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Evaluation of Fire Protection Systems for FRP Strengthened Concrete Elements

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ABSTRACT: The integrity of externally bonded fiber reinforced polymer (FRP) composites can be critical for the fire survivability of FRP-strengthened structures. Carbon fibers, for example, are capable of resisting high temperatures; however the adhesive systems used in their construction have a much lower threshold temperature known as the glass transition temperature (Tg). This low threshold limit is typically less than 100 ^{o}C, which renders most conventional fire protection systems ineffective for externally bonded FRP. To evaluate the feasibility of achieving a fire-rated FRP system, an investigative program was established that aimed at identifying adhesives with high Tg and insulation materials that can protect the externally bonded FRP system by maintaining its temperature below the Tg threshold.

The test program involved selecting adhesive systems with high Tg, examining and optimizing insulation material type and thickness, and then performing fire tests on reinforced concrete slabs strengthened with externally bonded carbon FRP and protected with the developed fire protection systems. Initial tests were performed to determine the glass transition temperature (Tg) of several adhesive systems as well as the insulation properties of commercially available fire protection systems. Two vinyl ester based adhesive were identified that have Tg of 270 ^{o}C F and 149 ^{o}C. The two insulation materials selected for the evaluation are 50 mm thick. Two adhesive/insulation systems were developed and evaluated to examine their fire performance. System 1 was tested on a reinforced concrete slab that was loaded to service level and exposed to a standard ASTM E119 fire for 4 hours. At the end of the 4 hrs test, the slab was loaded to failure and was able to achieve a capacity slightly below its theoretical nominal capacity. System 2 was tested on a FRP-strengthened and fire-proofed slab without loading and the temperature of the FRP after 2 hours was below the Tg of the resin system.

1 INTRODUCTION

Strengthening of reinforced concrete members with externally bonded fiber reinforced polymers (FRP) is now widely recognized for its effectiveness, durability and ease of application. While the fire endurance of conventional reinforced concrete members is well established, there is very little information available on how to produce a fire-rated FRP system. Fire tests conducted on beams and slabs strengthened with carbon FRP indicated that unprotected externally bonded FRP materials perform poorly during fire (Blontrock, Taerwe and Vandevelde, 2000 and 2001). To address this, ACI 440.2R requires that FRP reinforcement be designed under the assumption that it is completely lost during a fire event. In order to achieve a wider acceptance of these polymer based strengthening systems by the building officials, fire-rated FRP systems and practical methods for protecting FRP during fire are urgently needed.

The first step in designing a structural repair with adequate fire rating is to verify that the reduced strength of the fire-exposed element, R_{Fire}, is greater than the load demand during fire, U_{Fire}. The reduced or residual nominal strength, R_{Fire}, is calculated using fire-reduced material strengths that are determined based on the maximum expected temperature during the fire event. ASTM E119 provides a standard time-temperature curve that is can be used for fire calculations (Figure 1). During fire, the yield strength of reinforcing steel and the compressive strength of concrete reduce as temperature rises. As a result, the overall resistance of the reinforced concrete member is reduced. Graphs providing relationships between material strengths and temperature, as well as reinforcement temperature versus depth for different members are given in ACI 216R (1989). It should also be mentioned here that most national and international codes specify a strength reduction factor of $\phi = 1.0$ for strength evaluation during a fire event.

The factored design load considered during a fire event, (U_{Fire}) is typically lower than that used for normal temperature conditions. For example, the design load criteria during a fire event given in ASCE 7 and Eurocode (ECI) are as follows:

$$1.2DL + 0.5LL \quad \text{ASCE 7 (2005)} \tag{1}$$

$$1.0DL + 0.9LL \quad \text{ECI (1994)} \tag{2}$$

in which DL is the service dead load and LL is the service live load. These fire design criteria indicate that, during a fire event, structural members are essentially required to retain sufficient strength to carry only a portion of the normal factored design loads. This is a practical approach used by building codes to ensure that the structure will not collapse during a fire event, at least until all the building occupants have been safely evacuated. Evaluation of service loads under normal day-to-day conditions indicated that the ratio of loads during a fire to the factored design loads $(Load_{Fire})/(Load_{Cold})$ is 0.5 or less for most buildings (Buchanan, 2001).

For FRP design, ACI 440.2R uses a different approach in which it recommends that the existing strength of the structure be sufficient to resist the fire load given in ACI 216R as $R_{Fire} \geq (1.0\ DL + 1.0\ LL)_{new}$, in which the residual nominal strength R_{Fire} of the concrete member is determined per ACI 216R. Because of the degradation of FRP materials at high temperature, ACI 440.2R requires that the strength of externally bonded FRP be ignored unless a fire-protection system is used that can maintain the FRP temperature below its critical temperature. The critical temperature for FRP is defined by ACI 440.2R as the lowest Tg of its components. At a temperature close to its Tg, the mechanical properties of the polymer adhesive starts to degrade and loses the ability to transfer stresses from the reinforcing fibers to the concrete substrate.

The value of Tg depends on the type of adhesive used. For most FRP systems used for external strengthening applications, Tg varies between 60 to 100 ^{o}C. Insulating the FRP system to maintain its temperature below 100 ^{o}C is considered impractical due to the large amount (thickness) of insulation required to achieve this and the high cost associated with it. A more practical approach to produce a fire-rated FRP system is to use adhesive resin with high Tg.

This paper summarizes the results of an investigative program that aimed at developing fire protection systems for externally bonded FRP composites. Fire-rated FRP systems can be developed by addressing two performance issues; first, the use of adhesive resins with high Tg; and second, using protection materials with high insulation properties. These two critical items were evaluated in this investigative program and used to produce practical and cost-effective fire-rated FRP systems. Initial tests were performed on several adhesive systems to determine their effectiveness for strengthening applications. Once verified, fire tests were performed on FRP-strengthened and protected slabs that were exposed to a standard ASTM E119 fire for two to four hours. Two viable adhesive/insulation systems were identified in this program. The two systems are referred to hereafter as System 1 and System 2.

2 SYSTEM 1 EVALUATION

2.1 Material Selection

Several adhesives were evaluated to identify an adhesive with a relatively high glass transition temperature. V-Wrap 777 HTg, a 100% solids, vinyl ester based resin supplied by VSL Company was finally selected. Test performed in accordance with ASTM D3418 indicated that the resin has a Tg temperature that exceeded 270 ^{o}C. The selected insulation material was a semi-rigid mineral wool board manufactured from volcanic rock which is spun into fine threads and compressed to form panels that has high insulation and fire resistance properties. Initial tests were performed on 175 mm x 175 mm x 915 mm concrete columns wrapped with FRP and protected with 50 mm thick insulation board made with this material. The average temperature measured after 102 minutes was approximately 93 ^{o}C. This clearly indicated that this isolation system can maintain the temperature below the Tg of the resin for System 1.

The next step was to perform a fire test on a reinforced concrete slab strengthened with externally bonded carbon fibers and fire-proofed using the insulation board. The selected fiber for this application was type V-Wrap C100 carbon fabric provided by VSL Company. The carbon fiber sheets were installed using the high Tg vinylester resin.

2.2 Description of the Test Specimen

The test specimen consisted of a 710 mm wide x 915 mm long x 75 mm thick reinforced concrete slab that was internally reinforced with (4) T10 longitudinal bars placed at 175 mm on centers and (3) T10 transverse bars placed at 300 mm on centers. The main longitudinal bars were placed at mid-thickness of the slab. Reinforcement layout for the slab is shown in Figure 2. The average 28-day concrete cylinder compressive strength and the tensile yield strength of the steel reinforcement were 42.8 MPa and 472 MPa, respectively. The slab was strengthened with 3 strips 75 mm wide each of FRP, externally bonded to one side of the slab. The thickness of the final FRP laminate was approximately 0.27 mm. The strengthened side of the slab was then topcoated with intumescent paint after which the fire insulation system was installed. The insulation board was mechanically attached to the slab using four small powder actuated Hilti anchors (see Figure 3). The objective of the intumescent paint was to provide ASTM E-84 flame spread and smoke density ratings, typically required for interior applications by the building code. The mechanical anchors were used to ensure that the fire insulation system will not fall during a fire event. Installation of the fire protection system was relatively quick due to the light weight of the insulation board and the ease of using powder actuated anchors.

The slab was held vertically in a steel test frame and held against the test furnace. The test frame was designed to produce a closed-loop loading configuration. The test frame provided a simple supports condition at the top and bottom edges of the slab and was capable of applying up to 67 kN of out-of-plane load at the mid-span of the test specimen (see Figure 4). The load was distributed across the width of the slab using a steel beam, as shown in Figure 3. Several thermocouples were mounted on the test slab and furnace to record temperatures. One thermocouple was installed at the center of concrete surface, right below the FRP to measure the temperature at the concrete-FRP interface during the test. Two thermocouples were installed on the back side of the test specimens. Three additional thermocouples were mounted inside the furnace to monitor and adjust the furnace temperature during the test. One linear variation differential transducer (LVDT) with approximately 250 mm stroke was installed on the back side of the test specimens and was used to monitor the out-of-plane deflection of the slab during the test. The applied load was monitored using a pressure transducer connected to the hydraulic jack that was used to apply the load.

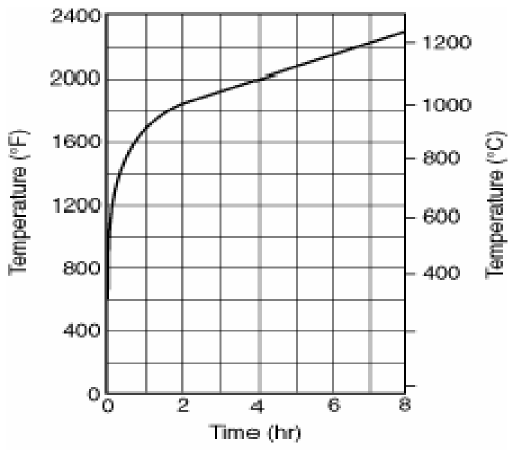

Figure 1. ASTM 119 fire curve.

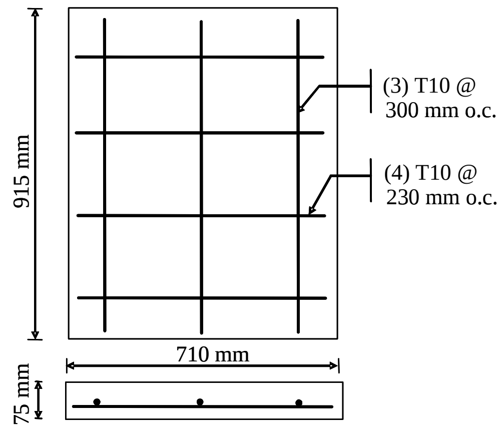

Figure 2. Details of the test slab.

2.3 Test Procedure

After the slab was secured in place, the test frame was attached to the furnace with its front side (fire protected side of slab) directly facing the heat source. A predetermined service load of approximately 22.2 kN was then applied to the slab. The furnace was ignited and the loaded slab was exposed to a standard ASTM E119 fire for the next 4 hrs.

2.4 Test Results

In general, the fire protected slab was able to support the service load without failure for the entire fire test duration. At the end of the 4 hours test, the load was immediately increased on the test slab until flexural failure occurred at a load of 37.8 kN. Failure was initiated by one major crack at mid-span followed by FRP rupture.

Figur 3. Insulated slab – Fire side.

Figure 4. Test frame – Back side.

The measured surface temperature on the protected side of the slab (exposed to fire) and on the back surface of the concrete slab (unexposed) after 2 hours were 237 °C and 71 °C, respectively, while the furnace temperature was 1010 °C. At 4 hours, the measured temperature of the fire protected concrete surface and the back surface of the concrete slab were 298 °C and 103 °C, respectively. The furnace temperature after 4 hours was 1088 °C. The measured reinforcing steel temperatures at 2 hours and 4 hours were 91 °C and 126 °C, respectively. Figure 5 illustrates the measured temperatures inside the furnace, FRP on the fire-exposed side, slab backside, and reinforcing steel. Figure 6 illustrates the load and deflection histories.

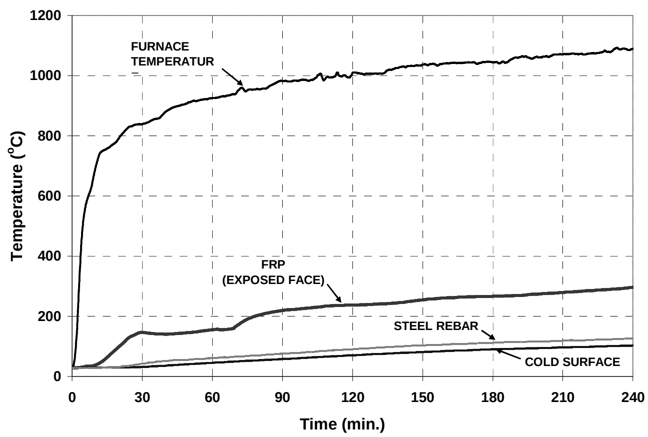

Figure 5. Measured temperature during the test.

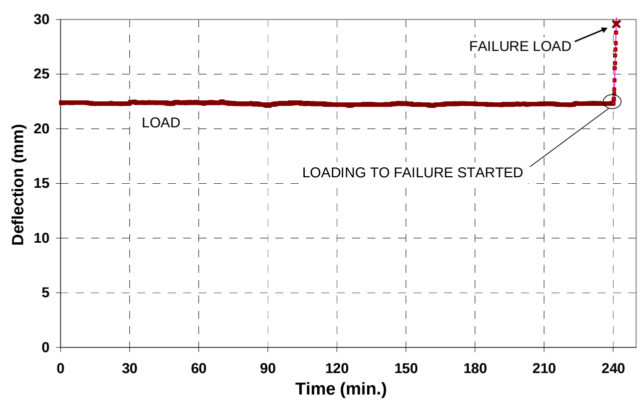

Figure 6. Measured load and deflection versus time.

2.5 *General Observations*

The test slab was able to support the service load throughout the 4 hrs fire test without any signs of failure. No smoke or strange odors were detected throughout the test. Upon completion of the test, the fire exposed side of the slab was examined. Except for some discoloration, the fireproofing system was completely intact and no sign of disintegration was observed. Based on the observed behavior of the slab during the test, it was concluded that the use of V-Wrap 777 high Tg vinyl ester resin with the mineral wool board performed adequately for the applied test load and provided a 4 hour fire rating based on ASTM E119. The slab had residual strength after 4 hours of fire exposure and at 37.8 kN. It should be noted that the nominal theoretical capacity of the strengthened slab with no reduction factors was approximately 41.4 kN. This nominal capacity was based on ambient temperature behavior and considering nominal strengths for concrete, steel and FRP materials. Although considered a small scale test, this test method clearly verified the viability of the approach used to develop a fire–rated FRP system. This test also demonstrated the fire resistance effectiveness of System 1.

3 SYSTEM 2 EVALUATION

3.1 Material Selection

After the viability of a fire-rated FRP system was confirmed, it was decided to develop a second system to optimize cost and constructability aspects of the fire-resistant system. Although System 1 was effective, the high Tg resin was relatively expensive. In addition, because of the semi-rigid nature of the insulation board used in System 1, encapsulation of the structural member had to be achieved using multiple pieces, basically boxing the member. This created a quality control concern in terms of the ability to always produce tight seems and joints between insulation boards in the field. To address these concerns, two improvements were achieved on System 2 – first, a lower cost vinylester resin, V-Wrap 700, with a a glass transition temperature, Tg, of 149 ^{o}C was selected; and second, a flexible insulation blanket that has high insulation properties was considered. The blanket is 50 mm thick and made with alkaline earth silicate wool. The carbon fiber selected for this second round of evaluation was V-Wrap C200 sheets supplied by VSL Company. With the performance requirements for the insulation system established (i.e., maintaining system temperature below Tg), for simplicity it was decided to pursue a simple fire test on an insulated slab without applying load for System 2. Once the performance of System 2 is confirmed, a second phase test on a full-scale loaded slab will be carried out per ASTM E119 to confirm the results (not included in this paper).

3.2 Description of the Test Specimen

The concrete slab for this test was 1650 mm x 1650 mm x 90 mm thick, reinforced with (5) T10 bars in each direction, placed at mid-depth of the slab. After the concrete surface was prepared using sandblasting, one layer of V-Wrap C200 fiber was installed using the V-Wrap 700 vinyl ester resin over the entire face of the slab.

To attach the insulation blanket, 63 mm long metal pins with a wide base where glued to the surface using the same resin. The thermal blanket was then installed and pushed onto the surface pins such that the pins penetrated through the insulation and extended 12 mm out of the insulation. Special metal caps were then installed on the pins to mechanically secure the blanket.

3.3 Test Procedure

The assembly was instrumented with a total of six thermocouples (TC). TC#1 and #3 were installed on the exposed side of the concrete (below the FRP), TC#2 and #4 on the exposed side of the carbon fiber (on top of the FRP), and TC#5 and #6 on the unexposed surface (see Figure 7). It should be noted here that thermocouples TC#3 and #4 were located under a joint between two pieces of insulation. The output of the thermocouples and furnace probes were monitored by a 300-channel Data Acquisition Unit that was programmed to scan and save data every 60 seconds. The ambient temperature and humidity when the test was initiated were 88°F and 63%

RH, respectively. For this test, the slab was placed in the horizontal position on top of the test furnace and subjected to the standard ASTM E 119 time-temperature curve.

3.4 Test Results

In general, the insulation system was able to maintain the temperature of the FRP system below its Tg throughout the fire test. Thermocouple TC#2 did not provide any reading. At the end of the 2 hours test, the average measured surface temperatures on the protected side of the slab (exposed to fire) and on the back surface of the concrete slab (unexposed) at 2 hours were 131 ^{o}C and 63 ^{o}C, respectively, while the furnace temperature was 1002 ^{o}C. Figure 9 illustrates measured temperatures on the thermocouples during the test.

3.5 General Observations

No changes were observed up to 120 minutes at which the test was terminated. When the assembly was removed from the furnace the outer foil scrim of the insulation material was consumed on portions of the exposed face, but the insulation was intact (see Figure 8).

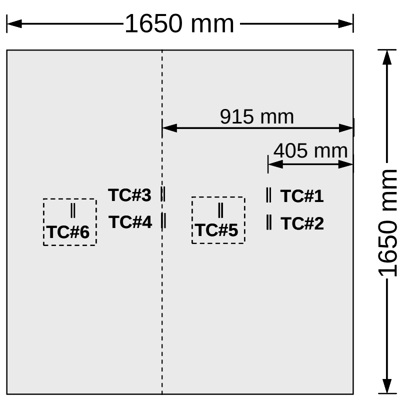

Figure 7. Layout of thermocouples

Figure 8. Test slab immediately after testing

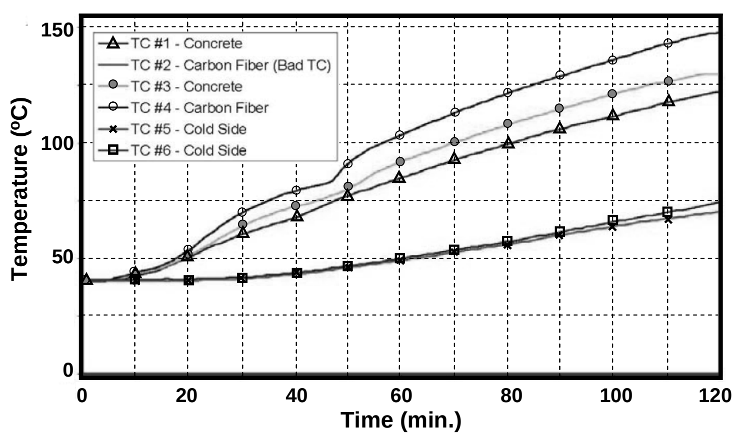

Fig. 9 – Individual TC Temperatures during System 2 test.

4 SUMMARY AND CONCLUSIONS

This paper summarizes the findings of an investigative program that aimed at developing a fire-rated externally bonded FRP strengthening system. This was achieved by identifying adhesive resins with high glass transition temperature Tg and fire protection systems with high insulation properties that can maintain the temperature of the FRP below Tg. The focus of the research team was on verifying system effectiveness while addressing cost and constructability concerns.

Two adhesive/insulation systems were evaluated that involved two types of adhesive resins and two insulation materials. Both resins were type V-Wrap vinyl ester based, and had Tg temperature of 270 ^{o}C and 163 ^{o}C for Systems 1 and 2, respectively. The insulation material was a semi-rigid mineral wool board for System 1 and a flexible thermal blanket for System 2. The flexible blanket can be easily wrapped around FRP-strengthened beams and columns to provide installation. Both systems can be mechanically anchored to the test slabs to improve durability and fire survivability. ASTM E119 test was performed on System 1 using FRP-strengthened slab that was loaded to service level. At the end of 4 hours test, System 1 achieved a capacity close to its nominal theoretical capacity, indicating minimal effect on the FRP system. System 2 was tested under ASTM E119 but without loading. Measured FRP temperatures after 2 hours were below the Tg of the adhesive resin. Additional full-scale tests for System 2 will be performed in the near future using loaded specimens.

This investigative program has clearly demonstrated the feasibility of achieving fire-rated externally bonded FRP systems for structural repair and strengthening applications. An FRP protection system must clearly show that it can maintain the temperature of the FRP system below the lowest Tg of the system. Considering that most available FRP systems are epoxy-based adhesives with Tg in the range of 60 ^{o}C to 100 ^{o}C, this requirement is very hard to achieve using commercially available insulation systems. Vinyl ester resins with high Tg represent a better choice where elevated service temperature or fire rating are required. It should also be noted that in many applications, the FRP is only providing a small level of strength increase and the existing member may still possess proper fire ratings even if the FRP is completely lost. Also, there are many cases in which additional fire rating can be achieved by simply providing additional protection to the concrete member (basically protecting the concrete and steel) and ignoring the FRP contribution.

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