VOT 71920

THE STUDY OF BONDING BEHAVIOUR BETWEEN FIBRE REINFORCED POLYMER COMPOSITE PLATE AND CONCRETE PRISM UNDER TROPICAL CLIMATE

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3. **DIRECT OUTPUT OF PROJECT** *(Please tick where applicable)*

Scientific Research	Applied Research	Product/Process Development
☐ Algorithm	☐ Method/Technique	☐ Product/Component
☐ Structure	☐ Demonstration/ Prototype	☐ Process
☐ Data		☐ Software

4. **INTELLECTUAL PROPERTY** *(Please tick where applicable)*

☐ Not patentable
☐ Patent search required
☐ Patent search completed and clean
☐ Invention remains confidential
☐ No publications pending
☐ No prior claims to the technology
☐ Technology proctected by patents
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☐ Monograph available
☐ Inventor technology champion
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5. **TECHNICAL DESCRIPTION AND PERSPECTIVE**

Please tick an executive summary of the new technology product, process, etc., describing how it works. Include brief analysis that compares it with competitive technology and signals the one that it may replace. Identify potential technology user group and the strategic means for exploitation.

a) Technology Description

The use of non-metallic advanced composite materials, in the form of fibre reinforced polymers (FRP), is now receiving widespread attention of the construction industry, particularly for the applications in plate bonding technology to upgrade (strengthening) and/or rehabilitate reinforced concrete (RC), wood or steel structural elements. Most of the published data to date are related to short term structural behaviour of CFRP-adhesive-concrete interfaces bonding performances and durability characteristics that are exposed to Europe and US wheathering environments, but no information related to tropical wheathering effects are reported so far.

The rate of natural deterioration of any material can be relaltively slow or rapid, but it is generally a steady state process. However, the processes of degradation in metals are very different from those in FRP's. In metals, the deterioration processes are mainly electrochemical in nature, whereas in FRPs these are largely physiochemical. However, when the FRPs are used in conjunction with concrete to form a plate composite beam, the long-term serviceability or integrity of the plate-adhesive-concrete member does not solely depend on the the plate material bu also equally, if not more importantly, on the properties, of the interfaces involved in the joint, namely, the plate-adhesive and adhesive-concrete interfaces. Therefore, the durability aspects of FRP plate bonding system whether using CFRP or GFRP plate is to be well understood before the system need to be applied in tropical wheather environments.

b) Market Potential

The finding of test results and data analysis have a good potential to be used to predict future mechanical integrity performances and durability characteristics of RC structures strengthened (externally bonded with epoxy) with FRP plate. The data are able to provide such important information for structural consultant/engineer in their design analysis.

c) Commercialization Strategies

Basically, the research that has been done was focused on gathering mechanical and durability characteristics data that could be used in strengthening the reinforced concrete structures such as beams, slabs and columns. The data can be published through meeting with Public Works Department personnel, applicators and journals, etc.

Signature of Projet Leader :- ______________________ Date :- ________________

8. RESEARCH PERFORMANCE EVALUATION

a) FACULTY RESEARCH COORDINATOR

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comment/Recommendations :

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b) RMC EVALUATION

	Excellent	Very Good	Good	Satisfactory	Fair	Weak
Research Status	( )	( )	( )	( )	( )	( )
Spending	( )	( )	( )	( )	( )	( )
Overall Status	( )	( )	( )	( )	( )	( )

Comments :-

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Recommendations:

☐ Need further research

☐ Patent application recommended

☐ Market without patent

☐ No tangible product. Report to be filed as reference

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ABSTRACT

Keywords: CFRP Plate, concrete, bond stress, tension-compression test

Carbon Fibre Reinforced Polymer (CFRP) composites have been used successfully as strengthening material for reinforced concrete structures by externally plate-bonded technique. The CFRP materials have characteristics such as lightweight, high tensile strength and modulus to weight ratio, non-magnetic and highly corrosion resistant. Many studies have shown that using plate-bonded technique, the performance of the strengthened concrete member was enhanced. In this technique, the surface preparation of concrete substrate and CFRP material along with the type of epoxy adhesive used are the critical factors affecting the bonding performance of the system. This paper discusses the experimental result on the bonding characteristics between CFRP plate and concrete. The bond stress was determined along the 200 mm bond length of the bonded CFRP plate to concrete. A 50 mm width by 1.6 mm thick CFRP plate was used and bonded to 100x100x300 mm concrete prism. The bonded CFRP plate to concrete prism was tested under tension-compression loads and the results have shown that at lower load level, the shear stress distribution along the bonded length was relatively linear and uniform. However, at higher load when micro cracking occurred along the lap joints the shear stress distribution became non-linear. The investigation on mode of failure of the sample shows that the bond between the CFRP plate and concrete was very good.

Key researchers:

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CHAPTER I

INTRODUCTION

1.0 Introduction

In the area of civil construction industry that rapidly expanded in the middle of last century is reaching a critical age, the security of bridges and buildings that represents investment of trillions of dollars is being now questioned. Deficiencies in the existing inventory range from those related to wear, environmental deterioration and aging of structural components, increasing of traffic demands and changing traffic patterns. The long term durability of any this construction material is very important in order to ensure that the structure able to maintain its integrity and provides the service according to its design throughout its service life. Thus the deteriorated concrete structures due to environmental attack require repair and preventive maintenance or sometimes need strengthening due poor initial design or to extend their service life.

In area of strengthening deteriorated reinforced concrete members, plate-bonding system using steel has been widely used [9]. However due to possible corrosion problems and handling aspect during installation, other alternatives materials are being investigated. With the advancement in the materials technology, a relatively high durability and high strength composite material known as Fibre Reinforced Polymer (FRP) is accommodate to replace steel plate [10]. The use of FRP materials i.e. carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) are now receiving widespread attention for applications in plate bonding technology to upgrade and / or rehabilitate the reinforced concrete (RC) structures. It is ranging from the retrofit and rehabilitation of buildings and bridges to the construction of new structural system in most of the developed country such as USA, Canada, Japan and most of the European countries [8]. FRP plate bonding technology advantages compare to steel joint such as low stress concentration, no bearing stress, lighter weight, high stiffness and strength-to-weight ratios, stiffer joints beside higher durability to most environment conditions. There is also serious concern about the long-term durability of CFRP materials as shown by the decision not to use these materials to strengthen the A3 trunk road in Europe [10]. Therefore, durability of FRP plate bonding system whether using CFRP or GFRP plate is needed to be well understood before the system need to be applied.

1.1 Research Objective

The objective of this research is to study the effects of designated exposure conditions onto adhesive bonding of CFRP plate and concrete prism characteristic.

1.2 Research Scope

The study focus on the mechanical properties of CFRP plate and concrete prism bonded system due to tropical climate exposure. The study cover on the short term exposure of test samples. Samples were exposed to three (3) types of conditions, namely:

- Laboratory (as control),
- Outdoor
- Plain water (Wet/Dry cycle).

The effects of tropical climate conditions were determined through Tension-Compression (Pull-out Test) and observation through samples mode of failures. The bond characteristic were determined by comparison in term of ultimate load at failure, bond strength and mode of failure between control and exposed samples.

1.3 Research Methodology

In this project, CFRP plate bonded to concrete prism using epoxy adhesive samples were prepared and exposed to different environmental conditions such as indoor, outdoor, and plain water. In short term (Phase I), the control sample was tested immediately after they are prepared to determine the bond properties. The rest of test samples were exposed to the designated environmental condition up to 6 months prior testing. The results obtain were compared with the control results.

Figure 1.1 shows the experimentation programme for the investigation of the effect the environment on the adhesive bonding properties between the CFRP plate and concrete. The CFRP plate bond to concrete specimens were prepared and exposed under wet-dry cycles to plain water conditions. During the exposure period, the CFRP plate and the adhesive will be monitored to detect any sign of durability problem. The strain changes with time of the concrete beam and CFRP plate were monitored by fixing demec discs on their surface. After that pull-out test was carried out to determine the bonding characteristic before and after the exposure.

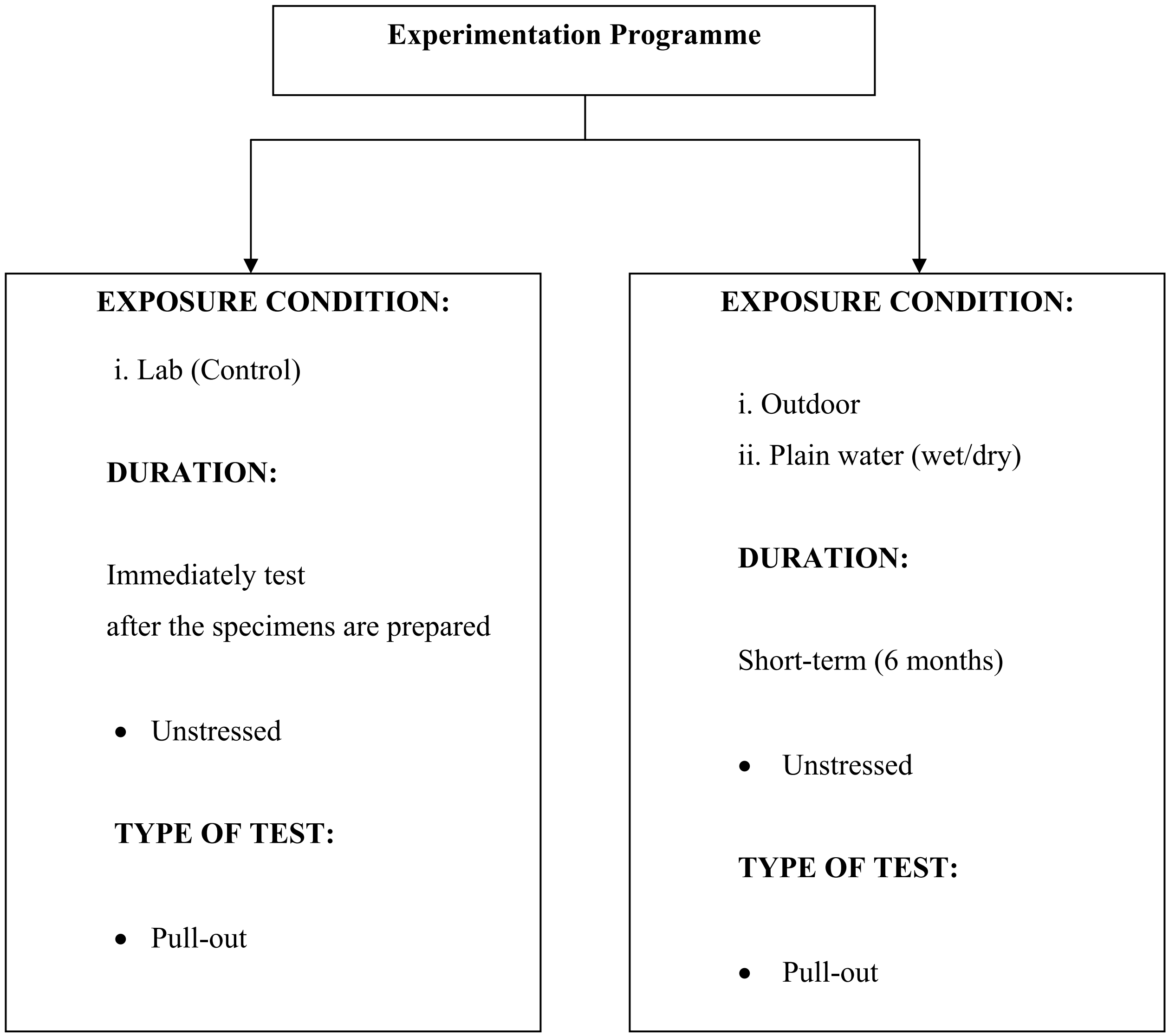


Figure 1.1: Research experimentation programme

CHAPTER II

LITERATURE REVIEW

2.0 Introduction

In this chapter, the study focuses on properties and characteristic of FRP composite materials, i.e. epoxy and concrete. Factors such as environmental conditions, temperature effect, creep, wet / dry behaviour and stress corrosion were studied.

2.1 Definition of Composite Material

A composite material is a combination of two or more materials (reinforcing elements, fillers and matrix binder), differing in form or composition on a macro scale. The constituents retain their identities; that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another [1].

2.1.1 Advantages of FRP

Among the benefits of FRP composites are as follows:

- Due to their multifunctional aspect, composites are able to meet diverse design requirements.
- Weight saving are significant.

- Corrosion resistance is outstanding.
- Fatigue and fracture attributes are numerous.
- Impact and damage tolerance characteristics are excellent.
- Flexibility in product styling and aesthetic.
- Low thermal expansion can be achieved, but will vary significantly with the matrix material selected, the fibre types and orientation.
- Manufacturing and assembly are simplified due to part integration.

2.2 General Properties of FRP

Fibre reinforced composite materials are blends of a high strength, high modulus fibre with a hard enable liquid matrix. In this form, both fibres and matrix retain their physical and chemical identities yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone [4]. The bonding of these aligned fibres into the softer matrix material results in a fibre-reinforced composite material with superior properties in the fibre direction [4]. Since the fibres are highly directional, the resultant composite will exhibit anisotropic behaviour much like steel acting in reinforced concrete.

Typical composite material properties include low specific gravity modulus-to-weight ratio. Most FRP materials are resistant to corrosion. Another characteristic of FRP materials is the linear stress-strain curve up to failure. Matrix materials deform plastically, whereas the fibres, in general, do not. The stress and strain relationship between resins, fibres and composites is shown in Figure 2.1[7].

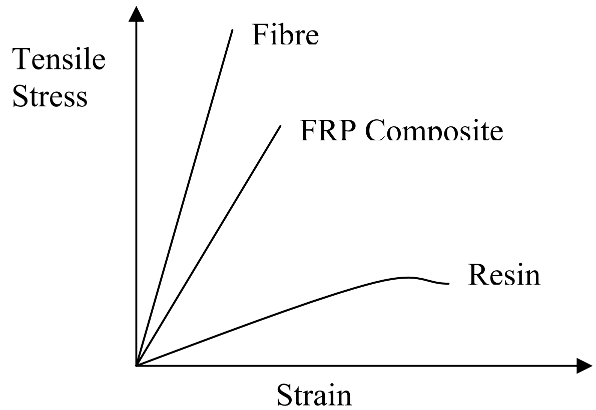


Figure 2.1: Stress-strain curves for typical fibre, resin and FRP composite [7]

Since the FRP composite strength performance are dominated by the reinforcement, this plastic deformation or yield is seldom exhibited by the composite for structural design purposes. Brittle failure is the typical failure mode for FRP composite under excessive mechanical loading stresses.

2.3 Reinforcing Fibres

Fibres ideally comprise 60% - 70% of volume fraction of the composite and are the principal load carrying members. Hand lay-up methods may produce laminates with lower fibre volumes, which may range in between 30%-50% of fibre content. Fibres primarily act in tension tend to have low transverse strength. For handling purposes, the individual fibres are brought together in 'bundles' called tows and roving. The fibres can be used in this form or further processed into tow sheets, fabrics or mats. The three most common fibres types used in polymer matrix composites are carbon, glass and aramid.

Figure 2.2 shows the relationship between stress and strain of the different fibres[7]. The gradient of each curve indicates the stiffness (modulus) of the fibre, the steeper gradient, the higher the stiffness.

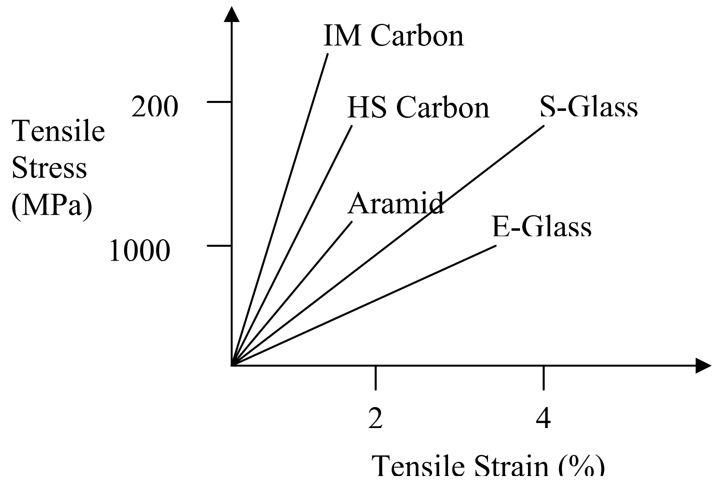


Figure 2.2: Tensile stress versus tensile strain of various type of reinforcing fibres

2.3.1 Carbon fibres

Carbon fibres consist of *tows*, each made up of numerous filaments (~10000). The filaments are 7 to 15 μm in diameter, and they consist of small crytallites of 'turbostatic' graphite, which is one of the allotropic forms of carbon. In the graphite crystal, carbon atoms are arranged in a hexagonal array plane. The planes are stacked together, with covalent bonds acting within the planes and weaker Van de Waals forces holding the planes together.

To obtain a high modulus and strength, the layered planes of graphite must be weaker Van der Waals forces that holding the planes together and the layered planes of graphite must be aligned parallel to the fibre axis [6]. However, the structure of the stacked planes is not ideally regular. Therefore, the properties of carbon fibres can vary over a wide range, depending upon the degree of perfection, which is function of production process.

Three precursor materials are used at present to produce carbon fibres: rayon, polyacrylonitrile (PAN), and isotropic and liquid crystalline pitches. Rayon and isotropic pitch precursors are used to produce low modulus carbon fibres (≤ 50 GPa). Higher modulus carbon fibres (≥ 200 GPa) are made from PAN or liquid crystalline (mesophase) pitch precursor. Carbon fibres are not wet by molten metals and difficult to wet with resins, especially the higher modulus fibres [1].

Carbon fibres are immune to moisture, corrosive environment, solvents bases and weak acids. However, oxidation becomes a problem at elevated temperature. The unidirectional type of carbon fibre is anisotropic material, and its transverse modulus is an order of magnitude less then its longitudinal modulus. The material has a very high fatigue and creep resistance.

Table 2.1: Mechanical properties of carbon fibre [3]

Typical Properties	**High Strength**	**High Modulus**	**Ultra-High Modulus**
Density (g/ cm^3)	1.8	1.9	2.0-2.1
Young's Modulus (GPa)	230	370	520-620
Tensile Strength (GPa)	2.48	1.79	1.03-1.31
Tensile Elongation (%)	1.1	0.5	0.2

2.4 Resin

Resin is a solid or pseudosolid organic material, usually of high molecular weight, that exhibits a tendency to flow when subjected to stress. In reinforced polymer, the material used to bind together the reinforcement material is called the matrix [1]. Matrix is the essentially homogeneous resin or polymer material in which the fibre system of a composite is imbedded. Both thermoplastic and thermoset resins may be used, as well as metals, ceramics and glasses [1].

Resins by their nature are at least an order of magnitude weaker than the reinforcing fibres embedded in them. They are more susceptible to heat and fire and generally more susceptible to solvents, water, acids and bases than the fibres. All resins exhibit substantial levels of creep and have large coefficient of thermal expansion (CTE). Resin matrices allow stresses to be shared across the reinforcing fibres in laminate. This sharing action allows the laminate to act in a more homogeneous manner that develops the superior properties of the FRP. Resins also act as protective coating that shields the fibres from abrasion and from certain environmental aggressive factors.

Long-term durability of polymer matrices is associated with a gradual change in physical properties, which occurs with time and loading. Pre-stressing composite materials may have significant long-term effects on the polymer matrix. Creep rupture has been known to occur in FRP composites due to viscoplastic behaviour of the polymer matrix and is not a function of the fibres. The three most commonly used resin systems are epoxies, polyesters and vinylesters.

2.4.1 Epoxies

Epoxy resins are used extensively in polymer composite materials for a variety of structural applications. They are the most versatile of the commercially available matrices. Depending on the chemical structures of the resin and the curing agent, the availability of numerous modifying reactants, and the conditions of cure, it is possible to obtain toughness, chemical and solvent resistance, mechanical response, ranging from extreme flexibility to high strength and hardness, resistance to creep and fatigue, excellent adhesion to most fibres, heat resistance and excellent electrical properties.

All epoxy resins contain the epoxide, oxirane, or ethoxylene group, where R represents the point of attachment to the remainder of the resin molecule. The epoxide function is usually a 1,2- or α-epoxide that appears in the form called the glycidyl group, which is attached to the remainder of the molecule by an oxygen, nitrogen, or carboxyl linkage, hence, the terms glycidyl ether, glycidyl amine, or glycydyl ester. Curing of the resin results from the reaction of the oxirane group with compounds that contain reactive hydrogen atoms:

Epoxies tend to have higher viscosities than both polyesters and vinylesters systems. They also have longer curing times and are the most expensive of the three systems. Typical physical and mechanical properties of epoxy system is given in Table 2.2 [4].

Table 2.2: Typical properties of epoxy

Properties	**Value**
Tensile Strength (MPa)	55-130
Tensile Modulus (GPa)	2.8-4.1
Elongation (%)	3.0-10.0
Density (g/ cm^3)	1.2-1.3
Shrinkage (%)	1-5

The epoxy resins constitute an important and rapidly growing class of resins for use in reinforced plastic and as adhesives system. However a fairly good model of the structure can be built and knowledge is increasing rapidly on the molecular structure and its various reactions. Property comparisons between an epoxy resin various reinforcements and various metals are given in Table 2.3 [1].

Table 2.3: Property comparisons between an epoxy resin with various reinforcements and various metals

Material	**Density (g/ cm³)**	**Unidirectional Strength**		
		Tensile (MPa)	**Compressive (MPa)**	**Unidirectional tensile modulus (GPa)**
Carbon (AS4)	1.55	1482	1227	145
Carbon (HMS)	1.63	1276	1020	207
S-glass	1.99	1751	496	59
E-glass	1.99	1103	490	52
Aramid	1.38	1310	290	83
Aluminum (7075-T6)	2.76	572 MPa		69
Titanium	4.42	1103 MPa		114
Steel	8.0	1241-1379 MPa		207

a) Effect of Fibre Reinforcements

Epoxies form a strong interphase; laminates made with these matrices reflect their fibre properties to a large extent. The three fibres most commonly used are glass, polyaramid and carbon. Carbon fibres are the most versatile and have the best balance of properties as epoxy matrix reinforcement. Compare to glass and polyaramid fibres, they are superior in tensile, flexural, compressive and fatigue (tension-tension) properties.

b) Advantages of Epoxy Resins

The advantages of epoxy resins over other polymers as adhesive agents for civil engineering use can be summarized as follows (Mays and Follows Hutchinson, 1992).

- High surface activity and good wetting properties for a variety of substrates.
- May be formulated to have a long open time (the time between mixing and closing of the joint).
- High cured cohesive strength, so the joint failure may be dictated by the adherend strength, particularly with concrete substrates.
- May be toughened by the inclusion of a dispersed rubber phase.
- Minimal shrinkage on curing, reducing bond line, strain and allowing the bonding of large areas with only contact pressure.
- Low creep and superior strength retention under sustained load.
- Able to accommodate irregular or thick bond lines.
- Blending with a variety of materials to achieve desirable properties can readily modify formulation.

These various modifications make epoxy adhesives relatively expensive in comparison to other adhesives. However, the toughness, range of viscosity and curing conditions, good handling characteristic, high adhesive strength, inertness, low shrinkage and resistance to chemicals have meant that epoxy adhesives have found many applications in constructions, for example, repair materials, coatings and as structural and non-structural adhesives.

2.5 Performance Characteristic of FRP Composites

2.5.1 Environmental Conditions

FRP composites can be expected to show excellent durability characteristic within a normal range of conditions, which includes:

Table 2.4: Environmental conditions

Temperature:	Range -30°C to 62°C for long term (greater than 1000 hours) exposure and 1100°C for short term (under 2 hours) fire exposure,
Moisture:	Full immersion in fresh or salt water for long term exposure at 0°C to 40°C,
pH:	3.0 to 10.0 for long term exposure, and
Ultraviolet radiation:	UV index of 10 for long term exposure, and
Hydrocarbons/pollutants:	Immersion in specific concentrations for extended periods of time.

2.5.2 Temperature Effect

The thermal energy supplied above the glass transition temperature Tg allows the resin chains to move and to become more flexible. This will lowers the load or sharing capacity of the resin and results in preferential loading of individual fibres (the shorter ones). Since the load is no longer shared among the groups of fibres the loading on individual fibres may exceed the capacity of that fibre and it breaks. The next shorter fibres pick up the load and if it high, they break and so on. Ultimate load carrying capacity of the FRP can be lowered by 30-40% in some extreme cases.

2.5.3 Creep

Of the FRP components discussed, only carbon and glass fibres do not creep. Aramids and all the matrices do exhibit creep to varying degrees. Creep in FRP's is a fibre-dominated property. If the fibre is either carbon or glass, is uncrimped and is securely fastened at the termination points there will be no creep, as the composite will act in an almost perfectly elastic manner. The fibres may straighten under load, the composite may slip in its anchorage and there is a possibility that relaxation stress relief of the polymer matrix can continuously load the fibre even after the external load is released (Karbhari, 1997) [4].

2.5.4 Stress-Rupture/ Stress Corrosion

Carbon fibre is relatively unaffected by this phenomenon at stress levels up to 80% of ultimate. Premature failure can be caused by the matrix being adversely affected by stress either with or without a hostile environment.

Glass and aramids fibres are susceptible to both stress rupture and stress corrosion, which can lead to premature failure under load. The quality of the matrix system used has a significant effect on the attack by alkalis, for example polyester and vinylester resins are more susceptible to chain scission (cutting or breaking) by hydroxyl ions because they contain ester linkages. Epoxy resin based composites, which do not contain these linkages, may be 2 to 4 orders of magnitude more durable.

2.5.5 Wet Behaviour

The resin matrix will absorb water. The amount of water is dependent on the resin type and water temperature. There are usually two immediate effects of water absorption on the matrix, first, lower the glass transition temperature (Tg) and the latter resin loses stiffness. Both of these effects are partially reversible in epoxy resin systems when the water is removed from the matrix by drying. With polyesters and vinylesters, the changes can be either reversible or not, depending on the time and temperature of the exposure.

Epoxies have no ester linkages in their structure, thus the polymer chain is not easily hydrolyzed 1- water exposure, vinylesters and polyesters, as their names imply, have these linkages and thus can be permanently damaged, particularly by high temperature water immersion. Damage to fibreglass/ epoxy laminates may be caused by the intrusion of moisture to the resin fibre interface. Such intrusions may break the 1-Hydrolysis is a form of scission where ester linkages C-O-C are split by water to form Hydroxyl groups (-OH) at the ends of the split chains. Further, the presence of moisture can leach sodium and other metallic ions from the glass causing strength loss over time. Moisture is thought to gain access into the FRP by three mediums, namely:

- By capillary action along the longitudinal axis of the fibre at the resin fibre interface.
- Through crack and voids in the structure.
- By diffusion through the matrix.

Factors 2 and 3 are demonstrable while factor 1 has been debated in the scientific literature. That there is water present at the glass –resin interface is not in question. How it comes to be present is the issue. The surface of glass fibres is highly processing by some accounts up to 8 molecular layers thick. Aramid fibres absorb up to 13% by weight moisture, which can have a deleterious effect on tensile strength and can affects the resin fibre interface. Carbon fibre is relatively inert to water and the only effects on carbon laminates are the effects of moisture on the resin matrix. As alluded to the above, the higher the temperature the faster and more severe the permanent affects of moisture intrusions become. Chemical reactions roughly double in speed for each 10°C increase in temperature.

2.6 Concrete

Concrete is composed of crushed stone, sand, Portland cement and water. When these materials are mixed together a plastic mass is formed which may be placed in a box and compacted in it. After a period the box may be stripped to reveal a block of hardened concrete having the same shape as the interior of the box into which it was placed [12].

2.6.1 Portland Cement

The fundamental property of Portland cements is that when it is mixed with water, chemical reactions (called hydration) take place, which change the structure of the plastic mass whereby it becomes hard and rigid [12]. This chemical reaction does not rely on the absorption of carbon dioxide will take place under water.

2.7 Hardened Concrete

2.7.1 Water: Cement Ratio Law

Duff Abrams in the U.S.A. stated the first fundamental law, which is the basis of all concrete technology; this is the famous water: cement ratio law, which may be stated as follows:

"For the same materials and conditions of test, the strength of fully compacted concrete depends only on the ratio of water to cement used in the mix."

The relation between 28-day compressive strength and the proportion of cement to water in the mix is shown in Figure 2.3, for weigh batching and for volume batching. This applies to ordinary Portland cement, average aggregates, reasonable site control and standard test procedure. In practice, the test result show considerable scatter and the curves on Figure 2.3 give the "minimum strengths" which may be expected at the various cement: water ratio by mass.

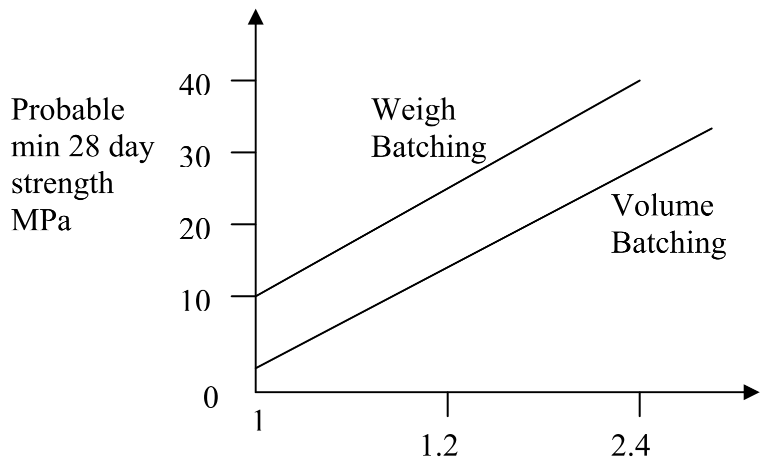


Figure 2.3: Relation between cement: water ratio and minimum 28-day compressive strength of concrete [12]

2.7.2 Gain in Strength with Ages

As the chemical reactions of hydration proceed, the strength of the concrete increases. The strengths at the various ages are referred to the strength developed at 28 days as 100%. The criterion of 28-days age was chosen arbitrarily and was adopted by early designers on the basis that it was desirable to load the structure about four weeks after the concrete had been placed.

Working stresses used by the design engineer are based on the strength at 28 days. At this age the concrete has reached a high proportion of its potential strength. The diagram is based on the compressive strength of standard concrete test cubes. So long as water is present the concrete will continue to gain strength and may be 20% higher than the 28-day strength at 3 months and 30% higher at 6 months.

2.8 Factors Affecting Concrete Strength

2.8.1 Compaction

The relation between strength and water: cement ratio is applicable only to concrete, which can be fully compacted with the available equipment. In badly compacted concrete there are air voids and spaces, which obviously reduce its strength. It is obvious that the elimination of voids by proper compaction is as important in securing good quality concrete as close control of the water: cement ratio. This was recognized by Duff Abrams and mentioned in his original paper on water: cement ratio.

Dry mixes of low workability cannot be consolidated by hand methods (damping, ramming, rodding and spading) and vibrators must be used. Vibration makes the concrete fluid so that it flows into the corners and round the reinforcement, and allows air to be expelled. Mixes of high workability should not be vibrated because vibration is liable to cause segregation. When vibrators are used it is imperative that adequate stand-by equipment is ready for immediate use in case of breakdowns.

2.8.2 Curing

As has been stated, the hardening of concrete is due to the chemical reaction between cement and water; if there is no water present the chemical reaction cannot proceed. Therefore, when concrete is allowed to dry out, the chemical reaction of hydration stops, the hardening process stops and there is no further gain in strength. Concrete must be kept continuously damp and the procedure for doing this is known as curing or damp curing. The effect of reducing the damp curing period is shown on Figure 2.4. The time taken for a structural member to dry out will vary with ambient conditions of temperature, humidity and wind, and also with the shape and size of the member. Thin floor slabs are particularly vulnerable and, as with plaster and floor screeds, the loss in strength can be particularly severe if curing is not maintained.

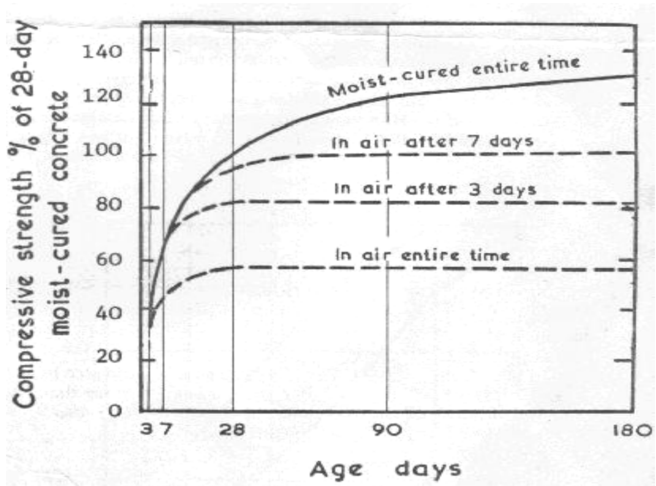


Figure 2.4: Effect of duration of damp curing on the strength of concrete (thick section) [12]

Curing may be achieved by:

a) Retaining the forms in position in beams, columns, soffits etc.
b) Ponding with water on large, level exposed surfaces.
c) Covering with sand, hessian etc., and keeping moist by spraying with water.
d) Spraying the uncovered surface with water at frequent intervals.
e) Precast units may be submerged in water.
f) Covering with waterproof paper or plastic sheeting.
g) Spraying the surface with a curing compound. (In the last two methods, no water is added but evaporation of mixing water is prevented)

2.8.3 Temperature

Most chemical reactions proceed more rapidly at higher temperatures. The hydration of cement follows this rule and consequently concrete gains strength more rapidly when the curing temperature is increase. On the other hand, the gain in strength is slower when the curing temperature is reduced. During cold spells it is advisable to place concrete on a rising temperature, not when the temperature is falling.

2.8.4 Heat of Hydration

As with many other chemical reactions, heat is generated when cement hydrates. This is useful in cold weather concreting because once the hydration has started the heat generated will compensate for the heat lost from exposed surfaces and through the shutters.

In large mass concrete dams the heat of hydration causes a rise in the temperature of the concrete because the rate of heat generation is greater than the rate at which it is dissipated to the atmosphere on the surface. Internal stresses may be created in the concrete, which might cause cracking in the structure. For such conditions, low heat cements are used the concrete mix is designed to have a low cement content.

2.9 Modulus of Elasticity

The stress-strain relationship for concrete is not linear, but the portion of the curve at low stresses may be regarded as being linear and the modulus of elasticity determined from it. The modulus of elasticity of concrete, $E_{c,}$ may be taken as 20 GPa for most design purposes.

2.10 Tensile Strength

The tensile strength of concrete is very much lower than the compressive strength and, although there is no direct relationship, the strength in tension if often assumed to be one tenth (1/10) that in compression. Concrete has a brittle type of failure and consequently the use of plain (unreinforced) sections could be dangerous if high tensile stresses occur. The compression strength and tensile strength of concrete are as below:

$$\sigma_{c/c} = 40 - 60MPa \qquad \text{(Compressive strength)}$$

$$\sigma_{c/t} = \frac{1}{10}(40 - 60)MPa \approx 4 - 6MPa \qquad \text{(Tensile strength)}$$

2.11 Literature Review on Bonded Joint

The literature review focuses on theory and mechanism of adhesive bonding, joint design, mechanism of bond failure, formulation of bond strength, force transfer and local shear stress distribution.

2.12 Bonded Joint Definition

Adhesive joint is the process of uniting material such as adherend with the aid of an adhesive, a substance that is capable to hold such materials together by surface attachment. Generally, as from its definition, bonded joint where the surface are held together by means of structural adhesive. This type of joint must satisfy all these following conditions to meet the purpose;

- The adhesive should not exceed it allowable shear stress. The performances of the joint depend to the adjustment of the maximum shear stresses to be less than the joint shear strength.
- The adhesive also not exceed an allowable tensile (peel) stress.
- The adherend is not exceed the through thickness tensile stress allowable
- The adherend must not exceed the allowable in-plane shear stress.

Typically, one or more of the three conditions above will become critical before in-plane shear stress limit in the adherends exceed.

2.12.1 Advantages and Disadvantages of Bonded Joint

In respect to the adhesive or bonded joint system, advantages and disadvantages offered by the system are described as follows:

1) Advantages

- Allows fabrication of smoother parts.
- Permits use of lighter weight materials which can minimizes the stress concentration.
- Joints different type of substrates.

2) Disadvantages

- Required suitable curing temperature, pressure and time to reach the maximum bond strength.
- Sensitive to aggressive environmental conditions such as in dry and wet cycles.
- The bonding process preparation is very critical and need to follow strict procedure.
- Difficult in accessing the bonding characteristic at site.
- Bonding inspection and measurement is relatively expensive.

2.13 Mechanism and Bond Models.

2.13.1 Mechanical Interlocking Model

This oldest adhesion theory considers adhesion to be result of the mechanical interlocking of polymer adhesive into the pores and other superficial asperities of substrates. The roughness and porosity of substrates (adherend) are generally the factors as wet ability by the adhesive is sufficient shown in Figure 2.5[A]. Otherwise, the nonwetted parts originate failures shown in Figure 2.5[B]. However, mechanical interlocking is not a mechanism at the molecular level. It is merely a technical means to increase the adsorption of the adhesive on the substrates.

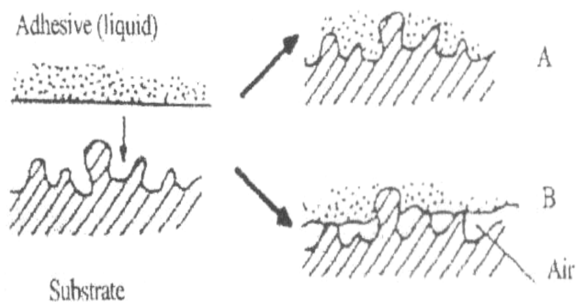


Figure 2.5: Good wetting [A] and poor wetting [B] [15]

2.13.2 Diffusion Model

According to this model, adhesion of two macromolecules in intimate contact results from the inter diffusion of the molecules of the superficial layers. The inter diffusion forms a transition zone or 'interface' as shown in Figure 2.6. In the case of polymer autohesion, i.e., two samples of identical polymers, adhesion under a constant assembly pressure, is a function of temperature and contact time following Fick's law. Thus the average interpenetration depth, x, of one phase into another is given as:

$$x \alpha \exp\left(-\frac{E}{2RT}\right)t^{\frac{1}{2}}$$

Where E is the diffusion activation energy, t, the contact time, R, the molar gas constant, and T the temperature. The application of this model is limited to the adhesion of compatible polymers as well as welding of thermoplastics.

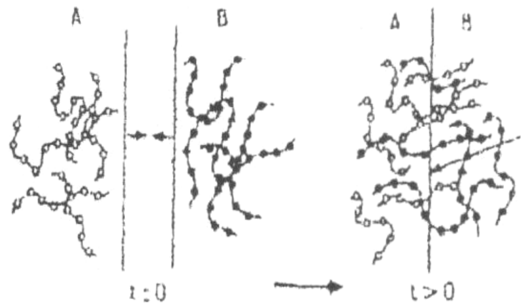


Figure 2.6: Inter diffusion across the interfaces [15]

2.13.3 Model of Weak Boundary Layer

Bikerman [15] showed that, in the separation of an assembly, the propagation of the failure is very unlikely to take place exactly at the interface. The fracture is, in fact, cohesively propagated in either solid in contact. Thus, whatever the mechanism governing the assembly formation, the strength of the assembly only depends on the bulk properties of the adherends.

Bikerman also indicated that another failure mechanism might occur when the fracture moves forward in a weak interfacial layer located between two materials. Figure 2.7 illustrates graphically the seven classes of weak boundary layers that were considered by Bikerman. The Bikerman model is simple, but was criticized in the past. It is now, admitted that many cases of poor adhesion can be attributed of these weak interfacial layers. Model of weak boundary layers. The seven Bikerman classes, (1) air pores, (2) and (3) impurities at the surface, (4) to (7) reactions between components and medium.

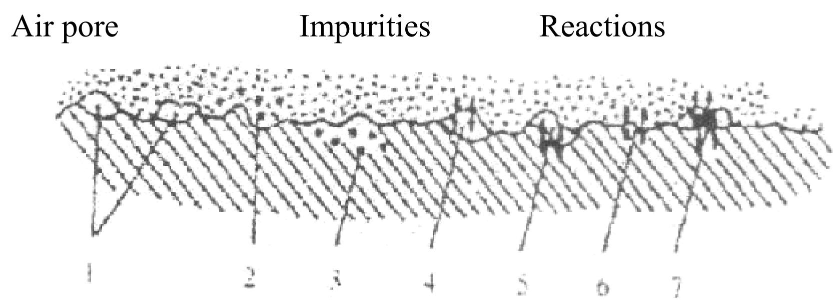


Figure 2.7: Seven classifications of weak boundary layers [15]

2.14 Bonded joint configurations

The joint using adhesive must be carefully designed and prepared. The aim of the joint is to obtain maximum strength for a given bond area. In designing adhesive joint the basic characteristics of adhesives must dictate the design. The type of joints used in adhesive-bonding flat adherends is shown in Figure 2.8.

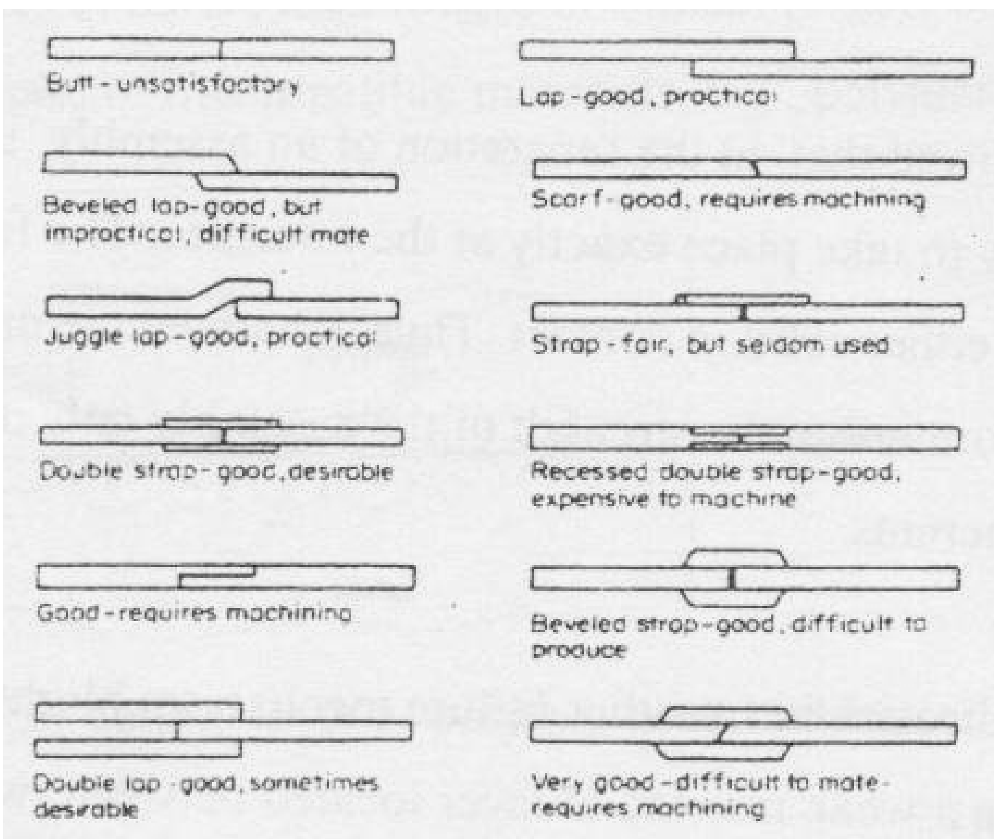


Figure 2.8: Type of joints used in adhesive-bonding flat adherends.(7)

2.15 Terminology and Hierarchy of Connection Design.

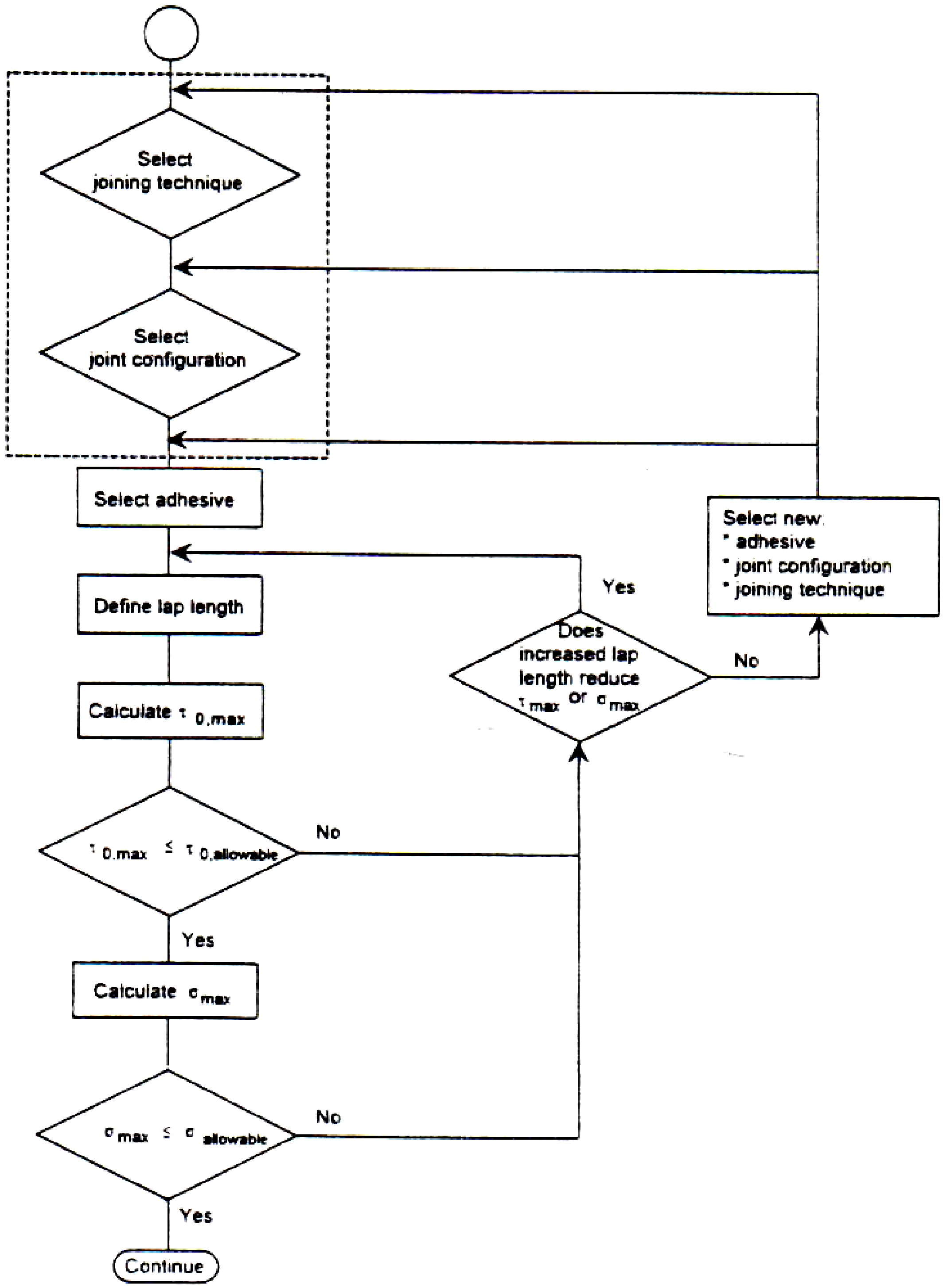


Figure 2.9: Design procedure of adhesive joint flowchart (1)

Referring to EUROCOMP design code and handbook, the procedure of joint design should follow the flow as shown in Figure 2.9. The process starts with recognizing the joint requirements such as to support and distributing the internal forces and moments then followed by selecting the joint category. This step is usually determined by loads that need to be transferred, or by the required joint efficiency as a fraction of the strength. The geometry of the member to be joint, suitability of the fabrication, component dimensions, manufacturing environment and number of components to be produced must also be considered. Another important factor effecting joint durability are service environment and the lifetime of the structure, requirements set for the reliability of the joint, and disassembly or not, weather tightness, aesthetics and cost.

The third step is selecting the joining technique. They are three most common methods usually applied namely;

- Mechanical connections: bolted and riveted joints (shear loaded fastener), bolted and riveted joints (axially loaded fasteners), clamped joints, threaded, contact joints, strap joints and embedded fasteners.
- Bonded connections: adhesively bonded joints, laminated joints, molded joints, bonded insert joints and cast-in joints.
- Combined connections: bonded-bolted joints and bonded-riveted joints.

Finally, the selection of joint configuration must be made. Typical of joint configurations and loading within each joining technique are illustrated in Figure 2.10 [1]:

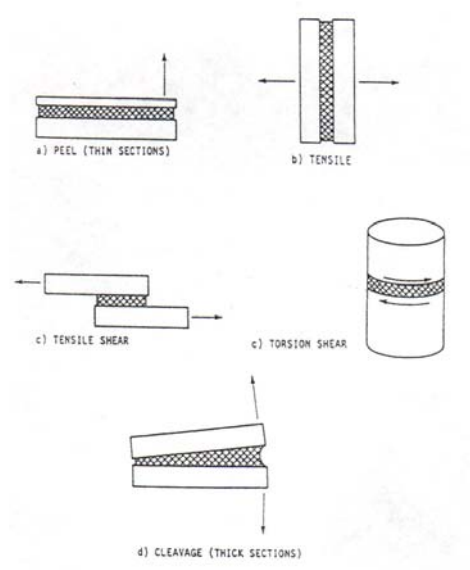


Figure 2.10: Loading modes or type of stresses.

2.16 Loading modes

In bonded joint [1], there is four main loading modes may occur and they are as follows:

- Out-plane loads acting on a thick adherend produce peel loads.
- Tensile, torsional or pure shear loads imposed on adherends produce shear stresses.
- Out-of-plane tensile loads produce tensile stresses
- Out-of-plane tensile loads acting on stiff and thick adherends at the end of the joint produce cleavage.

Simultaneously, the joint typically loaded by several of these load components. Using this joint, the tensile, cleavage and peel loads should be avoided because it will effect the joint connection. While the adhesive layers of bonded joint should primarily be stressed in shear or compression. The strains (deformation) should also be considered at the area where non-linear behavior of adherends or adhesive is expected.

2.17 Failure Modes

There are three primary failure modes [1] that can be seen on bonded joint failure namely;

- Adhesive failure that means a rupture of an adhesive bond, such that the separation is at the adhesive- adherend interface. This failure is mainly due to a material mismatch or in adequate surface treatment, so should be avoided.
- Cohesive failure of adhesive means that when the adhesive fails due to loads exceeding the adhesive strength.
- Cohesive failure of adherend means that when the adherend fails due to loads in excess of the adherend strength.

Figure 2.11 below shows the typical locations of possible failure initiation and critical strength.

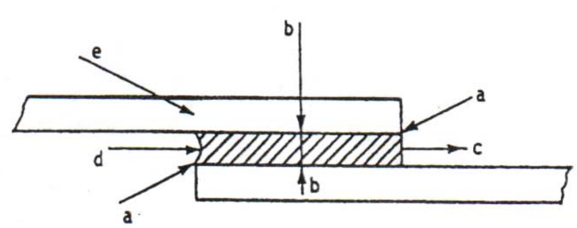


Figure 2.11: Areas of failure initiation and critical strength.

When the connection (single/double-lap and single/double strap) loaded with in-plane loads, the concentration of stress failure exist at the ends of the over lap. Figure 2.12 shows the shear stress distribution. The location where high shear stresses occurred can be said as the failure initiation.

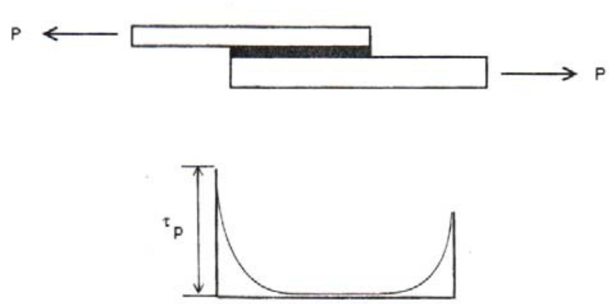


Figure 2.12: Stress distribution of lap joint.

2.18 Joint Geometry Effect on Joint Strength

The joint strength also affected by the joint geometry with certain configuration. The most basic problems of bonded joint are the unavoidable shear stress concentrations and inherent eccentricity of the forces. The two problems causing peel stresses in both, adhesive and adherends. From Figure 2.13, it can be seen that the shear stresses are maximum at the end of the overlap.

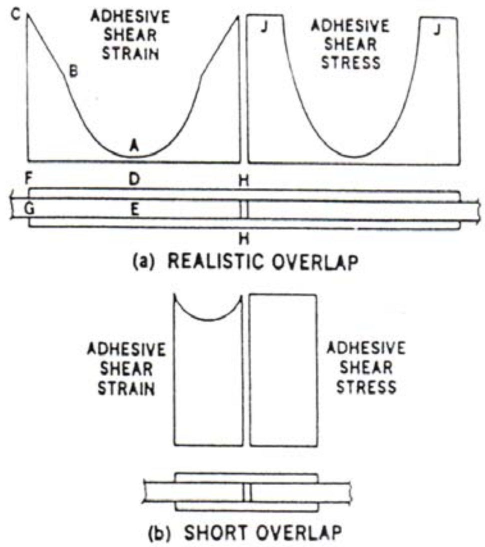


Figure 2.13: A typical adhesive shear stress distribution in a lap joint according to elastic-plastic model.

The effects of the eccentricity are the greatest in lap and strap joints. It should be known that the static load-bearing capacity of a bonded lap or strap joint cannot be increased significantly by increasing the lap length beyond the minimum needs. But, the bond length must long enough to provide a moderate loaded adhesive area in the middle to resist creep deformations of the adhesive.

The peel stresses can be reduced by increasing the adherend stiffness without increasing its thickness, increasing the lap length, tapering the ends of the adherends and using adhesive fillets. Adhesive fillets used and adherend ends tapered will reducing stress concentrations at the end of the overlap [1].

2.19 Adherends

The through thickness properties of the adherends must also be considered. Beside that, delamination due to peel and interlaminar shear stresses should be given an attention especially for highly orthotropic unidirectional materials [1]

2.20 Surface Treatments

Adherend surface treatment is greatly important because it will affect an adequate joint strength and produce bond failure. So, all the bond surfaces shall be properly treated prior to bonding and adhesive application procedure purposed by the supplier must strictly follows.

2.21 Bonded Joint Design Principle

In general, the loads imposed on the bonded joint structure must be obtained from the whole structure analysis. Besides, the bond line must ensure capable to transfer the applied loads between the joints members. While the adherends are capable of with-standing, the joint induced internal loadings. The evaluation of the basic components strength which to be joined under the applied external loads is a part of the component design process. (1)

The experimental specimen which will be tested is designed based on analytical models for plate-to-plate connection and supplemented by testing. The assumption made that the joint is a perfect bonding between the adhesive and the adherends. This means, there are no slip occurred along the bond area and the force applied were transferred uniformly to each part of the adherends. It is shown that from the failure of cohesive in the adhesive or adherend always occur before the adhesive failure at the interface. If the following have occurred, the assumption may become invalid; so must be considered properly.

- Non-suitable chemical of the adhesive and adherends. The adhesive cannot provide a good bonding and high strength needed. Besides, the adhesive will give a chemical reaction between the adhesive matrix and the adherends matrix.
- In adequate surface treatment. For examples, the surface is not roughen perfectly, the surface of bonding area is contaminated and not fully degrease by the solvent, the pressure applied while bonding is also not enough.
- Environment factors such as temperature and pressure during bonding. The bonding process should not been done during high humidity where the water will dissolved between the adhesive pore and will effect the bond strength. There must be enough time for the adhesive to cure and should be applied on suitable dry controlled environment.

Referring from the testing of the specimen, it is a perfect bonding if the failure mode is not an adhesive failure. If the slip occurred, the surface treatment should be improved or the adhesive or a joint configuration shall be changed. The design of bonded joints shall be based on practically and tolerances of the manufacturer.

Referring to the Figure 2.14, it can be seen that the different type of joint has it own mode of failure. For double strap joint, the major problem occurs is peel failure if compared to the others joint technique likely to have shear failure.

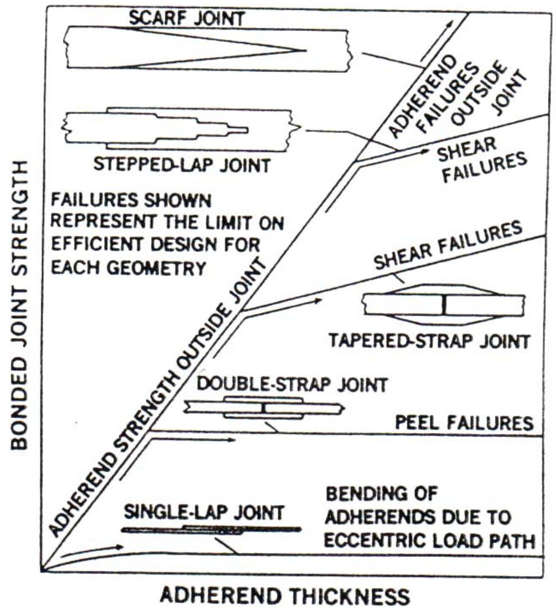


Figure 2.14: Relative joint strength of various joint configurations. (1)

2.22 Adhesive

There are a few ways that the adhesive have been categorized, such as:

- Adhesive type: this factor divide the adhesives based on the polymer type whether it has thermo set (infusibility and insoluble after curing) or thermoplastic (fusible and soluble and soften when heated) base.
- Curing process activation; whether it chemical, solvent, heat or other activation.
- Curing process requirements; it looks at curing temperature and cycle, curing pressure and cycle or post-curing.
- Form of adhesive; the form of adhesive whether paste, liquid or film.

2.22.1 Adhesive Mechanical Properties

In applications, there are few important mechanical properties have to be given full attention and understood;

- shear modulus
- shear strength
- maximum shear strain
- tensile modulus
- tensile (peel) strength.

All the properties should be obtained from the manufacturer or by testing. Consideration of environmental factors, such as temperature, moisture and chemical among the factors will affect the mechanical properties of the bond characteristics. From the Figure 2.15, it can seen that the adhesives have either ductile or brittle behavior and should be also considered when the joint is applied. Referring at creep property, adhesives will creep under constant load even at the room temperature especially at elevated temperature. Usually, thermo set adhesives have better creep resistance than thermoplastic adhesives.

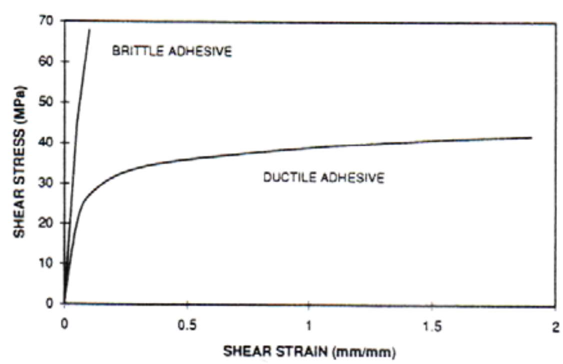


Figure 2.15: Typical brittle and ductile adhesive behavior. (1)

2.23 Elastic Properties and Deformation

Figure 2.16 shows the schematic figure of a single-lap joint with uniform lap thickness loaded in tension. Assuming the double lap joint deform as single lap joint configuration, theoretically the deformation and its failure occurred as shown in Figure 2.16. The upper and lower part represent as an adherends while adhesive in the middle. The members deform concentrically and the adhesive in shear when load applied. There are two type that the specimen can be categorized; rigid members and elastic members. If the members were rigid, equal amount of load would transfer along the adhesive, and the shear deformation would be equal in all part of adhesive.

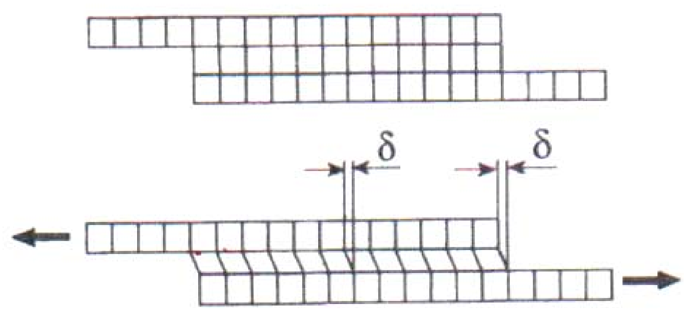


Figure 2.16: Deformation of rigid members. (1)

In reality, the members are always have elasticity and will deform continuously through their lengths. The greater amount of load were transferred at the load ends of the overlap mean by the higher displacement between the members occurs as shown in Figure 2.17.

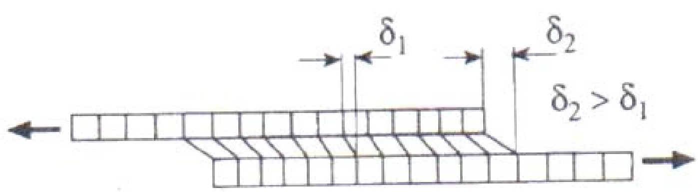


Figure 2.17: Deformation of elastic members. (1)

The strength of the joint is depending on the yield strength of the adherend, its modulus and thickness. The thickness of the adhesive bond is important. The layer must be as thin as possible to avoid joint starvation. The analysis of the durability of joint related to a few matters:

- Type of adhesive: Different adhesive provides different bond strength and characteristic. The selection of the adhesive should be done carefully based on the type of joint, strength needed, and the materials to be connected and considering the application.
- Adherend used: The adherends be used should be suitable and to the adhesive. Each adherend has it own properties that will provide different durability.
- Adherend preparations: Adherend should be prepared follows the correct procedure to give the good adhesion and absorption by the contact between adherend and the adhesive.
- Curing process; temperature and pressure: The adhesive only will give high bond strength if completely cured. To reach this situation, the bonding needs enough setting time, dry and clean environment and suitable curing temperature. Uncompleted curing process can cause slipping problems of the adherends.
- Adhesive thickness: The thickness of the adhesive should be controlled; not to thick or less. Thick bond layer will create an unexpected force and moment. Besides, it will risk a peel failure. The less thickness could caused lower strength of bonding and easily fractured.

2.24 Design Procedure for Tensile Shear Loading

This is the procedure need to be followed for designing double-lap joints which loaded by tensile shear loading by referring to Eurocomp, the following steps and formulation used as standard guidelines in designing double-lap joint of FRP-concrete.

Step 1

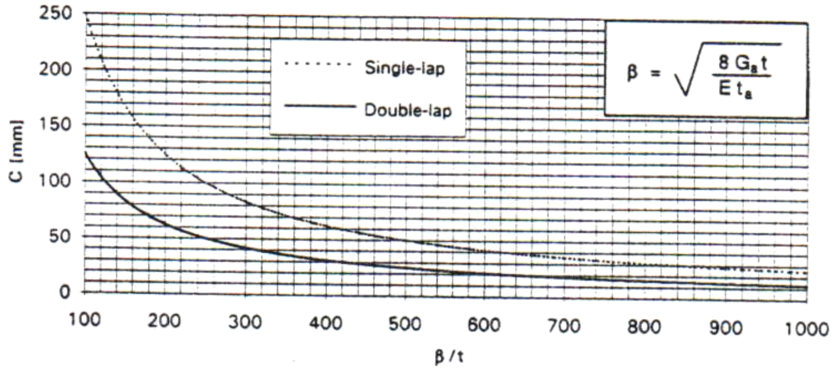


Figure 2.18: Half lap length (c) as a function of parameter β/t

Firstly, determine the lap length (L = 2c) using a standard graph of C versus B/t shows in Figure 2.18. Parameter *β/t* is defined from the equation (2.1):

$$\frac{\beta}{t} = \sqrt{\frac{8G_a t}{Et_a}} \quad \textbf{............(2.1)}$$

where;

G_a = adhesive shear modulus (N/mm^2)

E = adherend Young's modulus (N/mm^2)

t = minimum adherend thickness (mm)

t_a = adhesive layer thickness (mm)

Step 2

To calculate the maximum adhesive shear stress for double-lap joint, the equation (2.2) is used:

$$\tau_{o\max} = \frac{\lambda P_k \gamma_f}{4}\left[\frac{\cosh(\lambda c)}{\sinh(\lambda c)} + \Omega \frac{\sinh(\lambda c)}{\cosh(\lambda c)}\right] \quad \textbf{.........(2.2)}$$

where

$$\lambda^2 = \frac{G_a}{t_a}\left(\frac{1}{E_o t_o} + \frac{2}{E_i t_i}\right)$$

and

P_k = characteristic load per unit width

Ω = the greater of (1 – Ψ)/(1 + Ψ) or (Ψ – 1)/(1 + Ψ)

where

$$\psi = \frac{E_i t_i}{2 E_o t_o}$$

Step 3

The magnitude of the adhesive shear stress maximum value is determined by ;

$$\tau_{o\max} \leq \tau_{oallowable}$$

where

$$\tau_{oallowable} = \frac{\tau_{o,k}}{\gamma_m}$$

2.25 Factors Considered in Designing Adhesive Bond Joint

It is really need to give an attention to a few factors to make an appropriate and effective adhesive bond joint. Basically, it towards to four main points, the material involved the job requirement, the job design and cost. The sub-factors are referring to:

- Type of material to be joined
- Hardness conditions and surface finishes
- Adherends thickness
- Part function
- The temperature range that the joint or assemble must be able to withstand
- The temperature of environment for most of service life and time period
- Test referred
- Contamination in contact to the bond (solvents, oil and other fluids); the temperature and exposure type
- Electrical continuity
- Required joint strength
- Stress withstands (tensile, shear, peel, compression, impact, vibration and etc.)
- Tolerance of temperature and pressure of bonded part.(1)

2.26 Lap Joints

This is the most common adhesive joints configuration. It is simple to make, can be used with thin adherends and stress the adhesive in its strongest direction. The lap joint, however, is offset and their shear forces are not in line, as shownin Figure 2.19. It can be seen the stress is concentrated at the ends of the lap. The greater part of the overlap (adjacent to the center) carries a comparatively low stress. If the overlap length is increased by 100%, the load carrying capability is increased by a much lower percentage. The most effective way to increase the bond strength is to increase the joint width. In addition to overlap length width and length, the strength of the lap joint is dependent on the yield strength of the adherend. The modulus and the thickness of the adherend determine its yield strength, which should not exceed the joint strength.

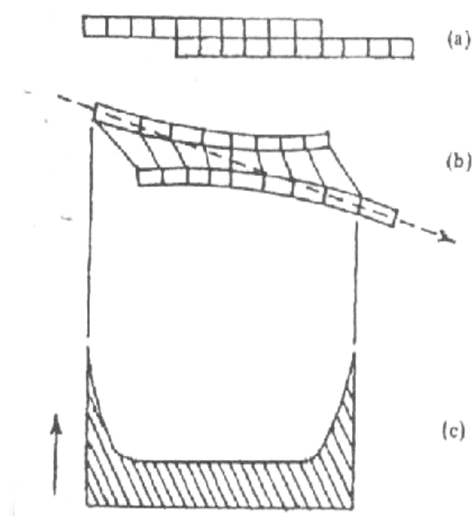


Figure 2.19: Tensile force on sinle-lap joint showing (a) unloaded joint, (b) joint under stress, and (c) stress distribution in adhesive [11]

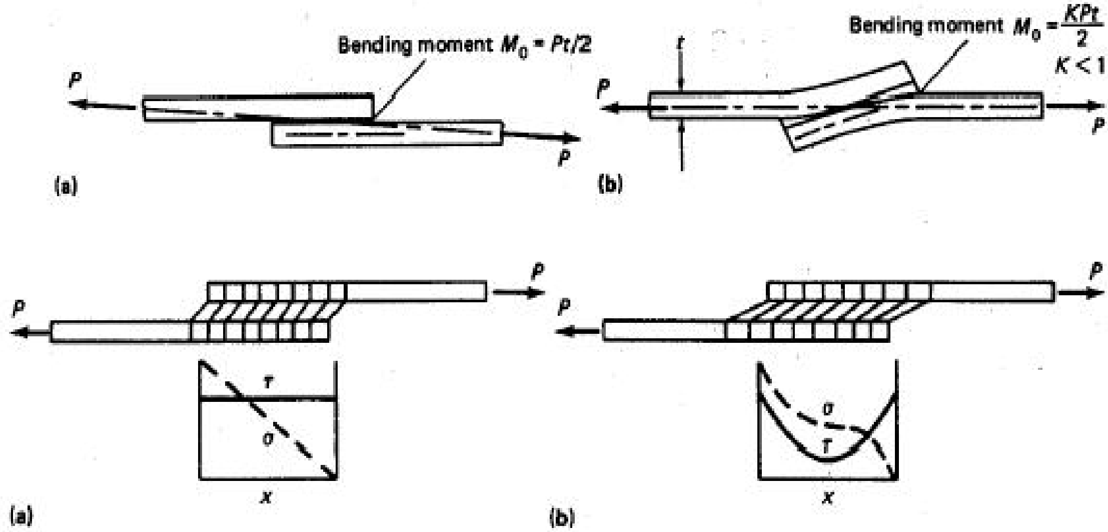


Figure 2.20: Exaggerated deformation in loaded single lap joint showing the adhesive shear stress, τ and the adherend tensile stress, σ (a) with rigid adherends, (b) with elastic adherends [11]

Consideration has to be done for the interpretation of the results between rigid and elastic adherends. Rigid adherends create constant shear lap strength along the thickness of the adhesives, while elastic adherends create a variable stress (Fig. 2.20).

2.27 Mechanism of Bond Failure

Failure of adhesive can occur in three different modes.

2.27.1 Failure at Interface (An Adhesive Failure) [16]

This may arise through failure of an interlayer between the parent adherend material and adhesive (an oxide coating or primer layer) or through failure of the adhesive to bond to the surface. In practice, the interface is not flat and the surface topography acts to create a layer where there is both adhesive and adherend present. The complexity of the layer militates against modeling at this level in any detail. However, the purpose of the layer is to transfer normal and shear loads between the adherend and the adhesive and its effect on joint performance (other than failure) is negligible.

2.27.2 Failure in the Adhesive (A Cohesive Failure)

Cohesive failure occurs through excessive strain with the adhesive material and may occur anywhere within the adhesive layer. Stresses and strains peak at the ends of the overlap however and generally close to an adherend. The various mode of failure are illustrated in Figure 2.21.

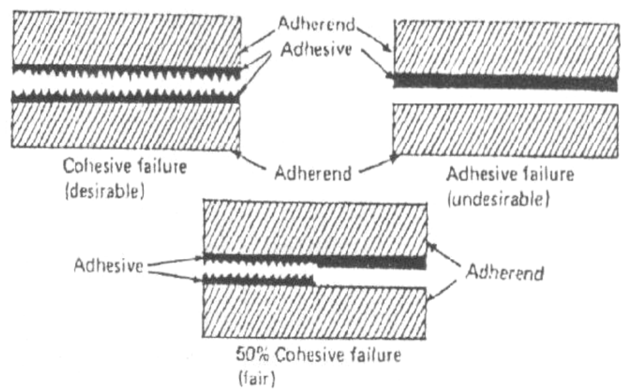


Figure 2.21: Cohesive and adhesive bond failure [14]

2.27.3 Failure in the Adherend [16]

This will arise through excessive strain within the adherend material and is more common for brittle materials. In particular, joints made with adherends of fiber reinforced composite material and toughened adhesive initially fail by adherend failure, usually delamination of ply closest to the adhesive.

2.28 Environmental Effects on Adhesive Bonded Joints

The effect of exposure condition on CFRP and concrete such as moisture absorption is studied. This chapter is divided into four sections, namely, Theory of Moisture Diffusion, Effects of Moisture Absorption on FRP Materials, Effects of Water Absorption on Adhesive Bonding, and Past Research Review.

2.29 Environmental Durability of Adhesive Joints

The environmental resistance of any bonded assembly FRP system depends on the durability of the individual components materials, as well as on the bond between them. For example, in the use of FRP materials for external strengthening of concrete, the individual components are the concrete, the fiber reinforced polymer composite and the adhesive, which is usually an epoxy. The long-term integrity of bonded joints implies both chemical and mechanical durability under varying temperature, moisture and other environmental factors, which for external purposes may include spray from de-icing salts or from the sea. Adhesive bonded joints with equivalent bond strength values in short-term static tests may differ markedly with respect to the durability.

The measured residual joint strength after environmental exposure is a function of change in the cohesive properties of the adherends and in the adhesion between the adhesives and the adherend. Therefore, joint durability demands a three-fold consideration of the structural integrity of the cured adhesive, the adherends and the environmental stability of the interface.

2.29.1 Environmental and Service Conditions

The bonded joints used in a civil engineering environment may be subjected to a variety conditions. The normal service conditions to be considered are shown as follows;

- Temperature fluctuation
- Moisture (humidity, liquid water, salt spray)
- Chemical attack (oil, fuel, chemical spills)
- Fire
- Loads (dynamic and static)

These service conditions should be considered in conjunction with the loading conditions, which, for bridge strengthening, relate primarily to peak short term static loading. Sustained loading (leading to creep), fatigue and impact may also need to be considered.

2.29.1.1 Resistance to Temperature

It has been established that water, in liquid or vapour form, represents one of the most harmful environments for bonded joints (Kinloch,1993). This problem is that water is found universally and the polar groups that confer adhesive properties make the adhesive inherently hydrophilic. High energy of substrate surfaces is also generally hydrophilic. For example, concrete itself is susceptible to the effects of moisture. The properties of the matrix resin in FRP materials, together with the properties of adhesives are susceptible to the effects of heat and moisture. The result of moisture absorption, which is reversible, is to lower the glass transition temperature (T_g) of these materials, leading to the change in their mechanical properties. The effect of elevated temperature is to reduce the strength and modulus of polymers: the T_g of the adhesive is likely to be rather less than that of the matrix resin, so that the adhesive is the governing factor.

2.29.1.2 Resistance to Moisture

Adhesive bonded joints are generally attacked by exposure to moisture and elevated temperature. In a well mode joint where a sound bond has been achieved, the main effect will be on the adhesive layer. A small amount of moisture-induced plasticization of the adhesive in highly stressed regions may actually be beneficial in reducing stress concentrations. However, a small reduction in joint strength should normally be anticipated in relation to the effects of environmental conditions on the adhesive itself.

2.29.1.3 Resistance to Chemical Attack

The resistance of connections to chemical attack depends upon the nature of the liquid and its effects on both the composite components and the adhesive. Alkalis can cause severe matrix resin softening with a consequent effect on any form of connection. Isophtalic polyesters provide better resistance than orthophthalic polyesters in terms alkalis and organic solvents and are to be preferred for the majority of glass fiber reinforced plastic (GFRP) components. FRP components made with vinyl ester resins are still better, but a little more expensive. Epoxy materials, both as the matrix resin and as adhesives, are regarded as very inert in acids and alkalis.

2.29.2 Resistance to Fire

The resistance of joints to the effects of fire implies consideration of the entire FRP structure, and a useful commentary is contained in the EURO COMP Design Code (Clarke, 1996). FRP materials and adhesives are very poor conductors of heat, which is an advantage over metals, but they can also possess a large coefficient of thermal expansion in directions that they do not have a significant amount of continuous fiber reinforcement. The effect of dimensional changes of the components and joints directly affected by fire or heat should therefore be considered. Adhesive are weaked by influence of elevated temperature and may burn if exposed directly to fire.

2.30 Factors Affecting Joint Durability

The main factors that influence joint performance and durability are briefly described as follows;

2.30.1 Adherend Type and Nature

One of the most important factors in joint durability is the environmental stability of the adhesive-adherend interface [4]. Changes in the adhesive and the adherend can be allowed for changes in adhesion. Thus, optimization of surface conditions and pretreatments often represents the key to minimizing joint durability. If properly prepared, the surfaces of both concrete and FRP materials are relatively stable and the durable bonds with epoxy adhesives are formed relatively easy. This is in contrast to the situation with the steel plate bonding, for which an adequate standard of surface preparation for mild steel surfaces is quite hard to achieve in practice.

Furthermore, the surface of steel is fairly unstable, especially in the presence of water, such that bonds to the oxide layer are susceptible to degradation. The substitution of FRP materials for steel strengthening is motivated in a large part by the assurance of superior bond integrity.

2.30.2 Adhesive Type/ Cure Cycle

The adhesive system selected is clearly very important. Generally a two-part cold curing paste-epoxy material is used without a primer. However, sometimes a primer may be required for substrate surfaces to ensure satisfactory adhesion. Conceptually, adhesives represent natural candidates for joining FRP materials because they are often similar in composition and nature to the composite matrix resin. The fundamental concepts involved in adhesive selection are that it should:

- Adhere well to the surface involved
- Exhibit low permeability to water
- Posses appropriate physical and mechanical properties

2.30.3 Quality of FRP Material

The quality of the FRP material itself should be high for several reasons. These include the need for reproducible and predictable properties (for design and prediction purpose), flatness (to ensure uniform bonding and bond line thickness) and excellent consolidation (to reduce permeability and mechanical weakness). A poorly made composite will give raise to durability problems sooner or later.

2.30.4 Bonding Operation

The bonding operation, including protection of the working environment, is important to give a high quality of joint. Trained operatives working under skilled supervision should ensure that the surface preparation, adhesive application, temporary clamping arrangements and adhesive curing details are handled adequately. Poor control of the bonding operation generally manifests itself subsequently in joint performance and durability problems.

2.30.5 Joint Design

Joint design has an important bearing on joint durability. The joint design concepts are allowed for a large bond area and to avoid unacceptable large stress concentration in the joint. The synergistic effects of high temperature, excess moisture and applied stress normal to the bond line are undoubtedly detrimental. Joint design should therefore seek to minimize the buildup of stress concentrations which give raise to indirect peel and cleavage loads at adherend/ adhesive interface.

2.30.6 Exposure Conditions

Experience with structural adhesive bonding has shown that the mechanical properties of bonded joints often deteriorate under warm and wet conditions. (Bodnar, 1997; Kinloch, 1983). This is because the joints comprise either high energy substrates such as metals, glasses and ceramics or else permeable substrates such as concrete and timber (Venable, 1984; Mays and Hutchnson, 1992). Furthermore, failure at the adhesive/ substrate interface, rather than the failure within the adhesive layer itself, is commonly found only after environmental exposure.

2.31 Theory of Moisture Diffusion

Experimental studies have shown that FRP are exposed to moisture or chemical solutions, free ions (i.e. OH^- and Cl^- ions) and water molecules would diffuse into the fiber matrix system and react with the fiber or matrix, thus causing micro cracking and fracturing of the matrix and loss in fiber cross-section. This would result in loss strength and stiffness of the composite. The single free phase model of absorption (i.e. Fick's law) was used to simulate moisture diffusion into the rebar and tendon specimens. Fick's law assumes that molecules are not bound by material, and the driving force behind diffusion is the ion concentration gradient. For example, tendon and rebar diffusion specimens were 102mm in length with both ends epoxy-coated in order for diffusion to occur only normal to the surface of the sample. (i.e. radial direction for cylindrical specimen. In order to simplify the analysis, the following two assumptions are introduced:

1. The radius to length ratio of test specimen is much less than one (i.e. $r_0 << 1$)
2. The diffusivity inside the composite material is constant.

Diffusion specimens were oven dried at temperature of 65ºC until no change in weight was observed. Then, they were immersed in solutions, and weight changes were recorded using a Mettler Balance. The objective was to determine the percent weight gain M (%) of the composite as a function of the square root of exposure time $(t)^{\frac{1}{2}}$.

2.32 Free Phase Model (Fick's Law)

The free phase model of absorption of Fick's law can be written as:

$$D\frac{\partial^2 c}{\partial x^2} = \frac{\partial c}{\partial t}$$

Where D is the diffusion coefficient (mm²/min), c is the ion concentration (mol/l) at a distance "x"(mm) measured in the direction normal to the surface, and "t" is the exposure time (min). A time dependent coefficient (G) can be related to the diffusion coefficient, D by:

$$G = \frac{m - m_i}{m_m - m_i} = 1 - \frac{\delta}{\pi^2}\sum_0^{\infty}\frac{\exp\left[(-2j+1)^2\pi^2\left(\frac{D_t}{h^2}\right)\right]}{(2j+1)^2}$$

Where "h" is the specimen thickness, $m_{i,}$ is the initial weight of moisture in the sample, and m_m is the weight of moisture when sample is fully saturated.

It is of interest to determine the moisture content as a percentage of weight gain of the composite (M). Thus, M (%) is calculated as:

$$M(\%) = \frac{W - W_d}{W_d} \times 100$$

Where W and W_d are the moist weight and the dry weight of the specimen, respectively. The initial part of the M (%) vs. $(t)^{1/2}$ relationship is linear indicating Fickian diffusion in samples, and after a period of time that is dependent on the type of fiber, matrix material, temperature, and type of solution, the curve would level off towards on asymptotic value corresponding to M_m at saturation. After an extended period of time that is also dependent on the same aforementioned factors, a rapid nonlinear increase in M with respect to $(t)^{1/2}$ occurs, indicating non-Fick's diffusion ceases to be valid. For a sufficiently short period of time, the diffusivity D can be calculated from the initial linear part of the M vs. $(t)^{1/2}$ relationship as follows:

$$D = \frac{\pi r_0^{\,2}}{16}\left(\frac{M_2 - M_1}{M_m}\right)^2\left(\frac{1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2$$

Where M_1 and M_2 are the percentage moisture content at times t_1 and t_2 corresponding to the beginning and end of the time interval, and 'r_0' is the radius of the test specimen.

It is important to determine the diffusivity D because it provides a direct measure of moisture penetration, which can be used to determine the depth of the damaged zone in which the matrix and fibers are assumed to no longer be able to transfer any tensile forces. The depth of the damaged zone "x" due to alkali OH^- and chloride Cl^- attack can be calculated from:

$$x = \sqrt{2.D.C.t}$$

Where C is hydroxyl or chloride ion concentration (mol/l). If the initial radius of the sample is 'r_0' (mm), the radius of the residual of the residual area is 'r_r' (mm) and the initial strength is P_u (kN), then the predicted residual tensile strength P_p (kN) is calculated as:

$$P_p = P_u\left(1 - \frac{x}{r_0}\right)^2 = P_u\left(\frac{r_r}{r_0}\right)^2$$

2.33 Effects of Moisture Absorption on FRP Components

Moisture is thought to gain access into FRP by three separate routes:

- By diffusion through the matrix resin
- By capillary flow along the longitudinal axis of the fiber at the fiber-resin interface
- Through the cracks and voids in the structure

In general, the effects of exposure to moisture or aqueous solution are discussed in the following section.

2.33.1 Weight Increase

Moisture absorption will caused weight gain of FRP material after certain duration of exposure. An environmental durability testing was performed on Master Builder. Inc. CF130/MBrace™ Saturant Epoxy carbon/epoxy composite system by engineering and Technology Group, THE AEROSPACE CORPORATION, EISegundo. MBrace™ [19] is a carbon/epoxy is a hand lay-up composite system that is fabricated in –situ on the structure being reinforced or repaired. The results of the experiment are shown in Table 2.5.

Table 2.5: Results of environmental durability testing [19]

Environmental exposure & durations	Weight	Change (%)
	2 ply (thickness: 1mm)	6 ply (thickness: 3mm)
100% humidity/38ºC		
1000 hours	1.13	0.95
2000 hours	1.41	1.03
10,000 hours	1.51	1.46
Salt water		
Immersion at 23ºC		
1000 hours	1.14	0.65
2000 hours	1.24	0.88
10,000 hours	1.48	1.37
Alkali solution		
Immersion in $CaCO_3$, pH= 9.5 and 23ºC		
1000 hours	1.24	0.44
2000 hours	1.27	0.88
10,000 hours	1.31	1.37

It is observed that the CF130/MBrace™ Saturant Epoxy System had positive weight changes; attributed to moisture absorption, after the humidity, salt water and alkali exposures. Moisture exposure was higher for the 2-ply panels than for the 6-ply panels. This is because the 2-ply panels equilibrated with the environmental more rapidly than the thicker 6-ply panels. Figure 2.22 shows the moisture absorption curves for the 10,000 hours. The plots show that 30-50% of the total moisture absorption occurred in the first 20 days for all exposure conditions. Moisture absorption appeared to reach saturation at 1.3-1.5% after approximately 150 days for the 2-ply panels. The 6-

ply panels were reaching this level of moisture absorption at the end of the 417-day exposure.

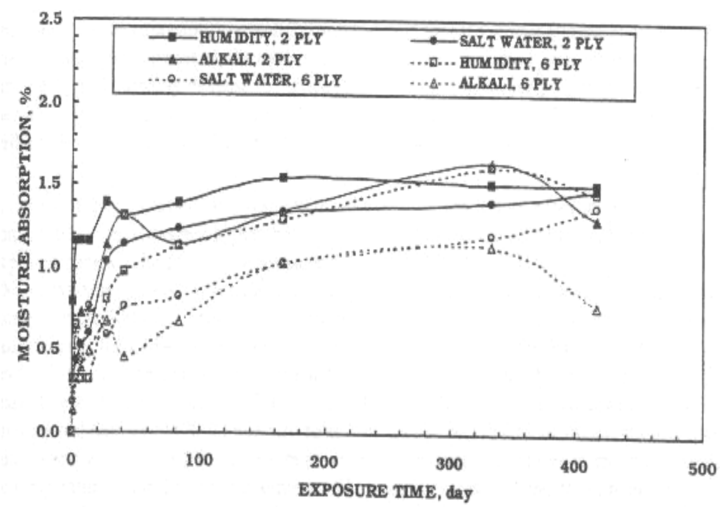


Figure 2.22: Moisture absorption curves for 10,000-h panels for CF130/Mbrace ™Saturant Epoxy [19]

2.33.2 Plasticization of Matrix and Decrease of Glass Transition Temperature

In general, glass transition temperature (T_g) was increased by elevated temperatures due to advancement of the cure state of the epoxy matrix and was decreased by moisture absorption due to plasticization of the epoxy. The glass transition temperature is the center of the temperature range in which a non-crystalline solid change from being glass-brittle to being viscous. The results of durability environmental testing on effects of moisture absorption on glass transition temperature are shown in Table 2.6.

The T_g's samples exposed to moisture were only 4-5ºC lower than those for the control samples. For the exposures in which the material was exposed to heat and temperature, the thermal effect dominated, and the T_g was increased. This indicates that the T_g will probably increase in service relative to the control samples due to exposure to summer temperatures. Thus, the baseline, dry T_g will probably be closer to 70ºC in service and probably will not decrease below 65ºC even after prolonged moisture exposure. The effect of temperature and moisture absorption is also demonstrated by plots of T_g versus exposure time. It is observed that most of the reduction in T_g for these exposure conditions occurred in the first 42 days (1000 hours). This is due to the fact that most of the moisture absorption occurred this period. Initially, T_g increased in the humidity chamber due to the elevated temperature, but with long term exposure to humidity, there was a slight decrease. But, even after 10,000 hours in the humidity chamber, T_g was higher than for the control panels. The competing effects of temperature and moisture absorption are also demonstrated by plots of T_g versus exposure day and weight gain shown in Figure 2.23.

Table 2.6: Results of environmental durability testing [19]

Environmental exposure & durations	Glass Transition Temperature (ºC)
Control	67, 73, 67, 70
100% humidity/38ºC	
1000 hours	75
2000 hours	80
10,000 hours	70
Salt water	
Immersion at 23ºC	
1001 hours	65
2000 hours	71
10,000 hours	63
Alkali solution	
Immersion in $CaCO_3$, pH= 9.5 and 23ºC	
1000 hours	65
2000 hours	73
10,000 hours	62
Dry heat at 60ºC	
1000 hours	84
3000 hours	91
20 Freeze/ Thaw Cycles	72

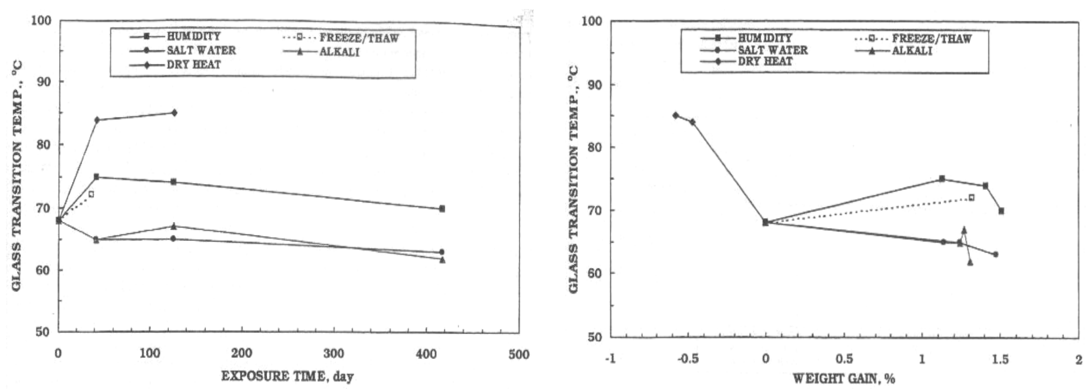


Figure 2.23: (a) Glass transition temperature versus exposure time (b) Glass transition temperature versus moisture absorption [19]

2.33.3 Reduction in Strength

The competing effect of moisture absorption is reduction in strength. Environmental durability testing performed on Master Builders Inc. CF130/MBrace™Saturant Epoxy carbon/ epoxy composite system showed that there is reduction in strength of the samples after certain exposure durations. The results are summarized as Table 2.7.

Table 2.7: Result of environmental durability testing [19]

Environmental exposure & durations	Tensile strength (ksi) and % of reduction compared to control	Short beam shear strength (ksi) and % of reduction compared to control
Control	636	7.8
100% humidity/38ºC		
1000 hours	591 (7.0%)	7.6 (2.6%)
3000 hours	540 (15.1%)	7.2 (7.7%)
10,000 hours	596 (6.3%)	6.9 (11.5%)
Salt water Immersion at 23ºC		
1000 hours	619 (2.7%)	7.5 (3.9%)
3000 hours	623 (2.0%)	7.6 (2.6%)
10,000 hours	610 (4.1%)	6.8 (12.8%)
Dry heat 60ºC		
1000 hours	637 (0.2% increase)	9.5 (21.8% increase)
3000 hours	582 (8.5%)	8.6 10.3% increase)
20 Freeze/ Thaw Cycles	561 (11.8%)	7.5 (3.9%)

Moisture absorption caused small decrease in SBSS and moisture dry-out and elevated temperatures caused increases in SBSS. The maximum decreases in SBSS were around 10-15% after 417 days in salt water, the alkali solution or the humidity chamber. The maximum increase was around 10-20% after the dry heat exposure. The beneficial effect of the elevated temperature in the humidity chamber on T_g was not observed for the SBSS data. Additional curing of the epoxy matrix did not diminish the degrading effects of moisture absorption on SBSS.

2.34 Effects of Water Absorption on Adhesive Bonding

An experiment carried out by K.B. Armstrong on wedge testing adhesive bonded joints made from dry, water immersed and dried, CFRP laminates based on Ciba Fibredux 914 showed the effect of water absorption on CFRP bonded system. Five groups of the samples were tested. The samples bonded with Hysol EA 9394 adhesive were tested on dry, immersed and dried, with CFRP adherend using mechanical abrasion as the surface preparation. Hysol EA 9390 repair resin was tested on abraded dry samples and on dry, and immersed and dried, peel ply surfaces. The test method used was the wedge test to ASTM D3762. From the result obtained, it is observed that the long term durability of repairs to CFRP laminates based on Ciba Fibredux 914 should be excellent if surface preparation and drying are properly carried out prior to bonding.

A research carried out by Department of Mechanical Engineering, University of Sheffield [21] shows the influence of aggressive exposure conditions on the behaviour of adhesive bonded concrete-GFRP joints. The details of materials geometry and instrumented gauges used in test programme used in the experiment are shown in Figure 2.24:

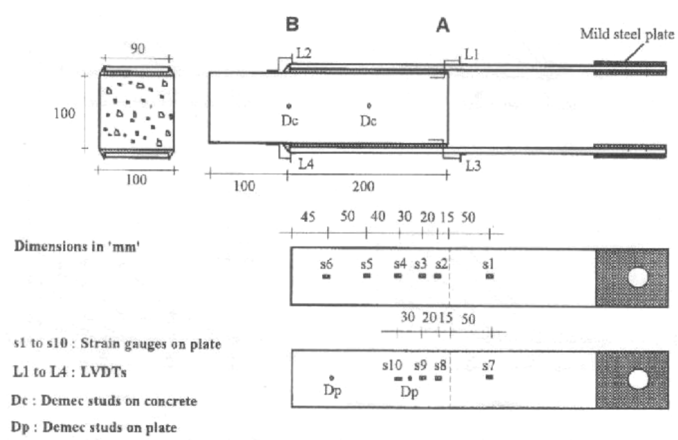


Figure 2.24: GFRP-Concrete Bonded System Details [21]

There are two type of concrete mixture used in this study namely type A and B. The typical longitudinal plate force transfer for concrete mix A and B are shown as Figure 2.25 and Figure 2.26. From the figures, it is observed that the load transfer from the plate to concrete at low loads are fairly linear, and occurs at a uniform rate, and this is occurs at a uniform rate, between 50 mm and 100 mm.

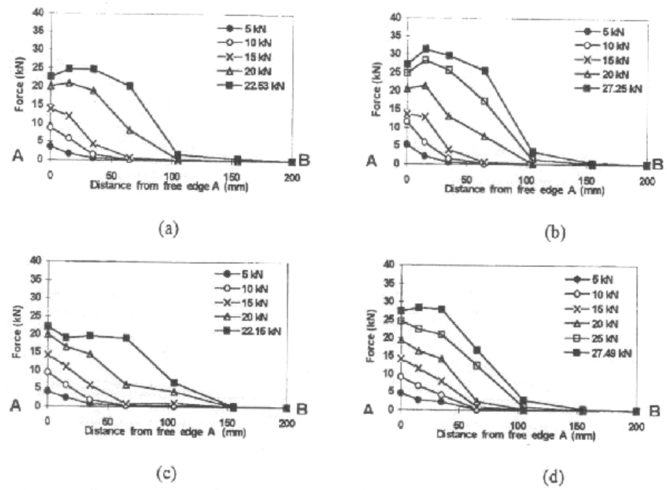


Figure 2.25: Typical longitudinal plate force transfer for mix A: (a) control, (b) wet/dry (c) freeze-thaw and (d) dual [21]

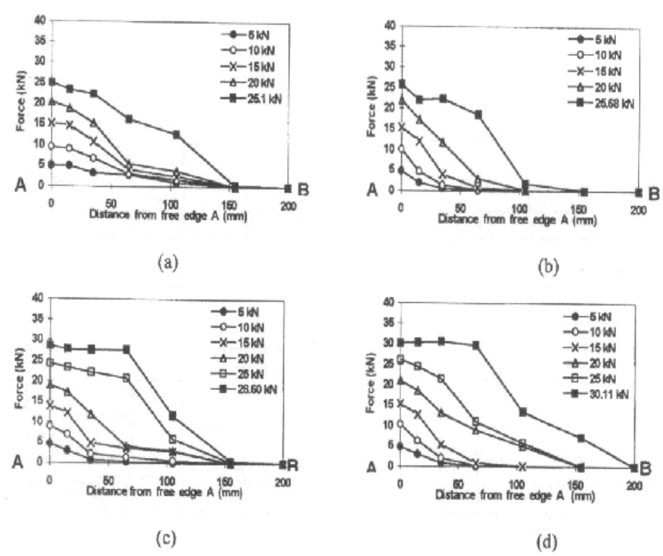


Figure 2.26: typical longitudinal plate force transfers for mix B: (a) control, (b) wet/dry (c) freeze-thaw and (d) dual [21]

The transfer of the longitudinal force from the plate to the concrete creates shear stresses both in the epoxy adhesive, at the concrete-adhesive and plate-adhesive interfaces. The typical shear stress distributions for concrete mix A and B are shown as Figure 2.27 and Figure 2.28. The overall trends shown by the data in Figure 2.27 and Figure 2.28 is that at low plate load levels, the bond shear stress is maximum near the free edge.

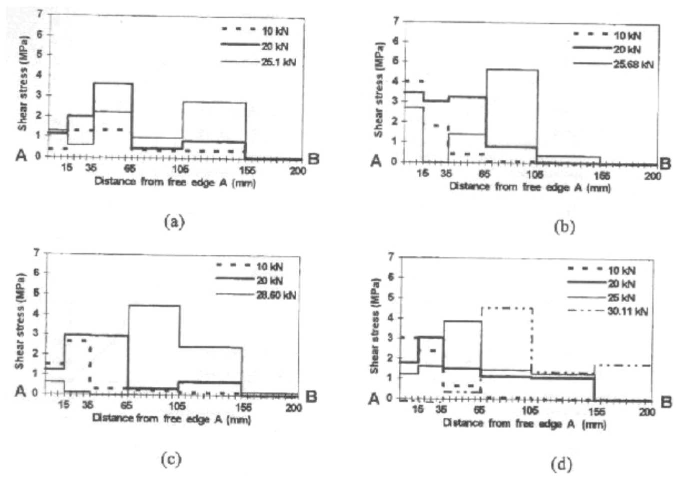


Figure 2.27: Typical shear stress distribution for mix A: (a) control, (b) wet/dry, (c) freeze thaw and (d) dual [21]

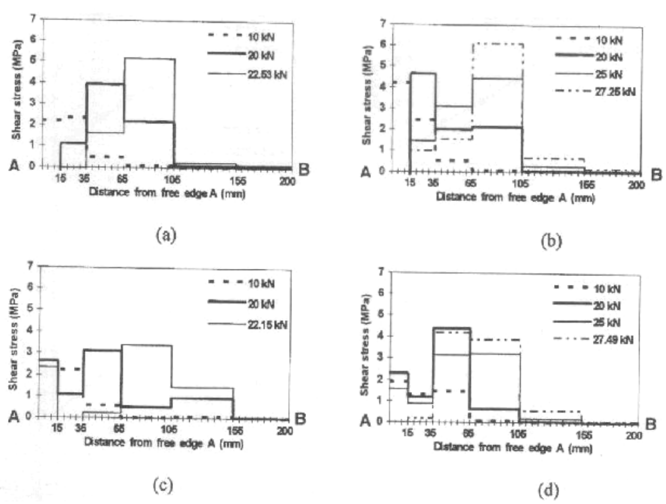


Figure 2.28: Typical shear stress distributions for mix B: (a) control, (b) wet/dry, (c) freeze thaw and (d) dual [21]

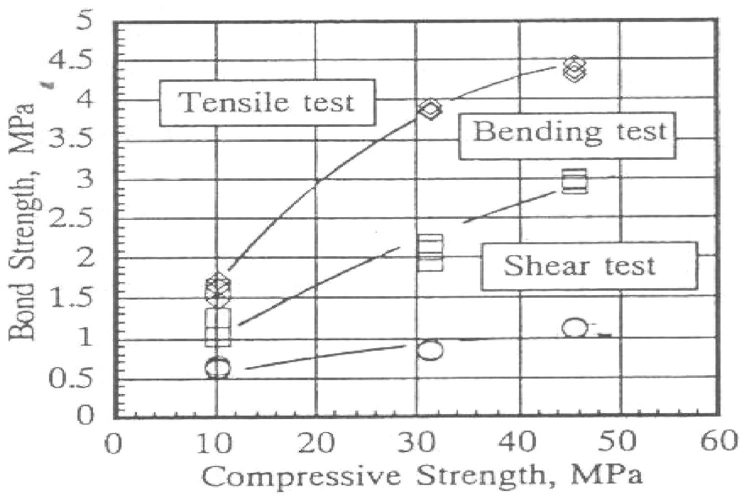


Figure 2.29: Relation between bond strength and compressive strength [7]

Another finding should be noted in Figure 2.29 is the increase of bond strength with the increase of compressive strength of concrete. In other words, the bond strength decreases with the decrease of the compressive strength of concrete. In case of concrete deterioration, the decrease of compressive strength affect strongly on the tensile-type of bond strength.

From the test, it is observed that, the failure of an adhesive bonded plate-concrete joint subjected to a uniaxial tensile can occur in three ways: (a) 'cohesive failure' in the adhesive layer (Figure 2.30a); (b) 'adhesion failure' (Figure 2.30b) and (c) 'concrete shearing failure' (Figure 2.30c). Besides, it was observed that in specimens with concrete mix A (strength lower than mix B) there were certainly more signs of 'adhesion failure' than specimens with concrete mix B. This relatively more severe deterioration of the interface with concrete mix A is primarily due to the strength of the concrete.

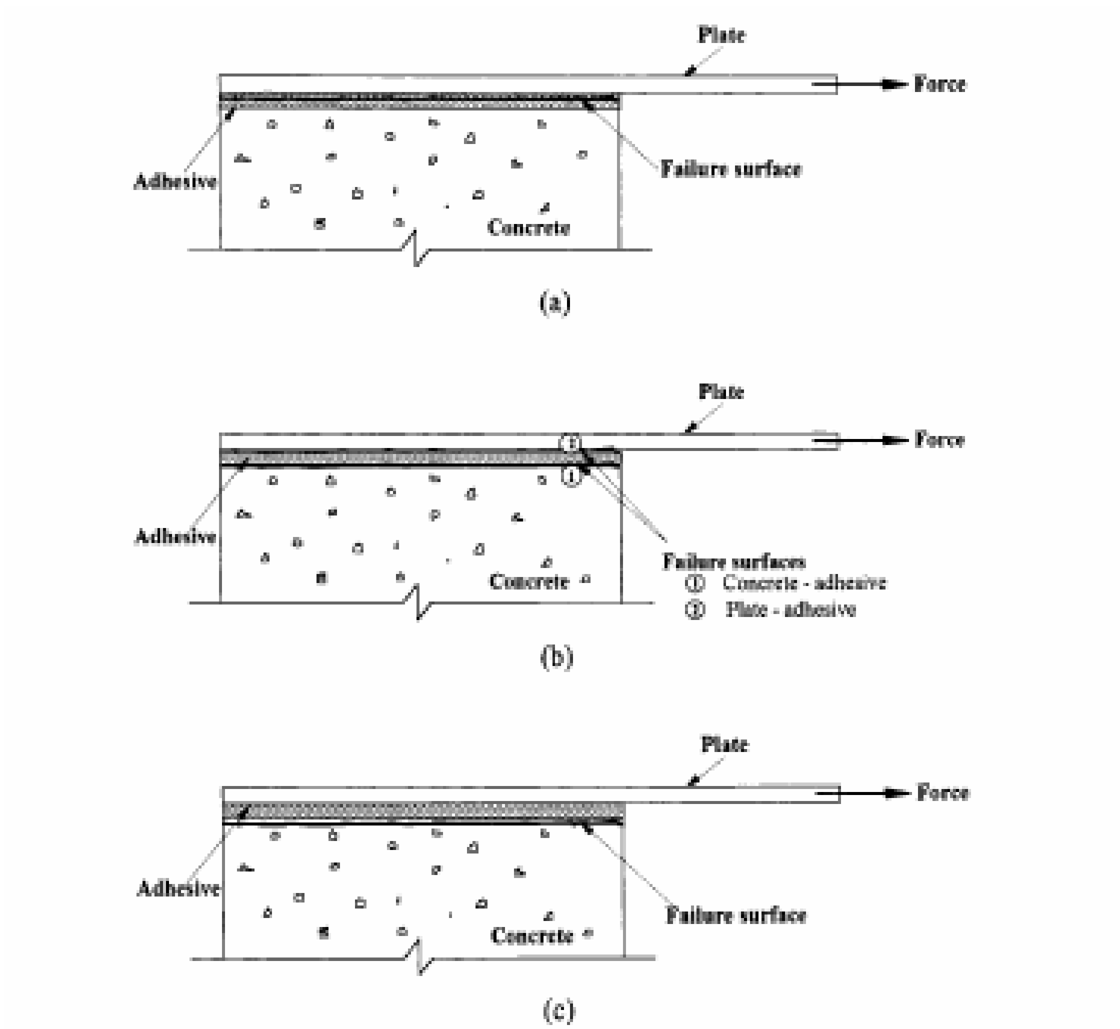


Figure 2.30: Different potential failure modes in a plate bonded joint (a) cohesive failure; (b) adhesive failure and (c) concrete shearing failure [21]

Summary

Long term durability is one of the most important properties of many adhesive bonds. Although it can be difficult to achieve in aggressive environments, there are some methods to slow the degradation process. Material selection and preparation, proper surface preparation and proper design of the joint may maximize the durability of joints.

The duration of the exposure indications that continuation of the exposure regimes will lead to loss of the load capacity and failure. The bond strength increases with the increase of compressive strength of concrete. The futures of FRP materials are very bright. They offer inherent advantages over traditional materials with regard to high strength-to-weight ratio, design flexibility, corrosion resistance, low maintenances and extended service life.

CHAPTER III

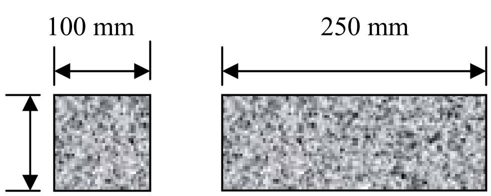
EXPERIMENTAL SETUP

3.0 Introduction

The experiment setup chapter is divided into three sections, namely; Details of Materials, Preliminary Test (Joint Properties of Mild Steel End Tab) and CFRP Plates bonded Concrete Prism Pull-out Test.

3.1 Details of Materials

3.1.1 Concrete Prism

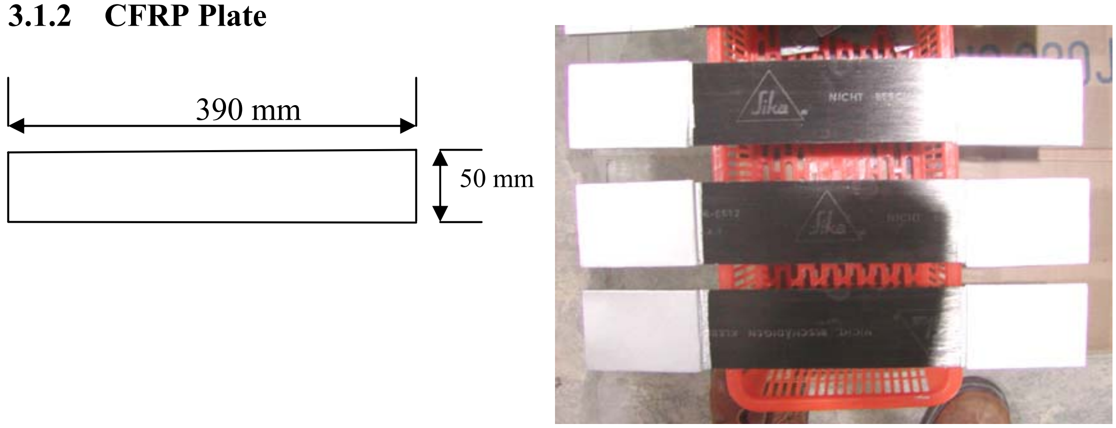


(b)

Figure 3.1: (a) Concrete prism dimensions (b) A CFRP plate bonded to each concrete prism

A total of three concrete prisms with the dimension of 100mm x 100mm x 250 mm were prepared. The geometry of the test samples used in this study is shown in Figure 3.1. The concrete was designed to reach compressive strength 40 MPa at the age of 28 days. The concrete was produced using maximum coarse aggregate size of 10 mm with water cement ratio of 0.47. Superplasticizer was used to enhance the workability of the fresh concrete.

3.1.2 CFRP Plate



(a) (b)

Figure 3.2: (a) CFRP plate dimensions (b) Two mild steel end tab bonded to each CFRP plate

The average thickness of the plate is 1.35 mm and the width is 50 mm shown in Figure 3.2. The CFRP plate used consist of unidirectional carbon fibre with 70% by volume fraction. The CFRP plate produced through pultrusion method and the CFRP plates known as Sika Carbodur type S512 have properties of the plate is shown in Table A1.2. The modulus elastic of CFRP plate obtained from manufacturer specification is 165 GPa and mean tensile strength is 2800 MPa.

3.1.3 Joint Adhesive

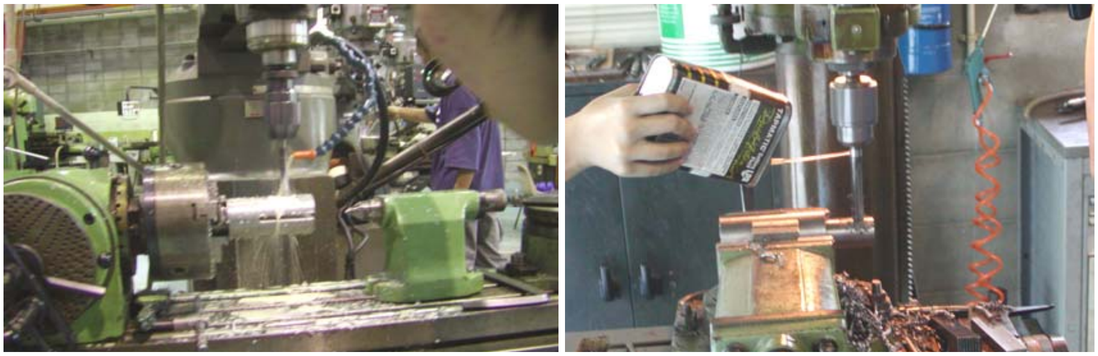
The adhesive used for bonding is epoxy-based 2-component adhesive mortar (Sikadur ® 30) with mixing ratio of 3:1. (parts by weight). The adhesive tensile strength is 30 MPa and shear strength is 20 MPa with the T_g value of 62 ºC was used for bonding of CFRP-concrete.

3.2 Preliminary Test (Joint Properties of Mild Steel End Tab – CFRP plate)

The objective of the testing is to determine the ultimate load and to study the mode of failure of mild steel end tabs and CFRP bonded at bolt hole region.

3.2.1 Test Rig Design and Preparation

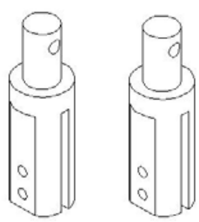
Two mild steel rods diameter of 65 mm and length of 175 mm had been used to produce the test rig. The diameter of the mild steel rod was reduced to 32 mm x length 55 mm and 55 mm x length 120 mm respectively. A solid plate width 8 mm x length 100 mm was slot out from the mild steel rod using Milling Machine. Both surface of the test rig were flatted so that it is easy to place bolt and nut and fasten to the CFRP. A hole diameter of 13 mm is made pass through the upper test rig (15.5 mm from upper edge). A pin is applied at the hole to connect to connector of Instron Machine. Another two hole (diameter 10 mm) were made (15 mm and 37.5 mm respectively from lower edge). High tensile mild steel Bolt and nut (M10) will be applied to fasten the CFRP plate to the rig. Part of the test rig preparation is shown in Figure 3.3.



(a) (b)

Figure 3.3: (a) (b) Test rig preparation (drilling process)

Finally, the finished test rig was sprayed with primer type paint to avoid corrosion. Upper and bottom test rig were shown in Figure 3.4.



(a)

Connector of
Instron-100 kN
Universal Testing
Machine

(b)

Figure 3.4: (a) Two units of test rig (b) Upper test rig pinned to connector of Instron-100 kN Universal Testing Machine

3.2.2 Specimen Preparation

Two mild steel strips geometries of 50 mm x 1.5 mm x 500 mm have been used as end tab for CFRP plate. One surface of the strip was sand blasted in order to remove any dirt or rust. After sand blasted, the strip was cut into size of 50 mm x 70 mm. For second attempt, the size of tab was changed to 50 mm x 150 mm. The plates were bonded to CFRP plate using Sikadur® 30-type epoxy. The adhesive is applied on the rough surface. The epoxy could be bonded perfectly at the rough surface. A hole was made at both the end tab after bonding using drilling machine. This plate is used as end tab in order to strengthen the CFRP plate. It is used to ensure that CFRP plate do not tear off prematurely under tensile loads. This hole will finally connected to CFRP/concrete test rig. The CFRP plate bonded with wild steel plate sample is shown in Figure 3.5.

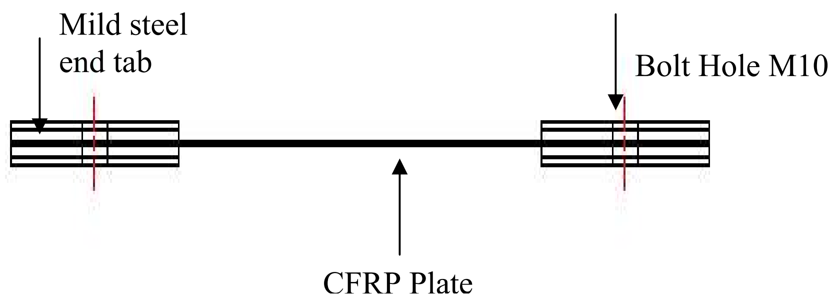
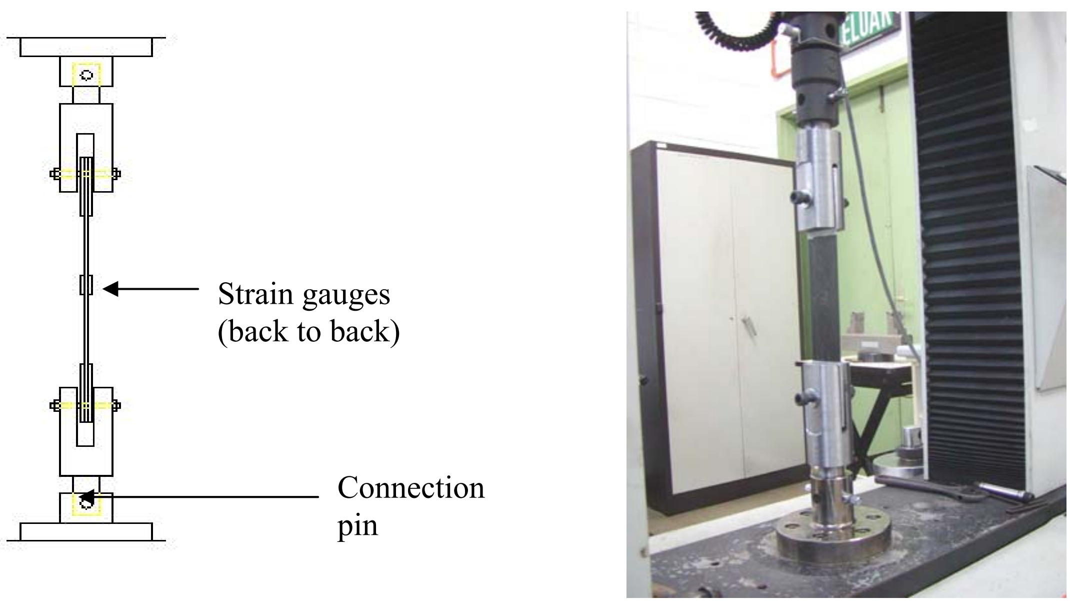


Figure 3.5: CFRP plate bonded with mild steel plate (end tab)

3.2.3 Test Set Up

The equipments were set up as Figure 3.6. Three specimens were tested in order to determine ultimate failure load and to study the failure behavior at end tabs pin/bolt hole.



(a) (b)

Figure 3.6: (a) Schematic diagram of specimen (b) Experiment set up for preliminary test

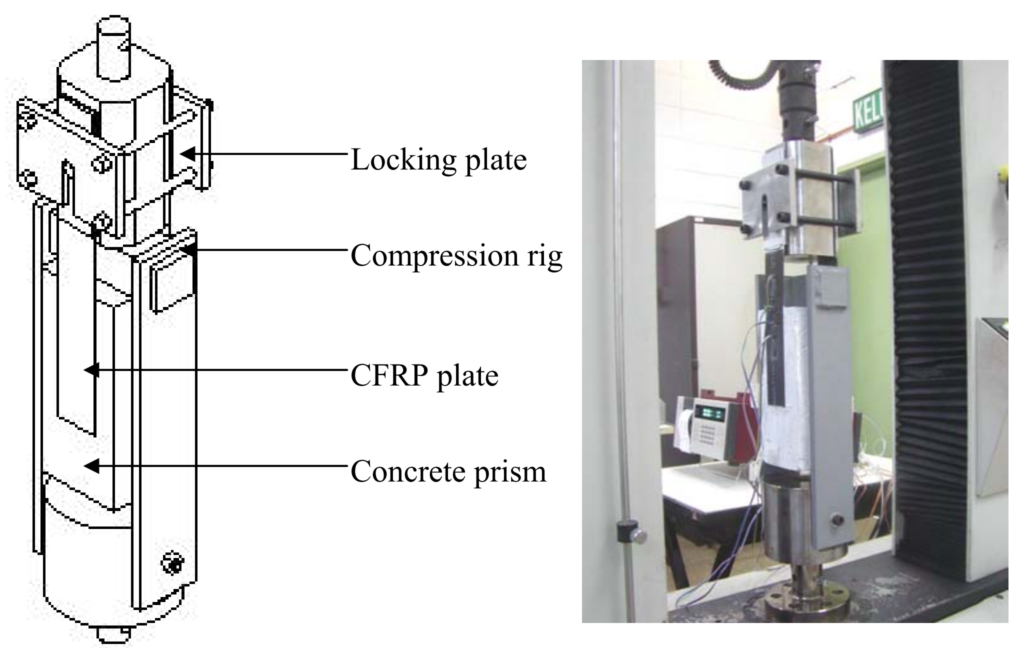
The strain gauge with 5 mm gauge length and 120 Ω electrical resistance model TML (BFLA-5-5-3L) have been used to measure the local mid-length strain of the CFRP plate. The specimen finally attached to the Universal Testing machine model Instron 100 kN. The loading rate of 1 mm/min has been applied to the specimen and the CFRP plate strains have been measured at every 1 kN of load increment.

3.3 CFRP Plates Bonded Concrete Prism Pull-out Test

The objectives of the testing are as follows:

1) To study and to determine load distribution, local shear stress distribution and bond strength of CFRP plate bonded to concrete prism.
2) To study the mode of failure of CFRP plate/concrete prism bonded system.

3.3.1 Test Rig Design and Preparation



(a) (b)

Figure 3.7: (a) Schematic Diagram of Tension-Compression Test rig (First trial)

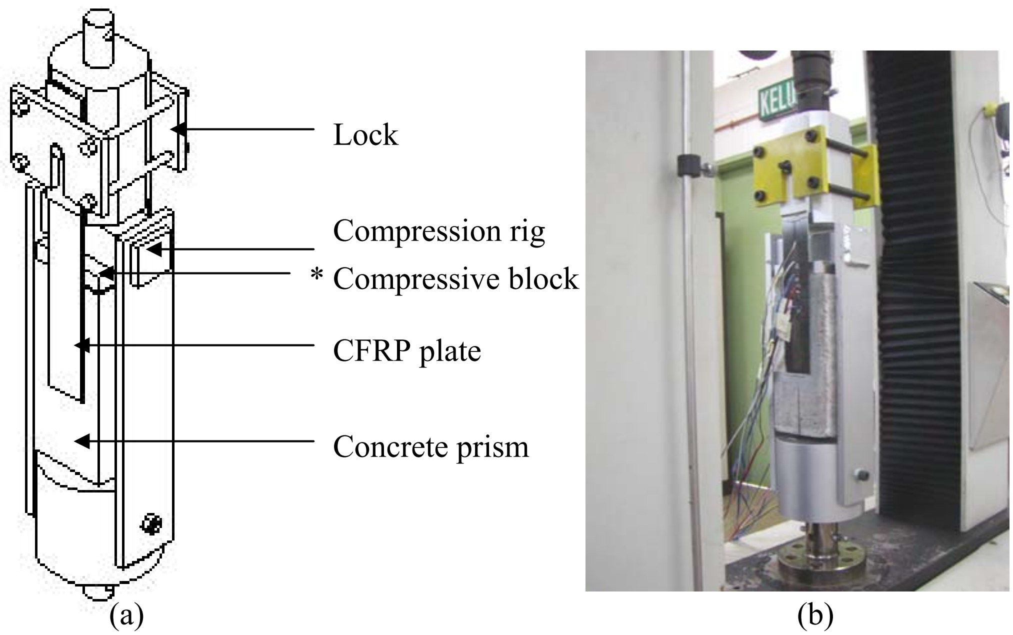


Figure 3.8: (a) Schematic diagram of Tension-Compression test rig (b) Test set-up (second trial)

Note: Compressive block is placed on top of concrete prism to provide uniform compressive load.

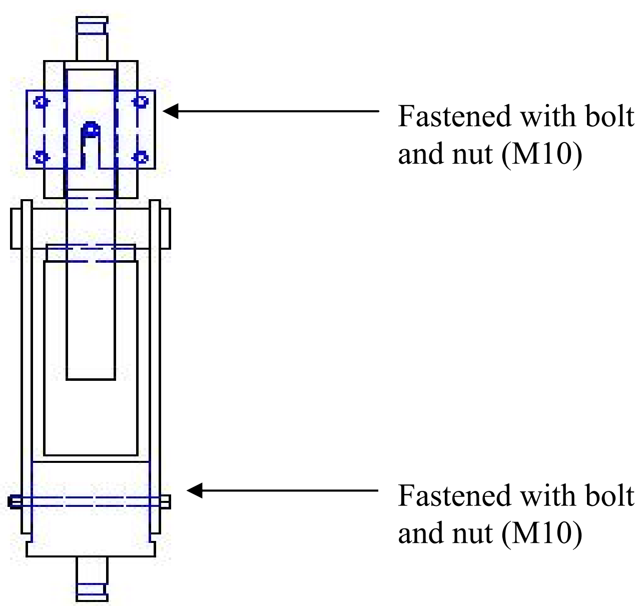


Figure 3.9: Front view of Tension-Compression test rig and test specimen for second trial

3.3.2 Specimen Preparation

1. Two mild steel plates with dimension 50 mm width x 150 mm length and 2 mm thickness were bonded to one of the CFRP plate. Total two CFRP plates with dimension 50 mm width x 390 mm length with mild steel end tab were prepared for each specimen.
2. A 10 mm diameter bolt hole was drilled at mild steel end tabs bonded CFRP plate for inserting bolt while setup the testing (Figure 3.10).

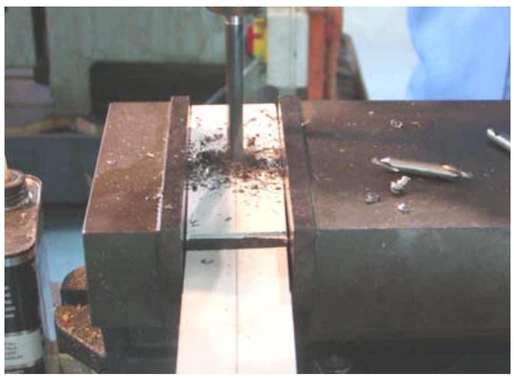


Figure 3.10: Mild steel end tabs bonded CFRP plate drilling process

3. The concrete surface that will be bonded to CFRP plate is roughed using Air Tool Hammer. The contact bond surface of the concrete prism is prepared by scrabbling tool until the course aggregate (i.e. > 8 mm) is visible (Figure 3.11). Total two opposite surfaces were hacked. This is to provide mechanical interlocking type surface for bonding purpose.

Hacked area (150 mm x 60 mm)

Figure 3.11: (a) Concrete prism with hacked area

4. The surface of the concrete is ensured free from dust, loose material by using vacuum cleaner. The surface also confirmed to be level as possible using standard leveling gauge.
5. CFRP plate surface was roughened with sand paper. During sanding, a precaution not to damage the fibre outer surface.
6. Two CFRP plate with mild steel end tab were bonded to both side of concrete prism referring Figure 3.12.

(a) (b)

Figure 3.12: (a) Bonding process (b) CFRP plates with mild steel end tab bonded to concrete prism preparation

7. Totally 10 unidirectional strain gauges were bonded to the CFRP plates (side A and B respectively) for Control I sample, referring to Figure 3.13 (a). For Control II and Hot/Dry/Wet samples, totally 12 unidirectional strain gauges were installed to the CFRP plates respectively, referring to Figure 3.13 (b). Besides that, three electrical strain gauges have been bonded to the concrete surface for both Control II and Hot/Dry/Wet samples, referring to Figure 3.13 (c) in order to investigate the level of compressive stress along the concrete prism length.

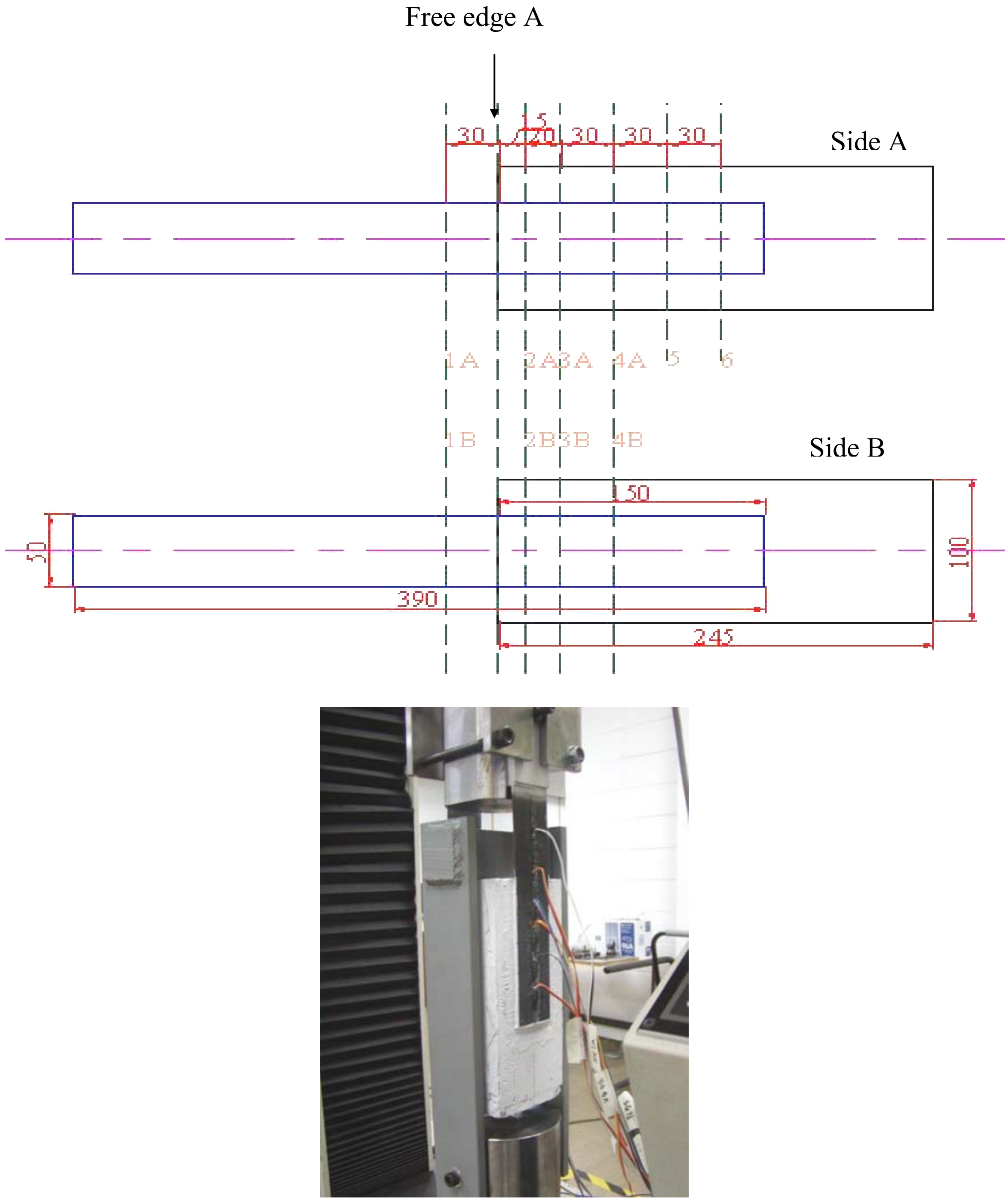


Figure 3.13 (a): (i) CFRP plates bonded concrete prism specimen details (Control I sample) (ii) Tension-Compression test set up

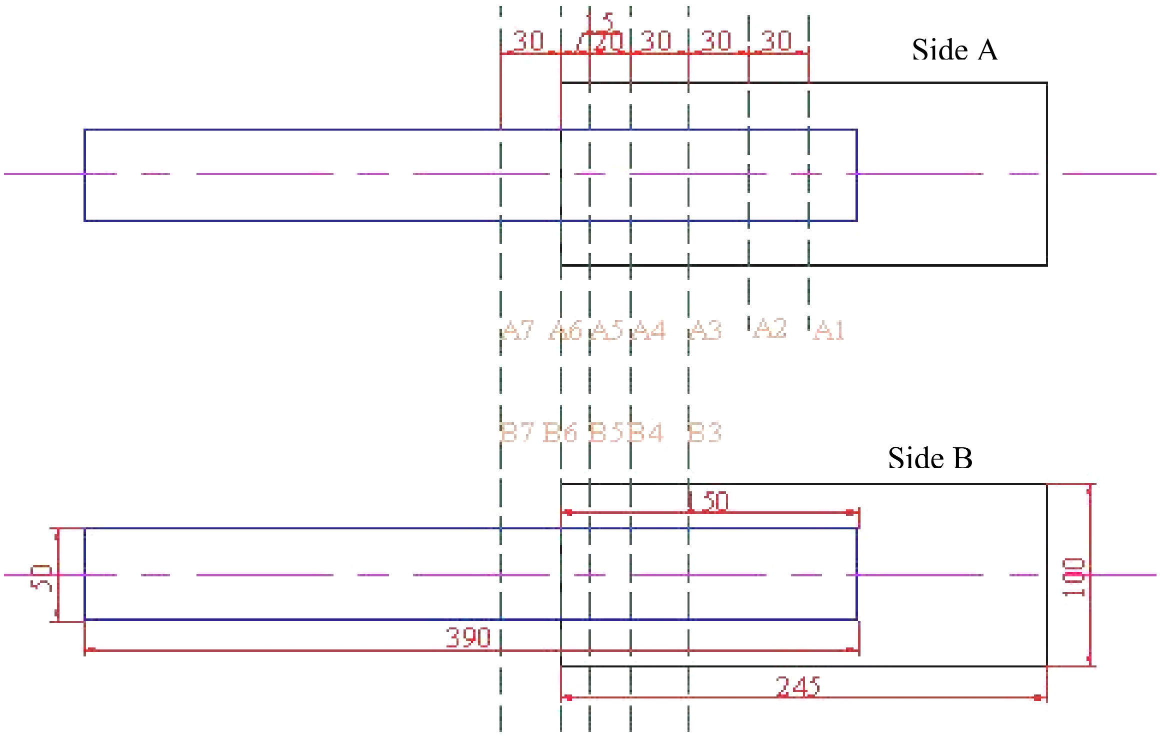


Figure 3.13 (b): CFRP plates bonded concrete prism specimen details (Control II and Hot/Dry/Wet samples)

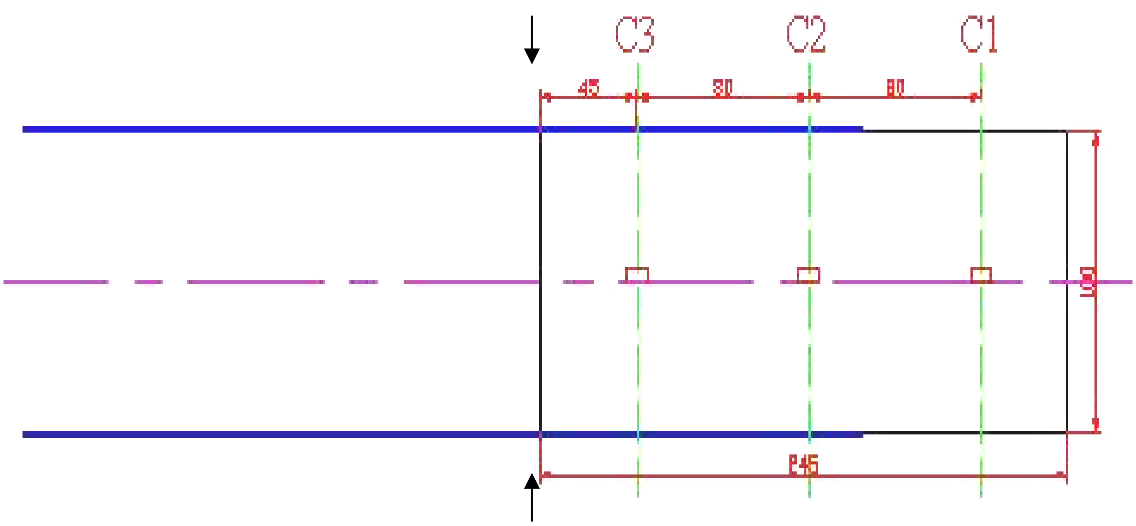


Figure 3.13 (c): Schematic diagram of Gauge locations on concrete prism for Control II and Hot/Dry/Wet samples

The specimens were exposed to the following conditions before undergone pull out test, and they are as follows;

1. Laboratory (as control) Code name: 2 L
2. Hot/Wet/Dry condition Code name: 3 HWD

Besides that, the Hot/Wet/Dry condition specimen was exposed to constant temperature 50ºC in the oven for 6 hours (10 am - 4 pm), then, it was placed into plain water (totally submerged) for 12 hours (starting 10 am) in lab condition. After that, the specimen is dried in laboratory environment. There were total 6 cycles have been carried out for the specimen starting from 31st of December 2002 until 12th of January 2003. The pH value of tap water was found at about 8.4 using HORIBA U10 (Figure 3.14), while DO is about 9.8 mg/l. There are no salt content in the water.

(a)

(b)

Figure 3.14: (a) Condition that Sample totally submerged into water (b) Procedure measuring pH water

There were 2 specimens used as control. One of them is used for first trial in Concrete Prism bonded CFRP Plate Pull-out Test. And the other is used for second trial of the test. Both control sample experienced different type of compressive load during final test. The loading conditions are shown in Figure 3.15 (a) and Figure 3.15 (b).

For first trial (Control I sample) of pull out test, compressive block was not installed in the Tension-Compression system. The load distribution is not uniform and high loads concentrate at middle top surface of concrete, which is shown in Figure 3.15 (a). Compressive load is more uniform acting on concrete top surface for samples Control II and Hot/Wet/Dry shown in Figure 3.15 (b).

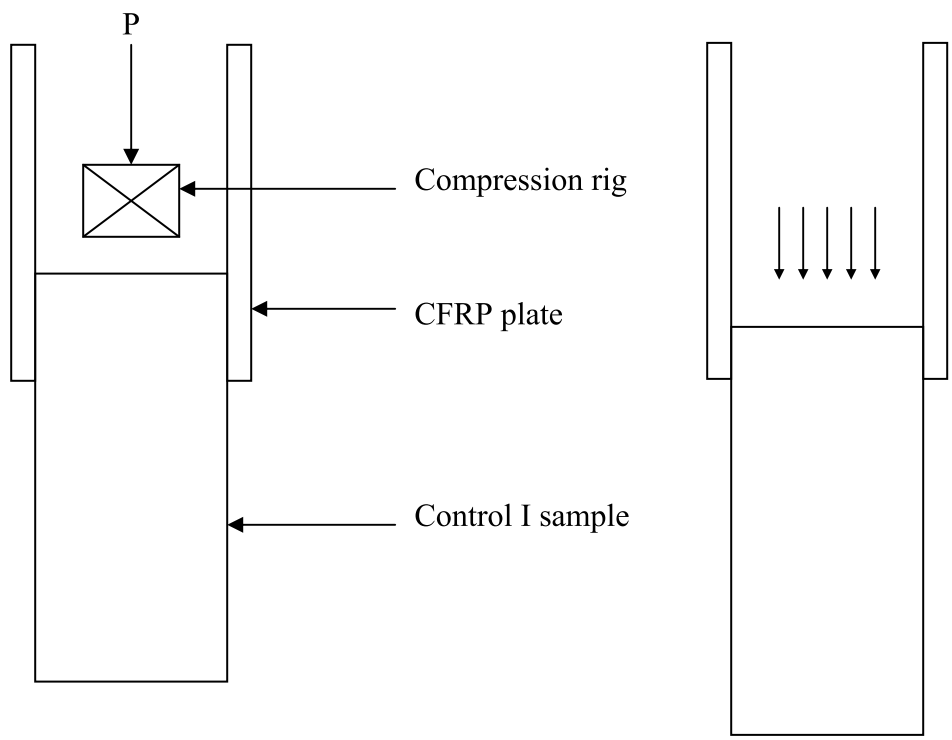


Figure 3.15 (a): Compressive load acting on 50% on top of concrete prism surface for sample Control I

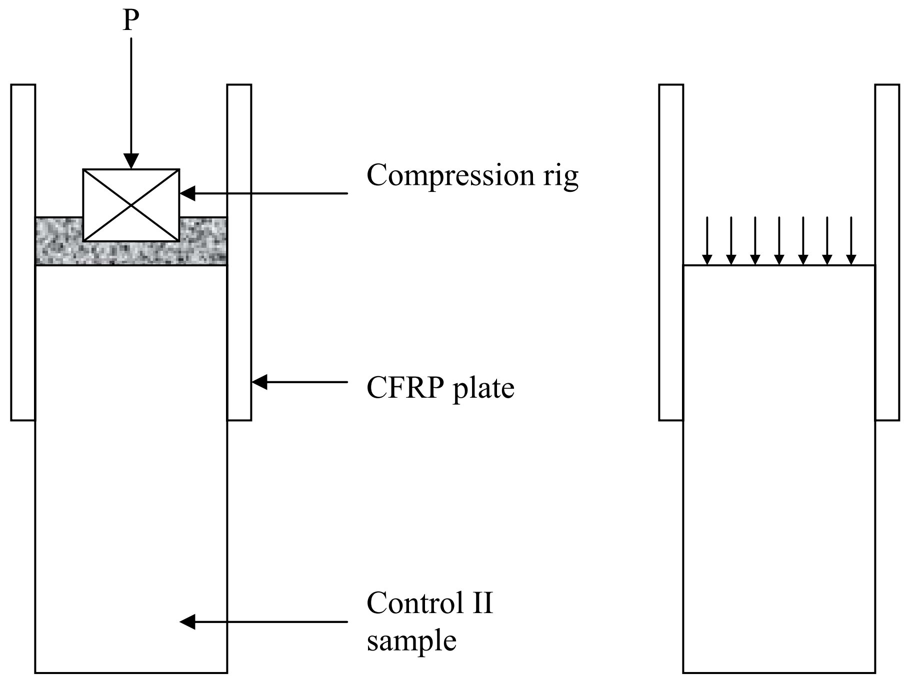


Figure 3.15 (b): Uniform compressive load acting on top of concrete prism surface for Control II and Hot/Wet/Dry samples

3.3.3 Test Set Up

Procedures:

The equipments set up as shown in Figure 3.16. Two laboratory condition samples and a Hot/Wet/Dry sample were tested in order to determine load distribution and local shear stress distribution. The Universal Testing Machine model Instron 100 kN has been used and tensile loading rate of 1 mm/min has been applied on the sample up to failure. The strains have been measured at every 5 kN of load increment.

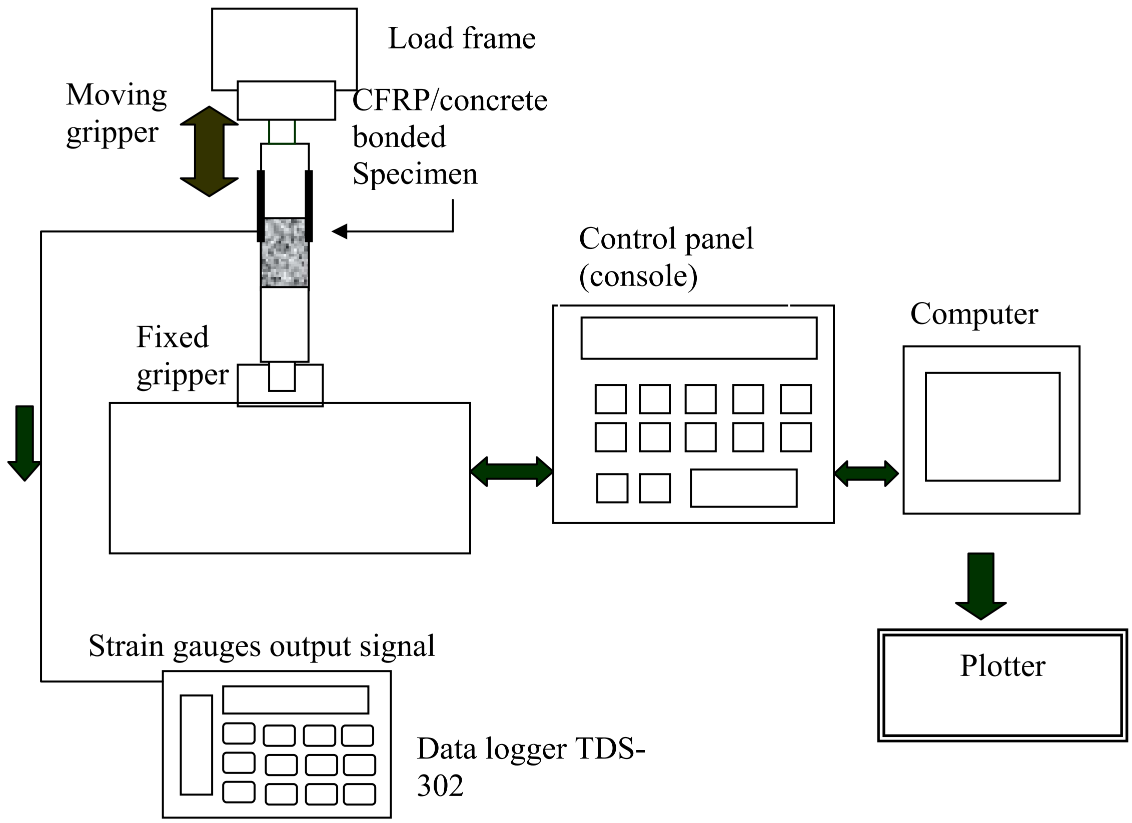


Figure 3.16: Instron-100kN Universal Testing Machine Instrumentation Set-up (CFRP plates bonded concrete prism pull out test)

3.3.3.1 Measurements And Instrumentation

The loading performances of test specimens were monitored through measurements of applied load and local strain distribution along the plate joint. The strain gauges (manufactured by Tokyo Sokki Kenkyujo Co. Ltd.) were bonded at specific location along the CFRP plate as shown in Figure 3.13. The measurements of strain were recorded at every 5 kN increment of applied load until the specimen fail. The specification of the strain gauge is shown in Table 3.1. Besides that, the installation process of the strain gauges is shown in Figure 3.17.

Table 3.1: Specification of TML strain gauge at CFRP plate

Type	BFLA-2-8
Gauge length (mm)	2
Gauge resistance (Ω)	120 ± 0.3
Gauge factor (%)	2.11 ± 1
Temperature compensation (/ºC)	8 x 10^{-6}

(a)

(b)

Figure 3.17: (a) Process roughing CFRP surface (b) Soldering process

CFRP plate bonded concrete prism pull out test carried out by using Instron +monotonically until failure. The two main components of the machine are load frame and control panel that is connected to a computer and plotter. Data logger TDS-302 is a strain-reading machine. It operated automatically to read the local strain along the CFRP plate.

3.4 Summary

Experimental set up is divided into two important parts, test sample preparation and test facilities set up. The data collected through the experiment is strains reading, obtained from the data logger. The local strain along the plate and applied tensile load were collected up to failure.

CHAPTER IV

RESULTS AND DISCUSSION

4.0 Introduction

In this chapter, the discussion focus onto the influence of aggressive exposure conditions on the behaviour of CFRP plate bonded concrete prism's joints. The result of the study will be presented in terms of bonding behaviour and the failure mode of the test samples.

4.1 Bonding Properties

In the analysis, we assumed perfect bonding between CFRP plate and concrete prism and considered concrete prism as a rigid adherend that create constant shear stress along the thickness of the adhesives.

In this section, the bonding properties, such as load at failure, bond strength, load transfer, local strain behaviour and local shear stress distribution for each sample will be discussed. The results will be presented in terms of graphs and charts.

The result directly obtained from the load tests and the recorded readings through data logger: Applied load of Instron Machine, (2) local strain on CFRP plate. These test data have been analysed and are discussed in the following sections.

4.2 Average Bond Strength

Referring Figure 4.1, when a CFRP/Concrete bonded system subjected to tension-compression (pull-out) loading system by assuming there is perfect bonding of the specimen, the average bond strength can be determined by the following equation,

$$\text{Average Bond strength, } \tau_{av} = \frac{P\max}{2A}$$

$$= \frac{P\max}{2\delta_0 L_B} \qquad (1)$$

Where,

P_{max} = Ultimate applied load (N)

A_B = Bond area (b x L_B) (mm^2)

δ_0 = Width of CFRP plate (mm)

L_B = Bond length (mm)

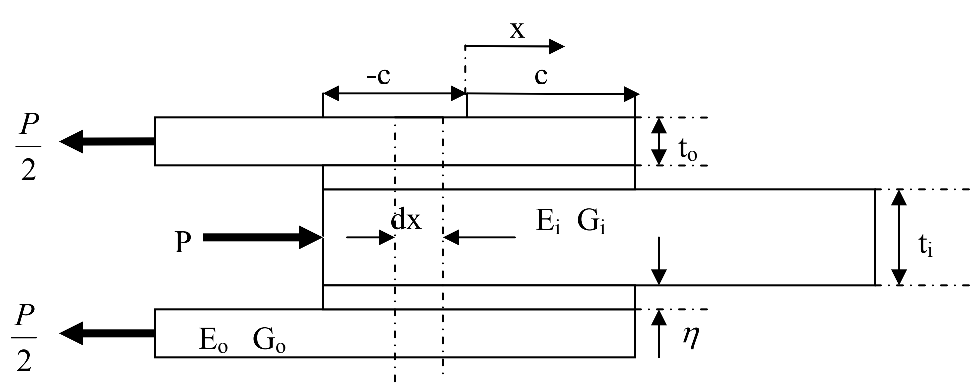
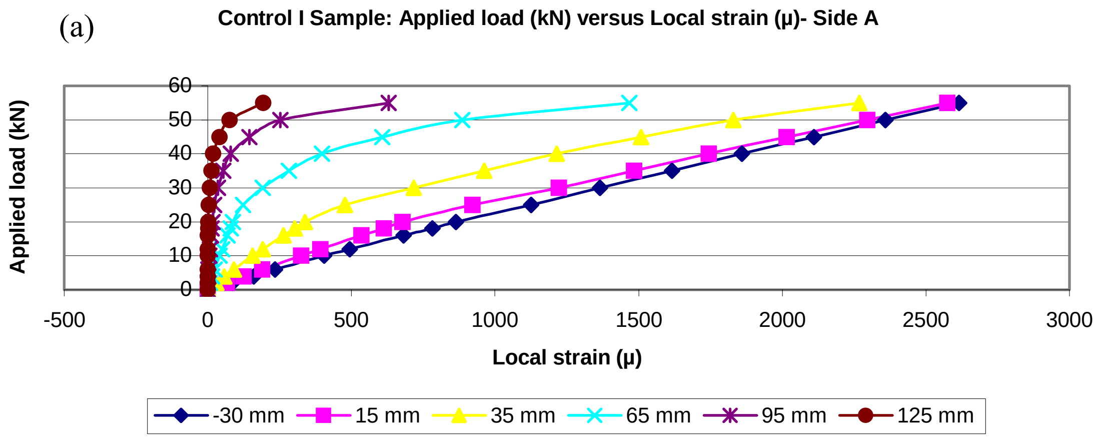


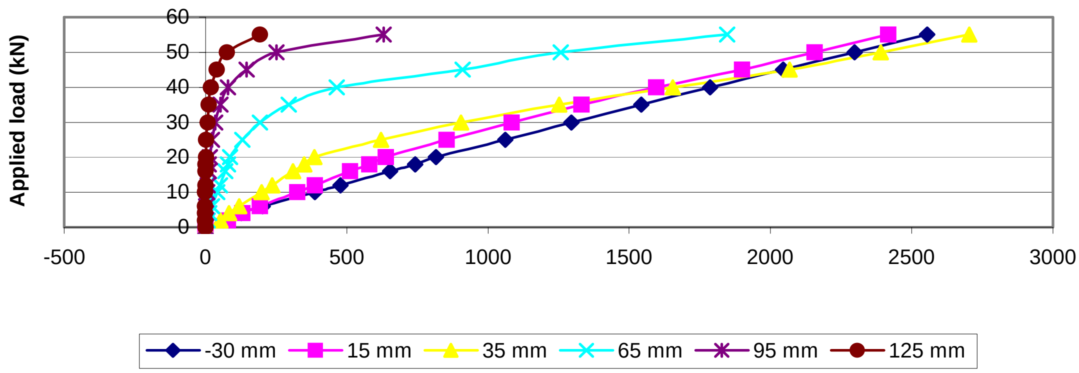
Figure.4.1: Geometry and material parameters of the CFRP Plate-Concrete Prism Under Tension-Compression

4.3 Local Strain

(a)



(b)



(c)

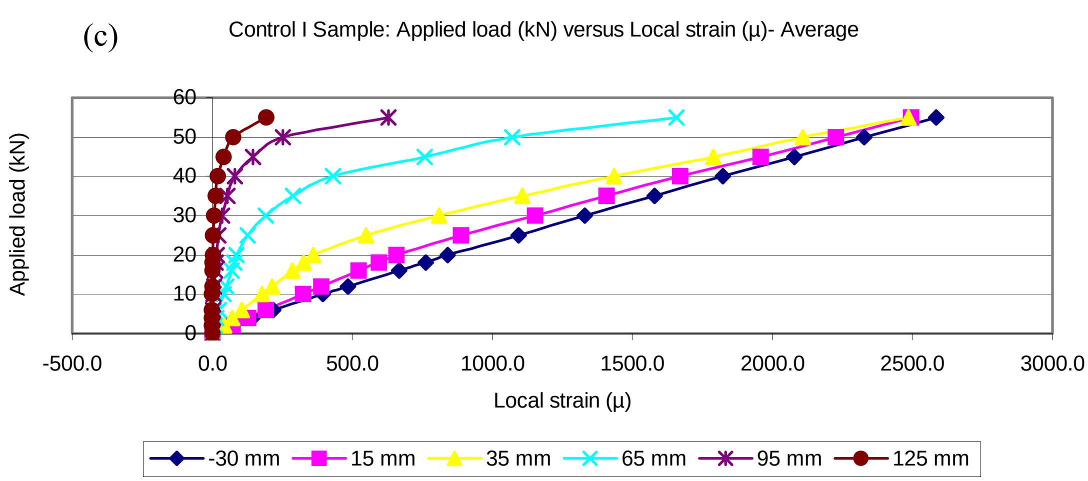


Figure 4.2: Graph Applied load versus Local strain for Control I sample (a) Side A (b) Side B and (c) Average

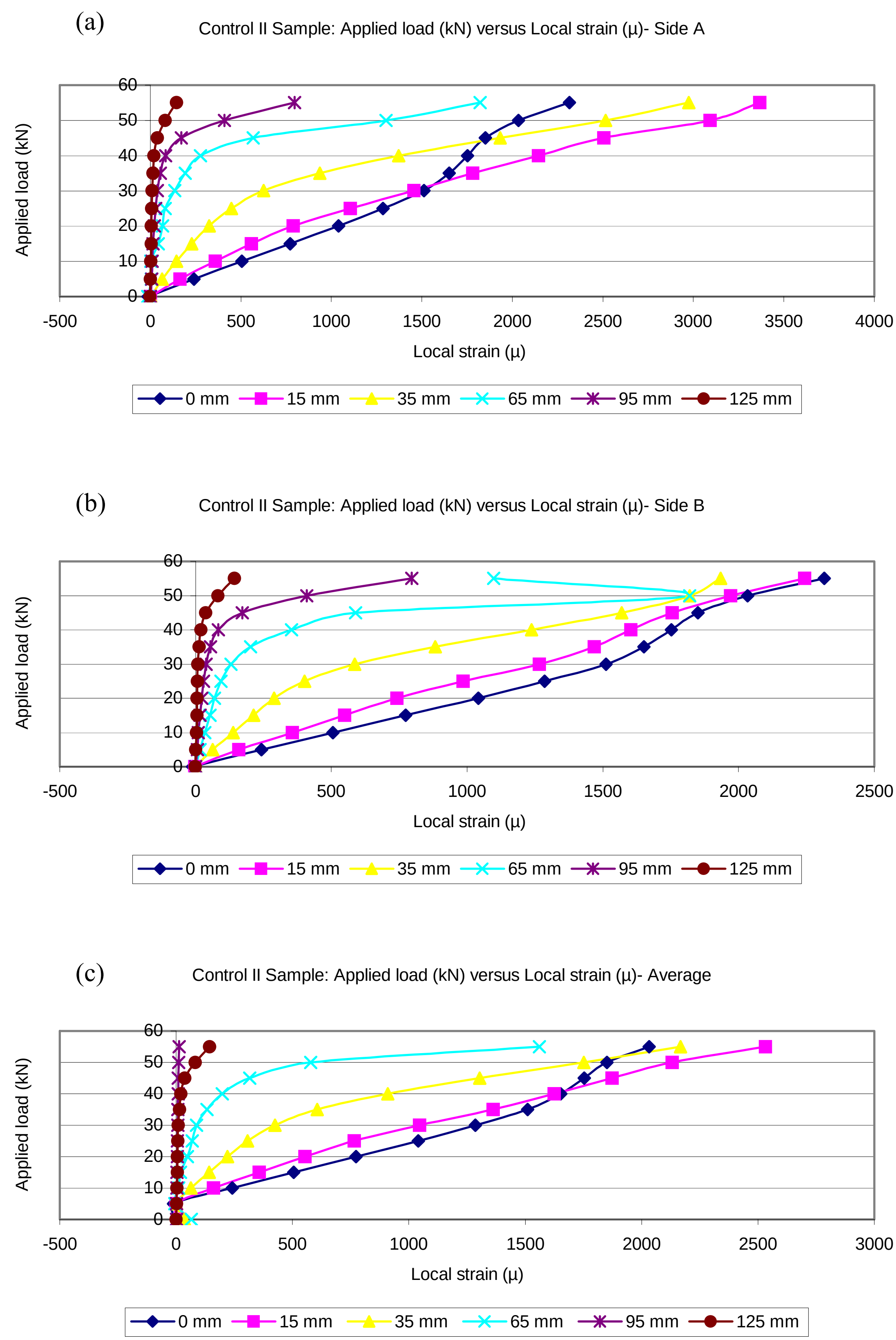


Figure 4.3: Graph Applied load versus Local strain for Control II sample (a) Side A

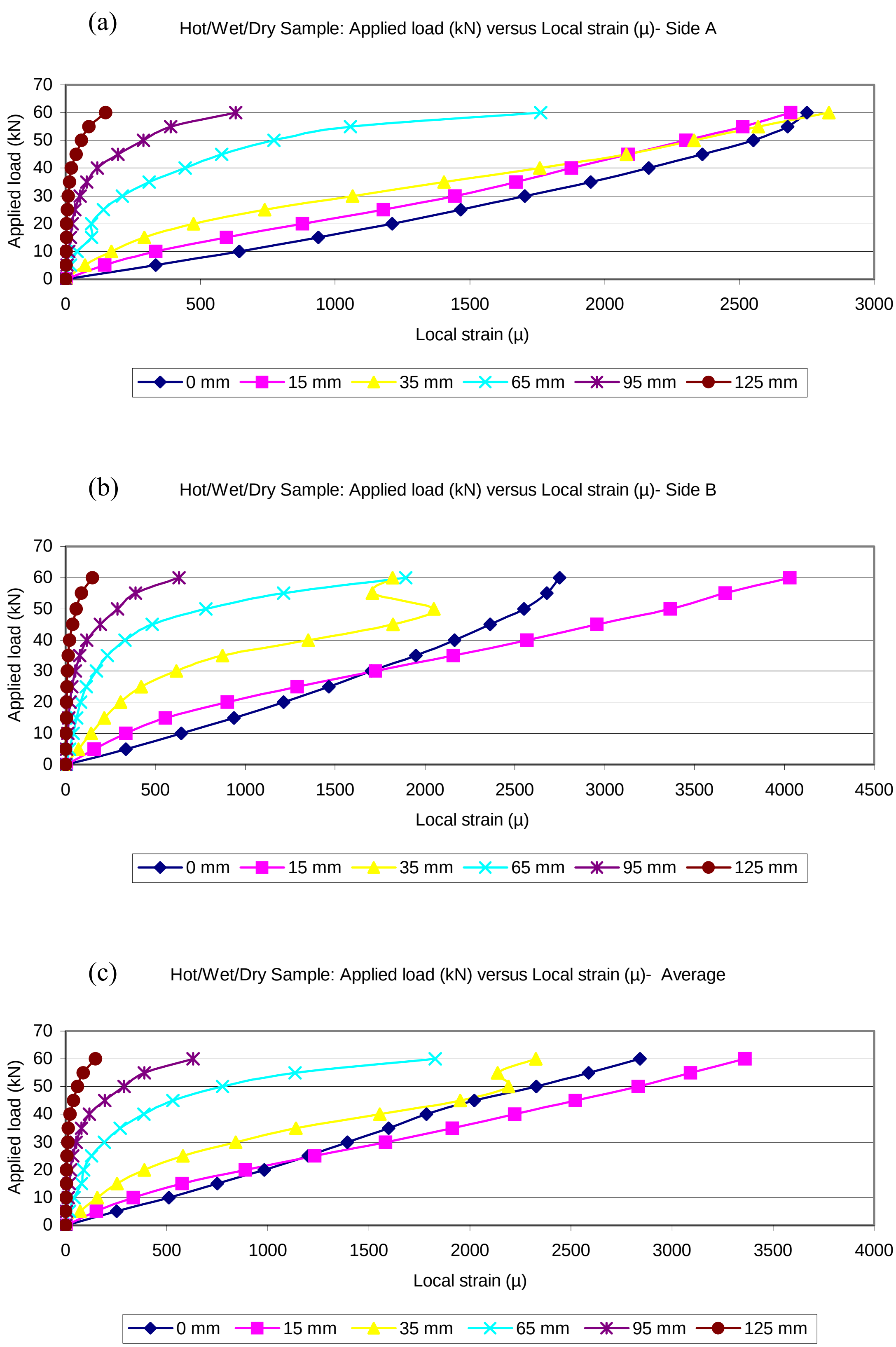


Figure 4.4: Graph Applied load versus Local strain for Hot/Wet/Dry sample (a) Side A (b) Side B and (c) Average

The local strain is recorded through data logger and the data listed as in Appendix A2, Table A2.1-A2.3. In this case, the strains are measured at every 5 kN increment of applied load up to failure. Graphs applied load versus local strain (Figure 6.-6.3) are plotted.

From the graphs applied load versus local strain (figure 4.2-4.4), at 0 mm (from free edge A), it showed linear line pattern. At 15, the line becomes bilinear which the strains increase steadily at uniform rate.

At 35 mm and 65 mm (located approximately at the center of bonded length), it showed ductile line pattern. The slope, $m = \frac{\Delta F}{\Delta \varepsilon}$ is high at low load levels referring to graphs (figure 4.2-4.4). At 95 and 125 mm, the slopes become steeper. The highest slope m is obtained at 95 mm, almost 90°.

It can be concluded that a high load is needed to increase $\Delta \varepsilon$ at interior bonded area (away from free edge A). The line at low load level is linear. The line become non linear at high load level due to cracking of concrete.

4.4 Force Transfer Between CFRP Plate and Concrete

The variations of the longitudinal plate force along the bonded CFRP plate length are being evaluated from the recorded strain along the plate. These forces are calculated at every 5 kN of applied load increment. The local load at CFRP plate can be computed from equation (17) Chapter III based on Hooke's Law. We assumed that the force transfer is linear along the bond line. The properties of equation (17) are as follows;

E = CFRP Young's Modulus

= 165 GPa (referred to manufacturer's specification),

A= cross-section area of CFRP plate

= 1.2 x 50 mm^2

ε = local strain on CFRP plate

In this case, we assumed that the tensile modulus of CFRP plates remain constant up to failure and the force distribution is linear along the plate. The calculated data is shown in Appendix A2, Table A2.4-A2.6. Gauge locations on CFRP plate for Control I and Control II samples were shown in Figure 4.4 and Figure 4.6 respectively. The local load distribution at CFRP plate for different samples is plotted and shown in following figures.

Forces transfer between CFRP plate and concrete prism can be calculated by the following equation with an assumption that perfect bonding occurs between CFRP plate and concrete prism. From Hooke's Law, it can be seen that;

$$E = \frac{\sigma}{\varepsilon} \qquad (2)$$

And it is known that; $\sigma = \dfrac{F}{A}$ (3)

Substitute into equation (2), finally yield

$$F = EA\varepsilon \qquad (4)$$

Where,

σ = Tensile stress at CFRP plate, MPa

A_c = Cross-section area of CFRP plate, m^2

E = CFRP Young's Modulus, GPa

F = Local load at CFRP plate, N

ε = Local strain at CFRP plate, $\mu\varepsilon$

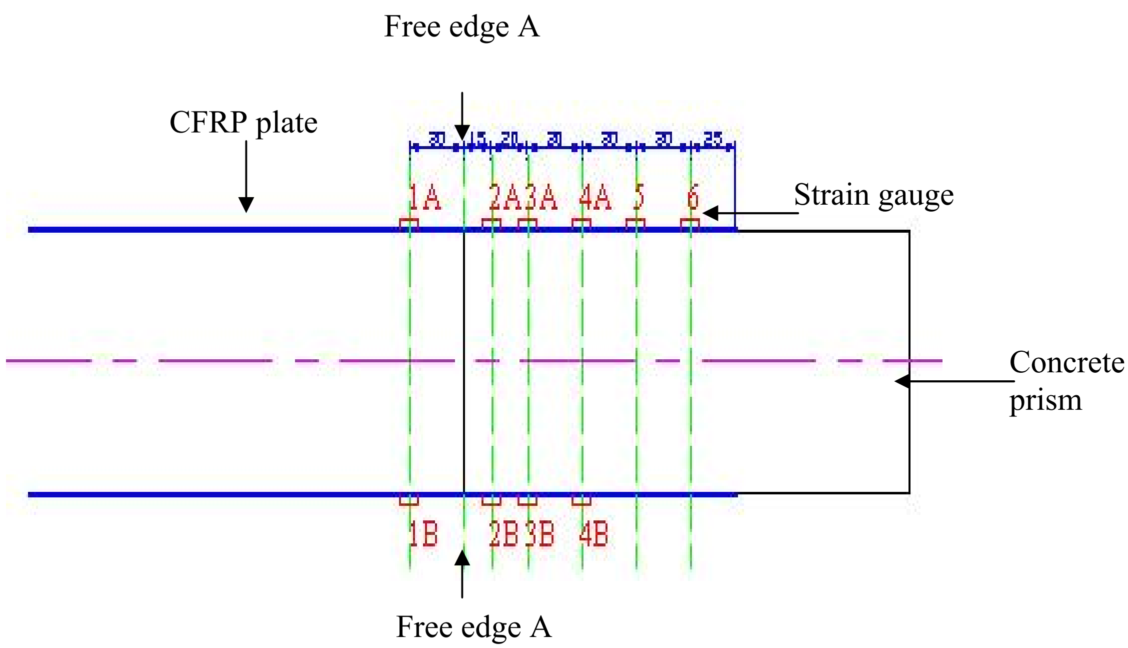


Figure 4.5: Schematic diagram of Gauge locations on CFRP plates for Control I sample.

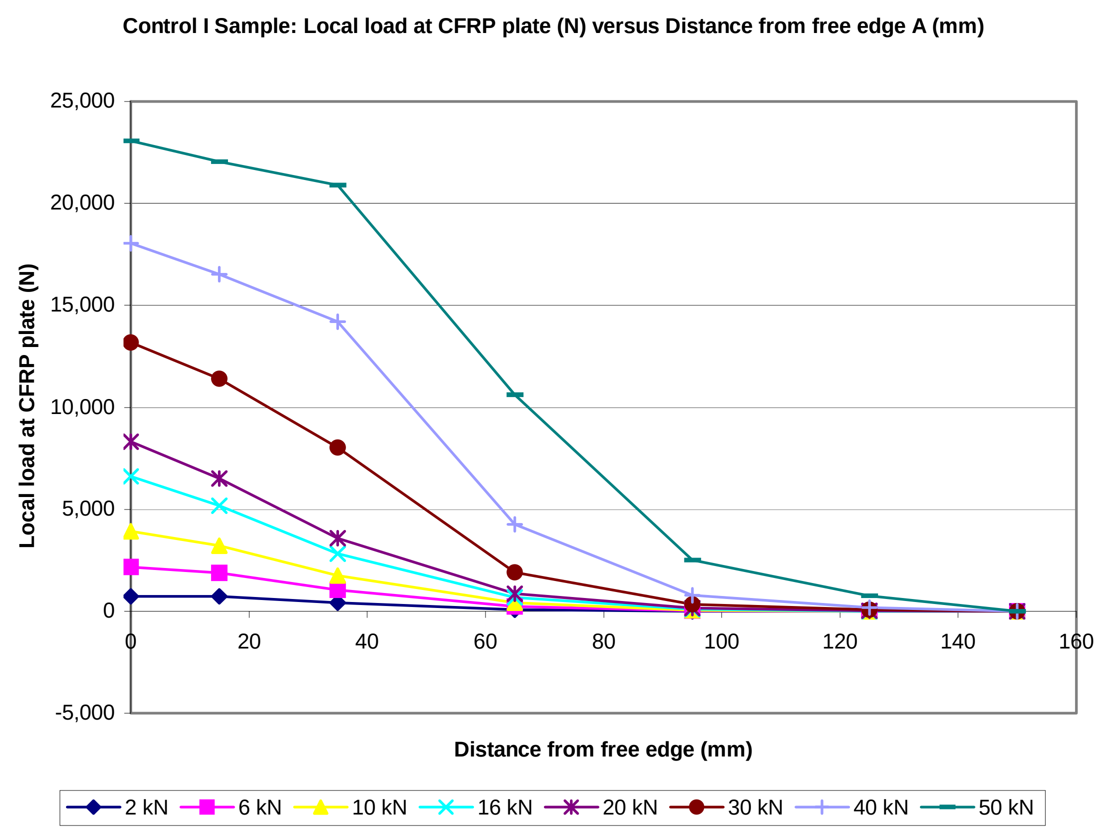


Figure 4.6: Local load distribution at CFRP plate for (a) control I sample.

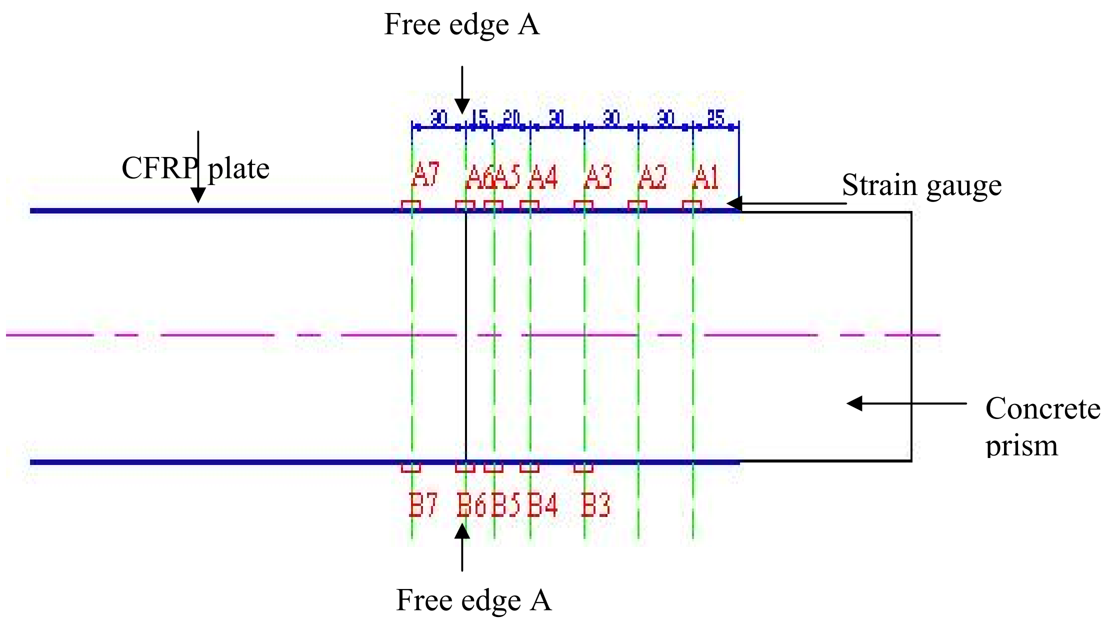


Figure 4.7: Schematic diagram of Gauge locations on CFRP plates for Control II and Hot/Wet/Dry samples.

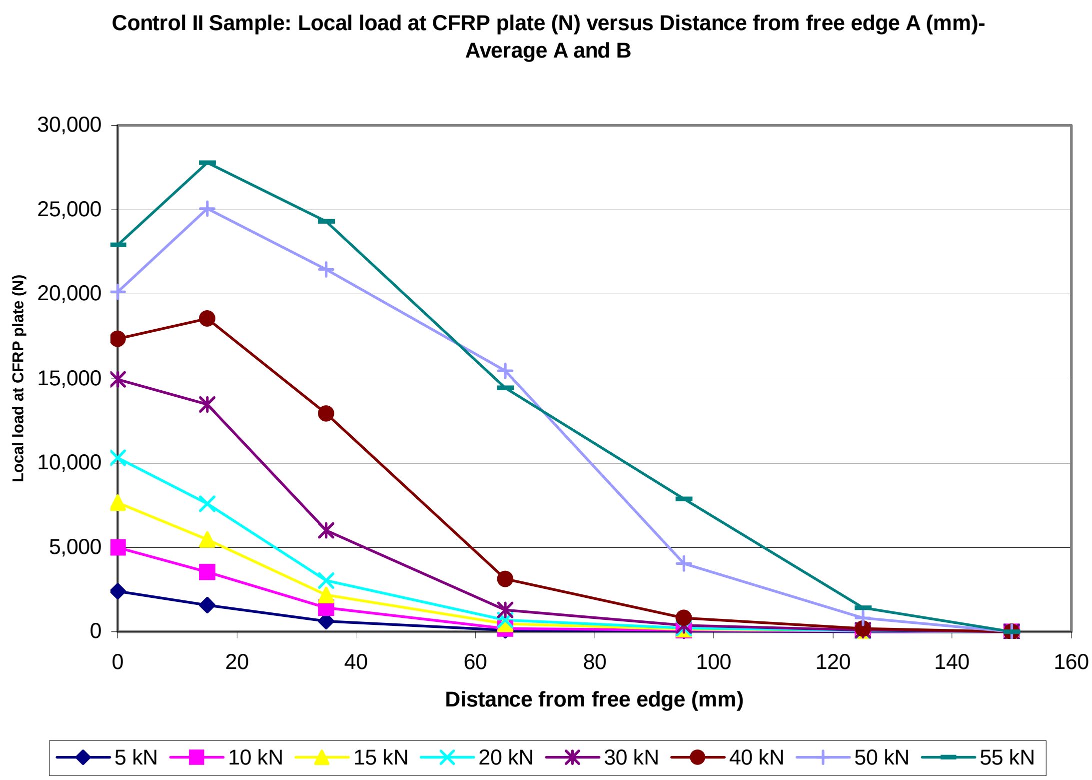


Figure 4.8: Local load distribution at CFRP plate for (b) control II sample.

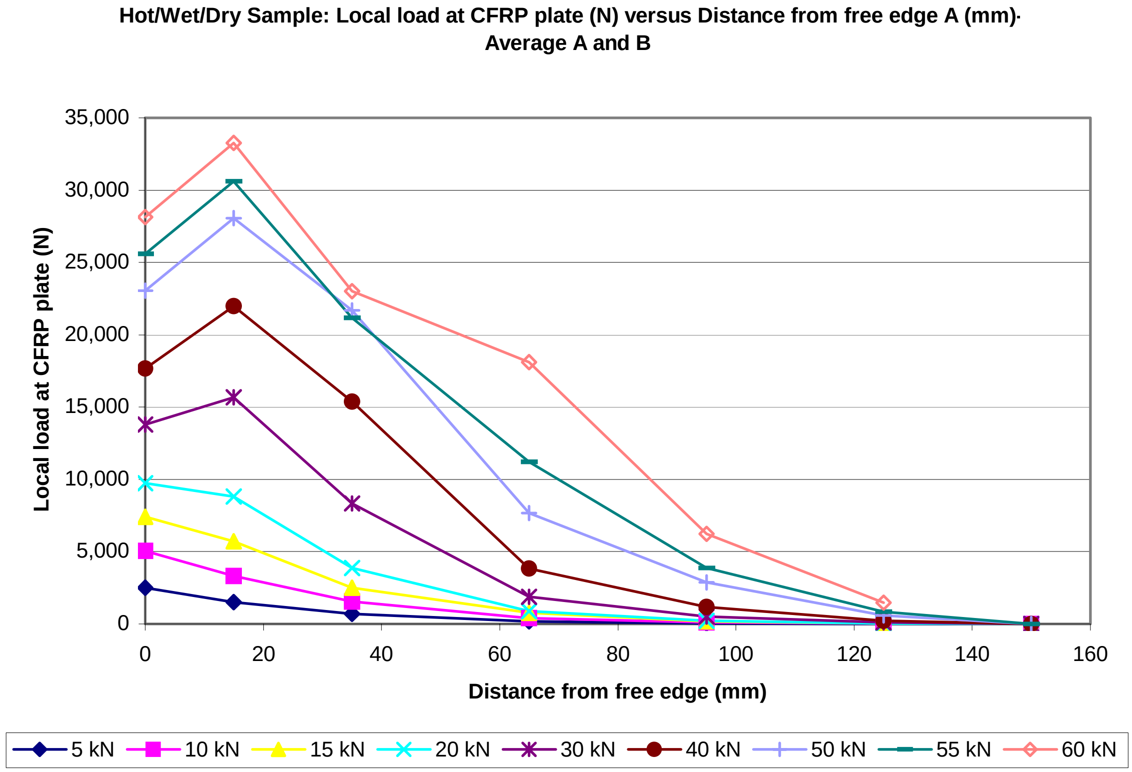


Figure 4.9: Local load distribution at CFRP plate for (c) Hot/Wet/Dry sample.

Firstly, The results obtained in graph local load at CFRP plate versus distance from free edge A (Figure 4.7,4.8 and 4.9) show that the load transfer from the plate to the concrete at low loads are fairly linear, and occurs at uniform rate. The force distribution becomes much more non-uniform and non-linear near the free edge A. It becomes increasingly uniform and constant implying local debonding or cracking of concrete at this location.

Secondly, the graph also clearly shows that higher force transfer lengths at higher loads. In other words, both the total force transfer length and the local separation at the edge A increase progressively with increase in the applied loads. The maximum applied load before failure for Control I, Control II and Hot/Wet/Dry sample are 55.22 kN, 57.93 kN and 64.94 kN respectively.

From graph (Figure 4.8), the maximum load transfer is in the range of 0-35 mm from free edge A at all load levels. The total forces transfer length at high loads level increase progressively. The maximum load transfer is at 55 kN applied load at 15 mm from free edge A. The lines at 50 kN and 55 kN applied loads intersect twice at the range 40-70 mm. In this case, concrete started to crack at 30 kN. The lines for 30 kN and higher applied load level become non linear. Cracking or local debonding causes non-uniform local loads at higher load levels. Applied force concentrated at cracking area due to high strain value is being suspected.

From graph (Figure 4.9), the maximum load transfer is in the range 0-40 mm from free edge A at all load levels. The graph clearly shows that higher force transfer lengths at higher loads level. The lines at 50 kN and 55 kN applied loads intersect twice at the range 40-60 mm. In this case, concrete started to crack at 20 kN. Non-uniform local loads at 20 kN applied load and higher load levels are due to concrete cracking and local debonding.

4.5 Local Shear Stress Distribution

The transfer of the longitudinal force from the CFRP plate to the concrete creates shear stress in the epoxy adhesive, and at the concrete-adhesive and plate-adhesive interfaces. Assuming a linear variation of the longitudinal force between two consecutive located strain gauges, the local shear stress along the bonded plate length can be computed from equation (18). The properties of equation (18) are as follows;

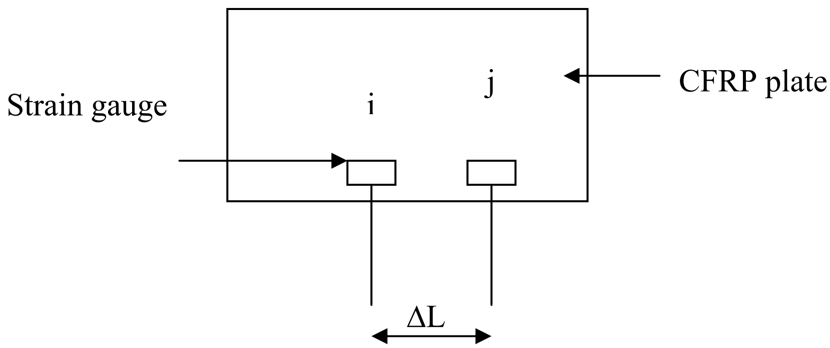


Figure 4.10: The strain gauges location notation

$$\text{Shear stress distribution, } \tau = \frac{\Delta F}{b \times \Delta L} \qquad (18)$$

where,

ΔF = Difference in longitudinal force between two consecutive strain gauge locations, N

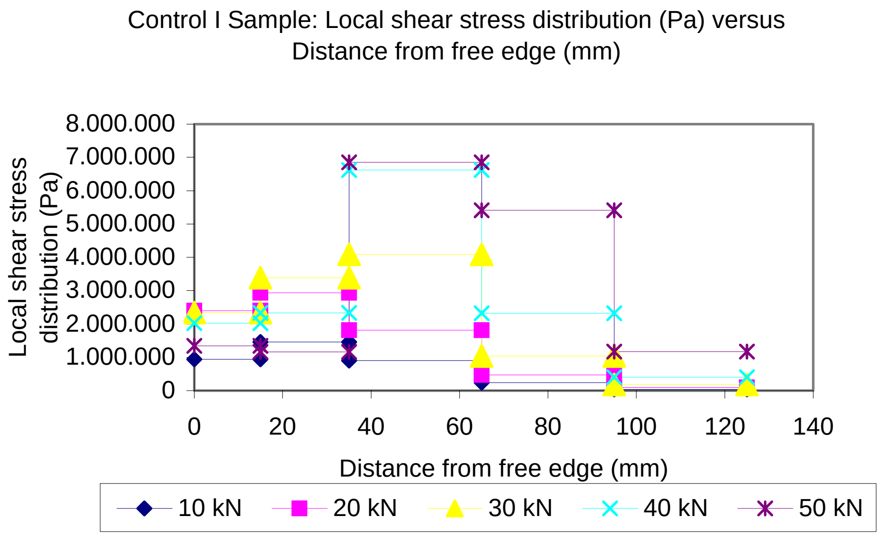
= $F_1 - F_2$ ($F_1, F_2, \ldots F_n$ = local load on CFRP plate)

ΔL = Spacing between two consecutive strain gauge locations, m

These local shear stress distributions were evaluated for Control I, control II and Hot/Wet/Dry samples and histograms were plotted as shown in Figure 4.10 (a), (b) and (c). Local shear stresses are shown in the form of histograms and curve line.

The overall trend shown by the graphs in Figure 4.11 is at low load levels, the bond shear stress is maximum near the free edge A. At these load levels, the force transfer length between the plate and the concrete is relatively short. However, with increase of the applied loads, the forces transfer length increases, and local cracking and debonding at the free edge A moved the location of the maximum force and shear stress further from the free edge A into the interior down the bonded length.

In conclusion, from the graphs local shear stress distribution versus distance from free edge A for the three samples above, the lines shifted to center of bonded area with increasing applied load. In other words, the maximum shear stress or bond strength shifted to interior bonded area with increasing applied load. At low load levels, the bond stress is maximum near the free edge A. At these load levels, the force transfer length between the plate and the concrete is relatively short. The force transfer lengths increase progressively at high loads level.



(b)

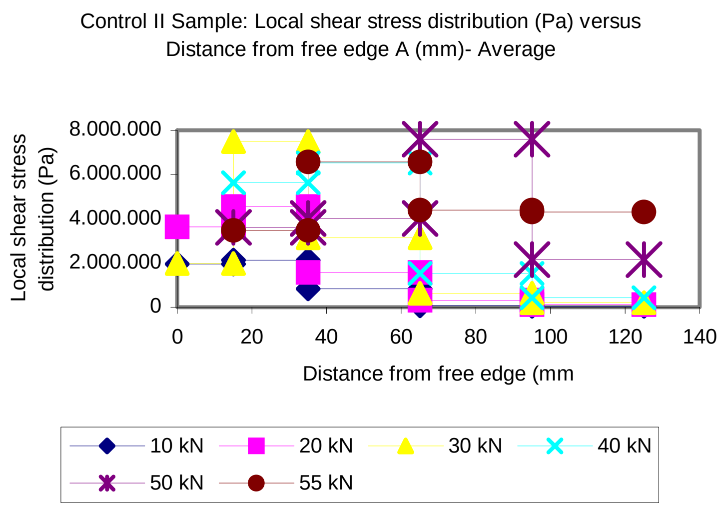


Figure 4.11: Shear stress distribution (a) for Control I sample and (b) for Control II sample

(c)

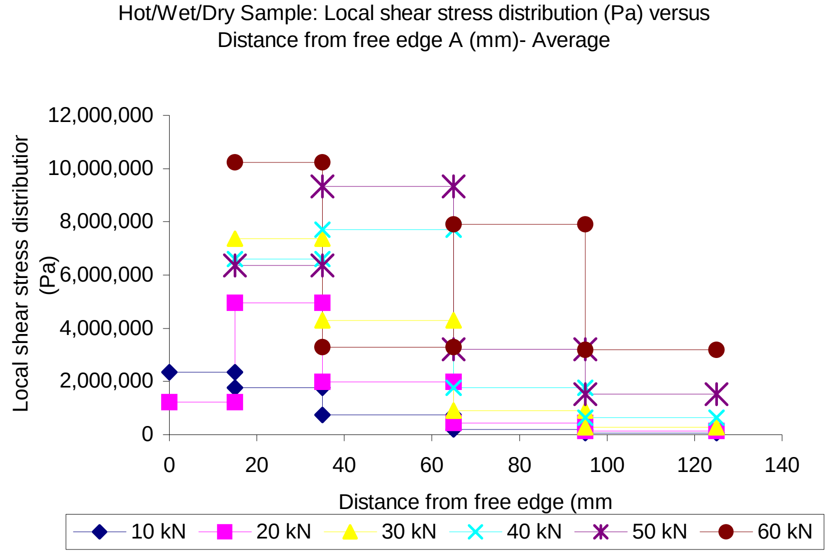


Figure 4.11: Shear stress distribution (c) for Hot/Wet/Dry sample

4.6 Average Bond Strength

The average bond strength can be computed referring equation (14) Chapter III. The properties of equation (14) are as follows;

P_{max} = Ultimate load, kN

A = Bonded area (b x L_B)

b = Width of CFRP bond plate

L_B = Bond length

The measured maximum applied load of Control I, Control II and Hot/Wet/Dry samples are 55.22 kN, 57.93 kN and 64.94 kN respectively. Therefore, the average bond strengths for Control I sample can be calculated as follows:

For Control I sample,

$$\tau_{av} = \frac{55.22kN}{2 \times 150 \times 50mm^2}$$

$$= 3.681 \text{ MPa}$$

Table 4.1: Average bond strengths and maximum applied load for Control I, Control II and Hot/Wet/Dry samples

Condition of samples	**Average bond strengths (MPa)**	**Maximum applied load (kN)**
Control I	3.681	55.22
Control II	3.862	57.93
Hot/Wet/Dry (6 cycles)	4.329	64.94

In comparison, average bond strength for Hot/Wet/Dry sample is the highest among three samples. The maximum recorded applied load before failure is 64.94 kN.

4.7 Maximum Bond Stress Concentration Factor

Table 4.2: Maximum local bond stress and location for Control I, Control II and Hot/Wet/Dry samples

Condition of samples	Location from free edge A, i-j (mm)	Maximum local bond stress (MPa)
Control I	35-65	6.85
Control II	65-95	7.73
Hot/Wet/Dry	15-35	10.24

Maximum bond stress concentration factor can be determined by,

$$\lambda = \frac{\tau_{\max}}{\tau_{average}}$$

For Control I sample,

$$\lambda = \frac{6850800Pa}{3681333Pa}$$

$$= 1.86$$

Table 4.3: Maximum bond stress concentration factor for Control I, Control II and Hot/Wet/Dry samples

Condition of samples	**Maximum bond stress concentration factor**
Control I	1.86
Control II	2.00
Hot/Wet/Dry	2.40

4.8 Failure Mode Analysis

The failure of adhesive bonded double lap shear of CFRP plate-concrete subjected to tension-compression loadings system can occur in three ways: (a) cohesive failure in the adhesive layer; (b) adhesion failure and (c) concrete shearing failure. After pull out test, the failure surfaces on the plate and concrete were carefully inspected and the results are discussed in the following sections.

4.8.1 Failure Mode Analysis For Control I Sample

The failure at side A of Control I sample was largely dominated by concrete shearing (Figure 4.12 (a)). There is 35 mm deep of concrete piece at the free edge A left after pull-out test. At side A of CFRP plate, there is 90 mm length of concrete left-over covered by 150 mm of total bond length (Figure 4.12 (b)). The shape of concrete left-over piece is similar to wedge, referring to Figure 4.12 (e). The compressive stress highly concentrated within the middle of top concrete surface. The crack propagated due to high compressive load on top of concrete surface. This mode of failure clearly show that the adhesive used was capable of providing stronger adhesion than the shear strength of the concrete.

At Side B, about 85 mm length of interlaminar filamentary shear out type of failure of CFRP plate at 50 mm from free edge A, referring to Figure 4.12 (c). The remaining area near the free edge A on the CFRP plate is still remain with thin piece of concrete that failure looked like concrete shearing failure (Figure 4.12 (d)). The failure at this side was mixed mode type of failure that combined concrete shearing and CFRP plate interlaminar filamentary shear out. Figure 4.12 (f) showed both side of CFRP plate surface after pull-out test.

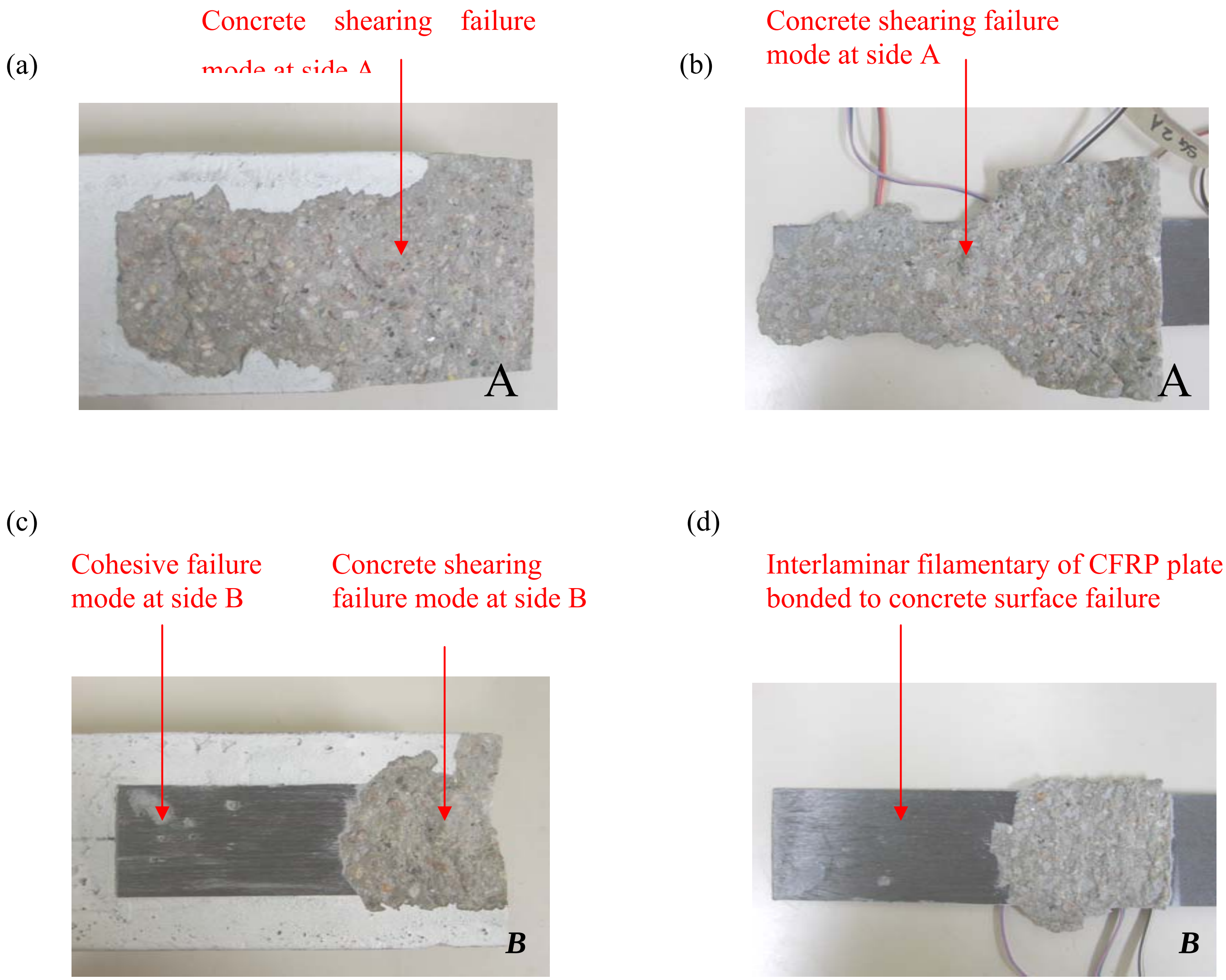
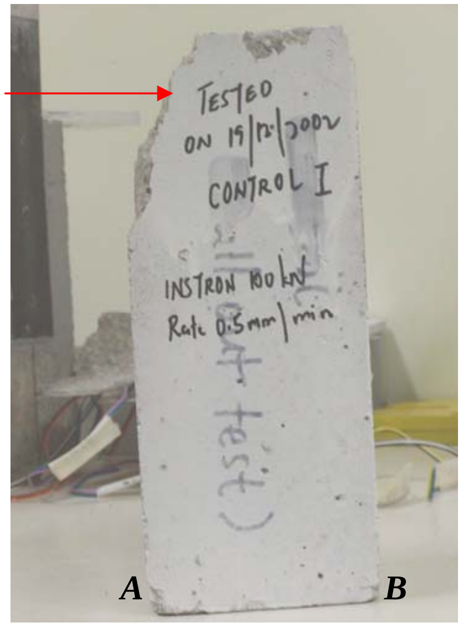


Figure 4.12: (a), (b), (c), (d) Failure mode analysis for Control I sample

(e)

Concrete shearing failure mode at side A



(f)

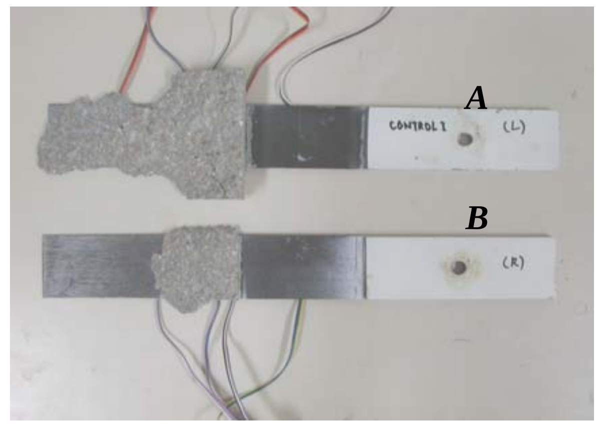


Figure 4.12: (e), (f) Failure mode analysis for Control I sample

4.8.2 Failure Mode Analysis For Control II Sample

For Control II sample, the CFRP plate fully debonded from concrete surface at side A (Figure 4.13 (a)). The failure at side A for Control II sample was fully dominated by concrete shearing. At side A concrete prism, appeared a groove with 5 mm deep at 100 mm from free edge A (Figure 4.13 (a)), local cracking has been created at this area progressively on concrete prism. Uniform compressive load acting on top of concrete prism. Therefore, the failure mode of CFRP/concrete behaved more consistent in term shear-out failure compared to Control I sample.

Thin left-over concrete piece remain bonded along 110 mm length started from free edge A on the CFRP plate (Figure 4.13 (b)). Besides that, there was a small area that has been affected by CFRP plate shear out failure, referring to Figure 4.13 (d). In this case, it is called mixed failure mode due to combination of concrete shearing and CFRP plate shear out failure. Concrete shearing failure mode is clearly showed in Figure 4.13 (e). At another side, by visual inspection, it shows that the CFRP plate still bonded to concrete prism (Figure 4.13 (c)). Due to visual inspection onto the bonding line and concrete surface, there is no indication of crack occurs within the suspected area.

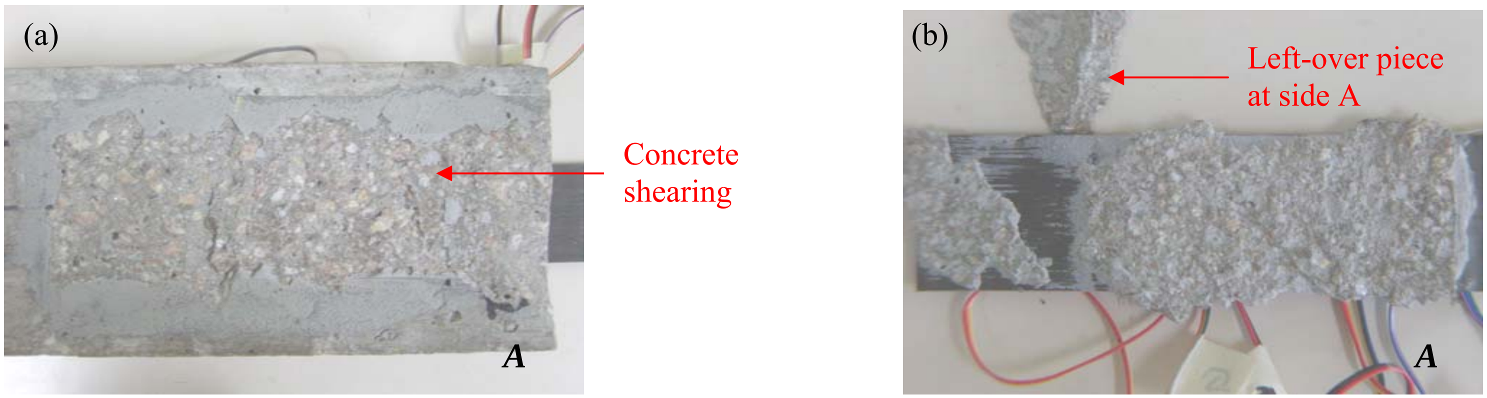


Figure 4.13: (a), (b), (c) Failure mode analysis for Control II sample

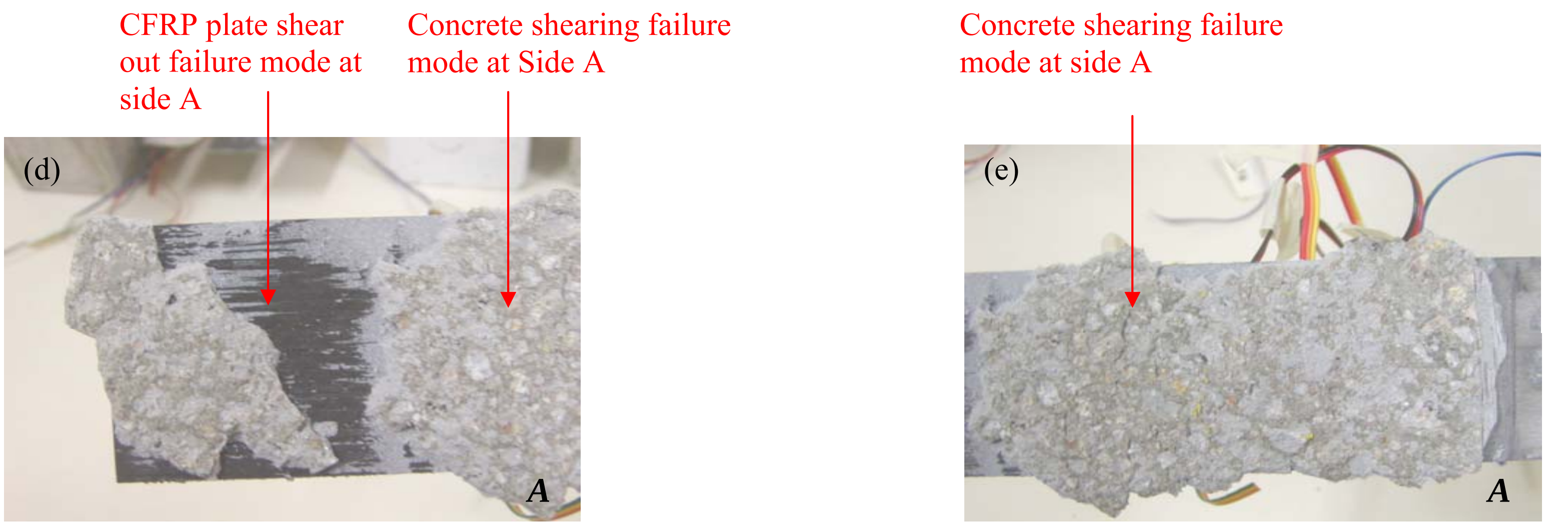


Figure 4.13: (d), (e) Failure mode analysis for Control II sample

4.8.3 Failure Mode Analysis Hot/Wet/Dry Sample

For Hot/Wet/Dry sample, by visual inspection it seen that the CFRP plate still in good condition while concrete prism shows indication of cracks along free edge A of side A(Figure 4.14 (a)).

The failure mode at side B for Hot/Wet/Dry sample can be categorized as mixed failure mode, referring to Figure 4.14 (b). It combined CFRP plate shear out failure, cohesive failure through adhesive and concrete shearing failure, referring to Figure 4.14 (b).

For CFRP plate at side B, it is equally affected by CFRP plate shear out, cohesive failure at the adhesive layer and concrete shearing failure mode, referring to Figure 4.14 (c). In addition, Figure 4.14 (e) and (f) showed CFRP shear out, cohesive failure and concrete shearing failure respectively.

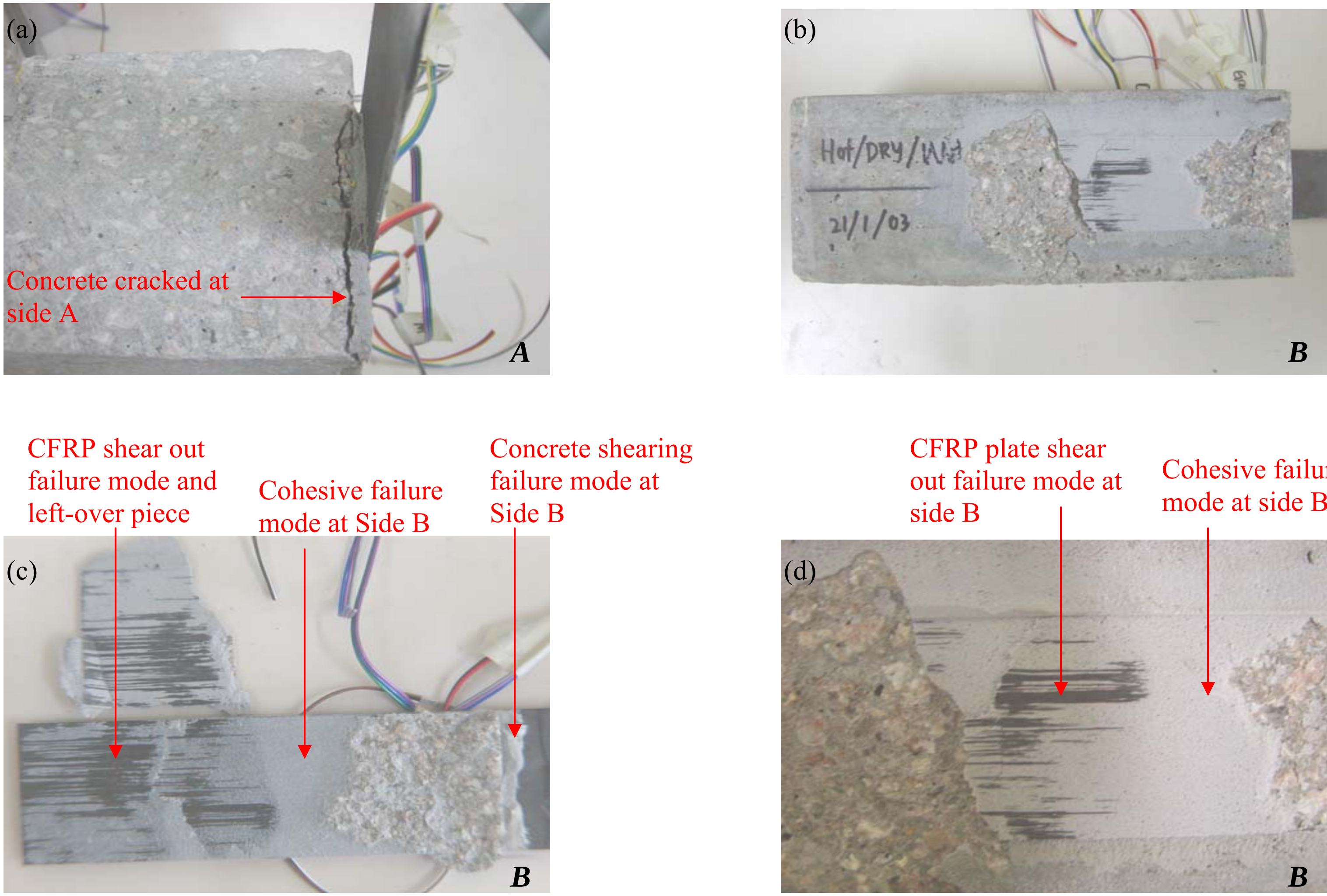


Figure 4.14: (a), (b), (c), (d) Failure mode analysis for Hot/Wet/Dry sample

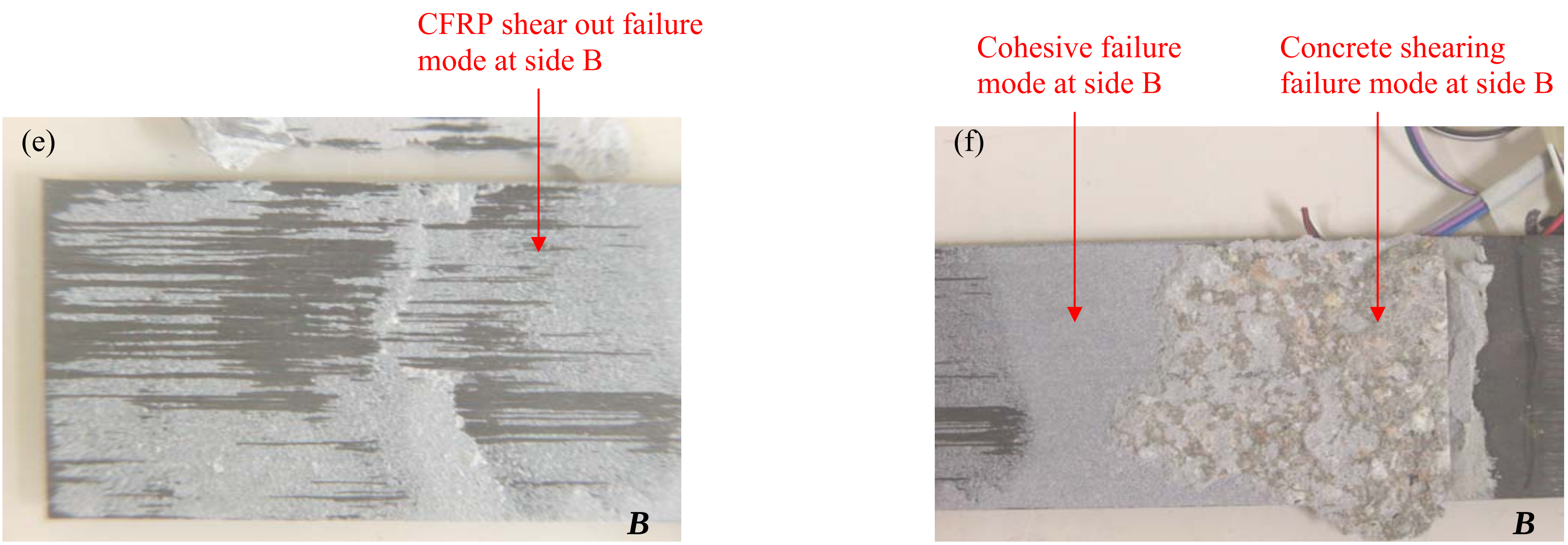


Figure 4.14: (e), (f) Failure mode analysis for Hot/Wet/Dry sample

Summary

The same point of three cases above is there was always concrete shearing failure at area near the free edge A. The bond strength of Hot/Wet/Dry sample is much higher that Control I and Control II samples.

CHAPTER V

CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDY

5.1 Conclusions

A series of concrete prism bond with CFRP plate have been tested under tension-compression loading system using Instron Universal Testing Machine in order to study the effects of Hot/Wet/dry exposure condition. An assessment in this project has been made of changes the exposure conditions. Comparison of bonding properties and failure modes based on the concrete prism bond with CFRP plate under two different exposure conditions has indicated different bonding characteristic. Based on this experiment, the major conclusions of this study are as follows:

Force Transfer Between Plate and Concrete

- Concrete prism bonded CFRP plates under Hot/Wet/Dry condition shows the highest force transfer length compared to Control samples.
- The forces transfer between plate and concrete is almost zero at end of bond area.
- The forces transfer decrease steadily (almost linear) from free edge A at low load levels and occurred at uniform rate.
- Higher force transfer lengths are found at higher load levels.

Shear/Bond Stress Distribution

- At low load levels, maximum local bond stress is found at near the free edge A.
- The force transfer length is relatively short at low load levels.
- Local cracking and debonding at the free edge A shift the location of the maximum force and shear stress further into the interior down the bonded length.
- Maximum bond stress shifted to interior down the bonded length with increase of load levels.

Local Strain on CFRP Plate

- High load is needed to increase $\Delta\varepsilon$ at interior bonded area (away from free edge A).
- Strain increases steadily (almost linear) with the increase of applied load at free edge A.
- Ductile curve pattern is found at center of bonded area for all samples.

Average Bond Strength and Maximum Applied Load

- Concrete prism bonded CFRP plates under Hot/Wet/Dry condition implied the highest average bond strength compared to Control samples.
- The highest applied load (before failure) is found on Hot/Wet/dry sample compared to Control samples with 12.1% increase of load.

Failure Mode Analysis

- Concrete shearing failure occurred at area near the free edge A for all samples.
- The failure mode for each sample was different.
- Mixed mode failure that combined concrete shearing, CFRP plate shear out and cohesive failure at adhesive interface is clearly shown on Hot/Wet/Dry samples.
- Loading configuration on top of concrete prism affected failure mode of sample.

Bond Stress Factor

- Highest bond stress factor is obtained at Hot/Wet/Dry sample and concentrated at area 15-35 mm from free edge A.

5.2 Suggestions for Future Study

During the preparation of the test samples experimentation and testing, few problems have been faced. These obstacles may affect the performance of the test data collected. Therefore, some suggestions were given as below to improve the overall performance of the study.

- In this project, the geometry of the concrete prism is not consistent throughout the length. Improper specimen and surface preparation was also the factors that affect the data collected. And, the surface and specimen should be well controlled within a clean room in order to avoid dust etc.

- In this project, one sample was tested for exposure regime (Hot/Wet/Dry sample). We suggested to increase the test samples for other type of conditions, so, more results can be compared.

- The test set up for this project is complex. High cost is needed to carry out the experimentation and testing. We suggested to simplify the test set up especially test rig design.

- Various thickness, width and bond length of composite, various adhesive thickness and adhesive type can be tested for the further observation of bonding properties.

- The concrete bond surface is suggested to be roughed using sand blast method instead of using air tool. The surface is improper by using air tool. It is difficult to control bond surface contour.

- The exposure duration instead of 6 cycles should be increased to study the long-term performance of the joint durability.

- For Hot/Wet/Dry sample, the specimen was exposed in different environment such as in Oven and submerged in water. The sample was left to dry at lab environment. We suggested sample should be exposed to natural environment. As alternative, a sample can be placed into weathering chamber because it save time and it is easier to handle.

- Comparison study by using finite element package such as MSC Nastran could be suggested in future in order to save time. FEM only could be suggested if only a complete database of materials properties being provided.

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APPENDIX

1. Paper entitled "BOND CHARACTERISTICS OF CFRP PLATE EPOXY BONDED TO CONCRETE UNDER TENSION-COMPRESSION LOADS" presented on Malaysia Science and Technology Congress (MSTC2003), on 23th – 25th September 2003, Kuala Lumpur, Malaysia.

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ABSTRACT:

Carbon Fibre Reinforced Polymer (CFRP) composites have been used successfully as strengthening material for reinforced concrete structures by externally plate-bonded technique. The CFRP materials have characteristics such as lightweight, high tensile strength and modulus to weight ratio, non-magnetic and highly corrosion resistant. Many studies have shown that using plate-bonded technique, the performance of the strengthened concrete member was enhanced. In this technique, the surface preparation of concrete substrate and CFRP material along with the type of epoxy adhesive used are the critical factors affecting the bonding performance of the system. This paper discusses the experimental result on the bonding characteristics between CFRP plate and concrete. The bond stress was determined along the 200 mm bond length of the bonded CFRP plate to concrete. A 50 mm width by 1.6 mm thick CFRP plate was used and bonded to 100x100x300 mm concrete prism. The bonded CFRP plate to concrete prism was tested under tension-compression loads and the results have shown that at lower load level, the shear stress distribution along the bonded length was relatively linear and uniform. However, at higher load when micro cracking occurred along the lap joints the shear stress distribution became non-linear. The investigation on mode of failure of the sample show that the bond between the CFRP plate and concrete was very good.

Keywords: CFRP Plate, concrete, bond stress, tension-compression test

1.0 INTRODUCTION

For cases where individual structural elements such as concrete beams, columns (for bridges, piers, parking lots, and even buildings) are in critical need of strengthening due to several reason such as corrosion of steel reinforcement in structural concrete, aging and deterioration of materials and changing or increasing traffic demands, therefore, direct replacement by new structural elements is not an option because of structural, practical, or economical constraints, making repair and rehabilitation a necessity [1]. In these cases, CFRP in the form of plate is applied to the tension surface of the concrete member is an easy and effective ways to increase the ultimate strength and the stiffness of the structural members [2,3,4].

CFRP is highly considered due to highly durable under various aggressive environmental conditions such as under polluted industrial area and under extreme temperatures. They are also considered to have relatively high durability when compared to that of metals used in construction. It is well known that many polymeric materials, like FRP, are prone to moisture absorption, and the swelling and dissolution can have serious implications on their mechanical properties. However, when FRP are used in conjunction with concrete to form a plate bonded composite beam, then the integrity of the plate-adhesive-concrete member does not solely depend on the plate material but also equally, on the properties of the interfaces involved in the joint, namely, the plate-adhesive and adhesive-concrete interfaces [6].

The epoxy synthetic based adhesives systems that currently developed by various manufacturers around the world have shown an excellence mechanical and physical behaviour when being used in civil construction for various applications [7]. The increasing used of this type of structural adhesive in strengthening and upgrading using bonded steel or FRP plates technique need to be understood by engineers especially about the bonding performances when epoxy being used to bond different type of materials, for example FRP to steel or FRP to concrete.

This paper presented the experimental study of bonding behaviour of CFRP plate-concrete prism joint under tension-compression loads while the results will be discussion onto local load distribution, load transfer length, bond stress distribution, and modes of failure.

2.0 Experimental Programme

2.1 Details of Materials for Tension-Compression Bond Test

A total of three CFRP Plate-epoxy-concrete prism control sample have been prepared namely BOSTUS-C01, BOSTUS-C02 and BOSTUS-C03. The concrete prisms size of 100 x 100 x 300 mm was designed to reach compressive strength of 40 MPa at the age of 28 days. The concrete was produced using maximum coarse aggregate size of

10 mm with water cement ratio of 0.47. The unidirectional CFRP plate of 1.6 mm x 50 mm x 390 mm with an average tensile strength and modulus of 2400 MPa and 135 GPa respectively, was used in this study [8]. The bonded of concrete prism was prepared by sand blasting technique and clean with chemical solvent (acetone) prior bonding to CFRP plate. Resifix 31, two-part (epoxy and hardener the ratio of 3:1) was mixed using a slow speed electric mixer until the mixture showed a uniform grey material. The epoxy was applied to both bonded surface of concrete and CFRP respectively just after the mixed. The bonding process has been done using special design of bonding jig that controlled bond alignment, bond pressure and adhesive thickness. The bonding process of CFRP Plate-epoxy-concrete is shown in Figure C1.

2.2 Measurements and Instrumentation for Tension-Compression Bond Test

The static tensile load was applied uniformly using Universal Testing Machine Model Instron 100 with loading rate of 1 mm/min. The load has been applied onto the specimen up to failure. Twelve 120-Ω TML type BFLA-2-5 electrical strain gauges of 2 mm gauge length have been installed onto the CFRP plates for both side A and B, respectively as shown in Figure C2. The CFRP plate strains have been measured at every 5kN load increment and were recorded using data logger TDS-303 up to failure. Four units of TML LVDT sensitivity of 500 x 10-6/mm and maximum displacement of 25 mm have been installed at both parallel side at upper stressed end and lower free end. These instruments have been used to measure a relative displacement (slip) between CFRP Plate and concrete.

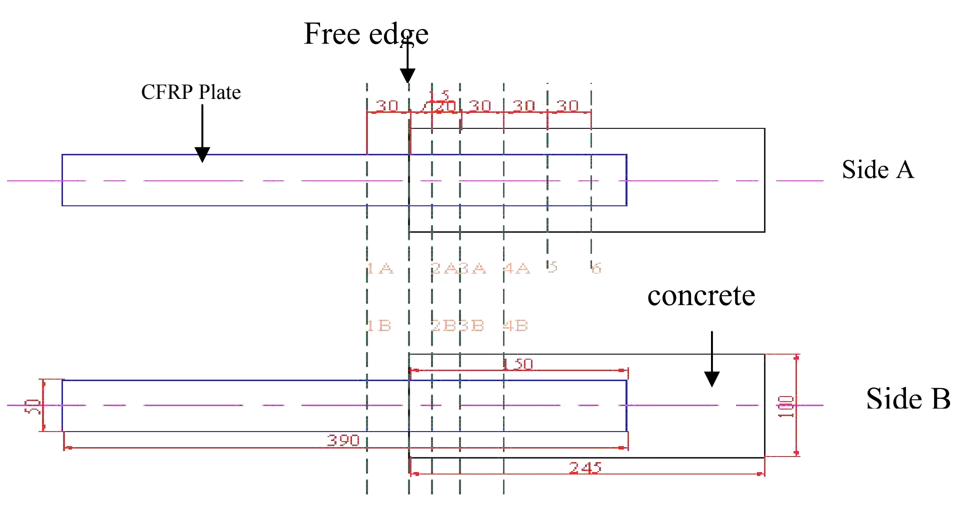

FIGURE C1: Electrical strain gauges location

3.0 Results and Analysis

The test data have been analysed and are discussed as follows;

3.1 Force Transfer between CFRP Plate and Concrete Prism

The ultimate tension applied load near to failure for specimen CI and CII is 55.22kN and 57.93kN respectively. By assuming perfect bonding between the CFRP plate and concrete prism, the local longitudinal force and load transfer at various load level along the bonded plate length for each specimen was analysed and calculated from the local CFRP strain data. The result obtained shows that local load at location 0 mm (free edge A) is half the value of applied load. From the plotted graph in Figure 3, it showed that the load transfer from the CFRP plate to the concrete for specimen CII at low load level is fairly linear and occurs at the uniform rate. At this stage, bond transfer length is quite short. However, when the applied load increased, it can be seen that the force distribution becomes much more non-uniform and non-linear.

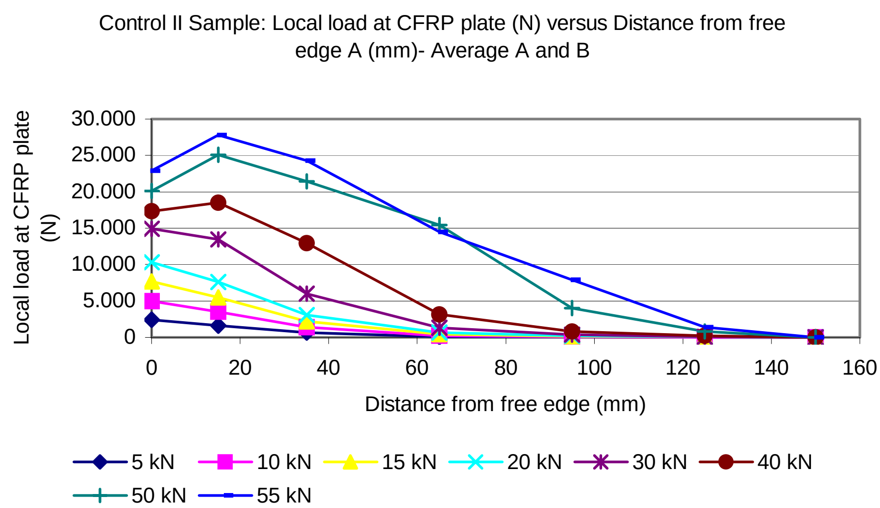

FIGURE 3: Local Load Distribution along CFRP Plate for Specimen CII

3.2 Strain distribution along the bonded CFRP Plate

The data of strain distribution along the bonded CFRP plate were analysed. Average strain at both side of CFRP plates for each specimen was calculated and plotted as shown in Figure 4. At low load level, strain distribution along the plates for both specimens are fairly linear and uniform but with further increase of loads, the local strain become non-uniform and non-linear.

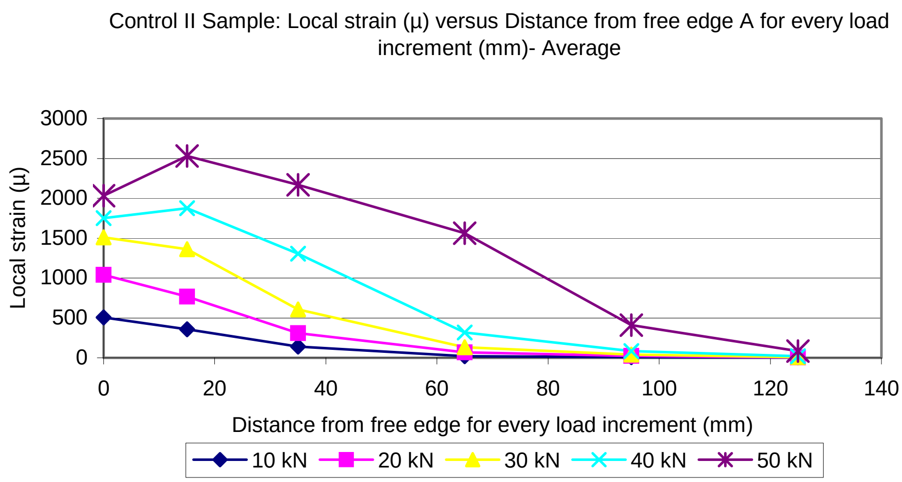

FIGURE 4: Graph Local Strain versus Distance for Specimen CII

3.4 Bond stress distribution

The average bond stress was calculated using formula [6,7], $\tau_{ave} = F_{ult} / (2 \times L_B \times w)$, where F_{ult} = ultimate applied load, L_B = length of bonded surface and w = width of bonded surface is shown in Table 1.

TABLE 1: CFRP Plate-Concrete Prism Bond Stress Experimental Results

Specimen	Average bond stress, τ_{ave} (MPa)	Maximum local bond stress, τ_{local} (MPa)	Maximum bond stress concentration factor, λ	Location from free edge A (mm)
CI	3.68	6.85	1.86	35 – 65
CII	3.88	7.73	2.00	65 - 95

The transfer of the longitudinal force from the CFRP plate to the concrete prism creates shear stress in the plate-adhesive, adhesive and concrete-adhesive interfaces. With the known value of plate width and distance between two gauges, local bond stress along the bonded length can be determined by using [6,7], $\tau_{local} = \Delta F_{i-j} / (b \times \Delta L)$. Where, ΔF_{i-j} = difference in longitudinal force between two consecutive strain gauge locations. ΔL_{i-j} = distance between two consecutive strain gauge location and b = with of the CFRP plate. The different between two consecutives local force are assumed linear. The local bond stress distribution along the bonded length is calculated on 10kN, 30kN, 50kN and at ultimate load for both specimens. The result on bond stress distribution for both specimens is easy to interprete in form of histogram as in Figure 5(a) and 5(b).

From Figure 5, both specimens show the maximum local stress concentration at nearby free edge A of bonding length at low applied load level. It can be explained by the force transfer length is short and the maximum plate force occur at this location. However, the increase of the applied load, the local shear stress propogated from free edge A into the interior bonded length. The increasing of local debonding between CFRP and concrete when further increased of the applied load is the main reasons contribute to full debonding of CFRP from concrete.

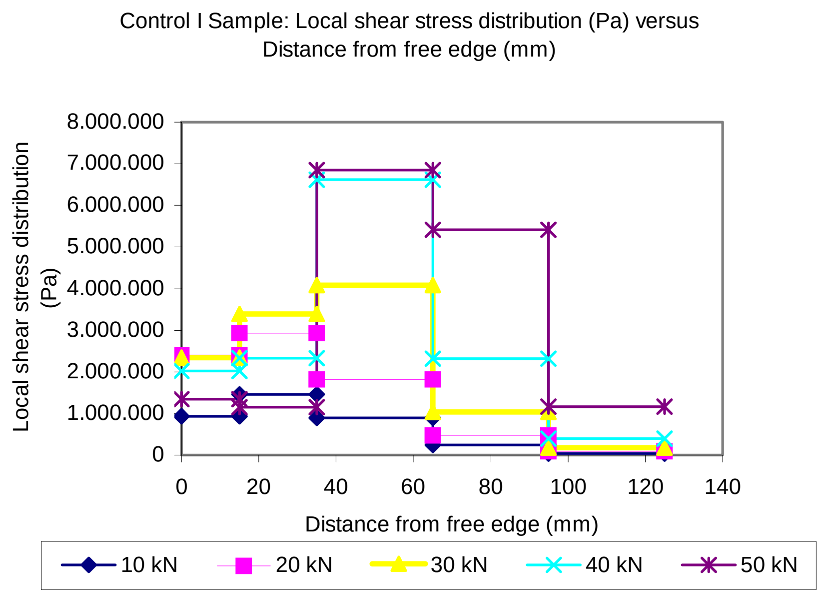

FIGURE 5(a): Typical Shear Stress Distribution for Specimen CII

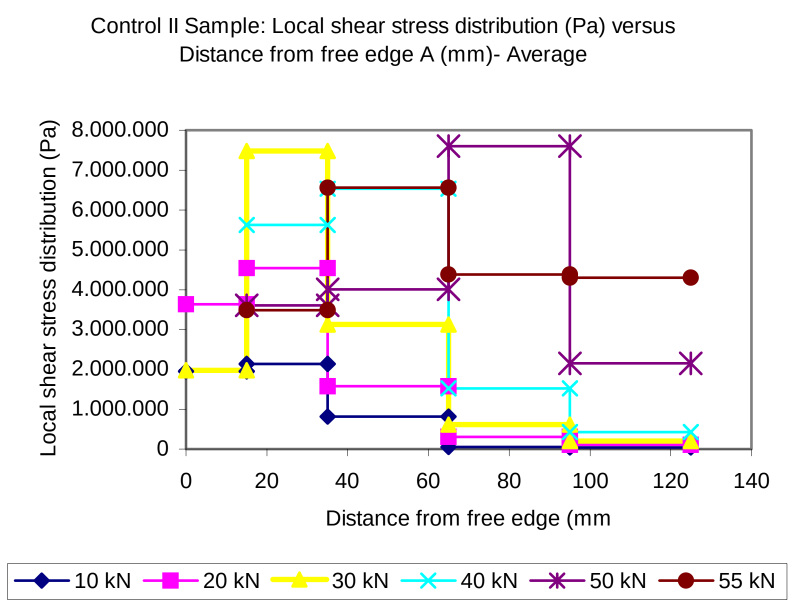

FIGURE 5(b): Typical Shear Stress Distribution for Specimen CII

3.5 Modes of failures

The type of modes of failure of CFRP-concrete can be occured in three conditions, that is: (1) cohesive failure; (2) adhesive failure, and (3) concrete shearing failure [6].

From the observation on specimen CII, the bond failure is mostly contibute by concrete shearing and this due to high stress developed at free edge A of the specimen. The crack is then propagated down and toward the bonded area. Both side of the bonded joint was pullout and failure mode on side A is dominant by concrete shearing as shown in Figure 6 (a).

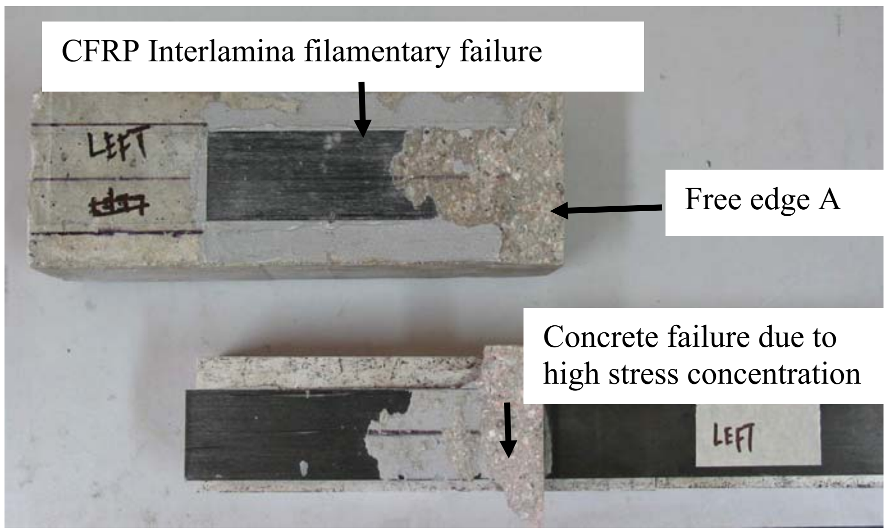

FIGURE 6 (a) : Failure Modes for Specimen CII (Side A)

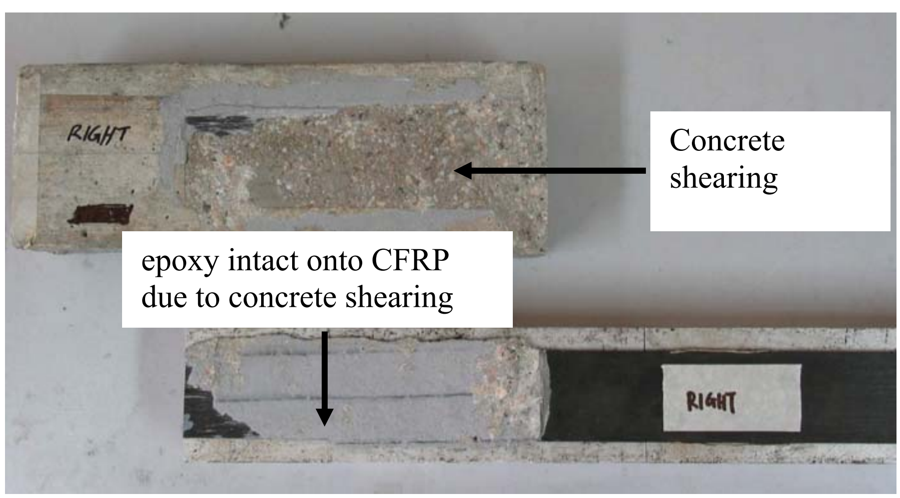

FIGURE 6 (b) : Failure Modes for Specimen CII (Side B)

The failure nearby free edge A of the bonding area at side B shown in Figure 6 (b) sustain concrete shearing and formed little interlamina filamentary type of failure of CFRP plate which bonded to concrete surface. Both conditions showed the bonding of epoxy used is still good. Failure mode on side A shows that shear strength of concrete is weak at high load level. The overall of failure mode for specimen CII is concrete shearing with uniform thickness for the most bonding area.

4.0 CONCLUSION

The conclusions of this study are as follows:

1. The load transfer from the CFRP plates to the concrete at low load level is fairly linear and occurred at a uniform rate.
2. At higher loads level, the local force distribution become non-uniform and non-linear with local debonding occurred at free edge A.
3. Local bond stress distribution and local strain are both influenced by crack history, where the debonding of the CFRP plate by concrete microcraking caused the progressive growth of bond transfer length.
4. CFRP-concrete failure mode mostly dominant by concrete shearing failure due to low tensile or shear strength of concrete compared with CFRP and epoxy adhesive.

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UNIVERSITI TEKNOLOGI MALAYSIA

BORANG PENGESAHAN
LAPORAN AKHIR PENYELIDIKAN

TAJUK PROJEK : THE STUDY OF BONDING BEHAVIOUR BETWEEN FIBRE FIBRE REINFORCED POLYMER COMPOSITE PLATE AND CONCRETE PRISM UNDER TROPICAL CLIMATE

Saya: _DR.YOB SAED ISMAIL

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