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Performance of heat-damaged partially-insulated RC beams strengthened with NSM CFRP strips and epoxy adhesive

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HIGHLIGHTS

- The furnace temperature-time curves followed the ISO 834.
- We investigate an experimental and numerical study of heated RC beams.
- The heated beams repair with epoxy adhesive.
- We study the flexural behaviour with and without insulation.
- The models apply to RC beams after exposure to elevated temperatures.

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ABSTRACT

This paper describes an experimental and numerical study of the behaviour of RC beams damaged by heating and subsequently strengthened using NSM CFRP laminates. In the experiments, two beams were normal temperature controls, and the other beams were heated under the ISO-834 standard fire curve. The flexural behaviour was studied after exposure to 700 °C and 800 °C with and without insulation on the top surface of the concrete. The parameters studied in this investigation were unheated and heat-damaged beams, level of heat exposure and use of insulation. Three beams were un-strengthened fire-damaged control beams and the other beams were strengthened with CFRP laminates after being heated. Although the ultimate load and stiffness decreased, repair with NSM CFRP laminates using epoxy adhesive was found to increase the load capacity and stiffness of the beams. Finite element models (FEMs) were able to predict the experimental behaviour reasonably well.

1. Introduction

The repair and strengthening of existing concrete structures with composite material has become more common during the last decade [1–3]. Since one of the problems facing buildings is exposure to fire, they should be provided with sufficient structural fire resistance to withstand such circumstances, or at least to give the occupants sufficient time to escape before strength and/ or stability failure ensue [4,5]. After a fire, an appraisal is normally required as soon as the building can be safely entered and generally before the removal of debris. To ensure safety, temporary false work may be required to secure individual members and stabilize the entire structure [6]. The primary on-site investigation technique is visual inspection, which is used to classify the degree of damage for each structural concrete member. Visually apparent damage induced by heating includes collapse, deflection, spalling, cracking, surface crazing, colour changes and smoke damage. A visual survey of reinforced concrete (RC) structures is performed using a classification scheme [7]. This scheme uses visual indications of damage to assign each structural member a class of damage from 0 to 4. Each damage classification number has a corresponding category of repair, ranging from decoration to major repair. The near-surface mounted (NSM) fibre-reinforced polymer (FRP) technique has been widely used to increase or restore the load-carrying capacities of RC beams [8–10]. The NSM FRP method has become widely used in carbon fibre-reinforced polymer (CFRP) strengthening applications because of the sensitivity of the externally-bonded (EB) FRP method to premature de-bonding [11,12]. In this technique, the CFRP materials are bonded into slots fabricated in the tensile face of the RC beam with a suitable epoxy adhesive [13].

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The repair and strengthening of existing RC structures throughout their life has become a critical issue worldwide for a number of reasons, including errors in design or construction, increased applied service loads, and deterioration due to ageing or fire damage [14,15]. CFRP materials have become an attractive option for the upgrade, repair, and strengthening of existing RC structures, because of their chemical and physical properties, including their light weight, resistance to corrosion, very high strength, reduced maintenance cost, and ease of installation [16–18]. The repair and strengthening of RC members using NSM CFRP has become an accepted technique to restore or increase the flexural and shear capacity of deficient RC members [19]. The NSM CFRP technique has important advantages compared to the EB CFRP technique. For instance, a NSM system does not require extensive surface preparation work as external bonding does, and no delamination between fibre and concrete at the ends occurs, particularly in flexural members. Therefore, no anchorage system is required with this technique, as it provides a larger bond surface area, which consequently increases the strength. However, EB systems cannot mobilize the full tensile strength of CFRP materials because of premature debonding, and their strength may be negatively affected by freeze/thaw cycles and decrease significantly when subjected to high and low temperatures [20,21].

The ultimate load capacity of strengthened beams increases with increasing cross-sectional area of NSM glass-fibre reinforced polymer (GFRP) bars and the use of epoxy adhesive gives great mechanical strength [22]. The use of sufficient bonded lengths of CFRP rods, greater than the cracked span length, causes an important increase in the ultimate load-carrying capacity of NSM CFRP-strengthened RC beams, because the failure type changes from premature failure by the concrete cover peeling-off to failure by pulling-out of the NSM CFRP rods with splitting of the concrete cover [23]. The NSM method is effective for increasing the flexural capacity by about 50–66% and 41–60% for beams strengthened with CFRP and GFRP, respectively, compared to that of the control RC beam, depending on the number and size of CFRP bars and the epoxy type [24].

Because of the important role of concrete in the structural performance of modern buildings, the reparability of concrete damaged in building fires is a central issue. Exposure of RC buildings to accidental fire may result in cracking and the loss of bearing capacity of their major components [1–4]. It is a challenge for structural engineers to develop efficient rehabilitation techniques to enable RC members to recover their structural integrity after exposure to intense fires for a long period of time [4,25–27]. The main critical issue, which requires investigation, is the repair of RC members after exposure to high temperature and/or fire using NSM systems instead of EB systems. The uncertainties in the use of empirically derived models for design purposes have motivated an increased interest in the use of finite element modelling (FEM) to gain a better understanding of the behaviour of concrete strengthened with NSM systems. FE numerical simulation has been employed by many researchers to predict the peak load and failure mechanism, in order to provide further understanding of the bond behaviour of flexurally-strengthened beams using CFRP [28–32]. Therefore, the aim of the numerical analysis approach adopted in this investigation is to validate the experimental data with those obtained from FEM using ATENA-GiD software [33,34].

The main purpose of the present investigation is to study the suitability and effectiveness of CFRP NSM laminate strengthening systems for the repair of RC members after exposure to high temperature and/or fire. This research also investigates the residual strength of RC members after heating and then cooling to room temperature. In addition, the results compared with the experimental data.

2. Experimental program

2.1. Specimen details

The experimental test program involved twelve RC beams to study the effectiveness of NSM CFRP laminate for the repair of concrete damaged by high temperature. Formwork was prepared and fabricated for the beams using plywood sheets to ensure the accuracy of the dimensions and a good quality of finish for the concrete surface. The beam dimensions were 140 mm wide, 260 mm deep and 2700 mm long. The beam dimensions in this program were designed to fit the furnace dimensions. Beam specimens were treated with oil before putting on the reinforcement or casting to prevent adhesion to the concrete after hardening. Steel reinforcement was provided for all beams, consisting of two N12 bars at the top of the beam and three N12 bars at the bottom. Shear reinforcement stirrups of N10 were distributed along the beam at 125 mm centres. The shear reinforcements were designed to resist the additional loads generated after exposure to high temperature to avoid shear failure prior to flexural failure. The variables considered in this test program were: (a) temperature, (b) heated and unheated beams, and (c) presence or omission of insulation for the top surface of the concrete. The beam dimensions and reinforcement details are illustrated in Fig. 1(a). These configurations were chosen to be similar to those used in other investigations [16,17]. The steel reinforcement was embedded in the formwork for all the concrete beams and supported by concrete cover spacers at the bottoms and sides of the beams to ensure it provided the required cover, as shown in Fig. 1(b).

Before casting, some beams were instrumented with Type-KK thermocouples. Of the twelve RC beams, only three were instrumented with thermocouples in order to measure the temperature at different places. The first was instrumented with four thermocouples to read the temperature at 700 °C for specimens without insulation. The other two beams were instrumented with six thermocouples to read the temperature at 700 and 800 °C for specimens with partial insulation. The thermocouples were positioned as follows: thermocouples 1–3 were located on the surface of the beam, at the mid-height of the beam at the centre of the cross-section, and 46 mm from the centre. Thermocouple no. 4 was attached to the middle reinforcing bar of the tension surface using an electrical spot welder, as shown in Fig. 2. Thermocouples 5 and 6 were located on the top of the concrete protected surface, and 30 mm from the top of the concrete protected surface.

The following proportions by weight were used for the concrete mix: 1 (cement): 1.8 (fine aggregate): 2.4 (30% hornfels and 70% granite coarse aggregate), and the water/cement ratio was 0.42. The maximum aggregate size used was 14 mm. The formwork was removed after 24 h of curing, and the outside of the beams was coated with a wax-emulsion curing compound. The beams were placed in the laboratory at ambient temperature (between 16 and 20 °C approx.) and relative humidity (approx. 65%), until they were ready for heating, repair, and testing. The top surfaces of the RC beams were protected from heating to simulate the concrete floor slab by using an insulation layer. The insulation was gypsum plasterboard, a lightweight fire-resistant plasterboard. It mainly consists of gypsum, and naturally-occurring material. The material is a crystalline form that consists of calcium sulphate combined with water and it is known as calcium sulphate dehydrate, CaSO4.2H2O The insulation consisted of two layers of the gypsum plasterboard. The first layer was installed on the top surface of the beam with a total length 2300 mm and a thickness of 32 mm, and the thickness of each layer was 16 mm. The second layer was installed on the top of the beam with a thickness of 25 mm and a depth of 60 mm. The density of gypsum board is