Preliminary Guidance for the Design of FRP-strengthened Concrete Members Exposed to Fire

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ABSTRACT: An overview on the fire performance of fiber-reinforced polymer (FRP) materials and FRP-strengthened reinforced concrete (RC) members is presented. Results from an experimental and numerical research program investigating the behavior of these types of members are briefly reviewed. Data from experimental studies are used to show that the fire behavior of FRP-wrapped concrete columns, using an appropriate fire protection system, is as good as that of unstrengthened RC columns. Preliminary guidelines for fire resistant design of FRP-strengthened systems are provided based on rational consideration of expected loads during fire. Finally, a case study is presented illustrating the application of these preliminary guidelines for achieving the required fire resistance ratings in FRP-strengthened concrete members.

KEY WORDS: fiber-reinforced polymers, reinforced concrete, strengthening, fire, insulation, slabs, columns, beams.

INTRODUCTION

Worldwide interest in the use of fiber-reinforced polymers (FRPs) in civil engineering applications has increased significantly in recent years due to its advantages, such as high strength and corrosion resistance, that FRPs offer over traditional materials such as concrete and steel.

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Fiber-reinforced polymers have been successfully used both as internal reinforcement [1–3] and as externally bonded reinforcement [3–7] for reinforced concrete (RC) structures. The FRP-reinforcing bars are used as an alternative to traditional steel reinforcement because of their high strength, corrosion resistance, nonmagnetic and light-weight properties, and ease of application. As an external reinforcement, the use of FRP sheets or plates is now a method of choice for the rehabilitation and strengthening of concrete members in many cases. In these applications, FRPs are commonly wrapped around columns to increase their strength and ductility, or bonded to beams to improve flexure and/or shear capacity, slabs to improve flexural or punching capacity, or to strengthen structural connections.

While widely accepted within the research community, the use of FRPs is, at present, restricted primarily to bridge structures, where fire resistance is not a primary design consideration. There is enormous potential for the use of FRPs in multistorey buildings, parking structures, and industrial structures [8]. However, FRPs have yet to see widespread application in these applications, due in large part to uncertainties associated with their performance during fire.

In buildings, structural members must be designed to satisfy appropriate fire resistance requirements in addition to other structural requirements specified in building codes. The structural fire resistance requirements are included in building codes to ensure that, when other measures of controlling and containing a fire fail, structural integrity is maintained for an adequate period of time.

One of the main impediments to using FRPs in buildings is the lack of knowledge about the fire resistance of these systems [9–11]. Before FRPs can be used with confidence in buildings, the performance of these materials during fire, and the ability of structural members with which they are reinforced or strengthened to meet the fire endurance criteria set out in building codes, must be evaluated.

In this article, the factors that differentiate the performance of FRPs at elevated temperatures compared to traditional materials, such as concrete and steel, are discussed. Based on the results of a series of full-scale fire endurance tests, conducted over the past four years at the National Research Council of Canada (NRC), preliminary rational guidelines are given for fire resistant design of FRP-strengthened reinforced concrete systems. Finally, a case study of the application of a fire-rated FRP system in an industrial building is given.

BACKGROUND

Fire represents one of the most severe environmental conditions to which a structure might be subjected during its lifetime, and hence the provision of appropriate fire safety measures is a critical requirement in building design. Building code requirements for most building structures address issues around flame spread, smoke generation, and maintenance of structural integrity during fire, all of which are significant when FRPs are contemplated for use.

Reinforced concrete (RC) structural members typically exhibit good performance in fire. However, only limited studies on fire performance of FRP-strengthened RC systems exist. A review of the existing literature [12] in this area indicates that insufficient information is currently available on FRP strengthening systems under these conditions.

FRP materials are extremely sensitive to the effects of elevated temperatures. Prior research indicates that severe deterioration in mechanical and/or bond properties can be expected at temperatures approaching the glass transition temperature (T_g) of the polymer adhesive/matrix [13,14]. This leads to a concern that loss of effectiveness of the FRP wrap during fire could result in sudden and catastrophic collapse, particularly if the FRP is used as primary reinforcement (which is not typically the case).

Furthermore, several concerns (including flame spread, smoke generation, and toxicity) must be considered when studying the overall fire performance of FRP reinforcement for RC members [12]. Most organic polymer matrix materials are combustible. Flame spread, smoke generation, and toxicity considerations, while important, are not addressed in detail in the current discussion, but are discussed elsewhere [15]. The current study focuses on the structural fire endurance of FRP-strengthened concrete members under standard fire exposure.

FRPs under Fire – Problems and Complexities

FRP materials are sensitive at elevated temperatures. As the temperature of the polymer matrix approaches its glass transition temperature, T_g, it transforms to a soft, rubbery material with reduced strength and stiffness [16]. Common room-temperature cure thermoset polymer matrices used in FRP strengthening of concrete structures exhibit glass transition temperatures in the range of 60–85°C. Under extreme heat, the polymer matrix may ignite, supporting flame spread and toxic smoke evolution.

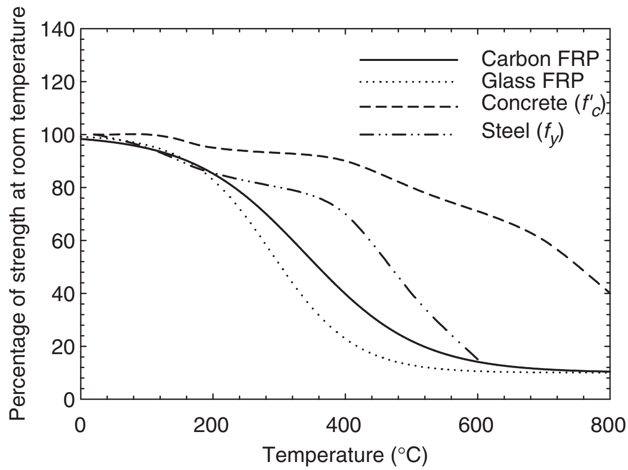

Figure 1. *Approximate variation in strength of FRP [17] and concrete and steel [8] with increasing temperature.*

Once a fire is over, the FRP materials may have suffered charring, melting, delamination, cracking and buckling, and their structural integrity may be seriously in doubt. The mechanical performance of currently used infrastructure FRPs at high temperature remains incompletely understood, and allowable temperature limits to ensure adequate residual performance of FRP materials and the structures they reinforce are not known.

To illustrate the difference in the behavior of FRP at elevated temperatures as compared with conventional construction materials, Figure 1 shows the approximate variation of ultimate tensile strength with temperature for glass and carbon FRPs, based on semiempirical relationships presented previously by Bisby [17], along with strength versus temperature curves for concrete in compression and mild steel in tension [8]. The FRP materials appear to be particularly sensitive to the effects of elevated temperature as compared with concrete and steel.

While the strength data for concrete, steel, and wood at elevated temperatures is reasonably well documented [18], the curve representing the strength degradation of FRP is based on limited information reported in the literature [8,13,17]. The rate of strength loss is greater for FRP than for concrete or steel, and thus the critical temperatures for FRPs during fire are likely to be lower than those currently used for steel. Detailed literature reviews [8,13,17] have revealed that the critical temperatures of FRPs are, in general, much lower than that of steel, and that the impact of elevated temperatures on the behavior of FRP composites is rapid and severe degradation of both mechanical and bond properties. It should also be noted that the critical temperatures for FRPs will depend on the specific formulation of the material, and generalizations will thus be more difficult to make as compared with steel.

In reinforced and prestressed concrete structural members, the required fire resistance is typically obtained through the provision of minimum member dimensions and minimum thickness of concrete cover to the steel reinforcement. The concrete cover ensures that the temperature in the reinforcement does not reach its critical temperature for the required duration during fire. The critical temperature is defined as the temperature at which the reinforcement loses so much of its strength that it can no longer support the applied load. For reinforcing steel, the critical temperature has been defined as 593°C, while for prestressing steel it is 426°C [18]. By providing the minimum member dimensions, the internal and unexposed temperatures are kept within allowable limits to achieve the required fire resistance rating. In rare cases where the required fire resistance cannot be achieved with these two provisions, external insulation, where a fire resistive barrier (insulation) is placed between the potential fire source and the member to be protected, can be used. In the case of conventional concrete members, concrete cover thickness requirements also serve to provide corrosion resistance.

In the case of FRP-strengthened RC members, where the FRP materials are typically bonded to the exterior of the RC structural members, no concrete cover is available for protection of the FRP reinforcement, and thus unprotected wraps can be expected to experience rapid degradation of structural effectiveness almost immediately under exposure to a standard fire. However, because FRP materials are rarely used as primary reinforcement (i.e., their structural effectiveness is not essential to prevent collapse under service loads), loss of FRP effectiveness during a fire may or may not be critical to ensure structural fire safety. As discussed below, it is important to remain cognizant of the fact that, in most cases, structural fire safety does not necessarily depend on the effectiveness of the FRP material during fire. Rather, it depends on the service loads on the structure during fire and the level of strengthening provided by the FRP.

FIRE RESISTANCE EXPERIMENTS

To study the performance of RC members strengthened with externally bonded FRP systems during fire, a major study has been conducted over the last five years as a collaborative effort between Intelligent Sensing for Innovative Structures Canada (ISIS), the National Research Council of Canada (NRC), and industry partners [19,20]. The overall objective of this research is to develop design guidelines for the fire resistance of

FRP-strengthened RC columns, beams, and slabs. The research is a combination of intermediate and full-scale fire tests, numerical modeling of thermal and structural behavior, and residual strength testing of specimens after they have been subjected to fire. The initial emphasis of this research has been to develop insulation systems that can protect FRP-strengthened structural systems during fire.

FRP-strengthened Concrete Slabs

As part of the development of insulation systems for FRP-strengthened structural systems, four intermediate-scale fire resistance experiments have been conducted on reinforced concrete slabs strengthened with carbon FRP sheets bonded to their soffits. Table 1 provides details of the slab specimens

Table 1. Details of specimens, FRP strengthening, and insulation schemes tested.

No.	FRP type	No. of layers FRP	Insulation system	Insulation thickness (mm)	Fire test load ratio[a]	Matrix T_g (°C)	Time to exceed T_b (min)[b]	ULC S101 fire resistance (min)
Intermediate-scale FRP-strengthened RC slabs [21,38]								
1	CFRP[c]	2	System 1[f]	19	0.0	93	42	147
2	CFRP[c]	2	System 1[f]	38	0.0	93	104	>240
3	CFRP[d]	1	System 2[g]	38	0.0	71	36	>240
4	CFRP[d]	1	System 3[g]	38	0.0	71	43	>240
Full-scale FRP-strengthened RC columns [17,23,24]								
1	CFRP[c]	1	System 1[f]	57	0.5	93	118	>300
2	CFRP[c]	1	System 1[d]	32	0.5	93	81	>300
3	GFRP[e]	3	System 1.1[h]	38	0.69	93	51	>240
4	CFRP[d]	2	System 2[g]	0	0.56	71	3	210
5	CFRP[d]	2	System 2[g]	53	0.56	71	31	>300
Full-scale FRP-strengthened RC beam-slab assemblies [26,27]								
1	CFRP[c]	1	System 1.1[h]	25	0.53	93	33	>240
2	CFRP[c]	1	System 1.1[h]	38	0.53	93	52	>240
3	CFRP[d]	1	System 2[g]	30	0.50	71	30	>240
4	CFRP[d]	1	System 2[g]	28	0.50	71	30	>240

[a] Ratio of load applied during the fire test to the design ultimate load of the strengthened column (with design ultimate load calculated according to ACI 440.2R-02 [4]).
[b] Based on manufacturer specified T_g values.
[c] Tyfo® SCH system – additional information available from http://www.fyfeco.com.
[d] MBrace® CF 130 system – additional information available from http://www.mbrace.com.
[e] Tyfo® SEH system – additional information available from http://www.fyfeco.com.
[f] Tyfo® EI/VG system – additional information available from http://www.fyfeco.com.
[g] Systems 2 and 3 are proprietary MBrace® systems and remain under development.
[h] Tyfo® VG/EI-R system – additional information available from http://www.fyfeco.com.

tested. The slabs were 954 × 1331 × 150 mm, were internally reinforced with conventional reinforcing steel, and were constructed from carbonate aggregate concrete. The slabs were also protected with one of three different supplemental fire insulation systems, applied to the exterior of the FRP wraps, and tested in fire according to ULC S101 [21], which is essentially equivalent to ASTM E119 [22]. All three insulation systems tested have proprietary spray-applied cementitous plasters developed by industry partners specifically for this application. An insulation System 1 is a proprietary two-part system [19] comprised of a 20–60 mm layer of cementitious spray-applied plaster with an exterior intumescent coating. The Insulation System 1.1 is identical to System 1, except that the intumescent coating has been replaced by a nonintumescent surface hardener and sealer coating. Further information on these insulation systems is provided by Bisby [17]. Insulation Systems 2 and 3 are also proprietary systems [20] that are spray-applied cementitious plasters with specialized lightweight fillers. Additional information on these systems is given by Williams et al. [23].

Thus far, fire tests on the slabs have been used to evaluate the performance of the supplemental fire insulation systems and to provide insight into the appropriate insulation configurations and thicknesses to be used when testing full-scale FRP-strengthened beams and columns (discussed below). As such, the slabs were tested under self weight only.

Figure 2 shows temperatures recorded at the FRP–concrete interface (the bondline) in all four slabs during fire testing according to ULC S101 [21]. It is evident that in all cases the insulation provided good thermal protection

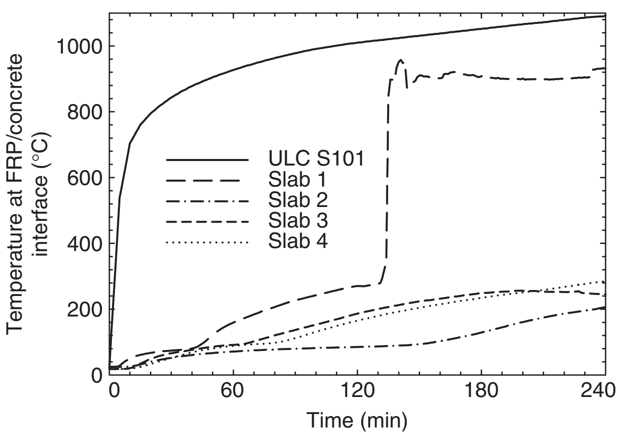

Figure 2. *Temperature as function of time at the FRP–concrete bondline for insulated FRP-strengthened reinforced concrete slabs [21,22].*

to the FRP sheets, although it is clear that the T_g of the FRP systems, which was less than 100°C for both FRP systems tested, was exceeded in less than 2 h in all four cases. It also appears that a minimum thickness of insulation is important to prevent debonding of the insulation during fire testing. For example, debonding occurred only in slab 1, as evidenced by the rapid increase in recorded temperatures at approximately 135 min of fire exposure. This slab had only 19 mm of insulation. Thus, more than 19 mm of insulation is necessary to prevent debonding for this specific insulation system. More details of the slab test results have been presented elsewhere [23].

Overall, these slab tests have demonstrated that, according to thermal fire endurance criteria for heat transmission and steel-reinforcement temperatures outlined in ULC S101 [21], a 4-h fire endurance rating can be achieved for an insulated FRP-strengthened concrete slab with as little as 38 mm of supplemental insulation applied to the exterior of the FRP wrap. A smaller thickness of insulation (19 mm) could provide 2 h of fire endurance for slabs carrying only their self weight. The tests also suggest that it will likely be very difficult to prevent the FRP temperature from exceeding the T_g of the polymer matrix for more than 1 h, even with 38 mm of supplemental insulation, and that providing sufficient insulation thickness is important in minimizing cracking and preventing possible delamination of the fire protection and FRP. The fire tests are required on loaded FRP-strengthened RC slabs to verify that these members will be able to resist service loads for the required duration of fire exposure. However, given the fact that the concrete and reinforcing steel were maintained at relatively low temperatures throughout the tests for slabs 2–4, it is likely that they retained their full unstrengthened strength for the duration of the fire exposure.

FRP-wrapped Concrete Columns

The column test program consisted of full-scale fire tests on five FRP-wrapped (confined) and insulated reinforced concrete columns [17,24,25]. Four 400 mm diameter, 3810 mm long circular columns, all strengthened with carbon FRP wraps, and one 400 mm square and 3810 mm long column strengthened with glass FRP wraps, have been fire tested under full sustained service load. All of the wraps were applied in the circumferential direction only, to provide confining reinforcement which increases the axial strength of the columns [26]. No attempt was made to enhance the flexural or buckling strength of the columns during these tests. All columns were internally reinforced with conventional steel reinforcing bars, spirals, and/or ties.

Table 2. Details of column specimens.

No.	Shape	Cross-section (mm)	Length (mm)	Longitudinal steel (mm ø)	Aggregate type	Transverse steel	f'_c 28-day (MPa)	f'_c Test day (MPa)
1	Circular	406ø	3810	8 × 20	Carbonate	11.3 mm ø spiral at 50 mm pitch	39	40
2	Circular	406ø	3810	8 × 20	Carbonate	11.3 mm ø spiral at 50 mm pitch	39	39
3	Square	406 × 406	3810	4 × 25	Carbonate	11.3 mm ø ties at 406 mm c-c	52	–
4	Circular	406ø	3810	8 × 20	Siliceous	11.3 mm ø spiral at 50 mm pitch	33	33
5	Circular	406ø	3810	8 × 20	Siliceous	11.3 mm ø spiral at 50 mm pitch	33	33

All but one of the columns were protected with supplemental fire insulation systems applied to the exterior of the FRP wrap. Three fire protection systems were studied (essentially the same systems as those studied in the slab testing discussed previously). The details of the columns tested are given in Table 2, and the insulation schemes used on each specimen are presented in Table 1. One of the columns (column 4) was tested without any supplemental insulation whatsoever, such that the FRP wrap was completely exposed to the fire.

Figure 3 shows temperatures recorded at the level of the FRP–concrete interface in all five columns tested. The insulation provided good thermal protection for the columns as a whole, even though the recorded FRP temperature exceeded T_g relatively early in the fire exposure for all columns. Figure 4 shows both unprotected and protected columns immediately before fire testing and immediately after failure. The unprotected column (column 4) in Figure 4 has completely lost its FRP wrap and has suffered a significant amount of spalling at failure, exposing the spiral reinforcement. The insulated column (column 5) is visually in good condition after failure, and the fire insulation remained intact even beyond failure. The failure was considered to have occurred when the hydraulic loading system, which has a maximum stroke rate of 2 mm/min, could no longer hold the sustained load. Failure of all columns appeared to be due to crushing of the core concrete, with some evidence of buckling effects. Because it was not possible to measure the lateral displacement of the columns during testing, it is not known to what extent buckling played a role in failure of these members. It is important to recognize that, apart from column 5, which failed in a

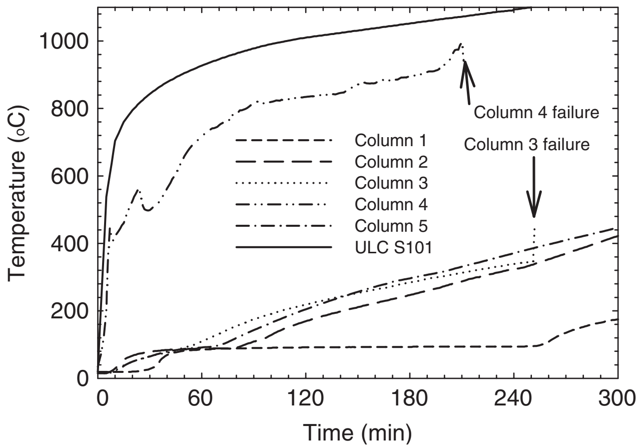

Figure 3. *Temperature as function of time at the FRP–concrete bondline for insulated FRP-strengthened (confined) reinforced concrete columns [17,23,24].*

slightly more gradual manner, the failure modes of the columns were typically sudden and accompanied by spalling of the concrete cover. The insulation systems actually remained intact right up until failure. All insulated columns behaved very well under fire exposure.

The uninsulated FRP-wrapped column also performed reasonably well during fire exposure and managed to sustain its required service load for about 3.5 h. However, the unprotected FRP-strengthening system burned within minutes of fire exposure and completely debonded from the column in less than 30 min. Clearly, the good overall performance of the column can be attributed to the fire resistance of the existing RC column – a result that demonstrates that loss of FRP effectiveness is not necessarily an appropriate failure criterion for fire resistant design of these types of members.

The column tests have demonstrated that the unique insulation systems which have been used thus far are effective fire protection systems for both circular and square FRP-wrapped reinforced concrete columns. The insulation systems remained intact during exposure to the standard fire, and provided good thermal protection for externally bonded FRP materials. The FRP-strengthened columns protected with these systems are capable of achieving satisfactory ULC S101 [21] fire endurance ratings, in excess of 5 h, even when the FRPs' T_g are exceeded early in the test. This occurs because the preexisting unstrengthened concrete column, which is designed based on ultimate loads but subjected to service loads only during fire, is protected by the supplemental insulation system and experiences only mildly increased internal temperatures that do not significantly decrease its capacity during fire.

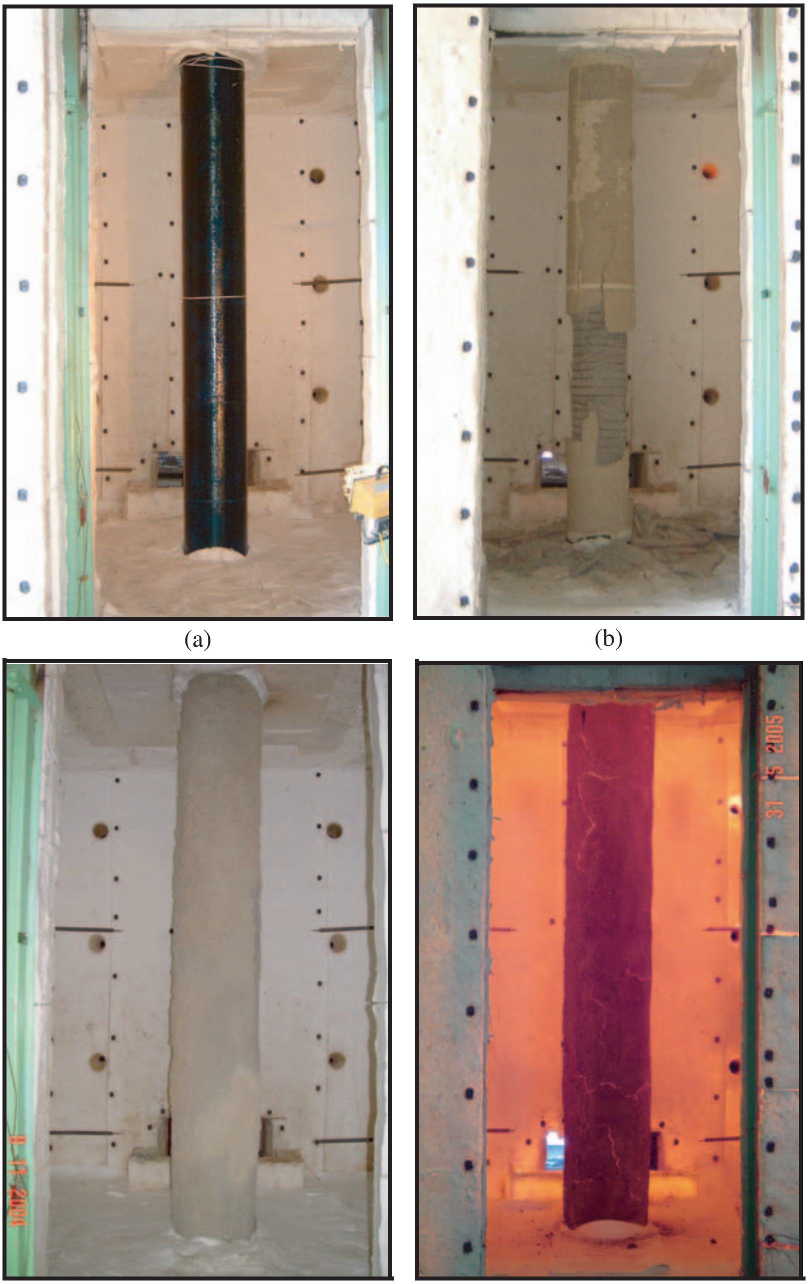

Figure 4. *Columns 4 (a, b) and 5 (c, d) immediately before fire testing and immediately after failure during fire testing, respectively. (The color version of this figure is available on-line.)*

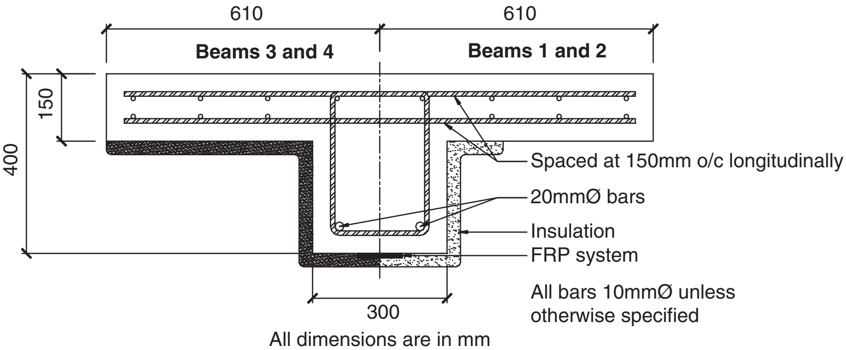

Figure 5. *Overall dimensions, reinforcement details, FRP-strengthening scheme, and insulation scheme for beam-slab assemblies [27].*

FRP-strengthened Beam-slab Assemblies

Four full-scale fire tests have been conducted on reinforced concrete beam-slab assemblies that were strengthened in flexure with one layer of externally bonded carbon FRP sheets on their soffits [27,28]. To provide anchorage for the flexural sheets, FRP sheets were wrapped around the web in a U-shape at ends of beams. Figure 5 shows the details of the beam-slab specimens, while Table 1 provides a summary of the fire tests conducted on these types of specimens. In a similar manner to the slabs and columns discussed previously, the beam-slab assemblies were protected with supplemental insulation around the web portion of the beams. The beam slabs were tested under full sustained service load according to ULC S101 guidelines [21].

All four beams were able to carry their full service load for longer than 4 h of exposure to the standard fire, and all four beams subsequently achieved fire endurance ratings of more than 4 h. The temperatures recorded in the FRP and internal tensile reinforcing steel during the tests are shown in Figure 6, where it is again evident that the insulation systems provided good thermal protection and maintained temperatures within the members at sufficiently low values so that the strength of the preexisting members could be relied upon to carry the loads even when the FRP-strengthening systems may be rendered ineffective. The rapid increases in temperature that are recorded at $\approx$85 min of fire exposure for beams 3 and 4 are attributed to localized cracking and debonding of the insulation at the locations of the thermocouples. These tests confirmed that the insulation systems were effective in protecting these types of structural systems from fire.

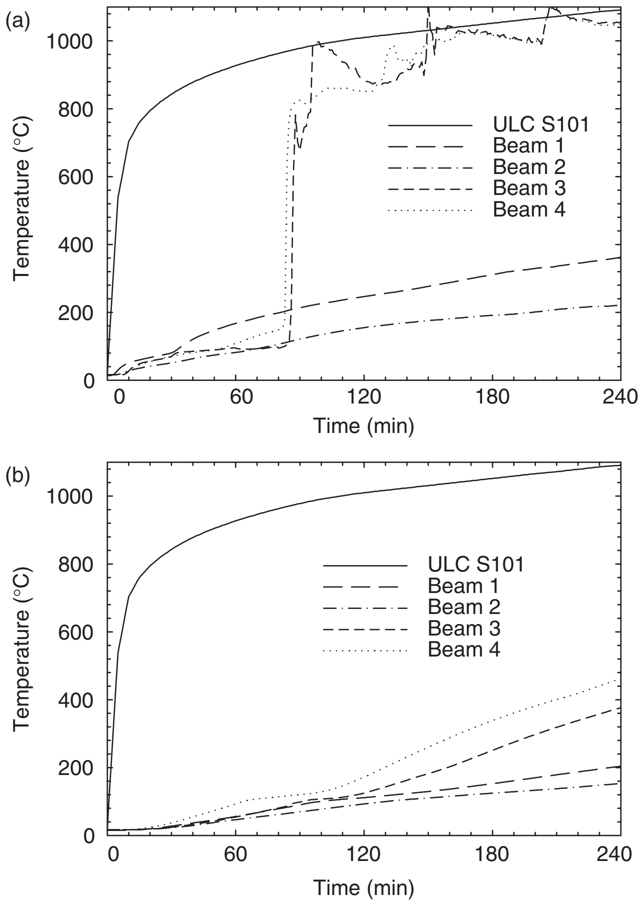

Figure 6. *Recorded temperature as a function of time at (a) the FRP–concrete bondline and (b) the level of the internal tensile steel reinforcement for insulated FRP-strengthened reinforced concrete beam-slab assemblies [26,27].*

Owing to limitations in the capacity of the hydraulic loading system in the beam-slab test furnace at NRC, it was not possible to fail the insulated FRP-strengthened beam-slab specimens during the fire tests, even though the applied load was increased to approximately the predicted room temperature flexural capacity of the members at about 4 h of fire exposure. Thus, after the beams had cooled to room temperature, they were tested for failure at Queen's University under monotonic load at room temperature. It was shown in these tests that the beams retained their full prefire predicted flexural strength. This testing suggests that beams strengthened with FRP materials and appropriately insulated against fire can retain their full unstrengthened capacity even after more than 4 h of fire exposure.

A second interesting implication of the results presented above has to do with the postfire repairability of fire-damaged FRP-strengthened members. The results presented above suggest that, for FRP-strengthened members protected with the fire protection systems used in the current study, the postfire capacity of the members is equivalent to the prefire capacity of the unstrengthened members. Thus, provided that reasonable FRP-strengthening limits are not exceeded, these members could be rewrapped after a severe fire and treated as essentially undamaged members.

NUMERICAL STUDIES

In addition to the experimental program described above, a series of numerical fire simulation software programs is also under development. The numerical models consist of one- and two-dimensional finite difference heat transfer algorithms, coupled with structural analyses based on strain compatibility and force equilibrium. Models have been developed to predict the heat transfer behavior and variation in load carrying capacity of various types of insulated, uninsulated, FRP-strengthened, and unstrengthened RC members during exposure to standard fire scenarios.

Three basic numerical models have been developed thus far. The first is a one-dimensional heat transfer model for predicting the thermal behavior of insulated FRP-strengthened slabs exposed to fire on one side. The second is an axisymmetric model for simulating the thermal and structural behavior of insulated FRP-confined circular reinforced concrete columns. The structural portion of the column model considers both buckling and axial crushing failure modes using a modified version of the Spoelstra and Monti confinement model [29]. The third model is a two-dimensional beam-slab model for predicting the thermal and structural behavior of insulated FRP-strengthened RC flexural members.

The models are capable of accounting for a wide variety of factors in their analyses, including: magnitude of the sustained applied load; type of standard fire (e.g., ULC, ASTM, ISO); specimen size and shape (rectangular or T-beams); concrete aggregate type; concrete moisture content; steel reinforcement ratios and bar layouts; FRP type, width, and thickness; and insulation type, thickness, and configuration. The analyses can also account for debonding of the insulation and/or FRP at predefined times during fire.

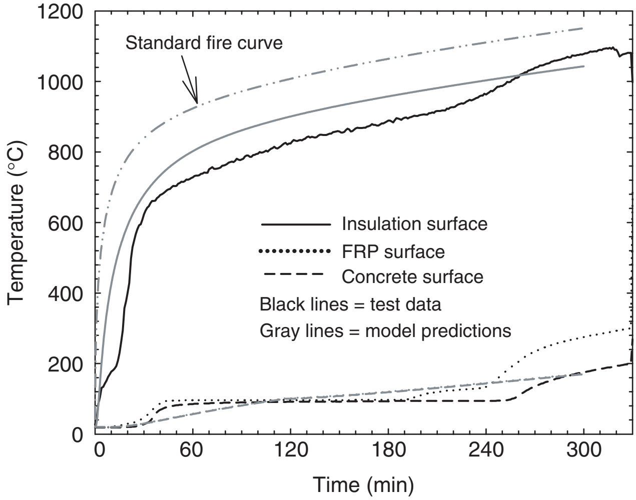

***Figure 7.** Predicted and recorded temperatures at various key locations in column 1 during fire testing [23].*

Specific details of the analyses are not included here because they have been presented elsewhere [17,23,27,30]. The models are being validated against the results of the fire tests. Once the models are satisfactorily validated, they will be used to perform parametric studies that can provide design guidance to engineers wishing to implement fire-safe FRP-strengthening systems. In most cases, the models have been found to predict reasonably the heat transfer behavior and temperatures within insulated FRP-strengthened RC members, although the ability of the models to predict temperatures near the T_g of the FRP polymer matrix requires some improvement. For example, Figure 7 shows a comparison of the model prediction against temperatures measured for column 1 during fire testing.

The column models have been shown to satisfactorily predict the load capacity of insulated FRP-wrapped concrete columns tested, although more tests are required before the models can be used with confidence. The beam-slab and slab load capacity models have not yet been verified due to a lack of experimental data.

PRELIMINARY DESIGN GUIDANCE

Fiber-reinforced polymers are high-performance materials that offer a number of advantages. In recent years, a significant research effort has been undertaken to quantify the behavior of the FRP-strengthened RC systems and to quantify the factors influencing their performance at room temperature. Guidelines have been developed for the design of these systems and these guidelines are now available in building codes and design documents [3–7]. However, there is limited research on fire performance of FRP systems, and hence few rational guidelines currently exist for fire resistance design of FRP-reinforced structural systems.

Fire design is concerned primarily with life-safety objectives. The existing design requirements for fire safety have evolved such that structural collapse is prevented during fire. In North America, structural members are required to carry their full service load for the required duration during fire. Until better information is available, FRP materials should be considered ineffective during fire, and FRP-strengthened RC members should be designed such that the nominal strength of the unstrengthened (preexisting) member remains greater than the strengthened (increased) service loads on the member for the required duration during fire. This approach is currently suggested by Committee 440 of the American Concrete Institute [5], which suggests the following load limit for fire-safe design of FRP-strengthening systems:

$$(R_{n\theta})_{\text{existing}} \geq 1.0S_{\text{DL}} + 1.0S_{\text{LL}}. \tag{1}$$

In the above equation, $(R_{n\theta})_{\text{existing}}$ is the nominal strength of the preexisting (unstrengthened) member subjected to the elevated temperatures associated with a fire and S_{DL} and S_{LL} represent the dead load and live load effects acting on the strengthened structure. The above equation is essentially a statement of the ULC S101 [21] or ASTM E119 [22] load-bearing fire endurance criterion for columns, assuming that the loads acting on a structure during fire can reasonably be taken as the unfactored loads. Other existing FRP design documents, such as Concrete Society Technical Report 55 [7] use a similar philosophy in justifying the use of FRP strengthening in situations where fire poses a potential threat. It is interesting to note that various other organizations allow less restrictive load combinations for fire design [31]. For instance, the Eurocodes [32] suggest a load combination for fire that would give the following version of Equation (1):

$$(R_{n\theta})_{\text{existing}} \geq 1.0S_{\text{DL}} + 0.9S_{\text{LLP}} + 0.5S_{\text{LLO}} \tag{2}$$

where S_{LLP} is the permanent live load and S_{LLO} is the other (transient) live load. The American Society of Civil Engineers [33] suggest:

$$(R_{n\theta})_{\text{existing}} \geq 1.2S_{\text{DL}} + 0.5S_{\text{LLP}} + 0.5S_{\text{LLO}} \tag{3}$$

Ellingwood and Corotis [34] have suggested that allowable design loads during fire could be reduced even further, as follows:

$$(R_{n\theta})_{\text{existing}} \geq 1.0S_{\text{DL}} + 0.5S_{\text{LLP}} + 0.5S_{\text{LLO}} \tag{4}$$

In fact, Buchanan [31] states that, under normal day-to-day conditions, all buildings have extremely low probabilities of failure because the ratio of the expected loads on the structure during fire to the loads that would cause collapse at normal temperatures is typically 0.5 or less.

Thus, depending on the load and resistance factors used in design and the live-to-dead load ratio for the member being strengthened, increases in strength due to FRP wrapping must typically be limited to between about 25 and 100% based on fire-safety considerations. It should be noted that other design considerations and good engineering judgment would almost always limit strength increases to significantly less than 100%.

Thus, while loss of effectiveness of the FRP during fire would likely cause a significant decrease in the ultimate strength of the member, this is not a problem provided that the preexisting member retains enough strength to carry its service loads. Fire exposure will typically decrease the strength of the preexisting member, and thus supplemental insulation is required in most cases to allow the preexisting member to resist increased service loads during fire.

For FRP-strengthened RC members that are protected with supplemental fire insulation, the insulation allows the members to retain much of their prefire strength, even after exposure to the standard fire for more than 4 h, and even if the FRP is rendered ineffective. Thus, the loads considered as acting during fire become a critical consideration in assessing the fire safety of these types of members, and additional studies are required to accurately elucidate issues of risk and reliability when FRP-strengthened members are designed using any given set of load and resistance factors.

The FRP strength could be relied on in a fire situation if and only if the temperature of the FRP is kept below some as yet unknown critical temperature. A conservative lower bound for the critical temperature would be the T_g (typically below 100°C), and an upper bound would probably be ≈300°C for currently used epoxy adhesives [35].

Fire Resistance Ratings

Recent fire endurance experiments conducted as part of the current study have resulted in the development of fire endurance ratings for insulated FRP-strengthened columns and beam-slab assemblies. The fabrication and testing of columns and beam-slab specimens has been witnessed and certified by a commercial laboratory [36]. Based on the results of these tests, standard fire ratings have been developed for the specific insulated FRP-strengthened beam-slab assemblies and columns tested, and these rated assemblies are listed [36].

With respect to FRP-strengthened beams, Design No. N790 [36] states that a loaded reinforced concrete beam, strengthened with FRP and protected with spray-applied fire resistive materials can provide a 4-h fire resistance rating under ANSI/UL 263 fire exposure in a restrained condition. Similarly, Design No. X842 [37] states that a loaded reinforced concrete column, strengthened with FRP and protected with spray-applied fire resistive materials, can provide a 4-h fire resistance rating under ANSI/UL 263 fire exposure. The full details of the beam and column dimensions, material specifications, preparation of the assembly, and application procedures for both the FRP and the fireproofing under which this rating is valid are explained in [36] and [37].

FIELD APPLICATION

The fire resistance ratings for FRP-strengthened concrete members described above have been instrumental in enabling the application of these types of systems in a number of field applications over the past two years. One such field application is described briefly below.

A large section of a concrete slab roof in a manufacturing plant in Denver, CO, USA was damaged by a severe fire several years ago. The fire damage led to a significant reduction in the load-carrying capacity and allowable fire rating of the roof slab assembly. The two repair options available to the structure's owner were rehabilitation using FRP sheets or removal and replacement of the concrete slabs. Through consultation with engineers, the owner selected a rehabilitation scheme using an externally bonded FRP system. The FRP system was chosen to minimize down-time for the company and reduce lost profits during construction. The resulting insulated FRP-strengthening system gave a minimum 1-h fire rating.

The rehabilitation of the slabs was accomplished by applying an externally bonded FRP-strengthening system to both faces of the roof slabs and subsequently providing sprayed insulation sufficient to give the required fire rating. The existing concrete cover on the underside of the roof slab was removed and replaced prior to strengthening of the slab with the FRP system. The removal and replacement of previously fire-damaged cover concrete on the underside of the slab was performed at the same time as structural FRP strengthening was installed on the topside of the roof slab. When this work was completed, FRP strengthening on the underside of the slab was also applied. Once the FRP had cured sufficiently, a steel mesh

Figure 8. *Overhead application of fire insulation over an FRP-strengthened concrete roof slab in a manufacturing plant (photo courtesy Fyfe Co. LLC, San Diego). (The color version of this figure is available on-line.)*

was mechanically attached to the underside of the slab, including the previously fire damaged areas, and a cementitious fireproofing material (Insulation System 1.1, described previously) was spray-applied to achieve the required fire rating for the structure, as shown in Figure 8.

In addition to the above field application, the fire-rated insulated FRP-strengthening systems described above have been used to obtain permissions to use FRP strengthening in several other building applications in both North America and Europe.

CONCLUSIONS

Unlike conventional reinforced concrete members, FRP-strengthened members in most cases require suitable fire protection to achieve the required fire endurance ratings under increased service load levels. The FRP-strengthened RC systems (columns, beams, and slabs), protected with the fire protection system discussed herein, are capable of achieving satisfactory fire endurance ratings (in the practical range) according to ULC S101 (or ASTM E119) requirements, under full service loads. The performance of insulated FRP-strengthened systems at high temperatures can be similar to, or better than, that of conventional reinforced concrete members. All insulated FRP-strengthened concrete members tested have achieved satisfactory fire endurance, even though the glass transition temperature (T_g) of the FRP polymer matrix was exceeded relatively earlier in the fire exposure. These results suggest that the fire endurance for FRP-strengthened concrete members should not necessarily be defined in terms of temperatures at the level of the FRP, but rather, should be based on the load-carrying capability of the structural member/system during fire, as required by existing fire testing guidelines. Thus, reaching the matrix T_g of an externally bonded FRP system during fire does not necessarily indicate failure of the FRP-strengthened concrete member.

The preliminary guidelines presented in this article can be used as guidance for achieving an appropriate level of fire safety for a given FRP-strengthened concrete member. However, additional information is required on the specific performance of FRP materials and externally bonded FRP systems at elevated temperatures, such that critical temperatures can be defined for these systems. The definition of critical temperatures must consider the effects of elevated temperature on strength, stiffness, and bond.

NOMENCLATURE

$(R_{n\theta})_{\text{existing}}$ = nominal strength of the preexisting (unstrengthened) member subjected to the elevated temperatures associated with a fire
S_{DL} = dead load effects acting on a strengthened structure
S_{LL} = live load effects acting on a strengthened structure
S_{LLP} = permanent live load effects acting on a strengthened structure
S_{LLO} = transient live load effects acting on a strengthened structure

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