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Fatigue performance of NSM CFRP strips embedded in concrete using innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) made with graphene oxide

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ABSTRACT

The efficiency of strengthening reinforced concrete (RC) structures using the near-surface mounted (NSM) fibre reinforced polymer (FRP) technique depends on the bond between the NSM FRP and the concrete substrate. This paper presents the results of an experimental study of NSM carbon FRP strips bonded to concrete substrate with innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) under fatigue loading using single-lap shear tests. Graphene oxide and cementitious materials were used to synthesise the IHSSC-CA. The test variables were: CFRP strip dimensions (1.4 × 10 mm, 1.4 × 20 mm) and CFRP strip surface conditions (smooth, rough). 61 specimens were tested under different fatigue load ranges to develop the load range (L_R)-fatigue life (N) relationships. Finally, equations were developed to predict fatigue lives based on the experimental results. It was found that the rough surface CFRP strips 1.4 × 20 mm in dimensions showed the best fatigue life under different fatigue load levels. Moreover, the test results confirm the effectiveness of using IHSSC-CA to bond NSM CFRP strips to the concrete substrate. Furthermore, the proposed equations can predict fatigue life reasonably well and can be used in the design of NSM CFRP-strengthened RC members.

1. Introduction

The near-surface mounted (NSM) fibre reinforced polymer (FRP) technique has been used widely to increase or restore the load-carrying capacities of reinforced concrete (RC) beams [1–3]. The NSM FRP method has become widely used in FRP strengthening applications because of the sensitivity of the externally-bonded (EB) FRP method to premature de-bonding [4,5]. In this technique, the FRP materials are bonded into slots fabricated in the tensile face of the RC beam with a suitable adhesive (typically an epoxy) [6]. Fatigue in RC bridge structures has become important in building and construction engineering, because these structures are subjected to millions of repeated loads from traffic throughout their designed service life. A typical RC bridge deck may be exposed to about 7×10^8 cycles during a 120-year life-span [7]. Cyclic loading may cause structures to fail at loads less than their ultimate monotonic capacity [8], depending on the fatigue loading rate, the maximum fatigue stress, the fatigue stress ratio (minimum/maximum fatigue stress), and the number of cycles [9]. This is due to the fact that repeated loading leads to progressive degradation of the bond at the FRP-adhesive-concrete interfaces and results in failure at bond stresses lower than those under ultimate monotonic bond stress [10]. This point is often missing in the design and analysis of RC structures strengthened with FRP material.

The direct pull-out test, using single- or double-faced shear tests, and the beam pull-out test are common tests of the bond between FRP and concrete. Although the beam pull-out test can capture the actual bond behaviour better than the direct pull-out test, it is less manageable due to the large test specimens. Therefore, the direct pull-out test is preferable to the beam pull-out test.

To date, very few studies of the bond behaviour between EB or NSM FRP materials and concrete substrate with cementitious materials using pull-out tests have been reported [11–13]. The ultimate pull-out load of cement-filled specimens has been found to be lower than that of epoxy-filled specimens, and the failure mode of cement-filled specimens has been shown to be splitting of the cement mortar, because of the lower tensile strength of the cement mortar [11]. Rough-surfaced CFRP strips 1.4 × 20 mm in dimensions show superior bond strength (pull-out force) due to the increased frictional force and mechanical interlocking at

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the adhesive material-CFRP strip interface, and the increased confinement of the surrounding concrete [12]. Modified polymer cement-based adhesive can be used within its 20-min pot-life as a bonding agent to bond CFRP textile strip with concrete [13]. However, to date no research available in the literature has investigated the bond behaviour between NSM FRP and the concrete substrate with cement-based adhesive using pull-out tests under fatigue loading.

In recent years, a number of studies have been published on the flexural and shear behaviour of RC beams strengthened using the EB FRP technique or the NSM FRP technique with cementitious materials [14–25]. One study [14] investigated the flexural behaviour of RC beams strengthened using a NSM CFRP system. The researchers recommended replacing the epoxy resin with cement grout to improve the NSM CFRP system's application on site. The flexural behaviour of RC beams strengthened by EB carbon fibre sheet with a polymer-modified mortar was investigated by [15]. The researcher concluded that only a 10–20% increase in ultimate capacity was achieved, without any improvement in the stiffness of the strengthened beams. The research by [16] investigated the effectiveness of the flexure strengthening of RC slabs using textile fabric bonded to the surface of the concrete with fine grained concrete. The researchers concluded that the strengthening method improves the ultimate load-carrying capacity of RC slabs without bond failure between the strengthening layers and concrete. The flexural behaviour of RC beams strengthened using EB CFRP sheets with inorganic epoxy has been examined [17]. The researchers concluded that, as the numbers of layers of CFRP sheets increased, the ultimate flexure capacity increased, the ductility decreased, and the failure modes changed from CFRP sheet rupture to delamination of CFRP sheets from the concrete surface. A study by [18] investigated the flexural behaviour of RC slabs and small-scale concrete beams strengthened by EB CFRP grids using a cementitious bonding agent. The researchers concluded that the slabs strengthened using cementitious bonded CFRP grids are equivalent to those strengthened using epoxy-bonded CFRP fabrics. Moreover, the tested concrete beams exhibited a good strengthening result and the stiffest cement mortar which had the highest mechanical strength gave the best result. The study by [19] examined the flexural response of RC beams strengthened with NSM CFRP rods. The researchers asserted that the RC beam strengthened using cement mortar adhesive showed less cracking and lower ultimate capacity compare to that strengthened using epoxy resin adhesive, due to early failure caused by debonding between the mortar and the concrete substrate. The flexural and shear strengthening of RC beams using EB by cementitious materials with and without carbon/glass fibre textile reinforcement has been investigated by [20]. The researchers concluded that RC beams strengthened in flexure using EB with carbon/glass fibre textile reinforcement and engineered cementitious composites (TR-ECC) showed an important increase in the flexural and shear capacity and improved ductility of the strengthened beams. The research by [21] investigated the shear strengthening of RC beams using EB CFRP grids and cementitious bonding agents. The researchers found that using CFRP grids and cementitious bonding agents for shear strengthening of concrete beams can be favourable and similar to that by using CFRP sheets and epoxy bonding agents. The flexural behaviour of plain concrete beams strengthening using carbon fibre-reinforced cement (CFRC) sheets bonded to the tension surface of the concrete beams has been studied [22]. The researchers concluded that EB CFRC sheets can increase the flexural strength and the ductility of strengthened concrete beams. The work by [23] investigated the flexural behaviour of RC beams strengthened by an EB system using fibre-reinforced embedded in a cementitious matrix. The researchers concluded that the effectiveness of this type of strengthening is dependent on the cement matrix properties. The flexural behaviour of RC beams strengthened by an EB system using ultra-high strength fibre meshes embedded in a cementitious matrix has been examined by [24]. The researcher concluded that the ultimate flexure capacity of strengthened RC beams increased by about 10–44%, depending on the steel and fibre reinforcement ratio, compared to that of control, un-strengthened beams. The research by [25] investigated the flexural behaviour of RC beams strengthened by EB CFRP with cementitious mortar. The researchers concluded that adequate composite action between CFRP-mortar-concrete could be achieved by the use of cement mortar as a bonding material. However, previous research has been limited to static loading conditions. To date, the flexural and shear strengthening of RC beams using EB FRP or NSM FRP techniques with cement-based adhesive under fatigue loading conditions has not been investigated.

The use of epoxy adhesive with the EB FRP and NSM FRP strengthening techniques 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 [18]. In addition, when exposed to hot climates (temperatures above 70 °C), epoxy adhesive loses its properties [26]. Moreover, it has low permeability and weakness to UV radiation [24]. 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) [18,23].

Therefore, the need for alternative bonding adhesives to epoxy resins has become necessary for EB FRP and NSM FRP applications. Mineral-based materials may be an alternative adhesive material, since they are safe at high temperatures or under fire conditions. There is also no emission of toxic fumes and they are non-flammable. Significant composite action has been achieved using polymer cement-based adhesives in the NSM CFRP strengthening technique [12].

However, polymer cementitious mortars are affected by hydrothermal conditions [27–29]. Therefore, it is necessary to fabricate high-strength non-polymer cement-based bonding material 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 [30] 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 graphene, was used to synthesise IHSSC-CA.

In recent years, some researchers have used GO to develop the properties of cement mortar [31–35]. 0.01–0.03% of GO cause an increase of 143.2% and 128.6% in flexural and compressive strengths respectively, compared with the control mix [31]. A higher compressive strength of 46.2 in a cement mix with 0.05% GO compared with pure cement paste has been reported [32]. The addition of GO in cementitious materials remarkably improves durability expressed by enhanced resistance to chloride ingress and freeze-thaw cycles [33,34]. Considerable resistance of IHSSC-CA to the effects of high temperatures has been reported [35]. These advantages of adopting GO are very important to maintain the durability of bonding systems through highly durable adhesive. This can help to solve the many durability problems with organic adhesives.

Since the bond between NSM CFRP-adhesive-concrete is the key to the success of this strengthening technique, it is desirable to understand the bond behaviour under fatigue loading using single-lap shear tests before the large scale utilisation of NSM CFRP