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

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Dedicated to:

My beloved parents

My lovely wife and daughter

My dear sisters

Thank you for your prayers and understanding

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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.

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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_∞		Ultimate mass absorption
P_0	-	Initial properties of the material
P_t	-	Properties of the material in time (t)
P_∞	-	Ultimate properties of the material
R	-	Ideal gas constant
T	-	Temperature in Kelvin
γ_e	-	Elastic shear strain of the adhesive
γ_p	-	Plastic shear strain of the adhesive
δ	-	Normal stress of the beam
δ_c	-	Normal stress of CFRP plate
ε_0	-	Initial strain
ε_d^c	-	Design value of the compression strain
ε_d^t	-	Design value of the tension strain
ε_{sd}^c	-	Design value of the compression strain capacity of steel beam
ε_{fd}^t	-	Design value of the tension strain of CFRP plate
ε_{sd}^t	-	Design value of the tension strain of steel beam
α_c	-	Coefficient of thermal expansion for CFRP
α_s	-	Coefficient of thermal expansion for steel
α_c	-	Coefficient of thermal expansion for CFRP
η	-	Conversion factor

ξ	-	Ductility of the steel beam
τ_a	-	Shear stress in adhesive layer
τ_c	-	Shear stress in CFRP plate
ΔT	-	Temperature difference
Δx	-	Distance between two consecutive strain gauge
Δu	-	Mid-deflection of the beam in the ultimate load
Δy	-	Mid-deflection of the beam in the yielding load
$\Delta\varepsilon$	-	Difference of longitudinal strain in two consecutives strain gauge

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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. C*onstruction 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 Boncrete 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 Gomposite 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). Infuence 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 structurs,* 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 Aggresive 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.