



Effect of concrete cover thickness and main reinforcement ratio on flexural behavior of RC beams strengthened by NSM-GFRP bars

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ABSTRACT. Experimental and numerical programs were conducted to investigate the effect of concrete cover and area of main steel reinforcement on the flexural behavior of strengthened RC beams by near-surface mounted glass fiber reinforced polymeric (NSM GFRP) bars of different lengths. Nine beams divided into three main groups were tested under four-point bending. The three beams of the first group were strengthened by different lengths of GFRP bars and having a concrete cover of 50 mm, while the three beams in the second group were strengthened in a similar manner as those of the first group but the concrete cover was 30 mm. The main steel reinforcement in the first and second groups was $2\phi 10$. The three beams of the third group were similar to those of the first and second group but the main steel reinforcement was $2\phi 16$. The 3-D FE commercial ANSYS program was used for the numerical work. The experimental results showed that decreasing the concrete cover increased the flexural capacity of the strengthened RC beams but this improvement disappeared by decreasing the NSM GFRP bar length. The numerical results showed an agreement with the experimental results.

KEYWORDS. Near Surface Mounted; Flexural Strengthening; Concrete Cover Separation; FE models.



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INTRODUCTION

The NSM is used in many countries for repairing and strengthening of structural members. The NSM technique is recognized as a promising method for increasing the load-carrying capacity of RC beams. The implementation process is divided into two main stages: the first stage is cutting grooves into the concrete cover of reinforced concrete elements. The second stage is the inserting of FRP rods into these grooves and bonding by an epoxy resin. The NSM technique is a very promising method for the rehabilitation of RC members. Many researchers have introduced the advantages of the NSM technique over the conventional methods [1-5]. Firstly, the NSM bars are protected by the concrete cover, thus they are less exposed to accidental damage such as fire, in comparison to bonded FRP plates. Secondly, the use of NSM is less time consuming and requires less efforts than many other techniques such as concrete jacketing or steel reinforcements.

Over the last twenty years, a great deal of research was deployed to the behavior and flexural strength of RC members strengthened by NSM FRP rods. Previous studies focus on many aspects of the behavior of RC beams strengthened NSM GFRP rods such as ultimate flexural and shear capacities, ultimate deflection and the failure modes [6-15]. Furthermore, A lot of laboratory experimental works were carried out to explore the bonding behavior between NSM FRP bars and concrete, the effect of FRP anchorage system, NSM FRP length, type of epoxy, dimensions of grooves, size, shape, and type of rebars and concrete strength [16-21]. Lot of studies have worked to increase the bonding capacity in order to increase both the flexural and shear capacity of the strengthened RC beams. On the other hand, other works [22-25, 29] used the finite element method [FE] in predicting the measured experimental results. Three-dimensional (3D) nonlinear FE model was developed for simulating the flexural behavior of RC beams strengthened by NSM technique systems. The numerical results obtained from these studies reflected the performance of NSM-FRP bars when used as internal reinforcement against flexure in RC beams.

This paper presents the results of an experimental and numerical study on flexural behavior of strengthened RC beams by glass fiber reinforced polymer (GFRP) rods. The study aimed to reduce the concrete cover from 50 mm to 30 mm while varying the steel reinforcement ratio and using different lengths of GFRP bars.

EXPERIMENTAL PROGRAM

Specimens Geometry and Reinforcement

The reinforced concrete beams were designed according to ACI 318 (2011) [26]. The cross-sectional dimensions of the specimens were 200 mm × 300 mm. The total length of the beams was 2300 mm and the loaded span was 2200 mm. The main steel reinforcement consisted of 2Ø10 mm bars or 2Ø16 mm depends on the type of test group with 2Ø8 mm bars as compression steel reinforcement as shown in (Fig. 1). The shear reinforcement consisted of 8 mm stirrups spaced 100 mm center to center throughout the beam span. After 28 days of curing time, the first stage of preparation was undertaken, i.e. cutting grooves into the concrete cover with 25 mm, and 30 mm in depth and width, respectively. The second stage were installing the GFRP rods in the grooves using epoxy. The specimens were kept for at least 7 days for the curing of epoxy before testing.

Experimental Matrix

A total of nine RC beams were tested. The nine beams were divided into three groups depending on the variable parameters studied. Each group consisted of three beams reinforced respectively with GFRP bars of lengths 550 mm, 1150 mm, 1800 mm. In Group A, the three beams have 2-Ø10 mm as a main reinforcement and the beams concrete cover was 50 mm and GFRP bars of lengths 550 mm, 1150 mm, 1800 mm for beams B_{0.55-A}, B_{1.15-A}, and B_{1.80-A}, respectively. In Group B the main reinforcement was 2-Ø10 mm and the concrete cover was reduced to be 30 mm with GFRP bars of lengths 550 mm, 1150 mm, 1800 mm for beams B_{0.55-B}, B_{1.15-B}, and B_{1.80-B}, respectively. In Group C, the main reinforcement was increased to 2-Ø16 mm and the concrete cover was 30 mm as group B with GFRP bars of lengths 550 mm, 1150 mm, 1800 mm for beams B_{0.55-C}, B_{1.15-C}, and B_{1.80-C}, respectively. Further details of the tested beams are presented in Tab. 1.

Material Properties

The specimens were cast from one batch using the same concrete mix design ratios. The casting was done using Type I ordinary portland cement (Cem 42.5N). The coarse aggregates were dolomite of 20 mm maximum aggregate size. Natural



sand was used as a fine aggregate. Clean tap drinking water was used for mixing and curing of all beams. The mix design for one cubic meter was, water/cement of 0.45, water contents of 180 kg., sand content equals 635 kg, dolomite content equals 1155kg, and Superplasticizer dosage equals 4.0 kg.

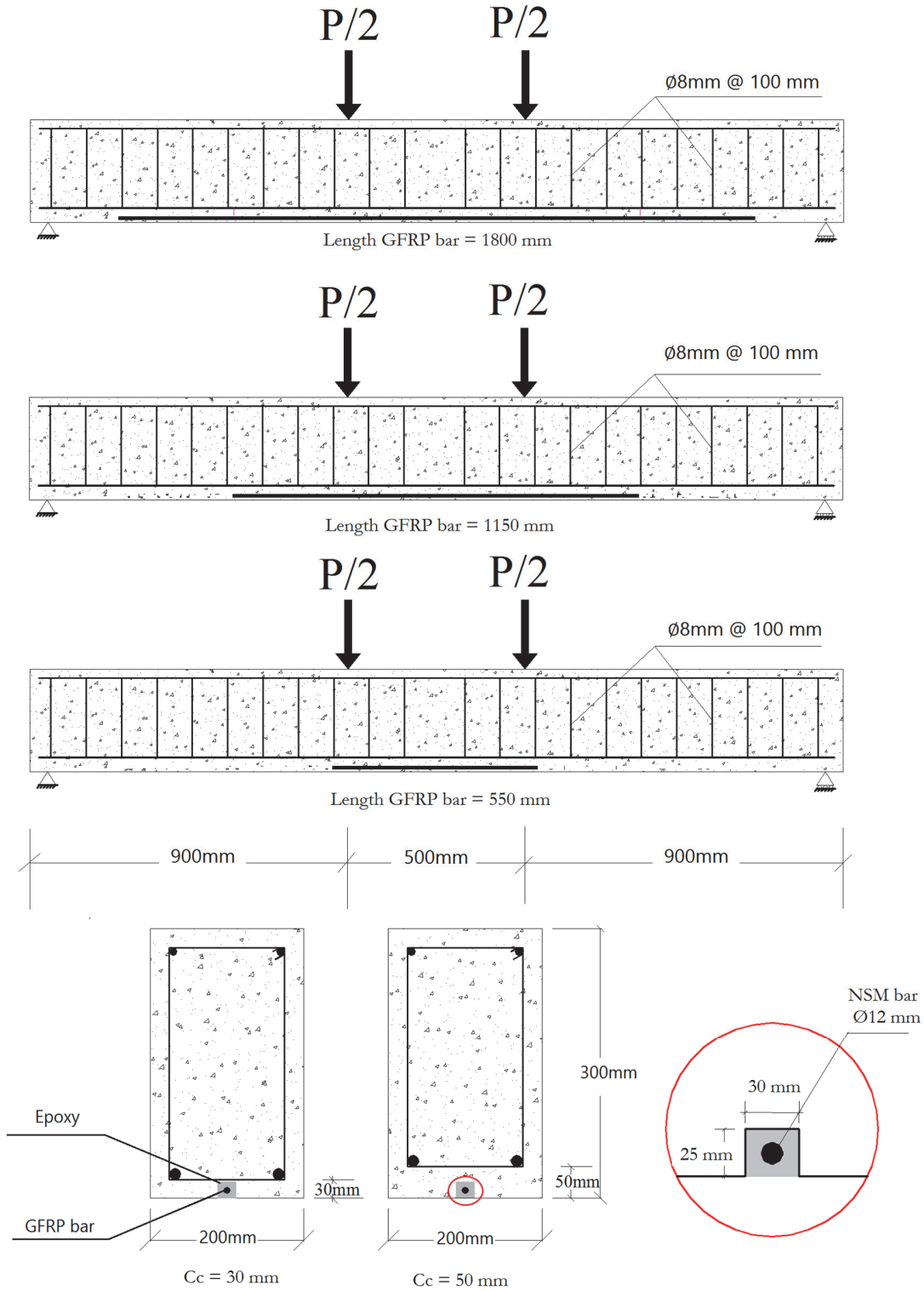


Figure 1: Specimens design details

Based on tests of three 150 mm x 150 mm x 150 mm concrete cubes, The 28-day average compressive strength of the concrete was 35 MPa, while splitting tensile strength was 2.95 MPa based on tests of three 150 mm x 300 mm concrete cylinders. The yield and ultimate strength of $\varphi 8$, $\varphi 10$, and $\varphi 16$ mm steel bars were 480 MPa and 590 MPa respectively. The modulus of elasticity for all bars was 200 GPa. The GFRP bars made in (Haining Anjie Composite Material Co., Ltd., Haining, China) of $\varnothing 12$ mm diameter for strengthening in this research. The GFRP tensile strength and modulus of elasticity were 750 MPa and 56 GPa respectively. The MASTERBRACE SAT 4500 (BASF) type epoxy was used to bond the NSM GFRP bars to the concrete grooves.

Type of Series	Sample ID	Length of GFRP	Main steel	Concrete cover
Group – A	B _{1.80-A}	1800mm		
	B _{1.15-A}	1150mm	2- $\varnothing 10$ mm	50mm
	B _{0.55-A}	550mm		
Group – B	B _{1.80-B}	1800mm		
	B _{1.15-B}	1150mm	2- $\varnothing 10$ mm	30mm
	B _{0.55-B}	550mm		
Group – C	B _{1.80-C}	1800mm		
	B _{1.15-C}	1150mm	2- $\varnothing 16$ mm	30mm
	B _{0.55-C}	550mm		

Table 1: Test matrix.

Instrumentation and test set up

All beams tested under four points bending using a universal testing machine of 1000 kN maximum capacity as shown in (Fig. 2-a). A solid steel spreader beam was used to apply the load to the RC strengthened beams. A load cell was mounted between the machine and the rigid beam as shown in (Fig. 2-a). Moreover, LVDT was used to measure the deflection at the beam mid-span. Strain gages were used to measure the strains at the main reinforcing steel and NSM-GFRP rods by bonding it to the middle of bars. The data logger system was used to collect the data as shown in (Fig. 2-b).

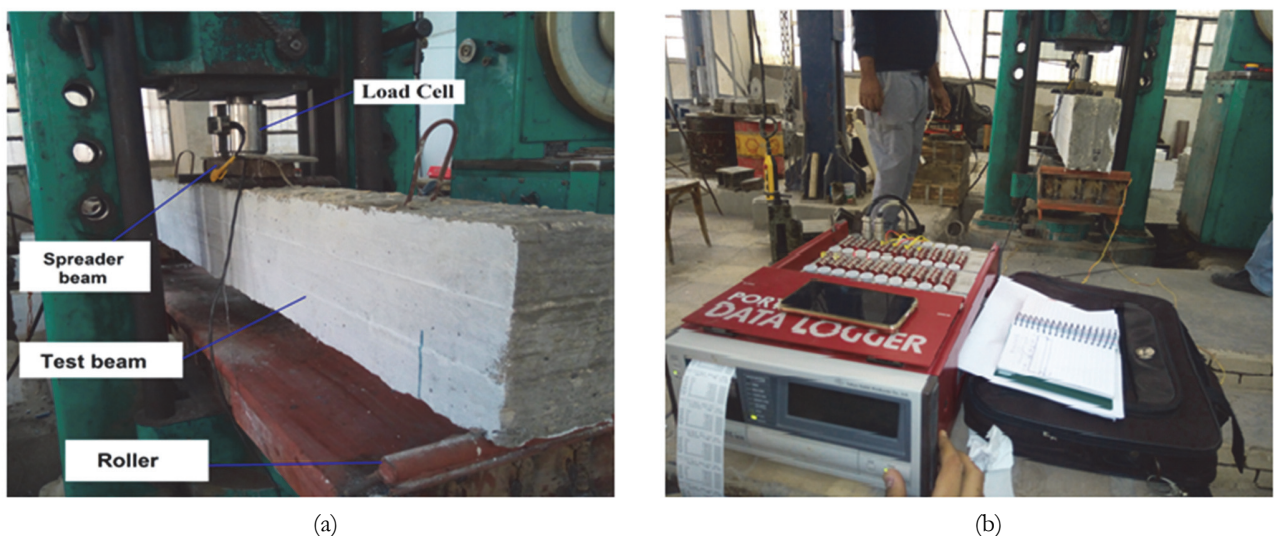


Figure 2: Flexural test setup and data logger

RESULTS AND DISCUSSION

The experimental results of the nine tested beams will be analyzed and discussed in the following sections. The effect of changing the depth of concrete cover from 50 mm to 30 mm on the efficiency of strengthening by NSM GFRP rods of different lengths will be mentioned. This is followed by analyzing the effect of main steel reinforcement on the flexural behavior of the strengthened RC beams by different lengths of NSM GFRP rods.

Effect of Concrete cover depth on Load – Deflection Curve

The effect of concrete cover depth on load-deflection behavior of strengthened RC beams by different lengths of NSM GFRP rods is shown in (Fig. 3). The solid line in the curves represents beams having a concrete cover of 50 mm while the dashed line is for the concrete cover of 30 mm. The ultimate loads for beams with 30 mm concrete cover thickness $B_{1.80-B}$, $B_{1.15-B}$ and $B_{0.55-B}$ increased by 13.4%, 5.56% and 9.0%, compared to beams with 50 mm concrete cover thickness $B_{1.80-A}$, $B_{1.15-A}$ and $B_{0.55-A}$, respectively. The results showed an improvement in the flexural capacity value of the strengthened RC beams with a 30 mm concrete cover compared to RC beams with a 50 mm concrete cover. This improvement reduced by decreasing the NSM GFRP bar length as shown in (Fig.3). It was also observed that, the improvement in the ultimate load of the strengthened RC beams of concrete cover 30 mm was very clear in the case of beam $B_{1.80}$.

Strain distribution on Main Steel Reinforcement and GFRP bars with alteration of Concrete cover.

Fig. 4 shows the effect of concrete cover on the load – main steel strain behavior for the strengthened beams by NSM GFRP rod of lengths 1800 mm and 550 mm (i.e. $B_{1.80}$ A and b and $B_{0.55}$ A and B). The strains were measured in the middle of the main steel bars in the mid-span of the tested beam. The main steel bar strains of beam $B_{1.80-B}$ strengthened with NSM GFRP bar of length equals 1800 mm with the concrete cover of 30 recorded the higher tensile strains in steel bar compared to beam $B_{1.80-A}$ with the concrete cover of 50 mm. So, it could be concluded that, reducing the distance between the main steel reinforcement and NSM GFRP rods increase the efficiency of the main steel leading to higher beam capacity and strains as shown in (Fig. 5).

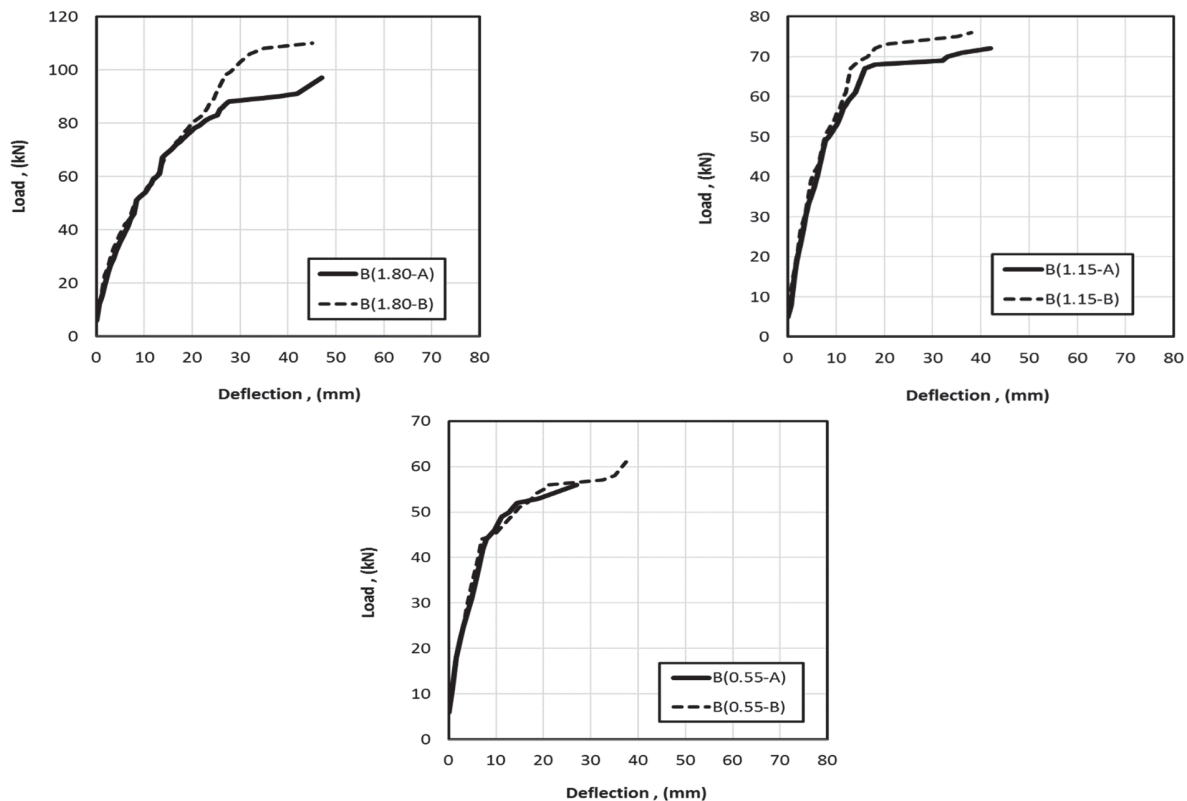


Figure 3: Effect concrete cover on load - deflection behavior at different lengths of strengthening GFRP bars

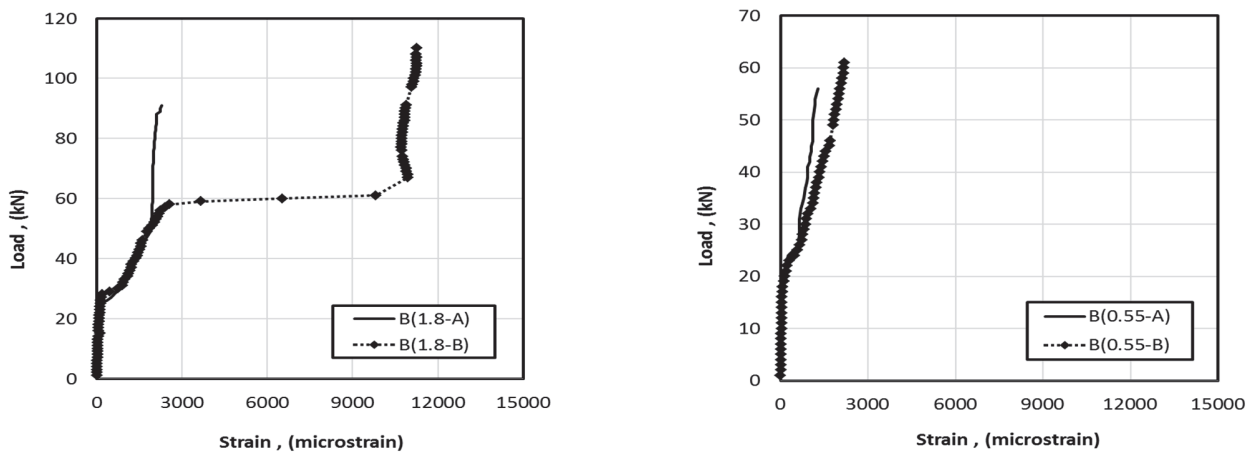


Figure 4: Effect concrete cover on strain in main reinforcements

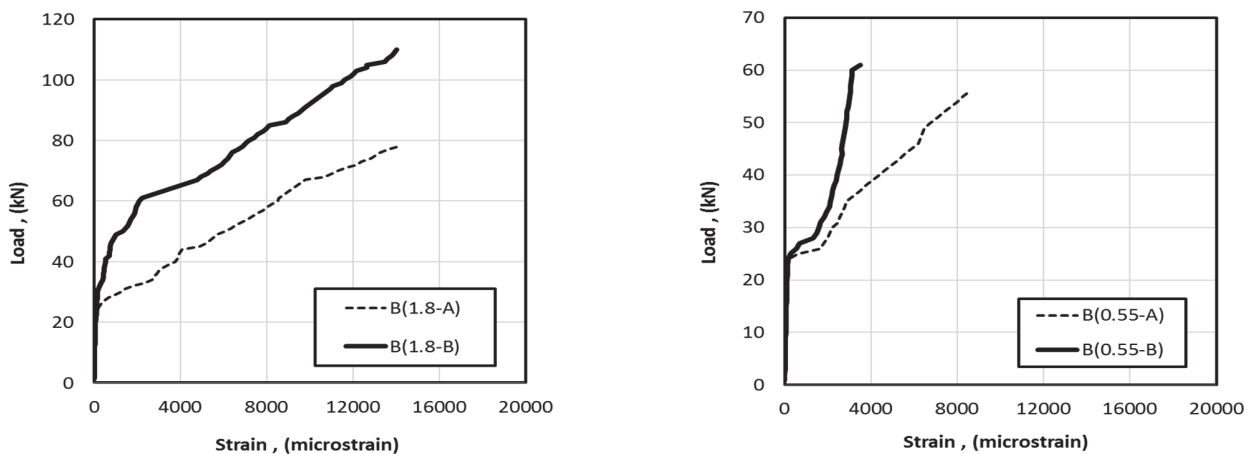


Figure 5: Effect concrete cover on strain in the middle of NSM GFRP bar

Effect of steel reinforcement ratio

Fig. 6 shows, the load-deflection curve for group b and c beams with 30 mm concrete cover but having different main steel reinforcement ratio. It can be seen that increasing the main steel reinforcement ratio leads to increasing the beam's ultimate loads. Besides, it reduces the efficiency of the GFRP bars as shown in Fig. (6). By increasing the main steel reinforcement from 2Ø10 mm to 2Ø16 mm, the RC beam flexural strength for the B1.80, B1.15, and B0.55 with a 30 mm concrete cover increased by 66.6%, 75.7%, and 133.3%, respectively. It can be concluded that the efficiency of the NSM-FRP system decreased with increasing the steel reinforcement ratio.

Effect of main steel reinforcement ratio on strain distribution in NSM GFRP bars.

The effect of the main steel reinforcement ratio on load –strain behavior in NSM GFRP bars for beams having a concrete cover of 30 mm and NSM GFRP bar lengths of 1800 mm and 550 mm is shown in (Fig.7). It is clear that the efficiency of the NSM-FRP system decreased with increasing the steel reinforcement ratio. So that the strain in the GFRP bars exhibited the same value with different steel ratios. It can be concluded that the steel reinforcement ratio affected the NSM-GFRP system's role in strengthening.

Crack Pattern and Mode of Failure

The failure modes of beams strengthened with NSM GFRP rods that have a concrete cover of 30 mm are shown in (Fig. 8) - Group B. For beam B_{1.80-B}, it is observed that the yielding of the reinforcing steel occurred firstly, then it is followed by debonding and separation of the concrete cover. Beam B_{1.15-B} failed in a flexural mode which is yielding of the reinforcing steel followed by GFRP debonding due to stress concentration at the ends of GFRP bar. A typical mode of



failure of under reinforced concrete beams was observed in the case of beam B_{0.55-B}, where the crack started at the critical section (end of the GFRP rod), which is near the constant moment region and then transferred to the strengthened section. Also, with increasing of bottom steel reinforcement ratio Group C, follows the same mode of failure of beams as in Group B

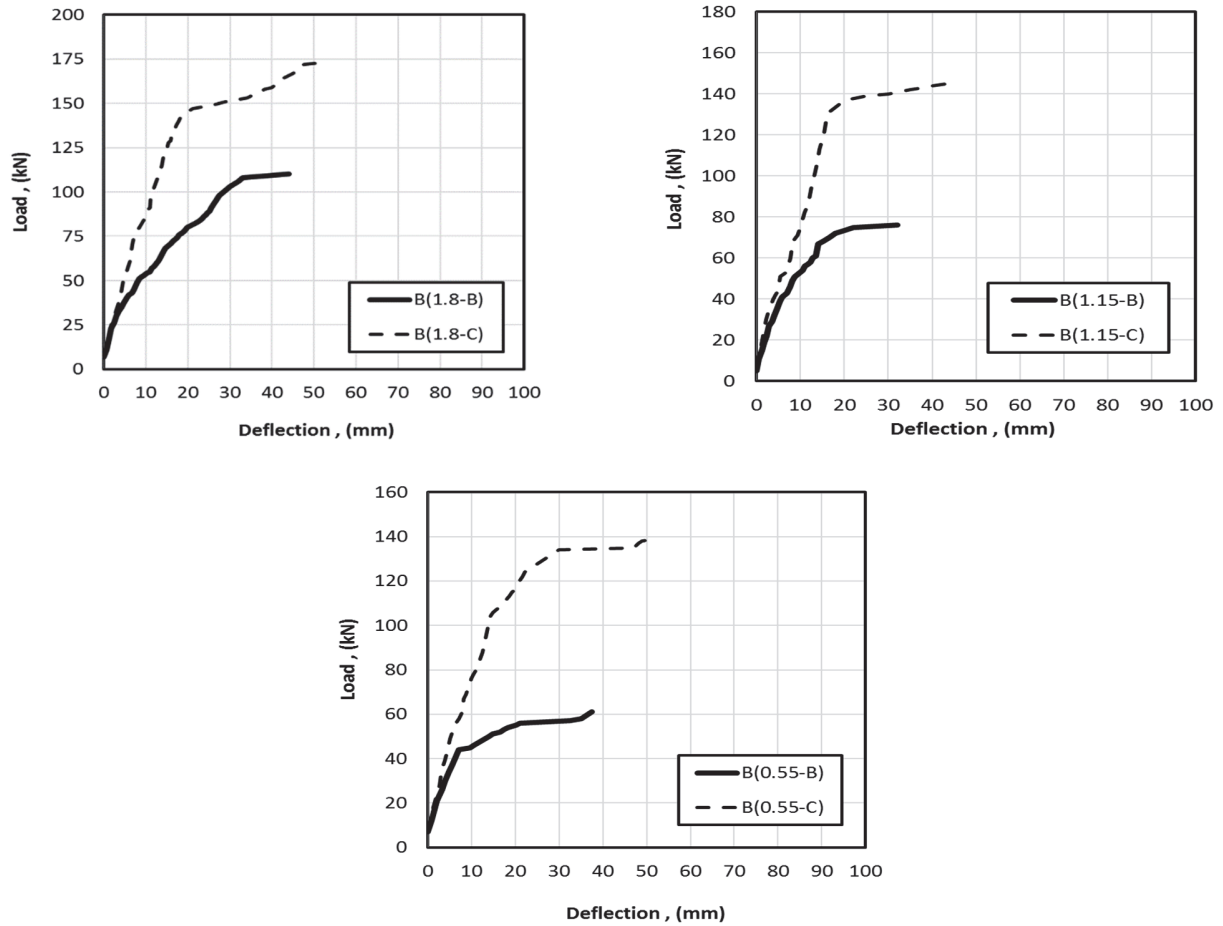


Figure 6: Load – Deflection Curve during effect of increase ratio steel

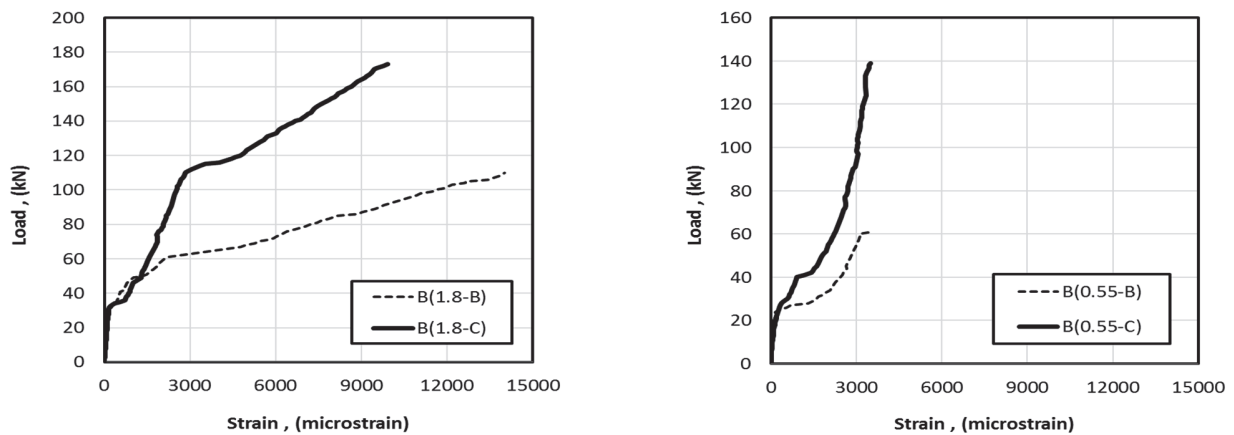


Figure 7: Strain distribution on GFRP bars during increase ratio steel reinforcement

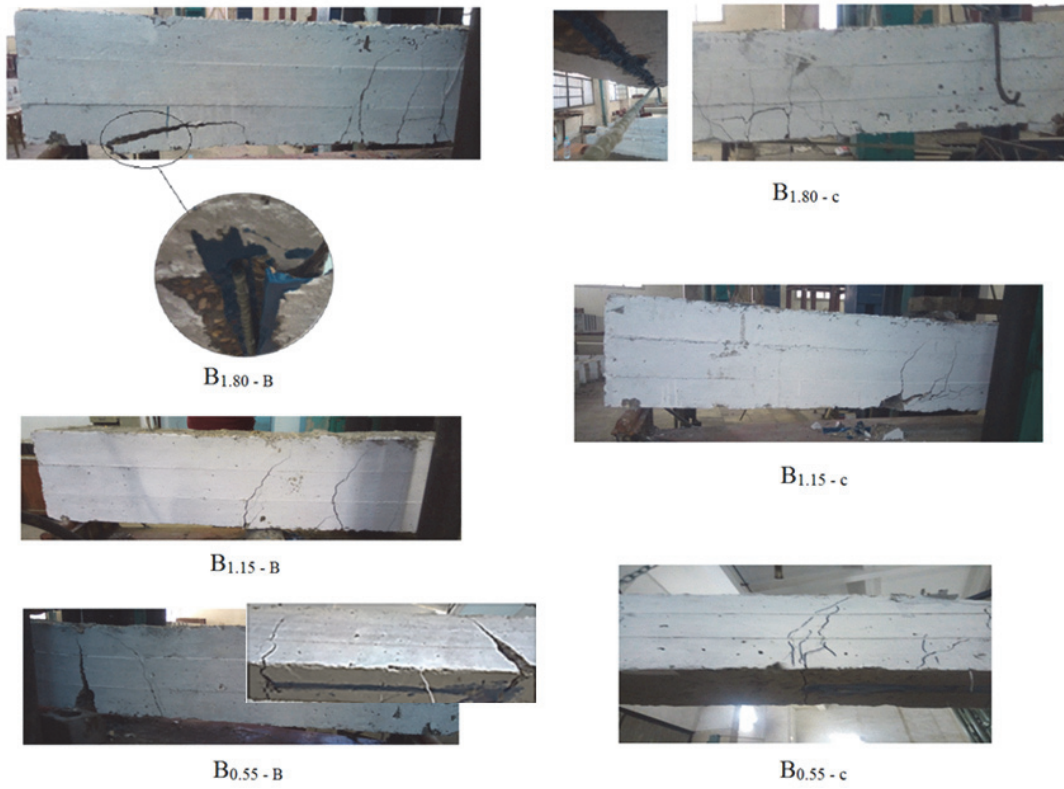


Figure 8: Modes of failure for Group B, C.

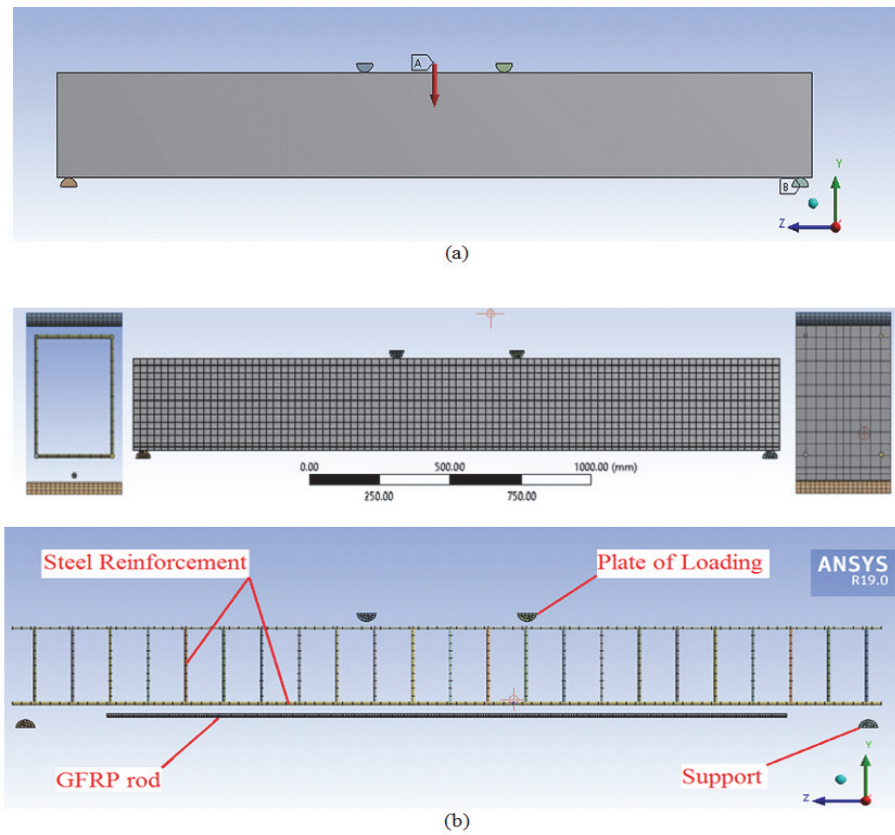


Figure 9: The Numerical Model: (a) RC beam, (b) Structural model and Meshing



NUMERICAL MODEL

The three dimensional (3-D) finite element (FE) analysis software ANSYS [28] was used for the analysis of the reinforced beams strengthened with NSM GFRP rods. Fig. 9(a) presents the modeled beam, supports and loading plates. The dimensions of the full-size beams were 2300 mm × 200 mm × 300 mm and the span between the supports was 2200 mm, while, Fig. 9(b) shows the structural model and mesh used in this study. The element size has been adopted to be 25 mm based on the mesh sensitivity. Solid element (Solid 65) has been used to define the 3-D of the structural reinforced concrete. Solid 65 able to crack in tension and crush in compression. This element was simulated by 8-nodes and three translational degrees of freedom at each node. However, the steel reinforcement was modeled using LINK 180. Furthermore, 3-D structural solid element (Solid 45) was used to model the loading plate and supports. Tab. 2 presents the mechanical properties of the materials used in the numerical modeling.

Material	Properties	Unit	Data
Concrete	Compression strength	MPa	31.0
	Tensile strength	MPa	2.0
	Young's modulus, E_c	MPa	17500
	Passion's ratio		0.2
Main Steel	Young's modulus, E_s	MPa	196000
	Yield stress, f_y	MPa	480
	Passion's ratio		0.2
Stirrups	Young's modulus, E_s	MPa	196000
	Yield stress, f_y	MPa	250
	Passion's ratio		0.2
GFRP rod	Young's modulus	MPa	56000
	Tensile ultimate strength	MPa	750
	Passion's ratio		0.2
Epoxy resin	Young's modulus	MPa	3780
	Tensile yield strength	MPa	30
	Passion's ratio		0.35

Table 2: Material properties used in the numerical study.

COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

Load – Deflection Curve

The load-deflection curves which obtained for Group-B and Group-C from the experimental results and the FE models are shown in (Fig. 10). It is clear that the experimental and numerical load-deflection results were in good agreement. So, the FE models demonstrated the ability to simulate the behavior of reinforced concrete beams strengthened by the NSM technique. The simulation perfectly reflected the bonding between concrete, steel reinforcement and strengthening by NSM-GFRP rods. Moreover, the FE models result in confirming to affect the flexural capacity of beams strengthened with alteration of the concrete cover. With the aid of Fig. 6, it can be concluded that the effect of increasing the amount of tensile reinforcing steel on the efficiency of strengthened beams is more pronounced in the case of short GFRP bar length.

Strain distribution on along NSM GFRP bars

Fig. 11 illustrates strains distribution along the GFRP bars by FE models compared to the strains measured experimentally. Good agreement between the experimental and predicted numerically GFRP rods are observed.

Crack patterns

Numerical results show that the concrete cover thickness seems to have little influence on the first crack loading compared to the variation of the internal main steel. Fig. 12 shows a crack pattern of beam B_{1.15-A} and beam B_{1.15-B} during loading. It can be observed that the first cracking load for B_{1.15-B} and having concrete cover equals 30 mm was recorded at 16 kN. While this load was 15kN for beam B_{1.15-A} having concrete cover equals 50 mm.

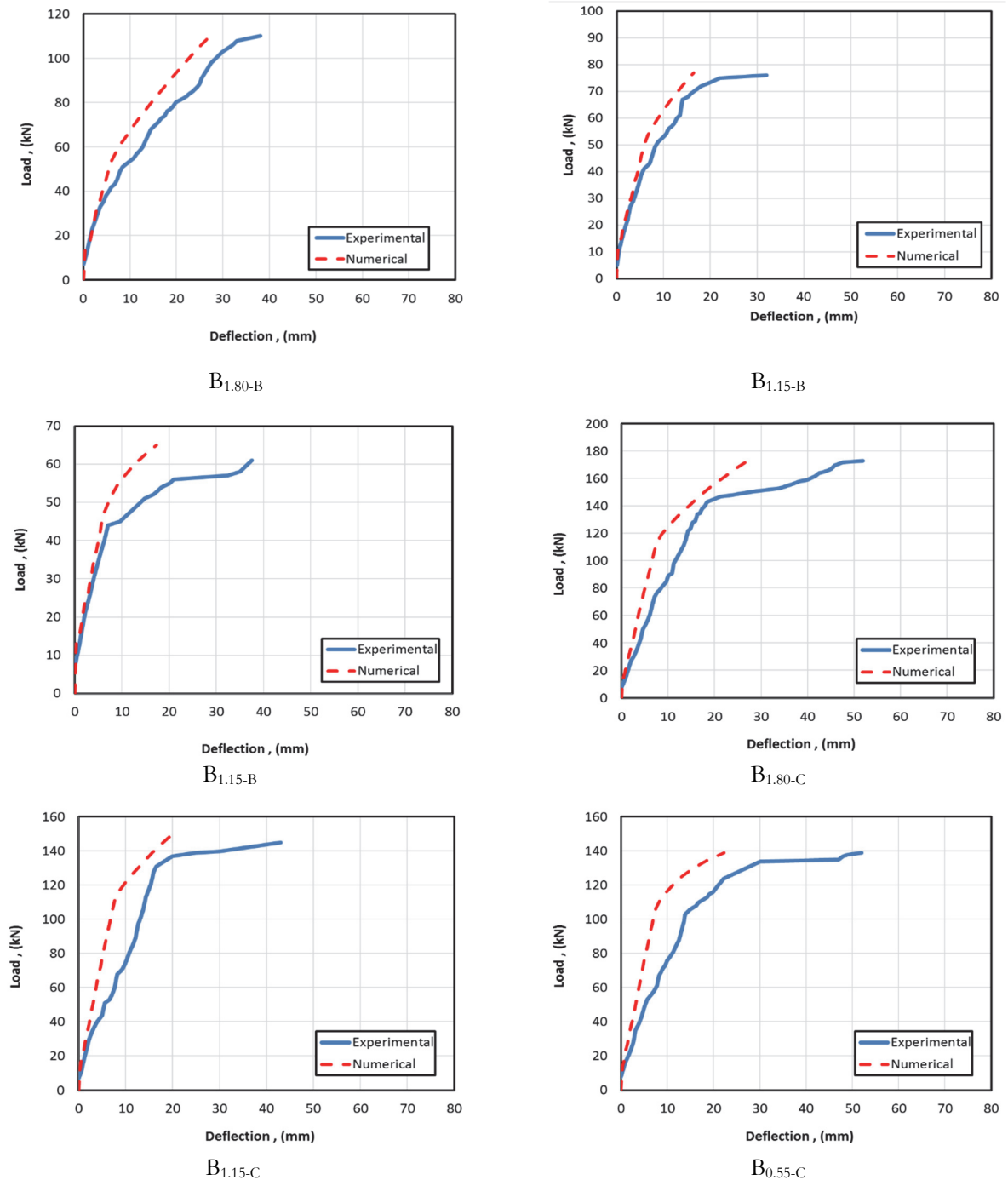


Figure 10: Comparison between experimental and numerical results

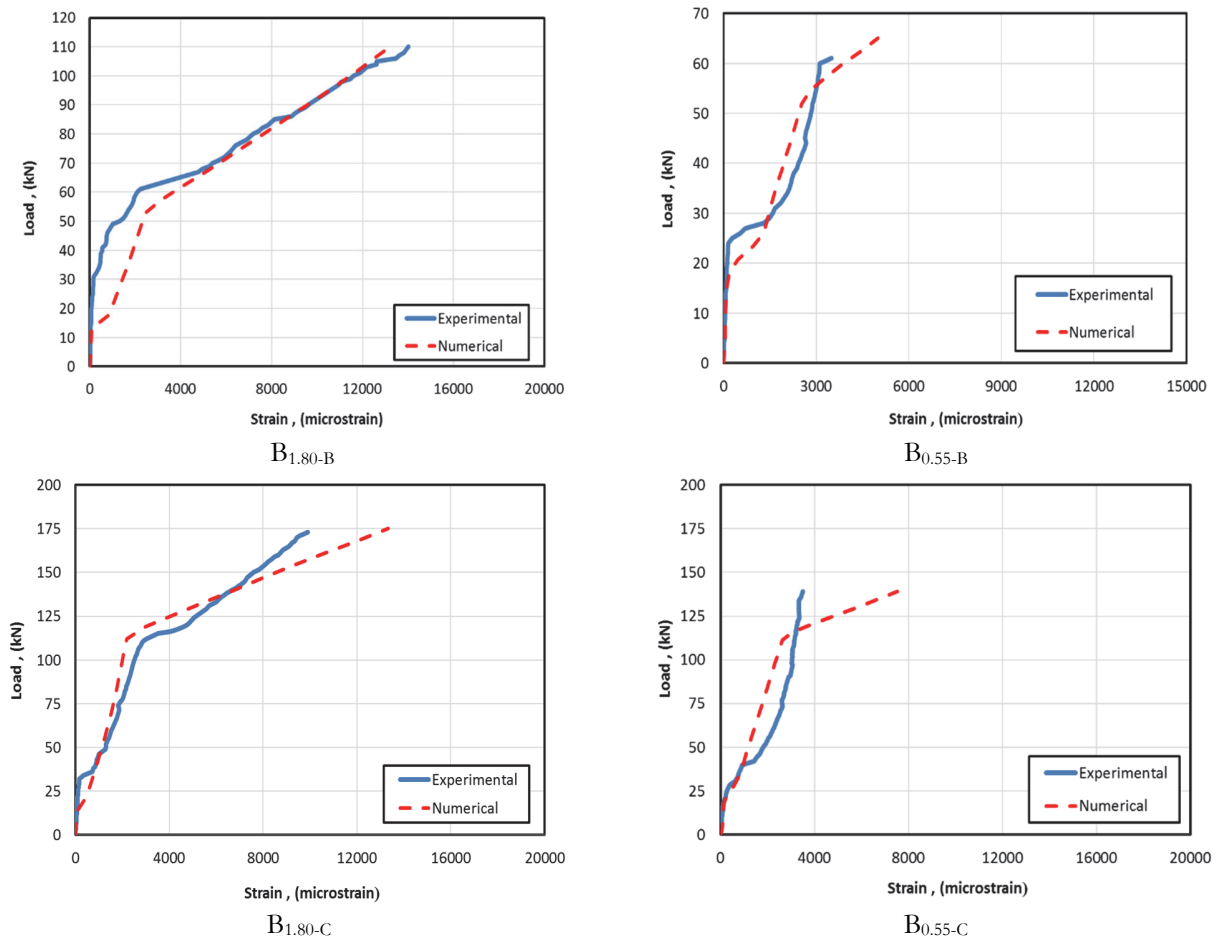


Figure 11: Comparison between the numerical and experimental strain at the mid-span of the GFRP bar

CONCLUSIONS

In this study, the behavior of the NSM GFRP-strengthened RC beams was investigated experimentally and numerically concerning the effects of variations concrete cover, steel reinforcement ratio and lengths of NSM GFRP bars. Based on the results of this work the following conclusions could be supported:

- Decreasing the concrete cover increased the flexural capacity of the strengthened RC beams by NSM GFRP rods. This improvement disappeared by decreasing the NSM GFRP bar length.
- The strengthened beams results illustrated that RC beam flexural strength increased with increasing the main steel reinforcement ratio. Increasing tensile steel reinforcement from 2-Ø10mm to 2-Ø16mm increased the ultimate load of the strengthened RC beams by about 57.27%, 90.7% and 127.8% for respectively NSM GFRP bar lengths of 1800mm, 1150 mm and 550 mm.
- Higher strain induced in NSM GFRP bars as the main tensile steel reinforcement ratio decreased and concrete cover increased.
- Strengthened beams with NSM GFRP bars length extended outside the constant moment region showed a similar mode of failure, i.e. yielding of the reinforcing steel followed by debonding and separation of the concrete cover. In the case of beams strengthened by shorter NSM GFRP rods, the crack started at the critical section (end of the GFRP rod), which is near the constant moment region and then transferred to the strengthened section.
- A 3-D FE model was developed using the commercial software ANSYS to simulate the flexural behavior of reinforced concrete beams strengthened by NSM GFRP rods. The model was able to predict the results found experimentally in an acceptable manner.

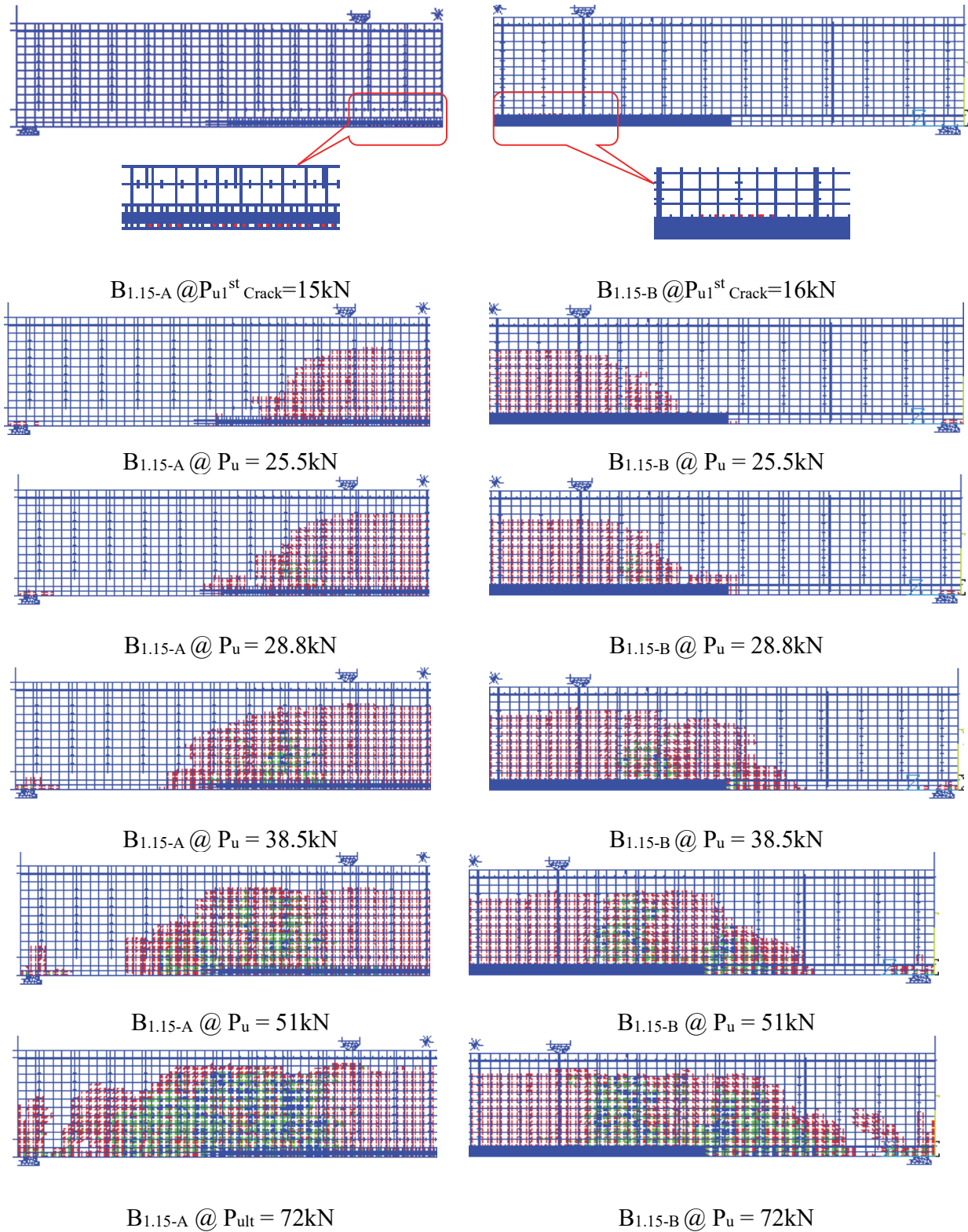


Figure 12: Comparison of a numerical crack pattern for strengthened beams with varying of concrete cover



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