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Experimental and numerical study of RC beams strengthened with bottom and side NSM GFRP bars having different end conditions

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HIGHLIGHTS

- Strengthening by bottom NSM bars of 180 cm lengths (straight and with 90° bent ends) recorded load capacity ratios of 177 and 185% respectively.
- A maximum enhancement in the load capacity ratio of 201% was recorded for beam strengthened with bottom NSM bars of 140 cm length and 45° bent ends.

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ABSTRACT

The present paper studied experimentally and numerically the behavior of RC beams strengthened with near surface mounted (NSM) GFRP bars with and without end anchorage. Both bottom and side NSM strengthening technique were investigated and compared. The end anchorage was made by bent 150 mm from the two ends of the NSM bars by 45° or 90°. The experimental results showed higher load carrying capacity for the RC beams strengthened by bottom NSM bars compared to those strengthened with side NSM ones due to the internal arm effect. The highest ratio of improvement in the load carrying capacity of strengthened beams compared with the control beam was 201% for strengthened beam with bottom NSM bars having end anchorage inclined by 45° while the lowest ratio was 142% for the same strengthened beam with side NSM. The experimentally investigated beams and other beams were numerically simulated using 3-D elastic-plastic finite element analysis. There is a good agreement between the numerical and the experimental results. Therefore, the numerical work was extended to focus on the effect of NSM location. These results showed that, strengthened beams by NSM bars with the same internal arms and without end anchorage recorded the same load carrying capacity regardless of the location of the NSM bars either bottom or side. Furthermore, strengthened beams by side NSM bars with end anchorage embedded horizontally in the confined portion of the beam cross section showed significant improvement in the load carrying capacity of the strengthened beams compared to those with end anchorage embedded vertically in the concrete cover of the beam side.

1. Introduction

Externally bonded (EB) and near surface mounted (NSM) using fiber reinforced polymer (FRP) reinforcements have become the most commonly strengthening methods used to upgrade the flexural and shear capacities of reinforced concrete members. In Both techniques the strengthening materials are bonded into the tensile face (bottom face) of RC beam. In the EB technique one or more strengthening plates or laminates are bonded to the tension surface of the strengthened beam while in the NSM technique the strengthening bars or strips is bonded to cutting grooves into the tensile face of the beam. The performance of NSM bond has been studied elsewhere [1–5].

Although bonding the NSM strengthening materials into slits increased the bond capacity and protects it from external damage and thus increasing both flexural and shear capacity of structural members, it still has several limitations. Among these limitations is the debonding of NSM strengthening materials and concrete

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cover separation before reaching the maximum tensile strength of the NSM materials or concrete compression failure [6–17].

Several studies were performed to enhance the bond efficiency and delay the concrete cover separation [7,18–23]. Mechanical mechanism (End anchorage steel bar bonded to the NSM CFRP bars and attached to the beam by steel connectors) and external wrapping [7] were used to anchorage the ends of the NSM FRP bars and thus delayed debonding failure and concrete cover separation. Reda et al. [18] suggested a new method to delay concrete cover separation and FRP bars debonding by bent NSM GFRP bars during their manufacturing with 45° and 90°. The inclined ends were used as end anchorage for the NSM bars to delay and prevent the NSM GFRP bars debonding and concrete cover separation and thus increasing the load carrying capacity of the strengthened RC beams. The pre-stressing of NSM reinforcement was also used to enhance the capacity of the strengthened RC beams [20–23].

Due to the many variables affecting the bond and behavior of RC beams strengthened with NSM reinforcement, the use of analytical and numerical analysis was become essential to understand the aspects of this technique and thus decreasing the experimental works. Obaidat et al. [24,25] studied experimentally and numerically the behavior of RC beams strengthened with CFRP bars. Two different models for the CFRP bars and two different models for the concrete–CFRP bars interface were investigated. The results showed that increasing the CFRP bar length increased the ultimate load which also justified with the numerical results. Hawileh [25] developed a numerically three dimensional (3D) nonlinear finite element (FE) model to predict accurately the load-carrying

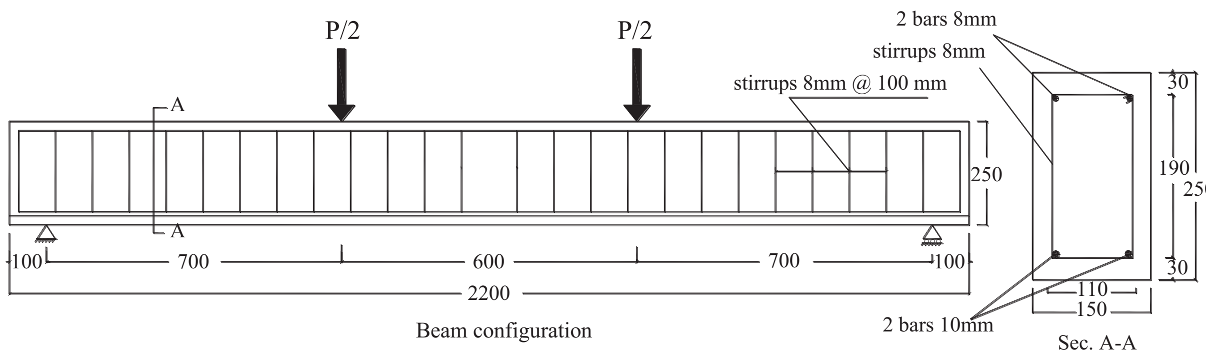

Fig. 1. Beam details.

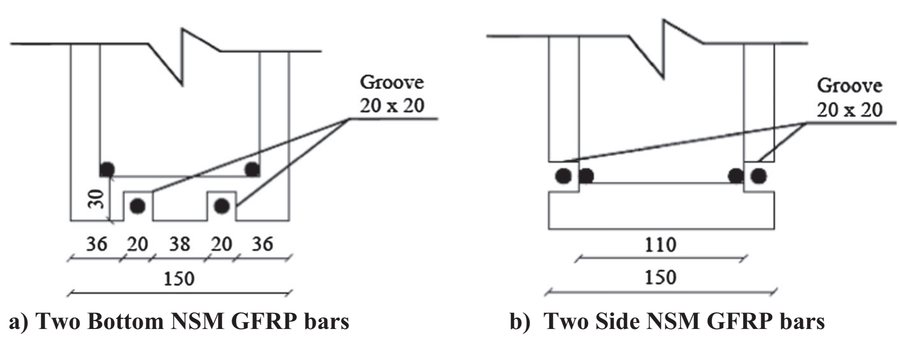

Fig. 2. Grooves locations.

Table 1
Details of the control and strengthened beams.

Group	Beam ID	N_b	Bar length (mm)	End conditions	Test variables
Control beam	CB	–	–	–	CB
Group-A	B2-180/0	2	1800	Straight	NSM strengthening
	B2-180/90	2	1800	90° inclined bent end	End anchorage
	B2-140/90	2	1400	90° inclined bent end	End anchorage and GFRP bar length
	B2-140/45	2	1400	45° inclined bent end	End anchorage bent angle
Group-B	S2-180/0	2	1800	Straight	NSM location
	S2-180/90	2	1800	90° inclined bent end	NSM location and end anchorage
	S2-180/45	2	1800	45° inclined bent end	End anchorage bent angle
	S2-140/90	2	1400	90° inclined bent end	NSM location and GFRP bar length
	S2-140/45	2	1400	45° inclined bent end	End anchorage bent angle and NSM bar length

N_b, number of GFRP strengthening bars.