Fire Protection for Beams with Fiber-Reinforced Polymer Flexural Strengthening Systems

by Nabil Grace and Mena Bebawy

Fiber-reinforced polymer (FRP) materials have been widely implemented in strengthening concrete structures. Their performance under fire events, however, has not been fully addressed. The lack of fire research imposes limitations on the use of FRP materials in structural applications, where fire is a concern. An experimental program was developed to investigate the performance of rectangular reinforced concrete beams flexurally strengthened with FRP materials under fire/loading events. Thirteen beams were constructed and tested to failure. Three beams served as control beams and were tested under three-point-loading setup at ambient temperature. Other beams were provided with supplemental fire insulation layers and were exposed to ASTM E119 fire scenario while being tested under the same loading setup. The experimental investigation revealed that the common hypothesis of ignoring the strength of the FRP system during fire is inaccurate and underestimates the performance of the strengthened structural element during fire events.

Keywords: fiber-reinforced polymer; fire resistance; reinforced concrete; strengthening.

INTRODUCTION

During the last few decades, fiber-reinforced polymer (FRP) materials have been extensively used in construction. The light weight and high strength of FRP materials grant them superiority over steel plates in nearly all strengthening and stiffening applications. Accordingly, FRP materials became the preferred choice for strengthening and stiffening reinforced concrete, prestressed concrete, and steel structures. Design guidelines and specifications for the use of FRP in flexural strengthening, shear strengthening, and confinement have been developed in countries all over the world.

Usually, FRP is bonded to the concrete surface using an organic thermoset resin. The most common types of thermoset resin are unsaturated polyesters, vinylesters, and epoxies. A major problem with thermoset resins, however, is their susceptibility to fire. The resins can easily ignite, burn, and produce toxic fumes, which obscure the rescue operation and jeopardize the lives of the occupants.

Most organic epoxies have a glass transition temperature (Tg) (ASTM D1356) or heat deflection temperature (HDT) (ASTM D648) within the range of 140 to 180°F (60 to 82°C). Tg or HDT defines the temperature at which the organic epoxy matrix loses most of its strength. During fire, temperature is expected to be much higher than Tg or HDT. Therefore, ACI Committee 440 (2008) assumes that the FRP strengthening system will lose its strength during fire. In addition, according to the committee, it is unlikely to effectively insulate the FRP strengthening system against fire because the required thickness of the insulation will not be realistic. Instead, the unstrengthened member should be capable of supporting a certain load level to avoid collapse during a fire event. This level of load is given as the service loads, which include dead and live loads.

To evaluate the performance of FRP-strengthened concrete members under fire events in light of available design codes, a recent extensive experimental/numerical investigation was conducted (Kodur et al. 2007). Slabs, columns, and beam-slab assemblies strengthened with carbon FRP (CFRP) sheets and insulated against fire using different fire insulation schemes were tested. Two epoxy matrixes with Tg of 160 and 200°F (71 and 93°C) were examined. The experimental investigation showed that Tg for both epoxy matrixes were exceeded in less than 2 hours. The structural elements, however, continued to sustain the imposed service loads for more than 4 hours. The researchers concluded that although the Tg of the epoxy was exceeded, the fire insulation layer protected the concrete and the steel from excessive heat. Therefore, the unstrengthened reinforced concrete member was able to support the imposed service load for an extended time. They suggested that the fire resistance rating of an FRP-strengthened structural member should be based on the capability of the unstrengthened structural element to support the service load during a fire event. Similar conclusions and recommendations were given by Williams et al. (2008) and Chowdhury et al. (2008).

Deuring (1994) conducted fire tests on six reinforced concrete beams strengthened with external CFRP strips and steel plates. The beams were tested according to the ISO 834 standard fire test to assess the post-fire residual strength. Four beams were strengthened with CFRP strips, one beam was strengthened with an adhesively bonded steel plate, and the remaining beam was left unstrengthened. Some of the strengthened beams were provided with fire insulations. During the fire test, the CFRP strips delaminated from the unprotected beams within 20 minutes. The insulated beams experienced CFRP debonding after nearly an hour.

In an attempt to study the influence of the temperature increase on the bond region between the concrete and the CFRP materials, Blontrock et al. (2000) tested two unstrengthened and six CFRP strengthened reinforced concrete beams. The beams were subjected to a fire event according to the ISO 834 standard fire test. It was concluded...
that some fire protection was necessary to keep the temperature of the epoxy below the glass transition temperature of 176 to 194°F (80 to 90°C).

Wu et al. (2005) investigated the temperature effect on bonding and debonding behavior between FRP sheets and concrete. Both ordinary epoxy and thermo-resistant epoxy were examined. Tg for the epoxies ranged between 100 and 104°F (38 and 40°C), and the HDT ranged between 118 and 134°F (48 and 57°C). The specimens were tested under load and a temperature ranging between 80 and 140°F (26 to 60°C). It was noted that before Tg, there was no significant loss in the bond strength between the concrete and the FRP sheet. The situation changed rapidly once the Tg was exceeded. It was also observed that the value of fracture energy decreased at temperatures near to or higher than the Tg or HDT.

Stratford et al. (2006) conducted a field investigation to study the performance of insulated FRP materials under a real fire event. The investigation took place inside a compartment in a building scheduled for demolition. The reinforced concrete ceiling of the compartment was strengthened with FRP plates and near-surface-mounted (NSM) FRP bars. Some of the FRP plates and bars were not insulated against fire. Others were insulated using two layers of 0.5 in. (12 mm) thick gypsum boards with intumescent sealer or just an intumescent layer. The average Tg for the epoxy adhesive ranged between 150 and 212 °F (65 and 100 °C). The results showed that the temperature of the FRP plates and NSM bars exceeded the Tg within the first 10 minutes of the fire test. FRP materials with gypsum board insulation, however, showed no visual signs of fire damage. FRP materials with the intumescent layer showed some signs of burning, while unprotected FRP materials completely delaminated and were burnt. The performance of NSM bars was superior to the performance of FRP plates during the fire test.

Through the current investigation, an experimental program was developed to investigate the performance of rectangular reinforced concrete beams flexurally strengthened with FRP materials under a fire/loading event. Thirteen beams were constructed and tested to failure. Three beams served as control beams, and were tested under a three-point-loading setup at ambient temperature. Other beams were tested under the same loading configuration along with a fire event according to the ASTM E119 standard fire test, where the beams were exposed to fire from four sides to simulate the worst fire scenario.

**RESEARCH SIGNIFICANCE**

Due to the lack of enough fire research, current design guidelines deal with FRP strengthening systems by ignoring their strength in case of fire. This approach, however, not only disqualifies FRP from being used in many strengthening applications, but also raises a concern regarding the suitability of FRP materials, as flammable materials, in any indoor application. The current investigation aims to provide the research community with a proper technique for protecting FRP strengthening systems against fire to ensure the safety of the occupants while maintaining the soundness of the structural system for an extended time.

**Fig. 1—Cross section of beam specimens with: (a) no insulation; (b) cementitious fire insulation; (c) gypsum boards fire insulation; and (d) gypsum boards and thermal blanket fire insulation.**

**EXPERIMENTAL INVESTIGATION**

Figure 1 shows the cross section dimensions and reinforcement of the test beams. The beams had a span of 12 ft (3.65 m) and cross section dimensions of 6 x 12 in. (152 x 305 mm). Each beam was reinforced with two No. 4 (13M) deformed steel reinforcing bars Grade 60 (yield strength of 413 MPa) as bottom reinforcement, and two No. 4 (13M) deformed steel reinforcing bars as top reinforcement. In addition, to control the shear cracks, No. 3 (10M) stirrups were provided along the span with center-to-center spacing of 6 in. (152 mm). A clear cover of 1.5 in. (38 mm) was provided at the soffit of the beam, while a clear cover of 1.0 in. (25 mm) was provided at the top and the sides. Type K thermocouples were attached to the bottom and top steel reinforcing bars at the midspan section and at the quarter-span sections before casting the concrete (Fig. 2). A Type K thermocouple has sensitivity of approximately 41µV/°C, and can function in a temperature range between −328 and 2462°F (−200 and 1350°C). Thermocouples were replaced with strain gauges in the control beams, tested at ambient temperature, to measure the developed strain in the reinforcement under different load levels.

The concrete mixture was a normalweight concrete designed to achieve a 28-day compressive strength of 7000 psi (48 MPa). After concrete casting, the beams were covered with wet burlap and plastic sheets, and allowed to cure for 72 hours. The concrete achieved an average 28-day compressive strength of 7300 psi (50.3 MPa). To avoid concrete spalling during fire testing, the beams were stored indoors for at least 6 months to allow for moisture escape.
Ten beams were selected for flexural strengthening with FRP materials. As shown in Fig. 2, two different strengthening schemes were applied. Five beams were strengthened with two layers of U-wrap ductile hybrid fiber (DHF) fabric. Five beams were strengthened with four layers of uniaxial carbon fiber (CF) fabric with four end wraps at both sides. A commercially available organic epoxy polymer was selected to form the matrix for both strengthening schemes.

DHF fabric is an innovative strengthening fabric that was developed recently (Grace et al. 2002). The average thickness of one layer of the fabric is approximately 0.039 in. (1.0 mm), and it is made by weaving multiple kinds of fibers in angles of 0, 45, and –45 degrees. In the longitudinal direction, the fabric comprises filaments of ultra-high modulus carbon fiber, high modulus carbon fiber, and E-glass fiber. In both diagonal directions, the fabric comprises filaments of high modulus carbon fiber and E-glass fiber. Combining fiber filaments with different elastic moduli and strengths allows the fabric to experience ductile plateau and avoid the common problem of sudden failure associated with FRP. Details of DHF fabric can be found in Grace et al. (2002).

The uniaxial CF fabric has fiber areal weight of 0.04 lb/ft² (200 g/m²), tensile strength of 493,000 psi (3400 MPa), tensile modulus of 3.3 × 10⁶ psi (227 GPa), elongation of 1.5%, cross-sectional area of 0.052 in.²/ft (1.11 cm²/m), and design thickness of 4.3 × 10⁻³ in. (0.11 mm). As CF is made solely from carbon filaments, it does not show any yield plateau. The stress-strain curve is linear until failure.

The organic epoxy was formed by mixing a high-purity bisphenol A diglycidylether epoxy resin with an epoxy hardener. The epoxy resin had a viscosity range of 4000 to 6000 cp at 77°F (25°C), and specific gravity of 1.16 at 77°F (25°C). According to the technical data sheet offered by the manufacturer, the cured organic epoxy matrix should achieve a flexural strength of 15,590 psi (107.5 MPa), flexural modulus of 4.05 × 10⁵ psi (2792 MPa), yield compressive strength of 15,840 psi (109.2 MPa), compressive modulus of 2.63 × 10⁶ psi (1813 MPa), tensile strength of 9620 psi (66.3 MPa), and ultimate elongation of 4.4%. In addition, the cured epoxy polymer should have and HDT of 224°F (107°C). The Tg was not provided by the manufacturer. Furthermore, the cured organic epoxy will go through thermal degradation and lose approximately 92% of its weight if exposed to a temperature of 320°F (160°C) for 100 hours. The flash point for the cured epoxy polymer was given as 485°F (250°C).

Before applying the strengthening systems, the concrete surface was ground and sandblasted to remove any loose particles and ensure a good bond between the fabric and the concrete. The organic epoxy polymer was prepared and applied to the concrete surface and to the FRP fabric as well. Excessive epoxy and air voids were removed by pressing the fabric. The strengthening system was allowed to cure for 72 hours before moving the beams.

Fire insulation schemes

Three fire insulation schemes were tested. The first fire insulation scheme included applying a newly developed cementitious fire protection layer. The second fire insulation
scheme included applying three layers of 5/8 in. (16 mm) thick Type X fire-rated gypsum boards. The third scheme included applying a 1 in. (25 mm) thick thermal blanket and three layers of 5/8 in. (16 mm) thick Type X fire-rated gypsum boards.

The first fire insulation layer was made by mixing the cemietitious powder with vermiculite using an adequate amount of water. The mixture ratio was set to 1:1 by volume (cement: vermiculite), while the water-cement ratio (by weight) was set to 0.25. The cementitious powder is the binding agent in the fire protection layer. It is a ceramic compound blend of inorganic components, mainly magnesia, potassium phosphate, recycled fly ash, calcium silicate, and polyethylene fibers. The cementitious powder has an approximate density of 130 lb/ft³ (2100 kg/m³), a thermal conductivity of 0.31 Btu/hr.ft.°F (0.53 W/m.K), and a specific heat of 80 Btu/lb.°F (326 kJ/kg.K). Vermiculite, on the other hand, is a natural mineral. In its raw state, it has a specific gravity of approximately 2.6. When the mineral is heated, however, it expands in a process called exfoliation. The flakes of vermiculite can expand up to 30 times their original size. The bulk density of the expanded vermiculite ranges from 4 to 10 lb/ft³ (64 to 160 kg/m³). Vermiculite is a noncombustible material that has a specific heat within the range of 0.2 to 0.26 Btu/lb.°F (0.84 to 1.08 kJ/kg.K), and a thermal conductivity within the range of 0.033 to 0.41 Btu/hr.ft.°F (0.058 to 0.071 W/m.K).

The fire resistance of this cementitious layer is attributed not only to its low thermal conductivity, but also to its capability of retaining moisture. The process of retaining water inside the cementitious layer is quite complicated, but on average, water represents approximately 10 to 20% by weight of the material. This water will evaporate when the insulation layer is heated during fire.

A shotcrete mixer was used to prepare the fire insulation mixture. The cement powder and the vermiculite were dry-mixed and fed to the mixer. Water was added later to the mixture. The mixture was sprayed on the surface of the beams using a shotcrete gun operated by an electric air compressor. Several spray rounds were executed to achieve an average insulation thickness of 2 in. (51 mm).

Gypsum boards have been used to protect structural steel elements such as columns and beams. Design guidelines such as ASCE/SEI/SFPE 29 (2005) provide recommendations and guidelines for the use of gypsum boards to achieve the required fire resistance of steel elements. The suitability of using gypsum boards to protect FRP strengthening systems, however, has not yet been investigated. Therefore, a part of this experimental investigation was dedicated to investigate the fire resistance of FRP beam strengthening systems when Type X gypsum board fire protection is provided.

Three layers of 5/8 in. (16 mm) thick Type X gypsum boards were used to form a fire protection layer for the FRP beam strengthening systems. The boards were attached to the concrete beams using masonry screws. After installing the second layer, the corners were secured against fire using aluminum corner beads. In addition, 16 gauge (1.29 mm diameter) steel wires were wrapped around the gypsum boards to hold them in place during fire. The third layer was then applied, and the joints were sealed using gypsum compound (Fig. 1).

The third fire insulation scheme consisted of three layers of 5/8 in. (16 mm) thick Type X gypsum boards and a 1 in. (25 mm) thick thermal blanket. The thermal blanket is produced from a blend of high quality alumina, silica, and kaolin using a spinning process. It is white in color, and has a density of 8 lb/ft³ (128 kg/m³); according to the manufacturer’s data sheet, it should survive temperatures up to 2300°F (1260°C). The thermal blanket was applied first to the concrete beam specimens. Wood studs and hangers were attached to the beam specimens using masonry screws to accommodate the thickness of the blanket. Sixteen gauge (1.29 mm diameter) steel wires were wrapped around the blanket to hold it in place. The gypsum boards were then attached to the wooden hangers, as shown in Fig. 1.

Test procedure

Beams tested at ambient temperature were loaded to failure using a displacement control module with a loading rate of 0.15 in. (3.8 mm) per minute. On the other hand, beams tested under load/fire events were loaded using a force control module with a loading rate of 500 lb (2.22 kN) per minute to a predetermined load. This predetermined load was maintained for the entire fire test. For the unstrengthened beams, the load level during the fire event was selected to be 50% of the ultimate load-carrying capacity of the unstrengthened beam. For the strengthened beams, the load level during the fire event was selected to be higher than the ultimate load-carrying capacity of the unstrengthened beam, but less than the ultimate load-carrying capacity of the strengthened beams. The load was applied before starting the fire test, which comprised a heating phase and a cooling phase. The heating phase followed the time-temperature curve provided in ASTM E119. It should be noted that the test beams were exposed to fire from four sides. While fire on three sides is more common for beams, a four-sided fire simulates the case scenario when multiple floors in the building catch fire and the structural elements in the floor are exposed to fire from all directions. The heating phase of the fire test was terminated with the failure of the beam. The fire chamber was allowed to cool through a cooling phase, which usually lasted for approximately 24 hours. The temperature readings from the thermocouples were recorded during the heating and cooling phases.

The abbreviation of each beam takes the format of beam-strengthening material-fire insulation material/testing condition. The strengthening material is given the acronym U, DH, or CF for unstrengthened, strengthened with DHF fabric, or strengthened with CF fabric, respectively. The fire insulation material is given the acronym O, C, G, or GB for no insulation, insulation with cementitious materials, insulation with gypsum boards, or insulation with thermal blanket and gypsum boards, respectively. The testing conditions were designated as either A or F for ambient or fire conditions, respectively. For instance, B-DH-G/F is a beam strengthened with DHF fabric, insulated against fire using the gypsum board scheme, and tested under fire event according to the ASTM E119 time-temperature curve.
EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 provides a summary for the results of the investigation. Test conditions, the applied load at failure, and the fire endurance time are given for each test beam. A detailed discussion for the test scenario is given in the following subsections.

Control Beams B-U-O/A, B-DH-O/A, and B-CF-O/A

Beams B-U-O/A, B-DH-O/A, and B-CF-O/A were unstrengthened, strengthened with DHF fabric, and strengthened with CF fabric, respectively. The beams were tested for flexure under a three-point-loading setup at ambient temperature.

Figure 3 shows the load deflection curves for the control beams. The first flexural crack of Beam B-U-O/A was noted at a load level of 2700 lb (12 kN). The flexural cracks propagated with increasing load. At a load level of 10,000 lb (44.5 kN), signs of steel yielding were noted as the beam specimen experienced excessive deflection with a slight increase in the load-carrying capacity. The beam specimen achieved a maximum load level of 12,920 lb (57.47 kN) with a corresponding midspan deflection of 1.75 in. (45 mm). With further loading, the beam specimen experienced a decrease in the load-carrying capacity with significant increase in the midspan deflection until the load was removed at a maximum deflection of 3.3 in. (84 mm). At a load level of 10,000 lb (44.5 kN), the strain in the concrete top surface reached approximately 500 με, while the strain in the bottom reinforcement reached approximately 3000 με. Although the selected reinforcement was made of Grade 60 steel with a guaranteed yield strength of 60,000 psi (413 MPa), it appears from strain readings that the actual yield strength of the reinforcement was much higher than the guaranteed value. The actual yield strength of the reinforcement was approximately 80,000 psi (551 MPa). As an under-reinforced beam, the failure of the beam specimen was characterized by yielding of the reinforcing steel accompanied by excessive deflection with a slight or no increase in the load-carrying capacity.

Beam B-DH-O/A experienced no signs of failure up to a load level of 25,000 lb (111 kN), when some clicking sounds were heard. The beam specimen continued to support additional load up to a level of 26,259 lb (116.8 kN). At this load level, a sudden delamination of the fabric took place.

<table>
<thead>
<tr>
<th>Beam</th>
<th>Fiber-reinforced polymer</th>
<th>Insulation</th>
<th>Load, lb (kN)</th>
<th>Fire endurance, min</th>
<th>Temperature at failure/test stop, °F (°C)</th>
<th>Air</th>
<th>Fiber-reinforced polymer</th>
<th>Concrete</th>
<th>Top reinforcement</th>
<th>Bottom reinforcement</th>
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<tbody>
<tr>
<td>B-U-O/A</td>
<td>—</td>
<td>—</td>
<td>12,920 (57.5)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
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<tr>
<td>B-DH-O/A</td>
<td>DHF</td>
<td>—</td>
<td>26,259 (117)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
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<td>68 (20)</td>
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<tr>
<td>B-CF-O/A</td>
<td>CF</td>
<td>—</td>
<td>22,570 (100)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
<td>68 (20)</td>
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<tr>
<td>B-U-O/F</td>
<td>—</td>
<td>—</td>
<td>6500 (28.9)</td>
<td>112</td>
<td>1885 (1029)</td>
<td>1730 (943)</td>
<td>814 (434)</td>
<td>962 (516)</td>
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<td>B-U-C/F</td>
<td>—</td>
<td>Cementitious</td>
<td>6500 (28.9)</td>
<td>360</td>
<td>2124 (1162)</td>
<td>1209 (653)</td>
<td>765 (407)</td>
<td>773 (411)</td>
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<td>157</td>
<td>1900 (1037)</td>
<td>252 (122)</td>
<td>694 (367)</td>
<td>232 (111)</td>
<td>227 (108)</td>
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<td>Cementitious</td>
<td>14,000 (62.3)</td>
<td>70</td>
<td>1752 (955)</td>
<td>257 (125)</td>
<td>211 (99)</td>
<td>148 (64)</td>
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<td>Cementitious</td>
<td>12,800 (56.9)</td>
<td>143</td>
<td>1892 (1033)</td>
<td>250 (121)</td>
<td>465 (240)</td>
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<td>—</td>
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<td>250 (121)</td>
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<tr>
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<td>—</td>
<td>18,800 (83.6)</td>
<td>—</td>
<td>68 (20)</td>
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<tr>
<td>B-DH-G/F</td>
<td>DHF</td>
<td>Gypsum</td>
<td>14,000 (62.3)</td>
<td>98</td>
<td>1815 (990)</td>
<td>250 (121)</td>
<td>206 (97)</td>
<td>160 (71)</td>
<td>146 (63)</td>
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<tr>
<td>B-DH-GB/F1</td>
<td>DHF</td>
<td>Gypsum and blanket</td>
<td>14,000 (62.3)</td>
<td>150</td>
<td>1912 (1044)</td>
<td>251 (121)</td>
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<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>B-DH-GB/F2</td>
<td>DHF</td>
<td>Gypsum and blanket</td>
<td>18,000 (80)</td>
<td>150</td>
<td>1913 (1045)</td>
<td>258 (126)</td>
<td>—</td>
<td>—</td>
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<tr>
<td>B-CF-GB/F</td>
<td>CF</td>
<td>Gypsum and blanket</td>
<td>15,500 (69)</td>
<td>125</td>
<td>1827 (997)</td>
<td>263 (128)</td>
<td>—</td>
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</table>

*Beam B-CF-G/F was tested under three-point-loading setup for residual strength after fire event.

Note: — = not applicable or not measured.

Fig. 3—Load-deflection curves for control beams tested under three-point-loading setup at ambient temperature.
near one of the ends. Delamination was accompanied by a loud clacking noise. The load-carrying capacity decreased to approximately 23,000 lb (102 kN) before complete delamination took place. The deflection at failure was approximately 1.27 in. (32 mm). The strain in the concrete reached approximately 2000 $\mu$e before the failure of the strengthening system. It appears that adding two layers of DHF delayed the yielding of the bottom steel reinforcing bars.

Beam B-CF-O/A reached a load level of 18,150 lb (80.7 kN), with a corresponding deflection of 1.09 in. (28 mm). With the increase in the load, clicking sounds were heard, and the end wraps showed visual signs of distress and partial delamination. The beam, however, continued to sustain an additional load up to 22,570 lb (100.4 kN). At this load level, progressive delamination of the end wraps occurred. The failure started in the wrap near the midspan, and progressed to the other wraps. Failure of the end wraps caused the longitudinal fabric to lose bond and delaminate from the concrete surface. Upon fabric delamination, the load-carrying capacity of the beam specimen dropped to that of the unstrengthened beam, and the load level dropped to 10,580 lb (47 kN) then increased again as the steel reinforcement continued to yield. Final failure took place at load level of 13,952 lb (62 kN) with a corresponding deflection of 3.35 in. (85 mm).

**Beams B-U-O/F and B-U-C/F**

Both Beams B-U-O/F and B-U-C/F were unstrengthened and tested under a three-point-loading setup with a fire event according to ASTM E119. Beam B-U-O/F did not have any fire insulation, while beam B-U-C/F was provided with a cementitious 2 in. (50 mm) thick fire insulation layer. Both beams were loaded with a vertical load of 6500 lb (28.9 kN), which was equivalent to 50% of the ultimate load-carrying capacity. The vertical load was maintained while the beams were subjected to the fire event. At the time of the test, the concrete beam was 6 months old, with average relative humidity of approximately 67% at an average concrete temperature of 73°F (23°C). At that level of relative humidity, spalling of concrete was unlikely.

No concrete spalling was observed in Beam B-U-O/F during the entire fire test. The beam sustained the vertical load under the fire event until the temperature of the bottom reinforcement exceeded 962°F (516°C). At that temperature, the tensile strength and the elastic modulus of the bottom reinforcement degenerated to the point where it failed to sustain the developed stresses due to the vertical load. The beam collapsed due to rupture of bottom reinforcement at the midspan section. Failure took place after 112 minutes from the start of the fire test.

While testing Beam B-U-C/F, the temperature of concrete and reinforcement gradually increased to 212°F (100°C), where the temperature was maintained for an extended time. It was noted that tiny vertical cracks developed in the insulation layer near the midspan section. The cracks initiated while applying the vertical load before the fire event. The cracks slightly widened after exposure to heat. Apart from the cracks at the midspan section, the rest of the fire insulation layer seemed sound and intact.

The fire test lasted for 6 hours without any signs of failure. By the end of the sixth hour, however, the loading column (steel tube filled with concrete) showed signs of buckling (Fig. 4). Therefore, it was decided to stop the fire test and remove the load.

After 6 hours of fire exposure, the temperature of the bottom reinforcement reached 773°F (411°C). The temperature of the bottom reinforcement was less than the recoded temperature after 112 minutes in the previous test (962°F [516°C]). In addition, the temperature recorded at the soffit of the beam was relatively higher than the recorded temperature at the top of the beam, most likely because of the developed cracks at the midspan section. The performance of the insulation layer at the midspan section, however, was no different from that at the quarterspan sections, as the temperatures of the bottom reinforcement were nearly similar at all points.

**Beams B-DH-C/F, B-CF-C/F1, and B-CF-C/F2**

These beams were strengthened with either DHF fabric or CF fabric, and were insulated against fire using a 2 in.
(51 mm) thick layer of the cementitious insulation. For Beams B-DH-C/F and B-CF-C/F1, the load level was maintained at 14,000 lb (62.3 kN), which represented 55 and 65% of the ambient ultimate carrying capacities of these beams, respectively. The load level for B-CF-C/F2 was maintained at 8000 lb (35.9 kN), which represented 35% of the ambient ultimate load-carrying capacity of this beam.

As shown in Fig. 5, three stages were observed in the time-temperature curve of Beam B-DH-C/F. First, the temperature of the DHF gradually increased from 68 to 212°F (20 to 100°C) in nearly 62 minutes. Second, the temperature of the DHF fabric was maintained at 212°F (100°C) for additional 83 minutes. Third, the temperature increased rapidly to reach 252°F (122°C) in 12 minutes. Finally, at 252°F (122°C), after 157 minutes from the start of the test, the epoxy matrix lost its bond strength, and the entire strengthening system delaminated and separated from the beam along with the fire insulation layer. Once exposed to direct heat, the epoxy matrix ignited, and flames were seen inside the fire chamber. When the strengthening system collapsed, the unstrengthened beam deflected rapidly under the load until the loading actuator triggered the minimum permissible position and stopped automatically. The temperature profile of the DHF at the quarterspan sections was similar to that at the midspan section, with a maximum temperature at failure of approximately 254°F (123°C). The heating phase of the fire test was terminated, and the fire chamber was allowed to cool down over time. After approximately 15 minutes, however, the reinforcement of the beam melted and caused the beam to break into two halves under its self-weight, as shown in Fig. 6. It appears that the wide flexural cracks that developed in the beam specimen after the collapse of the DHF strengthening system allowed the heat to penetrate into the bottom reinforcement. The heat caused a rapid increase in the temperature of the reinforcement, and consequently, a rapid loss in its tensile strength.

While loading Beam B-CF-C/F1, the beam specimen was inspected for potential cracks in the fire insulation layer. Vertical hair cracks were noted near the midspan section in addition to a transverse crack under the central load. The transverse crack separated the insulation on one side of the beam from the insulation on the top of the beam. These cracks propagated during the fire test, and the temperature of the carbon fiber fabric increased gradually up to 212°F (100°C) in approximately 60 minutes. Unlike Beam B-DH-C/F, the temperature stabilized at 212°F (100°C) for only few minutes, followed by rapid increase in the temperature to 257°F (125°C). The temperature at the concrete top surface reached 211°F (99°C) on one side, and 770°F (410°C) on the side facing the transverse crack. After 70 minutes from the start of the fire test, the strengthening system along with the fire insulation layer delaminated from the concrete beam and collapsed. The epoxy in the carbon fiber fabric was burnt off, leaving only loose filaments of the fiber. In addition, the unstrengthened beam experienced several flexural cracks. The reinforcement, however, held the beam intact.

Due to the premature failure of Beam B-CF-C/F1, the test was repeated using Beam B-CF-C/F2, which was a replica of Beam B-CF-C/F1. Certain measures, however, were taken to ensure the proper mounting for the fire insulation layer. Because insulation cracking was the main cause for the premature failure of the previous beam, the fire insulation of the current beam was fastened to the concrete beam specimen using masonry screws, and the load level was reduced to 8000 lb (35.9 kN) to avoid excessive cracking of the insulation layer. Minor flexural hair cracks were developed in the fire insulation layer due to the loading. No major cracks, however, were observed.
The performance of this beam was better than the performance of the previous beam. The temperature of the carbon fiber fabric increased gradually from 68 to 212°F (20 to 100°C) in 68 minutes. The temperature of the fabric remained at 212°F (100°C) for additional 67 minutes. A rapid increase in the temperature up to 250°F (121°C) then took place within 8 minutes. The total time taken for the temperature of the fabric to reach 250°F (121°C) was 143 minutes. During previous fire tests, the strengthening system failed to support the load once the temperature exceeded 250°F (121°C). The applied load on this beam specimen, however, was less than the ultimate load-carrying capacity of the unstrengthened beam. Therefore, no signs of failure were observed with the temperature of the epoxy matrix reaching 250°F (121°C).

To verify the failure of the strengthening system, the load level was increased while conducting the fire test. The beam sustained a load level up to 12,800 lb (56.9 kN), which represented the ultimate load-carrying capacity of the unstrengthened beam. The beam then experienced a large deflection, followed by complete failure.

**Beams B-CF-G/F and B-DH-G/F**

These beams were strengthened and insulated against fire using three layers of 5/8 in. (16 mm) thick Type X gypsum boards. Beam B-DH-G/F was loaded under a three-point-loading setup to a load level of 14,000 lb (62.3 kN). The load was maintained throughout the entire fire test until the failure of the beam. The loading scenario of Beam B-CF-G/F was slightly different. The beam was loaded with a central load of 14,000 lb (62.3 kN), which represented 65% of its ambient ultimate load-carrying capacity. The load, however, was maintained for only the first 15 minutes of the fire test. This loading scenario represented a situation where the occupants escape the building once a fire event occurs. Based on previous fire tests, it was determined that failure of the epoxy matrix and strengthening system took place when the temperature of the fibers reached 250°F (121°C). Therefore, the heating phase of this beam was terminated when the temperature of the strengthening fabric reached 250°F (121°C).

![Fig. 7—Time-temperature curves for beam B-DH-G/F during fire/loading event.](image1)

![Fig. 8—Beam B-CF-G/F before and after fire event.](image2)

Both beams exhibited similar performance during the fire test. The third layer of gypsum boards sustained the fire event for nearly an hour before collapsing. The second layer of gypsum boards cracked, but remained in place. The first layer of gypsum boards was not exposed to fire. The temperature of the DHF fabric increased gradually with time-temperature readings at quarterspan sections similar to those at the midspan section. Unlike the cementitious fire insulation, the temperature of the fabric increased steadily with time, with no significant temperature stabilization at 212°F (100°C).

As shown in Fig. 7, the temperature of the DHF in Beam B-DH-G/F reached 250°F (121°C) after 98 minutes. The epoxy matrix lost its structural capacity, and failed to sustain the induced stresses due to the applied load. The beam specimen showed a sudden drop in the load with the failure of the strengthening system. After removing the gypsum boards, it was noted that the epoxy was not burnt, but the fabric delaminated from the beam at different locations, mainly at the midspan section. It was observed that the remaining epoxy turned black in color, but was able to hold the fabric in place.

The heating phase of Beam B-CF-G/F, shown in Fig. 8, was terminated after 104 minutes from the start of the fire test, when the temperature of the CF fabric exceeded 250°F (121°C). After ending the heating phase, the fire chamber was...
allowed to gradually cool for 24 hours. During the cooling phase, the temperature of the carbon fiber fabric continued to slowly increase, and reached approximately 440°F (226°C). The temperature was less than the flash point of the epoxy as provided by the manufacturer (485°F [250°C]). After the cooling phase, the gypsum boards were removed. The CF fabric seemed sound, with no major signs of delamination (Fig. 9).

To evaluate the post-fire performance, the beam was loaded under a three-point-loading setup at ambient temperature, as shown in Fig. 9. The beam specimen achieved a maximum load of 18,800 lb (83.6 kN), with a corresponding midspan deflection of 3.46 in. (87 mm). The load-carrying capacity of the beam specimen then dropped down to 9900 lb (44 kN), and increased again to 14,000 lb (62.3 kN). The load-carrying capacity fluctuated until a total failure of the beam took place at a load level of 15,500 lb (69 kN), with a corresponding midspan deflection of 6.33 in. (161 mm).

By comparing the load-deflection curve of the beam with that of B-CF-O/A, it was determined that the stiffness of the strengthening system was slightly reduced due to the fire event. The maximum load-carrying capacity after the fire event, however, was approximately 83% of the maximum ambient load-carrying capacity of the beam. This implies that as long as the epoxy is not ignited, it is possible to retrieve most of the structural capacity of the strengthening system after a fire event.

Beams B-DH-GB/F1, B-DH-GB/F2, and B-CF-GB/F

These beams were strengthened and insulated against fire using 1.0 in. (25 mm) thick thermal blanket and three layers of 5/8 in. (16-mm) thick gypsum boards. Beam B-DH-GB/F1 was loaded under a three-point-loading setup to a load level of 14,000 lb (62.3 kN), which represented 55% of its ambient ultimate load-carrying capacity. Beam B-DH-GB/F2 was loaded to a load level of 18,000 lb (80 kN), which represented 68% of its ambient ultimate load-carrying capacity. Beam B-CF-GB/F was loaded to a load level of 15,500 lb (69 kN), which represented 69% of its ambient ultimate load-carrying capacity. The load was maintained for the entire fire test for all three beams.

The fire insulation layer exhibited similar performance during the fire test in all three beams. The third layer of gypsum boards cracked after approximately 40 minutes, partially collapsed after approximately 60 minutes, and fully collapsed after approximately 90 minutes from the start of the test. Meanwhile, the second layer of gypsum boards cracked and partially collapsed. After approximately 2 hours from the start of the fire test, the wood studs at the ends of each beam were exposed to fire and ignited. The thermal blanket, however, prevented the burning of the epoxy polymer and the strengthening system for some time. The flames continued to propagate at the ends of the beams for the subsequent 30 minutes. Finally, the flames propagated to the midspan section, and the strengthening system collapsed after nearly 2 hours and 30 minutes from the start of the fire test. The exact failure time for each beam is shown in Table 1.

As shown in Fig. 10, the temperature readings of the thermocouples were uniform during the first two hours of the test. With the collapse of gypsum boards during the last 30 minutes, however, the readings became highly non-uniform. This can be attributed to the failure or detachment of thermocouples with the collapse and failure of the gypsum boards. By the end of the test, the reading of the thermocouples that remained attached to the strengthening fabric at the midspan section and at the quarter points averaged 250°F.
The failure of all beams was characterized by the delamination of the fabric due to the loss of bond between the fabric and the concrete. The heating phase of the fire test was terminated after the failure of the strengthening system, and the fire chamber was allowed to gradually cool. During the cooling phase, however, the bottom reinforcement of the beams failed to resist the induced stresses due to the beam self-weight, which resulted in failure and breaking each beam into two halves, as shown in Fig. 11.

Figure 12 shows the midspan deflection of Beam B-CF-GB/F during the test. The test lasted for 163 minutes. First, a load of 15,500 lb (69 kN) was applied in 8 minutes during the loading phase. By the end of the loading phase, the deflection was approximately 1.07 in. (27 mm). The load was maintained for another 30 minutes, while all sensors, connections, and furnace control systems were being checked. The heating phase started after 38 minutes, with the beam sustaining a load of 15,500 lb (69 kN) and a corresponding deflection of 1.07 in. (27 mm). During the heating phase, the load level was maintained at 15,500 lb (69 kN), while the deflection increased to 2.86 in. (73 mm). The heating phase lasted for 125 minutes, and ended when the beam exhibited sudden loss in the load-carrying capacity, accompanied by the sudden increase in deflection.

CONCLUSIONS

This investigation addressed only concrete beams strengthened for flexure with FRP materials. Concrete beams strengthened for shear or concrete columns with FRP confinements were not addressed. Based on the results of this experimental investigation, the following conclusions are drawn:

1. An FRP flexural beam strengthening system maintains its structural integrity until its temperature exceeds the Tg or HDT of the organic epoxy matrix. Therefore, if the strengthening system is provided with a properly designed fire insulation layer, its full structural capacity can be maintained for an extended time during fire events. The epoxy matrix used in the current experimental investigation lost its strength when the temperature of the matrix reached 250°F (121°C). Comparing this temperature with its HDT (224°F [107°C]), it can be concluded that the structural performance of the epoxy matrix can be regarded as stable as long as the HDT is not exceeded. If the HDT is exceeded, the structural capacity of the epoxy matrix is likely to degenerate quickly over a short range of temperature change;

2. It is less likely to achieve a good fire resistance (more than an hour) for FRP beam strengthening systems prepared using organic epoxy matrix with a Tg or HDT lower than 212°F (100°C). On the other hand, FRP beam strengthening systems prepared using an organic epoxy matrix with a Tg or HDT higher than 212°F (100°C) are likely to achieve high fire resistance (more than 2 hours) if a fire insulation layer is properly designed and provided. It is therefore recommended that whenever fire is a concern, the FRP beam strengthening system should be prepared using an organic epoxy matrix with a Tg or HDT higher than 212°F (100°C);

3. The thermal properties of the fire insulation layers greatly influence the fire resistance of FRP beam strengthening systems. Moisture content and thermal conductivity in particular govern the performance of the fire insulation layer. Fire insulation materials that can preserve moisture or contain combined water in their molecular structures appear to be a suitable candidate for protecting FRP systems against fire, provided that the Tg or HDT for the organic epoxy is higher than 212°F (100°C);

4. Overall, beam specimens flexurally strengthened with CF fabric with end wraps appear to be more prone to failure...
than beam specimens flexurally strengthened with U-wrap DHF fabric. This can be attributed to the extra time that is needed for the heat energy to travel along the span of the beam and deteriorate the epoxy polymer over a larger surface area;

5. Under a fire event, a properly insulated FRP-strengthened concrete beam can achieve a higher service load-carrying capacity, a higher ultimate load-carrying capacity, and a higher fire resistance than those of an uninsulated, unstrengthened concrete beam; and

6. The post-fire performance of the strengthening system was addressed by testing one of the beams after a fire event. The results of the test showed that the strengthening system retained as much as 83% of its ambient load-carrying capacity after exposure to a fire event provided that the temperature of the epoxy matrix did not exceed its decomposition temperature or its flash point temperature.

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