Performance of Steel-Carbon Fibre Reinforced Polymer Plate Bonding System Under Various Environmental Conditions

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Abstract. The use of Carbon Fiber Reinforced Polymer (CFRP) as strengthening material for reinforced concrete and steel has been a focused of many researched around the world. Superior properties of the CFRP plate including lightweight, high tensile strength, and corrosion resistance make it a favorable material in strengthening of existing structures. However, one of the main drawbacks is the long-term durability of the steel-CFRP bonding system against various environmental conditions. This study evaluates the durability performance of the steel-CFRP plate bonding system exposed to different environments. Experimental work was conducted in which the CFRP plate, adhesive coupons, and CFRP double lap shear samples were prepared and subjected to either continuous or wet-dry cycles in different exposures including plain water, salt water, acidic solution, and outdoor. The exposed samples were tested at different ages. The results show that the CFRP plate was quite durable and the change on the properties was negligible. However, the results indicated that exposure to different environments had affected the adhesive strength properties significantly with exposure to salt water was found to have the most degradation effect on the adhesive.

Introduction

The use of steel plate to repair or retrofit steel structures has been a traditional method for many years. This technique normally increases dead load to the structure and requires heavy lifting equipment as well. Recently, Fiber Reinforced Polymer (FRP) material demonstrated a great solution to increase the strength of steel elements. The superior specifications of FRP material made it quite suitable for repair and strengthening of structures. Advantages such as high strength and stiffness, light weight, fatigue resistance, and high durability make it preferablecompared to the traditional methods. Previous studies showed Carbon Fiber Reinforced Polymer (CFRP) is the most suitable type of FRP for the strengthening of steel structures.

Many studies have been carried out related to steel/CFRP strengthening system. A number of research works have been conducted on rehabilitation of steel and steel-concrete composite beams and showed the method of CFRP bonding to tension flange was a very effective method [1,2]. In fact, using CFRP plate increased the flexural strength and stiffness of the beams significantly, especially in notched damaged beams [3]. Further studies demonstrated this technique enhanced the shear behavior of the beams as well [4]. The bonding characteristics was the focus of other investigations and showed the most successful adhesion between CFRP and steel was formed through mechanical interlocking [5].

Thus, the durability of steel-CFRP bonding is one of the main limitations to popular use of this system in strengthening of steel structures. Few studies exist on the environmental durability of the bond between CFRP materials and steel surfaces. The major environmental factors which influence the system are moisture, temperature, thermal cycles, chemical attack, wet/dry or freeze/thaw cycles, and ultra violet radiations (UV) [6]. In practice, the combination of these conditions might influence the system more seriously. The combination of saline water and high temperatures was investigated by Dawood and it was found the properties degraded rapidly in the first 2 to 4 months of exposure [7].

In this research the performance of steel-CFRP bonding system was investigated thoroughly using Double Lap Shear (DLS) joints. The specimens were subjected to various environmental exposures including outdoor natural climate, wet/dry cycles, plain water, salt water, and acidic solution. The mechanical properties were determined and compared to the control specimens. The durability of the CFRP and epoxy adhesive were also investigated individually.

Material properties

The materials used in the experimental tests were CFRP plate, epoxy adhesive and steel. These materials were tested based on the appropriate ASTM standards to determine their mechanical properties. The CFRP plate was Carboplate of a pultruded strips with the dimensions of 50 mm width and 1.4 mm thickness. A two part epoxy adhesive named as Adesilex PG2 was used to bond the CFRP plate to the steel surface. The steel plate used to fabricate the DLS specimens was a hot-rolled Grade A36 with 6 mm thickness and 50 mm width. The tensile properties of the steel were determined based on ASTM A370 using dog-bone steel coupons which were cut from the original material. The mechanical properties of these materials are presented in Table 1.

Environmental conditions

Several environmental conditions were chosen to study the effect of different factors on the behavior of the steel-CFRP bonding system. The scenarios for environmental conditions are given in Table 2. A total number of 52 DLS specimens were prepared which 4 specimens were tested after 2 weeks of adhesive curing to determine the mechanical properties of the joints before exposure as control specimens. The other specimens were subjected to exposure for upto 8 months. The temperature and relative humidity in the room was measured between 25-28ºC and 70-90% RH, respectively.

Table 1: Properties of CFRP, epoxy adhesive and steel

CFRP (Carboplate)						
Source	**Tensile strength (MPa)**	**Modulus of elasticity (GPa)**	**Ultimate elongation (%)**	**Fibre content (%)**	**Coefficient of expansion (m/m/°C)**	
Company	>3100	170	2.00	68	0.6×10^{-6}	
Lab tests	2850	158	1.81	-----	-----	
Epoxy adhesive (Adesilex)						
Source	**Tensile strength (MPa)**	**Modulus of elasticity (GPa)**	**Ultimate elongation (%)**	**Shearing strength (MPa)**	**Coefficient of expansion (m/m/°C)**	**Glass transition temperature (°C)**
Company	>18	-----	-----	> 28	46×10^{-6}	>40
Lab tests	19.5	11.5	0.199	-----	-----	-----
Steel plate						
Specimen	**Tensile stress at yield (MPa)**	**Young's modulus (MPa)**	**Ultimate tensile stress (MPa)**	**Ultimate tensile strain mm/mm)**		
Steel Plate	291.4	230.8	401.8	0.171		

Specimens’ geometry

The specimens consisted of two 6×50×200 mm steel plates joined together using two 1.4×50×100 mm CFRP plate as illustrated in Figure 1. The CFRP plate overlapped the steel plates by 50 mm on each plate. The steel plates were separated approximately 1 mm to minimize the effect of end to end bonding.

Table 2: Environmental conditions

Scenarios	Number of specimens	Environmental Conditions	Exposure duration (months)
Short term	4	----------	----------
Room ambient	8	Inside the lab	2, 4, 6, 8
A	8	Outdoor (Tropical Climate)	2, 4, 6, 8
B	8	Wet & dry in plain water	2, 4, 6, 8
C	8	Submerged in plain water	2, 4, 6, 8
D	8	Submerged in salt water (5%)	2, 4, 6, 8
E	8	Submerged in acidic solution (4<PH<5)	2, 4, 6, 8

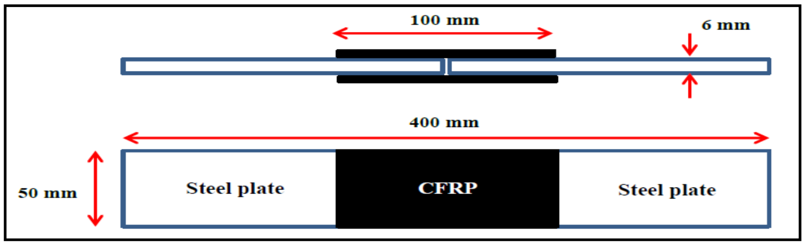

Figure 1: Geometry of DLS specimens

Mechanical properties of control specimens

Tensile test was carried out to determine the mechanical properties of the DLS joints. Figure 2 illustrates the load-stroke curve of the control specimens. The graphs show the behavior of the specimen was almost linear up to failure. When the load reached the ultimate load capacity of the joint, the load suddenly dropped to zero, indicating a sudden failure had occurred. The average failure load of the control specimens was recorded around 60.5 kN. Besides, the average stiffness was obtained from the slop of the load-stroke curve between 10 to 40 kN of about 24.4 kN/mm.

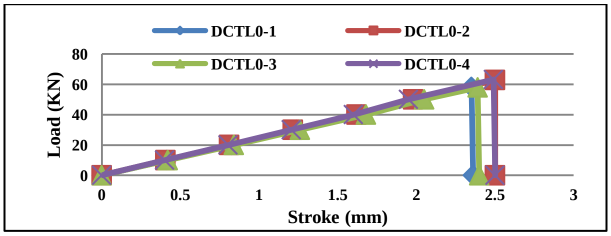

Figure 2: The load-stroke relationship of control DLS specimens

Mechanical properties of exposed DLS specimens

The mechanical properties of exposed specimens were determined through the same method by tensile tests. The properties of specimens are presented and discussed in the following sections separately.

i. Room ambient

The load-stroke relationship of the specimens is demonstrated in Figure 3. The graphs show almost linear behavior at the beginning but, it changed to slightly nonlinear before failure. It can be seen that the failure load was enhanced gradually when the time of exposure increased. The failure stress was found to increase from 60.5 kN to 67.4 kN which shows an enhancement of around 11%. Indeed, post curing of the adhesive in a moderate condition caused an increase in the bond strength with time. However, the tensile stiffness of the specimens was reduced by 8% at the end of exposure.

ii. Tropical climate

The graphs in Figure 3 illustrate the failure load increased significantly to 70.7 kN after 4 months of exposure which shows around 17% enhancement. However, it decreased to 64.1 kN after 8 months which indicates the outdoor environmental factors had degraded the bonding strength. Likewise, the stiffness of the specimens changed in the same trend. Basically, high temperature of the tropical climate accelerated the post curing of the adhesive and therefore, the properties improved significantly in a short period of time. Afterwards, the process of polymerization of the epoxy adhesive finished and the environmental factors began to influence it.

iii. Wet/dry condition

The load-stroke curves show the bonding strength and stiffness were degraded gently by about 11% and 9%, respectively after 32 cycles. These results may indicate water absorption and desorption degraded the bonding properties gradually. Overall, the properties was reduced compared to control specimens and showed the wet/dry condition slightly influence the bonding properties.

iv. Immersed in plain water, salt water and acidic solution

Almost the same degradation trend was observed for these environmental conditions as shown in Figure 3. The results indicate the strength of bonding and the tensile stiffness degraded in a range of 15% to 21% and 13% to 18%, respectively. In addition, the highest rate of degradation occurred within the first four months of exposure. The highest reduction in strength and stiffness was recorded for salt water and plain water specimens, respectively. This was because of the chemical attack by chloride ions which influenced the bonding and caused significant degradation in salt water exposure. In addition, water absorption had made softening and plasticization of the epoxy adhesive and reduced the stiffness substantially.

Properties of CFRP coupons after exposure

The mechanical properties of the CFRP plate was evaluated individually. For this purpose, CFRP coupons were prepared based on ASTM 3039 and tensile test was conducted after exposure to the same environmental conditions. The properties were compared with control specimens to determine the effect of exposure condition. The results indicated that the degradation on the mechanical properties of the CFRP coupons was negligible during this period of time as shown in Figure 4. Basically, the tensile strength and stiffness of the CFRP plate were mainly governed by the fiber properties. The highest reduction of strength and stiffness was recorded for salt water condition around 8% and 6%, respectively.

Properties of epoxy adhesive coupons after exposure

The epoxy adhesive coupons were prepared according to ASTM D638 and subjected to the same environmental condition and tested at the same intervals to be investigated individually. The most degradation of the properties was observed for the specimens of scenarios C, D and E by around 25% to 30%. Evidently, plasticization of the adhesive due to water absorption and chemical attack causes this degradation. Figure 5 compares the trend of changes in the strength of the DLS specimens and epoxy adhesive. The graphs show the trend of changes in the properties of DLS joints and epoxy adhesive coupons were relatively similar. Besides, the epoxy adhesive coupons were influenced more severely than DLS specimens. Obviously, all surfaces of the epoxy adhesive coupons were affected by the aging, while for the DLS joints the adhesive layer surfaces were confined by steel and CFRP plate. These results indicate the mechanical properties of the DLS specimens were mainly related to the epoxy adhesive behavior and the interfaces had minor influence.

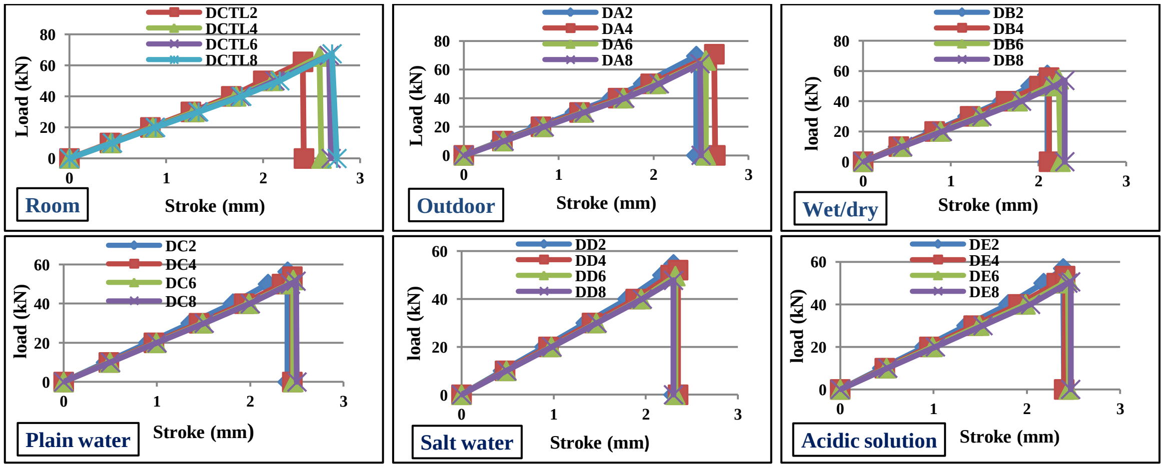

Figure 3: Load-stroke of DLS specimens exposed to various environmental conditions

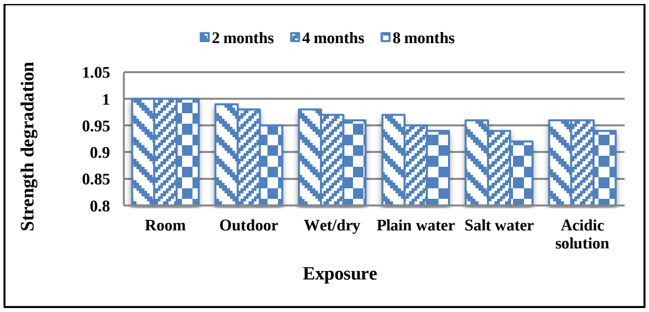

Figure 4: Strength degradation of CFRP coupons in various environmental conditions

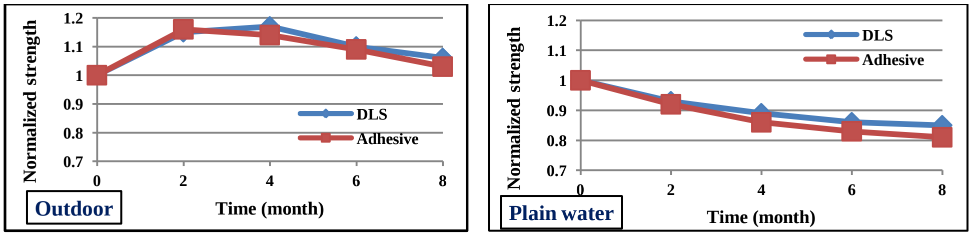

Figure 5: Trend of changes in strength of DLS specimens and epoxy adhesive coupons

Conclusions

The properties of the outdoor tropical climate specimens was enhanced significantly in first four months of exposure and then reduced gradually until the end of exposure. In addition, the strength and the stiffness of the DLS specimens in wet/dry condition reduced gradually indicating that water absorption and desorption degraded the bonding properties moderately in this condition. The highest reduction in strength and stiffness of the DLS specimens was recorded for salt water specimens (21%) and plain water specimens (18%), respectively. This was due to the penetration of salt into the voids and the effect of chloride ions which caused the properties to degrade in salt water exposure. The mechanical properties of the epoxy adhesive coupons reduced at a similar rate to DLS specimens exposed to the same environmental conditions. This indicates that the epoxy adhesive was the critical part and the performance of the bonding system was related directly to its behavior during exposure.

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