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Behavior of strengthened reinforced concrete beams under different CFRP strips arrangement

Mourad Boutlikht[1,2] · Noureddine Lahbari[1] · Seifeddine Tabchouche[2] · Kamel Hebbache[2]

Abstract

The Carbon Fiber Reinforced Polymer (CFRP) composite is widely used as a strengthening solution for repairing civil engineering structures. The main objective of this paper is to investigate the effects of strips arrangement on the behavior of Strengthened Beams (SB) using the Near-Surface Mounted (NSM) and the Externally Bonded Reinforcement (EBR) techniques. The experimental program consists of five strengthened beams by different configurations of CFRP. The beams were tested under bending in four-point test. The experimental program comprises two beams strengthened by one and two strips according to the NSM technique. Two other beams were strengthened by the same configuration with the EBR technique, whereas the last beam was un-strengthened and considered as the Control Beam (CB). The behavior of the control and strengthened beams was compared. The effectiveness of different CFRP configurations was evaluated. The obtained results revealed that the crack patterns were affected by the strips arrangement. These results showed also that the flexural load capacity, the ductility and the strains of concrete, steel and CFRP strips were influenced by the arrangement of plates. This paper also highlighted the beams failure modes due to the different configurations of strengthening.

Keywords Strengthened beam · Arrangement of strips · Four-point bending · Flexural capacity

Introduction

The Concrete Structures (CS) elements can be strengthened by different solutions, such as steel or concrete enclosures, external post-tension and strengthening using steel plates fixed by externally bonded technique. Although, these repairing methods can improve the strength, the load carrying capacity and stiffness of concrete structures. They can also increase the structures weight and take more repairing time. Thus, for repairing/strengthening structural elements, the recourse to other developed materials and reinforcement methods is required.

The Carbon Fiber Reinforced Polymer (CFRP) composite is widely used as a strengthening solution for repairing civil engineering structures. This composite has a high tensile strength, good corrosion resistance, fatigue resistance, easy installation, and a reduced application time. In civil engineering, two techniques are commonly adopted, the Near Surface Mounted (NSM) and the Externally Bonded Reinforcement (EBR).

In recent decades, many research projects have been conducted on the bending behavior of reinforced concrete beams strengthened by CFRP using the aforementioned techniques. Various materials and procedures have been used for strengthening [1, 2]. Many interesting experimental studies have been conducted on the behavior of retrofitted columns by CFRP sheets under cyclic loads [3–7]. Rodrigues et al. [4] have conducted an experimental investigation, where they studied the behavior of RC columns and retrofitted RC columns under biaxial cyclic loading. In this research [4], the used retrofit techniques were increasing the number of stirrups, steel plates jacketing, CFRP sheets and plates jacketing. They proved that the behavior of the retrofitted RC columns was affected by the biaxial loading patterns and the retrofit techniques.

Numerous researches focused on the enhancement of ductility, stiffness, displacement and carrying capacity. The aims were to reduce the resulting expenses from

✉ Seifeddine Tabchouche
    tabchouche.seifeddine@gmail.com;
    seifeddine.tabchouche@univ-setif.dz

1   Department of Civil Engineering, University of Batna 2, 05078 Fésdis, Batna, Algeria

2   Department of Civil Engineering, University of Ferhat Abbas-Setif, 1, El mabouda, 19000 Setif, Algeria

the rehabilitation of civil engineering structures and to improve their behavior [8–10]. Several experimental studies have examined the reinforced concrete beams strengthened by the NSM and EBR techniques, and eventually the pull-out effect. The examined parameters were the type and the shape of the CFRP and the anchorage length effects [1, 11–13]. Hawileh et al. [14] studied experimentally the parameters that influence the flexural performance of RC beams strengthened by Side-Bonded FRP sheets using the EBR technique. They have indicated that the side-bonded CFRP sheets improve the flexural strength capacity of beams. The width of CFRP sheets and the steel reinforcement ratio have a significant effect on the stiffness, the strength and the displacement capacity of strengthened RC beams. A comparative experimental study were conducted by Salama et al. [15] between strengthened beams using different configurations of bottom and side bonded CFRP sheets. They reveal that the bottom-bonded sheets strengthening enhance the flexural strength from 62 to 92%, compared to the Control Beam (CB). Where the side-bonded strengthened beams present an increase in the flexural strength over the CB ranged from 39.7 to 93.4%.

El-Hacha and Rizkalla [16] have examined the behavior at flexure of strengthened beams with NSM technique using CFRP. The examined parameters were the load patterns, the number of strips and rods. They showed that the debonding occurs prior between the CFRP and the adhesive interface.

Tang et al. [17] investigated the effects of concrete type and adhesive material type on the behavior of strengthened beams at flexure. The strengthened beams reached an increase of about 23% and 53% in their ultimate capacity loads compared to the control beam. Ceroni et al. [18] have examined the influence of concrete surface roughness, groove dimensions, FRP material and adhesive type, on the strengthened beams according to the NSM technique. In authors' view the change of these parameters leads to different distributions of axial strain in the reinforcement and shear stresses along the interfaces.

De Lorenzis et al. [19] investigated the effects of NSM-FRP reinforcement type and internal steel reinforcement ratio on the ultimate capacity and the bond. They obtained an increase of the ultimate load compared to the control beam.

Boukhezar et al. [20] studied the effect of reinforcement bars ratio on the behavior of strengthened beams with a low characteristic resistance of concrete. The analytical model results indicate that the increasing of reinforcement bars ratio gives appropriate results compared to the experimental curves. Recently, new developments and researches have studied some topics of the RCB strengthening methods, the advantages, the limitations, the challenges and the advancements of FRP composites in civil engineering construction as reviewed by Naser et al. [2, 21], and others [22–25].

Other parameters were studies, such as the type of the used FRP, the steel reinforcement ratio and the FRP amount. El-Gamal et al. [26] have studied the behavior of reinforced concrete beams strengthened by CFRP using the NSM technique. The examined parameters were the type of the used FRP (Carbon or Glass Rods), the steel reinforcement ratio and the amount of FRP (one FRP versus two FRPs). They have not examined the effect of the FRP arrangement. In fact, the CFRP ratio effect was studied. The authors claim that the strengthening with NSM technique present higher capacities with two CFRP rods and better ductility with GFRP rods.

Limited researches studied the effect of CFRP dispositions on the behavior of retrofitted/strengthened structural elements. The present study aims to investigate the effect of CFRP strips arrangement on the behavior of strengthened beams according to NSM and EBR techniques. This study highlights the effects of CFRP arrangement on the flexural load capacity, the displacement capacity, the ductility, the stiffness and the failure modes of reinforced concrete beams (RCBs) strengthened with different configurations. In addition, this experimental work investigates the effect of strips arrangement on the material strains of RCB under four-point bending load.

Experimental procedures

Specimens description and testing method

A total of five reinforced concrete beams were conducted. All the tested beams have the same cross section of 10×17 cm, 100 cm of total length, and 80 cm of clear span. The beams were reinforced with two ribbed steel bars of 8 mm diameter in the tensile side and two others of the same diameter in the compressive side. The shear reinforcements were composed of closed stirrups with 6 mm of diameter, spaced at interval of 10 cm (Fig. 1).

Three groups of specimens were considered. The first group presents un-strengthened beam (CB). The second group consists of two specimens reinforced by carbon strips (CFRP) using the EBR technique with an end-anchorage with CFRP sheets. The last one comprises two strengthened beams by carbon strips according to the NSM technique. The cross section of the carbon strips was kept constant for all the tested beams and arranged in one and two CFRP strips, respectively. A detailed information of the tested beams is presented in Fig. 1. The design criteria adopted in this study was the ACI440.2R.08 criteria.
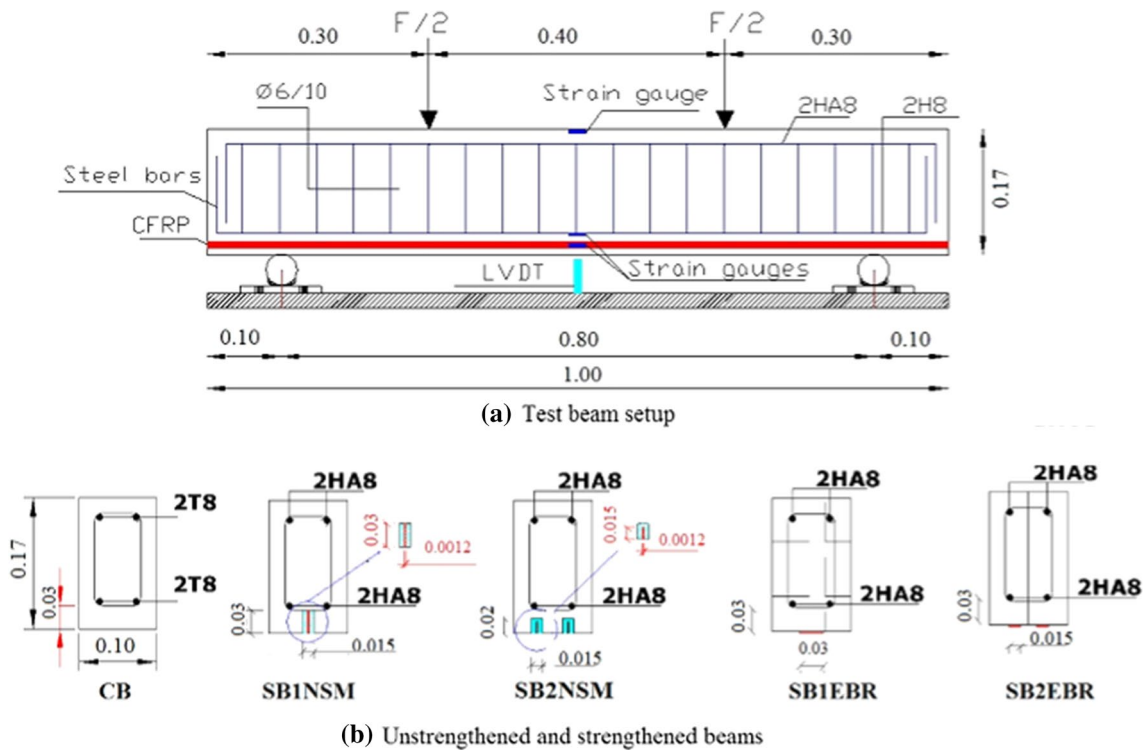
(a) Test beam setup

(b) Unstrengthened and strengthened beams

Fig. 1 Details of beams and bending tests setup (Dimensions are in m)

The specimens were tested under four-point bending load [27, 28]. A spreader beam with 400 mm of a gap was used for transmitting the loads to the specimens with a loading speed of 250 N/s.

Material properties

The beams were made using ordinary concrete formulated by local materials (Sand 0/5 mm, Gravel 7/15 mm and Gravel 15/25 mm). Ordinary Portland Cement (CPJ 42.5) was used for preparing the specimens. The average compressive strength of the concrete at 28 days and the elastic modulus measured on cylindrical samples (16×32 cm) were 35 MPa and 34.4 GPa, respectively [29]. The same steel reinforcement and the CFRP strengthening were provided for all tested beams. Two classes of reinforcing bars were used. High Adhesion (HA) bars serving as longitudinal reinforcement and smooth bars serving as shear reinforcement for all the specimens. Direct tensile characterization tests were carried out on six samples of 20 cm length taken from the reinforcement rebars used for the tested beams, according to the standard NF P18-408 [30]. Physical characterization tests were also carried out for all the concrete constituents [31]. The used CFRP plates are manufactured by SIKA Company. They are supplied in rolls form. The CFRP plates thickness was equal to 1.2 mm. All details of the reinforcement rebars and the CFRP strips are shown in Fig. 1b.

In EBR strengthening, the strips were fixed to the bottom side of beams. Furthermore, in NSM the strips were placed in grooves filled by an epoxy adhesive (Sikadur®-330). The used epoxy was prepared using an adhesive composed of two components (Resin (A) and Hardener (B)) mixed at a conventional ratio of 4 (A):1 (B)).

The main features of concrete, steel bars, CFRP strips and epoxy adhesive are summarized in Table 1. The steel rebar properties were obtained from direct tensile tests. However, the CFRP and the adhesive properties were obtained from the manufacturer's specifications (Sikadur®-330).

Specimens casting and strengthening procedure

A test of four-point bending was conducted on five reinforced concrete beams. The geometric characteristics of the tested beams were 17 cm of depth, 10 cm of width and 100 cm of length. The distance between supports and the shear span were 80 cm and 20 cm, respectively (Fig. 1a). The distance between the two loading points was 40 cm. The upper and lower longitudinal rebars have 8 mm of diameter. The stirrups of 6 mm diameter were provided with a spacing of 10 cm. In order to receive the concrete, wooden molds were prepared and soaked with oil to avoid any probable adhesion between the mold and the concrete [20]. After 24 h, the specimens were removed from the

Table 1 Material properties

| Concrete	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)
	35	2.90	34 400
Reinforcement bars	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)
Ø8	500	550	200 000
Ø6	235	410	200 000
CFRP strips CarboDur® S	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (MPa)
	1.2	3100	165 000
Adhesive Sikadur®-330	Thickness (mm)	Tensile strength (MPa)	Elastic modulus (MPa)
	/	30	4 500

molds and placed at an ambient temperature of 25 °C and relative humidity of about 40% [32].

Furthermore, two beams were reinforced externally on the bottom side by CFRP strips with a cross section of 3.6 mm^2, and two other beams were reinforced by inserting the CFRP strips in grooves. One more un-strengthened beam is considered as Control Beam (CB). The specimens were strengthened by one and two CFRP strips with a constant cross section. In order to clean the undersides of beams and grooves, a compressed air, a sander and a wire brush were used for ensuring a perfect adhesion between the adhesive and the concrete (Fig. 2). An acetone was used to remove any dirt and to well clean the used strips [33]. Figure 1 shows the details of CFRP reinforcements and grooves.

The reinforced beams by EBR technique were strengthened using an epoxy layer at about 1 mm of thickness. The epoxy adhesive was applied on the underside of concrete and the CFRP strips. A slight pressure was applied by a roller to wipe out voids. However, in strengthening by the NSM, the grooves were filled by the epoxy adhesive, and then the strips were placed in the grooves with a slight pressure to ensure that the epoxy envelops perfectly the CFRP plates. Finally, the epoxy resin was added to fill the grooves and the final surface was leveled [33].

Test instrumentations

The instrumentations used in these tests cover the Linear Variable Differential Transducer (LVDT) of ± 0.01 mm
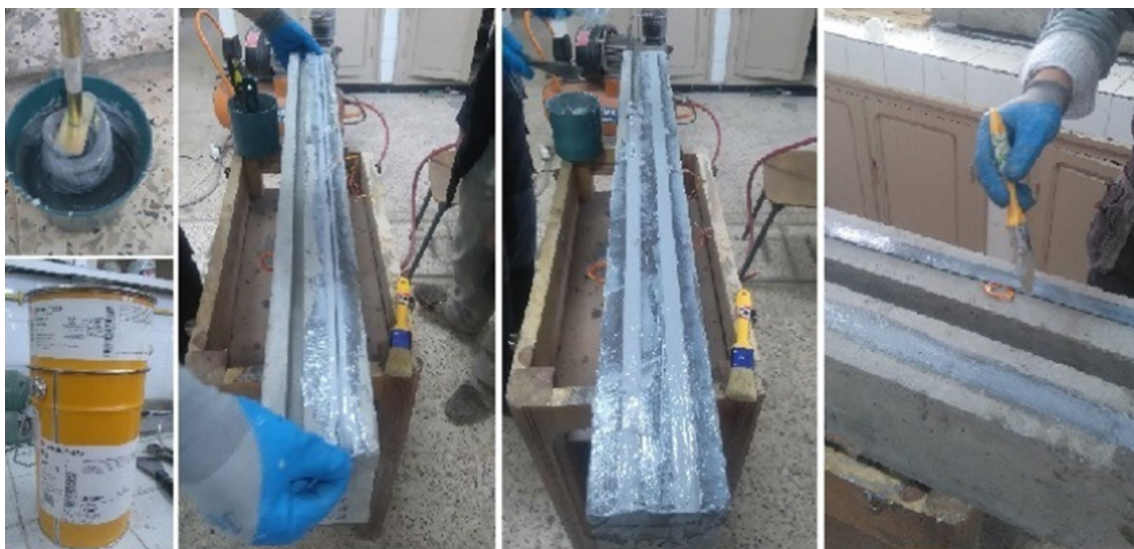
Fig. 2 Beams strengthening process

resolution with a working transverse range of 25 mm and strain gauges of different dimensions. The LVDT was used to measure the beams deflection at the mid-span [27]. Three strain gauges were attached to the mid-span of each beam, for measuring the strains. The first strain gauge of 15 mm was attached to the tensile reinforcement. The second strain gauge of 30 mm was attached to the middle of CFRP strips, and the last strain gauge of 60 mm was placed at the middle of the compressed concrete beam (Fig. 3) [33]. An automatic acquisition system was used to record the output data of the tests.

Results and discussions

The present experimental study investigates the strips arrangement effect on the response of the strengthened beams according to NSM and EBR techniques submitted to simple bending test (Fig. 4).

Table 2 presents the experimental results obtained from all tested beams. The results are presented in terms of the relationship between the applied load and the mid-span deflection (Fig. 8). A discussion of the test results is presented in the following sections in terms of failure modes, flexural strength, deflection, ductility, deformability of the beams and strains response of concrete, steel bars and CFRP strips.

Fig. 3 Installing of strain gauges in: **a** steels, **b** concrete and **c** strips

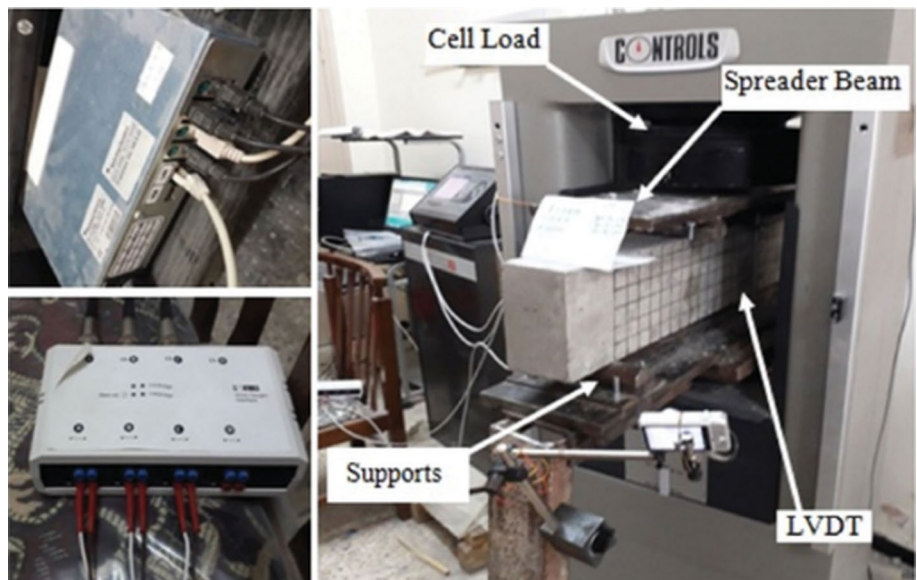**Fig. 4** Test setup and instrumentations

Table 2 Summary of loads and deflections

Beams	Fist crack		Yield		Ultimate		Failure	
	Load (F_{cr}) (kN)	Deflection (mm)	Load (F_y) (kN)	Deflection (mm)	Load (F_u) (kN)	Deflection (mm)	Load (F_f) (kN)	Deflection (mm)
CB	39.80	2.39	59.10	3.80	89.40	8.82	82.00	9.54
SB1NSM	41.37	1.94	101.70	6.26	111.10	7.60	109.60	7.75
SB2NSM	41.30	1.63	97.90	5.84	115.60	8.29	96.20	8.84
SB1EBR	43.60	2.42	72.70	4.19	111.70	8.55	104.80	9.01
SB2EBR	47.30	1.50	88.60	4.38	131.50	10.23	128.00	10.70

Fig. 5 Failure mode for un-strengthened beam

The cracking, yielding, ultimate and failure loads were analyzed to understand the responses of strengthened RC beams.

Failure modes

The failure modes of reinforced and un-reinforced beams under static loading are presented and discussed in the following section. The different failure modes observed during the tests are illustrated in Figs. 5, 6, 7. As shown in Fig. 5, the control beam exhibits slight flexural cracks due to bending. After that, Critical Diagonal Cracks (CDCs) were propagated on the tested beam. The different failure modes for strengthened beam by 1EBR are shown in Fig. 6a. The obtained results present an apparition of tensile cracks near to supports, followed by CDCs. They appeared at maximum shear zone. It was also observed an End Debonding (ED) of CFRP by failure at Concrete-Adhesive Interface (CAI) [34]. It was noticed, that the debonding has occurred on one side of the beam, of which the configuration was presumably insufficient to prevent the development of interfacial concrete-adhesive cracks.

Two types of cracks at failure are clearly visible in Fig. 6b. The first one propagates toward the loading point (CDCs), while the second is parallel to the tensile steel reinforcement at mid-span, which means a slightly Concrete

Cover Separation (CCS) failure was produced [35]. In this case, it was noticed that the CDCs were more important than in the case of NSM strengthening. The flexural cracks were not observed in this case. The shear, rather than flexure, dominated the EBR strengthened beams behavior, enabled beams to fail by shear cracks. Therefore, the full theoretical flexural capacity was not reached.

The strengthened beam with two strips by EBR technique exhibited an apparition of CDCs and External Debonding (EXD). However, the flexural cracks have not been observed (Fig. 6b). In this case, the full flexural capacity was not also reached. Probably, the CFRP cutting process disrupted the edges by severing fibers that were not completely aligned at the strips end.

The strengthened specimen by one NSM exhibited also higher tensile cracks than all the tested beams, particularly compared to the CB (Fig. 5). However, the diagonal cracks were less intense compared to the others. This can be explained by that, the grooving process (NSM technique) made an appropriate bond between CFRP strips and concrete beam; and the shear weakness of the beam was reduced. In this case (specimen SB1NSM), the debonding was not observed, but the CFRP strips breaking was occurred at the support points. This was not observed in the others. For the strengthened beam with two strips according to NSM, CDCs were developed from the supports to the loading points. In addition, cracks near to groove (bottom side) and others closer to the top side (loading point) were occurred (Fig. 7b). This outcome is obvious because the collapse was not occurred by CFRP strip breaking. Finally, a Concrete Cover Separation (CCS) failure at the beam edges was appeared. This is due to the excess of grooves number leads to weak the tensile side of the beam. Therefore, the concrete cover separation is appeared.

Load–Deflection behavior

Figure 8 presents the load versus mid-span deflection curves for strengthened and un-strengthened beams. The deflection increases along with load until the apparition of the first crack, as shown in Fig. 8, and the curve changes its

Fig. 6 Failure mode of strengthened beams by EBR technique

(a) Strengthened beam by 1EBR

(b) Strengthened beam by 2EBR

shape until the point corresponding to the steel yielding. Beyond this point, the load stabilizes and the displacement continues to undergo with a slight variation until the failure (case of NSM strengthening). The beams have a pseudo-plastic bearing ductility. This can be explained by the fact that CFRP materials exhibit no plastic deformation.

On the other hand, for the strengthened beams with EBR technique, the load and the deflection continue to increase until the collapse but with a greater displacement compared to the NSM values. The deflection at ultimate load was greater than obtained values from strengthening by NSM technique (8.55 mm, 10.23 mm for SB1EBR and SB2EBR, respectively, and 7.60 mm, 8.29 mm for SB1NSM and SB2NSM, respectively). This means that the beams strengthened by the EBR technique have slightly ductile behavior. The observed pseudo-ductility of the strengthened beams is due to the change in the position of the neutral axis due to the internal forces redistribution, causing the steel reinforcement to deform further.

The curves presented in Fig. 8 indicate that when the beams are strengthened, the displacement decreases while the load and stiffness increase significantly.

As previously mentioned, the tested specimens have the same parameters, such as concrete cross section, reinforcement and CFRP strips. The only difference was the strengthening technique and the arrangement of CFRP strips. Theoretically, all the strengthened beams must have the same behavior and ultimate loads [27].

The arrangement of the CFRP strips increases, the stiffness, the ultimate load and the maximum displacement increase as well, in the case of specimens strengthened by the EBR technique, which was not observed in the case of strengthening by the NSM technique, where the difference is not significant.

Fig. 7 Failure mode of strengthened beams by NSM technique

(a) Strengthened beam by 1NSM

(b) Strengthened beam by 2NSM

The strengthened beam by 1NSM CFRP strips shows a similar behavior compared to that observed for the beam with 2NSM until the yielding point. After that, a slight distinction was observed. The failure loads indicate that, in NSM technique, the use of more strips is not always advantageous for improving the failure load, because of excessive embrittlement of the concrete cover. This last promotes the cracks propagation in the beam tensile side. However, in the second instance (beams strengthened by EBR technique), the tests have shown a remarkable difference in the load–deflection curve, since the beginning of loading (Fig. 8b). After yielding of the steel reinforcement, the increasing of deflection rate was found higher than the beams reinforced by the NSM technique, which decreases the beam stiffness, due to the linear stress–strain characteristics of the CFRP strips.

All previous studies revealed that the NSM technique also allows better exploitation of the material properties, and has fewer bonding problems compared to the EBR technique [36]. In contrast, our tests reveal that this was not observed in the case of using more strips. The reinforcement by EBR with two strips presents higher failure loads and the debonding was less observed compared to NSM.

Flexural carrying capacity

The obtained results of flexural carrying capacity are presented in Table 2; these results underline the effect of arrangement strengthening on the flexural beams capacity. The results are presented in terms of first crack load, yield load, ultimate load, failure load, and deflection at mid-span. Reminding that, all beams have the same cross section of concrete, steel and carbon strips. The only difference is the layout of the CFRP.
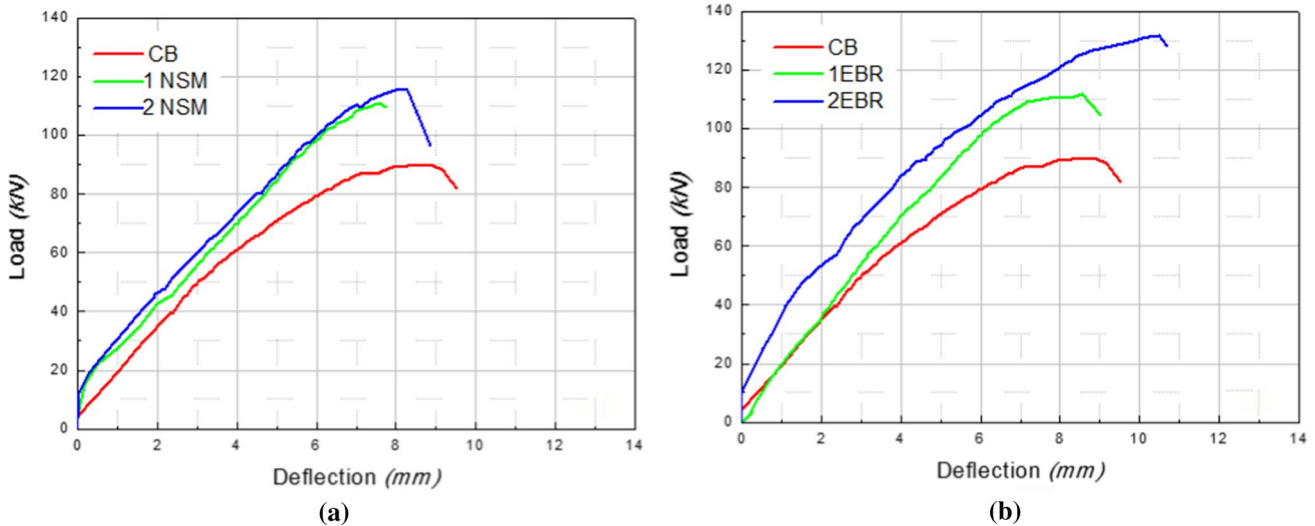
Fig. 8 Load mid-span deflection for tested beams. **a** Beams strengthened by NSM technique. **b** Beams strengthened by EBR technique
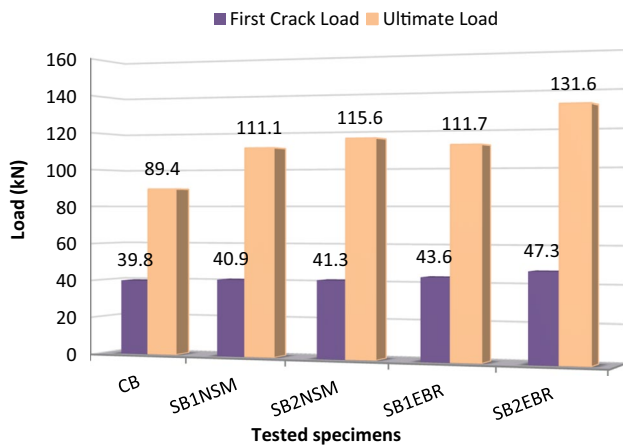

Fig. 9 Flexural carrying capacity of strengthened beams

The test results revealed that the addition of CFRP strips using NSM and EBR techniques enhances significantly the stiffness and the ultimate load-carrying capacity of the strengthened beams, as shown in Fig. 8. The RC specimens strengthened with carbon plates present a significant increase in ultimate load capacity by 24%, 29%, 25% and 47% for SB1NSM, SB2NSM, SB1EBR and SB2EBR, respectively, compared to the control beam Fig. 9.

The first crack and the yield load of the specimens also increased significantly after strengthening for both techniques, due to the restraining of the cracks opening.

Also, the CFRP distribution increases significantly the obtained results that cited above, which is more remarkable in the EBR reinforcement technique.

Furthermore, the effect of the strengthening technique on the ultimate load-carrying capacity is more remarkable

for two strips disposition than a single strip. Some reasons may be attributed to the better performance of EBR method when the strips arrangement is increased. This distributed arrangement allows a wider coverage by plates/adhesive of the bottom side of beams. Therefore, the development of cracks is delayed, leading to the improvement of the carrying capacity.

Ductility and deformability

The ductility is the ability of structures or section materials to tolerate inelastic deformation before collapse. In this section, the effect of reinforcement and arrangement of fiber carbon strips on the ductility of strengthened beams was examined.

The deformability of the beams is defined as the ability of the structural element to reach greater deflections with widening cracks. Several studies have found that increasing the beams strengthening leads to reduce the ductility [37]. To estimate the ductility and the deformability of beams, ductility ($\mu_{\Delta u}$) and deformability ($\mu_{\Delta f}$) factors are expressed as follows [38]:

$$\mu_{\Delta u} = \frac{\Delta_u}{\Delta_y} \tag{1}$$

$$\mu_{\Delta f} = \frac{\Delta_f}{\Delta_y} \tag{2}$$

where Δ_u, Δ_f and Δ_y are the displacements at ultimate load, failure and yielding load, respectively.

The test results presented in Table 3 reveal that the ductility decreases with the strengthening of beams for both

Table 3 Summary of ductility and deformability factors

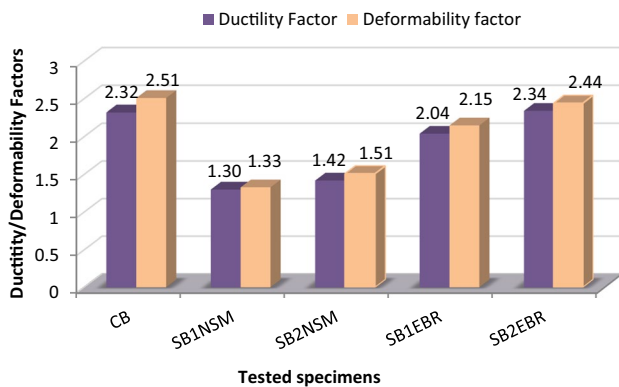| Specimens	Ductility Factor ($\mu_{\Delta u}$)	Ratio over CB	Deformability Factor ($\mu_{\Delta f}$)	Ratio over CB
CB	2.32	1.00	2.51	1.00
SB 1NSM	1.30	0.56	1.33	0.53
SB 2NSM	1.42	0.61	1.51	0.60
SB 1EBR	2.04	0.88	2.15	0.86
SB 2EBR	2.34	1.01	2.44	0.97

Fig. 10 Ductility and Deformability Factors of the beams

techniques (NSM and EBR) compared to the control beam. This ductility reduction is mainly attributed to the brittle behavior of the CFRP material [39]. However, the increasing of rearrangement strips enhances the beams ductility and it is higher in EBR technique. This is due that increasing the number of CFRP strips reduces their deformability because the internal forces on the strips have been divided at both of them. This leads to more deformation in the beam as well as in the reinforcement and consequently, the ductility increases.

The ductility improvement is less observed, in NSM technique when the number of strips increases. But in all cases, the strengthened beams ductility remains always lower than the CB.

It is clear that the use of two plate layouts of CFRP, especially in the case of reinforced beams by EBR, enhances the ductility. It is almost similar to the CB values. This is due that the steel tends to yield and its stress stabilizes and the strips take back the excess stress.

Moreover, the deformability of the reinforced beams increases with the increase in the CFRP strips number, particularly for the strengthening by EBR technique. However, it remains always lower than the CB results (Fig. 10).

This confirms that strengthening by a distributed arrangement of strips is beneficial for the ductility and the deformability of reinforced beams.

The ductility and the deformability values of reinforced beams by NSM technique are lower compared to those reinforced by EBR. This is due that the embedded of the CFRP plates in the cross section and the excessive quantity of used epoxy increase the beam rigidity and consequently decrease the ductility. This indicates a composite action between the beam and strengthening, where the total reinforcement capacity is used.

Strain response curves

Figures 11, 12 depict the loads versus strains of flexural reinforcement and compressive concrete at mid-span of
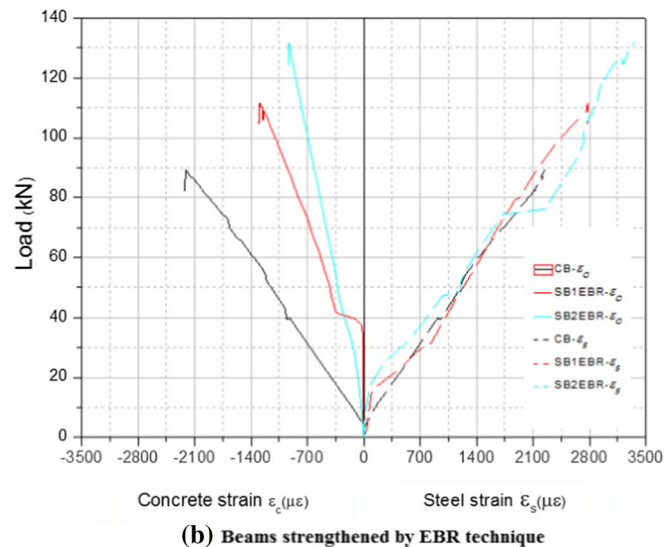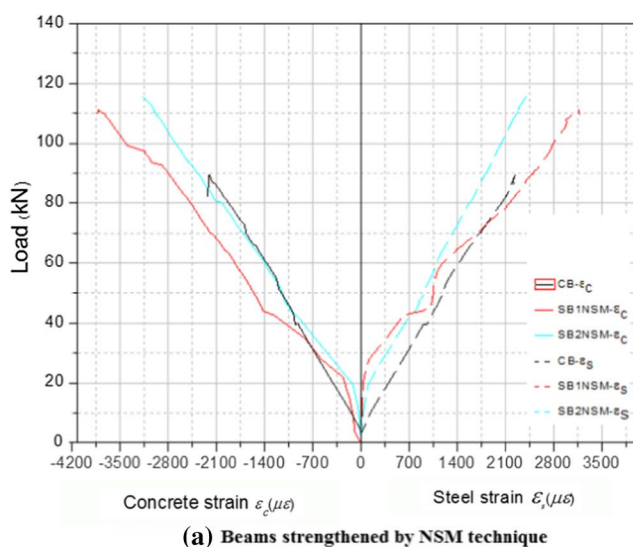

(a) Beams strengthened by NSM technique

(b) Beams strengthened by EBR technique

Fig. 11 Strain of the flexural reinforcement and top surface concrete at mid-span of the tested beams
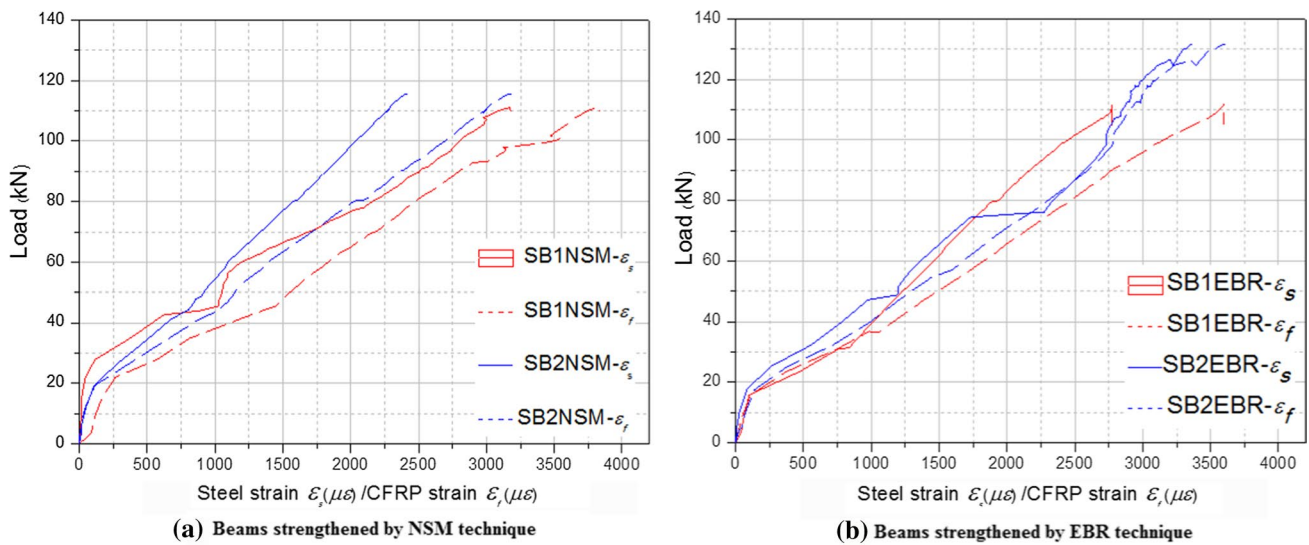
Fig. 12 Strain values in the main reinforcement and CFRP strips at mid-span of the tested beams

the beams. The strains of the concrete for all strengthened beams by NSM technique were greater than those observed for the CB (Fig. 11a). However, in the case of strengthened beams by EBR technique, the concrete strains were smaller than those in CB (Fig. 11b). This indicates that the concrete was more stressed in the NSM compared to the EBR. The increasing of strips arrangement leads to decrease the concrete strains for the strengthened beams by NSM.

The strain in the tensile bars of the strengthened beams by 1NSM was greater than the CB at the same load level, while, for the strengthened beams by 2NSM, the tensile bars strain was less compared to the CB (Fig. 11a). As shown in Fig. 11a, the increasing of strips arrangement decreases the tensile bars strains. However, for the strengthened beams by EBR, the increasing of the strips arrangement increases also the tensile strains of steel reinforcement (Fig. 11b). It was also observed from Fig. 11 that the carried load by the tensile bars of the strengthened beams with NSM is greater than the CB. Nevertheless, it was almost similar to the CB for those strengthened by EBR.

The tensile strains of the main tensile bars and the CFRP strips versus the loads are presented in Fig. 12. In the case of strengthening by NSM and below the yielding-point load, the strains of CFRP strips for the specimen SB1NSM were greater than the tensile rebar strains. The gap between both strains materials becomes lower beyond the yielding load. Furthermore, for the strengthened beam by 2NSM, the strains of the CFRP were also greater than the main steel rebar, but the gap was greater when the beam reaches higher loads (Fig. 12a). The CFRP strips, in the dispersed arrangement case, were more stressed than the tensile bars. Below the yielding load, the strains of CFRP strips of the strengthened beam by 1EBR were almost similar to those of

the main steel reinforcing bars. After the yielding load, the gap between the strains of both materials (steel rebar and CFRP) increased while the load increases. It means that, when the beam reaches higher loads, the CFRP strips are more stressed than the steel rebar. However, for the strengthened beam by 2EBR, the strains of the CFRP strips and tensile bars were too close before the yielding load. For high load values, the strains of CFRP and tensile rebar exhibited similar curves (see Fig. 12b). It indicates that the use of two strips in the EBR technique allows a better simultaneous exploitation of both materials (CFRP and tensile steel rebar).

Conclusions and recommendations

In this paper, we investigated the flexural behavior of reinforced concrete beams strengthened by CFRP strips. Five RC beams ($0.17 \times 0.10 \times 1$ m^3) were constructed and strengthened with different CFRP configurations. The test parameters included the strengthening technique (NSM and EBR) and the CFRP amount. The obtained results from this experimental study show that the load-carrying capacity increases significantly with increasing of the strips number. The increasing ranges from 24 to 29% for the NSM technique and from 29 to 47% for the EBR. The strengthening of RC beams with CFRP improved the first crack load, and the increasing of strips arrangement improves it even further. As a result, the increasing of strips number delays the first crack occurrence. It was also noted that the deflection of the strengthened beam by two EBR strips is greater than the CB, despite its stiffness was higher than all the other cases. In agreement with previous researches, the strengthening of RC beams reduced

the ductility compared to CB. However, these experiments showed that the increasing of the strips amount improves the ductility. This increasing brings the ductility to the CB values.

It is noted that the use of two CFRP strips increases significantly the beams deformability. This increasing is more observed in the EBR than the NSM. The strengthened beams by two CFRP strips presented a significant enhancement in energy dissipation capacity compared to those of strengthened beams by one plate and CB.

Summerly, the effect of strip arrangement on different parameters is more relevant in the EBR technique than the NSM.

Regarding the concrete strains in NSM technique, the increasing of strips arrangement reduces the concrete strains. This will minimizes the failure occurrence by concrete crushing. As seen in CB, the critical diagonal failure of concrete caused all strengthened beams to fail in flexure. However, tensile cracks were observed only in the strengthened beams with one plate. It is noted that the tensile cracks are prevented by increasing of the strips number. However, in the NSM approach this increasing favors the concrete cover separation.

In the current study, a preliminary experimental research is introduced giving a fundamental stage toward this aim. Further studies on the behavior of RC beams strengthened by CFRP are still required, with more parameters that may influence the behavior of strengthened beams. Many questions are still open concerning the influence of strengthening by CFRP on the response of RC structural elements. An extended experimental study will conducted taking into account the strengthening configurations by more than two strips arrangement using both techniques. Moreover, numerical models will generated in order to analyze the behavior of strengthened RC beams under different load patterns.

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