

Performance of Fire-deteriorated Concrete Beams Strengthened with NSM Laminates

A Jadooe ^{1,2}, R Al-Mahaidi ³ and K Abdouka ⁴

¹PhD Candidate, Swinburne University of Technology, Melbourne, Australia

²Lecturer, Kerbala University, Kerbala, Iraq

³Professor of Structural Engineering, Swinburne University of Technology, Melbourne, Australia

⁴Senior Lecturer, Swinburne University of Technology, Melbourne, Australia

Abstract: Exposure of RC beams to fire may lead to a decrease in their load capacity and stiffness of the beams, both during heating and after the beam has cooled following the fire. The degree of damage is related to the fire's intensity in terms of temperature and duration. This investigation is concerned with the effectiveness and suitability of the CFRP near-surface mounted (NSM) laminate system in terms of repairing RC beams after exposure to elevated temperatures. In the experimental work, the ISO-834 standard fire curve was adopted to test the beams. Two beams were tested at normal temperature exposure, while the other beams were heated to the target temperature using a large horizontal furnace. The experimental parameters involved in this study were the type of heat exposure, the level of heat exposure, and the insulation effect. Although a reduction did occur in the stiffness and ultimate load of affected beams, repairs with NSM laminates were found to offer an effective technique for increasing the overall stiffness and load carrying capacity of the beams.

Keywords: Rehabilitation, CFRP, High temperature, cement-based adhesive, epoxy adhesive, Insulation.

1. Introduction

Rapid heating resulting from fire can cause many changes in structures due to thermal dilatation, as well as creep and thermal shrinkage of concrete caused by water loss. These changes can create large internal stresses and thus lead to large fractures and cracking. In extreme cases, when heating by fire is particularly rapid, explosive spalling of concrete may occur. Obviously, calculations based on a knowledge of the mechanical properties of concrete after heating are required in such situations. It is also important to understand the properties of concrete during heating within various applications in civil engineering [1, 2]. The influence of heating is most readily seen in the form of surface cracking. Arioiz [3] demonstrated that at 600 °C, surface cracks were more visible and more obvious than when the temperature rose to 800 and 1000 °C, respectively. In addition, it was confirmed that irreversible damage could occur when the temperature exceeded 500 °C. According to Chan et al. [2], this loss of strength is significant above 400 °C. In a typical fire scenario, it was also noted that the temperature distribution during heating is quite different to that during the cooling phase, as heat continues to be transferred to the interior from the exterior, hotter, parts of the structure [4].

Numerous researchers have investigated the performance of strengthening and repairing techniques for deteriorated concrete slabs and beams using carbon fibre-reinforced polymers. Ji et al. [5] investigated the efficiency of using nano-clay enhanced fibre to promote the fire resistance of fibre-reinforced concrete; in their study, twenty-seven beams were tested under bending and 24 beams were repaired with FRP nano-clay or nano-clay FF88. The results showed that employing both types of nano-clay improved the performance and load resistance after exposure to fire damage.



Martinola et al. (2010) [6] used high-performance fiber-reinforced concrete (HPFRC) to repair and strengthen RC. Their research investigated the effectiveness of using a single thin layer of HPFRC. Four full-scale beams were manufactured with dimensions 4550 mm long x 500 mm deep x 300 mm wide. Testing was carried out under four-point bending, and the results demonstrated that an enhancement in stiffness and ultimate load values of 215% compared with the control beam was seen when HPFRC was used.

In a near-surface mounted (NSM) system, carbon fibre-reinforced polymer laminate and concrete are bonded together with cementitious or epoxy adhesives. The assembly of the concrete substrate, NSM FRP, and the adhesive can be referred to as an NSM CFRP technique. The bond properties of the NSM CFRP system play a critical role in ensuring the effectiveness of FRP strengthening, and it has been found that the increase in bond strength with the increase in bond length demonstrates a non-linear trend prior to peak load. In spite of the popularity of externally-bonded (EB) systems, however, these have a number of significant limitations in practice, such as the lack of capability to develop the full tensile strength of the FRP sheet [7-9].

The main purpose of this research is thus to study the effectiveness and suitability of application NSM systems in terms of repairing RC beams after exposure to high temperatures and/or fire. This research also investigates the reduction of strength in RC segments after heating and then cooling to room temperature.

2. Experimental program

The experimental test program involved nine RC beams, and it aimed to investigate the effectiveness of using NSM CFRP laminate to repair concrete deteriorated by high temperatures. Moulds were prepared and made for the beams using plywood sheets, and the dimensions of each experimental beam were 140 mm wide, 260 mm deep, and 2700 mm long. The beam dimensions in this program were designed to fit the furnace dimensions. All concrete beams were reinforced with steel 3 Ø12 mm at the bottom and 2 Ø12 mm at the top in the form of longitudinal deformed bars, while Ø10 mm deformed bars were used for transverse bars or stirrups (shear reinforcement), with a 25 mm top cover and 30 mm covering the other sides. These beam details are illustrated in Figure 1.

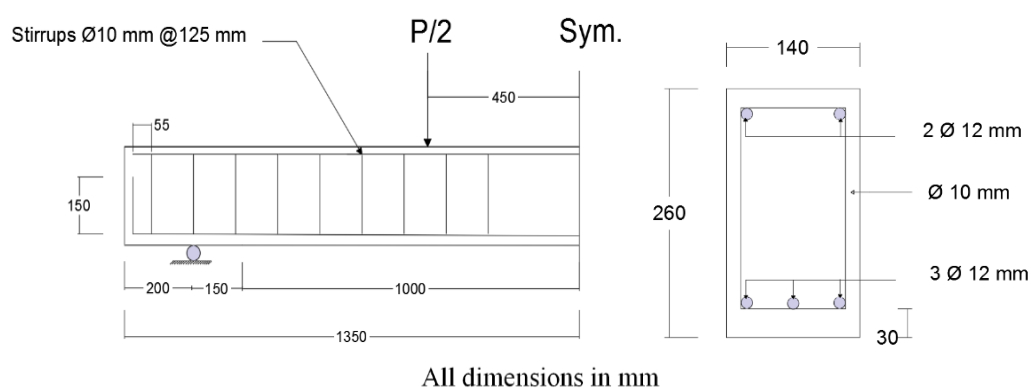


Figure 1. Beam geometrical details

The proportions by weight for the concrete mix were 1 (cement): 1.8 (fine aggregate): 2.4 (coarse aggregate), and the water/cement ratio was 0.42, with a maximum aggregate size of 14 mm. The moulds were removed after 24 hours of curing, and the beams were kept coated with a wax emulsion. The beams were placed in the laboratory at ambient temperature (between 16 to 20 °C) and relative humidity (approximately 65 %), until the test day. The top surface of RC beams was protected from heating to the temperature of the concrete floor slab by using an insulation system formed of gypsum plasterboard. This involves gypsum and a crystalline form of calcium sulphate and water that combined to create calcium sulphate dehydrates, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The insulation overall consisted of two layers of gypsum plasterboard. The first set of layers was installed on the top surface of the beam, with a total length of 2,300 mm and thickness of 32 mm, where the thickness was 16 mm for each layer. The second layers were installed on the top side, with a thickness 25 mm and depth of 60 mm, as demonstrated in Figure 2.

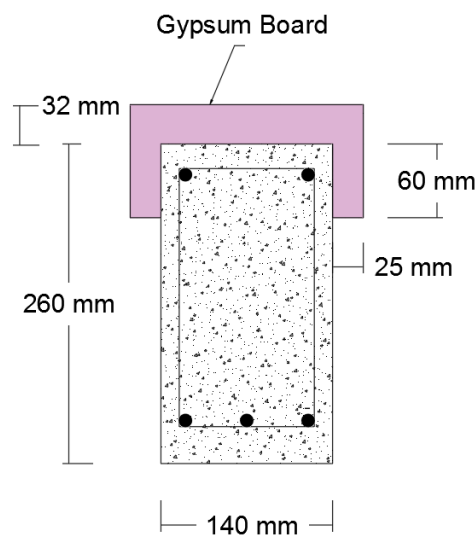


Figure 2. Layout of insulation layer

The beams were exposed to high temperature (600 and 800 °C) for two hours. All the RC beams were tested using the ISO-834 standard curve [10]. In addition, twelve cylinders of concrete of 100 x 200 mm and prisms with dimensions of 600 mm length x 150 mm width x 150 mm height, with equivalent steel reinforcement to that used in the full-scale RC beams, were heated to the same level for the same period. This was done to obtain the mechanical properties of the concrete and the tensile strength of the steel after heating and cooling. All tests of mechanical properties were done on the same day as the bending tests for the RC beams. After heating, the beams were repaired using NSM techniques. Table 1 illustrates the beam test variables. The specimen identity code “B-25” refers to unheated beams, “B-600” refers to beams exposed to 600 °C, “B-800” refers to beams exposed to 800 °C, and “R” means repaired. The letters “E” and “C” refer to epoxy adhesive and cement-based adhesive, which were used for repair after damage by high temperatures, “PI” refers to partial insulation, which was used on the top surface of the beam, and “2H” means two hours duration.

Table 1. Beam test variables

| Specimen ID | Number of beams | Details |
|---------------|-----------------|---|
| B-25 | 2 | Control |
| B-600-2H | 1 | Without repair |
| B-800-2H | 1 | Without repair |
| B-PI-800-2H | 1 | Without repair |
| BRE-PI-800-2H | 2 | NSM laminate and epoxy adhesive using partial insulation |
| BRC-PI-800-2H | 2 | NSM laminate and cement-based adhesive using partial insulation |

2.1 Material description

All beam specimens and cylinders were made of the same concrete mix, supplied by a single ready-mix manufacturer. The average compressive strength, splitting tensile strength, and modulus of elasticity of the concrete at the age of 10 months after casting were 38.6 MPa, 3.85 MPa, 33 GPa, respectively. Ten months was the age of the concrete beams at the time of testing. The mechanical properties of the concrete, steel reinforcement, and carbon fibre used are demonstrated in Table 2. Epoxy resin adhesive and cement-based adhesive were utilised to repair the specimens that deteriorated with heating and cooling to room temperature.

Table 2. Material properties

| Material | f'_c , (MPa) | f_t , (MPa) | f_y , (MPa) | f_u , (MPa) | E, (GPa) |
|-----------------------|-------------------|------------------|------------------|------------------|-------------|
| Concrete | 35 | 3.73 | - | - | 29.5 |
| Cement-based adhesive | 73.5 | 7.24 | | | |
| Steel Ø 12 mm | - | - | 587 | 655 | 209 |
| Steel Ø 10 mm | - | - | 561 | 652 | 206 |
| CFRP laminate | - | 3122 | - | - | 212 |

2.2 Test procedure for high temperature tests

Seven RC beams were heated to temperatures of 600 and 800 °C using a large horizontal furnace. They were kept constant during the test for two hours of exposure and then cooled gradually down to room temperature. Heating rates were based on the time-temperature curve of ISO-834. However, the cooling regime was chosen to represent natural cooling at a rate of 1 to 3 °C/min in the furnace until room temperature was reached. The furnace was supplied with a separate controller, which enabled the temperature to be controlled for the RC beams during the test procedure. The external dimensions were 2,000 mm long and 1,050 mm high. However, the internal dimensions were 1,700 mm long and 800 mm high, as shown in Figure 3.

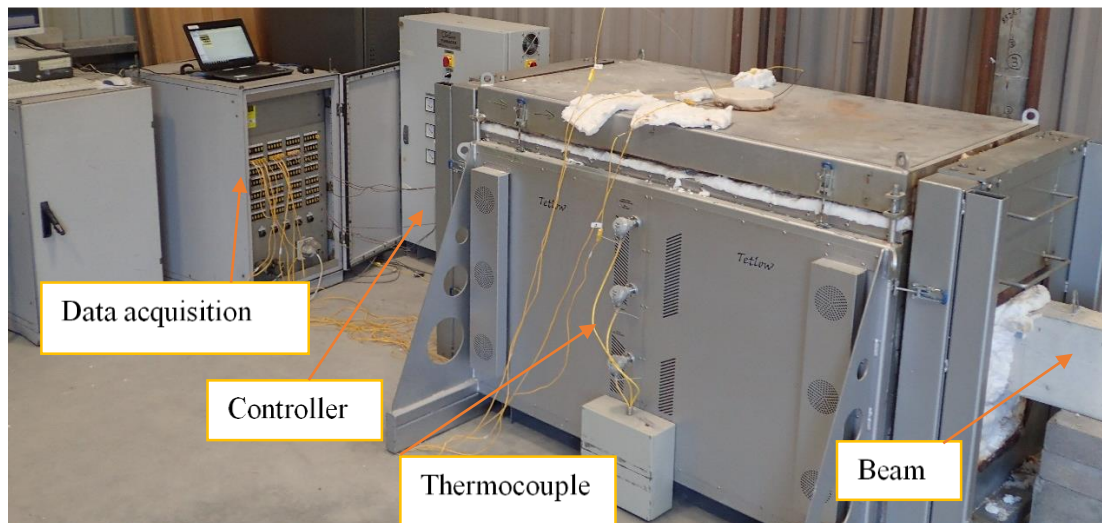


Figure 3. Horizontal beam test furnace

2.3 Specimen preparation for repair after deterioration

All RC beams were repaired after deterioration on heating with making grooves in the tension surface of the concrete. The groove dimensions were 2000 mm, 25 mm, and 5 mm length, depth, and width, respectively, as per ACI 440.2R-08 [11]. The bond length was kept constant at 2,000 mm for all the deteriorated beams to obtain a good composite between the deteriorated concrete and the CFRP laminates [12]. To clean the surface of the concrete of dust, a pressurized air jet was used. Two adhesives were implemented for the heat-deteriorated concrete beams in this investigation. Epoxy adhesive with a mix ratio of 3:2 was utilised to bond the CFRP laminate to the deteriorated concrete using NSM system. A cement-based adhesive with compressive and tensile strengths of 73.5 MPa and 7.25 MPa, respectively at 28 days, was also utilised in this research. This adhesive was formed from Portland cement, silica fume, micro cement, Primer (Mbrace primer), silica filler, and superplasticizer, similar to that reported in [12].

3. Testing set-up for RC beam

All the RC beams were tested using a 5 MN capacity Instron testing machine. The displacement rate of this machine was 1 mm/min. The setup of a beam in this machine is shown in Figure 4. The load was recorded by the load cell of the 5 MN Instron compression testing machine, and displacement data and strain gauge data were recorded by a data acquisition system which recorded all data every second throughout each increment of the test. The beams were loaded in a four-point bending configuration; the total span was 2,300 mm and the shear span was 700 mm for each side of the beam.

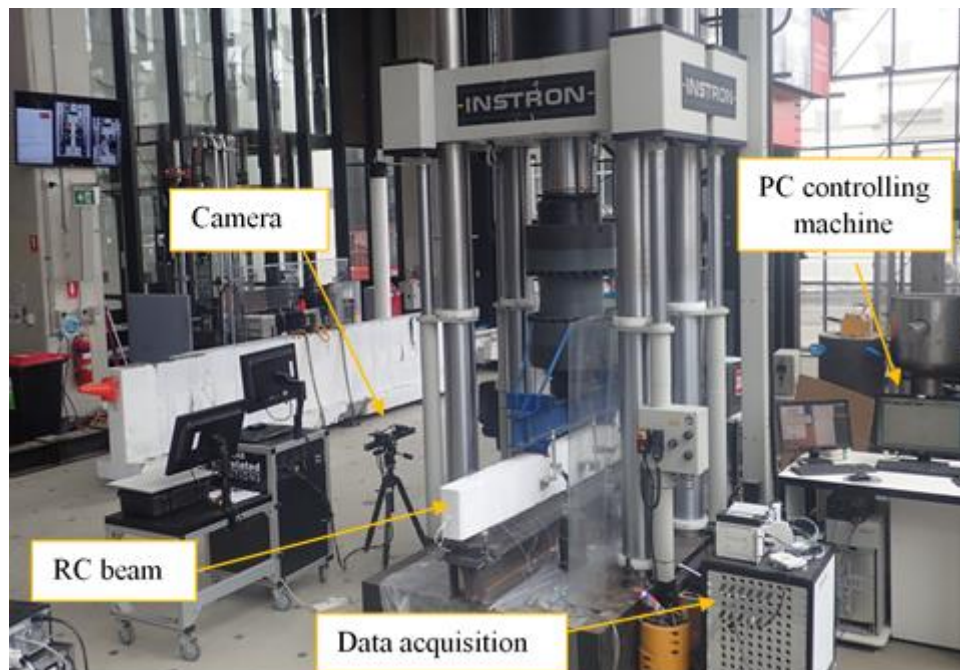


Figure 4. 5 MN Instron compression testing machine and test set-up

4. Discussion of experimental results

The test results for the RC beams are shown in Table 3. The samples in this table are unheated beams (control beams), beams exposed to 600 °C without repair (heat-deteriorated beams), and beams exposed to 800 °C and repaired with NSM applications using epoxy and cement-based adhesives. The results include the maximum load, deflection, and strain in CFRP laminates, the contribution of CFRP laminates to the repair of the beams deteriorated by high temperatures, as well as the reduction in strength after exposure to heating and subsequent increase in strength after repair.

4.1 Load-deflection for control beams, heated beams, and beams repaired with CFRP

The overall behaviours for control and heat-deteriorated RC beams were assessed by studying the load-deflection diagrams. The performance of beams was evaluated using the load deflection curves shown in Figure 5 and Figure 6. The control beams achieved an average ultimate failure load of 115 kN and the maximum deflection was 79 mm. The deflection increased steadily after the steel yielded as the load increased, demonstrating the ductility of the beams. The load capacity of the heat-deteriorated beams without insulation on the top surface of the concrete reduced after two-hour exposure to 600 and 800 °C by 5.2 % and 32 %, respectively. In addition, the load capacity of the heat-deteriorated beams using partial insulation also reduced after two-hour exposure to 800 °C, by 30 %. The results demonstrated that when the beam was exposed to 600 °C, the residual strength, and the stiffness of the beam decreased slightly. It is clear that at 600 °C, the decrease in flexural strength is related to the losses in compressive strength, tensile strength, modulus of elasticity, and tensile strength of steel reinforcement, which drop to about 51%, 63%, 70%, and 6.3% of their original values, respectively. However, at 800 °C, more dramatic losses of 77%, 89%, 91%, and 47% of original values during bending testing of RC beams were seen, respectively. It was noted, that the reduction in strength was very high when the RC beams were exposed to 800 °C due to the fact that the strength is controlled by the yielding of the steel reinforcement; Kigha [13] confirmed experimentally that the tensile strength of steel is greatly affected by heating where the fire temperature is more than 700 °C. Thus, the 800 °C exposure caused significant

reductions in strength and stiffness. The control beam failed at 115 kN, whereas the beams deteriorated by heating to 600 and 800 °C failed at 108 and 78.5 kN, respectively. The load carrying capacities of the heated beams were also lower than that of the unheated beams.

Specimens exposed to 800 °C only were then repaired with NSM CFRP laminates, using epoxy and cement-based adhesives, due to their high reduction in load carrying capacity compared with the unheated beam. The NSM system led to an enhancement in the capacity and stiffness of RC beams when the epoxy and cement-based adhesives were utilised. In general, the post-heated beams strengthened with NSM CFRP laminates regained more strength and stiffness than the unheated beams. This shows the possibility of restoring RC beams deteriorated by elevated temperatures by using NSM systems. For example, the flexural capacity of the deteriorated beams repaired subsequently with NSM CFRP using epoxy and cement-based adhesives increased by an average of 15% and 8%, respectively, compared with the control beam. This also illustrates that the presence of CFRP with cement-based adhesives improves the ductility of heat-deteriorated beams, as shown in Figure 6. This is seen in a comparison of the unheated control beam results with those of specimens exposed to 800 °C.

Table 3. Results of experimental tests of RC beams

| Specimen | Maximum load (kN) | Maximum deflection (mm) | Maximum strain in CFRP laminates (micro-strain) | CFRP efficiency ^(a) % | Change in ultimate strength ^(b) (%) | Failure mode |
|---|-------------------|-------------------------|---|----------------------------------|--|--------------|
| B-25-1 | 115.5 | 80 | - | | - | c |
| B-25-2 | 114.3 | 77.5 | - | | - | |
| B-600-2H | 108.9 | 70.4 | - | - | -5.2 | c |
| B-800-2H | 78.5 | 43 | | | -32 | f |
| B-PI-800-2H | 81.4 | 54.5 | | | -30 | c |
| BRE-PI-800-2H-1 | 132.4 | 51 | 4891 | 40 | 18 | d |
| BRE-PI-800-2H-2 | 130.8 | 50.6 | 4109 | 34 | 13 | |
| BRC-PI-800-2H-1 | 126.7 | 71.9 | 4053 | 33 | 12 | e |
| BRC-PI-800-2H-2 | 121.5 | 65 | 3902 | 32 | 10 | |
| a: Measured maximum CFRP strain laminate as percentage of ultimate strain capacity by laboratory testing (12000 micro-strain) | | | | | | |
| b: Positive value refers to increased value and negative value refers to decreased value before and after exposure to heating | | | | | | |
| c: Yielding and then compression failure with increase in number of cracks. | | | | | | |
| d: Concrete cover separation following by yielding and then compression failure. | | | | | | |
| e: Partial concrete cover separation followed by failure of concrete. | | | | | | |
| f: Sudden failure in compression zone | | | | | | |

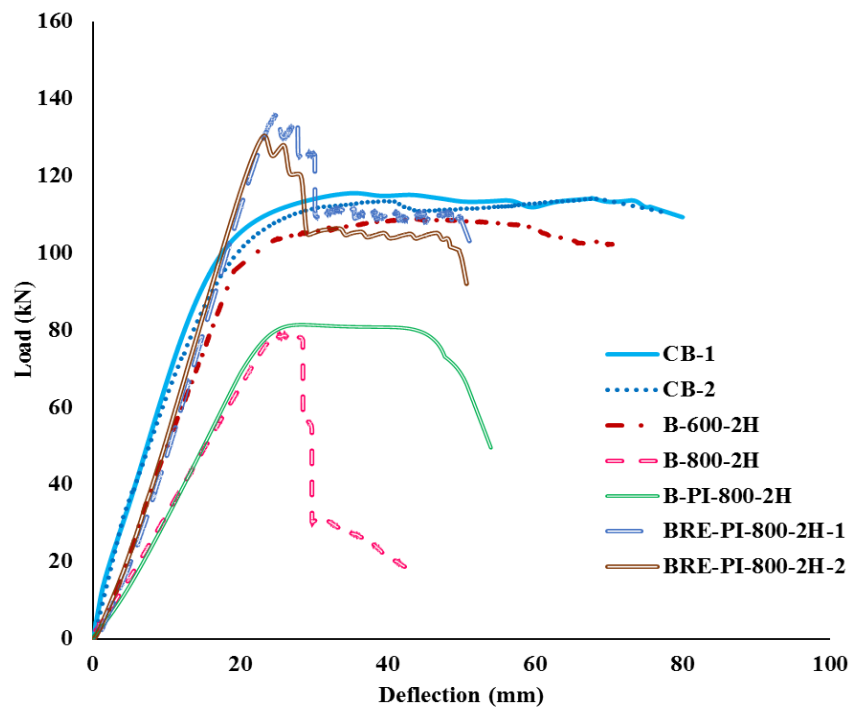


Figure 5. Load vs mid-span deflection using epoxy adhesive after exposure to 600 and 800 °C

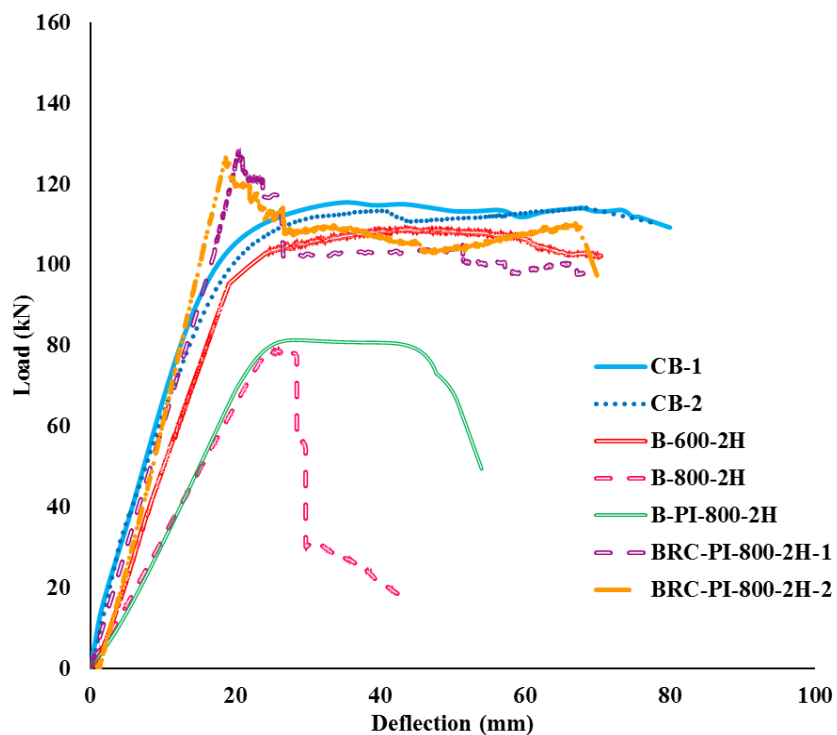
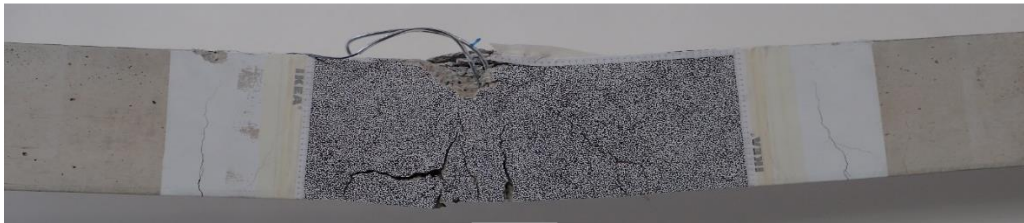


Figure 6. Load vs mid-span deflection using cement-based adhesive after exposure to 600 and 800 °C

4.2 Failure mode

Flexural failure was observed in the control beam and the heat-deteriorated beams exposed to 600 and 800 °C using partial insulation. However, in the beams heated to 800 °C without insulation, sudden failure occurred. The typical failure of the control beam was a yielding of the steel reinforcement, followed by a crushing of the concrete, as shown in Figure 7(a). For the beams heated to 800 °C using partial insulation, the flexural cracks were seen to be widespread throughout the region of pure bending, as shown in Figure 7(b). However, the beams heated to 800 °C without insulation experienced sudden failure due to degradation of concrete properties and the changes in thermal stress of the concrete microstructure [14], as shown in Figure 7(c). For those beams repaired with epoxy adhesives, the failure mode was concrete cover separation, beginning at the cut-off point of the CFRP laminates and propagating to the middle of the beam, followed by compressive failure of the concrete, as shown in Figure 7(d). This failure is similar to those reported by [12 and 15]. However, the beams repaired with cement-based adhesive failed due to partial concrete cover separation followed by large deformations and compressive failure of concrete, as shown in Figure 7(e).



(a)



(b)



(c)



(d)



(e)

Figure 7. Failure modes of some RC beams

5. Validation of the Proposed Approach

The average test results were used to verify the design guidelines of ACI 440.2R-08 [11] for the flexural strengthening of interior RC beams with NSM CFRP laminates after heating to a given temperature. The validity of the approach proposed was established by comparing the predicted response of beams with the results of the experiments. To demonstrate the usefulness of the proposed approach, the selected NSM CFRP laminate-strengthened deteriorated RC beams were subject to testing under several variations, such as epoxy and cement-based adhesives, compressive strength, modulus of elasticity, and tensile strength of steel reinforcement. A comparison of predicted ultimate flexural capacity (M_{pred}) with that seen in the experimental work (M_{exp}) is shown in Table 4. It can be seen that the approach proposed by ACI 440.2R closely predicts the ultimate flexural capacity of heat-deteriorated RC beams after repair with NSM CFRP laminate.

Table 4. Experimental versus predicted ultimate flexural capacity using ACI-440.2R

| Specimens | M_{exp} (kN/m) | P_{exp} (kN) | M_{pred} ACI-440.2R (kN/m) | P_{pred} ACI-440.2R (kN) | Change in moment capacity % |
|---|---------------------|-------------------|------------------------------------|----------------------------------|-----------------------------------|
| BRE-PI-800-2H | 46.1 | 131.6 | 44.8 | 128.04 | 2.8 |
| BRC-PI-800-2H | 43.4 | 124.1 | 41.8 | 119.54 | 3.7 |
| $M_{exp} = P_{exp} \cdot (L-a)/4$, where P_{exp} is the maximum load, L is the clear span distance, and a is the distance of two points load | | | | | |

6. Conclusion

The major focus of this investigation was to use an experimental perspective to study the performance of RC beams exposed to heating and gradual cooling, and to investigate the repair of heat deteriorated beams using NSM CFRP laminates with epoxy and cementitious adhesives. The NSM laminates were applied in grooves cut into the concrete surface to maximally utilise the benefits of this technique. Based on these experiments, the following conclusions can be drawn:

1. The residual concrete compressive strength, tensile strength, modulus of elasticity, and tensile strength of the steel reinforcement of the RC beams were found to reduce after exposure to 600 and 800 °C for two hours, with the greatest reductions being associated with the higher temperature.
2. For two-hour heating with a maximum temperature of 600 °C, the flexural capacity and stiffness of RC beams minimally affected, though the flexural capacity is reduced by 5.2%. This indicates that the tensile strength of the steel reinforcement reduced slightly after exposure to 600 °C.
3. The capacity of the heat-deteriorated beams without insulation on the top surface of the concrete reduced by 32% after two-hour exposure to 800 °C; for heat-deteriorated beams with partial insulation, this was also reduced by 30 %. This indicates that the effect of insulation is minimal; the beam failure is controlled by the yielding of steel rather than concrete compression failure.
4. Both adhesives proposed in this investigation appear to be promising methods for repairing specimens deteriorated by heating. The beams repaired with NSM CFRP laminate utilising epoxy adhesive displayed higher load carrying capacity than those repaired with cement-based adhesive, while the beams repaired with cement-based adhesive demonstrated higher ductility than those repaired with epoxy adhesive after being heated to 800 °C for two hours.
5. The strains in CFRP laminate increased when the load increased up to maximum for the beams strengthened with both epoxy and cement-based adhesives after heating. This is because the slope of the relationship between the load and strain increased; failure occurred at a maximum strain value.
6. It was found that the design equation suggested by ACI 440.2R-08 can be used to assess the flexural moment capacity of heat deteriorated and repaired beams in a similar way to unheated beams repaired with NSM CFRP.

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