



JISSE

JISSE

ISSN: 2636-4425

Journal of International Society for Science and Engineering

Vol. 7, No. 3, 55-62 (2025)

JISSE

E-ISSN:2682-3438

Flexural response of preloaded RC beams strengthened by NSM-FRP bars

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ARTICLE INFO

Article history:

Received:05-10-2025

Accepted:15-11-2025

Online:16-11-2025

Keywords:

Flexural Strengthening

Preloaded RC Beams

BFRP bars

GFRP bars

NSM

ABSTRACT

This research presents an experimental investigation of the flexural strengthening of preloaded RC beams. There are two parameters that were studied in this experiment: the preloading levels and the type of FRP bars. Two types of FRP bars were used: GFRP bars and BFRP bars. Two values of percentages of the preloading levels were used: 50% and 75% of the failure load of the control RC beam. Five RC beams are studied in this experiment; one of them was tested as a control RC beam, and the other four RC beams were divided into two groups. The first group included two RC beams strengthened with two GFRP bars, and the second group included two RC beams strengthened with two BFRP bars. The results of the experiment indicated that the strengthening RC beams preloaded to 50% of the failure load of the control RC beam had higher flexural load-carrying capacity and ductility than the strengthening RC beams preloaded to 75% of the failure load of the control RC beam, and the strengthening RC beams preloaded to 50% of the failure load of the control RC beam had lower deflection than the RC beams preloaded to 75% of the failure load of the control RC beam.

1. Introduction

Many reinforced concrete structures no longer meet their intended function because of ageing, overloading, and prior damage. Repair and strengthening are therefore preferred to full replacement for economic and environmental reasons [1–5].

Fiber-reinforced polymer (FRP) systems provide high strength with low weight and outstanding corrosion resistance. In flexural upgrading, the near-surface mounted (NSM) method places bars or strips inside shallow grooves filled with adhesive along the tension face. This arrangement protects the reinforcement and improves force transfer compared with surface bonding in many situations [6, 8]. Preloading before strengthening is common in practice. It changes the stiffness of the member and introduces cracks that reopen under loading; these effects influence how quickly the FRP engages after installation [9–11].

The response of an NSM-strengthened beam depends on FRP and adhesive properties, groove geometry, interface bond, and the reinforcement ratio relative to the internal steel. Insufficient development length or weak confinement at groove ends can trigger premature debonding, whereas adequate anchorage enables higher effective FRP strains [12–13].

NSM-FRP reduces deflection and crack width at working loads by improving tension stiffening; however, adhesive behavior at elevated temperature and under creep can increase interfacial slip, so both strength and service limits should be checked [14–16].

Different FRP types offer different balances of stiffness, strain capacity, and cost. GFRP generally has a lower modulus than carbon FRP, while BFRP provides outstanding corrosion resistance and reasonable stiffness.

Different FRP types offer different balances of stiffness, strain capacity, and cost. GFRP generally has a lower modulus than carbon FRP, while BFRP provides outstanding corrosion resistance and reasonable stiffness [17]. The choice of bar type

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and diameter should be coordinated with groove size and cover to avoid premature crushing or cover separation [18–19]. Previous experimental studies on beams strengthened with NSM-FRP report gains in capacity and improved ductility when bond and anchorage are adequate. At higher preload levels, the initial stiffness may be lower, and cracking can occur earlier, even when the ultimate capacity increases [20, 21].

Within this research, the present study evaluates the mechanical characteristics of preloaded simply supported RC beams under bending before and after strengthening with two distinct types of FRP bars, such as load-deflection behavior, ultimate load, and ductility. The NSM strengthening method involves adding these types of FRP bars to the bottom sides of simply supported RC beams. Then, the study compares the different preloading levels based on the determined mechanical properties. Finally, compare strengthening with GFRP bars and strengthening with BFRP bars according to the determined mechanical properties.

2. Experimental work

2.1. Test beams

Five RC beams were constructed for the current experiment. All RC beams were supported, featuring two supports, a rectangular cross-section measuring 120 mm by 250 mm, and a length of 1800 mm.

Each RC beam had bottom reinforcement of 2 Φ 10 and top reinforcement of 2 Φ 8, with a top cover of 25 mm, a side cover of 20 mm, and a bottom cover of 40 mm. To achieve sufficient shear strength, closed stirrups of Φ 10 were placed along each beam at approximately 10 cm spacing.

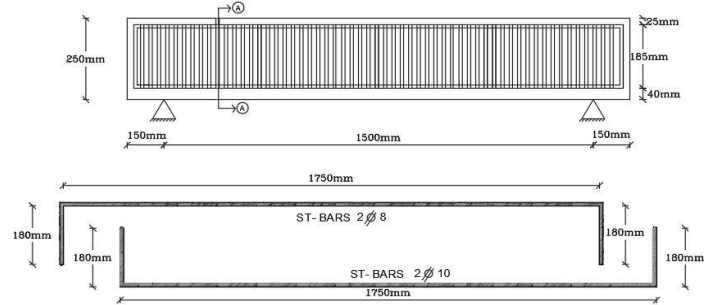
Before repairing, B1-CB was loaded until failure, and it was considered as the control RC beam. The other RC beams were subjected to the applied load until they reached either 75% or 50% of the ultimate capacity of the control RC beam. Two preloaded RC beams (B2-G-50 & B4-G-75) were strengthened by using GFRP bars planted inside the lower face in each RC beam, while the other two RC beams (B3-B-50 & B5-B-75) were strengthened by using BFRP bars planted inside the lower face in each RC beam. The FRP bars were plated in RC beams by the near-surface mounted strengthening method. The specimens' details are mentioned in Table 1 and Figure 1. Also, Figure 2 shows the strengthened RC beams reinforcement.

Table 1. Details of tested beams

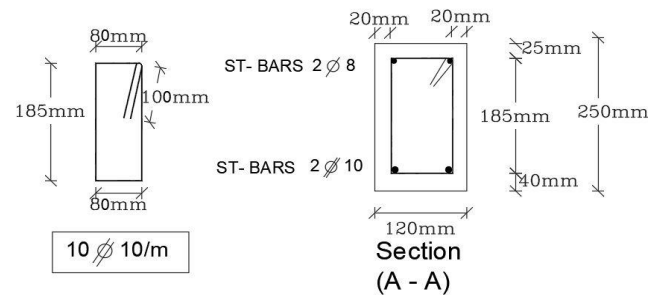
RC Beam	Dimensions (mm)		Reinforcement		Preloading	NSM FRP Bars	
	b	t	Top	Bottom		GFRP	BFRP
B1-CB	120	250	2 Φ 8	2 Φ 10	P_u	-	-
B2-G-50	120	250	2 Φ 8	2 Φ 10	50% P_u	2 Φ 10	-
B3-B-50	120	250	2 Φ 8	2 Φ 10	75% P_u	-	2 Φ 10

B4-G-75	120	250	2 Φ 8	2 Φ 10	50% P_u	2 Φ 10	-
B5-B-75	120	250	2 Φ 8	2 Φ 10	75% P_u	-	2 Φ 10

P_u : Capacity of B1-CB; B1-CB: Control RC Beam; G: GFRP Bars; B: BFRP Bars; 50: 50% Preloading Ratio; 75: 75% Preloading Ratio

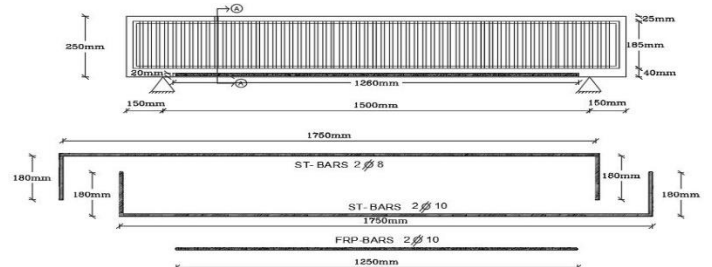


(a) Longitudinal section of preloaded beams

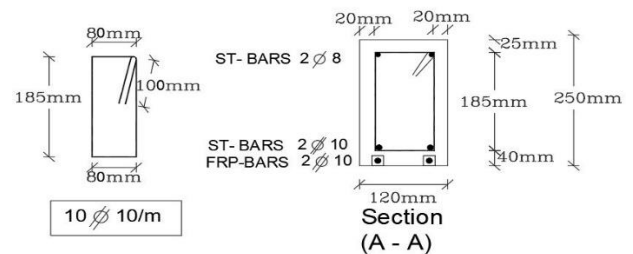


(b) Cross section of preloaded beams

Figure 1. Detailing the preloaded RC beams.



(a) Longitudinal section of preloaded beams



(b) Reinforcement of repaired beams

Figure 2. Detailing the strengthened RC beams.

2.2. Materials

During the placement of fresh concrete onto the beams' shapes, seven cubic samples (158x158x158 mm) were taken from the old mix that had been used for casting the RC beams. The samples were removed from the molds the next day and immersed in a water basin until they were tested. After 7 days of casting the specimens, three cubes were tested. Two cubes were examined at the testing day of specimens before strengthening, and the last two cubes were examined at the testing day of the strengthened beams. The compressive strength results of the cubes are shown in Table 2.

The specimens used in this experiment were made from available materials. The materials used in this experiment included standard Portland cement, crushed dolomite, natural sand, BVF admixture, and steel reinforcement. The dolomite that was used in the experiment was smooth, dry, angular, and free of impurities. The proportional maximum sizes in this range are no more than 25 mm and no less than 15 mm. The fine aggregate was impurity-free, dry, and well-graded. Potable water that was used in the experiment was free of any compounds or impurities. To ensure proper workability of casting, a high-range water reducing super plasticizer concrete admixture BVF was used with a water cement ratio of 0.5 weights. The weights of the materials used to make one cubic meter of concrete are listed in Table 3. The longitudinal steel bars applied in this experiment were deformed high tensile strength bars with a diameter of 10 mm and were used as reinforcement bars. Stirrups and shrinkage bars were made from mild steel bars with an 8 mm diameter.

Table 2. The cubes' compressive strengths

Age	Weight of each cube (kg)	Compressive strength (N/mm ²)	Average Compressive Strength (N/mm ²)
7 days	9.35	37.2	36.97
	9.30	36.6	
	9.38	37.1	
28 days	9.32	44.1	44
	9.35	43.9	
Preloading day	9.39	44.3	44.35

Table 3. The utilized concrete mixes per 1 m³

Material	Weights
Coarse Aggregate (1)	
>15mm	1260 kg
<25mm	
Sand	650 kg
Cement	350 kg
Water	175 liter
BVF Admixture	4 liter

For binding steel bars to concrete, use Kemapoxy 165 as a non-shrink epoxy adhesive mortar. Conface 2F is used to repair cracks, fill voids, and nest in concrete elements. BFRP bars provided longitudinal support. To make basalt fiber reinforced polymer (BFRP) bars with a diameter of 10 mm, continuous longitudinal basalt fibers are linked together with a vinyl ester resin using a pultrusion technique. Basalt fibers are produced

from a mixture of volcanic materials found in nature. Continuous longitudinal Type E glass fibers (73-78 % by volume) are used in the glass fiber reinforced polymer (GFRP) bars used in this experiment, which are impregnated with a thermosetting polyester resin matrix. To boost bond efficiency, helicoidally wound fiber glass strand windings and sand particles are used. Table 4 and Table 5 show the mechanical properties of BFRP and GFRP bars, respectively. Figure 3 shows the produced FRP bars.

Table 4. BFRP bars mechanical properties

Diameter (mm)	Modulus of elasticity (N/mm ²)	Tensile Strength (N/mm ²)	Ultimate Strain %
10	73,350	945	1.40

Table 5. GFRP bars mechanical properties

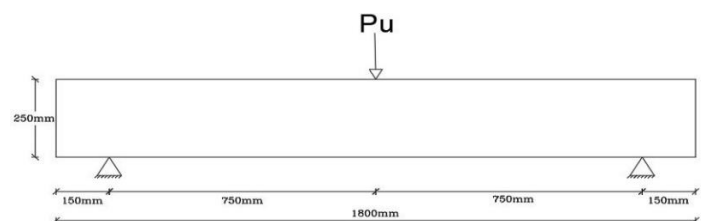
Diameter (mm)	Modulus of elasticity (N/mm ²)	Ultimate Strength F _u (N/mm ²)	Elongation %
10	25,700	555	2.20



Figure 3. FRP NSM bars

2.3. Test Setup

All the tested RC beams were simply supported RC beams. Each of the RC beams underwent one concentrated static load at mid-span. The first beam (B1-CB) was the control RC beam; it was loaded to failure. The second and third RC beams (B2-G-50) and (B3-B-50) were loaded with 50% of the control RC beam failure load, which was the cracking load for these specimens, and then strengthened with FRP bars on the lower of the specimens. The fourth and fifth RC beams (B4-G-75) and (B5-B-75) were loaded with 75% of the control RC beam failure load, which was the cracking load for these RC beams, and then strengthened with FRP bars on the lower of the RC beams. Thereafter, the strengthened RC beams were subjected to the applied loads until they all failed. An electrical pump was used to apply the load. The electrical load cells were attached to a data logger device that was operated by a computer. Figure 4 shows the test set up of beams. Figure 5 shows the strain gauge locations.



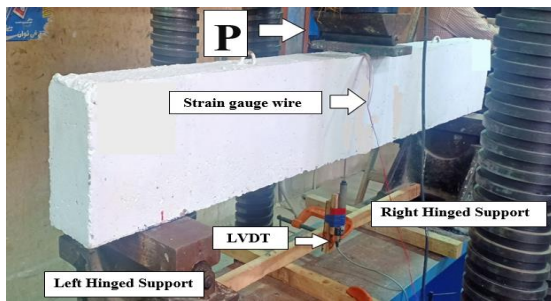


Figure 4. Test setup

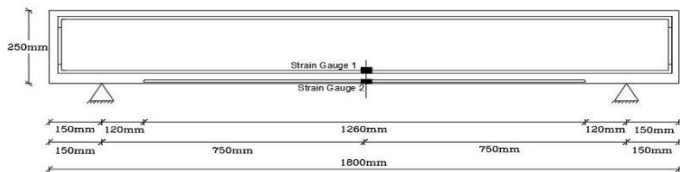


Figure 5. Strain gauge locations

2.4. Repairing by NSM bars

After loading the specimens to 50% and 75% of the failure load of the control RC beam, cracks appeared due to this loading. Consequently, a restoration process was initiated for these cracks, as shown in Figure 6. There are many ways to repair the cracks resulting from loading the beams, and these methods depend on variables, the most important of which is the depth and width of the crack resulting from the process of loading the beams. The crack repair process involves three steps: first, cleaning the surface of weak or loose concrete on the RC beam; second, ensuring the concrete surface is dry and thoroughly cleaning the cracks using an air pump; and third, applying a low-viscosity epoxy material, such as Conface 2F, to fill the cracks completely and seal their pores.

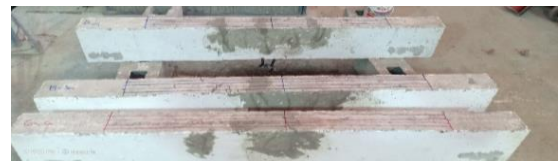


Expanding cracks Cleaning surfaces Filling the cracks

Figure 6. Repairing cracks steps

To strengthen the RC beams using FRP bars, workers prepare the surface from the lower side by planning the locations for grooves and placing the FRP bars. The planning locations are determined by the cutting missile, with a commitment to planning

and dimensions of the spaces as well. The concrete in the planned grooves is discharged within the specified area by using carving tools, with a depth of 2 cm and a width of 2 cm for each groove, and cleaning the groove well from any dents and leveling the internal surfaces of the grooves well. The grooves are cleaned from the inside using an air pump and then washed with water to avoid the presence of any dust or stuck impurities, and then they are dried well with an air pump. Both components of kemapoxy 165 adhesive were well mixed, and a percentage of the epoxy material for wrapping the FRP bars inside the grooves was put at 25% of the groove volume to maintain the entire covering of the FRP bar from all sides with the epoxy material and to achieve the required cohesion between the FRP bar and the concrete. The reinforcing NSM bars are placed, and then the rest of the space around the bars is filled with the epoxy material and the material, and surfaces are left until it reaches the desired consistency. Figure 7 shows the steps of repairing with NSM FRP bars.



(a) Grooves positioning



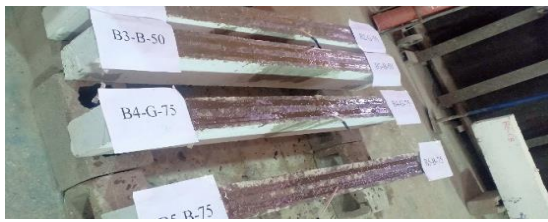
(b) Carving places of grooves



(c) Washing of the grooves



(d) Placing FRP bars in the grooves



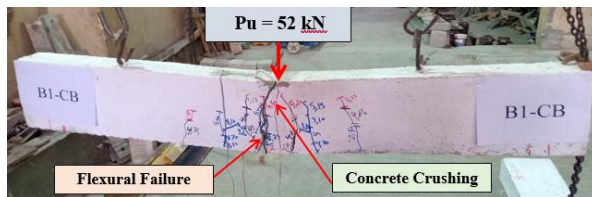
(e) Covering grooves with Kemapoxy 165

Figure 7. Repairing steps with NSM FRP bars

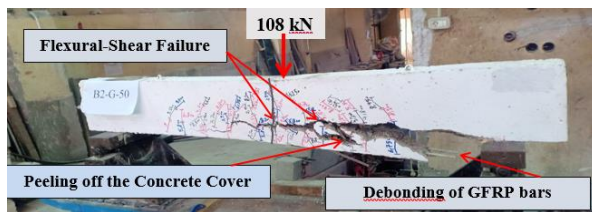
3. Results and Discussion

3.1. Mode of Failure

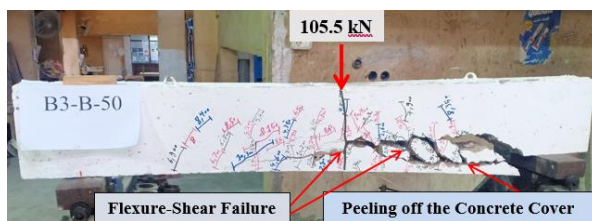
Figure 8 shows the failure mode of the tested beams. For B1-CB, the RC beam broke due to flexural failure and local concrete crushing on the upper surface of the mid-span of the RC beam with an ultimate load of 52 kN. For B2-G-50, the RC beam failed due to flexural-shear failure and peeling off the concrete cover on the bottom side of the RC beam and de-bonding of GFRP bars at an ultimate load of 108 kN. For B3-B-50, at an ultimate load of 105.5 kN, the RC beam broke due to flexural-shear failure and peeling off the concrete cover on the bottom surface. For B4-G-75, the RC beam failed due to flexural cracks and peeling of the concrete cover on the bottom side, specifically along the RFT steel level near the GFRP bars, at an ultimate load of 78 kN. For B5-B-75, at an ultimate load of 103.5 kN, the RC beam broke due to flexural-shear fractures and peeling off the concrete cover at the tension side along the RFT steel level near to the BFRP bars.



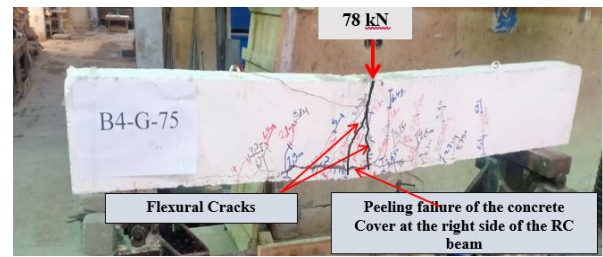
B1-CB



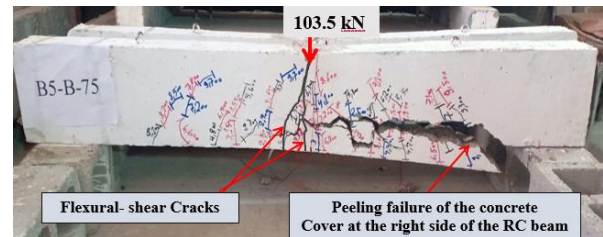
B2-G-50



B3-B-50



B4-G-75



B5-B-75

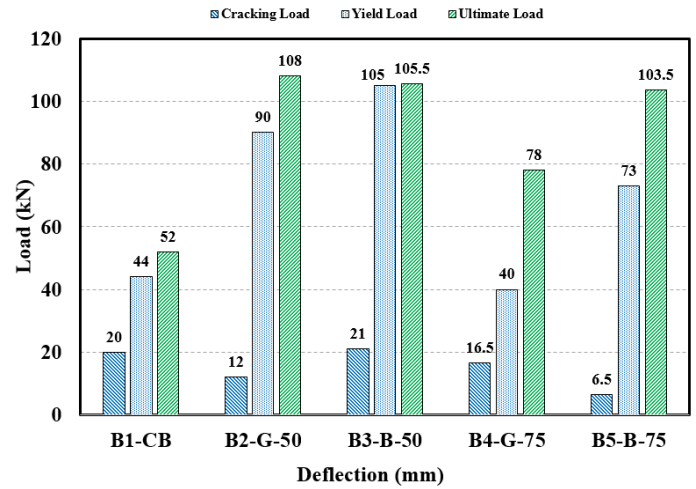
Figure 8. Failure mode of the tested beams

3.2. Effect of Strengthening Preloaded Beams

This comparison includes all the results of the tested RC beams to show the essential differences between the results of strengthening using the two types of FRP bars, which are BFRP bars and GFRP bars, and between the preloading ratios with which the tested RC beams were loaded, which are 50% and 75%. The tensile cracks occurred at the mid-span in the tested RC beams, with a considerably different rate of deflection, which exhibited almost dissimilar cracking patterns. These cracks propagated throughout the compression side of the RC beam as the applied load increased, and significant flexural-shear cracks formed. Following that, the bottom reinforcement steel in the RC beams yielded before failure. Table 6 displays the collapse modes of the tested RC beams following strengthening. All RC beams after strengthening showed a deflection on the vertical axis compared to the horizontal axis. The deflection grew as the applied load rose before the ultimate load of each RC beam was attained, as shown in Figure 9 and Figure 10 for BFRP and GFRP beams, respectively. The ultimate loads applied to tested RC beams were 52 kN, 108 kN, 105.5 kN, 78 kN, and 103.5 kN, respectively. The deflections observed at ultimate loads for the all-tested RC beams were 33 mm, 17.86 mm, 11.512 mm, 14.07 mm, and 12.856 mm, respectively. RC beam (B2-G-50) had the highest ultimate load of 108 kN and an ultimate deflection of 17.86 mm. The second highest was RC beam (B3-B-50) with an ultimate load of 105.5 kN and a deflection of 11.512 mm. The third was RC beam (B5-B-75) with an ultimate load of 103.5 kN and a deflection of 12.86 mm, while the lowest was RC beam (B4-G-75) with an ultimate load of 78 kN and a deflection of 14.07 mm. B2-G-50 increased its flexural load-carrying ability when compared with B3-B-50 by 4.3%, and its ultimate deflection increased by 38.9% compared to B3-B-50. Compared to B4-G-75, B5-B-75 increased the ultimate load by 32.7%, and decreased the maximum deflection by 18.2% as showed in Figure 11.

Table 6. Results of the tested RC Beams

Beam	P_{cr} (kN)	P_u (kN)	$\Delta_{ult.}$ (mm)	Increased Capacity (%)	Decreased Ductility (%)	Mode of Failure
B1-CB	20	52	33	-----	-----	Concrete crushing occurs locally, followed by flexural collapse.
B2-G-50	12	108	17.86	107.69	3.69	Peeling off the concrete cover followed by debonding of the GFRP bars and flexural - shear failure
B3-B-50	21	105.5	11.51	102.88	84.72	Peeling off the concrete cover followed by flexural-shear Failure
B4-G-75	16.5	78	14.07	50	89.90	Peeling off the concrete cover followed by flexural-shear Failure
B5-B-75	6.5	103.5	12.86	99.04	61.99	Flexural-shear failure followed by peeling off the concrete cover above the BFRP bars

**Figure 11. Resulted loads of the tested beams**

3.3. Effect of Preloading Levels

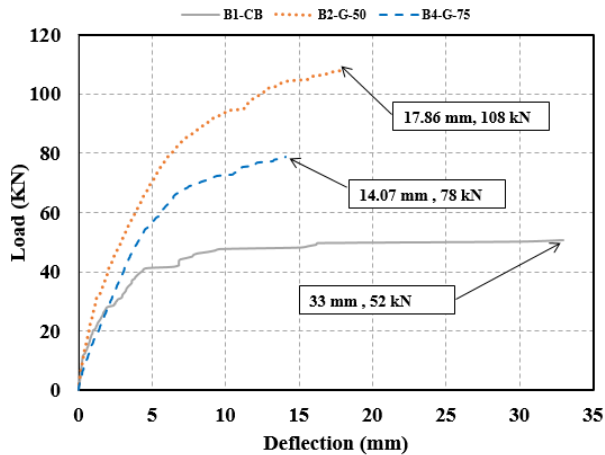
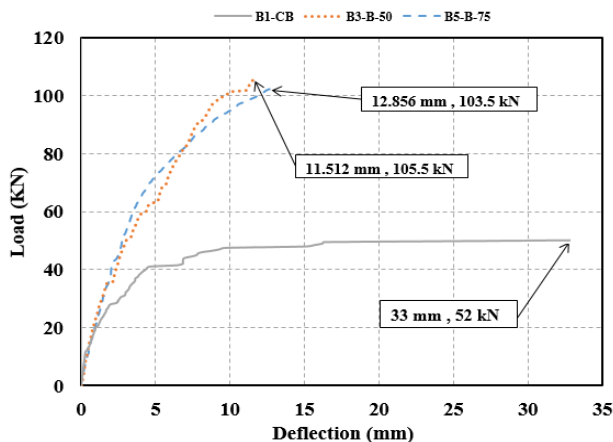
With 50% preloading, the GFRP-strengthened beam B2-G-50 showed a decrease in cracking load by 40.0% (12 kN vs 20 kN), an increase in ultimate load by 107.7% (108 kN vs 52 kN), and a decrease in maximum deflection by 45.9% (17.86 mm vs 33.00 mm). The BFRP-strengthened beam B3-B-50 exhibited a slight increase in cracking load by 5.0% (21 kN vs 20 kN), an increase in ultimate load by 102.9% (105.5 kN vs 52 kN), and a decrease in maximum deflection by 65.1% (11.512 mm vs 33.00 mm). At 50% preload, both NSM systems more than doubled their strength while significantly reducing peak deflection; the BFRP system achieved the largest reduction in deflection with only a slight improvement in cracking load, while the GFRP system attained the highest ultimate strength.

Under 75% preloading, B4-G-75 (GFRP) recorded a decrease in cracking load by 17.5% (16.5 kN vs 20 kN), an increase in ultimate load by 50.0% (78 kN vs 52 kN), and a decrease in maximum deflection by 57.4% (14.07 mm vs 33.00 mm). B5-B-75 (BFRP) showed a decrease in cracking load by 67.5% (6.5 kN vs 20 kN), an increase in ultimate load by 99.0% (103.5 kN vs 52 kN), and a decrease in maximum deflection by 61.0% (12.856 mm vs 33.00 mm). Thus, at 75% preload, BFRP nearly doubled capacity and achieved the largest deflection reduction, but it also suffered the greatest drop in cracking load; GFRP provided a balanced improvement with a moderate cracking-load penalty.

4. Conclusions

In this paper, six RC beams were tested until they failed to investigate the effect of RCA when changing the replacement ratio with and without the existence of web openings. Based on the experimental results, the following conclusions can be drawn:

1. Preloading the two RC beams which were strengthened by GFRP bars, and preloading levels of 50% and 75% increased the flexural load-carrying capacities more than the control RC beam by 107.69% and 50%, respectively. Also, it decreased the ultimate deflection compared to

**Figure 9. Load-deflection curves for beams with GFRP****Figure 10. Load-deflection curves for beams with BFRP**

the control RC beam by 45.88% and 57.37%, while the preloaded RC beam, which was preloaded to 75%, decreased the flexural load-carrying capacity compared to the RC beam, which was preloaded to 50%, by 38.46%, and decreased the ultimate deflection than RC beam which preloaded to 50% by 26.94%.

2. Preloading the two RC beams, which strengthening by BFRP bars with preloading levels of 50% and 75% reduced the ultimate deflection by 65.12% and 61.04%, respectively, and increased the flexural load-carrying capacities by 102.88% and 99.04%, respectively, compared to the control RC beam and preloading the RC beam to 75% of the failure load of the control RC beam decreased the flexural-carrying capacity compared to preloading the RC beam to 75% of the control RC beam by 1.93%. By lowering the preloading level to less than 75%, the load-carrying capacity of the strengthened RC beams will be improved, but the deflection of these RC beams will not be improved with the low ductility of the RC beams, because of the high strength of the FRP bars which are used in strengthening the RC beams.
3. The RC beams failed in flexure and shear after being strengthened by FRP bars, and also, they collapsed due to de-bonding between the FRP bars and the concrete covering it and the concrete covering peeling failure at the reinforcement steel level close to the FRP bars affixed to the tensile side of the RC beams by the near-surface mounted technique.
4. The ductility of the RC beams strengthened by FRP bars and preloaded to 50% has decreased by 3.69% and 89.9% compared to the control RC beam, while the ductility of the RC beams strengthened by FRP bars and preloaded to 75% has decreased by 84.72% and 61.99% compared to the control beam. It is clear that strengthening by using FRP bars can reduce the RC beam ductility. However, strengthening the RC beams with FRP bars has improved the flexural load-carrying capacity more than the control beam. The ductility of the RC beam which strengthened by GFRP bars has been higher than that of the RC beam which is strengthened by BFRP bars by 82.88% in the case of preloading them up to 50% of the failure load, but in case of preloading them up to 75%, the ductility of the RC beam which is reinforced by BFRP bars has been higher than that of the one which is strengthened by GFRP bars by 14.03%.
5. Strengthening RC simply supported beams with FRP bars increase strength and energy dissipation. However, using FRP bars reduces the mid-span deflection at ultimate load and affects the failure mechanism of RC beams. When comparing the cost of strengthening RC beams with FRP bars to the outcomes of this method, it was found that using FRP bars yielded acceptable results for strengthening.

Conflict of Interest

The authors declare no conflict of interest.

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