Behavior of RC Beams Strengthened with NSM-CFRP Strips Exposure to Fire

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Abstract. The behavior of reinforced concrete beams strengthened with Near-Surface-Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) strips using epoxy adhesive and insulated protection schemes after being exposed to fire was investigated in this paper. The following four beams will be subjected to an experimental test: As a reference specimen, a reinforced concrete beam flexural strengthened with NSM-CFRP strips using epoxy adhesive will be tested to failure at ambient temperature. Three RC beams were flexural reinforced with NSM-CFRP strips using epoxy adhesive, one of which was left uninsulated, while the other two were insulated with plastering, with the protection schemes including a thinner insulation layer along the bottom face of the beams (25 mm) and a thicker one at the CFRP anchorage areas (25 to 50 mm). These specimens will be exposed to fire in a gas furnace according to the ISO 834 standard fire curve, and adjustments will be observed after the specimens have been heated. In general, they were all heated without any load and then allowed to cool to room temperature. They were then subjected to four-point bending (simply supported and two-point load) until their failed. The fire behavior of NSM-CFRP reinforced RC beams will be investigated, with an emphasis on the NSM strengthening system's effectiveness during a fire. The conduct of the NSM-CFRP strengthening system on RC beams thermally insulated with fire protection schemes, on the other hand, will be evaluated in the event of a fire. Finally, the fire insulation's efficiency will be investigated.

Keywords: NSM; Carbon Fiber–Reinforced Polymer (CFRP); RC beams; Fire exposure;

1. Introduction

Strengthening technologies based on fiber-reinforced polymer composites have emerged as a possible solution to infrastructure issues in recent years. FRP materials are appealing to civil engineers because of their electrochemical corrosion resistance, high strength-to-weight ratio, and fabrication flexibility. FRP (Fiber Reinforced Polymers) is a modern type of building material made up of resin-saturated fibers (polymeric matrix). FRPs' relentless cost savings and major cost advantages over conventional construction materials. FRP materials often have high tensile strength, low thermal conductivity, corrosion resistance, residual stress strength, availability in a variety of configurations, lower maintenance costs, ease of installation, and mechanical fixing. Since the 1990s, it has resulted in the widespread use of FRPs in civil construction [1]. The consequences of high temperatures are highly susceptible to FRP materials. At a temperature close to the polymer adhesive matrix's glass transition temperature (Tg), previous research indicates that significant degradation of mechanical and/or bonding properties can be expected. This raises the possibility that a lack of FRP jacket effectiveness during a fire could result in a sudden and catastrophic failure. Furthermore, the majority of organic polymer matrix products are flammable. Considerations on the flame spread, smoke production, and toxicity [2].
Near-Surface Mounted Fiber Reinforced Polymer (NSM FRP) reinforcement has been used in a growing number of applications over the past decade. This system is based on the concept of embedding FRP reinforcements (e.g., bars or strips) into grooves created by slotting the surface of concrete members with an adhesive (organic or inorganic) in the concrete cover of the elements to be strengthened. The NSM system has many advantages over the externally bonded FRP reinforcement (EBR FRP): (a) It is possible to reduce the amount of site installation work needed. There is no longer a need for surface preparation other than grooving (for example, the plaster layer and the weak laitance layer on the concrete surface are not required to be removed), (b) NSM bars can be easily anchored into adjacent members to prevent debonding failures; (c) NSM reinforcement can be pre-stressed more easily; this feature is particularly appealing in the flexural strength. The FRP reinforcement in NSM is slitted instead of being externally bonded. This provides additional fire safety opportunities; (g) the NSM system has better bonding properties and protects the FRP bars or strips from accidental impact and mechanical damage, as well as fire and vandalism due to the concrete cover. The polymer binder in these composites does not have the same fire resistance as the fibers used in FRPs. As a result, fires damage concrete buildings reinforced with FRPs. In reality, when compared to the EBR, the NSM technique provides better effectiveness and anchoring capacity because the strengthening material is within the concrete cover (e.g., [3-6]).

2. Methodology of research

In brief, at least four fire resistance tests will be conducted to investigate RC beams' fire performance that has been flexural strengthened with NSM-CFRP strips and thermally insulated. Four RC beams flexural strengthened with NSM-CFRP strips by using conventional epoxy adhesive. The experimental tests will be performed as follows:

- One RC beam flexural strengthened will be tested as a reference specimen.
- One RC beam flexural strengthened and uninsulated.
- One RC beam flexural strengthened and thermally insulated with a thickness of 25 mm.
- One RC beam flexural strengthened and thermally insulated with a thickness of 25 mm at central zone and 50 mm at anchorage zone.

3. Experimental work

3.1 Materials

The concrete mix was used to make all of the beam specimens. All beam specimens had a design compressive strength of 21 MPa, and the cement used in the concrete mixture was ordinary Portland cement (OPC), which was tested according to the IQ. S5 /1984 Standard for Ordinary Cement. According to Iraqi Standard Specification No.45/1984, the gravel and sand used in this study were tested. A deformed steel bar 8 mm nominal diameter was used for all beam specimens as flexural, and shear reinforcement, bar 8 mm diameter was used as stirrups placed in the shear span. Steel rebars of 8 diameters were tested for yield stress and tensile strength; two rebar specimens were tested in the Consulting Engineering Bureau, College of Engineering, University of Baghdad. According to (ASTM, Standard Test Methods and Definitions for Mechanical Testing of Steel Products1, A370-18). The test results are in submission with the Iraqi Specification No. 2091/1999.

Sika® CarboDur® plates are pultruded carbon fiber reinforced polymer (CFRP) plates with a cross-section of 15 mm(width)*1.2 mm, which were used in this study. According to the manufacturer's specifications, the nominal tensile strength was 2800 MPa, and the elasticity modulus was 160 GPa. Sikadur®-30 LP was used as the bonding epoxy adhesive. The CFRP strips were bonded together with a two-component epoxy adhesive. According to the manufacturer, the adhesive had a tensile strength of 18 MPa, compressive strength of >85 MPa, shear strength of 7 MPa, and a Tg of 45 °C. It was specifically designed for use at higher temperatures between +25°C and +55°C. This product complies with international standards (EN 1504-4). As fire protection, local plaster was used. Before installing the fire insulation, the RC beams were cleaned and dried in the air for 24 hours. Plastering was used to cover two NSM-CFRP strengthened beams (BSHP-25 and PSHP-50) on three sides during installation.
Plaster was applied to the clean concrete surface to provide a better bond between the substrate and insulation. The plaster was a commercial product that is usually used as a building finishing layer.

3.2 Test specimens
This research looks at the fire behavior of RC beams that have been flexural strengthened with NSM-CFRP. The specimens were built in such a way that they are strong in shear but poor in flexure. The flexural and shear reinforcements were calculated based on the specifications of the [7] code requirements. The code requirements were used to assess the flexural and shear behavior of CFRP-strengthened RC beams [7,8]. The fire exposure according to ISO 834 stander fire curve. The RC beams are 1850 (mm) long, and all beams have a cross-section of 130 mm×225 mm. The flexural reinforcement consisted of two 8 mm diameter steel bars as top and bottom reinforcement. For shear reinforcement, 8 mm diameter stirrups with spacing 60 (mm) were used throughout the entire beam length and bent at 135° into the concrete core. To avoid shear failure before flexural failure, the shear reinforcements were designed to resist the additional loads generated after exposure to elevated temperature. The concrete cover thickness in all tested beams was maintained at 25 mm on the top and bottom sides and 20 mm on the vertical sides. The beams were strengthened with two CFRP strips that have a cross-section of 15 mm (width) × 1.2 mm (thickness). A total length of 1450 mm was applied to the beams’ grooves according to the NSM technique. The bond length was kept constant for all strengthened beams. The adhesive layer that was used is epoxy, as shown in Figure 1. Along the three sides of the RC beam were insulated with plastering. The specimens were tested under a two-point load, with a 1550 mm total span and a 500 mm shear span; the distance between loads was selected to be 550 mm.

![Figure 1.](image-url)
3.3 Test setup and instrumentations

One beam was tested at ambient temperature, and the other three beams were tested in the fire in two batches in the civil engineering department's structural laboratory at the University of Baghdad. The beams were placed over the open top of the horizontal gas furnace, consisting of a steel framework supported by steel columns and a fire chamber during the burning stage (external dimensions of 3.50 m length, 2 m width, and 0.80 m height), it has a removable top cover that allows specimens to be placed inside the furnace, as shown in Figure 2. Twenty gas burners are located on the side walls to supply thermal energy throughout the heating test, eight burners for each two opposite longitudinal sides and two for each transverse side, connect to ten gas canisters (i.e., one gas canister for each two gas burners). Two blowers were used during the fire test to provide air inside the furnace that helps maintain the fire's momentum and heat distribution, while two thermocouples (placed at the mid-long side of the test furnace) monitor the furnace temperature during a fire test, many small viewports on all sides of the furnace walls to provide a smooth visual observation of the heating test.

![Figure 2. The furnace.](image)

For each specimen, a set of four thermocouples (type K, external diameter of 1 mm) was used to measure the temperature distributions in two beams. The bonding adhesive temperature in both CFRP anchorage zones was determined using thermocouples (T1 and T2). Two of these sensors were placed in the midspan section in the following materials: bonding adhesive (T3) and the air above the top surface (T4). All of the thermocouples in the adhesive were located at a depth of the slits, which is worth noting. In addition, the temperature of the furnace was controlled by an internal type K thermocouple. A thermocouple is a temperature measurement system made of two metals that are not the same. A thermocouple junction is formed by welding metal to the tip of the thermocouple. The most popular thermocouples are type K, which have a wider operating temperature range of 1400 °C. At loading testing processes, an electrical hydraulic jack with a maximum capacity of 100 Tons was used to apply load on the beam specimen, with the applied load controlled by a 100-Ton load cell with a digital load reader, as shown in Figure 3. Three “Dial Gages” were positioned at the bottom surface along the centerline of the beam cross-section, one at mid-span and two under-point loads to measure deflections, as illustrated in Figure 4.

![Figure 3. Test model.](image)

![Figure 4. Dial gages installation and positioning.](image)
Beam specimens were coded according to the NSM-CFRP strengthening technique, temperature exposure, and fire insulation systems. So, the symbols became as shown in as follows:

- BSR: beam strengthened with NSM-CFRP strips and unburned.
- BSH: beam strengthened with NSM-CFRP strips and burned.
- BSHP-25: beam strengthened with NSM-CFRP strips, insulated with plastering have thickness 25 mm along with three faces of the beam and burned.
- BSHP-50: beam strengthened with NSM-CFRP strips, insulated with plastering have thickness 25 mm along with three faces of beam and thickness 50 mm in the anchorage zones and burned.

3.4 Test procedure for high-temperature test

Three RC beams were burned using a gas furnace which was controlled to reach maximum furnace temperatures of 600°C for two hours and then cooled down to room temperature. Heating rates were based on the time-temperature curve ISO-834. The temperature was controlled manually, according to the heat regime required.

3.5 Test Procedure for Loading Test

All of these beams, including one unburned as a reference beam, were loaded before failure by applying monotonic load downward over the midpoint of the stiffened I-section steel beam spreader to investigate the efficiency of insulation reinforced concrete beams flexural strengthened with NSM-CFRP strips and ultimate residual strength for beams after finishing the burning test stage. Two supports of 25 mm diameter bars supported the spreader beam. The load was recorded by the testing machine's load cell, and displacement data were recorded by three dial-gages located at three positions along the bottom of the beams (see Figure 4). These specimens were tested in the structural laboratory of the Civil Engineering Department/University of Baghdad.

4. Results and discussion

4.1 Experimental Results of Strengthened Unburned and Uninsulated Strengthened Burned Beams

The displacements in the curves reflect the deflections in the central of the beam. The average ultimate load obtained by the BSR and BSH beams was 73.72 kN and 53.71 kN, respectively. The failure of beam BSR began with steel yielding and tension crack propagation, followed by concrete crush in the compression zone. With growing load, the cracks spread vertically until the tensile steel reinforcement ruptured, followed by CFRP splitting or rupture. As shown in Figure 5, the deflection increased steadily until concrete crushing occurred at the beam compressive zone. The maximum capacity of the CFRP was achieved, while concrete cover separation began at the cut-off point of the fiber at the end of the beam due to the propagation of diagonal cracks through the concrete cover, as shown in Figure 6. With the load rising, concrete crushing occurred at the compressive zone at the top of the beam. The results revealed that due to fire exposure, the BSH beam loading capacity was reduced by 27% as compared to the BSR specimen.

Figure 5. BSR beam, failure mode, and cracking pattern.
4.2 Experimental Results of the Strengthened Insulated with Plaster and Burned Beams

Two of the same strengthened beams, but insulated, were tested to see how fire insulation affected the NSM-CFRP strengthened beam. The three faces of the BSHP-25 beam were plastered with a (25 mm) thick layer of plaster, while the anchorage zones of the BSHP-50 beam were plastered with (50 mm) of insulation plaster. The heating rate was kept constant. After 15 minutes of heating exposure, the insulation layer (i.e., plaster) of the bottom face deteriorated as a result of gypsum dehydration, large cracks appeared on both sides, but the plaster remained intact and was not removed from the beam. In addition to inside the furnace, no deboned was noticed. After removing the plaster, the hair cracks in the BSHP-25 beam specimen insulated with one plaster layer were less than in the beam without an insulating layer. Nonetheless, there were no hair cracks in the beam specimen that were insulated with a thicker plaster layer (50 mm) in the anchorage zones. Table 1 summarizes the test results in terms of crack, and ultimate loads, as well as deflection at the crack, and ultimate.

Figures 7 and 8 show the load versus deflection curves for the tested beams. The insulated beams' load capacity with a thicker plaster layer of 50 mm at the anchorage zones was clearly more significant than the insulated beams' load capacity with a thin plaster layer of 25 mm at the anchorage zones. There is some concrete discoloration for two-layer insulated beams, while for one-layer insulated beams, there is more. As shown in Figure 9, the failure mode of beam BSHP-25 was similar to the failure mode of beam BSR but with a lower ultimate load as shown in, while, the failure mode of beam BSHP-50 was a concrete cover separation that began at the fiber's cut-off point and spread to the center of the beam, followed by compressive concrete failure at the loading points, as shown in Figure 10.

Figure 7. Load-deflection curves for the strengthened beam and strengthened burned beam.
Figure 8. Load-deflection curves for the strengthened and strengthened insulated with plaster burned beams.

Figure 9. BSHP-25 beam, failure mode, and cracking pattern.

Figure 10. BSHP-50 beam, failure mode, and cracking pattern.

Table 1. Results of tested beams.

| Beam code | $P_{cr}$ (kN) | $\Delta_{cr}$ (mm) | $P_u$ (kN) | $\Delta_u$ (mm) | Failure mode         | % decreasing in $P_u$ |
|-----------|---------------|---------------------|------------|----------------|----------------------|-----------------------|
| BSR       | 14.67         | 1.30                | 73.72      | 15.22          | Crushing of concrete | -                     |
| BSH       | 2.45          | 0.35                | 53.71      | 16.68          | End cover separation| 27%                   |
| BSHP-25   | 2.11          | 0.21                | 57.73      | 14.25          | Crushing of concrete| 22%                   |
| BSHP-50   | 3.34          | 0.35                | 68.82      | 16.81          | End cover separation| 7%                    |
5. Conclusions
The NSM-CFRP reinforced RC beams were subjected to a series of fire tests using ISO-834 standard fire. The results of the reinforcement process, adhesives, fire insulation were all taken into consideration. More specifically, the current research focuses some light on how the NSM-CFRP strengthening mechanism develops fire resistance. The following conclusions can be drawn from the experimental data and analysis:

- In contrast to uninsulated beams, the flexural capacity and stiffness of thermally insulated RC beams reinforced with NSM-CFRP are little influenced by the high temperature after two hours of heating at a maximum temperature of 600 °C under the ISO standard curve.
- Fire insulation will improve the fire resistance of NSM-CFRP reinforced RC beams significantly. The NSM-CFRP-enhanced RC beams with well-protection withstood the standard fire for two hours, while the beam without protection demonstrated a different behavior.
- According to the test results, the U-shaped fire protection with thicker insulation at the anchorage zone has a significant thermal insulation advantage over the bottom side protection compared to insulation with the same thickness along the beam.
- Although the adhesive temperature exceeds Tg, the NSM-CFRP preserves its contribution to the strengthening mechanism. The difference in fire resistance is due to residual friction at the NSM-CFRP/matrix interface.
- The glass transition temperature Tg may be over-conservative as the critical temperature determines the fire resistance of the NSM-CFRP strengthening system. To establish rational failure criteria and design philosophy, a more comprehensive analysis of the thermal and structural responses of the NSM-CFRP strengthening system is needed.

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