# CHAPTER 4

# MECHANICAL PERFORMANCE OF CFRP PULTRUDED PLATE EXPOSED TO TROPICAL CONDITIONS

## 4.1 Introduction

The technical background knowledge and experiences pertaining to FRP materials, FRP structures behaviour under certain load cases and the factors contributing to the durability performances must be seriously looked at when applied the FRP composites into service. In Malaysia, most engineers are not aware of factors such as moisture/solution diffusion, thermal fluctuation, creep/relaxation, fatigue, alkali, fire and solar ultra-violet ray effects on FRP structures performances. These effects can either be under static load, dynamic load or under long-term exposure to natural weather or aggressive environments. Therefore, a comprehensive and reliable FRP composites database is needed to support the engineers in their respective fields.

In this chapter, the discussion focuses on the outcomes of tensile test on the experimentation specimens of CFRP plate that were exposed to tropical environmental conditions. The in depth discussions look into the mechanical and physical characteristics relationship between exposed specimens compared to the control ones.

## 4.2 Study Objective

The main objective of the experiment was to study the mechanical and physical properties of CFRP plates that were exposed to tropical environmental conditions. In addition, exposure to actual weather conditions in the tropical environment was seriously looked at in this study. The mechanical properties evaluation was made for comparison between the control and those exposed specimens to identify the effect of exposure condition on CFRP plate system. Among the results that were analyzed and discussed in this chapter are as follows;

i. Failure load;
ii. Tensile strength and modulus;
iii. Failure modes.

## 4.3 Scope of study

The scope of this study covered the following topics;

i. Literature study on the FRP material for structural applications (as discussed in Chapter 2);
ii. Literature study on the durability performances of FRP material exposed to various conditions (as discussed in Chapter 2);
iii. Specimen preparation and preliminary load test;
iv. Specimen experimentation and load test;
v. Results and discussions;
vi. Conclusions.

## 4.4 Methodology

The literature studies were carried out by sourcing the related information from journals, handbooks, books and theses. Firstly, literature review was carried out to understand the mechanical characteristics of the FRP composites system used in various structural applications. Then, the studies focused on the CFRP pultruded plate being used for rehabilitation of reinforced concrete members around the world. The suitable tensile test with standard specimen preparation procedure has also been investigated to suit with CFRP plate material system (i.e. high tensile strength grade).

The CFRP in the form of plate was cut into standard size to suit with standard test method. The prepared specimens were exposed to four designated tropical conditions, namely; Laboratory (CPLTUS-LB and CPLTUS50-LB), Outdoor (CPLTUS-OD and CPLTUS50-OD), Plain Water (CPLTUS-PW and CPLTUS50-PW: wet/dry) and Salt Water (CPLTUS-SW and CPLTUS50-SW: wet/dry). For the specimens being exposed to designated conditions of salt water and plain water environment, they had undergone 7 days of being wet followed by 7 days of being dry for 24 cycles. All the specimens were exposed for six months. After the completion of experimentation works, the specimens were taken to the materials testing laboratory for load test and loaded up to failure. The tensile test was carried out by using Instron Universal Testing Machine Series IX Model 4206. The fracture surface of the test specimens for each exposure condition was visually evaluated for analysis.

The specimen raw data were gathered from the instrumented measurement system that was connected directly to strain gauges being installed to the specimen. The specimen failure mechanism was observed during the testing and visual analysis was done to investigate in depth the source of failure mechanism. All the findings and results from the experiment were discussed and compared with previous research where necessary.

### 4.5 Specimen Preparation

The CFRP plate specimen had undergone various stages that needed very strict handling procedure during preparation. This was due to the limited amount of material supplied by Exchem Limited from United Kingdom. Therefore, each test was only limited to three specimens and each specimen needed a very careful handling as well as good finishing quality. The detailed descriptions of specimen preparation are described in the following sections.

### 4.5.1 Material Details

The CFRP pultruded plate used was Selfix Carbofibe. The plate was supplied by Exchem, EPC Group, United Kingdom. The list of CFRP plate properties used in the experimentation programme is shown in Table 4.1. Referring to the supplier's Technical Specification Brochure [35], the supplied CFRP plate consisted of a minimum of 68% carbon fibre (unidirectional form) by volume fraction. The plate was manufactured through Pultrusion processing technique. In this manufacturing process, the carbon fibre tows were aligned through the resin bath, wetted with Bisphenol A vinyl ester resin matrix. The plate was cured through heated temperature controlled die. Finally, the plate was supplied in roll form with peel ply on both their faces. During the application stage, the peel ply was removed from the plate before being bonded to the other adherend material. The plate bond surface was able to provide an excellent adhesion without any treatment prior to bonding.

In this study programme, the supplied CFRP plate came with a standard width of 50 mm. The plate was cut into pieces of 250 mm long by using hydraulic bandsaw machine prior to being cut into three equivalent width of 15 mm by using high speed steel slitting cutting saw with the diameter of 75 mm and thickness of 1.5 mm at the speed of 190 rpm as shown in Fig. 4.1 (a) and (b). The final quality and condition of CFRP plate after cutting is shown in Fig. 4.1 (c).

**Table 4.1:** Typical properties of Selfix Carbofibe Pultruded CFRP plate type S [35]

| Tensile strength (MPa) | Tensile Modulus (GPa) | Thickness (mm) | Fibre volume fraction (%) |
|---|---|---|---|
| 2800 | 150 | 1.4 | 68 (minimum) |

(a)

(b)

(c)

**Fig. 4.1 (a):** CFRP plate cut by hydraulic band saw machine, **(b):** CFRP plate cut into three equivalent widths and, **(c):** CFRP plate with marking after cutting process

### 4.5.2 CFRP Plate Specimen Geometry

The geometry of the tensile test of the CFRP plate specimen is shown in Fig. 4.2. The standard geometry of the test specimen was referred to ASTM D3039/3039M [78]. In this research programme the aluminium end tab was used to overcome premature failure around the loading machine jaw gripping region. A square type aluminium tab was used and was proven to be of no significant difference with tapered type [79].

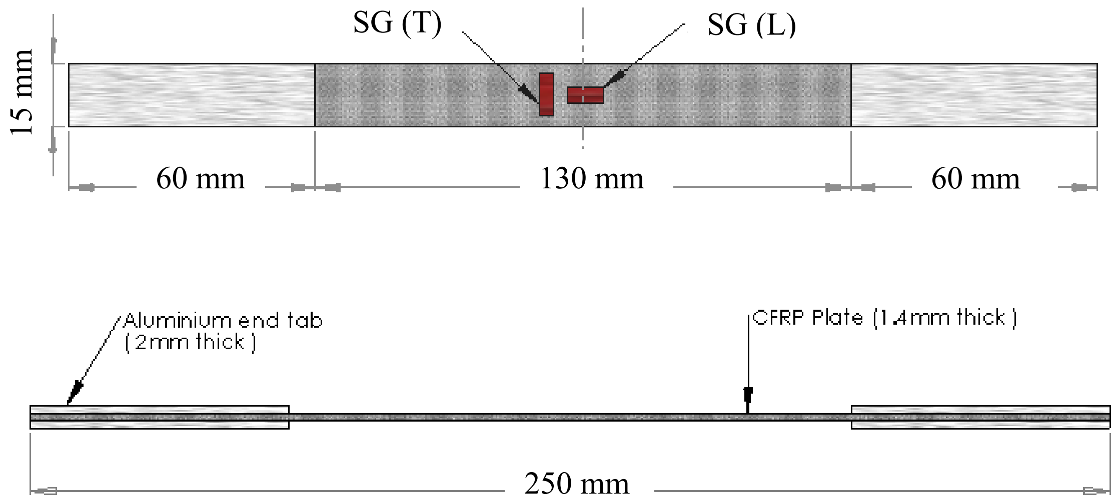



**Fig. 4.2:** CFRP plate tensile test specimen geometry

### 4.5.3 End Tabs and Bonding Adhesive

In order to overcome through-thickness plane weakness of CFRP plate specimen during loading, aluminium plates were bonded to both sides of the specimen. The bonding process was conducted by controlling the adhesive thickness and pressure by using a specially designed rig, as shown in Fig. 3.1 (section 3.2.1.1: Chapter 3). The room temperature cured epoxy adhesive Sikadur 30, and a rectangular 60 mm long *x* 2 mm thick of aluminium was used. The Sikadur 30 is a two parts epoxy adhesive system that is particularly suitable for the application of bonding of FRP plate to concrete, steel, wood or bricks. The adhesive system offers good mechanical properties as well as good chemical resistance against aggressive environment. The important adhesive mechanical properties are shown in Table 4.2.

**Table 4.2:** Typical properties of Sikadur 30 epoxy adhesive system [80]

| Compressive strength (MPa) | Adhesive strength on steel (MPa) | Adhesive strength on concrete (MPa) | Tensile modulus (GPa) |
|---|---|---|---|
| > 80 | > 26 | > 4 (concrete failure) | 12.8 |

### 4.5.3.1 End Tabs Preparation

The aluminium plate used for CFRP plate specimen end tabs that came with a standard 2 mm thick was cut into size of 15 mm width *x* 60 mm long by using hydraulic saw machine. Prior to bonding the tab surface were roughened by grit sandblasting using alumina grade grain size of 85 and blasting air pressure set at 35 psi (0.24 MPa). Acetone solution was used to remove dust or dirt after the process. Clean cotton cloth was used for final cleaning before being dried by blowing hot air. This process was done to ensure that no dust or oil remained on the aluminium surface. The sandblasting process and final quality of the tabs to prior bonding is shown in Figs. 4.3 (a) and (b).

(a)

(b)

**Fig. 4.3 (a):** Sandblasting process and, **(b):** Aluminium tab surface quality

#### 4.5.3.2 CFRP Plate-Aluminium End Tabs Bonding Process

The process of bonding aluminium end tabs to the specimen was carried out in a temperature and humidity controlled room. This was to avoid moisture diffusion into the adhesive. This adhesive system was a two-part thixotropic consisting of epoxy (white) and hardener (grey) and mixed with a ratio of 3:1 by weight. The materials were placed in a small plastic container and the mixing process was done by using a slow speed mixer for at least 3 minutes until the mixture colour turned grey in appearance. Three sets of 15 gram of hardener and 45 gram of epoxy were used for the bonding of 40 units end tabs with ten units CFRP plate specimens.

The CFRP plate of geometry 1.5 mm thick *x* 15 mm width *x* 250 mm long with an adhesive film (peel ply) was removed prior to bonding to end tabs. The rig was designed to control specimen alignment and to control adhesive thickness. In the early preparation process, the rig was waxed and polished to remove dirt or grease. The adhesive mixture was applied on top of end tab surfaces using standard steel scraper. After placing the end tabs onto the bonding rig using guides, the next step was applying adhesive onto the specimen surface for a specified length. Then, the specimens were placed on top of the end tabs before applying end tabs-adhesive on top of the specimen. The complete adhesive preparation, bonding process and final rig adjustment are shown in Fig. 4.4 (a) to (f).

**Fig. 4.4 (a):** Weighing Sikadur 30 epoxy

**Fig. 4.4 (b):** Mixing process

**Fig. 4.4 (c)**: Final mixture appearance

**Fig. 4.4 (d):** Removing adhesive film (peel ply)

**Fig. 4.4 (e):** Specimen alignment controlled by standard rig guides

**Fig. 4.4 (f):** Bonding pressure controlled by steel plates and screws at both ends

#### 4.5.3.3 Finishing Process

After being demoulded from the rig, the specimens were sent for milling to remove excessive cured epoxy on all sides. The machining process used four flutes solid carbide end mill tool bits diameter of 8 mm with machining speed of 560 rpm. The machine speed was maintained as low as possible to overcome an excessive thermal stress and dimensional changes that lead to the formation of micro-debonding between end tabs and CFRP plate specimen. The finishing process and final specimen measurement are shown in Figs. 4.5 (a), (b) and (c).

**Fig. 4.5 (a):** The cured specimens

**Fig. 4.5 (b):** Milling an excessive cured epoxy

**Fig. 4.5 (c):** Final specimen measurement and quality inspection

## 4.6 Preliminary Load Test for CFRP Plate Control and Pre-stressed Samples

The prepared CFRP plate specimens were divided into two groups, namely; (i). Unstressed (under code name of CPLTUS) and (ii). pre-stressed (under code name of CPLTPS50). The CPLTP50 specimens were initially stressed up to 50% of average ultimate failure load referred to as the average ultimate load of CPLTUS sample. The loading was then released to zero prior to exposure to respected exposure conditions, i.e. indoor (LB), outdoor (OD), in plain water (PW) and salt water (SW). The objective of conducting the loading process was to form the necessary micro fibre-matrix type of failure and to investigate the influence of exposure condition effect onto the CFRP plate system.

The number of test specimens per sample, number of wet-dry cycle and their exposure conditions are shown in Table 4.4 under section 4.7.1. The preliminary tensile load test was also conducted for CFRP plate specimen for control group listed under the code name CPSTUS-C.

### 4.6.1 Tensile Test for Control Sample (CPSTUS-C)

The objective of conducting the preliminary test for CPSTUS-C group of sample was to gather data to be used for the experimentation of sample group CPLTPS50 and for future discussion after the completion of the study programme.

Prior to tensile test, the CFRP plate specimen was installed with standard strain gauges suitable for detecting the FRP composites deformation. The CFRP plate gauge surface area was roughened by 1000 grade grain size sand paper and wiped with liquid acetone to remove grease, dust or dirt. Electrical strain gauges TML BFLA-5-3 were installed on both sides of each specimen in longitudinal and transverse directions. This was done to ensure that the measured and the recorded strain readings produced reliable test data and any errors due to misalignment could be detected. The important parameters of the gauge specification are shown in Table

4.3 while a complete strain gauge installation onto CFRP plate specimen is shown in Fig. 4.6 (a) to (d).

After the completion of strain gauge installation, the CFRP plate specimen was attached to the Instron Universal Testing Machine Series IX Model 4206. The strain data were measured and recorded by data logger TDS-302 while the loads were measured by loading machine controller. During testing, the machine cross head motion was set to 2 mm/minute and the strain was recorded at every 5 kN load increment. The difference in strain readings and an average between both sides were determined and analysed for comparison with other experimental results. The tensile load test process for CPSTUS-C specimen is shown in Fig. 4.7 (a) to (e).

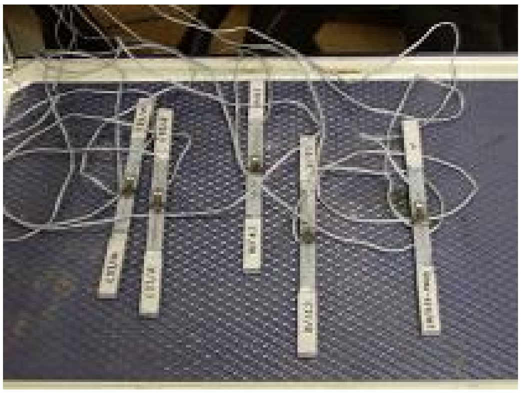
**Table 4.3:** TML BFLA-5-3 strain gauge technical data [81]

| | |
|---|---|
| Manufacturer | Tokyo Sokki Kenkyujo Co. Ltd. Japan |
| Gauge type | TML BFLA-5-3 |
| Gauge factor | 2.08 ± 1% |
| Coefficient of thermal expansion | 3 x 10-6/°C |
| Tolerance | ± 0.85 (µm/m)/°C |
| Temperature coefficient of gauge factor | + 0.12 ± 0.05%/10°C |

(a)

(b)


(c)



(d)

**Figs. 4.6 (a), (b), (c) and (d):** The process of strain gauge installation onto CFRP plate specimen

**Fig. 4.7 (a):** Test set-up for CPSTUS-C specimen


**Fig. 4.7 (b):** Data logger TDS 302 set-up

**Fig. 4.7 (c):** Final tightening of loading machine bottom gripping jaw

**Fig. 4.7 (d):** Final set-up of CPSTUS-C specimen instrumented with strain gauges

**Fig. 4.7 (e):** Machine computer controller displaying load and displacement.

### 4.6.2 Pre-stressed (Tensile) for CPLTPS50 Specimens

The pre-stressed samples of CPLTPS50 were stressed at 25 kN load level, i.e. representing about 50% of an average ultimate tensile load of control sample CPSTUS-C. The test specimens were loaded by Universal Testing Machine Instron equipped with a 100 kN load cell under tensile mode. The machine cross head speed rate was set at 2 mm/min. All the specimens were installed with strain gauges TML BFLA-5-3 on one side in both longitudinal and transverse directions. During pre-stressing, the specimen's strains were recorded by data logger TDS-302 at every 5 kN of load increment and decrement, i.e. the loading machine was set to 25 kN load before the load was set back to zero for load decrement. The increment and decrement loading process was conducted to record or to detect any possibility of residual strain that remained after zeroing the applied load. The specimens were left for 24 hours in the laboratory condition to monitor any sign of residual strain prior to exposure to the designated conditions. The specimen condition, test set-up and final preparation prior to exposure to their designated conditions are shown in Figs. 4.8 (a) and (b).

**Fig.4.8 (a)**: CPLTS50 specimen under pre-tensile load

**Fig. 4.8 (b):** CFRP specimen coated with environmental protective silicone paste

## 4.7 CFRP Plate Durability Experimentation Programme

In this programme, climatic tropical exposures that included laboratory condition, plain water wet/dry cycles, salt water wet/dry cycles and weathering (natural) resistance were established. The CFRP plate specimens were exposed to those four different environmental conditions for a duration of six months. The specimens that were exposed to plain water and salt water have undergone 7 days of wet followed by 7 days of dry cycles that simulated tropical climate conditions.

### 4.7.1 Environmental Exposure Conditions

The test matrix of environmental durability exposure conditions designed for this research programme is given in Table 4.4. The number of test specimens per sample for each condition and their number of cycles are clearly indicated. The individual effects of each exposure condition were evaluated.

**Table 4.4:** The Selfix Carbofibre Pultruded CFRP plate experimentation programme

| **Sample code** | **Experimentation conditions** | | | | |
|---|---|---|---|---|---|
| | **Laboratory (LB)** | **Outdoor (OD)** | **Salt water (SW) (wet/dry)** | **Plain water (PW) (wet/dry)** | **Remarks** |
| **CPSTUS** | 3S | | | | Test results used for comparison |
| **CPLTUS** | 3S | 3S | 3S (24 cycles) | 3S (24 cycles) | Six months exposure duration |
| **CPLTPS50** | 3S | 3S | 3S (24 cycles) | 3S (24 cycles) | Six months exposure duration Applied 50% of ultimate tensile load* |

Notes :
(i) CPSTUS used as a reference for ultimate load (*)
(ii). 3S represent three number of specimens per group of sample

For the laboratory (LB) exposure condition, the specimens were exposed to relative humidity (RH) and room temperature in the range of 75 to 90% and 23 to 33°C respectively. The test specimens were placed horizontally onto aluminium angle bars. The specimens' exposed surfaces were rotated weekly. The immersion test was selected for plain water and salt water to test the effects of prolonged immersion in tropical climate and ocean tropical water. Normal plain water was used for water resistance exposure condition.

Substitute of ocean (salt) tropical water was prepared according to manufacture's standard specification (i.e. tropical ocean salt for aquarium). The salt water was prepared by filling GFRP cylindrical tanks with plain water and salt by ratio of 1: 27.5, which meant 1 litre of plain water was added to 27.5 gram of tropical ocean salt. The mixture's salty level was measured by using a standard specific density gauge. The immersion of specimens in plain water and salt water was conducted by using a 50 litres capacity GFRP cylindrical tank. For the outdoor exposure conditions the specimens were placed on aluminium rails that were supported by mild steel frame. The specimens' surfaces were alternately rotated (weekly) with respect to their test duration. At the end of the exposure period, the specimens were brought to the laboratory and prepared for final load test. The specimen experimentation process for each conditions of exposure is shown in Fig. 4.9 (a) to (l). Table 4.5 to 4.7 list the important parameters of plain and salt water conditions and also the outdoor weathering conditions (average data) during experimentation.

**Table 4.5:** Exposure conditions parameters for Selfix Carbofibre Pultruded CFRP plate specimens

| Tank code | Specimen code | Exposure duration (month) | pH | Water temp. (°C) | Control room temp. (°C) | Relative humidity (%) | Conductivity |
|---|---|---|---|---|---|---|---|
| A (plain water) | CPLTUS and CPLTPS50 PW | 6 | 8.32 | 25.8 | 25.2 | 90.9 | 0.23 |
| B (Plain water-control) | - | | 8.46 | 26.5 | 26.3 | 85.8 | 0.113 |
| C (Salt water) | CPLTUS and CPLTPS50 SW | 6 | 8.79 | 26.1 | 28.2 | 79.2 | 70.7 |
| D (Salt water-control) | 11 litre plain water + 300g sea salt, specific gravity, Sg =1.021 | | 8.76 | 26.5 | 28.2 | 79 | 66.3 |

**Table 4.6:** Water quality measurement tested in the Environmental Laboratory, Faculty of Civil Engineering, UTM

| Parameter | Plain water | Plain water (control) | Salt water | Salt water (control) |
|---|---|---|---|---|
| Calcium (mg/litre) | 0.6 | 0.94 | 3.06 | 6.94 |
| Magnesium (mg/litre) | 0.192 | 0.3 | 0.882 | 2.04 |
| Chloride (mg/litre) | 4.59 | 6.77 | 15.6 | 14.55 |
| Alkalinity (u eq/litre) | 81 | 35 | 169 | 162 |
| Acidity (u eq/litre) | 16 | 11 | 3 | 5 |
| Suspended Solid (mg/litre) | 13.8 | 0.6 | 272.6 | 236.6 |
| pH | 7.92 | 8.14 | 8.28 | 8.26 |

**Table 4.7:** Experimentation average data conditions (measured in specimen research laboratory control room and outdoor)

| Environmental Durability Test | Test Condition | Test Duration |
|---|---|---|
| Laboratory | 70 to 90% RH at 22 to 33°C | 6 months |
| Plain Water Resistance | pH = 8.7 to 8.9 at 80 to 90% RH<br>Water temperature at 25 to 26°C<br>Wet/Dry cycles | 6 months<br>(24 cycles) |
| Salt Water Resistance | pH = 8 – 8.5 at 80 % RH<br>Water temperature at 25 to 26°C<br>Wet/Dry cycles | 6 months<br>(24 cycles) |
| Outdoor Resistance (Natural Weather) | 70 to 90% RH<br>Temperature at 22 to 35°C | 6 months |


(a)


(b)

**Fig. 4.9 (a) and (b):** Measuring plain water (left) and salt water (right) quality parameters


**Fig. 4.9 (c):** Horiba water quality checker U-10


**Fig. 4.9 (d):** Weighing the salt

**Fig. 4.9 (e):** Mixing process

**Fig. 4.9 (f):** Measuring salt water specific density using standard gauge

**Fig. 4.9 (g):** CFRP specimens in wet (salt water) condition

**Fig. 4.9 (h):** CFRP specimens in dry (salt water) condition

**Fig. 4.9 (i):** CFRP specimens exposed to laboratory condition

**Fig. 4.9 (j):** CFRP specimens immersed in plain water

**Fig. 4.9 (k):** CFRP specimens in dry (plain water) condition

**Fig. 4.9 (l):** CFRP specimens exposed to outdoor condition

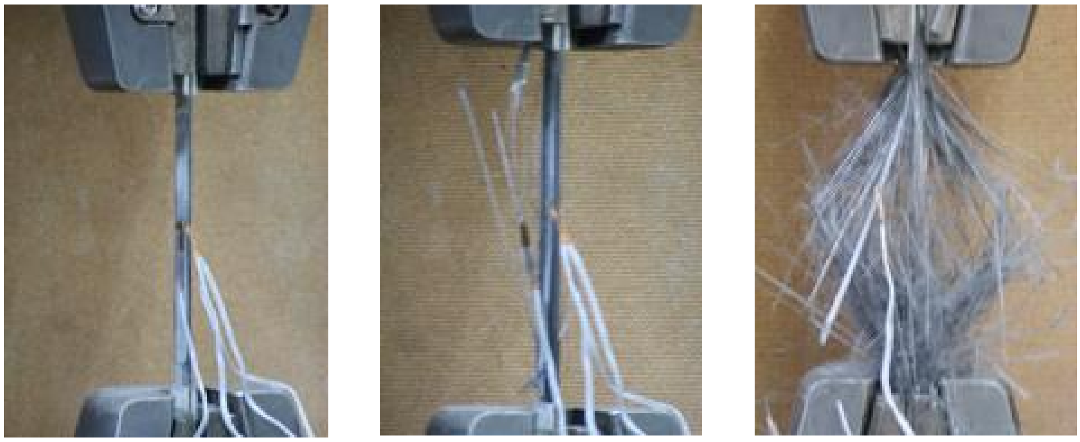
## 4.8 Results and Discussion for CPSTUS-C Sample and CPLTPS50 Pre-Stressed Samples

In the following sub-sections, the detailed analysis of tensile load test on the control sample (CPSTUS-C) and some pre-stressed results on CPLTPS50 specimens were discussed.

### 4.8.1 Observation and Test Results for CPSTUS-C Sample

During the tensile test, it was recorded that the specimen fibre-matrix started producing a cracking sound at about 6.9 kN, 5.0 kN and 9.5 kN for CPSTUS-C01, CPSTUS-C02 and CPSTUS-C03 respectively. The sound was produced continuously until a loud breaking sound occurred at near ultimate load. It could be seen that the fibre-matrix was slowly fracturing at its free edges until full fibre breakage occurred. The loud cracking sound started to occur at about 35 kN for CPSTUS-C01, 39 kN for CPSTUS-C02 and 47 kN for CPSTUS-C03 respectively.

At near to failure load level which was about 57 kN for CPSTUS-C01, 54 kN for CPSTUS-C02 and 51 kN for CPSTUS-C03, a very loud fracture sound was heard just before the specimen's fibre-matrix broke into broom-like pattern [79]. This indicated that the specimen was releasing high fracture strain energy during failure (i.e. sign of brittleness and high strength material). The specimen’s near to failure and final failure modes can be referred to in Fig. 4.10 (a) to (c), whereby Figs. 4.10 (d) and (e) show the final condition for the control specimen after load test.



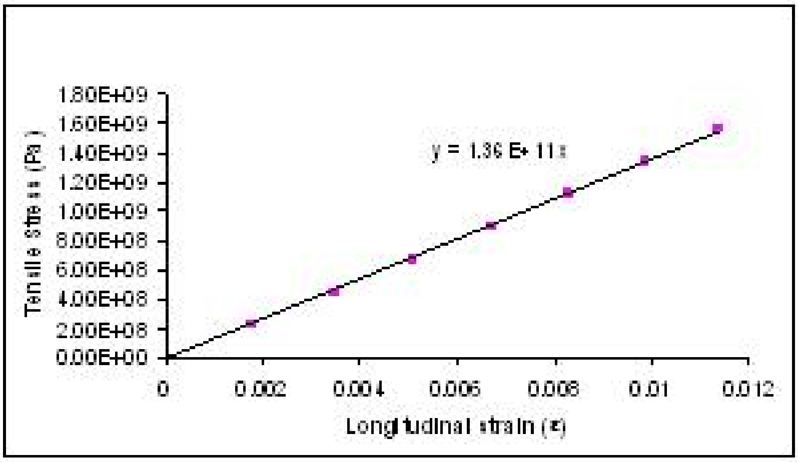
(a) (b) (c)

(d) (e)

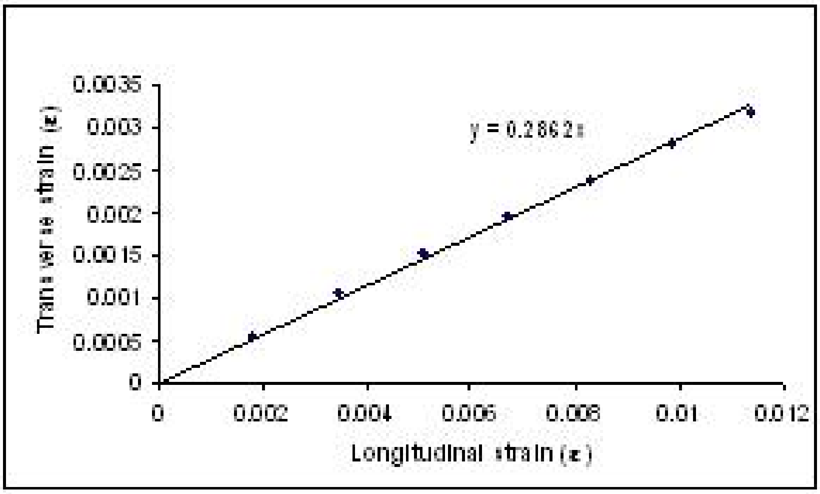
**Fig. 4.10 (a):** Fibre/matrix start fracture at specimen edges **(b):** End effect failure **(c):** Final fibre/matrix breakage and, **(d):** Closed up view CPSTUS-C02 failure condition and **(e):** CPSTUS-C specimens failure condition

### 4.8.2 Analysis of Graph for CPSTUS-C Sample

From the graph shown in Fig. 4.11 (a), it can be seen that the CPSTUS-C01 specimen linearly gained tensile load from the start up to failure. The stress-strain curves also showed that CPSTUS-C specimens failed in perfect brittle mode up to failure. The average ultimate tensile strength, $\sigma_{UTS}$ and tensile modulus, $E_T$ for CPSTUS-C specimens were 2,414 MPa (i.e. with standard deviation of 133) and 135 GPa, respectively. The average value of ultimate tensile strength, $\sigma_{UTS}$ and tensile modulus, $E_T$ were about 14% and 9.5% less than the average values stated in the supplier's technical brochure [35]. The average longitudinal and transverse strain to failure for CPSTUS-C specimens were 1.85% and 0.39% respectively, and the average Poisson's ratio value, $\nu_{12}$ was 0.28. This average Poisson's ratio is relatively similar to what was mentioned in most literatures [82]. The transverse versus longitudinal strain curves that represent Poisson's ratio for CPSTUS-C01 is shown in Fig. 4.11 (b), while the summary of CPSTUS-C test results is shown in Table 4.8.




(a)




(b)

**Fig. 4.11 (a):** Graph of tensile stress versus longitudinal strain (the maximum stress value in the graph was based on 60% of ultimate load) and, **(b):** Graph of transverse strain versus longitudinal strain for CPSTUS-C01

**Table 4.8:** The summary of tensile test results for CPSTUS-C specimens

| Specimen | Failure load (kN) | Maximum longitudinal recorded strain (με) | Maximum transverse recorded strain (με) | Tensile strength (MPa) | Tensile Modulus (GPa) | Poisson's ratio (υ) | Time to failure (s) | Failure mode |
|---|---|---|---|---|---|---|---|---|
| CPSTUS C01 | 56.94 | 18,345 | -4,070 | 2547 | 136 | 0.286 | 289.73 | Broom like failure |
| CPSTUS C02 | 53.93 | 17,419 | -3,458 | 2414 | 135 | 0.281 | 231.32 | Broom like failure |
| CPSTUS C03 | 50.98 | 19,765 | -4,020 | 2282 | 134 | 0.275 | 231.82 | Broom like failure |
| Average | **54** | **18,510** | **-3,849** | **2,414 (133)** | **135** | **0.28** | **251** | |

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

### 4.8.3 Tensile Pre-Stressed Loading for CPLTPS50 Samples

Fig. 4.12 shows an example of load versus longitudinal and transverse strain curves for the CPLTS50-SW01 specimen during pre-stressed (increment and decrement of loads). The plotted curves show a good agreement (coincide) between during loading and during unloading. The results also show an acceptable strain difference. A similar occurrence was also recorded by other specimens i.e. from each sample. Table 4.9 (a) and (b) show some pre-stressed data for CPLTPS50-OD and CPLTPS50-SW group of specimens respectively. From both tables, it can be seen that both strain values at zero load level (i.e. decrement level) did not return to initial zero strain. The longitudinal strain indicated that a quite significant value still remained after zeroing the load which was more than 100 με compared to transverse strain which is negligible. It was observed that the strain value was maintained within the 24 hours monitoring time. The matrix cracking (i.e. refer to low cracking sound) has occurred at a very early load level which was about 10% of the ultimate failure load of CPSTUS-C specimen.

**Table 4.9 (a):** Summary of pre-stressed (tensile) results for CPLTPS50-OD sample

| Properties | CPLTS50-OD01 | CPLTS50-OD02 | CPLTS50-OD03 |
|---|---|---|---|
| Stressed load (kN) | 25 | 25 | 25 |
| Longitudinal strain (με) | 8525 | 8373 | 8482 |
| Transverse strain at final stressed load (με) | -2242 | -2169 | -2414 |
| Longitudinal strain at zero load (με) | 174 | 149 | 130 |
| Transverse srain at zero load (με) | -10 | -34 | -8 |
| Remarks | cracking sound start at 7.2 kN and continuously sound up to final load stressed | cracking sound start at 7.0 kN and continuously sound up to final load stressed | cracking sound start at 8.9 kN and continuously sound up to final load stressed |

**Table 4.9 (b):** Summary of pre-stressed (tensile) results for CPLTPS50-SW sample

| Specimen | CPLTS50-SW01 | CPLTS50-SW02 | CPLTS50-SW03 |
|---|---|---|---|
| Stressed load (kN) | 25 | 25 | 25 |
| Longitudinal strain (με) | 8190 | 8400 | 8287 |
| Transverse strain (με) | -2499 | -2621 | -2223 |
| Longitudinal strain at zero load (με) | 133 | 107 | 165 |
| Transverse strain at zero load (με) | 0 | -40 | -59 |
| Remarks | cracking sound start at 8.2 kN and continuously sound up to final load stressed | cracking sound start at 6.5 kN and continuously sound up to final load stressed | cracking sound start at 6.7 kN and continuously sound up to final load stressed |

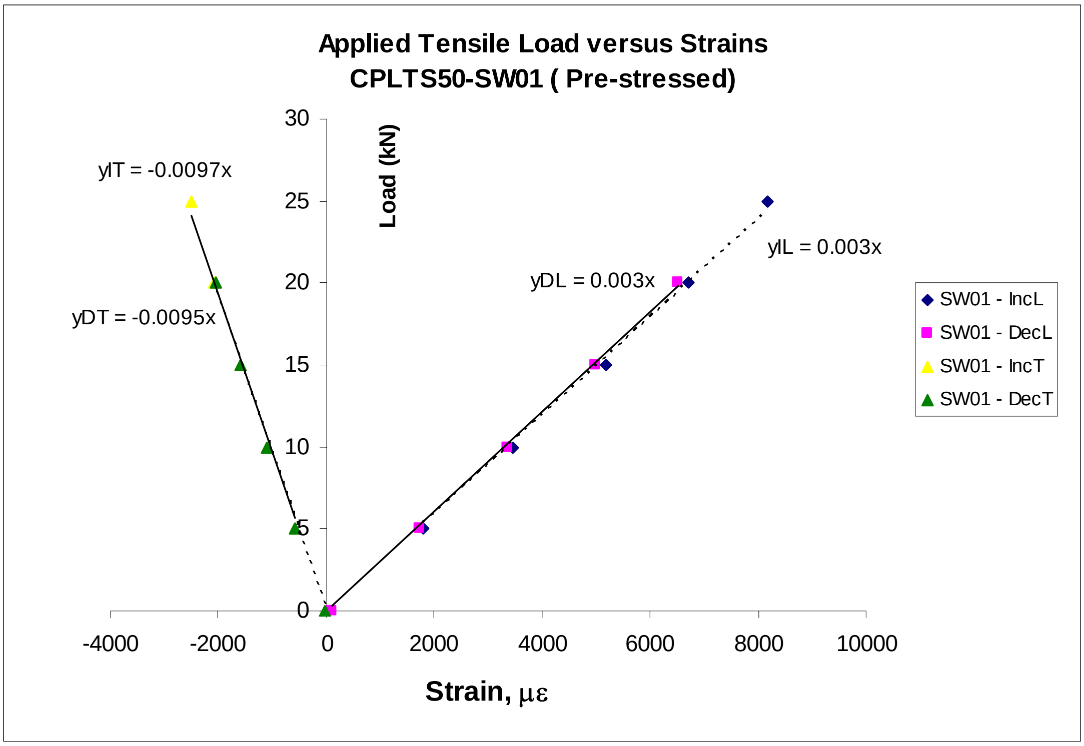



**Fig. 4.12:** Graph of applied tensile load versus longitudinal and transverse strains during pre-stressed for CPLTS50-SW01 specimen

### 4.9 Experimentation Test Results and Discussion

The results presented in the following sections were based on the average value for all specimen groups. The details of individual analysed test results for each specimen can be referred to Table B1 to B4 (Appendix B). In the following sections, the results and discussions focus on the mechanical performances, i.e. failure load, strength and modulus of CFRP plate specimens that were exposed to their respective conditions and were tested for tensile up to failure.

#### 4.9.1 Failure Load

From load test, it was observed that all specimens from each group failed in the same brittle mode and the average failure load for CPLTUS-LB, CPLTUS-OD, CPLTPS50-LB and CPLTPS50-OD group of samples showed no significant difference compared to control CPSTUS group sample, except a slight reduction for the groups CPLTUS-PW, CPLTUS-SW and CPLTPS50-SW (Fig. 4.13). From Table 4.10, it can be seen that the recorded cracking sound, fibre-matrix fracture initial load, time to failure and failure load were well established. The fibre-matrix fracture load for those two main groups of samples provided similar results. A quite significant reduction in test result values were produced for those exposed to plain and salt water conditions. There was quite a significant result range of initial matrix cracking sound which shows an increment of about 40 to 240% for most of the specimens groups compared to CPSTUS-C group. The increment of cracking load was suspected to be due to the reduction of the specimen’s brittleness to a certain unpredictable level. Even if the initial cracking load results were taken into account into the exposure effects, it could be seen that the CPLTUS-PW, CPLTUS-SW and CPLTPS50-SW groups of samples showed a significant effect of exposure results compared to other groups of samples. By referring to time to failure for each specimen, a quite significant effect due to exposure conditions could be suspected to occur for CPLTUS-PW, CPLTUS-SW, CPLTS50-PW and CPLTPS50-SW groups of samples. The reduction of 4 to 10% was recorded for those groups compared to control samples.

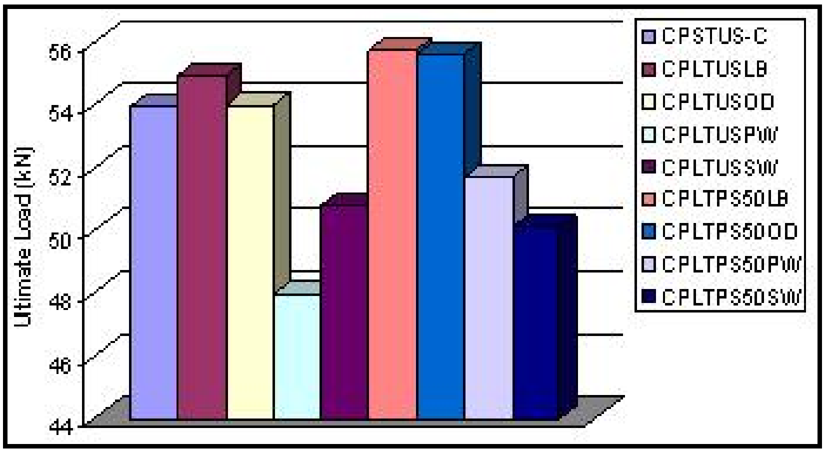



**Fig. 4.13:** Ultimate tensile load for CPSTUS-C, CPLTUS and CPLTPS50 samples due to exposure conditions

**Table 4.10:** Average failure data for CPLTUS and CPLTPS50 group of samples

| Sample | Cracking sound start at load (kN)) | Fibre-matrix fracture at load (kN)) | Time to failure (seconds) | Failure load (kN) |
|---|---|---|---|---|
| CPSTUS-C | 7 | 41 | 251 | 54 |
| CPLTUS-LB | 8 | 48 | 256 | 55 |
| CPLTUS-OD | 10 (**42**) | 43 | 246 | 54 |
| CPLTUS-PW | 14 (**100**) | 42 | 227 | 48 |
| CPLTUS-SW | 24 (**242**) | 39 | 234 | 51 |
| CPLTPS50-LB | 22 (**214**) | 44 | 242 | 56 |
| CPLTPS50-OD | 18 (**157**) | 42 | 248 | 56 |
| CPLTPS50-PW | 20 (**186**) | 42 | 228 | 52 |
| CPLTPS50-SW | 12 (**71**) | 33 | 240 | 50 |

**Notes:** The value listed in the bracket shows a significant percentage (%) increment/decrement

### 4.9.2 Strength and Modulus Durability Properties

In relation to the mechanical properties, it was best to observe the temperature and relative humidity (RH) pattern throughout the experimentation period of six months. The graphs shown in Figs. 4.14 (a) and (b) represent the curves pattern for exposure condition in laboratory and outdoor conditions. It could be seen that the RH values for outdoor condition were not constant throughout the day and also along the exposure condition compared to the laboratory condition. The average recorded RH value was about 70% and 60% for outdoor and indoor respectively. The high fluctuation was due to the normal characteristics of tropical weather pattern which is wet and dry throughout the year, as previously described in section 2.3: Chapter 2. In contrast, it could be seen that the temperature pattern was almost constant throughout the experimentation period for both conditions. The average temperature was about 29°C and 27°C in outdoor and indoor condition, respectively. From both graphs, it could be seen that the moisture content in the surrounding air throughout the exposure period was high and suspected to be the main agent other than their respective exposure condition in degrading the CFRP plate performances.

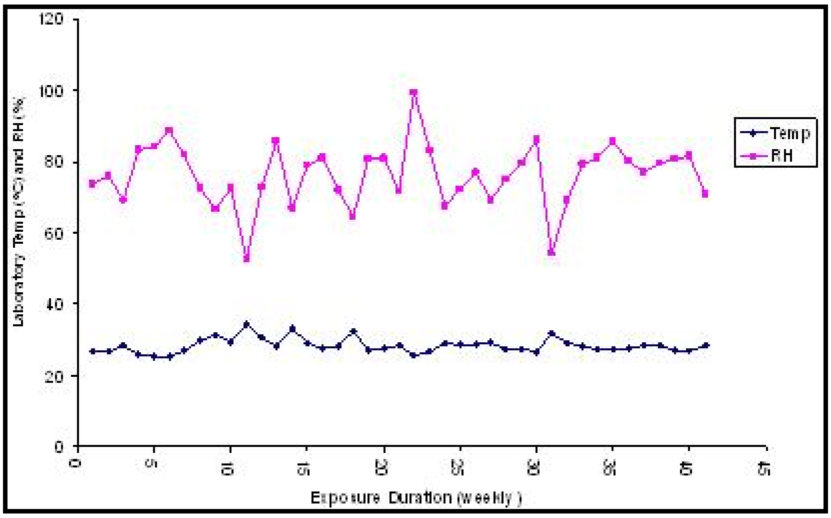



**Fig. 4.14 (a):** Laboratory temperature and relative humidity (RH) pattern during exposure condition

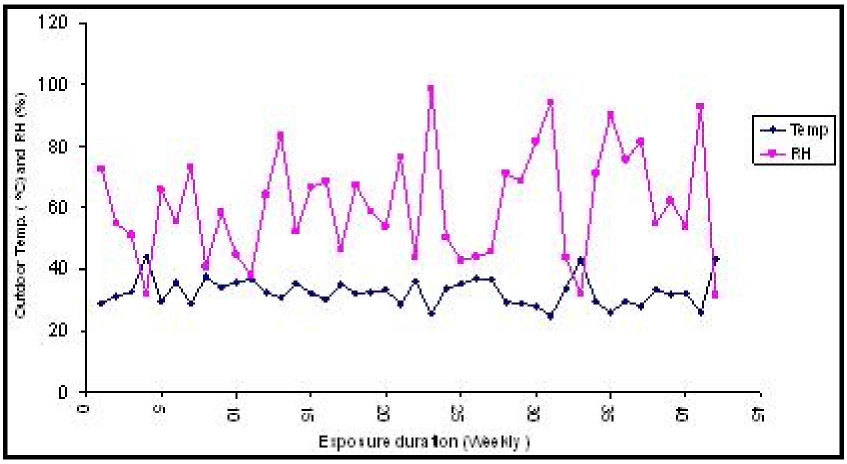



**Fig. 4.14 (b):** Outdoor temperature and relative humidity (RH) pattern during exposure condition

By referring to Fig. 4.15 (a) and (b), in general it could be noticed that all the tested specimens show linear stress-strain behaviour up to failure and failed in the same mode as CPSTUS-C sample except for specimens from PW and SW groups which showed quite a significant effect of exposure condition. By referring to Table 4.11, it could be seen that the reduction of strength value was 5 to 10% for CPLTUS-PW, CPLTUS-SW, CPLTPS50-PW and CPLTPS50-SW, respectively. In contrast to that, the group of CPLTPS50-OD showed an increment of strength value of 5% while CPLTUS-OD showed almost no significant changes compared to control group of CPSTUS-C. Meanwhile, the toughness of CFRP plate was significantly affected by exposure to salt water which gave the largest reduction of 15% and 7.5%

for CPLTUS-SW and CPLTPS50-SW respectively compared to CPSTUS-C group. Other groups of specimens recorded reductions of about 3% except for CPLTPS50-OD group which indicated an increment of 1%. The average reduction or increment of strength and modulus are best referred to the histograms in Figs. 4.16 (a) and (b). The increment in tensile modulus for CPLTPS50-OD group was probably due to post curing process that produced by sunlight. This could increase resin (matrix) strength and finally the toughness. The reduction of strength and modulus compared to CPSTUS-C was probably due to chemical reaction of resin matrix with water through absorption and diffusion mechanisms which caused swelling and plasticised the resin matrix which finally weaken the material shear capability in transferring stresses within the fibre-matrix system [83-85]. Another factor that could contribute and accelerate the process of degradation was high void content of CFRP plate materials compared to GFRP composites [86].

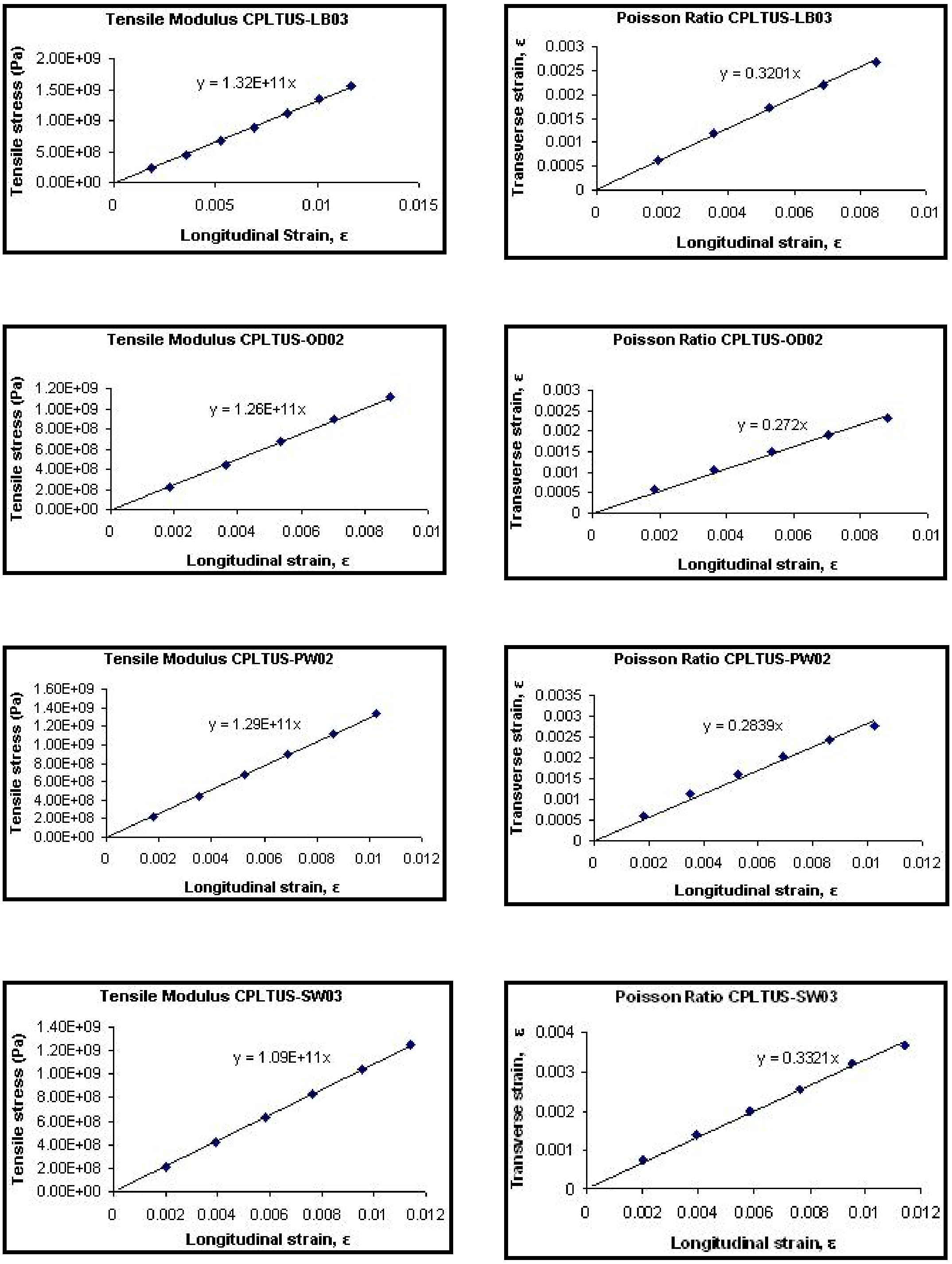



**Fig. 4.15 (a):** Graphs of tensile stress versus longitudinal strain (left) and transverse strain versus longitudinal strain (right) for each respected specimen CPLTUS samples (the maximum stress value was based on 60% of ultimate load).

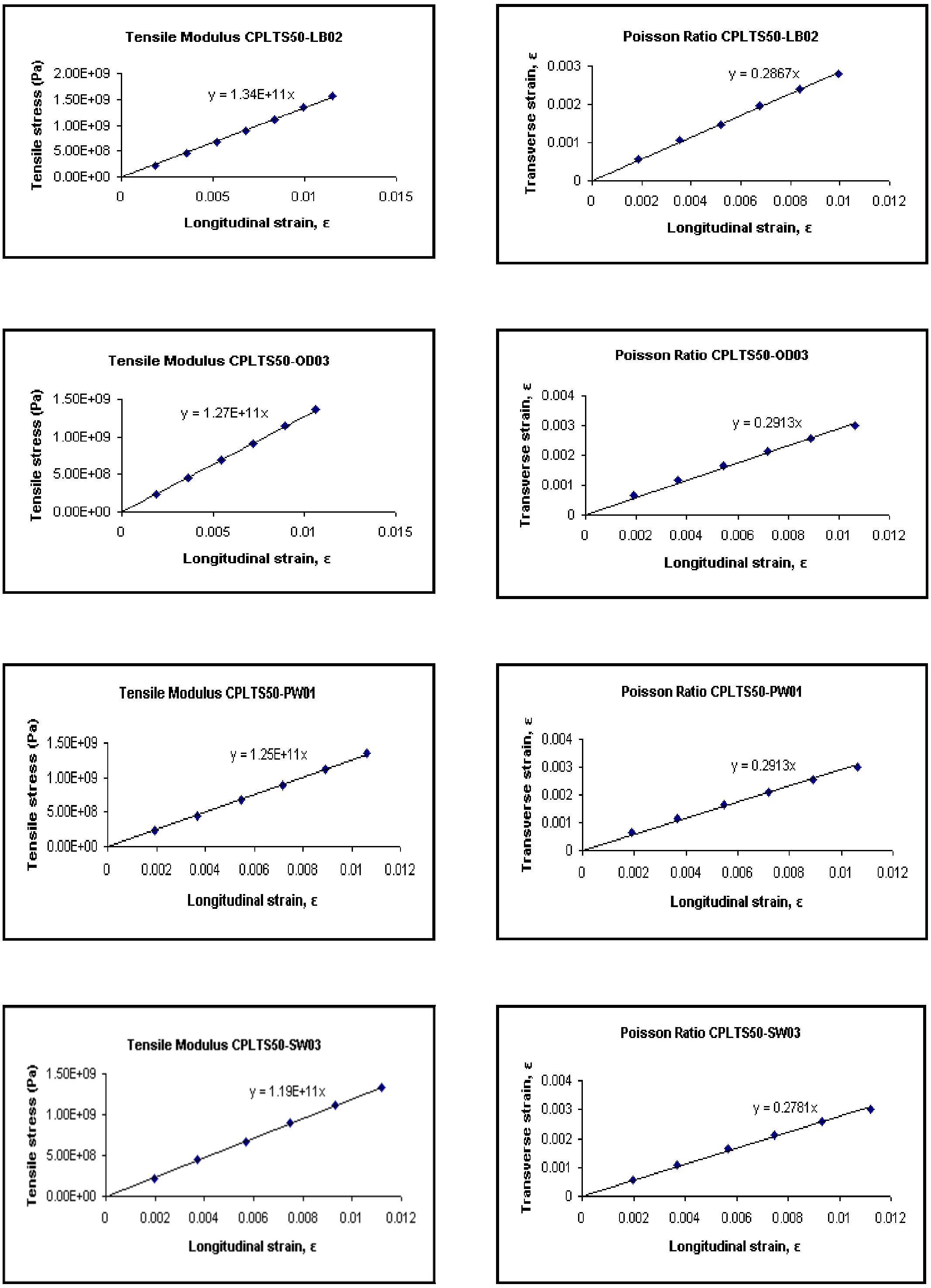



**Fig. 4.15 (b):** Graphs of tensile stress versus longitudinal strain (left) and transverse strain versus longitudinal strain (right) for each respected specimen CPLTS50 samples (the maximum stress value was based on 60% of ultimate load).

**Table 4.11:** Average strength and modulus durability data for CPSTUS and CPLTPS50 samples

| Sample | Tensile strength (MPa) | Percentage inc/dec (%) | Tensile modulus (GPa) | Percentage inc/dec (%) |
|---|---|---|---|---|
| CPSTUS-C | 2414 (**133**) | - | 135 | - |
| CPLTUS-LB | 2468 (**118**) | 1.8 | 130 | -3.7 |
| CPLTUS-OD | 2417 (**226**) | -0.3 | 131 | -3.0 |
| CPLTUS-PW | 2192 (**184**) | -9.6 | 131 | -3.0 |
| CPLTUS-SW | 2203 (**268**) | -9.2 | 115 | -15.0 |
| CPLTPS50-LB | 2510 (**224**) | 3.5 | 134 | -1.0 |
| CPLTPS50-OD | 2540 (**150**) | 4.7 | 136 | 1.0 |
| CPLTPS50-PW | 2312 (**77**) | -4.7 | 130 | -3.7 |
| CPLTPS50-SW | 2200 (**237**) | -9.3 | 125 | -7.4 |

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

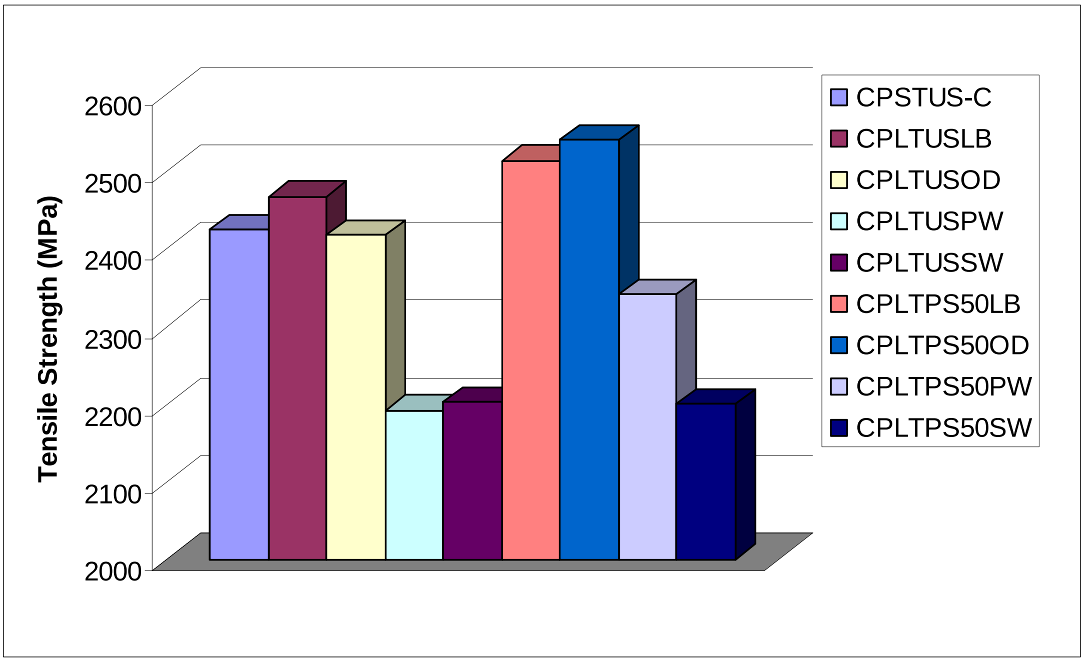



**Fig. 4.16 (a):** Average tensile strength for CPSTUS-C, CPLTUS and CPLTPS50 samples due to exposure conditions

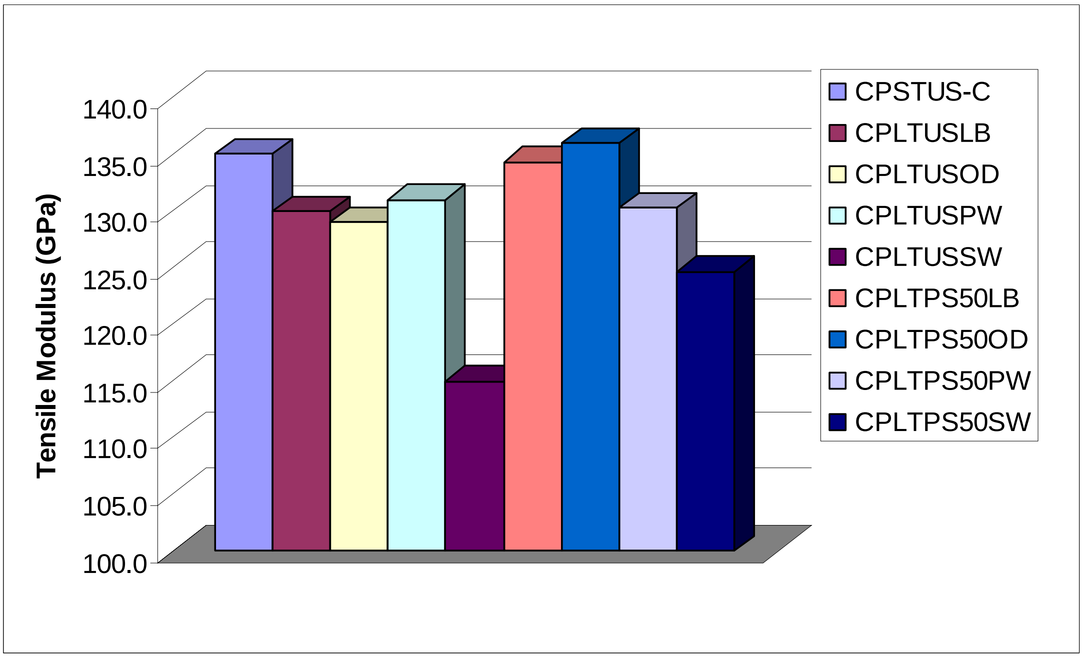



**Fig. 4.16 (b):** Average tensile modulus for CPSTUS-C, CPLTUS and CPLTPS50 samples due to exposure conditions

### 4.9.3 Failure Mode

In this section, the discussions on the failure mode for the experimentation of CFRP plate specimen are referred to CPLTUS-LB01 and CPLTUS-OD03 specimens, respectively. From the tensile load test conducted on all experimented specimens, it showed that all the specimens produced the same failure mode as CPSTUS-C that was previously described in section 4.8.1. Apart from that, the failure mechanism for CPLTUS-LB01 shown in Fig. 4.17 (a) to (c) initially started with fibre-matrix fracture at the edges due to end effects (i.e. zero stress transfer zone) at load of about 47.9 kN, followed by fast fibre-matrix fracture and finally followed by full fibre-matrix breakage (broom like failure) at ultimate load of 53.96 kN. The closed up view of full fibre-matrix pattern breakage is shown in Fig. 4.17 (d) whereby Fig. 4.18 (a) to (c) show the three important stages of the beginning of specimen failure until the final fracture stage for CPLTUS-OD03 in which the fibre-matrix started to fracture at load of about 39.7 kN and the full fibre-matrix breakage occurred at ultimate load of 59.44 kN. From closed up view shown in Fig. 4.18 (d), it can be observed that the specimen final failure texture condition was suspected to be affected by the outdoor weathering condition due to the formation of wool-like pattern on the fibre-matrix. Similar patterns could also be observed on CPLTPS50-PW03 and CPLTUS-SW01. Both specimens showed the sign of inter-laminar shear strength failure mode due to the formation of fibre-matrix delamination at outer parts of the specimens. The failure is shown in Figs. 4.19 (a) and (b).

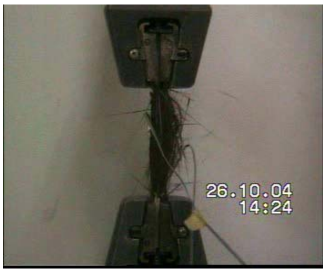

(a) (b) (c)

**Fig. 4.17 (a), (b), (c):** The stages of failure for CPLTUS-LB01


(d)

**Fig. 4.17 (d):** Closed-up view of CPLTUS-LB01


(a)

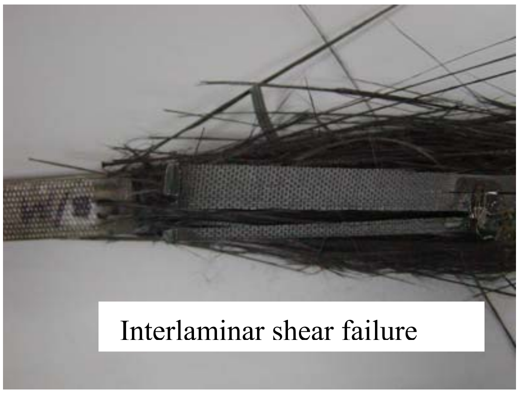



(b)


(c)

**Fig. 4.18 (a), (b), (c):** The stages of failure for CPLTUS-OD03

**Fig. 4.18 (d):** Closed-up view of CPLTUS-OD03





(a) (b)

**Figs. 4.19 (a) and (b):** Interlaminar shear failure produced by CPLTPS50-PW03 and CPLTUS-SW01

## 4.10 Conclusions

The experimentation programme has provided some useful findings that can be related to tropical exposure effects on CFRP plate specimens. Among the major conclusions that can be made from the study are presented as follows:

i. A consistence in failure mode was produced on CFRP plate specimens due to factors such as better controlling fibre-matrix volume fraction, better resin impregnation and better specimen preparation handling.
ii. Initial cracking sounds produced during load test were recorded at about 15 to 30% of the ultimate load. The development of micro-cracking was expected to affect the long-term durability mechanical performances of the CFRP plate through moisture diffusion.
iii. In relative to control specimens, all exposed CFRP plate specimens showed a sign of degradation due to moisture absorption. The influence of moisture had highly affected the CFRP plate specimens that were exposed to salt water and plain water conditions. The influence of moisture also increased the value of Poisson's ratio for some exposed specimens, especially specimens exposed to salt water.
iv. Exposure to salt water condition was classified as the most aggressive, which the effect had contributed to the reduction in tensile strength, tensile modulus and initial cracking load.
v. Overall, it can be said that both the unstressed and pre-stressed experimentation samples produced similar results when exposed to tropical conditions.