43
3.7.1 Textile reinforced composites	43
3.7.2 Textile structural composites	44
3.8 Manufacturing composites from spacer fabrics	46
3.8.1 Production of spacer composites using thermoplastic resins	46
3.8.2 Production of spacer composites using thermoset resins	47
3.9 Different types of sandwich structures and their properties	50
3.9.1 Stitch bonded sandwich structures	52
3.9.2 Z-pinned sandwich structures	55
3.9.3 Sandwich structures with corrugated cores	57
3.9.4 Sandwich structures with other core materials	61
3.9.5 Sandwich structures with hierarchical core materials	64
3.9.6 Honeycomb structures as core materials	65
3.9.7 Sandwich structures with knitted fabric cross-links	68
3.9.8 Sandwich structures with woven preforms	70
3.9.8.1 Sandwich composites connected with core piles	70
3.9.8.2 Woven spacer composites connected with woven cross-links	79
3.9.9 Disadvantages of conventional sandwich structures	80
3.9.10 Advantages of woven cross-link spacer structures	82
3.9.11 Applications of spacer composites	84
3.10 CNTs synthesis on glass-fibres for multifunctional structural composites	85
3.10.1 Carbon nanotubes	85
3.10.2 Different methods of CNT synthesis	85
3.10.2.1 Arc-discharge method	86
3.10.2.2 Laser-furnace method (laser ablation method)	87
3.10.2.3 Chemical vapor deposition process (CVD)	87
3.10.3 CNTs growth mechanism	89

3.10.4 CVD process parameters	90
3.10.4.1 Hydrocarbon	90
3.10.4.2 Catalyst	91
3.10.4.3 Growth temperature	91
3.10.5 CNT application to fibres	92
3.10.5.1 CNTs application through fibre sizing formulations	92
3.10.5.2 Mixing the CNTs with matrix	93
3.10.5.3 In situ growth of aligned CNTs	96
3.10.5.4 Advantages of CVD process	102
3.10.5.5 Advantages of CNTs grafted 3D composites	102
Chapter 4: Materials and Methods	103
4.1 Introduction	103
4.2 Materials	103
4.2.1 Glass Fibres	103
4.2.2 Epoxy Resin	104
4.3 Methods	106
4.3.1 Design and development of weaving system	106
4.3.2 Geometrical modeling for repeat unit weight and fibre volume fraction	107
4.3.3 Development of weave design and fabric samples for various spacer architectures	107
4.3.4 Composite processing and characterization	109
4.3.4.1 Composite processing: preparation of moulds and vacuum assisted resin infusion process	109
4.3.4.2 Characterization for compressive properties	112
4.3.4.3 Characterization for bending properties	113
4.3.5 FVF determination	115
4.3.6 Growth of aligned CNTs on 3D preform	116
Chapter 5: Design and development of weaving system for producing spacer fabrics	117
5.1 Introduction	117

5.2	Necessity of modification in take-up system	118
5.2.1	Modification of take-up system	118
5.3	Multi beam negative let-off system	122
5.3.1	Tension control in beams	124
5.4	Manually operated single rapier weaving machine	125
5.5	Working of electronically controlled shedding system	127
5.6	Outcomes of the chapter	130
Chapter 6:	Geometrical modeling of 3D woven spacer fabrics as reinforcement for lightweight sandwich composites	131
6.1	Introduction	131
6.2	Methodology	132
6.2.1	Production of spacer fabrics	132
6.2.2	Modeling approach	136
6.2.3	Sample Analysis	143
6.2.4	Prediction of fabric weight and FVF	143
6.3	Results and Discussion	144
6.3.1	Comparison of experimental and predicted geometrical parameters	144
6.3.2	Prediction of repeat unit weight and FVF	146
6.4	Conclusion	149
Chapter 7:	Development of weave design and fabric samples for various spacer architectures	151
7.1	Introduction	151
7.2	Determination of cell geometrical parameters	152
7.2.1	Cell geometrical parameters for triangular spacer structure	153
7.2.2	Cell geometrical parameters for trapezoidal pacer structure	155
7.2.3	Cell geometrical parameters for rectangular spacer structures	157
7.3	Phases of weaving for different structures	157
7.3.1	Phases of weaving for trapezoidal spacer structure	157
7.3.2	Phases of weaving for triangular spacer structure	158
7.3.3	Phases of weaving for rectangular spacer structures	159

7.4 Creating the weave designs and weaving of spacer structures	161
7.4.1 Weaving of triangular spacer structures	161
7.4.2 Weaving of trapezoidal spacer structures	165
7.4.3 Weaving of rectangular spacer structures	169
7.4.4 Weaving of trapezoidal double level spacer structures	175
7.4.5 Weaving of rectangular spacer structure with thickened face sheets (RECTTF)	180
7.4.6 Weaving of trapezoidal spacer structure with thickened face sheets (TPZTF)	183
7.4.7 Weaving of triangular spacer structure with thickened face sheets (TRTF)	187
7.4.8 Spacer fabric connected with pile yarns	189
7.5 Outcome of the chapter	192
Chapter 8: Development of composite specimens and evaluation of their mechanical performance	193
8.1 Introduction	193
8.2 Composite processing	194
8.3 Composite characterization	195
8.3.1 Compressive properties of sandwich composites	195
8.3.2 Three-point-bending test of sandwich composites	196
Section A	197
8.4.1 Methodology	197
8.4.2 Characterization of composites	201
8.4.2.1 Lateral compression testing	201
8.4.2.2 Three-point-bending test	201
8.4.3 Results and Discussions	202
8.4.3.1 Compression performance of sandwich composites	202
8.4.3.2 Failure Modes in compression	206
8.4.3.3 Bending performance of sandwich composites	210
8.4.3.4 Failure Modes in bending	213
8.4.4 Conclusion	216

Section B: Influence of cell geometrical parameters on the mechanical properties of 3D woven spacer sandwich composites	219
8.5.1 Methodology	219
8.5.2 Characterization of sandwich composites	222
8.5.2.1 Lateral compressive properties	222
8.5.2.2 Three-point-bending test	223
8.5.3 Results and Discussion	224
8.5.3.1 Lateral compressive performance of sandwich structures	224
8.5.3.1.1 Effect of change in width of rectangular cell	224
8.5.3.1.2 Effect of change in height of the rectangular cell	227
8.5.3.1.3 Effect of change in cell wall opening angle in trapezoidal structures	230
8.5.3.1.4 Effect of change in cell wall opening angle in triangular structures	233
8.5.3.2 Failure modes of the structures in compression	237
8.5.3.2.1 Failure modes of RECT structures in compression	237
8.5.3.2.2 Failure modes of TPZ and TR structures in compression	241
8.5.3.3 Bending performance of sandwich composites	246
8.5.3.3.1 Effect of change in width of rectangular cell	246
8.5.3.3.2 Effect of change in height of rectangular cell	249
8.5.3.3.3 Effect of change in cell wall opening angle in trapezoidal structures	252
8.5.3.3.4 Effect of change in cell wall opening angle in triangular structures	255
8.5.3.4 Failure modes of the structures in bending	258
8.5.3.4.1 Failure modes of RECT structures in bending	258
8.5.3.4.2 Failure modes of TPZ and TR structures in bending	263

8.5.4 Conclusions	267
Section C: Effect of face sheet thickening on the mechanical properties of 3D woven spacer sandwich composites	269
8.6.1 Methodology	269
8.6.2 Characterization of composites	272
8.6.2.1 Lateral compression testing	272
8.6.2.2 Three-point-bending test	272
8.6.3 Results and Discussions	273
8.6.3.1 Lateral compressive properties of sandwich composites	273
8.6.3.2 Failure modes in lateral compression	277
8.6.3.3 Bending performance of sandwich composites	282
8.6.3.4 Failure modes in bending	286
8.6.4 Conclusions	290
Section D: Mechanical properties of 3D woven spacer sandwich composites with single and double level spacer structures	293
8.7.1 Methodology	293
8.7.2 Characterization of sandwich composites	295
8.7.2.1 Lateral compressive properties	295
8.7.2.2 Three-point-bending test	295
8.7.3 Results and Discussion	296
8.7.3.1 Compressive performance of sandwich structures	296
8.7.3.2 Failure modes in compression	301
8.7.3.3 Bending performance of sandwich composites	308
8.7.3.4 Failure modes in bending	311
8.7.4 Conclusion	317
Chapter 9: Growth of aligned CNTs on 3D preforms for multifunctional structural composites	319
9.1 Introduction	319
9.2 Methodology	321
9.2.1 In situ growth of CNTs on the ‘I’ shaped preforms	322
9.2.1.1 Catalysis of the preform	322

9.2.1.2 CVD process	323
9.2.2 Composite manufacturing	325
9.3 Results and discussion	326
9.3.1 SEM and RAMAN analysis	326
9.3.2 Electrical conductivity results	329
9.3.3 Mechanical properties	332
9.3.3.1 Tensile test of CNTs grafted tows	332
9.3.3.2 Compression properties of ‘I’ shaped beam	333
9.4 Conclusions	335
Chapter 10: Summary and Conclusions	337
Scope for Future work	345
References	347
List of Publications	363
Curriculum Vitae	367

List of Figures

Figure No.	Title	Page No.
Figure 3.1	3D solid structures	12
Figure 3.2	Spacer fabric produced on Raschel warp knitting machine	14
Figure 3.3	3D knitted spacer fabrics produced on flat knitting machine (a) two surface layers, (b) three surface layers	16
Figure 3.4	Formation of perpendicular laid fabrics (Struto system)	18
Figure 3.5	Face-to-face weaving technique for velvet fabric production	19
Figure 3.6	Hollow structures with (s) even surface and (b) uneven surface	20
Figure 3.7	Different types of hollow structures (a) triangular, (b) trapezoidal, (c) complex shaped and (d) hexagonal shaped	21
Figure 3.8	Trapezoidal unit cell sub-division	22
Figure 3.9	(a) Schematic diagram of the conventional loom for spacer fabric production and (b) sectional view of zig-zag diagonal spacer fabric	24
Figure 3.10	Sectional view of (a) spacer with double rib in production and the fabric, (b) spacer fabric with longitudinal ribs	25
Figure 3.11	Woven spacer fabric with wave-like corrugated bonding layer	26
Figure 3.12	Woven preform with channels aligned in warp direction (a) composite (b) reinforced fabric	27
Figure 3.13	Production principle of cellular multi-ply structure	28
Figure 3.14	Production principle of cellular multi-ply structure	29
Figure 3.15	Cellular structure with tapered form	30
Figure 3.16	Tubular structures with ribs aligned in warp direction (a) fabric shape and (b) production principle	30
Figure 3.17	Weaving principle of honeycomb structures	32
Figure 3.18	Use of lancets with false picks in the production of spacer fabrics	33
Figure 3.19	Cross-sectional representation of the woven spacer with woven cross-links	35

Figure 3.20	(a) Weaving of top and bottom fabric layers, (b) Weaving of wall fabric, (c) Pull back of floated ground warp yarns	36
Figure 3.21	Weaving of spacer fabrics on modified narrow weaving machine	37
Figure 3.22	Production principle of stiffener fabric	39
Figure 3.23	Production stages of 'X' shaped spacer preforms	41
Figure 3.24	Woven spacer fabric with each section of structure as 3D orthogonal fabric	43
Figure 3.25	Outline of consolidation process of spacer structure with hybrid yarns	47
Figure 3.26	Schematic of vacuum infusion process used to manufacture spacer composites	49
Figure 3.27	Wooden blocks with inserted into fabrics with (a) rectangular and (b) triangular shapes; (c) experimental set up of vacuum infusion process	49
Figure 3.28	Images of composites produced from knitted spacer fabrics	50
Figure 3.29	Stitch bonded sandwich composite	52
Figure 3.30	Schematic of machine for stitch bonded sandwich structures manufacturing	53
Figure 3.31	Schematic representation of composite hybrid panel	59
Figure 3.32	Schematic of fabrication of beams with from composite sheets reinforced with carbon fibres (a) egg honeycomb core and (b) pyramidal honeycomb core	63
Figure 3.33	Cores for foldcore structures: composites made from (a) carbon fabric, (b) aramid fabric	64
Figure 3.34	Hierarchical lattice panel from woven sandwich structure	65
Figure 3.35	Honeycomb cell under compression	66
Figure 3.36	Schematic representation of arc-discharge method for CNTs production	86
Figure 3.37	Schematic representation of laser furnace apparatus	87
Figure 3.38	Schematic representation of CVD set-up	88
Figure 3.39	CNTs growth mechanisms (a) tip growth and (b) base growth	90

Figure 3.40	Illustration of interface between the two composite plies with aligned CNTs on fibre surfaces	97
Figure 3.41	CNT intralaminar and interlaminar reinforcement	99
Figure 4.1	Schematic representation of the VARIM process	110
Figure 4.2	Process steps of composite manufacturing from spacer fabrics	111
Figure 4.3	Experimental set-up for flatwise compression test	112
Figure 4.4	Experimental set-up for three-point-bending test	114
Figure 4.5	Photograph of Chemical vapour deposition (CVD) equipment	116
Figure 5.1	Conventional roller take-up system	119
Figure 5.2	(a) CAD diagram of the conveyor take-up system, (b) Fabricated take-up system with conveyor belts	121
Figure 5.3	(a) CAD diagram of designed let-off system, (b) Fabricated let-off system with eight beams	123
Figure 5.4	Dead weight tensioning system for negative let-off	124
Figure 5.5	(a) CAD Diagram of manual rapier weaving machine, (b) Fabricated manual rapier weaving machine	126
Figure 5.6	(a) Different components of shedding system, (b) Solidworks model of shedding system	128
Figure 5.7	(a) Design to be produced and (b) design fed in the software	129
Figure 6.1	Cross-sectional representation of trapezoidal spacer structure	133
Figure 6.2	Images of trapezoidal spacer fabrics (a) Tpz 1, (b) Tpz 2, (c) Tpz 3, (d) Tpz 4, (e) Tpz 5	134
Figure 6.3	Cross-sectional representation of rectangular spacer structure	134
Figure 6.4	Images of rectangular spacer fabrics (a) Rect 1, (b) Rect 2, (c) Rect 3, (d) Rect 4, (e) Rect 5	135
Figure 6.5	Schematic representation of trapezoidal spacer with subdivision of repeat unit	137
Figure 6.6	Microscopic image of cross-section of 2D fabric made from E-glass	142
Figure 6.7	Computed and measured repeat unit weight for trapezoidal spacer fabrics	144

Figure 6.8	Computed and measured repeat unit weight for rectangular spacer fabrics	145
Figure 6.9	Computed and measured FVF for trapezoidal spacer fabrics	145
Figure 6.10	Computed and measured FVF for rectangular spacer fabrics	146
Figure 6.11	Predicted values of repeat unit weight for trapezoidal structures with different heights and wall angles	147
Figure 6.12	Predicted values of FVF for trapezoidal structures with different heights and wall angles	147
Figure 6.13	Predicted values of repeat unit weight for rectangular structures with different heights and widths	148
Figure 6.14	Predicted values of FVF for rectangular structures with different heights and widths	149
Figure 7.1	Cell geometrical parameters of triangular spacer structure	153
Figure 7.2	Cell geometrical parameters of trapezoidal spacer structure	155
Figure 7.3	(a) Weaving of top and bottom ground fabrics, (b) Weaving of the wall fabric, (c) Pull back of floated ground warp yarns	158
Figure 7.4	(a) Weaving of top and bottom ground fabrics, (b) Weaving of wall fabric, (c) Pull back of floated ground warp yarns	159
Figure 7.5	(a) Weaving of top and bottom ground fabrics, (b) Weaving of the wall fabrics, (c) Pull back of floated ground warp yarns	160
Figure 7.6	Cross-sectional representation of triangular spacer structure	162
Figure 7.7	Weave design for TR47° structure	164
Figure 7.8	Fabric sample images for (a) TR35°, (b) 42.5° and (c) TR47° structures	165
Figure 7.9	Cross-sectional representation of trapezoidal spacer structure	166
Figure 7.10	Weave design of (TPZ65°) trapezoidal spacer structure	168
Figure 7.11	Fabric sample images for (a) TPZ45°, (b) TPZ50.5°, (c) TPZ57° and (d) TPZ65° structures	169
Figure 7.12	Cross-sectional representation of rectangular spacer structure	170
Figure 7.13	Weave design of RECTW1 spacer structure	172

Figure 7.14	(a) set-up on weaving machine for production of rectangular structures, (b) one of rectangular sample in production	173
Figure 7.15	Rectangular spacer structures with different widths (a) RECTW1, (b) RECTW2, (c) RECTW3, and (d) RECTW4; and heights (e) RECTH1, (f) RECTH3 and (g) RECTH4	175
Figure 7.16	Cross-sectional representation of the trapezoidal double level spacer structure	176
Figure 7.17	Weave design for the production of (TDL65°) trapezoidal double level structures	178
Figure 7.18	Fabric samples for trapezoidal double level structures with different cell wall opening angles (a) TDL45°, (b) TDL50.5°, (c) TDL57° and (d) TDL65°	179
Figure 7.19	Cross-sectional representation of the rectangular structure with thickened face sheets (RECTTF)	180
Figure 7.20	Weave design for RECTTF structure	181
Figure 7.21	Arrangements made on weaving machine for production of RECTTF structures	183
Figure 7.22	Produced fabric sample for RECTTF structure	183
Figure 7.23	Cross-sectional representation of TPZTF structure	184
Figure 7.24	Weave design used for the production of TPZTF structures	185
Figure 7.25	Produced fabric sample for TPZTF structure	186
Figure 7.26	Cross-sectional representation of TRTF structure	187
Figure 7.27	Weave design used for the production of TRTF structures	188
Figure 7.28	Produced fabric sample for TRTF structure	189
Figure 7.29	Cross-sectional representation of spacer fabric connected with pile yarns	190
Figure 7.30	Weave design used for production of SPY structure	190
Figure 7.31	Weaving of SPY spacer structure with insertion of moulds	191
Figure 7.32	Produced fabric sample for spacer structure connected with pile yarns	192

Figure 8.1	Cross-sectional representation of rectangular structure with single layer wall construction	198
Figure 8.2	Composite samples produced from (a) TR, (b) TPZ, (c) RECTSL, (d) RECTDL and (e) SPY spacer structures	200
Figure 8.3	Lateral compressive strength of different spacer composite structures	203
Figure 8.4	Components of force applied on (a) vertical and (b) inclined wall	203
Figure 8.5	Specific compressive load of different spacer composite structures	204
Figure 8.6	Strain energy per unit volume for different spacer composite structures	205
Figure 8.7	Load-deformation curves for (a) RECTDL and SPY structures, (b) RECTSL, TPZ and TR structures	207
Figure 8.8	Stages of failure for (a) RECTDL structure (i) elastic loading, (ii) wall buckling failure, (iii) deformation plateau, and (iv) structure failure; (b) SPY structure (i) elastic loading, (ii) pile buckling failure, (iii) deformation plateau, and (iv) densification stage	208
Figure 8.9	Failure stages of (a) RECTSL structure (i) start of loading, (ii) peak load (iii) deformation plateau, (iv) end of deformation plateau, (v) crack in buckled wall, (vi) structure failure; (b) and (c) TPZ and TR structures (i) start of loading, (ii) peak load (iii) deformation plateau, (iv) shortened walls start taking load, (v) second peak load, (vi) structure failure	209
Figure 8.10	(a) Maximum bending load and (b) Specific bending load for different spacer composite structures	212
Figure 8.11	Maximum flexural stress of different composite structures	213
Figure 8.12	Load-deformation curves for different composites in bending test	214

Figure 8.13	Damage caused to top face sheet, core and bottom face sheet of (a) RECTDL and (b) SPY structures	214
Figure 8.14	Schematic representation of damage caused to (a) RECTSL, (b) TPZ and (c) TR structures.	215
Figure 8.15	Damage caused by bending deformation to (a) RECTSL, (b) TPZ, and (c) TR structures	216
Figure 8.16	Composite sample for different structures	220
Figure 8.17	Compressive load for RECT structures with different cell widths	225
Figure 8.18	Specific compressive load for RECT structures with different cell widths	226
Figure 8.19	Strain energy per unit volume for RECT structures with different cell widths	227
Figure 8.20	Compressive load for RECT structures with different heights	228
Figure 8.21	Specific compressive strength of RECT structures with different cell heights	229
Figure 8.22	Strain energy per unit volume for RECT structures with different heights	230
Figure 8.23	Compressive load for TPZ structures with different cell wall opening angles	231
Figure 8.24	Specific compressive load for TPZ structures with different cell wall opening angles	232
Figure 8.25	Strain energy per unit volume for TPZ structures with different cell wall opening angles	233
Figure 8.26	Compressive load for TR structures with different cell wall opening angles	234
Figure 8.27	Specific compressive load for TR structures with different cell wall opening angles	235
Figure 8.28	Energy per unit volume for TR structures with different cell wall opening angles	236
Figure 8.29	Load-deformation curves for TR structures with different cell wall opening angles	237

Figure 8.30	Load-deformation curves for RECT structures with (a) different cell widths and (b) different cell heights	238
Figure 8.31	Failure stages of (a) RECTW1, (b) RECTW2, (c) RECTW3, (d) RECTW4, (e) RECTH1, (f) RECTH3, and (g) RECTH4 structures	241
Figure 8.32	Load-deformation curves for TPZ structures with (a) TPZ45° and (b) TPZ50.5°, TPZ57°, and TPZ 65° structures	243
Figure 8.33	Failure stages of (a) TPZ45°, (b) TPZ50.5°, (c) TPZ57°, and (d) TPZ 65° structures	245
Figure 8.34	Failure stages of (a) TR35°, (b) TR42.5°, and (c) TR47° structures	246
Figure 8.35	Maximum bending load for RECT structures with different widths	247
Figure 8.36	Specific bending load for RECT structures with different cell widths	248
Figure 8.37	Maximum flexural stress for RECT structures with different cell widths	249
Figure 8.38	Maximum bending load for RECT structures with different cell heights	250
Figure 8.39	Specific bending load for RECT structures with different cell heights	251
Figure 8.40	Maximum flexural stress for RECT structures with different cell heights	252
Figure 8.41	Bending load for TPZ structures with different cell wall opening angles	253
Figure 8.42	Specific bending load for TPZ structures with different cell wall opening angles	254
Figure 8.43	Maximum flexural stress for TPZ structures with different cell wall opening angles	255
Figure 8.44	Bending load for TR structures with different cell wall opening angles	256

Figure 8.45	Specific bending load for TR structures with different cell wall opening angles	257
Figure 8.46	Maximum flexural stress for TR structures with different cell wall opening angles	258
Figure 8.47	Damage caused to top face sheet, core and bottom face sheet of (a) RECTW1, (b) RECTW2, (c) RECTW3, (d) RECTW4, (e) RECTH1, (f) RECTH3, and (g) RECTH4 structures	261
Figure 8.48	Load-deformation curves for bending test of RECT structures with different cell (a) widths, (b) heights	262
Figure 8.49	Load-deformation curves for bending test of (a) TPZ and (b) TR structures with different cell wall opening angles	264
Figure 8.50	Damage caused to top face sheet, core and bottom face sheet of TPZ structures (a) TPZ45°, (b) TPZ50.5°, (c) TPZ57°, and (d) TPZ67°	265
Figure 8.51	Damage caused to top face sheet, core and bottom face sheet of (a) TR35°, (b) TR42.5°, and (c) TR47° structures	266
Figure 8.52	Different composite structures (a) RECT, (b) RECTTF, (c) TPZ, (d) TPZTF, (e) TR and (f) TRTF structures	271
Figure 8.53	Maximum compressive load for single layer face sheet and thickened face sheet composites	274
Figure 8.54	Specific compressive strength of single layer and thickened face sheet composites	275
Figure 8.55	Energy per unit volume for structures with single layer face sheet and thickened face sheet	276
Figure 8.56	Load-deformation curves in compression for (a) RECT and RECTTF structures, (b) TPZ, TPZTF, TR and TRTF structures	278
Figure 8.57	Stages of failure in compressive loading for different structures (a) RECT, (b) RECTTF, (c) TPZ, (d) TPZTF, (e) TR and (f) TRTF	282
Figure 8.58	Maximum bending load for single layer face sheet and thickened face sheet composite structures	283

Figure 8.59	Specific bending load for structures with single layer face sheet and thickened face sheet	284
Figure 8.60	Maximum flexural stress for structures with single layer face sheet and thickened face sheet	285
Figure 8.61	Load-deformation curves for different structures for bending test	287
Figure 8.62	Damages caused to top, core and bottom face sheets of various structures in bending: (a) RECT, (b) RECTTF, (c) TPZ, (d) TPZTF, (e) TR, and (f) TRTF	290
Figure 8.63	Composites for (a) single level and (b) double level TPZ spacer structures	294
Figure 8.64	Maximum compressive load for single and double level TPZ structures	297
Figure 8.65	Schematic representation of double level structure in compression	298
Figure 8.66	Specific compressive load for single and double level trapezoidal structures	299
Figure 8.67	Strain energy absorbed by single and double level TPZ structures	300
Figure 8.68	Strain energy per unit volume absorbed by single and double level TPZ structures	301
Figure 8.69	Load-deformation curves (a) and (b) for trapezoidal single layer, and (c) for trapezoidal double layer structures	305
Figure 8.70	Failure stages of trapezoidal single layer spacer structures (a) TPZ45°, (b) TPZ50.5°, (c) TPZ57°, and (d) TPZ65°	306
Figure 8.71	Failure stages of trapezoidal double layer spacer structures (a) TDL45°, (b) TDL50.5°, (c) TDL57°, and (d) TDL65°	307
Figure 8.72	Maximum bending load for single and double level TPZ structures	309
Figure 8.73	Specific bending load for single and double level TPZ structures	310
Figure 8.74	Maximum flexural stress for single and double level TPZ structures	311

Figure 8.75	Load-deformation curves for bending test (a) single and (b) double level TPZ structures	313
Figure 8.76	Damages caused to the top, core and bottom face sheet of single layer TPZ structures (a) TPZ45°, (b) TPZ50.5°, (c) TPZ57° and (d) TPZ65°	315
Figure 8.77	Damages caused to the top, core and bottom face sheet of double level TPZ structures (a) TDL45°, (b) TDL50.5°, (c) TDL57° and (d) TDL65°	317
Figure 9.1	Catalysis of the preforms (a) dip coating machine, (b) catalyzed glass strands and (c) catalyzed 'I' shaped preforms	322
Figure 9.2	Schematic representation of CVD process	324
Figure 9.3	(a) Experimental set of CVD process, 'I' shaped preform (b) before and (c) after CVD process	325
Figure 9.4	VARIM set-up for 'I' beam manufacturing, (b) neat glass fibre 'I' beam composite, (c) CNTs grafted 'I' beam composite	326
Figure 9.5	E-glass fibre surface scanning electron micrograph (a) neat E-glass fibre, (b) CNTs grafted E-glass fibre	327
Figure 9.6	CNTs grown E-glass fibre from 'I' beam preform	328
Figure 9.7	Raman Spectrum of CNTs-glass fibre	329
Figure 9.8	Resistance of neat glass tow and CNT grafted glass tow at 10V voltage	330
Figure 9.9	Measurement of electrical conductivity for CNTs treated (a) glass tows, (b) 'I' preform and (c) 'I' beam composite	331
Figure 9.10	(a) Electrical resistance of CNT coated glass in different forms, and (b) Electrical resistance of CNT coated 'I' beam composite	332
Figure 9.11	Tensile properties of tows at different stages of CNT synthesis	333
Figure 9.12	CNTs grafted 'I' beam composite in compression test	334
Figure 9.13	Compressive strength of neat and CNTs treated 'I' beam composites	335

List of Tables

Table No.	Title	Page No.
Table 4.1	Properties of E-glass fibres	104
Table 4.2	Properties of epoxy resin (LY 556)	105
Table 4.3	Properties of hardener ARADUR HY 951	105
Table 6.1	Cell structural parameters for trapezoidal spacer fabrics	133
Table 6.2	Cell structural parameters for rectangular spacer structures	135
Table 6.3	Specifications of individual fabric layer in polyester and E-glass samples	140
Table 6.4	Crimp analysis of different 2D fabrics	140
Table 6.5	Volumes of repeat unit for trapezoidal and rectangular structures	141
Table 7.1	Cell geometrical parameters for triangular spacer fabrics	163
Table 7.2	Cell geometrical parameters for trapezoidal spacer fabrics	167
Table 7.3	Cell geometrical parameters of rectangular spacer fabrics with different cell widths	171
Table 7.4	Cell geometrical parameters of rectangular spacer fabrics with different cell heights	172
Table 7.5	Cell geometrical parameters for trapezoidal double level spacer fabrics with different cell wall opening angles	177
Table 7.6	Cell geometrical parameters of RECTTF structure	183
Table 7.7	Cell geometrical parameters of TPZTF structure	186
Table 7.8	Cell geometrical parameters of TRTF structure	187
Table 8.1	Abbreviations used for different composite structures in the section	199
Table 8.2	Details for different spacer composite structures	200
Table 8.3	Specimen size used for lateral compression test of different composites	201
Table 8.4	Specimen size details for three-point-bending test of different composites	202
Table 8.5	Abbreviations used for different composites in the section	219

Table 8.6	Details of different composite structures	221
Table 8.7	Specimen size used for lateral compression test of different composites	222
Table 8.8	Specimen size details for three-point-bending test	223
Table 8.9	Abbreviations used for different composite structures in the section	270
Table 8.10	Details for different spacer composite structures	271
Table 8.11	Specimen size used for lateral compression test of different composites	272
Table 8.12	Specimen size details for three-point-bending test	273
Table 8.13	Abbreviations used for different composite structures in the section	293
Table 8.14	Details for spacer composite with single and double level trapezoidal structures	294
Table 8.15	Specimen size used for lateral compression test of different composites	295
Table 8.16	Specimen size details for three-point-bending test	296

Abbreviations

Abbreviation	Description
RECT	Rectangular spacer structure(s)
TPZ	Trapezoidal spacer structure(s)
TR	Triangular spacer structure(s)
TDL	Trapezoidal double level spacer structure(s)
SPY	Spacer structure connected with core piles
RECTW _n	Rectangular spacer structure with cell width variation (n = 1 to 4)
RECTH _n	Rectangular spacer structure with cell height variation (n = 1 to 4)
TPZ θ°	Trapezoidal spacer structure with θ° cell wall opening angle
TR θ°	Triangular spacer structure with θ° cell wall opening angle
TDL θ°	Trapezoidal double level spacer structure with θ° cell wall opening angle
RECTTF	Rectangular structure with thickened face sheets
TPZTF	Trapezoidal spacer structure with thickened face sheets
TRTF	Triangular spacer structure with thickened face sheets
FVF	Fibre volume fraction
VARIM	Vacuum assisted resin infusion moulding
CNTs	Carbon nanotubes
CVD	Chemical vapour deposition