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Compression Deformation of Glass Fibre Reinforcements in Composites Manufacturing Processes

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Abstract

Glass fibre reinforced polymer (GFRP) composites find application in diverse industries such as aerospace, marine, automotive, infrastructure and sport. GFRP composite products can be manufactured by a variety of methods, including the commonly employed Liquid Composite Moulding (LCM) group of techniques. Whatever the method, compression of the fibrous reinforcement is usually necessary in its natural dry state, and depending upon the technique, also after injection of a polymeric resin into a mould containing the reinforcement. A good understanding of the compression deformation behaviour of the reinforcement aids development of better models to describe and predict the manufacturing process, evaluate stresses acting on the mould, mould clamping and tooling forces required, and improvement of finished product quality.

LCM models commonly assume non-linear elastic deformation of the fibre reinforcement network, while some also take into account viscoelastic behaviour. Earlier investigations demonstrated reinforcement stress relaxation under constant compressive strain. Reinforcements under loading (compaction) and unloading (release) follow different paths for the two phases. These phenomena indicate viscoelastic behaviour. Cyclic loading and unloading of reinforcements show a progressive shift of the fibre volume fraction - compression stress curve, signifying non-recoverable strain. This research further investigated these complex compression deformation phenomena which are not normally considered for modelling simulations.

A series of experiments were conducted on glass fibre reinforcements of different architecture to determine and quantify in order of importance, different components of compression deformation. Permanent deformation was found to occur in all cases, and is comparable in magnitude to the elastic deformation of the reinforcement. Permanent deformation of the reinforcement considerably increased after just a few cycles of repeated compression and release. Time-dependent recovery of deformation on release of the compaction strain was found to largely depend on the number of layers of material in Continuous Filament Random Mat and Plain Weave Fabric reinforcements, it being of significant magnitude only with Plain Weave Fabric. A five component Maxwell-based model was developed to help explain and predict stress relaxation in the reinforcements under constant compressive strain.

X-ray micro-computed tomography (micro-CT) scanning and imaging technology was utilised to investigate fibre reinforcement deformation in manufactured composite laminates. It was hypothesised that permanent deformation in Biaxial Stitched Fabric and Plain Weave Fabric reinforcements occurs by means of changes to fibre bundle cross-sections, while time-dependent recovery of deformation on release of the compaction strain is related to the undulations of fibre bundles in the direction of loading, and also to the tow crimp in the case of Plain Weave Fabric reinforcements. Analysis of the micro-CT images proved correct the hypothesis in the case of Continuous Filament Random Mat, while there was support for Plain Weave Fabric. It was also proposed that permanent deformation in Continuous Filament Random Mat reinforcements is via filament bending and displacement, while time-dependent recovery of deformation is based on filament – filament interactions. In this case CT scanning images provide some support towards understanding filament spread but more information is needed to conclusively prove the hypothesis.

This doctoral thesis is dedicated to my late relatives Miss Ahalya Thirumurthy [8 October 1985 - 24 May 2005] and her family, father Mr. Vellore Padmanabhan Thirumurthy [7 May 1955 - 18 May 2005], mother Mrs. Suchitra Thirumurthy [20 June 1962 - 18 May 2005] and sister Miss Urmila Thirumurthy [8 May 1987 - 18 May 2005], b. India – d. New Zealand.

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Table of Contents

ABSTRACT	II
DEDICATION	IV
ACKNOWLEDGEMENTS	V
TABLE OF CONTENTS	VIII
LIST OF FIGURES	XII
LIST OF TABLES	XVII
LIST OF SYMBOLS AND UNITS	XVIII
1.0 INTRODUCTION	1
1.1 Aim	5
1.2 Objectives	5
1.3 Outline of Thesis	5
2.0 LITERATURE REVIEW	7
2.1 Introduction	7
2.2 Composites Manufacturing Methods	7
2.3 Reinforcement Materials	10
2.4 Research Survey	13
2.4.1 Compression of Random Fibre Assemblies	15
2.4.2 Compression Deformation Modelling	17
2.4.3 Compression Deformation Experimental Work	21
2.4.4 Micromechanics of Compression Deformation	25
2.4.5 Application of X-Ray Micro-Computed Tomography to Compression Deformation	26

3.0	EXPERIMENTS ON REINFORCEMENT VISCOELASTIC BEHAVIOUR	43
3.1	Introduction	43
3.2	Stress Relaxation Experiments	43
3.2.1	Introduction	43
3.2.2	Experimental Procedure	43
3.2.2.1	Varying Compaction Level Experiments	46
3.2.2.2	Varying Compression Speed Experiments	46
3.2.3	Results and Discussion	47
3.2.3.1	Continuous Filament Random Mat	47
3.2.3.2	Chopped Strand Mat	51
3.2.3.3	Plain Weave Fabric	55
3.2.4	Concluding Remarks	59
3.3	Long Term Behaviour Experiments	60
3.3.1	Introduction	60
3.3.2	Experimental Setup	60
3.3.3	Experimental Methods	61
3.3.4	Experimental Plan	62
3.3.5	Results and Discussion	63
3.3.6	Concluding Remarks	69
4.0	EXPERIMENTS ON COMPRESSION DEFORMATION COMPONENTS	71
4.1	Introduction	71
4.2	Experimental Procedure	72
4.2.1	Dynamic Reinforcement Thickness Measurement	72
4.3	Experimental Methods	74
4.3.1	Single Cycle Compaction Experiments	75
4.3.1.1	Components of Compression Deformation	75
4.3.2	Multiple Cycle Compaction Experiments	77
4.3.3	Cyclic Loading and Unloading Experiments	78
4.3.4	Reinforcement Samples	79
4.4	Experimental Plan	79
4.5	Results and Discussion	83

4.5.1	Single Cycle Compaction Experiments	83
4.5.1.1	Continuous Filament Random Mat	88
4.5.1.2	Plain Weave Fabric	89
4.5.1.3	Biaxial Stitched Fabric	90
4.5.2	Multiple Cycle Compaction Experiments	90
4.5.2.1	Continuous Filament Random Mat	91
4.5.2.2	Plain Weave Fabric	93
4.5.2.3	Biaxial Stitched Fabric	95
4.5.2.4	General Discussion	95
4.5.3	Comparison of Single Cycle and Multiple Cycle Compactions	101
4.5.4	Cyclic Loading and Unloading	101
4.5.4.1	Results	103
4.5.4.2	Discussion	105
4.6	Hypothesis on Mechanism of Compression Deformation	107
4.6.1	Continuous Filament Random Mat	110
4.6.2	Plain Weave Fabric	111
4.6.3	Biaxial Stitched Fabric	113
4.7	Concluding Remarks	113
5.0	STRESS RELAXATION MODELLING	115
5.1	Introduction	115
5.2	Stress Relaxation Model	118
5.3	Model Applicability to Experimental Data	121
5.4	Variation of Model Parameters with Fibre Volume Fraction	127
5.5	Stress Relaxation Prediction	131
5.6	Concluding Remarks	133
6.0	COMPRESSION DEFORMATION VISUALISATION AND IMAGE ANALYSIS	134
6.1	Introduction	134
6.2	Composite Laminates Manufacture	134
6.3	Micro-Computed Tomography X-Ray Scanner	138
6.4	Samples for Scanning	140
6.4.1	Biaxial Stitched Fabric	142

6.4.2	Continuous Filament Random Mat	143
6.4.3	Plain Weave Fabric	143
6.5	Results and Discussion	144
6.5.1	Biaxial Stitched Fabric	145
6.5.1.1	Weft Bundle Deformation	145
6.5.1.2	Warp Bundle Deformation	156
6.5.2	Continuous Filament Random Mat	163
6.5.3	Plain Weave Fabric	169
6.5.4	General Comments	176
6.6	Concluding Remarks	177
7.0	CONCLUSIONS AND RECOMMENDATIONS	180
7.1	Concluding Remarks	180
7.1.1	Experiments on Reinforcement Viscoelastic Behaviour	180
7.1.2	Experiments on Compression Deformation Components	181
7.1.3	Stress Relaxation Modelling	182
7.1.4	Compression Deformation Visualisation and Image Analysis	183
7.2	Recommendations for Further Work	184
	APPENDICES	185
A	List of Achievements	185
B	Stress Relaxation Model	187
C	Example SkyScan 1172 Micro-CT Scanner Log File	188
	LIST OF REFERENCES	191

List of Figures

Figure	Title	Page
1.1	Example composite products	2
1.2	Schematic drawing of LCM process	3
1.3	Schematic representation of RTM technique	3
1.4	Schematic diagram of cyclic loading and unloading of reinforcement	4
2.1	Schematic of pultrusion for (a) thermosets, and (b) thermoplastics.	8
2.2	Schematic drawing of filament winding process	8
2.3	Schematic of Resin Transfer Moulding	9
2.4	Schematic drawing of VARTM	9
2.5	Reinforcement material samples	12
3.1	Schematic diagram of the stress relaxation experimental setup	44
3.2	Schematic diagram of the stress relaxation experiment	44
3.3	Sample diagram of the compaction level experiment	46
3.4	Sample diagram of the compaction speed experiment	47
3.5	CFRM compaction level tests, CS = 2.0 mm/min.	48
3.6	CFRM compaction level tests, CS = 2.0 mm/min.	48
3.7	CFRM compaction level tests, CS = 2.0 mm/min.	49
3.8	CFRM compaction speed tests, $v_f = 0.415$.	50
3.9	CFRM compaction speed tests, $v_f = 0.415$.	50
3.10	CFRM compaction speed tests, $v_f = 0.415$.	51
3.11	CSM compaction level tests, CS = 2.0 mm/min.	52
3.12	CSM compaction level tests, CS = 2.0 mm/min.	52
3.13	CSM compaction level tests, CS = 2.0 mm/min.	53
3.14	CSM compaction speed tests, $v_f = 0.42$.	53
3.15	CSM compaction speed tests, $v_f = 0.42$.	54
3.16	CSM compaction speed tests, $v_f = 0.42$.	54
3.17	PWF compaction level tests, CS = 2.0 mm/min.	56
3.18	PWF compaction level tests, CS = 2.0 mm/min.	56
3.19	PWF compaction level tests, CS = 2.0 mm/min.	57
3.20	PWF compaction speed tests, $v_f = 0.625$.	58
3.21	PWF compaction speed tests, $v_f = 0.625$.	58

3.22	PWF compaction speed tests, $v_f = 0.625$.	59
3.23	Equipment arrangement for the long term behaviour experiments	61
3.24	Schematic diagram of the long term behaviour experiment	62
3.25	Sample plot of compression stress and v_f versus time	64
3.26	Sample plot of compression stress versus fibre volume fraction	65
3.27	CFRM – long term stress versus fibre volume fraction	66
3.28	CSM – long term stress versus fibre volume fraction	68
3.29	PWF – long term stress versus fibre volume fraction	68
4.1	Equipment setup on the Instron universal testing machine	73
4.2	Schematic diagram of the experiment	74
4.3	Schematic diagram of the single cycle compaction experiment	76
4.4	Example initial sample thickness recovery in the single cycle compaction experiments	78
4.5	Schematic diagram of the cyclic loading/unloading experiment	79
4.6	(a) Hydraulic cutting press, and (b) cutting blade.	81
4.7	Single cycle compaction tests: components of deformation versus constant strain holding time.	83
4.8	Single cycle compaction tests with variation of final fibre volume fraction: (a) deformation components, and (b) peak compaction stress.	84
4.9	Single cycle compaction tests with variation of compaction speed: (a) deformation components, and (b) peak compaction stress.	86
4.10	Single cycle compaction tests with variation of number of layers: (a) deformation components, and (b) peak compaction stress.	87
4.11	Multiple cycle compaction tests: example plot showing evolution of sample height and peak compaction stress from cycle-to-cycle.	90
4.12	Components of deformation in multiple cycle compaction tests with CFRM: (a) in relation to sample height at start of each cycle, and (b) in relation to sample original height.	92
4.13	Components of deformation in multiple cycle compaction tests with PWF: (a) in relation to sample height at start of each cycle, and (b) in relation to sample original height.	94
4.14	Components of deformation in multiple cycle compaction tests with BSF: (a) in relation to sample height at start of each cycle, and (b) in relation to sample original height.	96

4.15	Peak compaction stress in multiple cycle compaction tests	97
4.16	CFRM - evolution of compaction stress with fibre volume fraction in the multiple cycle compaction experiment	98
4.17	CFRM - variation of compaction stress over time in the multiple cycle compaction experiment	98
4.18	CFRM – long term stress as a percentage of peak stress in the multiple cycle compaction experiment	99
4.19	Comparison of deformation components between the single cycle compaction and multiple cycle compaction experiments	101
4.20	Typical cyclic loading/unloading compaction stress - v_f response	102
4.21	Permanent deformation and final cycle peak compaction stress in cyclic loading/unloading tests: variation of final fibre volume fraction.	103
4.22	Permanent deformation and final cycle peak compaction stress in cyclic loading/unloading tests: variation of compaction speed.	104
4.23	Permanent deformation and final cycle peak compaction stress in cyclic loading/unloading tests: variation of number of layers.	105
4.24	Schematic diagram of PWF and BSF tow compaction	111
5.1	Compaction and stress relaxation response of BSF	116
5.2	Normalised stress relaxation behaviour of BSF	116
5.3	Comparison of peak and long term stresses with BSF	117
5.4	Long term stress relaxation behaviour of BSF, final $v_f = 0.6$.	118
5.5	Three component Maxwell-based model using BSF compaction data	120
5.6	Schematic diagram of the five component Maxwell-based model	121
5.7	Normalised experimental and trial-fit curves for BSF, $v_f = 0.525$.	122
5.8	Normalised experimental and best-fit curves for BSF, $v_f = 0.525$.	122
5.9	Normalised experimental and best-fit curves for CFRM, $v_f = 0.415$.	125
5.10	Normalised experimental and best-fit curves for CSM, $v_f = 0.42$.	126
5.11	Normalised experimental and best-fit curves for PWF, $v_f = 0.625$.	126
5.12	Variation of model stress parameters with final fibre volume fraction for CFRM	127
5.13	Variation of relaxation time constants with final fibre volume fraction for CFRM	128
5.14	Variation of model stress parameters with final fibre volume fraction for CSM	128

5.15	Variation of relaxation time constants with final fibre volume fraction for CSM	129
5.16	Variation of model stress parameters with final fibre volume fraction for PWF	129
5.17	Variation of relaxation time constants with final fibre volume fraction for PWF	130
5.18	Variation of model stress parameters with final fibre volume fraction for BSF	130
5.19	Variation of relaxation time constants with final fibre volume fraction for BSF	131
5.20	Normalised experimental and predicted stress - time curves for BSF, $v_f = 0.55$.	132
5.21	Normalised experimental and predicted stress - time curves for BSF, $v_f = 0.625$.	132
6.1	Arrangement of equipment on the Instron universal testing machine for manufacture of composite panels	136
6.2	CFRM reinforcement for RTM	137
6.3	Manufactured BSF panel (from trial run)	137
6.4	SkyScan 1172 high-resolution micro-CT scanner	138
6.5	Schematic diagram of the principle of CT scanning: (a) scanning, and (b) reconstruction.	139
6.6	A selection of cut specimens for scanning	141
6.7	3D rendition of a PWF laminate sample used during initial CT scanning trials	142
6.8	Schematic diagram of cross-sectional image generation in laminate samples.	143
6.9	Example reconstruction cross-sectional images showing weft fibre bundles in BSF specimens: (a) from BSF_1, and (b) from BSF_4.	146
6.10	Photographs of BSF reinforcement showing the two sides of the fabric	147
6.11	Reconstruction image of a BSF material sample showing weft bundles	148
6.12	Sample BSF reconstruction image (from BSF_2) – weft bundles (shaded) analysed using ImageJ software	150
6.13	Schematic diagram of tow deformation (outline only)	151
6.14	Undulation of warp bundles in the direction of loading. (a) BSF_1 (single	

	compaction), and (b) BSF_4 (cyclic loading and unloading).	153
6.15	Undulation of warp bundles perpendicular to the direction of loading. (a) BSF_1 (single compaction), and (b) BSF_4 (cyclic loading and unloading).	154
6.16	Example sagittal images from BSF_1 (left) and BSF_4 (right), showing warp bundles in cross-section	157
6.17	Example sagittal image from BSF_2 showing warp bundles selected for analysis	158
6.18	Sample BSF_Raw sagittal image showing warp bundles in cross-section	159
6.19	Undulation of weft bundles in the direction of loading. (a) BSF_1 (single compaction), and (b) BSF_4 (cyclic loading and unloading).	161
6.20	Undulation of weft bundles perpendicular to the direction of loading. (a) BSF_1 (single compaction), and (b) BSF_4 (cyclic loading and unloading).	162
6.21	An example image from the CFRM scans (from CFRM_1)	164
6.22	CT scanner image of a CFRM raw material specimen	164
6.23	Example CFRM panel CT scanner image and its corresponding binary image (from CFRM_2)	166
6.24	Sample CT scanner image of CFRM_3 cross-section	167
6.25	Example image from CFRM_4 CT scanning	167
6.26	Example PWF reconstruction image (from PWF_1)	170
6.27	PWF reinforcement material	170
6.28	A sample PWF raw material reconstructed image	171
6.29	Example analysed image from PWF panels (from PWF_4)	171
6.30	CT scanner reconstruction image of a PWF_2 cross-section	172
6.31	Example PWF_3 CT scanner reconstruction image	173

List of Tables

Table	Title	Page
2.1	Specifications of reinforcement materials	11
2.2	Summary of papers reviewed	28
3.1	Experimental parameters for the stress relaxation experiments	45
3.2	Rheometer specifications	63
3.3	Stepwise target fibre volume fractions for the long term behaviour experiments	63
3.4	Long term stress as a percentage of peak stress	69
4.1	Testing programme for the single cycle compaction experiments	82
4.2	Testing programme for the multiple cycle compaction experiments	82
4.3	Testing programme for the cyclic loading/unloading experiments	82
5.1	Test parameters and results for the stress relaxation experiments	123
5.2	Model parameters	124
5.3	Predicted values of model parameters for BSF 2 and BSF 5	131
5.4	Normalised experimental and predicted stresses	133
6.1	Schedule of composite panels manufactured	135
6.2	CT scanning details	144
6.3	Average weft bundle cross-section data in BSF samples	149
6.4	Average of maximum peak-to-trough distances in BSF warp bundles	155
6.5	Average warp bundle cross-section data in BSF samples	160
6.6	Average of maximum peak-to-trough distances in BSF weft bundles	163
6.7	CFRM results	165
6.8	Average weft bundle cross-section data in PWF samples	174
6.9	Average of maximum peak-to-trough distances in PWF weft bundles	175
6.10	Schematic of deformation mechanisms	176

List of Symbols and Units

A	Area, area of cross-section, mm ²
CS	Compaction Speed, mm/min
E	Spring stiffness
h	Mould cavity (sample) thickness, mm
h ₀	Initial mould cavity (un-compacted sample) thickness, mm
h ₁	Final mould cavity (final compacted sample) thickness, mm
h _e	Sample height after elastic spring-back, mm
h _t	Sample height after time-dependent recovery, mm
m	Mass, g
P	Pressure, MPa (kPa)
t	Time, s
V	Volume, mm ³
v _f	Fibre Volume Fraction
ε	Strain, mm/mm
ε̇	Strain rate
η	Viscosity of dashpot
μ	Absolute viscosity, Pa.s
ρ	Density, g/mm ³ (kg/m ³)
σ	Compressive stress, MPa (kPa)
σ ₀ , σ ₁ , σ ₂	Stress constants
σ _(max)	Peak stress
σ(t)	Stress at time t
τ ₁ , τ ₂	Relaxation time constants