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Performance of RC beams rehabilitated with NSM CFRP strips using innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) made with graphene oxide

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ABSTRACT

This paper presents the results of an experimental study of near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP)-repaired and strengthened reinforced concrete (RC) beams with innovative high-strength self-compacting cementitious adhesive (IHSSC-CA), with the particular objective of improving the ductility. Graphene oxide and cementitious materials were used to synthesise the IHSSC-CA. An analytical model is developed to predict the maximum tensile strain in NSM CFRP strips based on the experimental results. ACI 440.2R-08 guide was used to calculate the ultimate flexural capacity of the tested specimens based on the predicted tensile strain in NSM CFRP strips. The test results confirm the effectiveness of using IHSSC-CA to improve the flexural strength, CFRP strip utilisation, stiffness, residual strength and ductility of RC beams repaired and strengthened with NSM CFRP strips. Moreover, the statistical model proposed to predict the maximum tensile strain in CFRP strips has good agreement with the experimental results and can be used in the design of NSM CFRP-repaired and strengthened RC members with cement-based (IHSSC-CA) and epoxy adhesives. Furthermore, the ultimate flexural capacity of the repaired and strengthened RC beams using NSM CFRP strips with cement-based (IHSSC-CA) and epoxy adhesives can be predicted adequately using the ACI 440.2R-08.

1. Introduction

The repair and strengthening of existing reinforced concrete (RC) structures throughout their life has become a critical issue worldwide for different reasons, including errors in design or construction, increased applied service loads and deterioration due to ageing or corrosion damage [1–3]. Moreover, most RC structures, especially those from the 1940s, are inadequate for current design codes and specifications [4]. Carbon fibre reinforced polymer (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, outstanding fatigue strength, very high strength, reduced maintenance cost, and ease of installation [5].

The repair and strengthening of RC members using near-surface mounted (NSM) fibre reinforced polymer (FRP) has become an accepted technique to restore or increase the flexural and shear capacity of deficient RC members [6–8]. The NSM FRP technique has important advantages compared to the externally-bonded (EB) FRP technique. For example, the NSM FRP technique has superior bond characteristics compared to the EB FRP technique. In addition, this technique can protect the FRP material and the adhesive from fire, environmental effects, and vandalism [9–11]. In the NSM FRP method, the FRP (rods/strips) is bonded into slits cut into the external surface of the concrete, using the appropriate adhesive (typically an epoxy) [12].

The concept of the NSM FRP strengthening technique originates from the strengthening of RC structures in Europe in the 1940s by placing steel rebar into grooves cut into the cover of the concrete, with cement mortar [13].

In recent years, a number of studies have been published on the flexural behaviour of strengthened concrete beams using the NSM FRP technique with epoxy adhesive [10,14–22]. The maximum CFRP tensile strength at the beginning of the debonding increases as the bonded length increases up to length equal to about 80 times the diameter of the CFRP bar [10]. The load-carrying capacity of NSM-strengthened beams is more than twice that of EB-strengthened beams [14]. The ultimate load capacity of the strengthened beams increases as the bonded length and the size

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of the groove increase [15]. Deformed FRP rods are more efficient than sandblasted FRP rods [16]. The minimum bonded length of NSM CFRP strips to ensure full composite mechanism between CFRP strips and concrete until rupture of CFRP strips is 850 mm from each side of the centreline of the strengthened RC beams [17]. The ultimate load capacity of the strengthened beams increases with increasing cross-section area of the GFRP bar and the use of epoxy adhesive gives high mechanical strength [18]. Using sufficient bonded length of CFRP rods, more 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 pull-out of NSM CFRP rods with splitting of concrete cover [19]. The cantilever beams exhibit failure modes similar to simply-supported beams. This means that there is no effect of the specific problem of cantilever beams: strengthening outward pressure [20]. The deformability of partially bonded NSM CFRP-strengthened beams is increased with a little decrease in ultimate capacity compared to fully bonded NSM CFRP-strengthened beams [21]. The NSM method is effective for increasing the load-carrying capacity by about 155.3–166.3% and 141.2–159.4% for beams strengthened with CFRP and GFRP, respectively, compared to that of the control RC beam, depending on the number and size of FRP bars and the epoxy type [22].

Although the NSM FRP system using organic adhesives (epoxy adhesives) shows an increase in the ultimate capacity of strengthened RC structures, the use of epoxy adhesive with the NSM FRP strengthening technique has significant issues, because of the emission of toxic fumes and steroids during curing, which may cause eczema and irritation to the skin, and are highly flammable [23]. In addition, when exposed to hot climates (temperatures more than 70 °C), epoxy adhesive loses its properties [24]. Moreover, it has low permeability and weakness to UV radiation [25]. In addition, it has limitations in the work environment on site, such as being impossible to use on humid surfaces and at low temperatures (less than 10 °C) [23,26].

To avoid these drawbacks of epoxy adhesive, several researchers have used composite systems consisting of from fibre reinforced materials with cementitious bonding agents, such as [25–27]. However, the flexural behaviour of concrete beams strengthened using NSM FRP embedded in a cementitious matrix has been studied by very few researchers [19,28]. The RC beam strengthened with NSM CFRP rods using cement mortar adhesive showed less cracking and lower ultimate capacity compared to one strengthened using epoxy resin adhesive, due to the early failure caused by debonding between the mortar and the concrete substrate [19]. A RC beam strengthened with NSM CFRP rods using polymer cement grout (BEMIX High Tech) had nearly the same increase in the ultimate capacity and ductility as an identical beam strengthened using epoxy adhesive [28].

The research shows that although the use of polymer cementitious mortars [28] to bond the FRP materials to the concrete substrate using NSM systems can improve the ultimate bearing capacity better than non-polymer cementitious agents [19]. However, polymer cementitious mortars are affected by hydrothermal conditions [29–31]. Therefore, it is necessary to fabricate high strength non-polymer cement-based bonding material able to improve the strengthening capacity of RC structures using FRP materials, by enhancing the bond between the concrete substrate and cement-based adhesive and FRP materials, and sustain structural integrity under fire conditions.

In a previous study [32] the authors developed an innovative high-strength self-compacting cementitious adhesive (IHSSC-CA), which has 28-day compressive and tensile strengths of 101 MPa and 13.8 MPa, respectively. This high mechanical strength is believed to be the key factor in the development of high strength in NSM CFRP repair and strengthening systems. Graphene oxide (GO), one of the most commonly used derivatives of grapheme, was used to synthesise IHSSC-CA.

In recent years, some researchers have used GO to develop the properties of cement mortar [33,34]. 0.01%–0.03% of GO caused an increase of 143.2% and 128.6% in flexural and compressive strengths respectively, compared with the control mix [33]. Higher compressive strength of 46.2 in a cement mix with 0.05% GO compared with pure cement paste has been reported by [34].

The improvement of the ductility of strengthened and/or repaired RC structures using FRP materials is an important safety concern, since structures strengthened and/or repaired using epoxy and polymer cementitious adhesives to bond FRP to concrete substrate have low ductility, which may cause sudden failure without warning.

In this study, the flexural performance and the effectiveness of the use of IHSSC-CA for repair and strengthening of RC beams using the NSM CFRP technique was investigated with the particular objective of improving the ductility. Five full-scale RC beams were fabricated and tested under four-point bending with different loading histories (with and without pre-loading) and different bonding adhesives (cement-based (IHSSC-CA) and epoxy). The load, deflection, strain in concrete, steel reinforcement and CFRP strips were recorded up to failure. An analytical model is proposed to describe the behaviour of RC beams repaired and strengthened using the NSM CFRP system.

The aim of this research is to provide experimental evidence for the effectiveness of the use of IHSSC-CA for the repair and strengthening of RC beams with the NSM CFRP system and the capability of using it in situ. Therefore, a durable, compatible and more efficient NSM method using CFRP strips with IHSSC-CA is proposed to enable application in the working environment on site for the upgrade, repair and strengthening of RC buildings and bridges. The development of durable NSM CFRP systems can extend the service life of rehabilitated infrastructures and guarantee people's safety.

2. Experimental program

2.1. Specimen details

A total of five full-scale RC beams were manufactured and tested under four-point loading until failure. One beam was a conventional RC beam (control beam), and the remaining beams were repaired and strengthened with NSM CFRP strips using IHSSC-CA and epoxy adhesives. The beams had a cross-section of 140 × 260 mm and a total length of 2700 mm. The bending span was 2300 mm and the shear span was 700 mm. The steel reinforcement configurations were identical for all RC beams, consisting of two N12 bars at the top of the beam as compression reinforcement and three N12 bars at the bottom of the beam as tension reinforcement. The shear reinforcement consisted of N10 stirrups spaced at 125 mm. The conventional RC beams were designed according to ACI 318-11 to ensure that flexural failure occurred prior to shear failure. The strengthened RC beams, after 28-day curing, were post-strengthened with NSM CFRP strips. The repaired RC beams, after 28-day curing, were pre-loaded first to 65% of the monotonic failure load of the control beam. These beams were loaded in a load control mode and the cracks were observed and recorded on the beam. The beams were then unloaded and repaired with NSM CFRP strips. Two NSM CFRP strips 20 mm wide × 1.4 mm thick were used, with a 56 mm^2 total fibre area, for each of the NSM CFRP strengthened and repaired RC beams. The CFRP strips showed lowest attends for debonding from the concrete substrate and highest utilisation compare to other shapes of CFRP (square, rectangular