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Bénichou, Noureddine; Mostafaei, Hossein; Green, Mark; Bisby, Luke; Kodur, Venkatesh

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THE IMPACT OF POST-FIRE EARTHQUAKES ON FRP-STRENGTHENED CONCRETE STRUCTURAL SYSTEMS

Noureddine Benichou and Hossein Mostafaei
National Research Council of Canada
Ottawa, ON, Canada
noureddine.benichou@nrc.gc.ca hossein.mostafaei@nrc.gc.ca

Mark Green
Department of Civil Engineering, Queen's University
Kingston, ON, Canada
greenm@civil.queensu.ca

Luke Bisby
Institute for Infrastructure and Environment, University of Edinburgh
Scotland, UK
luke.bisby@ed.ac.uk

Venkatesh Kodur
Civil and Environmental Engineering, Michigan State University
East Lansing, MI, USA
kodur@egr.msu.edu

ABSTRACT: This paper presents the results of a research project to study the structural fire resistance of FRP-strengthened concrete members under fire exposure. The items presented in this paper are: 1) Some of the results of an experimental program, conducted at NRC, on FRP-strengthened RC columns exposed to standard fires; 2) The numerical fire simulation models that were developed to predict the heat transfer behaviour of FRP-strengthened RC columns during fire exposure; 3) The recommendations for design guidance for FRP-strengthened RC structures in fire. The paper also presents the impact of lateral loading on structural columns after fire to assess the effectiveness of structural resistance of fire-damaged FRP-strengthened building elements in case of an earthquake.

1. INTRODUCTION

The use of fiber-reinforced polymers (FRPs) in civil engineering applications has increased significantly in recent years. FRPs offer advantages, such as high strength and corrosion resistance over traditional materials. FRPs have been successfully used both as internal reinforcement and as externally-bonded reinforcement for reinforced concrete (RC) structures. As an external reinforcement, the use of FRP sheets or plates is now a method of choice, in many cases, for the rehabilitation and strengthening of concrete members. 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, or bonded to slabs to improve flexural or punching capacity, or to strengthen structural connections.

The use of FRPs has been restricted primarily to bridge structures, where fire resistance is not a primary design consideration. However, there is enormous potential for the use of FRPs in buildings. Structural building members must be designed to satisfy appropriate fire resistance requirements in addition to other structural requirements specified in building codes. One of the main impediments to using FRPs in buildings is the lack of knowledge about the fire resistance of these systems. Before FRPs can be used with confidence in buildings, the performance of these materials under fire conditions, and the ability of structural members with which they are strengthened to meet the fire resistance criteria set out in building codes, must be evaluated.

This paper presents some results of a collaborative investigation between the National Research Council of Canada (NRC), Queen's University through the Intelligent Sensing for Innovative Structures Canada (ISIS), and industry partners to study the structural fire resistance of FRP-strengthened concrete members under standard fire exposure. The paper also presents the impact of lateral loading on structural elements after fire to assess how effective the structural resistance of fire-damaged FRP-strengthened building elements is in case of an earthquake

2. FRP MATERIALS UNDER ELEVATED TEMPERATURES

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 material with reduced strength and stiffness. Common room-temperature cure thermoset polymer matrices used in FRP strengthening of concrete structures, exhibit glass transition temperatures below 100°C. For 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 fire. However, because FRP strengthening materials are not usually used as primary reinforcement, loss of FRP effectiveness during a fire may or may not be critical to ensure structural fire safety.

3. FIRE RESISTANCE EXPERIMENTS

To study the performance of RC members strengthened with externally-bonded FRP systems during fire, a major experimental program was undertaken. The results of the column tests are summarized below.

The column test program consisted of full-scale fire tests on four circular concrete columns and one rectangular column, strengthened with FRP wraps, and tested under full-sustained service load. All of the wraps were externally applied in the circumferential direction only. All columns were internally reinforced with conventional reinforcing steel. All, but one, of the columns were protected with supplemental insulation systems applied to the exterior of the FRP wrap. Details of the tests are given in Table 1.

Table 1 – Summary of results from column fire tests.

Member	Dimensions (mm)	FRP	Insulation	Fire resistance (min)	Failure Load (kN)
Column 1	ϕ 400 × 3810	1 layer - CFRP-A	VG - 57 mm	> 300	4680
Column 2	ϕ 400 × 3810	1 layer - CFRP-A	VG - 32 mm	> 300	4437
Column 3	ϕ 400 × 3810	2 layers - CFRP-B	CEM - 53 mm	> 300	4583
Column 4	ϕ 400 × 3810	2 layers - CFRP-B	None	210	2635
Column 5	400 x 400 × 3810	3 layers - GFRP-C	VG - 38 mm	> 240	4437

Notes: CFRP-A – Tyfo® SCH system (www.fyfeco.com)
CFRP-B – MBrace® CF 130 system (www.mbrace.com)
GFRP-C – Tyfo® SEH system (www.fyfeco.com)
VG - gypsum-based insulation; CEM - cementitious insulation

Figure 1 shows temperatures recorded at the level of the FRP–concrete interface in the five columns tested. The insulation provided good thermal protection for the columns as a whole, even though the recorded FRP temperature exceeded the T_g relatively early in the fire exposure for all columns. Figure 2 shows a typical protected column immediately before fire testing and after failure. The insulated column is visually in good condition after its failure and the fire insulation remained in-place even beyond failure. Failure of all columns appeared to be due to crushing of the core concrete, with some evidence of buckling effects. It is important to recognize that, in general, the failure modes of the columns were typically sudden and accompanied by spalling of the concrete cover.

The column tests have demonstrated that the unique insulation systems used are effective fire protection systems for FRP-wrapped reinforced concrete columns. The FRP-strengthened columns protected with these systems are capable of achieving satisfactory ULC S101 fire resistance ratings (CAN/ULC 2007), in excess of 4 hours, even when the FRPs' T_g are exceeded early in the test. This occurs because the pre-existing 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.

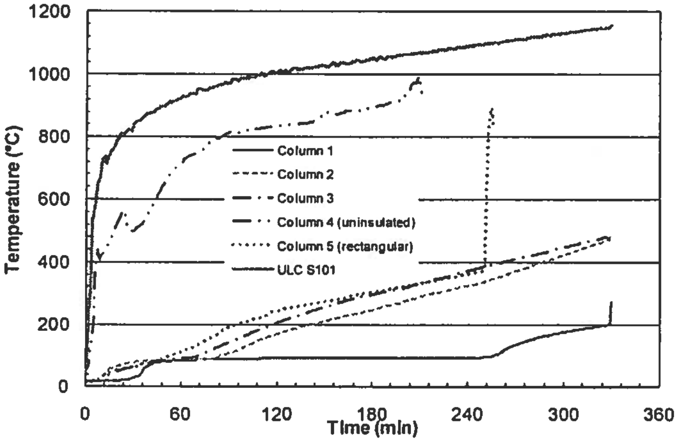

Fig. 1 – Column temperature at the FRP.

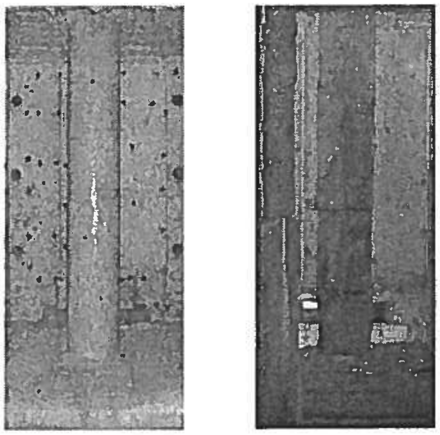

Fig. 2 – Column before and after test.

The uninsulated column also performed reasonably well during fire exposure and managed to sustain its required service load for about 3.5 hours. However, the unprotected FRP-strengthening system burned within minutes of fire exposure and completely debonded from the column in less than 30 minutes. Clearly, the good 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 members.

4. NUMERICAL STUDIES

In addition to the experimental program, numerical fire simulation models have been developed as part of this study (Bisby 2003 and Williams 2004). The numerical models consist of finite difference heat transfer algorithms, coupled with structural analyses based on strain compatibility and force equilibrium. The models can predict the heat transfer behaviour and variation in load-carrying capacity of FRP-strengthened, RC members during fire exposure.

The models can account for a variety of factors in their analyses, including: magnitude of the sustained applied load; type of fire; 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 FRP at predefined times during fire.

In most cases, the models have been found to reasonably predict the heat transfer behaviour 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 3 shows a comparison of the model prediction against temperatures measured for column 1 during fire testing. Further validation is needed to use the model with full confidence and to perform accuaret parametric studies that can provide design guidance.

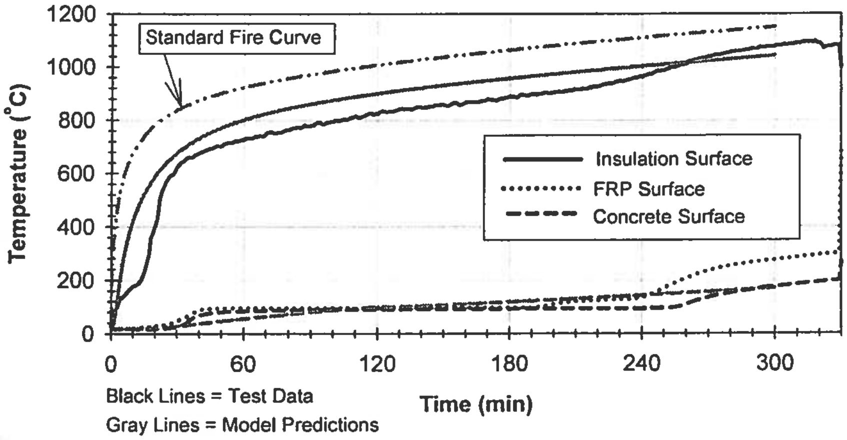

Fig. 3 – Comparison of measured and predicted temperatures at key locations in Column 1.

5. DESIGN GUIDANCE

There has been limited research on fire performance of FRP systems, and hence few rational guidelines exist for fire resistance design of FRP-reinforced structural systems.

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 assumed ineffective during fire, and FRP-strengthened RC members should be designed such that the nominal strength during fire of the unstrengthened (pre-existing) member remains greater than the strengthened (increased) service loads on the member for the required duration.

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 should typically be limited to between 25 and 70% based on fire-safety considerations.

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 pre-existing member retains enough strength to carry its service loads.

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 (Foster and Bisby 2005).

For FRP-strengthened RC members that are protected with supplemental fire insulation, the insulation allows the members to retain much of their pre-fire strength, even after exposure to the standard fire for more than 4 hours, and even if the FRP is rendered ineffective.

The experiments conducted here have resulted in the development of fire resistance ratings for insulated FRP-strengthened columns and beam-slab assemblies. Based on the test results, standard fire ratings have been developed for the specific insulated FRP-strengthened columns and beam-slab assemblies tested, and these rated assemblies are listed in UL listings (UL 2004).

6. IMPACT OF A LATERAL LOADING ON COLUMNS

To evaluate the impact of a lateral loading on columns after fires, a simple evaluation was carried out on the rectangular column tested (column 5). The dimensions of the column are shown in Table 1. The structural strengths of the concrete and steel were taken as the reduced values just after the fire exposure. The contribution of the FRP was not included since the FRP had lost its full strength during fire exposure. The insulation is assumed to have no structural contribution to the structural response.

The numerical evaluation was conducted using the structural analysis software SAFIR (Franssen 2007). Figure 4 shows the mesh and the loads applied to the column.

Three cases were evaluated, all with both axial and lateral loading:

1. A column that was strengthened with FRP and exposed to a standard fire for 4 hours. This reflects column 5 of the test program just after the fire test. In this case, the temperatures at the different locations were taken from the experimental results.
2. A column that is the same as column 5 but not FRP-strengthened, not insulated, and not exposed to fire. So it was evaluated at ambient conditions. This is considered as a reference case.
3. A bare column that is the same size as column 5, that is neither FRP strengthened nor insulated, but exposed to a standard fire for 4 hours. The heat transfer calculations were performed using SAFIR (Franssen 2007) and the temperature contours of the cross section after 4 hours are shown in Figure 5.

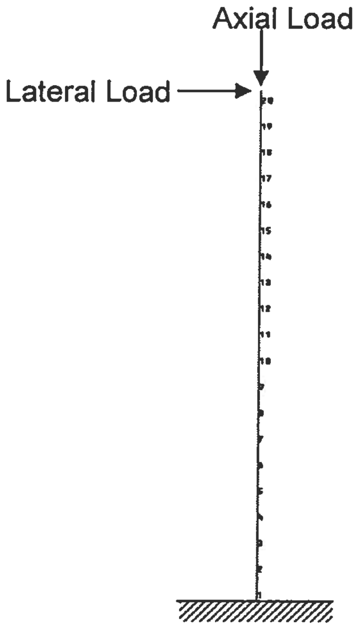

Fig. 4 – Mesh and loading used in the numerical simulation for Column 5.

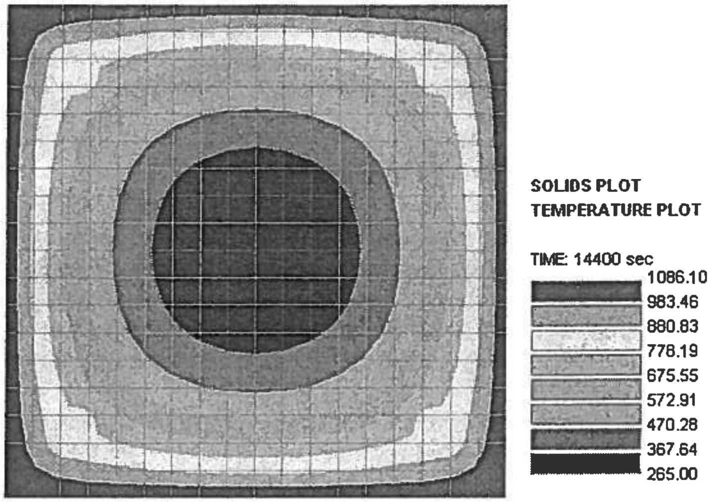

Fig. 5 – Temperature contours for the bare column after 4 hours for Column 5 using SAFIR.

Figure 6 shows the lateral load capacity versus the drift for the columns evaluated. The drift is defined as the ratio of the lateral deformation to the length of the column. As illustrated in the figure, the maximum lateral load is 273 kN for the FRP-strengthened column in fire, 288 kN for the cold column and 128 kN for the bare column in fire. This indicates that the residual capacity of the FRP-strengthened column in fire has not reduced much (5% reduction in the maximum lateral load capacity of the cold column case) compared to the bare column in fire (55% reduction in the maximum lateral load capacity of the cold column case). This shows that the existence of FRP and insulation protect the column well and an applied lateral load does not induce a high level of damage. Re-wrapping and insulating the column after a fire will be sufficient to resist another fire and a lateral loading. As for the maximum drift, the bare column in fire shows the highest value (0.030), the FRP-strengthened column shows a moderate value (0.018), and the cold column shows the lowest value (0.011). This explains that the ductility increases with increased temperatures. The highest temperatures are those recorded in the bare column exposed to fire. This large value of the drift will also result in a decrease in the residual lateral load capacity.

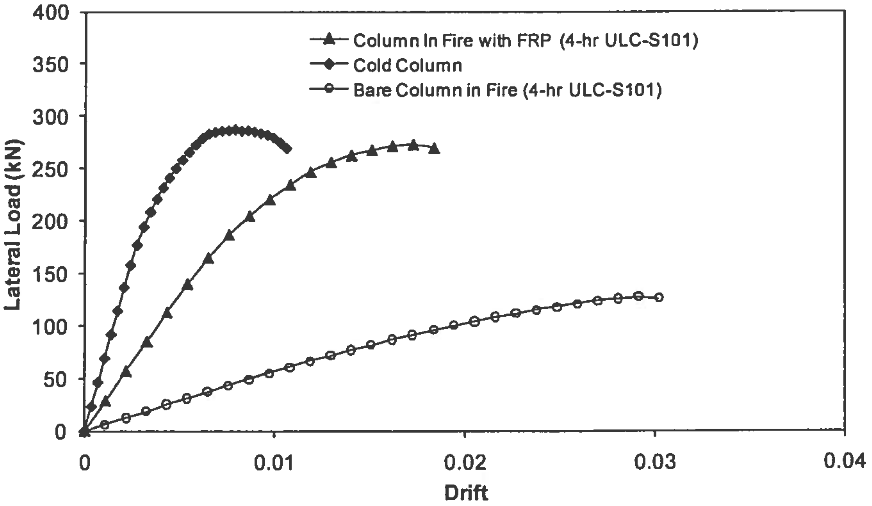

Fig. 6 – Lateral load versus drift for 3 different columns.

It is important to note that the columns in this analysis were modeled using the fiber elements of the SAFIR software. This model is only taking into account the flexure response and ignores the shear response of the element. Therefore, it is assumed that the dominant performance of these columns is flexural. Further studies are required to investigate the ductility and possible shear failure of the columns under the applied lateral loads.

7. CONCLUSIONS

FRP-strengthened RC systems, protected with the fire protection system, are capable of achieving satisfactory fire resistance ratings according to ULC S101 requirements, under full service loads. The fire performance of insulated FRP-strengthened systems can be similar to, or better than that of conventional reinforced concrete members.

Even though the glass transition temperature (T_g) of the FRP polymer matrix was exceeded relatively earlier in the fire exposure, all tested insulated FRP-strengthened concrete members have achieved satisfactory fire resistance. These results suggest that the fire resistance for FRP-strengthened concrete members should not 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 systems during fire. 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 guidelines presented in this article can be used as guidance for achieving an appropriate level of fire safety for a given FRP-strengthened RC 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.

A simple numerical evaluation was used to assess the strength of a rectangular column after a fire due to a lateral loading. The evaluation indicated that the FRP-strengthened and insulated column exposed to 4 hours of fire will keep most of its lateral and axial capacities if re-wrapped and insulated again.

8. ACKNOWLEDGEMENTS

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