Bond behaviour of NSM CFRP strips with innovative high-strength self-compacting cementitious adhesive (IHSSC-CA) made with graphene oxide

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ABSTRACT: Concrete structures are normally strengthened using fibre reinforced polymer (FRP) with epoxy adhesives and polymer cementitious mortars. Epoxy adhesives have significant issues, such as the emission of toxic fumes and steroids during curing, loss of strength and stiffness when exposed to hot temperatures, and low permeability and weakness to UV radiation. In the case of polymer cementitious adhesives, their properties are adversely affected by hydrothermal conditions. Recently an innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA) was developed by the authors using graphene oxide and cementitious materials to synthesise the adhesive. This paper presents the results of an experimental study of near-surface mounted (NSM) carbon FRP strips bonded to concrete substrate with IHSSC-CA, epoxy adhesive and polymer cement-based adhesive using single-lap shear tests. NSM CFRP specimens were tested under monotonic loading up to failure to investigate the bond between the NSM CFRP, the adhesive and the concrete substrate. In addition, an analytical model is proposed to predict the bond strength (pull-out force) based on the experimental results. The test results confirm the effectiveness of using IHSSC-CA to improve the bond strength, CFRP strip utilisation, stiffness, residual strength and ductility of NSM CFRP strips embedded in concrete substrate. Moreover, there is good agreement between the experimental and predicted bond strength (pull-out force) and the proposed analytical model can be used in the design of NSM CFRP-strengthened RC members.

Keywords: Bond; Near-surface mounted (NSM); Carbon fibre reinforced polymer (CFRP); Cement; Graphene oxide.

1 INTRODUCTION

The near-surface mounted (NSM) fibre reinforced polymer (FRP) technique has become an adopted method in the construction industry for FRP strengthening applications because of the sensitivity of the externally-bonded (EB) FRP technique to premature de-bonding (Fib, (2001); Täljsten and Blanksvärd, (2007)). Although the NSM FRP system using organic adhesives (epoxy adhesives) shows a suitable bond between the FRP, the organic adhesive and the concrete substrate, the use of epoxy adhesive with the FRP strengthening technique has significant issues, due to the emission of toxic fumes and steroids during curing, which may cause eczema and irritation to the skin, and are highly flammable (Täljsten and Blanksvärd (2007)). Moreover, when exposed to temperatures above 70°C, epoxy adhesive loses its properties (Gamage and Al-Mahaidi (2006)). In addition, it has low permeability and weakness to UV radiation (Ombres

(2011)). Furthermore, it has limitations in the work environment on site, such as being impossible to use on humid surfaces and at temperatures less than 10^{O}C (Täljsten and Blanksvärd (2007); D'Ambrisi and Focacci (2011)). To avoid these drawbacks of epoxy adhesive, several researchers have used composite systems consisting of fibre reinforced materials with cementitious bonding agents (Carolin et al. (2001); Al-Mahmoud et al. (2009)). The research shows that, the use of polymer cementitious mortars (Carolin et al. (2001)) to bond FRP materials to the concrete substrate using NSM systems can improve the ultimate bearing capacity better than non-polymer cementitious agents (Al-Mahmoud et al. (2009)). However, polymer cementitious mortars are affected by hydrothermal conditions (Park et al. (2009); Reis (2012); Rashid et al. (2015)). 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 material, in order to sustain structural integrity under harsh environmental conditions.

The bond between the FRP, the adhesive material and the concrete is vital for a successful BSM FRP strengthening system. Therefore, in this study, the bond behaviour between NSM CFRP strips, adhesives and the concrete substrate was investigated. A total of 9 concrete prisms (75 x 75 x 250 mm) were tested under monotonic loading until failure using single-lap shear tests with epoxy adhesive, polymer cement-based adhesive and innovative high-strength self-compacting non-polymer cementitious adhesive (IHSSC-CA). An analytical model is also proposed to predict the ultimate pull-out force (bond strength) using the direct pull-out test.

2 EXPERIMENTAL PROGRAM

The specimen details for the direct pull-out test (single-lap shear test) are shown in Figure 1. Nine specimens were manufactured and tested. Three series were tested and each series consisted of three specimens, as shown in Table 1. The test variable was the adhesive type (innovative non-polymer cement-based (IHSSC-CA), polymer cement-based and epoxy adhesives). The first letter of the specimen ID "M" means monotonic test, "IC" refers to innovative non-polymer cement-based adhesive (IHSSC-CA), "C" refers to polymer cement-based adhesive and "E" refers to epoxy adhesive.

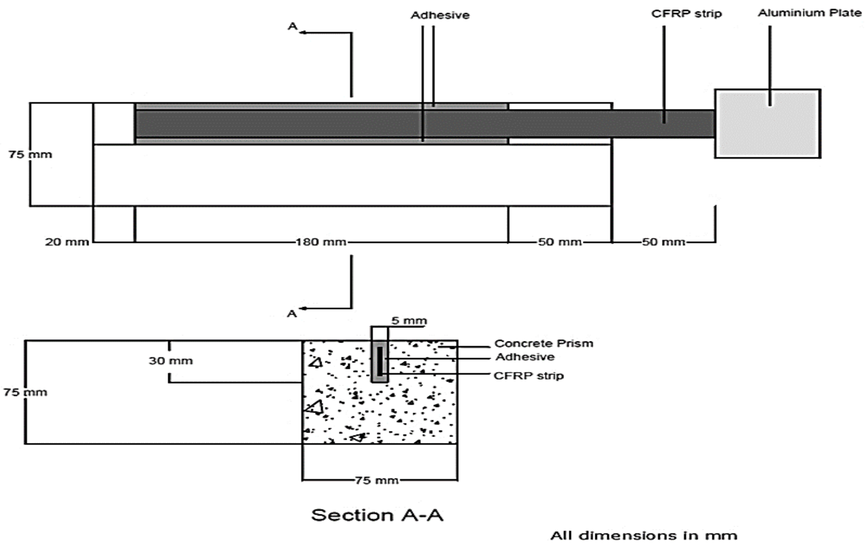


Figure 1. Specimen details.

Table 1. Specimen details

Specimen ID	Adhesive type	CFRP strip surface	CFRP strip dimension (mm)	Bond length (mm)	Groove dimension (mm)
MIC	Innovative non-polymer cement-based (IHSSC-CA)	Rough	1.4 x 20	180	5 x 30
MC	Polymer cement-based	Rough	1.4 x 20	180	5 x 30
ME	Epoxy	Rough	1.4 x 20	180	5 x 30

Normal strength concrete was used in this study to cast all the prisms. Polymer cement-based adhesive and innovative non-polymer cement-based adhesive (IHSSC-CA) were used in this study. The polymer cement-based adhesive used in this investigation is the same of that reported by (Al-Abdwais et al. (2013)). Graphene oxide and cementitious materials were used to synthesise the IHSSC-CA and for more information about it see (Mohammed et al. (2016)). The compressive and splitting tensile strengths of the concrete and polymer and non-polymer cement-based adhesives at the age of testing were determined in accordance with ASTM C39-14a and ASTM C496-11, respectively, as shown in Table 2. MBrace laminate adhesive was also used in this work and its properties, as specified by the manufacturer, are shown in Table 2. MBrace CFRP Laminate 210/3300 was used in this work and its properties were determined based on tension tests in accordance with ASTM D 3039-14, as shown in Table 2.

Table 2. Material properties

Material	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
Concrete	41.1	4.2	38.4
Innovative non-polymer cement-based adhesive (IHSSC-CA)	116.7	18.6	45.7
Polymer cement-based adhesive	61.2	6.6	30.6
MBrace laminate adhesive	60	32	10
MBrace CFRP laminate	_	3697	212

The monotonic pull-out loads were applied using an MTS universal testing machine (250kN capacity) with vertical pulling load, as shown in Figure 2. All NSM CFRP-pull-out specimens were tested at 0.1 mm/min loading rate. Each specimen was instrumented using one linear variable differential transformer (LVDT) to measure the loaded-end slip (Figure 2).

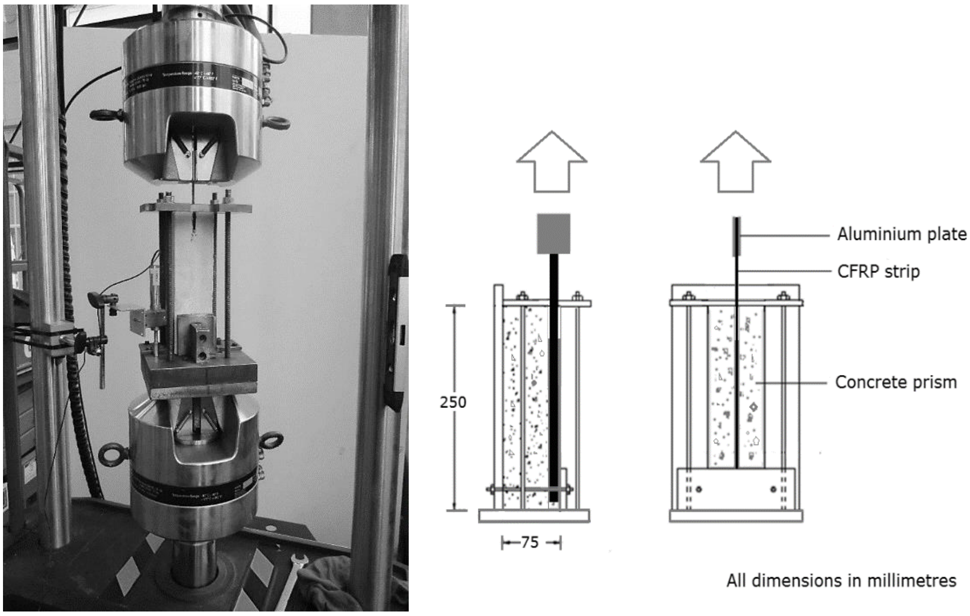


Figure 2. Pull-out test set-up.

3 RESULTS AND DISCUSSION

The average value of three specimens was considered as the bond characteristic of the NSM CFRP-specimens. Table 3 shows the average values of the monotonic pull-out test results.

Table 3. Monotonic pull-out test results

Specimens ID	$F_{s,\,max}$ (kN)	S (mm)	T_{max} (MPa)	б$_{max}$ (MPa)	б$_{max}$/ f_{fu}	Failure mode
MIC	34.53	1.78	4.80	1233.2	0.34	R
MC	22.25	2.29	3.09	794.7	0.21	P
ME	41.08	3.86	5.70	1467.2	0.39	D

where $F_{s,\,max}$ is maximum pull-out force (kN) during the test, S is slip (mm) at loaded end, at maximum pull-out force, T_{max} is maximum bond strength (MPa), б$_{max}$ is axial stress in CFRP strips (MPa) at maximum pull-out force, f_{fu} is laminate tensile strength (MPa) as laboratory tested, R is rupture of CFRP strip, P is pull-out of CFRP strip and D is debonding of CFRP strip.

3.1 *Bond-slip relations*

The bond stress-loaded-end slip relationships for NSM CFRP-specimens are shown in Figure 3. The experimental result curve is the average value of three tested specimens. The bond stress is the average bond stress calculated by dividing the pull-out force by the contact area between the adhesive material and the CFRP strip. Therefore, the bond stress and the loaded-end slip were assumed to be constant throughout the bonded length, although this behaviour may be non-linear

(De Lorenzis and Nanni (2002)). The bond stress-loaded-end slip response can be divided into two distinct periods: pre-peak and post-peak.

The pre-peak behaviour is indicated by an increase of the curve slope before reaching peak load. Figure 3 shows that there is a reduction in the stiffness, the slope of the bond -slip curve, in the case of NSM specimens with epoxy and polymer cement adhesives compared to NSM specimens with IHSSC-CA. This reduction of stiffness indicates a softening of the bonding system and the NSM CFRP strip-adhesive-concrete system, and an increase in the deformation prior to reaching ultimate pull-out strength.

The post-peak behaviour is the descending trend of the bond-slip curves after reaching peak load, which represents bond softening after peak load. Unlike NSM specimens with epoxy adhesive, the NSM specimens with IHSSC-CA and polymer cement adhesives show ductile behaviour with gradual reduction of the bond until the residual bond strength is reached, as shown in Figure 3. This residual bond strength represents the residual frictional stresses between the CFRP strips, adhesive and concrete.

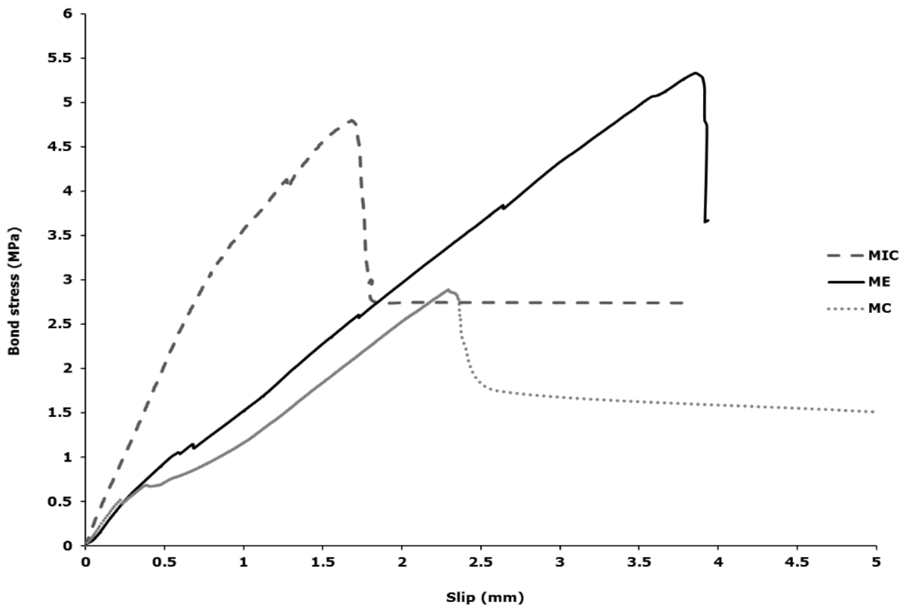


Figure 3. Bond stress-loaded-end slip relations of tested specimens.

3.2 *CFRP strip utilisation*

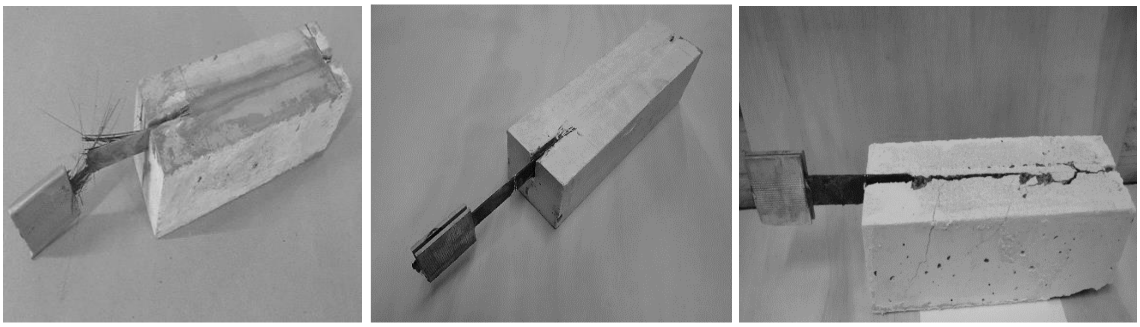
To assess the efficiency of NSM CFRP strip utilisation using different adhesives, the ratio of the maximum axial stresses in CFRP strips ($б_{max}$) to the laminate tensile strength (f_{fu}), as laboratory tested, was established and the results are presented in Table 3. The NSM specimens using epoxy adhesive showed better CFRP strip utilization of 39%, while the NSM specimens using polymer cement-based adhesive showed the worst CFRP strip utilization of 21%. The CFRP strip utilization in the case of NSM specimens using IHSSC-CA was found to be 34%. This utilization can be considered good compared to that of NSM specimens with polymer cement and epoxy adhesives.

3.3 *Failure mode*

MIC specimens failed by rupture of CFRP strips and no cracks were observed along the bond length or on the concrete surfaces. This type of failure occurs because of the efficient confinement and bond between concrete substrate and the IHSSC-CA and CFRP strips. When the loaded-end slip at the peak pull-out strength of NSM specimens is higher than the maximum allowable elastic elongation of the CFRP strips and after the peak pull-out strength, the carbon fibre of CFRP strips fractures gradually during the progress of the test near the loaded end until failure, as shown in Figure 4 (a).

MC specimens failed by pull-out of CFRP strips and no cracks were observed on the concrete surfaces, as shown in Figure 4 (b). This type of failure occurs due to slipping at the NSM CFRP strip–adhesive interface because of the weak bond between the adhesive and the CFRP strip, which can be due to low tensile strength of the polymer cement-based adhesive.

ME specimens failed by debonding of CFRP strips and cracks were observed along the bond length and on the concrete surfaces, as shown in Figure 4 (c). This type of failure occurs due to debonding between the CFRP strip, the epoxy adhesive and the concrete substrate along the bond length because of the high applied shear stress with cracking propagating in the concrete adjacent to the NSM CFRP strips.



(a) (b) (c)

Figure 4. Failure modes; (a) MIC specimens, (b) MC specimens and (c) ME specimens.

4 THEORETICAL ANALYSIS

There are many theoretical models to predict the bond strength of EB FRP to concrete joints, including empirical models, fracture mechanics models, and design proposal models (Teng et al. (2002)). On the other hand, there are very few theoretical models to predict the bond strength of NSM FRP-to-concrete joints.

In this study the statistical model in a previous work (Seracino et al. (2007)) is developed using regression analysis of test result data, as shown in Equation 1.

$$P_u = \alpha . \beta . \sqrt{f_c} . d_p^{1.36} . b_p^{0.21} \leq f_{rupt} . b_p . d_p \quad (1)$$

where P_u is the predicted pull-out force (kN), α is characteristic value to account for the influence of adhesive types with NSM CFRP strip system, $\alpha = 0.107$ for IHSSC-CA, $\alpha = 0.069$ for polymer cement-based adhesive and $\alpha = 0.127$ for epoxy adhesive, β equal to $L_b/200$, and L_b is the bonding length (mm), f_c is concrete compressive strength at 28 day (MPa), d_p is CFRP strip width (mm), b_p is CFRP strip thickness (mm) and f_{rupt} is laminate tensile strength (MPa) as laboratory tested.

The values of predicted pull-out force (P_u) compared to experimental pull-out force ($F_{s,\ max}$) are shown in Table 4. The results shown in Table 4 indicate that a good correlation exists between the experimental and predicted pull-out force values.

Table 4. Experimental pull-out force versus predicted pull-out force

Specimens ID	$F_{s,\ max}$ (kN)	P_u(KN)	P_u / $F_{s,\ max}$	($F_{s,\ max}$- P_u)/ $F_{s,\ max}$ (%)
MIC	34.53	34.38	0.99	0.43
MC	22.25	22.16	0.99	0.41
ME	41.08	40.80	0.99	0.68

5 CONCLUSION

In this study, the bond behaviour between NSM CFRP strips, adhesives and concrete substrate was investigated. The following conclusions can be drawn:

- IHSSC-CA is easier to use for NSM CFRP application than polymer cement and epoxy adhesives due to its properties, including its self-compaction, flow ability and workability, which are very important for site application.
- The pull-out test results confirm that NSM CFRP specimens using IHSSC-CA have better composite action with the concrete substrate and CFRP strips than NSM CFRP specimens using polymer cement and epoxy adhesives causing the NSM specimens made with IHSSC-CA to fail by rupture of CFRP strips, as the displacement of CFRP strips is higher than the maximum allowable elastic elongation.
- NSM specimens strengthened using IHSSC-CA showed high bond strength and CFRP strip utilisation, which can be considered as competitive with NSM specimens strengthened using epoxy adhesive.
- Unlike NSM specimens with epoxy adhesive, the NSM specimens with IHSSC-CA and polymer cement adhesives show ductile behaviour with gradual reduction of the bond after the peak pull-out strength until the residual bond strength is reached.
- The proposed analytical model can simulate experimental conditions reasonably well and can be used in the design of RC elements strengthened and repaired using the NSM CFRP technique.

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