

PERFORMANCE OF STEEL SECTIONS STRENGTHENED WITH  
CARBON FIBRE REINFORCED POLYMER PLATE UNDER  
TROPICAL CLIMATE

MEHRAN GHOLAMI

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering  
Universiti Teknologi Malaysia

FEBRUARY 2015

**Dedicated to:**

*My beloved parents*

*My lovely wife and daughter*

*My dear sisters*

*Thank you for your prayers and understanding*

## ACKNOWLEDGMENT

This study would not be possible without the guidance of my supervisors Prof. Dr. Abdul Rahman Mohd Sam and Prof. Dr. Jamaludin Mohamad Yatim. They offered me the opportunity to study at the Universiti Teknologi Malaysia and guided and supported this research. I am thankful for their insightful comments, encouragement and criticism. The suggestions and supports provided by Prof. Dr. Mahmood Md Tahir and Prof. Dr. Shukur Abu Hassan is much appreciated.

I wish to express my special thanks to dear Nazanin for her great inspiration, encouragement and support to ensure the completion of my research.

I would like to appreciate my dear friend Dr. Mohammad Reza Yadollahi for his valuable comments and suggestions. The results of experimental program would not have been a reality, without the contributions from my colleagues Dr. Bahram Marabi, Dr. Mohamad Ahmadi, Dr. Reza Mahjoub, Dr. Esmail Mohamadian, Dr. Taha Mehman Navaz and Dr. Meisam Razavi.

The financial funding received from the Research Management Center (RMC) and International Doctoral Fellowship (IDF) was invaluable for me to undertake this endeavor.

## ABSTRACT

The use of Carbon Fibre Reinforced Polymer (CFRP) to strengthen steel structures has attracted the attention of researchers in recent years. Previous researches demonstrated that bonding of CFRP plates to the steel sections has been a successful method to increase the mechanical properties. However, behaviour of the system under various environmental conditions has not completely been defined yet. The main objective of the study is to evaluate the performance of steel/CFRP bonding system after exposure in natural tropical climate. Environmental conditions including wet/dry cycles, submerging in plain water, salt water and acidic solution were considered to define the effect of different exposures on the system. In the experimental program, double lap shear specimens (DLS) and strengthened I-section steel beams were prepared and subjected to the environmental exposures up to 8 months. Further, CFRP and epoxy adhesive coupons were prepared and exposed to the same conditions to find the influence of aging on the materials individually. Tensile tests and four-point bending tests were performed after exposure and the mechanical properties were compared to the control specimens. The results demonstrated that the epoxy adhesive was the critical part. In addition, the strength and stiffness of the coupons which were subjected to tropical climate showed a remarkable increase around 16% and 11% at the beginning of exposure, respectively. However, these properties were reduced gradually until the end of exposure. The results of tests on DLS specimens and strengthened steel beams indicated the same rate of properties degradation as the adhesive coupons. The failure mode for strengthened steel beams was lateral-buckling which showed the bonding strength was still remained after exposure. Further, the properties of CFRP plate showed negligible changes for all environmental conditions. The theoretical analysis has been conducted to predict the properties of specimens before and after exposure and the results showed close agreement to the experimental tests.

## ABSTRAK

Penggunaan Polimer Bertetulang Gentian Karbon (CFRP) untuk mengukuhkan struktur keluli telah menarik banyak perhatian masa kini. Kajian lepas menunjukkan sistem lekatan plat CFRP kepada keratan keluli telah berjaya untuk meningkatkan sifat mekanikalnya. Walau bagaimanapun, prestasi sistem di bawah pelbagai keadaan persekitaran masih belum diketahui sepenuhnya. Objektif utama kajian ini adalah untuk menilai prestasi sistem lekatan keluli/CFRP selepas didedahkan kepada keadaan iklim tropika. Selain itu, dedahan kepada keadaan kitaran basah/kering, rendaman dalam air paip, air garam dan larutan berasid juga dibuat untuk menentukan kesannya kepada sistem. Dalam program eksperimen, sampel lekatan ricih (DLS) dan seksyen keluli yang diperkukuhkan disediakan dan didedahkan kepada keadaan yang dinyatakan sehingga 8 bulan. Selain itu, CFRP dan kupon epoksi juga disediakan dan didedahkan kepada keadaan yang sama untuk menentukan pengaruh dedahan terhadap bahan tersebut. Ujian tegangan dan ujian lenturan empat titik telah dijalankan selepas dedahan dan sifat mekanikal dibandingkan dengan sampel kawalan. Keputusan menunjukkan pelekat epoksi adalah elemen yang paling kritikal dalam system ini. Disamping itu, kekuatan dan kekukuhan kupon yang didedahkan kepada iklim tropika menunjukkan peningkatan masing-masing sekitar 16% dan 11% pada peringkat awal dedahan. Walau bagaimanapun, prestasi mulai merosot secara beransur-ansur sehingga akhir masa dedahan. Keputusan ujian ke atas sampel DLS dan rasuk diperkuatkan menunjukkan kadar pengurangan prestasi yang hampir sama dengan kupon epoksi. Mod kegagalan bagi rasuk diperkuatkan adalah sisi-lengkokan yang menunjukkan kekuatan ikatan masih ada selepas dedahan. Sementara itu ciri-ciri plat CFRP hanya menunjukkan perubahan yang kecil untuk semua keadaan dedahan. Analisis teori telah dijalankan untuk meramalkan sifat-sifat spesimen sebelum dan selepas dedahan dan hasil kajian menunjukkan keputusan yang hampir sama dengan keputusan eksperimen.

## TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENTS</b>	vii
	<b>LIST OF TABLES</b>	xv
	<b>LIST OF FIGURES</b>	xviii
	<b>LIST OF SYMBOLS</b>	xxiv
	<b>LIST OF APPENDICES</b>	xxvi
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background	1
	1.2 Problem statement	2
	1.3 Objectives	3
	1.4 Research significance	4
	1.5 Scope of the study	4
	1.6 Limitation of the study	6
	1.7 Thesis organization	6
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>8</b>
	2.1 Introduction	8
	2.2 Types of FRP materials and adhesives	9
	2.3 Strengthening of steel beams	11

2.4	Bonding characteristics	13
2.5	Improving fatigue behaviour	18
2.6	Durability performance	19
2.6.1	Thermal effects	20
2.6.2	Effect of moisture	23
2.6.3	Chemical attack	27
2.6.4	Ultraviolet radiations	30
2.6.5	Surface preparation	31
2.6.6	Combination of environmental factors	33
2.7	Guidelines recommendation	37
2.8	Tropical climate in Malaysia	40
2.9	Concluding remarks	43
<b>3</b>	<b>RESEARCH METHODOLOGY</b>	<b>47</b>
3.1	Introduction	47
3.2	Experimental tests	48
3.2.1	Material properties	48
3.2.1.1	Properties of CFRP plate	49
3.2.1.2	Properties of epoxy adhesive	50
3.2.1.3	Properties of steel	51
3.2.2	Environmental conditions	53
3.2.3	Double lap shear specimens	57
3.2.3.1	Specimens' geometry	57
3.2.3.2	Specimens' preparation	57
3.2.3.3	Environmental conditions	69
3.2.3.4	Test procedure and instrumentation	74
3.2.4	I-section steel beams	77
3.2.4.1	Specimens' geometry	77
3.2.4.2	Preparation of strengthened beams	78
3.2.4.3	Environmental conditions	85
3.2.4.4	Test procedure and instrumentation	89
3.2.5	Epoxy adhesive coupons	96
3.2.6	CFRP coupons	106
3.3	Theoretical analysis	110

3.3.1	Modelling of adhesive properties degradation	111
3.3.2	Analysis of double lap shear joints strength	114
3.3.3	Analysis of steel beam strengthened with CFRP plate	115
3.3.3.1	Serviceability limit state	116
3.3.3.2	Ultimate limit state	119
<b>4</b>	<b>EXPERIMENTAL RESULTS AND DISCUSSION OF CFRP, ADHESIVE AND DOBLE LAP SHEAR SPECIMENS</b>	<b>121</b>
4.1	Introduction	121
4.2	Test results of CFRP coupons and discussion	121
4.2.1	Mechanical properties of control CFRP coupons	122
4.2.2	Mechanical properties of exposed CFRP coupons	123
4.2.3	Weight observation of CFRP coupons	127
4.3	Test results of epoxy adhesive coupons and discussion	128
4.3.1	Physical properties of epoxy adhesive coupons	128
4.3.2	Test results of control epoxy adhesive coupons	130
4.3.3	Test results of epoxy adhesive coupons exposed to room ambient	131
4.3.4	Test results of epoxy adhesive coupons exposed to tropical climate	133
4.3.5	Test results of epoxy adhesive coupons exposed to wet/dry condition	135
4.3.6	Test results of epoxy adhesive coupons submerged in plain water	137
4.3.7	Test results of epoxy adhesive coupons submerged in salt water	140
4.3.8	Test results of epoxy adhesive coupons submerged in acidic solution	142
4.3.9	Weight observation of epoxy adhesive coupons	145
4.3.10	Theoretical analysis of epoxy adhesive degradation	146
4.4	Test results of DLS specimens and discussion	154
4.4.1	Physical properties of DLS specimens	155
4.4.2	Mechanical properties of control DLS specimens	158
4.4.3	Mechanical properties of DLS specimens exposed to	



	room ambient	160
4.4.4	Mechanical properties of DLS specimens exposed to tropical climate	163
4.4.5	Mechanical properties of DLS specimens exposed to wet/dry condition	166
4.4.6	Mechanical properties of DLS specimens immersed in plain water, salt water and acidic solution	169
4.5	Concluding remarks	174
<b>5</b>	<b>EXPERIMENTAL RESULTS AND DISCUSSION OF STRENGTHENED STEEL BEAMS</b>	<b>178</b>
5.1	Introduction	178
5.2	Mechanical properties of un-strengthened and strengthened beam	178
5.3	The effect of CFRP length on the flexural behaviour of strengthened beams	182
5.3.1	Failure modes of strengthened beams with different CFRP length	183
5.3.2	Mechanical properties of strengthened beams with different CFRP length	184
5.3.3	Ductility of the strengthened beams with different CFRP length	186
5.3.4	Strain distribution in CFRP plate and steel beam	187
5.3.5	Shear stress in adhesive layer	192
5.3.6	Location of neutral axis	194
5.4	Test results and discussion of the exposed beams	196
5.4.1	Failure modes of the exposed beams	196
5.4.2	Mechanical properties of the strengthened beams after exposure	198
5.4.2.1	Mechanical properties of the strengthened beams in room ambient	199
5.4.2.2	Mechanical properties of the strengthened beams in tropical climate	201

5.4.2.3	Mechanical properties of the strengthened beams in wet/dry condition	203
5.4.2.4	Mechanical properties of the strengthened beams submerged in plain water	205
5.4.2.5	Mechanical properties of strengthened beams submerged in salt water	207
5.4.2.6	Mechanical properties of the strengthened beams submerged in acidic solution	208
5.4.3	Ductility of strengthened beams after exposure	210
5.4.4	Strain distribution along CFRP plate	211
5.4.5	Shear stress in adhesive layer	215
5.4.6	Location of neutral axis	222
5.4.7	Mechanical properties of strengthened beams under sustained loading	222
5.4.8	Strain distribution along CFRP plate for the strengthened beams under sustained loading	225
5.4.9	Shear stress in adhesive layer for the strengthened beams under sustained loading	228
5.5	Comparing the properties of strengthened beams with epoxy adhesive coupons	230
5.6	Optimum size of strengthening plate	232
5.7	Concluding remarks	234
<b>6</b>	<b>CONCLUSIONS AND RECOMMENDATIONS</b>	<b>237</b>
6.1	Conclusions	237
6.2	Recommendations for future research	241
	<b>REFERENCES</b>	<b>243</b>
	Appendix A	252

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	UV index description (Malaysian Meteorological Department)	31
2.2	Recommended values for partial safety factors for adhesive joints ICE guidelines (McQuillan, 1999)	39
2.3	Environmental and time-related partial factors CIRIA guidelines (Cadei <i>et al.</i> , 2004)	39
2.4	Environmental reduction factors (National Research Council Advisory Committee, 2007)	40
2.5	Major studies concerning environmental performance of CFRP/steel bonding system	43
3.1	Properties of CFRP plate	49
3.2	Properties of epoxy adhesive	50
3.3	The properties of steel beam and plate	53
3.4	Environmental exposures	54
3.5	Environmental conditions for DLS specimens	70
3.6	The codes of DLS specimens	71
3.7	Specification of strain gauges (TML)	74
3.8	Environmental conditions for strengthened beams	86

3.9	Strengthened beam codes	90
3.10	Environmental conditions for epoxy adhesive specimens	97
3.11	Environmental exposures for CFRP coupons	106
4.1	Result of tensile tests for CFRP control coupons	122
4.2	Results of tensile tests for CFRP coupons	124
4.3	Result of tensile tests for epoxy adhesive control specimens	130
4.4	The results of tensile tests for the epoxy adhesive coupon subjected to room ambient	132
4.5	The results of tensile tests for the outdoor epoxy adhesive coupons	133
4.6	The results of tests for the epoxy adhesive coupons subjected to wet/dry cycles	136
4.7	The results of tests for the epoxy adhesive coupons submerged in plain water	138
4.8	The results of tests for the epoxy adhesive coupons submerged in salt water	140
4.9	The results of tests for the epoxy adhesive coupons submerged in acidic solution	142
4.10	The maximum moisture uptake and coefficient of diffusion in 26°C and 55°C	148
4.11	The results of tensile tests for epoxy adhesive coupons immersed in 55°C water	149
4.12	The values of parameters for strength and stiffness modelling	149
4.13	Degradation rate of epoxy adhesive in various environmental conditions	153
4.14	Result of tensile tests for DLS control specimens	159
4.15	Detail of test results for DLS specimens in room ambient	162

4.16	Detail of test results for DLS specimens in tropical climate	165
4.17	Detail of test results for DLS specimens in wet/dry condition	166
4.18	Detail of test results for DLS specimens submerged in plain water, salt water and acidic solution	170
5.1	The results of experimental tests and theoretical analysis	182
5.2	The results of bending tests for beams with different length of CFRP	185
5.3	Classification of steel beams based on ductility (Gioncu and Mosoarca, 2012)	187
5.4	The results of bending tests for the control beams	200
5.5	The results of bending tests for outdoor beams	202
5.6	The results of bending tests for the beams subjected to wet/dry cycles	204
5.7	The results of bending tests for beams immersed in plain water	205
5.8	The results of bending tests for beams immersed in salt water	207
5.9	The results of bending tests for beams immersed in acidic solution	209
5.10	Ductility of exposed beams	211
5.11	Strains along CFRP plate before failure	216
5.12	Shear stress in adhesive layer along strengthening plate for ICTL2	220
5.13	Shear stress in adhesive layer along strengthening plate for ICTL8	220
5.14	Shear stress in adhesive layer along CFRP plate at failure load	221

5.15	Results of permanent deflection for the beams under sustained loading	223
5.16	Ductility of the beams under sustained loading	226
5.17	Detail of CFRP strain in the beams under sustained loading	226
5.18	Detail of shear stress in adhesive layer	228

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
2.1	Typical stress-strain curves for CFRP, GFRP and steel (Schnerch and Rizkalla, 2008)	10
2.2	Mechanisms of bonding (Baldan, 2004)	14
2.3	Longitudinal strain in CFRP plate and shear stress in adhesive layer (Dawood <i>et al.</i> , 2007)	17
2.4	Dimensional expansion and swelling of CFRP laminate (Kumar <i>et al.</i> , 2008)	24
2.5	Strength and elastic modulus degradation of CFRP exposed in 50°C sea water (Nguyen <i>et al.</i> , 2012)	24
2.6	Moisture uptake in bulk adhesive (Nguyen <i>et al.</i> , 2012)	25
2.7	Glass transition temperature (T <sub>g</sub> ) as a function of absorbed water amount (Lettieri and Frigione, 2012)	27
2.8	Detail of specimens b) specimens under sustained loading (Shan <i>et al.</i> , 2011)	34
2.9	Strength degradation of CFRP/steel double lap shear joints improved with various methods (Dawood and Rizkalla, 2010)	35
2.10	Strength degradation of CFRP/steel joints immersed in simulated sea-water in 20°C and 50°C temperature (Nguyen <i>et al.</i> , 2012)	37
2.11	Rainfall acidity in Malaysia (Malaysian Meteorological Department)	42

3.1	The CFRP coupons before and after tensile test	49
3.2	Tensile stress-strain of CFRP plate in the laboratory	50
3.3	The epoxy adhesive coupons before and after tensile test	51
3.4	Tensile stress-strain of epoxy adhesive	51
3.5	The steel coupons before and after tensile test	52
3.6	Tensile stress-strain curve of steel plate	52
3.7	Tensile stress-strain curve of I-section beam	52
3.8	The changes in temperature during the period of study	54
3.9	The changes in relative humidity during the period of study	55
3.10	The number of rainy days in each month	55
3.11	The number of days with UV index of more than 8 degree	56
3.12	Geometry of DLS specimens	57
3.13	Grinder with a) various cup brushes b) various grinding blades	58
3.14	Using the grinder to clean the steel plate surface	59
3.15	Steel surfaces after grinding	59
3.16	Preparing rigs to make DLS specimens a) bonding small plates and Lining, b) Installing transparent, c) Ready rigs	60
3.17	Table with rigs, weights and grips	61
3.18	Set up the steel plate into the rig a) aligning b) fixing with grips	61
3.19	Cleaning steel surface by a) using vacuum cleaner b) using Acetone	61



3.20	Adhesive preparation process a) resin and hardener, b) weighting, c) mixing, d) ready adhesive mixture	62
3.21	Cutting CFRP plates a) cutting machine b) CFRP plates in small pieces	63
3.22	Putting the adhesive on the steel surface with a spatula	63
3.23	Removing the protect cover of CFRP plate	64
3.24	Rubbing epoxy adhesive on CFRP plate	64
3.25	Fixing CFRP plate on the steel plates	64
3.26	Using weights to press the bonding	65
3.27	Using level to have a uniform pressure a) longitudinal b) transversal	66
3.28	Cleaning extra squeezed adhesive	66
3.29	DLS specimen with one side completed	67
3.30	Using level to check the specimen alignment	67
3.31	Cleaning the second side of specimen with a) vacuum cleaner b) Acetone	67
3.32	Putting adhesive on the back of specimen	68
3.33	Removing CFRP protection cover	68
3.34	Bonding process a) using weight to press the bonding b) using level	68
3.35	Using digital calliper to measure the thickness of adhesive	69
3.36	Writing the code of ready specimens	69
3.37	The control DLS specimens in the room ambient	71
3.38	The outdoor DLS specimens in natural tropical climate	71

3.39	The containers inside the lab	72
3.40	Set up the container a) putting the specimens, b) pouring plain water	72
3.41	The salt used to prepare salt water	73
3.42	Placing the specimens inside the container for scenario D (salt water)	73
3.43	Sulphuric acid	73
3.44	Measuring the pH of acid Solution using pH-meter	74
3.45	Location of strain gauges on the specimens	75
3.46	The specimens before tensile test	75
3.47	Tensile test set up for DLS specimens	75
3.48	The data logger connected to computer	76
3.49	Tensile test of exposed specimens	76
3.50	Geometry of I-section steel beams strengthened with CFRP plate	77
3.51	Types of sand for sandblasting a) broken b) ball shape	78
3.52	Sandblasting the bottom flange of steel beams	79
3.53	Close view of steel surface after sandblasting	79
3.54	Sandblasted beams in the laboratory	79
3.55	Using steel plate as base plate for strengthening beams	80
3.56	Cleaning the beam surface using a) vacuum cleaner b) Acetone	80
3.57	Putting the adhesive on the steel beam	81

3.58	Removing the protect cover of CFRP plate	82
3.59	Rubbing epoxy adhesive on CFRP plate	82
3.60	Placing CFRP plate in right position	83
3.61	Fixing CFRP plate on the beam	83
3.62	Press the bonding using weights	83
3.63	Using level to press the bonding uniformly	84
3.64	Cleaning the squeezed adhesive	84
3.65	Strengthened beams	84
3.66	Writing beam codes	85
3.67	The outdoor beams	86
3.68	The control beams in room ambient	86
3.69	Loading on the beams to impose sustain loading	87
3.70	Tightening the nuts to maintain sustained loading	88
3.71	The beams under sustained loading inside the lab	88
3.72	The outdoor beams under sustained loading	88
3.73	Strain gauges on the beams with different length of CFRP	91
3.74	The strain gauges in the mid-span section of the beam	91
3.75	Welding steel plate to top the flange	91
3.76	Strain gauges layout on steel beams with different length of CFRP plate a) 800 mm, b) 700 mm, c) 600 mm, d) 500 mm	92

3.77	Spherically seated supports	93
3.78	Lateral supporting system	93
3.79	The LVDT at mid-span to measure the vertical beam deflection	94
3.80	The LVDT to measure lateral deformation	94
3.81	Strain gauges for exposed beams	94
3.82	Strain gauges layout for exposed steel beams	95
3.83	Demec discs used for the beams under sustained load	95
3.84	Demec reader used for outdoor beams under sustained load	96
3.85	Dimensions of epoxy adhesive dog-bone coupons	96
3.86	Covering the mould with Carnauba wax	98
3.87	Placing the adhesive into the mould with spatula	98
3.88	Pressing the adhesive specimens using weights	98
3.89	The specimens after pressing in the mould	99
3.90	The coupons taken out of the mould	99
3.91	Smoothing all sides of specimens using electric sander	99
3.92	Ready epoxy adhesive coupons	100
3.93	Control specimens in room ambient	100
3.94	Epoxy adhesive coupons in various conditions	101
3.95	Epoxy adhesive coupons in tropical climate	101
3.96	Epoxy adhesive coupons in 55°C plain water	101

3.97	Tensile testing machine for epoxy adhesive coupons	102
3.98	Weighting the epoxy adhesive coupons	102
3.99	Preparing the mould and cover it with wax	103
3.100	Putting the adhesive inside the mould with spatula	103
3.101	Using weights to pressure the moulded epoxy adhesive	104
3.102	Demoulding the square samples	104
3.103	Ready square samples	104
3.104	The samples inside plain water	105
3.105	The square epoxy adhesive samples inside 55°C plain water	105
3.106	Weighting of square epoxy adhesive samples	105
3.107	Cutting the CFRP plate by cutter to prepare coupons	107
3.108	The CFRP coupons in room ambient	107
3.109	The CFRP coupons in tropical climate	107
3.110	The CFRP coupons subjecting to wet/dry, plain water, salt water and acidic solution	108
3.111	Using electric sander to roughen the tabs before bonding	108
3.112	The CFRP coupons with end tabs	108
3.113	Strain gauges attached to the CFRP coupons	109
3.114	The CFRP coupon tensile test	109
3.115	CFRP coupon failure	110
3.116	The failure modes of steel beams strengthened with CFRP plate	115

3.117	Procedure for computing the flexural capacity(National Research Council Advisory Committee, 2007)	120
4.1	Stress-strain curve of CFRP control coupons	122
4.2	The failure of CFRP control coupon	123
4.3	The CFRP coupons after exposure	123
4.4	Normalized strength of CFRP coupons in various exposures	126
4.5	Normalized stiffness of CFRP coupons in various exposures	126
4.6	The failure of CFRP coupons in various exposures	127
4.7	Weight change of CFRP coupons in various conditions	128
4.8	Groups of Epoxy adhesive coupons after tensile test	129
4.9	Voids in the section of epoxy adhesive coupons	130
4.10	Stress-strain curves of epoxy adhesive control coupons	131
4.11	Stress-strain curves of epoxy adhesive coupons subjected to room ambient	132
4.12	Trend of changes in failure stress for epoxy adhesive coupons in room ambient	132
4.13	Trend of changes in tensile stiffness for epoxy adhesive coupons in room ambient	133
4.14	Trend of changes in failure stress for epoxy adhesive coupons in tropical climate	134
4.15	Trend of changes in tensile stiffness for epoxy adhesive coupons in tropical climate	135
4.16	Stress-strain curves of epoxy adhesive coupons subjected to tropical climate	135
4.17	Trend of changes in failure stress for epoxy adhesive coupons in wet/dry cycles	136

4.18	Trend of changes in tensile stiffness for epoxy adhesive coupons in wet/dry cycles	137
4.19	Stress-strain curves of epoxy adhesive coupons subjected to wet/dry cycles	137
4.20	Trend of changes in failure stress for epoxy adhesive coupons immersed in plain water	139
4.21	Trend of changes in tensile stiffness for epoxy adhesive coupons immersed in plain water	139
4.22	Stress-strain curve of epoxy adhesive coupons immersed to plain water	139
4.23	Trend of changes in failure stress for epoxy adhesive coupons immersed in salt water	141
4.24	Trend of changes in tensile stiffness for epoxy adhesive coupons immersed in salt water	141
4.25	Stress-strain curve of epoxy adhesive coupons immersed in salt water	141
4.26	Stress-strain curve of epoxy adhesive coupons immersed in acidic solution	143
4.27	Trend of changes in failure stress for epoxy adhesive coupons immersed in acidic solution	143
4.28	Trend of changes in tensile stiffness for epoxy adhesive coupons immersed in acidic solution	143
4.29	The trend of strength degradation of epoxy adhesive coupons in various conditions	145
4.30	The trend of stiffness degradation of epoxy adhesive coupons in various conditions	145
4.31	Weight change of epoxy adhesive coupons in various conditions	146
4.32	Weight change of epoxy adhesive coupons in wet/dry condition	146
4.33	Moisture uptake of adhesive coupons immersed in 26°C and 55°C plain water	147
4.34	Relationship between $\ln(D)$ and $1/T$	148

4.35	Normalized experimental and theoretical strength degradation of epoxy adhesive coupons immerse in 26°C and 55°C plain water	150
4.36	Normalized experimental and theoretical stiffness degradation of epoxy adhesive coupons immerse in 26°C and 55°C plain water	150
4.37	Experimental and theoretical strength degradation of epoxy adhesive in tropical climate	152
4.38	Experimental and theoretical stiffness degradation of epoxy adhesive in tropical climate	152
4.39	Experimental and theoretical strength degradation of epoxy adhesive in wet/dry condition	153
4.40	Experimental and theoretical strength degradation of epoxy adhesive in plain water	153
4.41	Experimental and theoretical strength degradation of epoxy adhesive in salt water	154
4.42	Experimental and theoretical strength degradation of epoxy adhesive in acidic solution	154
4.43	The DLS specimens in room ambient after failure	155
4.44	The DLS specimens in tropical climate after failure	156
4.45	The DLS specimens in wet/dry cycle after failure	157
4.46	The DLS specimens in plain water after failure	157
4.47	The DLS specimens in salt water after failure	157
4.48	The DLS specimens in acidic solution after failure	158
4.49	The control DLS specimens after failure	158
4.50	The load-stroke relationship of control DLS specimens	159
4.51	Load-stroke of DLS specimens in room ambient	161



4.52	Changes in failure load of DLS specimens in room ambient	161
4.53	Changes in stiffness of DLS specimens in room ambient	162
4.54	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in room ambient	162
4.55	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in room ambient	163
4.56	Load-stroke of DLS specimens in tropical climate	164
4.57	Changes in strength of DLS specimens in tropical climate	164
4.58	Changes in stiffness of DLS specimens in tropical climate	164
4.59	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in tropical climate	165
4.60	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in tropical climate	165
4.61	Load-stroke of DLS specimens in wet/dry condition	166
4.62	Changes in strength of DLS specimens in wet/dry condition	167
4.63	Changes in stiffness of DLS specimens in wet/dry condition	167
4.64	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in wet/dry cycle condition	167
4.65	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in wet/dry cycle condition	168
4.66	Load-stroke of DLS specimens immersed in plain water	169
4.67	Load-stroke of DLS specimens immersed in salt water	169
4.68	Load-stroke of DLS specimens immersed in acidic solution	169
4.69	Changes in strength of DLS specimens immersed in plain water, salt water and acidic solution	170

4.70	Changes in stiffness of DLS specimens immersed in plain water, salt water and acidic solution	171
4.71	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in plain water condition	171
4.72	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in plain water condition	172
4.73	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in salt water condition	172
4.74	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in salt water condition	172
4.75	The trend of changes in strength of DLS specimens and epoxy adhesive coupons in acidic solution condition	173
4.76	The trend of changes in stiffness of DLS specimens and epoxy adhesive coupons in acidic solution condition	173
5.1	Load-deflection of un-strengthened beam (CTIL00) and strengthened beam (ICTL0)	180
5.2	Sudden debonding of CFRP plate a) IL500, b) IL600	183
5.3	Global buckling of the beams a) IL700, b) IL800	184
5.4	Longitudinal crack along CFRP plate	184
5.5	Load-deflection of beams with different length of CFRP plate	185
5.6	Distribution of strain along CFRP plate a) IL800, b) IL700, c) IL600, (d) IL500	189
5.7	Distribution of strain along steel beam a) IL800, b) IL700, c) IL600, d) IL500	190
5.8	Comparing the rate of strain along CFRP plate and steel beam a) IL800, b) IL700, c) IL600, d) IL500	191
5.9	Shear stress distribution along bonding areas a) IL800, b) IL700, c) IL600, d) IL500	193
5.10	Location of neutral axis at middle-span section a) IL800, b) IL700, c) IL600, d) IL500	195

5.11	The strengthened beams after failure due to lateral-buckling	197
5.12	Load-deflection of the strengthened beams after 2 months	198
5.13	Load-deflection of the strengthened beams after 4 months	198
5.14	Load-deflection of the strengthened beams after 8 months	199
5.15	Load-deflection of the strengthened beams in room ambient after 2, 4 and 8 months exposure compared with control beam ICTL0	201
5.16	Trend of changes in mechanical properties of beams exposed to room ambient	201
5.17	Load-deflection of the outdoor strengthened beams after 2, 4 and 8 months exposure compared with control beam ICTL0	203
5.18	Trend of changes in mechanical properties of outdoor beams	203
5.19	Load-deflection of the beams subjected to wet/dry condition	204
5.20	Trend of changes in mechanical properties of beams subjected to wet/dry condition	205
5.21	Load-deflection of the beams immersed in plain water after 2, 4 and 8 months exposure compared to control beam ICTL0	206
5.22	Trend of changes in mechanical properties of the beams immersed in plain water	206
5.23	Load-deflection of the beams immersed in salt water after 2, 4 and 8 months exposure compared to control beam ICTL0	208
5.24	Trend of changes in mechanical properties of the beams immersed in salt water	208
5.25	Load-deflection of the beams immersed in acidic solution after 2, 4 and 8 months exposure compared to control beam ICTL0	209

5.26	Trend of changes in mechanical properties of the beams immersed in acidic solution	210
5.27	Strain distribution along CFRP plate for the beams exposed to room ambient	212
5.28	Strain distribution along CFRP plate for the outdoor beams	213
5.29	Strain distribution along CFRP plate for the beams subjected to wet/dry	213
5.30	Strain distribution along CFRP plate for the beams immersed in plain water	214
5.31	Strain distribution along CFRP plate for the beams immersed in salt water	214
5.32	Strain distribution along CFRP plate for the beams immersed in acidic solution	215
5.33	Shear stress distribution in adhesive layer for the beams exposed to room ambient	217
5.34	Shear stress distribution in adhesive layer for outdoor beams	218
5.35	Shear stress distribution in adhesive layer for the beams subjected to wet/dry condition	218
5.36	Shear stress distribution in adhesive layer for the beams immersed in plain water	219
5.37	Shear stress distribution in adhesive layer for the beams immersed in salt water	219
5.38	Shear stress distribution in adhesive layer for the beams immersed in acidic solution	220
5.39	Location of demec discs and permanent deformation after unloading	223
5.40	Load-deflection of the strengthened beams under sustained loading inside the lab	224
5.41	Load-deflection of the outdoor strengthened beams under sustained loading	224

5.42	Rate of changes in mechanical properties of the beams under sustained loading inside lab	225
5.43	Trend of changes in mechanical properties of the outdoor beams under sustained loading	225
5.44	Strain distribution along CFRP plate for the beams under sustained loading inside the lab	227
5.45	Strain distribution along CFRP plate for the outdoor beams under sustained loading	227
5.46	Shear stress distribution in adhesive layer for the beams under sustained loading inside the lab	229
5.47	Shear stress distribution in adhesive layer for outdoor beams under sustained loading	229
5.48	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in room ambient	230
5.49	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in tropical climate	230
5.50	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in wet/dry condition	231
5.51	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in plain water	231
5.52	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in salt water	232
5.53	The trend of changes in strength of strengthened beams and epoxy adhesive coupons in acidic solution	232
5.54	Comparing stress-strain relationship of CFRP plate in tensile test and bending test	233

## LIST OF SYMBOLS

$b$	-	Width of DLS specimen
$d_i$	-	Lever-arm distance
$k$	-	Rate of properties degradation
$n$	-	Modular ratio
$f_c$		Characteristic value of the tensile strength of CFRP plate
$t$	-	Aging time
$t_a$	-	Thickness of the adhesive layer
$t_c$	-	Thickness of the CFRP plate
$t_s$	-	Thickness of the steel plate
$x$	-	Length of material in Fick's law
$y$	-	Distance from the neutral axis
$A$	-	Material constant
$A_i$	-	Area of the composite beam cross section
$A_s$	-	Area of the steel beam cross section
$C$	-	Concentration in Fick's law
$D$	-	Diffusion coefficient
$D_0$	-	Material constant in Fick's law
$E_d$	-	Activation energy
$E_c$	-	Elastic modulus of CFRP
$E_s$	-	Elastic modulus of steel
$F$	-	Load

- $F_i, F_o$  - Ultimate load of DLS specimen per unit width  
 $I$  - Moment of inertia of composite beam  
 $I_s$  - Moment of inertia of steel beam  
 $M$  - Applied bending moment of the beam  
 $M_{Sd}$  - Bending moment produced by the design load combination  
 $M_{Rd}$  - Design value of the bending moment capacity  
 $M_t$  - Mass absorption after time (t)  
 $M_{\infty}$  - Ultimate mass absorption  
 $P_0$  - Initial properties of the material  
 $P_t$  - Properties of the material in time (t)  
 $P_{\infty}$  - Ultimate properties of the material  
 $R$  - Ideal gas constant  
 $T$  - Temperature in Kelvin  
 $\gamma_e$  - Elastic shear strain of the adhesive  
 $\gamma_p$  - Plastic shear strain of the adhesive  
 $\delta$  - Normal stress of the beam  
 $\delta_c$  - Normal stress of CFRP plate  
 $\varepsilon_0$  - Initial strain  
 $\varepsilon_d^c$  - Design value of the compression strain  
 $\varepsilon_d^t$  - Design value of the tension strain  
 $\varepsilon_{sd}^c$  - Design value of the compression strain capacity of steel beam  
 $\varepsilon_{fd}^t$  - Design value of the tension strain of CFRP plate  
 $\varepsilon_{sd}^t$  - Design value of the tension strain of steel beam  
 $\alpha_c$  - Coefficient of thermal expansion for CFRP  
 $\alpha_s$  - Coefficient of thermal expansion for steel  
 $\alpha_c$  - Coefficient of thermal expansion for CFRP  
 $\eta$  - Conversion factor

- $\xi$  - Ductility of the steel beam
- $\tau_a$  - Shear stress in adhesive layer
- $\tau_c$  - Shear stress in CFRP plate
- $\Delta T$  - Temperature difference
- $\Delta x$  - Distance between two consecutive strain gauge
- $\Delta u$  - Mid-deflection of the beam in the ultimate load
- $\Delta y$  - Mid-deflection of the beam in the yielding load
- $\Delta \varepsilon$  - Difference of longitudinal strain in two consecutives strain gauge



**LIST OF APPENDICES**

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	Computing the degradation rate of various environmental conditions	252

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Steel structures constitute a large number of existing infrastructures which have been largely expanded all over the world and now reaching a critical age with increasing signs of deterioration and reduced functionality. A number of factors responsible for the decline on the strength of structures and make them lose their serviceability. Environmental deterioration, fatigue, and aging of structural elements are major problems in steel structures. Lack of proper maintenance and use of substandard materials in initial construction are other factors that caused the deficiency of the structures. Besides that many structures nowadays require upgrading to carry larger loads or should be retrofitted according to new codes. The cost for strengthening in most cases is much less than the cost of replacement and usually takes less time and so reduces service interruption time. Conventional methods of repair and retrofit of steel sections generally use steel plates through bolting or welding to the structural member. Increasing considerable dead load to the structure, susceptibility to the corrosion and need to heavy lifting equipment are some drawbacks of this methods. In addition, welding is not a favorable solution due to fatigue problems. Furthermore, mechanical details such as bolted connections which have better fatigue life are time consuming and costly.

The use of Fibre Reinforced Polymer (FRP) materials has been demonstrated as a successful technique to increase the strength and stiffness of structural elements. FRP consists of high strength fibres embedded in a matrix resin. Many advantages

including light weight, high strength and stiffness, excellent durability performance, fatigue and corrosion resistance, and easy assembling make them quite promising for repair and strengthening of structures and highly preferred than the steel plates. Several types of FRP are currently available to provide strength to metal structures. Due to its initial success in strengthening concrete structures, glass fibre reinforced polymer (GFRP) is a readily available and the least expensive type of FRP commonly used for strengthening. However, other types of fibre, such as, carbon and aramid have been commonly used in recent years. Lately researches have showed that carbon fibre reinforced polymer (CFRP) is considered to be one of the most suitable for the purpose of strengthening of steel structures. This is essentially due to the higher stiffness of the CFRP comparing to other types.

## **1.2 Problem statement**

A number of experimental and theoretical researches have been conducted to find the behaviour of the steel/CFRP bonding systems recently. Most of these studies mainly concern to short term strengthening of steel sections under static loads. Bonding characteristics, flexural strengthening of beams, and developing theoretical/numerical models have attracted more attentions. Furthermore, performance of the system under fatigue loads and environmental effects have gained interest subsequently. Generally, previous researches demonstrated that bonding CFRP plates to the steel sections increased flexural stiffness and fatigue resistance significantly. Besides, deteriorated beams have been repaired to achieve initial strength successfully by this method.

However, one of the main limitations to popular use of this technique has been the durability of bonding between steel and CFRP in various environmental conditions. Actually, the performance of the system in long term is the most important issue especially for the structures such as bridges which are exposed to natural environment. Although previous studies emphasized CFRP strengthening method is quite acceptable, thorough researches need to be conducted to reveal long term durability problems.

However, relatively little literature exists concerning the durability performance of steel sections strengthened with CFRP plate. Particularly, in tropical climate the behaviour of steel/CFRP bonding system has not been studied yet. The durability of the steel/CFRP bonding system is a vital issue that needs to be clearly understood especially in the tropical climate region to gain the acceptance of the system to be used in construction industry. The knowledge and understanding of this aspect is important for engineers in tropical climate countries such as Malaysia.

### **1.3 Objectives**

The aim of this study is to investigate the bonding behaviour of steel/CFRP system expose to various environmental conditions including natural tropical climate, wet/dry cycles, immersed in plain water, salt water, and acidic solution. Meanwhile, tropical climate which is an extreme hot/wet weather is considered as the main environmental condition. Related objectives of the research are as follows:

- i. To characterize the bonding strength and stiffness of steel/CFRP double lap shear joints under natural tropical climate
- ii. To determine the short term flexural behaviour of I-section steel beam strengthened with CFRP plate
- iii. To determine the effect of CFRP length on the flexural behaviour of strengthened I-section steel beam
- iv. To evaluate the effect of tropical climate on the flexural stiffness and load capacity of I-section steel beams strengthened with CFRP plate
- v. To propose the appropriate analytical procedure to predict the behaviour of the steel/CFRP systems subjected to environmental exposure

## **1.4 Research significance**

The proposed research constitutes experimental and analytical investigation to study the performance of steel/CFRP bonding system after exposure to various environmental conditions. Although, some studies used accelerated tests to predict the bond behaviour in long term, the effect of natural environment is still unknown. In this research, natural tropical climate is considered as the main environmental condition to study the behaviour of the steel/CFRP bonding system in an extreme aggressive condition. The results of the study are expected to make contribution in understanding the behaviour of steel structures strengthened with CFRP material in tropical climate.

The study introduces an analytical procedure to estimate the mechanical properties of steel strengthening system as well. Besides, the novelty of the research is using steel beams (in addition to double lap shear specimens) to investigate the durability performance. While, all previous investigations used only lap shear joints to study the bonding durability, this research applied I-section steel beams strengthened with CFRP plate to find out the real behaviour of a structural element after exposure. The current study aims to evaluate the practical application of steel/CFRP strengthening system in the field.

## **1.5 Scope of the study**

In order to achieve the objectives, the research work was divided into two phases; experimental tests and theoretical analysis. The scope of the study related to these phases is as follow:

- i. In the experimental phase, a number of 52 double lap shear joints were prepared based on ASTM D3528 (2008b) and subjected to the various environmental exposures for specific periods. Then, tensile test was conducted to find the mechanical properties of the specimens.

- ii. A number of 28 I-section strengthened beams were prepared and subjected to the same various environmental exposures for specific periods. Afterwards, four-point bending test was carried out to investigate about the flexural behaviour of the strengthened beams.
- iii. The CFRP and adhesive coupons were prepared according to ASTM D638 (2010) and ASTM D3039 (2008a), respectively. Then, they were subjected to the same environmental conditions and were tested based on above standards to find the effect of exposures on these materials individually.
- iv. The exposures consisted of outdoor tropical climate, room ambient, wet/dry cycles in plain water, submerged in plain water, salt water and acidic solution.
- v. The duration of environmental exposure was considered 8 months for all the specimens.
- vi. In theoretical analysis, related equations for computing the bonding properties and durability estimation have been expressed.
- vii. The appropriate analytical approach is proposed to calculate the mechanical properties of steel sections after strengthening with CFRP materials. Meanwhile, relevant codes and guidelines contents related to this issue are presented.
- viii. Finally, the results of the experimental tests were compared to the theoretical analysis to find a model for estimating the properties of steel/CFRP bonding system.

## **1.6 Limitation of the study**

The study was limited in some aspects. The main limitation was related to the time of exposure for experimental program which was considered 8 months. In addition, the outdoor conditioning was natural tropical climate in southern part of Malaysia. High temperature and humidity combined with heavy raining and ultraviolet of the sun were the major detrimental factors of this specific weather condition. However, the tropical climate of other parts of the world might influence the bonding system differently. Moreover, the conditioning of the specimens in wet/dry cycles, plain water, salt water and acidic solution were conducted in the laboratory temperature (not accelerated).

The CFRP plate and epoxy adhesive were produced by Mapei Company to be compatible together. The results might be changed by using similar materials of other companies. Besides, diverse specifications of these materials might have different influence on the strengthening system. Obviously, the mechanical and thermal properties of the materials affect the behaviour of the bonding system significantly.

## **1.7 Thesis organization**

The thesis consists of six chapters. A summary of the contents of the next chapters is as follow:

Chapter 2: An entire overview of previous researches related to steel sections strengthened with CFRP plate is carried out focusing on environmental performance.

Chapter 3: The research methodology is presented in two main parts including experimental program and theoretical analysis. The experimental program consists of materials specifications, environmental conditions, instrumentation and tests set up. The theoretical analysis includes computing the strength of double lap

shear joints, analysis of strengthened beams, and degradation modelling of epoxy adhesive through empirical equations.

Chapter 4: The tests results of epoxy adhesive coupons, CFRP coupons and double lap shear specimens are presented and discussed in detail. The effect of diverse exposures on the mechanical properties of the specimens is explained. The results are compared with control specimens' properties to find out the impression of environmental factors on the steel/CFRP bonding system. Further, the result of theoretical model is compared with experimental results.

Chapter 5: A detailed description of test results related to steel strengthened beams is exhibited. The flexural behaviour of the strengthened beams is compared with control beam to find the effect of strengthening on the mechanical properties of the beam. Besides, the efficacy of CFRP length on flexural behaviour of strengthened beams is investigated thoroughly. Finally, the influence of various exposures, especially tropical climate, on the bonding characteristics and mechanical properties of the strengthened beams is studied.

Chapter 6: The final chapter summarizes the conclusions of present research and provides recommendations for future works.



## REFERENCES

- ACI, (2002). *440.2R-02*. Michigan, American Concrete Institute.
- Aiello, M., Frigione, M., and Acierno, D. (2002, April). Effects of Environmental Conditions on Performance of Polymeric Adhesives for Restoration of Concrete Structures. *Journal of Materials in Civil Engineering*, 14(2), 185-189.
- Al-Emrani, M., Linghoff, D., and Kliger, R. (2005). Bonding Strength and Fracture Mechanism in Composite Steel-CFRP Elements. *International Symposium on Bond Behaviour of FRP in Structures (BBFS)*. Hong Kong, China, 425-434.
- Al-Saidy, A., Klaiber, F., and Wipf, T. (2004). Repair of Steel Composite Beams with Carbon Fibre Reinforced Polymer plates. *Journal of Composites for Construction*, 8(2), 163-172.
- Al-Saidy, A., Klaiber, F., and Wipf, T. (2007). Strengthening of Steel-Concrete Composite Girders Using Carbon Fibre Reinforced Polymer Plates. *Construction and Building Materials*, 21, 295-302.
- Al-Shawaf, A., Al-Mahaidi, R., and Zhao, X. (2006). Study on Bond Characteristics of CFRP/Steel Double Lap Shear Joints at Subzero Temperature Exposure. *Third International Conference on FRP Composites in Civil Engineering (CICE)*, Miami, Florida, USA, 71-74.
- Al-Zubaidy, H., Al-Mahaidi, R., and Zhao, X. (2012). Experimental Investigation of Bond Characteristics Between CFRP Fabrics and Steel Plate Joints under Impact Tensile Loads. *Composite Structures*, 94, 510-518.
- Amaro, A., Reis, P., Neto, M., and Lour, C. (2013). Effects of Alkaline and Acid Solutions on Glass/Epoxy Composites. *Polymer Degradation and Stability*, 98, 853-862.

- Aoki, Y., Yamada, K., and Ishikawa, T. (2008). Effect of Hygrothermal Condition on Compression After Impact Strength of CFRP Laminates. *Composites Science and Technology*, 68, 1376-1383.
- ASTM. (2008a). *D3039*, Pennsylvania: American Society for Testing and Materials.
- ASTM. (2008b). *D3528*, Pennsylvania, American Society for Testing and Materials.
- ASTM. (2010). *D638*, Pennsylvania: American Society of Testing and Materials.
- ASTM. (2012). *A370*, Pennsylvania: American Society for Testing and Materials.
- Baldan, A. (2004). Adhesively-Bonded Joints and Repairs in Metallic Alloys, Polymers and Composite Materials: Adhesives, Adhesion Theories and Surface Pretreatment. *Journal of Materials Science*, 39, 1-49.
- Bardis, J. and Kedward, K. (2002). Surface Preparation Effects on Mode I Testing of Adhesively Bonded Composite Joints. *Journal of Composites Technology & Research, JCTRER*, 24(1), 30-37.
- Bordes, M., Davies, P., Cognard, J., Soheir, L., Moynot, V., and Galy, J. (2009). Prediction of Long Term Strength of Adhesively Bonded Steel/Epoxy Joints in Sea Water. *International Journal of Adhesion and Adhesives* 29, 595–608.
- Bowditch, M. (1996). The Durability of Adhesive Joints in the Presence of Water. *International Journal of Adhesion and Adhesives*, 16, 73-79.
- Cadei, G., Stratford, T., Hollaway, L., and Duckett, W. (2004). *Strengthening Metallic Structures Using Externally Bonded Fibre Reinforced Polymer*. London, UK: Construction Industry Research and Information Association (CIRIA).
- Chiew, S., Yu, Y., and Lee, C. (2011). Bond Failure of Steel Beams Strengthened with FRP Laminates – Part 1: Model Development. *Composites: Part B*, 42, 1114-1121.
- Chin, J., Nguyen, T., and Aouadi, K. (1997). Effects of Environmental Exposure on Fiber Reinforced Plastic (FRP) Material Used in Construction. *Journal of Composites Technology and Research*, 19(4), 205-213.
- Collings, T., Harvey, R., and Dalziel, W. (1993). The use of Elevated Temperature in the Structural Testing of FRP Components for Simulating the Effects of Hot and Wet Environmental Exposure. *Composites*, 24(8), 625-634.
- Colombi, P. and Poggi, C. (2006a). Strengthening of Tensile Steel Members and Bolted Joints Using Adhesively Bonded CFRP Plates. *Construction and Building Materials*, 20, 22-33.

- Colombi, P. and Poggi, C. (2006b). An Experimental, Analytical and Numerical Study of the Static Behavior of Steel Beam Reinforced by Pultruded CFRP Strips. *Journal of Composite: Part B*, 37, 64-73.
- Cromwell, J., Harries, K., Shahrooz, B. (2011). Environmental Durability of Externally Bonded FRP Materials Intended for Repair of Concrete Structures. *Construction and Building Materials*, 25, 2528-2539.
- Dawood, M. and Rizkalla, S. (2006). Bond and Splice Behavior of High Modulus CFRP Materials Bonded to Steel Structures. *Third International Conference on FRP Composites in Civil Engineering (CICE)*. Miami, Florida, USA.
- Dawood, M., Guddati, M., & Rizkalla, S. (2007a). Bond Behavior of a CFRP Strengthening System. *Asia-Pacific Conference on FRP in Structures (APFIS)*. Hong Kong, China.
- Dawood, M., Rizkalla, S., and Sumner, E. (2007b). Fatigue and Overloading Behavior of Steel-Concrete Composite Flexural Members Strengthened with High Modulus CFRP Materials. *Journal of Composites for Construction*, 11(6), 659-669.
- Dawood, M., Guddati, M., and Rizkalla, S. (2008). Bond Behavior and Durability of a CFRP Strengthening System for Steel Structures. *Fourth International Conference on FRP Composites in Civil Engineering (CICE)*. Zurich, Switzerland.
- Dawood, M. and Rizkalla, S. (2010). Environmental Durability of a CFRP System for Strengthening Steel Structures. *Construction and Building Materials*, 24, 1682-1689.
- Deng, J., Lee, M., and Moy, S. (2004). Stress Analysis of Steel Beams Reinforced with a Bonded CFRP Plate. *Composite Structures*, 65, 205-215.
- Dolan, C., Tanner, J., Mukai, D., Hamilton, H., and Douglas, E. (2009). *Research report for evaluating the durability of bonded CFRP repair/strengthening of concrete beams*. Washington, DC. Transportation Research Board.
- El-Hacha, R. and Ragab, N. (2006). Flexural Strengthening of Composite Steel-Concrete Girders Using Advanced Composite Materials. *Third International Conference on FRP Composites in Civil Engineering (CICE)*. Miami, Florida, USA, 741-744.

- Fam, A., Dougall, C., and Shaat, A. (2009). Upgrading Steel Concrete Composite Girders and Repair of Damaged Steel Beams Using Bonded CFRP Laminates. *Thin-Walled Structures*, 47, 1122-1135.
- Fawzia, S. and Karim, M. (2009). Investigation into the Bond Between CFRP and Steel Plates. *World Academy of Science, Engineering and Technology*, 53, 321-325.
- Gioncu, V., Mosoarca, M., and Anastasiadis, A. (2012). Prediction of Available Rotation Capacity and Ductility of Wide-Flange Beams: Part 1: DUCTROT-M Computer Program. *Journal of Constructional Steel Research*, 69, 8-19.
- Gioncu, V. and Mosoarca, M. (2012). Ductility Aspects of Steel Beams. *Civil Engineering & Architecture*, 55(1), 37- 60.
- Harris, A. and Beevers, A. (1999). The Effects of Grit-Blasting on Surface Properties for Adhesion. *International Journal of Adhesion and Adhesives*, 19, 445-452.
- Hart-Smith, L. (1973). *Adhesive-bonded Double-lap Joints*. California: Douglas Aircraft Company: Long Beach.
- Hollaway, L. and Cadei, J. (2002). Progress in the Technique of Upgrading Metallic Structures with Advanced Polymer Composites. *Progress in Structural Engineering and Materials*, 4, 131-148.
- Hollaway, L. (2010). A Review of the Present and Future Utilization of FRP Composites in the Civil Infrastructure with Reference to Their Important In-service Properties. *Construction and Building Materials*, 24, 2419-2445.
- Hulatt, J., Hollaway, L., and Thorne, A. (2002). Preliminary Investigation on the Environmental Effects on New Heavy Weight Fabrics for Use in Civil Engineering. *Journal of Composites: Part B*, 33, 407-414.
- Kabir, M. and Eshaghian, M. (2010). Flexural Upgrading of Steel-Concrete Composite Girders Using Externally Bonded CFRP Reinforcement. *Applied Composite Materials*, 17, 209–224.
- Karbhari, V., Rivera, J., and Dutta, P. (2000). Effect of Short-Term Freeze-Thaw Cycling on Composite Confined Concrete. *Journal of Composites for Construction*, 4(4), 191-197.
- Kim, Y. and Harris, K. (2011). Fatigue Behavior of Damaged Steel Beams Repaired with CFRP Strips. *Engineering Structures*, 33, 1491-1502.

- Kim, Y. Hossain, M., and Yoshitake, I. (2012). Cold Region Durability of a Two-Part Epoxy Adhesive in Double-lap Shear Joints: Experiment and Model Development. *Construction and Building Materials*, 36, 295-304.
- Kumar, S., Sridhar, I., and Sivashanker, S. (2008). Influence of Humid Environment on the Performance of High Strength Structural Carbon Fiber Composites. *Materials Science and Engineering A*, 498, 174-178.
- Landrock, A. (2009). *Adhesives Technology Handbook*. London: William Andrew.
- Lettieri, M. and Frigione, M. (2012). Effects of Humid Environment on Thermal and Mechanical Properties of a Cold-Curing Structural Epoxy Adhesive. *Construction and Building Materials*, 30, 753-760.
- Lopez, J., Sain, M., and Cooper, P. (2006). Performance of Natural-Fiber-Plastic Composites under Stress for Outdoor Applications: Effect of Moisture, Temperature, and Ultraviolet Light Exposure. *Journal of Applied Polymer Science*, 99, 2570-2577.
- Malaysian Meteorological Department (2014). Official website, URL: <http://www.met.gov.my/>
- Maxwell, A., Broughton, W., Dean, G., and Sims, G. (2005). *Review of accelerated aging methods and lifetime prediction techniques for polymeric materials*. Middlesex: National Physical Laboratory (NPL).
- Mazzotti, C. and Savoia, M. (2009). Stress Redistribution along the Interface between Concrete and FRP Subject to Long-Term Loading. *Advances in Structural Engineering*, 12(5), 651-661.
- McQuillan, D. (1999). *The Structural Use of Adhesives*. London, UK: Institution of Structural Engineering.
- Mertz, D. and Gillespie, J. (1996). *Rehabilitation of Steel Bridge Girders Through the Application of Advanced Composite Materials*. Washington, D.C, Transportation Research Board.
- Mertz, D. and Gillespie, J. (2002). *The Rehabilitation of Steel Bridge Girders Using Advanced Composite Materials*. Washington, D.C, Transportation Research Board.
- Miller, T., Chajes, M., Mertz, D., and Hastings, J. (2001). Strengthening of a Steel Bridge Girder Using CFRP Plates. *Journal of Bridge Engineering*, 6(6), 514-522.

- Narmashiri, K., Jumaat, M., and Ramli Sulong, N. (2010). Investigation on End Anchoring of CFRP Strengthened Steel I-Beams. *International Journal of the Physical Sciences*, 5(9), 1360-1371.
- National Research Council Advisory Committee. (2007). *Guidelines for Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures-Metallic Structures*. Rome, Italy, National Research Council.
- Nguyen, T., Bai, Y., Zhao, X., and Al-Mahaidi, R. (2011). Mechanical Characterization of Steel/CFRP Double Strap Joints at Elevated Temperature. *Composite Structures*, 93, 1604-1612.
- Nguyen, T., Bai, Y., Al-Mahaidi, R., and Zhao, X. (2012a). Time-Dependent of Steel/CFRP Double Strap Joints Subjected to Combined Thermal and Mechanical Loading. *Composite Structures*, 94, 1826-1833.
- Nguyen, T., Bai, Y., Zhao, X., and Al-Mahaidi, R. (2012b). Durability of Steel/CFRP Double Strap Joints Exposed to Sea Water, Cyclic Temperature and Humidity. *Composite Structures*, 94, 1834-1845.
- Nguyen, T., Bai, Y., Zhao, X., and Al-Mahaidi, R. (2012c). Effects of Ultraviolet Radiation and Associated Elevated Temperature on Mechanical Performance of Steel/CFRP Double Strap Joints. *Composite Structures*, 94, 3536-3573.
- Nozaka, K., Sheild, C., and Hajjar, J. (2005). Effective Bond Length of Carbon-Fiber-Reinforced-Polymer Strips Bonded to Fatigued Steel Bridge I-Girders. *Journal of Bridge Engineering*, 10(2), 195-205.
- Ochia, N., Matsumurab, M., and Nisabeb, N. (2011). Experimental Study on Strengthening Effect of High Modulus CFRP Strips with Different Adhesive Length Installed onto the Lower Flange Plate of I Shaped Steel Girder. *The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction*, Hong Kong, China, 506-512.
- Packham, D. (2005). *Handbook of Adhesion*. London: John Wiley and Sons.
- Pang, S., Li, G., Helms, J., and Ibekwe, S. (2001). Influence of Ultraviolet Radiation on the Low Velocity Impact Response of the Laminated Beams. *Composites: Part B*, 32, 521-528.
- Patnaik, A., Bauer, C., and Srivastan, T. (2008). The Extrinsic Influence of Carbon Fiber Reinforced Plastic Laminates to Strengthen Steel Structures. *Sadhana*, 33(3), 261-272.
- Peters, S. (1998). *Handbook of Composites*. London: Chapman and Hall.

- Phani, K., Bose, N. (1987). Temperature Dependence of Hydrothermal Ageing of CSM-Laminate During Water Immersion. *Composites Science and Technology*, 29, 79-87.
- Photiou, N., Hollaway, L., and Chryssanthopoulos, M. (2006). Strengthening of an Artificially Degraded Steel Beam Utilising a Carbon/Glass Composite System. *Journal of Construction and Building Materials*, 20, 11-21.
- Rege, S., & Lakkad, S. (1983). Effect of Salt Water on Mechanical Properties of Fibre Reinforced Plastics. *Fibre Science and Technology*, 19, 317-324.
- Rizkalla, S. and Dawood, M. (2006). High Modulus Carbon Fiber Materials for Retrofit of Steel Structures and Bridges. *International Composites Conference: Advanced, Infrastructure, Natural and Nano composites ACUN-5*. Sydney, Australia.
- Ryall, M. (2000). *Bridge Management four Inspection, Maintenance, Assessment and Repair*. London: Tomas Telford.
- Schnerch, D., Dawood, D., Rizkalla, S., and Sumner, E. (2007). Proposed Design Guidelines for Strengthening of Steel Bridges with FRP Materials. *Construction and Building Materials*, 21, 1001-1010.
- Schnerch, D. and Rizkalla, S. (2008). Flexural Strengthening of Steel Bridges with High Modulus CFRP Strips. *Journal of Bridge Engineering*, 13(2), 192-201.
- Segovia, F., Ferrer, C., Salvador, M., and Amigo, V. (2001). Influence of Processing Variables on Mechanical Characteristics of Sunlight Aged Polyester-Glass Fibre Composites. *Polymer Degradation and Stability*, 71, 179-184.
- Sen, R., Liby, L., Spillet, K., and Mullins, G. (1995). Strengthening Steel Composite Bridge Members Using CFRP Laminates. *2nd Int. RILEM Symposium*. London, UK
- Sen, R., Liby, L., and Mullins, G. (2001). Strengthening Steel Bridge Sections Using CFRP Laminates. *Composites: Part B*, 32, 309-322.
- Shan, L., Hui-Tan, R., Yi-Yan, L., and Mu-Huan, S. (2011). Environmental Degradation of Carbon Fiber Reinforced Polymer (CFRP) and Steel Bond Subjected to Hygrothermal Aging and Loading. *Materials Science Forum*, 559-562.
- Sheikh Ahmad, J. (2009). *Introduction to Polymer Composites*. Springer Science.

- Shervani-Tabar, B., and Davaran, A. (2010). Experimental on Bonding Improvement of CFRP Strips Used for Strengthening of Steel Beams. *Asian Journal of Civil Engineering*, 11, 57-70.
- Shirangi, M., and Michel, B. (2010). *Mechanism of Moisture Diffusion, Hygroscopic Swelling, and Adhesion Degradation in Epoxy Molding Componds*. Springer.
- Shokrieh, M., and Bayat, A. (2007). Effects of Ultraviolet Radiation on Mechanical Properties of Glass/Polyester Composites. *Journal of Composite Materials*, 41, 2443-2455.
- Smith, S. and Teng, J. (2001). Interfacial Stresses in Plated Beams. *Engineering structures*, 23(7), 857-871.
- Stratford, T. and Bisby, L. (2012). Effect of Warm Temperatures on Externally Bonded FRP Strengthening. *Journal of Composites for Construction*, 16(3), 235-244.
- Stratford, T. and Cadei, J. (2006). Elastic Analysis of Adhesion Stresses for the Design of a Strengthening Plate Bonded to a Beam. *Construction Building and Materials*, 20(1), 34-45.
- Tavakkolizadeh, M., and Saadatmanesh, H. (2001). Galvanic Corrosion of Carbon and Steel in Aggressive Environment. *Journal of Composites for Construction*, 5(3), 200-210.
- Tavakkolizadeh, M., and Saadatmanesh, H. (2003a). Repair of Damaged Steel-Concrete Composite Girders Using Carbon Fiber-Reinforced Polymer Sheets. *Journal of Composites for Construction*, 7(4), 311-322.
- Tavakkolizadeh, M. and Saadatmanesh, H. (2003b). Fatigue Strength of Steel Girders Strengthened Carbon Fiber Reinforced Polymer Patch. *Journal of Structural Engineering*, 129(2), 186-196.
- Tavakolizadeh, M., Saadatmanesh, H., and Mostofinejad, D. (2010). Environmental Effects on Mechanical Properties of Wet Lay-up Fiber Reinforced Polymer. *ACI Materials Journal*, 107(3), 267-274.
- Warid Husin, M., Mohd Sam, A., and Mohamad Yatim, J. (2008). *Advanced Composite Materials Properties and Applications*. Johor, Malaysia, UTM library.
- Wu, L., Hoa, S., and Ton-That, M. (2004). Effects of Water on the Curing and Properties of Epoxy Adhesive Used for Bonding FRP Composite Sheet to Concrete. *Journal of Applied Polymer Science*, 92, 2261-2268.



- Wu, G., Liu, H., Wu, Z., and Wang, H. (2012). Experimental Study on Fatigue Behavior of Steel Beam Strengthened with Different FRP Plates. *Journal of Composites for Construction*, 15(2), 127-137.
- Xia, S. and Teng, J. (2005). Behavior of FRP-to -Steel Bonded Joints. *International Symposium on Bond Behavior of FRP in Structures*. Hong Kong, China, 411-418.
- Yu, Y., Chiew, S., and Lee, C. (2011). Bond Failure of Steel Beams Strengthened with FRP Laminates-Part 2: Verification. *Composites: Part B*, 42, 1122-1134.
- Zhang, A., Zhang, J., Li, Y., Li, D., Zhang, D., and Xiao, H. (2011). Effect of Voids on Moisture Absorption of CFRP Laminates in Hygrothermal Environment. *Advanced Materials Research*, 310, 342-346.
- Zhang, A., Li, D., and Zhang, D. (2012). Effect of Moisture Absorption on the Bending Strength of CFRP. *Advanced Materials Research*, 450, 482-485.