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FRP confined concrete columns: Behaviour under extreme conditions

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Abstract

The behaviour of concrete columns wrapped with fibre reinforced polymer (FRP) materials when exposed to several extreme conditions is evaluated. Cold regions environments, FRP repair of corroding reinforced concrete columns, and fire resistance are all considered. For the cold regions exposure, FRP wrapped cylinders (152 × 305 mm) are exposed to temperatures as low as −40 °C or to up to 300 cycles of freeze-thaw (−18 °C to +15 °C). The combination of freeze-thaw exposure with sustained loading is also examined. For FRP wrapping of corroding reinforced concrete columns, the results of tests on cylinders and larger-scale circular columns (300 × 1200 mm) are presented. The specimens are corroded and then wrapped with FRP sheets. The rate of corrosion is monitored both before and after wrapping. The final extreme condition that is considered is fire exposure. Tests on full-scale reinforced concrete columns (400 × 3800 mm) exposed to a standard fire are described and discussed. Overall, the results demonstrate that FRP confined concrete columns tested in concentric axial compression have adequate performance under several extreme conditions such as low temperature, freeze-thaw action, corrosion of internal reinforcement, and fire exposure.

Keywords: Fibre reinforced polymers; Concrete; Cold regions; Freeze-thaw; Low temperature; Corrosion; Columns; Fire endurance; Repair; Rehabilitation; Strengthening

1. Introduction

Fibre reinforced polymer (FRP) materials are increasingly being applied for the rehabilitation and strengthening of reinforced concrete structures. The potential market for such applications is huge since the estimated annual cost of repairing bridges in the United States alone is 9.4 billion dollars [1]. One popular technique of FRP strengthening is the wrapping of reinforced concrete columns to increase their axial strength, shear strength, and seismic resistance. In this application, the FRP sheets are generally wrapped around the columns with fibres oriented mainly in the circumferential direction. The fibres confine the concrete and increase the axial strength by creating a triaxial stress condition. The FRP wraps also increase the shear resistance of columns and prevent premature spalling failures when columns are subjected to lateral loadings typical of those observed during earthquakes. In the current paper, the focus is on applications where FRP wraps are used to increase the axial strength of the columns.

Such FRP wrapped columns may be subject to harsh conditions during their service life. In cold regions, column repairs for bridges and exterior parking structures will be exposed to temperature extremes, freeze-thaw cycles, and potential corrosion due to de-icing salts. In interior building applications, FRP wrapped columns may be subjected to fire and thus wrapped columns must be able to maintain strength and integrity for a reasonable period during the fire to prevent collapse of the structure. This paper will discuss the effects of these extreme conditions on FRP wrapped concrete columns.

This paper considers three main extreme conditions in three separate sections: cold regions, wrapping of corroded reinforced concrete columns, and fire exposure. In each section, short literature surveys are provided and the results of investigations conducted by the authors are discussed. The paper concludes with a section discussing these extreme

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effects and potential interactions if these effects are combined.

2. Cold regions

Two basic effects occur when FRP materials are exposed to cold regions conditions: thermal incompatibility and polymer embrittlement. The first effect is related to the thermal expansion of the constituent materials of FRPs which consist of fibres embedded in a polymer matrix. The coefficients of thermal expansion (CTEs) for fibres typically differ considerably from those of matrices. These thermal incompatibilities can cause internal stresses to develop in the FRP at the fibre–matrix interface. Further, CTE differences can also cause bond issues when the FRP is applied to concrete structures. For column wrapping applications, bond is not a critical issue and thus will not be investigated in this paper.

The other major effect is polymer embrittlement whereby the strength and stiffness of the polymer increases at the lower temperature but the failure mode becomes more brittle. The increased stiffness may also reduce the effectiveness of the matrix to transfer stresses between fibres, or between the composite and the substrate concrete.

To examine these effects, some limited research has been conducted by other researchers. Karbhari and Eckel [2] tested FRP wrapped cylinders at low temperature (−18 °C) and found increased brittleness of FRP fibres at low temperature. Further work by Karbhari [3] showed strength reductions at low temperature after exposure to freeze-thaw in a saturated condition. Toutanji and Balaguru [4] exposed FRP wrapped concrete cylinders to 300 freeze-thaw cycles. They found some deterioration due to freeze-thaw with carbon FRP (CFRP) performing better than glass FRP (GFRP). Teng et al. [5] compared field evaluation of wrapped FRP columns to laboratory tests of freeze-thaw resistance. They found little deterioration in the field over a period of 2 years but some loss of ductility in wrapped cylinders subjected to large thermal cycles in the laboratory.

2.1. Low temperature

Two separate sets of tests [6,7] investigated the low temperature behaviour of CFRP and GFRP wrapped cylinders (152 × 305 mm). Table 1 presents the manufacturers' specified properties for the sheets used in these tests. In the first set of tests, six cylinders (two plain cylinders, four wrapped with CFRP-A) were kept at −18 °C for 200 days and subsequently tested for strength in axial compression at room temperature. Additionally, nine cylinders (three plain, six wrapped) were kept at room temperature as control specimens. In the second set of tests, 16 cylinders were wrapped with either a single layer of CFRP-B or two layers of GFRP-A. Half of these specimens were exposed to −40 °C for 16 days while the other half were kept at room temperature. In this second set of tests, the cylinders were tested in a frozen state immediately after being removed from the cold room. Table 2 summarizes the results of the tests on the cylinders.

For the first set of tests, the low temperature exposure did not affect the strength of the cylinders wrapped with one layer of CFRP-A. A slight reduction in strength (4 MPa loss) was noted for the specimens with two layers of wrap but this reduction was likely due to experimental scatter rather than to any actual strength loss. For the second set of tests, the wrapped cylinders increased in strength at low temperature by an average of 14%. This strength gain was attributed to freezing of porewater inside the concrete when the cylinders were tested in the frozen state. This effect was not observed in the first set of tests since the cylinders were tested at room temperature.

Table 2
Results from low temperature tests on cylinders [6,7]

Type of wrap	Temperature (°C)	Duration (days)	Average failure stress (MPa)	
			Room temperature	Low temperature
None	−18	200	46	46
One layer Carbon-A	−18	200	53	52
Two layers Carbon-A	−18	200	59	55
None	−40	16	59	
One layer Carbon-B	−40	16	70	80
Two layers Glass-A	−40	16	73	83

Table 1
Properties of FRP products as specified by the manufacturers

Designation	Manufacturer	Modulus per unit width (kN/mm/ply)	Ultimate strength per unit width (kN/mm/ply)	Ultimate strain	Type of matrix
Carbon-A[b]	Mitsubishi	22.4	0.237	0.015	Epoxy
Carbon-B[b]	Fyfe	70.3	0.881	0.013	Epoxy
Carbon-C[a]	Forca-Tonen	25.3	0.383	0.015	Epoxy
Carbon-D[a]	Wabo MBrace	38.0	0.625	0.017	Epoxy
Glass-A[b]	Fyfe	33.8	0.748	0.022	Epoxy
Glass-B[a]	Forca-Tonen	8.8	0.182	0.021	Epoxy

[a] Material properties calculated using fibre area only.
[b] Material properties calculated using total composite area.

Another interesting observation from these tests related to the failure mode. In all cases, the cylinders exposed to low temperature failed in a more brittle manner than those kept at room temperature. In the second set of tests, the CFRP wrapped cylinders failed in a more dramatic fashion than did the GFRP wrapped cylinders. Also, the axial strains at failure were lower for the frozen cylinders than for the room temperature specimens. These observations indicated that the low temperature exposure caused some embrittlement of the matrix that reduced deformability and led to more brittle failures.

2.2. Freeze-thaw

The freeze-thaw behaviour of FRP confined concrete cylinders was also examined [6,8,9]. Sixty-three specimens wrapped with two different types of FRP (CFRP-A and GFRP-B) were exposed to up to 250 freeze-thaw cycles (16 h of freezing at −18 °C and 8 h of thawing in a water bath at +15 °C). The cylinders were then tested in axial compression. Table 3 presents some of the results. The air entrainment for the CFRP wrapped cylinders was below 5% and yet the average strength loss for the wrapped cylinders was less than 10%. The corresponding unwrapped cylinders lost most of their strength because of freeze-thaw exposure. Thus, the CFRP wraps were able to protect the concrete from freeze-thaw damage.

For the GFRP-B wrapped specimens, the air entrainment of the concrete was approximately 6%. The average strength of the wrapped cylinders exposed to freeze-thaw was approximately 5% less than the average strength of the room temperature specimens. This difference in average strength was not found to be statistically significant, and thus no significant deterioration of the GFRP wrapped cylinders due to freeze-thaw exposure was observed.

It was also noted that the unwrapped cylinders experienced a gain in strength due to the freeze-thaw exposure that was not observed in the wrapped specimens. One possible explanation for this is that unwrapped cylinders cured during the freeze-thaw exposure due to the water exposure during the thawing process. For the FRP wrapped specimens, the wrap prevented the water from penetrating the concrete sufficiently to provide additional curing.

Table 3
Results from freeze-thaw tests on cylinders [6,9]

Type of wrap	Concrete air content (%)	No. of cycles	Average failure stress (MPa)	
			Room temperature	Freeze-thaw
None	6	250	54	58
Two layers Glass-B	6	250	62	59
None	<5	200	46	16
One layer Carbon-A	<5	200	53	47
Two layers Carbon-A	<5	200	59	52

The failure mechanism of the wrapped cylinders exposed to freeze-thaw was very sudden and catastrophic when compared to that of the control specimens. One explanation for this failure mechanism is that the freeze-thaw deteriorated the concrete such that the confinement of the wrap was the only mechanism holding the cylinder together. Thus, when the wrap broke, the cylinder failed immediately. The control specimens failed more gradually because the load was probably shared between undamaged concrete and the confining effect of the wrap. Thus, when the wrap broke, the concrete was still able to resist load.

2.3. Freeze-thaw under sustained loading

As an extension of the work on FRP wrapped cylinders in cold regions, light-weight concrete cylinders were wrapped with GFRP or CFRP sheets and then subjected to freeze-thaw cycles, while under sustained axial loads. To the authors' knowledge, the effects of this combined exposure have never been reported in literature. The residual compressive strengths of the specimens were compared to other specimens exposed to freeze-thaw only or sustained load only, in room temperature [10].

Sixty 152×305 mm concrete cylinders were fabricated using light-weight palletized slag aggregates. No air entrainment was used to simulate critical conditions for concrete. The cylinders had an average 28 days compressive strength of 40 MPa. Two sets of 22 cylinders each were wrapped with one layer of CFRP-B sheet or with one layer of GFRP-A sheet (Table 1). The remaining 16 cylinders were left unconfined. After the wrapped cylinders were fully cured, their ends were carefully ground to achieve a smooth surface perpendicular to the main axis of the cylinder. Before applying sustained loads and freeze-thaw exposure, all cylinders were first subjected to one monotonic loading cycle, up to a load level of 45% of their respective ultimate strengths, unloaded, and then submerged in water at room temperature for one week. This practice was adopted to increase the likelihood of freeze-thaw damage by inducing microcracks and increasing the internal moisture content.

Four loading frames were built to apply the sustained loads. Two frames were placed in an environmental chamber; one held five CFRP wrapped cylinders and the other held five GFRP wrapped cylinders, in series as shown in Fig. 1. The other two frames were kept at room temperature, with similar specimens being loaded. Fifteen control cylinders, five with CFRP, five with GFRP and five unconfined, were also placed in the environmental chamber but without sustained loads. An additional 25 control cylinders, seven with CFRP, seven with GFRP and 11 unconfined, were left at room temperature. Three of the 11 plain concrete cylinders were submerged in water for a period equivalent to the total number of thawing hours to simulate any curing effects during thawing in water in the environmental chamber.

Some cylinders included thermocouples to measure the concrete core temperature, to help programming the

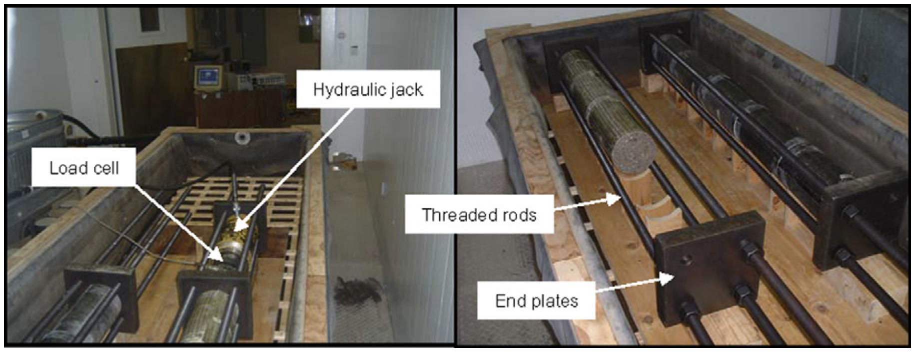

Fig. 1. Test setup for freeze-thaw exposure and sustained loading.

environmental chamber according to ASTM C666 [11], where the specimens were subjected to 300 freeze-thaw cycles, with the core temperature varying from +4.4 °C to −18 °C in 5 h and 15 min. The sustained load was applied to the cylinders via a 980 kN hydraulic ram. To monitor the sustained load, a 445 kN load cell was fitted in the frame to continuously monitor the load, which was maintained relatively constant throughout the duration of freeze-thaw. After completion of freeze-thaw cycles, all specimens were tested in compression using a 1000 kN MTS machine. Cylinders were instrumented with three 100 mm displacement-type strain gauges equally spaced around the perimeter to measure axial strains, and two 5 mm electric resistance strain gauges to measure hoop strains on two opposite sides.

The five unconfined cylinders placed in the water bath in the environmental chamber were completely disintegrated due to freeze-thaw damage after 150 cycles with virtually zero residual strength, due to the lack of air entrainment. FRP wrapped cylinders that survived the freeze-thaw exposure were tested to failure in compression. Fig. 2 shows a summary of test results for the GFRP and CFRP wrapped cylinders under various conditions, based on the average

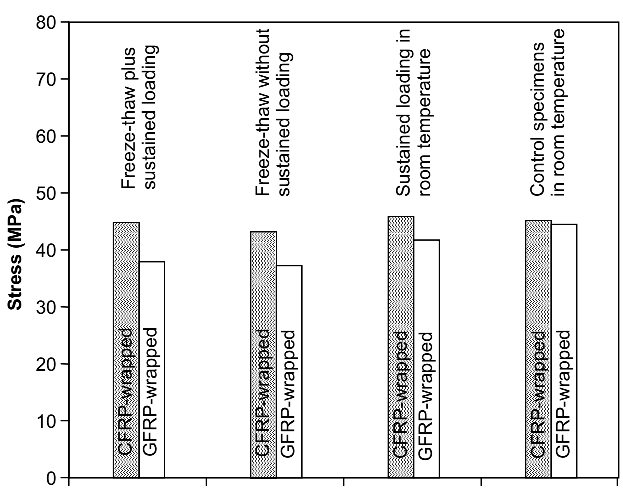

Fig. 2. Summary of test results for FRP-wrapped cylinders subjected to sustained loads and freeze-thaw cycles.

strength of several specimens. Sample stress–strain curves for CFRP wrapped cylinders, along with pictures of failure modes, are provided in Fig. 3.

In general, the FRP wraps did not produce substantial confinement or gain in strength for this light-weight concrete (about 10–12% only). This could be attributed to the different dilation mechanism of light-weight concrete, compared to standard normal weight concrete. It is noted, however, that the effect of freeze-thaw under sustained loading resulted in only 2% and 9% reductions in strength for the CFRP and GFRP wrapped cylinders, respectively. In absence of sustained loading, the effect of freeze-thaw resulted in 5% and 16% reductions in strength, respectively. This suggests that the restraining effect in the longitudinal direction of the column has a beneficial effect by controlling longitudinal expansion due to freeze-thaw, while the FRP wraps control expansion in the transverse direction. It should also be noted that the study is based on small-scale cylinders under purely axial compressive loads and that tests on larger specimens with eccentric loading may be needed to confirm these findings.

3. CFRP wrapping of corroded reinforced concrete columns

In cold regions, in addition to low temperature and freeze-thaw exposure, reinforced concrete structures are subjected to contamination with de-icing salts. Further, structures in coastal regions are also often contaminated with chlorides. The resulting corrosion of reinforcing steel in concrete members is one of the most significant causes of deteriorating infrastructure. FRP wraps are a potential repair material for such corrosion damaged structures, but concerns exist about the effects of the FRP wraps on the corrosion process and the resulting long-term structural integrity of the repaired members.

In this portion of the paper, the effects of CFRP wrapping of corroded reinforced concrete columns are considered. Using electrically accelerated corrosion inducing methods, other researchers have suggested that wrapping columns with FRP sheets can reduce corrosion [12,13]. Additionally, some field applications have specifically

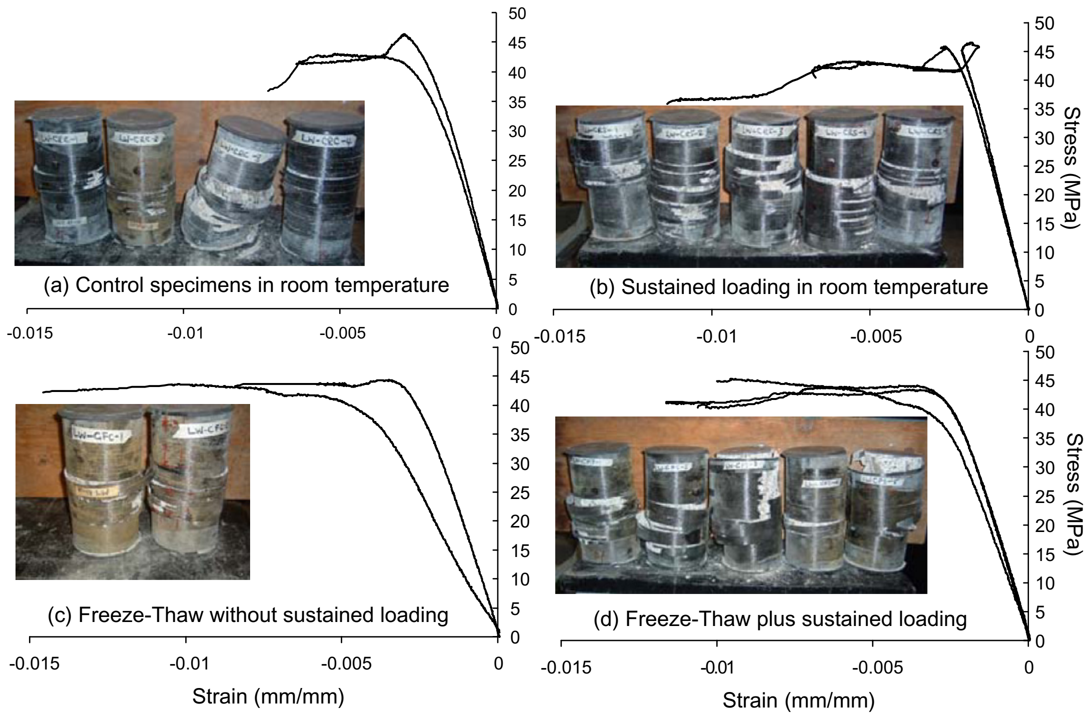

Fig. 3. Stress–strain responses of CFRP-wrapped cylinders.

considered the effects of FRP on the underlying corrosion [14]. Sen [14] conducted a thorough review of the literature in this field and readers are directed to his paper for more detailed discussion of previous research in this area. The research presented in this paper extends this work by considering "natural" corrosion.

The experimental investigation consisted of two types of tests: small-scale cylinder (152 × 305 mm) tests to study basic parameters, and larger-scale circular reinforced concrete columns (300 × 1200 mm). An aggressive environment (3% saline solution and +40 °C) was used to corrode the cylinders. The cylinders were wrapped with CFRP at several stages including a pre-corrosion wrapping to investigate the efficiency of the CFRP wraps when applied on columns with different corrosion levels. The on-going corrosion was monitored with half-cell potential and linear polarization resistance (LPR) measurements.

Ten larger-scale reinforced concrete columns were also exposed to corrosive conditions in a similar manner to the cylinders. An additional two columns were kept at room temperature as control specimens. After a reasonable level of corrosion was attained, eight of the columns were wrapped and then exposed again to the severe environment. Four of the wrapped columns were tested to failure in axial compression after an additional 240 days of the corrosive conditions, and the other four were exposed for an additional 3 years before testing.

Fig. 4 shows some typical LPR results from the small-scale tests. This figure plots the corrosion current density, i_{corr}, over time. For i_{corr} between 0.2 μA/cm^2 and 1.0 μA/cm^2, low to moderate corrosion is expected, while for i_{corr} between 1.0 μA/cm^2 and 10.0 μA/cm^2, moderate to high corrosion is expected. Thus, the results indicated that the fully wrapped specimens experienced low to moderate corrosion while the unwrapped specimens experienced much higher corrosion rates. Interestingly, wrapping the specimens at an intermediate stage during the corrosion process reduced the corrosion rates to levels similar to those measured for the specimens wrapped before exposure to the severe environment. The corrosion rates were reduced in the cylinders because the wraps reduced the penetration of chlorides, oxygen, and water into the cylinders. For the cylinders that were wrapped at an intermediate stage, water and chlorides had already penetrated the specimens.

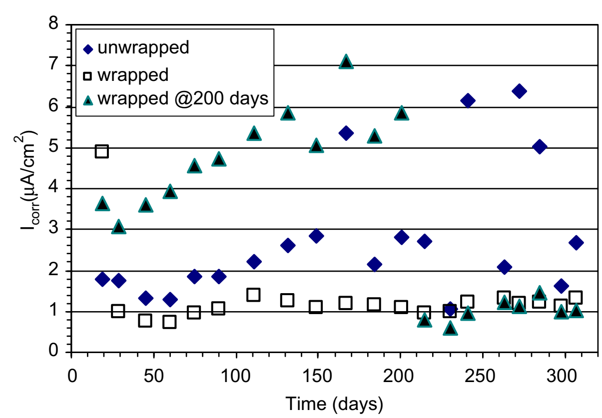

Fig. 4. Typical linear polarization resistance (LPR) measurements for cylinder tests (0.2 μA/cm^2 < i_{corr} < 1.0 μA/cm^2, low to moderate corrosion; 1.0 μA/cm^2 < i_{corr} < 10.0 μA/cm^2, moderate to high corrosion).

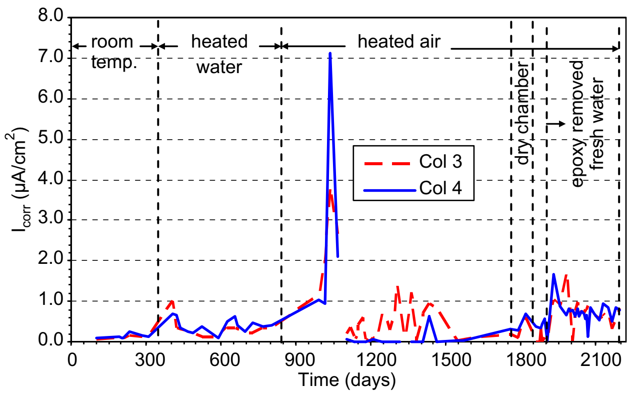

Fig. 5. Typical linear polarization resistance (LPR) measurements for columns tests ($0.2\ \mu A/cm^2 < i_{corr} < 1.0\ \mu A/cm^2$, low to moderate corrosion; $1.0\ \mu A/cm^2 < i_{corr} < 10.0\ \mu A/cm^2$, moderate to high corrosion) [18].

Thus, the reduction in corrosion rate was likely due to oxygen starvation.

The larger-scale specimens displayed similar behaviour to the cylinders in terms of the reductions in the rate of corrosion. Fig. 5 shows some typical LPR results for the columns. The columns were wrapped at approximately 1050 days and the corrosion rates dropped considerably after wrapping. The corrosion rates remained in the low to moderate region for up to 3 years after the CFRP wrapping. Once again, the effectiveness of the wraps at reducing the corrosion rate was likely due to the wraps reducing the rate of oxygen diffusion into the columns because sufficient moisture and chlorides to sustain the corrosion process were likely trapped inside the column after wrapping. More details on these results may be found in Refs. [15–18].

4. Fire

For exterior structures such as bridges, cold regions exposure and corrosion are very important effects but for interior applications in buildings, fire is a major concern. Indeed, fire has been identified as a critical research need [19,20] that must be addressed to enable the use of FRP systems in buildings and parking structures. In an attempt to address this important knowledge gap, an extensive research project is currently underway at the National Research Council of Canada and Queen's University, in collaboration with ISIS Canada and industry partners. As part of this program, the behaviour of FRP confined reinforced concrete columns during fire is being studied through full-scale fire endurance tests [21] and numerical fire simulations [22]. FRP strengthened reinforced concrete beams and slabs are also being studied [23,24].

4.1. FRPs and fire

Structural fire safety is a major requirement in the design of buildings, and adequate fire resistance of structural members ensures that, when measures for preventing, extinguishing, or containing a fire fail, structural integrity is maintained for a sufficient duration during fire. Appropriately designed reinforced concrete columns are known to exhibit good performance under fire exposure [25], but few studies have been performed on the fire performance of FRP strengthened reinforced concrete members. These limited studies [26,27] clearly indicate that thermal insulation of FRP materials is required to prevent rapid loss of the structural effectiveness of FRP systems during fire. A more detailed summary of research on the fire resistance of FRP strengthened reinforced concrete structures is available in Ref. [28]. Until recently, no information was available on the performance in fire of FRP wrapped reinforced concrete columns.

FRP materials are known to be sensitive to the effects of elevated temperatures [28]. Deterioration in mechanical and/or bond properties can be expected at temperatures approaching the glass transition temperature (T_g) of the polymer matrix/adhesive [28–30] which is typically less than 100 °C. Thus, several important fire safety concerns are associated with the use of FRPs as confining reinforcement for concrete columns. These include the potential for increased flame spread and smoke generation, loss of FRP strength and stiffness, and loss of bond between the concrete and the FRP [26]. Because of the lack of information in this area, design guidelines for FRP strengthening systems for concrete members currently require that the FRP be considered ineffective during fire [29]. Flame spread and smoke generation considerations are not treated in the current discussion, and interested readers are encouraged to consult specialized references for specific information in this area [31].

4.2. Fire tests on FRP wrapped columns

The test program to date has consisted of full-scale fire tests on five FRP wrapped reinforced concrete columns under full service load, in accordance with ASTM E119 [32]. Details of the column test program are presented in Tables 4 and 5. Four 400 mm diameter 3810 mm long circular columns strengthened with carbon FRP wraps have been tested. In addition, a single 400 mm square 3810 mm long column strengthened with glass FRP wraps has been fire tested. Four of the five columns were protected with supplemental fire insulation systems applied to the exterior of the FRP wraps. The two fire protection systems were developed specifically for this application by industry partners, and consisted of spray-applied cementitious mortars with specialized fillers and coatings. Further information on the insulation systems is provided by Bisby [33] and Williams [34].

Fig. 6 shows temperatures recorded at the level of the interface between FRP and concrete during fire exposure for all five columns tested to date. It is clear that good thermal protection is provided by the supplemental insulation systems, although the recorded FRP temperature exceeds its T_g relatively early in the fire exposure, even for well

Table 4
Details of FRP-wrapped columns tested in fire

No.	Section dimensions	Primary reinforcement	Lateral reinforcement	Aggregate type[a]	f'_c (MPa)	FRP wrap	T_g of FRP[b] (°C)	Fire insulation	Insulation thickness (mm)
1	400 mm Ø	8–20 mm Ø	10 mm spiral 50 mm pitch	CA	40	CFRP 1[c]	93	System 1[f]	32
2	400 mm Ø	8–20 mm Ø	10 mm spiral 50 mm pitch	CA	39	CFRP 1	93	System 1	57
3	404 × 404 mm	4–25 mm Ø	10 mm ties 406 mm c-c	SA	52	GFRP[d]	93	System 1.1[f]	38
4	400 mm Ø	8–20 mm Ø	10 mm spiral 50 mm pitch	SA	33	CFRP 2[e]	71	None	–
5	400 mm Ø	8–20 mm Ø	10 mm spiral 50 mm pitch	SA	33	CFRP 2	71	System 2[g]	53

[a] CA – carbonate aggregate, SA – siliceous aggregate.
[b] As reported by the manufacturer.
[c] One layer of the Carbon-B (Table 1).
[d] Three layers of Glass-A (Table 1).
[e] Two layers of Carbon-D (Table 1).
[f] Gypsum-based fire protection system.
[g] Cementitious fire protection system.

Table 5
Results of fire endurance tests conducted to date

No.	Design load capacity[a] (kN)	Applied load[c] (kN)	Fire test load ratio[d]	Failure load (kN)	Time to exceed T_g (h:min)[f]	Fire endurance (h:min)
1	5049	2515	0.50	4437[e]	1:21	>5:00
2	5049	2515	0.50	4680[e]	1:58	>5:00
3	5090[b]	3093	0.61	3093	0:51	>4:00
4	5158	2635	0.58	2635	0:02	3:30
5	5158	2635	0.58	4575[e]	0:31	>5:00

[a] Determined in accordance with ACI 440.2R-02 [29].
[b] Square column confinement modelled using equations suggested by Teng et al. [36].
[c] The applied load represents the full unfactored service load calculated in accordance with ASTM E119 [32].
[d] Ratio of load applied during the fire test to the design ultimate load of the strengthened column.
[e] If failure had not occurred at 5 h of exposure the load was increased until failure.
[f] Based on manufacturers' specified T_g values.

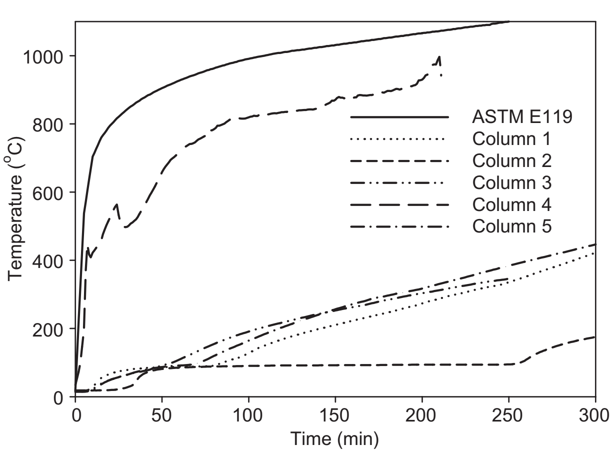

Fig. 6. Temperatures recorded at the FRP-concrete bond line for insulated FRP-wrapped reinforced concrete columns tested to date.

insulated systems (refer to Tables 4 and 5). At temperatures above T_g, the strength, stiffness, and bond properties of the FRP deteriorate. The amount of deterioration has not been quantified due to a lack of appropriate material properties at such high temperatures. Fig. 6 also suggests that the temperatures of the reinforcing steel and concrete inside the insulated columns remained significantly less than 400 °C for the full duration of the fire exposure. This indicates that the columns likely retained their full unconfined strength for the full duration of the fire exposure, since temperatures less than 400 °C are not considered structurally significant for concrete or reinforcing steel [21,25]. Thus, even if the contribution of the FRP is ignored, the columns would have adequate strength to resist loads expected during a fire event because of the thermal protection of the supplemental insulation.

Fig. 7 shows an FRP wrapped and insulated column (Column 5) immediately before fire testing and immediately after failure. The fire insulation remained intact beyond structural failure in this case. All five columns behaved well under fire, with the insulation systems remaining intact until failure. However, the performance of the insulated columns was far superior to that of the column without fire protection (Column 4), in which the FRP wrap combusted within a few minutes of fire exposure and completely debonded from the column.

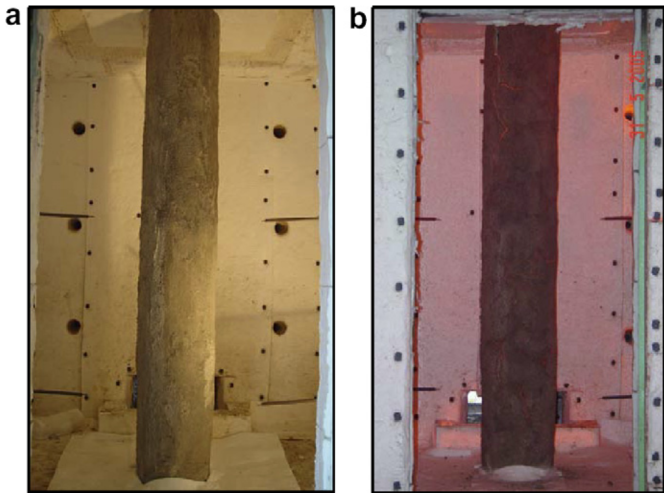

Fig. 7. Insulated FRP-wrapped column (Column 5) (a) before and (b) after exposure to the ASTM E119 standard fire [32] for more than 5 h.

These fire tests have demonstrated that supplemental insulation systems can be used to provide effective fire protection for both circular and square FRP wrapped reinforced concrete columns. Circular and square FRP confined columns protected with appropriate thicknesses of these systems are capable of achieving satisfactory fire endurance ratings [35], in excess of 4 h, even when the T_g of the FRP system is exceeded early in the test. Clearly, this effect is due to the fact that the pre-existing unconfined concrete column, which is subjected to service loads only during fire, is protected by the supplemental insulation system, and experiences only mildly increased internal temperatures which do not significantly decrease its capacity.

4.3. Significance of fire endurance studies for design

Fire safety engineering is concerned primarily with life-safety objectives, and structural fire resistance requirements for columns are intended to prevent structural collapse for a sufficient duration during fire. In actual fire situations, loads on members are typically less than ultimate [25], and load carrying requirements can thus be relaxed. For design of FRP confined columns, this suggests that the *unfactored service load* on a column should not exceed the *nominal strength of the unconfined member* for the required duration during fire. This is essentially a statement of the ASTM E119 [32] structural fire endurance requirement for columns, and confirms that loss of effectiveness of the FRP system is not explicitly a concern. Thus, if the nominal capacity of the unconfined member can be protected from fire (using supplemental fire protection, for instance) then the member will likely be able to achieve satisfactory fire endurance under service loads, as has been demonstrated by the fire tests presented in this paper. The reader will note that no specific requirement that the FRP temperature remain below its T_g is required.

The above design philosophy assumes complete loss of effectiveness of FRP confinement during fire because data pertaining to the mechanical properties of FRP at high temperatures are currently not available. The strength of FRP materials could be used in a fire situation if and only if the temperature of the FRP is kept below an as yet unknown *critical* temperature. The conservative lower bound is likely to be in the range of T_g (65–100 °C), while the upper bound could be as high as 300 °C based on available research [28]. While additional data are clearly required, the fire endurance studies conducted to date show that it is possible design fire-safe FRP confined reinforced concrete columns.

5. Summary and discussion

This paper has discussed the performance of FRP confined reinforced concrete columns under several extreme conditions. In cold regions, the presented experimental results showed that FRP materials performed very well for confinement of concrete under axial loads. Low temperature (−18 °C or −40 °C) exposure resulted in an increase in strength when cylinders were tested at the low temperature due to freezing of porewater. After exposure up to 250 freeze-thaw cycles, the average axial strength of confined cylinders decreased by 5–10% as long as the concrete were air entrained. Such decreases in strength were not found to be statistically significant. For concrete without air entrainment, the strength losses were much higher. Further, the combination of freeze-thaw exposure and sustained axial load was less severe than freeze-thaw exposure alone. The sustained load likely restrained axial deformations due to temperature changes and thus less damage occurred. Based on these results, freeze-thaw testing of FRP wrapped cylinders without sustained load provides a conservative estimate of freeze-thaw damage, and freeze-thaw damage is not significant in terms of axial strength. In terms of failure mode, however, the tests reported in this paper indicated that more sudden failures were noted when FRP confined cylinders were exposed to either low temperature or freeze-thaw.

The effects of FRP wraps on continuing corrosion in corroded reinforced concrete columns was studied, and the results showed that the rate of corrosion was reduced significantly after wrapping. Nevertheless, the corrosion still continued, albeit at a slower rate. To achieve such reductions in corrosion rate, the columns should be fully wrapped so that the further ingress of water, chlorides, and oxygen is reduced. In terms of practical applications, FRP wraps can be used to repair corroded reinforced concrete columns but the designer and owner should recognize that corrosion will continue unless it is addressed directly through another corrosion mitigation strategy. Thus, two basic approaches are available to the designer. The first approach would be to remove all chloride contaminated concrete and replace all corroded reinforcement before wrapping with FRP. Alternatively, the corroded column could be wrapped without such direct corrosion mitigation. In this case, a rigorous inspection or monitoring programme to evaluate the extent of the continuing corrosion would be essential. Such monitoring is particularly important since obvious signs of deterioration such as cracking, rust staining, and spalling would be masked by the FRP wrap.

For interior applications in buildings, the results in this paper have shown that FRP wrapped columns can achieve satisfactory fire resistance provided that supplementary insulation is provided to the exterior of the wrapped columns. The insulation acts to protect the FRP in the early stages of the fire and to delay burning of the FRP until late in the fire exposure. More importantly, however, the insulation reduces the temperatures in the concrete and the internal reinforcing steel so that the strength of the column without the FRP is increased during a fire scenario.

An interesting synergy may occur if corroded reinforced concrete columns were wrapped with FRP and subsequently exposed to fire. At normal service temperatures, the confinement provided by FRP wraps could offset losses of steel due to corrosion. However, during fire, the confinement effect of the FRP would be lost at some point and the strength of the column would then be dependent upon the strength of the remaining corroded reinforcement. Thus, an evaluation of the condition of the corroded column would be essential before FRP wrapping. Monitoring of the continuing corrosion would also be important in such situations.

The research presented in this paper has been focused on FRP column wrapping applications where the objective is to increase the axial strength of the columns. Thus, this research does not apply directly to seismic upgrading, shear strengthening, or flexural strengthening of columns.

6. Conclusions

Overall, the results presented in this paper have demonstrated that FRP confined concrete columns tested in concentric axial compression have adequate performance under several extreme conditions such as low temperature, freeze-thaw action, corrosion of internal reinforcement, and fire exposure. The following specific conclusions are drawn:

1. FRP confined concrete columns increase in strength when tested at low temperature due to freezing of pore-water in concrete.
2. The strength of FRP wrapped concrete cylinders exposed to freeze-thaw action is not reduced significantly as long as the concrete is adequately air entrained.
3. FRP wrapped light-weight concrete cylinders, without air entrainment, survived 300 freeze-thaw cycles with the residual strengths reducing by only 2–16%. Similar plain concrete cylinders were completely disintegrated after 150 cycles, resulting in virtually zero residual strength.
4. Sustained loading has a beneficial effect through longitudinal restraint of the column, which controls the longitudinal expansion of concrete under freeze-thaw cycles.
5. Freeze-thaw and low temperature exposure cause FRP wrapped cylinders to fail in a more sudden and dramatic fashion than specimens kept at room temperature.
6. FRP wraps can reduce the corrosion rate in corroded reinforced concrete columns especially if the columns are fully wrapped to reduce the penetration of water, chlorides, and oxygen into the columns.
7. FRP wrapped corroded reinforced concrete columns should be monitored after wrapping to evaluate the extent of the continuing corrosion.
8. FRP wrapped reinforced concrete columns can achieve fire endurance ratings exceeding 4 h if appropriate fire insulation is provided. The insulation does not protect the FRP for the full 4 h but reduces temperatures inside the reinforced concrete column and thus maintains the strength of the concrete and internal steel for a longer time.

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