The Ageing Effect of CFRP Plate Steel Members

by

Muhamad Azri Syazwi bin Samsudin

12707

A final report submitted for partial fulfillment of requirements for the

Bachelor of Engineering (Hons) (Civil Engineering)

MAY 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Ageing Effect of Carbon Fiber Reinforced Polymer (CFRP) Plated Steel Member

by

Muhamad Azri Syazwi bin Samsudin

A project dissertation submitted to the
Civil Engineering Program
Universiti Teknologi PETRONAS
in partial fulfillment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

Approved by,

____

Ibrisam Akbar, Ph.D., CEng

UNIVERSITI TEKNOLOGI PETRONAS
Tronoh, Perak
May 2013

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.

____

MUHAMAD AZRI SYAZWI BIN SAMSUDIN

ABSTRACT

Fiber Reinforced Polymer (FRP) has been used for many years in structures retrofitting and rehabilitation especially in concrete member. Numerous efforts have been employed to translate FRP-to-concrete application into steel retrofitting. Debonding of CFRP form steel surface have been a crucial issue in the field of strengthening and retrofitting of offshore steel structure. In this paper, the effect of CFRP-plated steel member under accelerated saltwater condition is presented by submerging the CFRP plated-steel member into accelerated seawater of 60°C for 1 month, 2 months, and 3 months. Since debonding is the most crucial aspect in CFRP-to-steel joint, the understanding on bond-slip characteristic is the focus of this paper. Additionally, two innovative theories, which are pull-test and numerical method, are demonstrated on the characteristics of bond-slip degradation. In addition, the material strength and stiffness of SikaCarbodur CFRP and Sika30 Adhesive is also measured. Based on the joint pull test, the weakest link of the bonded interfaces is the adhesive, provided that adhesion failure at steel/adhesive and CFRP/adhesive interface can be avoided by a good and appropriate surface preparation of steel and FRP. The failure mode and load-displacement curve will be analyzed in order to investigate the bond-slip relationship of CFRP-to-steel.

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Ibrisam bin Akbar for his endless support, assistance and knowledge sharing he had with me. With his encouragement and compassionate hospitality from the first meeting, till the end enables me to develop a better understanding of my project. This research studies would not have been made possible without his consistence effort fostering me to my very best in order to strive towards excellent.

I also would like to acknowledge and extend my heartfelt gratitude to the postgraduate student, Mr. Raffizee Ibrahim who always there to lend me a hand and nurtured me. With his endless and tireless motivation, he inspired me to become more competence, thought me very well and corrected the oversight I did though out the tasks I had undertake and gives constructive comments for me to further improve myself in any way possible. On the other hand, I want to thank lab technicians in Civil Engineering Department, who have spend their precious time to assist me whilst operating the machine and instrumentation.

Lastly, I also would like to also express my appreciation to my family and friends who gave endless support and motivation throughout all the difficulties that I had encountered in completing this dissertation.

Thank you,

MUHAMAD AZRI SYAZWI BIN SAMSUDIN

Civil Engineering

Universiti Teknologi Petronas

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1.1 Background of Study

Carbon fiber reinforced polymer (CFRP) is a material of choice in retrofitting or rehabilitation of concrete and steel structures. Its high stiffness-to-weight and strength-to-weight ratio has made it a good material for strengthening any damaged member. CFRP is an advance composite material made of continuous nonmetallic fibers with high strength and stiffness embedded a resin matrix. . CFRP is also thin, hence, does not shatter upon the head-room requirement [1]. CFRP is chosen as a means of treating offshore steel structure members due to its insusceptibility to corrosion and excellent environmental durability.

The performance of CFRP in actual environment can be strongly affected by the behavior of CFRP-to-steel joint. In service, the CFRP plated steel is subject to several possible failure modes including cohesion failure within adhesive, steel/adhesive failure, and adhesive/CFRP failure [2]. A research program has recently been initiated by the author with the supervision of a distinguish professor in offshore structural research, in pursuit of developing new approach for investigating bond-slip degrading due to saltwater effect. Experimental pull-off test have been extensively applied to the study of bond-slip relationship, particularly by applying tensile force to the CFRP plate.

1.2 Problem Statement

Offshore structures are prone to degradation mainly due to corrosion of their steel members. The harsh wet and dry condition of offshore environment could boost up the corrosion rate of the steel structure. Hence, CFRP plating is regard as the preeminent way to alleviate the problem.

Unfortunately, CFRP-to-steel member is susceptible to debonding whilst in service. Without resolving this barrier, the strengthening and rehabilitation purpose of CFRP may not be perfectly utilized. For specimens subjected to tensile forces, failure may occur either along the bonded length or at the end of bonded length via a range of failure modes.

1.3 Objectives

i. To study the mechanical properties of steel, CFRP, and adhesive materials.
ii. To study the effect of acceleratedseawater to the strength and stiffness of CFRP-plated steel member

1.4 Relevancy of the Project

This project explains the bond-slip characteristics of the adhesive CFRP-to-steel joint through numerous experimental, numerical, and empirical equation methods in order to exterminate the debonding setback. Debonding failures may significantly decrease the effectiveness of strengthening or repair application of CFRP. The feasibility of using CFRP in seawater environment need to be explored in terms of degradation of bond slip characteristic, adhesive response and strength.

The positive outcome of this study, as mention earlier, is to formulate a working and dependable CFRP plate, securely bonded with steel members for ease of application to strengthen the offshore structures.

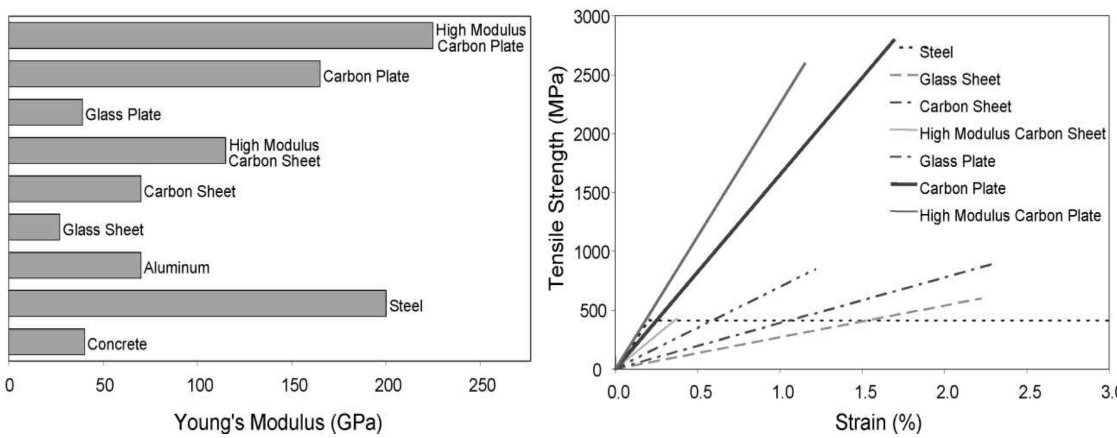
1.5 Feasibility of the Project

The overall timeliness of this project covers the duration of two semesters (8 months) and is broken down into two subjects namely Final Year Project I and Final Year Project II. Referring to the Gantt chart constructed in chapter 3.2, this project is expecting to be completed over the course of 8 months.

LITERATURE REVIEW

2.1 Introduction

The material and the type of the member to be strengthened played a big role on applicability and effectiveness of strengthening with FRP composites. Most research that has been done mainly focused on applications to RC members. Usually, the strengthening material is expected to have a similar or higher stiffness compared to the base material of the member being strengthened but the stiffness of most FRP composite systems are considerably less than that of structural steel. Fig. 1a compares the elastic modulus of concrete, aluminum and steel with those of several commercially available FRP composite systems and Fig. 1b shows a comparison of stress–strain behavior in tension [3].



(a) Elastic Young's modulus **(b) Stress-strain behavior**

Figure 1: Elastic and strength properties of FRP composites compared with conventional construction materials

From the Fig. 1, it shown that strengthening of steel members with FRP composites may be mechanically less advantageous and economically less feasible compared to concrete and aluminum members. Nevertheless, repair of fatigue damaged steel members with FRP composites is both mechanically and economically well justified. Due to continually decreasing costs of FRP materials, ease of installation and the potential of eliminating welded and bolted repairs, applications involving steel members have also increased.

Strengthening with FRP composites can be applied to various types of structural members including beams, columns, slabs and walls. Depending on the member type, the objective of strengthening may be one or a combination of several of the following: (1) to increase axial, flexural or shear load capacities; (2) to increase ductility for improved seismic performance; (3) to increase stiffness for reduced deflections under service and design loads; (4) to increase the remaining fatigue life; (5) and to increase durability against environmental effects [4]. Debonding problems are frequently encountered and play an important role in the behavior and performance of the member in shear and/or flexural strengthening of beams and repair of fatigue damaged steel members.

2.2 FRP-to-Steel Bonding

The key element in having a sound bond between steel and FRP composites are with obtaining its composite behavior. Most of the experiments with regards to FRP and steel that have been done indicate that debonding and delamination are the main failure modes. It is preferred that the fibres rupture before a failure of the adhesive occurs. The forces that go through the adhesive are transferred from the steel to the FRP. Due to that, the adhesive has to be able to transmit the forces efficiently and take advantage of the full capacity o f the composite.

Sen and Liby [5] have suggested that, when adhesives are not fully cap able of transferring these forces, additional fasteners may be employed. The bond must have good durability at both elevated temperature and freezing conditions, which is the case for bridges located in North America. In addition, adhesive that has demonstrated good durability under such environmental conditions is the epoxy resin and, as mentioned, bonding is enhanced when the surfaces are treated with silane.

Adhesive thickness is the other variable that affect the stress concentration on the adhesive. By increasing the thickness of the adhesive layer, the relative stress concentration level was reduced by 21%. Further reduction of the stresses could be accomplished by adding a fillet at the end of the bond line, wherein it was found that the corresponding stress concentration was reduced by 32%.

2.3 Bond-strength of CFRP-plated steel

The bonding strength of CFRP-to-steel adhesive is the most vital issue in strengthening the member. CFRP-to-steel joint tends to debonding while the members exposed to offshore salt water condition. This is because the fact that initial strength and stiffness of CFRP-to-steel member may weaken upon exposure to service environment due to moisture and temperature effect on the stiffness and strength of resin within CFRP composite and/or adhesive layer [6]. Hence, a sound investigation on bond-slip characteristic of the CFRP-steel component must be established.

The typical bond-slip relationship is presumed to be bilinear, as illustrated in Fig. 2. The bond-slip curve consists of relationship between elastic branch peaks on the maximum shear stress, τ_{max} and softening branch up to maximum slip, δ_{max}.

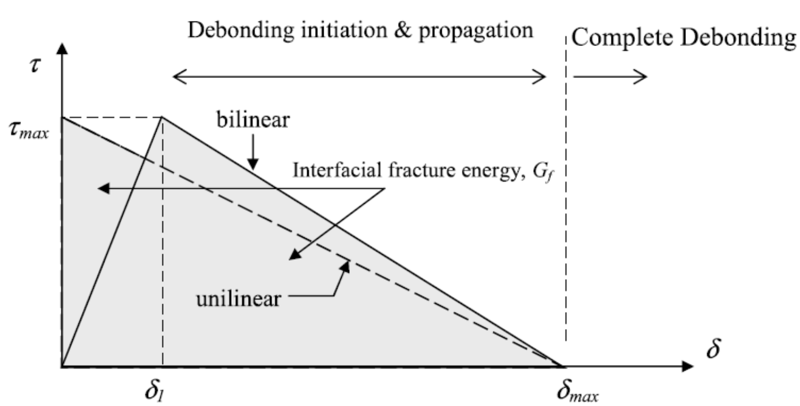
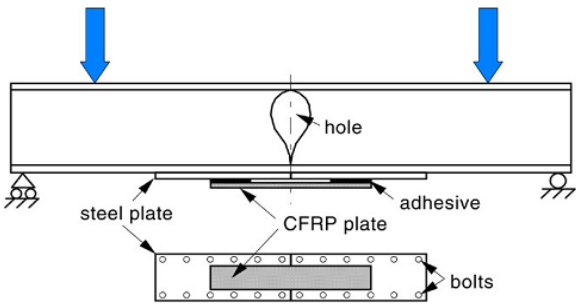


Figure 2. Local bond-slip model with bilinear curve.

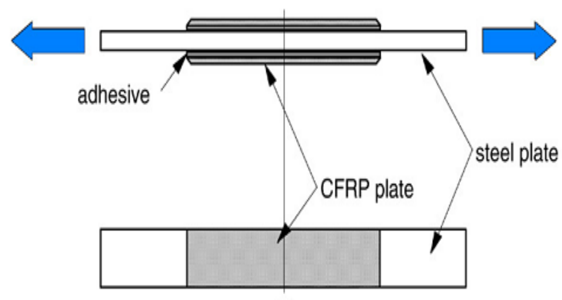
2.4 Types of Pull-tests

Several pull-test method had been used by various researcher to investigate the load-slip characteristic of the CFRP-plated steel specimen in order to study the bond characterization in between them.

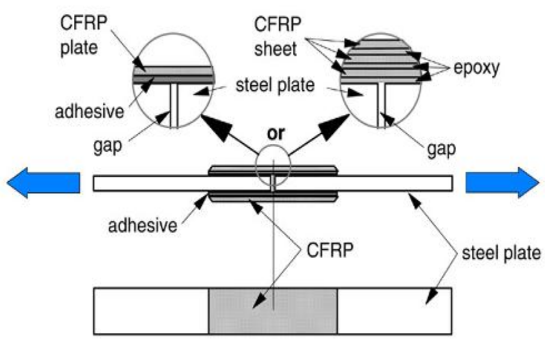
There are 4 types of method have done by various researchers for different purposes of study for bond testing. The categories are as follow:



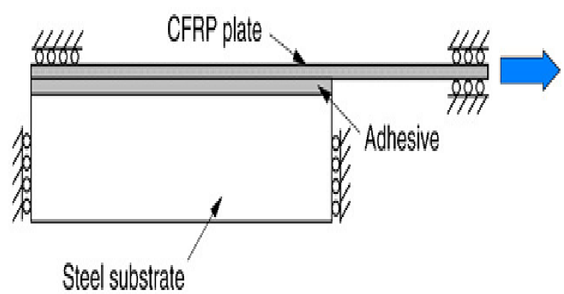
(a) Type 1: Loading is indirectly applied to the FRP and the steel plate beam.



(b) Type 2: Loading is directly applied to the steel element without any gap



(c) Type 3: Loading is directly applied to the steel element with a gap



(d) Type 4: Loading is applied directly to the FRP

Figure 3. Testing methods to determine bond between steel and FRP [7]

For type 1 method, the loading applied is applied on the beam to create a pure bending zone. It involves a steel plate bolted to the tensile flange of a beam. Developed a general bond model for steel I-sections beam strengthened by CFRP is the most suitable. The results are specimen-independent. However, the model developed cannot be directly applied to other types of sections, columns or connections even though some modifications applied.

The force is transferred from the steel element to the CFRP plates or sheets in type 2 method. Yielding of steel may occur outside the FRP strengthened area if the specimen has a uniform width [6]. This method is more suitable for studying strengthening rather than bonding steel and CFRP.

In type 3 method, double straps joints are often used to investigate the bond between steel plates and CFRP plates or sheets. The uncertainty of the debonding failure location gave major concern to this method. There are 4 possible locations exist for the propagation of debonding. Thus, this makes the experimental instrumentation and observation more difficult.

The forces that can be applied either compressive force or tensile force on FRP plates in the type 4 method. Adopted by Xia and Teng [7], the setup allows detailed monitoring and inspection of the failure process due to one path only that possible for debonding. It can be used for CFRP plates in establishing bond slip relationship between CFRP and steel in tension.

Some preliminary work was carried out several years ago to investigate the behavior of FRP-to-steel bonded joint by using single shear pull-off test [7].This purely empirical analysis is conducted by applying tensile force to FRP plate whilst steel block is supported at loaded end, as shown in Fig. 4.

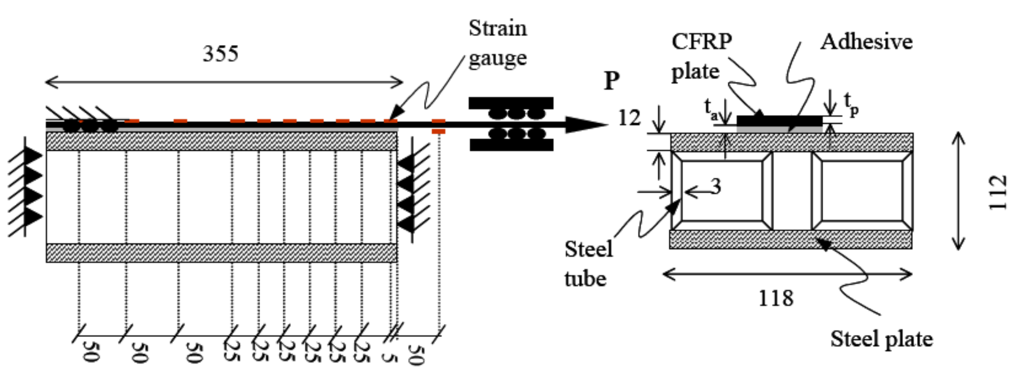


Figure 4. Typical pull test setup (Xia and Teng, 2005)

However, empirical procedures are prone to errors caused by complexity in measuring the strain distribution along the plate [8]. Ibrisam [8] has suggested that a simpler pull test method as in Fig. 5 can be conducted without measuring the strain but using structural mechanics theory instead, and this seems to be an innovative approach.

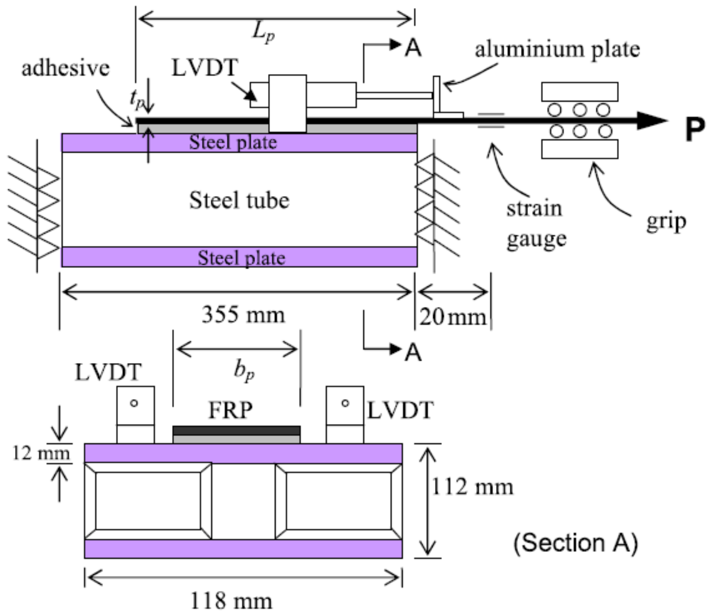


Figure 5. Typical pull test method (Ibrisam, 2010)

Two types of pull test is presented, which is a pull test with a fully anchored and not fully anchored, used to measure the value of maximum slip, δ_{max} and maximum shear stress, τ_{max} , respectively. Fully anchored experiment will resulted in load-displacement, P-Δ graph and the point where debonding starts to commence can be determined. As the P_{ic} value known, the value of δ_{max} and τ_{max} can be simply obtained by using Eq. (1). The second approach is done by using a not fully anchored in order to find τ_{max} directly. Next, it is needed to find δ_1 from Fig. 6 via numerical method.

$$P_{ic} = \sqrt{\tau\, max.\delta max}\sqrt{Lper(EA)p} \quad (1)$$

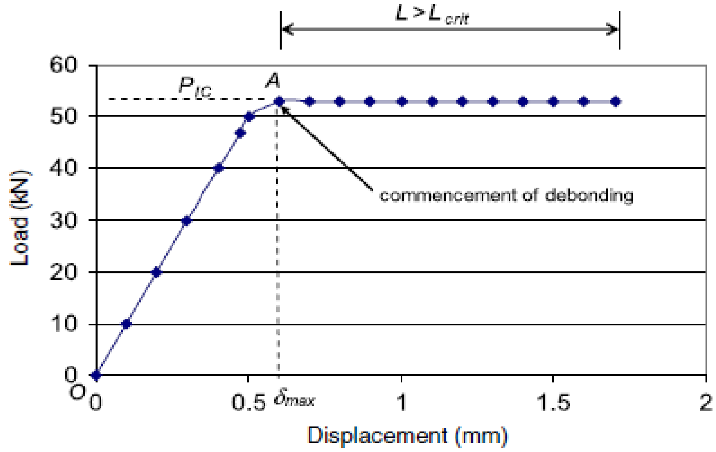


Figure 6. Typical load-displacement, P-Δ curve of FRP plated steel.

2.5 Failure modes of CFRP-to-steel member

For Type I the loading is applied on the beam to create an effective bonding zone. This method involve a steel plate bolted at the tensile flange of a beam and a general bond model for steel I-section beam strengthened by CFRP is developed. This model is only suitable for this particular section but ineffective for application on other types of sections, column or connection. In Type 2 testing method, the force is transferred from the steel element to the CFRP plates [4]. However, yielding of steel may occur occur outside the CFRP strengthened area in the case of uniform width specimen. This method is proved suitable for study of strengthening rather than bonding of steel and CFRP.

An increasing number of studies have found that the CFRP delamination is resulted principally from failure load of adhesive joint [9]. In an attempt to clarify this weakest link, a series of experiments have been done by numerous researchers. Most papers have demonstrated that debonding failure modes are mainly caused by adhesive. Xia and Teng [7] in their paper have extensively discussed the effect of properties and the thickness of the adhesive layer on bond behavior. The evidence from this study suggests that the failure mode is significantly affected by adhesive layer thickness. As far as adhesive thickness is concern, the fail by debonding in adhesive layer is influenced by the tensile strength of the adhesive. The main weakness in their study is that they offer only a limited range of variables, not to mention, the research is only depends solely on experimental approach.

Their findings might have been more convincing if more failure mode possibilities were analyzed. In bond-critical study, interfacial failure can possibly occur within adhesive layer (i.e. cohesion failure), at material interfaces (adhesion failure) between the steel and the adhesive, or between the adhesive and CFRP interface, CFRP delamination (separation of carbon fibers from resin matrix), CFRP rupture and steel yielding [10]. The Mechanical properties under dynamic tensile loads of commonly used adhesive namely Araldite 420 and Mbrace saturant adhesive is tested at quasi-static and intermediate strain rate [11]. Experimental approach, together with empirical equation, will initiate more consistent estimation of tensile properties of the adhesives.

2.6 Critical (Effective) bond length

The effective bond length and bond strength can be derived from bond–slip relationship. It is an important characteristic for FRP bonded concrete or steel systems. The bond–slip relationship is commonly determined from axial strains of the FRP measured with strain gauges along the bond length, or from load–displacement curves [12]. For the FRP–steel system, the bond–slip relationship could be simplified as a bilinear as shown in Fig. 2. The model are defined by three key points: the origin (0,0), the peak shear stress point (δ_1, τ), and the ultimate point $(\delta f, 0)$, with the area under the curve being the interfacial fracture energy (Gf).

A typical experiment to obtain the load slip, P - Δ response, is shown in Figure 6, where CFRP is glued on the steel block with a thin layer of adhesive (usually 1mm thick). Strain gauges are laid on the FRP surface to determine not only the bond stresses indirectly but also the end slip, Δ. The length of embedment L must be more than a critical bond length L_{crit} in order to achieve the peak strength of the interfacial crack debonding load P_{IC} [8]. The peak load, after which debonding propagates without any increase of load, is given by Equation 1, which is the closed form solution for the unilinear bond characteristic in Fig. 2; which is also applicable to any bond slip relationship, just as long as the fracture energy, which is the area encompassed by the bond slip characteristics as shown in Figure 10, is ½ = $\tau_{max}\delta_{max}$ [13].

2.7 CFRP-plated steel in harsh (offshore) environment

To simulate offshore environment, plain and epoxy-coated reinforcing steel bars were exposed in a synthetic seawater and 3% sodium chloride solution [14]. This laboratory simulation was monitored regularly using linear polarization and open-circuit potential techniques, known as marine environment simulated set-up (MESS) consisted of two chambers. Each chamber has two fiberglass-wooden tanks, a pump, heaters, and blowers [15]. A 2-h wet followed by a 4-h was chosen to give for complete cycles in 24-h period as resemblance to two tidal cycles in natural marine environment.

All those previous researches were conducted in dry circumstance and fall short to demonstrate the behavior of bond-slip relationship under saltwater environment. Submerging of the specimens with several variables under specified period of time will produce a further result on ageing effect of seawater on CFRP-plated steel.

Seawater degradation can cause swelling and plasticization of the polyester matrix and debonding at the fiber/matrix interface that may reduce the mechanical properties. Moisture absorption depends on the concentration of salt, the higher salt concentration produces a lower change in moisture absorption. Changes in mechanical properties of the composite material as a consequence of fluid ingress may be reversible, partially reversible, irreversible, or a combination of these types depending on the exposure time and conditions [16].For the reversible process which involves plasticization and swelling of the polymer matrix, the mechanical properties can usually be restored by drying [16].

3. METHODOLOGY

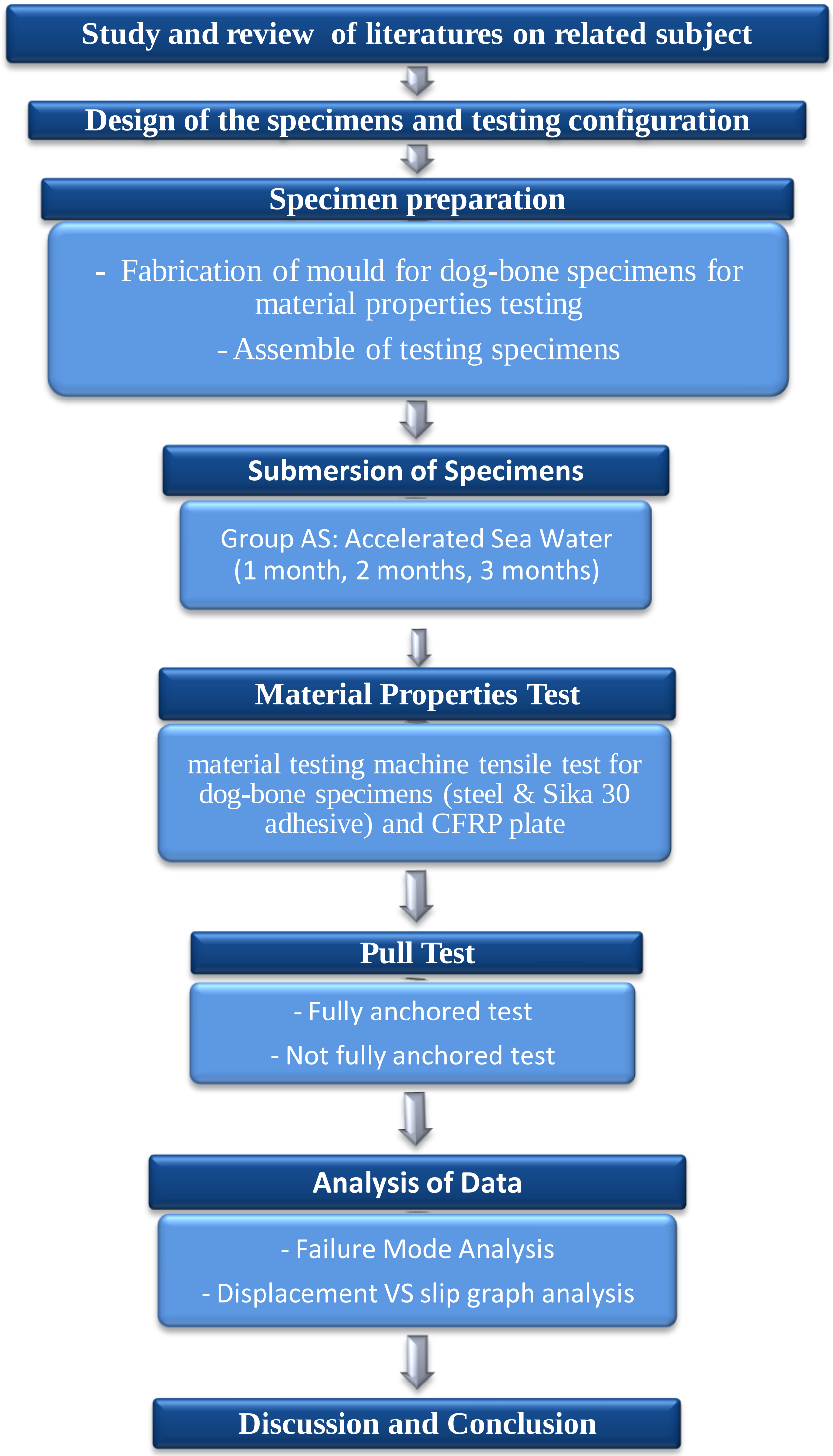


Figure 7. Methodology for development of saltwater effect on CFRP-plated steel

3.1 Specimen Preparation

A number of 16 specimens will be divided into 2 groups which are comprise of controlled specimens and accelerated specimens. The controlled specimens consisted of 2 specimens for fully anchored and another 2 for not fully anchored specimens. While the accelerated specimens group consisted of 3 subgroups for 1 month submersion, followed by 2 months and 3 months submersion.

Table 1. Specimen groups and condition

Group	Controlled (C)	Accelerated Seawater (AS)
Condition	Room atmosphere	Normal saltwater condition (Salinity of 35 ppt)
Temperature	Room temperature (32ºC)	60ºC
Curing Period	-	a) 1 month b) 2 months c) 3 months

Table 2. Specimen Details

Specimen	FRP thickness, t_p (mm)	FRP width, L_{per} (mm)	Bonded length, L (mm)	Test category
C1	1.2	50	300	Fully anchored
C2	1.2	50	300	Fully anchored
C3	1.2	50	20	Not fully anchored
C4	1.2	50	20	Not fully anchored
NS4	1.2	50	20	Not fully anchored
NS5	1.2	50	20	Not fully anchored
NS1	1.2	50	300	Fully anchored
NS2	1.2	50	300	Fully anchored
AS2-1	1.2	50	300	Fully anchored
AS2-2	1.2	50	300	Fully anchored
AS2-3	1.2	50	20	Not fully anchored
AS2-4	1.2	50	20	Not fully anchored

AS3-1	1.2	50	300	Fully anchored
AS3-2	1.2	50	300	Fully anchored
AS3-3	1.2	50	20	Not fully anchored
AS3-4	1.2	50	20	Not fully anchored

The specimens are subjected to 3 days of wet and 4 day of dry condition consecutively for the premeditated period of time. To accelerate corrosion activity, the portion of wet (68+-2^{o}C) and (32^{o}) cycle was chosen to give four complete cycles within 24-hours period. The simulation of offshore environment is illustrated in Fig. 8. As proposed by Ibrisam [8], steel block is formed by welding two 12 mm thick steel plate onto two 70 X 50 mm rectangular hollow sections. Before adhesive applying the adhesive, the test surfaces are sandblasted and cleaned with acetone to enhance the bonding capability. Then the specimens are left cured for overnight [6]. CFRP is glued at the centre of the steel bock with 2 sets of bonded length (20mm an 300mm) using Sika30 Adhesive. Several tiny steel rod of 1 mm diameter are glued to the steel surface before adhesive is laid out. Then, the FRP is pressed down onto the adhesive to ensure an even surface and adhesive thickness. While applying the adhesive, white tape was used on the steel uncovered surface to ensure the neatness of surface and equivalent dimension with CFRP Finally, the curing process takes place for 7 days by placing a weight of 25 kg on top of the CFRP to-steel-plate to promote even surface and thickness. Material properties of Sika Carbodur CFRP and Sika30 Adhesive are shown in Table 7 and Table 6, respectively. Then, a steel block with approximately weight of 25 kg was put on CFRP surface to apply some pressure for bonding to take place.

Figure 8. Sandblasting process

Figure 9. Fabricated steel block

Figure 10. Applying adhesive on steel member

Figure 11. Curing process with 25kg steel block on theCFRP plate.

The specimens from Group C are tested right after the 7-days curing, whereas for Group AS the testing will be conducted 7-days later upon the completion of their 1 month, 2 months, or 3 months submersion.

Prepared specimens were put under accelerated seawater taken from Lumut, Perak sea, with elevated heating to 60º. The conducted seawater effect conditioning must be resemblance to the tidal movement of actual seawater. For that reason, four days for wet cycle and three days for dry cycle of submersion are conducted [17]. During the dry cycle, seawater pumped out of the curing tank into reserve tank.

Figure 12: Curing Tank

Figure 13: Wet Cycle

Figure 14: Dry Cycle

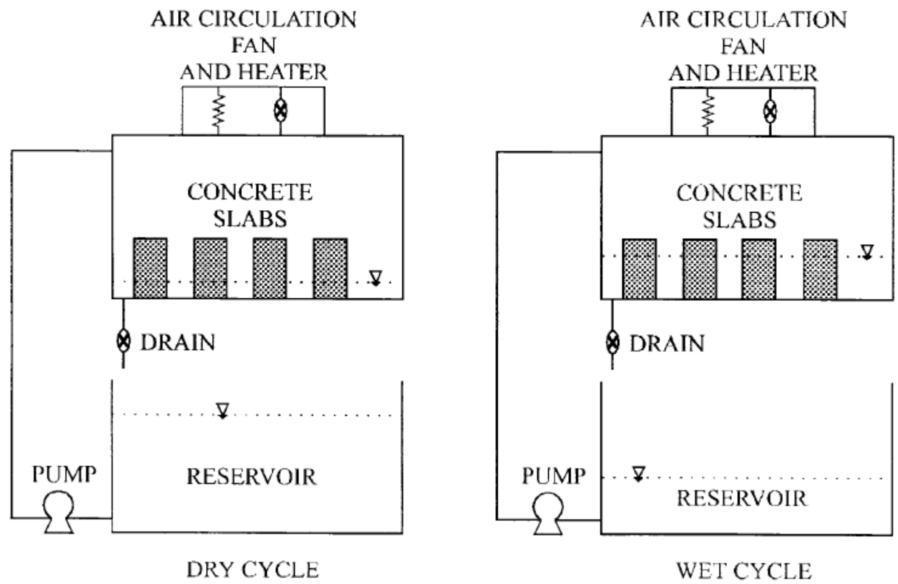


Figure 15: Schematic illustration of marine environment simulated set-up

3.2 Material Properties Testing

3.2.1 Carbon Fiber Reinforced Polymer (CFRP)

Two of three main materials used in the project, namely CFRP and adhesive were tested to obtain their mechanical properties for comparison with manufacturer's material properties. Five sample specimens from each material are tested using Gotech 100kN material testing machine.

Table 3: Material properties of Carbodur CFRP

Thickness (mm)	Tensile Strength (N/mm^2)	Tensile E-Modulus (N/mm^2)	Strain at Break (N/mm^2)
1.2	Mean Value: 3100	165000	>1.70%
	Min Value: >2800		
	5% Fractile-Value: 3000		
	95% Fractile-Value: 3600		

The carbon fiber reinforced polymer Sika CarboDur type S1014 prepared by Sika Corporation U.S. comes with a nominal thickness of 1.2 mm. It is a lightweight, unlimited length, high modulus of elasticity and non-corrosive material which make it fit for strengthening structural element. Characteristic of the dynamic tensile properties of the CFRP sheet was achieved by conducting tensile tests on Sika CarboDur specimens. The specimen's dimension and configuration, prepared accordance with ASTM: D3039 specification is illustrated in Fig.9 [18]. This test coupon is fabricated by cutting the sheet into specified dimension using shear machine. Aluminium is glued on both sides at the end of CFRP plate to avoid damage on gripping CFRP plates[19]. In addition, these tabs need to be sandblasted and cleaned with acetone prior to bonding to ensure contaminate-free surfaces. Surface-roughed tab provided a better contact friction with the machine grip and prevent slippage [20]. The CFRP specimens were tested by GoTech 100-kN Testing Machine with 10mm/min speed or $0.000334 \times 10^{-3}\ s^{-1}$ strain rate.

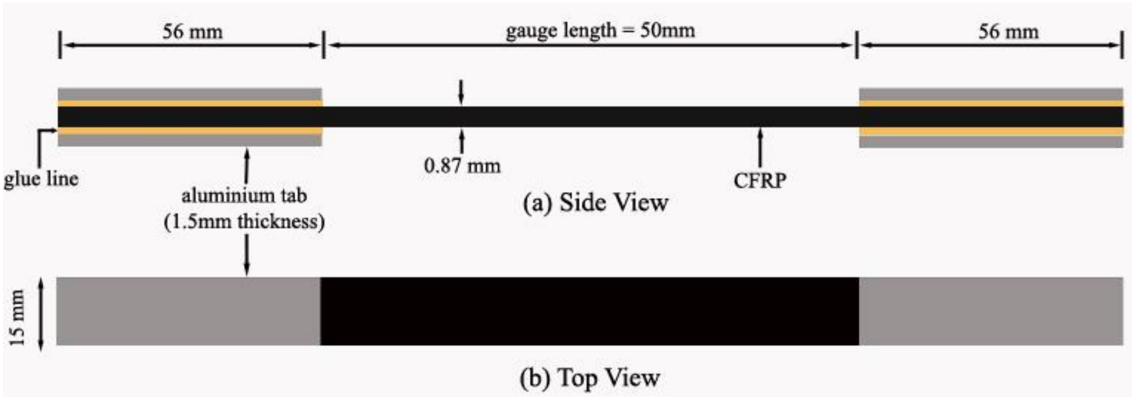


Figure 16: Configuration of CFRP plate for tensile testing

Figure 17: Gotech 100-kN tensile machine for testing of CFRP

3.2.2. Adhesive

Adhesive test samples were prepared in accordance to ASTM D638-10 using Sika30 Adhesive. [21]. The objective of this work is to study the mechanical behavior of an epoxy bi-component adhesive for structural bonding of CFRP plate and steel member. This Sikadur 30 epoxy resin is recommended to be used as external reinforcement onto CarboDur CFRP.

Table 4: Material properties of Sika30 Adhesive

<table>
<tr><th>Thickness (mm)</th><th>Tensile Strength (N/mm²)</th><th>Tensile E-Modulus (N/mm²)</th><th>Strain at Break (N/mm²)</th></tr>
<tr><td rowspan="3">1.2</td><td>Mean Value: 3100</td><td rowspan="3">165000</td><td rowspan="3">> 1.70%</td></tr>
<tr><td>Min Value: >2800</td></tr>
<tr><td>5% Fractile-Value: 3000</td></tr>
</table>

The geometry of the adhesive sample is clearly shown In Fig. 1a. A dog-bone mould made of Teflon, as shown in Fig. 10 was used for the specimen's preparation. Since the Teflon does not stick to adhesive [11], there was no need to use lubricant for the preparation which would react with adhesive epoxy and alter its mechanical properties. Sika30 Adhesive comes with two components namely A and B which are mixed together by 3:1 ratio. Following the pouring of the epoxy mixtures into the mould, the specimens were kept inside the mould for 2-3 days prior removing it. Then, the specimens were cured for 7-14 days according to the manufacturer's recommendation. [11]. Next, the specimens were employed with tensile test using Testometric materials testing machine. Strain gauges were placed at the central area within the gauge length of the specimens on both sides to measure the true strain during testing while the engineering strain was measured based on machine elongation measurement.

Figure 18: Mould for adhesive specimen’s preparation

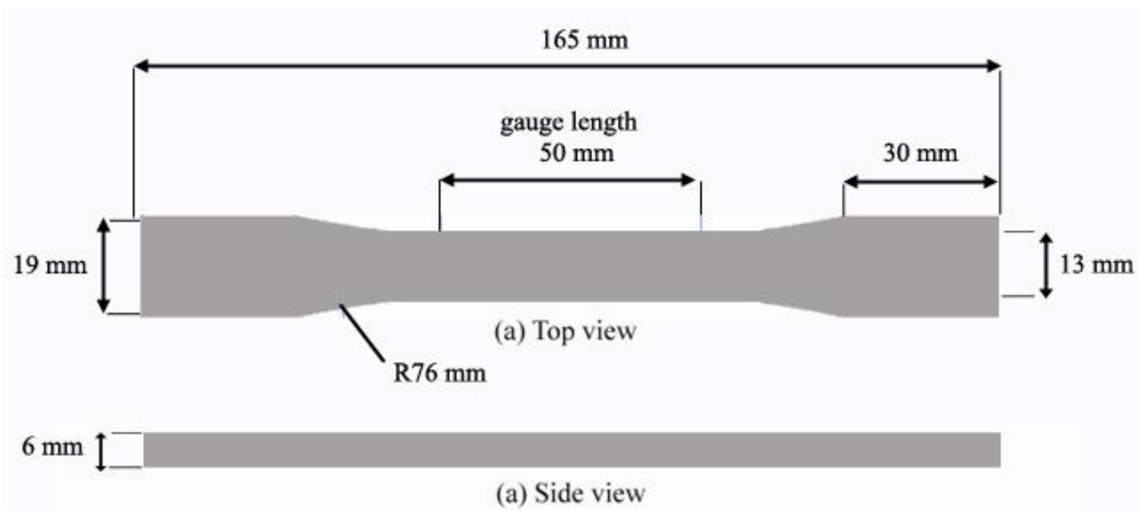


Figure 19: Schematic views of a dog-bone coupon

Figure 20: Test setups and instrumentation of dog-bone epoxy samples

3.2.3 Set-up and test method

The test method is designed to produce tensile property data for the control and specification of adhesive material. A number of five samples should be prepared and tested exactly the same way. Tensile test for CFRP specimens were performed using Testometric material testing machine at rate of 2mm/min [22]. The grips of the machine were clamped firmly onto the aluminum tab of the CFRP plate specimens to avoid slippage.

The width and thickness of the adhesive specimens is measured at the center of each specimen and within 5mm of each end of gauge length [21]. Then, the specimen was placed in the grips of the testing machine with the distance between the ends of the gripping surface of 115 mm. The grips were tighten evenly and firmly to prevent slippage of the specimen during the test. The speed of testing was set at 5 mm/min.

3.3 Pull Test Setup

A Universal Testing Machine (UTM) is used to conduct pull test in laboratory. The steel block is placed with CFRP-plated side facing upwards, while the bottom side of the steel is bolted to the UTP to minimize plate bending. Since the CFRP plate is too thin, two aluminum sheets (50mm X 50mm) with thickness of 2 mm is glued with both side of the CFRP to have a better grip and prevent CFRP plate from cracked by UTM clamp. L-shaped aluminum is glued on CFRP plate as a restrain mechanism for LVDT. The L-shaped aluminum will press the LVDT downward and the slip reading will start out. Whilst the bottom of steel block is bolted to UTM, concurrently the end of CFRP plate is pulled out and the displacement recorded by linear variable differential transformer (LVDT) is taken. Strain gauges are positioned 20 mm away from the load end. This is to provide information on CFRP plates Young's Modulus from the stress-strain curve derived from load and strain data.

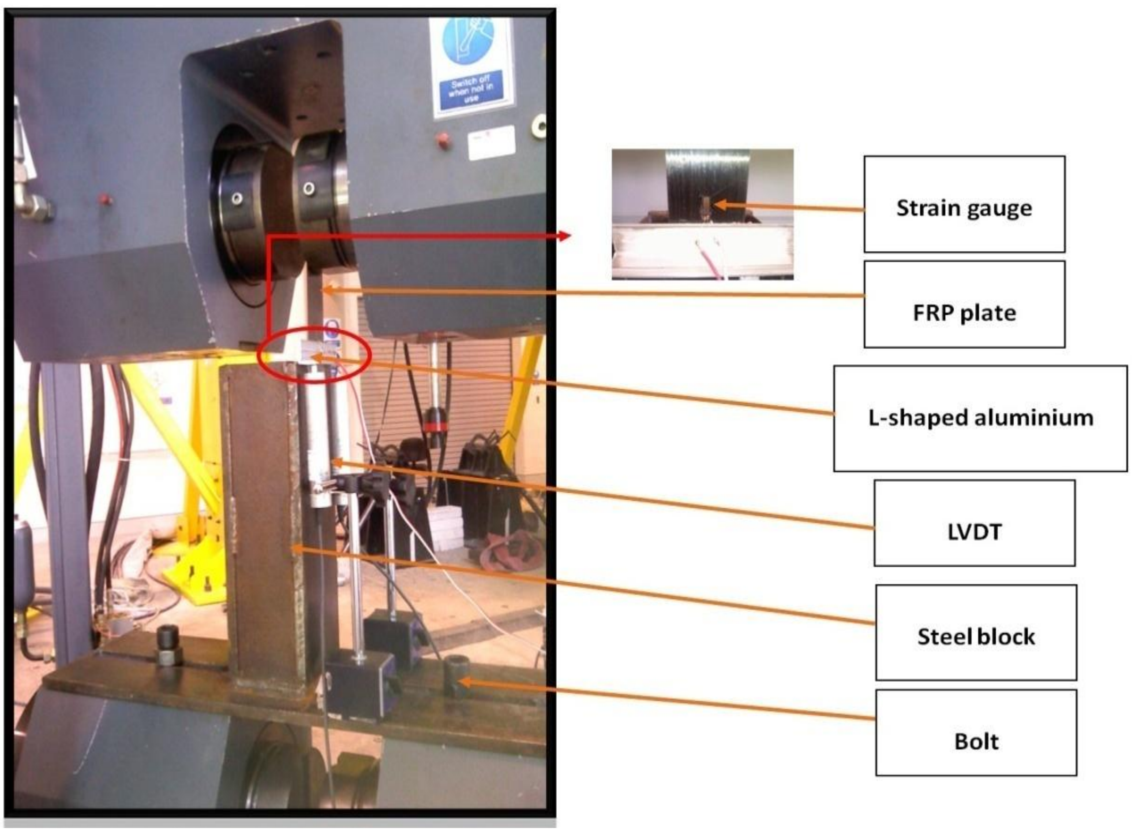


Figure 21: Assembly and configuration of CFRP-plated steel specimen ready to be tested

3.3 Gantt Chart

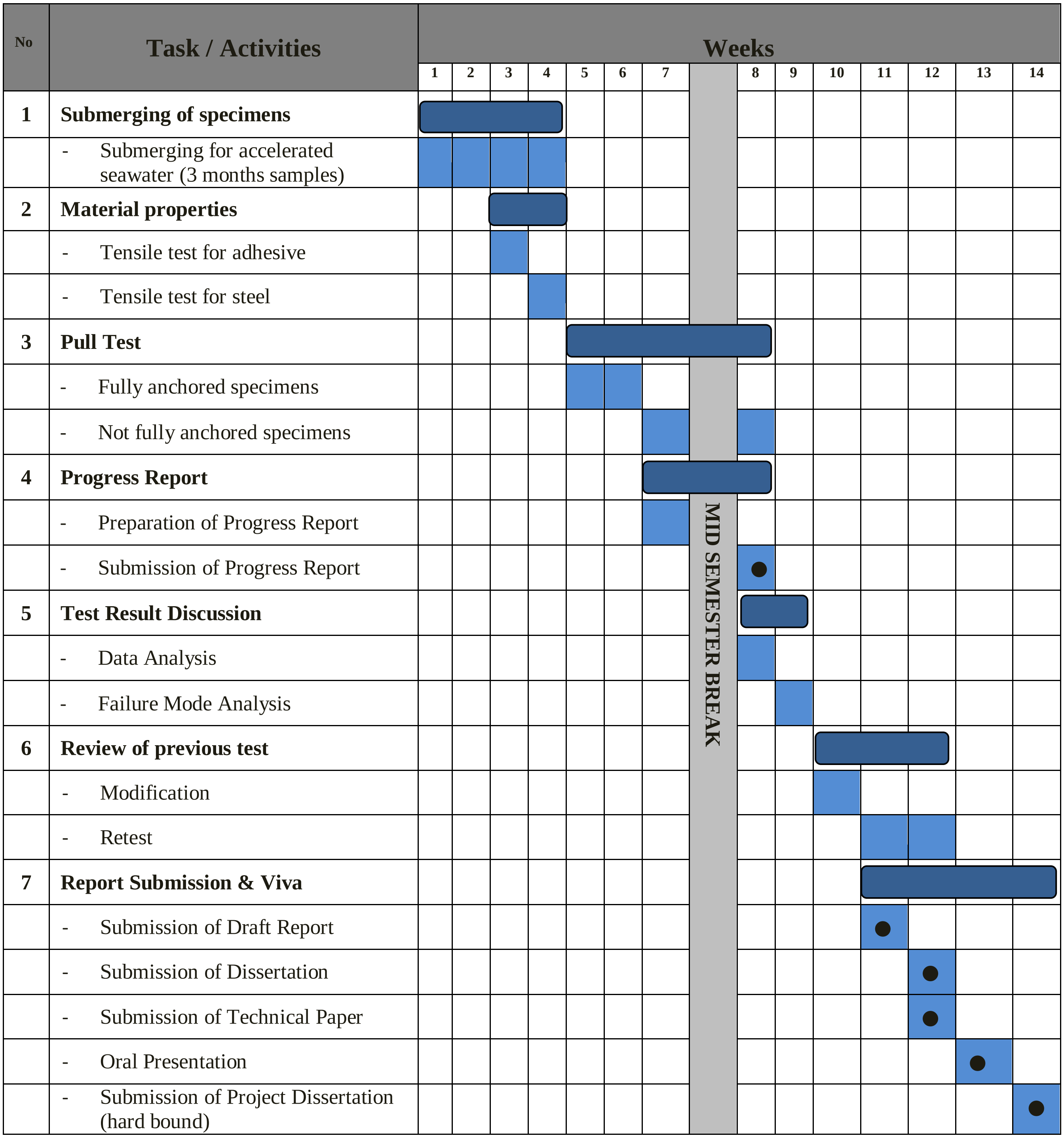


Figure 22: Gantt Chart and key milestones for continuation of project on FYP II

RESULT AND DISCUSSION

4.1 Material Properties

The tensile properties of SikaCarbodur S1014 CFRP and Sika30 Adhesive supplied by the manufacturer are shown in Table 2.

Table 5: Tensile properties from manufacturer's product datasheet

	SikaCarbodur S1014 CFRP	**Sika30 Adhesive**
Tensile Strength	2,800 Mpa	24.8 Mpa
Elongation at Break	1.69%	1%
Modulus of Elasticity	160 Gpa	4.48 Gpa

A typical load-displacement curve is obtained from the tensile test of Sika 30 Adhesive. The result of the test from five sample specimens is drawn in Fig. 23 and 24. In this graph, each curve represents specimen sample no.1, sample no. 2, and sample no. 3, no.4 and no. 5, respectively. The tensile properties results are clearly shown in Table 6. Sika 30 Adhesive is considered as a brittle material. This statement is clearly indicated by the absence of plastic deformation range from load-displacement curve which show linear behavior up to peak force followed by dropping.

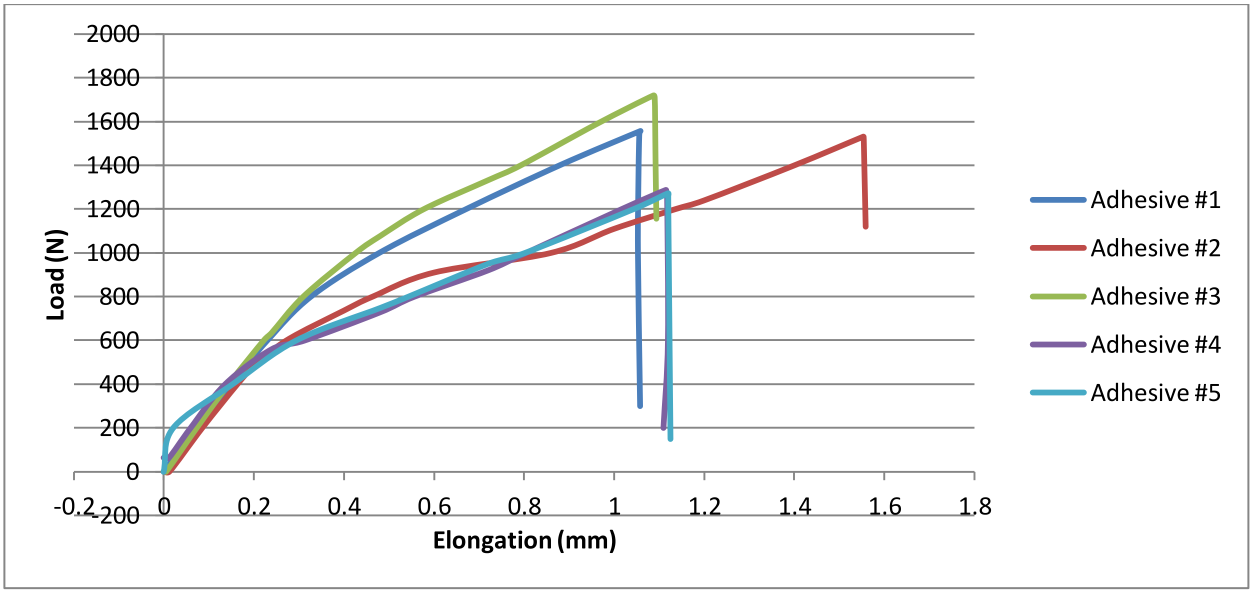


Figure 23: Load displacement curve of Sika30 Adhesive

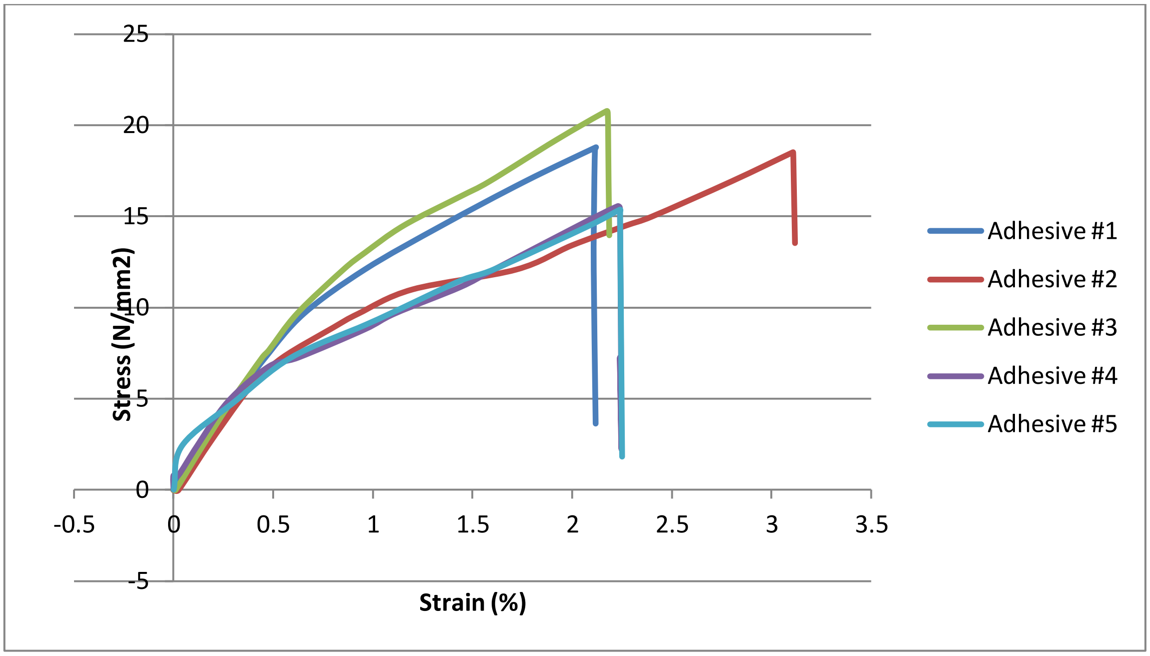


Figure 24: Stress-strain curve Sika30 Adhesive

Table 6: Tensile properties of Sika30 Adhesive specimens

	Elongation @ Break	Force @ Break	Strain @ Peak	Stress @ Peak	Elongation @ Peak
	(mm)	(N)	(%)	(N/mm2)	(mm)
	1.059	1555	2.098	18.788	1.049
	1.56	1525	4.097	18.425	1.549
	1.094	1720	2.175	20.781	1.088
	1.34	1605	2.55	21.627	1.344
	1.21	1595	3.01	19.114	1.11
Average	**1.25**	**1600**	**2.79**	**19.75**	**1.23**

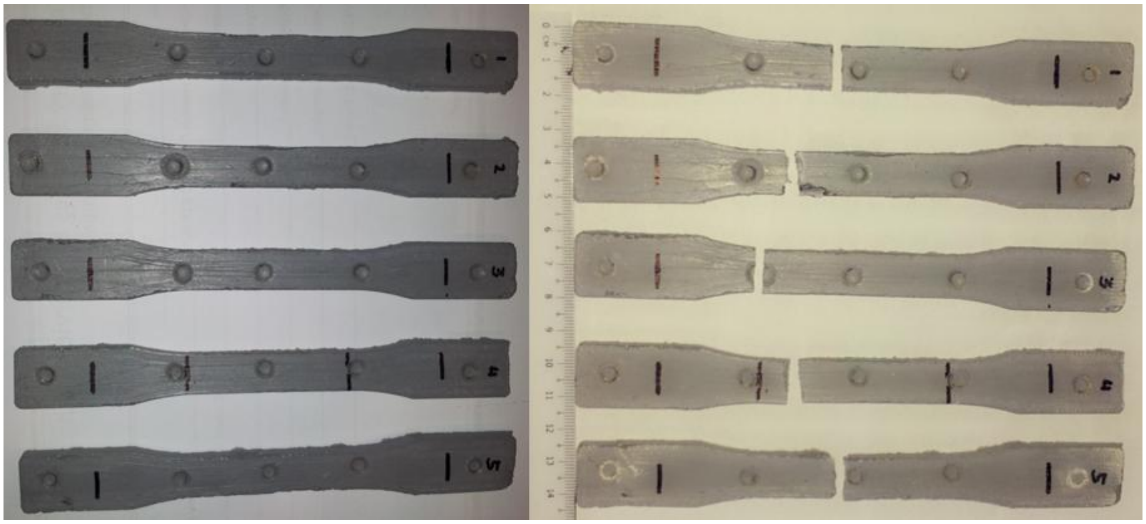


Figure 25: Failure mode of Sika30 Adhesive

Fig. 25 illustrates the failure mode of Sika 30 Adhesive following the tensile testing. All specimens undergo plastic deformation without any yielding since the material is a rigid material. Be reminded that the break of the specimen must occur within the gauge length of the specimen. Gauge length is where the specimens elongated and eventually snap. Any test that break outside the gauge length should be discarded [21].

The modulus of elasticity of any material indicates its stiffness. The Modulus of elasticity or Young's Modulus is calculated using the following formula:

$$Modulus\ of\ Elasticity, E = \frac{F/A_0}{\Delta L/L_0}$$

$$E = \frac{1277\ N/86.508\ mm^2}{1.117\ mm/164\ mm}$$

$$E = \mathbf{2.167\ Gpa}$$

Five Sika Carbodur CFRP specimen for material properties testing were tested. The result of the experiments are clearly shown below

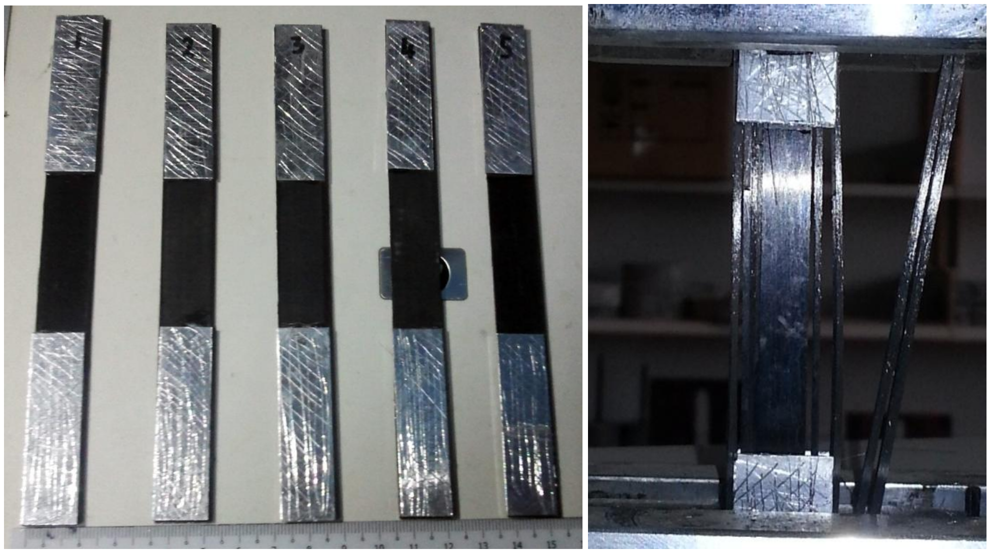


Figure 25: CFRP coupons prior to the tensile test and failure of CFRP under tensile loading

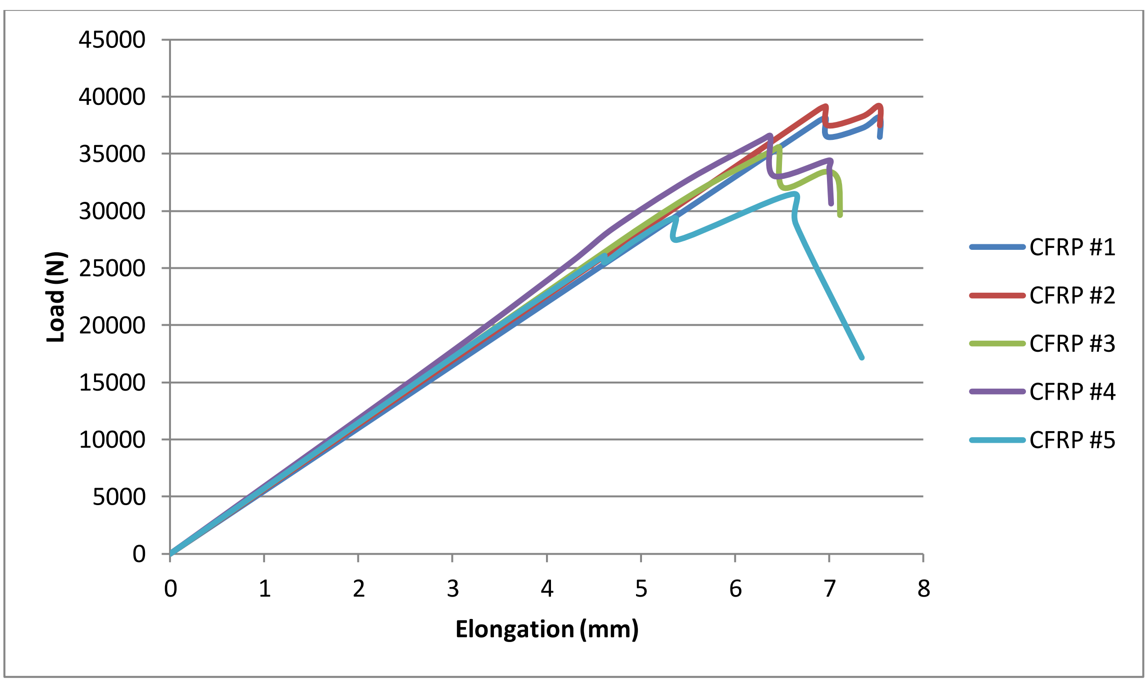


Figure 26: Load-displacement curve of CFRP

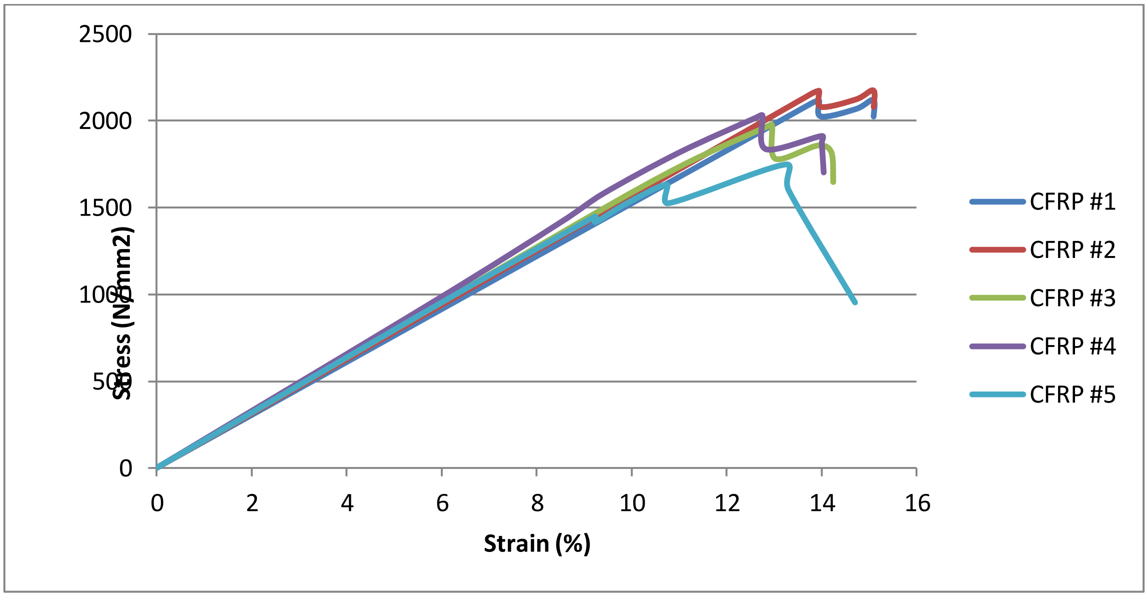


Figure 27: Stress-strain curve of CFRP

Table 6: Tensile properties of CFRP coupons

Elongation @ Break	Force @ Break	Strain @ Peak	Stress @ Peak
(mm)	(N)	(%)	(N/mm2)
7.539	38177.57	15.078	2120.98
7.54	39177.6	15.08	2176.53
6.475	35578.5	12.95	1976.6
6.375	36578.5	12.75	2032.14
6.62	31479.3	13.24	1748.85
6.91	**36198**	**13.82**	**2011.02**

Modulus of Elasticity or simply Young's Modulus is the measure of a material stiffness. Due to limitation of the tensile machine in the laboratory, in which they only provide Load-displacement graph, the measuring of stress over strain had been done by using manual method by taking each point in the load-displacement graph and inserts it into spreadsheet for graph generation.

To obtain stress, the average force is divided by the cross section area of 18 m2. Whereas, the strain percentage is acquired by division of elongation lenght and initial gauge length. The calculation for determining Young's Modulus is provided below:

$$Modulus\ of\ Elasticity, E = \frac{F/_{A_0}}{\Delta L/_{L_0}}$$

$$E = \frac{Stress}{Strain}$$

$$E = \frac{2011.02\ N/mm2}{13.82}$$

$$E = \mathbf{145.52\ Gpa}$$

Comparing the above result with Al-Zubaidy [11]'s mechanical properties, which using the same dimension and configuration of CFRP with this experiment, the tensile strength obtained from this experiment shows significant similarity (with slightly higher) with Al-Zubaidy's tensile test results. Based on Table 7(a), the specimen with 0.000242 s^{-1} CF130 CFRP specimens resulted in 1,934.82 MPa which is 96.65% match with Sika Carbodur CFRP used in this experiment.

Table 7(a): Tensile strength of CFRP sheet under various strain rates CFRP tests at different loading rates [11]

Strain rate	Tensile strength (MPa)					
	0.000242 s^{-1}	31.32 s^{-1}	42.02 s^{-1}	54.2 s^{-1}	67.2 s^{-1}	87.4 s^{-1}
Specimen1	1886.83	2116.54	2277.04	2254.42	2307.94	2826.37
Specimen2	1974.74	1925.73	2244.37	2251.15	2398.86	2586.11
Specimen3	1973.95	2182.33	2074.09	1995.38	2567.54	2535.06
Specimen4	1812.69	2175.54	2254.04	2644.38	2317.87	3093.66
Specimen5	2025.90	2142.90	2280.42	2527.94	2510.27	2794.91
Average	1934.82	2108.61	2225.99	2334.65	2420.50	2767.22
C.O.V. (%)	4.37	5.01	3.88	10.96	4.77	8.03

Table 7(b). Modulus of elasticity of CFRP sheet under various strain rates CFRP tests at different loading rates [11].

Modulus of elasticity (GPa)					
0.000242 s^{-1}	31.32 s^{-1}	42.02 s^{-1}	54.2 s^{-1}	67.2 s^{-1}	87.4 s^{-1}
211.14	229.99	232.62	239.01	238.21	252.00
203.28	210.50	225.09	240.94	239.08	254.91
203.31	230.24	227.07	247.29	241.32	243.97
211.24	225.47	233.40	242.14	253.07	244.69
204.27	223.73	233.94	243.90	249.15	257.71
206.65	223.99	230.42	242.66	244.17	250.94
2.02	3.59	1.76	1.30	2.70	2.44

However, the modulus of elasticity of elasticity result shows a variation with Al-ZUbaidy's. The modulus of elasticity value for this experiment only 145.52 GPa compared to 206.65 GPa by the previous experiment.

4.2 Pull Test Experiment

Submersion of the specimens prior to pull test will demonstrate the actual saltwater condition and its effect toward debonding of CFRP-plated steel. The variation of the submersion periods (1, 2, 3 months) will give a better insight towards the reaction of galvanic corrosion of the CFRP-to-steel. The failure modes, as well as bond-slip relationship of CFRP-to-steel under saltwater condition can be investigated by conducting pull test.

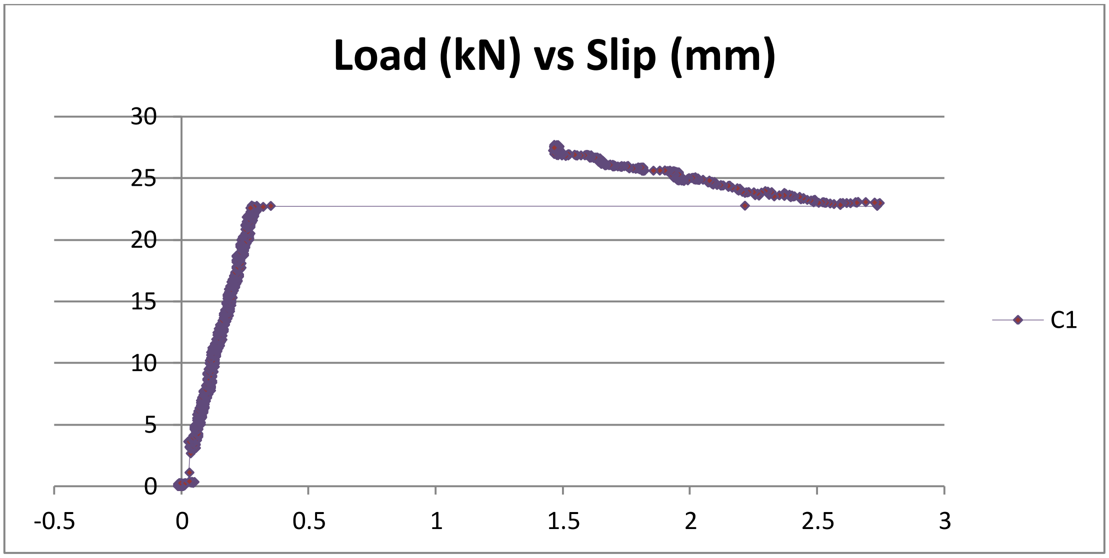


Figure 28: Load (kN) VS Slip (mm) for controlled specimen

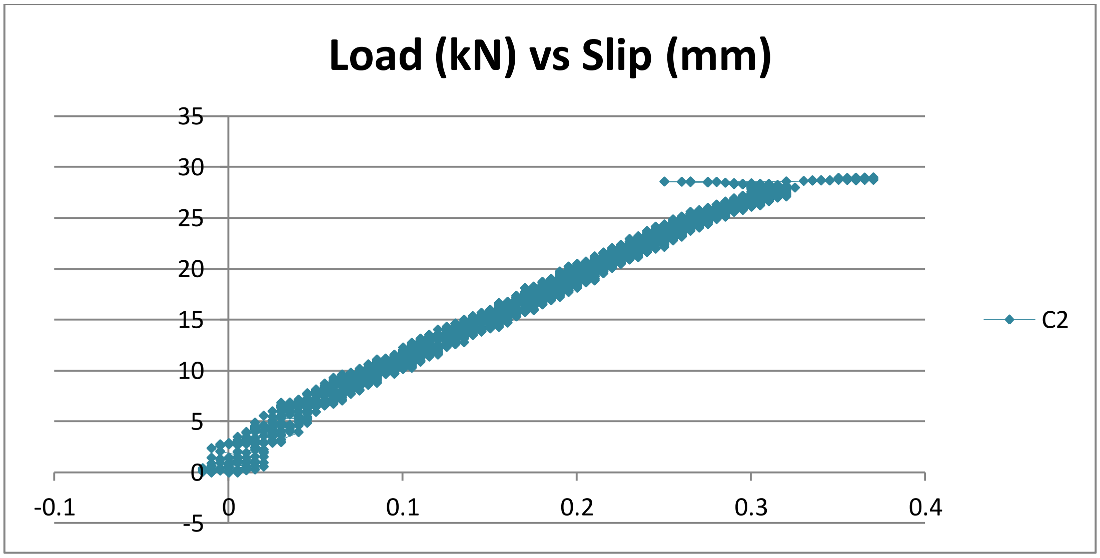


Figure 29: Load (kN) VS Slip (mm) for controlled specimen

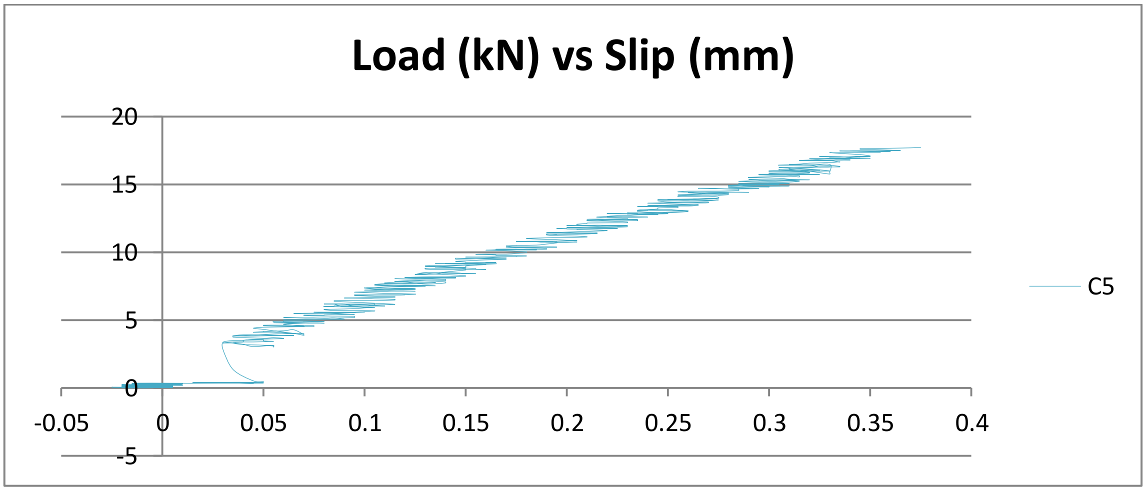


Figure 30: Load (kN) VS Slip (mm) for controlled specimen

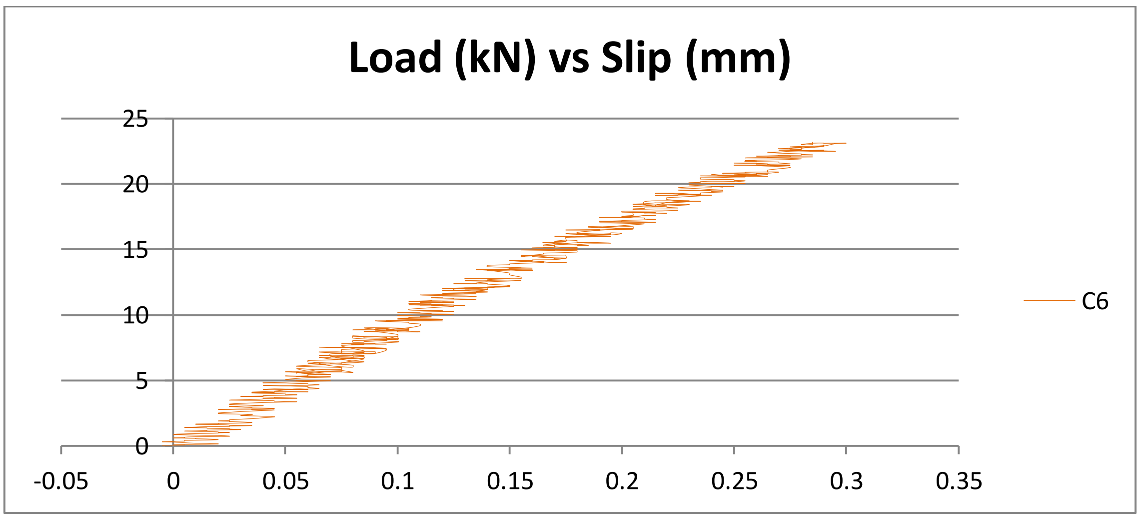


Figure 31: Load (kN) VS Slip (mm) for controlled specimen

Table 7: Test result for fully anchored and not-fully anchored control specimen

Specimen	**Debonding Load, P_{IC} (kN)**	**Slip (mm)**
C1 (Fully Anchored	21.647	0.275
C2 (Fully Anchored)	26.995	0.315
C3 (Not fully anchored)	17.728	0.375
C4 (Not fully anchored)	23.172	0.285

Figure 32: The failure modes of controlled specimens (fully anchored and not fully anchored)

Base from the observation, for the fully anchored specimens, the failure mode is identified as CFRP rupture and adhesive interfacial debonding. While for the not fully anchored specimens, the mode of failure can be identified as CFRP delamination which quite similar with fully anchored specimens. There is also minor CFRP rupture on specimens compared to the fully anchored specimens.

From the modifications that have been done on the specimen's preparation, all specimens for both set show similar modes of failures. Basically the failure modes are expected to come from the failure of adhesive because the strength of adhesive is much lower compared to steel and CFRP, based on material properties testing conducted.

Furthermore, from the data obtained, the P_{IC} values of fully anchored specimen ranging from 21.647kN to 26.995kN while the failure loads for not fully anchored specimens range from 17.73kN to 23.172kN. The slips for both set of specimens show inconsistency of result where the slip for fully anchored range from 0.175mm to 0.315mm and the slip for not fully anchored range from 0.285mm to 0.375mm.

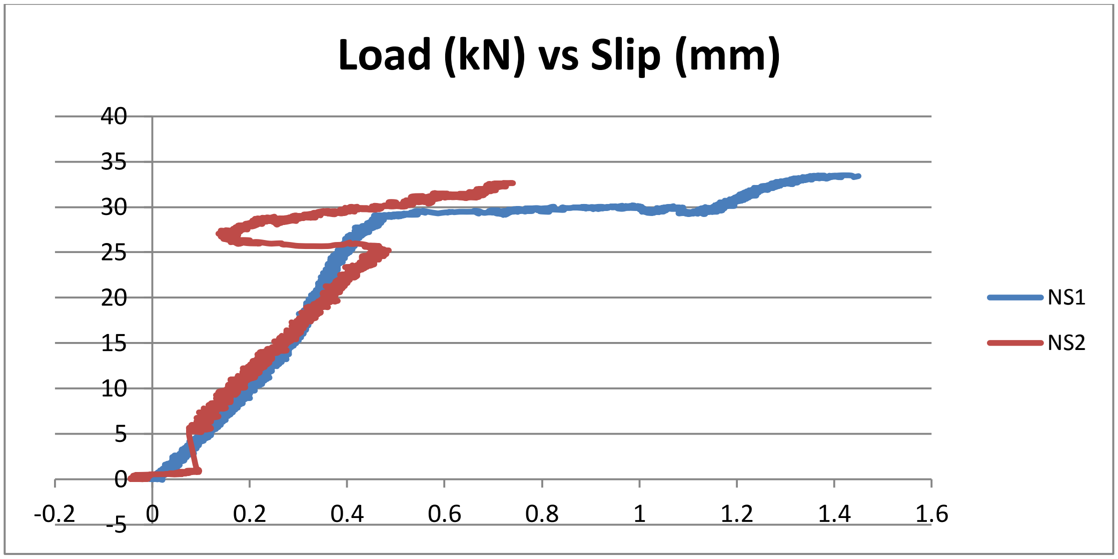


Figure 33: Load-slip curve for accelerated seawater of 1 month submersion for fully anchored specimen

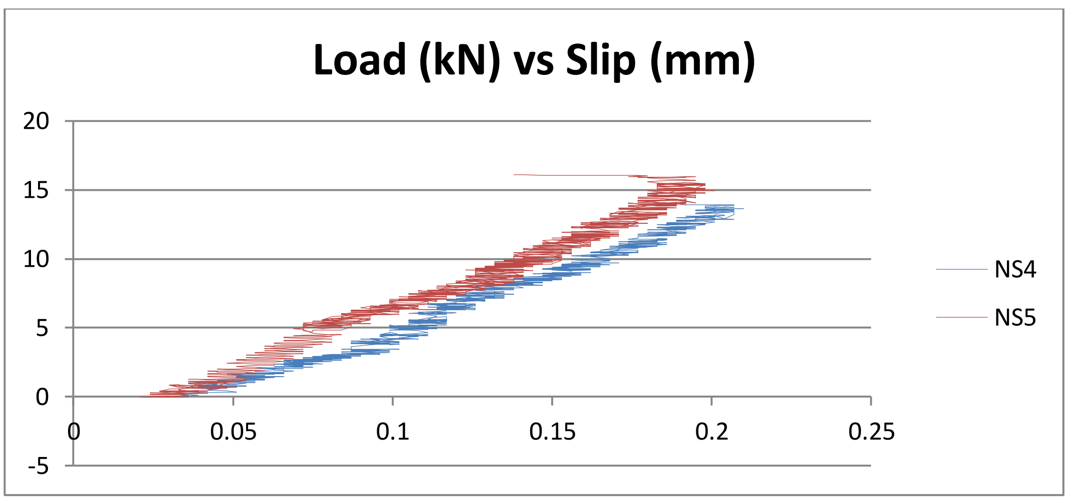


Figure 34: Load-slip curve for accelerate seawater of 1 month submersion for not fully anchored specimen

Table 8: Test result for fully anchored and not-fully anchored control specimen

Specimen	Debonding Load, P_{IC} (kN)	Slip (mm)
NS1 (Fully anchored)	27.754	0.455
NS2 (Fully anchored)	24.537	0.46
NS4 (Not fully anchored)	13.921	0.192
NS5 (Not fully anchored)	16.096	0.138

Figure 35: Failure mode of 1 month acclerated sea water for fully anchored specimen

Figure 36: Failure mode of 1 month acclerated sea water for not fully anchored specimen

Following submersion for 1 month under seawater environment, all 4 specimens have undergone pull test. For the fully anchored specimens, the mode of failure can be identified due to FRP rupture, adhesive interfacial debonding and there are delamintaion occur at the end of the bonded area. While for the not fully anchored specimens, the mode of failure can be identified as FRP delamination which quite similar with fully anchored specimens from previous experimentation. There is also minor FRP rupture on specimens compared to the fully anchored specimens.

The data obtained of P_{IC} values range from 24.537kN to 27.754kN while the failure loads for not fully anchored specimens range from 13.921kN to 16.1kN. The slips for both set of specimens show consistency of result where the slip for fully anchored range from 0.43mm to 0.46mm and the slip for not fully anchored range from 0.138mm to 0.192mm.

Based on the results achieved on pull test for both sets of specimen, the modes of failure show similarity where the most failure comes from adhesive. It shows that the strength of adhesive is lower than FRP and steel. For the fully anchored specimens, the mode of failure can be identified due to FRP rupture and adhesive interfacial debonding. While for the not fully anchored specimens, the mode of failure can be identified as FRP delamination.

In term of strength the seawater did not affect on the bonding between FRP and steel but in term of stiffness there are much affected. It shows that the result obtained justified the bond-slip relationship graph where the value of d_1 increased due to the affect on stiffness. While the maximum shear stress (t_{max}) and the interfacial fracture energy (*Gf*) which represents the P_{IC} value does not affected at all.

CONCLUSION

The experimental material properties for Sika30 Adhesive show a slight variation compare to those provided by manufacturer. It was possibly due to curing process, uneven surface preparation, presence of impurities during wet lay, or other conditioning factor such as temperature and/or humidity. With 90.56% of stipulated tensile strength achieved, the material properties experiment for Sika30 Adhesive is considered successful. On the other hand, tensile test result for Sika Carbodur CFRP gave a quite significant variation compared to manufacturer's datasheet. The experimental specimen resulted only 81.4% of the presumed value. This is quite alarming outcome as the variation is quite big. However, the value of tensile strength obtained in this experiment is identical with Al-Zubaidy's material characterization test. But bear in mind that Zubaidy's experiment is purposely to investigate the effect of different strain rate on material's strength, not to be compared with product datasheet. Hence, CFRP tensile test will be re-conducted, with different preparation, curing period, and testing speed. If the result obtained is still does not achieved the desired value, the manufacturer will be contacted to report the issue.

As a conclusion, thorough preparation of all specimens must be done properly to lessen the unexpected problems in future. More pull test experiments are needed to obtain plateau, hence will obtain the consistent P_{IC} value. The condition of the laboratory instrument should be in good condition and ready especially the LDT which is very prone to false reading when measuring slip.

The effect of seawater shows small significant effect on debonding of CFRP-plated steel. The result for not fully anchored specimen did not shows any major increase in term of strength. This is due to short bonded length lower than critical length.

The experiment for accelerated seawater specimen for 2 months and 3 months will be conducted soon in order to effectively investigate the seawater effect towards CFRP-plated steel member.

REFERENCES

[1] P. Colombi and C. Poggi, "Strengthening of tensile steel members and bolted joints using adhesively bonded CFRP plates," *Construction and Building Materials,* vol. 20, pp. 22-33, 2006.

[2] J. G. Teng*, et al.*, "Strengthening of steel structures with fiber-reinforced polymer composites," *Journal of Constructional Steel Research,* vol. 78, pp. 131-143, 2012.

[3] G. O. Buyukozturk O, Karaca E, "Progress on understanding debonding problems inreinforced concrete and steel members strengthened using FRP composites," *Construction and Building Materials,* pp. 9-19, 2003.

[4] O. Buyukozturk*, et al.*, "Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites," *Construction and Building Materials,* vol. 18, pp. 9-19, 2004.

[5] R. Sen*, et al.*, "Strengthening steel bridge sections using CFRP laminates," *Composites Part B: Engineering,* vol. 32, pp. 309-322, 2001.

[6] S. Fawzia, "Evaluation of shear stress and slip relationship of composite lap joints," *Composite Structures,* vol. 100, pp. 548-553, 2013.

[7] S. H. Xia and J. G. Teng, "Behaviour of FRP-to-steel bonded joints," *International Institute for FRP in Construction,* pp. 411-418, 2005.

[8] I. Akbar*, et al.*, "Derivation of the bond–slip characteristics for FRP plated steel members," *Journal of Constructional Steel Research,* vol. 66, pp. 1047-1056, 2010.

[9] X. Jiang*, et al.*, "Study on mechanical behaviors of FRP-to-steel adhesively-bonded joint under tensile loading," *Composite Structures,* vol. 98, pp. 192-201, 2013.

[10] K. Narmashiri*, et al.*, "Failure analysis and structural behaviour of CFRP strengthened steel I-beams," *Construction and Building Materials,* vol. 30, pp. 1-9, 2012.

[11] H. Al-Zubaidy*, et al.*, "Mechanical Behaviour of Normal Modulus Carbon Fibre Reinforced Polymer (CFRP) and Epoxy under Impact Tensile Loads," *Procedia Engineering,* vol. 10, pp. 2453-2458, 2011.

[12] X. Z. Lu*, et al.*, "Bond–slip models for FRP sheets/plates bonded to concrete," *Engineering Structures,* vol. 27, pp. 920-937, 2005.

[13] R. S. M. Seracino R, Oehlers DJ, "Generic debonding resistance of EB andNSMplate-to-concrete joints," *Composite for Constructions,* vol. 11(1):62-70, 2007.

[14] Ş. Erdoğdu*, et al.*, "Accelerated testing of plain and epoxy-coated reinforcement in simulated seawater and chloride solutions," *Cement and Concrete Research,* vol. 31, pp. 861-867, 2001.

[15] ASTM-D1141, "Standard Specification for Substitute Ocean Water," *ASTM International,* 1975.

[16] K. Liao*, et al.*, "Effects of environmental aging on the properties of pultruded GFRP," *Composites Part B: Engineering,* vol. 30, pp. 485-493, 1999.

[17] H. A. Toutanji and W. Gómez, "Durability characteristics of concrete beams externally bonded with FRP composite sheets," *Cement and Concrete Composites,* vol. 19, pp. 351-358, 1997.

[18] ASTM:D3039/D3039M-08, "Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials," *ASTM International,* vol. 15.03, 2008.

[19] X. L. Z. Haider Al-Zubaidy, Riadh Al-Mihaidi, "Mechanical behaviour of normal modulus carbon fibre reinforced polymer (CFRP) and epoxy under impact tensile loads," *Engineering Procedia,* 2011.

[20] K. Wang*, et al.*, "Mechanical properties of pultruded carbon fibre-reinforced polymer (CFRP) plates at elevated temperatures," *Engineering Structures,* vol. 33, pp. 2154-2161, 2011.
[21] ASTM-D638-10, "Standard Test Method for Tensile Properties of Plastics," *ASTM International,* 2010.
[22] T.-C. Nguyen*, et al.*, "Durability of steel/CFRP double strap joints exposed to sea water, cyclic temperature and humidity," *Composite Structures,* vol. 94, pp. 1834-1845, 2012.