DURABILITY OF FIBRE REINFORCED POLYMERS (FRP) USED IN CONCRETE STRUCTURES

by

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A thesis submitted in conformity with the requirements for the degree of M. A. Sc.
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ABSTRACT

The research on the structural performance of Fibre Reinforced Polymers (FRP) has shown that these materials have great potential for application in concrete structures. Not enough test data, however, are available to predict the long-term performance of the repaired and improved structures. Degradation problems can arise when polymers are exposed to heat, light, weathering, high-energy radiation, chemicals, and microorganisms.

The objective of this research is to study the durability of FRP used in concrete structures by exposing the material to simulated environmental conditions in the laboratory. The conditions that were studied in this research project are freeze-thaw and ultraviolet radiation.

Four types of specimen were studied for the freeze-thaw. The specimens are: 1) Fibre Reinforced Plastic (FRP) coupons, 2) FRP to FRP single lap bonded panels, 3) FRP wrapped cylinders, and 4) FRP to concrete bonded prisms. Only the first two types of the specimens were studied for the ultraviolet radiation. The results showed that the above exposures have minimal effect on the mechanical performance of Carbon- and Glass- FRP.
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Chapter 1

Introduction

Chapter 1

Introduction:

1.1 General

The aging and deterioration of a great number of bridges caused by a variety of factors such as corrosion due to the chlorides from de-icing salt and high chloride content in the air; freeze-thaw cycles; alkali-silica reaction; inadequate design; poor construction and maintenance; and increase in the weight of highway vehicles have created a major structural engineering problem in North America, Europe, and Japan.

Over the last three decades, there has been a great deal of research to develop cost-effective measures for extending the service life of civil engineering structures, improving the performance of infrastructure under severe loading conditions such as earthquakes,\textsuperscript{1,2} and rehabilitating structures deteriorated under severe environmental conditions.\textsuperscript{3} A great amount of research is devoted to discovering and developing new construction materials with better environmental resistance and durability. Fibre reinforced polymers (FRP) are new materials that show great promise. Numerous FRP products have been and are being developed worldwide. As reported in ACI 440R-96,\textsuperscript{4}
Japan and Europe are more advanced than the U.S. and Canada in this technology. Because of their early start in research and development, they have applied FRP in a larger number of projects in the field. Activity in Canada regarding FRP for concrete began in earnest in the late 1980’s.

The utilization of FRP, an advanced composite material, represents an innovative use of technology. Hybrid construction with concrete and FRP has been regarded as an efficient system with high stiffness- and strength-to-weight ratios. Table 1.1 compares their mechanical properties to the mechanical properties of steel.

Table 1.1: Comparison of mechanical properties of steel and epoxy matrix composites reinforced with various fibres

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Density (g/cm³)</th>
<th>Specific* Modulus (GPa)</th>
<th>Specific* Strength (MPa)</th>
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<tr>
<td>Carbon UHM</td>
<td>290</td>
<td>1380</td>
<td>1.68</td>
<td>173</td>
<td>820</td>
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<tr>
<td>Carbon HM</td>
<td>207</td>
<td>1520</td>
<td>1.56</td>
<td>133</td>
<td>974</td>
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<tr>
<td>Carbon HT</td>
<td>103</td>
<td>1520</td>
<td>1.53</td>
<td>67</td>
<td>993</td>
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<tr>
<td>Boron</td>
<td>248</td>
<td>2760</td>
<td>1.86</td>
<td>133</td>
<td>1484</td>
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<tr>
<td>Aramid</td>
<td>76</td>
<td>1380</td>
<td>1.38</td>
<td>55</td>
<td>1000</td>
</tr>
<tr>
<td>S-Glass</td>
<td>53</td>
<td>1820</td>
<td>2.08</td>
<td>26</td>
<td>875</td>
</tr>
<tr>
<td>E-Glass</td>
<td>46</td>
<td>-</td>
<td>1.45</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td>206</td>
<td>420</td>
<td>7.80</td>
<td>26</td>
<td>54</td>
</tr>
</tbody>
</table>

* Specific modulus and specific strength are the ratios of modulus and strength to specific weight, respectively.
† UHM: ultra high-modulus; HM: high-modulus; HT: high-strength

1.2 Background

FRP products were first used to reinforce concrete structures in the mid 1950s. Today, these FRP products take such forms as bars, cables, 2-D and 3-D grids, sheet materials, and plates. FRP products may achieve the same, or better, reinforcement objectives as the commonly used metallic products such as steel reinforcing bars, prestressing tendons, and bonded plates.
In the 1960s, corrosion problems began to surface with steel reinforced concrete in highway bridges and other structures. Road salts in colder climates or marine salt in coastal areas accelerated the corrosion of the reinforcing steel. Corrosion of steel reinforcements is termed as one of the major causes of deterioration of reinforced concrete structures. The volume of corrosion product is several times larger than the original steel. This results in cracking, sapling, or in delamination of concrete. The deterioration gives way to further corrosion due to the ingress of aggressive agents. Furthermore, the progress of corrosion, formation of electrochemical cell, reduces the cross-sectional area of the steel at the anode. The result is a reduction in load carrying capacity of the structure. One of the earliest remedies was a galvanized coating applied to the reinforcing bars, however, the electrolytic reaction between the steel and the zinc-coating caused the loss of the corrosion protection, consequently, this method has lost favours.

In the early 1970s, research led to the use of epoxy coated steel reinforcing bars. This is a specialized technique and can be helpful in addition to a low permeability concrete cover. Stainless steel coating of the bars is another, but expensive, option for corrosion protection. The glass FRP reinforcing bars were first manufactured when, in 1960s, it was found out that, due to incompatible thermal properties, steel reinforcement could not be used with polymer concrete. Commercial application of FRP reinforcement in conventional concrete was not recognized until the late 1970s. In the 1980s FRP bars were used where the reinforcement was subjected to severe chemical attack. Since 1986, starting with the world's first highway bridge using composite reinforcement in
Germany, there have been FRP reinforced bridges constructed throughout Europe and, more recently, in North America and Japan.⁴

Application and product development efforts in FRP composites are widespread to address the many opportunities for reinforcing concrete members. Some of these efforts are:⁴

- High volume production techniques to reduce manufacturing costs
- Modified construction techniques to better utilize the strength properties of FRP and reduce construction costs
- Optimization of the combination of fibre and resin matrix to ensure optimum compatibility with Portland cement and concrete

All FRP products, for applications in repair and maintenance of concrete structures, contain continuous fibres (glass, aramid, or carbon) embedded in a thermoset resin matrix (polyester, vinyl ester, or epoxy), which holds the fibres together and transfers the load between them.

The concrete industry’s primary interest in FRP reinforcement is in the fact that it does not ordinarily cause durability problems, such as those associated with steel reinforcement corrosion. Its qualities are light weight, high specific strength and modulus, durability, corrosion resistance, chemical and environmental resistance, and impact resistance.⁴ There still exists, however, the need for understanding the long-term durability of FRP in concrete structures.
This thesis examines the durability of FRP and its performance with concrete after exposure to accelerated freeze-thaw cycles and ultraviolet radiation. Four types of specimen for the freeze-thaw are studied by mechanical testing. The specimens are: 1) Fibre Reinforced Plastic (FRP) coupons; 2) FRP-to-FRP single lap bonded panels; 3) FRP-wrapped cylinders; and 4) FRP-to-concrete bonded prisms. Only the first two types of the specimens were studied for exposure to ultraviolet radiation. In order to establish a relation between the experimental results obtained from the laboratory and from the outdoor environment, the same types of specimens were also constructed for exposure to outdoor weathering for periods of one, two and three years.

Since FRP is new in civil engineering applications, many readers may wonder what these materials are and how they work. An introduction to the history, components, and the applications of FRP is presented in Chapter 2. Chapter 3 covers the durability aspects of the FRP. The experimental program and specimens-preparation are outlined in Chapter 4. The results of this study are discussed in Chapter 5. Conclusions of the test data and recommendations are presented in Chapter 6. A glossary of terms and detailed graphs are placed in the appendices.
Chapter 2

Fibre Reinforced Polymers (FRP)

2.1 Introduction

According to the ACI 440R-96 report, the term “composite” can be applied to any combination of two or more separate materials having a distinguishable interface between them. Often a surface treatment phase is introduced between the two combining materials, which improves the adhesion of the reinforcing component to the matrix phase. Presently in the literature, as well as in this paper, composites are defined as a polymeric matrix reinforced with fibres. They are also called Fibre Reinforced Polymers (FRP). In the case of structural applications, such as the FRP reinforced concrete, the fibres are continuous reinforcement phase supported by a stabilizing matrix material. The continuous fibres are usually stiffer and stronger than the matrix.

Feldman reports that a solution to the problems of reinforcing a brittle cement matrix with fibres was obtained in the later 19th century. Seymour writes that natural composites, such as wood, have been available for thousands of years. The relationship between the continuous and the discontinuous phases was recognized when pitch was used to bond reeds to produce composite boats 7000 years ago. Subsequently, in 1500 BC in Thebes, wood veneer was produced to improve the properties of wood. Prior to the 20th
century natural resinous products, such as pitch, casein, and albumin were used as continuous phase. The first synthetic laminating resin was a polyester produced by Brezelius in 1847, a precursor to phenolic resins introduced in early 1900's. The true beginning of the age of the composites is reported to be the production of fibreglass-reinforced unsaturated polyesters by Ellis and Rust in the late 1930's.

According to Feldman, the modern polymer matrix composite can be said to have started in 1940 with the realization of glass-phenolic polymer structures. Fabrication method was the main concern in the period between 1940 and 1960, whence the majority of the current techniques originate. The properties were worked on between 1960 and 1970, and various combinations for high modulus composites were tried. From 1970 to the present, the "thermoplastics era", in the polymer industry the concentration has been on the combination of fibres with thermoplastics.

The mechanical properties, orientation, length, shape and composition of the fibres; the mechanical properties of the resin; the bond between the fibres and the matrix influence the performance of the FRP. The main features of the composite materials are:

- High fracture energy
- Ease of fabrication
- Potential for low cost.

Feldman argues that the low cost is particularly true for the glass-reinforced polymers, which involve little or no strategic material cost and low capital equipment cost,
compared to metal processing. Properties of the composites may vary over a wide range with different reinforcing agents and matrices. Feldman⁹ lists the advantages of the composites over the conventional bulk materials as follows:

- They can be made with high strength and high specific strength (ratio of strength to specific weight)
- They can be made with high stiffness and high specific stiffness (ratio of stiffness to specific weight)
- Density is generally low
- Strength can be high at elevated temperature
- Impact and thermal shock resistance are good.
- Fatigue strength is good, often better than the metals
- Oxidation and corrosion resistance are particularly good
- Thermal expansion is low and can be controlled
- Thermal conductivity and electrical conductivity can be controlled
- Stress-rupture life is better relative to many metals
- Predetermined properties can be produced to meet individual needs
- Fabrication of large components can often be carried out at lower cost than for metals

Composites fall into the following groups:⁹ a) fibrous composites; b) laminar composites, laminates; and c) particulate composites.
In these groups the reinforcing agents are, respectively, in the forms of fibres, sheets (paper, textile, or other forms), and particles (stone aggregates or other fillers). In all three forms, the matrix, or the binder that holds the reinforcements together are polymers. In fibre reinforced polymers a coupling agent (surface treatment) for enhancement of the inter-phase bond is used.

2.2 Components of Fibre Reinforced Polymers

2.2.1 Reinforcing agents

As mentioned earlier in the definition of the composites, the following types of reinforcing agents are usually used in advanced composite materials: continuous filaments and fibres; sheet like materials; and fillers. Glass is the most common fibre used in the polymer-matrix composites. Others are carbon fibre, graphite fibre, boron fibre and steel fibre.\(^9\)

Fillers are solid, chemically inert substances added to a composite to modify its properties and/or the overall cost. Fillers may be used in the presence or absence of fibrous reinforcing agents. Chemical composition is a primary property of fillers, and is an essential consideration for their use in many systems. Essentially, chemical reactivity is the chief concern of the filler users. The most prominent physical effect of filler is the stiffening, or modulus increase, which they cause in composites.\(^9\)
In the composite fabrication, the continuous filaments are used in different forms such as: continuous strand mat, twisted (yarns), chopped, wound parallel (roving), and hammer milled (milled fibre).

When sheets of various materials are bonded together with a matrix, the end-product is called a laminate, and the reinforcing agent is called a laminating base. The most common laminating bases are woven fabrics and mats, paper and metal foils.

2.2.1.1 Fibres

One of the most important parts of polymeric composites is the fibres, which can be described as a flexible, macroscopically homogeneous body, with a high length-to-section ratio. The principal naturally occurring fibres used in the textile industry are cotton, linen, jute, silk, asbestos, and wool. Except asbestos, natural fibres are based on the natural organic polymers such as proteins and cellulose. Man-made fibres are manufactured from the naturally occurring polymers, synthetic polymers, and the minerals substances. Glass fibre is the only mineral man-made fibre in common use today, although other inorganic and metallic fibres are being developed, principally for fibre-reinforced composite materials.9

All fibres have one particular structural feature in common: a preferential orientation of their elemental units with respect to the fibre axis. In the case of man-made fibres, the preferential orientation is achieved through mechanical drawing operations, during which the filament is extended immediately after the extrusion to several times its initial length.
Drawing orients structural elements with respect to the fibre axis in order to bring these elements into optimal stress bearing positions and allows the development of a three-dimensional structural regularity. 

By definition, the fibres have a high aspect ratio (HAR), ratio of length to diameter. The extent of reinforcement is related to HAR values and orientation, which should be in the direction of the force profile. Since external forces are transferred from the continuous phase (resin) to the discontinuous phase (fibre), optimum adhesion between the two phases is essential for high performance.

2.2.1.2 Forms of Fibre

Fibres are commercially available in various forms suitable for different applications. Some of them are described in the following paragraphs and are illustrated in the Photographs (Fig. 2.1 and Fig. 2.2).

Figure 2.1: Glass fibre roving.
Fibre Roving: Fibre roving is a collection of parallel continuous ends of filaments. Conventional rovings are produced by winding together the number of single strands necessary to achieve the desired yield (number of metres of roving per kilograms of weight). Generally, rovings are made with fibres of diameter 9 or 13 μm. Roving yields vary from about 450 to 3600 m/kg and typically have 20 strands. Rovings are directly used in pultrusion, filament winding, and prepreg (pre-impregnated) manufacturing.

Woven Roving: Roving may be woven into a heavy, coarse-weave fabric for applications that require rapid thickness build-up over large areas. This characteristic is especially useful in the manufacture of fibreglass boats, various marine products, and many types of tooling. Woven rovings are available in different widths and weights.

Chopped-Strand Mat and Other Mats: There are three basic forms of fibre mat: chopped-strand mat, continuous-strand mat, and surfacing mat or veil.
Chopped-strand mat is a nonwoven material in which the fibre strands from rovings are chopped into 25-50 mm lengths, evenly distributed at random onto a horizontal plane, and bound together with an appropriate chemical binder. These mats are available in widths of from 5cm to 2m and weight 0.25 – 0.92 kg/m².

Continuous-strand mat consists of un-chopped continuous strands of the fibre deposited and interlocked in a spiral fashion. This mat is open and springy but, as a result of mechanical interlocking, does not require much binder for adequate handling strength.

Surfacing mat is a very thin mat of single continuous filaments often used as surface reinforcing layer in hand lay-up or moulding process to provide a smoother surface.

*Textile Fibre Yarn:* A yarn is a combination of strands that can suitably be woven into textile materials. The continuous individual strand as it comes from the bushing represents the simplest form of textile fibre yarn and is referred to as a *single yarn*. In order for this yarn to be properly and efficiently utilized in a weaving operation, they are slightly twisted, usually less than 40 turns per metre.

Many woven fabrics, however, require yarns heavier than can be conveniently drawn from a bushing. These can be produced by combining single strands by twisting and plying operations (i.e., twisting two or more of the twisted strands together).
Fibre Fabric: Fibre yarns are woven into fabric by standard textile operations. The properties and contribution to the product performance of fibre fabric are dependent on the fabric construction, that is, the number of yarns per inch in each direction, weave pattern, and yarn type.

Chopped-strand Milled Fibres: Continuous fibre strands can be chopped to specific lengths or hammer-milled into very short fibre lengths (generally 0.4 – 6.5 mm). The actual lengths are determined by the diameter of the screen openings through which the fibres pass during the milling. Milled fibres are used as reinforcements and fillers for thermoplastic and thermosetting resins. Glass and carbon fibres are of interest in this study.

2.1.2.3 Glass Fibres

Seymour\textsuperscript{1} gives a historical, chemical, and physical background on the glass fibre. He states that the American Society for Testing and Materials (ASTM), in Standard C167-71, defined glass as ‘an inorganic product of fusion, which has cooled to a rigid condition without crystallizing. Since glass is amorphous, it is isotropic. Like other amorphous polymers it has a glass transition point rather than a melting point or first-order transition characteristic of crystalline products.

Sheet glass was used for glazing in 2500 B.C., but fibreglass was not produced until 1620 by Antonio Neri in Florence. Glasslike fibres, called Pele's hair, formed by the wind passing over volcanoes, had been known for many centuries before the fibres were
produced by Neri. Nevertheless, these fibres were not available commercially until 1930's when Owens Illinois and Corning Glassworks formed Owen-Corning Fibreglass Corporation for the production of fibreglass. Several other firms are now producing this important product as well.

Fibreglass is made from molten glass marbles forced at 1266°C through orifices in the base of bushings to produce continuous fibres or staples (discontinuous fibres). The glass is not a definite compound. It is, primarily, silica produced by heating sand (SiO₂); limestone (CaCO₃); and boric acid (H₃BO₃) in a high-temperature refractory furnace.

Continuous filaments are produced by allowing the molten glass, held in platinum alloy tanks (bushings), to flow by gravity through multiple orifices. The molten filaments formed are gathered together and attenuated to specific dimensions before being quenched by a water spray. The cooled filaments are carried on a belt where they are coated with a lubricant or sizing and grouped together in bundles (strands) that are then wound on spools. The strands are wound together to produce rovings. In addition to being available as continuous filaments and staples in mats, fibreglass textiles are also available as biaxial, triaxial, knitted, and three-dimensional braided patterns.

A lime-alumina-borosilicate glass called E Glass containing, in addition to silica (SiO₂), relatively high percentage of alumina (Al₂O₃), calcium oxide (CaO), and boric oxide (B₂O₃) was developed specifically for the production of fibreglass for electrical (E)
applications. This high tensile glass is the major product used as the reinforcement for plastic composites.

High alkali glass (soda or bottle glass), called A Glass, is used as a general-purpose reinforcement for composites. Another type of glass called C Glass is a sodium borosilicate glass with a high tensile strength used in corrosive environments. Still other commercial types called S Glass and R Glass have higher tensile strength and maintain more of their strength at elevated temperature than E glass. AR Glass is an alkali-resistant glass used for the reinforcement of concrete. There are also a few specialized types of glass fibres, such as Type 30, used for continuous pultrusion; S-2 Glass used for filament winding; and leached glass, which is a high-silica glass.

Single filaments (single yarn) are twisted 40 times per metre. Heavier yarns are produced by twisting two or more strands together. If the twist resembles the letter S when the yarn is held in a vertical position, it is said to have an “S” twist; if the spirals resemble the letter Z, the singles yarn is said to have a “Z” twist.

The composition of glass is designated by the letters, A, C, E, S, and, R. A second letter is used to show whether the filaments are continuous (C), staple (S), or textured (T). Texturing or bulking is produced by impinging air on the yarn surface to produce random breakage of the surface filaments (fluffing). A third letter is used to designate the diameter of the yarn; G indicates 9 mm, and P indicates 18 mm. Thus a yarn designated as ECG has continuous filaments of E glass with a 9 mm diameter. It is customary to
apply sizing (film), such as polyvinyl acetate (PVA), and a coupling agent to the fibreglass rovings.

2.1.2.4 Carbon Fibres

Carbon fibre was first employed by Edison in 1880 as a filamentary material in early development of the electric light.\textsuperscript{12} The efforts for obtaining high modulus composites superior to steel, which could not be obtained using glass, led to the development of boron and carbon fibres. Carbon fibres are obtained by the carbonization of various polymeric materials, such as rayon, polyacrylonitrile (PAN), and certain pitches.\textsuperscript{6} The properties of the fibre depend on the type of precursor polymers and nature of heat treatment. PAN carbon fibres possess high strength and high-modulus. The principal disadvantage of these fibres is their low ductility.

Seymour\textsuperscript{10} adds that the term "carbon fibre" is used for fibres processed at temperatures below 1700°C and with tensile moduli less than 345 GPa. The graphite fibres, which are heat treated at a higher temperature (above 1700°C) have tensile moduli of at least 345 GPa and a high degree of orientation. The carbon fibres are also produced by melt spinning isotropic pitch and carbonizing and stress-graphitizing the product at higher temperatures. Spinning of the PAN fibre in a clean atmosphere results in a decrease in the average number of surface flaws, giving rise to carbon fibres with better mechanical properties. The mechanical properties of final carbon fibres also depend on the rate of heating and the final treatment temperature during carbonization; although the final heat treatment during stabilization remains the property-determining step.
According to Donnet and Bansal\textsuperscript{6} the carbon fibres have been classified into three main types depending on their fibre structure and the degree of the crystallite orientation. Type I carbon fibres are highly graphitized and are characterized by a high modulus (HM). When incorporated into structures, they give the highest stiffness per unit weight. Type II carbon fibres, which are heat-treated to a lower temperature, have a low modulus but a very high strength (HS). Type III carbon fibres have random orientation of the crystallites and display neither the high modulus of Type I, nor the high strength of Type II carbon fibres. Their main advantage is their low cost.

To increase the interlaminar shear strength of carbon fibre composites, which is attributed to the adhesion and bonding between the fibre and the matrix, the carbon fibres are given surface treatment. Boron and carbon fibres both exhibit high specific strength and a high specific modulus. Carbon fibre is considered suitable for applications in which the critical requirements are strength, stiffness, lower weight, and outstanding fatigue characteristics. They are reported to have found application where high temperature, chemical inertness, and high damping are important.\textsuperscript{6}

2.1.2.5 Aramid Fibre

Agarwal and Broutman\textsuperscript{11} describe the aramid fibres as follows:

Polymer aramid fibres (Kevlar) were first introduced in 1971. The aramid fibre forming polymers, that is, the aromatic polyamides, are believed to be made by solution-polycondensation of diamines and diacid halides at low temperatures. The polymers are
spun from strong acid solutions (e.g., concentrated H₂SO₄) by a dry-jet wet spinning process. The polymers are made by rapidly adding a diacid chloride to a cool (5 – 10°C) amine solution while stirring. The polymer thus formed is recovered from the crumbs or gel of pulverizing, washing, and drying. To form filaments, the clean polymer, mixed with a strong acid, is extruded from spinnerets at an elevated temperature (51 – 100 °C) through a 0.5 – 1.9 cm layer of air into cold water (0 – 4 °C). The fibres are then washed thoroughly in water and dried on bobbins. Fibre properties can be altered by using solvent additives, varying the spinning conditions, and using post-spinning heat treatments.

Kevlar fibres possess unique properties. Tensile strength and modulus are substantially higher and fibre elongation is significantly lower for Kevlar fibres than for other organic fibres. Kevlar fibres have poor characteristics in compression, with compressive strength being only one-eighth of the tensile strength. This results from their an-isotropic structure, which permits rather easy local yielding, buckling, and kinking of the fibre in compression. They are not as brittle as the glass or the graphite fibres and can be readily woven on conventional fabric looms. Representative properties of Kevlar fibres are given in Table 2.1.

<table>
<thead>
<tr>
<th>Property, units</th>
<th>Kevlar 29</th>
<th>Kevlar 49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mm</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Density, g/cm³</td>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>Tensile strength, MPa</td>
<td>2760</td>
<td>3620</td>
</tr>
<tr>
<td>Tensile modulus, GPa</td>
<td>62</td>
<td>124</td>
</tr>
<tr>
<td>Tensile elongation, %</td>
<td>3-4</td>
<td>2-8</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (0-100°C), m/m°C</td>
<td>-2 x 10⁻⁶</td>
<td>-2 x 10⁻⁶</td>
</tr>
<tr>
<td>In axial direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In radial direction</td>
<td>60 x 10⁻⁶</td>
<td>60 x 10⁻⁶</td>
</tr>
</tbody>
</table>
2.2.2 Polymer Matrix

The matrix generally has several functions, of which the most important are:

- to act as a bridge to hold the fibres in place;
- to protect the filaments from damage by abrasion and chemical attack;
- to transmit stresses to the fibres.

Feldman\(^9\) writes that many schemes of classification are possible for the polymers. One of the most used classifies polymers as synthetic (man made) or natural. Synthetic polymers could be further classified taking into account different criteria such as: monomer type, polymer structure, processing techniques, preparation techniques, physical properties, and end uses. A classification according to the thermal behaviour might first divide polymers into thermoplastics and thermosets and carry on from there. A more comprehensive classification divides polymers into organic polymers, element-organic or semi-organic polymers, and mineral polymers.

The organic polymers, the group of interest for the present study of the composites, includes compounds containing, apart from carbon atoms, hydrogen, oxygen, nitrogen, sulphur and halogen atoms, even if the O, N or S is in the backbone chain.

Many different organic resin matrices are in use, but the emphasis here will be on epoxy resins. While strength and stiffness are controlled primarily by the reinforcements, the resinous matrix contributes to thermal conductivity and flexibility. The ultimate
properties of these composites are based on a harmonious contribution of both the continuous and discontinuous phases.

2.2.2.1 Epoxy

Delmonte\textsuperscript{12} in his book covers the history and performance of the thermosetting polymers. He states that prominent among the thermosetting resin binders for advanced structural composites are epoxy resin systems. Development in epoxy resin systems spans at least 50 years, starting with the Ciba Swiss patents in the late 1940's and the Shell Chemical Company patent in the early 1950's. In their application to Carbon/Glass composites, they have been notably successful because of their excellent adhesion characteristics; a lower order of shrinkage during cure than with other competitive thermosetting materials; and a good balance of physical and electrical properties. The graphite/epoxy composites enjoy the advantage of several years of successful service applications which, of course, make them more difficult to replace with newer materials unless there is a dramatic improvement in some properties.

Discussion of epoxy resin systems entails examination of the basic epoxy polymers on the one hand, and the curing agents on the other hand. A wide variety of structures can be obtained depending upon the chemical combinations. Epoxy polymers (resins) are generally made by the interaction of epichlorohydrin and bisphenol A (diphenol propane). These were produced by DeTrey Freres in 1936.\textsuperscript{10} The useful properties of these polymers appear only after curing. This step transforms the low molecular-weight product to highly cross-linked space network.\textsuperscript{9} Epoxy resins may be cured at ordinary
temperatures by Lewis basis, such as amines, which react with the terminal oxirane (epoxy) groups. Primary amines react twice as fast as secondary amines, and this rate is accelerated in the presence of hydroxyl compounds. Epoxy resins may also be cured at elevated temperature (200+ °C) by the addition of cyclic anhydrides, which react with the hydroxyl pendant groups. Epoxy resins may also be cross-linked by the addition of amino or phenolic resins.  

While epoxy has a low order of toxicity and is not a carcinogen or mutagen, the amine curing agents may cause dermatitis if handled without protective gloves or protective clothing. As epoxy polymers are sometimes too viscous for use in certain applications, they are often reduced by adding solvents, plasticizers, modifying agents, and reactive diluents.

Feldman adds that epoxy polymers have a wide range of applications mainly because of the versatility of the system. Proper selection of the polymers and its cross-linking agents allows tailoring of properties for the cross-linked products. This versatility has been a major factor in the steady growth rates of this group of polymers. The main characteristics of the properly cured product are the following:

- outstanding adhesion to a variety of substrates, especially metals and concrete;
- excellent chemical resistance;
- very low shrinkage on cure;
- high tensile, compressive, and flexural strength;
- excellent electrical insulation properties;
- corrosion resistance;
- ability to cure over a wide temperature range.

Epoxy polymers are used in a large number of fields, including surface coatings, adhesives, polymer-concrete composites, laminates in flooring, and to a small extent in road surfacing.

2.3 Composites in Construction

The use of composites in construction gives the designer the flexibility of using the structural shapes that are made on site or in the factories. FRP has demonstrated superiority over many conventional materials. They are generally ready made and require very little finishing process. Also, they require very little maintenance when exposed to weather. They may, however, need complicated systems for pigmentation, and machinery.

They can be very advantageous when the speed on construction is a major concern. In the case of in situ casting, the rate of polymerization can be controlled and adjusted; as an example, for bolts in ground reinforcement, where polyester and aggregates are used in a mix as grouting cements for fast curing floors or for roadways. Rapid construction is also made possible by the use of prefabricated elements, but these are not, of course, uniquely made of polymers or composites since many traditional materials are offered in
prefabricated forms for use in the building industry. Additionally, the lightweight of composite polymers is a big labour saving factor in installation.  

2.4 FRP in Repair of Concrete Structures

Composite materials are utilized for repairing and/or strengthening of existing concrete structures, reinforcing and prestressing concrete members, and ground anchoring. Here only the forms of FRP that are used in repair and maintenance of existing concrete structures are discussed. These include bonded plates and sheets, wraps, and prestressing tendons.

2.4.1. Concrete Repair With Externally Bonded FRP Laminates

It is possible to improve the flexure stiffness and strength of concrete beams, slabs, and walls with bonded composite plates.\textsuperscript{14-16} The bonding of steel plates, using epoxy resins, to the tension zone of concrete beams is a method of improving structural performance (Fig. 2.3). The technique is effective and has been used extensively in the rehabilitation of bridge and buildings. Corrosion of the steel plates, however, can cause deterioration of the bond at the glued steel-concrete interface, thus, rendering the structure vulnerable to loss of strength and collapse.
The inherent corrosion property of ferrous materials, has focused attention to FRP as a

potential structural strengthening agent to be used in rehabilitation and post-tensioning applications. The FRP plates, which are considerably lighter than steel plates, could be handled on the site with minimal lifting equipment and scaffolding. This, for example, shortens the time and extent of traffic lane interruptions during bridge rehabilitation. It has been reported that thin CFRP sheets can replace steel as flexural strengthening reinforcements of concrete beams, and cut overall cost by 25\%.\(^4\) This technique has already been successfully applied to several beams in a number of countries including Switzerland\(^{17}\) and Japan.\(^1\) The reinforcing fibres imbedded in the fabric can be set in a single direction, or in multiple directions depending on the anticipated loads. The plates can be prefabricated and be bonded on the site, or be made on the job by impregnating and bonding the reinforcing fabric to the structure using wet lay-up techniques.
Manual lay-up fabrication consists of the placement of multiple layers (plies) of resin-impregnated sheets or fabrics onto the concrete surface. This can be done with prepreg tapes or dry-fibre sheets that are impregnated at the time of installation. The terms “tape” and “sheet” are used interchangeably and indicate a unidirectional product. The term “fabric” is used to indicate a product where fibres have been arranged in more than one direction.\textsuperscript{13}

The in-the-field-installation process of externally bonded FRP reinforcement consists of the following basic steps: concrete surface preparation – cleaning, sealing cracks, rust proofing existing steel reinforcement, and smoothening; application of a primer coat; application of the resin undercoat (Fig. 2.4); adhesion of the sheets (Fig. 2.5); application of resin; curing; and application of the finish coat.\textsuperscript{13} A few examples of the experimental studies and applications of FRP are present later in this section.

The selection of glass, aramid or carbon fibre reinforced composite sheets for rehabilitation purpose depends on the anticipated or required performance of the
rehabilitated structure in terms of its longevity after repairs and increased performance level (strength or stiffness) per unit cost. For example, CFRP may be five times stiffer and 50% stronger than GFRP; however, CFRP may be five to eight times more expensive than GFRP. In such situations, a more detailed cost analysis is recommended before arriving at a decision based solely on cost of the material per unit weight.18

Triantafillou19 reports the work by Meier. Meier showed that advanced composite materials could replace steel plates with overall cost savings emanating from the simplicity of the construction method. Shahawy et al.20 reports the project results from the I-95 bridge over Blue Heron Boulevard at West Palm Beach, Florida. The bridge sustained severe structural damage caused by oversized vehicles colliding into it. The cracked and damaged girders with loss of concrete in the bottom flange were strengthened to the original capacity utilizing externally bonded carbon fibre composites.

Meier and Kaiser21 strengthened concrete beams using FRP sheets by prestressing the sheets before applying them to the concrete surface. Clamping devices were needed at the ends of the composite sheets to provide confinement to the concrete and so increase the prestressing force from about 10% to about 50% of the sheet’s tensile capacity. Meier et al.17 in the application of the method to large-scale specimens tested in flexure under static, fatigue and sustained loads demonstrated that pretensioning of the bonded element represents a significant contribution towards improving the serviceability of a concrete structure.
Saadatmanesh and Ehsani\textsuperscript{22} studied the static behaviour of reinforced concrete beams with GFRP plates bonded to their tension zone. They made the following conclusions: concrete surface preparation and selection of the adhesive is of primary importance; and strengthening technique is particularly effective for beams with relatively low steel reinforcement ratios.

They introduced prestressing in both un-cracked and pre-cracked rectangular concrete beams by cambering the beams before bonding a GFRP plate to their tension face. The beams were then tested in bending and failed suddenly in shear through the concrete layer between the plate and the reinforcing bars.

In the Igach bridge,\textsuperscript{23} core borings performed in 1991 to mount new traffic signals damaged one of the tendons in the outer web. The bridge was strengthened with four CFRP sheets 150 mm wide and 5.0 m long. The sheets were epoxy-bonded to the tension face of the span. Approximately 6.2 kg of CFRP were used instead of 175 kg of steel.

Following the January 17, 1994 Northridge earthquake, FRP sheets were applied to a tilt-up concrete building in southern California. The method proved to be the most cost-effective alternative to repair this damaged building in a very short time. More than 20,000 ft\textsuperscript{2} of wall surface area were strengthened, making this project the largest reported application of this technique.\textsuperscript{14}
The soffit of a bridge deck at Hiyoshikura on the Tokando Highway, Japan was strengthened to increase the load rating of the structure. The bridge consisted of a reinforced concrete deck supported by steel girders. The soffit of the deck was also affected by considerable map cracking. The cracks were sealed before application of the FRP reinforcement as part of the surface preparation process. A total concrete area of 164 m² was covered with two plies of dry carbon fibre sheet placed parallel and perpendicular to the roadway. To demonstrate the efficiency of the strengthening method, some of the steel reinforcing bars at the underside of the deck were exposed, instrumented with strain gages, and patched. Instrumentation was also installed for the slab deflection measurements. After the completion of the job in March 1994, running vehicle tests were conducted. It was confirmed that the reduction in tensile strain in the steel reinforcement ranged between 30 and 40 %.

In April 1994, the beams and the deck soffit of the waterfront pier at Wakayama Oil Refinery in central Japan were repaired to arrest the steel reinforcement corrosion. A total of 300 m² of beam surface and 90 m² of deck soffit surface were cover with a single ply of dry carbon fibre sheet. In some locations two plies were used. A urethane-base finish coating was applied to further increase weathering resistance.

In the summer of 1994, the concrete lining of twin tunnels along the Yoshino Route on Kyushu Island, Japan were strengthened using externally bonded FRP sheets. Cracking of the lining resulted from unexpected fluctuations in the underground water pressure. The repair in the first tunnel used two plies of dry sheet placed parallel and perpendicular
to the tunnel covering 500 m$^2$. In the second tunnel, three plies were placed parallel, perpendicular and parallel to the tunnel and covered a surface area of 590 m$^2$. The purpose of the repair was to strengthen and stiffen the lining. As work proceeded, it was not necessary to close the tunnel to vehicle traffic. No loss in tunnel cross-sectional area results from this type of repair.

2.4.2. Composite Wraps on Columns.

The wrapping of reinforced concrete columns with FRP provides the needed flexural and shear strength enhancement to allow concrete columns to resist seismic loads and increases the axial capacity.$^{14,15,24-26}$ This idea is becoming very familiar because of work that has been publicized in Japan$^1$ and California,$^2$ where a number of columns have been wrapped already to increase their earthquake resistance. The technique has provided markedly increased ductility to concrete columns in the laboratory tests, but has yet to undergo a significant test in an actual earthquake. Fife and Arnold$^2$ reported that recent testing indicates FRP’s ability to contain corrosion stresses and seal the column from the intrusion of corrosive agents. The composite material has demonstrated superior long-term properties when wet, and when back-filled against wet soil. The composite materials do not corrode, and also shield and separate the column from the environment.$^{26}$

In the mid-eighties, Ohbayashi Co. and Mitsubishi Kasei Co.$^{13}$ developed the concept of strengthening and retrofitting existing RC structures using CFRP strands and tapes. Three types of structures were targeted: building columns, bridge columns, and chimneys.$^{23}$ In their method, CFRP strands impregnated with resins are spiral wound onto
the surface of an existing RC member. In the case of the bridge columns and chimneys, CFRP tapes may be glued first to the concrete in the longitudinal direction so that flexural strength is also enhanced. The primary function of the spiral wound strand is to improve shear capacity and ductility of the reinforced concrete member.

Experimental work to evaluate the potential of this method and development work on the first winding machine has been undertaken at the Technical Research Institute of Ohbayashi Co. Improvements in strength of up to 50% and maximum deformation ability of up to four times greater than that of the original member were recorded using non-prestressed winding. Both circular and prismatic cross-section elements were investigated; however, test samples did not include conventional steel hoop or spiral reinforcement. Specimens were not subjected to axial load, only shear and bending were applied. Tests have shown that the low strain capacity of carbon fibre and its brittleness (even when epoxy impregnated) are a limiting factor. For prismatic elements, corners needed to be bevelled prior to fibre winding.13

Nanni et al.27 reported an experimental analytical study on the effect of wrapping conventional concrete compression cylinders, double-length compression cylinders, and ¼-scale columns-type reinforced concrete specimens with different longitudinal/transverse steel reinforcement characteristics. Significant enhancement of strength and ductility were reported.

Jinno28 tested five ½-scale models of the columns and two of the actual columns cut out of an old reinforced concrete building, both strengthened by carbon fibre blanket. It was
concluded that: a) strengthening by fibre blanket around the reinforced concrete columns largely enhances their shear strength and ductility without any changes in the initial stiffness, b) the increase of the shear strength can be reliably estimated by regarding the carbon fibre blanket as shear reinforcement, c) the carbon fibre blanket increases the ductility of columns with the increase in the number of layers, d) strengthening with the carbon fibre blanket can be also applied to columns with side walls, leading to the prevention of shear failure at columns up to at least 1.9% of a story drift angle.

Fyfe\textsuperscript{29} reports the repair of 18 bridges using FRP between 1992 and 1994. Two of eight repaired before January 1994, showed no damage due to January 17, 1994 Northridge Earthquake.

\textbf{2.4.3. Prestressing.}

Although the potential of FRP’s for prestressing applications was recognized more than 40 years ago, it is only since the 1980’s that there has been a worldwide resurgence of interest in their applications.\textsuperscript{30}

Under-designed, damaged, or deteriorated steel and concrete superstructures and substructures can be strengthened with non-corroding composite external prestressing.\textsuperscript{26,31} This technique is already being used with steel tendons and anchors, although protection is required for the exposed steel. Experimental results obtained from the study of FRP prestressed T-beams showed that FRP tendons could be used successfully as prestressing strands.\textsuperscript{31} The bond developed between the FRP tendon and
the concrete were satisfactory. One of the problems faced in developing optimum prestressing, has been the availability of the right type of anchorage system.\textsuperscript{31} The use of grouted anchorage, however, has proved successful in the external posttensioning of double-T reinforced concrete beams which were considerably deteriorated due to steel reinforcement corrosion in a South Florida condominium.\textsuperscript{3}

The applications of the carbon and fibreglass cables for the prestressing of bridge decks and the carbon cables for prestressing piles\textsuperscript{32,33} that are exposed to corrosive environments have proved satisfactory. Durability and long-term performance, however, are important factors that should be further investigated. If FRP prestressing or reinforcing elements in concrete elements fail, a catastrophic collapse could result. The result of studies\textsuperscript{30} showed that no great difficulties are experienced in pretensioning aramid, carbon and fibreglass in commercial facilities used for fabrication of steel pretensioned elements. The study, however, demonstrated the inadequacy of epoxy resin in protecting glass fibre from alkaline attack.
Chapter 3

Durability of Fibre Reinforced Polymers (FRP)

3.1 Introduction

The term durability is used to denote the period of time over which a material will perform its given and required task in a given environment. Durability is often difficult to assess and requires a keen judgement of what constitutes sufficient duration and adequate performance. Accelerated tests may be undertaken to provide information on the long-term behaviour of plastics, but inevitably they have limitations. This is principally due to:

a. the difficulty of correlating the results of the accelerated laboratory test with normal weathering conditions;
b. the lack of an interrelationship between the optical, mechanical, and surface appearance properties of plastic materials.

The aging and deterioration of a great number of bridges is caused by a variety of factors: corrosion due to chlorides from de-icing salt and high chloride content in the air; freeze-thaw cycles; alkali-silica reaction; inadequate design; poor construction and maintenance;
and increase in the axle load of highway vehicles. All these factors create major material and structural engineering problems.

As a result of the many applications of FRP, there is a great need to understand the long-term performance of the structures rehabilitated or strengthened by these materials. The experiments on different types of FRP show that the long-term physical, chemical, and mechanical properties of the composites change gradually due to temperature, moisture, biological degradation, ultra-violet rays, chemical reactions, surface corrosion, fatigue, and other natural phenomena.

3.2 Environmental Factors Affecting Fibre Reinforce Polymers

The influence of environmental factors such as elevated temperatures, temperature cycling, high humidities, corrosive fluids, freeze-thaw, and ultraviolet (UV) rays upon the performance of polymeric matrix composites is of concern in many applications. These environmental conditions may cause degradation in the mechanical and physical properties of a fibre-reinforced polymer for one or more of the reasons discussed below.33

3.2.1 Temperature

Changes in temperature dramatically alter the properties of materials. The strength and stiffness of most materials decreases as the temperature increases. Furthermore, sudden catastrophic changes may occur above the critical temperature. High temperatures may change the structure of engineering materials or cause polymers to melt or char.
Many composites have good to excellent properties at elevated temperatures. Most composites do not burn easily.\textsuperscript{4} The effect of high temperature is more severe on resin than on fibre. At elevated temperatures, epoxies soften and degrade and suffer significant reduction in strength and stiffness. The fire resistance is currently addressed by the use of fire retardant drywall products over the epoxy carbon fibre system.\textsuperscript{35,33}

Mallick\textsuperscript{33} in his book states that thermal aging due to sustained exposure to elevated temperatures even without load can cause deterioration in the properties of a polymeric matrix composite. He reports that Kerr and Haskins studied the effects of 100-50,000 h of thermal aging on the tensile strength of carbon fibre-epoxy and carbon fibre-polyamide unidirectional and cross-ply laminates. For the carbon-epoxy systems, thermal aging at 121°C produced no degradation for the first 10,000 h. Matrix degradation began between 10,000 and 25,000 h and was severe after 50,000 h. The carbon-polyamide systems were aged at higher temperature but showed less degradation than the carbon-epoxy systems.

ACI440R-96\textsuperscript{4} reports that the temperature effect over 100 freeze-thaw cycles from +20°C to -25°C on concrete beams strengthened with CFRP showed no negative influence on the flexural capacity. A study by Karbhari and Eckel\textsuperscript{16} on the short-term effects of three environmental conditions of interest in civil engineering applications: water, sea water, and 0°C on the strengthening efficiency of glass-, carbon-, and aramide-reinforced epoxy composite-jacket systems, stated that damage mechanisms in the glass system showed considerable potential for the development of ductile and plastic-like failure modes. All systems showed increasing stiffness with exposure to a 0°C environment.
Dutta\textsuperscript{37} studied the behaviour of FRP in an arctic environment. After cycling the material between $-60^\circ C$ and room temperature, he concluded the following:

1. Low temperature induces residual stresses in composites, which on developing microcracks can change both the strength and the stiffness properties of unidirectional and multidirectional fibre composite laminates.

2. The strength of the unidirectional composites when loaded in the fibre direction decreases with decreasing temperatures.

3. The strength of multilayered laminates progressively decreases with increasing thermal cycles.

Soudki and Green\textsuperscript{38} studied the performance of circular columns strengthened with CFRP wraps in cold weather conditions. The specimens were conditioned in four different environments, as follows: a) room temperature (+20°C), b) low temperature (-18°C), c) freeze/thawing cycles (-18°C to 20°C) and d) under water. Based on the result of their experimental program, they concluded that for their ability to protect the columns from freeze/thaw degradation, CFRP sheets are feasible in strengthening columns in cold regions. The CFRP wrapped cylinders exposed to freeze/thaw had 15% lesser increase in strength compared to the ones conditioned at the room temperature.

3.2.2 Moisture

Mallick\textsuperscript{33} states that when exposed to humid air or water, many polymeric matrix composites absorb moisture by instantaneous surface absorption followed by diffusion
through the matrix. Analysis of moisture absorption data for epoxy and polyester matrix composites shows that the moisture concentration increases initially with time and approaches an equilibrium (saturation) level after several days of exposure to a humid environment (Fig. 3.1). The rate at which the composite laminate attains the equilibrium moisture concentration is determined by its thickness and the ambient temperature, in addition to the relative humidity. Upon drying, the moisture concentration is continually reduced until the composite laminate returns to the original as-dry state. In general, the rate of desorption is higher than the rate of absorption, although for the purposes of analysis they are assumed to be equal.

Water vapour is the most deleterious component of the atmospheric. Excessive absorption of water in composites could result in significant loss of strength and stiffness.
Water absorption produces changes in resin properties and could cause swelling and warping in composites (Fig. 3.2). There are, however, resins reported which are formulated to be moisture-resistant and may be used when a structure is expected to be wet at all times. It is recommended that in the cold regions, the effect of freeze-thaw cycles must also be considered. In such an environment, a resistant resin layer has been advised to prevent penetration of water into the laminates.

![Diagram of Water Absorption](image)

**Figure 3.2: Effect of moisture absorption on FRP**

### 3.2.3 Chemicals

Chemical resistance of FRP has been termed very good in most of the literature. There is a wide range of chemicals that can come in contact with FRP. The FRP resistance to the chemicals that are of concern when dealing with concrete structures are reviewed here. According to Dechma, composite materials are always resistant to potassium hydroxide if they consist only of components resistant to potassium hydroxide. Examples of such
materials are graphite fibre reinforced plastics such as polyethylene, PVC, epoxy, resins and fluorocarbon resins. In the case of glass fibre reinforced polymers, resistance can be achieved only if the reinforced plastic is additionally covered with glass-free plastic layer resistant to potassium hydroxide so that no glass fibres penetrate to the surface.

It is suggested when glass fibre reinforced epoxy resins are used where sodium hydroxide solution and chlorine are present, they must be thoroughly cured and an inner coating, free from glass fibre, be applied. This is because the protruding glass fibres would be attacked by sodium hydroxide solution and would result in rapid destruction of the material.

3.2.4 Ultraviolet Radiation
Radiation from the sun with wavelengths greater than 290 nm can reach the surface of the earth. The ultraviolet spectrum ranges from 200 to 400 nm. The range between 400 and 700 nm represents visible light. The UV range is divided into three regions: UV-A, radiation in wavelengths between 315 nm and 400 nm; UV-B, radiation in wavelength between 285 nm and 315 nm; and UV-C radiation in wavelengths between 200 nm and 285 nm (ASTM G 53). Radiation below 290 nm is absorbed by the various gases in the atmosphere and is not of environmental concern. At the surface of the earth, the molar ratio of Visible:UV-A:UV-B is approximately 100:10:1; however, the content of UV-B is highly variable. The radiation incident on a surface is expressed in watt/m².

Feldman writes that composites can be damage by ultraviolet rays present in sunlight. These rays cause chemical reactions in a polymer matrix, which can lead to degradation
of properties. Although the problem can be solved with the introduction of appropriate additives to the resin, this type of damage is not of concern when FRP elements are used as internal reinforcement of concrete structures, where these are not subject to direct sunlight. Substances capable of strongly absorbing UV will provide good protection for plastics used for out-door purposes. Carbon black can absorb the entire range of UV and visible radiation and transforms the absorbed energy into less harmful infrared radiation.

Snow reports that field observations from polymer pile encapsulation revealed that a number of jacket failures appeared to be related to ultraviolet (UV) deterioration. The jackets readily broke when bent and the surface appeared chalky. The jackets all had some white or grey internal pigmentation and most appeared to be fabricated with random glass fibres.

Snow adds that UV resistance is increased in recent applications where jackets are hand laid up, using a combination of woven roving and mat screening agents mixed with the resins. Translucent jackets that are 3 mm thick, consisting of one woven roving and two mats plus a gel coat, have passed 500 hour accelerated weathering tests without any measurable distress.

Snow suggests the following to minimize the effects of UV deterioration:

- Use hand laid up or pultruded jackets with proper resin cover over the glass. Chopper gun fabricated jackets do not have sufficient resin cover over the glass, unless a special gel coat is added at the time of fabrication.
• UV screening agents may be added to the jacket resins, if tests indicate the need.

• Under extreme UV exposure, the completed encapsulation can be coated with a compatible paint to block the UV rays.

3.3 Degradation of FRP Components

3.3.1 Degradation of Glass Fibre and GFRP

The environmental stress-corrosion cracking of glass-fibre reinforced plastics (GFRP) has become an important consideration for applications involving exposure to the corrosive environments. Many GFRP elements fail catastrophically after a critical time when exposed to acids. The catastrophic failure of GFRP elements occurs due to the time-dependant degradation of glass fibres that are highly susceptible to attack by acidic environments. It has been reported that glass plates absorb water from the air with relative humidity above 84%. They are, therefore, subject to general attack and gradual decomposition.42

According to Dechema (Corrosion Handbook)39 Glass fibres lose weight insignificantly in an artificial cement extract due to alkali content, and retain their strength for a long period. Hence, these fibres can be used for reinforcing concrete and, in particular, may replace asbestos in asbestos cement.

It has been reported that the composite materials made of glass fibre and epoxy resin have proved to be suitable in 25% lime hydrate up to 93°C.43 The 50% strength mixtures are resisted up to 66°C. The weight losses of E glass samples tested in sodium hydroxide and
calcium hydroxide were as follow: NaOH (1 mol L⁻¹, 72°C, 90 min) weight loss 6%, Ca(OH)₂ (Saturated, 90°C, 120 min) weight loss 0.3%.

The effect of alkali solutions of different pH-values on silicate glass of the composition 15.5% Na₂O, 12.5% CaO, and 72.0% SiO₂ has been investigated. The attack on the glass surface increases in the order of: Ca(OH)₂ < N(CH₃)₄OH < LiOH < NaOH < RbOH < NH₄OH < Sr (OH)₂ < Ba (OH)₂. The low activity of calcium hydroxide can be explained by the very low solubility of the calcium silicate formed.

Degradation of glass fibres due to environmental attack can severely affect the performance of GFRP laminates. The fibres in GFRP laminates are protected from the environment by the resin matrix. It can be said that the resistance of the polymer matrix is an important factor in durability of GFRP.

3.3.2 Degradation of Carbon Fibres and CFRP

Donnet and Bansal⁶ state that carbon fibres, although generally non-graphitic and non-graphitizing, form intercalation compounds with alkali metals such as potassium and cesium, nitric acid, and halogens. They report that Herinckx et al. studied the intercalation of sodium, potassium, and cesium vapours into rayon base carbon fibres, WyB and WyD (Thornel), heat-treated to 2800 °C, using a thermo-gravimetric balance at several temperatures between 125 and 300 °C. The structure of the intercalated carbon fibre was examined by x-ray diffraction fibre diagrams. Hernickx et al. concluded that sodium is taken up and retained by the WyD carbon fibres in appreciable amounts (ratio
C/Na = 61 at 300 °C and 99 at 400 °C) but apparently does not form interstitial compounds. Potassium, however, forms well-defined intercalation compounds. Below 200 °C, the reaction with potassium is slow and the equilibrium value was not obtained in a reasonable time. Above 250°C, however, the reaction attained equilibrium in a few minutes. The intercalation with potassium did not alter the essential characteristics of the preferred orientation, the layer size, the layer stacking and the pore structure. The mechanical properties of the carbon fibres were not affected significantly, although, electrical conductivity was appreciably increased by intercalation of potassium. The intercalation cesium follows the same behaviour as that of potassium.

Donnet and Bansal⁶ report observations stating that oxygen intercalates into acrylic Type I fibre when the oxidation is carried out electrochemically using an acidic or alkaline medium. They also report the work by Vogel and Vogel and co-workers who observed that high-modulus carbon fibres could be readily intercalated by immersion in red fuming nitric acid. The measurements of conductivity of the carbon fibres before and after intercalation showed that the process is very fast and takes place in only a few minutes at room temperature. No intercalation was observed in the case of pitch-based carbon fibres with poor orientation of the graphitic crystallites.

For their very good resistance against stress-corrosion, carbon-epoxy fibre has replaced glass-reinforced composites in alkaline environments. Composites have excellent environmental resistance as long as they are prepared with a suitable matrix system.
The coefficient of thermal expansion of a composite depends not only on the orientation of the carbon fibres, but also on the thermal behaviour of the matrix material. The expansion of the matrix material is greater than the expansion of carbon fibres. This can result in a thermally induced stress in the composites. These stresses, however, can be absorbed by resin matrices since they are ductile and have larger elastic strain regions. Thus the properties of the composites are not affected as long as fibre-matrix interfacial bond strength is not exceeded.

3.3.3 Degradation of Epoxy Matrix

Changes in the properties of the matrix due to the environmental exposure are important considerations for polymer composites. Changes in temperature and moisture content affect the properties of polymer matrices. In addition, the distribution of temperature and moisture concentration is influenced by the environment.

Epoxy resins belong to the plastics with good resistance to chemicals. This property is dependent on the type of curing agent and on the nature and the quantity of the fillers. Epoxy resins are resistant to most inorganic salts and their aqueous solutions, even under oxidizing conditions. Thermal degradation of polymers can be divided roughly into two general categories, (1) random chain scission and (2) depolymerization. Depolymerization is the inverse of synthesis through polymerization, namely, a stepwise separation of the monomers from the growing chain end.
Feldman\(^9\) states that the cross-linked (cured or hardened) epoxy polymers were formed by the reaction of a difunctional or polyfunctional cross-linking agents (hardening) with the functional or polyfunctional epoxide. It is stated that the different types of commercially available epoxies may be cured with a variety of hardeners such as aliphatic or aromatic diamines, acid anhydrides and dicarboxylic acids, making it possible to formulate a very large number of epoxy structures with thermal stabilities dependent on the particular epoxy-hardener combination.

It is reported that the mechanical properties of the resins changed only slightly when exposed to salts and their aqueous solution over a long period of time and at high temperature. No changes in the appearance and the mechanical properties could be detected on exposure to 20% sodium chloride solution for 6 months at 100°C of epoxy resin which had been cured at 160°C. The resistance to chlorides was very good up to 60°C. Epoxy resins proved successful as protection against 50% potassium chloride solution on concrete floors at 29°C and were also not susceptible to de-icing salts.\(^{42}\)

The mechanical properties of the glass fibre-reinforced epoxy and the unsaturated polyester resin laminates are reported to be negatively influenced by exposure in moisture saturated atmosphere. In such an environment, a corrosion-resistant resin layer has been suggested to prevent penetration of water in to the laminates.\(^{42}\)

According to studies carried out in potassium hydroxide of various concentration (3% to 30 %) the mechanical properties of epoxy resins change under stress, the direction of
stress (stress, compression) having differing effects. Epoxy resins of various compositions are generally described as being resistant to 20% potassium hydroxide. Potassium hydroxide is reported todiffuses into epoxy resins more slowly than acids, but the diffusion takes place more rapidly than in polyesters. The diffusion rate in 40% potassium hydroxide between 20°C and 80°C was in the order of about $10^{-8}$ cm/s and was affected by the composition of the resin.
Chapter 4

The Experimental Program

4.1 Introduction

This thesis studies the durability of FRP laminates and their bond characteristics as affected by exposure to cycles of freeze-thaw (50, 100, 200, and 300 cycles) and ultraviolet radiation (1200, 2400, and 4800 hrs.). The project is part of a more comprehensive durability study of the FRP laminates, which also evaluates the effects of temperature cycles (between -20°C and +40°C), alkali solutions (pH 10, 12, and 14), moisture, and outdoor exposure on the long-term performance of the FRP. Four types of specimens were used to study the effects of freeze-thaw and UV exposures on the tensile strength of FRP, bond strength of FRP-to-FRP, efficiency of FRP wraps in confining concrete cylinders, and on bond strength of FRP-to-Concrete.

4.2 Specimens

The specimens used in this study were as follows:

- FRP Tensile Coupons (Figure 4.1)
- FRP Single Lap Bonded (SLB) Specimens (Figure 4.2)
- FRP Wrapped Concrete Cylinders (Figure 4.3)
- FRP Bonded Concrete Prisms (Figure 4.4)
Tensile Test Coupon

Figure 4.1: FRP Tensile Test Coupons
Dimensions in (mm)

Single Lap Bonded Specimen

Figure 4.2: Single Lap Bonded Specimen
Dimensions in (mm)
Figure 4.3: FRP Wrapped Concrete Cylinder

Figure 4.4: FRP Lap Bonded Concrete Prism

Dimensions in (mm)
The FRP tensile coupons were made in accordance to ASTM D 3039. The tensile strength, stiffness, and the strain at failure for exposed and unexposed specimens were determined using these coupons. The SLB specimens were used to determine the lap-shear strength of exposed and unexposed epoxy bonded panels. The mechanical properties obtained from the SLB specimen tests are the lap-shear strength, lap-shear rigidity, and the slip at failure. The incremental slip was measured using a 25.4 mm wide clip gauge.

The FRP-wrapped cylinders were tested for the mechanical performance; thus, the effect of exposure on the confinement efficiency of the FRP was evaluated. The FRP-bonded prisms were used to study the lap shear strength between FRP and concrete and qualify the effect of freeze-thaw exposure on the durability of such bond.

4.3 Materials

4.3.1 Fibres and Matrix

Carbon fabric, glass fabric, and epoxy are the components of FRP laminates. The materials used here were from the TYFO™ S Fiberwrap™ System. The properties of the hand wet lay-up composites as provided by the supplier are shown in Table 4.1.
Table 4.1: Properties of TYFOTM S Fiberwrap™ System GFRP and CFRP

<table>
<thead>
<tr>
<th>Property</th>
<th>Carbon (SCH 41) FRP</th>
<th>Glass (SHE 51) FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength (N/mm/layer)</td>
<td>850-950</td>
<td>490-560</td>
</tr>
<tr>
<td>Rupture Strain (mm/mm)</td>
<td>0.0142</td>
<td>0.0197</td>
</tr>
<tr>
<td>Nominal thickness of the Fabric (mm)</td>
<td>1.04</td>
<td>1.24</td>
</tr>
<tr>
<td>Weight of the Fabric (grams/m²)</td>
<td>658</td>
<td>923</td>
</tr>
<tr>
<td>Weight of FRP Sheet gr/mm²/layer</td>
<td>1660</td>
<td>2500</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion/°C</td>
<td>-0.5 x 10⁻⁶</td>
<td>7.7 x 10⁻⁶</td>
</tr>
</tbody>
</table>

The fabric used comes in the form of woven rovings (Figure 4.5). The main rovings, which carry the applied loads, are aligned in the longitudinal direction and held together by non-structural Kevlar wefts. The epoxy, the TYFOS® system, is a two part resin, TYFO™ A and TYFO™ B, and is mixed together in ratios of 100:42, respectively. They were mixed thoroughly for 5 minutes using powered mixing blade at a speed of 400-600 rpm. According to the manufacturer’s data, the TYFO® S Epoxy resin has a three hour working life at 35°C, and about 10 hours at 25°C. The gel time at 20°C is about 14 hours.
The gel time is the time that the resin form strings that gradually break off when a capillary wood stick is moved up and down with resin on one end.

4.3.2 Concrete
The concrete used for the cylinders and the prisms was made using Ontario Hydro's pre-packaged mix (King Mix No. 4003 July 30/96). The average 28-day strength of the moist-cured concrete was about 35MPa. To obtain a workable and freeze-thaw resistant concrete, super-plasticizer and air entraining admixture were used. The void ratio, density, and the slump of each mix were measured and found to be reasonably consistent throughout the mixes. The details of the concrete mix are given in Table 4.2.

<table>
<thead>
<tr>
<th>Mix Proportions</th>
<th>Cement (kg/m³)</th>
<th>347</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>(kg/m³)</td>
<td>1822</td>
</tr>
<tr>
<td>Water</td>
<td>(kg/m³)</td>
<td>132</td>
</tr>
<tr>
<td>Air entrainment admixture (AEA)</td>
<td>mL/kg cement</td>
<td>0.043</td>
</tr>
<tr>
<td>Super-plasticizer (SP)</td>
<td>mL/kg cement</td>
<td>6.50</td>
</tr>
<tr>
<td>Physical Properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density (fresh)</td>
<td>kg/m³</td>
<td>2301</td>
</tr>
<tr>
<td>Air void ratio</td>
<td>% Net</td>
<td>7.2</td>
</tr>
<tr>
<td>Slump</td>
<td>mm</td>
<td>216</td>
</tr>
<tr>
<td>W/C</td>
<td></td>
<td>0.38</td>
</tr>
</tbody>
</table>

4.4 Specimens Preparation

4.4.1 FRP Coupons
FRP coupons were made in accordance with the ASTM D 3039. The Carbon and Glass fabrics were cut into sheets of size 175 x 500 mm and 50 x 500 mm. The 175mm dimension is the length of the coupons, where each coupon has 75 mm gauge length and 50 mm grip length at each end. The main fibers run along the 175 mm length of the sheets. The grip portions of the coupons were strengthened by GFRP tabs on both faces.
The 175 x 500 mm sheets were impregnated with TYFO epoxy resin. The resin was roll-brushed on both faces. Then, the 50 x 500 mm glass sheets were placed on the grip portions of the large sheet (Figure 4.6) and were roll-brushed on with epoxy. The assembly was cured for seven days at room temperature, after which it was cut into two panels of 175 x 250 mm using a band saw. The panels were separated and were used as either exposed or as exposed and control specimens.

Figure 4.6: FRP Panel for Tensile Test Coupons

Because of the size of the pans in the freeze-thaw chamber, the 175 x 250 mm FRP panels for the freeze-thaw exposure had to be cut into test coupons of 175 x 25 mm (Figure 4.1). Ten coupons were obtained from each panel. While eight coupons were
used for the mechanical testing, the remaining two coupons from the edges of the panels were put away for future chemical analysis. In total, 64 CFRP and 64 GFRP coupons were used to evaluate the freeze-thaw effects; and 48 CFRP and 48 GFRP coupons to evaluate the effects of the UV radiation on the mechanical properties. The break down of the batches is shown in Table 4.3 for the two types of tests.

The control specimens were kept under room condition (22°C and ~50% r.h.) while the exposed specimens were placed in the designated chambers. It should be mentioned that the panels for UV exposure were not cut into test coupons till after the end of the exposure period. This was done to eliminate the edge effects on the properties that were evaluated.

<table>
<thead>
<tr>
<th>Environment</th>
<th>CFRP</th>
<th>GFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exposed</td>
<td>Control</td>
</tr>
<tr>
<td>Freeze-thaw</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 cycles</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>100 cycles</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>200 cycles</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>300 cycles</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Ultraviolet Radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hours</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>2400 hours</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>4800 hours</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

4.4.2 **Single Lap Bonded (SLB) Specimens**

The 25 x 300 mm SLB specimens for lap shear strength were prepared in accordance with ASTM D 3136 (Figure 4.2). Glass and carbon fabrics were cut into sheets of 200 x 500 mm (A, the main panels) and 90 x 500 mm (B, the tab). The rovings run along the
200 and 100 mm lengths of the sheets. The sheets were impregnated separately and then were put together to form the SLB's panels. Sheets A and B were placed side by side on a flat board as shown in Figure 4.7 with a distance of 10 mm between them. The second sheet A was placed on the top overlapping the first sheet A by 100 mm, bridging the 10 mm gap and extending over the sheet B. The second sheet B was placed on the first sheet A beside the second sheet A with a distance (gap) of 10 mm. The reason for keeping the gap down to 10 mm is to control the sag of the wet fabric, thus, preventing misalignment and kink in the SLB's.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Exposed CFRP</th>
<th>Control</th>
<th>Exposed GFRP</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze-thaw</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 cycles</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>100 cycles</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>200 cycles</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>300 cycles</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Ultraviolet Radiation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hours</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
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<tr>
<td>2400 hours</td>
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<td>8</td>
<td>8</td>
</tr>
<tr>
<td>4800 hours</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>
The panels were cured for 7 days at room temperature. They were cut into two 300 x 250 mm panels and were separated as exposed and control. The grouping of the specimens is shown in Table 4.4.

4.4.3 FRP Wrapped Cylinders

Concrete cylinders 75 mm in diameter and 150 mm long were cast from the mix described in Section 4.3.2. The cylinder size was determined by the size of the freeze-thaw chamber. The concrete cylinders were moist cured for 28 days at 95% R.H. and 23°C. They were end-ground until smooth, parallel, and flat end surfaces were obtained. Glass and carbon fabrics were cut for the number of cylinders to be wrapped. They were laid on thin polyethylene plastic sheets and were impregnated with epoxy. The impregnated fabrics were cut along with the polyethylene, into sheets of 140 x 340 mm. The polyethylene sheet was to act as a backing to the impregnated fabric for the ease of the handling and to prevent unravelling of the fabric rovings.

The cylinders were coated with the epoxy and were left to get tacky. Afterwards, the Glass/Carbon impregnated fabrics were wrapped on to them with an overlap of 100 mm. The wrapped cylinders were left to cure for one day, then the polyethylene backers were removed and the wrapped cylinders were given another coat of epoxy. They were further cured for six days and then grouped into control and exposed batches. Meanwhile, the batches of the exposed and control unwrapped cylinders were prepared to go alongside the wrapped cylinders. Each group was subdivided for 50, 100, 200, and 300 freeze-thaw cycles. The exposed cylinders were put into the freeze-thaw chamber and the control
specimens were kept at the room condition. A total of 72 cylinders were divided into groups of 12 as shown in Table 4.5.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>CFRP Wrapped</th>
<th></th>
<th>GFRP Wrapped</th>
<th></th>
<th>Unwrapped</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exposed</td>
<td>Control</td>
<td>Exposed</td>
<td>Control</td>
<td>Exposed</td>
<td>Control</td>
</tr>
<tr>
<td>Freeze-thaw</td>
<td>50 Cycles</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>100 Cycles</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
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<td>3</td>
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</tr>
<tr>
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<td>12</td>
<td>12</td>
<td>12</td>
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<td>12</td>
</tr>
</tbody>
</table>

4.4.4 FRP-to-Concrete Bonded Prisms

Durability of FRP-to-concrete lap-shear strength was studied using concrete prisms that were designed and prepared after some discussion and testing of a couple of trial models. The moulds were made of wood laminated with formica sheet on one side. Five specimens could be cast simultaneously in each of the moulds as shown in Figure 4.8. Each specimen is comprised of two halves held together by a 12.5 mm thick concrete rim and reinforced with the 25 x 262.5 mm FRP laminates (Figure 4.4).
In each half of the specimens a bolt-plate assembly was installed before casting, which provided the means to apply the load without causing direct tension in the concrete. The bolt was 15.8 mm in diameter and 200 long and the plate was 50 x 50 x 6.25 mm. The assembly was fabricated by welding. Six 12.5 x 12.5 x 12.5 mm hard plastic spacers were glued in the centre of the sidewalls and the bottom plate of the moulds to support the plates of the bolt-plate assembly (Figure 4.9). Concentrically placed plastic pipe sleeves, 150 mm long x 19.4 mm diameter, were used on the bolts to avoid contact between the bolts and the concrete. The ends of sleeves were sealed with silicon calking (Figure 4.10). To break the bond between the two halves of the prism, a 1 mm thick by 50 x 50 mm square formica plate was inserted between the two steel end-plates. The free ends of the bolts were fastened by steel nuts to prevent the inward sliding of the bolts.
during the casting and vibration. The outward slide were prevented by putting stiff steel plates on the bolt ends and clamping them using C-clamps (Figure 4.11). The rims of the moulds were covered with duct tape and the walls were oiled using WD-40. (Figure 4.11)

Figure 4.9: Gluing Plastic Spacers

The concrete was mixed in accordance with the mixing guidelines available at Ontario Hydro. Then, the moulds were filled and vibrated long enough to get the air bubbles out of the concrete but stopped before any segregation could take place. The moulds were covered by wet hemp cloth and plastic sheets for one day. On the following day all the moulds were stripped by taking them apart and the prisms were stored in the moist room for 28-day curing. At the end of 28 days the prisms were taken out and air-dried at room temperature. Afterwards, the two side-faces of the prisms where the FRP sheets were to be bonded were sand blasted to get rid of the weak surface and obtain a uniform bond surface for all the prisms.
Figure 4.10: Sealing the Sleeve Ends with Silicone calking

Figure 4.11: Molds Ready for Casting
Lines were drawn on the sand blasted faces of the prisms to mark the location where the FRP laminate strips were to be bonded. At the mid length of the 300 mm long prism where the two 150 mm long halves were designed to separate a 25 mm wide smooth surface duct tape was wrapped around the prism section (Figure 4.4). The purpose of the tape was to break the bond between the FRP and the prism at and around the location of impending crack.

Carbon or glass fabrics were cut into sheets for the number of prisms to be reinforced. The sheets were laid on the thin polyethylene plastic sheets and were impregnated with epoxy. They were then cut into strips of 25 mm wide x 275 mm long along the length of the main fibers rovings. The previously marked 25 mm wide strips on the sides of the prisms were coated with epoxy and were left to get tacky. The Carbon or glass impregnated strips were then glued on the epoxy coated sides of the prisms and pressed hard enough to hold uniformly in place. The FRP-bonded prisms were left for one day to cure. The next day the polyethylene backings were stripped off the top of the FRP strips which were then given another coat of epoxy. The prisms were left to cure for six more days; grouped into batches of exposed and control; and placed in the respective environments. A total of 64 prisms were grouped as shown in Table 4.6.

<table>
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<th>Exposure</th>
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<th>GFRP Lamine</th>
</tr>
</thead>
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<td></td>
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<td>Control</td>
</tr>
<tr>
<td>Freeze-thaw</td>
<td></td>
<td></td>
</tr>
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<td>4</td>
</tr>
<tr>
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<tr>
<td>Total</td>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>
4.5 Exposure Environments

Neville states that it is important that every concrete structure should perform its intended functions, that is to maintain its required strength and serviceability, during the specified or traditionally expected service life. It follows that concrete must be able to withstand the processes of deterioration to which it can be expected to be exposed. Such concrete is said to be durable. Inadequate durability manifests itself by deterioration which can be due either to external factors or to internal causes within the concrete itself. The various actions can be physical, chemical, or mechanical.

The present applications of FRP in concrete structures have raised the question of "How does the FRP-Concrete composite perform in their service environments in long-term?" Of course, there are numerous factors that should be investigated. Here the effects of the freeze-thaw and ultraviolet (UV) radiation on the mechanical properties of CFRP and GFRP as well as their bonds are evaluated. The environments to which these specimens are exposed are discussed.

4.5.1 Controlled Environment

The control specimens were kept in the laboratory where the room conditions were controlled. For the tensile coupons and the single lap bonded specimens the ambient temperature was about 22°C and the relative humidity was approximately 40%. For the concrete cylinders and the prisms the temperature and relative humidity were about 22°C and 50%, respectively.
4.5.2 Freeze-thaw Cycles

As the temperature of saturated concrete in service is lowered, the water held in the capillary pores in the hardened cement paste freezes and expansion of the concrete takes place. If subsequent thawing is followed by re-freezing, further expansion takes place, so that repeated cycles of freezing and thawing have a cumulative effect.

This phenomenon applies to other porous materials too, where the size of the pores are such that allows the freezing pressure to develop. Besides, the integrity of materials, such as FRP, that are bonded to concrete is affected. Being deleterious, freeze-thaw effects should be evaluated for all materials used in concrete structures that are exposed to the outdoors in cold regions.

To qualify the resistance characteristics of FRP and FRP-Concrete specimens against freeze-thaw, four types of the specimens described earlier are exposed to cycles of freeze-thaw and tested for their residual mechanical properties.

The freeze-thaw chamber at IRC-NRC is a standard chamber manufactured by Logan Freeze-Thaw Mfg. Co. It was run at (-18°C to +4°C). The unit contains eighteen (18) pans of 75 x 75 x 359 mm size, of which two were used for the monitoring and controlling of the temperature in the chamber. It operated just under 5 cycles/day (32 cycles/week). The FRP panels and the FRP single lap bonded specimens were placed in this chamber to undergo 50, 100, 200, and 300 cycles of freeze-thaw exposure. Because of the lightweight and the small size of the panels, they were stuck into silica sand, and then topped with water. After each of the predefined number of cycles, eight (8) CFRP
and eight (8) GFRP specimens were taken out, rinsed, and prepared for the test. There weren’t any visible signs of damage to most of the specimens, except a bit of surface polish fade. However, the 200 and 300 cycles of freeze-thaw had eaten away the epoxy on the edges of the panels. It is important to note that the edges are the borders to the saw cut, where most of the epoxy was powdered or minutely fractured.

The freeze-thaw units at the Ontario Hydro Technologies were of similar type. However, the specimen holding pans used here had the dimensions 87.5 x 100 x 400 mm. Only one FRP bonded prism could be placed in one pan (Figure 4.12). The steel bolts stick out of the prisms by 50 mm on the each end. To prevent water ponding, and thus the high freezing pressure built up, styrofoam blocks of 50 x 75 x 75 mm size were put onto the bolts at the ends of the prisms (Figure 4.12). The specimens were topped with water and exposed to 50, 100, 200, and 300 cycles. The cylinders were exposed to the same environment as the prisms. The cylinder dimension are 75 x 150 mm, therefore, two of them could be place in one pan, and the remaining space of the pans were filled with styrofoam blocks. These specimens also underwent 50, 100, 200, and 300 cycles of freeze-thaw exposure.
4.5.3 Ultraviolet Radiation

In Section 3.2.4 the range of different natural occurring UV radiation was presented. In this section it is described how the UV radiation was simulated in the laboratory. To simulate the solar radiation in the laboratory, a variety of lamps and apparatuses are used. One of the most commonly used and economical types is the fluorescent UV lamp. Fluorescent UV lamps have phosphorous that transforms the 254 nm radiation from a low-pressure mercury arc to longer wavelengths at approximately 300 nm (tanning lamp) and 350 nm (black light). UV-B lamps are commonly used in fluorescence UV-condensation devices. For most applications, they produce the fastest polymer degradation. However, this degradation mechanism does not occur when materials are exposed to sunlight, as the UV-B lamps emit UV below the normal sunlight cut-on, 300 nm (Figure 4.13). For certain applications, the longer wavelength spectrum emitted by
Figure 4.13: Spectral Power Distribution (SPD) of UV-B Lamp (ASTM G53)

Figure 4.14: SPD of UV-A Lamp with 340 nm Peak versus Sunlight (ASTM G53)

UV-A lamps is useful. Because UV-A lamps typically have little or no UV output below 300 nm (the “cut-on” wavelength for terrestrial sunlight) (Figure 4.14), they usually do
not degrade materials as rapidly as UV-B lamps, but they may allow enhanced correlation with actual outdoor weathering. Tests using UV-A lamps have been found useful for comparing different polymers, textiles and UV stabilizers. The lamps are mounted in two bands of four lamps each in the test chamber. (ASTM G 53) The specimens are mounted in the specimen racks with the test surfaces facing the lamp.

Ultraviolet radiation is a concern to building and structural components exposed to direct sun light. This has been a concern in other engineering disciplines as well as in civil engineering. Although, the UV degradation is mostly a surface phenomenon, certain wavelengths do penetrate into transparent materials. Therefore, in addition to the tensile strength of FRP, the FRP-FRP bond strength was also studied. ASTM D 904 covers the basic principles and operating procedures for UV light aging of adhesive bonded joints.

The UV radiation chamber used for the specimens in this study is a Q-UV manufactured by The Q-Panel Company. The unit has a capacity of about 0.56 m² and the light is maintained by 8 UV bulbs. The bulbs used are UV-A 340 with an irradiance range of between 295 and 365 nm, and at peak (340 nm) it has radiation energy of about 0.9 W/m²/nm (manufactures data). They are the most appropriate available simulation of sunlight in the critical, short wave, UV region. The temperature at the chamber was set at 35°C (black panel temperature) and controlled by air blower. The relative humidity of the chamber was kept close to the ambient lab condition that is close to 40%.
The FRP panels and the FRP single lap bonded panels were exposed to the UV radiation. The 175 x 250 mm FRP coupon panels and the 300 x 250 FRP single lap bonded specimens’ panels were placed in the chambers parallel to the UV fluorescent lamps for 1200, 2400, and 4800 hours. Only one face of the specimens was exposed to the radiation. At the end of the radiation periods the panels were retrieved and examined for any visible changes. No micro-optical observation has been conducted on the specimens to see the changes in the matrix and fibre structures.

The amount of radiation energy between 295 nm and 365 nm fallen on the specimens was approximated using lamp manufacturer’s chart. With a wavelength distribution similar to Figure 4.14 and a given irradiances of 0.9 watt/m²/nm at 340 nm, the radiation energy of the entire wavelengths of one lamp is about 39 watt/m². The radiation energy is the area under irradiance vs. wavelength curve of the lamp. This gives about 156 watt/m² for four lamps that are mounted in each side of the chamber. As a result, the amount of energy fallen of the panels is 670, 1350, 2700 MJ/m² for the duration of 1200, 2400, and 4800 hrs, respectively. Example calculation:

\[
1200 \times 3600 \text{ sec} \times 156 \frac{\text{J}}{\text{m}^2/\text{sec}} = 670 \times 10^6 \frac{\text{J}}{\text{m}^2}
\]

The ASTM E 1596 recommends that the specimens be exposed for a duration that will accumulate a total ultraviolet (wave length shorter than 385 nm) exposure of 2000 MJ/m², which is roughly equivalent to 72 months exposure in southern U.S. latitudes. For
similar degradation in materials, the equivalent exposure to sunlight accumulates 48 000 MJ/m².

After the predetermined hours of exposure, the exposed and the control panels were cut into strips of 25 mm width. The specimens, then, were tested for their mechanical properties. The test data from the exposed specimens were compared with the data from the control (unexposed) ones.
Chapter 5

Results and Discussions

5.1 Introduction

Results from the tests performed on durability are presented in this Chapter. The freeze-thaw tests, were conducted for FRP characteristics, FRP-to-FRP bond, FRP wraps confinement efficiency, and FRP-to-concrete bond. The UV radiation tests were conducted to evaluate the properties of FRP under tension and FRP-to-FRP bond as affected by the exposure. The chapter is divided into four sections, each of which discusses one type of the specimens. The sections start with a state-of-the-art report on the type of tests carried out in this study.

5.2 FRP Tensile Coupons

5.2.1 The state of the art

Norris et al.\textsuperscript{45} studied the performance of glass-reinforced polyesters exposed to outdoor weathering in England under stress (20% and 25% of the ultimate strength). The specimens were placed in the racks facing south and at an angle of 45\(^\circ\) from the horizontal. After the exposure period, the specimens were retrieved and tested for residual flexural and tensile strength. The dimensions of the panels were 12.7 x 76 mm and 12.7 x 230
mm, respectively. The nominal thickness of the sheets used in making the specimens was 2.8 mm.

After 64 weeks of exposure to the outdoors weather while under tensile stress, a pattern of changes in several properties of the glass reinforced plastics, had been observed. There had been changes in the stress and strain values corresponding to gelcoat failure and ultimate failure, in tension and in flexure. On average, these values increased by about 10% during the first 2-4 weeks of exposure, followed by a comparable decline over the next 30 weeks, and then a second, generally smaller, increase up to 64 weeks after the initial exposure date. The changes were explained to be the results of two compensating actions, one the widely recognized deleterious weathering action and the other a strengthening reaction which correlates with the quantity of solar radiation experienced by the specimens and is probably a cross-linking reaction. Applied stress appeared to have little effect at this stage, and a 5% decline caused by a 25% stress loading in the ultimate tensile strength of laboratory specimens over as 32-week period has been termed as barely significant.

Dutta studied the behaviour of fibreglass-epoxy and graphite-epoxy in cold environments. Unidirectional and multidirectional layered composites were exposed to temperature cycles and tested at room and low temperatures.

Graphite-epoxy, both unidirectional and multi-layered multidirectional specimens were exposed to 10 thermal cycles between room temperature (RT) of 24°C and the liquid
nitrogen temperature (LNT) of −180°C. Unidirectional graphite-epoxy composite with 0°, 45°, and 90° fibre orientation to the load direction were cut from large seven ply laminates. They were thermally cycled and were tested at room temperature. The strength values were compared with the values of their unexposed control counterparts. The 0° oriented specimens showed an increase of about 6% with the thermal cycling. However, the specimens with 45° and 90° fibre orientation failed at about 10% and 6% lower strength values, respectively, which may have been caused by the growth of coalescence of micro cracks in the matrix with thermal cycling. The change in the modulus remained within three percent of the control specimens for all orientations. Unidirectional longitudinal unexposed graphite-epoxy composites were also tested at −56°C and showed a strength reduction of about 13% to 16% compared with the values obtained at room temperature.

The fibreglass-epoxy laminate specimens were prepared by hand lay-up and autoclave cured using unidirectional prepreg. Unexposed specimens were tested at −40°C, -35°C, -20°C, -5°C, and 24°C. The results showed that with the decreasing test temperature, the unidirectional laminates have a decreasing trend of strength compared to laminates of other stacking configuration. For example, the unidirectional [0]₆ (six layers with 0° angle to the direction of loading) fibreglass-epoxy tested at −35°C showed about 17% reduction in its strength compared to its room-temperature strength, where the [+45°,−45°]₆ had the same strength at all temperatures.
The reduced strength of unidirectional composites at lower temperature has been attributed to the shrinkage of the matrix and the resulting waviness of the fibers. Besides, the epoxy gets too hard to allow uniform load distribution across all the fibers under load. When the fibers are not oriented in the loading direction, the mode of failure tends to become matrix dominated. Both the stiffness and the strength of the matrix material increase at low temperature. The results concluded that in matrix-dominated failure modes the strength tends to increase with decreasing temperatures, whereas in fibre-dominated failure modes the strength decreases with decreasing temperatures.

Bi-directional [90/0]s fibreglass-epoxy laminates were thermally cycled up to 150 cycles between −60°C and RT. The strength of the laminates progressively decreased with increasing thermal cycles. The decrease is significant in the first few cycles, and the rate of decrease diminishes after about 100 cycles.

Dutta’s study concluded that the strength of unidirectional composites decreases with decreasing temperature, however, the strength of multidirectional laminates decreases with increasing thermal cycles.

5.2.2 Current Experimental Study

The results from the FRP coupons tested in tension are discussed here. The specimens were tested using an MTS machine at NRC-IRC testing facilities. The tests were conducted in displacement control mode at a rate of 1.27 mm/min. The data was collected by a computer-based data acquisition system, which recorded the load increments (in
pound force) and the instantaneous head movements (in millimetres). Later, the values were transferred to load per unit width (N/mm) and strain (mm/mm). A consistent stress calculation is not feasible as the thickness of the laminates in a hand lay up is not uniform (between about 1 to 2 mm). This happens because the fabric is not uniformly stretched and epoxy thickness varies from one specimen to the other. Therefore, the test data are presented in force per unit width (N/mm) rather than stress (MPa). The calculated strain is based on the machine head movement that was divided by the unsupported length of the specimens between the grips. No bonded or clipped strain gauges were used with these specimens. However, to quantify the range of the error, two sets of eight (8) CFRP and eight (8) GFRP coupons were tested with a clip gauge added to the set-up. The average strain values (from the specimens with strength values deviating less than 10% from the average) obtained using the clip gauge were compared to the strain values calculated using the head movement. Figure 5.1 shows the comparison of the material behaviour based on the strain values calculated from the two methods. There is a close agreement between the responses based on two different approaches to calculate strain.

The maximum strength and the strain at rupture were obtained from the test data. The failure in a majority of the cases occurred with no post peak behaviour. It can be seen in Figures 5.2 to 5.5 for the averages of each batch that there is a rapid drop in strength after the peak, represented in most cases by only one point. The only exception is when some of the strands failed before the maximum strength of the coupon was utilized, in which cases the load-strain curve manifests stress reduction in steps. The load-strain relationship is almost linear up to the failure load.
Figure 5.1: Comparison of the Strain Values Calculated using the Clip-gauge with the Strain Values Calculated using Machine Head Movement
Figure 5.2: Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 50 Freeze-thaw Cycles and Control Coupons

Figure 5.3: Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 100 Freeze-thaw Cycles and Control Coupons
**Figure 5.4:** Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 200 Freeze-thaw Cycles and Control Coupons

**Figure 5.5:** Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 300 Freeze-thaw Cycles and Control Coupons
The tensile stiffness was calculated using a line averaging the points between 5% and 40% of the maximum strength. The three properties, i.e., the maximum strength, maximum strain, and the stiffness was averaged for sets of eight specimens, based on which the effects of freeze-thaw was quantified by comparing the results of the exposed and the control specimens. It should be pointed out that the test data with an average deviation of more than 10% was not included in the analysis. Only nine specimens out of a total of two hundreds and twenty four specimens were found to be in this category. Besides, nineteen specimens that failed under the grips were also discarded. Figures 5.6 and 5.7 show typical GFRP and CFRP failed specimens, respectively.

5.2.2.1 Effect of Freeze-thaw Cycles

Figures 5.2 to 5.5 show typical force-strain behaviour of GFRP and CFRP specimens. Figures 5.8 to 5.10 and Table 5.1 compares the tensile strength, tensile stiffness, and strain at failure of these specimens to their control counterparts for exposure to 50, 100, 200, and 300 cycles of freeze-thaw.

Figure 5.8 shows that the change in the strength of the freeze-thaw exposed GFRP specimens is negligible when compared to their control counterparts. The stiffness and the strain at rupture of GFRP are not affected by the freeze-thaw exposure when compared to control specimens. With age between 0 days and 66 days corresponding to 50 and 300 cycles respectively, there is a slight increase in the stiffness. In Figure 5.10 it can be seen that on average the rupture strain of GFRP decreased with age.
Figure 5.6: Modes of Failure in GFRP Coupons

Figure 5.7: Modes of Failure in CFRP Coupons
Figure 5.8: Strength of CFRP and GFRP Panels Exposed Freeze-thaw Cycles

Figure 5.9: Stiffness of CFRP and GFRP Panels Exposed to Freeze-thaw Cycles
Figure 5.10: Strain at Rupture of CFRP and GFRP Panels Exposed to Freeze-thaw Cycles
Table 5.1: Summary of the Test Results for GFRP and CFRP Coupons Exposed to Freeze-thaw Cycles

<table>
<thead>
<tr>
<th>Exposure Detail</th>
<th>Specimen Designation</th>
<th>Max. Strength (N/mm)</th>
<th>Stiffness (kN/mm)</th>
<th>Strain at peak load (mill-strain)</th>
<th>Comments</th>
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<td><strong>GFRP</strong></td>
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</tr>
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<td>Control</td>
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<td>839.9</td>
<td>'47.25</td>
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</tbody>
</table>

* The specimens that deviated in strength more than 10% of the average were discarded

The CFRP coupons behaved in a manner similar to GFRP specimens, however, a slight drop in the tensile strength due to freeze-thaw exposure was observed. The stiffness and the strain at rupture of the CFRP specimens were not affected by the freeze-thaw exposure. It can be concluded that the exposure to up to 300 cycles of freeze-thaw has no significant effects on the mechanical properties of CFRP and GFRP, taking into account the scatter in the test results of the specimens from the same panel and environment.

5.2.2.2 Effects of UV Radiation

Figures 5.11 to 5.13 present force-strain responses of the UV-exposed GFRP and CFRP coupons and their control partners. Figures 5.14 to 5.16 compares the tensile strength,
tensile stiffness, and tensile strain at rupture of these specimens. On average the strength values of exposed CFRP and GFRP remained slightly higher than those of the control specimens for the 1200 to 4800 hours of UV radiation. The tensile stiffness and the strain at rupture are affected by the UV radiation as well as by aging in the controlled condition. The stiffness of CFRP increased and its strain at rupture decreased due to the UV exposure. However, in the GFRP the changes in the stiffness and the strain at rupture were small.

Based on the general trend of changes in the properties, it can be concluded that UV radiation up to 4800 hours no significant negative effects on the mechanical properties of CFRP and GFRP. Further studies are needed to qualify the effects of extended exposure time. It should be mentioned that the only visible physical change after exposure was the change in the colour of epoxy as shown in Figure 5.17. No cracks or other signs of degradation were observed.
Figure 5.11: Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 1200 hrs. of UV Radiation and Control Coupons

Figure 5.12: Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 2400 hrs. of UV Radiation and Control Coupons
Figure 5.13: Tensile Force-Strain Behavior of CFRP and GFRP Specimens Exposed to 4800 hrs. of UV Radiation and Control Coupons

Figure 5.14: Strength of CFRP and GFRP Panels Exposed to UV Radiation
Figure 5.15: Stiffness of CFRP and GFRP Panels Exposed to UV Radiation

Figure 5.16: Strain at Rupture of CFRP and GFRP Panels Exposed to UV Radiation
Figure 5.17: Color Changes in GFRP Color due to Exposure to 1200 and 2400 hours of UV-B Radiation
Table 5.2. Summary of the Test Results for GFRP and CFRP Coupons Exposed to UV radiation

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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hrs.</td>
<td>Exposed G1200E#</td>
<td>654.5</td>
<td>23.74</td>
<td>31.54</td>
<td></td>
</tr>
<tr>
<td>Control G1200C#</td>
<td>627.4</td>
<td>25.55</td>
<td>28.41</td>
<td></td>
<td>One discarded*</td>
</tr>
<tr>
<td>2400 hrs.</td>
<td>Exposed G2400E#</td>
<td>631.0</td>
<td>25.88</td>
<td>30.38</td>
<td></td>
</tr>
<tr>
<td>Control G2400C#</td>
<td>646.8</td>
<td>27.60</td>
<td>28.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4800 hrs.</td>
<td>Exposed G4800E#</td>
<td>631.5</td>
<td>26.61</td>
<td>26.67</td>
<td>Two failed at grip</td>
</tr>
<tr>
<td>Control G4800C#</td>
<td>626.2</td>
<td>26.88</td>
<td>27.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CFRP Coupons</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hrs.</td>
<td>Exposed C1200E#</td>
<td>906.7</td>
<td>53.24</td>
<td>18.51</td>
<td></td>
</tr>
<tr>
<td>Control C1200C#</td>
<td>874.3</td>
<td>47.56</td>
<td>20.83</td>
<td></td>
<td>One failed at grip</td>
</tr>
<tr>
<td>2400 hrs.</td>
<td>Exposed C2400E#</td>
<td>853.4</td>
<td>55.16</td>
<td>16.80</td>
<td></td>
</tr>
<tr>
<td>Control C2400C#</td>
<td>849.3</td>
<td>45.96</td>
<td>20.58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4800 hrs.</td>
<td>Exposed C4800E#</td>
<td>809.7</td>
<td>55.87</td>
<td>14.57</td>
<td>Three discarded*</td>
</tr>
<tr>
<td>Control C4800C#</td>
<td>791.0</td>
<td>53.08</td>
<td>16.06</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The specimens that deviated more than 10% of the average from the average were discarded.

5.3 FRP Single Lap Bonded (SLB) Specimens

5.3.1 The state of the art

Crasto and Kim[47] studied the durability of a composite-to-composite joint under simulated outdoor environmental exposure using a double-lap shear test coupon. The specimens were subjected to various combinations of moisture, thermal cycling and fatigue; the residual lap shear strengths were determined at various temperatures. The results were compared with those of unexposed specimens. The specimens were made out of unidirectional multi-layer composite laminates and were bonded using a two-part epoxy adhesive that cures under ambient conditions. One batch of specimens was retained as a control under ambient lab conditions. Another batch of specimens was immersed in water at ambient temperature until they were saturated with moisture, as
determined from periodic measurements of weight gain. The third batch of specimens, immersed in a container of water, was placed in a chamber that was thermally cycled for up to 1000 cycles (200, 400, 600, 800, and 1000) between \(-23^\circ C\) and \(27^\circ C\) (chamber temperature), where the specimens’ temperature cycled between \(-5^\circ C\) and \(20^\circ C\). The thermally cycled specimens were tested at \(23^\circ C\). Failure in all cases was predominantly interfacial with very little adhesive residue on the mating adherends. Contrary to expectations, there was a steady increase in the lap shear strength with thermal cycling until it appears to plateau after about 800 thermal cycles at a value of approximately 15 percent higher than that of the control sample. One possible explanation for this trend is an increase in adhesive strength over time in the thermal cycling chamber. However, from the manufacture’s data, the adhesive achieves 90 percent of its ultimate strength after 24 hours and full strength after three days with a room-temperature cure. The thermal cycling and testing were conducted over several weeks. A more likely explanation is the increase in adhesive toughness with increasing moisture pickup during thermal cycling through plasticization of the resin in its glassy state at room temperature. This conforms to the moisture cured specimens which showed that the lap shear strength at \(23^\circ C\) were 23% higher than corresponding (dry) control specimens.

5.3.2 Current Experimental Study

The Single Lap Bond (SLP) specimens were tested under direct tension and the bonded overlaps experienced a shear-dominated mode of failure. In other words, the FRP-FRP bonds were tested for lap shear strength by subjecting the SLB specimens to direct tension. Three parameters: incremental tension load, incremental head movement, and
incremental lap slip, were recorded by a computer based data acquisition system. Figure 5.18 shows the test set-up.

The bond slip was measured using a 25.4 mm (1 in) clip-gauge. However, the readings from the clip-gauge are not pure slippage of the bonded lap, the tensile elongation of a 25 mm section of the specimens' length is also part of the clip-gauge readings (Figure 5.19). In this 25 mm span there is about 10 mm gap which is bridged by a single layer of FRP panels and the remaining 15 mm is two layer thick FRP where the ends of the overlap and the tab terminate (Figure 4.2 and Figure 5.19). This can be accounted for by using FRP tensile coupons and SLB specimens with no gap between the ends of the overlap and the tab. The data reported here (Figures 5.20 to 5.26) does not include this correction since all the tests were performed with 10 mm gap as shown in Figure 5.19.

The lap shear strength of the specimens was calculated by dividing the applied load by the actual lap bonded area. The lap shear stiffness, the slope of stress-slip curve which is an indication of the stiffness of the bond, was calculated by linearly averaging the data points between 5% and 40% of the maximum lap shear strength.

Figure 5.18: Clip-gauge Mounted FRP SLB Specimen Under Tensile Load
5.3.2.1 Effects of Freeze-thaw Cycles

Figures 5.20 to 5.23 show the average lap shear stress versus lap slip behaviour of SLB specimens. Figure 5.24 to 5.26 and Table 5.3 present summaries of lap shear strength, lap shear stiffness, and lap slip of CFRP and GFRP single lap bonded (SLB) specimens.

The lap shear strength of the GFRP specimens was affected by the freeze-thaw cycles. Although, there existed a wide scatter in the output data, a clear trend was obvious that the average strength of exposed specimens decreased with the increase in the number of freeze-thaw cycles. The strength of control specimens on average did not change much with age.

The lap shear stiffness and lap slip of the exposed GFRP specimens were not affected by the freeze-thaw cycles when compared to their control counterparts. However, it should be mentioned that there existed a very wide scatter in the maximum slip data and to a lesser extent in the stiffness. The maximum variation in slip at peak load was about 60% of the average. In the case of stiffness the variation was up to 27%.
### Table 5.3: Summary of the Test Results for GFRP Single Lap Bonded Specimens Exposed to Freeze-thaw

<table>
<thead>
<tr>
<th>Exposure Condition</th>
<th>Specimen Designation</th>
<th>Max. Lap Shear Strength (MPa)</th>
<th>Lap Shear Stiffness (MPa/mm)</th>
<th>Max. Slip at Rupture (mm)</th>
<th>Comments *</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GFRP SLB Specimens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Cycles Exposed</td>
<td>GL050FE#</td>
<td>5.43</td>
<td>7.83</td>
<td>1.05</td>
<td>Three discarded</td>
</tr>
<tr>
<td>Control</td>
<td>GL050FC#</td>
<td>5.61</td>
<td>7.82</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>100 Cycles Exposed</td>
<td>GL100FE#</td>
<td>5.44</td>
<td>6.99</td>
<td>1.04</td>
<td>Two discarded</td>
</tr>
<tr>
<td>Control</td>
<td>GL100FC#</td>
<td>4.42</td>
<td>7.85</td>
<td>1.10</td>
<td>One discarded</td>
</tr>
<tr>
<td>200 Cycles Exposed</td>
<td>GL200FE#</td>
<td>4.20</td>
<td>7.25</td>
<td>0.95</td>
<td>One discarded</td>
</tr>
<tr>
<td>Control</td>
<td>GL200FC#</td>
<td>5.26</td>
<td>7.87</td>
<td>1.03</td>
<td>Two discarded</td>
</tr>
<tr>
<td>300 Cycles Exposed</td>
<td>GL300FE#</td>
<td>4.53</td>
<td>7.55</td>
<td>1.00</td>
<td>One discarded</td>
</tr>
<tr>
<td>Control</td>
<td>GL300FC#</td>
<td>5.50</td>
<td>7.51</td>
<td>0.99</td>
<td>One discarded</td>
</tr>
<tr>
<td><strong>CFRP SLB Specimens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Cycles Exposed</td>
<td>CL050FE#</td>
<td>7.33</td>
<td>18.15</td>
<td>0.57</td>
<td>Five discarded</td>
</tr>
<tr>
<td>Control</td>
<td>CL050FC#</td>
<td>6.70</td>
<td>18.36</td>
<td>0.42</td>
<td>Three discarded</td>
</tr>
<tr>
<td>100 Cycles Exposed</td>
<td>CL100FE#</td>
<td>6.33</td>
<td>16.76</td>
<td>0.48</td>
<td>Five discarded</td>
</tr>
<tr>
<td>Control</td>
<td>CL100FC#</td>
<td>5.90</td>
<td>16.74</td>
<td>0.49</td>
<td>Two discarded</td>
</tr>
<tr>
<td>200 Cycles Exposed</td>
<td>CL200FE#</td>
<td>5.19</td>
<td>16.95</td>
<td>0.44</td>
<td>Two discarded</td>
</tr>
<tr>
<td>Control</td>
<td>CL200FC#</td>
<td>5.96</td>
<td>16.29</td>
<td>0.54</td>
<td>Three discarded</td>
</tr>
<tr>
<td>300 Cycles Exposed</td>
<td>CL300FE#</td>
<td>5.95</td>
<td>17.43</td>
<td>0.45</td>
<td>Five discarded</td>
</tr>
<tr>
<td>Control</td>
<td>CL300FC#</td>
<td>5.75</td>
<td>17.86</td>
<td>0.48</td>
<td>Two discarded</td>
</tr>
</tbody>
</table>

* The specimens that deviated more than 10% of the average from the average were discarded

Figure 5.20 to 5.23 and Table 5.3 also show that the CFRP SLB specimens were affected in the same manner as the GFRP specimens; however, the range of scatter was wider with CFRP. Besides, a large variety was observed in the mode of the failure of CFRP specimens. A large number of the specimens did not utilize the full width of the bond, because of twisted or slant rovings in the fabric at the overlap (Figures 5.27 and 5.28). The stress values in these specimens were based on the actual area that contributed to the strength and debonded at the failure not based on the total area of the overlap; however, the effect of the size of the lap area on the lap shear strength was not investigated. Previous experiences had shown that the lap shear stress values were different for different length and width of specimen.
Twenty-eight out of one hundred and twenty-eight specimens whose strength values deviated more than 10% from the average were discarded. Meanwhile, the data from the specimens that failed under grip were not used either. These two limitations in CFRP, in some cases, left as few as only three data points to be used for the calculation of the average values (Table 5.3). This is true for CL050FE#, CL100FE#, and CL300FE# specimens. The other values were averaged over at least five specimens.

Figure 5.24 and Table 5.3 show that the lap shear strength of CFRP exposed SLB specimens was affected by the freeze-thaw exposure when compared to the control specimens of the same age. The trend indicates that the strength of the bond increased in the early stages of the exposure but after further exposure it started to deteriorate. The lap shear stiffness in CFRP SLB specimens experienced no changes with the freeze-thaw exposure. However, the amount of lap slip at failure of the exposed specimens decreased compared to their control counterparts.

5.3.2.2 Effect of UV radiation

Figures 5.29 to 5.31 show the lap shear stress versus lap slip behaviour of the SLB specimens exposed to 1200, 2400 and 4800 hours of UV radiation, respectively. Figures 5.32 to 5.34 and Table 5.4 compares the effects of UV radiation on the strength, stiffness, and slip at failure for GFRP and CFRP SLB specimens. The lap shear strengths of GFRP and CFRP specimens were not degraded by the exposure. The values of the lap shear stiffness and the lap slip of the GFRP and CFRP specimens have wide scatters, however,
on average it could be seen, Figures 5.33 and 5.34, that neither the stiffness or the slip was significantly affected by the UV exposure.

Table 5.4: Summary of the Test Results for CFRP and GFRP Single Lap Bonded Specimens Exposed to UV Radiation

<table>
<thead>
<tr>
<th>Exposure Condition</th>
<th>Specimen Designation</th>
<th>Max. Lap Shear Strength (MPa)</th>
<th>Lap Shear Stiffness (MPa/mm)</th>
<th>Max. Slip at Rupture (mm)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GFRP SLB Specimens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hrs Exposed</td>
<td>GL1200E#</td>
<td>5.35</td>
<td>7.04</td>
<td>1.01</td>
<td>6 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>GL1200C#</td>
<td>5.77</td>
<td>6.63</td>
<td>0.98</td>
<td>6 specimens averaged</td>
</tr>
<tr>
<td>2400 hrs Exposed</td>
<td>GL2400E#</td>
<td>5.61</td>
<td>6.26</td>
<td>0.95</td>
<td>8 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>GL2400C#</td>
<td>5.64</td>
<td>7.46</td>
<td>1.00</td>
<td>5 specimens averaged</td>
</tr>
<tr>
<td>4800 hrs Exposed</td>
<td>GL4800E#</td>
<td>5.63</td>
<td>7.59</td>
<td>0.97</td>
<td>6 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>GL4800C#</td>
<td>5.67</td>
<td>7.59</td>
<td>1.02</td>
<td>8 specimens averaged</td>
</tr>
<tr>
<td><strong>CFRP SLB Specimens</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1200 hrs Exposed</td>
<td>CL1200E#</td>
<td>7.32</td>
<td>18.37</td>
<td>0.51</td>
<td>4 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>CL1200C#</td>
<td>7.65</td>
<td>18.84</td>
<td>0.54</td>
<td>4 specimens averaged</td>
</tr>
<tr>
<td>2400 hrs Exposed</td>
<td>CL2400E#</td>
<td>7.50</td>
<td>16.73</td>
<td>0.64</td>
<td>6 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>CL2400C#</td>
<td>6.69</td>
<td>18.91</td>
<td>0.45</td>
<td>4 specimens averaged</td>
</tr>
<tr>
<td>4800 hrs Exposed</td>
<td>CL4800E#</td>
<td>7.32</td>
<td>18.69</td>
<td>0.50</td>
<td>8 specimens averaged</td>
</tr>
<tr>
<td>Control</td>
<td>CL4800C#</td>
<td>7.71</td>
<td>19.02</td>
<td>0.54</td>
<td>8 specimens averaged</td>
</tr>
</tbody>
</table>

It can be concluded that the effect of UV radiation on the bond strength of FRP is minimal. Figures 5.35 and 5.36 show the modes of failure in GFRP and CFRP specimens and Figure 5.37 shows GFRP's colour change due to the UV radiation.
Figure 5.20: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 50 Freeze-thaw Cycles

Figure 5.21: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 100 Freeze-thaw Cycles
Figure 5.22: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 200 Freeze-thaw Cycles

Figure 5.23: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 300 Freeze-thaw Cycles
Figure 5.24: Lap Shear Strength of CFRP and GFRP Single Lap Bonded Specimens Exposed to Freeze-thaw Cycles

Figure 5.25: Lap Shear Stiffness of CFRP and GFRP Single Lap Bonded Specimens Exposed to Freeze-thaw Cycles
Figure 5.26: Lap Slip of CFRP and GFRP Single Lap Bonded Specimens Exposed to Freeze-thaw Cycles
Figure 5.27: Modes of Failure in CFRP Single Lap Bonded Specimens

Figure 5.28: Modes of Failure in CFRP Single Lap Bonded Specimens
Figure 5.29: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 1200 hours of UV radiation

Figure 5.30: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 2400 hours of UV radiation
Figure 5.31: Behaviour of CFRP and GFRP Single Lap Bonded Specimens after Exposure to 4800 hours of UV radiation

Figure 5.32: Lap Shear Strength of CFRP and GFRP Single Lap Bonded Specimens after Exposure to UV Radiation
Figure 5.33: Lap Shear Stiffness of CFRP and GFRP Single Lap Bonded Specimens after Exposure to UV radiation

Figure 5.34: Lap Slip of CFRP and GFRP Single Lap Bonded Specimens after Exposure to UV Radiation
Figure 5.35: Modes of Failure in GFRP Single Lap Bonded Specimens Exposed to 2400 hrs. of UV

Figure 5.36: Modes of Failure in CFRP Single Lap Bonded Specimens Exposed to 2400 hrs of UV
Figure 5.37: Color Changes in GFRP SLB Specimens due to 1200 and 2400 Hours of Exposure to UV Radiation in Comparison to the Unexposed Specimen
5.4 FRP Wrapped Concrete Cylinders

5.4.1 The state of the art
The concept of using FRP wraps for confinement of concrete members is gaining popularity. These materials have been used successfully to provide ductility in earthquake applications. An experimental study was performed at the University of Toronto on rehabilitation of concrete columns damaged by corrosion. In this study a fabric made of E-glass and Kevlar fibers was used to wrap the specimens. The wrapping was accompanied by a number of repair techniques, to determine the most effective procedure. The half scale columns that were repaired showed that FRP could fully recover the strength of corroded columns and enhance their ductility substantially. Additionally, the ductility of the repaired columns was significantly higher than that of the originally undamaged column.

The confinement of concrete by carbon fibre wraps was examined by Slattery and Harmon. They used 100 mm tall x 50 mm in diameter concrete cylinders with compressive strength values ranging from 41 to 103 MPa, and composite reinforcement ratios from 0% to 5%. The compression tests showed that the axial stress-strain curves were bilinear with a yield point somewhat higher than the failure stress of the corresponding unwrapped specimen. Reinforcement ratio had only a slight effect on the ascending portion of the curve, but considerably improved the slope of the second portion (post yield). Increasing the fibre ratio increased the ultimate stress, but had a minor effect on the yield stress. In the carbon fibre wrapped concrete cylinders the amount of ultimate transverse strain increased dramatically after the failure stress of the unconfined
concrete cylinder. The ultimate transverse strain decreased as the circumferential fibre ratio increased. The increase in failure stress was approximately 39 MPa for each percent increase in the ratio of the confining carbon fibre. In addition, the effect of cyclic loading was experimented briefly. The result suggested that cyclic loading had little degradation effect on the wrapped cylinders.

Zanganeh\textsuperscript{50} studied the effect of the CFRP wrap on 100 mm and 200 mm diameter cylinders, having one, two, and three layers of wrapping. 50 mm overlap for the 100 mm diameter and 80 mm overlap for 200 mm diameter cylinders were used. However, later during the compression testing, the overlaps appeared to be insufficient as the specimens failed at the seam. Hence, an additional 100 mm long fibre sheet was installed over the exterior seam, extending 50 mm on each side.

It was found out that the FRP wrap increased the axial load carrying capacity of the concrete cylinders, however, at the peak they had a sudden failure due to the rupture of the CFRP wrap. In general, it was found that the strength of the cylinder increased by adding more wrap layers. One layer of wrap increased the strength of the concrete cylinder by about 10\%. In studying the effects of size on the strength of wrapped cylinders, he found out that with one layer the size effects are not influential and that the 100 mm and 200 mm diameter cylinders had equal strength, but adding more layers increased the strength of the small specimens relative to those of the larger ones. The rate of increase in strength is lower from 2 to 3 layers than from 1 to 2 layers. The results showed more scatter as the number of layers increased.
Karbhari and Eckel\textsuperscript{36} investigated the effect of environmental exposure on the strengthening efficiency of composite-jacketed concrete column stubs. The effects of short-term exposure to ambient and \(0^\circ\text{F} (-18^\circ\text{C})\) conditions as well as to water and sea water on glass-, carbon-, and aramid-epoxy jackets were studied. Concrete cylinders were cast to nominal sizes of 150 mm in diameter x 300 mm tall. The 28 days cured concrete had strength of 52 MPa with an average secant modulus of 5.73 GPa. The CFRP, GFRP, and AFRP were wrapped using wet lay-up technique. The specimens (both concrete and concrete wrapped with the composites) were subjected to one of the four environmental conditions: (1) ambient, (2) water, (3) sea water, and (4) \(0^\circ\text{F}\). In the case of exposure to water and sea water the specimens were immersed 230 mm in the fluid and left until the moisture take-up reached a steady state, 60 days. After the exposure, the specimens were tested under axial compression until failure. The results showed that the damage mechanism in the glass system shows considerable potential for the development of ductile and plastic-like failure modes. The load carrying capacity of the system was only slightly affected by the exposures (less than 8\%). All systems showed increased stiffness with exposure to a \(0^\circ\text{F}\) and water environments. The seawater had a distinct effect on degradation of the fibre-matrix interface; i.e., the diffusion of the solution and the subsequent retention of the salt in the pores and the water by the gel resulted in degradation through formation of cracks and micro cracks. The study emphasized that although composite jackets provide an efficient means of strengthening damaged and functionally deficient columns, there was a need for continued long-term and accelerated environmental testing of the composite systems, as well as the need for
further understanding of the behaviour of the interface between concrete and composites under loading.

Soudki and Green\textsuperscript{38} studied the performance of CFRP wrapped cylinders in the cold weather condition. They tested 150 mm diameter x 300 mm long plain and reinforced columns wrapped with 0, 1, or 2 layers of CFRP, after exposure to a) room temperature (+20\textdegree C), b) low temperature (-18\textdegree C), c) freeze-thaw cycles (-18 to +20\textdegree C), and d) under water. After the exposures the specimens were tested for axial strength and load versus axial and circumferential strain plots were obtained. Based on the results of the study, the following conclusions were drawn: 1) confinement with CFRP wraps appears efficient in strengthening concrete columns; 2) for CFRP wrapped columns at room temperature, 1-layer of wrap increased the strength by 20\%, while 2 layers of wrap increased the strength by 30\%; 3) concrete columns wrapped with one layer of CFRP and exposed to freeze-thaw cycling showed a significant increase in the strength (up to three times) when compared to unwrapped columns exposed to the same conditions. A second layer of CFRP wrap provides an extra 15\% increase in strength; 4) the wrapped columns subjected to freeze-thaw cycles failed in a more catastrophic manner than those kept at room temperature; and 5) low temperature exposure and under water exposure did not affect the strength significantly but affected the failure mode.

Toutanji and Balaguru\textsuperscript{51} studied the performance of concrete columns wrapped with carbon and glass FRP sheets subjected to cycles of wet-dry and freeze-thaw. Concrete columns were wrapped with three different types of FRP tow sheets: two types of carbon
and one type of glass. Test variables included the type of fibers and the exposure conditions. The specimens were conditioned in the following three different environments: 1) room temperature (+20°C); 2) 300 wet-dry cycles using salt water; and 3) 300 freeze-thaw cycles. The result of the study showed that CFRP is superior to GFRP when exposed to harsh environments. Exposure to wet-dry environment had little effect on the compressive strength of CFRP-wrapped specimens; however, exposure improved the stiffness of the specimens. The GFRP-wrapped specimens exposed to wetting and drying exhibited a 10% reduction in strength but showed no changes in stiffness. Exposure to freeze-thaw cycles caused a significant degradation in strength of both CFRP- and GFRP-wrapped specimens. The GFRP-wrapped specimens exhibited a higher degree of degradation as compared to the CFRP-wrapped specimens. The freeze-thaw exposure seems to cause no effects on the stiffness of CFRP- or GFRP-wrapped specimens.

Exposure to wet-dry environment produced no loss in ductility of the specimens wrapped with CFRP; however, reduction was observed in GFRP wrapped specimens. Freeze-thaw cycles caused a significant reduction in ductility of both the CFRP and GFRP wrapped specimens. The wrapped specimens subjected to freeze-thaw cycles exhibited more catastrophic failure behaviour as compared to the unconditioned and the wet-dry conditioned specimens.
5.4.2 Current Experimental Study

The concrete cylinders were tested under direct compression for their mechanical properties (Figure 5.38). Axial and circumferential strain values were measured using bonded strain gauges for one third of the specimens that were tested at U of T testing facilities (Figure 5.39). Using the results of the strain gauged cylinders, the data from the cylinders without stain gauges were adjusted to account for the excessive deformation of the cylinder ends. The cord modulus of elasticity and the energy absorbing capacity of the specimens were calculated and are summarized in Table 5.5. The chord modulus of elasticity was obtained by fitting a straight line through the data points between 10% and 40% of the maximum strength on the stress-strain curve. The absorbed energy is the area under stress-strain curve up to the ultimate stress in units of energy per unit volume (N·m/mm³). The wrapped specimens did not show any post peak stress-strain behaviour. The failure was sudden, especially in CFRP wrapped cylinders, whether the testing was carried out under load control or displacement control. The stress-strain curves for both the CFRP and the GFRP cylinders were somewhat bilinear with a yield point almost equal to the failure stress of the unwrapped control specimens. This yield point was more pronounced in the case of GFRP wrapped cylinders, in which the stress has a post yield drop resembling ductile steel.

Wrapping concrete cylinders with FRP is an effective and easy way of increasing the load carrying capacity of the cylinders. Table 5.5 shows that on average one layer of CFRP wrap increases the compressive strength of a 75 mm diameter x 150 mm long concrete cylinder by a factor of about 1.8. This increase in strength with a GFRP wrap is on
Figure 5.38: CFRP Wrapped Cylinder Failed under Compression

Figure 5.39: GFRP Wrapped Concrete Cylinder Axially and Circumferentially Strain Gauged under Compression
average by a factor of about 1.3 to 1.4. The average energy absorbing capacity of the control cylinders increased by a factor of about 14 with CFRP wrap and by a factor of about 11 with GFRP wrap.

Figures 5.40 to 5.43 show the stress-strain behaviour of CFRP and GFRP wrapped and unwrapped concrete cylinders. One structurally important behaviour of the CFRP and GFRP passive wrap is that the stiffness of a concrete cylinder remains unchanged up to the failure stress of the unwrapped concrete cylinder. The circumferential and axial strains of wrapped cylinders at the peak load were much higher than that of the unwrapped cylinders. Table 5.5 shows that the circumferential deformations increased by a factor of up to about 8 for the CFRP wrapped and up to about 12 for GFRP wrapped cylinders. The axial deformations increase by factors of about 7 and 6 for CFRP and GFRP, respectively. Figure 5.44 shows the circumferential strains versus the axial strains of wrapped and unwrapped cylinders. It can be seen that up to a strain value of about 75% of the maximum strain of the unwrapped concrete cylinders, all specimens (wrapped and unwrapped) behaved linearly elastic with a Poisson ratio of about 0.26. Afterward, the circumferential strain increased with a much higher rate. This rapid increase in circumferential strain can be attributed to the growth of internal cracks in the concrete cylinders. From the figure it can be concluded that the stress induced cracks grow wider in the GFRP wrapped cylinders than in the CFRP wrapped cylinders. This is because GFRP has lower modulus of elasticity than CFRP and allows more lateral expansive of the concrete cylinders.
Table 5.5. Summary of the Test Results for Plain and C/G-FRP Wrapped Concrete Cylinders Exposed to Freeze-thaw

<table>
<thead>
<tr>
<th>Exposure Condition</th>
<th>Specimen Designation</th>
<th>Max. Strength (MPa)</th>
<th>Absorbed Energy (Nmm/m²)</th>
<th>Circum. Strain at Peak Load ($\times 10^{-3}$)</th>
<th>Axial Modulus of Elasticity</th>
<th>Axial Strain at Peak Load ($\times 10^{-3}$)</th>
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<tr>
<td>50 Cycles</td>
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<td>0.061</td>
<td>0.80</td>
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<tr>
<td></td>
<td>Control</td>
<td>UC050FC#</td>
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<td>0.73</td>
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<td>Control</td>
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</tr>
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<tr>
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<td>Exposed</td>
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<td>1.111</td>
<td>11.95</td>
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</tr>
<tr>
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<td>1.104</td>
<td>10.64</td>
<td>33.9</td>
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</tbody>
</table>

Before looking into the effects of the exposure to freeze-thaw cycles on the mechanical properties of concrete cylinders, it should be mentioned that the freeze-thaw chambers broke down while the cylinders were being exposed. During the 75 days that the chamber was out of function, the exposed specimens were kept in water at room temperature while the control specimens stayed under the room conditions. The age of
Figure 5.40: Compressive Stress-Strain Behavior of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders Exposed to 50 Freeze-Thaw Cycles

Figure 5.41: Compressive Stress-Strain Behavior of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders Exposed to 100 Freeze-Thaw Cycles
Figure 5.42: Compressive Stress-Strain Behavior of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders Exposed to 200 Cycles of Freeze-Thaw

Figure 5.43: Compressive Stress-strain Behavior of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders Exposed to 300 Cycles of Freeze-Thaw
Figure 5.44: Circumferential versus Axial Strains of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders

Figure 5.45: Absorbed Energy in CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw
Figure 5.46: Stored Energy in CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw

Figure 5.47: Modulus of Elasticity of CFRP and GFRPWrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw
Figure 5.48: Circumferential Strain of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw

Figure 5.49: Axial Compressive Strain of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders after Exposure to Freeze-thaw
the specimens is calculated from the day they were put into the freeze-thaw chamber; i.e., after first exposure. All of the specimens were wrapped after 28 days of moist curing. The warps were allowed to cure for 6 days before the exposure sequence began. In Figures 5.45 to 5.49 the scale on the horizontal axes shows the number of freeze-thaw cycles. The axes also contain the age of the specimens at the time of the test. The age corresponds to the number of days between the time of the first exposure and the time of the test. As mentioned before the two freeze-thaw chambers broke down while the specimens were under exposure. The two chambers did not break down at the same time; therefore, the number of the cycles and the age since the first exposure are not linearly related. However, all specimens that were exposed to 50, 100, 200, or 300 cycles had the same age at the time of the test.

Figure 5.45 to 5.49 compare the axial compressive strength, the energy absorbing capacity, the modulus, and the circumferential and axial strains of the wrapped and unwrapped concrete cylinders exposed to different number of freeze-thaw cycles with their control counterparts.

The strength of exposed unwrapped cylinders dropped by about 15% to 20% with the 300 freeze-thaw cycles when compared to their unexposed counterparts. The energy absorbing capacity of the unwrapped cylinders decreased significantly with the increase in the number of freeze-thaw cycles. The modulus of elasticity (Figure 5.47) of unwrapped cylinders on average was only slightly affected by the exposure.
Figures 5.45 to 5.49 and Table 5.5 show the effects of freeze-thaw exposure on the mechanical properties of the GFRP wrapped cylinders. The exposed GFRP wrapped specimens experienced up to 10% loss in strength when compared to their control partners. However, it should be noted that the scatter in the strength values ranged up to 8%. The energy absorbing capacity was affected slightly by the exposure, but considering the scatter, the effects are negligible. No significant changes were observed in the modulus of elasticity of the GFRP wrapped cylinders with the exposure when compared to their control counterparts, however, the axial strain values at peak load exhibited an increase as the number of freeze-thaw cycles increased. This increase was up to 8% of the axial strain of control specimens. Figure 5.47 shows that the circumferential strains of control GFRP wrapped specimens increased with age, but this change is more due to the scatter in the strain gauge readings than due to the freeze-thaw exposure.

From Figures 5.45 to 5.49 and Table 5.5, it can be seen that the CFRP wrapped cylinders experienced no negative changes in their mechanical properties due to the exposure to the freeze-thaw cycles. Figures 5.45 shows that the energy absorbing capacity of the CFRP wrapped cylinders exposed to 50 and 100 freeze-thaw cycles dropped, however, this difference between the control and the exposed specimens is mainly due to the scatter in the strain gauge readings close to the failure of the specimens.

As it was described in the specimen preparation, all specimens had an overlap of 100 mm. This length was chosen to avoid the pealing-off of the wrap, as reported by Zanganeh, and utilize the maximum strength of the FRP. As shown in Figures 5.50 and
Figure 5.51, mode of failure in all of the specimens tested in this study was the rupture of the FRP, as planned and desired. At the peak loads, the maximum circumferential strain values conform to the maximum strain values of the FRP tensile coupons (For the stress-strain curves of individual specimens please refer to the Appendices). The CFRP tensile coupons failed at about 19 milli-strains and the maximum CFRP strain in the wrapped cylinders was measured to be in the range of 15 milli-strains. The GFRP coupon’s peak load was reached at about 23 milli-strains, and the maximum GFRP strains measured in the cylinders was in the range of 21 milli-strains. It should be noted that the FRP strains measured in the cylinders were not at the location of FRP rupture where the strain would be higher, but they were the averages measured by strain gauges over a 60 mm length of FRP hoop.

From the test results, it can be stated that one layer of CFRP and GFRP wraps increased the load carrying capacity of concrete cylinders by factors of about 1.8 and 1.4, respectively. The ultimate strength was achieved when the FRP wrap reached its failure strain. The freeze-thaw cycles had a minimal effect on the residual strength of the FRP wrapped cylinders, but the strength of unwrapped cylinders was reduced significantly after the 300 cycles of the freeze-thaw. The energy absorbing capacity of the concrete cylinders increased by factors of more than ten when wrapped with the FRP. The modulus of the concrete cylinders did not change much due to FRP wrapping.
Figure 5.50: Modes of Failure in GFRP Wrapped Concrete Cylinders Exposed and Control for 50 Freeze-thaw Cycles

Figure 5.51: Modes of Failure in CFRP Wrapped Concrete Cylinders Exposed and Control for 50 Freeze-thaw Cycles
5.5 FRP Bonded Concrete Prisms

5.5.1 The state of the art

Chajes et al.\(^5\) studied the bond strength and force transfer of graphite/epoxy composite material plates adhered to concrete using a single-lap shear test specimen. Using test specimens with a constant bond length, the influence of the surface preparation of the concrete, adhesive type, and concrete strength on the overall bond strength was studied. The test specimens consisted of a 25.4-mm-wide composite plate bonded to a concrete block (150-mm-wide x 150-mm-high x 225-mm-long) with a 75-mm bond length (Figure 5.52). To determine the characteristics of force transfer from the plate into the concrete, additional bond tests (with bond length varying from 50 to 200 mm) were conducted. From the test results the following conclusions were drawn:

1. Surface preparation of the concrete can influence the ultimate bond strength. To achieve the best possible bond, the concrete surface should be mechanically abraded or sand blasted, and a primer should be applied.
2. An “off-the-shelf” epoxy can be effectively used to bond composite material plates to concrete.
3. If the failure mode of the joint is governed by shearing of the concrete directly beneath the bond, the value of the ultimate bond strength will be proportional to $\sqrt{f'_c}$.

4. The strain in the composite plate along the bonded length decreases at a fairly linear rate (specially at or below service load levels), meaning the force transfer is largely uniform. This leads to a constant value of bond resistance ($R$).

5. There is a bond development length $L_{jd}$ for a joint, beyond which no further increase in failure load can be achieved.

6. For a joint having a bond length $L_b$ the ultimate capacity $T_u$ can be approximated by
   \[ T_u = RL_b \quad L_b < L_{jd} \]
   \[ T_u = RL_{jd} \quad L_b \geq L_{jd} \]

Yoshizawa et al.\(^{53}\) studied the influence of carbon fibre sheet (CFS) and concrete bonding condition on the reinforcement of concrete structures. The variables were the method of concrete surface preparation (water jet and sander), the kind of carbon fibre, and area debonding rate under bond strength tests. Besides, the relationship between surface preparation and beam flexural strength was studied through four points bending test of beams with the same surface conditions. The specimens for the bond test were (100 x 100 x 620 mm) concrete prisms in which a M24 bolt was driven at both ends as the grip for tension test, and a notch was carved in the centre of the specimen (Figure 5.53). Then a 50 mm wide CFS was bonded on the two opposite surface of the specimen by means of epoxy resin adhesive.
Figure 5.53: Specimens for testing FRP-concrete bond

Figure 5.54: Configuration of adhesive test specimens
They concluded that the surface treatment by water jet greatly increases the bonding strength of the concrete and the CFS. Beam bending tests showed that the treatment improves proof stress as well as deformation performance. Besides, it was revealed that the artificial debonding of the CFS, up to 10% in area ratio, has no influence on bonding strength.

Iketani and Jinno\textsuperscript{54} examined the adhesive properties of a carbon fibre sheet (CFS) bonded to the concrete surface in terms of effects brought on this bond by differences in the strength of concrete, in the length of bonded strip, and in the number of sheet layers pasted. The specimens were made of ordinary and high-strength concrete cast in wooden form to 100 x 100 x 300 mm and 100 x 100 x 600 mm sizes (Figure 5.54). Through the specimens axis a 19 mm diameter shaft was embedded. Pairs of specimens, positioned end to end, were joined together with strips of either single or triple layered CFS pasted with the epoxy resin. In one pair of test specimens, strain gages were fixed on to the sheet surface at 50 mm intervals for measuring strain during test. The specimens were tested in tension after the concrete aged at least 28 days and the epoxy resin aged 7 days.

The study concluded the followings:

1. Proof load (failure load) was relatively little influenced by difference in the concrete strength

2. Increasing the number of layers, on the other hand, enhanced the rigidity of the sheet and distributed the stress over a wider area to raise the proof load
3. Prolonging the length of strip beyond 100 mm did not contribute appreciably to enhancing proof load.

4. The stress imparted to the strip was gradually transmitted toward the extremes of the test specimen, as the sheet peeled off in successive sections, until final parting.

Kobatake et al.\textsuperscript{23} studied the development length (Figure 5.55), the development length of lap (Figure 5.56), and the bond durability of UV exposed carbon fibre sheet (CFS) bonded to concrete (Figure 5.57). The test results are shown in Tables 5.6 and 5.7 and Figure 5.58.

**Table 5.6: The CFS development length.\textsuperscript{23}**

<table>
<thead>
<tr>
<th>$L$ (mm)</th>
<th>Maximum Load (kN)</th>
<th>The state of damage</th>
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</thead>
<tbody>
<tr>
<td>40</td>
<td>11.0</td>
<td>Carbon fibre peels off</td>
</tr>
<tr>
<td>100</td>
<td>13.6</td>
<td>Carbon fibre peels off</td>
</tr>
<tr>
<td>200</td>
<td>14.9</td>
<td>Carbon fibre breaks</td>
</tr>
</tbody>
</table>

**Table 5.7: Development length of lapped joint.\textsuperscript{23}**

<table>
<thead>
<tr>
<th>$L$ (mm)</th>
<th>Maximum Load (kN)</th>
<th>The state of damage</th>
</tr>
</thead>
<tbody>
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<td>40</td>
<td>11.8</td>
<td>Carbon fibre peels off</td>
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<tr>
<td>100</td>
<td>16.5</td>
<td>Carbon fibre breaks</td>
</tr>
<tr>
<td>200</td>
<td>16.3</td>
<td>Carbon fibre breaks</td>
</tr>
</tbody>
</table>

From the results it was calculated that the CFS development length should be more than 200 mm, and that the CFS lapped joint length should be more than 100 mm. The results from the UV exposure indicated that the adhesive strength between concrete surface and CFS decreased with the time of exposure, a decrease of about 10\% at 2,000 hours and about 15\% at 4,000 hours compared with the non-exposed specimen was observed (Figure 5.58).
Dolan et al. studied the effectiveness of bonded CFRP laminates. The program examined the tensile strength of the CFRP laminate; the bond between the CFRP and the concrete; the effectiveness of CFRP on shear-friction test specimens developed by Mast; and development of modified shear-friction test specimens.

The tensile capacity of the aluminium tabbed CFRP laminates was tested. The tensile capacity and the modulus of elasticity were found to be 170 kN and 163 GPa (for a 500 mm long, 50 mm wide, and 1.3 mm thick specimen), respectively. The bond between CFRP and the concrete was determined using a push-apart test. The test consisted of two 150 mm concrete cubes and two bonded laminates (Figure 5.59). The end lap of all laminates was 100mm. The average lower-bound bond strength of the lap was 3.6 MPa. The shear-friction (Figure 5.60) test failed to produce the desired results due to the failure of concrete block ends. The modified shear-friction test using Iosipescu shear test (Figure 5.61) proved adaptable to their study. The concrete shear specimens were tested as control and reinforced with CFRP laminates with bond lengths of 75 mm, 115mm, and 250 mm. Additional samples with two layers of laminates on both sides were tested as well. They concluded that for small connections, reinforcement with externally bonded CFRP laminates provides a predictable shear capacity gain in the concrete.

Green and Soudki studied the performance of FRP laminate-reinforced concrete beams exposed to 50 cycles of freeze-thaw between -18°C and +18°C. The beams were reinforced by FRP laminates for flexural and shear strength and tested at room
Figure 5.55: Specimens for test on carbon fiber development length

Figure 5.56: Specimen for carbon fiber development length of lapped joint

Figure 5.57: Specimens for testing durability of UV exposed carbon fiber bond to concrete
Figure 5.58: Maximum load-time of accelerated UV exposure relationship\textsuperscript{23}

Figure 5.59: Push-apart bond test\textsuperscript{25}
Figure 5.60: Matt/Matlock shear-friction test specimen^55

Figure 5.61: Iosipescu shear test sample^55
temperature. The result of their study showed that the bond between the concrete and the FRP did not appear to be damaged by the exposure to the freeze-thaw cycles.

5.5.2 Current Experimental Study

The FRP-bonded concrete prisms (Figure 4.4) were used to study the durability of the bond between the FRP and the concrete as affected by exposure to the cycles of freeze-thaw. The specimens were tested by applying tension at the ends of the embedded bolts. Pulling apart the bolts causes the FRP-Concrete interface to shear. The bond failure took place at the epoxy-concrete interface. In some specimens, small chips of concrete broke off from the surface of the concrete. Table 5.8 shows that the average lap shear strength of the CFRP bonded specimens is about 3.40 MPa and of the GFRP bonded specimens is about 2.50 MPa. The reason for a lower GFRP-to-Concrete lap shear strength than that for CFRP-to-Concrete can be partly attributed to the texture of the particular fabric used in this study. The weft in CFRP fabric is very fine and gives the fabric a flat surface, where the GFRP fabric is woven with much thicker Kevlar weft and the fabric surface is very wavy. This can result in lesser GFRP area available to the bond. The epoxy may be too fluid to stay in place and fill the wavy gaps under the sheet. The voids under the GFRP strips could be seen in the tested specimens. Another possible reason can be the stiffness of the fabrics. The GFRP has a lower modulus of elasticity and, thus, deforms more under the same load than the CFRP. This can force the epoxy in the bond to deform more and reach its shear failure strain much quicker under the GFRP than under the CFRP.
Table 5.8: Summary of the Test Results for FRP Lap Bonded Concrete Prisms Exposed to Freeze-thaw

<table>
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<th>Stiffness MPa/mm</th>
<th>Slip at failure (mm)</th>
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</tr>
<tr>
<td><strong>CFRP Lap</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 Cycles Exposed</td>
<td>CP050FE#</td>
<td>3.23</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Control CP050FC#</td>
<td>3.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 Cycles Exposed</td>
<td>CP100FE#</td>
<td>3.25</td>
<td>56.4</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Control CP100FC#</td>
<td>3.37</td>
<td>60.3</td>
<td>0.55</td>
<td></td>
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</tr>
<tr>
<td>200 Cycles Exposed</td>
<td>CP200FE#</td>
<td>3.24</td>
<td>63.1</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Control CP200FC#</td>
<td>3.34</td>
<td>72.3</td>
<td>0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 Cycles Exposed</td>
<td>CP300FE#</td>
<td>3.20</td>
<td>67.4</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>Control CP300FC#</td>
<td>3.55</td>
<td>74.5</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As shown in Figure 5.62, concrete in some of the prisms exposed to 200 and 300 freeze-thaw cycles cracked. However, none of the cracks caused debonding at the FRP-concrete interface, and were repaired with epoxy. Out of the 32 FRP bonded prisms that were exposed to freeze-thaw cycles, two CFRP bonded specimens were discarded. One was too damaged to be tested and another one failed prematurely. It should be mentioned that while the specimens for 200 and 300 freeze-thaw cycles were undergoing exposure, the freeze-thaw chamber broke down twice. The specimens were left in the water while their respective control counterparts were kept under room conditions. In total, the 200 and 300 cycles exposed specimens were in the water at room temperature for 12 and 87 days, respectively. Additionally, for 7 days the specimens exposed to 200 and 300 cycles were taken to dry room condition for repair of the freeze-thaw induced cracks in the concrete.
The slip of the specimens was measured by mounting LVTD's on the short leg of specimens (Figure 5.63 and 5.64). The LVTD's recorded the amount of the slip between the FRP panel and the concrete block in millimetre. Figures 5.65 to 5.68 show some of the tested specimens and their modes of failure.

![Figure 5.62: Freeze-thaw Damaged Concrete Prisms](image)

Figures 5.69 to 5.72 show the lap shear stress versus lap slip of the tested specimens. It should be mentioned that in the 50 freeze-thaw cycles exposed specimens, the elongation of the FRP over the debonding tape interfered with the slip value readings due to improper installation of LVTD’s. Except in Figure 5.67, i.e. the 50 freeze-thaw exposed specimens, the stress-slip curves resemble ductile steel. Each curve displays an elastic range followed by a plastic range. The FRP laps on the two sides of each prism had different slip values, due to possible bending of the prism; however, the average slip
Figure 5.63: GFRP Bonded Prism under Loading with LVDT's Installed to Measure the Lap Slip

FRP Lap Bonded Prism
View Showing the location of LVDT's

Figure 5.64: FRP Bonded Prism under Loading with LVDT's installed to measure the bond slip
Figure 5.65: GFRP Lap Bonded Prism Exposed to 50 Freeze-thaw Cycles after Strength Test

Figure 5.66: CFRP Lap Bonded Prism Exposed to 50 Freeze-thaw Cycles after Strength Test
Figure 5.67: GFRP Lap Bonded Prism Exposed to 300 Freeze-thaw Cycles after Strength Test

Figure 5.68: CFRP Lap Bonded Prism Exposed to 300 Freeze-thaw Cycles after Strength Test
Figure 5.69: Behavior of CFRP and GFRP Lap Bonded Concrete Prisms Exposed to 50 Freeze-thaw Cycles

Figure 5.70: Behavior of CFRP and GFRP Lap Bonded Concrete Prisms Exposed to 100 Freeze-thaw Cycles
Figure 5.71: Behavior of CFRP and GFRP Lap Bonded Concrete Prisms Exposed to 200 Freeze-thaw Cycles

Figure 5.72: Behavior of CFRP and GFRP Lap Bonded Concrete Prisms Exposed to 300 Freeze-thaw Cycles
Figure 5.73: Lap Shear Strength of CFRP and GFRP to Concrete after Exposure to Freeze-thaw Cycles

Figure 5.74: Lap Shear Stiffness of CFRP and GFRP to Concrete after Exposure Freeze-thaw Cycles
Figure 5.75: Lap Slip of CFRP and GFRP to Concrete after Exposure Freeze-thaw Cycles
value of two sides, as show in Appendix D, was almost identical for all four prisms of a batch. Figures 5.73 to 5.75 compare the effects of freeze-thaw on lap shear strength, lap shear rigidity, and lap slip at failure of the FRP bonded concrete prisms with their control counterparts. The lap-shear stiffness and lap slip for the 50 cycles exposed and control specimens could not be calculated due to the improper installation of the LVTD's. The lap shear stiffness values for 100, 200 and 300 freeze-thaw cycles exposed specimens have a wide scatter; therefore, they could not be easily used to quantify the effects of freeze-thaw exposure. It is recommended that they should be studied in future using different instrumentation set-ups.

Table 5.8 and Figure 5.73 show that on average the lap-shear strength of GFRP specimens dropped only slightly due to the freeze-thaw exposure when it is compared to the strength of control specimens. Due to the wide scatter, it is difficult to evaluate the effects of freeze-thaw exposure on the lap shear rigidity and lap shear slip. The effect, however, seems minimal. On average the GFRP-to-concrete bonded lap slipped by about 0.72 mm before the failure.

The effects of freeze-thaw on the CFRP bond are a slightly more than on the GFRP bonds. Table 5.8 and Figure 5.73 show that on average the lap shear strength of CFRP bonded specimens dropped by about 5% with the freeze-thaw exposure. Due to the wide scatter, the lap shear rigidity and lap shear slip were not used to evaluate the effects of freeze-thaw exposure. On average the CFRP-to-concrete bonded lap slipped by about 0.50 mm before the failure.
The FRP panels on each side of the specimens had two bonded lengths, i.e. 115 mm (the short leg) and 140 mm (the long leg). The difference of length was aimed to cause failure on the instrumented short leg. This was decided, after some trial specimens were tested. However, during the actual test it was observed that some of the specimens failed in the long leg, which was later remedied by using C-clamps to strengthen the long leg.

The average axial load carried under tension was about 18.5 kN for CFRP bonded and 13.0 kN for GFRP bonded prisms. This load is distributed into two 25 mm wide FRP panels, thus approximately each CFRP panel receives 9.3 kN and GFRP panel 6.5 kN of load. From the FRP tensile test it was seen that the average loads carried by CFRP and GFRP coupons are about 22 kN and 13.7 kN, respectively. This indicates that the 100 mm long lap length of FRP-to-Concrete fails only under less than half of the FRP’s load maximum strength. Therefore, it can be concluded that the 100 mm lap length between FRP and concrete is not enough for the FRP to develop its full strength. This is in agreement with the study by Kobatake et al. where three different lengths were tested. In their study, the specimens with 40 and 100 mm development length failed in the bond, but the one with 200 mm development length failed in the CFRP strip.

It can be concluded that the exposure to freeze-thaw cycles affects the mechanical properties of FRP-to-concrete bond. However, the effect is very small when the scatter in the test data is taken into account. Detailed instrumented testing, however, needs to be conducted before final conclusion can be drawn with regards to the shear lap stiffness.
Chapter 6

Conclusions and Recommendations

6.1 Introduction

This chapter presents the conclusion of this thesis. The results obtained from the experimental program are summarized here. The aspects of the research that are found to need further studies are pointed out and some further investigations have been recommended.

6.2 Conclusions

Concerns about the long-term performance of fibre reinforced polymers (FRP) have increased with the increase in the number of FRP applications in concrete structures. Therefore, it is vital to study the long-term mechanical performance of the FRP materials exposed to harsh environments.

The tensile properties of carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP), their bond properties, confinement efficiency, and the properties of their bond with concrete were studied for their resistance to freeze-thaw cycles. Besides, the effects of UV radiation on the tensile and bond properties of CFRP
and GFRP were evaluated. Four types of specimens - i.e. FRP coupons, FRP single lap bonded specimens, FRP wrapped concrete cylinders, and FRP bonded concrete prisms - were prepared and exposed to 50, 100, 200, and 300 cycles of freeze-thaw. The FRP coupons and single lap bonded specimens were also exposed to 1200, 2400, and 4800 hours of UV radiation. The conclusions from the study are summarized as follow:

- CFRP and GFRP coupons exposed to up to 300 freeze-thaw cycles or 4800 hours of UV radiation experienced very little negative changes in their mechanical properties.

- CFRP and GFRP single lap bonded specimens exhibited about 15% loss in their lap shear strength with the exposure to 300 freeze-thaw cycles, but no changes were observed in their lap shear stiffness.

- The effect of up to 4800 hours of UV radiation on the bond properties of CFRP and GFRP single lap bonded specimens was negligible. Only a slight discoloration on the exposed surface of the epoxy matrix was visible.

- Unwrapped concrete cylinders lost about 15% to 20% of their axial compressive strength when exposed to 300 freeze-thaw cycles. Their energy absorbing capacity decreased significantly. However, no changes were observed in their initial modulus of elasticity.

- GFRP wrapped concrete cylinders experienced a slight loss in their axial compressive strength and energy absorbing capacity when subjected to 300 freeze-thaw cycles. However, the changes were small considering the amount
of scatter in the test results. No changes in the initial modulus of elasticity of GFRP wrapped cylinders were observed.

CFRP wrapped cylinders experienced almost no changes in their axial compressive strength when exposed to freeze-thaw cycles. The energy absorbing capacity was not affected much either. However, a wide scatter was observed in the values of energy absorbing capacity of all the cylinders tested. The modulus of elasticity of CFRP wrapped concrete cylinders was not any different from those of GFRP wrapped and unwrapped cylinder and was not affected by the freeze-thaw exposure either.

The lap shear strength of CFRP and GFRP panels bonded to concrete prisms was slightly affected by the exposure to 300 freeze-thaw cycles. However, the changes on average remained below 5% of the strength of the control specimens. The lap shear stiffness and lap shear slip values of the CFRP and GFRP bonded prisms had large scatters and could not be readily used to quantify the effects of freeze-thaw exposure. However, on average the effects of the exposure seem to be small.

From the results of the study it can be concluded that CFRP and GFRP and their bonds are resistant to the freeze-thaw cycles and UV radiation. On average the change in the tensile strength of the coupons, bond strength of the single lap bonded specimens, compressive strength of wrapped cylinders, and bond strength of CFRP and GFRP panels to concrete prisms were small considering the scatter in the test data. The effects of the exposure can be considered within a small range. The CFRP and GFRP specimens tested
here showed great potential in strengthening concrete member and excellent resistance to harsh environments.

6.3 Recommendations

This study brought several points to the attention that are important to be noted for future research work. A few of these are mentioned below.

The single lap bonded specimens should be tested with less than 100 mm bond lengths and various widths, to quantify the effects of the size (bond area) on the bond properties. Lengths longer than 100 mm may not be useful as the failure shifts from the bond to the material. In single lap bonded specimens, attention should be paid in alignment of the fibre rovings. Slanted and twisted rovings can cause scatter in the test results.

The FRP lap bonded concrete prisms did not develop the full strength of the FRP panels. The specimen with various lap lengths should be tested to find the optimum overlap length for the type of the fabric used. The lap shear slip and lap shear stiffness of the FRP bonded prisms need to be studied further with different instrumentation set-up.
Reference:


Appendix A

Force-Strain Behaviour of CFRP and GFRP Tensile Test Coupons
Figure A5: CFRP Coupons Exposed to 200 Freeze-thaw Cycles

Figure A6: CFRP Control Coupons for 200 Freeze-thaw Cycles

Figure A7: CFRP Coupons Exposed to 300 Freeze-thaw Cycles

Figure A8: CFRP Control Coupons for 300 Freeze-thaw Cycles
Figure A 9: GFRP Coupons Exposed to 50 Freeze-thaw Cycles

Figure A10: GFRP Control Coupons for 50 Freeze-thaw Cycles

Figure A11: GFRP Coupons Exposed to 100 Freeze-thaw Cycles

Figure A12: GFRP Control Coupons for 100 Freeze-thaw Cycles
Figure A13: GFRP Coupons Exposed to 200 Freeze-thaw Cycles

Figure A14: GFRP Control Coupons for 200 Freeze-thaw Cycles

Figure A15: GFRP Coupons Exposed to 300 Freeze-thaw Cycles

Figure A16: GFRP Control Coupons for 300 Freeze-thaw Cycles
Figure A17: CFRP Coupons Exposed to 1200 hrs. UV Radiation

Figure A18: CFRP Control Coupons for 1200 hrs. UV Radiation

Figure A19: CFRP Coupons Exposed to 2400 hrs. UV Radiation

Figure A20: CFRP Control Coupons for 2400 hrs. UV Radiation
Figure A25: GFRP Coupons Exposed to 2400 hrs of UV Radiation

Figure A26: GFRP Control Coupons for 2400 hrs of UV Radiation

Figure A27: GFRP Coupons Exposed to 4800 hrs of UV Radiation

Figure A28: GFRP Control Coupons for 4800 hrs of UV Radiation
Appendix B

Lap Shear Stress-Lap Slip Behaviour of CFRP and GFRP Single Lap Bonded Specimens
Figure B9: GFRP SLB Specimens Exposed to 50 Freeze-thaw Cycles

Figure B10: GFRP Control SLB Specimens for 50 Freeze-thaw Cycles

Figure B11: GFRP SLB Specimens Exposed to 100 Freeze-thaw Cycles

Figure B12: GFRP Control SLB Specimens for 100 Freeze-thaw Cycles
Figure B13: GFRP SLB Specimens Exposed to 200 Freeze-thaw Cycles

Figure B15: GFRP SLB Specimens Exposed to 300 Freeze-thaw Cycles

Figure B14: GFRP Control SLB Specimens for 200 Freeze-thaw Cycles

Figure B16: GFRP Control SLB Specimens for 300 Freeze-thaw Cycles
Figure B17: CFRP SLB Specimens Exposed to 1200 hrs of UV Radiation

Figure B18: CFRP Control SLB Specimens for 1200 hrs. of UV Radiation

Figure B19: CFRP SLB Specimens Exposed to 2400 hrs. UV Radiation

Figure B20: CFRP Control SLB Specimens for 2400 hrs. of UV Radiation
Figure B21: GFRP SLB Specimens Exposed to 1200 hrs of UV Radiation

Figure B22: GFRP Control SLB Specimens for 1200 hrs. of UV Radiation

Figure B23: GFRP SLB Specimens Exposed to 2400 hrs. of UV Radiation

Figure B24: GFRP Control SLB Specimens for 2400 hrs. of UV Radiation
Figure B25: GFRP SLB Specimens Exposed to 4800 hrs of UV Radiation

Figure B26: GFRP Control SLB Specimens for 4800 hrs. of UV Radiation

Figure B27: CFRP SLB Specimens Exposed to 4800 hrs. UV Radiation

Figure B28: CFRP Control SLB Specimens for 4800 hrs. of UV Radiation
Appendix C

Stress-Strain Behaviour of CFRP and GFRP Wrapped and Unwrapped Concrete Cylinders
Figure C1: Unwrapped Concrete Cylinders Exposed to 50 F-T Cycles

Figure C2: Unwrapped Control Concrete Cylinders for 50 F-T Cycles

Figure C3: Unwrapped Concrete Cylinders Exposed to 100 F-T Cycles

Figure C4: Unwrapped Control Concrete Cylinders for 100 F-T Cycles
Figure C5: Unwrapped Concrete Cylinders Exposed to 200 F-T Cycles

Figure C6: Unwrapped Concrete Cylinders Exposed to 300 F-T Cycles

Figure C7: Unwrapped Control Concrete Cylinders for 300 F-T Cycles
Figure C12: CFRP Wrapped Cylinders Exposed to 200 F-T Cycles

Figure C14: CFRP Wrapped Cylinders Exposed to 300 F-T Cycles

Figure C13: CFRP Wrapped Control Cylinders for 200 F-T Cycles

Figure C15: CFRP Wrapped Control Cylinders for 300 F-T Cycles
Figure C16: GFRP Wrapped Cylinders Exposed to 50 F-T Cycles

Figure C18: GFRP Wrapped Cylinders Exposed to 100 F-T Cycles

Figure C17: GFRP Wrapped Control Cylinders for 50 F-T Cycles

Figure C19: GFRP Wrapped Control Cylinders for 100 F-T Cycles
Fm-
GPRP)
Wroppad
Cylinders
Expoaed
to
200 F-T
Cycles

Fm-
C21:
GFRP
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Cycles

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Expod
to 300 F-T
Cycles

Fm-
C23:
GFRP
Wrappeû
Control
Cyiinders
for 300 F-T
Cycles

* These specimens, number three in each set, were instrumented with axial and circumferential strain gauges
Figure C24: Unwrapped Concrete Cylinders Exposed to 50 F-T Cycles

Figure C25: Unwrapped Control Concrete Cylinders for 50 F-T Cycles

Figure C26: Unwrapped Concrete Cylinders Exposed to 100 F-T Cycles

Figure C27: Unwrapped Control Concrete Cylinders for 100 F-T Cycles
Concrete Cylinders Exposed to 200 F-T Cycles

Figure C28: Unwrapped Concrete Cylinders Exposed to 200 F-T Cycles

Concrete Cylinders Exposed to 300 F-T Cycles

Figure C29: Unwrapped Concrete Cylinders Exposed to 300 F-T Cycles

Figure C30: Unwrapped Control Concrete Cylinders for 300 F-T Cycles
Figure C31: CFRP Wrapped Cylinders Exposed to 50 F-T Cycles

Figure C32: CFRP Wrapped Control Cylinders for 50 F-T Cycles

Figure C33: CFRP Wrapped Cylinders Exposed to 100 F-T Cycles

Figure C34: CFRP Wrapped Control Cylinders for 100 F-T Cycles
Figure C35: CFRP Wrapped Cylinders Exposed to 200 F-T Cycles

Figure C36: CFRP Wrapped Control Cylinders for 200 F-T Cycles

Figure C37: CFRP Wrapped Cylinders Exposed to 300 F-T Cycles

Figure C38: CFRP Wrapped Control Cylinders for 300 F-T Cycles
Figure C39: GFRP Wrapped Cylinders Exposed to 50 F-T Cycles

Figure C40: GFRP Wrapped Control Cylinders for 50 F-T Cycles

Figure C41: GFRP Wrapped Cylinders Exposed to 100 F-T Cycles

Figure C42: GFRP Wrapped Control Cylinders for 100 F-T Cycles
Figure C43: GFRP Wrapped Cylinders Exposed to 200 F-T Cycles

Figure C44: GFRP Wrapped Control Cylinders for 200 F-T Cycles

Figure C45: GFRP Wrapped Cylinders Exposed to 300 F-T Cycles

Figure C46: GFRP Wrapped Control Cylinders for 300 F-T Cycles
Appendix D

Stress-Slip Behaviour of CFRP and GFRP Bonded Concrete Prisms
Figure D1: CFRP Lap Bonded Concrete Prisms Exposed to 50 Freeze-thaw Cycles
Figure D 2: CFRP Lap Bonded Control Concrete Prisms for 50 Freeze-thaw Cycles
Figure D 3: CFRP Lap Bonded Concrete Prisms Exposed to 100 Freeze-thaw Cycles
Figure D 4: CFRP Lap Bonded Control Concrete Prisms for 100 Freeze-thaw Cycles
Figure D 5: CFRP Lap Bonded Concrete Prisms Exposed to 200 Freeze-thaw Cycles
Figure D 6: CFRP Lap Bonded Control Concrete Prisms for 200 Freeze-thaw Cycles
Figure D 7: CFRP Lap Bonded Concrete Prisms Exposed to 300 Freeze-thaw Cycles
Figure D 8: CFRP Lap Bonded Control Concrete Prisms for 300 Freeze-thaw Cycles
Figure D 9: CFRP Lap Bonded Concrete Prisms Exposed to 50 Freeze-thaw Cycles
Figure D10: GFRP Lap Bonded Control Concrete Prisms for 50 Freeze-thaw Cycles
Figure D11: GFRP Lap Bonded Concrete Prisms Exposed to 100 Freeze-thaw Cycles
Figure D12: GFRP Lap Bonded Control Concrete Prisms for 100 Freeze-thaw Cycles
Figure D13: GFRP Lap Bonded Concrete Prisms Exposed to 200 Freeze-thaw Cycles
Figure D14: GFRP Lap Bonded Control Concrete Prisms for 200 Freeze-thaw Cycles
Figure D15: GFRP Lap Bonded Concrete Prisms Exposed to 300 Freeze-thaw Cycles
Figure D16: GFRP Lap Bonded Concrete Prisms Control for 300 Freeze-thaw Cycles
Appendix E

Glossary

Adhere to cause two surfaces to be held together by adhesion.
Adherend a body held to another body by an adhesive.
Adhesion the state in which two surfaces are held together by interfacial forces which may consist of valence forces or interlocking action, or both.
Adhesive a substance capable of holding materials together by surface attachment.
Bond a union of materials by adhesives
Bond strength the unit load applied to tension, compression, flexure, peel, impact, cleavage, or shear, required to break an adhesive assembly with failure occurring in or near the plane of the bond.
Continuous fibre reinforcement continuous fibres may be defined as fibres that are continuous throughout the whole length of the laminate, resulting in the load being applied directly to them; the stress throughout the length of the fibre is constant.
Chopped strands These are made from continuous strands that are chopped into short lengths (usually 50 mm).
Cohesion the state in which the constituents of a mass of material are held together by chemical and physical forces.
Chord modulus The slope of the chord drawn between any two specified points on the stress-strain curve, below any two specified points on the stress-strain curve, below the elastic limit of the material.
Critical length The critical length of a fibre is the length that is required for the fibre stress to develop its maximum value when under a particular load condition.
Crosslink to form chemical bonds between molecules to produce a three-dimensional network.
Cure to change the physical properties of an adhesive by chemical reaction, which may be condensation, polymerization, or vulcanization; usually accomplished by the action of heat and catalyst, alone or in combination, with or without pressure.
Curing agent a substance or mixture of substances that is part of an adhesive and is used to promote curing by taking part in the reaction.
Curing temperature the temperature to which an adhesive or an assembly is subjected to cure the adhesive.
Curing time the period of time during which an assembly is subjected to heat or pressure, or both, to cure the adhesive.
Delamination the separation of layers in a laminate because of failure of the adhesive, either in the adhesive itself or at the interface between the adhesive and the adherend.
**Durability**  the endurance of an element relative to the required service conditions

**Fibre**  Any material in an elongated form such that the ratio of its minimum length to its maximum average transverse dimension is 10:1, its maximum cross-sectional area is 1.975x10^{-3}mm^2 (corresponding to a circular cross section of 0.25 mm diameter) and its transverse dimension is not greater than 0.25 mm.

**Fibre composite material**  A material consisting of two or more distinct physical phases, one of which is a fibrous phase dispersed in a continuous matrix phase.

**Filament**  A continuous fibre.

**Fluorescence**  Emission of light by an excited atom or molecule.

**Glass transition temperature**  The temperature at which a sudden change in slope of various physical properties versus temperature curves occurs (commonly measured in terms of the standard heat distortion temperature). It very nearly approximates the temperature below which a polymer fails in a brittle manner and above which it behaves as a leathery or rubbery solid.

**Hydrophilic**  The property of possessing strong affinity for water.

**Intercalate**  to insert between or among existing elements or layers—intercalation

**Irradiance**  (1) The rate at which light energy falls on a unit area of surface (W/m^2), or (2) the radiant power incident upon a unit area of surface.

**Laminate joint**  a joint made by bonding layers of adherends face to face to form thicker stock.

**Lap joint**  a joint made by placing one adherend partly over another and bonding together the overlapped portions

**Lewis acid/base**  a substance that is capable of accepting/donating and unshared pair of electrons from a base/acid to form a covalent bond

**Matrix**  A bonding material which adheres to and contains the fibres. Many materials such as the thermoplastic and thermosetting resins, metals, glass or ceramic materials, can form a matrix. Resins are the most widely used.

**Monomer**  The monomer is the low molecular weight starting materials from which the polymer is formed.

**PAN**  A precursor used in the manufacture of carbon fibres. PAN is the abbreviation for polyacrylonitrile.

**Plasticizer**  Materials deliberately added to polymers to reduce their stiffness.

**Polymer**  a compound formed by the reaction of simple molecules having functional groups which permit their combination to proceed to high molecular weights under suitable conditions. Polymers may be formed by polymerization (addition polymer) or polycondensation (condensation polymer). When two or more monomers are involved, the product is called a copolymer

**Polymerization**  a chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When tow or more monomers are involved, the process is called co-polymerization or heteropolymerization.

**Pre-preg**  (pre-impregnated fibre) — An intermediate product consisting of fibres or tows which have been coated with a matrix material such as resin. The fibres are aligned in the majority of cases to give a flat sheet or tape.
Usually the resin is not fully cured so that the aggregate remains flexible and the sheet can be built up in piles to form a composite.

**Radiant exposure**  
(1) the accumulated light energy which has fallen on a unit area over time (J/m²), or (2) the irradiance integrated with respect to time.

**Resin**  
(1) a solid, semisolid, or pseudosolid organic material that has an indefinite and often high molecular weight, exhibits a tendency to flow when subjected to stress, usually has a softening of melting range, and usually fractures conchoidally, (2) liquid resin—an organic polymeric liquid which, when converted to its final state for use, becomes a resin.

**Shear**  
stress, strain or failure resulting from applied forces that tend to cause adjacent planes of a body to slide parallel in opposite directions.

**Shear modulus**  
the ratio of shear stress to corresponding shear strain below the proportional limit

**Shear strain**  
the tangent of the angular change, due to force between two lines originally perpendicular to each other through a point in the body.

**Shear strength**  
in an adhesive joint, the maximum average stress when a force is applied parallel to the joint.

**Slippage**  
the movement of adherends with respect to each other during the bonding process.

**Spectral irradiance**  
The distribution of irradiance in accordance with wavelength.

**Spectral power distribution (SPD)**  
The amount of radiation present at each wavelength.

**Strand**  
This is associated with filaments of glass fibres. A strand is a bundle of 204 filaments of glass fibre. The diameter of a filament is up to 1/400 mm.

**Surface preparation**  
a mechanical or chemical method used to make a substrate more receptive to forming an adhesive bond.

**Tack**  
the property of an adhesive that enables it to form a bond of measurable strength immediately after adhesive and adherend are brought into contact under low pressure.

**Tangent modulus**  
The slope of the stress-strain curve at a specified value of stress or strain

**Thermoplastic plastics**  
a material is thermoplastic when it can be softened by heating and hardened by cooling without undergoing a chemical change.

**Thermosetting plastics**  
a material is thermosetting when it can be changed or has been changed into a hard infusible product by a non-reversible chemical reaction initiated by the use of heat or curing agents.

**UV-A**  
ultraviolet A radiation (wavelength range, 320 to 400 nm)

**UV-B**  
ultraviolet B radiation (wavelength range, 290 to 320 nm)

**UV-C**  
ultraviolet C radiation (wavelength range, 200 to 290 nm)

**Visible light**  
the spectral region visible to humans (wavelength range, 400 to 700 nm). This is the photosynthetically active region of the spectrum as well.

**Wavelength**  
the description of radiation (or radiant energy) as the distance between two consecutive peaks in an electromagnetic wave. Units are normally in nm.

**Woven cloth**  
This is a more refined product of the above. It is usually a bi-directional reinforcement.
Woven rovings  These are chopped strands which may be unidirectionally or bi-directionally oriented.

Yarn of tow  A number of filaments in a bundle which can be handled as a single unit. A tow is usually bigger than a yarn, having thousands of filaments, whereas a yarn usually has a few hundred filaments. A yarn may be spun and twined from staple fibre, but a tow is formed from constant filaments.

Yield point  The maximum stress recorded in a tensile or compressive test of a ductile specimen prior to entering the inelastic region of the material.

Yield stress  A term denoting the yield strength or yield point of a material as defined above.

Young's modulus  The ratio of tensile or compressive stress to corresponding strain below the proportional limit of the material.