



# **Behaviour of Glass FRP Composite Tubes Under Repeated Impact for Piling Application**

By

**Ernesto Jusayan Guades**

Supervised by

**Prof. Thiru Aravinthan**

**Dr. Mainul Islam**

A dissertation submitted for the award of

**DOCTOR OF PHILOSOPHY**

Centre of Excellence in Engineered Fibre Composites

Faculty of Engineering and Surveying

University of Southern Queensland

Toowoomba, Queensland, Australia

May 2013

# Abstract

Fibre composites have been a viable option in replacing traditional pile materials such as concrete, steel and timber in harsh environmental conditions. On the other hand, the emergence of fibre reinforced polymer (FRP) composite tubes as a structural component and their corrosion-resistant characteristics made these materials potential in piling application. Driving these piles, however, requires more careful consideration due to their relatively low stiffness and thin walls. The possibility of damaging the fibre composite materials during the process of impact driving is always a concern. Research has therefore focused in understanding the impact behaviour of these materials in order for them to be safely and effectively driven into the ground.

This study investigated the behaviour of composite tubes subjected by repeated axial impact. The effects of impact event (incident energy and number of impact) on the instantaneous response and the residual properties of composite tubes were examined. Tubes made of glass/vinyl ester, glass/polyester, and glass/epoxy materials of different cross sections were considered. The impact behaviour of the tubes was experimentally and analytically investigated.

An experimental study on the repeated impact behaviour of square composite tube was conducted. The result showed that the dominant failure mode of the tube repeatedly impacted was characterised by progressive crushing at the upper end. This failure was manifested by inter and intra laminar cracking and glass fibre ruptures with simultaneous development of axial splits along its corners. It was found that the drop mass and impact velocity (or drop height) have pronounced effects on the collapse of the tubes at lower incident energies. Their effects, however, gradually decrease at relatively higher energies. The result also indicated that the incident energy is the major damage factor in the failure of tubes for lower number of impacts. On the contrary, the number of impacts becomes the key reason as soon as the value of incident energy decreases.

The effects of the damage factors such as the level of impact energy, the impact repetitions, and the mass impactor on the residual (post-impact) properties were also examined. The result of the investigation revealed that these factors significantly influenced the residual strength degradation of the impacted tubes. In contrast, the residual modulus was found to be less affected by these factors since the

damage brought by them is localised in most of the cases. The maximum reduction on the residual moduli is roughly 5%. On the other hand, the residual strengths degraded by up to 10%. The flexural strength of the tube was the most severely affected by the impact damage than its compressive and tensile strengths. This result was due to the fact that the impact damage on matrix and fibre both contributed on the flexural strength degradation. Moreover, the presence of matrix cracks or delamination lead to an increase in buckling instability during the flexural test, resulting to a much higher degradation compared to the other strengths. The comparison of the residual compressive strengths sourced at different locations along the height of the tube revealed that the strength reduction varied with its location. The degradation of the compressive strength of the impacted tube decreased when its location from the top of the tube increased. This result indicated that the influence of impact damage on the degradation of residual compressive strength of the tube is concentrated only in region closer to the impact point.

Finally, theoretical prediction using the basic energy principle was performed to gain additional understanding on the damage evolution behaviour of composite tubes subjected by repeated axial impact. The damage evolution model was verified through experimental investigation on a 100 mm square pultruded tube. The model was applied to composite tubes of different cross sections and materials made from vinyl ester/polyester/epoxy matrix reinforced with glass fibres. It was found that the experimental results on a 100 mm square pultruded tube and the proposed damage model agreed well with each other. The variation is less than 10% indicating that the model predicted reasonably the damage evolution of the tube subjected by repeated impact loading. It was also found that the energies describing the low cycle, high cycle, and endurance fatigue regions of the composite tubes are largely dependent on their corresponding critical energy  $E_c$ . The higher the  $E_c$  values, the higher the range of energies characterising these regions. The repeated impact curves (or  $E_c$ ) of tubes made from glass/epoxy is higher compared to the other matrix materials. Similarly, circular tubes have greater  $E_c$  values of comparable square and rectangular tubes.

From this study, an improved understanding of the behaviour of glass fibre FRP composite tubes under repeated axial impact can be achieved. The information provided in this study will help in developing efficient techniques and guidelines in driving composites piles.

# Certification of Dissertation

I certify that the ideas, experimental work, results, analysis and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any award, except where otherwise acknowledged.

-----

/ /

Signature of Candidate

Endorsed:

-----

/ /

Signature of Supervisor/s

-----

/ /

Signature of Supervisor/s

# Acknowledgements

With humble gratitude I must acknowledge the following that have in one way or the other contributed to the successful completion of this dissertation.

Prof. Thiru Aravinthan, my Principal Supervisor, for giving me the opportunity to do a PhD at the University of Southern Queensland (USQ). I am grateful to him for coaching me and willingly providing invaluable input and direction. I learned a great deal of things from him in my entire journey of PhD. I am also indebted to Dr. Mainul Islam, my Associate Supervisor, for sharing his time and ideas to make this dissertation a success. I greatly appreciate Dr. Allan Manalo for his support in my application to study at USQ. His technical suggestions and assistance were indispensable in improving the quality of this research. The generosity he extended to me during my study is greatly appreciated.

I would like to acknowledge the people behind USQ who provided the Post graduate Scholarship Grant. I thank the supports of the Faculty of Engineering and Surveying and the Centre of Excellence in Engineered Fibre Composites (CEEFC) for making this research possible. My thanks to Assoc. Prof. Karu Karunasena, Dr. Jay Epaarachchi, Dr. Francisco Cardona for all the useful discussions and suggestions. I owe an appreciation for the technical and administrative support from Martin Geach, Wayne Crowell, Atul Sakhiya, and Mohan Trada. Thanks to CEEFC staff and postgraduate students for the support and friendship. I especially thank Michael Kemp and all the staff of Wagners Composite Fibre Technology for providing the precious test samples. Thanks are expressed to the administration and staff of Northwest Samar State University for the Study Grant that would pave the way for my travel to Australia in pursuit of another academic achievement.

My unending recognition to Myla, who always, in all ways, was there for me. I am grateful to her for unselfishly setting aside her personal needs to give way to my personal dreams and aspiration. Very special thanks to my family who have been a source of encouragement and inspiration throughout my life. My appreciation to the Inocentes family, Jen, and the Filipino community of Toowoomba for welcoming me into their homes. Their incredible hospitality and generosity helped me overcome my homesickness. Above all, I am thanking the Almighty God for guiding me all throughout this endeavour. To those whom I missed to mention but have been a great part of my study, thank you very much.

## Associated Publications

### *Journal*

1. **E.J. Guades**, T. Aravinthan, M.M. Islam, and A.C. Manalo (2012). *A review on the driving performance of FRP composite piles*. Composite Structures, Volume 94, May issue, p 1932-1942.  
<http://www.sciencedirect.com/science/article/pii/S0263822312000451>
2. **E.J. Guades**, T. Aravinthan, A.C. Manalo, and M.M. Islam (2013). *Experimental investigation on the behaviour of square FRP composite tubes under repeated axial impact*. Composite Structures, Volume 97, March issue, p 211-221.  
<http://www.sciencedirect.com/science/article/pii/S0263822312005296>
3. **E.J. Guades** and T. Aravinthan (2013). *Residual properties of square FRP composite tubes subjected to repeated axial impact*. Composite Structures, Volume 95, January issue, p 354-365.  
<http://www.sciencedirect.com/science/article/pii/S0263822312004072>
4. **E.J. Guades**, T. Aravinthan, A.C. Manalo, and M.M. Islam (2013). *Damage modelling of repeatedly impacted square fibre-reinforced polymer composite tube*. Journal of Materials and Design, Volume 47, May issue, p 687-697.  
<http://www.sciencedirect.com/science/article/pii/S0261306912008801>

### *Conference Papers/Poster Presentation*

1. **E.J. Guades**, T. Aravinthan, M.M. Islam, and A.C. Manalo (2012). *Effects of energy levels on the impact fatigue behaviour and post-impact flexural properties of square FRP pultruded tubes*. Proceedings of the 22<sup>nd</sup> Australasian Conference on the Mechanics of Structures and Materials (ACMSM22), 11-14 December, Sydney, New South Wales, Australia.
2. **E.J. Guades**, T. Aravinthan, M.M. Islam, and A.C. Manalo (2012). *Stiffness degradation of FRP pultruded tubes under repeated axial impacts*. Proceedings of the 3<sup>rd</sup> Asia-Pacific Conference on FRP in Structures, February 2- 4, Hokkaido, Japan. Paper no F1B05.
3. **E.J. Guades**, T. Aravinthan, and M.M. Islam. (2011). *Driveability of composite piles*. Proceedings of the 1<sup>st</sup> International Postgraduate Conference on Engineering, Designing and Developing the Built Environment for Sustainable Wellbeing, April 27-29, QUT, Brisbane, Australia. p. 237-242
4. **E.J. Guades**, T. Aravinthan, and M.M. Islam. (2010). *An overview on the application of FRP composites in piling system*. Proceedings of the Southern Region Engineering Conference, November 11-12, 2010, Toowoomba, Australia. Paper no T3-4.

5. **E.J. Guades**, C. S. Sirimanna, T. Aravinthan & M.M. Islam. (2010). *Behaviour of composite pile under axial compression load*. Proceedings of the 22<sup>nd</sup> Australasian Conference on the Mechanics of Structures and Materials (ACMSM21), December 7-10, Melbourne, Australia. p. 457-462.
6. **E.J. Guades**, T. Aravinthan, and M.M. Islam (2011). *Impact behavior of pultruded tubes as hollow FRP piles*. Poster presentation during the USQ Community Engaged Research Evening. November 15, Sacred Heart Church Function Room, Toowoomba, Queensland, Australia.
7. **E.J. Guades**, T. Aravinthan, and M.M. Islam (2010). *Application and impact behavior of pultruded tube as FRP composite pile*. Poster presentation during the USQ Community Engaged Research Evening. November 10, USQ Refectory, Toowoomba, Queensland, Australia.

# Table of Contents

<b>List of figures</b>	xii
<b>List of tables</b>	xvii
<b>Notations</b>	xx
<b>Chapter 1 Introduction</b>	
1.1 General.....	1
1.2 Background.....	1
1.3 Fibre composites as an alternative in piling applications.....	2
1.4 FRP tubes as composite piles.....	4
1.5 Challenges in using hollow FRP pipe piles.....	5
1.6 Research needs related to their driving performance.....	6
1.7 Objectives.....	7
1.8 Scope of the thesis.....	8
1.9 Outline of the thesis.....	9
1.10 Summary.....	10
<b>Chapter 2 Review of composite piles and their driving performance</b>	
2.1 General.....	11
2.2 Types of composite piles.....	11
2.2.1 Steel pipe core piles.....	11
2.2.2 Structurally reinforced plastic piles.....	12
2.2.3 Concrete-filled FRP pipe piles.....	13
2.2.4 Fibreglass pultruded piles.....	14
2.2.5 Fibreglass reinforced plastic piles.....	15
2.2.6 Hollow FRP pipe piles.....	16
2.2.7 FRP sheet piles.....	17
2.3 Driving performance of composite piles.....	18
2.3.1 Types of driving hammer and its effect.....	18
2.3.2 Resistance to driving offered by the soil.....	20
2.3.3 The ability of the pile to transfer driving stresses.....	23
2.3.4 Strength of the pile to resist driving stresses.....	25
2.4 Recent developments on hollow FRP pipe piles.....	30
2.5 Study on the impact behaviour of FRP composite tubes as a research needs.....	35
2.6 Behaviour of FRP composite plates/laminates repeatedly impacted or tubes under repeated transverse impact.....	35
2.7 Conclusions .....	39

<b>Chapter 3</b>	<b>Characterisation of the properties of composite tubes</b>	
3.1	General.....	41
3.2	Composite tubes under study.....	41
3.3	Manufacturing of tubes using pultrusion process.....	42
3.4	Glass fibre content.....	43
3.5	Coupon tests.....	45
3.5.1	Compressive test.....	45
3.5.2	Tensile test.....	47
3.5.3	Flexural test.....	49
3.6	Full scale tests.....	51
3.6.1	Compressive test.....	51
3.6.2	Flexural test.....	54
3.7	Finite element (FE) analysis on full scale specimen.....	59
3.7.1	FE simulation on the compressive behaviour.....	60
3.7.2	FE simulation on the flexural behaviour.....	63
3.8	Summary of the mechanical properties of composite tubes.....	69
3.9	Conclusions.....	71
<b>Chapter 4</b>	<b>Investigation on the behaviour of square FRP composite tubes under repeated axial impact</b>	
4.1	Introduction.....	72
4.2	Experimental program.....	73
4.2.1	Test specimen.....	73
4.2.2	Test set-up and procedure.....	73
4.2.3	Data processing.....	78
4.3	Experimental results and discussion.....	80
4.3.1	Mode of damage.....	80
4.3.2	Progressive failure pattern.....	80
4.3.3	Impact load.....	83
4.3.4	Impact energy.....	87
4.3.5	Impact damage tolerance limit.....	92
4.4	Conclusions.....	96
<b>Chapter 5</b>	<b>Residual properties of square FRP composite tubes subjected to repeated axial impact</b>	
5.1	Introduction.....	98
5.2	Experimental program.....	99
5.2.1	Test specimen and repeated impact testing.....	99
5.2.2	Residual properties testing.....	101
5.3	Experimental results and discussion.....	106
5.3.1	Mode of damage.....	106
5.3.2	Summary of coupon test results.....	106

5.3.3	Effects of impact energy.....	108
5.3.4	Effects of impact repetitions .....	112
5.3.5	Effects of mass of the impactor.....	116
5.3.6	Comparison between compressive, tensile and flexural properties.....	120
5.3.7	Residual strength versus modulus.....	122
5.3.8	Variations of residual compressive strength with the height of the tube.....	124
5.4	Conclusions.....	125
<b>Chapter 6</b>	<b>Damage modelling of repeatedly impacted FRP composite tube</b>	
6.1	Introduction.....	128
6.2	Theoretical prediction methods.....	128
6.3	Quasi-static compressive test.....	131
6.3.1	Specimen and testing.....	131
6.4	Repeated impact test results.....	132
6.5	Evaluation of damage using parameter $D$ .....	134
6.6	Proposed damage response model.....	134
6.6.1	Minimum number of impacts to failure of the tube, $N_f$ .....	136
6.6.2	Minimum incident energy to fail the tube for one impact (critical energy), $E_c$ .....	136
6.6.3	Determination of $(E_c)_{Quasi-static}$ using quasi-static compressive test.....	138
6.6.4	Solving $b$ value.....	140
6.7	Comparison with the experimental data.....	141
6.7.1	Verification of the repeated impact curve.....	141
6.7.2	Validation of the proposed model.....	142
6.8	Summary of procedure in establishing the damage evolution curve .....	144
6.9	Application of the model to FRP composite tubes with square and rectangular cross sections .....	146
6.9.1	Square and rectangular FRP composite tubes.....	146
6.10	Conclusions.....	153
<b>Chapter 7</b>	<b>Application of the damage evolution model to other types of composite tubes</b>	
7.1	Introduction.....	155
7.2	Background on the constituents of composite tubes used in the model.....	156
7.2.1	Vinyl ester resin.....	156
7.2.2	Polyester resin.....	157
7.2.3	Epoxy resin.....	157

7.3 Glass/vinyl ester composite tubes.....	158
7.4 Glass/polyester composite tubes.....	163
7.5 Glass/epoxy composite tubes.....	170
7.6 Discussion on the repeated impact and damage evolution curves of FRP composite tubes.....	176
7.7 Discussion on the application of FRP composite tubes in piling system .....	178
7.8 Conclusions.....	181
<b>Chapter 8 Conclusions</b>	
8.1 Summary.....	182
8.2 Main conclusions from the study.....	182
8.2.1 Behaviour of composite tubes subjected by impact loading.....	182
8.2.2 Effects of impact loading on the residual properties of composite tubes.....	183
8.2.3 Prediction on the damage evolution of composite tubes.....	184
8.3 Recommendations for future study.....	185
<b>References</b>	<b>186</b>
<b>Appendix A Summary of results of the coupon and full scale tests on CT1 and CT2 specimens</b>	
A.1 Fibre fraction test.....	A-1
A.2 Compressive test on coupon specimen.....	A-2
A.3 Tensile test on coupon specimen.....	A-3
A.4 Flexural test on coupon specimen.....	A-5
A.5 Compressive test on full scale specimen.....	A-7
A.6 Flexural test on full scale specimen.....	A-9
<b>Appendix B Summary of specimen dimension and snapshots of the machine/apparatus used in repeated impact test</b>	
B.1 Summary on the details of the specimens.....	B-1
B.2 Repeated impact testing set-up and specimen snapshots.....	B-3
B.3 Apparatus used in the micro observation of damage.....	B-4
<b>Appendix C Variation of acceleration data and impact stress with the height of the tube</b>	
C.1 Analytical study on the variation of acceleration data.....	C-1
C.2 Finite element modelling.....	C-5
C.3 Finite element analysis results and discussion.....	C-13
C.4 Conclusions.....	C-21

**Appendix D Summary of specimen dimension and results in residual properties testing**

D.1 Summary of the details of the tubes.....	D-1
D.2 Summary of results of coupon compressive test.....	D-1
D.3 Summary of results of coupon tensile test.....	D-6
D.4 Summary of results of coupon flexural test.....	D-8

# List of Figures

## Chapter 1 Introduction

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
1.1	Problems of traditional piles installed in harsh environments	2

## Chapter 2 Review of composite piles and their driving performance

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
2.1	Steel pipe core piles.....	12
2.2	Structurally reinforced plastic piles.....	13
2.3	Concrete-filled FRP pipe piles.....	14
2.4	Fibreglass pultruded piles.....	15
2.5	Fibreglass reinforced plastic piles.....	16
2.6	Geometry of hollow FRP pipe piles used in the application.....	16
2.7	FRP sheet piles.....	17
2.8	Condition of the composite piles after driving.....	26
2.9	Condition of the composite piles after driving.....	27
2.10	Composite pile installed in Route 40 Bridge.....	28
2.11	Composite piles driven near Route 351 Bridge.....	29
2.12	Hollow FRP pipe piles replacing deteriorated timber piles.....	31
2.13	Pultruded composite tubes used in shoring-up boardwalks.....	32
2.14	Impact driving of 125 mm square pultruded tubes.....	33
2.15	Impact driving of 475 mm diameter hollow FRP pipe pile.....	34

## Chapter 3 Characterisation of the properties of composite tubes

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
3.1	Oblique view of the composite tubes.....	42
3.2	The basic pultrusion process concept.....	43
3.3	Coupon specimens and residue showing the fibre glass orientation.....	44
3.4	Compressive test set-up on coupons.....	46
3.5	Compressive stress-strain relationship.....	47
3.6	Compressive failure mode and condition of the specimens after the test.....	47
3.7	Tensile test set-up on coupons.....	48
3.8	Tensile stress-strain relationship.....	49
3.9	Tensile failure mode and condition of the specimens after the test.....	49
3.10	Flexural test set-up on coupons.....	50
3.11	Flexural stress-strain relationship.....	51
3.12	Flexural failure mode and condition of the specimens after the test.....	51
3.13	Compressive test set-up on full scale specimens.....	52
3.14	Compressive stress-strain relationship of full scale specimens.....	53
3.15	Compressive failure mode and condition of the full scale specimens.....	54
3.16	Flexural test on full scale specimens.....	55
3.17	Flexural load-displacement relationship (3-point bending test).....	56
3.18	Flexural load-strain relationship (3-point bending test).....	57
3.19	Typical failure modes for in 3-point bending tests.....	57
3.20	Flexural load-displacement relationship (4-point bending test).....	58
3.21	Flexural load-strain relationships (4-point bending test).....	59
3.22	Typical failure modes for in 3-point bending tests.....	59
3.23	Material modelling of the composite tube.....	60
3.24	Lamina lay-up arrangement used in FE model.....	61
3.25	Compressive stress-strain relationships.....	62
3.26	Compressive failure mode of the tested tube.....	63

3.27	Actual tube (length varies from 1.2 m to 1.5 m).....	63
3.28	FE model (3-point bending, L=1.2 m).....	64
3.29	FE model (4-point bending, L=1.5m).....	64
3.30	Support condition during flexural test (both ends).....	65
3.31	Flexural load-displacement relationships (3-point bending).....	66
3.32	Flexural failure mode in 3-point bending test.....	67
3.33	Flexural load-displacement relationships (4-point bending).....	68
3.34	Flexural failure mode in 4-point bending test.....	69

#### **Chapter 4 Investigation on the behaviour of square FRP composite tubes under repeated axial impact**

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
4.1	Impact testing set-up.....	74
4.2	Typical acceleration-displacement curves in impact testing .....	80
4.3	Condition of the tubes after impact test.....	81
4.4	Damage progressions of collapsed tube impacted by 476.8 J.....	83
4.5	Impact load histories of repeatedly impacted composite tubes.....	85
4.6	Peak load progressions of repeatedly impacted tubes.....	87
4.7	Typical energy curves.....	88
4.8	Impact energy histories of repeatedly impacted composite tubes.....	90
4.9	Comparison of the damage degree curves of repeatedly impacted tubes...	91
4.10	Incident energy vs. $N_f$ curve of repeatedly impacted tubes.....	94
4.11	$N_f$ vs. drop mass curve of repeatedly impacted tubes.....	95
4.12	$N_f$ vs. impact velocity curve of repeatedly impacted tubes.....	96

#### **Chapter 5 Residual properties of square FRP composite tubes subjected to repeated axial impact**

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
5.1	Conditions of the tubes after impact test .....	101
5.2	Cutting plan of coupons used in residual properties testing.....	102
5.3	Compressive test specimens.....	103
5.4	Tensile test specimens .....	104
5.5	Flexural test specimens .....	105
5.6	Scanned images showing typical micro-cracks on the surface of the tubes	106
5.7	Residual strength and impact energy relationships .....	109
5.8	Enlarged view: Residual compressive strength-impact energy relationships.....	109
5.9	Enlarged view: Residual tensile strength-impact energy relationships.....	110
5.10	Enlarged view: Residual flexural strength-impact energy relationships...	110
5.11	Residual modulus-impact energy relationships .....	111
5.12	Enlarged view: Residual compressive modulus- impact energy relationships.....	111
5.13	Enlarged view: Residual tensile modulus- impact energy relationships ...	111
5.14	Enlarged view: Residual flexural modulus-impact energy relationships...	112
5.15	Residual strength-number of impacts relationships .....	113
5.16	Enlarged view: Residual compressive strength-number of impacts relationships .....	113
5.17	Enlarged view: Residual tensile strength-number of impacts relationships	114
5.18	Enlarged view: Residual flexural strength-number of impacts relationships.....	114
5.19	Residual modulus-number of impacts relationship .....	115
5.20	Enlarged view: Residual compressive modulus-number of impacts relationships.....	115

5.21	Enlarged view: Residual tensile modulus-number of impacts relationships.....	115
5.22	Enlarged view: Residual flexural modulus-number of impacts relationships .....	116
5.23	Residual strength-drop mass relationships at different energy levels and number of impacts.....	117
5.24	Enlarged view: Residual compressive strength-drop mass relationships at different energy levels and number of impacts.....	117
5.25	Enlarged view: Residual tensile strength-drop mass relationships at different energy levels and number of impacts.....	118
5.26	Enlarged view: Residual flexural strength-drop mass relationships at different energy levels and number of impacts .....	118
5.27	Residual modulus-drop mass relationships at different energy levels and number of impacts.....	119
5.28	Enlarged view: Residual compressive modulus-drop mass relationships at different energy levels and number of impacts.....	119
5.29	Enlarged view: Residual tensile modulus-drop mass relationships at different energy levels and number of impacts .....	119
5.30	Enlarged view: Residual flexural modulus-drop mass relationships at different energy levels and number of impacts .....	120
5.31	Comparison of residual compressive, tensile, and flexural strengths.....	121
5.32	Comparison of residual compressive, tensile, and flexural moduli.....	122
5.33	Strength and modulus curves plotted at increasing impact energy levels...	123
5.34	Variation of residual compressive strengths with the height of the tube...	125

## Chapter 6 Damage modelling of repeatedly impacted FRP composite tubes

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
6.1	Quasi-static compressive test.....	132
6.2	Normalised energy and number of impacts relationship.....	133
6.3	$D$ vs. $N$ curve of the representative composite tube.....	134
6.4	Idealised lifetime response curve of the repeatedly impacted tube.....	135
6.5	Typical curve described by $E_{in} = aN_f^{-b}$ .....	136
6.6	Variation of the correlation $\beta$ of glass/vinyl ester composite tubes .....	137
6.7	Data points with the fitting line showing $\beta$ and $\alpha$ relationship.....	138
6.8	Typical load-displacement curves from quasi-static compressive test.....	139
6.9	Schematic diagram used in computing $(E_c)_{Quasi-static}$ .....	139
6.10	$b$ values using Excel 2010 “Solver” function.....	140
6.11	Comparison between the experimental data and repeated impact curve ...	141
6.12	Proposed model vs. experimental data for collapsed tubes .....	143
6.13	Proposed model vs. experimental data for non-collapsed tubes .....	144
6.14	Flow chart in establishing the damage evolution curve .....	145
6.15	Square and rectangular composite tubes .....	147
6.16	Crushed composite tubes.....	148
6.17	Load-displacement curves of S125 specimen .....	148
6.18	Load-displacement curves of R75x100 specimen .....	149
6.19	Repeated impact curves of the square and rectangular tubes.....	151
6.20	Damage evolution curves of square and rectangular tubes .....	152

## Chapter 7 Application of the damage evolution model to other types of composite tubes

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
7.1	Repeated impact curves of glass/vinyl ester tubes.....	161
7.2	Damage evolution curves of GV-C tube .....	162
7.3	Damage evolution curves of GV-S tube .....	162

7.4	Damage evolution curves of GV-H tube .....	162
7.5	Data points with the fitting line showing $\beta$ and $\alpha$ relationship of glass/polyester tubes .....	164
7.6	Repeated impact curves of glass/polyester tubes .....	167
7.7	Damage evolution curves of GP-C1 tube .....	168
7.8	Damage evolution curves of GP-C2 tube .....	168
7.9	Damage evolution curves of GP-C3 tube .....	169
7.10	Damage evolution curves of GP-S1 tube .....	169
7.11	Damage evolution curves of GP-S2 tube .....	169
7.12	Damage evolution curves of GP-S3 tube .....	179
7.13	Repeated impact curves of glass/epoxy tubes .....	173
7.14	Damage evolution curves of GE-C1 tube .....	174
7.15	Damage evolution curves of GE-C2 tube .....	174
7.16	Damage evolution curves of GE-C3 tube .....	175
7.17	Damage evolution curves of GE-C4 tube .....	175
7.18	Damage evolution curves of GE-C5 tube .....	175
7.19	Damage evolution curves of GE-S1 tube .....	176

## Appendix A Summary of results of the coupon and full scale tests on CT1 and CT2 specimens

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
A.1	Compressive load-displacement relationship of coupon specimens (CT1)	A-3
A.2	Compressive load-displacement relationship of coupon specimens (CT2)	A-3
A.3	Tensile load-displacement relationship of coupon specimens (CT1).....	A-4
A.4	Tensile load-displacement relationship of coupon specimens (CT2).....	A-5
A.5	Flexural load-midspan deflection relationship of coupon specimens (CT1).....	A-6
A.6	Flexural load-midspan deflection relationship of coupon specimens (CT2).....	A-6
A.7	Simplified cross section of the tube.....	A-7
A.8	Compressive load-displacement relationship of full scale specimens (CT1, L=100 mm).....	A-8
A.9	Compressive load-displacement relationship of full scale specimens (CT1, L=200 mm).....	A-9
A.10	Compressive load-displacement relationship of full scale specimens (CT2, L=100 mm).....	A-9
A.11	Specimen cross section lay-out .....	A-10
A.12	Schematic plan of 3-point bending test .....	A-10
A.13	Schematic plan of 4-point bending test .....	A-10
A.14	Flexural stress-displacement relationship (3-point bending test) of CT1...	A-11
A.15	Flexural stress-displacement relationship (3-point bending test) of CT2...	A-12
A.16	Flexural stress-strain relationship (4-point bending test) of CT1.....	A-12

## Appendix B Summary of specimen dimension and snapshots of the machine/apparatus used in repeated impact test

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
B.1	Repeated impact testing set-up data logger and fixtures.....	B-3
B.2	Condition of the specimen after impact test (Test matrix from Table 4.2).	B-4
B.3	Condition of the specimen after impact test (Test matrix from Table 4.3).	B-4
B.4	MOTIC® SMZ 168 Series stereo zoom microscope.....	B-4

## Appendix C Variation of impact stress with the height of the tube using finite element (FE) analysis

<i>Figure</i>	<i>Figure caption</i>	<i>Page</i>
C.1	Schematic view of the impacted tube and the idealised model.....	C-2
C.2	Comparison of $a_{L/2}$ and $a_1$ values at varying impact mass .....	C-2
C.3	Material modelling of the composite tube.....	C-7
C.4	Lamina lay-up arrangement used in FE model.....	C-7
C.5	Factor vs. time table for the impulse period of 0.01 second.....	C-9
C.6	Variation of the static load case with the measured acceleration.....	C-9
C.7	Factor vs. time table simulating repeated impact loading (E630).....	C-10
C.8	Factor vs. time table simulating repeated impact loading (E480).....	C-10
C.9	Factor vs. time table simulating repeated impact loading (E420).....	C-11
C.10	Factor vs. time table simulating material degradation (E630).....	C-12
C.11	Factor vs. time table simulating material degradation (E480).....	C-12
C.12	Factor vs. time table simulating material degradation (E480).....	C-12
C.13	Comparison of time steps for E630.....	C-13
C.14	Variation of peak axial stress in longitudinal direction.....	C-14
C.15	Variation of peak axial stress in transverse direction.....	C-16
C.16	Variation of peak axial strength degradation with number of impacts.....	C-17
C.17	Absolute peak axial strength degradation at failure.....	C-18
C.18	Comparison of the simulated damaged length at the start of failure.....	C-19
C.19	Damaged length simulation using FE analysis.....	C-20

# List of Tables

## Chapter 2 Review of composite piles and their driving performance

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
2.1	Comparison of pile impedance.....	25
2.2	List of applications of hollow FRP pipe piles.....	31
2.3	Mechanical properties of the 125 mm square tube.....	32
2.4	Summary of recent experimental studies on repeated impact test.....	36

## Chapter 3 Characterisation of the properties of composite tubes

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
3.1	Section properties of the 100 mm square tube.....	42
3.2	Details of the specimen for fibre fraction test .....	44
3.3	Summary of glass fibre content of each ply .....	44
3.4	Details of the specimen for coupon tests .....	45
3.5	Material properties of the tube wall laminate ply .....	61
3.6	Summary of mechanical properties from coupon tests .....	70
3.7	Summary of mechanical properties from full scale tests.....	70

## Chapter 4 Investigation on the behaviour of square FRP composite tubes under repeated axial impact

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
4.1	Details of the specimen .....	73
4.2	Test matrix used in defining the impact behaviour.....	78
4.3	Test matrix used in defining the impact damage tolerance.....	78
4.4	Summary of $N_f$ values.....	92

## Chapter 5 Residual properties of square FRP composite tubes subjected to repeated axial impact

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
5.1	Details of the specimen.....	99
5.2	Repeated impact test matrix.....	100
5.3	Details of the specimen for coupon tests.....	102
5.4	Summary of compression test results.....	107
5.5	Summary of tensile and flexural tests results.....	107

## Chapter 6 Damage modelling of repeatedly impacted FRP composite tubes

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
6.1	Details of the specimen used in quasi-static compressive test.....	131
6.2	Summary of $(E_c)_{Quasi-static}$ values.....	140
6.3	Comparison of incident energies at different $N_f$ .....	142
6.4	Comparison of incident energies at average $N_f$ .....	142
6.5	Properties of S125 and R75x100 specimens .....	147
6.6	Summary of parametric values of square and rectangular tubes.....	149

## Chapter 7 Application of the damage evolution model to other types of composite tubes

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
7.1	Details of GV-C, GV-S, and GV-H tubes .....	158
7.2	Summary of $(E_c)_{Quasi-static}$ and $\beta$ values of glass/vinyl ester tubes .....	159

7.3	Summary of the repeated impact equation of glass/vinyl ester tubes .....	160
7.4	Details of glass/polyester tubes (circular cross section).....	163
7.5	Details of glass/polyester tubes (square cross section).....	163
7.6	Summary of $(E_c)_{Quasi-static}$ and $\beta$ values of glass/polyester tubes.....	165
7.7	Summary of the repeated impact equation of glass/polyester tubes .....	165
7.8	Details of glass/epoxy tubes (circular cross section).....	170
7.9	Details of glass/epoxy tubes (circular and square cross sections).....	171
7.10	Summary of $(E_c)_{Quasi-static}$ and $\beta$ values of glass/epoxy tubes.....	172
7.11	Summary of the repeated impact equation of glass/polyester tubes.....	172

## Appendix A Summary of results of the coupon and full scale tests on CT1 and CT2 specimens

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
A.1	Summary of results of fibre fraction test for CT1.....	A-1
A.2	Summary of results of fibre fraction test for CT2.....	A-1
A.3	Summary of results of coupon compressive test for CT1.....	A-2
A.4	Summary of results of coupon compressive test for CT2.....	A-2
A.5	Summary of results of coupon tensile test for CT1.....	A-4
A.6	Summary of results of coupon tensile test for CT2.....	A-4
A.7	Summary of results of coupon flexural test for CT1.....	A-5
A.8	Summary of results of coupon flexural test for CT2.....	A-6
A.9	Summary of results of full scale compressive test for CT1 (L = 100 mm). A-7	
A.10	Summary of results of full scale compressive test for CT1 (L = 200 mm). A-8	
A.11	Summary of results of full scale compressive test for CT2 (L = 100 mm). A-8	
A.12	Summary of results of full scale flexural test (3-point loading) for CT1... A-11	
A.13	Summary of results of full scale flexural test (3-point loading) for CT2... A-11	
A.14	Summary of results of full scale flexural test (4-point loading) for CT1... A-11	

## Appendix B Summary of specimen dimension and snapshots of the machine/apparatus used in repeated impact test

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
B.1	Dimension of specimen E630.....	B-1
B.2	Dimension of specimen E480.....	B-1
B.3	Dimension of specimen E420.....	B-1
B.4	Dimension of specimen E320.....	B-2
B.5	Dimension of specimen E210.....	B-2
B.6	Dimension of specimen E160.....	B-2
B.7	Dimension of specimen E630-1.....	B-2
B.8	Dimension of specimen E480-1.....	B-3
B.9	Dimension of specimen E480-2.....	B-3
B.10	Dimension of specimen E420-1.....	B-3

## Appendix C Variation of impact stress with the height of the tube using finite element (FE) analysis

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
C.1	Material properties of the tube wall laminate ply.....	C-7
C.2	Summary of applied static load cases used in FE analysis.....	C-10

## Appendix D Summary of specimen dimension and results in residual properties testing

<i>Table</i>	<i>Table caption</i>	<i>Page</i>
D.1	Summary of the dimension of the tubes.....	D-1

D.2	Coupon dimension and compressive test result for E160-80 (Top).....	D-1
D.3	Coupon dimension and compressive test result for E320-80 (Top).....	D-1
D.4	Coupon dimension and compressive test result for E480-10 (Top).....	D-2
D.5	Coupon dimension and compressive test result for E630-10 (Top).....	D-2
D.6	Coupon dimension and compressive test result for E160-80 (Middle).....	D-2
D.7	Coupon dimension and compressive test result for E320-80 (Middle).....	D-2
D.8	Coupon dimension and compressive test result for E480-10 (Middle).....	D-3
D.9	Coupon dimension and compressive test result for E630-10 (Middle).....	D-3
D.10	Coupon dimension and compressive test result for E480-40 (Middle).....	D-3
D.11	Coupon dimension and compressive test result for E480-80 (Middle).....	D-3
D.12	Coupon dimension and compressive test result for E630-30 (Middle).....	D-4
D.13	Coupon dimension and compressive test result for E740-10 (Middle).....	D-4
D.14	Coupon dimension and compressive test result for E160-80 (Bottom).....	D-4
D.15	Coupon dimension and compressive test result for E320-80 (Bottom).....	D-4
D.16	Coupon dimension and compressive test result for E480-10 (Bottom).....	D-5
D.17	Coupon dimension and compressive test result for E630-10 (Bottom).....	D-5
D.18	Coupon dimension and compressive test result for E480-40 (Bottom).....	D-5
D.19	Coupon dimension and compressive test result for E480-80 (Bottom).....	D-5
D.20	Coupon dimension and compressive test result for E630-30 (Bottom).....	D-6
D.21	Coupon dimension and compressive test result for E740-10 (Bottom).....	D-6
D.22	Coupon dimension and tensile test result for E160-80.....	D-6
D.23	Coupon dimension and tensile test result for E320-80.....	D-6
D.24	Coupon dimension and tensile test result for E480-10.....	D-7
D.25	Coupon dimension and tensile test result for E630-10.....	D-7
D.26	Coupon dimension and tensile test result for E480-40.....	D-7
D.27	Coupon dimension and tensile test result for E480-80.....	D-7
D.28	Coupon dimension and tensile test result for E630-30.....	D-8
D.29	Coupon dimension and tensile test result for E740-10.....	D-8
D.30	Coupon dimension and flexural test result for E160-80.....	D-8
D.31	Coupon dimension and flexural test result for E320-80.....	D-8
D.32	Coupon dimension and flexural test result for E480-10.....	D-9
D.33	Coupon dimension and flexural test result for E630-10.....	D-9
D.34	Coupon dimension and flexural test result for E480-40.....	D-9
D.35	Coupon dimension and flexural test result for E480-80.....	D-9
D.36	Coupon dimension and flexural test result for E630-30.....	D-10
D.37	Coupon dimension and flexural test result for E740-10.....	D-10

# Notations

Roman alphabets

<b><i>Notation</i></b>	<b><i>Description</i></b>
$A$	Cross-sectional area of tube/coupon specimen
$a$	distance between one of the end supports and the nearest applied load, parametric constant, acceleration
$a_t$	Acceleration as a function of time or at present time increment
$a_{t-1}$	Acceleration at previous time increment
$b$	Width of the tube/coupon specimen or parametric constant
$c$	Neutral axis depth of the tube or parametric constant
$c_w$	Compression wave velocity
$D$	Damage parameter
$d$	Depth of the tube
$E$	Modulus of elasticity
$E_{abs}$	Absorbed energy
$E_c$	Critical energy (energy causing the failure of tube at one impact)
$E_{comp}$	Compressive elastic modulus of tube/coupon specimen
$(E_c)_{Dynamic}$	Critical energy obtained from dynamic (impact) test
$E_f$	Flexural elastic modulus
$E_{im}$	Impact energy
$E_{in}$	Incident energy
$E_K$	Kinetic energy
$E_P$	Potential energy
$(E_c)_{Quasi-static}$	Critical energy obtained from quasi-static compressive test
$E_{sat}$	Saturation energy
$E_t$	Tensile elastic modulus
$E_T$	Total energy
$E_{ws}$	Energy as a function of displacement
$E_{wt}$	Energy as a function of time
$F_s$	Load at present displacement increment
$F_{s-1}$	Load at previous displacement increment
$F_t$	Impact load as a function of time
$g$	Acceleration due to gravity
$h$	Drop height
$h_0$	Drop height (used in Appendix C)
$j$	Inner depth of the tube
$k$	Inner width of the tube
$l$	Length of the tube /coupon specimen
$l_s$	Test span in flexure
$L$	Length of the tube (used in Appendix C)
$M_g$	Fibre glass content in mass percentage
$m$	Mass of the impactor
$m_c$	Critical impact mass

$m_0$	Initial mass of the specimen used in fibre fraction test
$m_1$	Initial mass of the dry crucible used in fibre fraction test
$m_2$	Initial mass of the dry crucible plus dried specimen used in fibre fraction test
$m_3$	Final mass of the crucible plus residue used in fibre fraction test
$m_m$	Equivalent mass at the $m^{th}$ point (used in Appendix C)
$N$	Number of impact
$N_f$	Number of impacts to initiate failure/collapse of the tube
$N_{max}$	Maximum number of impact
$P_{pc}$	Peak compressive load of tube/coupon specimen
$P_{pf}$	Peak flexural load of tube/coupon specimen
$P_{pt}$	Peak tensile load
$(P_m)^0$	Maximum load at the 1 <sup>st</sup> impact
$(P_m)^N$	Maximum load at the $N^{th}$ impact
$I$	Moment of inertia
$I_x$	Moment of inertia along the x-axis
$I_y$	Moment of inertia along the y-axis
$t$	Thickness of the coupon specimen
$R(N_f)$	Reliability of $N_f$
$r_i$	Internal radius of the chamfered corner of the rectangular tube
$r_e$	External radius of the chamfered corner of the rectangular tube
$s_m$	Travelled distance by the wave at the $m^{th}$ point (used in Appendix C)
$s_t$	Displacement as a function of time
$t$	Present time increment
$t-1$	Previous time increment
$v$	Impact velocity
$v_{ff}$	Volume of the specimen used in fibre fraction test
$v_m$	Wave velocity at the $m^{th}$ point (used in Appendix C)
$v_0$	Initial velocity of the impactor before hitting the target
$v_t$	Velocity as a function of time or at present time increment
$v_{t-1}$	Velocity at previous time increment
$z$	Pile impedance

## Greek letters

<b>Notation</b>	<b>Description</b>
$\alpha$	Ratio of the loading rates between quasi-static compressive and impact tests
$\beta$	Correlation factor
$\varepsilon_{pc}$	Peak compressive strain of tube or coupon specimen
$\rho$	Mass density/specific mass
$\rho_t$	Mass density of the tube (used in Appendix C)
$\sigma_{pc}$	Peak compressive stress of tube or coupon specimen
$\sigma_{pf}$	Peak compressive stress
$\sigma_{pt}$	Peak tensile stress
$\sigma_1$	stress measured at the strain values $\varepsilon_1 = 0.0005$
$\sigma_2$	stress measured at the strain values $\varepsilon_2 = 0.0025$
$\theta$	Life duration