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Side Near Surface Mounted (SNSM) technique for flexural enhancement of RC beams

Md Akter Hosen, Mohd Zamin Jumaat *, A.B.M. Saiful Islam

Department of Civil Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

The rehabilitation of existing Reinforced Concrete (RC) structures constitutes one of the leading challenges in civil engineering. The crucial reasons for the strengthening of RC structures comprise frequent increases in design loads, engineering errors in design or workmanship issues during construction, changes in code and functional requirements. This paper introduces an innovative approach comprising the Side-Near-Surface-Mounted (SNSM) technique, which incorporates Carbon Fiber Reinforced Polymer (CFRP) and steel bars as strengthening reinforcement. Experimental and analytical investigation was adopted to explore flexural strengthening of RC beams with them. Analytical models are presented to predict the ultimate load, crack spacing and deflection. Four-point bending tests were performed up to failure on the rectangular RC beams strengthened with different ratios of SNSM reinforcement. The failure characteristics, yield and ultimate capacities, deflection, cracking behavior, ductility and energy absorption capacities were evaluated. The SNSM technique significantly enhanced the flexural behavior of the beams. The yield and ultimate load carrying capacities of the beams increased by a factor of 2 and 2.38 times, respectively. The cracking loads improved more notably (3.17 times). Predicted results from the analytical models showed good agreement with the experimental results, which confirmed proficient implementation of the proposed SNSM technique.

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1. Introduction

The RC structural members of buildings and bridges throughout the world require repair and strengthening, which underlines the significance of these actions in the concrete construction industry. To date, Externally Bonded Reinforcement (EBR) and Near Surface Mounted (NSM) are the two strengthening techniques that have attracted the most attention from the international engineering community [1–8]. The EBR system consists of one or more strengthening plates or laminates that are bonded to the tension side of the strengthened member. The main disadvantage of this method is that it often suffers from premature debonding due to the high interfacial shear stresses at the plate ends [9–13]. The Near Surface Mounted (NSM) strengthening technique was presented to overcome this type of limitation. This technique involves the insertion of strengthening strips or rods into pre-cut grooves in the concrete cover and then filling the grooves with epoxy adhesive [14]. NSM strengthening offers an advanced level of strengthening that is less prone to premature failure and improves safety against fire, mechanical damage, aging effects and natural acts of destruction [15]. It also reveals better durability, stress sharing mechanisms and fatigue performance, as the reinforcement is located inside the structural member [16]. However, the NSM method has some restrictions. The beam specimens to be strengthened must have sufficient width for the necessary edge clearance and clear spacing between the adjacent NSM grooves. Another essential issue to be considered is when two or more grooves, which are cut into a beam of limited width, have a greater probability of the occurrence of debonding due to stress overlapping [17]. However, in many cases, from the design considerations, the strengthening of a structural element needs more CFRP bars to meet the current service load requirement.

An experimental investigation of RC beams flexurally strengthened with NSM and the externally bonded technique using AFRP bars and sheets, respectively were performed by Kishi et al. [18]. The experimental results indicated that the load capacity increased as the bond length increased and two types of failure mode occurred. One was debonding in the concrete epoxy interface and the other was debonding in the CFRP rod epoxy interface.

Jung et al. [19] compared the NSM CFRP strengthened beams with externally bonded CFRP strengthened beams. The NSM CFRP bars and EB reinforcement strengthened specimens failed by debonding.

* Corresponding author.
E-mail address: zamin@um.edu.my (M.Z. Jumaat).

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The flexural performance was assessed of NSM GFRP strengthened beams where normal and lightweight polystyrene was used as a variable in the study of Tang et al. [20]. The dominant failure mode was debonding, which occurred either in shear, by splitting of the epoxy paste, or rupture of the NSM GFRP bars. The flexural responses were evaluated of NSM CFRP strengthened RC beams under four point bending loads by Al-Mahmoud et al. [21]. The flexural strength was enhanced irrespective of the groove filler and concrete strength; the failure mode for all beams was debonding (pullout with splitting and peeling-off).

Sharaky et al. [22] evaluated the flexural response of NSM strengthened RC beams using CFRP and GFRP bars. All the strengthened beams failed by debonding. Among the strengthened beams with double grooves, the CFRP strengthened beams displayed concrete cover separation whereas the GFRP exhibited concrete splitting.

The efficiency of flexural strengthened of RC beams with CFRP NSM strips and EBR plates were assessed [23]. The strengthened specimens failed by end debonding, critical diagonal crack debonding and concrete cover separation. The effect of bond length, FRP characteristics and construction details on the flexural performance of partially or fully bonded with NSM technique were investigated [24]. It was found the strengthened specimens failed by concrete cover separation, concrete splitting and debonding between concrete epoxy interfaces.

However, the NSM strengthening technique have some limitations in application. Debonding failure mode becomes more common when two or more grooves are cut for strengthening with NSM bars in a beam of limited width due to stress overlapping. Moreover, it has the opportunity to edge breaking of the concrete section due to limited width. Therefore, adequate width of beam need to be provided for the NSM technique aimed at getting proper clear spacing between two nearby NSM grooves and edge clearance. Moreover, when the RC beam of the structural assemblage need to be strengthened though there is no room at the soffit to make groove for NSM strengthening or even externally bonded reinforcement due to the presence of wall beneath the RC beam, an updated NSM approach is desired.

Hence, to overcome the limitations of NSM technique, the present research has an aim to introduce Side Near Surface Mounted (SNSM) technique in order to look at the possibility to increase the flexural strength and enhance the serviceability of the RC beams. The study explores the structural behavior of RC beams strengthened by means of the SNSM technique using CFRP and steel bars. Flexural strengthened beams are tested under four-point bending conditions. A different SNSM reinforcement type and ratio are used for the strengthening of the RC beams. The load carrying capacity, deflection and strain data are analyzed for the ductility, energy absorption capacity, failure modes and cracking behavior of the tested beams. The analytical models predict the flexural responses of the RC beams and show excellent agreement between the experimental and predicted results.

2. Experimental program

2.1. Test matrix

To investigate the feasibility of the Side Near Surface Mounted (SNSM) technique in upgrading the flexural capacity of RC beams with CFRP or steel bars, a subsequent test matrix was designed in which a total of seven RC rectangular beams were tested. The beams were divided into three groups. The first group consisted of one beam as the control specimen (unstrengthened). The three specimens in the second group were strengthened using SNSM steel bars. Another three specimens in the third group were strengthened using SNSM CFRP bars. Table 1 shows the test matrix for this experimental investigation.

2.2. Test specimens

The specimen dimensions and reinforcement details are shown in Fig. 1. The beams were designed as under reinforced beams to initiate failure in flexure in accordance with the ACI code [25]. The dimensions of the beams were width: 125 mm, height: 250 mm, and length: 2300 mm with 2000 mm as the effective span and a shear span of 650 mm. Three types of steel bar were employed in constructing the beam specimens. The internal tension reinforcement of all the beams consisted of two deformed steel bars, 12 mm in diameter, which were bent ninety degrees at both ends to fulfill the anchorage criteria. Two deformed steel bars, 10 mm in diameter, were used as hanger bars in the shear span zone. The shear reinforcement consisted of plain steel bars, 6 mm in diameter, distributed at the shear zone of the beams, as shown in Fig. 1.

2.3. Material properties

Normal cement was used to cast the beam specimens. Crushed granite with a maximum size of 20 mm was used as the coarse aggregate and natural river sand was mixed in the concrete as the fine aggregate. Fresh tap water was used to hydrate the concrete mix during the casting and curing of the beams, cubes, prisms and cylinders. The 28-day compressive strength of the concrete was 40 MPa based on the tests of three 100 mm concrete cubes. The compressive strength of the concrete was calculated according to BS EN [26].

The yield strength for the 6 mm, 8 mm, 10 mm and 12 mm steel bars was 520 MPa and the ultimate strength was 570 MPa. The modulus of elasticity for all bars was 200 GPa. Ribbed CFRP bars were used for SNSM strengthening in this study. The tensile strength for the 8 mm, 10 mm and 12 mm CFRP bars was 1850 MPa, and the modulus of elasticity was 124 GPa. An epoxy adhesive, Sikadur® 30, was used to bond the strengthening materials to the concrete substrate. Sikadur® 30 has two components, namely, component A and component B. Component A is white in color while component B is black. The two components were mixed in a ratio of 3:1 until a uniform gray color was achieved. The density was 1.65 kg/l at 23 °C after mixing. The epoxy bond strength for the steel and concrete was 21 MPa and 4 MPa, respectively. The compressive, tensile and shear strengths and the modulus of elasticity of the adhesive are shown in Table 2, according to the manufacturer [27].

3. Strengthening procedure

The strengthening method used in this study has been termed as the Side Near Surface Mounted (SNSM) technique. In this

Table 1
Test matrix.

Beam ID	Strengthening materials	
	Type	Diameter (mm)
CB	Unstrengthened	
SNS8	Steel	8
SNS10		10
SNS12		12
SNC8	CFRP	8
SNC10		10
SNC12		12

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