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Assessment of residual strength of concrete girders rehabilitated using NSM CFRP with cementitious adhesive made with graphene oxide after exposure to fatigue loading

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ABSTRACT

This paper presents the residual strength of reinforced concrete (RC) beams strengthened and repaired by using near-surface mounted (NSM) carbon fibre reinforced polymer (CFRP) with innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) and epoxy adhesive after being subjected to fatigue loading. Cementitious materials and graphene oxide were used to synthesise the IHSSC-CA. Ten full-scale beams were manufactured and tested under four-point loading with different loading histories. Five beams were tested under monotonic loading up to failure, and another five beams were then tested under fatigue loading at service load levels up to failure or 3 million cycles, whichever happened first. The fatigue load range and frequency used in this study for testing the beams were designed to simulate the typical fatigue loading and frequency of an actual RC bridge girder under service loading conditions. The effect of fatigue loading was determined by comparing the performance of beams before and after fatigue loading. Finally, 3-D laser profilometry analyses was used to study the deformation of the CFRP strips after fatigue loading. The findings confirm the effectiveness of using IHSSC-CA to strengthen and repair RC beams with NSM CFRP system.

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1. Introduction

In recent years, carbon fibre reinforced polymer (CFRP) has been found to be an excellent alternative to steel plates and bars, because of its properties. The main benefits of using CFRP are its lightweight, resistance to corrosion, high strength, outstanding fatigue strength, reduced maintenance cost, and ease of installation [1].

The strengthening of current reinforced concrete (RC) structures using FRP composite can be either externally-bonded (EB) FRP system or near-surface mounted (NSM) FRP system. In the EB FRP system, the unidirectional or multidirectional FRP fabric, laminate or sheets are bonded to the concrete surface using a suitable adhesive, commonly an epoxy, after preparing the external surface of concrete using grinding, water jet or sandblasting to take away weak surfaces. While, NSM FRP system is based on bonding FRP strips or rods into grooves cut into the concrete surface using a suitable adhesive (commonly an epoxy). The term NSM is used to differentiate it from the EB method. The concept of EB FRP for strengthening existing RC members originates from steel plate bonding techniques and it has been investigated by many researchers since 1970 [2]. While, NSM FRP method originates from the rehabilitation of concrete structure in the 1940s in Europe through placing steel bars into slits cut into the external concrete surface using cement mortar [3].

The NSM FRP system has significant benefits over the EB FRP system. For instance, NSM FRP method has better bond strength than EB FRP method. Moreover, NSM FRP method can keep the FRP composite and the adhesive safe from vandalism and harsh environmental effects [4–6].

There are significant numbers of highway and railway concrete bridges worldwide, which are subjected to fatigue loadings. A concrete bridge deck can be subjected to approximately 7×10^8 cycles throughout a life span of 120-year [7]. Repeated loading can possibly cause buildings to collapse at applied loads lower than their static capacity, because of the degradation of the bond between adhesive-FRP interface and adhesive-concrete interface [8–10]. This point is frequently omitted in the analysis and design of concrete structures repaired and strengthened using FRP composite.

To date, a few studies have been published on RC beams strengthened by the NSM FRP system with epoxy adhesive and

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subjected to flexural fatigue loading [11–20]. For example, NSM specimens show not any signs of debonding when tested at low-fatigue loading level and show a few signs of bond degradation when tested at high- fatigue loading level [11]. The NSM CFRP strengthening system provides superior crack control and stress transfer, showing superior bond efficiency [12]. Girders strengthened using NSM CFRP bars and strips showed similar behaviour, possibly because they had similar CFRP areas and similar groove dimensions [13]. NSM beams strengthened using prestressed and non-prestressed CFRP rods increases the endurance limit (fatigue limit) compared to unstrengthened control beams [14]. All fatigue NSM CFRP-specimens survived 2,000,000 cycles without affecting the ultimate strength [15]. RC beams strengthened by NSM CFRP showed an increase in the endurance limit of approximately 24% over unstrengthened RC beams [16]. The failure mode was debonding at epoxy- CFRP rod interface under the loading-point [17]. Debonding between the concrete substrate and the epoxy adhesive for NSM specimens strengthened by CFRP strips prestressed to low prestress ranges (0 and 20%) is more likely to happen at the beam's mid-span. As the prestress level in CFRP strips increases (60%), anchor slippage is more likely [18]. The dimension of the groove has a big effect on the bond characteristic result than the geometry of the CFRP composite [19]. RC specimens strengthened using prestressed NSM CFRP rods failed at lower fatigue load levels than RC specimens strengthened using non-prestressed NSM CFRP rods [20].

On the other hand, the flexural strengthening and/or repair of RC beams using NSM FRP techniques with cement-based adhesive under fatigue loading conditions has not been investigated to date.

The use of organic resins (epoxy adhesives) with EB FRP and NSM FRP strengthening systems has serious issues, due to the emission of steroids and toxic fumes throughout curing (can cause irritation to the skin and eczema) and these organic resins are highly flammable [21]. Moreover, when exposed to temperatures above 70 °C (hot environments), organic resin loses its properties [22,23]. In addition, it has low permeability and is susceptible to UV radiation [24]. Furthermore, 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) [21,25].

Therefore, the need for alternative bonding adhesives to epoxy resins has become necessary for EB FRP and NSM FRP applications. Mineral-based materials such as cement-based materials can be an alternative adhesive material, as they are safe at high temperatures and 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 with EB FRP and NSM FRP strengthening techniques [21,26–31]. However, polymer cementitious mortars are affected by hydrothermal conditions [32–34]. 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-cement-based adhesive and FRP materials, and sustaining structural integrity under different conditions.

In a previous study [35] the authors developed an innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA), which has 28-day tensile and compressive strengths of 13.8 MPa and 101 MPa, respectively. This high mechanical strength is believed to be the key factor in the development of high strength in NSM CFRP strengthening and repair 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 [36–41]. 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 [36]. A higher compressive strength of 46.2 in a cement mix with 0.05% GO compared with pure cement paste has been reported [37]. The addition of GO to cementitious materials remarkably improves durability, indicated by enhanced resistance to chloride ingress and freeze-thaw cycles [38,39]. Considerable resistance of IHSSC-CA to the effects of high temperatures has been reported [40]. NSM CFRP-specimens made using IHSSC-CA can survive a long fatigue life and sustain a high fatigue load range [41]. These advantages of adopting GO are very important to maintain the durability of bonding systems by using highly durable adhesive. This can help to solve the many durability problems with organic adhesives.

In the present study, the effectiveness of the use of cement-based adhesive (IHSSC-CA) for the strengthening and repair of RC beams with the NSM CFRP system after exposed to fatigue loading was investigated. Ten full-scale beams were tested under different loading histories (with and without pre-loading) and different bonding adhesives (IHSSC-CA and epoxy). Five beams were tested under monotonic loading up to failure, and five beams were then tested under fatigue loading at service load levels up to failure or 3 million cycles, whichever happened first. The effect of fatigue loading was determined by comparing the behaviour of beams before and after fatigue loading. 3-D laser profilometry analyses was used to describe the CFRP strip deformation behaviour of RC beams strengthened and repaired with the NSM CFRP system after exposure to fatigue loading.

The aim of this study is to provide experimental evidence for the effectiveness of the use of IHSSC-CA for the strengthening and repair of RC members with the NSM CFRP system and the ability 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, reduce maintenance costs and guarantee people's safety.

2. Experimental program

2.1. Beam details

Ten full-scale beams were manufactured and tested under monotonic and fatigue loading using four-point bending. Two beams were conventional beams, and the remaining beams were strengthened and repaired with NSM CFRP system using cement-based (IHSSC-CA) and epoxy adhesives. Four beams were pre-cracked before strengthening to simulate a real RC bridge girder with many years of service. The conventional monotonic RC beam was designed consistent with ACI 318-11 to make sure that flexural failure happened prior to shear failure. The monotonic strengthened RC beam was designed consistent with ACI 440.2R-08 to get an increase in ultimate capacity of about 40% over a monotonic

Table 1
Test matrix.

Beam ID	Loading type	Description	Adhesive type
MC	Monotonic	Control	–
FC	Fatigue	Control	–
MSC	Monotonic	Strengthened	Cement-based (IHSSC-CA)
FSC	Fatigue	Strengthened	Cement-based (IHSSC-CA)
MRC	Monotonic	Repaired	Cement-based (IHSSC-CA)
FRC	Fatigue	Repaired	Cement-based (IHSSC-CA)
MSE	Monotonic	Strengthened	Epoxy
FSE	Fatigue	Strengthened	Epoxy
MRE	Monotonic	Repaired	Epoxy
FRE	Fatigue	Repaired	Epoxy

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