Bond Characteristics of Externally Carbon Composite Plate-Concrete Bonded System under Combined Mechanical Load and Tropical Outdoor Conditions

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ABSTRACT

The technique for strengthening structures such as reinforced concrete beam, column and slab by method of externally bonded Fibre Reinforced Polymer (FRP) system is successfully being promoted to the Malaysian construction players over the past few years. Deteriorated concrete structures require repair and maintenance or sometimes need strengthening to extend their service life, therefore, the long-term durability of the bonded system is the key element in ensuring that a material system used is able to maintain its integrity throughout its service life. From the study, it shows that the specimens subjected to sustained load for the duration of six and twelve months and exposed to tropical outdoor condition produced a sign of deterioration on the overall bond performances.

Keywords: Bond Durability, Load Sustainable, Tropical Weathering, CFRP Plate-Concrete Bonded System, Construction industry

1.0 Introduction

Deterioration caused by mechanical loading and weathering has forced many reinforced concrete structures all over the world need to be repaired and maintained throughout their service life. In addition to that, sometimes there is a need to upgrade the load capacity of the structures due to some changes in the structure loading condition or design needs. In this respect the use of externally bonded metallic plates to strengthen and rehabilitate existing reinforced concrete structures have been in the construction industry for quite some time [1, 2]. The main concept of applying this technique is to strengthen and stiffen the stress-critical areas of such structural system. The wide acceptance of FRP externally bonded system as a new technique for strengthening application is based on production of high quality, reliability and durability of such materials bonding system combined with rapid handling and assembly at site. The state of the art of current composites materials and epoxy system has been successfully applied in most European countries and in the United States of America. This can be a good technological benchmark for the Malaysian authority to accept the technology but with certain precaution on the long-term durability aspects.

Compared to steel plate system, the FRP composites is lighter than steel and said to be immune to atmospheric and electro-chemical corrosion [3]. FRP composites is being seen as more cost-effective than steel due to ease of handling at site compared to steel. However, several aspects of structural implications and long-term bond characteristics and durability of the plate-adhesive and concrete-adhesive interface exposed to tropical environment with heavy rain and sunshine throughout the year is an important factor to determine the suitability of the FRP plate-bonded system to be used in this region. Researches on the short-term structural performance of reinforced concrete beams externally strengthened with FRP plate bonded system that have been conducted showed a significant improvement in the ultimate flexural capacity of the beams [4, 5, 6, 7]. It could be seen that the bond between adhesive-FRP plate and adhesive-concrete interface was of particular importance for the member to develop maximum flexural capacity and affected the long-term performance of the strengthened member [8, 9, 10, 11, 12]. Toutanji and Gomez [13] in their durability study of FRP composites bonded to concrete beams have shown that exposure to salt water and dry condition at 35°C under 90% humidity under wet/dry cycles have exhibited less improvement in terms of ratio of ultimate load for both exposed and control specimens. A similar study conducted by Chajes, *et al.* [14] on durability of concrete beams externally bonded with aramid, glass and carbon composites exposed to freeze/thaw and calcium chloride solution under wet/dry conditions showed that the effects of aggressive environments degraded the FRP externally bonded beam strength performances. The beams bonded with aramid and glass fibre system exhibited about 50% reduction of strength due to both exposure conditions. Experimental studies conducted by Karbhari and Zhao [15] have shown that the effect of exposure conditions to fresh water, salt water, freeze thaw and below freezing on externally bonded beams bonded of GFRP and CFRP composite-concrete interfaces was degradation due to moisture uptake. The flexural load test results indicated that the degradation occurred primarily at the interface level of FRP-concrete and FRP itself due to changes in composite stiffness caused by resin plasticization. They also discovered that the moisture absorption rate was high in exposure to fresh water compared to sea water. The environmental resistance of any bonded assembly of FRP system depends on the durability of the individual components materials, as well as on the bond between them [16]. One of the most important factors in bond durability is the environmental stability factor occurring at adhesive-adherend interfaces. The changes in the adhesive and the adherend mechanical or chemical properties, respectively, can be the factors that allowed for changes in adhesion properties. Therefore, bond surface conditions and pre-treatments often represent the key to enhancing the bond durability.

The substitution of FRP materials for steel in strengthening reinforced concrete members is motivated by the assurance of superior bond integrity. Mukhopadhyaya *et al.* [11] studied on GFRP-epoxy-concrete exposed to various selected aggressive conditions had discovered that aggressive environmental conditions such as wet and dry cycles and freeze/thaw did create further damage to the plate-concrete-adhesive interfaces. The specimens exposed to aggressive regimes showed higher dimensional changes and differential movement between the plate and concrete compared to the control specimens. They also found that the exposure regime had a distinct and strong influence on the nature of the bond transfer length. The exposure regime not only increased the length over which the force was transferred from the plate to the concrete, but also progressively increased the process of debonding at the stressed end.

1.1 Overview on Malaysia Weathering Conditions

Generally, Malaysia is a humid tropical country and its climate is characterised by maritime monsoon winds which produce a uniform temperature, high humidity and heavy rainfall. Winds are generally light. Located at the equatorial doldrums area, it is extremely rare to have a full day with completely clear sky even in periods of severe drought [17]. Like most of the world, Malaysia also cannot escaped from the global warming or "climatic changes" effects. This environmental threat can produce serious economic losses to the society in various sectors and the nation as a whole. Nowadays, the global warming issue has become among the hottest topic spoken in academic forums around the world. There are many factors identified as the cause of climate change, and can be categorised as local or global factors. Open burning (haze) is one of the global factors of which the effect is trans-border; while clearing land for agriculture that affects the ecosystem is an example of localised factor. In recent years, attention on climate change has been targeted at global warming effects of atmospheric concentration of the greenhouse gases (i.e. CO_2) which have increased markedly from about 280 to 379 ppm over the last 650,000 years and 180 to 300 ppm as a result of human activities since 1750. In the context of global warming, extreme weather and climate events including longer droughts and heavy floods have been observed over wider areas since the 1970's, particularly in the tropics and subtropics regions. Natural disasters such as floods and landslides are common in Malaysia, as well as in many countries in this region [18, 19].

As recorded data referred to Senai Meteorological Service Station [17], located in southern part of the State of Johor, Malaysia, from the year of 1975 to 2004, the temperature distribution is almost constant throughout the years. The mean temperature is at an average of 26.0ºC, with the highest temperature of 27.1ºC and lowest was at 25.3ºC as shown in Figure 1. Furthermore, the average mean maximum temperature was 31.8ºC with the highest and lowest temperatures were at 32.8ºC and 31.1ºC, respectively. In addition, the mean minimum temperature averaged about 22.6ºC where the highest was 23.6ºC and 21.7ºC was the lowest.

Meanwhile, the mean monthly relative humidity falls within 80 to 90% annually. On average, the annual mean relative humidity recorded from 1974 to 2004 was about 84.5 to 88.8% (Fig. 1). This averaged about 86.7% for the mentioned period. In general, Peninsular Malaysia receives rainfall with pH value between 4.8 and 5.2. The areas that experience high levels of acidity are located in and around the Klang Valley (Kuala Lumpur) and southern part of Johor state. Coincidently, these areas are the rapid growth centres with heavily industrialised as well as high population density. Based on the Wet Fallouts 1993-2004 data, the analysis of the results depicted several findings that could determine the trend of rainfall in Senai. From sixteen minerals contained in the rainfall there are seven main minerals that dominate the rain content in Senai as shown in Table 1. In addition, there is a slight increase in mineral rain contents which are manganese and lead. From the figure, it can be seen that the mineral rain content such as chloride, sodium, nitrate, potassium, ammonium and sulfate were recorded among the highest density increment since 1993. In terms of percentage increment, chloride was the highest mineral content recorded in year 2003 and year 2004, which was in the range of 2800 to 3000% increment compared to the average annual data from year 1993 to 2002. These followed by sodium and nitrate, which were about 2500 to 2700% and 800 to 1300%. The most probable factor of the large increment was the fast economic development in southern part of Johor since 1990's resulting in the increment of the number of motor vehicles on the roads that could be related to the increment of sulfur dioxide gas to the atmosphere.

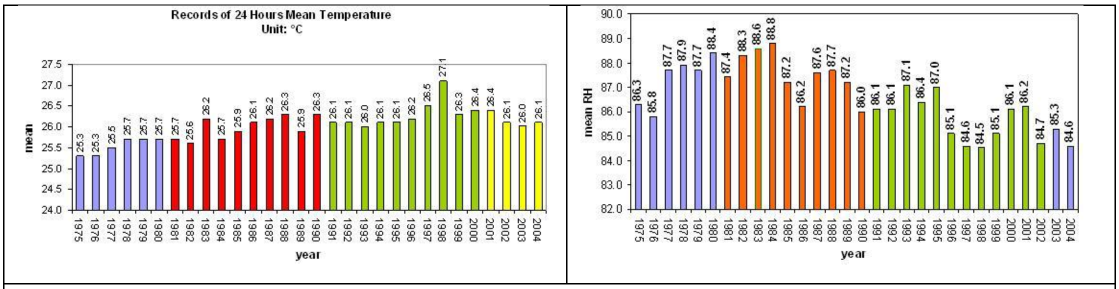

Fig. 1: Mean Temperature and annual mean relative humidity recorded from year 1975 to 2004 [17]

Table 1: The mineral rain content

Mineral/Density	Minimum 1993 to 2002 (mg/litre)	Maximum 1993 to 2002 (mg/litre)	Average 1993 to 2002 (mg/litre)	2003 (mg/litre)	Increment (%)	2004 (mg/litre)	Increment (%)
Sodium	0.2	1.02	0.435	12.08	2677	11.12	2456

Potassium	0.07	0.32	0.161	1.74	980.	2.26	1303
Ammonium	0.12	0.81	0.337	3.02	796	2.30	582
Calcium	0.14	0.47	0.235	4.65	1837	6.27	2512
Nitrate	0.14	0.51	0.275	4.10	1390	2.58	838
Sulfate	0.3	1.08	0.785	6.79	765	7.13	808
Cloride	0.37	0.75	0.539	16.71	3000	15.61	2796

1.3 Problem Background

Studies on the long-term performance of the FRP plate system, epoxy adhesive system and FRP plate bonded to concrete being exposed to tropical climate are very limited. A numbers of experiments have been conducted to investigate for short-term bond performances of Fibre Reinforced Polymer (FRP) plate-concrete system around the world but very little had focused on the study relating to the effect of combination of sustainable mechanical load and weathering conditions. World climate change caused by greenhouse effects is part of the objective of the study on bond properties of FRP composite to concrete under tropical climatic. Since the tropical climate experiences abundant rain and sunshine throughout the year, it would be essential to assess the long-term durability of the FRP plate-bonded system in this Southeast Asian region [20]. Therefore, the bond characteristics of CFRP plate-bonded to concrete prism using structure adhesive system exposed to tropical climate under sustainable pull-push load being is to be studied.

1.4 Research Objective

The aim of this research is to study the performance of adhesive bonding of the CFRP plate-concrete bonded system exposed to tropical climate environment. In addition, the research will provide data and results on the performance of CFRP plate bonded system under tropical environment in which at present there are very limited data available. The finding is vital and will be used as a reference in future studies and projects.

2.0 Laboratory Works

In this following sub-sections, the detail of specimen preparation prior being exposed to the designated conditions are described.

2.1 Specimen Configuration

The complete specimen configuration is shown in Fig. 2, which provides information regarding the specimen's geometry and location of strain gauges. The prepared specimen consisted of three main materials (i.e. CFRP plates, concrete prism and epoxy structural adhesive) to form a complete double-lap joint system that was designed to suit with the load test loading configuration.

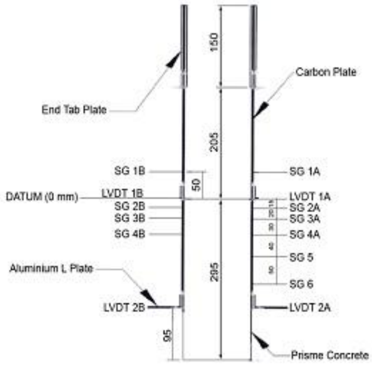

Fig. 2: CFRP plate-epoxy-concrete prism specimen

2.1.1 CFRP Plate

The CFRP plate, classified as Carbofibre type S (high strength), was supplied by Exchem EPC, United Kingdom [21]. There were two pieces of CFRP plates bonded to both sides of a concrete prism. The plate dimension was 1.5 mm thick by 50 mm width and 555 mm long. Their mechanical properties are shown in Table 2.

Table 2: Typical mechanical properties of CFRP Plate

	Tensile strength (MPa)	**Tensile modulus (GPa)**	**Longitudinal tensile strain at ultimate (με)**	**Transverse tensile strain at ultimate (με)**	**Poisson's ratio (υ)**	**Fibre volume (%)**
Manufacturer Data [35]	2,800	150	Na	na	na	70
Laboratory Test (*)	2,409	135	18,500	3,850	0.28	na

2.1.2 Concrete Prism

A batch of concrete prism with the dimension of 100 mm *x* 100 mm *x* 300 mm was produced using the maximum coarse aggregate size of 10 mm with water-cement ratio of 0.47. As a standard practice, the cast concrete cubes with the size of 100 mm *x* 100 mm *x* 100mm have undergone compression tests at the ages of 3,7, 28 and 60 days to evaluate the compressive strength characteristics. Table 3 shows the compression test results of concrete test cubes. The specimens were tested under compressive load at loading rate of 2 kN/s in accordance to BS 1881 Part 116 [22]. The means compressive strength at 28 days was 47.37 MPa.

Table 3: Concrete cube test data

Curing Period (days)	Specimen Weight (kg)	Crushing Load (kN)	Average Compressive Strength (MPa)
3	2.36	333	33.3
7	2.34	379	38.0
28	2.37	474	47.4
67	2.35	494	49.4

2.1.3 Epoxy Adhesive

The epoxy system under the brand name of Selfix Carbofibe Epoxy Adhesive is a two-part system consisting of a blend of modified epoxy resin and organic fillers, whilst the hardener is thixotropic formulated amine. The typical mechanical and physical properties of Selfix Carbofibe epoxy adhesive is shown in Table 4 [21].

Table 4: Typical mechanical and physical properties of Selfix Carbofibe epoxy adhesive

Property	Value
Compressive strength (MPa) aged of 7 days at 20 °C	90
Tensile strength (MPa)	23
Thermal expansion /°C	33×10^{-6}
Tensile modulus (GPa)	10
Shear modulus (GPa)	na
Single lap shear strength (MPa)	> 18
Glass transition temperature (DMTA) °C	> 65
Water absorption	0.4%

2.1.4 Bonding Process

The concrete prism bond surface was prepared by removing cement’s rich layer by using air tool hammer. The bonding process was done using a rig that was designed principally to control the bonding alignment, bond pressure and adhesive thickness. The rig was designed to maintain a 1 mm adhesive thickness which has not taken into account the adhesive that penetrated into concrete substrate bond surface. The bonded CFRP plate was left for curing on the fixture within 12 to 24 hours depending on the outdoor weather condition. The bonding process preparation is shown in Fig. 3(a) and 3(b). For bonding preparation, both adhesive materials (i.e. epoxy and hardener) were mixed in a plastic container using low speed electrical mixer. The mixing process was done in the laboratory control room where the temperature and relative humidity was in between 24 to 26°C and 40 to 55%, respectively. The temperature and relative humidity difference was due to outdoor weathering condition within a day.

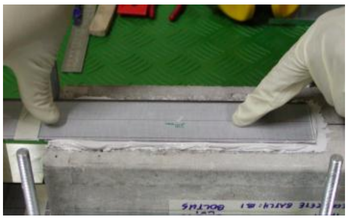

Fig. 3(a): Pressing the CFRP plate onto bond surface to remove excessive epoxy mixture.

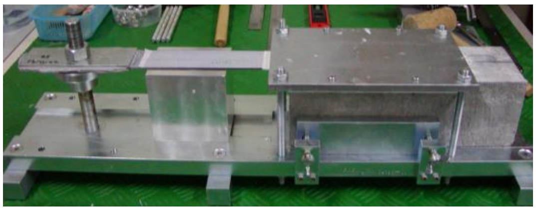

Fig. 3(b): Applying pressure onto the bond surface by mechanical rig.

2.1.5 Strain Gauge Installation

In order to determine the local load and local bond stress distribution along the specimen bond length, ten units of BFLA-2-5 electrical strain gauges brand TML with 2 mm gauge length and 120 Ω gauge resistances were used. A total of six pieces of strain gauges were installed on side A and on other four units on side B of CFRP plates, respectively (Fig. 2). The strain gauge was selected due to its compatibility with polymeric based composites materials [23].

2.2 Bond Load Test for Control Sample

There are three specimens classified control given name as BOLTUS have been tested in pull-push loading condition. The full description of the machine used is described in section 3.0. In principal, the test was carried out in the loading speed rate control mode, and the static load was applied monotonically until failure. The machine’s loading rate was set up at 1 mm/min to represent quasi-static loading mode to the test specimen. The load was applied up to 40 kN load, and at this stage the LVDT transducers were taken off before continuing the test up to failure. The CFRP plate strain and bond slip data were recorded at every 5 kN load level up to failure. Fig. 4(a) and 4(b) show the pull-out test rig used and during laboratory loading test, respectively. The recorded average strain from both sides of CFRP plates was analysed to determine the specimen bond stress characteristic.

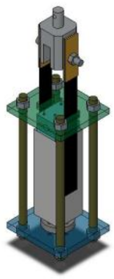	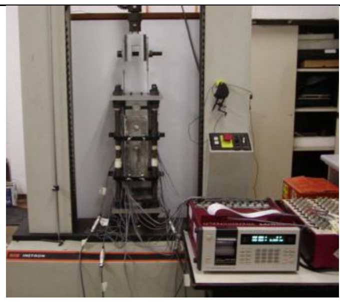
Fig. 4(a): Pull-out test rig for this study programme [24]	**Fig. 4(b): Bond load test for control BOSTUS specimen**

2.2.1 Results Analysis

The analysis on bond characteristics was done for this BOSTUS sample used as a reference to experimental exposure test results. In overall, it showed that the total applied failure load for BOSTUS specimens, namely; BOSTUS-C01, BOSTUS-C02 and BOSTUS-C03 was 63.44 kN, 55.27 kN and 61.74 kN, respectively. The best example in analysing the bond characteristics for BOSTUS group was by referring to BOSTUS-C03 specimen. Table 5 shows the summary of the important parameters used to describe the specimen bond characteristics at three most preferred load levels. From the table, it can be seen that BOSTUS-C01 and BOSTUS-C02 specimens represented a consistency bond stress characteristics at those three load levels compared to BOSTUS-C03. These three specimens experienced the same location of initial micro-cracking with the formation of three different final debonding locations. This could probably occur due to uneven and dissimilar concrete surface roughness that was formed during surface preparation (Fig. 5).

Table 5: Local peak bond stress and location from stressed end for BOSTUS specimens

Specimen	Plate Force 10 kN		Plate Force 20 kN		At Failure	
	Bond stress, τ (MPa)	Location from loaded end (mm)	Bond stress, τ (MPa)	Location from loaded end (mm)	Bond stress, τ (MPa)	Location from loaded end (mm)
BOSTUS-C01	8.57	15-35	12.40	15-35	7.09	35-65
BOSTUS-C02	10.38	15-35	11.81	15-35	9.82	15 - 35
BOSTUS-C03	4.38	15-35	7.95	15-35	5.75	65-105
Average	**7.78 (3.08)**		**10.72 (2.42)**		**7.55 (2.07)**	

Note: The value listed in the bracket represents the standard deviation

From observation made on the failure specimen, it could be seen that no epoxy adhesive remained on the concrete surface and it showed that the epoxy adhesive was much stronger than concrete under shear deformation. Finally, it could be said that the full debonding of CFRP plate-epoxy from epoxy-concrete interfaces was due to an excessive interfacial shear stress that developed at epoxy-concrete interface.

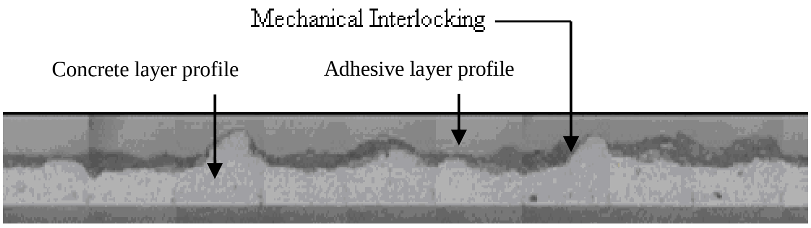

Fig. 5: Sharp profiles referred as mechanical interlocking formed at concrete-adhesive bond interfaces

2.2 Pre-Stressed for BOLTALS50

The BOLTALS50 specimens group (BOLTALS50-LB6M, BOLTALS50-OD6M AND BOLTALS50-12M) were stressed up to 40 to 50% of the ultimate bond failure load. The stressed limit load was referred to control sample group (BOSTUS). The pre-stressed was performed through a specially designed and built rig [25]. The specimen mechanical performances at the early stage is monitored through CFRP plate strains performances using data logger TDS-302 at every 15 minutes for the first 24 hours, followed by every 30 minutes for the next 48 hours and finally by every 24 hours for the duration of 45 days (Fig. 6).

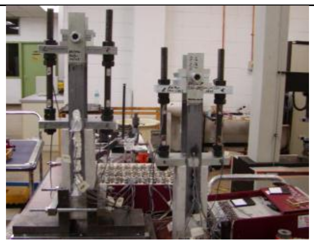

Fig. 6: Stressed BOLTALS50 specimens mechanical performances under observation

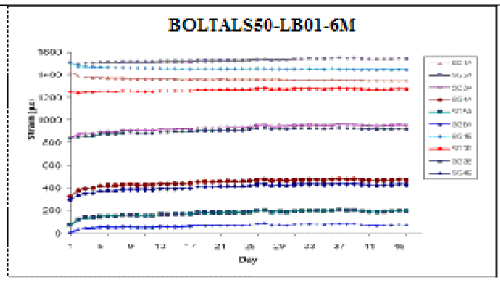

Fig. 7: Strain reading for BOLTALS50-LB01-6M specimen during 45 days observation

From Fig. 7, it can be observed that the readings of CFRP plates strain were almost constant throughout the observation periods, i.e. after reaching their full statics equilibrium. It can be seen that the strain readings were yet not stable within the two week time period after applying the sustained loads. The temperature and humidity parameters had not significantly affect the stressed conditions due to very small fluctuation of the overall strain readings during the periods. After that period, the specimens were brought to their respective designated exposure condition i.e. indoor (six month period) and outdoor condition for the periods of six and twelve months, respectively. The specimens were left in their designated conditions without any maintenance during that period.

2.3 Outdoor Durability Experiment Program

The test matrix of environmental durability exposure conditions designed for this study programme is given in Table 6.

Table 6: The experimentation durability programme

Sample Code	Exposure Condition	
	Laboratory	Outdoor
Control (unstressed) **BOSTUS**	3 specimens	
Exposure (stressed) **BOLTALS50-LB**	3 specimens	
Exposure (stressed) **BOLTALS50-OD**	6 specimens	Three (3) specimens for 6 months Three (3) specimens for 12 months (permanently stressed up to 40 to 50% of average bond failure load of BOSTUS group)

For the laboratory (LB) exposure condition, the sample was experiencing 75 to 90% relative humidity (RH) and 23 to 33°C of room temperature. The test specimen was placed on mild steel angle bars that were supported by mild steel rack and held in a vertical position (i.e. exposed to laboratory and outdoor condition as shown in Fig. 8 and Fig. 9).

Fig. 8: Part of the BOLTALS50 specimen under six6 month exposure to laboratory environment

Fig. 9: BOLTALS50 specimens under six and twelve month exposure to outdoor environment

3.0 Final Bond Load Test

After the completion of experimental period, all the specimens were inspected for their physical condition and the gauges conditions prior to testing (Fig. 10). The Instron Universal Testing Machine Series IX Model 4206 assisted with a specially built pull-out test rig (Fig. 4a) was used to create the loading shear mode within the materials system. The machine loading rate was controlled at 1mm/min to represent quasi-static loading mode. Four units of LVDT transducers brand TML with the sensitivity of 500 µ/mm and maximum displacement of 25 mm were installed at both parallel sides at the top (stressed end) and bottom (free end) of the test specimen. The instruments were used to measure a relative displacement or bond slips between the CFRP plates and concrete prism during loading. These LVDT instruments were released just after the applied total load reached 40 kN to avoid the instruments from being damaged at failure. The load then continued to the specimen up to failure. The CFRP plate strains and relative displacement were recorded at every 5 kN load increment through data logger type TDS-302. After the completion of experimental period, all the specimens were inspected for their physical condition and the gauges conditions prior to testing. Fig. 11 and Fig. 12 respectively show BOLTALS50 specimen that ready for final pull-out load test and final specimen condition just after bond failure, respectively.

		
Fig. 10: Sustainable-load ready to be released	Fig. 11: BOLTALS50 ready for pull-out test	Fig. 12: Specimen condition just after bond failure

4.0 Results and Discussion

In the following sections, the experimental results are discussed in three sub-topics that represent each main sample group (i.e. BOSTUS and BOLTALS50) involved in this study. The temperature, relative humidity, CFRP plate strain, concrete strain are also included in the respective sample discussion. At the end of the results and discussion, the summary of those two main groups of samples is established. The bond performances for BOLTALS50 group of specimens were evaluated, discussed and presented in the formed of graphs and tables. The summary of bond load test data for BOLTALS50 group of samples can be referred in Table 7.

Table 7: Important load test data for BOLTALS50 samples

Sample	Specimen	Applied total load (kN)
BOLTALS50-LB-	01-6M	52.59
	02-6M	54.93
	03-6M	61.21
	Average	**56.24**
BOLTALS50-OD	01-6M	67.49
	02-6M	59.7
	03-6M	61.82
	Average	**63.00**
BOLTALS50-OD	01-12M	57.45
	02-12M	85.26
	03-12M	64.8
	Average	69.17

4.1 Bond Force Transfer Length

In this discussion, the bond force transfer length at various load levels for BOLTALS50-LB-OD02-6M and BOLTALS50-OD02-6M will be discussed and BOSTUS-C03 was chosen as a reference (Fig. 13). From the plotted graphs, it can be seen that the load transfer from the CFRP plate to the concrete at low load was fairly linear and occurred at almost uniform rate. At this stage, the effective bond transfer length was quite short. However, when the applied load was further increased up to failure, it was noticed that the load transfer distribution became much more non-uniform and non-linear. From the graphs, it also can be seen that the effective force transfer length was constrained within the bond region of 65 to 105 mm at low load level and increased up to 155 mm at intermediate load level before slightly increasing to 200 mm of bond length near failure load level except for BOLTALS50-OD02-12M. The main factor that brought to the long effective force transfer length at low load level was the formation of cracking or debonding near the stressed ends of bond region affecting from the pre-stressed loading condition (Fig. 14). The effective bond transfer length was highly constrained within 155 mm of overall bond length at failure load. This probably showed no sign of exposure effect or influences on the permanently stressed specimen during experiment except for BOLTALS50-OD03-12M.

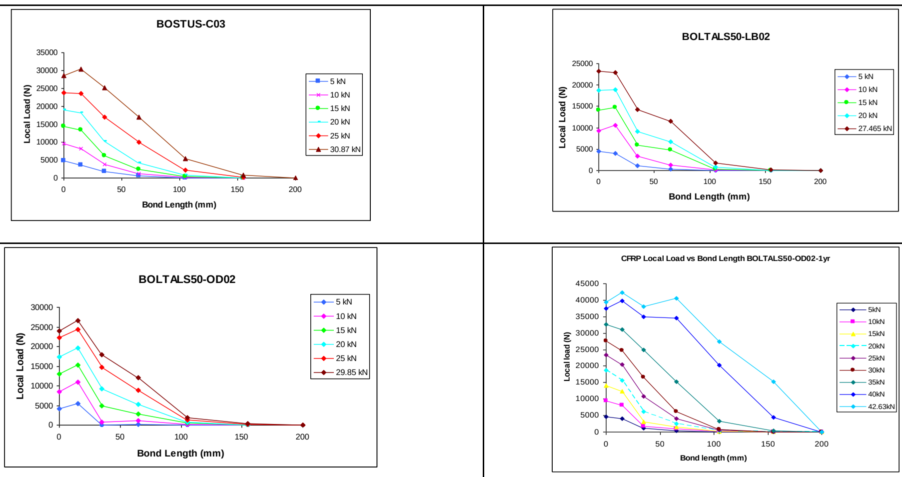

Fig. 13: Graphs of local load versus bond length for selected specimens

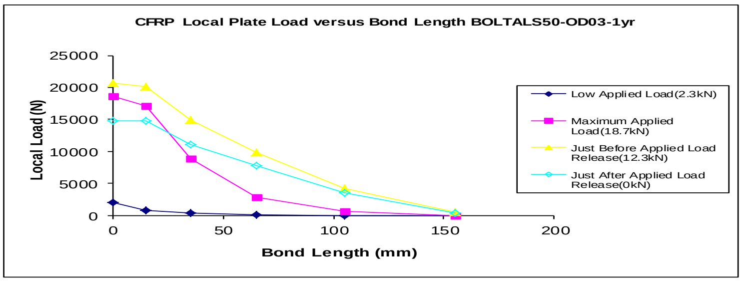

Fig. 14: Graphs of local load versus bond length for BOLTALS50-OD03-12M

4.2 Bond Stress Distribution Characteristics

From the histogram graph shown in Fig. 15, it can be seen that BOSTUS-C03 exhibits the maximum local bond stress of 4.38 MPa, 7.95 MPa and 5.75 MPa at 10 kN, 20 kN and near to failure load level, respectively. At near to failure load level, the local bond stress was seen to be uniformly distributed along the overall bond length. Compare to the group of BOLTALS50, at the 10 kN load level, the local bond stress distributions for the rest of the specimens showed almost the same characteristic of short bond transfer length and produced the maximum value of local bond stress near the stressed end region. Again, it could be seen that the maximum stress occurred at near the stressed end and decreased towards the free ends. Meanwhile, at the 20 kN load level, all the specimens showed almost uniform local bond stress distributions along the bond length. This indicated that a formation of bond integrity (or state of equilibrium) of CFRP plate-epoxy and epoxy-concrete interfaces had been reached. Finally, at the failure load level, it could be seen that the local bond stress distribution became much more non-uniform and non-linear for all the specimens. The local peak shear stress occurred at the 15 to 35 mm bond region and shifted to the adjacent region once the formation of interfaces bond failure had occurred. By referring to the analysed data listed in Table 8, it can be seen that the maximum local peak bond stress occurred at the same location, i.e. bond region of 15 to 35 mm for all BOLTALS50 specimens. Meanwhile, at 20 kN load level, it could be seen that the full bond development length was achieved which indicated the bond integrity between all the involved materials. Since BOLTALS50 specimens have been subjected to sustained load for the long-term duration, it might experience excessive tensile, shear and compressive deformation which could deteriorate the mechanical performances in combination with exposure conditions.

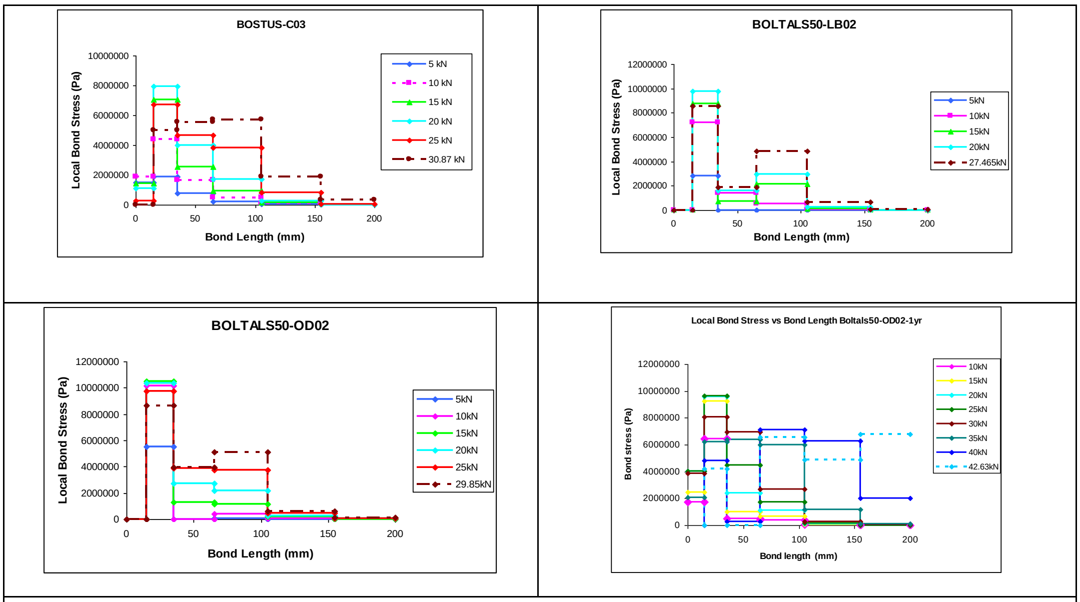

Fig. 15: Typical bond stress distributions for selected specimens

Table 8: Bond stress characteristics at three significant load levels for selected BOLTALS50 specimens

Specimen	Plate Force 10 kN		Plate Force 20 kN		At Failure	
	Bond stress (MPa)	**Location from loaded end (mm)**	**Bond stress (MPa)**	**Location from loaded end (mm)**	**Bond sress (MPa)**	**Location from loaded end (mm)**
BOSTUS-C03	4.38	15-35	7.95	15-35	5.75	65-105
BOLTALS50-LB02-6M	7.2	15-35	9.76	15-35	8.57	15-35
BOLTALS50-OD02-6M	10.17	15-35	10.34	15-35	8.67	15-35
BOLTALS50-OD02-12M	6.46	15-35	9.56	15-35	6.77	150-200

4.3 Failure Mode Analysis for BOLTALS50 Samples.

At the final load test, the most dramatic event was the occurrence of a brittle bond failure produced as shown in Fig. 16. The full specimen bond failure occurred for less than a second with a production of very loud sound that indicated the release of large fracture (strain) energy by the specimen. All the failure started with low up to high cracking sound before producing a complete debonding of the CFRP plate-epoxy from concrete prism. By visual inspection shown in Fig. 17, it could be seen that a thick layer of concrete remained adhered on the CFRP plate due to concrete shearing failure. This formation has covered on most of the highly stressed bond region. It also can be seen that the formation of yellowish effect that is highly suspected to be influenced through oxidation process. The figures also shows that there was an area at the ends bond region that experienced CFRP shear out that occurred on BOLTALS50-OD02-6M and BOLTALS50-OD-12M. This failure mode was suspected to be due to moisture absorption by CFRP plate around the unstressed region that weaken the bond interface between CFRP and epoxy adhesive layer.

The average time to failure could also provide a good indication in measuring durability level of specimen effect due to exposure condition (Table 9). In general, based on an average value, the BOLTALS50-OD sample show among the quickest average time to failure compared to BOSTUS sample. It was a good indication of the effect of outdoor exposure condition on the bond properties of the specimen through oxidation process which finally caused the materials system to become more brittle but for unstressed region could easily attacked by moisture which slowly reduced the CFRP plate stiffness in long-term service.

Table 9: Specimen average time to failure

Samples	Average Time to Failure (s)
BOSTUS	260 (C02:303.28sec)
BOLTALS50-LB-6M	240 (-7.7%) –(LB01:316.75sec)
BOLTALS50-OD-6M	210 (-19.2%)
BOLTALS50-OD-12M	236 (OD02:276sec)

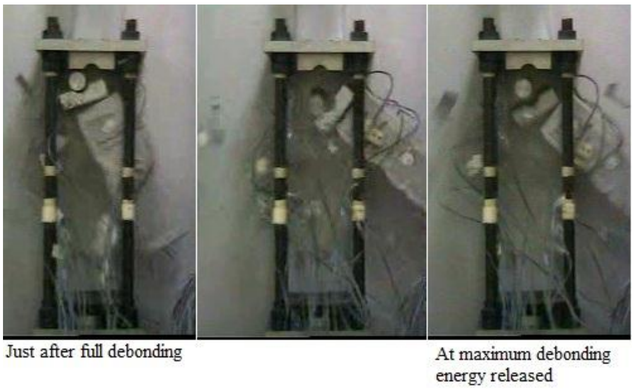

Fig. 16: The brittle failure of BOLTALS50 captured at ultimate load

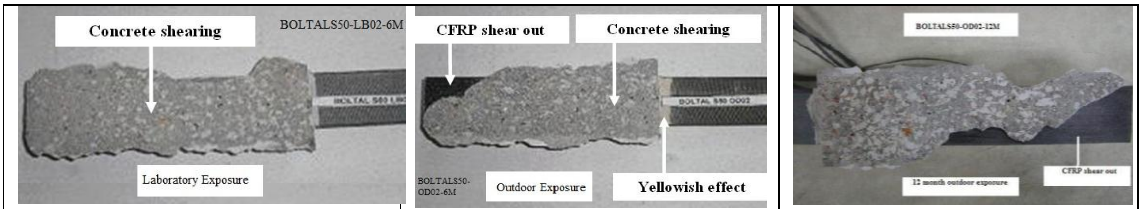

Fig. 17: Typical failure CFRP plate-adhesive surfaces of BOLTAL-S50

5.0 Conclusions

CFRP plate-bonded system is a relatively new technology in the construction industry even though the design concept is quite similar to the steel plate bonding system. Therefore, there are still many areas of material and structural implication arising from the use of CFRP plates-bonded system that are not yet clear and need further research especially in durability aspects. The environmental resistance of any bonded assembly of FRP system depends on the durability of the individual components materials, as well as on the bond between them. Adhesive bonded joints are generally attacked by exposure to moisture and elevated temperature. A small amount of moisture will induce plasticization of the adhesive in highly stressed regions and may actually be beneficial in reducing stress concentrations. However, a small reduction in joint strength should normally be anticipated in relation to the effects of environmental conditions on the adhesive itself. One of the most important factors that affect durability of bonding is the environmental stability factor occuring at adhesive-adherend interfaces. The changes in the adhesive and the adherend mechanical or chemical properties can be the factors that allowed for changes in adhesion properties. Therefore, bond surface conditions and pre-treatments often represent the key to enhancing the bond durability. In this experimental programme, specimens from two designated exposure conditions were loaded to failure under pull-out tests. As previously stated, the main objective was to investigate the effect of tropical exposure conditions on the bond stress distribution characteristics. The conclusions that can be made from the study are as follows;

i. The parameters of bond slips and time to failure have indicates the level of durability effect on the outdoor exposed for both samples. From the results, it showed that both parameters have indicated the influences of tropical climate on the specimen's bond performances.
ii. Both BOLTALS50 samples showed a significant difference of bond force distributions at near to failure load level probably influenced by their respective exposure conditions.
iii. From visual observation, it showed that the six and twelve month exposure period to outdoor condition produced some sign of bond degradation especially within the specimen bond unstressed region. This significant result could lead to the conclusion of the effect of outdoor tropical exposure conditions which rich of moisture along the year round.

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