sciendo

Civil and Environmental Engineering
Vol. 21, Issue 2, 1181-1192, DOI: 10.2478/cee-2025-0087

FLEXURAL STRENGTHENING OF REINFORCED CONCRETE BEAMS BY DIFFERENT FRP PRODUCTS USING NEAR-SURFACE MOUNTED TECHNIQUE

Najwan S. H. BDAIR[1, *], Nameer A. H. ALWASH[1]

[1] Faculty of Engineering, Department of Civil Engineering, University of Babylon, Babylon, Iraq.
* corresponding author: Najwan.hamood.engh413@student.uobabylon.edu.iq

Abstract

An experimental study was performed on reinforced concrete (RC) beams enhanced in flexural capacity using the Near Surface Mounted Fiber Reinforced Polymers (NSM-FRPs) method. This study evaluated the efficacy of various FRP application processes and provided quantitative data on the bonding behavior between FRP and concrete. Effects of FRP type and shape, with equivalent area, on load-bearing capacity, midspan deflection, and failure mode of RC rectangular beams were tested under simply supported conditions with two-point loading up to failure. Beam dimensions are 150 mm × 200 mm × 1700 mm with flexural reinforcement (2ϕ10 at top and 3ϕ12 at bottom) and shear reinforcement (ϕ8@70 mm stirrups). Variables expected to affect strengthening system efficacy are discussed, specifically the type of fibers (carbon, glass, and basalt) and shape of elements (sheet, bar). Using different fiber types is an efficient method to enhance flexural strength of RC beams; capacity increased by 19.6% for NSM-FRP sheets and up to 107.6% for NSM-FRP bars. Strengthening with basalt, glass, and carbon NSM-FRP bars increased ultimate load by approximately 92.9%, 75.6%, and 107.6%, respectively, compared with the control beam. In contrast, NSM basalt, glass, and carbon sheets showed lower increases in ultimate load (about 11%, 16.3%, and 19.6%), respectively.

Keywords:

Near surface mounted;
Fiber reinforced polymers;
Reinforced concrete;
Simply supported.

1 Introduction

Reinforcement and restoration of present structures have garnered considerable attention due to the aging of infrastructure. Over time, concrete constructions may sustain damage, necessitating repairs owing to diminished load-bearing ability. Alternatively, existing structures may require enhancements to their resistance or stiffness to accommodate heightened load demands or construction faults. Reinforced concrete structural members are augmented when their strength or stiffness is inadequate due to heightened traffic loads on bridges, construction errors in reinforced concrete buildings, or suboptimal initial detailing that result in lower-than-anticipated member strength. As an alternative to externally bonded EB, NSM-FRP bars can be used for shear and flexural enhancing of RC elements. This technique involves cutting vertical or inclined grooves at side surfaces of beam and embedding the FRP bars in epoxy-filled grooves. Advantage of NSM bars in this application is that no preparation surface is required in previous case, as opposed to case of EB layers where adequate bond to concrete surface must be ensured to achieve an effective strengthening system. NSM method is based on bonding the FRP layers or bars into small open grooves in the concrete cover of the to-be-strengthened element [1]. Numerous researchers have employed NSM as a promising method to enhance the bending and shear strength of concrete parts [2].

In recent years, many methods have been devised for the repair and reinforcement of reinforced concrete beams utilizing diverse strengthening techniques, including concrete, steel, and FRP composites [3]-[8]. Among these FRP technologies, glass, carbon, and basalt fibers, as well as bars and sheets, have been thoroughly examined [9]-[10]. Application of FRP to enhance reinforced concrete elements is markedly more successful than conventional methods, including steel or concrete jackets, bonded steel plates, and external tensioning [11]. Furthermore, FRP has been demonstrated enhances both flexural and shear performance of RC structures [12]-[18].

Flexural strengthening beams by different types of FRP products have received a lot of interest from most researchers through experimental tests.

In 2017, Brózda et al. [19] performed a computational analysis of the static behavior of simply braced beams reinforced with FRP (fiber-reinforced polymer) bars. The main objective of this computational analysis was to determine the effectiveness of different types of FRP bars as reinforcement for concrete beams under flexural conditions. During the analysis, flexural strength and long-term deflection were considered. The results of the research allowed for determining the most effective type of reinforcement. The flexural strength analysis of the beams identified differences in nominal moment capacities between beams reinforced with CFRP, AFRP, and GFRP bars, these nominal moment capacities were 22.14 kNm, 16.83 kNm, and 15.79 kN.m, respectively.

Shah et al. (2022) [20] conducted a comparative experimental analysis between steel-reinforced concrete (SRCC) beams, dimensioned according to NBR 6118 (2014), and glass-fiber-reinforced polymer (GFRP) beams, dimensioned according to ACI 440.1R (2015), after subjecting them to a four-point bending test. The beams were dimensioned to withstand the same force and meet the serviceability limit state (SLS). The results show that the two groups of beams exhibit similar vertical displacement behavior up to SLS-DEF, while the GFRP beams exhibit larger deflections. At maximum load, the beams with GFRP bars exhibit approximately 64% higher strength than those with steel bars.

In 2023, Ghobashy et al. [21] studied the behavior of concrete beams reinforced with basalt, carbon fiber reinforced polymer (CFR) bars, and conventional steel. A comparison was made between the results to investigate the effect of fire on the reinforced concrete beams, considering the following factors: flexural capacity, deflection behavior, and cracking pattern. It was observed that the use of FRP bars significantly increased the maximum load of the specimens, with an increase ranging from 34–73% of the maximum load for the C-S specimen under static load. The maximum load was achieved by the CFR beam. It was also observed that the use of FRP bars significantly increased the deflection of the beams. The increase ranged from 45–170% of the maximum deflection for the C-S specimen under static load. The effect of fire was observed on FRP-reinforced beams, where the load-bearing efficiency of the beams after fire decreased by 11–18% compared to their actual load-bearing efficiency. For beams reinforced with conventional steel bars, their efficiency decreased by 15% compared to their actual capacity.

Chaudhari et al. (2023) [22] conducted an experimental study on the feasibility of using externally bonded glass fiber reinforced polymer (BFRP) fabrics to strengthen reinforced concrete beams. The results showed that adding basalt fibers to the beams increased their flexural strength from 14.17% to 59.5% and their load-bearing capacity from 14.12% to 60% compared to standard beams.

Pour et al. (2024) [23] experimentally investigated the effectiveness of various strengthening techniques in improving the flexural properties of reinforced concrete (RC) beams using glass fiber reinforced polymer (GFRP) laminates, including externally bonded reinforcement (EBR), externally bonded reinforcement on grooves (EBROG), externally bonded reinforcement in grooves (EBRIG), and near-surface mounting (NSM). The results showed that the NSM technique, in addition to maintaining the reinforcing materials, can enhance the load-bearing capacity and ductility of RC beams by up to 42.3% more than the performance of EBR, EBROG, and EBRIG. The use of EBR, EBIRG, and EBROG significantly increased the load-bearing capacity and deformation of RC beams; these responses were further enhanced when reinforcing steel was placed under the GFRP laminates.

In 2024, Biradar et al. [24] conducted a study on the mechanical properties of basalt rebar and the flexural performance of reinforced concrete beams. They varied the flexural reinforcement ratios, such as 0.2%, 0.4%, and 0.6% basalt rebar, compared to steel-reinforced beams. The results also investigated the flexural strength of the beams. The results showed that the deformation of concrete beams reinforced with basalt rebar was three to four times greater than that of steel-reinforced beams. The flexural strength of the reinforced concrete beams reduced the difference to 40% at the ultimate loading stage.

In 2025, Turzewski and Bachcharz [25] studied the effectiveness of strengthening reinforced concrete beams using NSM CFRP ropes, comparing this solution to the conventional solution using NSM CFRP laminates. All beams reinforced with CFRP ropes achieved higher than expected load-bearing capacity and never collapsed due to delamination.

Present research aims to examine the flexural behavior of RC beams that have been strengthened using the new suggested technique for sheet fibers, which we can name NSM-FRP sheets, and compare results with the NSM-FRP bars. To achieve the goal of the current study, seven RC specimens were fabricated and tested in a simply supported configuration.

2 Program of the work

Experimental program of this study was established to investigate behavior and ascertain capacity enhancement of RC beams that have been strengthened using NSM FRP (basalt, glass, and carbon) bars and sheets methods as compared to control beams. Seven RC rectangular beams were fabricated and subjected to monotonous two-point bending test till to fail. Primary test variables included in this investigation were types of fiber bars (carbon, glass, and basalt fibers) and type of sheets (carbon, glass, and basalt sheet fibers) with the same equivalent area of each strengthen technique. This section describes the specimen's specifications, including construction technique, material characteristics, and reinforcement techniques, together with the testing protocols, are delineated.

2.1 Beams description

To fulfill the aims of this work, seven RC specimens with same dimensions: total depth of 200 mm, width of 150 mm, and clear span of 1500 mm were examined, as shown in Fig. 1.

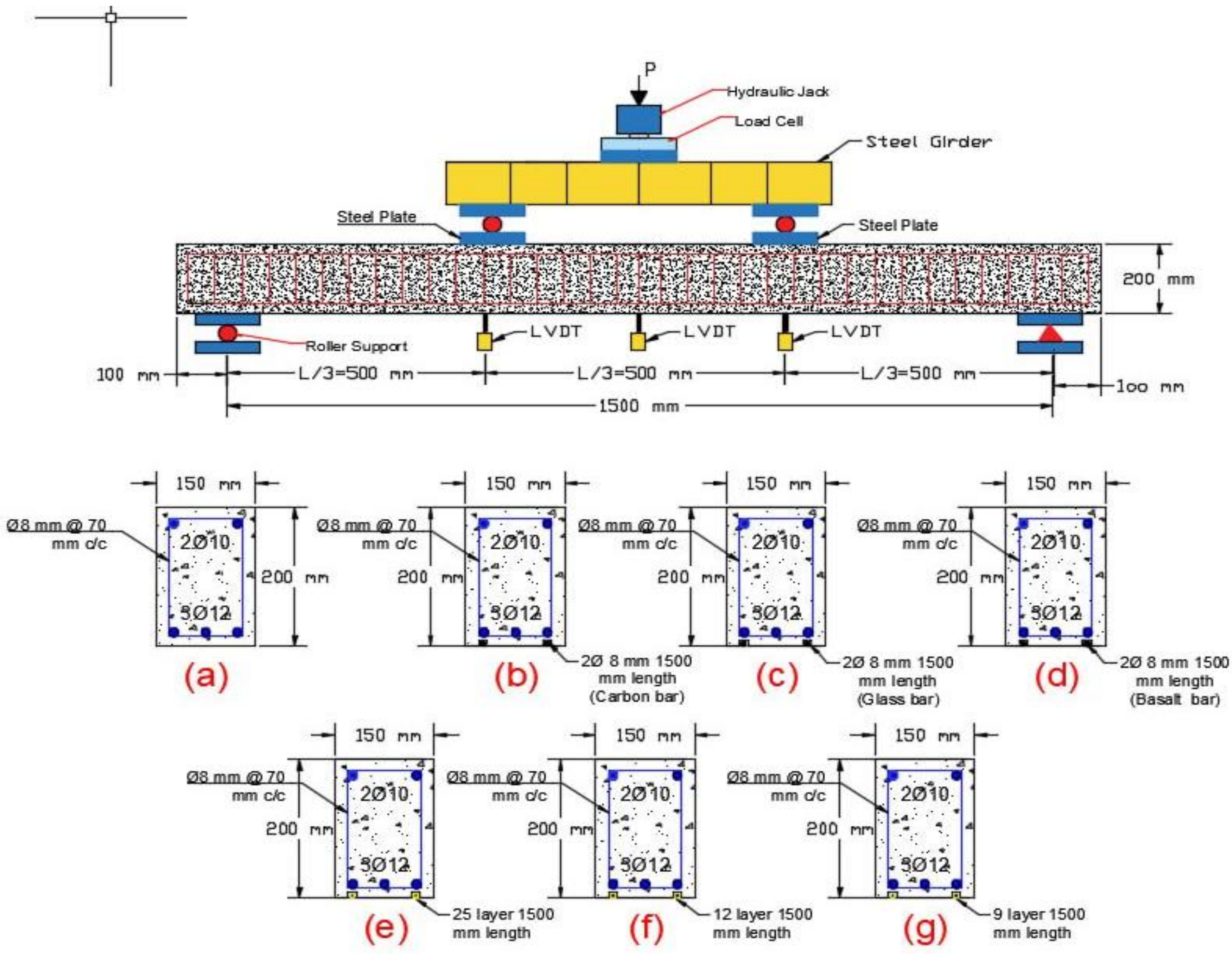
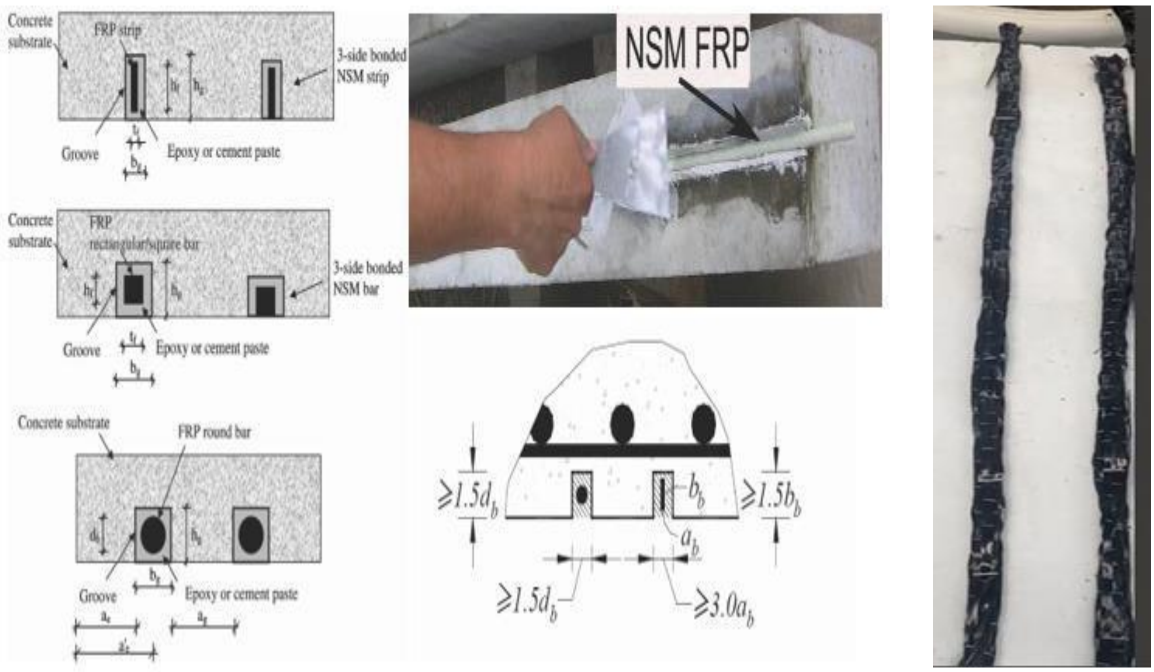


Fig. 2: Details of cross-sectional dimensions, strengthing, and reinforcement of beams (CB, NCb, NGb, NBb, NCs, NGs and NBs).

Test specimens were designed by guidelines supplied by ACI-318-19 [19]. Each of these specimens reinforced with 2Ø10 mm at top, 3Ø12 mm at bottom, and Ø 8@70 mm for shear. Moreover, each specimen included 30 mm clear cover at all sides to warranty flexural failure. Materials properties used in the current research are presented in Table 1. The first specimen, designated as a control beam (CB) is shown in Fig. 1-a. The second three specimens were identified as NSM-CFRP, NSM-GFRP, and NSM-BFRP bars of 2ϕ8mm put in 16x16mm groove along 1500 mm of the beam tension face symbolized by (NCb), (NGb), and (NBb) respectively as shown figure1-b, c, d. The last three specimens were identified as NSM-CFRP, NSM-GFRP, and NSM-BFRP sheets composed of 9, 12, and 25 layers respectively, along 1500 mm of the beam length. These specimens are symbolized by (NCs), (NGs), and (NBs) respectively as shown in Fig. 1-e, f, g. Number of sheet layers of fibers depends on equivalent area of bars (No. of layers = [area of bar/ (1.5d_b*thickness of fiber sheet)] and is put in a 16x20mm groove.

The technique of the NSM method, which is represented by the bar-shape or sheet (strip-shaped) FRP elements, is mounted in the groove made of concrete cover, and they are embedded in epoxy or cement resins (adhesives), which provide adhesion and mounting of the material, as shown in Fig. 2.



a) NSM FRP "bar or sheet" elements. b) Shape of NSM-FRP sheet.

Fig. 2: Application of NSM FRP elements.

2.2 Materials

The current study used identical materials (cement, aggregate, steel) to fabricate and reinforce all beam specimens. Concrete was designed to achieve compressive strength of cube 38 MPa in accordance with BS EN 12390-2:2009 [26]. Three concrete cubes measuring 150 x 150 x 150 mm were produced from identical concrete batch utilized for specimens in each group. Subsequently, all specimens (beams and concrete cubes) underwent water curing for 28 days prior to testing. Mean compressive strength of concrete cubes, fc', across all groups was 38 MPa. Steel reinforcement has been evaluated by ASTM A615M-15, 2015 [27]. Mean yield strength of three steel bars was determined to be 520 MPa. Sikadur-31/41, epoxy resin was used in this research as the matrix phase of the FRP composite as shown in Fig. 3. Material properties of employed epoxy resins were received straight from manufacturers. A summary of material properties is given in Table 1.

Fig. 3: Mixing two components of epoxy resin.

Table 1: Materials properties used in the current research.

Materials	Properties	Values		
Concrete	Concrete strength (MPa)	38		
	Modulus of rupture (MPa)	2.713		
	Modulus of elasticity (GPa)	33		
Steel		Bar diameter		
		8mm	10mm	12mm
	Yield strength MPa	419	490	513
	Ultimate strength MPa	516	633	643
	Elongation %	9	11	13
Epoxy Resin Sikadur-31/41	Tensile Strength MPa	25		
	Modulus of elasticity in compression MPa	4600		
Fiber	Modulus of Elasticity of carbon fiber GPa	150		
	Modulus of Elasticity of glaee fiber GPa	44		
	Modulus of Elasticity of basalt fiber GPa	68		

2.3 Strengthening procedure

This study examined two types of flexural strengthening FRP materials. Strengthening of RC beams was conducted for 28 days post-casting and curing. As previously discussed, seven tested specimens were categorized into three groups. Beam initially functioned as a control beam, lacking flexural reinforcement, and was classified by ACI 318-19 [28]. The three specimens of second group were strengthened by NSM-FRP (carbon, glass, and basalt) bars. The tension face of the beams in this group was cut into two grooves by using concrete saw. Grooves possessed square cross-sections measuring 16 mm. These grooves were cleansed using water jet and air blast to eliminate powdered concrete generated by cutting process and any potential loose materials. Epoxy resin, Sikadur 31/41, was formulated by combining two components (resin and hardener) in weight ratio 2:1 using a power mixer. Groove was filled to the midpoint with paste; thereafter, the bar was positioned in the groove and gently pushed. This compelled paste to circulate bar and occupy the space between bar and groove sides. Grooves were subsequently filled with additional paste, and surfaces were smoothed. Three beams of third group were strengthened with NSM-FRP (carbon, glass, and basalt) ropes. In this group, the longitudinal 16x20mm of two grooves were filled by Sikadur-31/41 and the layered FRP sheets were inserted inside the grooves, as the same procedure used in bars above, with dimensions 12 mm depth and 4.186 mm width depending on equivalent area of bars. Table 2 presents a detailed summary of the specifications for each specimen.

Table 2: Detail of beam specimens.

Beam No.	Specimen designation	Type fiber bars	Diameter of bar [mm]	type fiber sheets	Thickness of sheet	Numbers of layers	Tensile Strength [Mpa]	Reinforcement	
								Flexural	Shear
B1	CB	-	-	-	-	-	-	2Ø10 mm at the top and 3Ø12 mm at the bottom	Ø 8@70 mm
B2	NCb	Carbon	8	-	-	-	2200		
B3	NGb	Glass	8	-	-	-	1080		
B4	NBb	Basalt	8	-	-	-	900		
B5	NCs	-	-	Carbon	0.45	9	3400		
B6	NCs	-	-	Glass	0.354	12	1500		
B7	NBs	-	-	Basalt	0.167	25	2100		

2.4 Specimens testing

Every beam was supported at both ends using rollers, constituting a simply supported beam. Specimens were subjected to midspan two-point loading until failure using testing equipment with a capacity of 3000 kN. The midspan and two-point load deflections were measured using a precision dial gauge for the specified application. Figure 4 depicts the testing configuration.

Fig. 4: Setup of the beam for the test procedure.

3 Results and discussion

3.1 Cracks pattern and failure mode

All specimens are designed to show flexural fractures in midspan area as they get close to certain failure stress caused by flexural strains. At 20 kN, CB mid-span experiments first crack, which is then worsened at a specific rate exacerbated at prescribed rate, also wide cracks develop in mid-span area, leading to flexural failure at 78.6 kN. Emerge first cracks at midspan of beams (B1, B2, and B3) at loads of 28, 27, and 38 kN, respectively. In this study, the beams show numerous vertical cracks in central section with uneven widths, then the crack of broad nature extends to top, failing (B2 at 163.2 kN, B3 at 138.0 kN, and B4 at 151.6 kN). Refer to Table (3) for details. Results encompass ultimate load, midspan deflection, failure mode, and enhancement of percentage of ultimate load for each specimen tested. Overall, for everyone specimens, concrete cover separation was observed during testing, with debonding of the FRP bar commencing at the end of FRP material, followed by concrete crushing on upper surface of specimen (compression zone). Separation of concrete cover signifies the efficacy of grooving approach, as this failure mode demonstrates that FRP is effectively bonded to concrete surface, successfully altering failure mode to cover separation rather than other undesirable modes. Fig. 5a, 5b illustrates instances of failure mechanisms seen during the testing of the specimens.

Table 3: Experimental results of normal mix tested beams-effect of different type NSM-FRP bars.

Beam No.	Beam symbols	First Crack Load [kN]	Def. at First Crack [mm]	Ultimate Load [kN]	Def. at Ultimate Load [mm]	Increase Percentage of Ultimate Load [%]	Mode of Failure
B1	CB	20	1.2	78.6	16.7	-	Flexural
B2	NCb	28	1.34	163.2	27.2	107.6	Debonding of FRP bar initiated at end of strengthen material (next to sliding support) followed by crushing concrete at top surface of beam (compression zone)
B3	NGb	27	1.33	138.0	19.4	75.6	
B4	NBb	38	1.15	151.6	28.2	92.9	

In addition, the first cracks emerge at the midspan of specimens (B5, B6 and B7) at loads of 25, 30, and 27 kN, respectively. The beams exhibit numerous vertical cracks in the central section with varying crack widths, and the extensive nature of the cracks extends to the top, failing (B5 at 93.7 kN, B6 at 91.4 kN, and B7 at 87.2 kN), as shown in Table 4. The percentage of ultimate load and midspan deflection was augmented for reinforced beams, along with the failure mode of each tested beam. Typically, for all beams, the rupture of the FRP rope is succeeded by compressive crushing of the concrete on the beam's upper surface. Fig. 6 illustrates instances of failure mechanisms seen during the testing of the specimens.

3.2 Load-deflection response

Loads versus midspan deflection responses for all beams were plotted to illustrate the influence of elements strengthened with different types and forms of FRP using NSM technique as shown in Fig. 7 and Fig. 8. Values of maximum deflection, deflection at first crack, load at first crack, and ultimate load are given in Table 4.

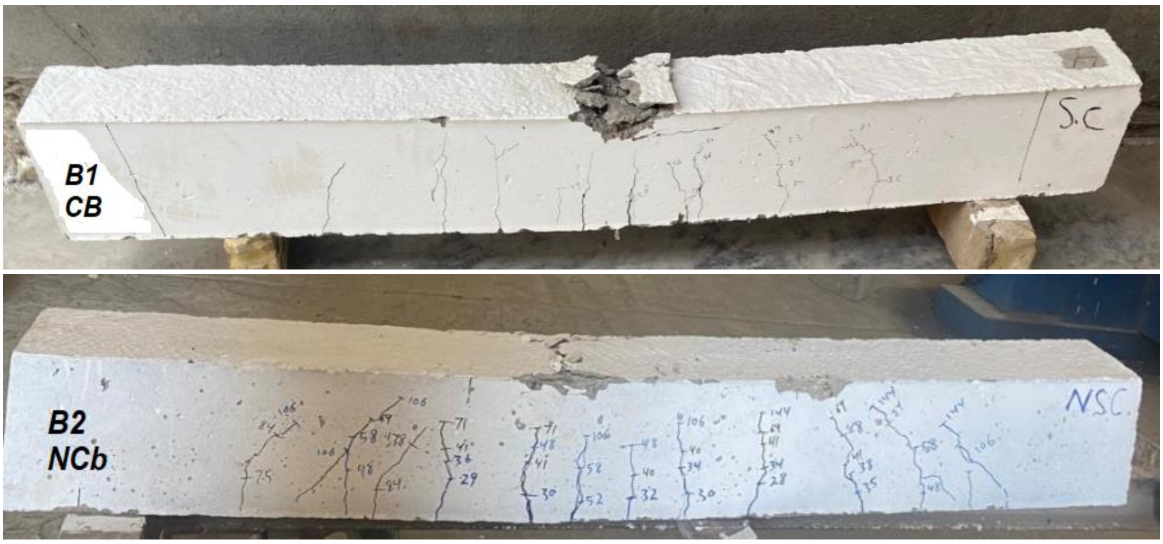


Fig. 5a: Cracks pattern for CB, NCb.

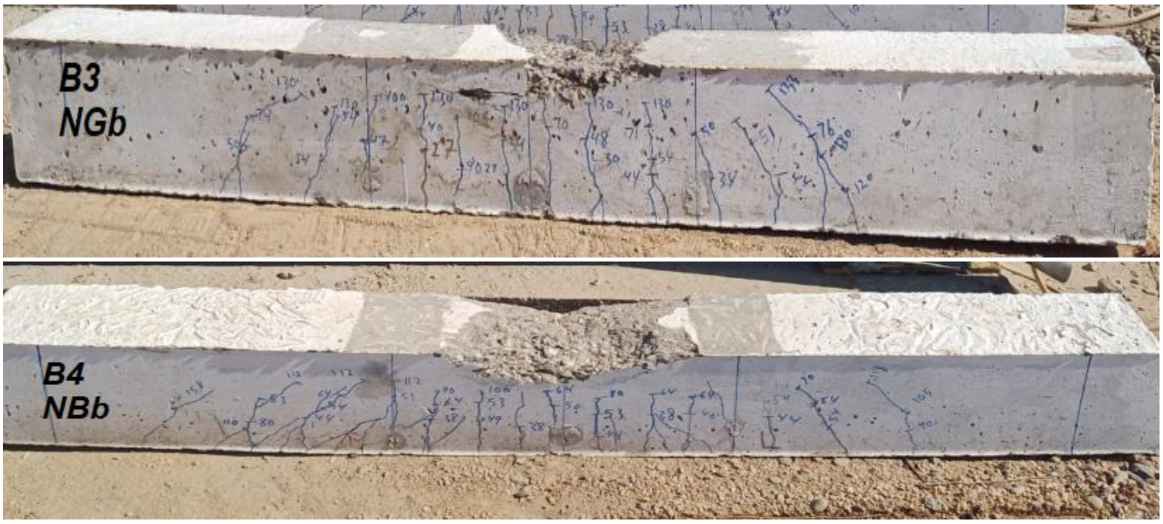


Fig. 5b: Cracks pattern for NGb and NBb.

Fig. 6: Cracks pattern for NCs, NGs and NBs.

3.2.1 Load deflection response NSM-FRP bars

Curves in Fig. 7 were plotted to illustrate the influence of using FRP bars (carbon, glass and basalt) on load-midspan deflection beams. The behavior of the concrete beam reinforced with (NSM) with bonded different types FRP bar was compared with that of the reinforced concrete beam without strengthening with FRP bars (control beam). Most of the data has been reduced to graphical form for ease of interpretation. Experimental failure mode and failure load of the beams are also analyzed.

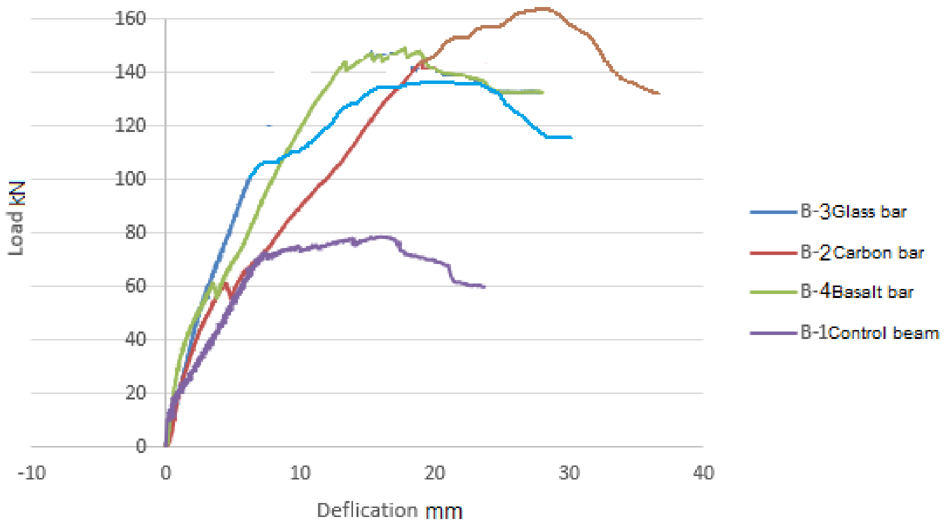


Fig. 7: Load-deflection relationships of beams strengthen by NSM-FRP bars.

Table 4: Experimental results of normal mix tested beams-effect of various types of NSM-FRP sheet.

Beam No.	Beam Symbols	Load at First Crack [kN]	Def. at First Crack [mm]	Ultimate Load [kN]	Def. at Ultimate Load [mm]	Increase Percentage of Ultimate Load [%]	Mode of Failure
B1	CB	20	1.2	78.6	16.7	-	Flexural
B5	NCs	25	1.1	93.7	11.2	19.6	Rupture of NSM-FRP sheet followed by concrete compressive crushing on the top surface of the beam
B6	NGs	30	1.5	91.4	17.9	16.3	
B7	NBs	27	1.5	87.2	11.7	11	

This corresponded to an increase in ultimate load of 107.6% for specimen CFRP bar B2 when compared with control beam B1. In this beam, diagonal flexural cracks formed, widened, and propagated as applied load increased. The rest of the specimens B6 and B7 also recorded an improvement in behavior and the subsequent increase in succession for specimen GFRP bar B3 and BFRP bar B4 increasing (75.6 and 92.9) % compared to B1.

3.2.2 Load deflection response - NSM-FRP sheets

Curves in Fig. 8 were plotted to illustrate the influence of NSM-FRP sheets (carbon, glass, and basalt) on load midspan deflection beams. Concrete beams reinforced with NSM-FRP sheets were compared with RC beam without strengthened with NSM-FRP sheets. Deflection at midspan and the flexural span are shown in Fig. 8 depending on the ultimate loads that have shown the improvement in the ultimate loads lead to decreased deflection and cracking value.

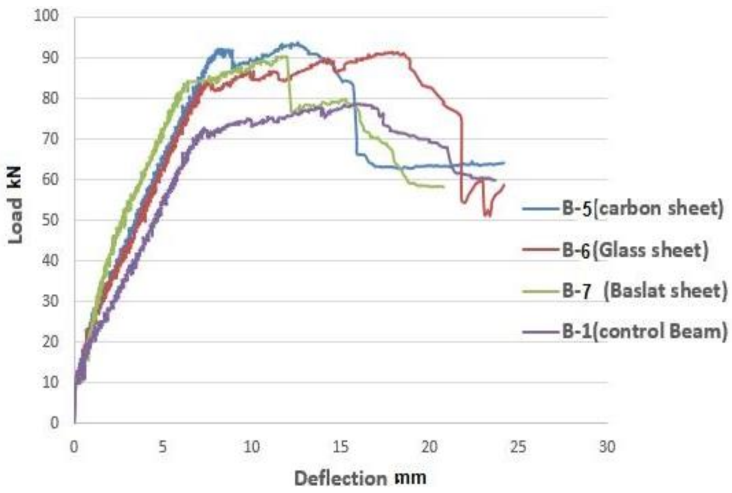


Fig. 8: Load-deflection relationships of specimens strengthen with NSM-FRP sheets.

This corresponded to an increase in ultimate loads of B5 (19.6) % when compared with control beam B1. Diagonal flexural cracks formed also in this beam, widened, and propagated as the applied load increased. The others using FRP sheets glass B6 and FRP sheets basalt B7 also verified an enhancement in behavior and the subsequent increase in succession for specimens B6 and B7 increasing (16.3 and 11) % compared to B1.

4 Conclusions

Most relevant conclusions of this research can be summarized as follows:

1) Overall, specimens strengthened by NSM-FRP bars exhibited greater ultimate loads than the unstrengthen CB; average increase is about 107.6%.

2) For beams strengthened with NSM-FRP sheets exhibited higher ultimate load compared with CB, average increase is about 20%.

3) Stiffer load-deflection response is observed for specimens enhanced by NSM-FRP bars and NSM-FRP sheets as compared with response of CB.

4) Decrease in the width of cracks due to the presence of NSM-FRP bars and NSM-FRP sheets occur compared with CB.

5) Higher ultimate loads were achieved at 107.6% for specimens enhanced by NSM-CFRP bars as compared with un-strengthened CB improvement in behavior and the subsequent lower increase in succession for specimen NSM-GFRP bars and NSM-BFRP bars the increasing (75.6 and 92.9) % compared to control beam.

6) Ultimate loads were achieved at 19.6% for specimens strengthened with NSM-CFRP sheets as compared with unstrengthening specimen (CB) improvement in behavior and the subsequent lower increase in succession for specimen NSM-GFRP sheets and NSM-BFRP sheets the increasing (16.3 and 11) % compared to CB.

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