DURABILITY OF FIBER REINFORCED POLYMER COMPOSITES UNDER TROPICAL CLIMATE

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Abstract

A lack of in-depth knowledge of the long-term durability of fiber reinforced polymer (FRP) composite in real service condition restricts its extensive use in structural rehabilitation works. The organic nature of the matrix of the FRP composites, and the reinforcing fibers, make them susceptible to attacks of various tropical weathering factors, namely, ultraviolet (UV) ray from sunlight, moisture and heat, when used externally.

Therefore, in the first part of this study, the tropical climate was characterized and reproduced in an in-house designed weathering chamber to induce accelerated weathering effects on FRP composites and FRP-strengthened structural elements. In the second part, the observed glass fibers reinforced polymer (GFRP) mechanical properties variations in the accelerated weathering tests were incorporated in a proposed analytical model to predict the time-dependent behavior of FRP-strengthened beams under the weathering effects of tropical climate.

Comparison with weathering test results showed that the effects of tropical climate weather were reproduced well in the proposed accelerated weathering test scheme. The tensile strength of the GFRP dropped over time when subjected to outdoor tropical climate, and the reduction of tensile strength of GFRP laminates is matrix dependent.

In addition to the tensile coupons, 48 beam specimens were fabricated, exposed to 3 exposure conditions and tested to validate the applicability of the proposed model. The failure modes and ultimate loads of small-scale GFRP-strengthened beams changed with weathering time, and can be well predicted using the proposed model incorporating the material properties after weathering.
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Nomenclature

\( A_s \) \hspace{1cm} \text{area of internal longitudinal tensile reinforcement}

\( A_s' \) \hspace{1cm} \text{area of internal longitudinal compression reinforcement}

\( A_p \) \hspace{1cm} \text{cross section area of FRP laminate}

\( b \) \hspace{1cm} \text{width of beam}

\( c \) \hspace{1cm} \text{depth of neutral axis}

\( d_{s'} \) \hspace{1cm} \text{distance from extreme compression fiber to the centroid of compression steel}

\( d_s \) \hspace{1cm} \text{distance from extreme compression fiber to the centroid of tension steel}

\( d_p \) \hspace{1cm} \text{distance from extreme compression fiber to FRP laminates}

\( E_c \) \hspace{1cm} \text{elastic modulus of concrete}

\( E_s' \) \hspace{1cm} \text{elastic modulus of compression steel reinforcement}

\( E_s \) \hspace{1cm} \text{elastic modulus of tensile steel reinforcement}

\( E_p \) \hspace{1cm} \text{elastic modulus of FRP laminate}

\( E_{p,X}(t) \) \hspace{1cm} \text{elastic modulus of Type X FRP laminate at age } t

\(* E_{p,X}(t) \) \hspace{1cm} \text{elastic modulus of Type X FRP laminate at accelerated age } t

\( f_c(x) \) \hspace{1cm} \text{compression stress in concrete fiber at distance } x \text{ away from neutral axis}

\( f_c' \) \hspace{1cm} \text{cylinder compressive strength of concrete}

\( f_{cu} \) \hspace{1cm} \text{cube compressive strength of concrete}

\( f_s \) \hspace{1cm} \text{stress in internal longitudinal tensile steel reinforcement}

\( f_s' \) \hspace{1cm} \text{stress in internal longitudinal compression steel reinforcement}

\( f_{pu} \) \hspace{1cm} \text{rupture strength of FRP laminate}

\( f_{sy} \) \hspace{1cm} \text{yield strength of internal longitudinal tensile steel reinforcement}

\( f_{sy}' \) \hspace{1cm} \text{yield strength of internal longitudinal compression steel reinforcement}
\( h \)  
overall beam depth

\( k_a \)  
weathering acceleration factor

\( L \)  
FRP bond length

\( L_e \)  
effective FRP bond length

\( M_{cc} \)  
ultimate moment resistance of strengthened flexural members failing by concrete crushing

\( M_{fr} \)  
ultimate moment resistance of strengthened flexural members failing by rupture of FRP

\( M_{db} \)  
ultimate moment resistance of strengthened flexural members failing by debonding of FRP

\( M_u \)  
ultimate moment of resistance

\( P_u \)  
ultimate load for flexural members

\( T_{am,ch} \)  
ambient temperature in chamber

\( T_{am,ou} \)  
outdoor ambient temperature

\( T_{ex,ch} \)  
surface temperature in chamber

\( T_{ex,ou} \)  
outdoor surface temperature

\( t_{ch} \)  
elapsed chamber time

\( t_{ou} \)  
elapsed outdoor time

\( t_p \)  
thickness of FRP laminate

\( w_p \)  
width of FRP laminate

\( \bar{x} \)  
distance from the top concrete fiber to the centroid of compression stress block

\( \alpha \)  
bond strength calibration factor

\( \beta_L \)  
bond length coefficient

\( \beta_p \)  
bond width coefficient

\( \delta_u \)  
beam deflection at failure

\( \delta_y \)  
beam deflection at yield of internal steel reinforcement
\( \varepsilon_c(x) \) concrete strain at distance \( x \) from neutral axis

\( \varepsilon_{co} \) concrete strain corresponding to \( f_{c'} \)

\( \varepsilon_{cu} \) ultimate compressive strain of concrete

\( \varepsilon_p \) strain in FRP laminate

\( \varepsilon_{pu,X}(t) \) rupture strain of Type \( X \) FRP composite at age \( t \)

\( \varepsilon_{pu,X}^{*}(t) \) rupture strain of Type \( X \) FRP composite at accelerated age \( t \)

\( \varepsilon_{pdb} \) debonding strain of FRP laminate

\( \varepsilon_s \) strain in internal tensile steel reinforcement

\( \varepsilon_s' \) strain in internal compression steel reinforcement

\( \varepsilon_{sy} \) yield strain of tensile reinforcement

\( \varepsilon_{sy}' \) yield strain of compression steel reinforcement

\( \phi_X(t) \) residual value of \( X \) at age \( t \)

\( \mu \) ductility index

\( \rho_b \) balanced steel reinforcement ratio

\( \rho_{max} \) maximum steel reinforcement ratio

\( \rho_{min} \) minimum steel reinforcement ratio

\( \sigma_{dbic} \) debonding stress of FRP laminate

\( \tau_{pu,X}^{*}(t) \) interfacial bond strength between Type \( X \) FRP and concrete at accelerated age \( t \)
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Chapter One

Introduction

1.1 General

Externally bonded fiber-reinforced polymer (FRP) composites, either by wet lay-up of fiber sheets or adhesive bonding of composite strip/panel, gained popularity in structural retrofitting and rehabilitation of deteriorated infrastructures due to the high strength-to-weight ratio and ease of installation, as compared to other materials such as steel plate. The use of FRP materials significantly shortens downtime for rehabilitation works in bridges and outdoor infrastructures, which in turn reduces the inconvenience caused to the public (Hag-Elsafi et al., 2001). In addition, FRP composites are not susceptible to corrosion induced by oxidation in the presence of water, unlike steel. This unique property of FRP composites implies a longer outdoor service life of rehabilitated structures, thus assuming a lower life cycle cost in many cases (Chiu et al., 1990).

Despite the excellent performance and overall cost saving features offer by this advanced composite, a lack of in-depth knowledge of the long-term durability of the material in real service condition restricts its extensive use in structural rehabilitation works. Early durability tests were focused on the effects of alkalinity on the performance of FRP rods embedded in concrete (Micelli et al., 2001; Dejke et al., 2001; Benmokrane et al., 2001; Mutsuyoshi et al., 2001). However, the organic nature of the matrix of the FRP composites, as well as the reinforcing fibers, make them also susceptible to attacks of various weathering factors, namely, ultraviolet (UV) ray from sunlight, moisture and heat, when used externally (Uomoto, 2001). As
such, deterioration in mechanical properties after prolonged outdoor weathering is conceivable.

The geographical area of South East Asia close to the Equator is characterized by an intense solar radiation, long sun hours with hot and humid atmosphere accompanied by occasional sudden and heavy showers. Such weather encompasses all the deteriorating effects in which FRP are susceptible to. Therefore, it is important to study the durability of the FRP composites under such conditions to ensure that the rehabilitated structures would continue to be of service within the prescribed design lifetime.

1.2 Background

1.2.1 Fiber Reinforced Polymer

FRP for external structural retrofitting usually takes the form of continuous fiber sheets impregnated with polymeric resin to achieve the desired engineering properties. The reinforcing fibers provide the strength and modulus while the matrix resin ensures the stability of the fibers by increasing the bulk, and provides a relatively impermeable and chemical-resistant protective surface to the fiber (Nicholls, 1976).

1.2.2 Resins

The majority of commercial resins are organic plastics, that is, they are based on carbon chemistry (Irfan, 1998). Plastics can be generally classified as shown in Figure 1.1. Both the crystalline and amorphous thermoplastics are processed in a molten state at elevated temperatures and capable of being reshaped repeatedly by
heating and deforming while hot. On the other hand, all thermosets are amorphous which are usually being processed in an uncured liquid state, and then cured by adding hardener or catalyst to promote cross-linking reaction of monomers to form long polymer chains. The cured thermoset can never be reshaped (Pritchard, 1999). The plastic part of the hand lay-up FRP system usually consists of a liquid thermosetting resin which will set and solidify when chemical catalyst and accelerator are added. Epoxy and polyester are the two commonly used thermosetting resins in FRP systems meant for strengthening works.

1.2.2.1 Types

**Epoxy Resin** - Epoxy is a compound with more than one ethylene oxide group (also known as oxirane) per molecule, as shown in Figure 1.2. It is formed by reacting epichlorohydrin with bisphenol A or bisphenol F in aqueous caustic soda to form diglycidyl ethers of bisphenol A (DGEBA) or diglycidyl ethers of bisphenol F (DGEBF), as shown in Figure 1.3 (Irfan, 1998). The viscosity and melting point of the compound are determined by the ratio of the two components. The toughness, rigidity and high-temperature performance of the epoxy resin are offered by the bisphenol moiety, whereas chemical resistance and adhesive properties are imparted by the ether linkages and epoxy groups respectively. In general, DGEBF has better acid resistance than DGEBA.

**Polyester** - Unsaturated polyester is produced by condensation reaction between anhydrides or unsaturated acids (maleic anhydride or fumaric acid) and polyhydric alcohol, as depicted in Figure 1.4. The reaction of maleic anhydride (MA) with diethylene glycol (DEG) is an example of a typical preparation of unsaturated polyester as shown in Figure 1.5. Similar to epoxy, the physical and chemical
properties of polyester can be modified by adding inhibitors, accelerators, fillers, pigments, mold release agents and other additives (Gaylord, 1974).

**Orthophthalic and Isophthalic Polyester** - Orthophthalic polyester (ortho polyester) is formed through the reaction between phthalic anhydride and maleic anhydride, or fumaric acid, whereas isophthalic polyester (iso polyester) resin includes isophthalic acid instead of phthalic anhydride in the formation process. Iso polyester resins are more costly than ortho polyester but offer better mechanical properties, improved chemical resistance and greater moisture resistance as compared to the latter (ACI, 1996).

1.2.2.2 Glass Transition Temperature

When thermosets are heated above their glass transition temperatures ($T_g$), the modulus, tensile, compressive strength, as well as water resistance and color stability, will drop sharply, as shown in Figure 1.6. Therefore, the service temperature of resin should always be below its $T_g$. The glass transition temperatures for some moisture-free resin are listed in Table 1.1. The value of $T_g$ is proportional to the degree of cure but inversely proportional to the percentage of moisture absorbed. It is stated that 1% of moisture absorption by resin matrix would lower $T_g$ by 20°C (Pritchard, 1999).

1.2.2.3 Curing of Resin

Active chemical compounds known as hardeners are to be added into epoxy resin to promote cross-linking reaction by either polyaddition or by homopolymerization. The wide range of epoxy curing agents is commonly amine-
based. Figure 1.7 shows a basic reaction of the epoxy group with aliphatic amines. To improve the chemical and physical properties of epoxy, additives, such as plasticizers, pigments, fillers, accelerators, retarders, ultraviolet stabilizers, are added to basic epoxy resin prior to curing (White et al., 1994). On the other hand, addition of styrene and catalyst (that is, organic peroxides) into uncured polyester will initiate the cross-linking process and the polyester will be cured in two distinct stages, firstly the formulation of soft gel, and then followed by rapid heat evolution and set into solid, as shown in Figure 1.8.

The curing process of epoxy and polyester resin, as also for other thermosets, is dependent on the curing temperature. Complete cure of resin requires the utilization of all potentially reactive chemical groups involved in the process and can only be completed with stepwise elevated temperature post-cure, as depicted in Figure 1.9 (Pritchard, 1999).

1.2.2.4 Curing Degree and Durability of Resin

The degree of cure on resin affects the characteristics and durability of FRP (Figure 1.10). Fully cured thermosets have higher cross-link density compared to those partially cured, and hence have higher modulus, T_g and better resistance to moisture ingestion. By immersing FRP composites with resin of different cross-linked density in sulphuric acid for 1 month, Hattori et al. (2000) found that the infiltration depth of sulphur was small for resin with higher cross-link density, as shown in the lower and narrower peak of scanned-line near surface resin in Figure 1.11 (c) compared to that of Figure 1.11 (b).
1.2.3 Reinforcing Fibers

1.2.3.1 Types

Carbon, aramid and glass are the most common types of continuous fiber used to produce fiber sheets for structural strengthening application. The fiber sheets can be further categorized according to the arrangement of fiber, that is, either uni-directional, bi-directional or multi-directional, and weaving method, as shown in Figure 1.12. Figure 1.13 depicts the typical stress-strain behavior of various reinforcing fibers (ACI, 1996). In general, all the fibers exhibit a linear stress-strain relationship up to rupture failure without any plastic regime.

**Carbon Fibers** - Carbon fibers can be manufactured from four types of raw materials, that is, polyacrylonitril (PAN), rayon, coal tar (pitch) and phenol precursors. PAN-based type is the most commonly used carbon fiber in a form of layered graphite. Figure 1.14 shows an example of a graphene (hexagonal) layer present in graphite. The parallelism of graphene layers with the fiber axis and flaws in the graphene determine the modulus and tensile strength of the fibers, respectively. Carbon fibers can be generally classified to either as high modulus (HM) or high tensile (HT) type, depending on their mechanical properties.

**Aramid Fibers** - Aramid is an abbreviation of aromatic polyamide, which is the generic name for polyparaphenylene-terephthalamide, as shown in Figure 1.15. The aromatic ring structure contributes high thermal stability, while the para-linkage leads to stiff, rigid molecules that contribute high strength and high modulus. Aramid fibers can be classified according to their moduli. High modulus (HM) aramid fibers, such as Kevlar™ 49 and Twaron 1055, are more common for structural applications.
than their low and ultra-high modulus counterparts due to the good combination of strength, strain and relaxation limit (ACI, 1996).

**Glass Fibers** - Glass fibers are classified according to their chemical formulation into E-Glass, S-Glass, C-Glass and A-Glass. Table 1.2 shows the typical chemical compositions of each of the type of the glass, and the corresponding characteristics (Leggatt, 1984; ACI, 1996). E-Glass is the most widely used due to its low cost and availability.

1.2.3.2 Influence of Resin on Mechanical Properties of Composite

The mechanical properties of the composites are controlled by the strength and the elastic properties of the fibers, the resin matrix and the fiber-matrix interfacial bond which governs the stress transfer (Mahiou et al., 1998). Rot et al. (2001) demonstrated the influence of the unsaturated polyester composition on the interfacial bond strength between E-glass fiber and resin. The tensile strength of the laminates was reduced as a result of the decrease in fiber-matrix bond due to different composition of the constituents (that is, amount of maleic anhydride and diethylene glycol added), as shown in Figure 1.16. They also concluded that adhesion of resins to fiber can be improved by using more flexible (low modulus) resins, which in turn improves the tensile strength of laminates.

1.2.4 Weathering of Polymer

Weathering is the natural tendency of materials to return to their elemental forms by means of corrosion, oxidation, chalking, delamination or depolymerization
under the action of weathering factors, such as heat (temperature), sunlight (or ultraviolet ray) and moisture (PDL, 1994).

1.2.4.1 Weathering Factors and Degradation Mechanisms of Polymer

The various weathering factors and their associated degradation effects on polymers are illustrated in Figure 1.17. The factors shown in solid octagonal boxes are the primary factors of natural outdoor conditions, whereas the factors in dashed-line box only arise when materials are exposed under highly polluted environments with high acidity or alkalinity and/or active microorganism activities. Among all, photo-oxidation process is believed to be the main degrading mechanism of polymer under outdoor weathering.

1.2.4.2 Ultraviolet Ray and Photo-Oxidation Process

The electromagnetic energy from sunlight is normally divided into ultraviolet (UV) ray, visible light and infrared energy, as shown in Figure 1.18. The UV ray is further divided into UV-A, UV-B and UV-C as shown in Table 1.3. UV-A is the major portion of UV ray found in the sunlight spectra power distribution with high penetrating ability as compared to UV-B and UV-C. It is the high energy photons of UV ray that breaks the chemical bonds and alter the properties of plastics. On the other hand, the damage of different types of plastics is also sensitive to the wavelength of incident UV ray, as shown Table 1.4. The damaging portion of UV that acts on the plastics, with the presence of oxygen, induced photo-oxidation process that can either cause breakdown of the polymer chains by chopping them up (chain-scission), or further reaction between the chain which make the plastic more brittle (cross-linking), as depicted in Figure 1.19.
The chain-scission and cross-linking processes caused by photo-oxidation lead to degradation of polymers (Kelen, 1984; White, 1994). The scission and cross-linking of long polymer chains produce small molecules such as ketones, alcohols and acids, which in turn evaporate or are washed away by moisture contact, thus causing embrittlement and cracking on the polymer film. For pigmented polymer, material loss also increases the pigment volume concentration at the coating surface, resulting in a brittle top layer over an elastic lower layer which leads to crazing and chalking, which in turn renders the gloss loss of the film; the effects of weathering factors on polymer are enhanced in the presence of external stresses and mechanical abrasion (Sharman et al., 1989; Armstrong et al., 1995; Puterman, 1996).

However, quantitative studies on the damage induced by physicochemical processes of various weathering factors on the mechanical properties of different polymers are still extremely limited, hence hindering the development of degradation rate equations. In order to evaluate and predict the durability of polymers, weathering test is usually needed (Liao et al., 1998; White, 1994).

1.2.4.3 Weathering Tests

To evaluate the physical and chemical changes in materials under the action of various weathering factors, it is best to subject the materials to weathering tests and then assess the changes promoted by appropriate characterization techniques. Weathering tests can be generally classified into natural outdoor weathering or artificial indoor weathering test. Acceleration can be included in both the outdoor or indoor weathering test. However, almost all the artificial indoor weathering tests are conducted in an accelerated manner (PDL, 1994).


**Natural Outdoor Weathering Test** - The durability and time-dependent performance of materials can be best evaluated by exposing them under the service conditions. Florida and Arizona State of U.S.A are the two well-known areas for outdoor weathering test site for materials that need to undergo sub-tropical hot-wet and desert hot-dry exposures, respectively (Master et al., 1999). The climatic data of the two exposure site areas are shown in Figure 1.20. It is worth noting that, due to seasonal variations, the average annual solar irradiance and temperature of Florida is lower than those of Singapore, as compared in Section 2.1.1 and 2.1.2.

During weathering test, specimens are mounted on rack and tilted at different angles under direct or indirect sun exposure, as illustrated in Figure 1.21. Changes in exposure angle and type of test rack will influence the radiant energy received by the specimens, which in turn causes different degradation rates and damage levels.

**Accelerated Outdoor Weathering Test** - Outdoor weathering test can be accelerated by introducing artificial water spray and sunlight concentration on the specimens undergoing direct or indirect sunlight exposure. The schematic diagram of such a device is shown in Figure 1.22. The device, which traces the position of the sun, has mirrors that are capable of increasing the sunlight intensity by eight times. Alternatively, “Black Box Exposure”, which results in higher exposure temperature and greater total wet time than normal open rack exposure, can also be used in order to speed up the weathering process (PDL, 1994; Wypych, 1995; Master et al., 1999).

**Artificial Indoor Weathering Test** - Weathering tests conducted in simulated environmental conditions in laboratory are aimed at providing better controlled and accelerated conditions compared to outdoor exposure. Commercial weathering testers for plastics enable the precise control and reproduction of all the
weathering factors, namely, full sunlight spectrum (or ultraviolet ray spectrum), moisture and temperature, as the one shown in Figure 1.23. Modern commercial weathering testers are generally classified according to the light sources used (that is, carbon arc, xenon arc, fluorescent UV lamps, mercury vapor lamp and metal halide UV lamp) to reproduce the full sunlight or ultraviolet ray spectrum (Wypych, 1995; Martin et al., 1999).

Alternatively, artificial weathering tests could also be carried out by reproducing only one or two weathering factors to investigate the effects of particular weathering factors on the properties of material of interest, or to screen and rank the durability of different material systems. Hot water or acid/alkaline solutions immersion, oven dry heating, cyclic wetting-drying and freezing-thawing are typical weathering tests.

**Correlation of Natural and Artificial Weathering Test** - If both the natural and artificial weathering tests promote similar trend of degradation on the test specimens, the tests are said to be well-correlated. Most of the correlation studies of natural and artificial weathering tests were conducted qualitatively, and no definitive conclusion have yet been made (White et al., 1994; Liao et al., 1998; Master, 1999; Wypych, 1995; Fedor et al., 1996).

In the review by White et al. (1994), it was concluded that no good correlation exist between natural and artificial weathering tests, as well as between different artificial tests using different light sources, due to (i) limited test period; (ii) variation in sensitivity of materials to specific weathering factors; (iii) diurnal and seasonal variations of outdoor weather versus the constant indoor simulation; and (iv) the exclusion of other important weathering factors (such as dark period) in the artificial tests.
However, by simulating the UV spectrum and hygrothermal effects, Fedor et al. (1996) claimed to produce consistent degradation on 15 different polymers with natural and artificial weathering tests, though with different material-dependent weathering acceleration factors. By subjecting different polymeric sealant under both natural and artificial weathering tests, Marechal et al. (1996) found that the weathering acceleration factors are material specific. Good correlation results were found between 6 months of accelerated weathering to that of 2 years of outdoor weathering on low density polyethylene films (Hamid et al., 1995), indicating an accelerated rate of 4. In another instance, 2000 to 4000 hours of artificial UV plus condensation weathering on alkyd paints reproduce the weathering effects of eastern Mediterranean warm-humid weather up to 2 years well (Puterman, 1996).

1.2.5 Durability of FRP

1.2.5.1 Past Durability Studies on FRP

The mechanical properties, such as tensile strength and modulus, and bond strength of externally bonded FRP composites are of paramount importance among all the other properties in structural retrofitting. In order to access the mechanical performance under the expected service conditions, durability studies on the effects of various weathering factors on FRP composites are needed. In view of the absence of mid- to long-term performance data, researchers resorted to artificial weathering tests in accessing and predicting the durability of FRP composites under outdoor exposure. However, from all the surveyed literatures, it is clear that the artificial weathering test schemes employed are highly varied. Despite the importance of the effect of sunlight and ultraviolet ray, heat and moisture (either imposed individually
or combined) appear to be the two weathering factors that are being widely reproduced in indoor weathering tests on FRP composites. In addition, hygrothermal effect of heat and moisture was reproduced by either continuous immersion of specimens (constant hygrothermal) or intermittent immersion with drying or thawing effect at prescribed intervals (cyclic hygrothermal) in pure water or acidic/alkaline solutions at sub-zero, room or elevated temperatures. The different composite systems, test periods and characteristics of techniques used in previous FRP durability tests further complicate the situation.

1.2.5.2 Environmental Effects on Tensile Characteristics

**Heat** - Test data from Kshirsaga et al. (2000) and David et al. (2001) showed that the tensile strength of epoxy-based FRP composites was increased by dry heating between 60 to 70°C for 2 months. The stiffness of epoxy impregnated CFRP laminate also increased by 20% when dry heated at 150°C for 9 months (Parvatareddy et al., 1995). Such observed changes are expected as sub-$T_g$ heating provides post-curing on polymeric resin matrix and further improves its properties (Boey et al., 2001). However, heating at temperature closed to $T_g$ decreased the static and fatigue strength of carbon fiber-epoxy composite (Naruse et al., 2001).

**Moisture** - The semi-permeable polymeric resins absorb water when in contact with moisture. Kellas et al. (1990) found that tensile strength of notched carbon-epoxy laminates increased when an optimum amount of moisture were absorbed at room temperature. They attributed this to the residual stress relaxation and matrix toughening due to plasticization of polymer under the action of moisture. However, further moisture absorption caused strength reduction due to matrix
cracking as a result of excessive matrix swelling. Short-term (2 months) immersion of iso polyester in water at room temperature also did not cause any strength reduction (Chin et al., 1997). On the other hand, longer period (15 months) of water immersion at room temperature led to reduction in the tensile strength of glass-epoxy and carbon-epoxy laminates by 36% and 15%, respectively (David et al., 2001). It was suggested that the higher drop in glass-epoxy laminate strength was due to hydrolysis of silane coupling agent which is only present in glass fiber-epoxy matrix interface.

**Hygrothermal Effects** - Under the constant hygrothermal condition, Kellas et al. (1990) reported that tensile strength of notched carbon-epoxy laminates increased when the conditioning temperature and/or moisture absorbed attain an optimum degree due to the notch blunting effects. David et al. (2001) found that the $T_g$ of E-glass and carbon-epoxy laminated were increased after 1 year of conditioning in 100% relative humidity at 40°C due to post-curing effects. Nevertheless, when an alkaline solution was used to weather E-glass- and aramid-epoxy at 60°C for only two months, the strength and ultimate strain dropped by 40% and 32% respectively and the composite became more brittle (Kshirsagar et al., 2000).

Cyclic hygrothermal effect induced by freezing and thawing between -10°C and 23°C for 3 months caused 10% reduction in mechanical properties of carbon-vinlyester composite due to fiber-matrix debonding as a result of hydrolysis and plasticization of resin matrix, while freezing alone has no significant effect. The deterioration was more severe for E-glass- and aramid-epoxy composites and higher damage levels were noticed within shorter weathering period (Rivera et al., 2001).
On average, however, the damaged level caused by the effect of cyclic hygrothermal is less severe than that of constant hygrothermal (Kshirsagar et al., 2000).

**Ultraviolet Ray** - Despite the fact that UV-A is the main portion of UV that reaches the earth surface, UV-B ray was frequently used in past weathering tests as it causes faster degradation on polymeric material. Uomoto (2001) reported that aramid fiber is highly sensitive to UV ray attack. Exposure under 5,555 $\mu$J/s/cm$^2$ of UV ray for 6 month reduced the strength of aramid-epoxy rods by more than 20%. UV-B ray, with a much lower irradiance of 30 $\mu$J/s/cm$^2$, acting on A-glass-polyester rod also caused the tensile strength to drop by 5% after the same period of exposure (Tannous et al., 1999). By subjecting the carbon-epoxy composites to 48 hours of 25,000 $\mu$J/s/cm$^2$ of UV-B ray prior to evaluation of residual compressive bulking strength, Pang et al. (2001) suggested that the toughness and cracking resistance of E-glass-epoxy laminates is reduced with or without the presence of moisture.

**Synergistic Effect of Heat, Moisture and UV** - Under the 1 year effects of outdoor cool winters with sparse rainfall and hot summers with high humidity, glass-polyester laminates exhibit a reduction in strength and strain at failure, but an increment in the modulus, as shown in Figure 1.24 (Al-Bastaki et al., 1994).

### 1.2.5.3 Environmental Effects on FRP-Concrete Bond Strength

Leung et al. (2001) studied the bond performance of carbon fiber plates to small concrete prisms with different types of epoxy resins. It was observed that no bond deterioration occurred after 2 months of dry heating at 60°C, but bond strength was significantly reduced as ambient moisture level increased. Similar trend was
observed by Tan and Liew (2002) with pull-apart double lap shear test at different moisture levels up to 6 months.

Nonetheless, the effect of UV-A on bond strength of urethane adhesive bonded FRP joints was claimed to be insignificant, as the joint interfaces were protected from UV-A ray by opaque FRP laminates (Ramani et al., 2000). Freezing-thawing or freezing alone also did not seem to affect the bond strength (Karbhari et al., 1998).

1.2.5.4 Environmental Effects on FRP-strengthened Structural Elements

**Beams** - Hygrothermal effects were studied on either small-scale (less than 0.5 meter span) or middle-scale (about 1 meter span) beams with width-to-height (b/h) ratios of more than 1.0 and less than 0.7, respectively (Chajes et al., 1994; Toutanji et al., 1997; Almusallam et al., 2001; Gheorghiu et al., 2001).

Chajes et al. (1994) found that the effect of cyclic wetting and drying at room temperature for 3 months caused a greater drop in the enhanced strengths of small-scale reinforced concrete beam compared to that of freezing and thawing, and the damage was more severe for epoxy reinforced with glass and aramid than that of carbon fibers. The detrimental effect of wetting and drying on carbon and glass fiber bonded small-scale plain concrete beams up to 2 months was also observed by Toutanji et al. (1997). Figure 1.25 shows the load-deflection curves of the weathered and virgin beams. The stiffness of all the beams increased after weathering and strength drops were observed for all cases. In addition to the drop in enhanced strength, the results of Chajes et al. (1994) and Toutanji et al. (1997) suggested that the failure modes of the beam were also affected by the effects of weathering.
For middle-scale beams, however, Almusallam et al. (2001) found no degradation in the flexural strength and rigidity in the GFRP strengthened beams after 1 year exposure under outdoor arid climate and indoor cyclic wetting and drying, despite the simulated conditions being similar to that of Toutanji et al. (1997). They attributed this to the superior quality of the epoxy used. Meanwhile, no degradation and change of failure mode were observed by Gheorghiu et al. (2001) after immersing CFRP strengthened beams in both water and salt solution and subjected to wetting and drying or continuous immersion for 3 and 5 months respectively.

**Columns** - Although continuous dry heating on GFRP and AGRP confined cylinders at 65°C up to 1 year did not reduce the compressive strength, a reduction of 25% in compressive strength was observed after immersion in alkaline solution with the same temperature and period (Kshirsagar et al., 2000). On the other hand, two months of cyclic wetting-drying did not cause any reduction while freezing-thawing caused 8% reduction in compressive strength of AFRP confined cylinders (Toutanji et al., 2002).

All effects of weathering factors reviewed above are summarized in Table 1.5. As most of the artificial weathering tests were conducted within a limited period, it is therefore decided to consider test results obtained with less than 3 months as short-term weathering results, whereas those with longer period as long-term weathering results.
1.3 Objectives of Study

It is clear that past weathering schemes employed on FRP were highly subjective and did not seem to give good correlation to outdoor weathering conditions, as in most cases not all the vital weathering factors are reproduced. Meanwhile, durability studies on FRP strengthened structures were limited to phenomenal observations and no attempt has yet been made to propose model to predict the time-dependent changes in structural response due to deterioration of FRP. The objectives of this study are therefore to

1) devise and verify an accelerated artificial weathering test scheme that is able to impose the same outdoor weathering effects on FRP,

2) study the effect of tropical climate weathering on the behavior of FRP-strengthened beams,

3) propose a model to predict the changes in the failure mode of FRP-strengthened beam under the weathering effects of tropical climate, and finally

4) forecast the long-term behavior of beams strengthened by FRP under the weathering effects of tropical climate.

1.4 Report Organization

This chapter provides background information on the various issues related to the material properties of FRP, weathering factors, durability test schemes and the susceptibility of FRP under the effects of individual, as well as synergistic, weathering factors.

Chapter 2 is focused on the development of the artificial weathering test scheme that aims to simulate the outdoor tropical climatic weathering effects. The tropical weather is first being characterized, followed by the detailed description on
the reproduction of weathering effects in an in-house designed chamber. The results on the efficiency and correlation of the artificial weathering test scheme with natural outdoor weathering are also reported.

A time-dependent FRP-strengthened beam failure mode prediction model is presented in Chapter 3. Experimental program on model verification based on outdoor weathering test is then reported. The long-term beam failure mode and behavior under the tropical climate is forecast by utilizing both the model and accelerated weathering scheme.

Finally, the study findings are summarized and concluded in Chapter 4, along with comments and recommendation for future works.
### Table 1.1: Glass transition temperature of moisture free resins (Pritchard, 1999)

<table>
<thead>
<tr>
<th>Type of Resin</th>
<th>$T_g$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermoplastics</strong></td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>-78</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>-15</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>101</td>
</tr>
<tr>
<td>Acetal</td>
<td>-75</td>
</tr>
<tr>
<td>Nylon</td>
<td>56</td>
</tr>
<tr>
<td>Poly methyl methacrylate (PMMA)</td>
<td>104</td>
</tr>
<tr>
<td>Polyethylene terephthalate</td>
<td>68</td>
</tr>
<tr>
<td>Polybutylene terephthalate</td>
<td>82</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>145</td>
</tr>
<tr>
<td>PVC</td>
<td>87</td>
</tr>
<tr>
<td><strong>Thermosets</strong></td>
<td></td>
</tr>
<tr>
<td>DGEBA epoxy</td>
<td>145</td>
</tr>
<tr>
<td>TGDDM epoxy</td>
<td>240</td>
</tr>
<tr>
<td>Unsaturated Isophthalic polyester</td>
<td>&gt;230</td>
</tr>
</tbody>
</table>

### Table 1.2: Typical chemical composition of commercial glass fibers (Leggatt, 1984; ACI, 1996)

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>E-Glass</th>
<th>S-Glass</th>
<th>A-Glass</th>
<th>C-Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Silica</td>
<td>52</td>
<td>65</td>
<td>73</td>
<td>66</td>
</tr>
<tr>
<td>% Boron oxide</td>
<td>11</td>
<td>-</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>% Sodium / Potassium oxide</td>
<td>1</td>
<td>-</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>% Aluminium / iron / calcium / magnesium oxide etc.</td>
<td>36</td>
<td>35</td>
<td>13</td>
<td>21</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>General purpose</th>
<th>High-strength</th>
<th>Good acid resistance</th>
<th>Good chemical stability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1.3: Wavelength regions of UV (Sharman et al., 1989)

<table>
<thead>
<tr>
<th>Region</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV-A</td>
<td>315 to 400 nm</td>
</tr>
<tr>
<td>UV-B</td>
<td>280 to 315 nm</td>
</tr>
<tr>
<td>UV-C</td>
<td>100 to 280 nm</td>
</tr>
</tbody>
</table>

Table 1.4: Maximum photochemical sensitivity for different plastics (Sharman et al., 1989)

<table>
<thead>
<tr>
<th>Type</th>
<th>Wavelength, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic (polymethyl methacrylate)</td>
<td>290 – 315</td>
</tr>
<tr>
<td>ABS (acrylonitrile butadiene styrene)</td>
<td>300 – 310, 370 – 385</td>
</tr>
<tr>
<td>CAB (cellulose acetate butyrate)</td>
<td>296</td>
</tr>
<tr>
<td>Nylon</td>
<td>290 – 315</td>
</tr>
<tr>
<td>Polymides (aromatic)</td>
<td>360 – 370</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>290 – 310</td>
</tr>
<tr>
<td>Polyester</td>
<td>325</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>300 – 310, 340</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>290 – 300, 330, 370</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>310 – 325</td>
</tr>
<tr>
<td>Polyurethane (aromatic)</td>
<td>350 – 415</td>
</tr>
<tr>
<td>PVC</td>
<td>320</td>
</tr>
<tr>
<td>SAN (styrene acrylonitrile)</td>
<td>290, 310 – 330</td>
</tr>
</tbody>
</table>
### Table 1.5 Summary of weathering effects on FRP

<table>
<thead>
<tr>
<th>Weathering factors</th>
<th>Tensile properties</th>
<th>Bond strength</th>
<th>Structural Element</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength</td>
<td>Stiffness</td>
<td></td>
</tr>
<tr>
<td>Heat (&lt; $T_g$)</td>
<td>++</td>
<td>++</td>
<td>±</td>
</tr>
<tr>
<td>(≥ $T_g$)</td>
<td>--</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>± / -</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Constant hygrothermal</td>
<td>-</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Cyclic hygrothermal</td>
<td>--</td>
<td>--</td>
<td>- / 0</td>
</tr>
<tr>
<td>UV ray</td>
<td>--</td>
<td>++</td>
<td>±</td>
</tr>
<tr>
<td>UV ray + hygrothermal</td>
<td>-</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- ++  Increase after short-term weathering
- +   Increase after long-term weathering
- 0   Not affected after long-term weathering
- ±   Not affected after short-term weathering
- -   Decrease after long-term weathering
- --  Decrease after short-term weathering
- “blank”  Unknown/Not identified
Figure 1.1: Classification of polymeric materials (Budinski et al., 2002)
Figure 1.2: Epoxy group

(a) Bisphenol A based epoxy (DGEBA)

(b) Bisphenol F based epoxy (DGEBF)

Figure 1.3: Synthesis of epoxy (Irfan, 1998)
Chapter One: Tables and Figures

Figure 1.4: Production of polyester (Gaylord, 1974)

\[
\begin{align*}
\text{ Unsaturated Dibasic Acids } & : \text{ Fumaric acid, Maleic acid, Maleic anhydride, etc.} \\
\text{ Saturated Dibasic Acids } & : \text{ Phthalic anhydride, isophthalic acid, adipic acid, orthophthalic acid, etc.} \\
\text{ Glycols } & : \text{ Ethylene glycol, diethylene glycol, propylene glycol, etc.}
\end{align*}
\]

\[
\begin{array}{c}
\text{ Unsaturated Polyesters } \\
\text{ Polyesters } \\
\text{ Cured Polyester}
\end{array}
\]

\[
\begin{align*}
\text{ Monomers } & : \text{ Styrene, diallyl phthalate, methyl methacrylate, etc.} \\
\text{ Catalyst}
\end{align*}
\]

\[
\begin{align*}
\text{ Maleic anhydride} & + \text{ HOCH}_2\text{CH}_2\text{OCH}_2\text{CH}_2\text{OH} \Rightarrow \\
\text{ Unsaturated polyester}
\end{align*}
\]

Figure 1.5: Formation of unsaturated polyester (Pritchard, 1999)
Figure 1.6: Changes in the properties of thermosets at the glass transition temperature (Pritchard, 1999)
Figure 1.7: Basic reaction of epoxy group with aliphatic amines during polymerization (Pritchard, 1999)

Figure 1.8: Cross-linking reaction of unsaturated polyester (Pritchard, 1999)
Figure 1.9: Effect of post-cure on thermosets quality (Pritchard, 1999)

Figure 1.10: Schematic showing effects of degree of cure on Vinylester FRP characteristics (Karbhari, 2001)
Chapter One: Tables and Figures

Figure 1.11: Sulphur distribution in FRP after 1 month immersion in sulphuric acid (Hattori et al., 2000)

Roving    Woven Roving  Fabric    Chopped Strand Mat
(a) Uni-directional    (b) Bi-directional    c) Multi-directional

Figure 1.12: Typical forms of fiber sheets (Nicholls, 1976)

Figure 1.13: Typical stress-strain behavior of fibers (ACI, 1996)
Chapter One: Tables and Figures

Figure 1.14: A fraction of the graphite network layer
(source: http://www.psrc.usm.edu/macrog/carfib.htm)

Figure 1.15: Repeating unit of poly(paraphenylene-terephthalamide) (aramid)
(source: http://www.psrc.usm.edu/macrog/aramid.htm)

Figure 1.16: Tensile strength variation of polyester laminates with different amount of primary constituents (Rot et al., 2001)
Figure 1.17: Schematic representation of weathering factors and associated degradation mechanisms
Figure 1.18: The sunlight spectral power distribution (ASTM G151-97)

Photolysis
Absorption and excitation of binder or other film components

Energy dissipation and bond cleavage with formation of free radicals

Autooxidation
Peroxy radical formation

Peroxy radical attack on polymer chains with hydrogen abstraction to form hydroperoxide and free radical

Fragmentation of hydroperoxide by ultraviolet radiation

Embrittlement
Intercal cross linking between free radicals in adjacent chains and eventual embrittlement

Figure 1.19: Chain-scission and cross-linking of plastic under photo-oxidation (Kelen, 1984)
Chapter One: Tables and Figures

(a) Total monthly solar irradiance (wavelength = 295 to 2500 nm)

(b) Average monthly temperature of Florida

Figure 1.20: Climatic data for Florida, U.S.A. for the year 2001 (source: http://www.atlaswsg.com/weath/2001.pdf)
Figure 1.21: Natural outdoor weathering test (Wypych, 1999)

Figure 1.22: Construction of Equatorial Mount with Mirror for Acceleration (EMMA) device (Wypych, 1999)

Figure 1.23: QUV/Spray weathering tester
Figure 1.24: Tensile stress-strain curves for GFRP exposed 12 months to atmospheric conditions in Bahrain (Al-Bastaki et al., 1994)

Figure 1.25: Load-deflection response of beams before (magenta) and after (black) wetting and drying (Toutanji et al., 1997)
Chapter Two

Simulation of Tropical Climate

2.1 Characterization of Tropical Climate

Singapore lies near the Equator on latitude 1°22’N and longitude 103°55’E. The climate of Singapore is uniformly hot and humid throughout the year with very little seasonal variation in temperature. The diurnal ambient temperature range is small and the ambient temperature of areas unexposed to sunlight is rarely below 23°C or above 30°C. Being an island situated on the southern tip of the Malayan Peninsular and exposed on the eastern side to the South China Sea, it has equatorial monsoon weather.

The monsoon seasons are broadly classified as the North-East monsoon (December-March) season and the South-West monsoon (June-September) season. During these periods, the winds largely blow from the indicated directions bringing abundant rains, especially during the North-East monsoon, making it the wettest season. The inter-monsoon periods of April-May and October-November are hot and humid. Brilliant sunshine following rainfall is common during this period and the greater part of the rain falls in thunder storms of short duration. It is noted that November, December and January are the coolest period and the hottest days fall within the months of February and March (Alexander, 1959; Tan et al., 1976).

2.1.1 Solar Irradiance

The mean daily solar radiation energy received on earth surface (including UV ray, visible light and infrared ray) in each month for an eleven-year period from 1987 to 1997 in Singapore is summarized in Figure 2.1 (Meteorological Service
Comparing with that of Florida measured at 5° tilt, it is obvious that while the mean daily solar radiation dosage is comparable, the radiation is more uniform throughout the year in Singapore with no significant seasonal variation. Therefore, the photodegradation effect of sunlight is expected to last consistently throughout the year under local outdoor exposure.

2.1.2 Ambient Temperature

Figure 2.2 shows the summarized mean monthly ambient temperature in Singapore from 1987 to 1997. The temperature profile was superimposed on that of Florida for the year 2001. Similar to sunlight radiant energy, the local temperature is relatively consistent throughout the year and ranges between 25 to nearly 30°C. It is worth noting that the measured ambient temperature is always lower than that of material surface temperature due to the exclusion of infrared ray heating effect. In other words, the surface temperature of a material exposed under direct sunlight should show a higher temperature on its surface compared to that of the ambient (Tan et al, 1992).

2.1.3 Relative Humidity

Despite the high temperature, the mean daily relative humidity is constantly high. The relative humidity ranges between 95 to 100% at night and 50 to 60% at noon. On raining days, the ambient relative humidity could even reach almost 100% saturation, as depicted in Figure 2.3.
2.1.4 Rainfall

The mean monthly rainfall is shown in Figure 2.4. It is clear that the rainfall data obtained are more scattered than that of solar radiant energy and temperature for each month. However, it can be seen that the monthly rainfall ranges between 100 to 180 mm from February to October, with distinctively higher amount of rainfall for November, December and January.

By reviewing the past 11 years of metrological records of Singapore, it was found that November, December and January had about 20 rainy days per month, while the dry months of June, July and February have an average of 12 days. The relationship between the monthly rainfall and the fraction of rainy days per month was deduced and plotted in Figure 2.5.

2.1.5 Sunshine Hours

The 20-year (1967 to 1986) mean daily sunshine hour (Tan et al, 1992) is depicted in Figure 2.6. In accordance with the heavy rainfall in November and December, the sunshine hours are shortest in these two rainy months. However, on average, Singapore receives not less than 4 hours of sunshine per day throughout the year.

All the above local weather factors are summarized in Table 2.1 and form the basis of artificial weathering scheme used in this study. A review on the available commercial weathering testers showed that those testers with the capability of reproducing the effects of UV ray, heat and moisture are very limited in size and are not adequate to accommodate medium to large reinforced concrete specimens.
Therefore, a customized weathering chamber was needed for weathering test of FRP-strengthened reinforced concrete structural elements.

2.2 Weathering Chamber

A ferrocement weathering chamber, as shown in Figure 2.7, of size 1500mm × 1000mm × 700mm, was constructed in the laboratory to reproduce the weathering effects of local outdoor tropical climate. The side walls and base of the chamber were made of 30 mm thick wire mesh reinforced concrete and covered with wooden lid on top. The chamber was then placed to sit on top of a water tank, which was also made using the same material. In order to reproduce all the weather factors, the chamber was equipped with various devices, namely UV light, water pump, atomizers, ceramic heaters and thermostats.

2.2.1 UV Light

A 400 Watt high power metal halide UV-A flood light was used to reproduce the UV ray in the chamber. Figure 2.8 shows the relative spectral power distribution (SPD) of the light. The light being produced covers mainly UV-A and part of UV-B and visible light. This SPD is nearly similar to that of the florescent UV-A ray recommended by ASTM-G154-00a for artificial weathering test for plastics, as shown in Figure 2.9. The irradiance of the UV-A ray received at different distances from the light was measured using EIT™ High Energy UV Radiometer and plotted in Figure 2.10. This will be used to relate the irradiance imposed on the specimens in the chamber to the actual irradiance under outdoor exposure (Section 2.2.5).
2.2.2 Heaters

Two high power (1000 Watt) ceramic heaters were installed on the top wooden lid to raise and regulate the temperature within the chamber. The heaters were connected to and controlled by thermostats which turn on and off the power supply to the heaters by monitoring the air temperature in the chamber.

2.2.3 Water Atomizers

Water atomizers were assembled in the chamber to provide a water spraying mechanism thereby introducing the weathering and mechanical erosion effects of photo-oxidized surface materials on the specimens. The water was supplied from the water pump which drew water from the water tank underneath the weathering chamber. The flow rate was controlled by adjusting the hose valve located near the pump outlet. After the specimens were wetted, the water was recycled by flowing back to the water tank through the small opening located at the base of weathering chamber.

2.2.4 Weathering Cycle

All the above devices were connected to a switchbox and controlled by dual timers that drive the motor contactors to switch on and off the appropriate items one at a time at the pre-programmed intervals. By considering the outdoor average diurnal sun hour percentage and monthly rainfall fraction, a continuous light-wet-dark cycle was generated in the weathering chamber. In each cycle, the light period lasted for 1.5 hours, during which both the UV-A floodlight and ceramic heaters worked together to generate heat and UV-A ray that simulate the daytime weathering effects. It is then followed by 1.5 hours of wet period where the entire specimens
were wetted by water sprayed through atomizers, similar to wetting of outdoor specimens during raining time. To better simulate the outdoor temperature and humidity fluctuation, one hour of dark (that is, idle period) was employed immediately after the wet period, during which all the gadgets were switched off. Hence one complete cycle of weathering took 4 hours to complete and 6 weathering cycles can be done within a day, as shown in Figure 2.11.

### 2.2.5 Acceleration by Intensified UV-A Ray

The weathering test time can be shortened by employing significantly increased levels of irradiance and/or temperature during weathering test under simulated conditions. Boxhammer (2001) showed that intensifying the irradiance has a good proportionality between the changes in material property and the amount of radiant energy. On the other hand, acceleration through increased temperature promotes different ageing behaviors on different materials with different formulations. In view of this, weathering processes were accelerated through increased UV-A irradiance in the current weathering scheme in order to maintain the same degradation mechanism at an increased rate and to achieve a good correlation with outdoor weathering results.

Referring to Table 2.1 and assuming that 6.8% of the total solar radiance was contributed by UV-A ray (300 – 400 nm wavelength) (ASTM-G151-97 - Table 1: Spectral Global Irradiance, as shown in Appendix A), it was found that the mean daily UV-A radiance energy is equal to 6.8% of 463 or 31 mWh/cm². This amount of UV-A radiant energy was reproduced using the UV-A floodlight within the light period of 1.5 hours by placing the specimens 675 mm away from the light source,
which yields an UV-A irradiance of 20 mW/cm² or radiant energy of 30mWh/cm² on the specimen surface (refer to Figure 2.10).

### 2.3 Verification Tests

The efficiency and applicability of the artificial weathering scheme was verified by first comparing the reproduced weathering factors followed by the assessment of weathering effects on mechanical properties (that is, elastic modulus, ultimate strain and strength) of FRP tensile coupons subjected to both in-chamber and outdoor weathering exposure.

#### 2.3.1 Patterns of Weathering Factors

##### 2.3.1.1 Temperature and Humidity Measurement

As the ambient air temperature is always lower than the surface temperature of materials exposed to sunlight (Tan et al., 1992), the temperatures of chamber and outdoor were monitored in two approaches. First, the ambient air temperature in outdoor space sheltered from sunlight was measured using SK-L200TH® data logger manufactured by Sato Keiryoky Manufacturing Co. Ltd. The inner ambient temperature was then measured using the same device in the weathering chamber by blocking the probe from the radiated UV-A ray by placing a plank in between the device and the light source. This set of temperature is referred as the ambient temperature ($T_{am}$) for both exposures.

Meanwhile, Cu-Cn thermocouples were installed on the surface of bluish FRP composites that were exposed under the outdoor sunlight or UV-A ray in weathering chamber (Figure 2.12). The exposed temperature ($T_{ex}$) was measured and
captured using TML® data logger (Model TDS 303) manufactured by Tokyo Sokki Kenkyujo Co. Ltd.

As the SK-L200HT® is also capable of measuring and recording relative humidity (RH), the ambient RH was also measured and recorded together with the ambient temperature.

2.3.1.2 Outdoor Solar Irradiance Measurement

While the chamber UV-A irradiance level was known and constant, the actual outdoor UV dosage varies and needs to be monitored in order to obtain the total amount of UV energy received by the specimen during the weathering period. For the purpose of monitoring and comparison, the outdoor solar radiant energy was measured using an Eppley™ Precision Pyranometer (Model 8-48) as shown in Figure 2.13. The pyranometer integrates the radiant energy of full solar spectrum (wavelength from 300 to 2800 nm) instead of UV-A only waveband (wavelength from 320 to 400 nm). Therefore, the measured values were factored with 0.068, that is, 6.8% of the full spectral band (Appendix A), to obtain the corresponding UV-A radiant energy.

2.3.1.3 Results and Discussion

Temperature - Figure 2.14 shows the ambient temperature in the weathering chamber (T_{am,ch}) and outdoor ambient temperature (T_{am,ou}) at different times, in which 1 day in chamber is being compared to 6 days outdoors. The observed outdoor temperature was well reproduced in the chamber in terms of peak temperature level and periodical occurrences. As expected, the value of T_{am,ch} was uniform while that of T_{am,ou} was affected by rainfalls as shown by the disruption between 22^{nd} and 23^{rd}
of July 2002. It is noted that the $T_{am,ch}$ value during the dark period is slightly higher than that of $T_{am,ou}$, which is unavoidable due to heat preservation effect of concealed ferrocement walls.

On the other hand, the surface temperature of bluish FRP composite exposed under UV-A ray in chamber ($T_{ex,ch}$) and sunlight outdoors ($T_{ex,ou}$) is depicted in Figure 2.15 together with $T_{am,ou}$. It is shown that the FRP surface temperatures attained the same peak level in weathering chamber and outdoors. It is also noted that the maximum surface temperature was about 10°C higher than the ambient temperature.

Humidity - The humidity patterns for outdoors and in the weathering chamber are shown in Figure 2.16. It was found that the periodical occurrences of humidity in weathering chamber and outdoors match well with slight differences for the diurnal maximum and minimum humidity level. Comparing Figure 2.16 with Figure 2.3 reveals that the humidity level in chamber was in fact fluctuating between the mean maximum (95%) and minimum (55%) monthly relative humidity of the past 11 years. In other words, the average humidity level is being reproduced well in the weathering chamber in addition to diurnal reoccurrences in the accelerated timescale.

Solar Irradiance - The typical total solar irradiance observed in outdoor is shown in Figure 2.17. The peaks of the irradiance occurred at noon time and were lower during rainfall, as observed during the noon time of 22nd and 23rd of July 2002. The irregularities of the irradiance level were due to the effect of clouds which caused overcast. The total UV-A energy per day was calculated by first integrating
numerically the area under the irradiance curves and then factored with 0.068. The cumulative outdoor UV-A energy for 180 days is shown in Figure 2.18 with crosses. On the other hand, the cumulative chamber UV-ray energy was plotted as a straight line in the same figure on one-sixth the timescale for outdoor exposure; it takes the form

\[ E_{\text{UV-A}}(t_{\text{ch}}) = 180t_{\text{ch}} \]  

in which \( t_{\text{ch}} \) = chamber elapsed time (day), as the chamber UV-A irradiance was 180 mWhr/cm\(^2\)/day (that is 20 mW/cm\(^2\)/hr \times 9 hours of light periods per day). It is clear that the UV-A dosage in the controlled chamber environment reproduced 6 times that of outdoor sunlight reasonably well.

### 2.3.2 Weathering Effects on FRP Tensile Coupons

#### 2.3.2.1 Materials

In order to have significant changes in properties in the shortest possible time, the relatively less durable glass fiber was chosen for study in the validation of the effectiveness of the weathering chamber. Two types of E-glass fiber reinforced polymer (GFRP) systems, denoted as G1 and G2, were used in the verification test. System G1 consisted of uni-directional roving fiber sheet impregnated with bluish two-part amine-cured epoxy resin, whereas G2 consisted of bi-directional woven roving fiber sheet impregnated with clear unsaturated polyester resin. The detail as-received material properties of fiber and resin for G1 and G2 are tabulated in Table 2.2.
2.3.2.2 Fabrication of Tensile Coupons

GFRP tensile coupons were fabricated using the G1 and G2 composites in accordance with JSCE-E-541 (2000) test method. The continuous fiber sheet was first cut into the appropriate size of about 700mm × 400mm. To facilitate cutting of strips from the plates, three bundles of fibers were removed in between the test pieces, which left gaps that can be chopped and trimmed without breaking the resin-embedded fibers (Figure 2.19 (a)). The sheet was placed on a steel mould which was pre-laid with a plastic sheet that had been wetted with resins (Figure 2.19 (b)). The steel plate was used as the base to ensure the evenness and flatness of the final product, while the plastic sheet was required to make separation of FRP plates from the mould easier after it has hardened. The fiber sheet was then pressed and rolled with grooved roller to ensure the resin between the fiber sheet and the pre-laid plastic sheet impregnated thoroughly into the fiber bundles. Another topcoat of resin was applied evenly while maintaining the fiber axis in straight line. It was then followed by laying a second piece of plastic sheet onto the fiber sheet. The air voids that were trapped in the resin were squeezed out using a grooved roller in the fiber direction before a few pieces of wood were placed on top of the fully saturated fiber sheet (Figure 2.19 (c)). The plate was then left to cure in the ambient laboratory condition for 1 day and demoulded.

The finished composite plates were trimmed to a size of about 250 mm in length and 80 mm in width for G1 and G2 specimens as shown in Figure 2.20, in which five tensile strips can be further cut out post to weathering exposure. All the plates were allowed to continue to cure under ambient condition in the laboratory for at least two weeks before being subjected to weathering tests.
2.3.2.3 Weathering of Specimens

The tensile coupons were divided into two series. The first series, denoted as OC-G1 for G1 and OC-G2 for G2 was exposed at the rooftop of Engineering Workshop 1 of Department of Civil Engineering, National University of Singapore (Figure 2.21). The coupons were weathered for 0, 1, 3, 6, 9 and 12 months prior to tensile tests. On the other hand, the second series was put inside the weathering chamber for 5, 15, 30, 45 and 60 days and denoted as CC-G1 and CC-G2 for G1 and G2 tensile coupons respectively.

2.3.2.4 Test Setup and Instrumentation

After the weathering tests, five strips of FRP tensile coupons were cut and trimmed from the FRP plates and tabbed with aluminum pieces at both ends and strain gauges at the middle one day before the tensile test, as shown in Figure 2.22. The specimens were then quasi-statically tensioned up to failure at 1% strain rate, that is, 1 mm/min for the effective gauge length of 100 mm of the specimens, using 500 kN Instron® Universal Tester. The typical test setup is shown in Figure 2.23.

It is worth noting that, due to the technical difficulties encountered during the first two batches of tensile tests, the strain gauges were later replaced with an extensometer for strain measurement and the results were found to be coherent.
2.3.2.5 Test Results and Discussion

General

Upon the completion of the respective weathering programs, the FRP plate specimens were removed from the weathering chamber and outdoor exposure site and visually inspected for changes in their colors and surface appearances. For all OC-G1 weathered up to 1 year (OC-G1-1y) and CC-G1 weathered up to 2 months (CC-G1-2m), the original bluish color of epoxy faded and the plate surfaces lost their gloss. The epoxy on the surface has deteriorated and was washed away due to the weathering effects, revealing the originally embedded whitish E-glass fibers, as shown in Figure 2.24. Meanwhile, the translucent polyester resin turned whitish and the surface texture became powdery for OC-G2-1y and CC-G2-2m. Similar to G1 plates, the bi-directional E-glass fibers were also exposed after the plate loses its surface polyester resin, as shown in Figure 2.25.

Of all the different series of specimens before and after weathering exposure, OC-G1 and CC-G1 coupons typically ruptured with longitudinal splits between unidirectional fibers roving (Figure 2.27) whereas OC-G2 and CC-G2 coupons ruptured with cracks perpendicular to direction of tensile load (Figure 2.28). The rupture patterns of outdoor and chamber exposed coupons did not differ with respect to exposure time.
Tensile Characteristics

The measured ultimate strains, elastic modulus and ultimate stress of OC-G1, CC-G1, OC-G2 and CC-G2 coupons are depicted in Figures 2.29, 2.30 and 2.31 respectively at different time scales, of which 1 day in chamber corresponds to 6 days outdoors. The outdoor- and chamber-weathered specimens were plotted with solid circles and checked boxes, respectively. The measured values were also regressed linearly on the logarithmic time scales to obtain the regressed FRP property functions for ultimate strains, elastic modulus and tensile strength.

Ultimate strain – From the regressed FRP ultimate strain functions, that is \( \varepsilon_{\text{pu,G1}}(t_{\text{ou}}) \) and \( *\varepsilon_{\text{pu,G1}}(t_{\text{ch}}) \), it is obvious that the ultimate strain of G1 coupons dropped after outdoor and chamber exposure, and the deterioration rates were close to each other (Figure 2.29 (a)), which signified the embrittlement of G1 coupons after the weathering process. On the other hand, no significant variations were observed for G2 coupons in terms of ultimate strains for both outdoor and chamber exposure [\( \varepsilon_{\text{pu,G2}}(t_{\text{ou}}) \) and \( *\varepsilon_{\text{pu,G2}}(t_{\text{ch}}) \) in Figure 2.29 (b)].

Elastic Modulus - Contrary to ultimate strain, the elastic modulus for OC-G1 and CC-G1 remained unchanged post to weathering test as indicated by the regressed elastic modulus functions \( E_{p,G1}(t_{\text{ou}}) \) and \( *E_{p,G1}(t_{\text{ch}}) \) in Figure 2.30 (a), but reductions were observed for OC-G2 and CC-G2 [\( E_{p,G2}(t_{\text{ou}}) \) and \( *E_{p,G2}(t_{\text{ch}}) \) in Figure 2.30 (b)]. This is probably because the less water-resistant ortho polyester was used and greater plasticization (i.e. reduction of polymer elastic modulus under the action of weathering effects) took place for G2 resin matrix in both the outdoor and chamber weathering conditions.
**Tensile Strength** - It is clear that both the outdoor and chamber weathering conditions caused the same strength reduction levels in G1 and G2 coupons up to 1 year (or equivalent) of weathering. By superimposing the product of strain and modulus function, that is \( \varepsilon_{pu,G1}(t_{ou})E_{p,G1}(t_{ou}) \); \( \varepsilon_{pu,G2}(t_{ou})E_{p,G2}(t_{ou}) \); \( \varepsilon_{pu,G1}(t_{ch})E_{p,G1}(t_{ch}) \) and \( \varepsilon_{pu,G2}(t_{ch})E_{p,G2}(t_{ch}) \), and the regressed tensile test results for G1 and G2 (that is, \( f_{pu,G1}(t_{ch}) \) and \( f_{pu,G2}(t_{ch}) \)) in Figure 2.32, it is evident that both the results matched well.

**Residual Tensile Strength**

The variations in GFRP tensile strength for G1 and G2, \( \phi_{f_{pu,G1}} \) and \( \phi_{f_{pu,G2}} \), were obtained based on the regressed GFRP tensile strength functions obtained from accelerated weathering test, which take the form of

\[
\phi_{f_{pu,G1}} = \frac{f_{pu,G1}(t_{ou})}{f_{pu,G1}(1)}
\]

for G1, and

\[
\phi_{f_{pu,G2}} = \frac{f_{pu,G2}(t_{ou})}{f_{pu,G2}(1)}
\]

for G2, where \( k_a \) is the assumed acceleration factor of 6.

The functions are plotted in Figure 2.33. It is deduced that both G1 and G2 will lose half of its original strength after exposing directly in outdoor tropical climate for 6 years. Further exposure up to 50 years could even result in 70%
strength reduction. Comparing to the various proposed environmental reduction factors (Byars et al., 2001), such reduction apparently exceeded most of the proposed reduction factors for GFRP, as extracted and shown in Table 2.3.

The test results showed that the GFRP composites may deteriorate severely within a short period of time when exposed directly to synergistic effects of heat, UV and rain. It is therefore recommended that GFRP composites, when used outdoor, should be properly shielded by applying additional layer of non-polymeric coating which can effectively prevents the UV and rain from reaching resin surface of GFRP composites.

2.4 Summary

From the comparison of weathering parameters and the time-dependent tensile characteristic variations of G1 and G2 composites weathered outdoor and in chamber, it is clear that the artificial weathering scheme employed had successfully reproduced all the outdoor weathering factors. The presumed acceleration factor of 6 is verified and the acceleration seemed to induce the same degradation mechanisms for chamber and outdoor-weathered FRP composites of different types.

The test results also suggested that the tropical climatic exposure causes strength reduction in GFRP. It is forecasted that both the E-glass reinforced composite may lose up to 70% of their original tensile strength after exposing for 50 year under tropical climate, an amount which is substantially higher than that of the environmental reduction factors proposed currently by various institutions.
### Table 2.1: Outdoor weathering factors for Singapore (1987-1997)

<table>
<thead>
<tr>
<th>Weathering Factor</th>
<th>Yearly</th>
<th>Monthly</th>
<th>Daily</th>
</tr>
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<tbody>
<tr>
<td>Total Solar Radiance Energy (mWh/cm²)</td>
<td>Mean</td>
<td>13875.90</td>
<td>462.53</td>
</tr>
<tr>
<td>Rainfall (mm)</td>
<td>Mean</td>
<td>2044.80</td>
<td>170.40</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>Average</td>
<td>27.47</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>33.50</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>23.40</td>
<td>--</td>
</tr>
<tr>
<td>Relative Humidity (%)</td>
<td>Average</td>
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<td>--</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>98.70</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>54.10</td>
<td>--</td>
</tr>
<tr>
<td>Sunshine</td>
<td>Max hours</td>
<td>--</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>%</td>
<td>--</td>
<td>34</td>
</tr>
<tr>
<td>Rainfall &quot;a&quot;</td>
<td>%</td>
<td>48</td>
<td>--</td>
</tr>
</tbody>
</table>

"a Calculated using average rainfall of 170.40 mm and cross-referred with Figure 2.5"
<table>
<thead>
<tr>
<th></th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manufacturer</strong></td>
<td>Master Builder Technology</td>
<td>Singapore High Polymer Co.</td>
</tr>
<tr>
<td><strong>Fiber Type</strong></td>
<td>E-Glass</td>
<td>E-Glass</td>
</tr>
<tr>
<td><strong>Sheet form</strong></td>
<td>Unidirectional roving</td>
<td>Bidirectional woven roving</td>
</tr>
<tr>
<td><strong>Tensile strength (MPa)</strong></td>
<td>1700</td>
<td>130</td>
</tr>
<tr>
<td><strong>Elastic Modulus (GPa)</strong></td>
<td>71</td>
<td>11</td>
</tr>
<tr>
<td><strong>Ultimate strain (%)</strong></td>
<td>2.0</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>Fiber areal density, ω (g/m²)</strong></td>
<td>900</td>
<td>800</td>
</tr>
<tr>
<td><strong>Fiber density, ρ (g/m³)</strong></td>
<td>2.58 x 10⁶</td>
<td>--</td>
</tr>
<tr>
<td><strong>Nominal thickness, ω/ρ (mm)</strong></td>
<td>0.353</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Resin Type</strong></td>
<td>Two part, 100% solid, low viscosity amine-cured epoxy</td>
<td>Pre-accelerated, non-waxed, quick-cured and anti sagging orthophthalic unsaturated polyester</td>
</tr>
<tr>
<td><strong>Tensile strength (MPa)</strong></td>
<td>54</td>
<td>30</td>
</tr>
<tr>
<td><strong>Elastic modulus (GPa)</strong></td>
<td>3</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Ultimate strain (%)</strong></td>
<td>2.5</td>
<td>4.4</td>
</tr>
<tr>
<td><strong>Primer</strong></td>
<td>Applicable</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

*b Based on manufacturers’ product specifications*
Table 2.3: Environmental tensile strength reduction factors for GFRP (Byars et al., 2001)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Concrete Institute (ACI)</td>
<td>0.70 – 0.80</td>
</tr>
<tr>
<td>British Institution of Structural Engineers (BISE)</td>
<td>0.30</td>
</tr>
<tr>
<td>Norwegian Standard (NS3473)</td>
<td>0.50</td>
</tr>
<tr>
<td>Canadian Highway Bridge Design Code (CHBDC)</td>
<td>0.75</td>
</tr>
<tr>
<td>Japanese Society of Civil Engineer (JSCE)</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Figure 2.3: Singapore (from 1987 to 1997) mean monthly relative humidity (Meteorological Service Singapore, 1987-1997)

Figure 2.4: Singapore (from 1987 to 1997) monthly rainfall (Meteorological Service Singapore, 1987-1997)
Figure 2.5: Fraction of raining days per months with respect to average monthly rainfall (Meteorological Service Singapore, 1987-1997)

Figure 2.6: Mean daily sunshine hours in Singapore (Tan et al., 1992)
Figure 2.7: Construction of ferrocement weathering chamber

- UV Light
- Ceramic heaters
- Thermostats
- Atomizers
- Water tank
- Wooden Lid
- Weathering Chamber

All dimensions in mm

PLAN

FINAL CONSTRUCTION

FRONT

SIDE

Water pump
Figure 2.8: Spectral power distribution of metal halide UV-A floodlight

Figure 2.9: Spectral power distribution of sunlight and florescent UVA-340 lamp (ASTM-G154-00a) for artificial weathering
$y = 59885x^{-1.2235}$
$R^2 = 0.9941$

Figure 2.10: Measured UV-A ray irradiance level on exposed surface with respect to distance from light source

Figure 2.11: Artificial weathering cycles within a day
Figure 2.12: Thermocouple wires attached on FRP composite surface for outdoor material surface temperature measurement

Figure 2.13: Pyranometer for total outdoor solar radiation measurement
Figure 2.14: Outdoor and weathering chamber ambient temperature

Figure 2.15: FRP surface temperature exposed under UV-A in chamber and sunlight outdoors
### Chapter Two: Tables and Figures

#### 2.16 Ambient relative humidity - outdoor and in weathering chamber

![Graph](image)

*Figure 2.16: Ambient relative humidity - outdoor and in weathering chamber*

#### 2.17 Outdoor total diurnal solar irradiance

![Graph](image)

*Figure 2.17: Outdoor total diurnal solar irradiance*
Figure 2.18: Cumulative equivalent solar UV-A and chamber UV-A dosage
(a) Gap in between test piece for chopping and trimming of tensile coupons

(b) Steel base pre-laid with plastic sheet and wetted with resin

(c) Placing weight on top of assembly before hardening of resin took place

Figure 2.19: Fabrication of FRP composite tensile coupons
Figure 2.20: G1 and G2 tensile coupons for weathering test

Figure 2.21: Outdoor exposure of G1 and G2 tensile coupons
Figure 2.22: Typical G1 and G2 tensile coupons with strain gauges

Figure 2.23: Typical test setup for G1 and G2 tensile coupon test
Figure 2.24: Surface conditions of ambient, outdoor and chamber exposed G1 plates

Figure 2.25: Surface conditions of ambient, outdoor and chamber exposed G2 plates
Figure 2.27: Failure of G1 tensile coupon by lateral splitting in between fiber bundles

Figure 2.28: Failure of G2 tensile coupons by transverse cracks
Chapter Two: Tables and Figures

Figure 2.29: Ultimate strain variations of G1 and G2 for outdoor and chamber weathering
Figure 2.30: Elastic modulus variations of G1 and G2 for outdoor and chamber weathering
**Figure 2.31: Strength variations of G1 and G2 for outdoor and chamber weathering**

(a) OC-G1 and CC-G1

\[ f_{pu,G1}(t_{ch}) = 395 - 63 \log(t_{ch}) \quad [R^2 = 0.78] \]

\[ f_{pu,G1}(t_{ou}) = 460 - 65 \log(t_{ou}) \quad [R^2 = 0.78] \]

(b) OC-G2 and CC-G2

\[ f_{pu,G2}(t_{ch}) = 234 - 46 \log(t_{ch}) \quad [R^2 = 0.73] \]

\[ f_{pu,G2}(t_{ou}) = 240 - 35 \log(t_{ou}) \quad [R^2 = 0.77] \]
Figure 2.32: Strength variation of G1 and G2 as a result of decrease in $E_p$ and $\varepsilon_{pu}$

(a) Type G1

(b) Type G2
Figure 2.33: Deduction of residual strength of G1 and G2 composite
Chapter Three

Time-Dependent Behavior of FRP-strengthened Beams

3.1 General

External strengthening of reinforced concrete beams with FRP plate-sheet increases the ultimate moment capacity and flexural stiffness while decreasing the total deflection at failure. The short-term ultimate flexural strength of a FRP-strengthened beam can be predicted conveniently by using principles of compatibility of deformations and equilibrium of forces with appropriate material constitutive laws for concrete, steel and FRP (Chaallal et al., 1998; Wang et al., 2003).

Addition of FRP laminates to the beams also alters the failure modes, which include: (i) compression crushing of concrete, (ii) rupture of FRP, (iii) debonding of FRP at cut-off point, (iv) delamination of concrete layer along rebar, (v) peeling of FRP at shear-induced cracks and (vi) shear failure, depending on the FRP-to-steel reinforcement ratio, existing amount of shear reinforcements, crack configuration prior to strengthening, laminate length, relative laminate / adherent / concrete stiffness, and others (Buyukozturk et al., 1998). The failure modes of retrofitted beam are depicted in Figure 3.1.

Shearing of beam, rupturing and debonding of FRP reinforcement at cut-off point are brittle and catastrophic. Therefore, it is preferable to design and strengthen a beam to fail by crushing of concrete (Chaallal et al., 1998; Arya et al., 2002). However, when FRP laminates were simply bonded at the beam soffit, Bonacci et al. (2001) found that failures by debonding of FRP and other failure modes were more prevalent even where the retrofitted beams were predicted to fail by compressive
crushing of concrete, as shown in Figure 3.2. To prevent such premature failures, anchorages at the cut-off point and along the FRP laminates (Figure 3.3) were provided to effectively enhance the strengths of FRP-concrete bond and beam shear capacity up to the designated ultimate loads and failure modes (Spadea et al., 1998).

### 3.2 Proposed Model

With proper anchorage at the sheet/plate cut-off points at beam ends including the use of adequate transverse reinforcement, failure modes of beams strengthened with FRP laminates can be reduced to (i) compression crushing of concrete, (ii) rupture of FRP and (iii) debonding of FRP near flexural cracks vicinity, as depicted in Figure 3.4. However, as the engineering properties of FRP changes under the effects of outdoor weathering (Section 2.3.2.5), alteration in the original beam failure mode and moment capacity over time is conceivable.

In this study, an analytical model is proposed to predict the time-dependent variation in failure modes and ultimate loads of reinforced concrete beams externally strengthened with FRP under the effects of tropical weathering. This model considered the three major failure modes of compression crushing of concrete, rupture of FRP and debonding of FRP at flexural cracks vicinity. This model is based on the strain compatibility and force equilibrium and incorporates the time-dependent engineering properties of FRP.

#### 3.2.1 Assumption

The main assumptions considered in the analytical model for the section at ultimate are:
Chapter Three: Time-Dependent Behavior of FRP-strengthened Beams

1. plane section remains plane under bending. Consequently, a linear strain
distribution exists across the concrete section up to ultimate limit state,

2. perfect bond exists between concrete and steel reinforcements, and between
concrete and FRP reinforcement. As a result, any strain change in the
longitudinal steel/FRP reinforcement is equal to that in the concrete at the same
level as the steel/FRP reinforcement under a given change in the applied load,

3. tensile force of concrete is negligible and can be ignored, and

4. the material constitutive relations for concrete, steel and FRP are idealized as
shown in Figure 3.5.

3.2.2 Failure Mode and Flexural Capacity

3.2.2.1 Flexural Analysis

Referring to Figure 3.6, the internal resisting moment of the beam at failure
can be calculated as

\[ M_u = A_p \varepsilon_p E_p \left( d_p - \bar{x} \right) + A_s \varepsilon_s E_s (d_s - \bar{x}) - A_s' \varepsilon_s' E_s' (d_s' - \bar{x}) \]  

(3.1)

where \( A_p \), \( A_s \) and \( A_s' \) = area of FRP, tensile and compressive steel reinforcement, respectively; \( E_p \), \( E_s \) and \( E_s' \) = modulus of FRP, tensile steel reinforcement and compressive steel reinforcement, respectively; \( \varepsilon_p \), \( \varepsilon_s \) and \( \varepsilon_s' \) = strains in FRP, tensile steel reinforcement and compressive steel reinforcement, respectively; \( d_s \) and \( d_s' \) = distance from the top concrete fiber to the centroid of the tensile steel reinforcement and compressive steel reinforcement, respectively; \( c \) = neutral axis;
\( \bar{x} \) = location of resultant compressive force with respect to extreme top concrete
fiber; \( b \) = beam width, \( h \) = beam depth (= distance from the top concrete fiber to the
Chapter Three: Time-Dependent Behavior of FRP-strengthened Beams

centroid of FRP reinforcement, \( d_p \). For tensile and compressive steel reinforcement, \( \varepsilon_s E_s \) and \( \varepsilon'_s E'_s \) are taken to be less than \( f_{sy} \) and \( f_{sy}' \), that is, the yield stress of tensile and compressive reinforcement, respectively. \( f_c(x) \) = concrete stress which is modeled as Hognestad stress-strain curve taking the form of

\[
f_c(x) = f'_c \left[ 2 \left( \frac{\varepsilon_c(x)}{\varepsilon_{co}} \right) - \left( \frac{\varepsilon_c(x)}{\varepsilon_{co}} \right)^2 \right]
\]  

(3.2)

where \( \varepsilon_c(x) \) = the corresponding concrete strain at distance \( x \) away from the neutral axis, \( \varepsilon_{co} \) = the concrete strain corresponding to a concrete stress equaled to the concrete cylinder compressive strength, \( f_c' \) (MPa), which is assumed to be 0.002 as shown in Figure 3.5 (c).

The beam moment capacity corresponding to concrete crushing (\( M_{cc} \)) and FRP rupture (\( M_{fr} \)) can be found by substituting values for \( \varepsilon_c \) or \( \varepsilon_p \), that is,

\[
\varepsilon_c = \varepsilon_{cu} \text{ for concrete crushing}
\]  

(3.3)

or

\[
\varepsilon_p = 0.8 \varepsilon_{pu} \text{ for FRP rupture}
\]  

(3.4)

where \( \varepsilon_{cu} \) and \( \varepsilon_{pu} \) are the ultimate compressive strain of concrete (taken as 0.003) and ultimate tensile strain of FRP laminates respectively, then solving numerically other terms by iteration until the following equilibrium condition is achieved

\[
b \int f_c(x) dx + A_s \varepsilon_s E_s' = A_c \varepsilon_c E_c + A_p \varepsilon_p E_p
\]  

(3.5)
The coefficient of 0.8 in Eq. (3.4) accounts for the average lower strains of FRP rupturing when bonded to beams compared to strains measured from material tensile test (Bonacci et al., 2001).

To predict the moment capacity due to flexural crack induced debonding \( (M_{db}) \), the associated strain in FRP laminates can be taken as (Teng et al., 2002)

\[
\varepsilon_p = \varepsilon_{pdb} = \frac{\sigma_{dbic}}{E_p} = \frac{\alpha \beta_p \beta_L}{E_p} \sqrt{\frac{E_p f'_{c}}{t_p}}
\]

(3.6)

in which, \( \varepsilon_{pdb} \) = FRP debonding strain; \( \alpha \) = calibration factor (taken as 1.1); \( E_p \) = modulus of FRP; \( f'_{c} \) = concrete cylinder compressive strength; \( t_p \) = thickness of FRP laminates; and \( \beta_p \) = bond width coefficient and \( \beta_L \) = bond length coefficient, defined respectively as

\[
\beta_p = \sqrt{\frac{2 - \frac{w_p}{b}}{1 + \frac{w_p}{b}}}
\]

(3.7a)

\[
\beta_L = \begin{cases} 
1 & \text{if } L \geq L_e \\
\sin \left( \frac{\pi L}{2 L_e} \right) & \text{if } L < L_e 
\end{cases}
\]

(3.7b)

where \( w_p \) = width of FRP laminates; \( b \) = beam width; \( L \) = bond length and \( L_e \) = effective bond length taken as

\[
L_e = \frac{E_p f'_{c}}{f'_{c}}
\]

(3.7c)
The final failure mode and ultimate beam capacity are then determined from the minimum moment capacity of all the three failure modes, that is,

\[ M_u = \min(M_{cc}, M_{fr}, M_{db}) \]  

(3.8)

where \( M_{cc} \) = moment capacity corresponding to concrete crushing, \( M_{fr} \) = moment capacity corresponding to GFRP rupture and \( M_{db} \) = moment capacity corresponding to debonding of FRP.

3.2.2.2 Time-dependent Behavior

To predict the time-dependent beam capacity and failure mode, the properties of internal steel reinforcement and concrete are assumed unchanged since the former is protected by concrete while the latter gained most of its strength with good initial curing and is not susceptible to moisture, heat and UV. Therefore, the variation in the failure modes and moment capacity is associated with changes in GFRP laminates properties. With adequate outdoor or well represented accelerated weathering test data, the time-dependent FRP properties can be expressed as

\[ Q(t_{ou}) = \phi_p(t_{ou}) P_o \]  

(3.9)

where \( P_o \) is the initial property (for example, the as-received material engineering properties), \( \phi_p(t_{ou}) \) is the material property variation function and \( Q(t_{ou}) \) is the predicted property at time corresponding to outdoor age, \( t_{ou} \). The property variation function can be derived from regression function of outdoor weathering data, that is,
\[ \phi_p(t_{ou}) = \frac{P(t_{ou})}{P(t_i)} \quad (3.10a) \]

where \( P(t_{ou}) \) is the regressed material property function from outdoor weathering tests, and \( t_i \) is the age where no weathering effects have taken place on the material properties. If regression is obtained from artificial weathering test data with an acceleration factor of \( k_a \), then Eq. (3.10a) becomes

\[ \phi_p(t_{ou}) = \frac{\ast P\left(\frac{t_{ou}}{k_a}\right)}{\ast P(t_i)} \quad (3.10b) \]

where \( \ast P \) is the regressed material property function based on accelerated weathering tests and \( \frac{t_{ou}}{k_a} \) is equivalent to the chamber age, \( t_{ch} \). With the above considerations, the beam capacity and failure mode after a period of weathering can be estimated from Eq. (3.1) by incorporating Eq. (3.10), with Eq. (3.3), (3.4) and (3.6) taking the form

- Concrete crushing (at age \( t_{ou} \)):
  \[ \varepsilon_c(t_{ou}) = \varepsilon_{cu} \quad (3.11a) \]

- GFRP rupture (at age \( t_{ou} \)):
  \[ \varepsilon_p(t_{ou}) = 0.8 \phi_{\varepsilon_p}(t_{ou}) \varepsilon_{pu} \quad (3.11b) \]

- GFRP debonding (at age \( t_{ou} \)):
  \[ \varepsilon_p(t_{ou}) = \phi_{\varepsilon_{pdb}}(t_{ou}) \varepsilon_{pdb} \quad (3.11c) \]

where \( \phi_{\varepsilon_p}(t_{ou}) \) = residual ultimate strain of FRP at outdoor age \( t_{ou} \) and \( \phi_{\varepsilon_{pdb}}(t_{ou}) \) = residual bond strength of FRP-concrete interface at outdoor age \( t_{ou} \). Also, the FRP laminates modulus in Eq. (3.1) is taken as
Chapter Three: Time-Dependent Behavior of FRP-strengthened Beams

\[ E_p(t_{ou}) = \phi_{E_p}(t_{ou}) E_p \]  \hspace{1cm} (3.12)

where \( \phi_{E_p}(t_{ou}) \) = residual modulus of FRP at outdoor age \( t_{ou} \).

3.3 Test Program

Forty-eight reinforced concrete beam specimens were prepared to verify the validity of the proposed model. Some of them were strengthened with G1 or G2 composites that were being used in the weathering tests in Section 2.3.2. Each group of these beams was further divided into three series, and each series was subjected to different exposure conditions, to investigate, verify and predict the time-dependent flexural behavior of the FRP-strengthened beams.

3.3.1 Specimen Designation

The overall test matrix is shown in Table 3.1. The beams were labeled using the format of “Series-Type-Duration”. There were three series of beam based on their weathering conditions, namely ambient (not subjected to any weathering factors), outdoor and artificial in-chamber weathering scheme of Chapter 2 (denoted as “AB”, “OB” and “CB”, respectively). Of each series, there were three types of beams which were denoted as “C” (unstrengthened control beam), “G1” (strengthened with G1 composite) and “G2” (strengthened with G2 composite). The durations of weathering exposure prior to flexural tests were indicated by a number followed by a postfix of “d”, “m” or “y” which stands for days, months or years, respectively. Therefore, specimen labeled as CB-G2-15d represents a specimen strengthened with G2 composite and subjected to in-chamber weathering...
for 15 days before flexural test. It is worth noting that to facilitate calculation and recording, 30 days are considered to be equivalent to 1 month in this study.

### 3.3.2 Specimen Details

The dimensional and reinforcement details of the beam specimens are depicted in Table 3.2. The steel reinforcement ratio was chosen to be within the minimum and maximum limit for an under-reinforced beam, that is minimum ratio of $\rho_{\text{min}} = 1.4/460 = 0.003$ and the maximum reinforcement ratio of $\rho_{\text{max}} = 0.75\rho_b$, where $\rho_b$ is the balanced steel ratio, (ACI, 2002). All the beams were over-reinforced in shear to prevent shear failure due to increased shear capacity of the strengthened beams.

For group G1 and G2 beams, a layer of G1 and G2 composite were bonded to the soffit of the beams, respectively, to enhance the flexural capacity. In addition, carbon fiber sheets (CFS) were wrapped at the GFRP cutoff points to prevent premature delamination.

In order to achieve similar strengthening ratio, the G1 composite was bonded over half the width of the beams where G2 was bonded for the full width of the beam. It was expected that the amount of G1 and G2 bonded would cause the specimens to fail by compressive crushing of concrete prior to weathering tests.
3.3.3 Material Properties

**Concrete** - A low strength concrete was preferred as the concrete strengths of most deteriorated structures are low in nature. The DOE method (BRE 1998) was used to design the concrete mix targeted for a 28 days cube compressive strength of 30 MPa. A mix proportion of 1:2.33:3.49:0.8 (by weight of ordinary Portland cement; natural sand; 10 mm crushed granites and water) was adopted for all the specimens. It was found that the concrete strength of weathered specimen increased at different magnitudes with respect to the exposure conditions and age. The mean concrete cube compressive strength, $f_{cu}$, attained after weathering exposures is tabulated in Table 3.3.

The Young’s modulus of the concrete, $E_c$, were estimated as (ACI 318, 2002)

$$E_c = 4730\sqrt{f_c'}$$

(3.13)

where $f_c' = \text{concrete cylinder compressive strength}$, which is taken to be 0.8 times to that of $f_{cu}$.

**Steel Reinforcement** - Round smooth mild steel bars were used as the compressive reinforcement while deformed high yield steel bars were used as the tensile reinforcement. Tensile tests were carried out on three specimens for each type of the steel reinforcement, and the results are presented in Figure 3.7.

**Glass Fiber Reinforced Polymer (GFRP)** - The individual fiber and resin properties of G1 and G2 supplied by the manufacturers are tabulated in Table 2.2 and
described in Section 2.3.2.1. On the other hand, the mechanical properties of G1 and G2 laminates obtained by testing GFRP tensile coupons are shown in Table 3.4. The ultimate stress, $f_{pu}$, and elastic modulus, $E_p$, were calculated based on gross laminate area, $A_p$.

### 3.3.4 Fabrication

The reinforcement cages were first fabricated before strain gauges were mounted, as shown in Figure 3.8. The cages were then placed in the wooden moulds sitting on plastic spacers that maintain a uniform concrete cover of 15 mm around the steel reinforcements.

Concrete mix was prepared in the laboratory and cast into the moulds followed by adequate compaction of concrete using the vibration table. Three 100 mm concrete cubes were cast together for each batch of concrete to assess the cube compressive strength.

The specimens were removed from the mould 24 hours after casting and put into water tank for additional curing up to 7 days. Specimens were removed from water and two-third of them was mechanically ground on the soffit for GFRP bonding. All the specimens were kept in the laboratory and allowed to dry completely before GFRP laminates were bonded at the soffit and wrapped with CFS at the cut-off points. For G1-bonded specimens, a layer of primer was first applied on the beam soffit before the laminates were bonded to conform to the application specification.

All the specimens were left in the laboratory to cure for another 7 days before being subjected to the designated exposure conditions.
3.3.5 Exposure Conditions

Specimens of Series AB were kept in the laboratory premises from any harsh environmental effects. Series OB were placed outdoors and subjected to natural weathering effects whereas Series CB were weathered in the in-house weathering chamber, as shown in Figure 3.9 (a) and (b) respectively. The specimens were overturned so that the GFRP laminates were faced towards the incident sunlight or UV ray to receive maximum weathering effects.

3.3.6 Test Setup and Instrumentation

At the end of each designated weathering period, the specimens were tested in 4 points bending using Instron® universal testing machine with a constant cross-head speed of 0.3 mm/min up to failure. Strain gauges were mounted on both the top concrete compressive fiber and on the surface of GFRP laminate to measure the associated strains at each load level. The mid-span deflection was monitored by a Linear Variable Displacement Transducer (LVDT) placed underneath the center of the specimen, as illustrated in Figure 3.10. Crack widths were measured in the pure moment zone and shear span of the specimens at 5 kN interval using a crack microscope.
3.4 Test Results and Discussion

3.4.1 Visual Inspection on GFRP Laminates

The surfaces of the G1 and G2 laminate on all the beam specimens were visually inspected and some are shown in Figure 3.11 and Figure 3.12. Both the observed aesthetical changes in G1 and G2 laminates of OB specimens are similar to that of the G1 and G2 tensile coupons described in Section 2.3.2.5.

In general, no changes were observed on G1 and G2 laminates of AB specimens, as all the AB specimens were kept in indoors and were not subjected to any active weathering factors.

In case of Series OB specimens, the bluish color of G1 laminates faded and the resin charked after being exposed up to 6 months outdoors. Whereas for G2 laminates, yellowing and chalking of the translucent G2 laminate were noticeable. The chalking of resin caused a small amount of the E-glass fibers to be exposed on the G1 and G2 laminates surface in 1-year-old specimens.

Due to the intensified weathering effects, the G1 and G2 laminates of CB series exhibited color changes and chalking more rapidly than their OB counterparts. Prominence of E-glass fibers on the G1 and G2 laminate were noticeable even only after 2 month of weathering in the chamber. Due to the constant repetitive water sprays, the whitish chalked layer were effectively washed away thus leaving a relatively “clean” appearance of the laminates as compared to OB specimens.

The similar variations in laminate surface appearance in OB and CB further increase the confidence in predicting the outcomes of outdoor weathering on FRP composite based on chamber weathering test. From the 6- and 12-month-old CB specimens, it was suggested that the laminates will continue to loss their surface
resin under the action of outdoor weathering factors and completely exposed the whitish E-glass fibers after 6 years of continuous outdoor direct exposure to tropical weathering factors, as shown in the lower right photos in Figures 3.11 and 3.12. It is worth noting the fibers were still adhered to the concrete beam even they were completely exposed, as the layer of resin in between the concrete and fibers was shielded from weathering effects by the exposed E-glass fibers.

### 3.4.2 Ultimate Load and Failure Mode

The load-deflection curves of Type C, G1 and G2 specimens are characterized by 4 regimes as depicted in Figure 3.13, that is: (a) pre-crack regime (O-C); (b) post-crack regime (C-Y); (c) post-yield regime (Y-F) and (d) post-peak regime (F-B or F-B’).

**Type C Specimens** – The load-deflection curves and appearance for failed specimens after various exposure periods are shown in Figures 3.14 and 3.15, respectively, and the ultimate loads, $P_u$, and failure modes are tabulated in Table 3.5. In general, no significant differences were observed for all the beams of Series AB, OB and CB in terms of ultimate load and failure mode. All beams failed by yielding of steel reinforcements which caused wide crack openings at the tension side of the specimens prior to compression crushing of concrete at the top concrete fiber, as shown in Figure 3.15. This validates the assumption that the concrete and steel reinforcements are comparatively inert to the outdoor tropical climatic weathering effects as compare to FRP reinforcement, which therefore caused no (or very little) variations in the beam load-deflection responses.
Type G1 Specimens – The load-deflection curves and crack patterns of aged G1 specimens are shown in Figures 3.16 and 3.17, respectively, while the ultimate load, $P_u$, and failure modes are tabulated in Table 3.6.

On average, the ultimate load, $P_u$, and the post-crack flexural stiffness of the specimen were significantly increased by bonding one layer of G1 laminates, as shown in the higher peak and more inclined ascending branch in Figure 3.16, compared to Figure 3.14.

All the AB specimens failed by compressive crushing of concrete at the top compressive fiber when the peak load was attained, regardless of the age of the specimens. Local incremental disintegration of G1 laminate by lateral splitting of fiber bundles was observed post to the on-set of concrete crushing, which caused intermittent and marginal sudden drop of loads, as shown in Figure 3.16 (a).

Despite the unexpected behavior shown by the 9-month-old specimen, the failure mode of OB specimens changed from the default concrete compressive crushing to rupturing of G1 laminates after 6 months or more of outdoor exposure. Complete rupture of G1 laminates by lateral splitting of fiber bundles upon approaching the ultimate load of 1- and 3-month-old specimens (pointed by arrows in Figure 3.16 (b)) caused a brittle-type of failure where considerable capacities of the specimens dropped. However, these specimens that failed in a premature manner still sustained the capacity closes to their un-strengthened counterparts, that is, the ultimate strength of OB-C specimens (Figure 3.14 (b)).

The same changes were observed for CB specimens that underwent equivalent period of accelerated weathering in the chamber. The default concrete compressive failure of the 5-day and 15-day-old specimen changed to rupture of G1 laminate after being weathered 1 month (that is, equivalent to 6 months outdoors) or
more in chamber. It is also shown clearly in Figure 3.16 (c) that the longer the weathering period of specimens, the earlier the rupturing of FRP took place at lower load and deflection levels.

It is also worth highlighting that for the specimens that were weathered less than 1 month in chamber or outdoor, the intermitted marginal drops in load post to concrete crushing was not pronounced. As G1 laminates ruptured through lateral splitting between the constituent fiber bundles, it is suggested that short-term exposure under the heat and UV-A had further cured the epoxy matrix that binds the fiber bundles. As a result, the bond between fibers bundles were enhanced, which in turn reduced the like hood of splitting between fiber bundles. However, such enhanced strength was reduced as the continuous weathering effects were more predominant in the latter stage.

**Type G2 Specimens** – The ultimate loads and failure modes of aged G2 specimens are listed in Table 3.7 and the corresponding load-deflection curves and failure patterns are illustrated in Figures 3.18 and 3.19 respectively.

Similar to Type G1 specimens, all AB specimens of Type G2 failed by compressive crushing of concrete regardless of their age (Figure 3.18 (a) and 3.19 (a)). However, no intermittent marginal load drops were observed after the top compression concrete started to crush. This is probably due to the absence of lateral splitting of constituent fiber bundles, as all the longitudinal fiber bundles were held effectively by the transverse bundles in the case of G2 laminates. However, continual application of external load finally caused the G2 laminates to rupture in a brittle manner through the formation of a transverse crack, and caused the capacities of the specimens to drop back to that of their unstrengthened counterparts.
On the other hand, the failure modes of OB specimens changed to FRP rupture after being weathered in outdoors for 9 months or more. The new failure mode was brittle and sudden, and happened at lower deflection and load levels with increased outdoor exposure times. It is also seen that all the failed specimens sustained their original capacities post to G2 laminate rupture, which resemble the load-deflection behavior of Type G1 specimens post to laminate rupture.

The variations in failure mode and ultimate load of CB series of Type G2 specimens that underwent the equivalent exposure periods in artificial weathering were, again, in good agreement with their OB counterparts. From the results shown in Figure 3.18 (c), it is suggested that while maintaining the gain in stiffness, the G2-strengthened specimens will probably have lost its enhanced load carrying capacity after 6 years of direct exposure to tropical weathering factors.

### 3.4.3 Ductility

The ductility indices of Type C, G1 and G2 specimens are shown in Table 3.8. The index is defined as (MacGregor, 1997)

\[
\mu = \frac{\delta_u}{\delta_y}
\]  

(3.14)

where \(\mu\) = ductility index, \(\delta_y\) = deflection at yielding and \(\delta_u\) = maximum deflection at on-set of concrete crushing or rupturing of GFRP, as shown in Figure 3.13.

The flexural ductility of the specimen remained about the same after being strengthened with G1 and G2 laminates, as shown in Figure 3.20 (a). Nevertheless, the ductility of the specimens seemed to reduce after both G1 and G2-strengthened specimens had underwent weathering exposures, as shown in Figure 3.20 (b) and (c). This is in good agreement with the observed failure condition where the specimen
failure became more and more brittle as the failure mode changes over time. For G1-strengthened specimens, the ductility index reduced after 9 months exposure outdoor, whereas for G2-strengthened specimens, it decreased after 1 year exposure outdoor.

### 3.4.4 Crack Width

The monitored maximum crack widths at 60% of the ultimate load (that is the assumed service load of a structure in service) of specimen at different age are listed in Table 3.9 and plotted in Figure 3.21. In view of the small specimen size employed in this study, the magnitude of crack openings might not be comparable for large-scale beams. However, the plot does give good indication on the weathering effects on serviceability of the beam in terms of the crack width development.

By aggregating 1, 3, 6 and 12 months data, the mean values and 95% confidence intervals (bounded by vertical lines on the bars) of maximum crack widths for pure moment zone and shear span of all the Series AB specimens are shown in Figure 3.21 (a). It seems that bonding of G1 laminates increased the crack widths at the post-strengthened service load, while bonding of G2 laminates did not. However, as the capacities of the specimens were increased by 50% for G1 compared to that of 30% of G2, the wider crack widths in G1 are anticipated.

Considering the mean and spread of the maximum crack widths of the non-weathered G1 specimens (AB-G1) in Figure 3.21 (b), the maximum crack widths at pure moment zone decreased as the failure mode and ultimate load level of the weathered Type G1 specimens dropped over time. As the load-deflection curve of the beams up to the yield load remained about the same post to weathering (Figures 3.16 (b) and 3.16 (c)), the decrease in residual ultimate load of the specimen resulted a lower deflection (or curvature) of the beam, and thus smaller crack widths, at the corresponding service load level. Comparably, no significant variation in the
maximum crack widths in the pure moment zone was observed for Type G2 specimens, as the residual ultimate load and the corresponding mid-span deflection at 0.6\(P_u\) of the beams were not significantly different (Figure 3.18 (b) and 3.18 (c)).

In case of the shear span, as the spread of the maximum crack widths was large for Type G1 specimens, the variations were not considered as significant. Also, no significant variation was found in maximum crack widths for Type G2 specimen as most of the measured values falls within the 95% confidence interval.

### 3.4.5 Strains in Concrete, Steel Reinforcements and GFRPs

The strains in top concrete fiber, steel reinforcement and GFRP at failure are depicted in Figures 3.22 to 3.29.

The observed concrete strains at failure were in good agreement with the variation in failure mode over time. For all Type C specimens which failed by compressive crushing of concrete, the concrete strains exceeded the assumed crushing strain of concrete, that is 0.003 (Figures 3.22 to 3.24). In the case of Type G1 and Type G2 specimens where the failure mode had changed to rupture of GFRP, the observed concrete strains at ultimate were lower than the crushing strain and kept decreasing with increasing duration of weathering (Figure 3.23 (b), 3.23 (c), 3.24 (b) and 3.24 (c)).

Some of the stress-strain curves of steel reinforcement in Figures 3.25 to 3.27 show a significantly low strain values up to failure for Type C, G1 and G2 specimens. These were probably due to faulty strain gauges embedded in the concrete. Therefore, these curves are excluded from the discussion. All the steel reinforcements yielded at ultimate load as the value of measured strains exceeded the assumed yield strain of 0.0035. In general, the load versus strain in steel
reinforcement plots of beams failing by the default concrete crushing mode, display two distinctive turning points (which correspond to the onset of beam cracking and yielding of internal steel reinforcements, respectively) and followed by a plateau prior to failure. However, as the failure modes of Type G1 and G2 specimens changed to FRP rupture over time, the plateau was less distinctive and often disrupted with a sudden drop of applied load.

No clear trend was observed from the measured ultimate GFRP strains over time for all the specimens (Figures 3.28 to 3.29). This is probably due to the fact that the strain gauges were placed at the middle span of the GFRP laminates, whereas the laminates all ruptured near loading point close to the pinned end. Therefore, the measured ultimate strains were likely to be different to that of the real ultimate strain in GFRP.

3.4.6 Comparison of Test and Predicted Results

The regressed material property functions in Eq. (3.10) for ultimate strains and elastic modulus can be obtained from in-door accelerated weathering tests as shown in Figure 2.29 and 2.30 in Section 2.3.2.5. For G1 specimens, the regressed ultimate strain function and regressed elastic modulus function take the form of

\[ \varepsilon_{pu,G1}(t_{ou}) = \varepsilon_{pu,G1}(t_{ch}) = 19280 - 3230 \log(t_{ch}) \]  

(3.15)

and

\[ E_{p,G1}(t_{ou}) = E_{p,G1}(t_{ch}) = 21250 - 15 \log(t_{ch}) \]  

(3.16)

respectively.
Similarly, in case of G2 specimens, the regressed ultimate strain function and regressed elastic modulus function take the form of

\[
\varepsilon_{pu,G2}(t_{ou}) = a \varepsilon_{pu,G2}(t_{ch}) = 20308 + 214 \log(t_{ch})
\]

and

\[
E_{p,G2}(t_{ou}) = a E_{p,G2}(t_{ch}) = 13015 - 2950 \log(t_{ch})
\]

respectively.

To account for the debonding of FRP, the regressed bond strength variation function was obtained from the work of Tan et al. (2001) on the bond strength variation of the same G1 and G2 composite under the same weathering condition, as shown in Figure 3.30. The functions take form of

\[
\tau_{pu,G1}(t_{ou}) = a \tau_{pu,G1}(t_{ch}) = 1.560 - 0.280 \log(t_{ch})
\]

for G1, and

\[
\tau_{pu,G2}(t_{ou}) = a \tau_{pu,G2}(t_{ch}) = 0.400 - 0.082 \log(t_{ch})
\]

for G2.

By examine the minimum load among the different valid failure modes, the computed ultimate loads and failure modes were determined and tabulated in Table 3.10 to compare with the experimental results. It can be seen that the transition of failure mode from compressive crushing of concrete to rupture of FRP for both Type G1 and G2 specimens with respect to their exposure time were predicted by the proposed model reasonably well.

At initial stage, the residual load capacities of the test specimen did not show a constant decreasing trend over time as predicted by the model, which is likely due to the early strength gain in the concrete (Table 3.3) that were more prevailing than the strength drop in GFRP. However, as the concrete matured and strength drop in
GFRP became more significant, the strength of the specimens dropped correspondingly.

3.5 Summary

A model was proposed to predict the time-dependent behavior of FRP-strengthened beam. Three series of beams were tested and the applicability of the model was verified. The changes in ultimate load and failure mode were well predicted by the proposed model, except for the initial inconsistency in the strength of test specimens which was probably due to spread in the early concrete strengths.

Specimens kept in the ambient condition exhibited no changes in their ultimate load and failure mode over time. On the other hand, the GFRP laminates of those exposed to outdoor weathering suffered from resin degradation and leads to fiber prominence, which resemble to that of the weathered tensile coupons used in verification test of accelerated weathering scheme proposed in Chapter 2. The default failure mode changed from the “ductile” concrete crushing to the brittle GFRP rupture as the ultimate load decreased with exposure time. Ductility of the specimen also reduced while no significant changes were found in the crack widths after outdoor or equivalent chamber exposure.
<table>
<thead>
<tr>
<th>Exposure condition [Series]</th>
<th>Exposure Duration [Duration]</th>
<th>GFRP composite [Type]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>None [C]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G1 [G1]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G2 [G2]</td>
</tr>
<tr>
<td>Ambient [AB]</td>
<td>1 month [1m]</td>
<td>AB-C-1m AB-G1-1m AB-G2-1m</td>
</tr>
<tr>
<td></td>
<td>3 months [3m]</td>
<td>AB-C-3m AB-G1-3m AB-G2-3m</td>
</tr>
<tr>
<td></td>
<td>6 months [6m]</td>
<td>AB-C-6m AB-G1-6m AB-G2-6m</td>
</tr>
<tr>
<td></td>
<td>1 year [1y]</td>
<td>AB-C-1y AB-G1-1y AB-G2-1y</td>
</tr>
<tr>
<td>Outdoors [OB]</td>
<td>1 month [1m]</td>
<td>OB-C-1m OB-G1-1m OB-G2-1m</td>
</tr>
<tr>
<td></td>
<td>3 months [3m]</td>
<td>OB-C-3m OB-G1-3m OB-G2-3m</td>
</tr>
<tr>
<td></td>
<td>6 months [6m]</td>
<td>OB-C-6m OB-G1-6m OB-G2-6m</td>
</tr>
<tr>
<td></td>
<td>9 months [9m]</td>
<td>OB-C-9m OB-G1-9m OB-G2-9m</td>
</tr>
<tr>
<td></td>
<td>1 year [1y]</td>
<td>OB-C-1y OB-G1-1y OB-G2-1y</td>
</tr>
<tr>
<td>Chamber [CB]</td>
<td>5 days [5d]</td>
<td>CB-C-5d CB-G1-5d CB-G2-5d</td>
</tr>
<tr>
<td></td>
<td>15 days [15d]</td>
<td>CB-C-15d CB-G1-15d CB-G2-15d</td>
</tr>
<tr>
<td></td>
<td>1 month [1m]</td>
<td>CB-C-1m CB-G1-1m CB-G2-1m</td>
</tr>
<tr>
<td></td>
<td>1.5 months [1.5m]</td>
<td>CB-C-1.5m CB-G1-1.5m CB-G2-1.5m</td>
</tr>
<tr>
<td></td>
<td>2 months [2m]</td>
<td>CB-C-2m CB-G1-2m CB-G2-2m</td>
</tr>
<tr>
<td></td>
<td>6 months [6m]</td>
<td>CB-C-6m CB-G1-6m CB-G2-6m</td>
</tr>
<tr>
<td></td>
<td>1 year [1y]</td>
<td>CB-C-1y CB-G1-1y CB-G2-1y</td>
</tr>
</tbody>
</table>
Table 3.2: Geometrical and reinforcements details of test beams

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>C</th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, $b$ (mm)</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth, $h$ (mm)</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Span, $L$ (mm)</td>
<td></td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cover (mm)</td>
<td></td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to compression steel reinforcements, $d_s$ (mm)</td>
<td></td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to tensile steel reinforcements, $d$ (mm)</td>
<td></td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth to GFRP, $d_p$ (mm)</td>
<td></td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression steel reinforcement Type</td>
<td>Mild steel, R</td>
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<td></td>
<td></td>
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<tr>
<td>No</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter, $\phi'$ (mm)</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area, $A_s'$ (mm$^2$)</td>
<td></td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile steel reinforcement Type</td>
<td>Deformed high yield steel, T</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter, $\phi$ (mm)</td>
<td></td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area, $A_s$ (mm$^2$)</td>
<td></td>
<td>57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFRP width, $w_p$ (mm)</td>
<td></td>
<td>--</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>GFRP thickness, $t_p$ (mm)$^a$</td>
<td></td>
<td>--</td>
<td>0.80</td>
<td>0.70</td>
</tr>
</tbody>
</table>

$^a$ mean measured GFRP tensile coupon thickness
### Table 3.3: Concrete cube compressive strength post to various exposure conditions

<table>
<thead>
<tr>
<th>Duration of exposure, ( t_{on} ) or ( t_{ch} )</th>
<th>Mean, MPa</th>
<th>[ Coefficient of Variation, CoV(^b)(%) ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient</td>
<td>Outdoors</td>
</tr>
<tr>
<td>5 days</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>15 days</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>1 month</td>
<td>29.91 [ 0.28 ]</td>
<td>30.27 [ 10.41 ]</td>
</tr>
<tr>
<td>1.5 months</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>2 months</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>3 months</td>
<td>29.59 [ 2.38 ]</td>
<td>33.28 [ 13.71 ]</td>
</tr>
<tr>
<td>6 months</td>
<td>31.34 [ 1.25 ]</td>
<td>31.68 [ 7.77 ]</td>
</tr>
<tr>
<td>9 months</td>
<td>--</td>
<td>36.07 [ 4.95 ]</td>
</tr>
<tr>
<td>1 year</td>
<td>30.12 [ 8.67 ]</td>
<td>32.74 [ 3.70 ]</td>
</tr>
</tbody>
</table>

\(^b\) CoV = \( \frac{\text{Std.Deviation}}{\text{Mean}} \) \times 100\%, based on three cubes.
Table 3.4: GFRP laminate properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Type</th>
<th>G1</th>
<th>G2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength, $f_{pu}$ (MPa)</td>
<td></td>
<td>470</td>
<td>270</td>
</tr>
<tr>
<td>Ultimate strain, $\varepsilon_{pu}$ ($x10^{-6}$)</td>
<td></td>
<td>21400</td>
<td>19400</td>
</tr>
<tr>
<td>Elastic moduli, $E_p$ (GPa)</td>
<td></td>
<td>22</td>
<td>14</td>
</tr>
</tbody>
</table>

*From GFRP tensile coupon test and derived based on gross laminate area

Table 3.5: Ultimate load and failure mode of Type C (unstrengthened) specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate load, $P_u$ (kN)</th>
<th>Failure Mode$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB-C-1m</td>
<td>27.77</td>
<td>CC</td>
</tr>
<tr>
<td>AB-C-3m</td>
<td>28.57</td>
<td>CC</td>
</tr>
<tr>
<td>AB-C-6m</td>
<td>28.12</td>
<td>CC</td>
</tr>
<tr>
<td>AB-C-12m</td>
<td>28.65</td>
<td>CC</td>
</tr>
<tr>
<td>OB-C-1m</td>
<td>28.29</td>
<td>CC</td>
</tr>
<tr>
<td>OB-C-3m</td>
<td>28.22</td>
<td>CC</td>
</tr>
<tr>
<td>OB-C-6m</td>
<td>29.64</td>
<td>CC</td>
</tr>
<tr>
<td>OB-C-9m</td>
<td>29.26</td>
<td>CC</td>
</tr>
<tr>
<td>OB-C-12m</td>
<td>29.96</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-5d</td>
<td>(1m) 28.03</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-15d</td>
<td>(3m) 28.18</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-1m</td>
<td>(6m) 29.24</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-1.5m</td>
<td>(9m) 29.03</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-2m</td>
<td>(1 y) 29.15</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-6m</td>
<td>(3 y) 28.92</td>
<td>CC</td>
</tr>
<tr>
<td>CB-C-12m</td>
<td>(6 y) 29.54</td>
<td>CC</td>
</tr>
</tbody>
</table>

*CC: Concrete crushing, FR: FRP rupture, DB: FRP Debonding
### Table 3.6: Ultimate load and failure mode of type G1 specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate load, $P_u$ (kN)</th>
<th>Failure Mode(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB-G1-1m</td>
<td>45.38</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G1-3m</td>
<td>45.57</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G1-6m</td>
<td>46.67</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G1-12m</td>
<td>45.12</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G1-1m</td>
<td>45.93</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G1-3m</td>
<td>43.89</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G1-6m</td>
<td>46.52</td>
<td>FR</td>
</tr>
<tr>
<td>OB-G1-9mf</td>
<td>46.74</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G1-12m</td>
<td>47.49</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G1-5d (1m)</td>
<td>46.20</td>
<td>CC</td>
</tr>
<tr>
<td>CB-G1-15d (3m)</td>
<td>43.70</td>
<td>CC</td>
</tr>
<tr>
<td>CB-G1-1m (6m)</td>
<td>47.98</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G1-1.5m (9m)</td>
<td>46.72</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G1-2m (1 y)</td>
<td>44.73</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G1-6m (3 y)</td>
<td>44.16</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G1-12m (6 y)</td>
<td>41.59</td>
<td>FR</td>
</tr>
</tbody>
</table>

\(^f\) Oddly-behaved specimens

### Table 3.7: Ultimate load and failure mode of type G2 specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ultimate load, $P_u$ (kN)</th>
<th>Failure Mode(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB-G2-1m</td>
<td>39.02</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G2-3m</td>
<td>39.54</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G2-6m</td>
<td>40.24</td>
<td>CC</td>
</tr>
<tr>
<td>AB-G2-12m</td>
<td>39.59</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G2-1m</td>
<td>39.91</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G2-3m</td>
<td>40.68</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G2-6m</td>
<td>43.19</td>
<td>CC</td>
</tr>
<tr>
<td>OB-G2-9m</td>
<td>41.45</td>
<td>FR</td>
</tr>
<tr>
<td>OB-G2-12m</td>
<td>34.45</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G2-5d (1m)</td>
<td>40.43</td>
<td>CC</td>
</tr>
<tr>
<td>CB-G2-15d (3m)</td>
<td>42.29</td>
<td>CC</td>
</tr>
<tr>
<td>CB-G2-1m (6m)</td>
<td>42.60</td>
<td>CC</td>
</tr>
<tr>
<td>CB-G2-1.5m (9m)</td>
<td>41.78</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G2-2m (1y)</td>
<td>42.35</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G2-6m (3y)</td>
<td>40.43</td>
<td>FR</td>
</tr>
<tr>
<td>CB-G2-12m (6y)</td>
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\(^e\) CC: Concrete crushing, FR: FRP rupture, DB: FRP Debonding
Table 3.8: Ductility indices for AB, OB and CB series specimens

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<th>Deflection at yield, $\delta_y$ (mm)</th>
<th>ultimate, $\delta_u$ (mm)</th>
<th>Ductility index, $\mu = \frac{\delta_u}{\delta_y}$</th>
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### Table 3.9: Maximum crack widths at 60% $P_u$ (mm)

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### Table 3.10: Comparison of predicted and test results

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<th>Test</th>
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<th>Failed by $^b$</th>
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$^a$ CC: Concrete crushing; FR: GFRP rupture; DB: GFRP debonding

$^b$ $P_{am}$ = average ambient beam ultimate load

$^c$ Oddly-behaved specimen
Figure 3.1: Failure modes of beams externally retrofitted with FRP. (a) FRP rupture, (b) concrete compression, (c) shearing of beam, (d) peeling of concrete cover along longitudinal reinforcements, (e) debonding at FRP cut-off points, and (f) debonding of FRP at vicinity of shear cracks (Buyukozturk et al., 1998).
Figure 3.2: Reported versus predicted beam failure mode (Bonacci et al., 2001)

Figure 3.3: Anchorages for FRP laminates to prevent debonding of laminated and shearing of beams (Spadea et al., 1998)
Figure 3.4: Reduced failure modes of FRP-strengthened beam after installation of proper anchorages at laminates cut-off points

(a) Compression crushing of concrete

(b) Rupture of FRP

(c) Debonding of FRP at flexural cracks vicinity
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Figure 3.5: Idealized material stress-strain curves

(a) Bi-linear steel model

(b) Linear elastic FRP model

(c) Hognestad's parabolic concrete model

Figure 3.6: Strain and stress distribution of a beam section

(a) Beam section

(b) Strain distribution

(c) Stress distribution
Figure 3.7: Steel mechanical properties

(a) Reinforcement steel

(b) Specimen dimension

Note: all dimensions are in millimeters

Figure 3.8: Reinforcement and specimen dimensional details
(a) Outdoor weathering (Series OB)

(b) In-chamber weathering during light period (Series CB)

Figure 3.9: Outdoor and in-chamber weathering of specimens
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Figure 3.10: Test setup

(a) Schematic view

(c) Test

Note: all dimensions are in millimeters
Figure 3.11: G1 laminates surface after weathering exposures

*period in parentheses indicates equivalent outdoor exposure time
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</table>

*period in parentheses indicates equivalent outdoor exposure time

Figure 3.12: G2 laminates surface after weathering exposures
Legend:

- **O-C**: Pre-crack deformation
- **C**: First crack
- **C-Y**: Post-crack deformation
- **Y**: Yielding of reinforcements
- **Y-F**: Post-yield deformation prior to failure
- **F**: Failure due to concrete crushing/debonding/FRP rupture
- **F-B**: Post-peak deformation (due to concrete crushing)
- **F-B’**: Post peak deformation (due to FRP rupture/debonding)
- **Pu**: Ultimate load
- **δy**: Deflection at yield
- **δu**: Deflection at ultimate load

**Figure 3.13**: Idealized load-deflection curve for C, G1 and G2 specimens
Figure 3.14: Load-deflection responses of Type C (unstrengthened) specimens
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(a) Ambient (AB)

(b) Outdoor (OB)

(c) Chamber (CB)

Figure 3.15: Failure patterns of Type C specimens
Figure 3.16: Load-deflection responses of Type G1 specimens
Figure 3.17: Failure patterns of Type G1 specimens
Figure 3.18: Load-deflection responses of Type G2 specimens
(a) Ambient (AB)

6 months

1 year

(b) Outdoor (OB)

9 months

1 year

(c) Chamber (CB)

6 months (3 years)

1 year (6 years)

Figure 3.19: Failure patterns of Type G2 specimens
Figure 3.20: Ductility indices of specimens over outdoor (or equivalent) age
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Figure 3.21: Maximum crack widths of specimens over outdoor (or equivalent) age
Figure 3.22: Concrete strains of Type C specimens
Figure 3.23: Concrete strains of Type G1 specimens
Figure 3.24: Concrete strains of Type G2 specimens
Figure 3.25: Steel reinforcement strains of Type C specimens
Figure 3.26: Steel reinforcement strains of Type G1 specimens
Figure 3.27: Steel reinforcement strains of Type G2 specimens
Figure 3.28: GFRP strains of Type G1 specimens
Figure 3.29: GFRP strains of Type G2 specimens
Figure 3.30: GFRP-Concrete bond strength variations (Tan et al., 2002)
Chapter Four

Conclusions

4.1 Review of Work

The tropical climate was characterized by reproducing the vital weathering factors in an in-house designed weathering chamber on an accelerated scale of six. The employed artificial weathering scheme was verified by weathering patterns and the effects on the mechanical properties of GFRP composites.

An analytical model incorporating the time-dependent mechanical properties of GFRP was proposed to predict the behavior of FRP-strengthened beams under the effects of tropical weathering over time. Forty-eight beams, which were divided into three series and subjected to different exposure environments prior to four-point load tests, were prepared to verify the proposed model. The effects of weathering on the failure modes, ultimate loads, ductility and crack widths of the strengthened beams were discussed.

4.2 Conclusions

From the verification test on the devised accelerated weathering scheme, it can be concluded that

(a) the outdoor tropical weathering effects were well reproduced in the artificial weathering scheme,

(b) the artificial weathering scheme introduces accelerated degradation on GFRP with similar aging behavior to that of outdoor,

(c) chalking of surface resin matrix and fiber prominence are good indications of deterioration of the composite mechanical properties,
(d) the tensile strength of GFRP laminates reduce as a result of outdoor or equivalent in-chamber weathering,

(e) the forecast total reduction in tensile strength of GFRP laminates after tropical weathering exposure seems to exceed the proposed environmental reduction factors of various national/international standards.

Also, the test program on 48 beam specimens subjected to 3 different exposure conditions suggested that:

(a) the changes in failure modes and ultimate loads of FRP-strengthened beams over time are predicted reasonably well by the proposed model,

(b) GFRP-strengthened beams sustain all the initial strength gain and exhibit the same design failure mode over time when protected from weathering effects,

(c) short-term (less than 1 month) outdoor exposure improves the properties of epoxy and delays the lateral splitting rupture of unidirectional G1 laminates post to crushing of concrete, and

(d) the design ductile failure mode of GFRP-strengthened beams changed to brittle GFRP rupture after 6 to 9 months of outdoor weathering with marginal drop in the enhanced strength, while longer period of weathering (up to 6 years) causes substantial drop in the enhanced strength.
4.3 Recommendations for Future Research

The reproducibility of the tropical weathering effects and the time-dependent behavior of small-scale GFR-strengthened beams under the weathering effects were focused in this study. Further works are recommended in the following areas:

(a) A study on the time-dependent behavior of large-scale beams strengthened with GFRP under tropical weathering effects to verify the general validity of the proposed model.

(b) A study on the effects of weathering on loaded GFRP-strengthened beams.

(c) A study on the effects of weathering on GFRP-strengthened beams with different pre-designed failure modes, that is, different steel reinforcement, GFRP ratios and concrete strengths.

(d) A study on the effects of weathering on beams strengthened with different types of FRP composites.
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ACI Committee 440R (1996), State-of-the-Art Report on Fiber Reinforced Plastic Reinforcement for Concrete Structures, American Concrete Institute (ACI) Committee 440, Farmington Hills, Michigan, USA.


ASTM-G154-00a: Standard Practice for Operating Fluorescent Light Apparatus for UV Exposure of Nonmetallic Materials.


### TABLE 1 Spectral Global Irradiance (condensed from Table 4 of CIE Publication No. 85 – 1989) *

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Irradiance (Wm(^{-2}))</th>
<th>Percent Total (300-2450 nm)</th>
<th>Percent of UV and Visible (300-800nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-320</td>
<td>4.1</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>320-360</td>
<td>28.5</td>
<td>2.6</td>
<td>4.2</td>
</tr>
<tr>
<td>360-400</td>
<td>42.0</td>
<td>3.9</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>300-400</strong></td>
<td><strong>74.6</strong></td>
<td><strong>6.8</strong></td>
<td>11.0</td>
</tr>
<tr>
<td>400-800</td>
<td>604.2</td>
<td>55.4</td>
<td>89.0</td>
</tr>
<tr>
<td>300-800</td>
<td>678.8</td>
<td>62.2</td>
<td>100.0</td>
</tr>
<tr>
<td>800-2450</td>
<td>411.6</td>
<td>37.8</td>
<td>…</td>
</tr>
<tr>
<td><strong>300-2450</strong></td>
<td><strong>1090.4</strong></td>
<td><strong>100.0</strong></td>
<td>…</td>
</tr>
</tbody>
</table>

*Source: ASTM-G-151-97*