Resilience and sustainability of FRP-retrofitted concrete structures

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Abstract: Damaged, deteriorated and deficient structures can prove to be among the biggest obstructions in an otherwise resilient community. An innovative rehabilitation technique using fibre reinforced polymers (FRPs) was developed to build resilience in such structures. Lab investigations found that deteriorated concrete columns sustained about 20% loss in strength and larger reduction in ductility and energy dissipating capacity as a result of corrosion induced deterioration. Experimental results showed that utilising FRP and special grouts not only recovered but enhanced the mechanical performance of these structures. Long-term testing in the lab and observations in the field found excellent durability in FRP and FRP-retrofitted structures. This innovative repair technique resulted in remarkable reduction in risk of deterioration and performance degradation. It was concluded that resilience can be built into deficient or damaged structures through incorporation of innovative retrofitting techniques and utilisation of durable materials that are economical and superior to traditional methods.

Keywords: glass fibre reinforced polymer; bridge column; freeze-thaw cycles; durability; temperature cycles; alkali solutions; ultraviolet radiation; long-term performance; coupons; single-lap-bond.

Reference to this paper should be made as follows: Homam, S.M. and Sheikh, S.A. (2021) ‘Resilience and sustainability of FRP-retrofitted concrete structures’, *Int. J. Sustainable Materials and Structural Systems*, Vol. 5, Nos. 1/2, pp.35–49.

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This paper is a revised and expanded version of a paper entitled 'Durability of fibre reinforced polymers (FRP) wraps and external FRP-concrete bond' presented at Third International Conference on Concrete under Severe Conditions, BC, Canada, 18–21 June 2001.

1 Introduction

Resilience of a city exposed to severe events, such as earthquakes or hurricanes, depends on many factors, an important one being the safety of its structures. Critical infrastructure such as hospitals and bridges must remain functional during an extreme event, and thus should be designed to withstand the forces and deformations imposed on them. But if a building or a bridge collapses in the vicinity of a hospital and blocks access to the critical structure, the planned strategy would not bear the expected results. There is a huge inventory of structures that are prone to collapse during a severe event. These structures are deficient either because of inadequate designed capacity or due to deterioration as a result of aging. Corrosion of steel, one of the most common building materials in the world, is a major cause of this deterioration. A 2010 study estimated that the total annual cost of corrosion from all sectors worldwide was USD \$2.2 trillion, about 3% of the world's GDP of over USD \$73 trillion (Hays, 2010); approximately 16.4% of this total corrosion cost was attributed to the infrastructure sector. Typically, corrosion in infrastructure occurs in bridge decks, beams, and columns leading to about \$14 billion in annual direct cost for highway bridges in the USA alone (NACE International, 2013). Figure 1 shows a bridge in Toronto in 1990s before it was rehabilitated. Although originally it was designed and built properly, over time it became a potential hindrance to the resilience of the city, especially since a major hospital was within several metres of this bridge.

In a complex structure, attention needs to be paid to the components that play a vital role in maintaining the integrity of the structure. While the bridge in Figure 1 was damaged due to corrosion after decades of service, many existing structures are deficient as a result of design flaws or outdated design codes. Some members of a structure may have inadequate ductility, sudden failure of which would result in a brittle collapse of the entire structure during a severe earthquake. Research was undertaken at the University of Toronto to address these issues as well as the sustainability of fibre reinforced polymer (FRP) over time when subjected to extreme environments such as freeze-thaw cycles, alkalis and ultraviolet (UV) radiation (Homam, 2005; Sheikh, 2007; Colalillo and Sheikh, 2014; Liu and Sheikh, 2013). Results from the field monitoring and lab research on the durability of FRP are presented in this paper.

Figure 1 Highway bridge columns deteriorated as a result of steel corrosion (see online version for colours)

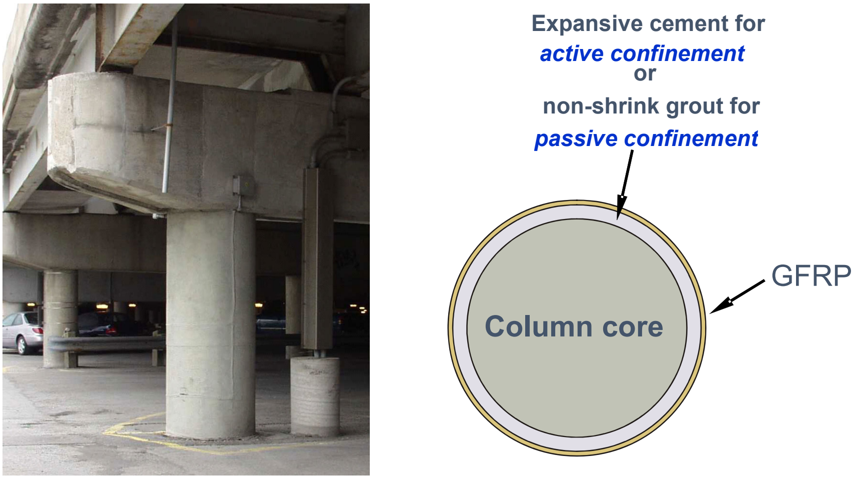
2 Upgrade of deficient structures

In structures such as the one shown in Figure 1, corrosion is often concentrated in the transverse reinforcement. Expansion generated by corrosion products cracks and spalls off the concrete cover that exasperates the rate of steel corrosion and subsequently adversely affects the load carrying capacity as well as ductility of the structure. To evaluate the impact of deterioration, half scale models of the bridge columns, 406 mm in diameter and 1.37 m long, were tested in the lab. Due to the deterioration caused by spiral steel corrosion, the axial load carrying capacity of the columns was reduced to less than 80% of that of the healthy columns. The deformation capacity and ductility of the columns was affected to a much larger extent (Sheikh, 2007).

Traditional upgrading methods for deteriorated concrete columns are cumbersome and usually require closing of the entire facility for rehabilitation. They would invariably require providing temporary supports to the structure while the damaged concrete and corroded steel are removed and rehabilitation is carried out. The materials often used for the upgrade are regular black steel and cementitious materials including concrete. This procedure is costly and generally would not last for more than ten years before requiring a repetition of the repair, again due to corrosion of steel. The rehabilitation techniques developed in this ongoing research program allow most regular function of the structure to continue with minimal disruption and provide a durable solution not requiring a repeat of the repair every few years. The cost is also much lower than that for traditional methods.

The application of the retrofit technique is shown in Figure 2 in which the column is first built to its original shape using either expansive cement-based grout or non-shrink grout without removing the contaminated concrete or corroded steel. The column is then wrapped with glass or carbon FRP. The bridge columns in Figure 1 were retrofitted using this procedure and actively monitored for more than ten years. One of the retrofitted columns is also shown in Figure 2.

Figure 2 Rehabilitated bridge columns after 20 years of service (see online version for colours)



3 Durability of FRP

While the columns in the field were monitored for their performance, a parallel research program was carried out in the lab to evaluate FRP's resistance to aggressive environments to which concrete structures are exposed. The influence of environmental factors such as elevated temperatures, temperature cycles, high relative humidity, corrosive fluids, freeze-thaw cycles, and UV radiation on the performance of polymeric matrix composites is of concern in many applications. While a number of studies have been reported on the subject, the work presented here was specifically carried out to investigate the long-term performance of the FRP tested in the lab in a comprehensive and consistent manner and compare that with the performance of the same FRP material used in the field.

3.1 Exposure conditions

The FRP specimens were subjected to the following laboratory environments:

- *Freeze-thaw cycles:* Freeze-thaw exposure was conducted in accordance with ASTM C666. The specimens were placed in water filled pans within a freeze-thaw unit, and because of their low density and small size, were covered with non-reactive silica sand. The freeze-thaw unit cycled between –18°C and +4°C and completed about 32 cycles/week. Specimens underwent 50, 100, 200, and 300 cycles of exposure before being removed and tested.
- *UV radiation:* Exposure to UV radiation was conducted in a QUV unit which simulated solar radiation. The unit had a sample exposure area of about 0.56 m^2 that was irradiated by 8 UV-A 340 bulbs with an irradiance wave length ranging between

295 nm and 365 nm and an energy output of about 156 watt/m^2. The temperature of the chamber was maintained at 35°C (black panel temperature) while the relative humidity was determined by the moisture content of the air in the lab (21°C and 40% relative humidity). The specimens were exposed to 1,200, 2,400, and 4,800 hours of radiation, resulting in accumulations of 670, 1,350, and 2,700 MJ/m^2 of energy, respectively. The ASTM E1596 recommends that the specimens be exposed for a duration that will accumulate a total UV (wave lengths shorter than 385 nm) exposure of 2,000 MJ/m^2, which is roughly equivalent to 72 months of exposure in southern US latitudes or 4,800 MJ/m^2 of sunlight.

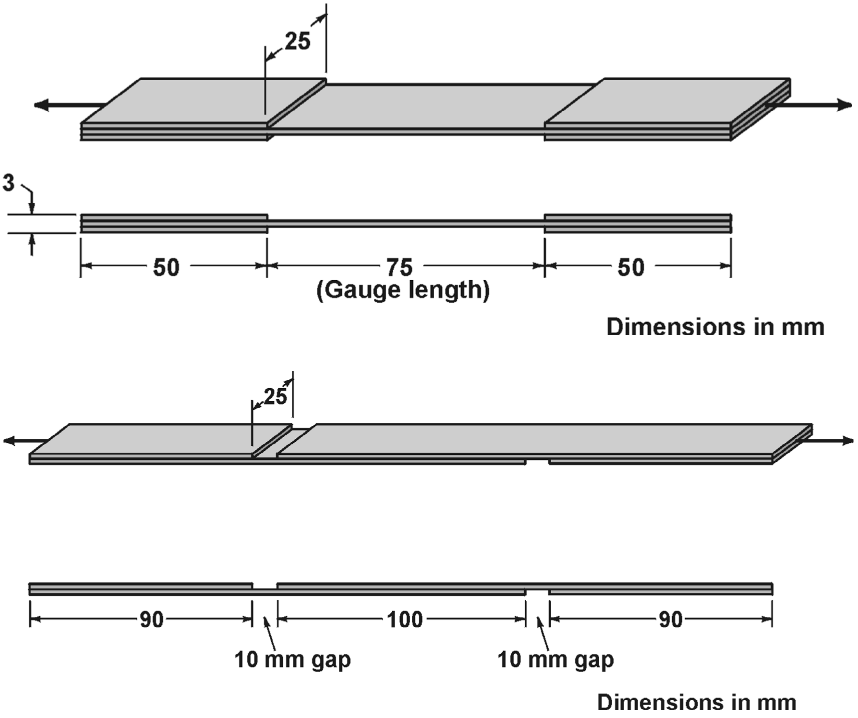
- *Temperature cycles:* Exposure to temperature cycling was conducted in an environmental chamber (Thermatron) where only the temperature, and not the relative humidity, was controlled. The temperature was pre-set to vary continuously between –20°C and +40°C, in the following cyclical manner; one hour at –20°C, a linear ascending ramp lasting two hours to +40°C, one hour at +40°C and a linear descending ramp lasting two hours to 20°C. Four cycles were performed each day with specimens being tested after 7, 14, 28 and 84 days of exposure.
- *Alkalis:* Exposure to alkalis was conducted using two concentrations of sodium hydroxide solution, pH 10 and pH 12. The FRP coupons were immersed in the alkaline solutions and stored at room temperature. However, the single-lap-bonded specimens were placed in an oven, whose temperature was maintained at 38°C, to accelerate the effects of alkaline exposure. Prian and Barkatt (1999) reported that raising the conditioning temperature up to 80°C did not change the degradation mechanism and it was an acceptable procedure for accelerating the aging process in degradation studies of FRP materials. The alkali-exposed specimens were retrieved from the baths and tested for strength and deformation after 7, 14, 28, and 84 days of exposure. They were rinsed with water and dried with a cloth before being tested.
- *Water:* Exposure to water was conducted at room temperature. Specimens were immersed in a bath of tap water (kept at about 23°C) and retrieved for testing after 7, 14, 28 and 84 days.
- *Control environment:* Control specimens for the tests were stored in the laboratory, which was generally maintained at about 23°C and 40% relative humidity.

3.2 Materials and specimens

The materials comprised of a commercially available system. The properties of the wet lay-up laminate using manual procedures, as provided by the supplier, are as follows: ultimate tensile strength = 575 N/mm/layer, rupture strain = 0.022, nominal thickness of the fabric = 1.3 mm and weight of the fabric = 923 grams/m^2. The glass fabric rovings, which carry the applied loads in tension, are aligned in the longitudinal direction in the fabric rolls and held together in the transverse direction by non-structural Kevlar wefts. The epoxy is a two-part resin in volumetric ratio of 100:42 (resin: hardener). The parts were mixed together for five minutes using a powered mixing blade.

The specimens used were FRP tensile coupons and FRP single-lap-bond (SLB) specimens (Figure 3). The 25 × 175 mm FRP tensile coupons were made in accordance with ASTM D 3039. The 25 × 300-mm SLB specimens were prepared in accordance with ASTM D 3165. Both sets of 25 mm wide specimens were made from 500 mm wide panels. The 500 mm panels were cut in half, with one half yielding a group of eight specimens for exposure to an artificial environment and the other half for eight specimens designated as the control set. To minimise edge effects during exposure, the panels were not cut into the 25 mm wide specimens until after the completion of the prescribed duration. The only exception was in the case of freeze-thaw cycling, where the size of the pans in the unit required the 25 mm wide specimens for exposure.

Figure 3 Tensile FRP coupon and FRP-FRP SLB specimens



3.2.1 Testing procedure

The tensile coupons were tested in displacement control mode at a rate of about 1.27 mm/min. The failure load was not reported in units of stress (MPa) because the thickness of the coupons using the manual wet lay-up technique was not uniform (ranging up to 2 mm). The load intensity was therefore expressed as force per unit width (N/mm). The axial FRP strain presented was obtained using the displacement of the machine head. To check the accuracy of the strains thus determined, eight coupons were also tested with a 25 mm clip gauge. The strains obtained using the clip gauges showed close agreement with the strains obtained using the machine head movement. SLB specimens were tested under direct tension similar to that used for tensile coupons causing bond stress between the two layers of GFRP resulting in lap-shear mode of failure in the lapped sections.

4 Results and discussion

Results from about 350 tensile coupons and 350 SLB specimens are presented and discussed here. Each data point shown in figures represents the average of eight specimens in a group. For a few data points, less than eight specimens were averaged when one or more specimens in the group were rejected for construction defects/deficiencies or grip induced failures. The coefficient of variation in the tensile strength of coupons was between 2.1% and 6.7%; while it varied between 2.3% and 9.9% for SLB specimens.

4.1 Tensile coupons

Typical failure modes in GFRP coupons were caused by rupture of fibres at close to the mid height of the specimens. The failure in a majority of cases occurred with no post-peak behaviour. The typical load-deformation relationship for GFRP is almost linear up to failure. The only exception occurred in some samples when strands began to fail progressively with increasing displacement. This sequential failure produced a saw-tooth force-strain curve with a somewhat lower peak load than anticipated. The tensile stiffness of the coupons was obtained by calculating the slope of a line which best-fitted points lying between 5% and 40% of the peak force. Average peak load and stiffness values of the exposed and control specimens were compared to quantify the effects of each accelerated environmental exposure on the tensile properties of CFRP and GFRP.

4.1.1 Effects of exposures on tensile properties

Freeze-thaw cycles

Figure 4 compares the tensile strength and tensile stiffness of exposed GFRP specimens to their control counterparts after exposure to 50, 100, 200, and 300 cycles of freeze-thaw. The strength and stiffness of GFRP coupons were not found to be significantly affected by exposure to freeze-thaw cycles. The same applies to their strains at rupture. While some researchers (Won and Park, 2006) have reported some adverse effects of freeze-thaw cycles on GFRP strength, others (Karbhari and Engineer, 1996) observed similar results as reported here including a small increase in stiffness of glass composites.

UV radiation

UV light induces degradation of organic polymers that are used in the manufacture of fibre reinforced plastics. This degradation may produce organic acids within FRP that are corrosive to glass fibres (Jones and Chandler, 1985). Lee and Lee (1999) observed that photon energy of wavelengths below 350 nm can rupture most chemical bonds, such as carbon-carbon and carbon-hydrogen, at the surface of the epoxy and thereby cause degradation. However, UV rays in the 400–450 nm range can heighten cross-linking of the polymer surface and thus improve its mechanical properties.

Figure 5 compare the tensile strength and tensile stiffness of UV-A exposed GFRP coupons to their control counterparts. On average, the strength of the exposed GFRP coupons remained slightly higher than those of the control specimens for the three durations (1,200, 2,400 and 4,800 hours) of UV radiation. This increase may be partly attributed to the elevated temperature of the UV chamber (35°C). However, the effects on stiffness varied. Initially, GFRP coupons initially sustained a slight, about 7%, loss of stiffness with respect to the control samples but later recovered as the duration of the exposure increased. The stiffness of the specimens after 4,800 hours of exposure was slightly greater than the stiffness of specimens exposed for 1,200 hours. No major negative effects on the mechanical properties were observed and UV radiation appeared to affect only the surface of FRP.

Figure 4 Strength and stiffness of GFRP coupons exposed to freeze-thaw cycles

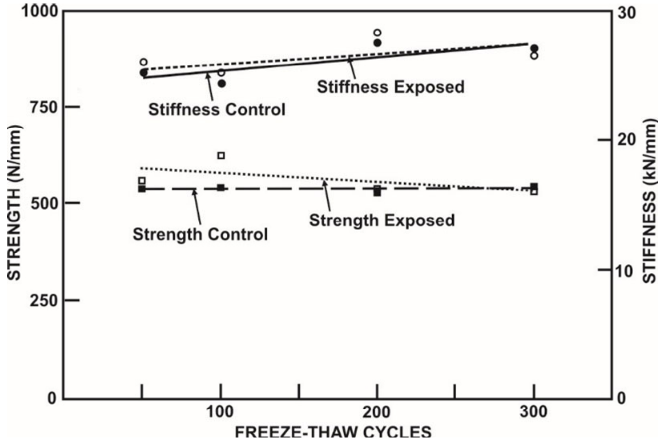
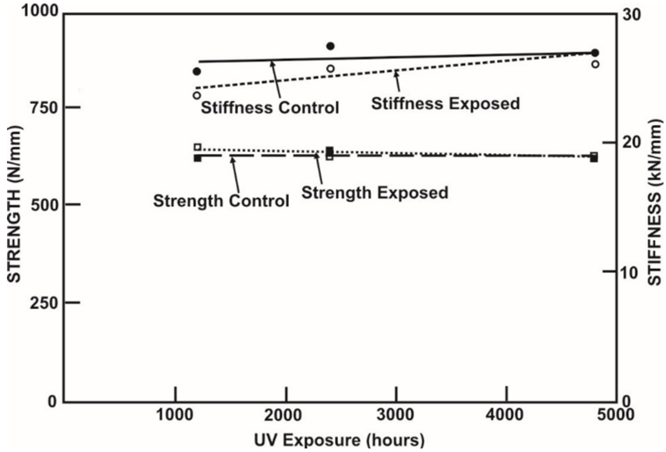


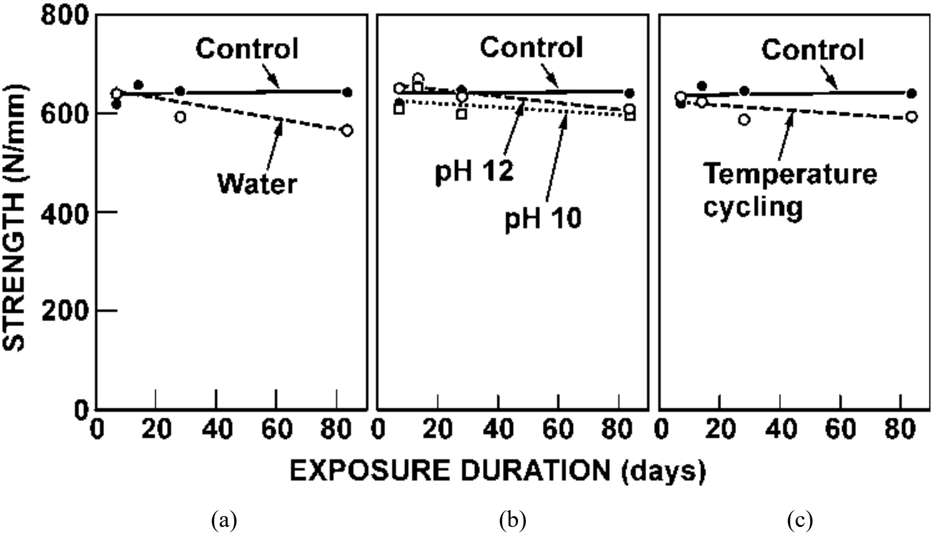
Figure 5 Strength and stiffness of GFRP coupons exposed to UV radiation



Temperature cycles, alkali solutions and water bath

As shown in Figures 6 and 7, strength and stiffness of GFRP coupons were only slightly affected by temperature cycling. The average drop in strength after 84 days of cycling between –20°C and 40°C (336 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 23°C. On the other hand, the strength of GFRP coupons dropped by about 11% when immersed in a water bath for 84 days. Changes in stiffness were small with all four types of exposure. Karbhari and Engineer (1996) observed that immersion in water for 60 days caused severe degradation in the strength of glass and carbon reinforced polymer specimens. They suggested that moisture absorption produced changes at the macroscopic level that lead to the deterioration of the resin. The intake of water caused plasticisation of the resin, which reduced its mechanical properties, and degradation of the bond to the fibre as well as to substrate materials. The same observation was made by Toutnaji and El-Korchi (1999) after exposing GFRP and CFRP materials to 300 wet-dry cycles. They suggested that penetration of water into the composite occurred by diffusion through the resin and capillary flow via microcracks and voids along the interface between the fibres and the resin. Prian and Barkatt (1999) explained the degradation of the glass fibre-resin interface in aqueous medium to be the result of hydrolysis of the resin matrix and leaching of alkali from the fibres in the interface region.

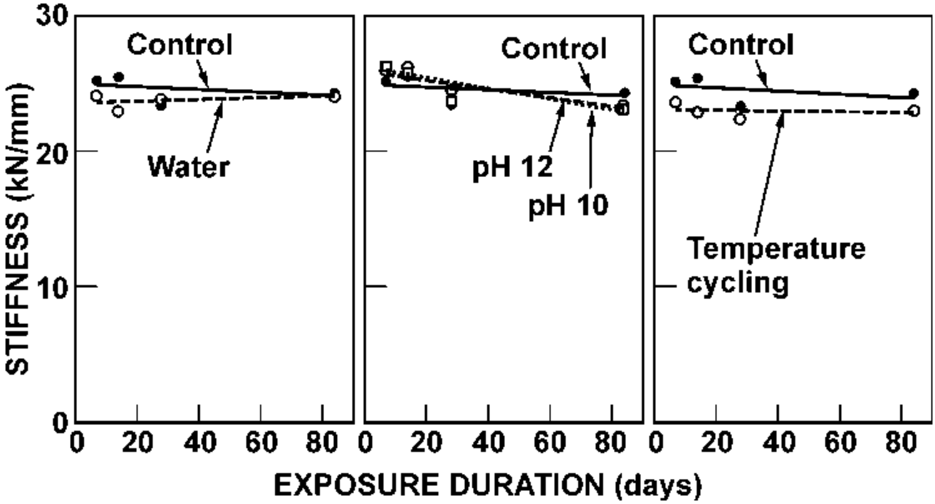
Figure 6 Strength of GFRP coupons exposed to (a) water, (b) sodium hydroxide solution and (c) temperature cycling



It is interesting to note that tap water had a greater adverse effect on the strength of GFRP than the alkali solutions. It is likely that the size of solvated sodium ions (Na^+) present in the alkali solutions prevented the intrusion of water molecules into the microscopic pores and cracks of the resin. Figure 6 shows that GFRP coupons exposed to pH 12 solutions were slightly stronger than those exposed to pH 10 solutions or water.

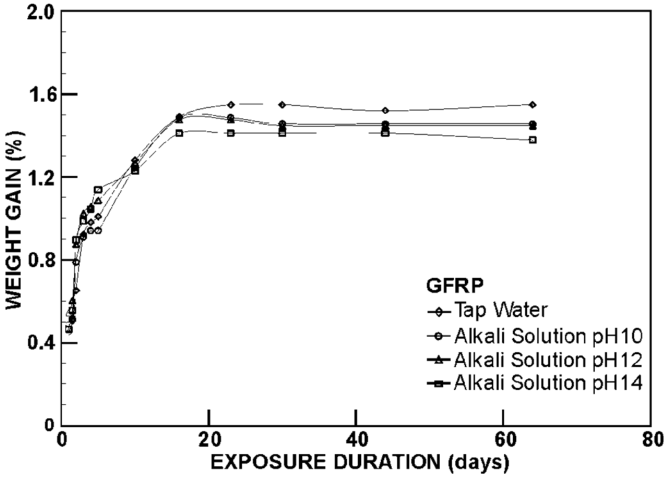
Absorption tests on GFRP specimens submerged in tap water and pH 10, pH 12, and pH 14 NaOH solution at 38°C were carried out. After 60 days, the highest weight gain was observed in the specimens submerged in tap water and the lowest weight gain was observed in specimens submerged in pH 14 NaOH solution (Figure 8). Chin et al. (1997) also observed that at 22°C, epoxy vinylester absorbed slightly more moisture when submerged in water than in concrete pore solution (pH 13.5). In another study, higher moisture absorption in $Ca(OH)_2$ solution was reported and was attributed to an increase in ester hydrolysis in the bulk resin that induced micro-cracks leading to increased weight gain (Chu et al., 2004).

Figure 7 Stiffness of GFRP coupons exposed to (a) water, (b) sodium hydroxide solution and (c) temperature cycling



(a) (b) (c)

Figure 8 Water absorption in GFRP specimens

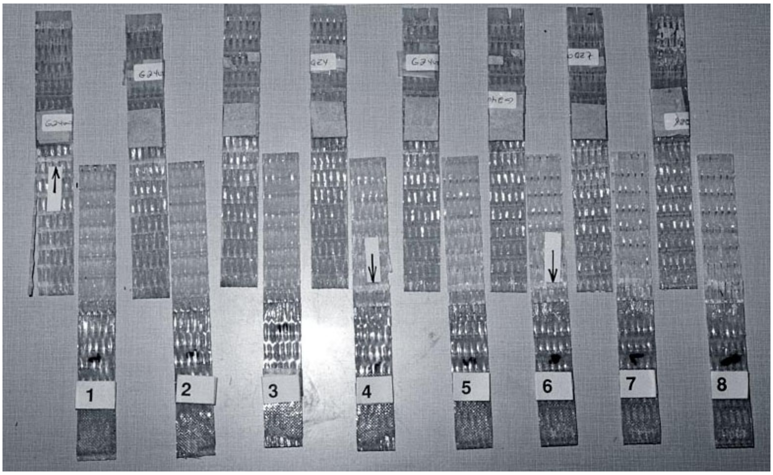


From the test results of all the specimens subjected to various exposure conditions, it can be concluded that water exposure was the most deleterious environment for GFRP and caused about 11% loss in its tensile strength reducing it from around 640 N/mm to 570 N/mm.

4.2 Single-lap-bonded specimens

The SLB specimens, in general, experienced a shear-dominated mode of failure in the bonded overlaps when the specimens were loaded in direct tension. Typical modes of failure in GFRP specimens are shown in Figure 9. The average bond stress was calculated by dividing the applied load by the actual de-bonded lap-area.

Figure 9 Modes of bond failure of GFRP SLB specimens



4.2.1 Effects of exposures on bond properties

Freeze-thaw cycles

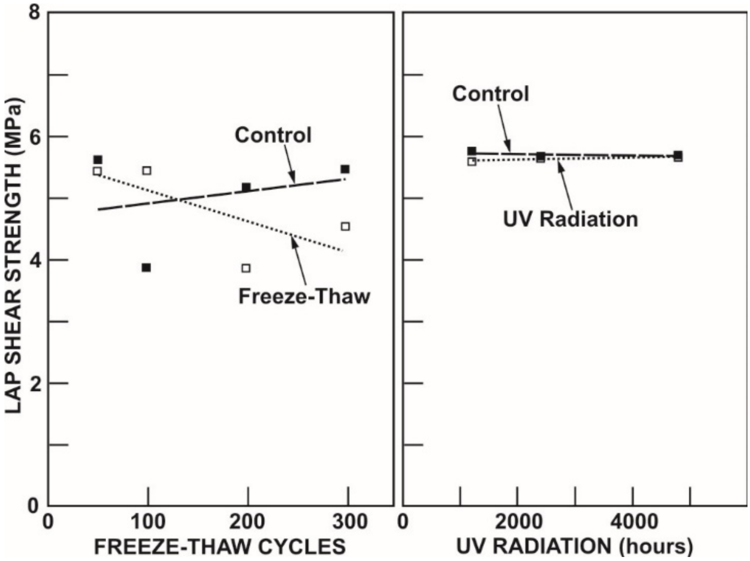
Figure 10 presents the variation in the lap shear strength of GFRP specimens as a result of freeze-thaw exposure.

Although, a large scatter in the test data was observed, a clear trend was obvious that the average bond strength of exposed GFRP specimens decreased by as much as 18% after 300 freeze-thaw cycles. Initially, the bond strength stayed constant or increased slightly, but it deteriorated thereafter as the number of freeze-thaw cycles increased. The early strengthening can be attributed to an increase in the cross-linking within the matrix (Karbhari and Engineer, 1996) and the subsequent drop in strength to the damage caused by the formation and propagation of ice crystals within voids at the bonded interface. The weave of the glass fabrics leaves a high percentage of air gaps at the bonded interface which may not be filled with epoxy. However, in hardened resin, these air pockets can get filled with water, especially in submerged specimens, and cause damage at the interface when frozen.

UV radiation

The lap shear strength of GFRP specimens was hardly affected by UV radiation (Figure 10). These results were expected because UV radiation mainly affects exposed surfaces of the fibre material and does not degrade or chemically alter the epoxy at the interface region.

Figure 10 Lap shear strength of GFRP SLB specimens exposed to (a) freeze-thaw cycles and (b) UV-A radiation



(a) (b)

Temperature cycles, alkali solutions and moisture

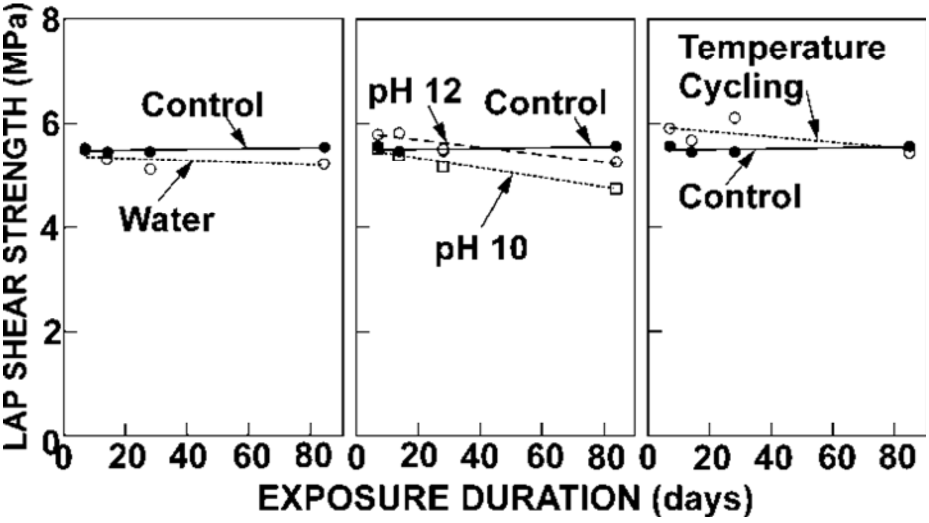
It can be observed from Figure 11 that for up to 28 days (112 cycles) of temperature cycling between –20°C and +40°C, no adverse effects were observed on the strength of the GFRP SLB specimens. At the early stages of exposure, slight increase in strength was observed, but the difference in strength of control and exposed specimens disappeared after 84 days (336 cycles).

Exposure to NaOH solution at 38°C caused varied effects on the lap shear strength of GFRP specimens (Figure 11). Strength drops of up to 15% in GFRP specimens were observed due to the exposure to pH 10 solutions. However, much smaller changes in strength values were observed in specimens exposed to pH 12 solutions. This could be due the difference in the amount of moisture absorption in each type of solution as it was shown in Figure 8 and discussed earlier. Since the strength of the GFRP SLB is governed by the changes in the mechanical properties of epoxy and the texture of the composite, it does not follow the same pattern of changes that was observed in the GFRP coupon tests where strength is primarily governed by the mechanical properties of the fibres.

Immersion in water caused a drop of only about 5% in the strength of GFRP SLB specimens after 84 days of exposure (Figure 11). It should be noted, however, that the range of scatter in the strength values was significant with the coefficient of variation ranging between about 2% and 10%.

The results presented above show that the bond strength of GFRP is affected adversely by various exposures. The largest loss, 18%, was observed due to the freeze-thaw exposure of the GFRP specimens. It appears that this exposure affects the rough surface texture of GFRP to the detriment of bond strength.

Figure 11 Lap shear strength of GFRP SLB specimens exposed to (a) water, (b) sodium hydroxide solution and (c) temperature cycling

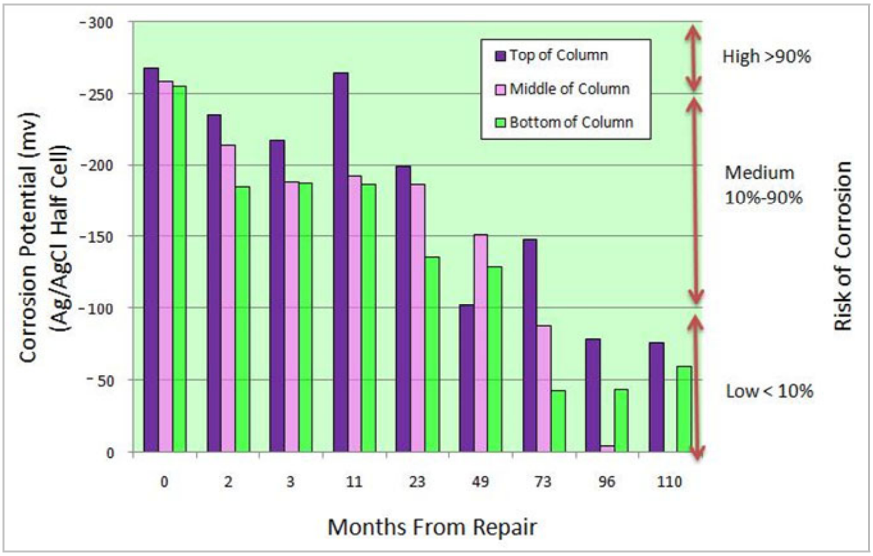


(a) (b) (c)

5 Results from field monitoring

Several columns in the bridge were instrumented to collect strain data from GFRP wraps and to monitor corrosion over time. Field data for up to first 73 months of field monitoring was reported by Sheikh (2007). Beyond that time, corrosion activity continued to be monitored for another 37 months. Figure 12 shows the corrosion potential and risk of corrosion in a field column different location along its height for over 110 months. This data is based on the measurements from half-cells embedded in the columns. At the time of the repair, from the average of potential measurements at three locations, top, middle and bottom, along the height of each column, it was determined that the risk of corrosion in repaired columns was medium or intermediate. Eight years later, the risk of corrosion in all the column was found to be low. Reduction in the corrosion activity and reduced risk of corrosion can be clearly seen for one of the columns, in Figure 12. It is clear that GFRP wraps protected the columns from adverse environmental effects by starving the corrosion of its essential ingredients, water and oxygen, resulting in reduced corrosion activity. The field data corroborated the tests conducted in the lab on small specimens as discussed above. Monitoring of the columns over the years through visual inspection and field data on strain and corrosion rate indicated a sound performance of the retrofit techniques. No distress or deterioration was observed in these columns after about 20 years of service. Field monitoring was terminated when the performance was ensured to be of no further concern.

Figure 12 Corrosion activity in repaired bridge column (see online version for colours)



6 Concluding remarks

This paper describes selected results from an extensive long-term research on the repair and upgrade of concrete structures that are damaged or deficient. A highway bridge was taken as a field prototype for which half-scale models of its columns were tested in the lab. A repair technique developed for the upgrade of columns was applied to the bridge and was monitored for performance for over ten years. The repair technique used specially developed grouts and GFRP. A parallel lab investigation was carried out to study the long-term performance of GFRP under extreme environmental conditions. The salient conclusions drawn are presented below.

Concrete columns deteriorated due to steel corrosion were weakened by over 20% in their load carrying capacity. Reductions in the deformation capacity and ductility were even larger. The innovative techniques developed resulted in substantial cost saving and required minimal closure time of the structure during the repair. The non-traditional materials used in the upgrade/repair included glass FRPs and non-shrink and expansive grouts. Although the corroded steel and the contaminated concrete were not removed from the deteriorated columns, field measurements of over ten years showed that the corrosion activity and risk of corrosion had reduced significantly with time in the repaired columns. The upgraded structure has performed flawlessly for over twenty years indicating high durability. It can be concluded that resilience can be built into the deficient or damaged structures through innovative durable techniques employing new materials such as FRPs.

The lab study carried out on the GFRP materials used in the field concentrated on the effects of extreme environment. GFRP coupons and single-lap-bonded specimens were subjected to freeze-thaw cycles, UV radiation, temperature cycles, alkaline environment (pH 10 and pH 12 of NaOH solution) and water. The exposed and control specimens were tested under direct tension and lap shear to evaluate the effects of environmental conditions on the long-term performance of FRP and FRP-to-FRP bond.

Tensile strength of GFRP was affected due to the exposure to water that caused about 11% strength loss. GFRP coupons exposed to sodium hydroxide solution displayed drops in tensile strength less than 10%. It should be noted that the strength of GFRP under normal conditions is quite high at about 575 MPa. So the reduced strength is over 500 MPa. All other conditionings had little effect on GFRP strength or stiffness.

The GFRP-to-GFRP bond strength degraded by up to 20% due to freeze-thaw effects. Exposure to water and sodium hydroxide solutions reduced the lap bond strength of GFRP by as much as 14%. Considering the scatter in bond strength data, the extent of reduction in bond strength is considered to be low. Other extreme environmental conditions did not affect the GFRP properties significantly.

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