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Effect of axial stiffness of NSM FRP reinforcement and concrete cover confinement on flexural behaviour of strengthened RC beams: Experimental and numerical study

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ABSTRACT

An experimental and numerical study was performed to study the effectiveness of axial stiffness and of the type of confinement of near-surface mounted (NSM) fibre reinforced polymer (FRP) reinforcement on the strengthened beam bearing capacities and failure modes. To improve the performance in front of concrete cover separation and enhance bond strength, the use of mechanical interlocking with shear connectors (concrete cover confinement) or transverse wrapping was also investigated. The experimental results showed that confinement significantly enhanced the load carrying capacity of the RC beams with small increase in their steel reinforcement yielding load. The ultimate load of the strengthened beams without concrete cover confinement ranged between 150% and 170% of the ultimate load of the control beam. By applying mechanical interlocking with shear connectors or transverse wrapping, the load carrying capacity was increased by up to 23.3% for strengthened beams and by 33% for the ultimate load of conventional strengthened beams. The results indicated that the yield load ratio of the strengthened beams (with respect to the control beams) was proportional to the axial stiffness ratio of NSM FRP reinforcement. It was found that the failure of the strengthened beams became concrete cover separation when the axial stiffness ratio reached a critical value, and subsequently the ultimate load of strengthened beams was not affected by increasing axial stiffness ratio beyond this value.

This critical value of stiffness ratio was experimentally found to be at about 1.25. The numerical results also showed excellent agreement with the experimental ones in terms of load–deflection behaviour and maximum load capacity.

1. Introduction

The use of near surface mounted (NSM) fibre reinforced polymer (FRP) reinforcement to enhance the flexural and shear strength of reinforced concrete (RC) and masonry structures has recently acquired increased significance because NSM offers several advantages over the externally bonded (EB) technique [1–5]. For instance, in the EB technique, the plates or sheets are bonded to the surface of the structural element, whereas when NSM is used, FRP bars or strips are bonded into grooves cut into the concrete cover either on the top and bottom or in the lateral sides of the beams. The NSM strengthening is reported to have been firstly used in 1949 by Asplund [6] to overcome an excessive settlement of the negative moment reinforcement during construction of an RC bridge in Sweden, where steel reinforcement was installed in the negative moment region through grooves filled with mortar. Advantages of using NSM compared to EB FRP laminates have been reported elsewhere [1–5], being the most noteworthy among them the possibility of anchoring the reinforcement to adjacent members, the opportunity of upgrading elements in their negative moment region with the reinforcement not exposed to potential mechanical damage that may occur in floor deck systems, the better protection against environment, and the unchanged aesthetics of the strengthened structures [1–5]. Furthermore NSM FRP rods were extensively used for shear and flexural (negative/positive moment region) strengthening in different structures such as bridges (decks/girders), columns, frames, cement silos, and masonry walls. More details about design problems and considerations are reported in [1–5]. The efficiency of NSM strengthening depends mainly on the bond at its two interfaces and on the effect

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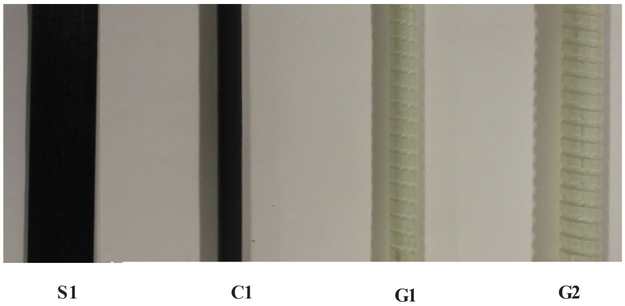

Fig. 1. Material type, size and surface treatment of the FRP reinforcement.

of the stresses generated on the concrete cover. Direct pull-out [7–14] and beam pull-out tests [15–17] are the two procedures most commonly used to study NSM FRP reinforcement and concrete bonds in structural elements. The aforementioned studies indicated that by increasing the groove size (width or depth) and the bonded length, the load capacity of the joint increased, and that concrete strength has no significant effect on the load carrying capacity when failure occurs in the NSM system (interface failure, epoxy splitting or bar rupture).

RC beam strengthening (both shear and flexure) with NSM FRP has been studied elsewhere [18–36]. Previous research has shown that while beams strengthened with partially bonded lengths experienced higher deflection values than those with full bond lengths, the load capacity decreased slightly. The effect of bond length, internal steel reinforcement ratio, groove size and FRP properties on the load capacity of beams strengthened with NSM FRP bars has also been studied [19,20]. Results showed that as the bonded length and groove size increased, the load capacity of the beams increased no matter what the FRP properties are [19,20]. The results also showed that increasing the bonded length beyond a certain length did not produce any significant increase in the load capacity of the strengthened beams, as failure was due to either epoxy and concrete splitting or concrete cover separation [19,21]. Additionally, the effectiveness of the NSM reinforcement decreased as the area of internal reinforcement increased [19].

Sharaky et al. [24] studied the effect of mechanical properties, number and area of FRP bars in addition to epoxy type on the flexural behaviour and maximum load capacity of beams strengthened using NSM methodology. The type of failure of the strengthened beams greatly affected their maximum load capacities consistent with the axial stiffness of the NSM FRP bar. The increase in yielding load for beams strengthened with the same areas of CFRP and GFRP bars, compared to that of an un-strengthened beam, was 55.8% and 27.6% respectively, while the increase in maximum load was 66.3% and 59.4%. The failure of beams strengthened with GFRP (low axial stiffness) was caused by epoxy and concrete cover splitting, whereas for beams strengthened with two NSM CFRP bars (high axial stiffness) it was concrete cover separation. When the failure of the tested beams was concrete cover separation the epoxy type had trivial effect on the yielding and ultimate loads of the strengthened beam [24].

Further results from the beams tested in [25] led to the conclusion that the failure mode of the strengthened elements was greatly influenced by the bonded length NSM FRP. For those beams with longer bonded lengths, the failure mode was FRP rod pull-out, while for those with shorter bond lengths it was concrete cover peeling. Based on the obtained results of the tested beams in [21], a development length of the embedded NSM bars was recommended to be not less than 80 times the diameter of the NSM bars. The effect of adhesive type (mortar or epoxy), and concrete strength on the load capacity of beams strengthened with NSM FRP reinforcement was also investigated [21,23]. From the obtained results in [21], it was concluded that increasing the concrete compressive strength and using of high strength epoxy delayed the concrete split and epoxy split failures respectively. In terms of concrete strength, the beams tested in [23] (concrete strength ranged between 35.1 MPa and 67.2 MPa) showed this parameter had no effect on the maximum load when the failure mode was pull-out of the NSM bar. The obtained results of strengthened beams with NSM stainless steel bars and CFRP strips [29] showed further increase of the flexural strength when external transverse anchoring reinforcement were used. On the other hand, concrete confinement achieved high strength properties of the EB and NSM strengthening systems. The effect of CFRP trapezoidal bars as NSM reinforcement was also studied [30]. The strengthened beams with NSM CFRP trapezoidal bars experienced an increase in their ductility and the load carrying capacity. In addition, the use of NSM CFRP trapezoidal bars in combination with bolted U-type metal fittings attained superior composite action of the strengthened beams.

The main drawback of strengthened RC beams by NSM/EB techniques is the unexpected failure due to debonding or concrete cover separation. The previous researches showed that RC beams strengthened with either NSM FRP or EB have relatively low values of strength efficiency when failure is due to NSM/EB reinforcement pull out and concrete cover separation, since these types of failure greatly decrease the load carrying capacity [37,38]. The main objective of this paper is to experimentally and numerically examine what relevance the axial stiffness of the NSM bar/strip has to bear on the failure modes of strengthened beams. Additionally, a new technique denoted as mechanical interlocking with shear connectors (causing concrete cover confinement, CCC), which may be useful for beams where it is difficult or not possible to apply transverse wrapping (sides of the beam not easily accessible), is also proposed to delay or prevent failure caused by concrete cover separation or splitting.

2. Experimental programme

2.1. Material properties

All the beams were cast using ready-mixed concrete. The properties of the hardened concrete were obtained using standard cylinder tests (150 × 300 mm) on the date testing took place. The average concrete properties were 31.9 MPa, 2.75 MPa and 31.4 GPa respectively, for compressive strength, tensile strength and modulus of elasticity [39–41]. Epoxy resin was used for bonding both NSM FRP reinforcements (POLYFIXER EP and ROBERLO). The properties of the resin were experimentally obtained with 8000 MPa, 95.5 MPa and 23.0 MPa, respectively, for modulus of elasticity, compressive and strength tensile strength [42,43]. Four types of NSM FRP reinforcement, plus two materials, (carbon, Mbrace BASF) and (glass, ComBar Schok), along with different sizes and surface treatments were used in the experimental

Table 1
Mechanical properties of the FRP reinforcements.

FRP type	FRP material	d_b (mm)	$w \times h$ (mm^2)	f_{fu} (MPa)	E_f (GPa)	ε_{fu} (–)	Surface treatment
C1	CFRP	8	–	2350	170	0.013–0.015	SST
S1	CFRP	–	1.4 × 20	$2500^{(f)}$	$165^{(f)}$	$0.015^{(f)}$	SST
G1, G2	GFRP	8, 12	–	1350	64	0.0167	GR

d_b = diameter of the FRP bar, w × h = cross section of the FRP strip, f_{fu} = ultimate tensile strength of FRP, E_f = modulus of elasticity of FRP, ε_{fu} = ultimate tensile strain of FRP, SST = smooth surface texture; GR = grooves and $^{(f)}$ = from manufacturer.

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