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

MEHRAN GHOLAMI

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Faculty of Civil Engineering
Universiti Teknologi Malaysia

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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.
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<tr>
<td>b</td>
<td>Width of DLS specimen</td>
</tr>
<tr>
<td>$d_i$</td>
<td>Lever-arm distance</td>
</tr>
<tr>
<td>k</td>
<td>Rate of properties degradation</td>
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<tr>
<td>n</td>
<td>Modular ratio</td>
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<tr>
<td>$f_c$</td>
<td>Characteristic value of the tensile strength of CFRP plate</td>
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<td>t</td>
<td>Aging time</td>
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<tr>
<td>$t_a$</td>
<td>Thickness of the adhesive layer</td>
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<tr>
<td>$t_c$</td>
<td>Thickness of the CFRP plate</td>
</tr>
<tr>
<td>$t_s$</td>
<td>Thickness of the steel plate</td>
</tr>
<tr>
<td>x</td>
<td>Length of material in Fick’s law</td>
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<tr>
<td>y</td>
<td>Distance from the neutral axis</td>
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<tr>
<td>A</td>
<td>Material constant</td>
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<tr>
<td>$A_i$</td>
<td>Area of the composite beam cross section</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Area of the steel beam cross section</td>
</tr>
<tr>
<td>C</td>
<td>Concentration in Fick’s law</td>
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<tr>
<td>D</td>
<td>Diffusion coefficient</td>
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<tr>
<td>$D_0$</td>
<td>Material constant in Fick’s law</td>
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<td>$E_d$</td>
<td>Activation energy</td>
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<td>$E_c$</td>
<td>Elastic modulus of CFRP</td>
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<tr>
<td>$E_s$</td>
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\[ \text{Fi, Fo} \quad - \quad \text{Ultimate load of DLS specimen per unit width} \]
\[ I \quad - \quad \text{Moment of inertia of composite beam} \]
\[ I_s \quad - \quad \text{Moment of inertia of steel beam} \]
\[ M \quad - \quad \text{Applied bending moment of the beam} \]
\[ M_{\text{Sd}} \quad - \quad \text{Bending moment produced by the design load combination} \]
\[ M_{\text{Rd}} \quad - \quad \text{Design value of the bending moment capacity} \]
\[ M_t \quad - \quad \text{Mass absorption after time (t)} \]
\[ M_{\infty} \quad - \quad \text{Ultimate mass absorption} \]
\[ P_0 \quad - \quad \text{Initial properties of the material} \]
\[ P_t \quad - \quad \text{Properties of the material in time (t)} \]
\[ P_{\infty} \quad - \quad \text{Ultimate properties of the material} \]
\[ R \quad - \quad \text{Ideal gas constant} \]
\[ T \quad - \quad \text{Temperature in Kelvin} \]
\[ \gamma_e \quad - \quad \text{Elastic shear strain of the adhesive} \]
\[ \gamma_p \quad - \quad \text{Plastic shear strain of the adhesive} \]
\[ \delta \quad - \quad \text{Normal stress of the beam} \]
\[ \delta_c \quad - \quad \text{Normal stress of CFRP plate} \]
\[ \varepsilon_0 \quad - \quad \text{Initial strain} \]
\[ \varepsilon^c_d \quad - \quad \text{Design value of the compression strain} \]
\[ \varepsilon^t_d \quad - \quad \text{Design value of the tension strain} \]
\[ \varepsilon^c_{sd} \quad - \quad \text{Design value of the compression strain capacity of steel beam} \]
\[ \varepsilon^t_{fd} \quad - \quad \text{Design value of the tension strain of CFRP plate} \]
\[ \varepsilon^t_{sd} \quad - \quad \text{Design value of the tension strain of steel beam} \]
\[ \alpha_c \quad - \quad \text{Coefficient of thermal expansion for CFRP} \]
\[ \alpha_s \quad - \quad \text{Coefficient of thermal expansion for steel} \]
\[ \alpha_c \quad - \quad \text{Coefficient of thermal expansion for CFRP} \]
\[ \eta \quad - \quad \text{Conversion factor} \]
\( \xi \) - 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 consecutive 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.
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