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EXPERIMENTAL INVESTIGATION ON THE EFFECT OF NATURAL TROPICAL WEATHER ON INTERFACIAL BONDING PERFORMANCE OF CFRP-CONCRETE BONDING SYSTEM

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Abstract

The existing reinforced concrete structures may require rehabilitation and strengthening to overcome deficiencies due to defect and environmental deterioration. Fibre Reinforced Polymer (FRP)-concrete bonding systems can provide solution for the deficiencies, but the durability of the bonded joint needs to be investigated for reliable structural performance. In this research the interfacial bonding behaviour of CFRP-concrete system under tropical climate exposure is main interest. A 300 mm concrete prism was bonded with CFRP plate on its two sides and exposed for 3, 6, and 9 months to laboratory environment, continuous natural weather, and wet-dry exposure in 3.5% saltwater solution at room and 40 °C temperature. The prisms were subjected to tension and compression load under bonding test to measure the strain and determine stress distribution and shear stress transfer behaviour. The results of the bonding test showed that load transfer was fairly linear and uniform at lower load level and changed to non-linear and non- uniform at higher load level. The force transfers causes the shear stress distribution being shifted along the bonded length. The combination of climate effects may have provided better curing of the bonded joints, but longer duration of exposure may be required to weaken the bond strength. Nevertheless, CFRP-concrete bonding system was only minimally affected under the tropical climate and salt solution.

Keywords: Strengthening, Interfacial stress, Bonding, Concrete, durability.

1. Introduction

Strengthening of concrete structures using externally bonded FRP composite system raises a two key concern on the durability of the system. One is the durability of the FRP material itself and the other which is more critical is the

Nomenclatures

τ_{frp}	Bond stress on FRP plate for dx element
b	Width of the FRP plate
t_{frp}	Thickness of the FRP Plate
dx	length of an element (or between two consecutive strain gauges)
E	Modulus of Elasticity
F_{frp}	Local force in fibre materials
ε	Strain

durability of bonding between the FRP material and concrete substrate. The latter concerns with the durability of the interface bond in the FRP-concrete bonding system [1-3]. The success of this strengthening method using external bonded FRP plate depends highly on the interface bond between FRP material and the concrete. The bonding is fulfilled by suitable adhesive such as epoxy. The interface bonding is vital by providing the effective shear stress transfer from the concrete to the externally bonded FRP. Thus, the composite action of structures being externally bonded with FRP material should be preserved during the loading until failure by having a capable and efficient adhesive to transfer stresses between adhesive concrete and adhesive plate bonding [4].

Mukhopadhyaya et al. [2] observed that concrete shearing failure was significantly predominant in control specimen for GFRP plate bonded to concrete surface subjected to long term aggressive environmental exposure proving stronger bond adhesion in the samples. Concrete shearing failure was also dominant in an investigation performed by AbuHassan [5] to study the effect of tropical climate on the bonding behaviour of external reinforced FRP to concrete by exposing specimens to wet-dry cycles in sodium chloride solution. Results of works carried out by Yao *et al.* [6] and Sharma *et al.* [7] showed that failure modes by debonding occurred in concrete adjacent to the adhesive concrete interface with noticeable thin layer of concrete attached to the FRP strips after failures.

The concrete sharing failure or debonding is associated with perfect bonding and the behaviour of strain distribution along the bonded length. The results of experimental investigation by Bizindavyi and Neale [8] showed that as the applied load was gradually increased, the strain distribution decreased starting from the loaded end area. Similar trend can be obtained from studies carried out by other researches with regards to the strain distribution and the applied load [6, 9-11]. Taljsten [9] describes the typical strain distribution behaviour for bonded system before concrete began cracking and failure until fracture with the occurrence of strains higher at the end of plates and smooth-linear at low load levels and the concrete fracture or fail at higher load levels. The formations of cracks were indicated by the change in slope of strain-distance curve and critical strain level could be determined at the change of slope from lower load to higher loads.

Ali-Ahmad *et al.* [11] made a distinct observation by identifying the strain distribution stress transfer zone in which there is a constant stress transfer length between the concrete and the FRP sheets, which was found to be approximately equal to 90 mm as the cracks propagates and in the fully debonded zone the strain were fairly constant with increasing loading activities. Chajes *et al.* [12] describes the strain distribution as a rate of shear flow for which load being transferred from the fibre composite to concrete. The force transfer length is defined as the distance from the loaded end of the joint to the point where strain curve reach zero strain [8]. The transfer length is associated with the cracking and debonding pattern of the bonded joint. Mukhopadhyaya *et al.* [2] and AbuHassan [5] showed that the load transfer from FRP plate to concrete at lower loads level is fairly linear and occurred at uniform rate irrespective of the strength of concrete and exposure regime. At higher loads level the force distribution appeared more non-uniform and non-linear with the existence of local debonding at the free edge. Low level loads also resulted in shorter force transfer length compared to higher load level. Crack can be observed at the loaded end. The maximum local bond stress occurred in the region of most stress areas near the loaded end. The failure and stress shifted to adjacent and towards the free end region as load increased.

Sharma *et al.* [7] and AbuHassan [5] observed that the shear stress is larger at the area of nearest to the loaded end and reach a peak value before beginning in decreasing trend. The decreasing trend indicated the initiation of plate debonding and initial cracking at the most stressed region. The section showing an increasing trend in shear stress before decreasing indicated there was a shift of active bond transfer activity in that section. As the results of increasing loads and the increased in transfer length, the local cracking and debonding at the loaded edge, location of maximum force and shear stress shifted away from the loaded edge. A very important point made from testing the bonded joints between FRP-adhesive-concrete systems is the existent of effective bond length in which beyond certain bond length the ultimate load experienced no noticeable variation [7].

Important issue that need deeper consideration in understanding the interfacial bond strength in using externally plated FRP reinforcement is concrete surface preparation because of the bonding failure that happen within the concrete layer beneath the adhesive [13]. It is necessary to carry out surface treatment to remove contaminant or weak surface layer to have a satisfactory bond between the FRP and concrete surface [6, 14-16] The environment for the adhesive to be used is another factor that needs cautious attention in selecting the right adhesive to maintain adhesion while exposed to harsh environments such as climatological changes or aggressive solution or exposure to high humidity, water, and or high temperature [1, 17-20].

2. Experimental Programme

2.1. Raw materials, fiber reinforced polymer and epoxy

Locally produced Ordinary Portland Cement (OPC) that conformed to MS:522: Part 1: 2003 (Second Revision) [21] was used as one of the materials in the investigation of fibre composite bonding system. The maximum size of coarse aggregates used in this investigation was 10 mm and crushed in type. The coarse and fine aggregates were air dried for the preparation of concrete prisms and also subjected to sieve analysis and moisture content test which were carried out according to the relevant British Standards, BS 812 -103.1:1985 [22] and BS 812-109:1990 [23], respectively. The two types of test were conducted on the aggregates in order to assess the suitability of aggregates to be used in preparing the concrete prisms. Ordinary clean tap water which was readily available in the laboratory was used as the main source of water for mixing the concrete. A superlastisizing admixture, Rheobuild 1100 obtained from BASF Malaysia was added to concrete mix in order to increase the workability of the concrete. The dosage rate used in this study was 0.75 L per 100 kg of cementitous materials as recommended by the manufacturer.

Specific name for the CFRP plate used to study the interfacial bonding is Carboplate E 170 and the CFRP plate was manufactured as a high tensile strength and low modulus CFRP thin plate composite. Table 1 shows the mechanical properties of carbon plate used in this investigation. Two component thixotropic Adesilex PG2 SP adhesive meant for structural bonding was used as the adhesive for the bonding of CFRP plate to concrete prism as well as between mild steel end tab and CFRP plate. The epoxy is suitable for higher tropical weather and is used for structural repair, internal and external reinforcement of concrete elements, natural stone, mortar and brick. A mix ratio of 3:1 for Component A (epoxy) to Component A (hardener) was used at every stages of bonding. The mix was thoroughly subjected to rotation of low speed electrical mixer for duration of 2 to 3 minutes until the color of component turned soft grey.

Table 1. Properties of CFRP used in the investigation.

FRP Materials	Tensile Strength (MPa)	Tensile Modulus (GPa)	Thickness (mm)	Elongation At break (%)	Fibre Volume (%)
Carboplate E170	3100	170	1.4	2.0	68

The determination of physical properties for epoxy and CFRP plate were also subjected to tensile test which was necessary to assess the ability of the materials to resist loading during service life. Hence, the materials used are considered reliable and durable for the bonding of the FRP system. The understanding of the basic property of the CFRP plate and epoxy by itself under various selected exposure condition was also important for studying the CFRP-Concrete bonded system as one entity. Tensile strength of the adhesive epoxy (dog bone shape specimen) used was determined according to method stipulated in the ASTM D 638-03 [24]. Meanwhile, the preparation and testing of CFRP plate for tensile strength was also performed in accordance to ASTM D3039/D 3039 M: 2006 [25]. However, the results of both tests were not reported in this paper.

2.2. Casting of concrete prisms

The dimensions of each concrete prism were 100 mm x 100mm x 300 mm and were cast using formwork made of plywood. The designed grade of concrete was 50 MPa. Thirty eight numbers of prisms were cast with typical sequence of casting, curing and demoulding of the concrete prisms. The cast concrete prisms were demoulded after seven days of curing. The surface of the concrete prism required to be bonded was roughened using air tool hammer for the purpose of perfect bonding between the plate and concrete. The surface was ground for about 1 – 2 mm depth on both longitudinal sides for a later application of epoxy adhesive.

2.3. Bonding mild steel end tab to carbon plate prisms

A mild steel end tab having dimension of 150 mm length, 50 mm width and 3 mm thick was bonded to a 50 mm wide and 555 mm length carbon plate to overcome premature composite shear out failure and excessive bearing stresses around pin hole during loading. The surface of the end tab was sandblasted to provide good surface for bonding. A special built fixture consisted of two components which were designated as the base and top plate was used to bond the mild steel end tab to the carbon plate. Two components of Adesilex PG2 SP Adhesive A and B were mixed in order to bond mild steel end tab to the carbon FRP plate.

2.4.Bonding CFRP plate to sides of concrete surface

The main preparation works of the bonding test specimens was the bonding of CFRP plate to concrete surface. The concrete surface must be free from any dust or tiny concrete pieces produced during surface exposure. This was carried out by applying high pressure air unto the exposed concrete surface. The exposed surface was also required to be dried of any moisture. These processes were necessary to ensure the concrete surface was cleaned and dried for ensuring good bonding between FRP and concrete. Adhesive was applied to the surface of concrete and CFRP plate for bonding purposes. Even though the thickness of adhesive was not the parameters being studied, the adhesive was applied to about the thickness of concrete surface exposed approximately 2 mm. About 1 mm thickness of adhesive was applied on the FRP plate. The CFRP plate was applied gently onto the concrete surface that was positioned on a special rig as shown in Fig. 1 according to the length and orientation required. Figure 2 shows the dimension of a complete bonded concrete specimen. Initially the pressure was applied using hand for homogenous bonding on the concrete surface and to ensure complete epoxy coverage and right after that steel plate was used to apply the pressure during the curing process. During the curing process of both bonded sides, a steel plate was used to provide pressure to homogenize the thickness.

2.5.Conditioning of bonded FRP-concrete prism

All thirty eight numbers of prisms were conditioned accordingly in cycle programme as shown in Table 2 and Fig. 3 (BS40DL) until the testing day. The saltwater in this experiment was heated by means of immersion water heater with temperature control at 40 °C through 240V, 2500W power supply. Sodium chloride solution was prepared for the conditioning by using Australian Sea salt obtained from local distributor to simulate the seawater condition. An average dosage of 35 g (3.5%) of fine grain salt was used for every one litre of normal tap water for the simulation of sodium chloride solution in the actual seawater. The consistency of the pH and salinity of the saltwater was constantly monitored to ensure homogenous effect on the specimens immersed in the solutions. The level of saltwater in the heated saltwater was filled up frequently to maintain the required level due to loss of water because of condensation.

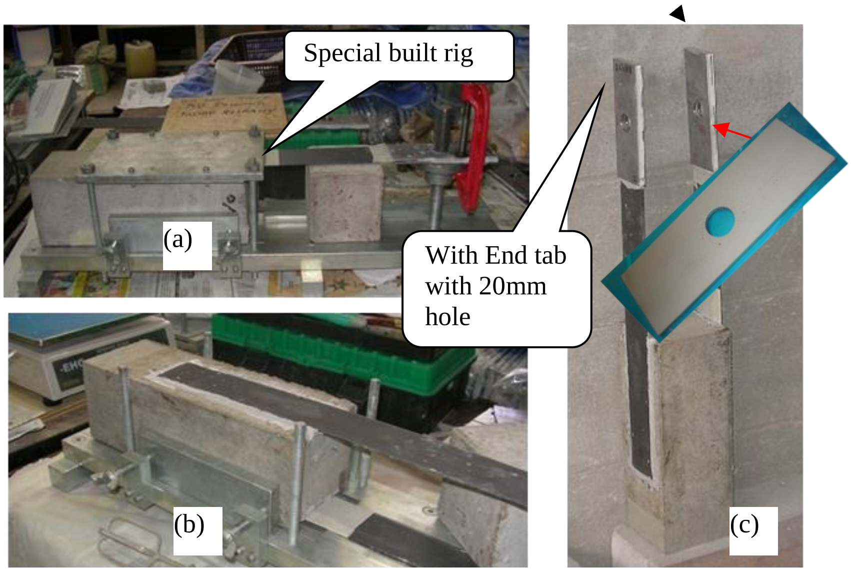

Fig. 1. Selected bonding process of CFRP to concrete (a) bonding of one side complete (b) bonding on both sides of concrete (c) Concrete prism completely bonded and ready for conditioning and testing.

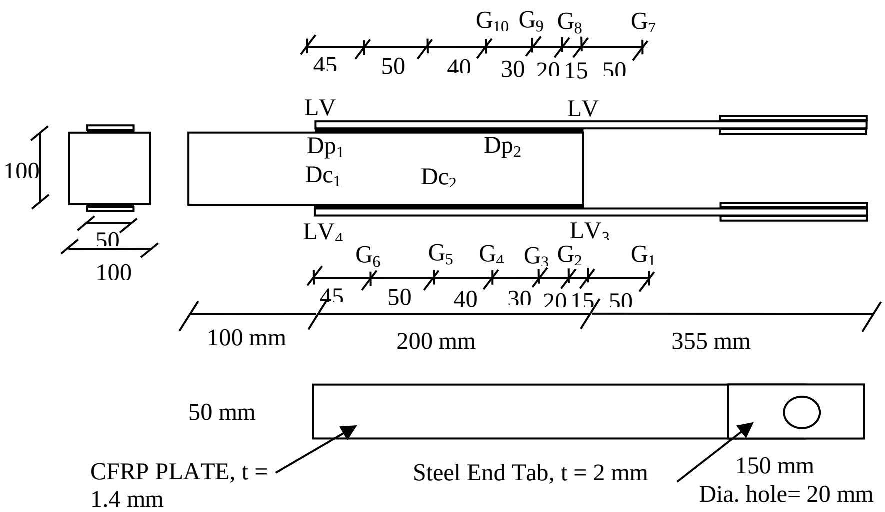

Fig. 2. Specimen dimension and instrumentation location.

Table 2. Test programme for CFRP bonded prisms, tensile adhesive and CFRP tensile plate

EXPOSURE CONDITION	Duration			
	28 days	3 months	6 months	9 months

B-CL Control (Laboratory Air)	-	Continuous	Continuous	Continuous
BC-CT (Exposed Continuous under Tropical Climate Exposure)	-	Continuous	Continuous	Continuous
B-SDL (Wet-Dry Saltwater at room temperature in laboratory) BS40DL (Wet-Dry Saltwater at 40 °C in Laboratory)	- -	3 days wet– 4 days dry (1 week/cycle) 12 cycles Similar : wet @ 40 °C ..	3 days wet– 4 days dry (1 weeks/cycle) 24 cycles Similar : wet @ 40 °C ..	3 days wet– 4 days dry (1 weeks/cycle) 52 cycles Similar : wet @ 40 °C ..
B-SDT (Dual Exposure - Saltwater in Laboratory at room temperature and tropical climate exposure) B-S40DT (Dual Exposure - Saltwater in Laboratory at 40 °C and tropical climate exposure)	- -	3 days wet- 4 days dry- 7 days tropical (2 weeks/cycle) 6 cycles Similar : wet @ 40 °C ..	3 days wet- 4 days dry- 7 days tropical (2 weeks/cycle) 12 cycles Similar : wet @ 40 °C ..	3 days wet- 4 days dry - 7 days tropical (2 weeks/cycle) 26 cycles Similar : wet @ 40 °C ..

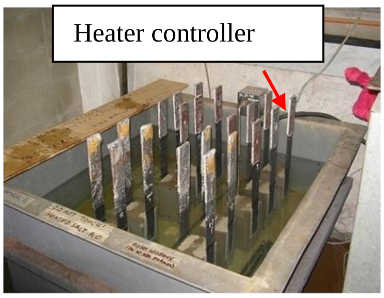

Fig. 3. Concrete prism under immersion in saltwater for three days

2.6.Test Set up and Instrumentation

The bonded concrete prisms were instrumented with strain gauges, demec disc and Linear Variable Displacement Transducers (LVDT) in order to access the performance of exposed bonded area of the prism. Information from the strain reading was used to determine the bonding stress distribution with regards to local force and bonded length of the prism. The LVDTs were intended to determine displacement (slip behaviour). Each bonded prisms were also instrumented with ten numbers of 120-Ω TML, BFLA-2-8 (2 mm) electrical strain gauges prior to loading to record the strain profile along specific intervals of the bonded CFRP plate. Six electrical strain gauges were installed on one side of the CRRP plate and another four on the other side. The other four was installed in order to ensure proper alignment of the prism during loading and also to ensure the balance force applied on both sides of the prism. The CFRP plate strain was measured and recorded at every 5 kN interval using data logger.

2.7.Determination of bond stress through bonding test

The bond stress between the CFRP plate and concrete was derived from tension forces acting on the bonded system by pulling up the CFRP plate bonded to concrete surface. The transfer of forces from the FRP plate to concrete during loading creates shear stress in both interface of concrete-adhesive (epoxy) and plate-adhesive. The bond stress in the strengthened concrete prism was determined by considering an arbitrary element in FRP bonded plate as shown in Fig. 4. The equilibrium of forces of equation in longitudinal direction was expressed by considering the summation of forces in *x* direction, $\Sigma F_x = 0$

$$\tau_{frp}\, b\, dx + \sigma_{frp}\, b\ \tau_{frp} = (\sigma_{frp} + d\,\sigma_{frp})\, b\, \tau_{frp} \tag{1}$$

Bond shear stress can be derived by solving both sides of the above equations

$$\tau_{frp} = \tau_{frp}\ d\,\sigma_{frp}/dx \tag{2}$$

Knowing that from mechanic of properties, $\sigma = E\ \varepsilon$, and ε = the strain, thus Eq. (2) can be simplified where the bond stress is proportional to the FRP plate thickness and the strain gradient along the fibre.

$$\tau_{frp} = E_{frp}\, \tau_{frp}\ d\,\varepsilon_{frp}/dx \tag{3}$$

Further solving both sides of Eq. (3) can result in an expression for local force in fibre materials, F_{frp}:

$$F_{frp} = E_{frp}\, \varepsilon_{frp}\, b\ \ t_{frp} \tag{4}$$

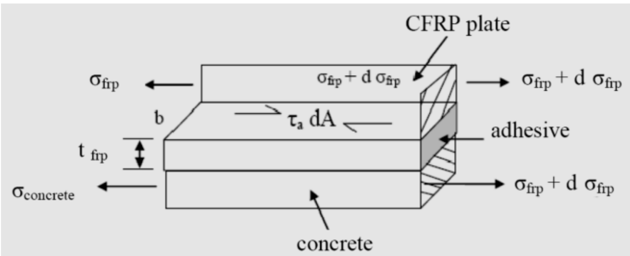

Fig. 4. Equilibrium of element of bonded joint [26]

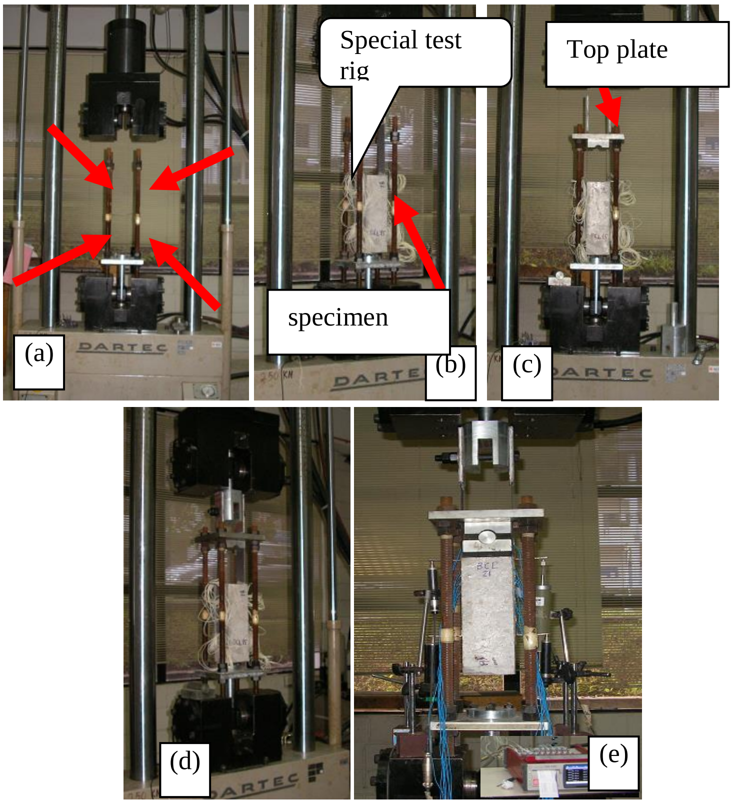

Fig. 5. Testing sequence of the bonded concrete prism (a) placing and securing the bottom holder of test rig on tensile machine (b) placing the specimen inside the test rig (c) inserting the top plate of test rig (d) securing the test rig top holder and specimen into the machine and (e) specimen ready for testing

2.8.Bonding Test

A special built test rig as shown in Fig. 5 was developed and assembled in the mechanical engineering laboratory of Universiti Teknologi Malaysia, Skudai, specifically for this kind of investigation. The rig was designed by a previous researcher [5] in which the design was adopted from a similar study at Sheffield University, United Kingdom [2]. The bonded concrete prism was fixed into the special built rig prior being fitted into a 250 kN Dartec Universal Testing Machine. By applying a tensile force by means of pulling off the CFRP plate, a pushing off compressive can be applied onto the concrete prisms by means of 75 mm roller bearing. Figure 5 also shows the process of testing the bonded prism initiated by placing the test rig unto the testing machine frame. The CFRP bonded prism was inserted into the test rig once the test rig securely positioned and placed in the frame. Then the upper test rig plate was screwed into the test rig. This was followed by connecting the previously installed strain gauges wires and LVDTs to the data logger for load and strain automatic reading and recording. Loading was applied to the specimens by means of tensile and compression reaction with a loading rate of 0.05 kN/s and reading recorded from the data logger at increment of 5 kN until failure. Compressive load was initially applied unto the concrete prism through a bearing plate placed on top of the prism. This can be achieved by pulling the steel end-tabs bonded at the end of the CFRP plate. The bearing plate produced a bearing stress that was transmitted to the top of concrete prism. Shear bond stress developed in the bonded areas once the tension and compression are in action.

3.Experimental Results and Discussion

The bonding behaviour of CFRP-concrete bonding system by means of epoxy as the adhesive is the main investigation of this research. The performance was observed in term of the maximum failure load upon application of tensile and compressive forces towards the concrete prism. The recorded applied load and strain were used as the main input for determination of interfacial shear stress between the main materials of bonded concrete prism. The force transfer lengths were also calculated and the failure modes were observed from the results.

After various environmental exposures, the most noticeable changes on the physical appearance of the specimens were on the colour of epoxy applied for the bonding between plate and concrete. The colour of the adhesive changes from white grey to yellowish. This was especially true for specimens being exposed to tropical climate either continuously or on alternating basis. This may imply the influence of UV or the heat of surrounding temperature on the materials. Some concrete looked like being soaked with water even though it was dry. This was the effect of alternating immersion in salt solution. There was also existence of salt crystal on specimen subjected to alternating wet dry immersion in saltwater at 40°C and drying either in the laboratory or under tropical weather.

3.1.Plate Strain along Bonded Joint

Figure 6 shows the strain profile of CFRP plate along the bonded joint at applied load of 20 kN and 45 kN after being conditioned under various environmental conditions for a duration of 3, 6, and 9 months. At lower load level of 20 kN and at all exposure durations, the values of strain were observed to be closer to each other for all conditions of exposure as shown. As load was being increased the strain in the CFRP plate recorded diverge values between the exposure conditions. It can be seen that at higher load of about 45 kN the three months exposure duration showed a closer values similar to the lower load level. This phenomenon may have indicated the effect of saltwater, heat and tropical environment on the deformability of the bonded system that eventually may affect the resistance of the bonding system towards environmental degradation.

The strain distributions of the CFRP plate as a function of bonded length after being exposed for selected exposure duration are shown in Fig. 7. The strain distribution along the bonded length illustrates the rate of tensile loads being transferred from the CFRP plate to the concrete. The load transfer was essentially the interfacial shear stress flow in the bonded joint. The bonded prism in the nine months exposure group demonstrated similar typical strain distribution behaviour with the three and six month of exposure. In all cases of exposure and duration, the strains levels were found to be high nearest to the applied load or the free edge and lower at the other end of plates bonded on the concrete prisms. This behaviour was typical on all specimens before concrete began to fracture near the ultimate failure. The results showed that the CFRP plate strains were linearly distributed along the bonded length at lower load level for all specimens under all exposure conditioned even after nine months of exposure. The strains were also distributed in non-linear and non uniform pattern at higher load level. The strain distribution patterns were fairly uniformed especially at lower load level for all conditioned of exposure.

However, at higher load level there was evident of non uniform distribution of strain by the existence of intersection of strain at certain local force, especially for specimen subjected to higher temperature and dual exposure as shown in Fig. 8. The intersection of the strain curve occurred approximately at load level between 35 kN to 45 kN. In the nine months of exposure, the intersection was noticeably occurred in specimens subjected to immersion in higher temperature of saltwater and laboratory exposure (BS40DL) as well as dual exposure (BS40DT). The intersection also occurred in specimens subjected to dual exposure after being conditioned in saltwater in room temperature (BSDT). In the case of three and six months of exposure the intersection was more obvious in BS40DL specimens. The intersection was believed to cause the initial occurrence of micro-cracking that lead to debonding in the bonded joint. The distribution of CFRP strains at lower load level was also fairly linear from initial loading until failure at 105 mm to 200 mm of bonded length from the loaded end.

3.2.Force Transfer between Plate and Concrete

The force transfer length is the length where the local load derived from the strain reading reaches zero values. The local force is where the location and the length are very significant in showing the stress transfer behaviour of the specimens subjected to tensile load. The results clearly show that there was a direct relationship between strain reading and the local force based on the similarity of the charts of strain distribution along bonded length and the local force along bonded length. The local force behaviour of CFRP plate as a function of bonded length demonstrated that the nine months of exposure behaved in similar trend with the three and six months exposure specimens irrespective of the exposure environment. The distribution of local force of the tested specimens along the bonded length also showed the initiation of the force transfer on that bonded length as shown in Table 3 selected at load level of 10 kN and 30 kN respectively. The force transfer also occurred at about 155 mm from the loaded end edge measured at the same load level of 30 kN.

On the overall, the trend of the local force behaviour for the nine months duration was very similar to the ones in three and six months. The results also showed that the force transfer at lower load level were typical of being fairly linear and moving at uniform rate. However, as the applied load increased the force transfer became non linear and also non uniform which was also demonstrated in the three and six months of exposure specimens. This was maybe due to the effect of increasing load and higher strain in the CFRP of bonded specimens at the most stress region. The local force on the CFRP plate at the bonded joints at the most stress region of the bonding system was also about half of the applied load. The load transfer along the bonded length at selected applied load of 10 kN, 20 kN and 45 kN at 3, 6 and 9 months of exposure was higher between zone 0 mm and 35 mm, then started reducing towards the other ends of 200 mm zone. The local force line was almost horizontal for all load level at the end region beyond 105 mm indicating that the transfer load was getting very small and almost zero which also meant less force transfer activities. The results showed that higher rate of force transfer occurred between sections 65 mm to 105 mm after the loaded end area which was indicated that larger magnitude of local force activities was being shifted towards the other end.

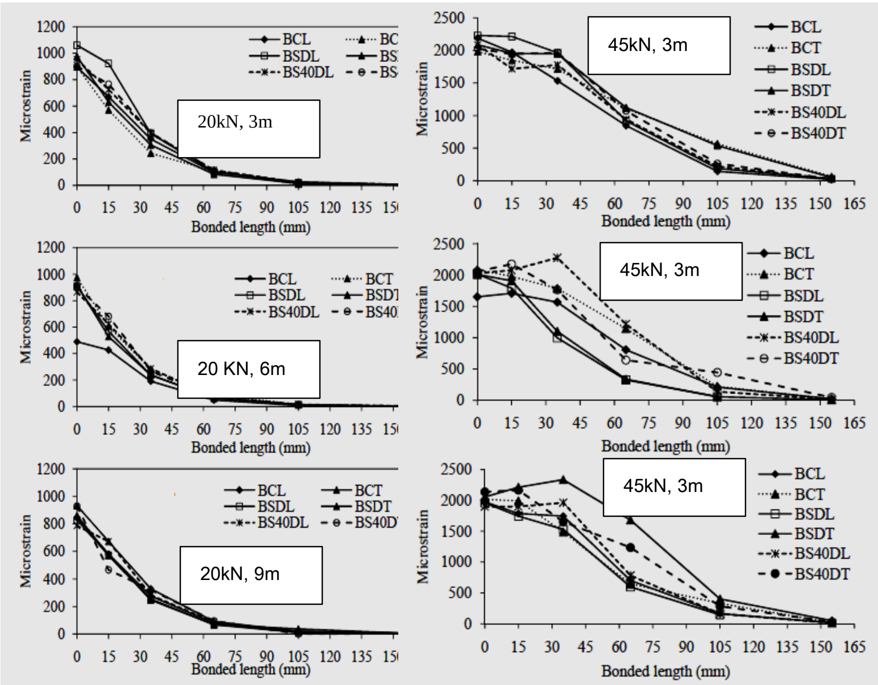

Fig. 6. Strain distribution at load level 20kN (left) and at 45 kN (right) along bonded joint under various exposures condition

Figure 9 and 10 illustrate the magnitude of local force for each exposure conditions along the bonded length at selected applied load of 20 kN and 45 kN at 3, 6, and 9 months of exposure. At the applied load of 20 kN the local force transfers among the exposure condition behave almost in similar magnitude and direction. As load was increased such as at 45 kN, there was evidence of the local force being diverted from each exposure condition which may indicate the effect of the environmental conditions on the bonding performance of CFRP-concrete system. This was noticeable in specimens subjected to dual exposure that were exposed in saltwater in room temperature (BSDT) and higher temperature (BS40DT). In fact, specimens from both exposure conditions recorded the lowest tensile load after nine months of exposure which also indicated the reduction in bonded system capacities to resist further load.

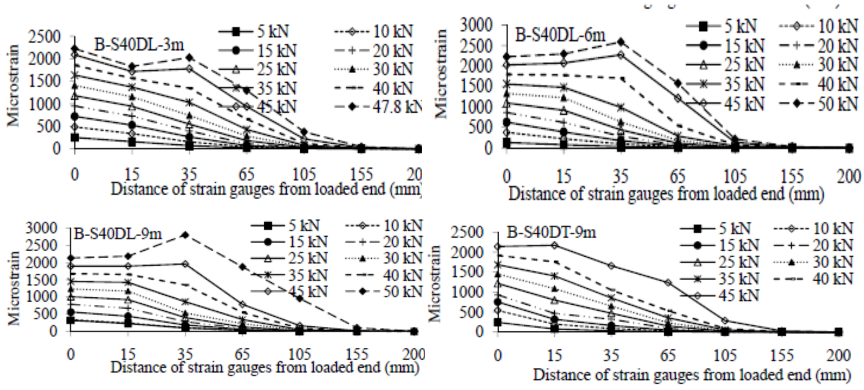

Fig. 7 Strain distribution along bonded joint under various environmental conditions at selected exposure duration

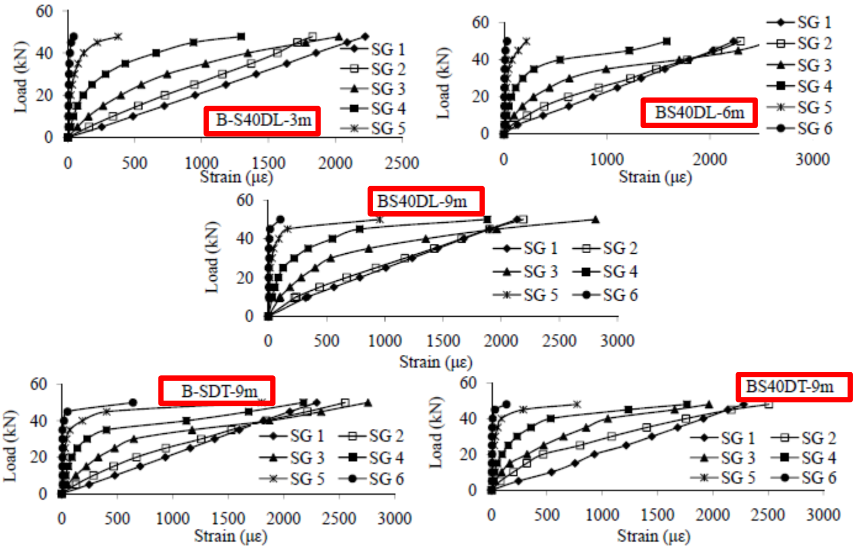

Fig. 8. Intersection of strain distribution for selected exposure condition and duration at each load level

Table 3. Force transfer length at three, six and nine month's exposure

Specimen	Ultimate Failure applied load			Bond Transfer Length				
				Lower local force			Higher Local Force	At Failure
	3m	6m	9m	3m	6m	9m		
	(kN)			10 kN (mm)			10 kN (mm)	(mm)
BCL	54.16	51.50	54.39	200	155	155	200	200
BCT	51.90	51.50	54.65	155	155	200	200	200
BSDL	49.16	52.52	52.81	200	200	155	200	200
BSDT	46.63	58.33	51.17	155	155	200	200	200
BS40DL	49.02	54.33	53.08	200	155	155	200	200
BS40DT	49.41	55.96	47.94	155	155	105	200	200

3.3.Bonding Shear Stress Distribution

The application of load on the CFRP plate bonded prism caused the transfer of longitudinal local force of the plate to the concrete in which created interfacial shear stress in the bonded joint. The interfacial shear stress developed both in the interface between concrete-adhesive and plate-adhesive. The interfacial shear stress from the control and exposed specimens were illustrated by using histogram charts for the best descriptions of the stress distribution behavior along the bonded length as shown in Fig. 11 (for selected specimens and duration). Only several selected plate force levels of 10 kN, 20 kN, 30 kN, 40 kN and 45 kN or 50 kN were depicted in the histogram charts for clarity purposes. These shear distribution diagrams were important in a sense that the charts described the magnitude, location and the development of debonding in a CFRP –concrete bonding system. The results of this bonding test for all duration of exposures showed that at lower load levels, the maximum interfacial shear stress occurred near the loaded end. This was expected since the maximum local plate force occurred at this zone near the loaded end. As the applied load increased, the maximum shear stress shifted to the other end of the bonded prism. The shift of the maximum location of shear stress away from the high stress zone at the loaded edge as can be seen on the entire bonded concrete prism tested as shown in Fig. 11. The shift was assumed to be caused by the cracking and debonding of the CFRP bonded plate initiated at that high stress zone.

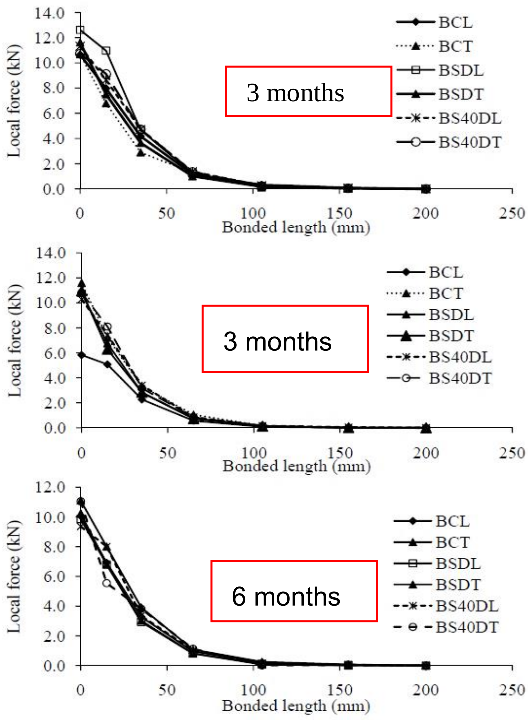

Fig. 9. Local force distribution at applied load of 20kN along bonded joint under various exposures condition

The interfacial shear stress distribution along the bonded length is also presented to highlight the effect of saltwater, temperature and tropical weather on the FRP-concrete bonding system. In term of development of stress at lower load such as 20 kN, the effect of exposure conditions was very consistent. This can be seen in the location of the peak stress between 15 to 35 mm. However, as crack started to develop in the bonding system, the location of shear stress shifted to the other end at and peak occurred at various locations with section 35 mm to 65 were the most occurrences. It was found that the stress resistant was lower at the lower applied load compared to the higher applied load of 45 kN. Specimens exposed to dual environment at high temperature of solution (BS40DT) developed low environmental resistance by having lower shear stress after nine months of exposure. As such, the combination of tropical climate, saltwater and higher temperature can affect the FRP-concrete bonding performance.

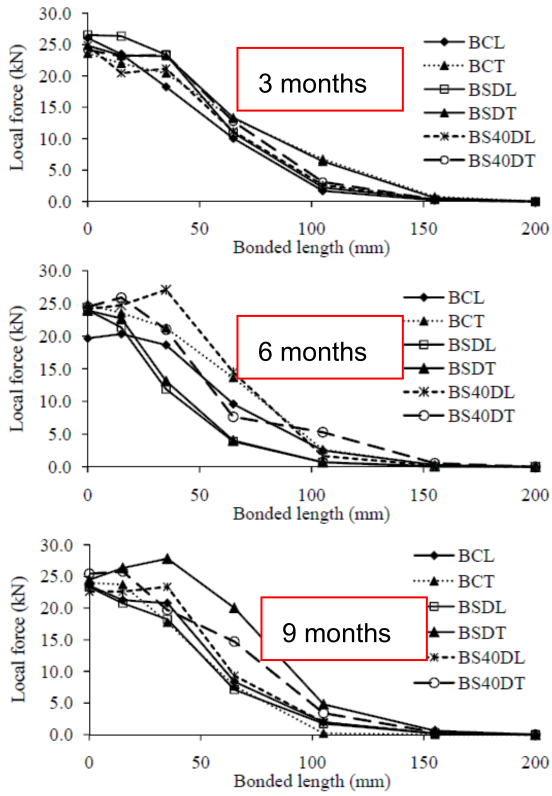

Fig. 10. Local force distribution at applied load of 45 kN along bonded joint under various exposures condition

The shear distribution in various zones of the bonded length can also be illustrated to study the shear stress pattern with a function of relative load level. The results show the shear stress at various exposure conditions between certain locations reached a peak value and decreased abruptly in most cases of exposure at certain normalized load. The normalized load was obtained by dividing the current applied load to the near ultimate load level able to be recorded in the experiment. This abrupt decreasing of shear stress indicated the initiation of plate debonding which was also indicated by previous studies done by Bizindavyi and Neale [8] and Sharma *et al.* [7]. The trend of decreasing of shear stress after reaching the peak indicated the initiation of cracking which was shown by almost all specimens in the three , six and nine months group. The normalized load at which the initiation of debonding occurred varied from 0.40 to 0.85 covering all duration of exposures as depicted in Fig. 12. After three months of exposure, the laboratory conditioned prism (BCL) had the highest normalized load at 0.83 for the debonding to commence compared to other exposed prisms at 0.4, 0.5, 0.60, 0.65 respectively for BSDL, BS40DT, BS40DL, and BCT. The normalized load after six months of exposure which was believed to initiate the debonding varied at lowest of approximately 0.55 to the highest of 0.75. In the case of nine months testing, the normalized load varied from an approximately 0.5 to 0.8. Most of the conditioned prisms recorded a relative load of less than 0.6 except for prism bonded with CFRP plate that was subjected to dual condition of saltwater immersion at higher temperature and continuous exposure to tropical weather. The results as illustrated in Fig. 12 also demonstrated that even though the exposed specimens recorded variance in the tensile strength, the normalized load was about the same at about 0.55, especially after six and nine months of exposure. This may indicate the epoxy has reached certain duration of good curing to produce good FRP-concrete bonding to resist environmental degradation. Also, the normalized load of 0.55 may be the optimum load required for the failure of bonding to occur regardless of environmental condition to initiate the degradation.

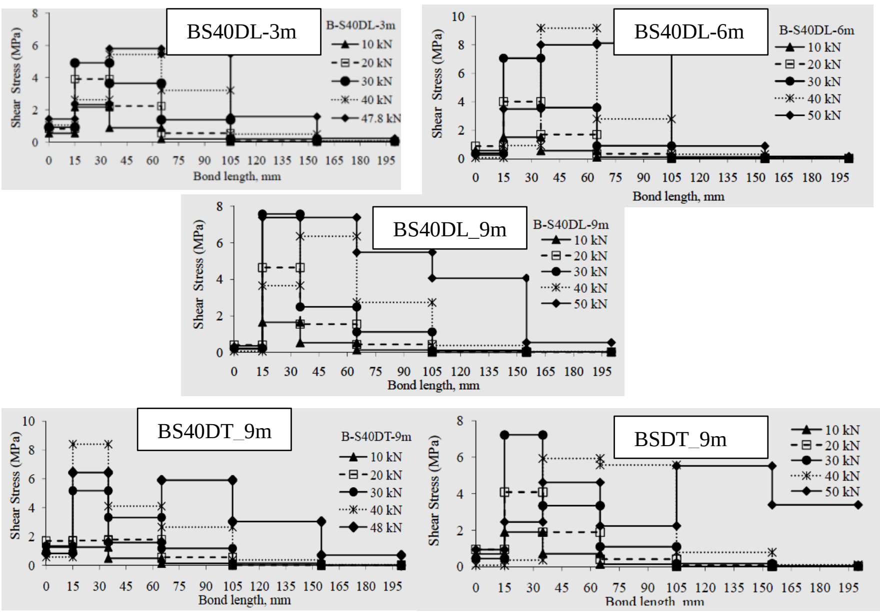

Fig. 11. Shear stress distribution for selected specimen

In most cases the average shear stress of other section beyond 35 mm zone increased indicating the shift of critical bonding activity away from this particular zone. The shifting behaviour of the peak shear stress to the next zone was also progressively occurred until the total failure. The peak shear stress and the location of the peak shear stress for all conditions at all duration of exposures are summarized in Table 4 which the magnitude, the location and the development of the peak shear stress activities towards the end zone of the bonded prism can be clearly seen.

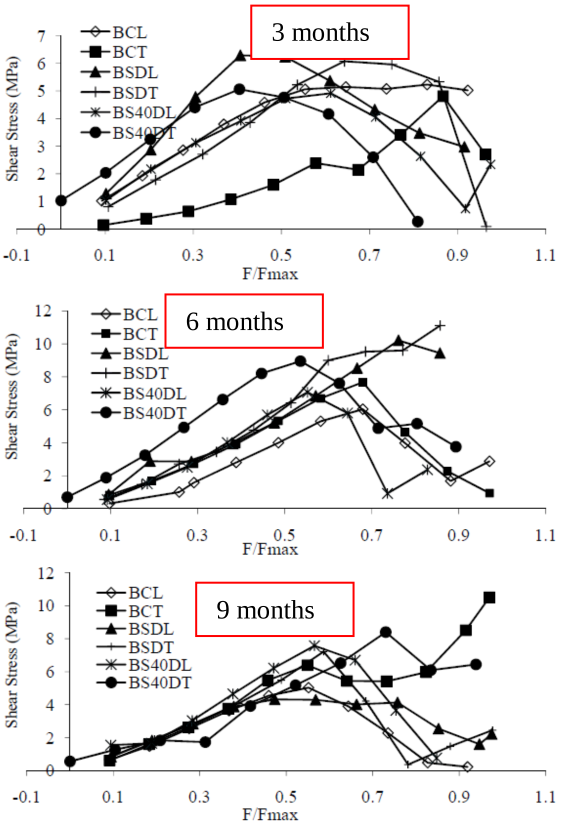

Fig. 12. Shear stress distribution at normalized load at various exposure conditions and duration

3.4.Failure Modes

The failure surface of the bonded prism were thoroughly inspected and investigated immediately after testing. In all cases of exposure and duration of exposure, the bonded CFRP plate was detached from the prism at the time of failure. The detachment occurred in a sudden manner during the loading stage with a loud sound produced by the specimen. The loud sound was possibly generated by a high strain energy produced in the bonded CFRP plate. The abrupt failure or detachment of the CFRP plate was sudden that make the sound on the formation of cracking barely noticeable. The failure was initiated by the formation of cracking at the adhesive and concrete interface followed by the formation of macro cracking at the CFRP concrete bond interface. In other word, the development of high interfacial shear stress at the adhesive concrete interface resulted in full debonding of the CFRP plate.

Table 4. Location of maximum shear stress for 3, 6 and 9 months of exposure

Exposure Condition	At applied force 10 kN		At applied force 20 kN		At applied force 45 kN		Near Ultimate failure kN	
	Peak stress (MPa)	**Peak Zone (mm)**	**Peak stress (MPa)**	**Peak Zone (mm)**	**Peak stress (MPa)**	**Peak Zone (mm)**	**Peak stress (MPa)**	**Peak Zone (mm)**
3 months								
BCL	1.93	15	3.80	15	5.46	35	6.20	35
BCT	0.99	35	1.83	35	4.81	65	4.81	65
BSDL	2.87	15	6.29	15	8.29	35	8.29	35
BSDT	1.78	15	3.86	15	6.55	35	6.55	35
BS40DL	2.87	15	3.92	15	6.66	35	5.80	35
BS40DT	2.87	15	4.40	15	7.09	35	7.09	35
6 months								
BCL	1.01	15	2.80	15	6.02	35	6.02	35
BCT	1.69	15	3.92	15	5.49	65	5.99	65
BSDL	2.88	15	3.94	15	9.44	15	7.42	35
BSDT	1.46	15	3.45	15	9.60	15	11.11	15
BS40DL	1.51	15	4.01	15	8.39	35	8.12	65
BS40DT	1.88	15	4.93	15	8.90	35	7.66	35
9 months								
BCL	1.48	15	3.64	15	8.27	35	9.46	35
BCT	1.59	15	3.76	15	6.68	35	8.51	15
BSDL	1.82	15	3.88	15	7.40	35	6.61	35
BSDT	1.90	15	4.09	15	7.62	65	5.52	105
BS40DL	1.65	15	4.65	15	9.35	35	7.39	35
BS40DT	1.27	15	1.79	35	6.09	15	6.44	15

The failure modes of the concrete prism tested after 3, 6, and 9 months of exposure were dominated by concrete shearing which occurred almost on the entire bonded surface of each tested specimens as shown in Fig. 13. This indicates good bonding between CFRP plate and concrete. Adhesive failure can also be seen between CFRP plate and adhesive on few smaller spots on the debonded plate. The failure on the surface of debonded CFRP plate was accompanied by a thin layer of concrete about 5-10 mm attached to the plate surface as shown in the figure. In some cases, the top part of the concrete prism was angled rip-off for a length between 30 mm and 40 mm at failure load. The concrete shearing indicated the weak tensile and shear capacity of concrete exposed up to nine months of exposure under saltwater immersion and tropical climate compared to CFRP plate. Thus, the results of the investigation showed that the adhesive was able to provide good and stronger bond compared to the shear strength of concrete after being subjected to saltwater and tropical climate. However, the aggressive exposure condition in saltwater and high temperature did not greatly influence the failure pattern even after nine months. Hence it can be said that longer duration of aggressive environmental exposure may be required to observe any significant effect on the deterioration of the CFRP-adhesive-concrete bonded system.

Fig. 13. Failure modes of selected tested prism and CFRP plates under various exposure conditions after exposure

Zooming further on the specimens shows that the plate was almost fill- up with concrete and adhesive during the bonding process. It can be seen that the concrete was in fairly homogenous mix with epoxy, but in some areas there was also cohesion failure between plate and adhesive on small areas. The existence of voids was found on some of the specimens at all duration of exposures. As an example, in the three month duration of exposures the void can be seen in specimens BSDL and BS40DL. The voids can also be found in specimens BSDT and BS40DL for six months of exposure and specimens BCT and BSDL for nine months exposure. The present of these voids may have affected the failure strength of the prism by reducing the bond capacity between plate and concrete. On the overall, the exposure condition was not affected by the pattern of adhesive homogeneity on the concrete or plate or the existence of void in bond. However, the lower tensile strength in the three months exposure may be due low curing stage of the adhesive at that stage. On the other hand, the reduction in the nine months of exposure may be due to the effect of environmental deterioration after nine months. Evidence can be seen in the surface of debonded plate that was almost fully covered with detached concrete. Even though, a perfect bonding existed, but the strength was possibly being deteriorated by environment.

4. Conclusions

Studying the bonding performance of CFRP-concrete-bonding system under various environmental exposures of tropical climate and saltwater solutions can be concluded as such:

- The strain distribution along the bonded length was directly related to the local force along the bonded length. The local force distribution was significant in determining the local force transfer behaviour of the CFRP bonded joint.
- The load transfer at lower load level was fairly linear and occurred at uniform rate at all duration of testing which was at three, six, and nine months. The load transfer became non-linear and non-uniform at higher load level for all duration tested in the investigation.

- Peak interfacial shear stress developed near the loaded end of the specimen which was also the highest stress zone. As loading was further increased, the maximum peak shear stress was shifted along the bonded length and away from the loaded end. The shift also indicated that the peak shear stress and the interfacial stress activity moved towards the other end and finally subsided horizontally to zero.
- The failure of the bonded prism was so sudden and accompanied by a loud sound believed due to high interfacial shear stress energy developed in the bonded joint as load were being applied.
- The debonding of the CFRP plate was accompanied by a thin layer of concrete attached on the plate which also indicated that most of the specimens failed due to concrete shearing modes.
- Similar failure modes of concrete shearing were found in all duration of testing indicating environmental condition of saltwater solution either at laboratory or higher temperature has not greatly influence the concrete bond interface.

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