CERTIFICATION OF APPROVAL

Experiment Investigation on Pull-Off Strength between Fiber Reinforced Polymer (FRP)-Concrete Interface under Marine Condition

By

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MASLAILY BINTI AHMAD FAUZI)

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ABSTRACT

For the past decades, extensive research and studies have been conducted on fiber reinforced polymer (FRP) composite which is widely practiced for strengthening structures. FRP materials has been chosen in retrofitting of existing structures because FRP has higher strength-to-weight ratio and provides additional corrosion resistance, in comparing to conventional repair material such as steel. For this research purpose, concrete beams and slabs have been strengthened with carbon FRP to study the effect on marine environmental condition particularly in continuous immersion and wet-dry cyclic using salt water on the performance on the interfacial bond between FRP and concrete (substrate). However, due to debonding behaviour in long term performance and environment deterioration, the strengthening systems are remained largely uncertain and unanswered. The direct tension pull-off test has gained popularity as a test method used in the laboratory as well as in the field including at construction site or during inspection, in assessing the quality of bond between externally bonded fiber-reinforced polymer (FRP) repair materials.

For this research purpose, a long-term durability study was conducted in the laboratory vis-à-vis to evaluate the behavior of the bond between the repairing material which is FRP and the substrate; concrete. Small concrete specimens, with no reinforcement bars have been prepared, externally reinforced with FRP material, and subjected to various environmental scenarios stimulated in laboratory which are wet-dry cycles as well as constant and continuous immersion in salt water. Direct tension pull-off tests and three-point flexural tests have been conducted on these specimens to determine degradation in bond strength over ageing time.

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Last but not least I would like to dedicate this work to my Mother and Father who are by my side from the beginning of my journey at Universiti Teknologi PETRONAS for the supporting and encouragement.

1 INTRODUCTION

Concrete structures in a marine environment are exposed to chemical deterioration process that may affect by sea water constituents and physical erosion due to wave action. Since long time ago, it has been realized that moisture affect the mechanical properties of FRP. In small test specimens, it is simple to determine moisture content and diffusion constants by drying the specimen, weight it and monitor the weight as a function of moisture absorption. The moisture profile can be calculated by using Fick's diffusion laws. For a real structure however, there is a need to be able to measure, non-destructively, the moisture content.

This final year project paper is intended to provide the experimental results in the study area of the interfacial bond between the fiber and the concrete under the effects of harsh conditions such as in marine environment. Fiber-reinforced polymer composites have well-known to their excellent properties such as high tensile strength and stiffness, light weight and resistance to corrosion.

1.1 FIBER REINFORCED POLYMER

FRP is a composite material made of a polymer matrix reinforced with fibers. The fibers can be made of glass, carbon, steel and other materials [1]. Carbon is commonly used for externally bonded applications which have a wide range in sport equipment aerospace and automobiles industries. FRP is applied in rehabilitation of existing concrete structure surfaces by means of epoxy adhesion and provide tensile strength to the structural member. However, the procedures in applications of FRP should be carefully followed including appropriate adhesion of the FRP onto the concrete surface. According to Carillo (2012) [2], he described where in most cases in applying FRP for strengthening an existing structure, the FRP-concrete bond is very essential. He explained on the bond is needed for proper transfer of stresses among interfaces. The most major concern in FRP reinforcement is due to the deterioration of the FRP material over time and its long term bonding performance especially under marine environment.

1.2 PROBLEM STATEMENT

The current condition on RC bridges and jetties in the coastal line of Malaysia shore is very low due to limited funds available in maintenance such as rehabilitant the aging infrastructure. Hence, FRP which has been widely known to its non-corrosive nature, is been used as one of the solutions. It is worth noting that, the interlocking mechanism of FRP-concrete is crucial to transfer stresses properly among the interbonding surfaces.

After observing throughout this final year project, according to previous studies that have been conducted extensively by other researches, most of them solely focused on the bond characteristics between CFRP and concrete when subjected to cycling loading [3], flexural strengthening slab-column connection [4] and durability [5] whilst less attention had been given to the effect of environmental exposure to concrete structures and retrofitting the existing ones. Due to the lack of research in pull-off strength and bond strength between FRP-concrete interfaces, the author finds it is very essential to have solid and firm groundwork and achievable objectives for the research project.

1.3 RESEARCH OBJECTIVES

For deeper understanding of FRP in strengthening concrete members, its long-term behaviour must be further identified when exposed to various environments. Therefore, three objectives are targeted in this project:

1.3.1 To conduct an experiment evaluation on pull-off strength between FRP and concrete surface under the condition of marine environment

1.3.2 To perform a feasibility study in the laboratory to characterize the potential deterioration of a FRP-concrete bonding under marine environment

1.3.3 To investigate the bond strength and interfacial bond behavior of CFRP-concrete under marine environment

1.4 METHOD AND APPROACH

Pull-off tests are chosen as the main test method for this project, hence a thorough study vis-à-vis to this method must be taken into consideration. A literature review on previous researches involving pull-off tests has been conducted and their results are analysed. Special observations regarding the interpretation of these results are further discussed, as well as the limitations of this test method and its suitability for application in the laboratory.

However, the three-point flexural test has been conducted to evaluate the long term strength and interfacial bond behavior of CFRP-concrete under marine environment.

1.5 ORGANIZATION OF PROJECT

Generally, this dissertation is divided into five main chapters. Following the Introduction in Chapter 1, Chapter 2 contains a literature review of FRP studies that have been completed in the previous and the different test procedures which the former researchers have used to assess the FRP-concrete bond. Chapter 3 is focused on the Methodology and the study approach in the project. It comprises the descriptions on the marine environmental condition in the laboratory, the details of the specimens, pull-off tests procedure and FRP sheets installation. In addition, this chapter describes the environmental scenarios chosen for the long term study, as well as the testing procedures and discussion of results from direct tension pull-off tests. On top of that, the three-point flexural tests are conducted to estimate the interfacial bond strength of concrete beams and strain gauges are installed to measure the strain distribution over the length of CFRP. Chapter 4 contains the results and discussions based on the laboratory works. This chapter analyses the pull-off test method as a method to collect bonding data. Finally, conclusion and further recommendations are given based on the findings from the results and the analysis based on this research.

2 LITERATURE REVIEW

This paper presents and analyses the results of an experimental research program in conducting a test to identify the pull-off strength of Carbon Fiber Reinforced Concrete (CFRP) and concrete interfaces under marine environment for FYP 1 and FYP 2. This test method requires determining the force required to extract a coating from hardened concrete. Results of this method will provide an actual measurement of in-place strength and can be beneficial for construction. In addition, this study is conducted to further understand the property changes in bond strength and its debonding mechanisms with respect to variable environmental conditions such as the heat and moisture.

Degradation of bond strength is quantified by the tri-layer fracture toughness such as shows in Figure 1 [6]. Concrete/FRP bond joints, such as those in FRP-strengthened concrete structural members, can be simplified as a three-layered system consisting of concrete, epoxy and FRP. In [6] the authors added that, crack can propagate in five regions – bulk concrete, FRP sheet, bulk epoxy, the interface between concrete and epoxy and interface between epoxy and FRP. To top that, the influence of the loading rate on the pull-off strength is also analysed. Moreover, this paper is concerned with the suitability of pull-off tests in laboratory field and how the results from the tests can be interpreted in the long run.

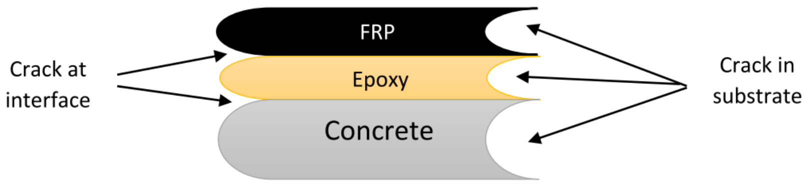


Figure 1 A three-layered system consisting of FRP, epoxy and concrete

2.1 ENVIRONMENTAL CONDITION

An extensive study should be carried out which involves the exposure of FRP and concrete to the effects of moisture, for example constant immersion in water or other kinds of solutions such as salt water in order to stimulate the marine environmental condition. Wet-dry cycles have been considered by several studies to evaluate the effects of wet dry cycling on the interfacial bond performance. [5]

Soudki et al. conducted an investigation about the durability of concrete beams reinforced with CFRP material, after being exposed to a corrosive environment in the number of cycles which were 0, 100, 200 and 300 cycles [7]. Inspection of the beams after the test was run, showed that a premature de-bonding failure which started at the end of FRP sheets and propagated towards the entire length of the reinforcement. Towards the end of study [7], it was observed that the beams which exposed to wet-dry cycles, the load capacities decreased rapidly as soon as the bonding was observed. On the top of that, the number of wet-dry cycles had affected the degradation of bond strength. To be specific, the specimens strengthened with FRP strips, that were exposed to 100, 200 and 300 cycles experienced a decrease in strength of 2, 6 and 11% respectively.

One additional study involving exposure to sodium chloride includes the work done by Pan et. al. in order to perform the effect of chloride content on the behavior of bond between concrete and FRP [8]. A total number of fourteen concrete blocks were reinforced with two layers of FRP and were fully immersed in chloride solution to ensure that the concrete-FRP interface was eroded [8]. Four solutions with 3%, 6%, 10%, and 15% of sodium chloride concentration were used. Corresponding to the test, all specimens showed a debonding failure, mainly due to the deterioration of the epoxy adhesive when exposed to the chloride.

2.2 PULL OFF TEST

The standard for pull off tests before 2009 that has been used as a guidance; was American Society of Testing and Materials (ASTM) (2009b) D4541. Initially, this standard was created as a test method for the pull off strength of coatings. With the increase in popularity of this specific test application, ASTM Standard D7234 is used to measure the adhesion strength between a coating (FRP) and a substrate (concrete). This pull off test determines the greatest tension force (applied perpendicular to the bond) that the bond can withstand. Figure 2 illustrates a pull-off test scenario.

According to ASTM Standard D7234, this test method covers procedures for evaluating the pull-off adhesion strength of a coating on concrete. The test determines the greatest perpendicular force (in tension) that a surface area can bear before a plug of material is detached. Failure occurs along the weakest plane within the system comprised of the test fixture, adhesive, coating system, and substrate, and to be exposed by the fracture surface.

Referring to Figure 2, the maximum pull force recorded during each pull off test is used to calculate the pull off bond strength (MPa). It is simply deduced by dividing the failure load (N) by the cross sectional area of the dolly (mm^2), as shown in Equation (1), where σ_p = pull off strength; F_p = maximum pull-off force; and D = diameter of the dolly (puck)

$$\sigma_p = \frac{4F_p}{\pi D^2} \qquad (1)$$

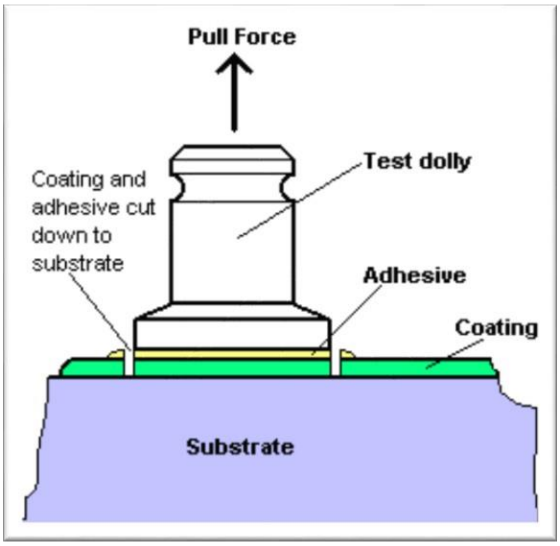


Figure 2 Pull Off Test (Courtesy by DFD Instruments)

On this research, the pull off testing is used to verify bond strengths for fiber reinforced polymer (FRP) which is externally applied to strengthen the concrete or the substrate.

In the previous studies on direct tension pull-off tests conducted in the laboratory, Karbhari and Ghosh used pull off tests to study on the long term bond durability of different types of CFRP adhered to concrete under various environmental conditions at such immersion in salt water and different humidity levels. This paper presented results from a two year study of effects of environmental exposure on durability of bond strength between different commercially available strengthening systems and concrete.[9] Karbhari et al explained that while conditions of continuous immersion of the entire system could be considered as a severe, and hence indicated significant deterioration in bond strength showing over 40% loss in pull-off strength over the two year period of investigation.

2.2.1 ADVANTAGES OF PULL OFF TEST

The pull off test is based on the concept that the tensile strength of a layer of surface concrete can be related to the compressive strength of the concrete. From the recorded tensile force obtained in the pull off instrument test, a nominal tensile strength is calculated on the basis of the disc diameter (50mm). [10].

The main advantage of the pull off test is that, it is simple and quick to conduct. The entire procedure of preparing the surface and applying the metal disc with adhesive should not take more than 15 minutes. However, the adhesive/ bonding is let for curing at least up to certain standard period; within 48 hours.

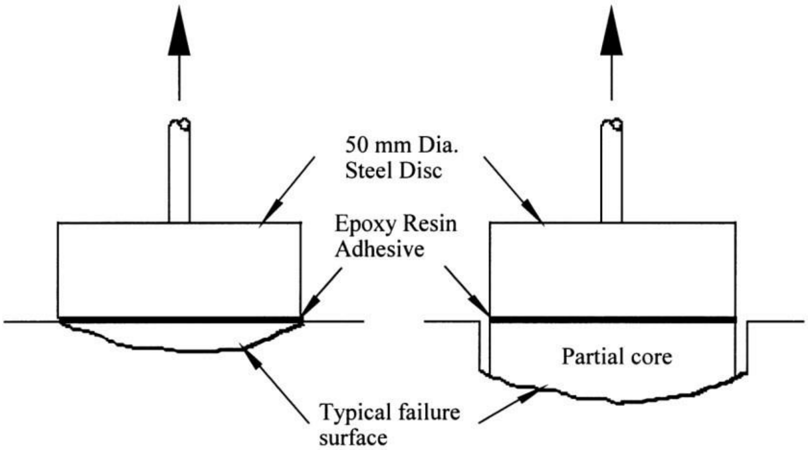


Figure 3 Schematic diagram showing the procedures used to complete [10]

Another advantage is that the damage caused to the substrate/ concrete surface after a test is not unduly severe. As mentioning earlier, the main limitation of this method the rather long curing time required for most adhesives. When comparing to other tests, pull off test is the simplest in tensile bonding test. Referring to Figure 3 above, to evaluate the adhesion strength of an adhesive material that bonds a concrete overlay to an existing concrete substrate, the pull off test with a partial coring technique is usual.

2.2.2 MODE OF FAILURE

Following completion of the test, different failure characteristics may be witnessed at the bond surfaces. BS EN 1542 classifies these failure modes into three types, labelled from Type A, Type B, and Type A/B. Pull-off strength is measured and failure mode is registered: A – in the repair material, A/B – at interface and B – in the concrete substrate. Figure 5 shows the interfaces which these three failure modes represent. However, the image is not to scale. The adhesive and FRP layers have been magnified for clarity. [11]

Looking to the type of failure in Figure 4 (Type B), an effect of microcracking is clearly visible where the failure happened in the superficial zone of substrate. For polishing, all failures appeared at the interface (type A/B, Figure 4), probably due to insufficient mechanical interlocking between substrate and repair layer and lower effective surface of contact.

TYPE B TYPE A/B

Figure 4 Failure Mode based on EN 1542

Generally, a failure mode type B is desirable as it means that the bond between the substrate and repair material is so good that it surpasses the strength of the origin material. However, it is important to analyze the failure mode together with the value of bond strength.

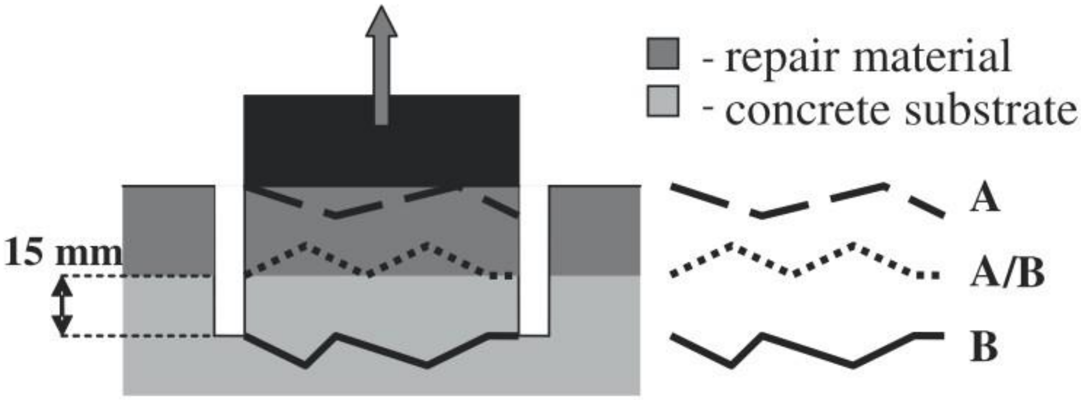


Figure 5 Pull-off test failure modes. (NOT TO SCALE) [11]

2.3 BOND STRENGTH

Ouyang & Wan [12] found that:

> *"Adsorption theory and mechanical interlocking theory have been widely applied to study the adhesion phenomena of liquids onto solids, such as the adhesion between primer and concrete. The adsorption force normally is Van de Waals force, which bonds adhesive and concrete together. When adhesive is applied on concrete surface, the penetrated adhesive will provide mechanical interlocking resistance after it is cured. Such interlocking resistance, which consists of mechanical contact and friction force, combines the cohesive strength of both adhesive and concrete to form an interface that acts as a composite material. Moisture at the bond interface can decrease the free surface energy and the adhesion strength of the epoxy/concrete bond interface. The accumulation of moisture at the bond interface region will also induce vapor and osmotic pressure, which may cause local debonding. In addition, the absorption of moisture might degrade the mechanical properties of the adhesive. The decrease of mechanical properties might lower the effect of the interlocking mechanism, which is one of the primary mechanisms for the bond between FRP and concrete." (p. 425)*

In this study, concrete specimens with Carbon FRP sheets under accelerated aging test by immersion in salt/sea water at elevated temperature have been investigated. Pull-off loading tests have been carried out and the degradation behaviour of strengthening of concrete by the FRP sheet under marine environment have been also discussed.

Despite of FRP that is low in cost, this repair method has not yet been widely practised due to the fact that the lack of knowledge on the long term behaviour and their bonding between FRP and concrete themselves [1]. In addition, premature debonding is likely to occur, if it is poorly reinforced with FRP. To top that, such failure is caused by environmental condition which may significantly lead to deterioration and affect the bond performance over time. Hence, a sound bond of FRP-concrete is very important to assure high strengthening performance.

One of the many researcher group [12] has investigated on the mechanical properties of epoxy changed with respect to the moisture uptake in test specimens after a period of immersion in water.

2.3.1 MECHANISM OF DETERIORATION FOR REINFORCED CONCRETE

According to Long et al. [10] in their paper, the mechanisms of deterioration and their rate are controlled by the environment and the fracture strength of the concrete. They added, environmental factors such as seasonal temperature variations, rainfall and relative humidity changes, and water in contact with the concrete are the main causes of degradation.

Moisture is continuously transported in the state of vapour and liquid, from the surrounding environment or the internal body of the concrete if the surface is relatively dry. Concrete is inherently weak in tension, hence, its fracture strength is one of the most important factors vis-à-vis to the rate of deterioration.

3 METHODOLOGY

3.1 ENVIRONMENTAL CONDITION

To stimulate the marine environmental condition such as a hundred percent humidity, salt water solution and alkalinity, three stainless steel tanks are designed and fabricated with a dimension of 2.5 m long, 1.5 m wide and 1.5 m height (Figure 6). In monitoring the water temperature inside the tank, two water heaters and thermocouples are installed in each tank to increase the water temperature up to 60°C as per ASTM standards.

The specimens are to be removed from tanks after 3, and 6 months during wet-dry cycles where the system loops between 3 days of fully-immersion in salt water and 3 days dry in the room temperature. In order to circulate the water, two pumps are installed for the first and the second tanks. However, the third tank is used for continuous condition of immersion in salt water.

Figure 6 Specimens in Water Tank during Dry-Cyclic

3.1.1 AGING CONDITIONS

All FRP-strengthened concrete slabs and beams are exposed to saturated humidity and 3.5% salinity in water tanks, at a temperature of 60°C, to develop a model to identify the concrete-FRP bonding strength which are under the harsh environment exposure.

By using three fabricated stainless steel tanks, the specimens are placed inside the respective tank. The specimens are separated apart with 100 mm x 100 mm and 150 mm x 150 mm concrete blocks to ensure all the specimens have adequate soaking.

Each tank has two water heaters to increase 3.5% salt water temperature up to 60°C as per ASTM standards. In order to keep the circulation of the water, two pumps are installed.

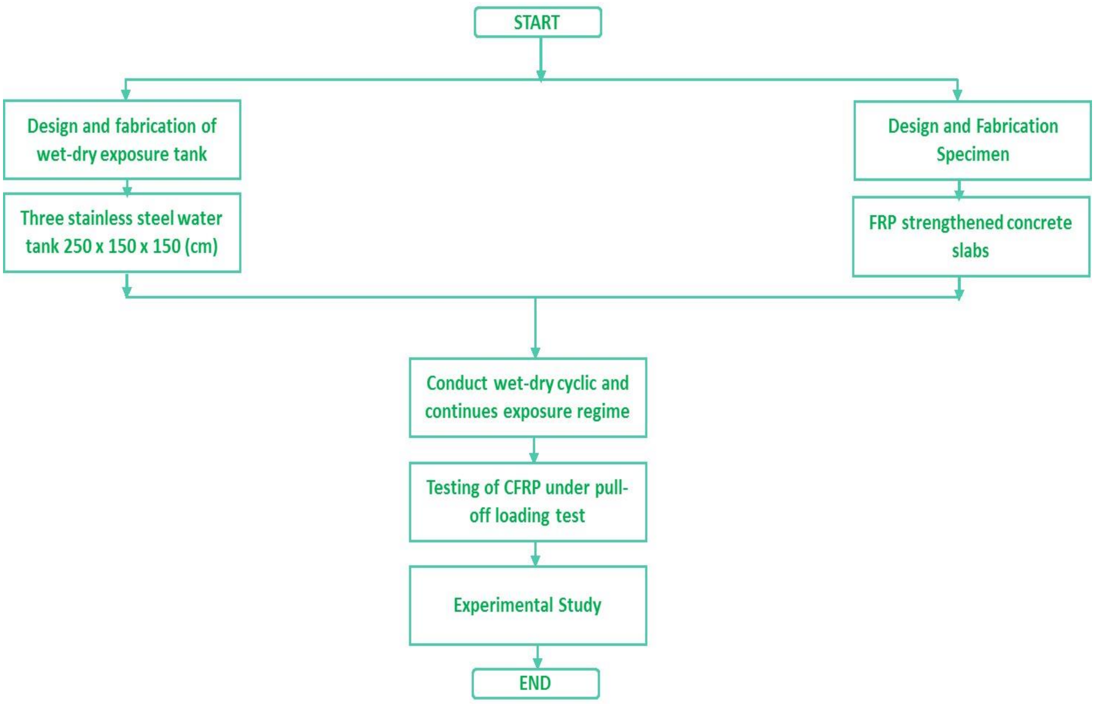


Figure 7 Flow Diagram on Environment Condition Procedure

Figure 7 above summarises that the design and fabrication of water tanks and specimens are conducted simultaneously.

3.2 PULL-OFF TESTS

This test is to determine the greatest tension force (applied perpendicularly to the bond) that the FRP-concrete bond can withstand before the weakest plane starts to fail. The method consists of adhesively bonding a metallic circular loading fixture, also referring to a dolly or puck, to the surface that is being tested. The dolly contains a threaded hole in the centre that allows for attachment of the fixed alignment adhesion testing device.

Referring to Table 3-1, five concrete slabs are casted with concrete grade 35 and strengthened with CFRP in two groups and two cycles. Two slabs are placed in the first tank under wet-dry cycles for 3 and 6 months. Meanwhile, the second tank with another 2 slabs expose to continuous environmental condition in corrosive salt water and one specimen is a control specimen. All these slabs will be used for pull-off test to evaluate the adhesion bond strength between FRP and concrete interfaces. The test cannot be classified as non-destructive, but due to its relatively small scale, surface repairs are minimal. [2]

Table 3-1 Details of Pull-Off Test Program

Slab No	L (mm)	W (mm)	H (mm)	Wrap Scheme	Distribution	Environmental Condition		
						Type	Duration (months)	Cycles
SL1	300	300	50	EXTERNALLY	C	CYCLIC	3	12
SL2						CYCLIC	6	24
SL3						FULL	3	-
SL4						FULL	6	-
SL5				-	-	ROOM	28 DAYS	NA

Figure 8 Proceq® DY-225, an Automated Pull-Off

Figure 9 Measuring the Adhesive Strength of Applied Coatings

3.2.1 TESTING METHODS

Adhesive bond characterizations are conducted at room temperature by pull-off loading tests according to ASTM D 4541. A partial core has been first drilled around the test zone (Fig 10-a), with an approximate depth of 4mm within the concrete substrate. A cylindrical steel body of diameter 50mm is the glued to the test zone using epoxy adhesive (Fig 10-b). The circular hole cutter is purposely bored to isolate the area being tested from the rest of the surface.

All specimens are kept at room temperature for 24 hours before the beginning of the pull-off loading test, to allow polymerization of epoxy adhesive. Finally, a tensile loading is applied to the steel body by mean of Proceq DY-2 device, until debonding occurred where the weakest plane has failed.

(a) (b) (c)

Figure 10 Concrete slabs strengthen by FRP and followed by pull-off tests

3.3 3-POINT FLEXURAL TEST

The 3-point bending tests represent the second FRP-concrete bond test method selected for this study. In relation to pull-off strength tests, bending tests provide more realistic behavior of the FRP concrete bond when subject to flexural loads.

The specimens for the test are prepared in 5 concrete beams, to evaluate the interfacial bond strength as per table below. The concrete specimens are to be cut at midspan until half the height of the beam to create an initial bending crack. No reinforcement bars are installed and each beam is 750mm long with a 150x150mm square cross section. CFRP strip is installed to the grind soffit of the beam. Most importantly, the total number of 10 strain gauges, which mainly to measure the strain distribution over the length of the CFRP, have been applied on the CFRP laminate (Figure 11). However, steel clamps are installed to one side of the beam, to make sure the debonding occurs at the other side, as well to reduce the number of strain gauges that need to be used.

Table 3-2 Details of bending-type shear test program

				ENVIRONMENTAL CONDITION		
SLAB	L (mm)	W (mm)	H (mm)	TYPE	DURATION (MONTHS)	CYCLES
CTRL	750	150	150	ROOM	28 DAYS	NA
CYC3				CYCLIC	3	12
CYC3				CYCLIC	6	24
FULL3				FULL	3	-
FULL6				FULL	6	-

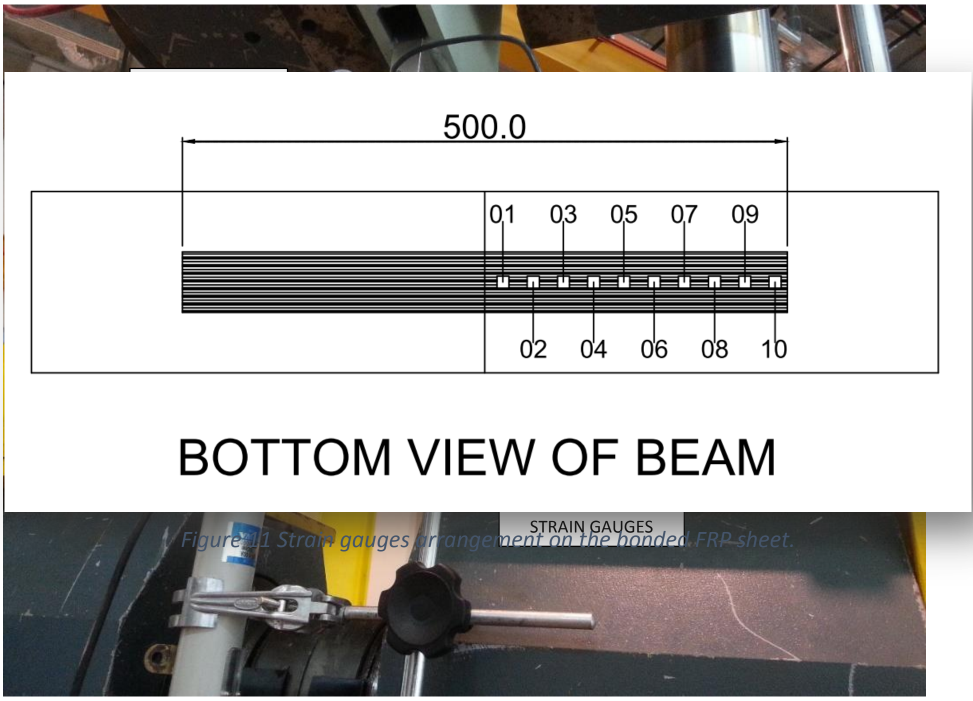


Figure 11 Strain gauges arrangement on the bonded FRP sheet.

Figure 12 Setting on Bending Shear Bond Test

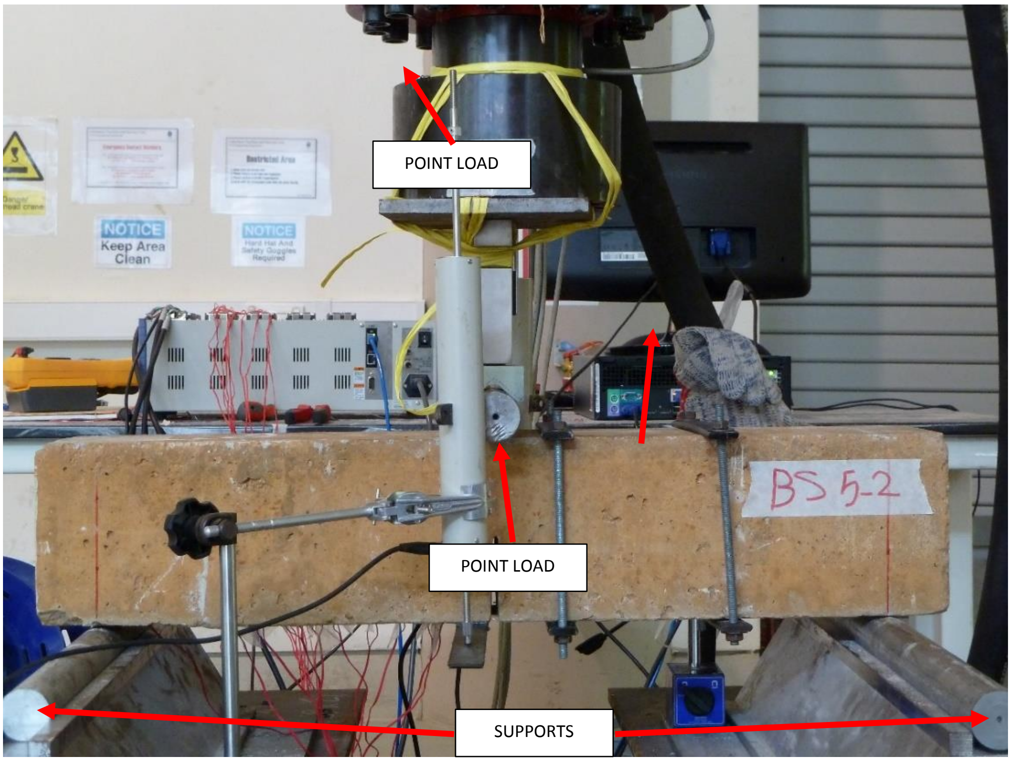


Figure 13 Setting on Bending Shear Bond Test (Front View)

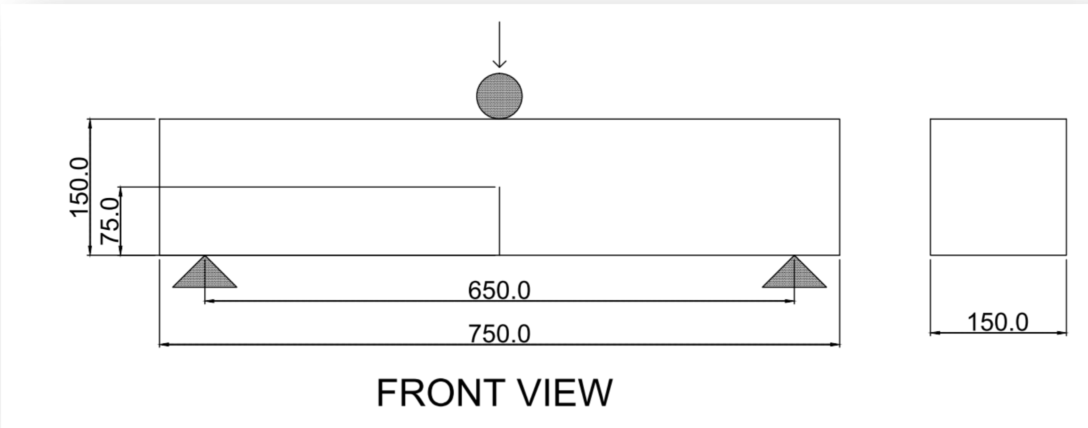


Figure 14

Figure 15 CFRP installed with strain gauges, debonded from substrate

3.4 FRP FABRICS INSTALLATION

Carbon fiber reinforced polymer (CFRP) fabrics SikaWrap-231C sheets will be bonded to the specimens as per instructions provided by the manufacturer; Sika, Malaysia. The concrete surface of the specimen will be grinded by masonry-grinding and hand-grinder to remove irregularities. To fill the voids and low spots on the surfaces; saturating epoxy is used. The mechanical properties of the carbon fibers and composite CFRP sheets are tabulated in Table 3-3[a]

Table 3-3 Mechanical Properties of Carbon Fibres and Composite Sheets

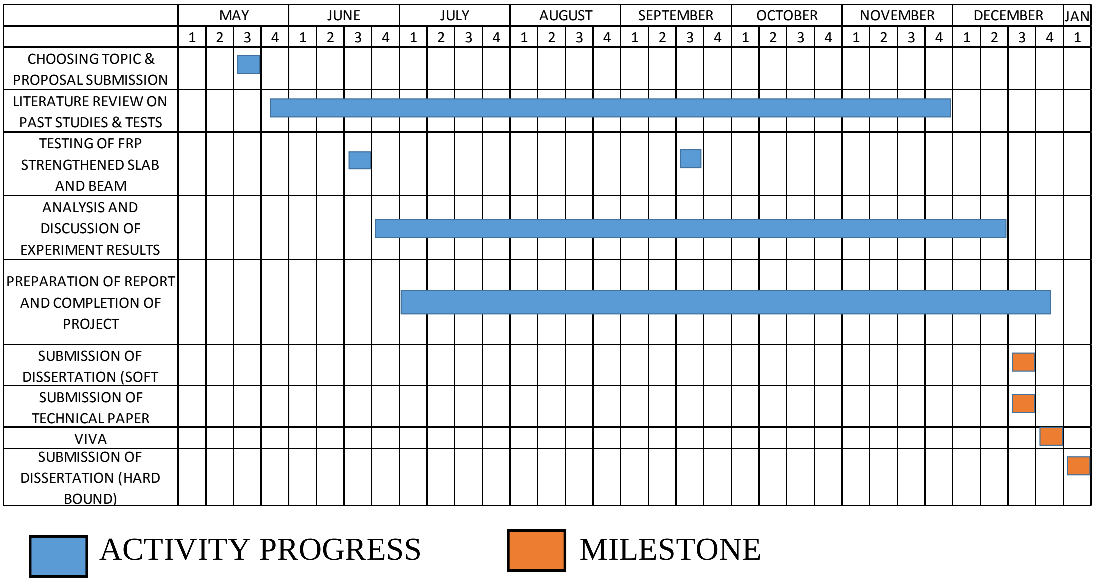
	CARBON FIBER PROPERTIES (DRY FIBERS)			COMPOSITE SHEETS PROPERTIES (FIBER+RESIN)		
TYPE	Thickness (mm)	Tensile Strength (MPa)	Modulus Of Elasticity	Ultimate Strength/1m width (kN/m)	Modulus Of Elasticity (GPa)	Elongation at break (%)
SIKA WRAP-231C	0.127	4900	230	420	25	2.1

[a]Obtained from the manufacturers' technical data sheets

3.5 PROJECT SCHEDULE

To keep track on the progress of the work programme, the schedule has been prepared to provide a visual timeline for starting and finishing specific task. Table 3-4 below shows the timelines for the Final Year Project.

Table 3-4 PROJECT TIMELINE



4 RESULTS AND DISCUSSIONS

4.1 PULL OFF TEST

For the first aging process of 3 months, a set of data was tabulated to evaluate on the pull off strength of bonding between concrete and FRP under marine environmental exposure stimulated in laboratory. A total of 3 slabs with dimensions of 300 x 300 x 50 mm where one of the side is externally reinforced with FRP sheets with adhesives whilst the other side is non-strengthened with FRP. All the data tabulated in the tables in Section 4.1.1 and 4.1.2 below are the specimens that have been exposed to environmental conditions for 3 months on continuous and cyclic conditions.

Table 4-1

	CFRP STRENGTHENING	NON-STRENGTHENING
CONTROL CONCRETE SLAB	A1	A2
CYCLIC 3-MONTH CONCRETE SLAB	B1	B2
CONTINUOS 3-MONTH CONCRETE SLAB	C1	C2

4.1.1 CONTROL SPECIMEN

For control purposes, one specimen with a total of 18 pull off tests was conducted, which the specimen have been not exposed to any conditioning (kept in dry conditions at room temperature). The test results are summarized from this stage are provided in Table 4-2.

Table 4-2

ID	Test Disc Ø (mm)	Average (kN)	Pull Off Strength (MPa)
A1	50	6.71	3.418
A2	50	5.43	2.766

Results from these tests are shown in Figures 16, 17 and 18 which show pull-off strength variation.

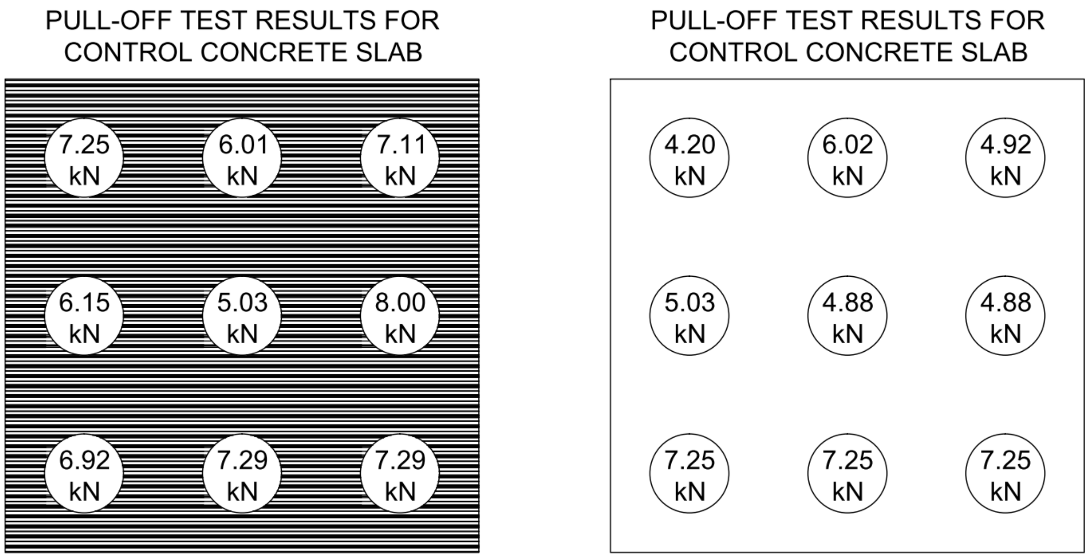
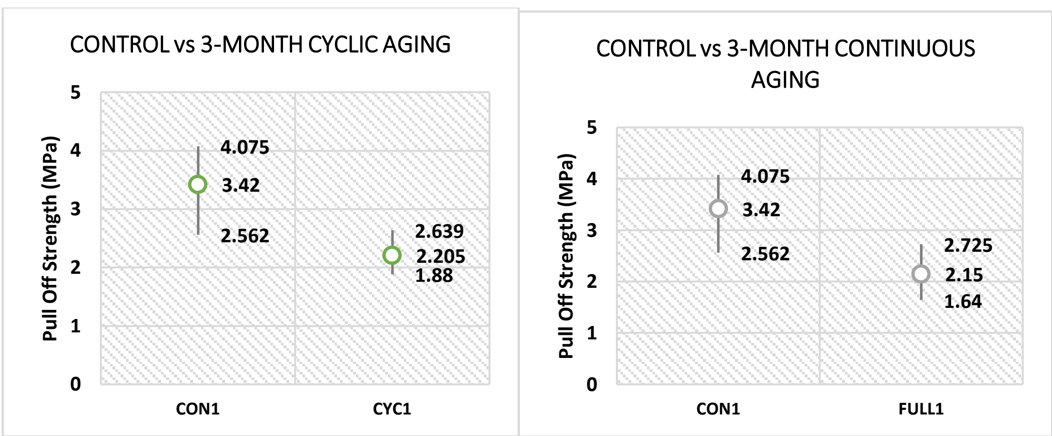


Figure 16 Pull off test results on FRP-strengthened slab (right) and non-strengthening slab

Based on Equation (1), the control specimen of FRP strengthening and non-strengthening show the average pull-off strength which are 3.42 MPa and 2.77 MPa respectively. These results show that FRP increases the strength in comparing to without externally FRP bonding concrete slabs. Slabs bonded with FRP experienced 19% increment in strength. Two graphs in Graph 4-1below plotted based on control specimen which is externally strengthened with FRP sheet; on comparison with 3-month aging on we-dry cyclic exposure and continuous regime respectively. Based on these graphs, Slab B1 and C1 experienced reduced in strengthened of 35.5% and 37.13% respectively.



Graph 4-1

4.1.2 3 MONTH AGING SPECIMEN

For stimulation of accelerated aging purposes, 2 specimen slabs with a total of 36 pull off tests have been conducted. The two environmental exposures included wet-dry cycles in salt water at elevated condition and constant/continuous immersion in the same condition.

After 3 months of conditioning in salinity and humidity environmental exposures, two additional groups of specimens have been tested. Table 4-3 shown below, is the summary to the results for pull off tests performed in the laboratory.

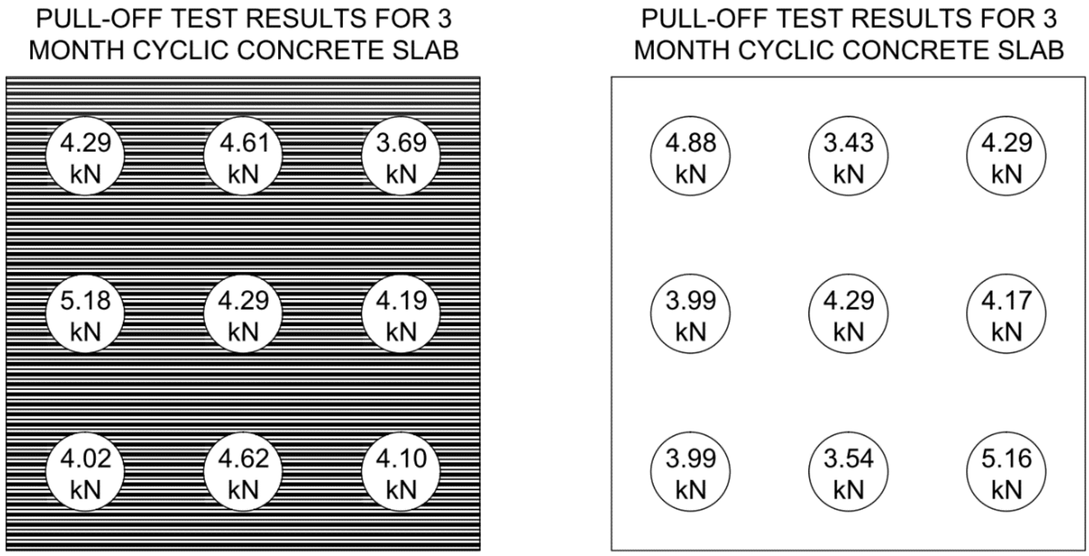


Figure 17 PULL-OFF TEST RESULTS FOR 3-MONTH CYCLIC SPECIMEN

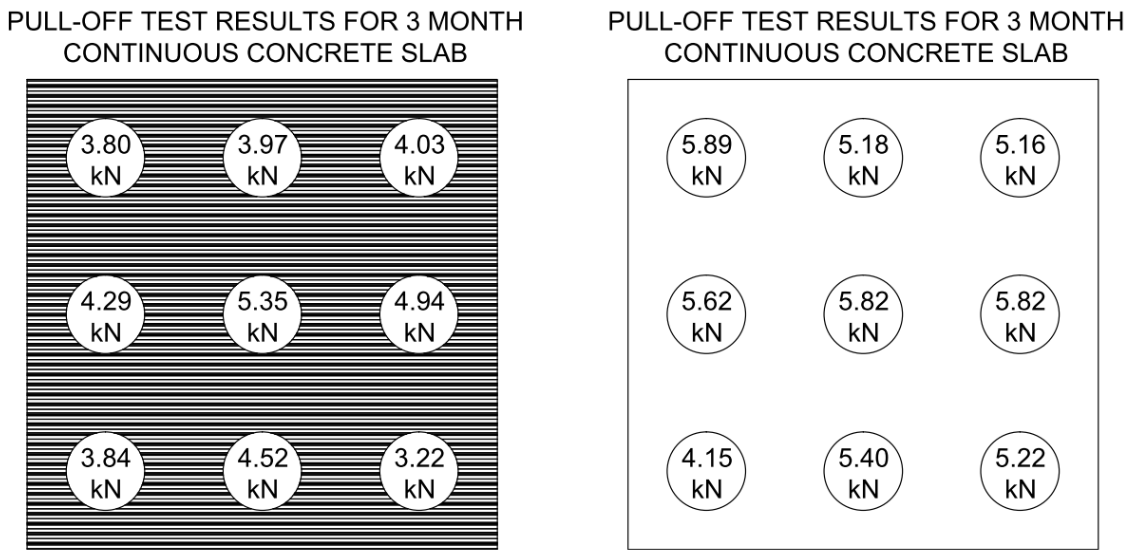
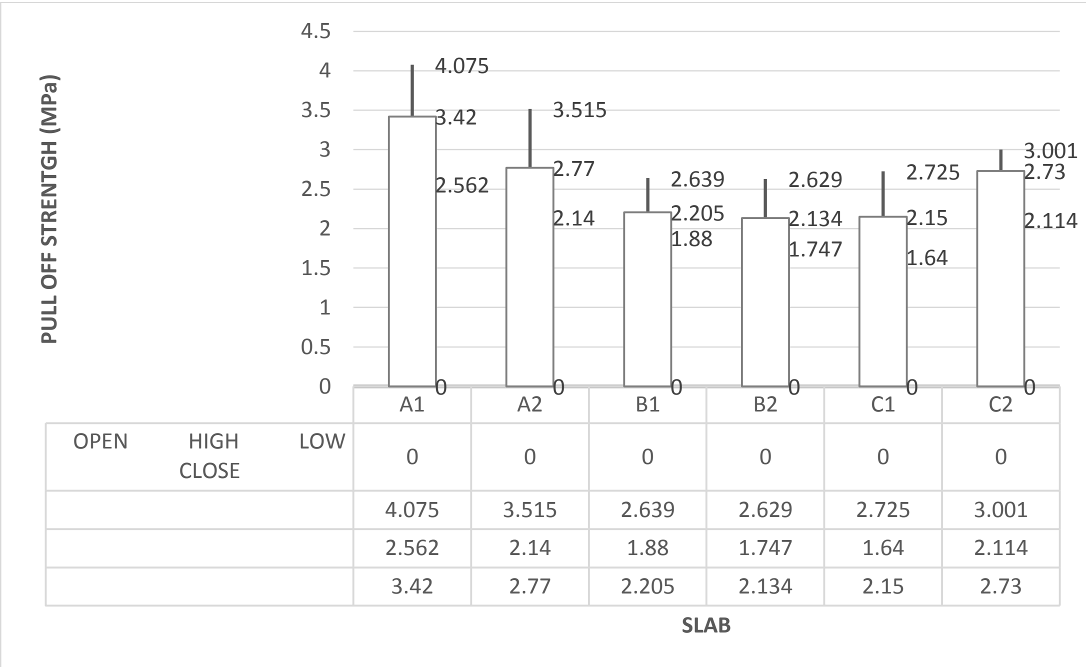


Figure 18 PULL-OFF TEST RESULTS FOR 3-MONTH CONTINUOUS SPECIMEN

Table 4-3

ID	Test Disc Ø (mm)	Average (kN)	Pull Off Strength (MPa)
	CYCLIC 3 MONTH		
B1	50	4.33	2.206
B2	50	4.19	2.134
CONTINUOUS 3 MONTH			
C1	50	4.220	2.150
C2	50	5.360	2.731

Based on the summary shown in the Graph below, degradation in strength was seen in the specimens undergoing water immersion, wet-dry cycles and continual immersion. However, an increase in strength is witnessed for the control specimens which is laminated with CRFP sheets. For conclusion, the presence of moisture induced bond strength of interlocking between CFRP-concrete where the aging specimens result the lowering of pull-off strength in the test.

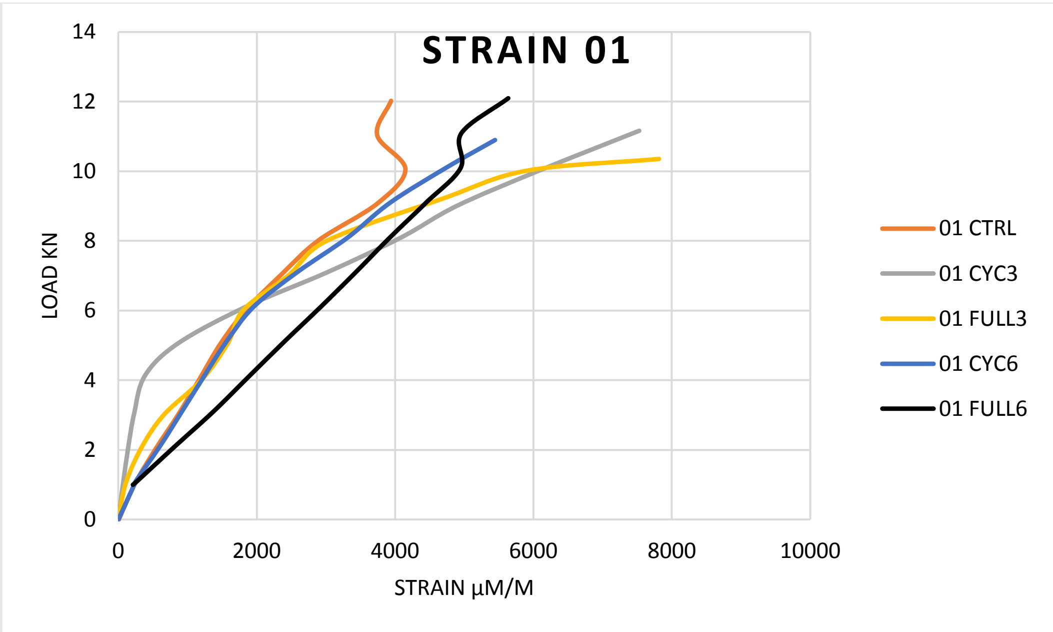


Graph 4-2 Comparative Histogram of the Pull off Strength Values in the Control, Continues and Wet-Dry Cyclic after 3 Months for FRP-Concrete Bonded Interfaces

4.2 3-POINT FLEXURAL TEST

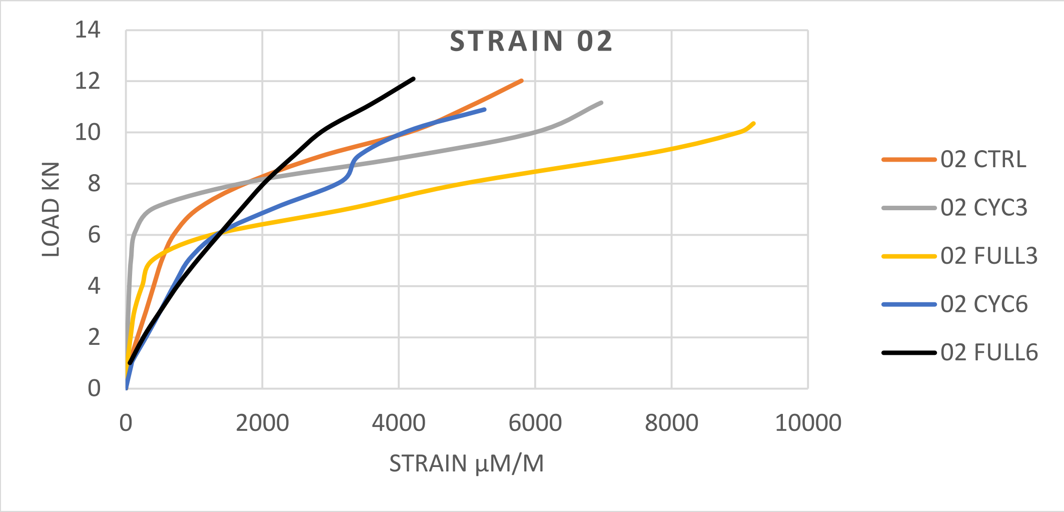
Based on this flexural test, the tension develops at the bottom of the beam where the CFRP is located, shear stresses develop to transfer forces between the concrete and FRP. The saw cut is placed at mid-span to ensure that failure starts to develop at the top of the cut, which forces the CFRP reinforcement to fully mobilize its development length. [2] Generally, based on from all the graphs in Section 4.2, it is shown that the most strain reading happened to the gauge situated at the midspan on beam where the highest deflection occurred.

As the concrete cracked, the tensile forces are transferred to the CFRP laminate at the crack location [13]. Further away from supports, the tensile stresses in the concrete rapidly increase and the stresses in the CFRP sheet rapidly drop to a low level. This abrupt variation of the stress distribution along the rod creates high local shear stresses at crack locations that decrease with distance closer to the supports. As mentioning in section 3.3, in order to monitor the FRP strengthening effect, a series of strain gauges are bonded on the bottom of the FRP sheets, as shown in Figure 11, to measure the strain distribution.

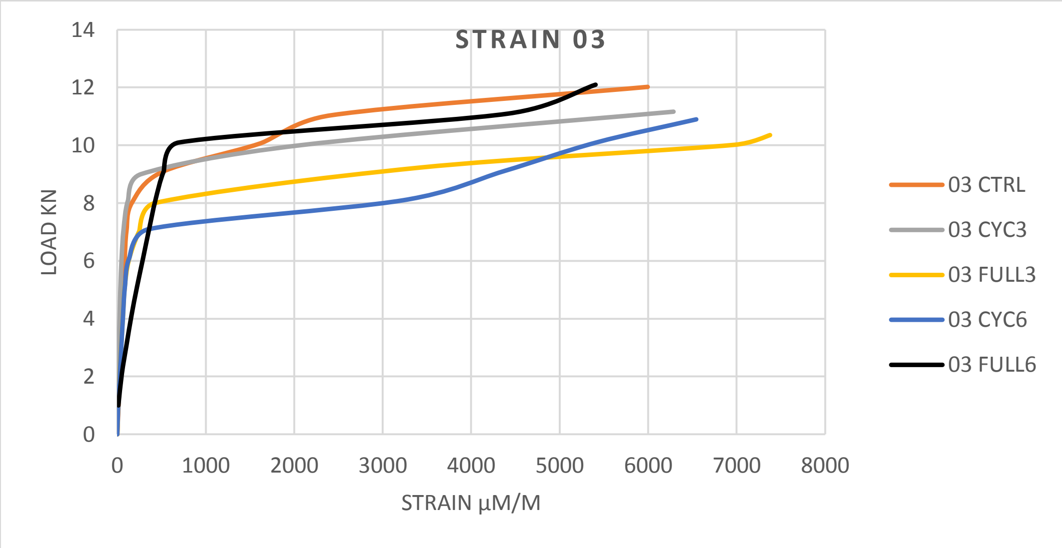


Graph 4-3

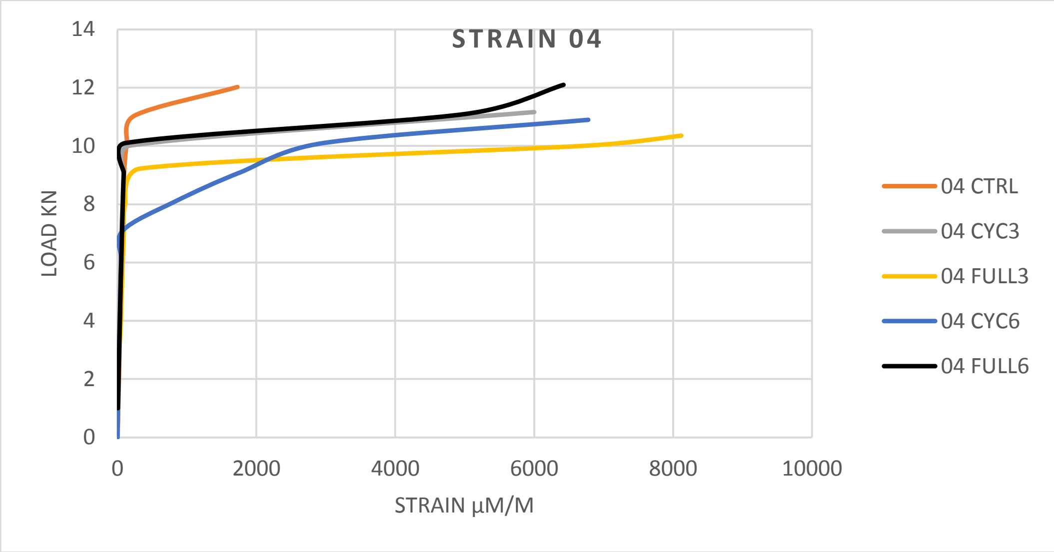
From the graph above, it shows the relationship on Strain 01 readings of control, 3 months and 6 months aging. Based on load versus strain graph, specimen FULL6, which has been aging continuously for 6 month-period; has strained linearly subjected to the loading in the test. CYC3 indicates rapid straining until 4.2 kN loading and it strains linearly throughout the bending test.



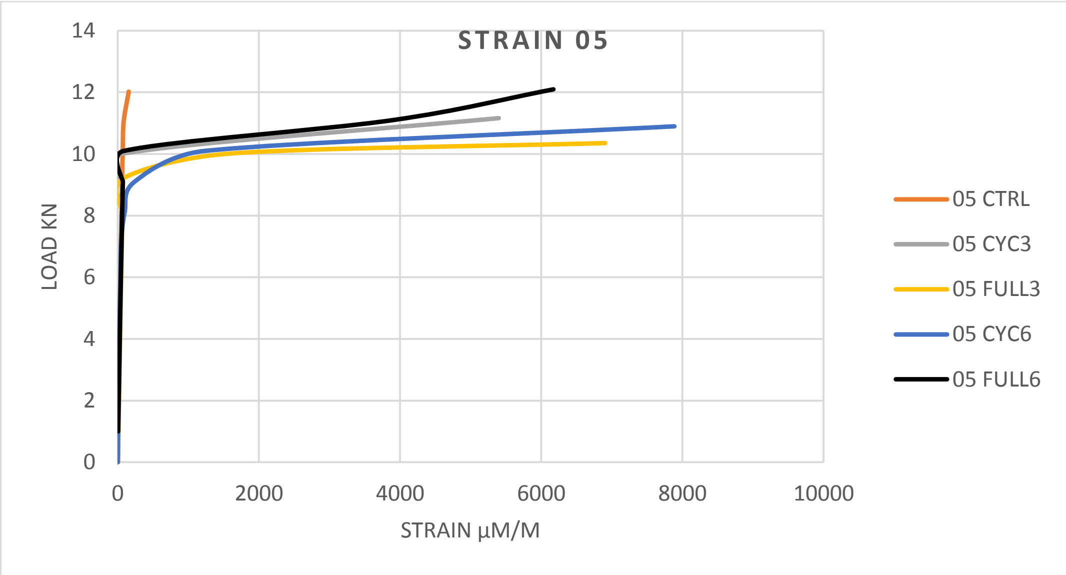
Graph 4-4



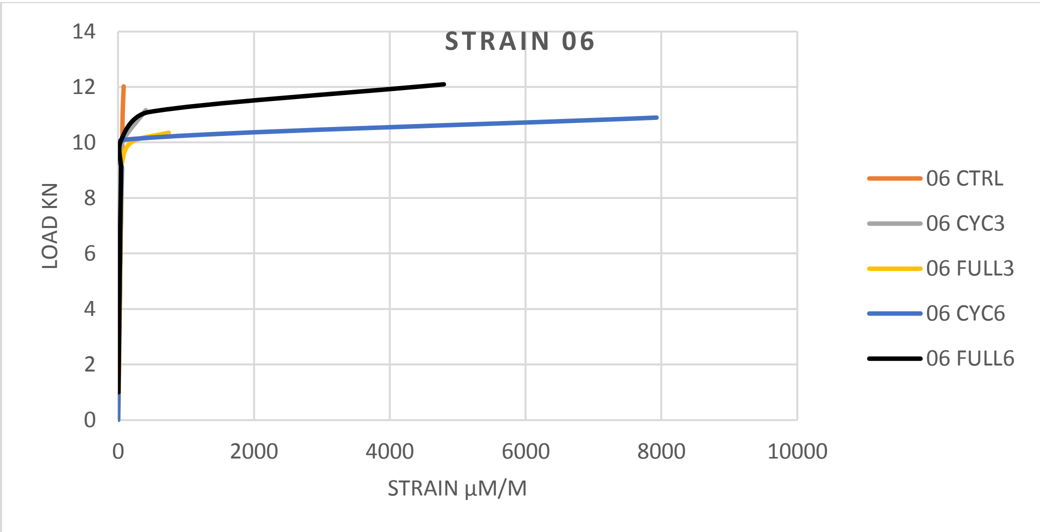
Graph 4-5



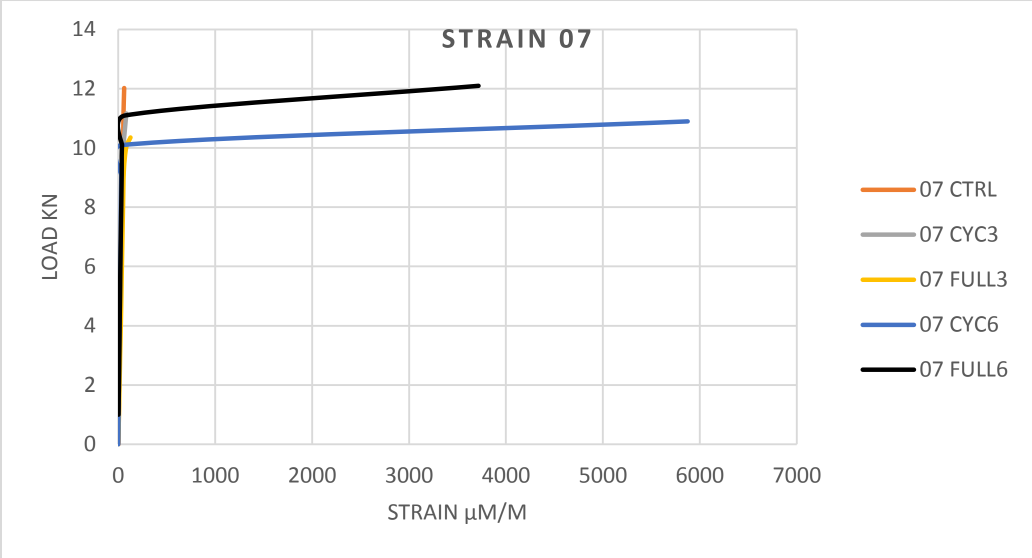
Graph 4-6



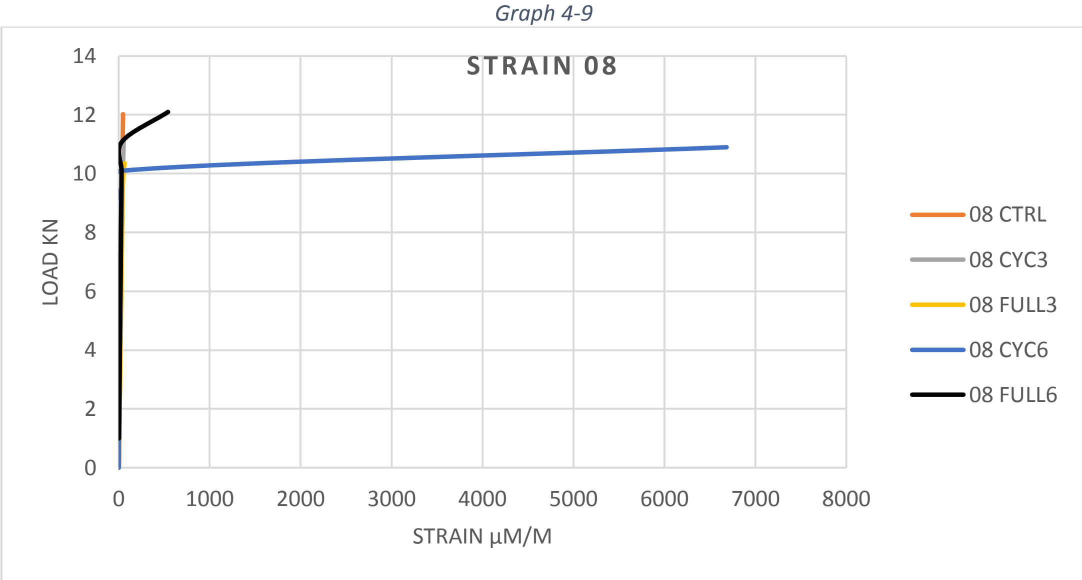
Graph 4-7



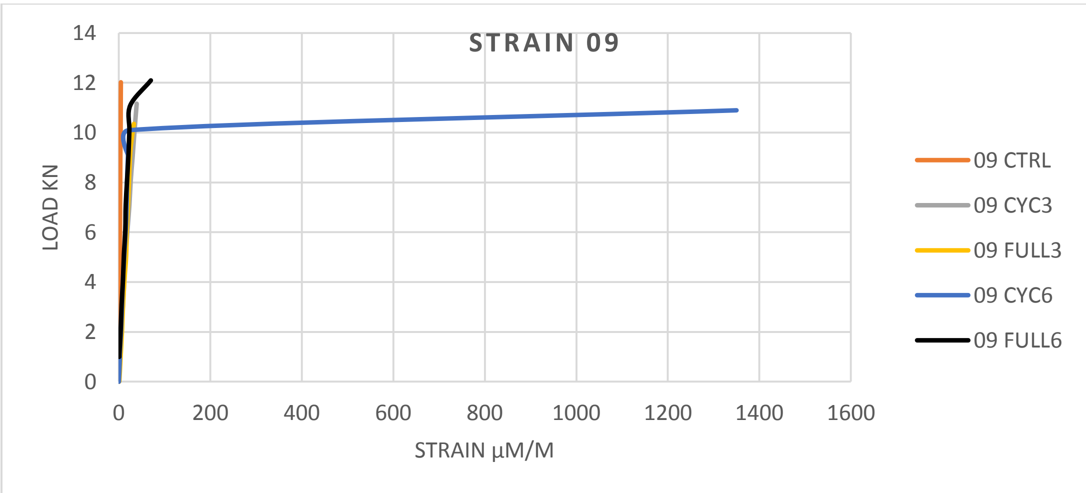
Graph 4-8



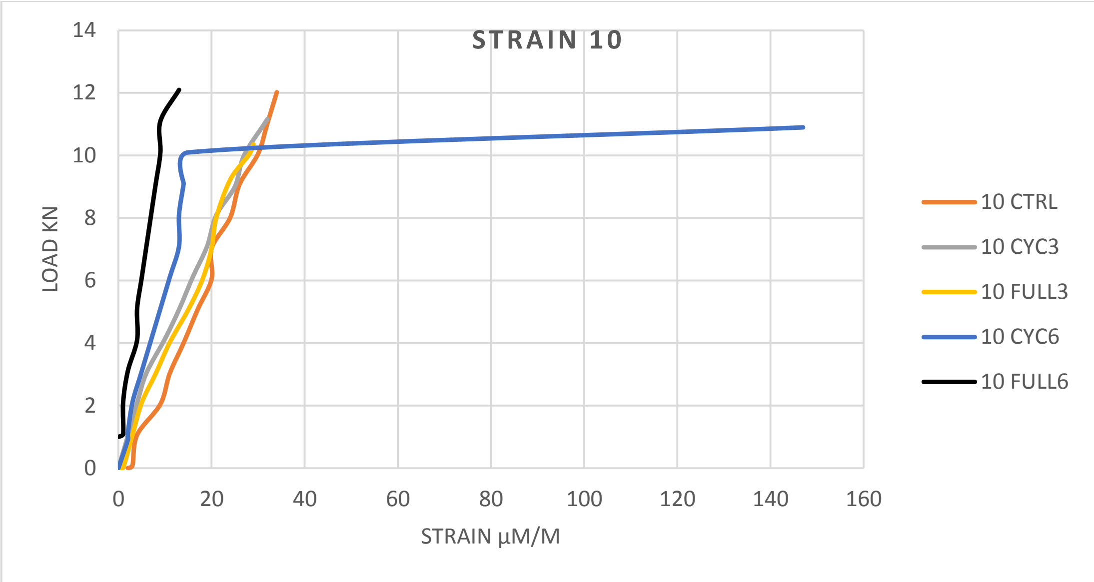
Graph 4-9



Graph 4-10



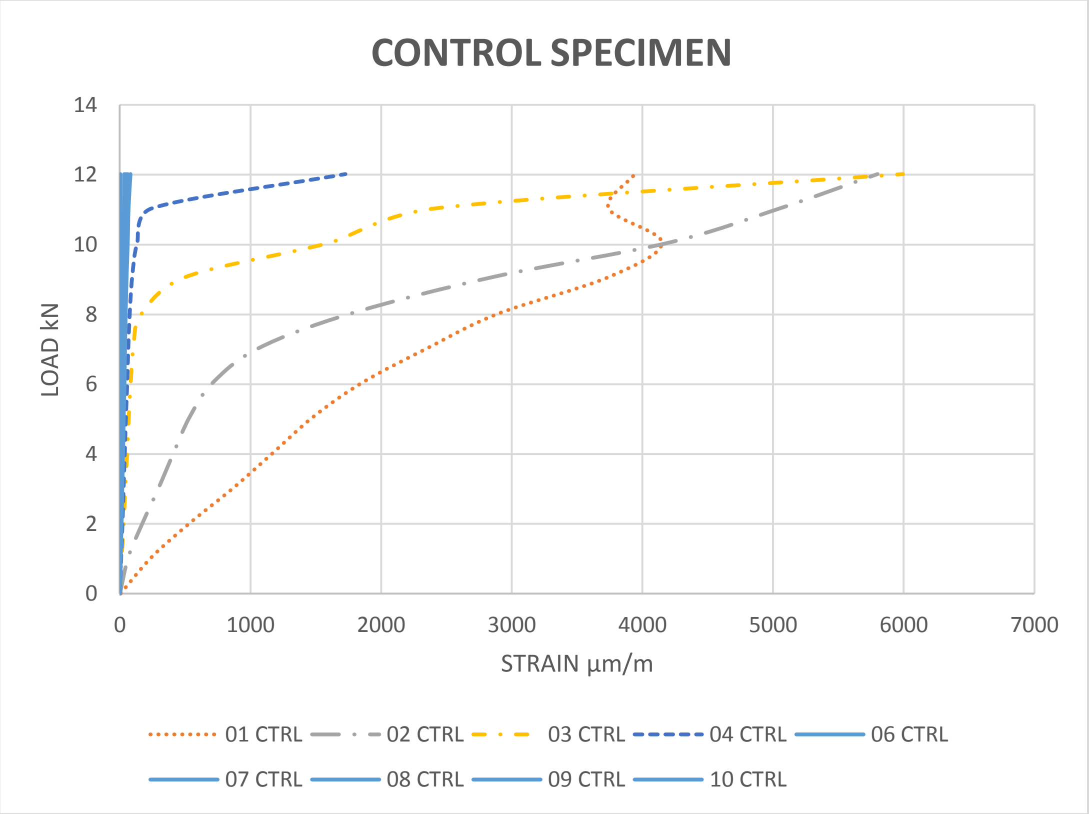
Graph 4-11



STRAIN 10
LOAD KN
14
12
10
8
6
4
2
0
0
20
40
60
80
100
120
140
160
STRAIN µM/M
10 CTRL
10 CYC3
10 FULL3
10 CYC6
10 FULL6

Graph 4-12

4.2.1 CONTROL SPECIMEN

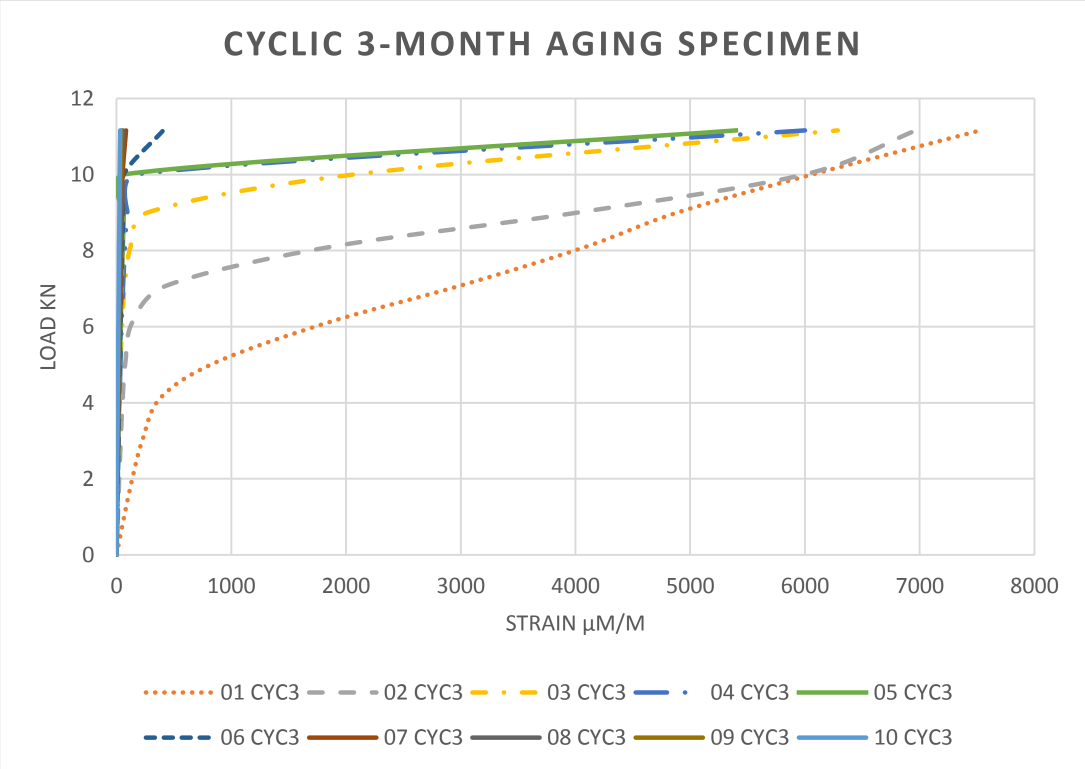


Graph 4-13

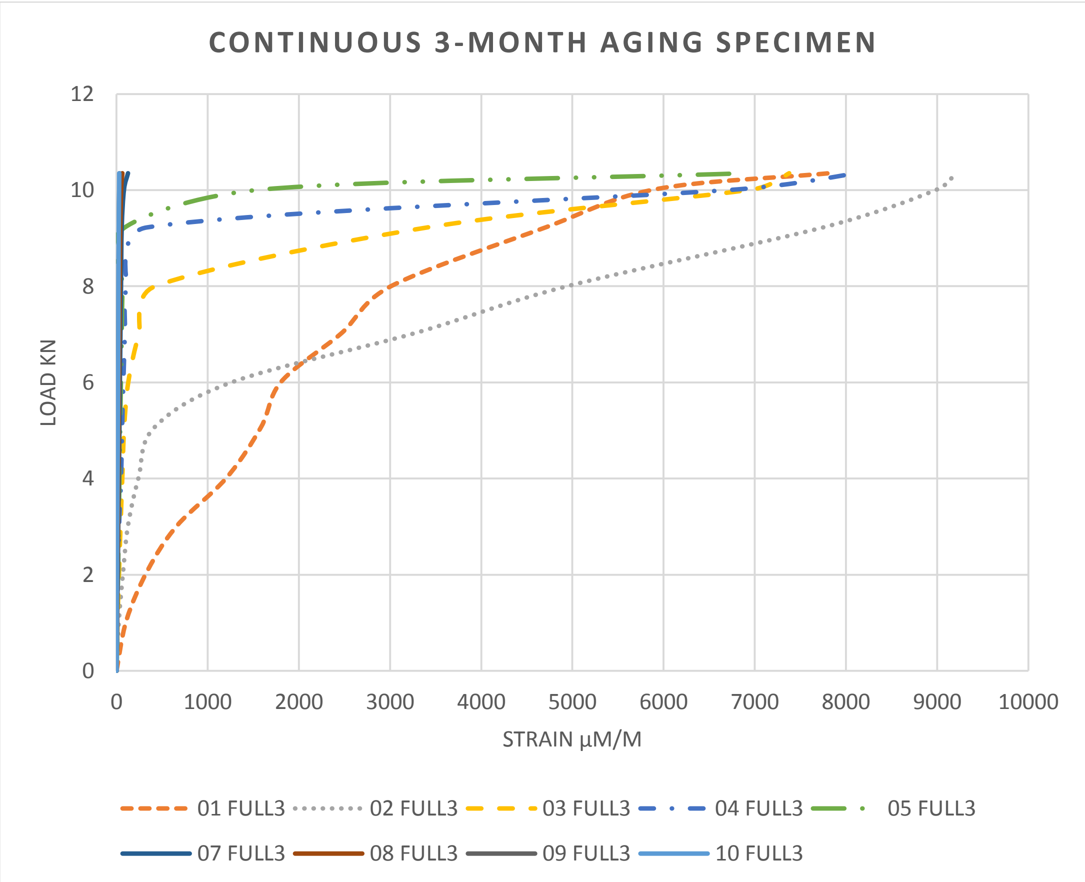
Based on the graphs above, Strain 01 indicates the strain gauges which is the furthest away from the support, in other words situated at the mid span of the beam whilst Strain 10 is the strain gauge which is the nearest to the support. As discussed in previous sections, the de-bonding between the CFRP rod and the epoxy starts at midspan then extends towards the supports situated on the end of beams. [13]

The development of cracking behaviors during the loading process of each case until final failure is observed during the flexural test. For all the cases, the initial crack always occurred near the mid-span.

4.2.2 3-MONTH AGING SPECIMEN



Graph 4-14



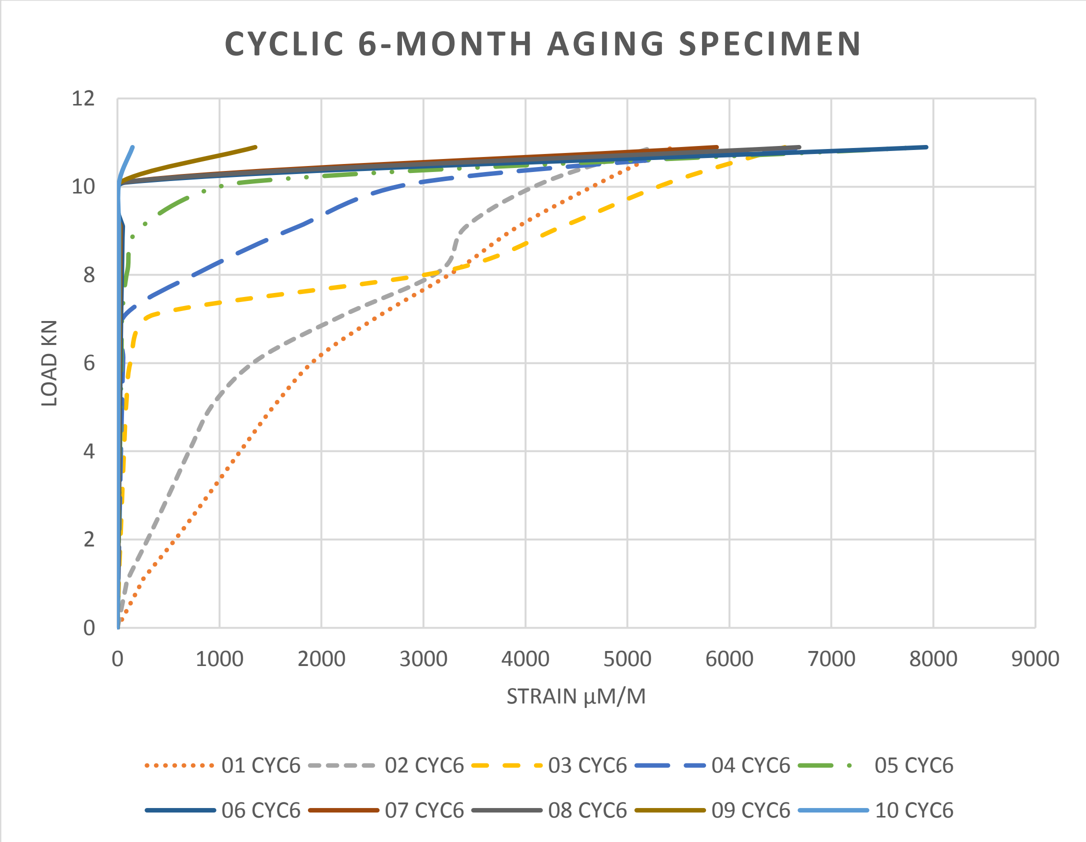
Graph 4-15

After 3 months of aging process taking place, the debonding of CFRP starts to occur at greater rate compare to control specimen. However, comparison between 3 month cyclic (Graph 4-13) and 3 month fully immersion (Graph 4-14) specimens in salt water, shows that Strain 01 of FULL3 specimen strains with 1206 μm/m at 4 kN whilst CYC3 strains at 386 μm/m which is lower. These results show on bond strength on each beam subjected to the aging process. Saltwater degradation effects on the interface mechanisms of FRP-concrete member and reduce the mechanical bonding properties. Either in cyclic or continuous aging process, both procedure cause the higher rate in moisture diffusion. The durability of the bond in moist presence is mainly controlled by rate at which water and the deleterious ions move through the system. [12]

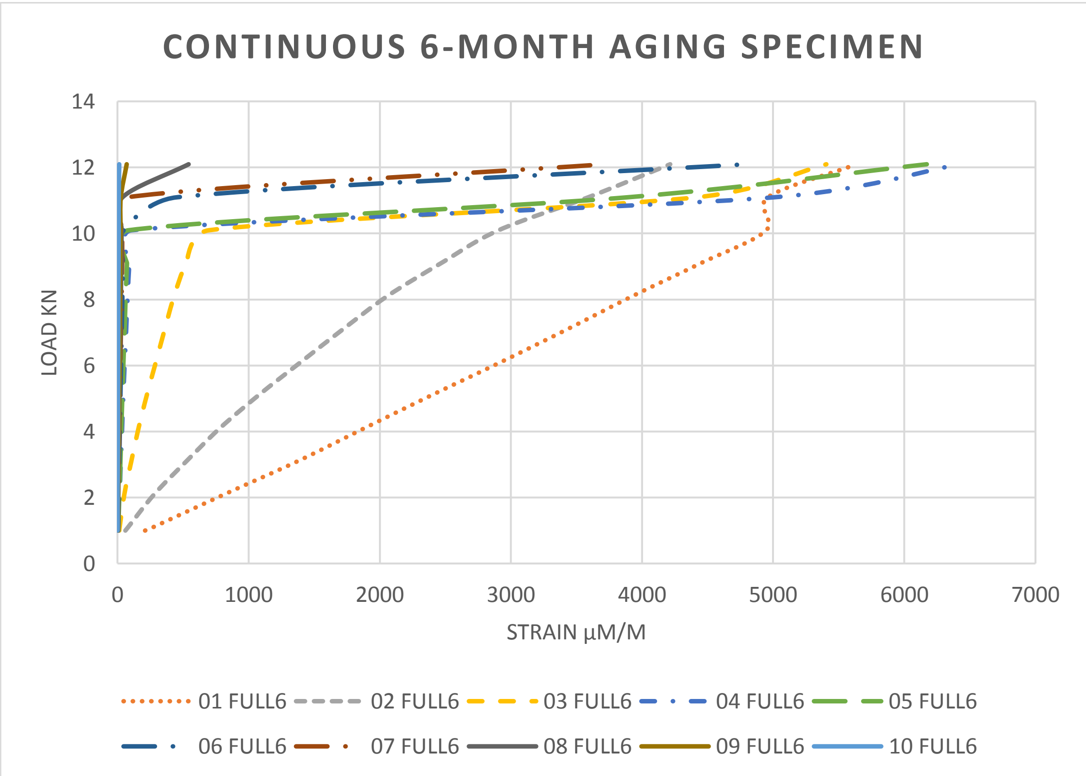
Figure 19 Continuous 3 month-exposure

Figure 20 Wet-dry cyclic 3 month-exposure

4.2.3 6-MONTH AGING SPECIMEN

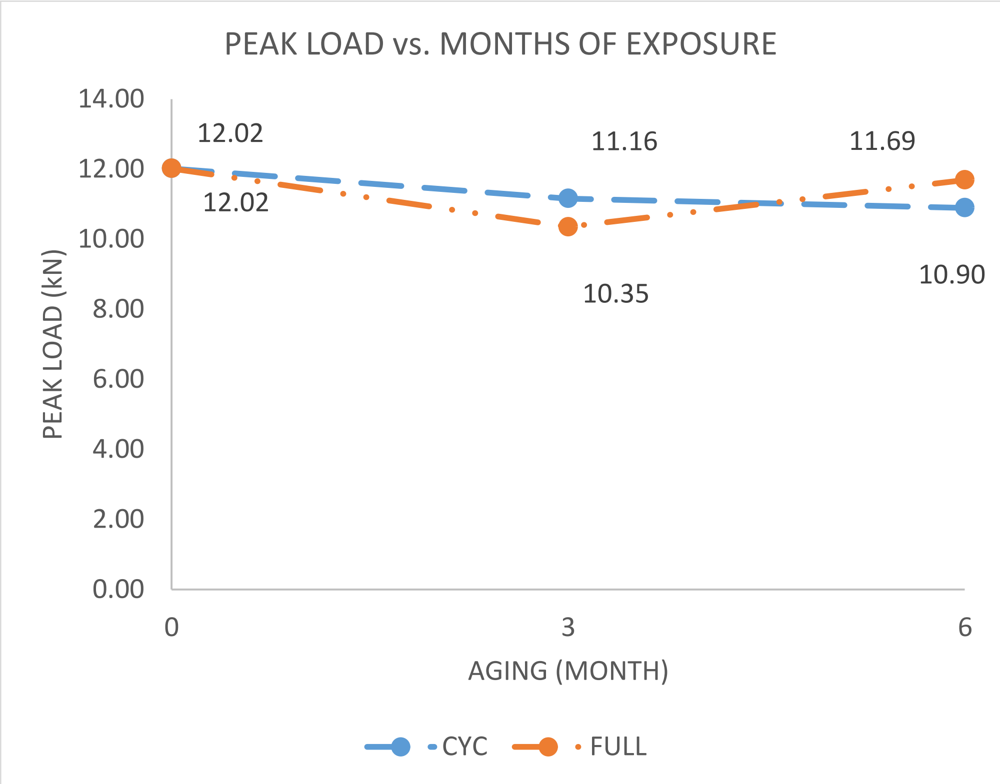


Graph 4-16



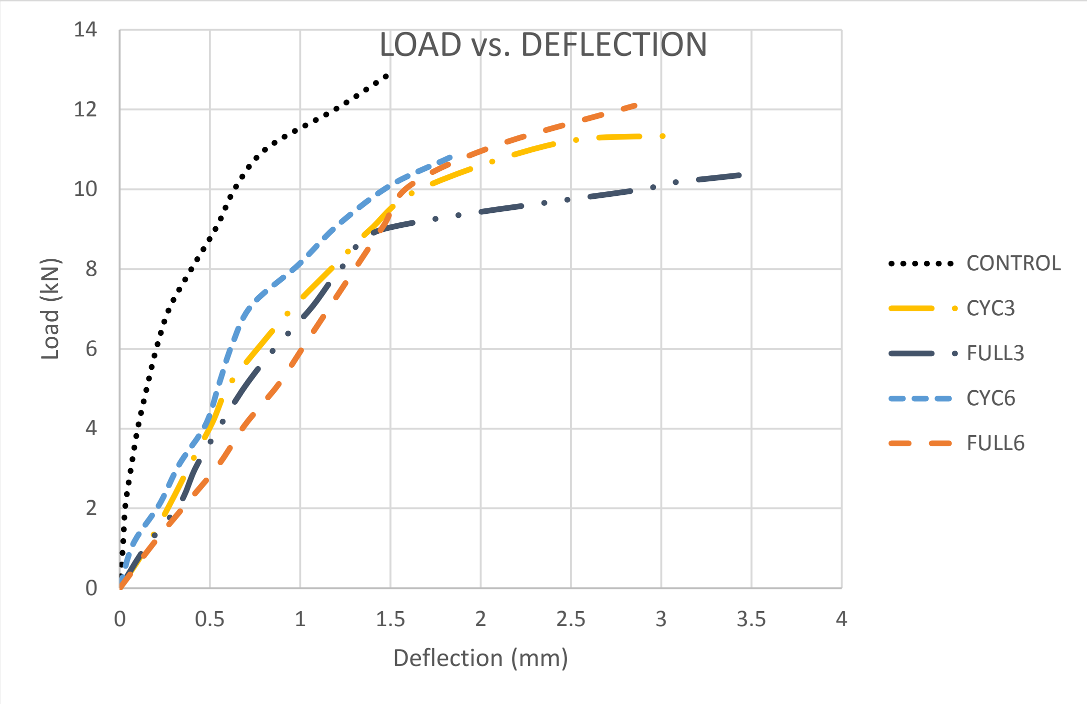
Graph 4-17

Based on the two graphs in Graph 4-15 and 4-16, where both graphs curve are almost identical and exhibit same pattern. Based on the author observations, the straining reading on the FRP sheet shows on intersection between loading and the strain. On wet dry cyclic ageing condition, the graph lines are converged at the straining ranged of 5000 µm/m and 6000µm/m whilst the continuous aging of 6 months exposure results converged between 4000 µm/m to 5000µm/m. Failure loads ranged from 11.0 kN and 11.6 kN on both conditions. On average, as expecting from previous tests, the control specimens showed the highest strength. All beams showed a similar failure mode, wherein a single flexural crack is started at the top of the saw cut and shear failure debonding on one of the FRP-concrete interfaces is witnessed.



Graph 4-18 Average beam results for the 3-month and 6-month exposure

Graph above presents on a comparison plot of the beams tested at all aging stages process. As estimated, the dry (control) beams are the strongest ones throughout the entire durability study. In addition, a decrease in strength was witnessed in the wet dry cyclic environmental exposure. However, for unknown reason there was an increase in strength during the last three months of exposure for the full continuous exposure specimen beam.



Graph 4-19 Load-deflection relations of FRP-strengthened beams.

Figure 4-18 shows the plot of the load displacement from five different 150mm depth of beam test specimens. The behavior shown is typical of that noted for most of the specimens. For the aging specimens, the initial slopes are linear up to cracking, which occurred between 8 and 10 kN. Failure occurred when the CFRP composite completely debonded from the concrete on one side of the saw cut and at sudden and without warning as per Figure 21. The graph above clearly indicates on control specimen deflects at minimal displacement at the greater peak loading in contrast to the rest of four ageing specimens.

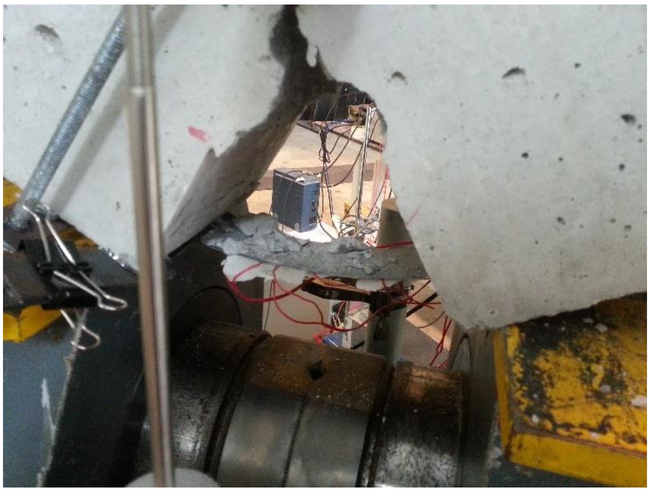


Figure 21

4.3 RELATIONSHIP OF PULL OFF RESULTS, FLEXURAL TEST AND FRP-CONCRETE BONDING

Based on discussions in Section 4.1 and 4.2, as far as degradation in relation to the control beams is concerned, no significant pattern is encountered compared to the results from both laboratory tests. For example, in Section 4.2.3, due to some reason there is a sudden increase in strength during the last three months of exposure for the full continuous exposure specimen beam during the flexural test.

As previously considered, high variability and discrepancies have been witnessed, especially in the pull-offs. Factors such as an increase in strength over time within the same specimens make analysis of results challenging. Carillo in his study had able to point out on potential discrepancies correlated to inconsistencies in drawing a solid conclusion in the pull-off test results [2]. He discussed on potential reasons why such discrepancies in the results would be created:

- Inconsistencies in the depth of the core drilling prior to puck adhesion
- Varying volumes of epoxy used per dolly
- Irregularities on the surface of the specimen that would prevent a fully flat adhesion, which lead to variations in thickness across a bond surface
- Inconsistencies in the mixing of epoxy
- Improper cleaning and sanding of the FRP surface or aluminum dollies.

5 CONCLUSION AND RECOMMENDATIONS

It has been proven that FRP has been enhancing in strengthening concrete structures and increase the additional load carrying capacity. Researches have been conducted across the globe on this economical solution. However, it must be noted on the circumstances where environmental influence serve impacts on the surfaces and eventually failure the structural quality. The applications of FRP and exposure to moisture and heat will effect on its interlocking and bonding mechanism across time. Based on this project, the effects are studied due to marine environment including the bond behavior, effective bond strength, and failure modes under monotonic loading.

In determining the strength of retrofitted concrete, various reliable test procedures for have been found for a number of years. Up to some extent, there an indication that the substrate concrete was the weakest plane link in the repair system. In this way, the pull-off strength reflects the tensile strength of the substrate. Hence, this research has presented a groundwork that can be constructed as the establishment of pull-off strength and bond behavior under marine environment.

Based on the research objective mentioned in Section 1.3

- ✓ Pull-off tests have been conducted for evaluation on pull-off strength between FRP and concrete surface under the condition of marine environment. The author found that moist aging causes the significant reduce in pull-off strength of the bonded surface between FRP-concrete specimen.
- ✓ Environmental-like condition has been set up in the laboratory where stainless tanks are used to immerse all slabs and beams as well as to heat the salt water at constant temperature. The adhesive bond between the fiber-substrate has been investigated under accelerated aging test at 60°C.

The adhesion strength between the FRP-concrete has been determined as well as the bonding interfacial strength has been evaluated when the bending test is conducted. To further increase the interpretation of the results, the total number of specimens are recommended to be higher to enhance the accuracy as well as reducing the uncertainties. As more results are gathered, it will eventually support to a solid conclusion towards the end of the project.

In conclusion, hopefully, this project is able to be a rigid study in retrofitting industry since the fibers are indeed sustainable and better performance comparing to conventional steel reinforcement. In fact, the tensile properties and its high strength-to-weight ratio material can be viable to construction industry.

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