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Numerical Study on Strengthening of RC Beams with Side Near Surface Mounted Technique Using CFRP Bars

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***Abstract*—The global flexural performance of reinforced concrete beams strengthened internally with Carbon Fiber Reinforced Polymer (CFRP) rods using the Side Near Surface Mounted (SNSM) technique is investigated using non linear finite element modelling in ABAQUS software. In this study, the CFRP rods are strategically placed laterally, adjacent to the longitudinal steel bars inside pre-cut grooves which are created in the concrete cover. After that, the groove is filled with an epoxy paste. The strengthening length and position of CFRP rods, bar diameter as well as groove size are the main parameters investigated in this study. Furthermore, the paper includes a comprehensive comparison between the Side Near Surface Mounted (SNSM) and Near Surface Mounted (NSM) techniques for the strengthening of RC beams using CFRP rods. This comparison aims to validate and assess the effectiveness of the SNSM technique in enhancing the structural performance of reinforced concrete beams. The study results revealed that the failure mode was affected by both the length and diameter of CFRP rods, whereas the variation of position of the rod from the neutral axis showed minor effect. The SNSM strengthening technique offers an alternative to the NSM method and helps to prevent the unconventional failure modes such as CFRP rod pull-out or premature debonding failure.**

***Keywords*—CFRP Rod, SNSM reinforcement, Finite element analysis, RC beam and Failure mode.**

I. INTRODUCTION

Since the 1990s, degraded reinforced concrete (RC) structures resulting from exposure to natural hazards and extreme weather events have been rehabilitated using Fiber Reinforced Polymers (FRPs). A wide range of studies have been conducted on strengthening or retrofitting RC elements using externally bonded (EB) FRP laminates or sheets [1–3]. Despite the mechanical strengthening advantages of using the EB-FRP technique, some drawbacks, which include the pretreatment process, installation time, premature debonding failure due to interfacial stresses, and the mechanical damages resulting from accidental impacts. In the past decade, Near Surface Mounted (NSM) technology has emerged as a promising alternative to EB-FRP strengthening. It has become a prevalent method for reinforcing existing concrete structures using FRP reinforcement [5]. NSM offers various advantages: (1)The NSM-FRP system simplifies the process, requiring minimal surface preparation. FRP components are inserted alongside longitudinal steel bars and embedded in precut grooves in the beam soffit, bonded to concrete with epoxy-based pastes or modified cement grouts [6]. (2) RC members strengthened with NSM-FRP reinforcement exhibit increased ductility and failure resistance compared to EB-FRP members [7,8]. (3) NSM strengthens RC components with higher bonding efficiency and better FRP reinforcement protection compared to EB techniques [9].

Several experimental studies on NSM-FRP technique highlight its potential for reinforcing RC beams. For instance, Almahmoud et al. [9] demonstrated that using CFRP rods in the NSM method significantly enhances the ultimate strength of RC beams by at least 50% over non-strengthened beams.

The effectiveness of NSM-FRP reinforcement in enhancing the flexural behavior of RC beams has been demonstrated in various studies, showcasing increased ultimate capacity. However, practical limitations and operational obstacles may hinder the widespread application of NSM techniques, especially in active building environments. These limitations include constraints on the number of FRP bars due to groove spacing, difficulties in application over supports, challenges related to concrete cover quality, and potential for non-conventional failure modes such as peeling off and pull-out failures. In response to these challenges, the Side Near Surface Mounted (SNSM) technique has been proposed as a novel alternative for strengthening RC members using FRP reinforcing bars. While research on SNSM is still limited, preliminary studies have shown promising results. For instance, Akter et al. [10] observed significant increases in flexural strength when using SNSM-CFRP rods in RC beams. However, further investigation into variables such as reinforcement ratio, CFRP length and positioning is needed. This study aims to explore the global behavior of RC beams strengthened with SNSM-CFRP rods, considering key parameters like strengthening length and position. Additionally, a comparison between SNSM and NSM strengthening approaches is conducted to understand failure mechanisms and bearing capacity.

II. VALIDATION

A. Description of Experimental Model

The nonlinear finite element model presented in this work was validated using the results from the experimental work, published by M. Abdallah [7]. A total of ten RC rectangular beams, including one control beam (CB), were numerically modelled and four-point bending load is applied. The RC beams were designed to experience flexural failure in accordance with the ACI code [18];the beam having dimensions such as 3000mm span and cross section 280mm*150mm.They were reinforced with two ordinary 12-mm-diameter deformed steel bars in the tension zone and two 6-mm-diameter ribbed bars in the compression zone. The deformed steel bars in the compression zone were utilized as hanger bars; and they were running along the shear zones. Closed 6-mm-diameter stirrups were provided against the maximum shear with a 150mm center-to-center spacing. The concrete cover thickness in all tested beams was maintained at 20mm for the vertical faces and 30mm at the top and bottom faces. Figure 1 and 2 shows the Longitudinal section and cross section of control beam.

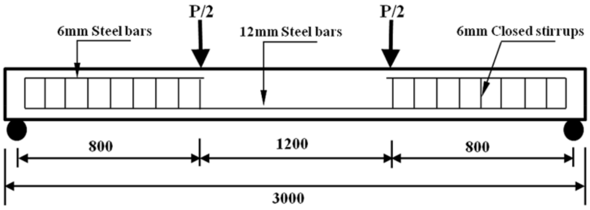

Fig-1: Longitudinal section of control beam (M. Abdallah [7])

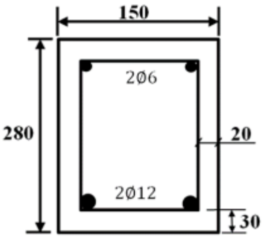

Fig-2: cross section of control beam (M. Abdallah [7]) (All dimensions are in mm)

To simulate the behavior of the SNSM reinforced beams, a three-dimensional finite element modeling of the strengthened specimens is carried out using the FEA software ABQSUS. The validation was done on a concrete specimen which was strengthened with SNSM method using two CFRP bar of 8mm diameter as the SNSM material and groove size is two times the diameter of CFRP bar. Here, both steel and FRP reinforcements are modeled as discrete truss elements inside concrete. The stirrups are modeled using 2D wire elements. The reinforced concrete beams with grooves are modeled using 3D solid elements. The major embedded elements are the internal stirrups and two 6mm bars at the top and two 12-mm bars at the bottom. The bond between FRP and epoxy is assumed to be perfect, while the bond between epoxy and concrete is modeled using cohesive elements considering response in terms of traction and separation. The model requires meshing in Finite element analysis. In meshing one of the important step is selection of mesh density. The size of the coarse aggregate used in the concrete model controls the smallest element dimension in the finite element modelling. When the adequate number of elements are used, the result will be converged. To strike a balance between computational efficiency and accuracy of results, an average mesh size of 25mm was determined, ensuring satisfactory outcomes without convergence issues and minimizing computational burden. Cohesive elements are used to model the interface between concrete and adhesive (epoxy). A linear elastic traction-separation law prior to damage and a linear damage evolution based on energy dissipation is assumed for defining the interface behavior as mentioned in section 29.5.1 of the Abaqus analysis user's manual (Dassault Systèmes Simulia Corporation 2010). When a cohesive element is completely damaged, then that element is deleted. Cohesive behavior is enforced only for portions of surfaces that are in contact at the start of the analysis. The concrete-epoxy interface behavior is initially linear elastic followed by damage initiation and evolution based on energy dissipated due to failure. The fracture energy of concrete is calculated using the Remmel (1994) method as given in Equation 1.

$$G_f=65\ln(1+f_{ck}/10)\text{.........}(1)$$

f_{ck} = characteristic compressive strength of concrete in MPa.

G_f = the fracture energy of concrete in N/m.

In the present study, for M30 concrete, fracture energy of 90.1 N/m is used

Boundary conditions of RC beam are the two ends pinned. Figure-3 shows the (a) FEA Model of control beam and (b) Yeilding of steel reinforcement

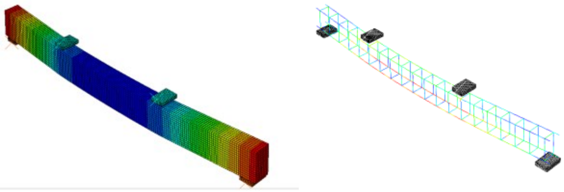

Fig-3: (a) FEA Model of control beam

(b) Yeilding of steel reinforcement

III. PARAMETRIC STUDY

A. Effect of the CFRP strengthening length

To study the effect of CFRP Strengthening length two RC beams are numerically modelled. One RC beam having CFRP length of 270cm provided at the level of steel(BC1(270-S)) and other RC beam having CFRP length of 210cm provided at the level of steel (BC2(210-S)) . The tension steel in beams BC1(270-S) and BC2(210-S) yielded at about 90kN and 94.5kN, respectively, which represents an increase of 40% and 47% over the yielding load of the control beam. Beam BC1(270-S) failed due to crushing of brittle compressed concrete at loading of 116 kN (experimentally obtained value is 120KN) with an increase of about 59.3% in the failure load compared to the control beam, whereas beam BC2(210-S) failed as a result of concrete peeling-off at loading of 106.4kN(experimentally obtained value is 110kN) with an increase of 46.2% in the failure load.

Consequently, increase in length of the CFRP bars led to increase in the failure load of the beam and the maximum measured strain of the SNSM-CFRP bars. It was noted that 60cm of supplementary length of the CFRP rods helped to avoid non-conventional failure mode (peeling-off) or delayed the debonding failure, and therefore, the CFRP rods worked more efficiently as an additional tensile reinforcement

B. Effect of The Strengthening Position

Hea To study the effect of the strengthening position CFRP bar is provided 20mm above the level of steel bar.Figure-4 shows the Beam cross section after strengthening with CFRP rod at the level of steel bar and figure-5 shows the Beam cross section after strengthening with CFRP rod 20mm above the level of steel bar. Figure 6,7,8 are the FEA model of BC1(270-S), BC2(210-S) and BC3(270-U).

Beam BC3(270-U) yielded at 83.2 kN before the yielding load of beam BC1(270-S) (difference about 6.8 kN). The beam BC5(270-U) failed due to concrete crushing, which is similar to the failure mode of BC1(270-S), at 102.7 kN(experimentally obtained value is 105kN). Although, this value is about 41.1% higher than that of the control beam, it is also about 11.5% lower than the failure load of beam BC1(270-S).

Consequently, the slight drop in the yield and ultimate load carrying capacities of beam BC3(270-U) compared with beam BC1(270-S) was due to the position of CFRP rod above the steel bar in beam BC3(270-U) caused an additional tensile stress because of reduction of leverarm.

Table 1 shows the tabulated value of ultimate load and mid span deflection of control beam, BC1(270-S), BC2(210-S) and BC3(270-U). Figure-4 shows the relation between load and mid span deflection of of BC1, BC2 and BC3 obtained numerically and Figure-5 shows the load and mid span deflection of BC1, BC2 and BC3 obtained experimentally.

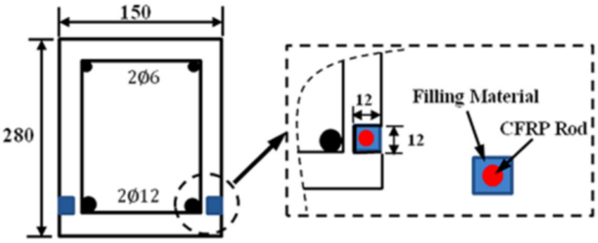

Fig- 4: Beam cross section after strengthening with CFRP rod at the level of steel bar

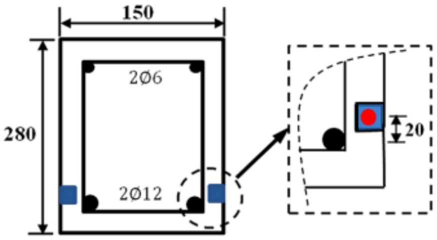

Fig 5: Beam cross section after strengthening with CFRP rod 20mm above the level of steel bar

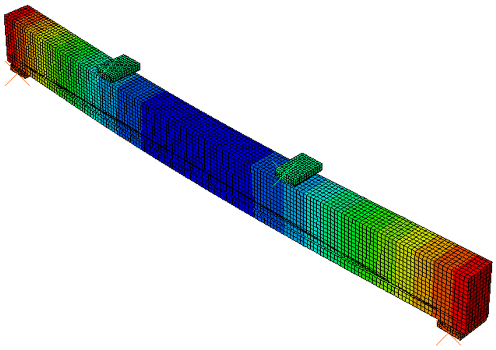

Fig-6: FEA Model of BC1(270-S)

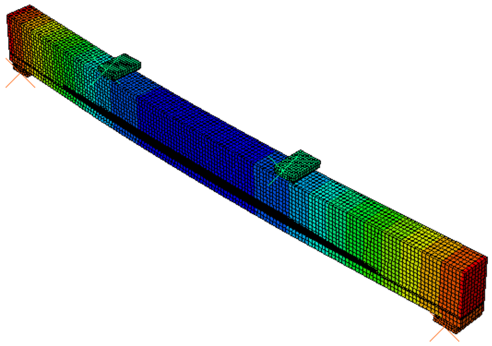

Fig-7: FEA Model of BC2(210-S)

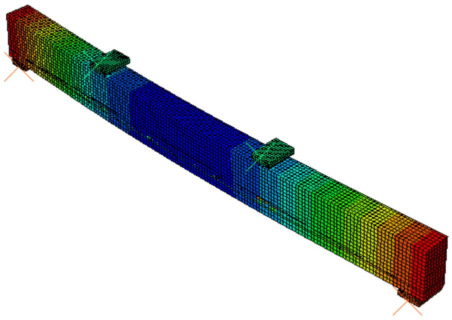

Fig-8: FEA Model of BC3(270-U)

Table -1: Ultimate Load and Mid-Span deflection of BC1, BC2 and BC3

	Control beam	BC1 (270-S)	BC2 (210-S)	BC3 (270-U)
Ultimate Load (kN)	70	116	106	102
Mid-Span deflection (mm)	55	50	23	40

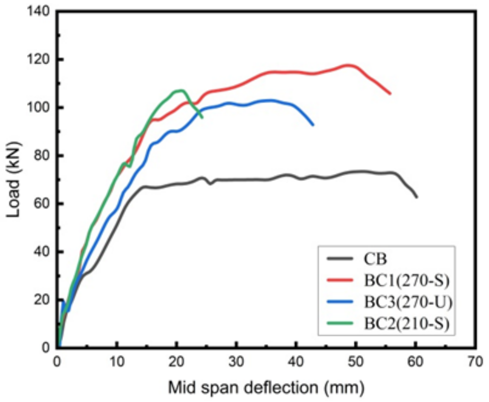

Fig -9: Load V/S deflection curve of BC1, BC2 and BC3

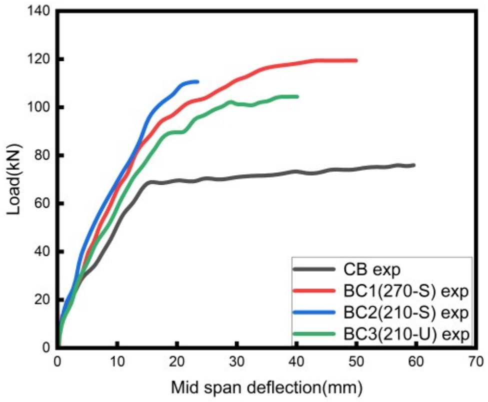

Fig -10: Load V/S deflection curve of BC1, BC2 and BC3 experimentally

C. Effect of bar diameter

In this study, bar diameter seemed to be another important factor in the increase of load capacity. Varying CFRP bar diameter on BC1(270-S) specimen, it is observed that Increasing the diameter of CFRP bar from 6mm to 8mm, the failure load increased from 95kN to 116KN. Increasing the diameter of CFRP bar from 8mm to 12mm, failure load increased from 116kN to 135kN. Table 2 shows the tabulated value of ultimate load and mid span deflection of control beam and beams having CFRP of 6mm diameter,8mm diameter and 12mm diameter. Figure-11 shows the relation between load and mid span deflection of beams having CFRP diameter of 6mm,8mm and 12mm.

Table -2: Ultimate Load and Mid-Span deflection of beams having CFRP of 6mmdia, 8mmdia and 12mm dia.

	Control beam	Bar dia 6mm	Bar dia 8mm	Bar dia12mm
Ultimate Load (kN)	70	95	116	135
Mid-Span deflection (mm)	55	57	58.5	59

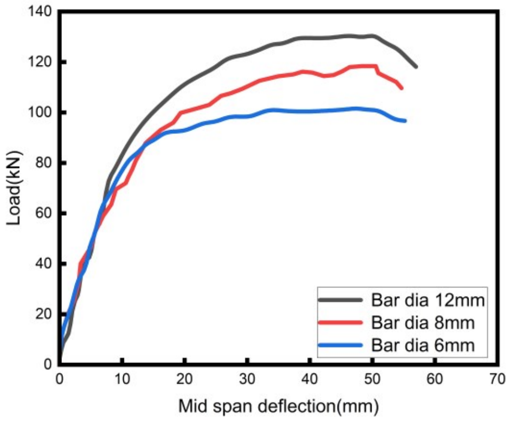

Fig -11: Load V/S deflection curve of Beams having CFRP diameter of 6mm,8mm and 12mm.

D. Effect of groove size

By varying groove width on BC1(270-S) specimen, it is observed that the ultimate strength of specimens with groove widths lesser than 2 d (2 times the diameter of the CFRP bar) remained almost in the same range. However, when the groove width is 2.5 d, strength of the beam declines. This can be explained by the fact that with the increase in groove width there is a decrease in the effective area of concrete along the cross section, which leads to decline in strength. The specimen with groove width 1.5d shows 14% higher load carrying capacity than that of the control beam. Table 3 shows the tabulated value of ultimate load and mid span deflection of control beam and beams having groove size 1.5d, 2d and 2.5d. Figure-12 shows the relation between load and mid span deflection of beams having groove size 1.5d, 2d and 2.5d.

Table -3: Ultimate Load and Mid-Span deflection of beams having Groove size 1.5d, 2d and 2.5d.

	Control beam	Groove size 1.5*d*	Groove size 2*d*	Groove size 2.5*d*
Ultimate Load (kN)	70	99	116	119
Mid-Span deflection (mm)	55	56.5	57	58

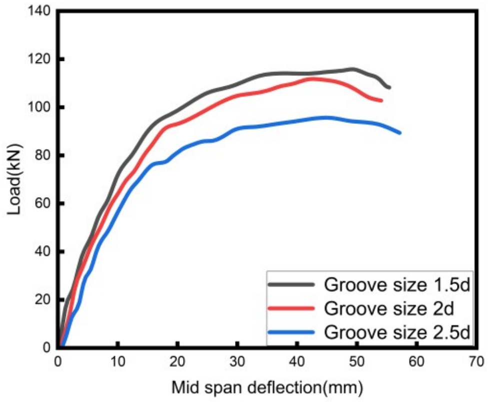

Fig -12: Load V/S deflection curve of beams having Groove size 1.5d, 2d and 2.5d.

IV. DUCTILITY

Design standards require adequate ductility in order to prevent brittle failure of RC members, and therefore provide warning of impending collapse. In this study, the displacement ductility index (μ) is obtained from the load-deflection response of the beam specimens (Fig. 9).
Ductility index = Ultimate deflection (δu)/Yielding deflection (δy)

- $\mu=\delta u/\delta y$
- $\mu=3.25$ for BC1(270-S)
- $\mu=1.48$ for BC2(210-S)
- $\mu=2.97$ for BC3(270-U)

Placing CFRP rods above the level of steel bars to reduce the beam ductility. The decrease percent in μ -index of beams BC5(270-UR), with respect to the control beam was 33%, whereas the decrease percent of BC1(270-SR) beam was 26.6%. The large reduction in ductility values of beams BC2(210-SR) was due to the insufficient strengthening length (210- cm), which led to non-conventional failure modes (peeling off or early debonding failure) as a result of degradation of the strengthening system. The percentages of decrease in the μ index of beams BC2(210-SR) was found equal to 66.6% with respect to the control beam (CB). .

V. COMPARISON OF NSM AND SNSM

The comparison of ultimate load and displacement at failure of numerical model of NSM and SNSM strengthened RC-beam is shown in the Figure-13 and the results are tabulated in Table 4 Here 8mm diameter CFRP bar is provided along full length of beam in the longitudinal sides(SNSM) and in the bottom side(NSM). From the Load v/s deformation curve found that SNSM imparts higher ductility to the beam when compared to NSM. Premature failure such as debonding failure occurs in NSM strengthened beam.

Table -4: Ultimate Load and Mid-Span deflection of NSM and SNSM strengthened beam

FEA model	Ultimate Load (kN)	Displacement at failure (mm)
NSM	125	28
SNSM	135	57

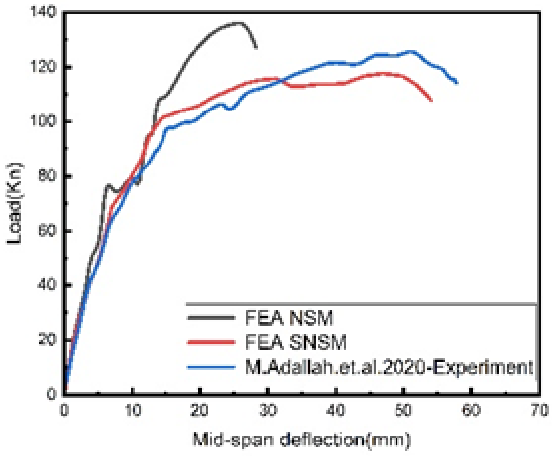

Fig -13: Comparison of Load V/S deflection curve of NSM and SNSM

VI. CONCLUSIONS

The present study aimed to analyze the global flexural response of RC beams strengthened with CFRP rods using the SNSM technique. From the numerical results obtained the following conclusions.

- The length of CFRP rods was found to have a considerable influence on the failure mode. BC2(2100-S) showed premature failure due to the insufficient strengthening length (2100mm).
- The strengthening position did not display significant impact on the failure mode.

- Beams BC1(2700-S) and BC3(2700-U) were both failed due to concrete crushing.
- By increasing CFRP bar diameter, bond strength increases because of that load carrying capacity increases
- Increase in the groove width beyond 2 times the NSM FRP bar diameter decreases the load carrying capacity.

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