FLEXURAL BEHAVIOR OF RC BEAMS STRENGTHNED WITH CFRP SHEETS USING DIFFERENT STRENGTHENING TECHNIQUES

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ABSTRACT: Due to the advantages of Fiber Reinforced Polymer (FRP) materials, they have been utilized to strengthen several reinforced concrete (RC) elements such as slabs, beams and columns. In this paper, five RC beams (200 mm width, 300 mm height, and 2750 mm length) were constructed. Four of these beams were strengthened with CFRP sheets whereas the last beam was used as a reference. Test parameters include the amount of FRP and the strengthening technique. Three strengthening techniques were used including the externally bonded technique (EB), the near surface mounted (NSM) technique using folded CFRP sheets inserted in near surface grooves, and a hybrid technique. All beams were tested under four point bending setup until failure. The control beam failed by the yielding of the tension steel followed by concrete crushing. The strengthened beams failed by steel yielding followed by either rupture or debonding of CFRP sheets at higher loads compared to the reference one. The stiffness after steel yielding and the ultimate capacity increased as the amount of CFRP increased. The strengthening technique affected the ultimate capacity of the strengthened beams. The NSM beam showed the lowest increase in the ultimate capacity (25.2%) whereas the hybrid beam showed the best performance with the highest increase in the ultimate capacity (58%) compared to the reference beam.

***Keywords**:* Carbon fiber reinforced polymers; Experimental work; Flexural behavior; Reinforced concrete beams; Strengthening techniques.

السلوك المرن للعوارض الخرسانية المسلحة المقواة بألياف الكربون البوليمرية باستخدام تقنيات تقوية مختلفة

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الملخص: نظرا لمزايا مواد البوليمر المقوى بالألياف فقد تم استخدامها لتقوية العديد من العناصر الخرسانية المسلحة مثل البلاطات والعوارض والأعمدة. في هذا البحث، تم بناء خمسة عوارض خرسانية مسلحة بأبعاد 200 × 300 × 2750 مم. وتم تقوية أربع من تلك العوارض باستخدام ألياف الكربون البوليمرية في حين تم استخدام العارضة الخامسة بدون تقوية كمرجع. وتضمنت عوامل الدرسة كل من كمية ألياف الكربون البوليمرية وكذلك التقنية المستخدمة في التقوية. وقد تم استخدام ثلاث تقنيات تقوية بما في ذلك تقنية الترابط الخارجي (EB) بين الألياف و السطح الخارجي للعوارض وتقنية التركيب القريب من السطح (NSM) باستخدام نسيج ألياف الكربون المطوية التي تم إدخالها في أخاديد على سطح العوارض ، وتقنية هجينة من التقنيتين السابقتين. تم اختبار جميع العوارض باستخدام حملين مركزين حتى الإنهيار. فانهارت العارضة المرجعية غير المقواة عن طريق خضوع حديد التسليح متبوعًا بتهشم الخرسانة. بينما انهارت العوارض المقواة على أحمال أعلي من العارضة المرجعية عن طريق خضوع حديد التسليح متبوعا إما بتمزق ألياف الكربون البوليمرية أو تفكك التصاقها بالعوارض الخرسانية. وقد لوحظ كذلك زيادة كل من جساءة و قوة التحمل القصوى للعوارض المقواة بزيادة عدد طبقات ألياف الكربون البوليمرية. كما أثبتت الدراسة أيضا أن تقنية التقوية المستخدمة أثرت على قوة التحمل القصوى للعوارض المقواة. هذا وقد أعطت تقنية التركيب القريب من السطح (NSM) أعطت أقل زيادة في قوة التحمل القصوى للعوارض المقواة بنسبة زيادة بلغت 25.2٪ مقارنة بالعارضة المرجعية. بينما التقنية الهجينة أعطت أفضل أداء من حيث قوة التحمل القصوى للعوارض المقواة بنسبة زيادة بلغت 58٪ مقارنة بالعارضة المرجعية.

الكلمات المفتاحية: ألياف الكربون البوليمرية ؛ دراسة معملية ؛ السلوك المرن ؛ العوارض الخرسانية المسلحة ؛ تقنيات التقوية.

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1. INTRODUCTION

Due to harsh environmental conditions such as high humidity and temperatures, several reinforced concrete (RC) structures in the Arabian Gulf region, especially those close to shorelines, suffer from steel corrosion problems. This requires strengthening and/or rehabilitation of these structures Almusallam *et al*. (2013). In other cases, strengthening of RC structures is required to overcome design or construction mistakes, to upgrade the capacity of an existing structure, or to fulfill revisions in codes and standards Al-Salloum *et al*. (2013).

Several strengthening/rehabilitation techniques of RC structures have been used in the last decades. Due to their high strength, less weight, corrosion resistance, and easy in application, Carbon Fiber Reinforced Polymer (CFRP) sheets have been widely used for strengthening of several RC elements including RC columns, beams, and slabs El-Gamal *et al*. (2012).

Several studies have investigated the behavior of RC beams strengthened in flexure with FRP composites. Many research studies have used the near surface mounted (NSM) technique where FRP bars are inserted and bonded to near surface longitudinal grooves in the tension surface of the beam using bonding materials (Al Mahmoud *et al*. 2009; Soliman *et al*. 2011; Sharaky *et al*. 2014; El-Gamal *et al*. 2014). Other studies used the externally bonded (EB) technique where FRP sheets are bonded to the tension surface of the beams (Al-Tamimi 2011; Mostofinejad and Shameli 2011, 2013; Jiangfeng *et al*. 2012; Attari *et al*. 2012; Dong *et al*. 2013; Hawileh *et al*. 2014; Al-Saidy *et al*. 2015; El-Gamal *et al*. 2017). Furthermore, other studies used both techniques (Choi *et al*. 2007; Jung *et al*. 2007; Seracino *et al*. 2007; Rasheed *et al*. 2010; Ceroni 2010; El-Gamal *et al*. 2016).

Among those studies was the investigation conducted by Choi *et al*. (2011) who investigated the behavior of seven T-shaped RC beams strengthened with both EB-CFRP plates and NSM-CFRP bars. Their test parameters included bonded length (fully and partially bonded length) and strengthening technique (EB and NSM). In the EB specimens with partially bonded length, they used transverse anchorage FRP sheets to increase the bond strength. Test results of the EB beams showed that the fully bonded specimens failed by FRP debonding. Whereas the partially bonded beams with transverse anchorage failed at higher load by FRP rupture. The NSM specimens, however, utilized the full strength of the CFRP bars and the failure modes varied between FRP bar slipping after sustaining a very large deflection in fully bonded beam and concrete crushing at mid-span for the partially bonded beams. They concluded that the effectiveness of the NSM system was better than the EB system. The EB and NSM strengthening techniques increased the ultimate loading capacity by 6% to 23% and 36% to 53%, respectively, compared to the reference beam.

Jung *et al*. (2007) investigated the flexural behavior of eight RC beams strengthened with CFRP strips and rods using EB, NSM and NSM with mechanical interlocking (MI) grooves, and NSM with pre- stressing strengthening techniques under four-point bending setup. Test results showed that the maximum measured strains in the FRP reinforcement for the EB specimens was about 30% of the ultimate strain, 82-87% for the NSM specimens, and approximately 100% for the NSM specimens with the MI grooves and the pre-stressed specimens, which proved that NSM system had utilized FRP reinforcement sufficiently compared to EB specimens. The pre-stressed NSM specimens showed a behavior similar to the NSM specimens with the MI grooves.

Mostofinejad and Shameli (2011, 2013) conducted two experimental studies to investigate the performance of new flexural strengthening techniques using CFRP sheets. They called the first technique “Externally Bonded Reinforcement On Grooves” (EBROG) where the FRP sheet is laid over longitudinal grooves filled with epoxy resin with the same concept of EB technique. The second technique is called Externally Bonded Reinforcement In Groove (EBRIG). This technique is similar to the NSM technique; however, the FRP sheets are bonded to the internal surfaces of the grooves as well as to the tension face of the beams. In both studies, they constructed small-scale concrete beam specimens with no internal flexural reinforcement. They used only internal steel stirrups to prevent shear failure. CFRP sheets with different number of layers (one to three layers) were used for strengthening the beams using four strengthening techniques i.e. EB, NSM, EBROG and EBRIG. They concluded that the beams strengthened with EBROG and EBRIG techniques had considerable higher capacities compared to the beams strengthened with EB technique. In addition, the EBRIG technique permitted for higher failure loads and displacements compared to the EBROG technique.

Dong *et al*. (2013) conducted an experimental study to investigate the flexural behavior of seven RC beams strengthened with one or two layers of CFRP sheets. The aim of the study was to investigate the effectiveness of strengthening on cracking load, ultimate load, strains and deflections. All the beams were simply supported over a clear span of 1500 mm and were tested under four-point bending. The test result showed that the strengthened beams failed due to either rupture or debonding of FRP sheets. The overall flexural capacity of all strengthened beams varied between 41% and 125% over the control beams. They also concluded that FRP sheets controlled cracks and increased the ductility of the beams.

Rasheed *et al*. (2010) constructed six beams and strengthened them using four strengthening techniques and materials: EB CFRP sheets, NSM CFRP strips, EB steel reinforced polymer (SRP) sheets, and NSM stainless steel bars. They used different configurations of external transverse reinforcement to improve ductility and control debonding of the strengthening systems. Test results showed that all strengthened beams showed much higher capacities compared to the reference beam. They concluded that the use of external transverse anchoring reinforcement further increased the flexural capacity of the strengthened members and allowed for better utilization of the high strength properties of the strengthening materials.

Ceroni (2010) constructed 21 RC beams to investigate the behavior of RC beams strengthened with EB CFRP sheets or NSM CFRP bars. All beams were tested under four point bending setup. Test results indicated that most of the EB beams without anchoring devices failed by debonding. An adequate ductility was attained by introducing anchorage devices that eliminated or delayed the debonding. They also concluded that the best result was reached by applying distributed U-shaped FRP strips. The increased strength in the EB beams varied between 18% and 51%. The NSM beams achieved higher load capacity (46–72%) greater than the EB beams having similar equivalent reinforcement percentage.

Hawileh *et al*. (2014) conducted an experimental study on five RC beams strengthened with EB FRP sheets to investigate their flexural performance. The beams were strengthened with combinations of EB glass and carbon FRP sheets and were tested under four point bending setup. In addition, they developed an analytical model to predict the load–deflection response and the carrying capacities of the beams and they compared the model with their experimental results and with the ACI 440.2R-08 predictions. They recorded an increase in the ultimate capacity of the strengthened beams ranging between 30.7 and 98% compared to the control beam. They observed that the beams strengthened with hybrid glass and carbon FRP sheets developed higher ductility than those strengthened with a single carbon sheet, however, the beams strengthened with a single glass FRP sheet developed the highest ductility among all strengthened beams. They concluded that using a hybrid system of glass and carbon FRP sheets was the best as it combined both the high strength of the carbon sheets that improved strength and the low stiffness of glass sheets that improved ductility. They also concluded that the ACI provisions were accurate for the beams with one layer of strengthening sheet; however, they were less accurate for hybrid specimens as the number of strengthening layers increased.

El-Gamal *et al*. (2014, 2016) conducted experimental studies to investigate the flexural behavior of RC beams strengthened with glass and carbon FRP composites using NSM and EB techniques. The experimental investigation included four parameters; strengthening technique, type of FRP, amount of FRP, and steel reinforcement ratio. Test results indicated that all strengthened beams showed an increase in the ultimate load capacity ranging between 55 and 133% compared with the reference beam. The NSM-CFRP strengthened beams showed higher capacities than the NSM-GFRP strengthened ones; however, they showed much more brittle behavior. They recommended conducting further experimental studies to investigate other parameters.

It can be noticed that most of the above mentioned research studies used the NSM technique where FRP bars are inserted into longitudinal grooves on the tension surface of the beams or the externally bonded (EB) technique where the CFRP sheets are attached to the tension surface of the beams. However, to the best knowledge of the authors, very limited research studies investigated the use of CFRP sheets inserted in NSM grooves Mostofinejad and Shameli (2013) or used a hybrid technique (NSM and EB).

This research study aims to fill this gap by investigating the behavior of RC beams strengthened with CFRP sheets using different techniques. This includes the regular EB technique, a modified NSM technique using CFRP sheets that were folded and embedded into near surface grooves, and a hybrid technique (EB and NSM). The experimental work includes the construction and testing of five RC beams. One beam was a reference beam without strengthening. Another beam was strengthened with two CFRP sheets folded and inserted into two grooves, which is similar to the NSM technique. Two beams were strengthened with one/two layers of EB CFRP sheets. The last beam was strengthened with a hybrid technique where one CFRP sheet was inserted in a near surface groove while a second CFRP sheet was bonded to the surface of the beams using the EB technique. The measurements included mid-span deflection, cracking, ultimate capacity, and mode of failure.

2. TEST SPECIMENS AND SET-UP

2.1 Materials

The five beams were cast using a ready mix concrete. Standard concrete cylinders of 150 mm diameter and 300 mm height were taken from the concrete mix during casting and were cured with the beams. Standard compressive and splitting tests were conducted on the cylinders after curing (Fig. 1). The measured concrete compressive strengths was 56.3 MPa, whereas the tensile strength was 3.2 MPa.

Deformed steel bars of 12 mm diameter were used for the bottom longitudinal reinforcement of the

(a) (b)

Figure 1. (a) Brazilian test; (b) Compressive strength test.

beams, whereas 8 mm diameter bars were used for the top reinforcement and stirrups. The steel bars were tested in the laboratory to determine their tensile properties. Test results showed that the average yield strength of the steel bars was 480 MPa for both diameters.

Unidirectional CFRP sheets were used to strengthen the beams. The ultimate tensile capacity of the CFRP sheets was 350 kN/m-width as given by the manufacturer. Fig. 2 shows a photo of the CFRP sheets used in this study. Epoxy resin was used to bond the CFRP sheets with concrete. The technical information of both CFRP sheets and epoxy resin can be found in (SIKA Group, 2018; BASF, 2018), respectively.

2.2 Description of Test Specimens

Five RC beams with typical reinforcement and dimensions were constructed. All the beams had dimensions of 2760×300×200 mm (length × depth × width). All beams were reinforced with two steel bars of 8 and 12 mm diameters in the top and bottom longitudinal direction, respectively. Steel bars of eight mm diameter spaced at 100 mm center-to-center were used in all beams as shear reinforcement to prevent any shear failure. Fig. 3 shows the reinforcement details and dimensions of the beams.

Figure 2. Unidirectional CFRP sheets used in this study.

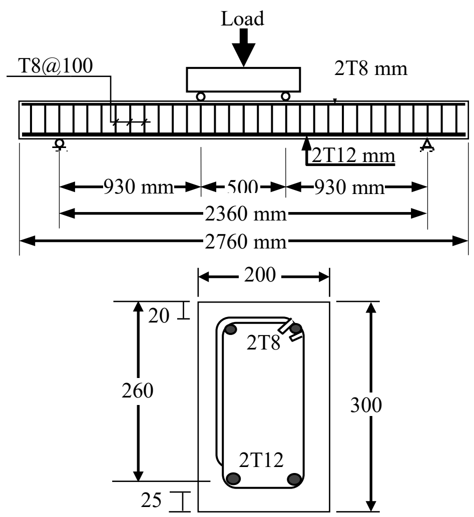


Figure 3. Elevation and cross section of the beams (All dimensions are in mm).

Out of the five constructed beams, the first beam was used as a control specimen without strengthening (Fig. 3). All the other four beams were strengthened (in the bottom face) with CFRP sheets (200 mm width) using different procedures. Two beams (EB1 and EB2) were strengthened using the well-known EB technique. Beam EB1 was strengthened with one CFRP sheet, whereas beam EB2 was strengthened with two CFRP sheets as shown in Fig. 4a,b. The third beam (NSM) was strengthened with two CFRP sheets folded and inserted into two near surface grooves (10 mm width and 20 mm depth) in the tension side of the beam. In this technique, which is similar to the NSM technique, the CFRP sheets were unconventionally embedded into the near surface grooves, which were filled with epoxy as shown in Fig. 4c. The fourth beam (HYB) was strengthened by a hybrid technique using one CFRP sheet inserted in a groove and one CFRP EB sheet. Table 1 lists the matrix of beams, whereas Fig. 4 shows the cross sections of all strengthened beams.

Table 1. Schedule of test specimens.

Beam	Strengthening reinforcement	Strengthening technique
Control	-	-
EB1	One EB CFRP sheet	Externally Bonded
EB2	Two EB CFRP sheet	Externally Bonded
NSM	Two CFRP sheets imbedded into two near surface grooves	NSM
HYB	1 CFRP sheet imbedded in near surface groove and one EB CFRP sheet	Hybrid (NSM and EB)

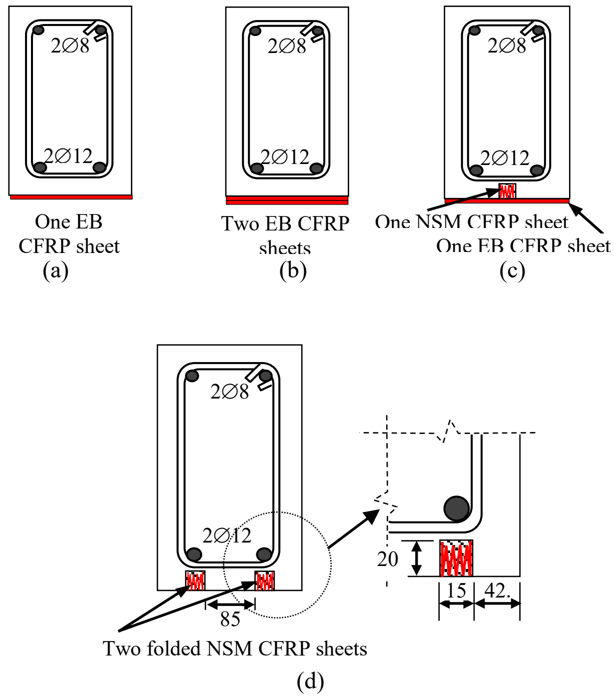


Figure 4. Cross sections of strengthened beams: (a) EB1; (b) EB2; (c) HYB; (d) NSM (All dimensions are in mm).

2.3 Construction of Test Specimens

After preparing the steel cages of the five beams, the cages were placed into wooden molds before concrete casting using a ready mix concrete. Fifteen standard concrete cylinders were cast with the beams for measuring compressive and tensile strength of concrete. All beams were cured for 28 days before testing. Fig. 5 shows the specimens before and after casting.

2.4 Strengthening of Test Specimens

For the beams with external layers of CFRP sheets (EB beams), the concrete surface was prepared before applying the fibers. The bottom surfaces of the beams were roughened and cleaned well before adding the epoxy on the surface and installing the CFRP sheets. For the EB2 beam, a second layer of epoxy was added before installing the second CFRP sheet. Fig. 6a shows one of the EB specimens after installing the sheets. For the NSM beam, each groove was cleaned and partially filled with the epoxy resin. Afterwards, the dry CFRP sheet was folded and inserted into the groove then covered with more epoxy resin. The same procedure was repeated for the second groove. Fig. 6b shows the NSM beam after installing the CFRP sheets. For the HYB beam, the first CFRP sheet was inserted in the groove as described in the NSM beam above. After that, a second CFRP sheet was installed on the surface as described in the EB beams.

2.5 Test Set-up

All beams were tested under four-point bending setup with a clear simply supported span of 2360 mm as shown in Fig. 3. Three linear variable differential transformer (LVDTs) were used at mid and quarter spans of the beams for deflection measurements. Two concrete strain gauges were installed at the top mid-span of the beams for concrete compressive strains measurements. Load was applied gradually at a rate of 1 mm/min until failure. All data were automatically recorded using a data acquisition system connected to a computer. Fig. 7 shows one beam during testing.

Figure 5. Test specimens before and after casting.

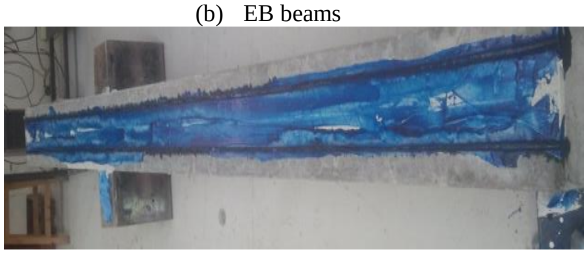
3. TEST RESULTS AND DISCUSSIONS

3.1 Description of Test Results

Table 2 shows the main results of test specimens. The ultimate capacity of the control beam was 76.4 kN and the maximum mid-span deflection was 53.4 mm. The first crack was recorded at a load of about 24 kN. Figure 8 shows the load versus mid-span deflection curve of the control beam. It can be noticed that the curve shows three different stages. The first part represents the behavior of the beam with its gross inertia before cracking. The second part shows the behavior after cracking until steel yielding. The third part presents the behavior of the beam after steel yielding until failure. As expected, the control beam failed by yielding of tension steel followed by crushing of concrete after large deflections.

All strengthened beams had almost the same cracking load as the control beam (24 kN to 25 kN), which depends mainly on the gross inertia of the cross section of the beam. However, Table 2 shows a big difference between the control beam and the strengthened beams in terms of yield load, maximum load, mid-span deflection, number of cracks at failure, and failure mode. The strengthened beams revealed higher capacities (95.7 to 120.9 kN) compared to the control beam (76.4 kN) as shown in

(b) EB beams



(a) NSM beams

Figure 6. Installation of CFRP sheets.

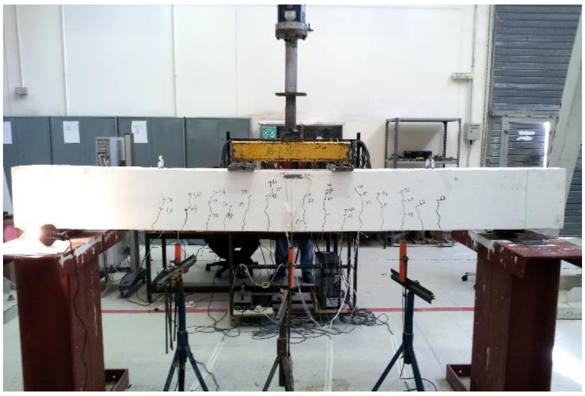


Figure 7. Photo of one beam during testing.

Fig. 9. The increase in the ultimate capacity of the strengthened beams ranged between 25.3% in the NSM beam and 58.3% in the HYB beam. The control beam, however, showed higher deflections at maximum load. Three different failure modes were recorded. The control beam failed in a ductile manner by tension steel yielding followed by concrete crushing after large deflections. Beam EB1 failed by yielding of tension steel followed by rupture of CFRP sheet, whereas the other three strengthened beams (EB2, NSM, HYB) failed by yielding of steel followed by CFRP debonding.

Figure 10 shows the beams after failure. It can be seen that the strengthened beams had more cracks at

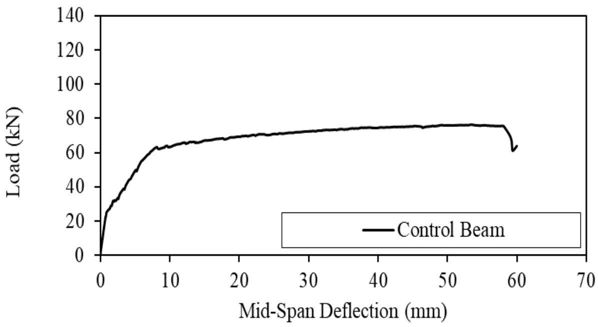


Figure 8. Load–deflection curve of the control beam..

Table 2. Main test results.

Beam	P_{cr} kN	P_y kN	P_{max} kN	Δ_{max} mm	Capacity increase (%)	Failure mode
Control	24	64	76.4	53.4	-	SY→CC
EB1	24	72	101.2	22.8	32.6	SY→RUP
EB2	25	100	119.2	17.2	56.1	
HYB	24	79	120.9	26.0	58.3	SY→DEB
NSM	24	90	95.7	21.1	25.3	

where **P_{cr}** is the cracking load, P_y is the yield load, **P_{max}** is the maximum load, Δ_{max} = mid-span deflection at maximum load, SY = steel yielding; CC = concrete crushing; RUP= rupture of CFRP; DEB = debonding of CFRP.

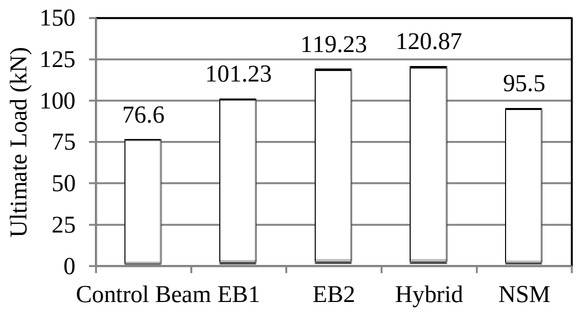


Figure 9. Comparison between the ultimate loads of tested beams.

failure compared to the control beam. The number of recorded cracks ranged between 18 and 24 cracks in the strengthened beams compared to only 14 cracks in the control beam.

3.2 Effect of the Amount of CFRP Reinforcement

Figure 11 shows mid-span deflection versus load in beams EB1, EB2, and the control beam. The figure shows that the capacity of the strengthened beams increased as the amount of CFRP increased. Using one CFRP sheet (in EB1) increased the capacity by about 32.6%, whereas using two CFRP sheets (in EB2) increased the capacity by about 56.1% compared to the control beam.

Both beams failed in a brittle manner; however, the mode of failure was not similar. Beam EB1 failed by CFRP rupture, which means that the strains in the CFRP sheet reached the ultimate strain of the CFRP fibers. Beam EB2, however, failed by CFRP debonding before reaching the ultimate strength of the sheets, which was in agreement with several research studies. This means that the capacity of this beam could be further increased if the debonding problem was delayed or eliminated using transverse anchorage as described by different researchers (Choi *et al*. 2007; Rasheed *et al*. 2010; Ceroni, 2010) or by using EBROG system as given by Mostofinejad and Shameli (2011, 2013). Therefore, it is recommended to conduct further investigations on the best anchorage technique in a future study.

The strengthened beams showed a slightly higher stiffness after cracking compared to the control beam, which is expected as the stiffness at this stage depends on both steel and FRP material. After steel yielding, Fig. 11 shows that the stiffness significantly increased as the amount of CFRP increased as the stiffness at this stage is mainly depending on the FRP material.

It can be concluded from this parameter that the amount of FRP reinforcement did not show a significant effect on the behavior of the beam at the elastic stage. However, it affected the mode of failure, the ultimate capacity and the stiffness after steel yielding. Both ultimate capacity and stiffness of the beams after steel yielding increased as the amount of the CFRP increased.

Figure 10. Tested beams after failure.

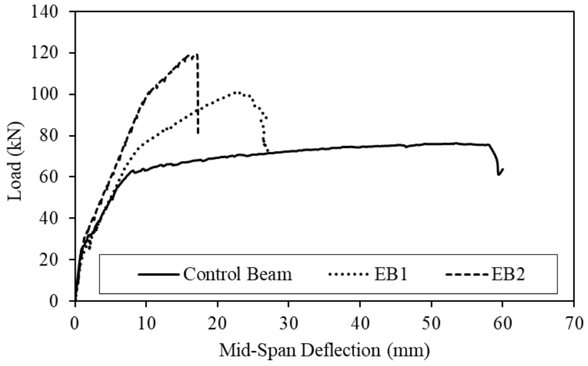


Figure 11. Effect of the amount of CFRP reinforcement.

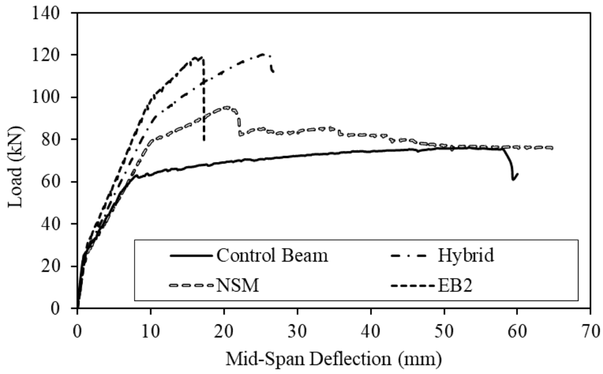


Figure 12. Effect of strengthening technique.

3.3 Effect of the Strengthening Technique

Load versus mid-span deflection curves of beams EB2, NSM and HYP are given Fig. 12. In the three strengthened beams, the same amount of CFRP (two sheets) were used. However, the strengthening technique was different. The three strengthened beams had a similar failure mode (yielding of tension steel followed by CFRP debonding). Debonding started at the end of the CFRP sheets in beams EB2 and HYB, however, it started from the middle part of the sheet in the NSM beam.

The ultimate capacities of the three strengthened beams were higher than that of the control beam, which demonstrates the advantage of using FRP as an effective strengthening material. Although the same amount of CFRP was used in the three beams, the capacities were not similar. Compared to the control beam, the NSM beam gave the lowest increase in the ultimate capacity (25.1%) among the three beams. In the EB2 and HYB beams, the increase in the capacity was about 56.1 and 58.3% compared to the control beam, respectively. This demonstrated that the NSM technique using CFEP sheets imbedded in near surface grooves was not effective and had a limited effect on the ultimate load enhancement. This could be related to the strengthening procedure used in this technique, which might be prevented the epoxy resin from saturating all the CFRP fibers and resulted in an early debonding of the CFRP in one groove at low load level followed by a debonding in the second groove. The NSM beam, however, showed the best ductile behavior among all strengthened beams, which was the only advantage of this technique in this research study. It is recommended, when using this technique in the future, to fully saturate the CFRP sheets in resin before inserting them into grooves. This will increase the bond and consequently result in higher capacities.

The ultimate capacity of the HYB beam was almost similar to that recorded in the EB2 beam. However, it can be seen from Fig. 12 that the HYB beam showed more ductile behavior compared to the EB2 beam. The recorded mid-span deflection at maximum load was about 26 mm in the HYB beam compared with an only 17.2 mm in the EB2 beam. In general, it can be concluded that strengthening technique had a significant effect on the behavior of the strengthened beams and that additional studies are required to find the best way to delay the debonding of the FRP sheets and consequently increase the capacity and the ductility of the strengthened beams.

4. CONCLUSION

Based on this research study, the following concluding remarks can be drawn:

1- All strengthened beams showed higher ultimate capacities compared to the control beam. This increase ranged between 25.3 and 58.3%.

2- The amount of CFRP reinforcement did not show a significant effect on the behavior of the beams at the elastic stage. However, it affected the mode of failure, the ultimate capacity and the stiffness after steel yielding. The stiffness after steel yielding and the ultimate capacity increased as the amount of CFRP increased.

3- The strengthening technique affected the ultimate capacity of the strengthened beams. The Hybrid beam showed the highest improvement in the ultimate capacity (58.3%). It also showed better ductile behavior than EB2 beam. This indicates that the hybrid beam gave the best performance in all strengthened beams tested in this study.

4- The NSM beam strengthened with CFRP sheets inserted in near surface grooves gave the lowest ultimate capacity among all strengthened beams. This could be related to the procedure used in this study where the dry fibers were folded and inserted into the grooves. It is recommended, when using this technique in the future, to fully saturate the CFRP sheets in resin before inserting them into the grooves. This will increase the bond and the ultimate capacities of the strengthened beams.

5- The debonding of the CFRP sheets was the main reason of failure in the strengthened beams with two CFRP sheets. More studies are still needed to find the best way to eliminate the debonding problem and increase the capacity and the ductility of the beams.

CONFILCT OF INTEREST

The author declares no conflicts of interest.

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