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Behaviour of fibre reinforced polymer (FRP) and FRP bond under freeze-thaw cycles and sustained load

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ABSTRACT: The structures repaired or retrofitted with FRP have shown enhanced load capacity and improved response to simulated earthquake loads in numerous short-term tests. However, only a limited number of long-term studies have been reported on their durability. This paper addresses this issue with the emphasis on the FRP reinforcement and FRP bond performance subjected to extreme winter condition under sustained load. Results showed that the severe exposure did not have significant effects on the ultimate strength of FRP and FRP bonds. Also, Scanning Electronic Microscopy (SEM) analysis revealed that the quality of bond between fibres and the matrix is crucial to the durability of FRP against environmental deteriorations.

1 INTRODUCTION

For a variety of reasons, such as the increase of service load levels, severe environmental exposure, revision of building codes or natural aging process, the once properly designed structures can, over time, display deterioration or deficiencies that need to be addressed. The replacement of these inadequate structures is not only costly, but also time-consuming and environmentally unacceptable. Hence, there exists a need to seek solutions that are effective, durable, economical and easy to implement to enhance the service life of such structures.

In the past decade, the use of Fibre Reinforced Polymers (FRP) in concrete structures has become a popular technique to repair and strengthen the deficient structures. Numerous studies have been conducted on the performance of FRP-retrofitted structural components, and the results are promising. Furthermore, structures not originally designed for seismic loads can be retrofitted with relative ease to meet the current seismic provisions. While FRP is effective for its short-term behaviour, its durability has not yet been investigated to an extent that provides the same level of confidence to designers as they have for the traditional materials.

Like all other materials, FRP ages and is prone to deterioration under certain environments, such as moisture, UV radiation, alkaline effect, etc. (Toutanji & El-Korchi 1999; Green et al. 2000, Homam et al. 2001, 2005; El-Hacha et al. 2004, Saenz et al. 2004; Debaiky et al. 2006). For the retrofitted structures in Canada, the extreme winter conditions are of particular concern. Therefore, FRP reinforcement and FRP bond need to be fully investigated for the freeze-thaw exposure under sustained load. The work presented here is specifically aimed to address such issues.

2 RESEARCH PROGRAM

The primary goal of this paper is to investigate the effects of both individual and combined conditioning of freeze-thaw cycles and sustained stress on FRP reinforcement and FRP bond. Freeze-thaw effect is of concern because it represents a typical outdoor condition in many countries, while sustained stress application is of equal importance for it simulates service load conditions that FRP reinforcement may experience in practice. In order to provide end users enough confidence to consider the use of FRP in design, it is essential to understand the post-exposure behaviour of FRP and FRP bond.

The specimens tested included 48 FRP coupons, 48 FRP-to-FRP single-lap-bonded specimens, 48 FRP bonded concrete prisms and 24 FRP bonded concrete beams (Fig. 1). These specimens were designed to study the FRP material, the bond between FRP and FRP under tension, the bond between FRP and concrete under tension, and the FRP-to-concrete bond under bending, respectively. Specimens were subjected to certain load and exposure conditions and then tested to failure for their post-exposure mechanical properties. Four different conditions were investigated: controlled room conditions, 300 freeze-thaw cycles, sustained load (approximately 30% of the specimen capacity) at room temperature and simultaneous application of sustained load and freeze-thaw cycles. Based on the observed changes, the durability of FRP materials and their bond characteristics were evaluated. Table 1 describes the overview of the experimental program.

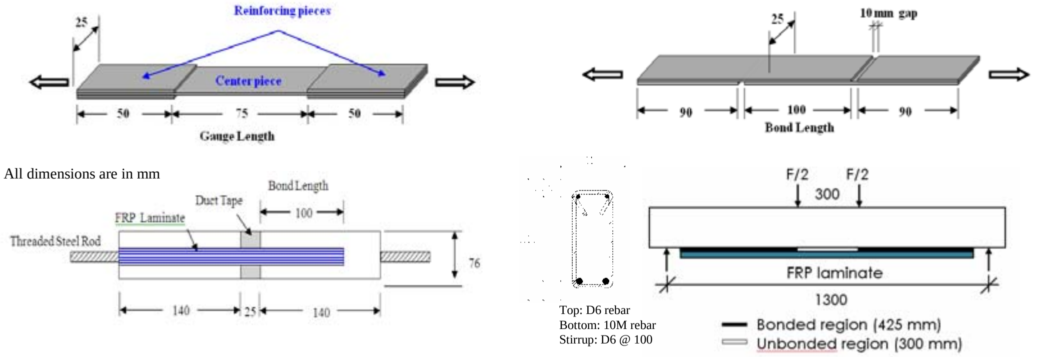

Figure 1. Four types of specimens (starting from top left corner going clockwise): FRP coupon, FRP-to-FRP overlap, FRP bonded beams and FRP bonded concrete prisms

Table 1. Specimens for each of four load and exposure conditions

	Bond Length (mm)	*Coupon*		*FRP-to-FRP Overlap*		*FRP Bonded Prism*		*FRP Bonded Beams*		
		CFRP	GFRP	CFRP	GFRP	CFRP	GFRP	CFRP	GFRP	No FRP
4 types of exposures were applied*	50	-	-	3	3	-	-	-	-	-
	75	6	6	-	-	-	-	-	-	-
	100	-	-	3	3	3	3	-	-	-
	200	-	-	-	-	3	3	-	-	-
	425	-	-	-	-	-	-	2	2	2

*The applied exposures include 1. room temperature, 2. 300 freeze-thaw cycles, 3. sustained load, and 4. simultaneous application of freeze-thaw cycles and sustained load. There are a total of 168 specimens.

3 RESULTS

3.1 *FRP Coupons*

Specimens were tested under direct tension, and strain gauges were adhered at the center of the coupons to measure displacements. Table 2 presents the results of the ultimate strength and tensile stiffness of carbon and glass FRP coupons subjected to various conditions.

Results show that after being subjected to freeze-thaw or sustained stress exposures, carbon FRP (CFRP) lost between 6% and 9% of residual strength and stiffness. In the specimens subjected to both exposures simultaneously, CFRP coupon lost as much as 12% in the residual strength. In the glass FRP (GFRP) specimens, however, a more durable response was noted. Strength of exposed specimens was virtually unaffected; the change in mechanical properties was less than 3%. In fact, small increases in the tensile stiffness were observed in some cases.

Comparatively, GFRP was more durable against both individual and combined exposure of freeze-thaw cycles and sustained load. This conclusion is somewhat contradictory to the traditional thinking. To investigate the reasons behind, a Scanning Electronic Microscopy (SEM) analysis was carried out at the University of Shérbrooke Laboratories on the tested specimens (Cousin & Benmokrane 2007).

Table 2. Average strength and stiffness of FRP coupons subjected to various exposures

	Strength (MPa)				Stiffness (GPa)			
	Control	Freeze-thawed	Sustained Load	Combined Exposure	Control	Freeze-thawed	Sustained Load	Combined Exposure
CFRP	938	852	876	829	76.4	71.3	71.8	71.3
GFRP	647	643	658	631	31.9	34.3	34.0	33.0

SEM analysis revealed that, the interface of glass fibres and epoxy was intact. Even at high magnification, no defects, such as micro-cracks or pores, were detected. The sound integrity of GFRP explains why only marginal differences in strength and stiffness were noted after conditioning. On the contrary, SEM analysis found microcracks and voids in the CFRP control specimens, which suggested poorer integrity between fibre-matrix interface. This could be attributed to the incompatibility of fibres and resin caused by the fibre surface treatment. After being subjected to combined exposure, the already poorly bonded interface was aggravated; large gaps were found around the carbon fibres, which led to reduction in mechanical properties.

Based on these results, it was inferred that good binding of epoxy and fibres is crucial to the durability of FRP. The relatively poor integrity of CFRP coupon exemplified why synergistic exposure has larger adverse effect on CFRP than on GFRP coupons. However, it should be noted that CFRP, despite its relatively poorer integrity, displayed only 12% loss in strength after being subjected to the load and exposure conditions that are significantly more severe than the expected field conditions.

3.2 *FRP Single-Lap-Bonded Specimens (SLB)*

Tested under direct tension, SLB specimens help study the bond between FRP and FRP. Table 3 presents the average bond strength and bond stiffness of FRP overlaps subjected to various conditions. It should be noted that the bond stiffness values should not be taken as absolute values. The measurement presented also included the elongation of FRP reinforcement. However, since the material stiffness was not adversely affected by the exposures (from coupon tests), the representative bond stiffness values were used to estimate the effects of exposures on bond based on the changes in residual properties.

Table 3. Average bond strength and stiffness of FRP-to-FRP bond subjected to various exposures

	Strength (kN)				Stiffness (MPa/mm)			
Bond Length	Control	Freeze-thawed	Sustained Load	Combined Exposure	Control	Freeze-thawed	Sustained Load	Combined Exposure
CFRP								
50 mm	18.7	18.2	17.5	16.2	33.9	35.9	33.9	31.7
100 mm	18.8	16.5	17.5	16.0	18.3	17.9	19.4	11.4
GFRP								
50 mm	15.3	16.1	16.4	15.5	16.8	16.7	18.8	16.7
100 mm	14.8	14.2	15.2	14.2	7.5	6.8	7.4	7.1

Results from the control specimens show that beyond a length of 50 mm, there was no significant increase in load capacity. Also, it was noted that the average bond strength was less than the tensile failure load of FRP. Hence, the failure mode was governed by bond or a combination of bond and material failure, which implies the full tensile strength of FRP was, in fact, never achieved.

After being exposed to 300 freeze-thaw cycles, the 50 mm long carbon overlap joints showed only minimal reduction in bond strength. However, about 12% drop in strength was observed in the specimens with longer bond length. No detrimental effects were found in the residual bond stiffness. In specimens subjected to sustained load, post-exposure strength was reduced slightly in both bond lengths, and bond stiffness remained virtually unchanged. Similar to coupon tests, the combined application of freeze-thaw exposure and sustained stress caused the most deleterious effect on residual properties. The 50 and 100 mm long overlap joints saw about 13% and 15% reductions in bond strength, respectively. As for the bond stiffness, small reductions (about 7%) was observed in 50 mm bond length specimens, while the 100 mm overlaps exhibited a drastic reduction of approximately 40%. This large variation is difficult to explain. One of the potential causes, in addition to error in measurements, may be the deterioration of matrix. Unlike coupon specimens, bond properties of FRP overlaps are matrix-dominant; thus, the performance of FRP-to-FRP bond depends heavily on the performance of matrix. Since carbon fibres were poorly bonded to epoxy (from SEM analysis), the residual bond strength and stiffness of CFRP could be significantly reduced after being subjected to the synergistic exposure.

In GFRP overlap joints, neither freeze-thaw cycles nor sustained stress were found individually harmful to the residual bond properties. Changes in lap shear strength and stiffness were minimal. The worst effect observed was about 9% reduction in residual bond stiffness in 100 mm lap joints. In some cases, improvements in bond stiffness were actually observed. As well, GFRP overlaps subjected to the freeze-thaw cycles and sustained load simultaneously were not adversely affected. All changes were within 6%. This durable behaviour could be attributed to the comparatively superior bond between glass fibres and matrix, which appeared to reduce the potential damage by environment exposure and sustained load. The superior bond could also explain why glass specimen test data has relatively smaller standard deviation.

3.3 *FRP Bonded Concrete Prisms*

The prism specimens comprised two air-entrained concrete parts, which were held together by two strips of FRP on the opposite faces. Direct tension was applied during testing so the behaviour of FRP-to-concrete bond could be investigated. Table 4 presents the average bond strength and stiffness of prism specimens for each category of tests. Similar to FRP overlaps, results from the control specimens demonstrated that doubling the bond length did not increase the failure load. Also, 47 out of 48 specimens failed in FRP-to-concrete interface. This indicates that although the full bond strength was obtained, the tensile capacity of FRP was not developed.

Table 4. Average bond strength and stiffness of FRP-to-concrete bond subjected to various exposures

	Strength (kN)				Stiffness (MPa/mm)			
Bond Length	Control	Freeze-thawed	Sustained Load	Combined Exposure	Control	Freeze-thawed	Sustained Load	Combined Exposure
CFRP								
100 mm	9.0	8.4	8.5	9.8	N/A			
200 mm	8.6	10.8	10.1	10.2	27.6	31.5	40.9	33.5
GFRP								
100 mm	7.1	6.9	7.6	6.9	N/A			
200 mm	6.4	8.9	7.8	8.0	29.8	10.7	23.6	24.9

When studying the CFRP-to-concrete bond, no drastic changes in bond strength were found in the specimens exposed to freeze-thaw cycling, sustained load and simultaneous application of aforementioned. In fact, enhancements were recorded in many cases. Similar results were also observed in the bond stiffness, measured by the initial rising slope. However, it should be noted that a wide scatter existed in the data. This was due to the concrete contact between the two parts of the prisms. Despite an effort to separate them, fractions of the two prism parts remained in contact before testing. Shortly after the test began, the two parts were separated, but the abrupt separation could cause some damages to the tip of the FRP-to-concrete bond, and change the bond stiffness of the specimens. Smaller bond stiffness was thus observed at this stage of loading in the prism specimens. Since it was difficult to control the separation of prisms, a wide range of scatter was found in the data. Therefore, the effects of exposures on bond rigidity were difficult to quantify. For future study, a different design is suggested to isolate FRP-to-concrete bond during testing.

In the GFRP specimens, the residual bond strength was found to be durable against the exposures applied. In addition, specimens with 200 mm bond length saw significant increase after being conditioned. Nonetheless, when studying bond stiffness, unusual results were found in the measurements. Much larger reduction in bond stiffness was observed in the specimens subjected to freeze-thaw exposures than in those exposed to the combined conditions, which was considered more deleterious. This large reduction is difficult to explain, and could be attributed to an error in measurements. Considering the scatter in the data and possible errors in measurements, results are inconclusive on the quantitative effects of sustained load and freeze-thaw exposure on bond stiffness. However, it can be stated that the changes in stiffness are not significant.

3.4 *FRP Bonded Concrete Beams*

Twenty four small-scale beams were tested to investigate FRP-to-concrete bond under bending (Fig. 1). All beams were first pre-loaded until tensile reinforcement yielded. The applied load at yielding was about 66 kN and the average crack was about 0.4 mm. After load was removed, FRP sheets were then applied to the lightly sandblasted concrete surfaces accordingly, after which, specimens were conditioned and later tested for post-exposure behaviour. The typical load vs. mid-point deflection responses of the control specimens are presented in Figure 2. Although the stiffness of strengthened beams remained similar to the un-strengthened ones, the load capacities of CFRP- and GFRP-strengthened beams were augmented by about 34% and 20%, respectively.

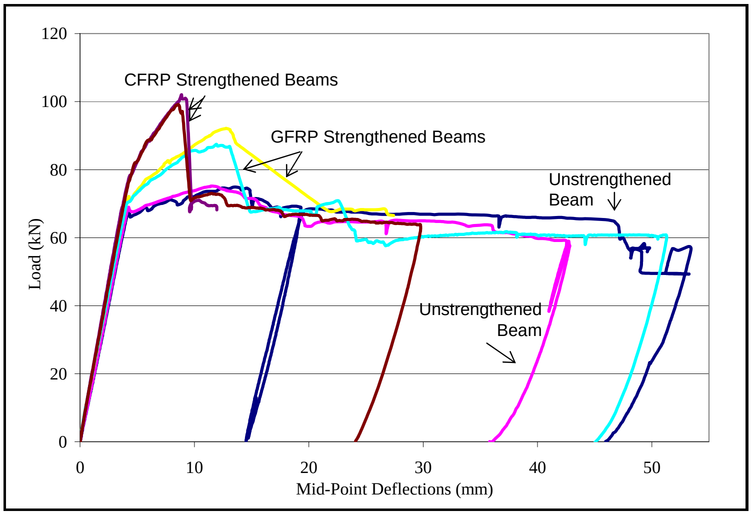

Figure 2. Load – deflection plot of strengthened and un-strengthened beams with no conditioning

Table 5 presents the maximum load and the initial stiffness (based on Figure 2) of the tested beams. Results show that the strength of un-strengthened beams was not detrimentally affected by the applied exposures; variation was between 2% and 5%. Also, the post-exposure stiffness response remained fairly constant. The largest change was still within 10%. Similar results were found in the strengthened specimens as well. The largest reduction observed in CFRP strengthened beams was about 7%, while improvements between 7% and 15% were recorded in the residual stiffness. In the GFRP strengthened specimens, results show an average of about 7% and 17% increase in strength and stiffness, respectively. The post-exposure performances indicate that both CFRP and GFRP strengthened beams were durable against the severe exposures of 300 freeze-thaw cycles and/or sustained load.

Despite the excellent residual performance, it should be noted that all strengthened beams failed in de-bonding of FRP. FRP sheets were bonded over a length of 425 mm to the concrete surface, yet, it was not enough to develop the full tensile capacity of FRP reinforcement, which suggests that there exists a higher capacity in strengthened beams if de-bonding can be avoided. This can be accomplished by installing appropriate mechanical anchorage to ensure the FRP reinforcement is fully utilized.

Table 5. Average strength and stiffness of beam specimens subjected to various exposures

	Strength (kN)				Stiffness (kN/mm)			
	Control	Freeze-thawed	Sustained Load	Combined Exposure	Control	Freeze-thawed	Sustained Load	Combined Exposure
No FRP	75.0	77.8	73.3	78.2	16.0	17.1	16.1	17.5
CFRP	100.6	99.9	103.9	93.9	18.5	20.0	19.7	21.3
GFRP	89.8	98.9	92.9	96.7	17.0	19.4	19.7	20.7

4 CONCLUSIONS

This paper is aimed at addressing the durability issue of FRP with the emphasis on freeze-thaw and sustained stress exposures. The effect of applied exposures on FRP reinforcement, FRP-to-FRP bond, and FRP-to-concrete bond (under tension and bending) were studied. Experimental results showed durable performance of FRP against the applied conditions, which are likely more severe than the expected field conditions. Moreover, SEM analysis revealed the quality of bond between fibres and matrix is crucial to the durability of FRP. Well bonded GFRP coupons demonstrated better residual properties than that of CFRP specimens with relatively poorer bond.

After being conditioned, both FRP-to-FRP and FRP-to-concrete bonds performed well under tension. In addition, it was noted that beyond a certain bond length, the failure load remained constant, which was lower than the tensile capacity of FRP. This suggests that FRP reinforcement was never fully utilized.

No adverse effects were observed on the residual properties of FRP-strengthened beams as a result of sustained load and freeze-thaw exposures. However, as in prism specimens, FRP-to-concrete bond failure was the governing failure mode. This implies higher beam capacity can be obtained provided that appropriate mechanical anchorages are installed.

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