Performance of Thermally Insulated Reinforced Concrete Beams Strengthened with Near-Surface Mounted-Carbon Fiber Reinforced Polymer Strips under Elevated Temperature

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Abstract. This paper investigated the performance of reinforced concrete beams strengthened with near-surface mounted (NSM) carbon fiber reinforced polymer (CFRP) smooth and rough strips using cement based adhesive and insulated with plasterboards for protection the beams subjected to high temperature. An experimental work was carried out on ten large scale RC strengthened beams and strengthened insulated beams. The experimental program subject the strengthened beams to high temperature degrees up to 600 °C in electric furnace and observe changes after beams been heated. Results showed that the plasterboards provided excellent protection and decreased the CFRP temperature of about 42-24%. The insulated beams behaved as good as that of strengthened beams prior to expose to 600°C.

1. Introduction

The method of Near-surface mounted (NSM) is strengthening technique for reinforced concrete members to increase the flexural and shear strength. The approach of strengthening using this technique is to make grooves within the cover distance of a RC concrete member and then embed the FRP reinforcement into these premade grooves using adhesive materials as a bonding agent such as epoxy [1]. FRP also have large deformation capacity and great resistance to corrosion in comparison with traditional steel. Furthermore, FRP is also well known for its use in FRP-concrete composites which can be added to new and existing buildings for repair, strengthening of structures and seismic retrofitting of beams [2]. Moreover, NSM FRP reinforcement is embedded into the concrete substrate, and the concrete cover provides a certain level of protection to NSM FRP and minimizes any damage to FRP due to adverse mechanical impact or heat exposure [3, 4].

Experimentally or analytically investigating fire effect on structural members essentially requires the understanding test materials at high temperature. Commonly used structural materials properties, such as steel and concrete, under high temperatures have been extensively investigated, researched and reviewed in many research activities [5-8]. On the other hand, FRP’s thermal and mechanical properties at high temperatures are not expected to perform well at high temperatures [9]. On the other hand, polymer matrix in FRP members are excellent binding materials where it provides important support for fibers, it is weak...
in high temperature where their strength, stress transferring ability are deteriorate [10]. The glass transition temperature (Tg) represents the point at which the polymer became viscous and rubbery and when this point is reached a portion of polymer strength already lost. Due to this loss, polymer will no longer transfer loads in between fiber which results in reducing the composite’s strength [11].

According to the study performed by Gamage et al. [12] on a concrete member strengthened with CFRP, it was found that a rapid loss in the resins strength when subject to a temperature above 600°C. Furthermore, Wang et al. [13] conducted a study to determine the temperature at which only 50% of an FRP material strength at room temperature conditions is sustained. The results show that FRP materials has lost half of their strength at 325°C and 250°C respectively.

Firmo et al. [14] studied the fire resistance behaviour of RC beams strengthened with CFRP laminate using the NSM techniques. The results showed that the loss of effectiveness of the CFRP system occurred when the average temperature in the adhesive at the CFRP anchorage zones attained values ranging from 2.2 to 5.6 times its Tg. Namrou [15] conducted an experimental program on concrete block specimens with NSM CFRP strengthening systems and bonded with low viscosity, high viscosity adhesives and high-temperature adhesive at elevated temperatures up to 200°C to investigate flexural performance. He concluded that the strength reduction was related to the three types of adhesives over the temperature range from 25°C to 200°C. The failure of the test specimens was brittle, irrespective of adhesive type.

Serious drawbacks associated with the use of epoxy adhesive as a bonding agent with FRP strengthening have been identified. However, providing excellent bond properties between fibre and substrate. The emission of toxic fumes and steroids during the curing phase may cause environmental problems. Flammability and smoke under fire are other critical issues related to epoxy resin [16]. Therefore, epoxy resin cannot be used in strengthening structures where high-temperature resistance is required. Cement-based adhesive (mortar) were used as a bonding agent for strengthening RC beams by externally-bonded FRP and results showed that the mortar used as a bonding material effectively contributed to the increased load carrying capacity and ductility of structural members [17].

Adolfo et al. [18] experimented with the use of grancrete paste as adhesive for strengthening RC structures. Grancrete is a cementitious material that is environmentally friendly. The test results indicated that the proposed grancrete paste adhesive for strengthening systems can achieve good flexural strengthening of concrete structures and having higher resistance to fire and improving the overall ductility of the strengthened structure.

From the above, FRP strengthening systems are known to perform poorly at elevated temperatures. This can be attributed to the relatively poor performance of both adhesive and FRP matrix polymers at temperatures in the range of their glass transition temperatures. Hence, there is a need for thermal protection of such elements. Previous study [19] indicate there are two main categories of fire insulation materials, insulation board (or mats) and sprayed insulation.

Palmieri et al. [20] investigated the fire endurance of NSM FRP concrete beams under standard fire conditions and insulated with three passive fire protection systems: Aestuver, Promatect H, and Super VG. Aestuver is a cement-bonded glass-fibre fire protection board, Promatect H is a steam hardened silicate plate, and the third fire protection system consisted of a layer of Super VG insulation (a lightweight fire resistant cementitious plaster). The authors concluded that all beams appeared to withstand 2 hours of fire. The insulation system maintained low temperatures in the beam such that they did not fail under service load levels during fire exposure.

Rizkalla et al. [21] explored a thin hybrid insulation system to protect a full-scale RC slab strengthened with NSM CFRP bars bonded with an inorganic matrix. The insulation system consisted of a 13mm compressible ceramic blanket placed directly onto the soffit of the concrete slab followed by a 25mm ceramic insulation board. The authors concluded that 15 mm overlap on either side of each rod is sufficient to keep the rods below their glass transition temperature, with a margin of safety, A full-scale slab withstand for over two and a half hours of fire.
2. Experimental Work

2.1. Materials

2.1.1. Concrete

The concrete material was supplied by a ready-mixed concrete local supplier (Hanson-Heidelberg Cement Group) in order to minimize the variations of all constituents and to achieve good quality control. The concrete mix was proportioned to achieve a minimum compressive strength of 32 MPa on the 28th day with slump of 80 mm. To ensure the required slump, a slump test was done upon delivery of the concrete prior to beams casting and it confirmed the 80 mm slump. Batch proportions of concrete mix are given in Table 1.

Table 1. batch proportion of concrete per one cubic meter Cement

| Mix parameter                               | Quantity |
|---------------------------------------------|----------|
| Grade (MPa)                                 | 32       |
| CA Goliath Type GP Cement (kg)              | 331      |
| ICL GGBFS (Slag) (kg)                       | 99       |
| Hanson Kilmore 14mm aggregate (kg)          | 1150     |
| Hanson Yannathan sand (SSD) (kg)            | 775      |
| Tap Water (Liter)                           | 180      |
| Nominal slump (mm)                          | 80       |

2.1.2. Cement-Based Adhesive

Cement-based adhesive was chosen as a binder with CFRPs in strengthening system because it was expected that it’s mechanical and bond properties would be less affected by temperature compared to the conventional epoxy one. For strengthening beams with NSM-CFRP, a cement-based adhesive consisting of cement, micro cement, silica fume, silica filler, primer, super-plasticizer and water were used. The mix design mentioned in Table 2 had been used which are the similar mix ratio to that used by [17]. Mortar cylinders with mix proportions shown in table 2 were cast, 50mm diameter and 100mm in height to calculate the mechanical properties of cement-based adhesive. The results are shown in table 3.

Table 2. Mix proportions of cement-based adhesive per 0.001 m3

| Material       | Content (gram) |
|----------------|----------------|
| Portland Cement| 674.3          |
| Micocement     | 168.6          |
| Silica fume    | 84.3           |
| Filler (Silica)| 716.5          |
| 200G           |                |
| Primer (A+B)   | 88.6           |
| Superplasticizer| 16.9          |
| Water          | 354            |

Table 3. Mechanical properties of cement-based adhesive

| Age  | Compressive | Splitting Tensile | Modulus of |
|------|-------------|------------------|------------|

2.1.3. Steel Reinforcements
Deformed steel bars with diameters of 12 and 10 mm were used as main and shear reinforcement respectively. Tensile tests were carried out to determine the properties of the steel bars. The properties of the tested steel bars are shown in Table 4.

| Nominal Diameter, mm | Yield strength (MPa) | Ultimate strength (MPa) | Ultimate Strain % | Modulus of Elasticity (GPa) | Elongation % |
|----------------------|----------------------|-------------------------|------------------|---------------------------|-------------|
| 12                   | 550                  | 680                     | 0.125            | 214                       | 14.9        |
| 10                   | 530                  | 660                     | 0.12             | 208                       | 13.55       |

2.1.4 Carbon Fiber Reinforced Polymer, CFRP
The CFRP strips manufacturer are BASF Construction Chemicals Australia. The strips (rough and smooth) surfaces have cross section dimensions of 18mm wide x 1.4 mm thickness. The mechanical properties of the laminates are shown in Table 5 as provided by the manufacturer and as laboratory tested results.

| Property                                | CFRP smooth surface laminate | CFRP rough surface laminate |
|-----------------------------------------|------------------------------|------------------------------|
| Tensile strength (MPa)                  | 2400-2600                    | 3300                         |
| Modulus of elasticity (GPa)             | 205                          | 210                          |
| Ultimate strain %                       | 1.3                          | 1.4                          |

2.1.5 Plaster Boards
Plaster board type fire shield insulation were used. Plaster board is made from a core of a naturally occurring mineral called gypsum, also known as calcium sulphate or CaSO\(_4\).2H\(_2\)O. The core is sandwiched between two layers of heavy duty recycled paper. Its weight as specified by manufacturer is 10.5 kg/m\(^2\). Plasterboard is naturally fire resistant and is classified as non-combustible according to the Building Code of Australia (BCA) [22]. It is non-toxic and non-flammable. The core slows down the spread of fire by releasing chemically bound water when heated. The thermal insulation ability equal to 0.076 W/m2-K.

2.2 Specimens preparation
Specimens includes construction, strengthening, and flexural testing of eight large scale reinforced concrete beams, five of these beams were NSM strengthening technique using CFRP rough surface laminates and the other five using CFRP smooth surface laminates. All beams were tested in four-point bending under monotonic load. Beams were tested under two exposure conditions: constant ambient temperature (21-25°C), and elevating temperature (up to 600°C). Mainly it divided into three parts. Part one cover the test done at room temperature to establish a reference information in order to compare them with the results from other experimental parts. Part two comprises the flexural testing at elevated temperature. The testing was intended to provide knowledge about the effect of elevated temperature on performance of NSM-CFRP strengthened reinforced concrete beams using cement-based adhesives as
well as the failure mode. Part three deals with generate data on behavior of the protected reinforced concrete beams strengthened with NSM-CFRP technique at elevated Temperatures. Eight beams were provided with two chromel-alumel thermocouples wire type fiber glass KK-Q/Q 0.51, each embedded with the CFRP inside the grooves at 900mm distance from both ends of the beam to record the temperature of the CFRP material during the test and they were encoded as TN and TS. See Figure 1.

![Thermocouples location in the groove](image)

**Figure 1.** Thermocouples location in the groove

2.3 Specimen Dimensions and Designation

The preliminary configuration was used for normal temperature testing and later for high temperature exposure. All the beam specimens tested in the study, had a rectangular cross section with dimensions of 140 mm wide, 260 mm height, and total length of 2700 mm with clear span of 2300mm, the beam dimensions are illustrated in Figure 2. Steel reinforcement was provided for all beams, consisting of 3 $\phi$12 as tensile reinforcement at the bottom of the beam and 2 $\phi$12 at the top of the beam to hold the stirrups.

![Beam dimensions and reinforcement details](image)

**Figure 2.** Beam dimensions and reinforcement details a) Elevation, b) Section, all dimensions in mm

The eight beams were divided into three groups:
- Group (1) consisted of two beams tested at room temperature;
- Group (2) consisted of four beams heated to a 600°C and then tested;
- Group (3) consisted of four beams protected with plasterboard then heated to 600 °C, thereafter tested.
Beams were named according to the type of CFRP used in NSM strengthening technique, temperature exposure, and presence of the fire protected layer. So, the symbols that have been used in coded the beam specimens became as follows:

RL: beam strengthened with rough surface strips and unheated.
SL: beam strengthened with smooth surface strips and unheated.
SLH1 and SLH2: beams strengthened with smooth surface CFRP strips and heated to 600˚C.
RLH1 and RLH2: beams strengthened with rough surface CFRP strips and heated to 600˚C.
SLHP1: beam strengthened with smooth surface CFRP strips protected with one layer plasterboard and heated to 600˚C.
SLHP2: beam strengthened with smooth surface CFRP strips protected with two layer plasterboard and heated to 600˚C.
RLHP1: beam strengthened with rough surface CFRP strips protected with one layer plasterboard and heated to 600˚C.
RLHP2: beam strengthened with rough surface CFRP strips protected with two layer plasterboard and heated to 600˚C.

3. Results and Discussion:

3.1 Experimental Results of strengthened unheated beams (Group One):

Table 6 showed the results of the tested beams in terms of ultimate load P_u, cracking load P_cr, yielding load P_y, deflection, and mode of failure. Load versus deflection for SL and RL beams showed in Figure 3. The rough surface strips enhance the flexural strength of beam more than the smooth surface strips. This can be attribute to the surface nature of CFRP strips, rough surface CFRP strips provided more bond strength than the smooth surface CFRP strips. The increase in ultimate load was 24% than that of SL. Initial cracks started on RL beam at load of 68 kN which it was a higher load than the SL. The NSM-CFRP rough surfaces beam showed higher yield load, approximately 36% over the SL beam. The deflection kept on increasing till the test was stopped.

Table 6. Results of the tested RC beams, Group One

| Beam Code | P_cr (kN) | P_y (kN) | P_u (kN) | δ_cr (mm) | δ_u (mm) | Failure mode |
|-----------|-----------|----------|----------|-----------|----------|--------------|
| SL        | 60.9      | 93.8     | 114.5    | 7.8       | 35.7     | Concrete crushing after debonding between the fiber and adhesive |
| RL        | 68.4      | 127.9    | 140.9    | 8.1       | 22.9     | Concrete crushing after debonding between the fiber and adhesive |
Figure 3. Load-deflection curves for the strengthened unheated beams

3.2 Experimental Results of the strengthened heated Beams (Group Two):
Two beams strengthened with CFRP smooth strips (SLH1, SLH2), and Two strengthened with CFRP rough strips (RLH1, RLH2) using modified cement adhesive were exposed to temperature 600˚ C in an electrical furnace for two hours without any loading then left to cool to room temperature. Afterwards they were subjected to four point loading till failure. The test is aiming at evaluating the degradation of load bearing capacity of NSM-CFRP strengthened RC beams after elevated temperature exposure (i.e. post-fire strength and stiffness).

All beam specimens were initially cracked (i.e. hair cracks). The test results in the form of ultimate load, deflection and mode of failure are shown in Table 7.

Table 7. Results of the tested RC beams, Group Two

| Beam ID. | $P_y$ (kN) | $P_u$ (kN) | $\delta_y$ (mm) | $\delta_u$ (mm) | Failure mode |
|----------|------------|------------|----------------|---------------|--------------|
| SLH1     | 94.83      | 102.72     | 25.87          | 82.62         | Concrete crushing after steel yielding and debonding between: (adhesive-concrete interface) and between (fiber and adhesive) after fiber degradation |
| SLH2     | 94.77      | 103.46     | 25.77          | 80.86         |              |
| RLH1     | 91.98      | 103.4      | 25.1           | 78.75         |              |
| RLH2     | 91.7       | 102.12     | 25.77          | 78.22         |              |

The load versus deflection curves for four beams are shown in Figure 4. It is evident that there was slightly decrement in ultimate capacity of SLH beams of 11 % compared to the same strengthened beam (SL) at room temperature. While, there was a significant decrement in ultimate capacity of strengthened beam of 27.1 %, compared to the same strengthened beam (RL) at room temperature. To evaluate the behaviour of CFRP strips in RLH and SLH beams, the degradation in CFRP rough strips considered higher than the smooth strips. Taking in consideration their effects on the ultimate capacity, the CFRP rough strips contributed to a load carrying capacity in a less rate than the smooth strips with referencing to their control beams.

The failure mode for SLH and RLH beams waere crushing of top concrete and loss of the contribution of the fibre at mid-span, resulting in excessive deflection with widening of cracks due to the degradation of the fibre composite, extensive cracking of the grout adhesive and CFRP tows partially ruptured was observed in RLH beams only.
3.3 Experimental Results of the Strengthened Insulated with Plasterboard and Heated Beams (Group Three):

To study the effect of fire insulation on the NSM-CFRP strengthened beam, tests were conducted on four of the same above strengthened beams but insulated. Beam SLHP1 was fitted with a 13 mm thick layer of plaster board covering the whole beam and were fixed by screws followed the manufacture instruction, while beam SLHP2 was protected by 26 mm of insulation plaster board in the same locations. The other two beams were followed the same manner of protected with plaster boards but the difference were in the CFRP strips (i.e. strengthening with NSM-CFRP rough strips). The same heating rate was applied. The insulation layer (i.e. plaster board) was deteriorated during the period of heating exposure as a result of gypsum dehydrated, major cracks were appeared in all sides but the plaster boards still valid and not separated from beam. In addition to inside the furnace, the unexposed beam with insulation was checked and no debonded was observed (refer to Figure 4).

After removing the plaster boards, two beam specimens that insulated with one plaster board layer (i.e. SLHP1 and RLHP1) were showed hair cracks but by less than what occurred in the beams without an insulating layer. Nevertheless, the two beam specimens that insulated with two plaster board layers (i.e. SLHP2 and RLHP2) didn’t show any hair cracks. The test results in the form of ultimate, yield, and failure load, deflection at ultimate, yield, and failure are shown in Table 8.

| Beam Code | Py (kN) | Pu (kN) | Pf (kN) | δy (mm) | δu (mm) | δf (mm) |
|-----------|---------|---------|---------|---------|---------|---------|
| SLHP1     | 83.3    | 110.4   | 106.88  | 15.15   | 33.8    | 65.56   |
| SLHP2     | 85.8    | 113.1   | 108.19  | 14.41   | 32.05   | 61.61   |
| RLHP1     | 105.7   | 133.06  | 115.9   | 18.11   | 27.9    | 64.6    |
| RLHP2     | 124.4   | 140.4   | 118.88  | 17.57   | 20.7    | 60.6    |

The load versus deflection curves for four beams are shown in Figure 5. It is obvious that the insulated beams strengthened with rough CFRP strips showed higher load capacity than the insulated beams strengthened with smooth CFRP strips and this behavior was similar to the corresponding in strengthening but unheated. There is no discoloration of the concrete with two-layer insulated beams while it was achieved with one-layer insulated beams.
4. Conclusions
Based on the experimental work results, the following conclusions can be drawn:

1- The two beam specimens that insulated with one plaster board layer (i.e. SLHP1 and RLHP1) were showed hair cracks but by less than what occurred in the beams without an insulating layer. Nevertheless, the two beam specimens that insulated with two plaster board layers (i.e. SLHP2 and RLHP2) did not show any hair cracks.

2- The deflection of the beams insulated with one layer of plaster-board (SLHP1 and RLHP1) were reduced of about 15% and 23% respectively compared with the un-insulated beams due to the increased in stiffness.

3- The ultimate capacity of beams (SLHP1 and RLHP1) improved significantly so has become so close to their value in beams strengthened with NSM-CFRP strips smooth and rough and unheated while reached the same value in beams that insulated with two layers of plaster-board.

4- No degradation in CFRP strips and the NSM strengthening system still effective and workable to load bearing capacity.

5- The insulation systems, though cracked, did appear to remain relatively intact upon removal from the furnace.

6- For beams insulated with two layers of plaster-board, strips temperature were much lower than those in beams insulated with one layer at any given heat exposure time, mainly due to duplicate the thickness of protection of fire insulation. This indicate that the increase in thickness can effectively reduce heat progression within the beam.

7- Failure modes in strengthened heated insulated beams were similar to the strengthened unheated due to the efficiency of the plasterboards and well maintained the CFRP strips integrity.

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