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Effect of Internal and External Reinforcement Ratios on RC Beams Strengthened with NSM Prestressed Fiber Reinforced Polymer Rods

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ABSTRACT: In recent years numerous investigations have been conducted on strengthening of reinforced concrete (RC) beams using fiber reinforced polymer (FRP) bars or sheets. However, the studies on the application of varying FRP prestressing are sparse. The present finite element analysis (FEA) study involves flexural strengthening of RC beams with near surface mounted (NSM) pre-stressed carbon fiber reinforced polymers (CFRP). The FEA beam model was first validated using the data from an existing experimental study in the literature. The beam model had a good agreement with the experimental results. Parameters considered were internal steel and external CFRP reinforcement ratios of the RC beams under 0 %, 20%, 30%, and 40% pre-stressing levels. The finite element results revealed that for all CFRP reinforcement ratios, the 30% pre-stressing level showed significant ultimate load and considerable ductility. The increase in pre-stressing level of CFRP up to 30% resulted in higher load capacity for all steel reinforcement ratios.

1 INTRODUCTION

Fiber reinforced polymers (FRP) have gained popularity in recent years for strengthening of deteriorating RC structures. Strengthening with FRP is achieved by two main methods, namely, externally bonded reinforcement (EBR) and near surface mounted (NSM). The NSM strengthening technique involves inserting the FRP reinforcement (bars or strips) in a pre-cut groove on the surface of RC members, which is then filled with epoxy adhesive. The use of EBR has various disadvantages such as debonding and strength loss due to exposure to severe environmental conditions (freeze and thaw). Whereas, there are several advantages associated with NSM technique including easier and faster field application, concrete and FRP bar bond improvement, and damage prevention due to environmental exposure.

Although NSM technique has been proven to increase the load carrying capacity of RC beams; however, the use of NSM technique along with suitable pre-stressing level of FRP results in higher load carrying capacity without exceeding the serviceability limit state (SLS) deflection level of RC beam (Rezazadeh et al., 2014). Furthermore, NSM prestressed CFRP strips for strengthening of RC beams revealed higher first-cracking, and steel-yielding capacities up to a certain pre-stressing level of no more than 60% (You et al. 2012). Kim et al. (2008) used pre-stressed CFRP sheets to strengthen RC beams and they studied the effect of different pre-stressing levels. Similar to Barros (2009), their findings revealed that the optimum pre-stressing level of CFRP sheet was between 10-20% and that with higher pre-stressing level, smaller crack width was observed. Moreover, the use of CFRP sheets or strips for strengthening improved the failure mode of the unstrengthened beam from concrete crushing to CFRP failure in the strengthened beam (Xue et al. 2008). On the other hand, the application of prestressing FRP elements enhanced the failure mode from FRP debonding to FRP rupture (Xue et al. 2008; Hosseini et al. 2014). It is worth to mention that the use of pre-stressed FRP elements to strengthen RC beams improved the load carrying capacity and decreased the ultimate deflection.

In the present study, finite element analysis (FEA) of RC beams were generated using ANSYS software program. The models were validated with an experimental study by Nordin and Taljsten (2006). The beams were further pre-stressed with NSM FRP rods at different levels (20%, 30%, 40%). Internal and external reinforcement ratios parameters combined with various prestressing levels were also investigated. To achieve an optimum strengthening strategy for RC beams, load capacity, deflection, and modes of failure were analyzed under all these variables.

2 VALIDATION OF FEA BEAM MODELS

The FEA beam models were validated with an existing experimental study in the literature in order to confirm the accuracy of the results in terms of predicting the flexural behavior, load carrying capacity, load versus displacement curves and ductility. The validations were considered acceptable when the difference between the FEA models and the experimental results was less than 10%.

2.1 Details of selected experimental study for validation RC beam models

Nordin and Talsjsten (2006) tested fifteen RC beams. One as-built beam called reference beam (ref.), four strengthened beams with non-prestressed NSM-CFRP rods, and ten strengthened beams with pre-stressed NSM-CFRP rods. Each beam was strengthened with 10 x 10 mm square CFRP rod inserted into a pre-cut groove of 15 x 15 mm and the groove was filled by epoxy to provide bonding between CFRP rod and concrete. The simply supported beams had a length of 4,000 mm, and a rectangular cross-section of 200 mm x 300 mm. The beams were reinforced internally with two steel bars of a 16 mm diameter for tensile and compressive longitudinal reinforcement, and 10 mm bar stirrups with 75 mm spacing for transverse reinforcement. The parameters of the experiment were, the bond length (3,200 mm, 4,000 mm), the CFRP rods type (Sto BPE NMSR 101S, and and Sto BPE NMSR 101M), and the targeted pre-stressing forces were 32 and 56 kN. The beams were tested under monotonic static loading in a four-point loading configuration. The pre-stressing forces were applied to the rods by jacking against the supports outside, and not in contact with, the beams. Concrete material had a modulus of elasticity of 35 GPa, compressive strength of 61 MPa, and tensile strength of 3.5 MPa (Nordin and Taljsten, 2006). The epoxy used in the pre-cut groove of 15x15 mm, has a modulus of 7 GPa, and a tensile strength of 31 MPa. The longitudinal reinforcement and stirrups have modulus of elasticity of 200 GPa, and tensile strength of 496 MPa. CFRP material properties are defined in Table 1. To validate the FEA models, the beams with 101S CFRP rods were selected.. Figure 1 shows the beam's cross-section dimensions and reinforcement details. To ensure the accuracy of the FEA models, the reference beam and the beam with pre-stressed CFRP rod (Type 101S) of 3,200 mm length were simulated.

Table 1. CFRP rods material properties

Material	Modulus E (GPa)	Strain ε_{ult}	Tensile Strength (MPa)
101S	160	5	2,800
101M	250	0	2,000

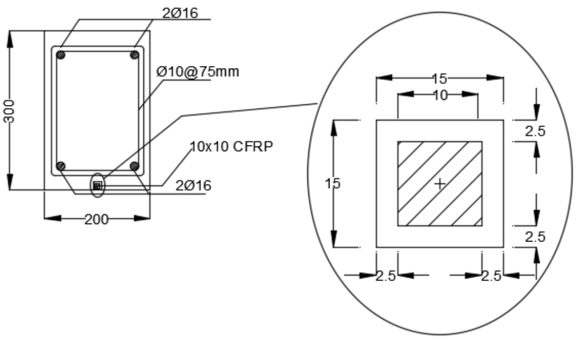


Figure 1. Dimensions, and reinforcement details of RC beams cross-section (all dimensions in mm).

2.2 Comparison of FEA beam models and experimental results

In this section, the FEA beam models and experimental results and overall flexural behavior were compared, and they were in good agreement. Table 2 depicts the cracking, yielding, ultimate loads and displacement values of the FEA beam models as compared to those of the experimental study. The validated models showed less than 10% difference with the experimental results. Similar to the experiment, in the FEA beam models, the reference beam had concrete crushing as a failure mode, and the non-prestressed and prestressed NSM-CFRP strengthened beams failed due to CFRP rod rupture. The rupture of the CFRP rod in FEA model was characterized at 70% of ultimate strain described by the design guidelines (ACI 440.2R, 2008). While in the experiment, the failure might have been occurred after all the fibers of the rod have ruptured. Therefore, the displacements in the FEA models were smaller compared to those of the experimental values. As it can be shown from the experiment and the FEA models results, the use of NSM CFRP strengthening improved the load capacities. Subsequently, the ductility increased when compared to the ref. model. However, the use of pre-stressed NSM CFRP rods reduced the ductility due to stiffer behavior that the pre-stressing method provides.

Table 2. Load and deflection values and failure modes comparison of FE model and test specimen

	Type	P_{cr} (kN)	D_{cr} (mm)	P_y (kN)	D_y (mm)	P_u (kN)	D_u (kN)	I_D	Failure mode
Ref.	Exp.	10	1.2	70	33	75	61	1.844	Mode a
	FE model	10.85	1.14	73.24	30.79	76.37	56.41	1.832	Mode a
	Conv. (%)	8.50	5.10	4.60	6.70	1.80	7.50	0.65	Mode a
PBS3	Exp.	23	2.3	105	26	120	38	1.46	Mode b
	FE model	24.76	2.21	106.46	25.46	125.65	35.43	1.39	Mode b
	Conv. (%)	7.6	3.9	1.4	2.1	4.7	6.8	4.8	Mode b

Exp.= Experiment, Conv.= Convergence, P_{cr} and D_{cr} = load and deflection at cracking, P_y and D_y = load and deflection at yielding, Pu and D_u = load and deflection at ultimate, I_D (D_u/D_y) = ductility index, Mode a= Concrete crushing, Mode b= CFRP rupture.

3 PARAMETRIC STUDY ON BEAMS WITH VARIOUS PRE-STRESSING LEVELS

The literature review discussed in the introduction summarizes some of the studies performed on pre-stressing of FRP-strengthened RC beams (Rezazadeh et al., 2014; You et al. 2012; Kim et al. 2008; Barros 2009; Xue et al. 2008; Hosseini et al. 2014; and Nordin and Taljsten, 2006). Those studies had examined the effect of various parameters; however, the combination of different parameters at different pre-stressing levels of FRP have not been studied. Therefore, the parametric studies in this section focused on investigating the effect of steel and FRP reinforcement ratios at different pre-stressing levels (Table 3).

Table 3. Parameters of study for various pre-stressing levels (0%, 20%, 30%, 40%)

Parameters	Values	
	%	Bars (mm)
Longitudinal steel reinforcement ratios	0.79	2ø16
	0.60	2ø14
	0.44	2ø12
CFRP reinforcement ratios	0.20	10*10
	0.13	8*8
	0.07	6*6

HSC = high strength concrete, NSC = normal strength concrete, LSC = low strength concrete

The models analyzed in the parametric studies were labeled as follows. The first number indicates the pre-stressing level i.e. 0, 20, 30, 40 refer to 0%, 20%, 30%, 40% pre-stressing level, respectively, followed by CFRP wording to refer to the rod material type. The third part of the models ID refers to the reinforcement amount and type. For steel reinforcement ratio, 79S, 60S, and 44S refer to 0.79%, 0.60%, and 0.44% steel reinforcement ratios, respectively. Similarly, for CFRP reinforcement ratio, C refers to CFRP, and the number preceding refers to its ratio. For instance, model ID, 30CFRP-44S, refers to the beam with CFRP pre-stressed to 30% level and 0.44% steel reinforcement ratio.

3.1 Effect of steel reinforcement ratio

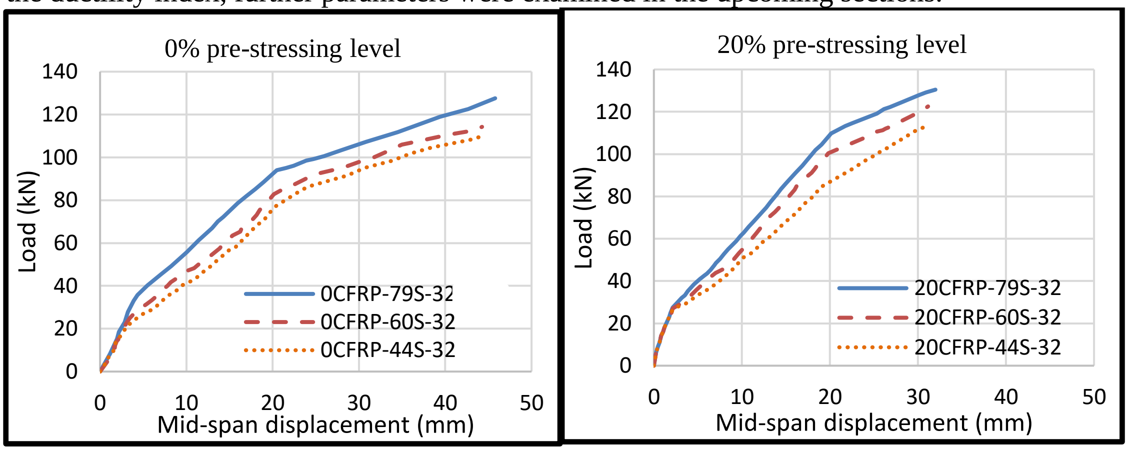
The FEA validated model of the beam strengthened with NSM CFRP had the steel reinforcement ratio (ρ_s) of 0.79%, while other parameters (concrete, epoxy and CFRP properties, and reinforcement ratio) were kept constant as in the experiment of Nordin and Taljsten (2006). Two other steel reinforcement ratio values of 0.60% and 0.44% were considered and compared with the validated beam model. The 0.60% ratio was equivalent to a 75% of the original validated beam model reinforcement ratio, while the 0.44% ratio represented the minimum reinforcement ratio required per ACI 318. Lower reinforcement ratios were used to reduce the effect of the tensile strength provided by steel bars in order to investigate the effect of NSM-CFRP rods under different pre-stressing levels. As mentioned before, the beam's tensile and compressive steel reinforcement ratios were the same. For each steel reinforcement ratio value, the FRP rod had a pre-stressing level of 0%, 20%, 30%, and 40%. The effect of steel reinforcement ratio in terms of cracking, yielding, and ultimate loads, and their relative displacements with respect to all pre-stressing levels are presented in Table 4.

Table 4. Effect of steel reinforcement ratio under different pre-stressing levels

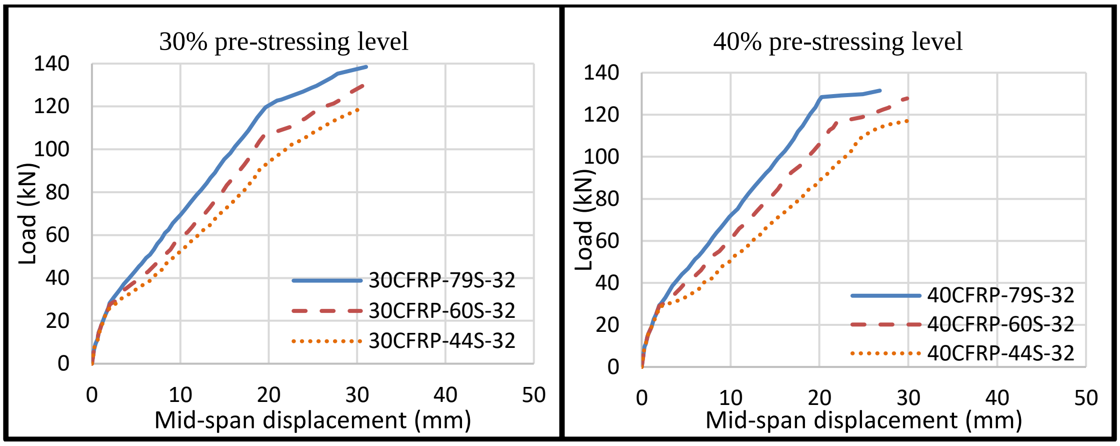
Model ID	P_{cr} (kN)	D_{cr} (mm)	P_y (kN)	D_y (mm)	P_u (kN)	D_u (mm)	I_D (D_u/D_y)
0CFRP-79S	15.2	1.96	93.9	20.46	127.6	45.78	2.24
20CFRP-79S	27.5	2.15	110.7	20.01	130.4	31.99	1.60
30CFRP-79S	28.6	2.00	120.5	19.63	138.3	31.02	1.58
40CFRP-79S	29.3	1.98	128.5	20.25	131.5	26.79	1.32
0CFRP-60S	14.2	1.92	82.7	20.15	118.6	44.91	2.23
20CFRP-60S	27.1	2.14	100.3	19.81	122.5	31.15	1.57
30CFRP-60S	27.5	2.01	106.4	19.47	130.2	30.85	1.58
40CFRP-60S	28.4	1.98	116.5	21.97	127.7	29.87	1.36
0CFRP-44S	13.9	1.83	72.7	19.31	109.6	44.01	2.28
20CFRP-44S	26.5	2.10	84.5	19.01	112.5	30.55	1.61
30CFRP-44S	25.8	1.98	90.8	18.98	118.8	30.24	1.59
40CFRP-44S	27.9	1.94	102.8	23.58	117.1	30.02	1.27

P_{cr} and D_{cr} = load and deflection at cracking, P_y and D_y = load and deflection at yielding, Pu and D_u = load and deflection at ultimate, I_D (D_u/D_y) = ductility index

As illustrated in Table 4, higher steel reinforcement ratio resulted in higher values of cracking, yielding, and ultimate loads. However, at the same pre-stressing level, lower steel reinforcement ratio did not significantly decrease the deflection. The reduction in deflection did not exceed 6% in cracking, yielding, and ultimate stage. This is due to the small variations in steel reinforcement ratios which would not result in a significant deflection reduction. Furthermore, at the same pre-stressing level, decreasing the steel reinforcement ratio did not yield in high decrease in cracking load, and this shows that the steel reinforcement had little effect on the load in cracking stage. Although the increase in steel reinforcement ratio was small, the yielding load was significantly increased. This suggests that the FRP postponed the steel yielding. The ultimate load slightly decreased with the reduction of steel reinforcement ratio. However, the ultimate load kept ascending to 30% pre-stressing level and it decreased after with 40% pre-stressing level. This indicates that the most effective pre-stressing levels were 20% and 30% for the beam in this study. Another observation regarding the contribution of FRP pre-stressing can be made by comparing the ultimate load of no FRP pre-stressed beams with 0.79% (control) and 0.44% reinforcement ratios. The reduction in the ultimate load carrying capacity was about 14%, while this reduction decreased to 7% with 30% pre-stressing level. In conclusion, the beam reinforced with 0.79% steel reinforcement ratio and strengthen with FRP under 30% pre-stressing level achieved the highest load carrying capacity. Additionally, based on the ductility index, it was worth to mention that, for the same reinforcement ratio, the ductility index decreased by the increase of pre-stressing level. Whereas, the ductility did not significantly decrease with the decrease of steel reinforcement ratio at the same pre-stressing level (Table 4). This is attributed to the minimum decrease in the yielding and ultimate displacements. Also, the higher the pre-stressing level is the stiffer the beam becomes; therefore, the ductility was decreased by the increase of pre-stressing level (Figure 2). In the non-prestressed beams, the minimum reinforcement ratio gave the highest ductility index. The same was true for 20% and 30% pre-stressing. In conclusion, in order to postpone the cracking of the concrete, the beam with FRP 20% pre-stressing with any steel reinforcement ratio would provide the highest cracking displacement. While, in order to enhance the ductility index, further parameters were examined in the upcoming sections.



(a) (b)



(c) (d)

Figure 2. Comparison of load versus midspan displacement curves for various steel reinforcement ratios under (a) 0%; (b) 20%; (c) 30%; (d) 40%, pre-stressing levels

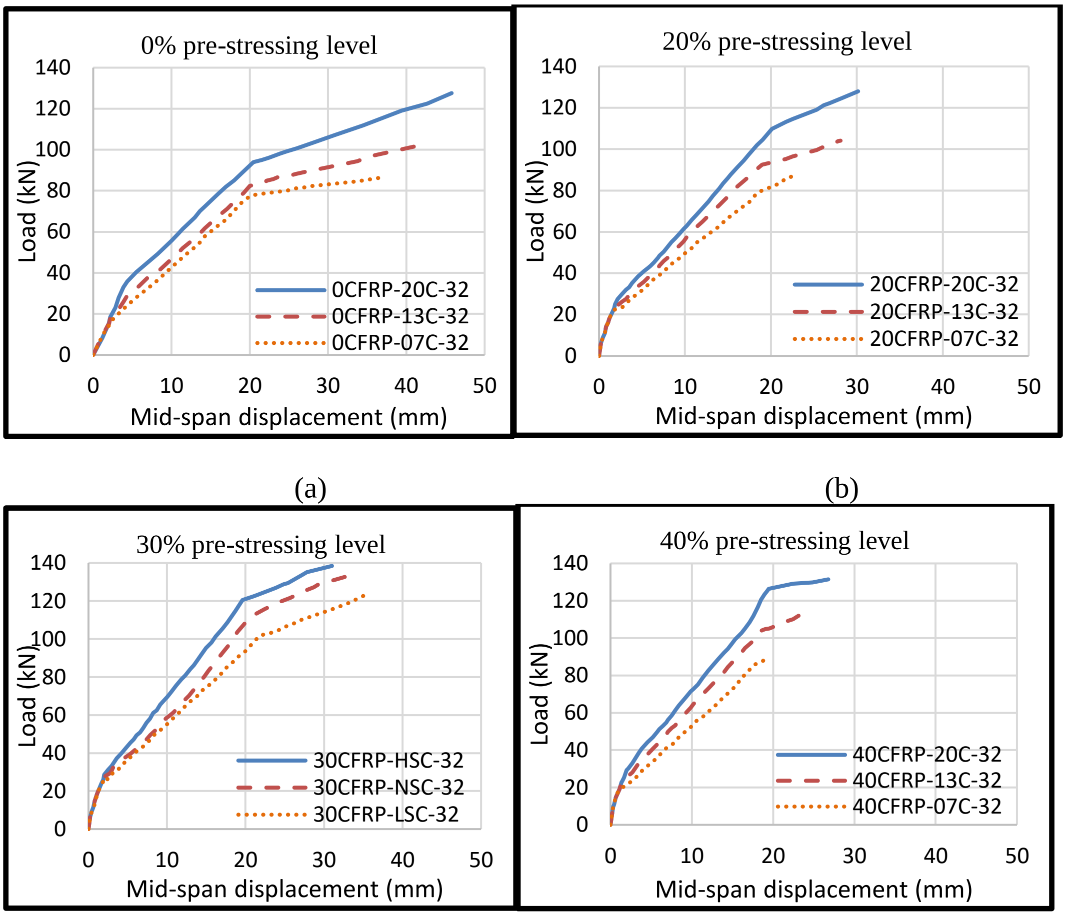
3.2 Effect of CFRP reinforcement ratio

Similar to the steel reinforcement ratio, the CFRP ratio (ρ_f) was calculated by dividing the area of CFRP rod cross-section to the beam cross-section area. The selected reinforcement ratios were 0.20%, 0.13%, and 0.07% (one equal to and the others 35% and 65% lower than the experimental value used by Nordin and Taljsen (2006)). The lower reinforcement ratio was to examine the effectiveness of CFRP pre-stressing levels on minimally reinforced RC beams. Table 5 shows at the same pre-stressing level, lower CFRP reinforcement ratio resulted in load and displacement capacities reduction (Figure 3). At the same CFRP reinforcement ratio, the cracking and yield loads enhanced with the increase in pre-stressing level up to 40%. While the ultimate load increased up to 30% pre-stressing level. It can be concluded that to achieve the highest load carrying capacity, 30% is the most effective pre-stressing level for every CFRP reinforcement ratio. The enhancement due to the increase in pre-stressing level reduced with the decrease of CFRP reinforcement ratio (Table 6). At every pre-stressing level, much larger reduction was observed in the ultimate than yield displacement resulting in lower ductility index. Based on the design strengthening requirements, the most effective CFRP ratio can be selected. For example, with 0.20% CFRP ratio, higher load carrying capacity can be obtained with 30% pre-stressing level. While to achieve higher displacement capacity, lower pre-stressing level should be applied.

Table 5. Effect of FRP reinforcement ratio at different pre-stressing levels

Model's ID	P_{cr} (kN)	D_{cr} (mm)	P_y (kN)	D_y (mm)	P_u (kN)	D_u (mm)	I_D (D_u/D_y)
0CFRP-20C	15.2	1.97	93.9	20.46	127.6	45.78	2.24
20CFRP-20C	27.5	2.15	109.7	20.1	130.5	31.99	1.59
30CFRP-20C	28.2	1.99	119.5	19.63	138.5	31.01	1.58
40CFRP-20C	29.3	1.97	126.5	19.46	131.5	26.79	1.38
0CFRP-13C	14.5	1.91	82.4	20.01	101.7	41.25	2.06
20CFRP-13C	24.5	2.13	92.5	18.98	104.1	28.11	1.48
30CFRP-13C	24.9	1.93	95.2	17.55	115.6	26.07	1.49
40CFRP-13C	25.3	1.82	103.5	18.37	114.5	24.87	1.35
0CFRP-07C	13.9	1.82	77.2	19.95	86.5	36.82	1.85
20CFRP-07C	22.8	2.09	79.1	18.53	88.4	22.98	1.24
30CFRP-07C	23.7	1.86	85.2	17.01	91.6	20.85	1.23
40CFRP-07C	24.2	1.75	80.2	16.51	89.2	19.66	1.19

P_{cr} and D_{cr} = load and deflection at cracking, P_y and D_y = load and deflection at yielding, Pu and D_u = load and deflection at ultimate, I_D (D_u/D_y) = ductility index.



(c) (d)

Figure 3. Comparison of load versus midspan displacement curves for various FRP reinforcement ratios under (a) 0%; (b) 20%; (c) 30%; (d) 40%, pre-stressing levels

Table 6. Difference in Load capacities of beams with various FRP reinfrocement ratios as compared to control beam under all pre-stressing levels

Model's ID	Cracking		Yielding		Ultimate	
	P_{cr} (kN)	increase compared to 0%	P_y (kN)	increase compared to 0%	P_u (kN)	increase compared to 0%
0CFRP-20C	15.2	-	93.9	-	127.6	-
20CFRP-20C	27.5	81%	109.7	17%	130.5	2%
30CFRP-20C	28.2	86%	119.5	27%	138.5	9%
40CFRP-20C	29.3	93%	126.5	35%	131.5	3%
0CFRP-13C	14.5	-	82.4	-	101.7	-
20CFRP-13C	24.5	69%	92.5	12%	104.1	2%
30CFRP-13C	24.9	72%	95.2	16%	115.6	14%
40CFRP-13C	25.3	74%	103.5	26%	114.5	13%
0CFRP-07C	13.9	-	77.2	-	86.5	-
20CFRP-07C	22.8	65%	79.1	2%	88.4	2%
30CFRP-07C	23.7	70%	85.2	10%	91.6	6%
40CFRP-07C	24.2	74%	80.2	4%	89.2	3%

P_{cr} = load at cracking, P_y = load at yielding, P_u = load at ultimate

4 CONCLUSIONS

In the present paper, FEA models of RC beams strengthened with NSM rods were validated with an experimental study in the literature. The validated beam models were used to perform parametric studies. Parameters considered were steel and CFRP reinforcement ratios, and their effects on the load, displacement, ductility and failure mode of the beams. The objective was to achieve higher ductility and, in some cases, higher load carrying capacity. The following conclusions can be drawn:

- The validated FEA beam models and experimental results were in good agreement with less than 10% difference.
- The effect of various internal steel reinforcement ratios was examined on FEA RC beam models. Lower steel reinforcement ratios than the validated models were selected purposely to represent retrofitting of deficiently reinforced beams. The CFRP rods were more effective in beam cases carrying lower steel reinforcement ratio.
- The increase in pre-stressing level of FRP up to 30% resulted in higher load capacity for all beams.
- CFRP reinforcement ratio was another variable of study. The results revealed that for all CFRP reinforcement ratios, the 30% pre-stressing level showed significant ultimate load and considerable ductility. 0.2% CFRP with 30% pre-stressing achieved the highest ductility whereas the maximum load was attained by 0.13% CFRP reinforcement ratio and 30% pre-stressing level.

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