# Durability of Fibre Reinforced Polymers Used in Concrete Structures

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## ABSTRACT

Use of Fibre Reinforced Polymers in new and existing structures is increasing at a rapid pace. The effectiveness of structural upgrade in the short-term tests has been demonstrated repeatedly in the laboratory tests and field applications. However, the long-term durability of the FRP and FRP-reinforced concrete has not been investigated to a point that a designer can suggest the application of FRP with the same confidence as the traditional materials.

In this paper, selected results from an extensive test program are presented in which the durability of FRP materials and FRP-reinforced concrete was investigated. The environmental parameters to which the specimens were subjected included freeze-thaw cycling (50, 100, 200, and 300 cycles), UV radiation (1200, 2400, and 4800 hours), temperature variation (28, 56, 112, and 336 cycles), NaOH solutions with pH 10 and pH 12 concentrations (7, 14, 28, and 84 days), and moisture (7, 14, 28, and 84 days). Specimens comprised FRP coupons and FRP-FRP single lap bond specimens. The tests carried out on the specimens examined the influence of various environmental conditions on their mechanical properties such as stress-strain characteristics and bond between FRP and FRP. Results to-date indicate that the exposure to most of the environmental conditions has minimal effects on the properties tested during this experimental program. Freeze-thaw cycles and moisture exposure seemed to be the two environmental conditions with noticeable effects on the bond properties of single lap bonded specimens.

## INTRODUCTION

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 performance of infrastructure under severe loading conditions such as earthquake and rehabilitating structures deteriorated under severe environmental conditions. A large amount of research is devoted to discovering and developing new construction materials with better environmental resistance and durability. Fiber reinforced polymers (FRP) are the new material that show great promise. Numerous FRP products have been and are being developed worldwide.

Although the use of FRP in new and existing concrete structures has demonstrated excellent structural performance, there still exists the need for understanding the long-term durability of FRP in the environments to which the concrete structures are exposed. The influence of environmental factors such as elevated temperatures, temperature cycling, high humidities, corrosive fluids, freeze-thaw, and ultraviolet (UV) rays on the performance of polymeric matrix composites is of concern in many applications.

In an extensive research program, glass and carbon FRP and FRP-reinforced concrete specimens were subjected to various environmental conditions such as freeze-thaw cycles, UV radiation, temperature variation, NaOH solution with pH 10 and pH 12 concentrations, and moisture to evaluate their effects on material and structural properties of the specimens. This paper reports results from a selected group of specimens and examines the durability of FRP and its bond after exposure to these.

## EXPERIMENTAL PROGRAM

### Exposure Environments

The environments to which the specimens were exposed are as follows:

1. Control Environment: 22$^{o}$C and about 40% relative humidity
2. Freeze-thaw: cycling between –18$^{o}$C and +4$^{o}$C submerged in water
3. UV radiation: exposure to UV-A lamp radiation at 156 watt/m$^{2}$ and 38$^{o}$C
4. Temperature variations: 4 cycles/day between -20$^{o}$C and +40$^{o}$C in dry chamber
5. Alkali Solutions: submersion in pH 10 and pH 12 NaOH solution
    i. 22$^{o}$C for FRP coupons
    ii. 38$^{o}$C for FRP Single Lap Bonded Specimens
6. Water: submersion in water at 22$^{o}$C room temperature

### Materials and Specimens

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 1. The fabric used comes in the form of woven rovings. The main glass and carbon rovings, which carry the applied loads, are aligned in the longitudinal direction and held together by non-structural Kevlar wefts. The epoxy system is a two-part resin and is mixed together in ratios of 100:42. 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 resin has a three-hour working life at 35°C, and about 10 hours at 25°C.

The specimens used in this study were FRP Tensile Coupons (Fig. 1) and FRP Single Lap Bonded (SLB) Specimens (Fig. 2). The 25 x 175 mm FRP tensile coupons were made in accordance to ASTM D 3039. The 25 x 300 mm SLB specimens were prepared in accordance with ASTM D 3136. Specimen preparation is explained in detail elsewhere (Homam et al., 2000). Results from a total of 1,728 specimens are summarized here. Each point shown in a graph represents a value averaged for 8 specimens in all cases except when some specimens were rejected for obvious reasons.

## DISCUSSIONS

### FRP Tensile Test Coupons

The tensile test coupons were tested in displacement control mode at a rate of 1.27 mm/min. A consistent stress calculation in units of stress (MPa) is not feasible as the thickness of the laminates is not uniform (ranging between 1 mm and 2 mm). The load intensity is therefore expressed as force per unit width (N/mm/layer). The calculated strain is based on the machine head movement that was divided by the unsupported 75 mm length of the specimens between the grips.

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 behavior. Fig. 3 shows typical force-strain response of CFRP and GFRP coupons. At peak the strength dropped rapidly. 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 strength reduction in steps. The load-strain relationship is almost linear up to the failure load.

The tensile stiffness was found by calculating the slope of a line fitting the points between 5% and 40 % of the maximum strength. The three properties, i.e., the maximum strength, maximum strain, and the stiffness were averaged for sets of eight specimens, based on which the effects of a particular environmental exposure was quantified by comparing the results of the exposed and the control specimens. There existed an average deviation of about 5% in the calculated mechanical properties.

### Exposure Effects on Tensile Properties

Effects of Freeze-thaw Cycles: Figs. 4 and 5 compare the tensile strength and tensile stiffness of freeze-thaw exposed GFRP and CFRP specimens to their control counterparts for exposure to 50, 100, 200, and 300 cycles of freeze-thaw. It appears that the properties of CFRP and GFRP coupons are not significantly affected by exposure to the freeze-thaw cycles in the controlled laboratory environments. With age of the specimens, their strength seems to reduce slightly but this variation is within the range of the experimental scatter.

Effects of UV Radiation: Figs. 6 and 7 compare the tensile strength and tensile stiffness of the UV-exposed GFRP and CFRP coupons and their control partners. On average the strength and stiffness values of exposed FRP specimens remained slightly higher than those of the control specimens for the 1200 to 4800 hours of UV radiation. The strain at rupture was somewhat reduced by an increase in stiffness with age and to a lesser degree due to exposure to UV radiation.

Effects of Temperature Cycling, Alkali Solutions and Moisture: As shown in Fig. 8, the strength of GFRP coupons was only slightly affected by the temperature cycling. The drop in strength after 84 days (320 cycles) was about 7%. A drop of about 7% was also observed in the strength of the GFRP coupons after 84 days of exposure to pH 10 and pH 12 NaOH solutions at 22°C. The strength of GFRP coupons dropped by about 11%, when exposed to moisture for 84 days. However, no changes were observed in the strain values at rupture. It is interesting to note that tap water had more adverse effects on the strength of GFRP than the alkali solutions. It is important to further investigate the effects of moisture on the strength of GFRP with longer duration of exposure. The changes in stiffness and strain at rupture of GFRP were negligible as a result of these exposures.

Temperature variation between –20°C and +40°C produced no degradation in the mechanical properties of CFRP as shown in Fig. 9. The first 14 days (56 cycles) of exposure increased the strength of CFRP but the effects diminished after 84 days (336 cycles). CFRP coupons experienced slight increase in strength and stiffness after 14 days of exposure to pH 10 and pH 12 NaOH solutions; however, this effect diminished after 84 days of exposure. No significant changes were observed in the strain at rupture of CFRP due to these two solutions. The strength and stiffness of CFRP specimens dropped by about 18% and 8%, respectively, after the first 7 days of exposure to tap water; however, after 84 days of exposure no significant differences were observed between the exposed and control specimens. The significant drop in strength and stiffness at the beginning of the exposure could be due to effects other than the moisture. Nonetheless, negative moisture effects were also observed in the GFRP specimens, as discussed above.

**Single Lap Bonded Specimens**

The Single Lap Bond (SLB) specimens were tested under direct tension and the bonded overlaps experienced a shear-dominated mode of failure.

The bond slip was measured using a 25.4 mm wide clip-gauge. The readings from the clip-gauge are not pure slippage of the bonded lap, the tensile elongation of a 25.4 mm section of the specimens' length is also part of the clip-gauge (Fig. 2). This elongation can be accounted for by using FRP tensile properties. The data reported, however, does not include this correction since all the tests were performed with the same clip gauge.

The lap shear strength of the specimens was calculated by dividing the applied peak load by the actual bonded lap-area. The lap shear stiffness, the slop of stress-slip curve which is an indication of the stiffness of the bond, was calculated from a line fitting the points between 5% and 40% of the maximum lap shear strength. Fig. 10 shows typical stress-slip responses of CFRP and SLB specimens. It should be mentioned that on average there existed scatter of up to 8% in the calculated stiffness with a few extremes as high as

20%. The range of scatter in the slip values was much larger than for bond strength which was about 6%.

**Exposure Effects on Bond Properties**

Effects of Freeze-thaw Cycles: Fig. 11 presents summaries of lap shear strength of freeze-thaw exposed and control GFRP and CFRP SLB specimens.

Although, a large scatter in test data was observed, a clear trend was obvious that the average strength of exposed GFRP specimens decreased with the increase in the number of freeze-thaw cycles. The bond strength of CFRP specimens was also adversely affected by freeze-thaw but to a lesser extent.

The lap shear stiffness of the exposed GFRP and CFRP specimens was not affected much by the freeze-thaw cycles when compared to their control counterparts. The slip at failure in exposed specimens was found to be smaller than in control specimens primarily as a result of reduced strength.

Effects of UV radiation: The lap shear strengths of GFRP and CFRP specimens were not affected by the exposure. The values of the lap shear stiffness and the lap slip showed wide scatters, however, on average neither the stiffness nor the slip was significantly affected by the UV exposure.

Effects of Temperature Cycling, Alkali Solutions and Moisture: It can be observed from Fig. 12 that temperature variations (112 cycles in 28 days) did not produce any adverse effects on the strength of the GFRP SLB specimens, however, after 84 days with 336 cycles drop of about 7% in strength was observed. This value is small considering the range of scatter in the strength of SLB specimens. The lap strength of CFRP specimens was not affected by the temperature variation as shown in Fig. 13. On average the effects of temperature cycling on the stiffness and slip at failure were small in both GFRP and CFRP.

Exposure to NaOH solution at 38$^{o}$C caused varied effects on the lap strength of GFRP and CFRP specimens (Fig. 12 and 13). Strength drops of up to 14% in GFRP specimens and up to 15% in CFRP specimens were observed by exposure to pH 10 solutions. However, much smaller changes in strength values were observed in specimens exposed to pH 12 solutions. The stiffness of SLB specimens was not affected much by this exposure.

Submersion to water caused a drop of about 10% in the strength of GFRP SLB specimens after 84 days of exposure (Fig. 12). Their stiffness showed a slight drop between the ages of 7 and 84 days in both the control and exposed environment, and the corresponding bond slip values increased accordingly. The lap shear strength of CFRP SLB specimens was not affected by the exposure to tap water, however, the stiffness dropped by up to 10%. The slip at failure showed wide scatter, however, on average the ultimate slip was not much different in exposed and control specimens.

## CONCLUSIONS

Glass and Carbon FRP tensile and bond specimens were subjected to freeze-thaw cycles, UV radiation, temperature variations between –20°C and 40°C, alkaline environment (pH10 and pH12) and moisture. The exposed and control specimens were tested under direct tension and direct shear to evaluate the effects of environmental conditions on the long-term performance of FRP. Results so far indicate outstanding resistance of both CFRP and GFRP to the exposed conditions. The only noticeable adverse changes in tensile strength of GFRP and CFRP were observed due to exposure to moisture. The bond strength was adversely affected by freeze-thaw cycles in both materials. However, the maximum drop in strength was of the order of 8% to 10%. A more interesting observation made during the test was related to the decrease in lap shear stiffness with age in both materials under controlled environment.

## REFERENCE

Homam, S. M., Sheikh, S. A., Pernica, G., Mukherjee, P.K. (2000), *Durability of Fiber Reinforced Polymers (FRP) Used in Concrete Structures,* Research Report, Department of Civil Engineering, University of Toronto, January 2000, p. 53

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**Table 1:** Properties of TYFO™ S Fiberwrap™ System GFRP and CFRP

| **Property** | **Carbon (SCH 41) FRP** | **Glass (SHE 51) FRP** |
|---|---|---|
| Ultimate Tensile Strength (N/mm/layer) | 850-950 | 490-560 |
| Rupture Strain (mm/mm) | 0.0142 | 0.0197 |
| Nominal thickness of the Fabric (mm) | 1.04 | 1.24 |
| Weight of the Fabric (grams/m$^2$) | 658 | 923 |
| Weight of FRP Sheet gr/mm$^2$/layer | 1660 | 2500 |
| Coefficient of Thermal Expansion/ °C | -0.5 x 10$^{-6}$ | 7.7 x 10$^{-6}$ |