# Durability of GFRP Composite Rods

## Results from preliminary field tests don't match data from accelerated lab tests

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One of the most pressing durability concerns of our time is the rapid corrosion of reinforcing steel that occurs in concrete structures subjected to chloride-rich environments. It's often argued that if the steel reinforcement in such structures could be replaced by chemically inert reinforcement such as fiber-reinforced polymers, the problem of corrosion could be eliminated. Of the various options, the most economical choice is glass-fiber-reinforced polymer (GFRP), but it is reported to be highly vulnerable to the alkaline environment of concrete.

A report summarizing the results of several published studies on the alkali resistance of GFRP categorically concluded that "GFRP should not be used in direct contact with concrete."[1] Similar conclusions were drawn by other researchers.[2-4] Unfortunately, all of these studies were conducted by subjecting GFRP to an idealized, simulated, high-pH fluid environment often involving high temperatures. Such environments are unduly harsh as they provide an unlimited supply of hydroxyl ions—a condition not present in real concrete. Also, they provide full saturation, which is also rarely the case. Field conditions should therefore be expected to be different from these idealized laboratory conditions.

In 2004, a major study by ISIS Canada was launched to obtain field data with respect to the durability of GFRP in concrete exposed to natural environments. Concrete cores containing GFRP were removed from several 5- to 8-year-old exposed structures, and the GFRP was analyzed for its physical and chemical composition at the microscopic level. Direct comparisons were carried out with control GFRP rods preserved under controlled laboratory conditions.

## FIELD STUDIES

The five structures selected for the study were exposed to a wide range of environmental conditions. The GFRP reinforcement in the structures was E-glass in a vinylester matrix.

### Hall's Harbor Wharf

The 5-year-old Hall's Harbor Wharf was the first marine structure in Canada built using GFRP-reinforced concrete.[5] The wharf, located on the Bay of Fundy shore in Nova Scotia, comprises externally restrained precast concrete deck slab panels reinforced with GFRP bars and concrete pile cap beams reinforced with a hybrid GFRP-steel bar system. Concrete with a compressive strength of 45 MPa (6500 psi) was used in the panels and beams. The structure is exposed to temperatures between –35 and 35 °C (–31 and 95 °F), frequent wetting-and-drying and freezing-and-thawing cycles, continual chloride-laden moisture, and frequent splashes with salt water.

### Joffre Bridge

Located in Sherbrooke, QC, Canada, over the St-Francois River, this 7-year-old bridge contains GFRP bars as reinforcement in the sidewalks and traffic barriers constructed with 45 MPa (6500 psi) concrete.[6] The temperature in the region ranges between –35 and 35 °C (–31 and 95 °F), and the bridge is subjected to frequent wetting-and-drying and freezing-and-thawing cycles. Deicing salts are used on the bridge during the winter.

### Chatham Bridge

This 8-year-old, four-span bridge (Fig. 1) located in Chatham, ON, Canada, contains steel-free deck slabs in

Fig. 1: Cores were taken from the barrier wall of the Chatham Bridge in Chatham, ON, Canada

Fig. 2: Cores were taken from the barrier wall of the Waterloo Creek Bridge on Vancouver Island, BC, Canada

the two outer spans to which the barrier walls are attached by means of double-headed stainless steel bars.[7] The barrier walls were constructed of ordinary 35 MPa (5100 psi) concrete reinforced with a GFRP grid comprising 131 $mm^2$ (0.20 $in.^2$) elements at a 100 x 100 mm (4 x 4 in.) spacing. The temperature range in Chatham is between –24 and 30 °C (–11 and 86 °F). The bridge deck experiences frequent wetting-and-drying and freezing-and-thawing cycles and is sprayed with deicing salt in the winter months.

### Crowchild Trail Bridge

This 8-year-old bridge located in Calgary, AB, Canada, has ribbed-deformed GFRP reinforcement in its barrier walls and deck slab.[8] The bridge was built with 35 MPa (5100 psi) concrete and experiences a temperature range of –15 to 23 °C (5 to 73 °F), frequent freezing-and-thawing cycles, and sprays of deicing salts in the winter months.

### Waterloo Creek Bridge

Located on Vancouver Island, BC, Canada, this 6-year-old bridge (Fig. 2) has barrier walls connected to the steel-free deck slab with double-headed steel bars. Concrete with a compressive strength of 35 MPa (5100 psi) was reinforced with GFRP grid in the barrier walls.[9] The temperature range in the region is 0 to 23 °C (32 to 73 °F). Deicing salts are used frequently on the bridge deck.

## SAMPLE PREPARATION AND ANALYSIS

Experienced contractors were employed to extract at least ten 75 mm (3 in.) diameter cores containing GFRP from each of the five structures. Three concrete cores from each of five structures were sent to three teams of material scientists working independently at various Canadian universities for analysis. The removal of GFRP samples along with surrounding concrete and the polishing of the samples required special care given that GFRP and concrete have different hardness values.

After sample preparation, the GFRP reinforcement and surrounding concrete were analyzed using several analytical methods. The entire surface of each sample was examined and photos were taken at various locations. Scanning electron microscopy (SEM) was used for a detailed examination of the glass fiber/matrix interface and individual glass fibers. The specimens used in SEM analyses were also analyzed by energy dispersive x-ray (EDX) to detect potential chemical changes in the matrix and glass fibers due to the ingress of alkali from the concrete pore solution. Chemical changes in the polymeric matrix of GFRP were characterized by Fourier transform infrared spectroscopy (FTIR). Finally, changes in the glass transition temperature $T_g$ of the matrix due to exposure to severe environmental conditions were determined using differential scanning calorimetry (DSC).

## RESULTS AND DISCUSSION

The results obtained by the three research teams were very similar. A complete account of their findings was provided in their respective individual reports.[10-12]

### Scanning electron microscopy

SEM was used to visually examine the effects of exposure at a high magnification on the constituent materials of the GFRP. Typical SEM micrographs are shown in Fig. 3. In each of the five structures, there was no sign of any damage to the GFRP. None of the fibers lost any cross-sectional area, and no degradation of the fibers was visible. Furthermore, individual fibers were intact with no gaps between the fibers and the matrix. There was also no evidence of deterioration at the glass/matrix interface—good contact was noted between individual glass fibers and the surrounding polymer matrix as well as between the sand grains and the matrix. Although drying in the SEM chamber can lead to interfacial damage and therefore make it difficult to observe the integrity of the FRP-concrete bond, examination with an optical microscope indicated that good contact was maintained at the FRP-concrete interface.[10,12]

### Energy dispersive x-ray analyses

This technique was used in conjunction with SEM and its aim was to identify the elements in the material. A 10 to 20 keV electron beam was directed at the surface of a sample. The energy of x-rays emitted from a depth of about 2 microns (0.08 mils) depends on the material from which they are being emitted.

In Fig. 4, the EDX plot for in-service glass fiber from the Hall's Harbor Wharf is compared with the plot for companion control GFRP rods stored under controlled conditions in the laboratory. The chemical composition of fibers in each rod showed the absence of zirconium (Zr), thus confirming that the investigated GFRP contained E-glass and not alkali-resistant (AR) glass. This was true for all structures. Figure 4 also shows that the EDX plots for glass fiber in in-service GFRP samples were virtually identical to those for control specimens. This indicates that there was no deterioration of the glass fiber. In Fig. 5, EDX plots for the polymeric matrix from the in-service GFRP in the Joffre Bridge are compared with control GFRP bars kept under controlled conditions in the laboratory. The two spectra are alike, indicating that no deterioration occurred in the field. As expected, the matrix in both specimens contained mainly carbon (C); however, some additional elements such as silicon (Si), aluminum (Al), and calcium (Ca) were also detected.

It's well known that silica glass dissolves in strong alkaline solutions such as concrete pore solution. To attack glass fibers, alkalis from the concrete pore solution must first penetrate the polymer matrix. When glass fibers degrade as the result of various processes such as

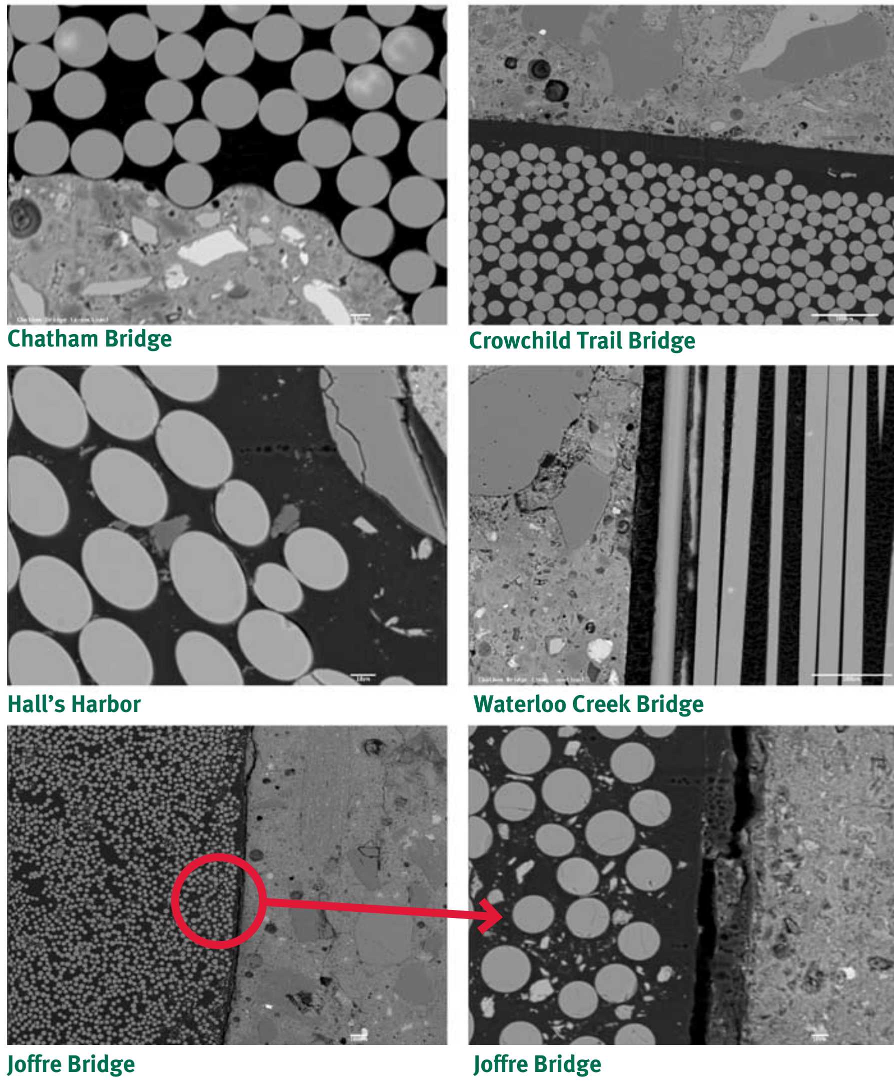



**Fig. 3: Scanning electron micrographs of GFRP extracted from each structure indicated no signs of deterioration in the fibers or polymer matrix. The visible interfacial damage is apparently the result of drying in the SEM chamber, as no such damage was observed using an optical microscope**

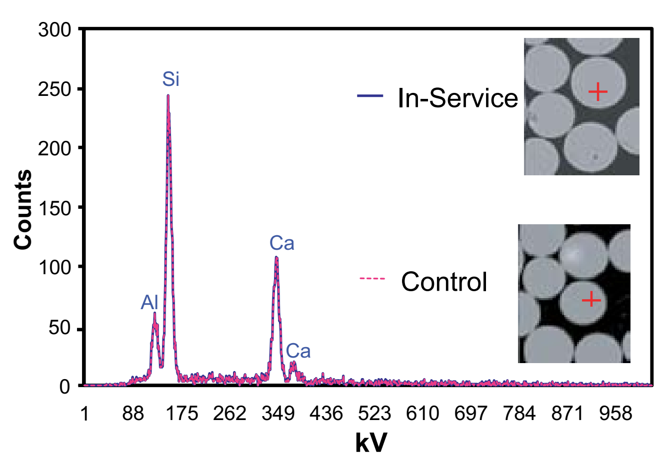
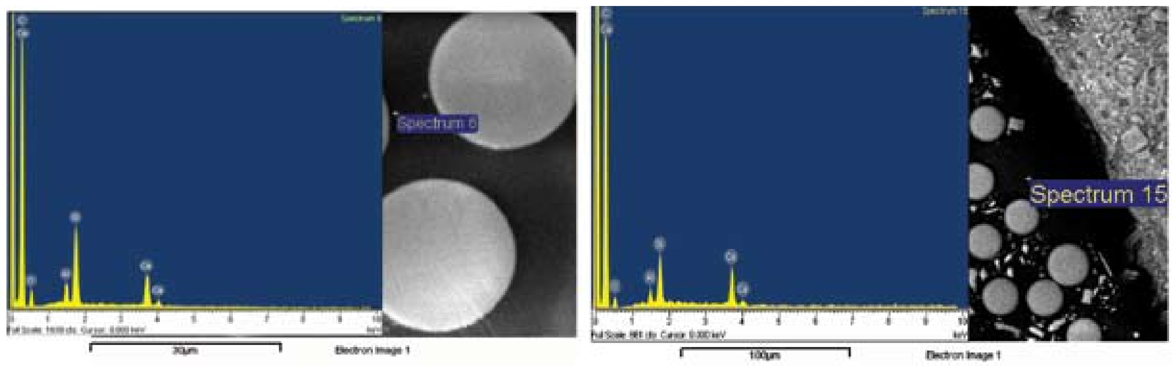
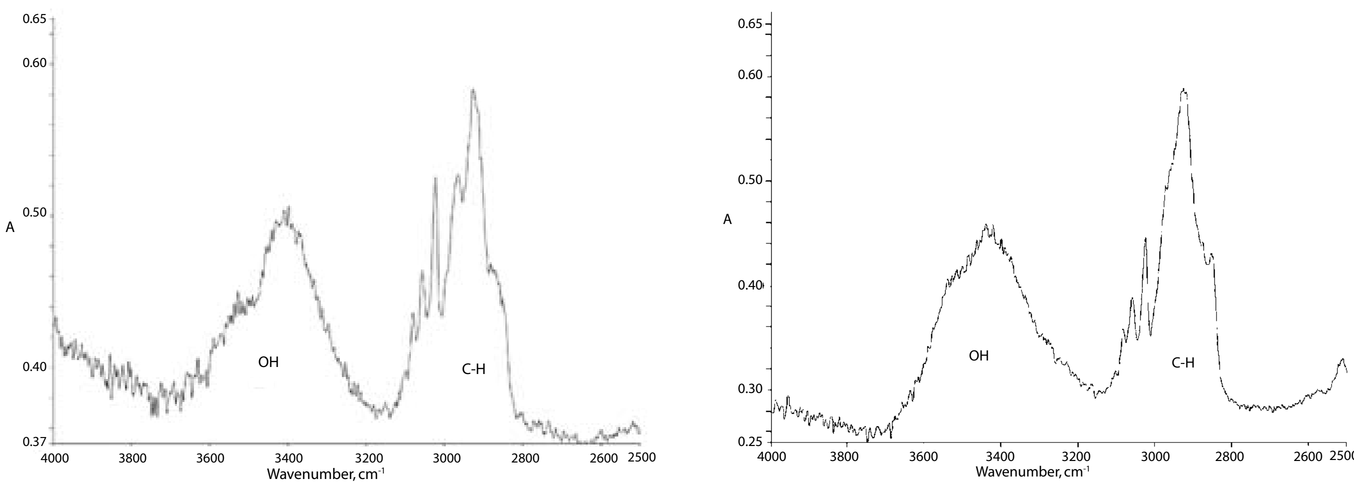



**Fig. 4: EDX scans for in-service and control glass fibers from Hall's Harbor Wharf**




(a) (b)

**Fig. 5: EDX scans for the polymer matrix from the Joffre Bridge: (a) in-service matrix; and (b) control matrix**




(a) (b)

**Fig. 6: FTIR spectra for GFRP in the Joffre Bridge: (a) in-service GFRP; and (b) control GFRP**

dissolution, leaching, and ion exchange, the chemical compositions of the glass and matrix change. The concrete pore solution consists mainly of sodium ($Na^+$) and potassium ($K^+$) ions with hydroxyl ions ($OH^–$) as counter ions. Other elements present in the solution are either very insoluble, such as calcium ions ($Ca^{2+}$), or have low solubility such as magnesium (Mg), aluminum (Al), silicon (Si), iron (Fe), and sulfate ions ($SO_4^{2–}$). Because the EDX can't detect elements lighter than sodium (Na), the $OH^-$ cannot be detected. The $OH^-$ and cations ($Na^+$, $K^+$), however will diffuse together for charge neutrality to be satisfied. Therefore, a strong indication of alkali migration from concrete pore solution toward the glass fibers would lead to the presence of Na or K in the matrix. Observations on several specimens indicated that neither Na nor K was present in the matrix (Fig. 5).

## Fourier transform infrared spectroscopy

All resins have ester bonds that are the weakest link of the polymer. A possible degradation mechanism of the matrix is the alkali hydrolysis of the ester linkages. Due to the alkaline environment in concrete, alkali hydrolysis is expected to some extent. During the hydrolysis reaction, the $OH^–$ induces ester linkage attack, and the resin chain is broken. Consequently, the structure of the resin is disrupted, and the material properties change. Eventually, if the resin degrades, it will not be able to transfer stresses to the glass fibers or protect the glass fibers against alkaline attack. Changes in the amount of hydroxyl groups present in the composite material provide insight into the hydrolysis reaction.

To conduct the FTIR spectroscopy, small portions of the GFRP extracted from the cores were crushed and ground

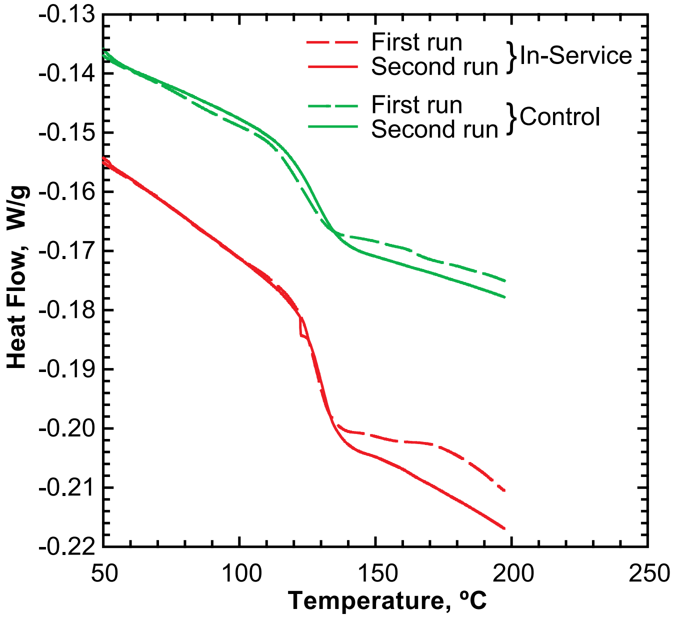



**Fig. 7: DSC results for the in-service and control polymer matrix in GFRP from the Joffre Bridge. The $T_g$ for the matrix is indicated by the sharp drop in the curves**

into powder. The pellet method with spectroscopic grade potassium bromide (KBr) was used to obtain the infrared spectra. The relative amounts of hydroxyl groups in the specimens were measured by determining the ratio of the maximum of the band corresponding to the hydroxyl groups (at a wavenumber of 3430 $cm^{-1}$) and the band corresponding to the carbon-hydrogen groups (at a wavenumber of 2900 $cm^{-1}$) in the FTIR spectra. The C-H content was assumed to be constant. Because the vinyl-ester resins naturally contain hydroxyl groups, all the spectra present a strong absorption band in this region. Typical results of the FTIR analysis for control and in-service GFRP samples from the Joffre Bridge are presented in Fig. 6 and show that there was no significant change in the spectra of the specimens. Similar conclusions were drawn for rods from other structures.

## Differential scanning calorimetry

The glass transition temperature ($T_g$), an important physical property of the matrix, is not only an indicator of the thermal stability of the material but is also an important indicator of the structure of the polymer and its mechanical properties. For example, as a result of breakage of the Van der Waals bond between the polymer chains, moisture in the matrix reduces $T_g$ of the resin through plastification. The swelling stresses associated with moisture uptake or the presence of alkalis can cause permanent damage in the resin such as matrix cracking, hydrolysis, and fiber-matrix debonding.

The $T_g$ measurements were carried out on small pieces cut from GFRP extracted from the cores. The measurements were taken in air between 40 and 200 °C (104 and 392 °F) at a heating rate of 10 °C/minute (18 °F/minute). Typical results are given in Fig. 7. There was no appreciable difference between the glass transition temperature for in-service GFRP and control GFRP. Similar conclusions were drawn for all other structures.

## CANADIAN BRIDGE CODE CHANGES

Based on the results of the analyses, there was no degradation of the GFRP in the structures exposed to natural environmental conditions for durations of 5 to 8 years. The results from the study of actual engineering structures are not in agreement with the results obtained in some simulated laboratory studies.

The results from SEM and EDX analyses confirmed that there is no degradation of the GFRP in the real-life concrete structures. The EDX analyses also indicated no alkali ingress in the GFRP from the concrete pore solution. The matrix in all GFRPs was intact and unaltered from its original state. It's encouraging to note that the results from the FTIR and DSC analyses supported the results from the SEM examinations. The FTIR and DSC results indicated that neither hydrolysis nor significant changes in the glass transition temperature of the matrix took place after exposure for 5 to 8 years to the combined effects of the alkaline environment in the concrete and the external natural environment.

The results of this study were the basis for the new version of the Canadian Highway Bridge Design Code[13] allowing the use of GFRP both as primary reinforcement and prestressing tendons in concrete components provided the stress level in GFRP at the serviceability limit state does not exceed 25% of its ultimate strength.

## Acknowledgments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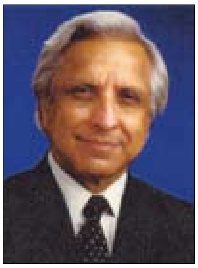

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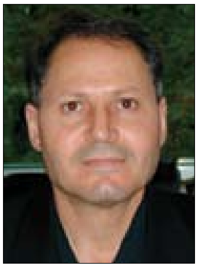

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