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Evaluating the Fire Performance of FRP-strengthened Concrete Structures

With the increased use of externally-bonded FRP strengthening systems for concrete structures, the fire performance of FRP materials needs to be established.

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The infrastructure of the developed world, essential for economic health and prosperity, is crumbling. Decades of neglect and overuse have resulted in unacceptable levels of deterioration to roads, buildings and bridges, and new materials and techniques are urgently needed for structural rehabilitation and strengthening. Fibre reinforced polymers (FRPs), which represent a new class of high-strength, non-corrosive, and lightweight structural rehabilitation and construction materials, have garnered significant research attention in recent years, and their effectiveness as externally-bonded repair materials for concrete is now widely recognized[1]. Nevertheless, the high-temperature performance of FRP materials remains largely unknown, and this issue urgently needs addressing before FRP materials can be used with confidence in buildings and other structures where fire safety is a critical design consideration. Tragic events in recent years have demonstrated that design for fire safety is critically important for public safety. In addition, recent research gap analyses for the use of FRP materials in structural applications have identified fire performance as an area in which additional information is urgently required[2, 3].

Fire and FRPs

FRPs are susceptible in fire for two reasons. First, most FRPs suffer degradation of mechanical properties at temperatures that are only slightly higher than ambient temperatures. Further, at much higher temperatures (i.e., over 400°C) FRPs will combust. Current design recommendations for FRP-strengthened concrete members[4] assume that the FRP is completely lost during fire. Although this assumption is conservative, it can be unnecessarily restrictive. Another overly conservative recommendation is that the FRP temperature must be kept below its glass transition temperature (T_g); the temperature above which the FRP's polymer matrix suffers thermal degradation of mechanical properties. However, it remains unclear what the consequences of exceeding the polymer matrix T_g might be for the overall performance of FRP-strengthened concrete structures in fire. Given the life-safety objectives of structural fire engineering, rational design recommendations that are more holistic in philosophy are urgently needed.

To address the above gaps in knowledge, researchers at Queen's University, Canada, (working under the auspices of the Intelligent Sensing for Innovative Structures Research Network, ISIS Canada), and the Institute for Research in Construction at the National Research Council of Canada, in collaboration with industry partners (Fyfe Co. and Watson-Bowman Acme, a division of Degussa Construction Chemicals), are actively investigating the fire performance of concrete members strengthened with FRP sheets.

Fire tests on FRP-strengthened concrete

The research program involves extensive fire endurance experiments on both intermediate and full-scale FRP-strengthened concrete columns, slabs, and beams, and associated numerical modelling and analysis software development[5, 6]. At this point in the research, fire tests on three loaded full-scale reinforced concrete columns (two circular and one square), four unloaded intermediate-scale reinforced concrete slabs, and two loaded full-scale reinforced concrete beam-slab assemblies have been conducted in accordance with ASTM E119[7]. All members tested to date have been strengthened with carbon and/or glass FRP wraps and insulated with specially designed fire protection systems. Table 1 provides an overview of the fire tests conducted to date.

Table 1. Details of fire tests conducted to date.

Type/No.	Cross-section	FRP System	Insulation System	Insulation Thickness (mm)	Test Load Intensity	Fire Endurance (hrs)
Column 1	400mm Ø circular	Tyfo SCH	Tyfo VG/EI	32	0.73	> 5
Column 2	400mm Ø circular	Tyfo SCH	Tyfo VG/EI	57	0.73	> 5
Column 3	406mm x 406 mm	Tyfo SEH	Tyfo VG/EI-R	38	0.65	> 4
Slab 1	150mm thickness	Tyfo SCH	Tyfo VG/EI	19	0.0	> 2
Slab 2	150mm thickness	Tyfo SCH	Tyfo VG/EI	38	0.0	> 4
Slab 3	150mm thickness	MBrace CF130	Sonowall R	38	0.0	> 4
Slab 4	150mm thickness	MBrace CF130	Fireshield 1350	38	0.0	> 4
Beam-Slab 1	refer to Fig. 3	Tyfo SCH	Tyfo VG/EI-R	25	0.63	> 4
Beam-Slab 2	refer to Fig. 3	Tyfo SCH	Tyfo VG/EI-R	38	0.63	> 4

Fire Test Outcomes

Columns

Three full-scale columns have been tested to date using Tyfo Fibrwrap FRP and Tyfo VG/EI or Tyfo VG/EI-R fire insulation. For concrete columns, current fire testing procedures in North America require that members carry their full service load for the required duration during fire. As such, all three columns were subjected to a sustained concentric axial load during testing. The magnitude of the applied load was representative of service load conditions on the FRP-wrapped (strengthened) columns, determined using existing guidelines for FRP strengthening of reinforced concrete members[4,8,9] and assuming a live to a dead load ratio of 1:1. Load intensities (ratios of test loads to design ultimate loads) for all three members are given in Table 1.

Figure 1 shows a typical circular column before and after exposure to fire for more than 5 hours. Figure 2 shows temperatures recorded during fire for an FRP-wrapped circular column protected with 57 mm of insulation, where it is evident that the FRP temperature was maintained below 150˚C for more than 4 hours. Columns 1 and 2 failed at 5.5 hours, but only after the load had been increased to an intensity of 1.21 (greater than the design ultimate load), whereas Column 3 failed under its service load at 4.25 hours of exposure. Thus, all columns achieved fire endurances in excess of 4 hours under load.

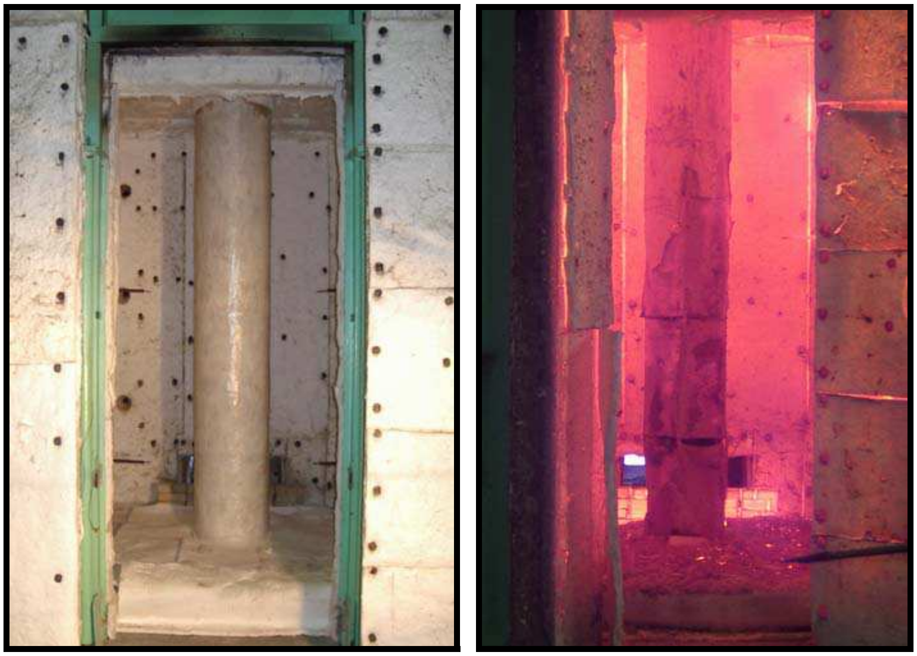

Figure 1. Typical circular FRP-wrapped and insulated column before and after fire testing (Fyfe's Tyfo system).

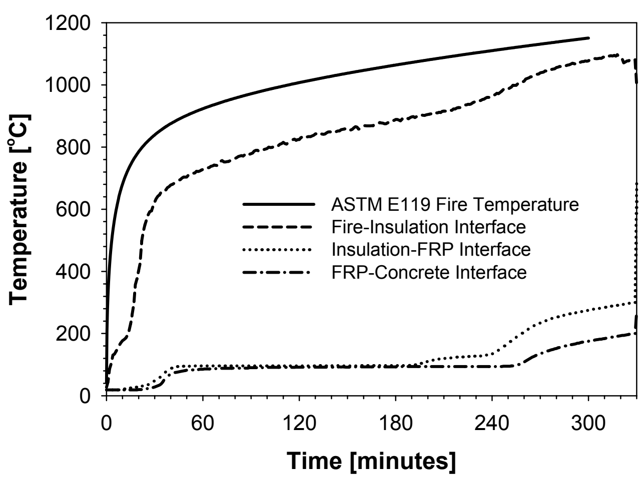

Figure 2. Temperatures recorded at various locations for a circular FRP-wrapped and insulated concrete column during fire (Fyfe's Tyfo system).

Slabs

Four intermediate-scale slabs have also been tested, using either Tyfo Fibrwrap and Tyfo VG/EI or WaboMBrace with Sonowall R or Fireshield 1350 fire insulation, to investigate the performance of various insulation types and thicknesses during fire. The slabs were not loaded during testing and the data obtained during these tests have been used to design insulation schemes for full-scale fire tests on FRP-strengthened reinforced concrete beam-slab assemblies. The data indicate that various spray-applied cementitious insulation materials can provide outstanding fire protection for externally-bonded FRP materials, even when applied overhead with no mechanical anchorage. All of the insulation materials have achieved four hour fire endurance ratings according to the thermal requirements of ASTM E119[7].

Beam-Slab Assemblies

Two beam-slab assemblies have been tested to date using Tyfo Fibrwrap FRP and Tyfo VG/EI-R fire insulation. Again, both assemblies performed well during fire exposure and achieved fire endurances in excess of 4 hours under load. Load intensities for the beam-slab assemblies are provided in Table 1, with sustained uniformly distributed service loads calculated in accordance with CSA S806[10]. After 4.5 hours of fire exposure with the members exhibiting no signs of impending failure, the applied load on the beam-slab assemblies was increased to an intensity of 1.26 without failure.

Figure 3 shows a typical strengthening and insulation configuration for the beam-slab assemblies tested to date, and Figure 4 shows temperatures recorded during fire at various locations in Beam-Slab Assembly 2, with 38mm of insulation. The outstanding thermal protection provided by the insulation is evident, with temperatures in the FRP reaching an average of only about 320˚C after more than four hours of exposure. The insulation remained intact for the entire duration of fire exposure. The fire test data indicate satisfactory structural performance of the FRP-strengthened members after more than 4 hours of fire exposure, even though the temperature at the level of the FRP had exceeded T_g relatively early in the fire tests.

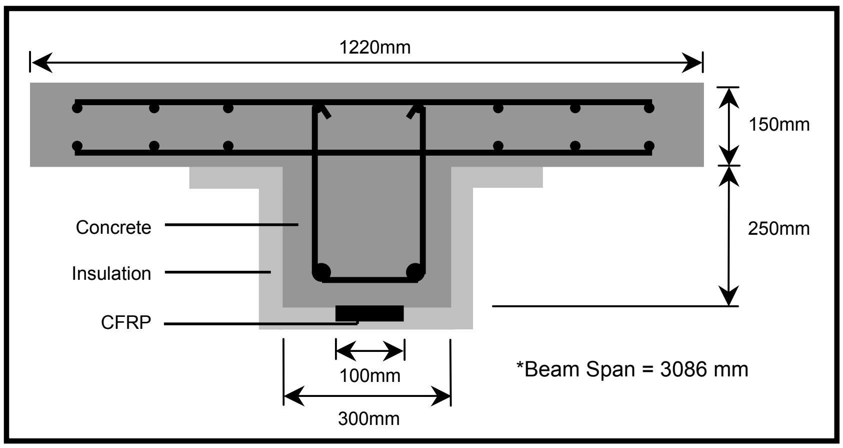

Figure 3. Configuration for the strengthened and insulated beam-slab assemblies (Fyfe's Tyfo system).

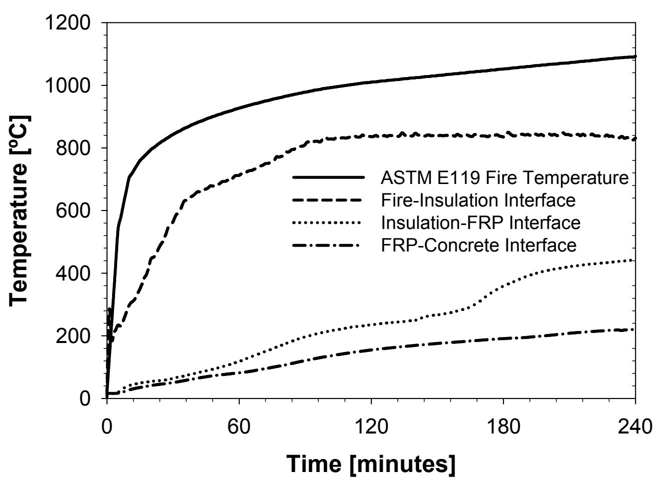

Figure 4. Temperatures recorded at various locations during fire in an FRP-strengthened and insulated concrete beam-slab assembly with 38 mm of insulation (Fyfe's Tyfo system).

Conclusion and future work

From the various fire experiments conducted thus far, it appears that both square and circular FRP-wrapped columns, and FRP flexurally-strengthened concrete beam-slab assemblies, can, when appropriately designed and adequately protected, demonstrate satisfactory fire endurance under load according to the requirements of current fire testing procedures[7]. All insulated FRP-strengthened concrete members tested to date have achieved satisfactory fire endurances, even though the glass transition temperature of the FRP polymer matrix/adhesive was generally exceeded much 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 during fire.

Over the next year, a series of further tests is planned that will include full-scale fire tests on an additional two FRP-strengthened concrete columns and two beam-slab assemblies. These tests will examine the fire performance of different FRP-strengthening materials and insulation systems, and will further the verification and extension of numerical analysis tools and fire-design guidelines for FRP-strengthened concrete members. From the results of experiments conducted thus far, the performance of insulated FRP-wrapped columns can be considerably greater than is commonly believed.

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