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BEHAVIOR OF I-SECTION REINFORCED CONCRETE DEEP BEAMS STRENGTHENED WITH CFRP STRIPS SUBJECTED TO MONOTONIC AND CYCLIC LOAD FAILING IN SHEAR

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ABSTRACT

This research is devoted to investigate the effect of CFRP strips on the behavior and load carrying capacity of strengthened I-section reinforced concrete deep beams. The experimental program variables include configurations of CFRP, spacing between CFRP and type of loading (monotonic or cyclic load) on the behavior of strengthened deep beams. The experimental test results confirm that the strengthening technique of CFRP system is applicable and can increase the shear capacity for strengthened of RC beams. In this study, the ultimate load capacity of the strengthened beams ranged between 18% to 38% under monotonic load and between 11% to 26% under cyclic load over the ultimate load capacity of the reference beam. For beams including CFRP changing the spacing of the strips from 50mm to 20mm, increased the strength of the beam by 17%. For beams subjected to cyclic load the mode failure is nearly the same as that of beams subjected to monotonic load and the cyclic loading produced somewhat less brittle behavior in beam under cyclic loading.

تصرف العتبات(I) المقواة بشرائح ألياف الكاربون الخرسانية العميقة ذات المقطع المعرضة إلى أحمال تزايدية وأحمال دورية الفاشلة بالقص

الكلمات المفتاحية

ألياف الكاربون، حمل دوري، التقوية مقطعI.

الخلاصة

أن الغرض من هذا البحث هو التحري عن سلوك وقابلية التحمل للعتبات الخرسانية المسلحة العميقة ذات المقاطع بشكل (I-section). تتضمن متغيرات البرنامج العملي أولا: ترتيب شرائح ألياف الكاربون بأشكال مختلفة. ثانيا: المسافة بين أشرطة ألياف الكاربون. ثالثا: نوع الحمل; حمل تزايدي وحمل دوري. وقد تم دراسة تأثير هذه المتغيرات على تصرف العتبات المقواة بأشرطة ألياف الكاربون. محصلة الفحص أظهرت إن التقوية بألياف الكاربون قادرة على زيادة التحمل للعتبات. وفي هذه الدراسة كانت الزيادة في الحمل تتراوح بين (18%-38%) للحمل التزايدي وبين (11%-26%) للحمل الدوري. وعند نقصان المسافات بين أشرطة ألياف الكاربون من50mm إلى 20mm تكون هناك زيادة في الحمل بمقدار 17%. اما بالنسبة للنماذج المعرضة إلى أحمال دورية فيكون لها نفس نمط الفشل للعتبات المعرضة إلى أحمال تزايدية. وان العتبات المعرضة إلى أحمال دورية تكون أكثر مرونة من العتبات المعرضة إلى أحمال تزايدية.

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Introduction

Some of the reinforced concrete deep beams may need upgrading or rehabilitation programs so that they can cope with the extra loads. Externally strengthening with advanced composite materials, namely, Carbon Fiber Reinforced Polymers (CFRP) represents the state-of-the-art in upgrading or rehabilitation techniques. Carbon Fiber Reinforced Polymer (CFRP) laminates are becoming widely used in upgrading and rehabilitation of reinforced concrete members. CFRP offers the design engineer excellent properties not available in traditional materials. This strengthening composite is light in weight and corrosion resistant and possesses higher strength and stiffness compared to steel. The ease of handling and application gives CFRP an advantage over traditional materials for certain applications [1]. Some researchers work in CFRP such as; Ma'en, investigated the shear behavior of reinforced concrete beams strengthened by the attachment of different configurations and quantities of CFRP using epoxy adhesives [2]. Dias and Barros study the effectiveness of the Near Surface Mounted (NSM) technique with Carbon Fiber Reinforced Polymer (CFRP) laminates for the shear strengthening of T cross section Reinforced Concrete (RC) beams [3]. Lee, a series of experimental tests were carried out to investigate the behavior and performance of reinforced concrete (RC) T-section deep beams strengthened in shear with CFRP sheets [4]. Beside of the known types of monotonic loadings, many concrete structures may be subjected to different types of cyclic loadings during their life span. These cyclic loadings may arise from traffic movements or earthquakes. Further, structural inelastic deformations due to these repeated and reversed cyclic loadings must be anticipated during the design of reinforced concrete members, and also reliable information on strength, failure, ductility and energy absorption capacity is required for the design of systems such as offshore structures, nuclear containment vessels, bridges, and other reinforced concrete structures. And some researchers work in cyclic load such as; Reed, studied the effects of traffic loads applied during and after strengthening on the performance of a reinforced concrete bridge strengthened with externally boded CFRP laminates [5]. And Mohammed, investigated structural behavior of reinforced rectangular concrete deep beams with web openings under repeated loading [6].

Experimental Work

The main purpose of the test program is to generate data and provide information about the effect of CFRP that are attached by special epoxy material to increase their shear capacity and structural behavior of I-section reinforced concrete deep beam under monotonic and cyclic loads. Standard tests according to the American Society for Testing and Materials (ASTM) [7,8,9] and Iraqi specifications [10,11] are carried out to determine the properties of materials. All of these tests have been conducted in the Structure Laboratories for the College of Engineering in Basrah University.

Carbon Fiber Reinforced Polymer (CFRP) Strips

Carbon fiber fabric laminate of type Sika Wrap Hex-230C and epoxy based impregnating resin of type Sikadur-330 have been used to externally strengthen the reinforced concrete deep beams. All strips used in this study are 30 mm width. The properties of carbon fiber laminate used (according to the manufacturer instructions sheet) are shown in Table (1).

Table 1: Properties of carbon fiber strips.

Type	Tensile Strength (MPa)	Elongation at Failure (%)	Tensile Modulus (GPa)	Thickness (mm)
Sika Wrap Hex-230C	3500	1.5	230	0.13

Concrete Mix Proportions

Normal concrete was used to cast nine I-section reinforced concrete beams. It was decided to choose a mix of 1:1.7:2.77 (by weight) cement, sand, gravel respectively and 0.54 water/cement ratio. This mix was designed to give cylinder compressive strength of about 25.0 MPa at age of 28 days and slump of about 120 mm.

CFRP Installation

The concrete surface for all faces of the deep beam sides was cleaned from lousy materials by a surface cleaning machine. Also the four corners of the specimen (for bottom flange that strengthened with U shape of CFRP) were chamfered at a radius about (R=10mm) to reduce the decrease in strength that would arise due to sheet bending at the corners, then they were washed by water and dried. Firstly, the two-parts of epoxy (A and B) was mixed in 4:1 ratio by using electrical drilling machine attached to mixing bullet, the resulting material was gray paste. The epoxy mixer has been applied to the surface of concrete at location of CFRP strips to fill the cavities. Also the epoxy mixer poured on surface of CFRP strips and these strips applied to the surface of concrete.

Beams Details

The experimental program consisted of testing nine I-section reinforced concrete deep beams. Beams designed to fail in shear with (a/d =1) as a deep beams. First group involving (5) of monotonic loaded I-section deep beams and second groups involving (4) of cyclic loaded I-section deep beams. For this group that subjected to cyclic load, the load is subjected in deferent load levels (20%, 40%, 60%, 80% from the static load of corresponding beam in first group and monotonically to failure). Tables (2) and (3) show the description of the tested beams and Figure (1) shows the control of the tested beams.

Table 2: Details and description of the tested beams for first group.

Beam No.	Details of strengthening
N.C.M	Reference beam (control beam) without strengthening
N.C.M.1	strengthened with two opposite side with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
N.C.M.2	strengthened in the U configuration with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
N.C.M.3	strengthened with two opposite side with 45° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
N.C.M.4	strengthened with two opposite side with 45° CFRP strips (the width of CFRP 30mm along the web with space is 20mm)

Table 3: Details and description of the tested beams for second group.

Beam No.	Details of strengthening
N.C.C	Reference beam (control beam) without strengthening
N.C.C.1	strengthened with two opposite side with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
N.C.C.2	strengthened in the U configuration with 90° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)
N.C.C.3	strengthened with two opposite side with 45° CFRP strips (the width of CFRP 30mm along the web with space is 50mm)

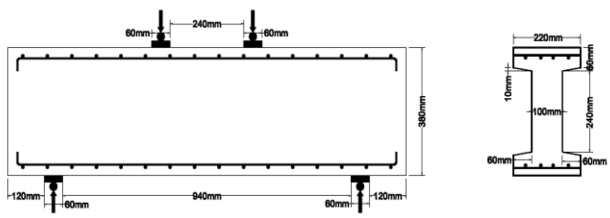

Figure 1: Reference deep beam (control beam).

Experimental Results & Discussion

At low load levels, all tested beams behaved in elastic manner. At the first stages of loading, the beams free from cracks, the deflections were small and proportional to the applied load, consequently the stresses were small and full cross section was active in carrying the loads. At 25.3 to 38.3% of failure load, the first diagonal shear crack was occurred and developed suddenly in the web and propagated toward the top and bottom flanges at which point they turned and ran horizontally along the longitudinal compression and tension reinforcements located at the interface between the web and flanges. The horizontally crack in the flanges is believed to be caused by the moderate amount of longitudinal steel in the flanges designed to give the beam adequate flexural capacity to ensure shear failure. However, the small amount of concrete provided by the narrow flange and thin web offer little confinement and thus the large stresses in the flange result in buckling of the longitudinal reinforcement. But this load did not cause failure. This means, there is reserve strength in these deep beams after the appearance of shear crack. The inclined crack became wider gradually with increasing load.

At load levels closed to failure, a second parallel inclined crack appeared closer to the support than the first one and extended upwards and as load increased. The final failure is due to the destruction of the portion of concrete between these two cracks which acts like a strut between the load and the support points. In some cases crushing of the regions near the load and the support points occurs. For beams strengthened with CFRP they have same behavior of the control beam, since the CFRP laminates delay the crack initiation and arrested their propagation. In fact, the amount of CFRP laminate has a significant effect on initiation and extension of cracks. This mode was a diagonal shear crack which caused debonding of CFRP strips located in the shear zone at ultimate load level. This mode of failure of the laminate has been observed to occur due to the loss of aggregate interlock in the concrete which results in a large shear crack. When a crack forms, high tensile stresses are developed in the portion of the CFRP laminate that bridges the crack. As the crack continues to grow, stress in the laminate continues to increase. These tensile stresses must be transferred to the concrete through the bond interface. Debonding of the laminate occurs when failure of the bond between the laminate and concrete substrate occurs before CFRP rupture. This occurs due to the fact that since the laminate has a high modulus of elasticity, the stress in the laminate can not increase indefinitely and must be released or transferred somewhere else. This stress is released by debonding that occurs at the crack edge and propagates throughout the laminate causing failure of the system. Much like the steel stirrups the CFRP laminates are considered as ties resisting the tensile stresses along cracks between the concrete struts. For beams subjected to cyclic load, the mode of failure is nearly the same as that of beams subjected to monotonic loading. The cyclic loading produced somewhat less brittle behavior in beams under cyclic loading, over their identical beams under static loading. For example, the deflection is (5.1mm) for the (**N.C.M**) beam at load 300 kN, whereas the deflection is (6.8 mm) for the (**N.C.C**) beam at same load level. The reason may be due to the fact that the beam under cyclic loading exhibited more deflections.

The results from the two-point loading tests on the I-section reinforced concrete deep beams (for the first and second groups) made with normal concrete are summarized in Table (4) and the shear crack patterns of these deep beams after failure are shown in Figures (2) to (6).

Table 4: Ultimate loads of the beam specimens for the first and second groups

Group No.	Beam designation	First crack load (kN)	Ultimate applied load (kN)	Percentage increase in ultimate load with respect to reference beam
1	N.C.M	100.0	395.0	-----
	N.C.M.1	140.0	466.0	18%
	N.C.M.2	190.0	510.0	29%
	N.C.M.3	150.0	494.0	25%
	N.C.M.4	210.0	545.1	38%
2	N.C.C	90.0	355.5	-----
	N.C.C.1	110.0	396.1	11%
	N.C.C.2	170.0	443.7	25%
	N.C.C.3	120.0	449.9	26%

Figure 2: Shear crack patterns of N.C.M beam.

Figure 3: Shear crack patterns of N.C.M.1 beam.

Figure 4: Shear crack patterns of N.C.M.2 beam.

Figure 5: Shear crack patterns of N.C.M.3 beam

Figure 6: Shear crack patterns of N.C.M.4 beam.

Cracking and Ultimate Loads

Shear cracking load is defined as the load at which the first major inclined diagonal shear crack appears in the shear span. The crack is sudden and is usually originated at the middle of the shear span and propagates toward the support and loading points during subsequent increase in the applied load. Maximum crack width along the major inclined crack in the shear span occurred almost at mid depth of the beam. For the first group, the I-section reinforced concrete deep beam designated as **N.C.M** was taken as a control deep beam. The beam was tested without any strengthening by CFRP strips. In the specimen **N.C.M**, when the applied load reached approximately (100kN), shear crack suddenly appeared throughout the shear span. When load increased, the shear crack was widening and propagating until failure occurred, because the diagonal crack became wide (the main shear crack), at a total applied load of 395kN. The strengthened beams (**N.C.M.1**, **N.C.M.2**, **N.C.M.3 and N.C.M.4)** have the same behavior of the control beams except that the inclined crack was delayed more than the control beam. For **N.C.M.1** the inclined crack appeared when the load reached approximately (140 kN), then the crack width increased till the CFRP failed (by debonding failure with CFRP strips separated from concrete) with a total applied load of 466kN. In beam **N.C.M.2** which were strengthened by inclined CFRP that the load failure was higher which was 510kN and more delay for first crack that was begin at 190 kN. When the **N.C.M.3** beam that strengthened with (U) configuration presents a high stiffness and high load compared with **N.C.M.1** that strengthened with two opposite side with 90° CFRP strips, the reduction in deflection is due to the high stiffness characteristic of the CFRP. Also, the laminates acted as a form of confinement which in a sense "hold" the beam and keep it from severely deflecting. Where the inclined crack appeared when the load reached approximately (150 kN), then the crack width increased till the CFRP failed (by debonding failure) at total load 494 kN. For **N.C.M.4** beam, when decrease the spacing between CFRP strips (from 50mm to 20mm) the load failure was higher that was 545kN with delay of first crack (at 210 kN) and less width when compared with **N.C.M.2**. The external strengthening of reinforced concrete beams showed better enhancement in first cracking load when compared with reference beams.

For the second group, the control deep beam (**N.C.C)** was without by CFRP strips and failed at ultimate load equal to 355.5 kN, at early stages of loading, the beam deformations were initially within the elastic range, then the applied load was increased until the crack occurred which was observed in the shear zone when the applied load reached approximately (90 kN) in first cycle at second amplitude (second load level) of the ultimate load. The width of the inclined crack increased more and more until failure (shear failure). The deep beams (**N.C.C.1** and **N.C.C.2**) were strengthened by vertical and inclined CFRP strips respectively. This types of strengthening results in an increase in ultimate load capacity of 11% and 25% respectively with respect to the ultimate load of the control deep beam **N.C.C** and with first crack (110 kN and 170 kN) respectively in first cycle at second amplitude of the ultimate load. For the U configuration (**N.C.C.3**), when the applied load reached approximately (120 kN) in first cycle at second amplitude of the ultimate load appear the first crack and result an increase the ultimate load of 26% with respect to the ultimate load of the control deep beam **N.C.C**. from these results, can be observed that inclined cracking loads were reduced for specimens under cyclic loading than under static loading.

Load Versus Mid-span Deflection Results

Nine reinforced concrete I-section deep beams under two point loads were strengthened by CFRP strips to examine the effect of strengthening patterns on their behavior and ultimate load. Experimental investigation on the behavior of load versus mid-span deflection curves for the tested deep beams at different loading stages is presented. The maximum deflections at failure were not obtained to avoid dial gauge damage. Figure (7) shows the load-deflection curves of deep beam of the first group. From the load deflection curves of tested deep beams under monotonic load, it can be observed that the load versus mid-span deflection response for **N.C.M** beam (control beam) can be explained as following;

In the first stage of loading, the applied load (applied shear force) was carried by the concrete only which was the same in all beams till the appearance of the first diagonal crack. It can be noticed that a change in slope of the curves occurred after the formation of inclined cracking because the formation of the first major inclined crack significantly reduced beam stiffness, therefore the deflection was increased. There was a drop in deflection curve was due to the shear crack appeared at 100kN after that beam **N.C.M** continued in carrying load with the new slope (stiffness) till failure. Finally, when the load near its ultimate value, the rate of increase in deflection is substantially exceeding the rate of increase in the value of the applied loads. The strengthened beams had a similar behavior to that of the reference beams at the earlier loading stage. With increasing load the shear cracks were formed and increased causing a reduction in the stiffness of strengthened beam specimen. After that the CFRP strips resisted the applied shear force. This was clear because the curve continued with the same inclination.

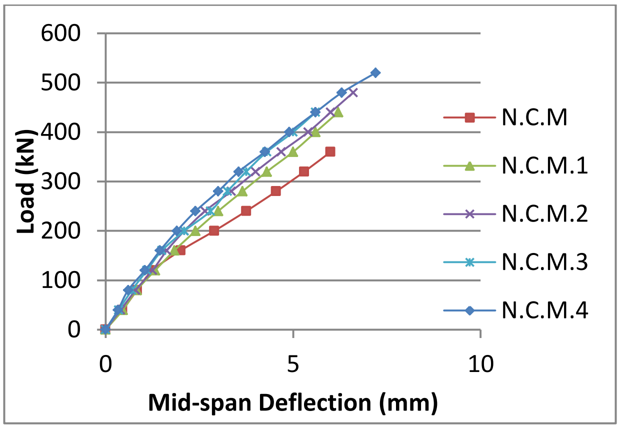

Figure 7: Experimental load versus mid-span deflection curves for the first group

Figures (8) to (11) show the load-deflection curves of deep beam of the second group. From the load deflection curves of tested deep beams under cyclic load, it can be observed that the beams subjected to cyclic loading always caused some increase in the deflection in consecutive cycles. However, the consecutive increase of deflection with repeated loads always decreased (at the same applied load level). In other words, the applied load of the first cycle leads to a residual deflection, and the second cycle also leads to another residual deflection, but with smaller value relative to the effect of the first cycle. Therefore the accumulative residual deflection increases as the number of cycle increases. The residual deflection may be due to cracking. In general, cyclic loading was found to increase the total deflection at failure when compared with beams subjected to monotonic loading.

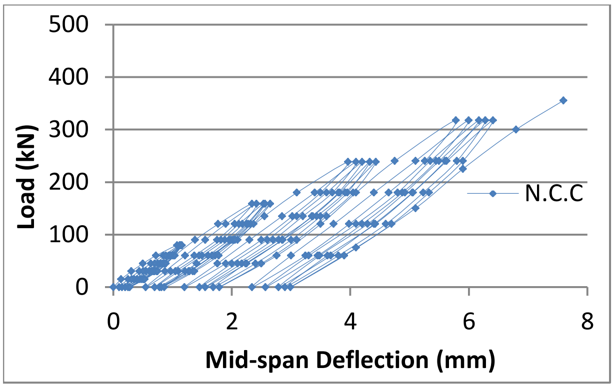

Figure 8: Experimental load versus mid-span deflection curve for N.C.C

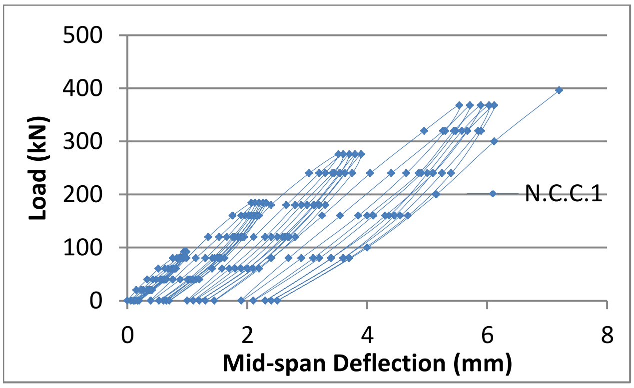

Figure 9: Experimental load versus mid-span deflection curve for N.C.C.1

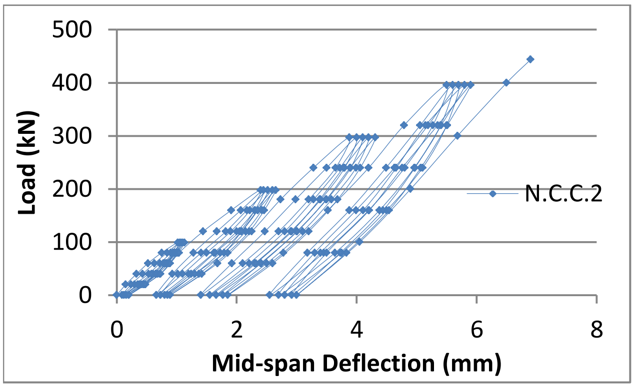

Figure 10: Experimental load versus mid-span deflection curve for N.C.C.2

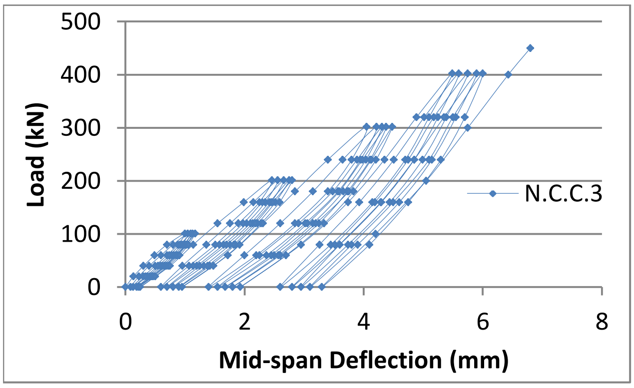

Figure 11: Experimental load versus mid-span deflection curve for N.C.C.3

Concrete Strains

The distribution of concrete strains at mid-span of each tested deep beam is measured using seven demec points over the depth of beam. Figures (12) to (16) show the concrete strain distribution over the depth for all deep beams at different load levels. From these figures, it can be seen that the strain distribution was nonlinear in tensile and compressive zones even at low load levels, and then became increasingly nonlinear with increasing load. Also can be observed the strain in tension zone began to decrease after the major inclined diagonal shear crack appears in the shear span, this due the beam behaves as arch action after inclined crack appears. In compression zone continue with nonlinear behavior due to effect of strut action between the two point loads.

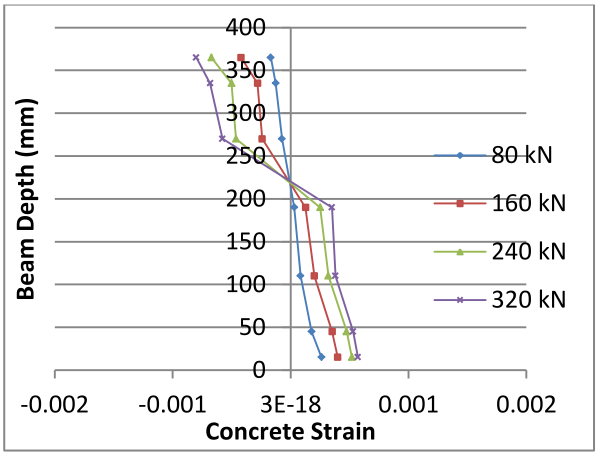

Figure 12: Concrete strain distribution for deep beam N.C.M

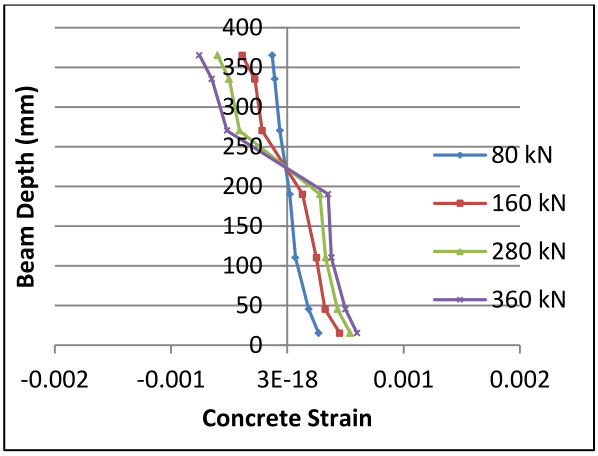

Figure 13: Concrete strain distribution for deep beam N.C.M.1

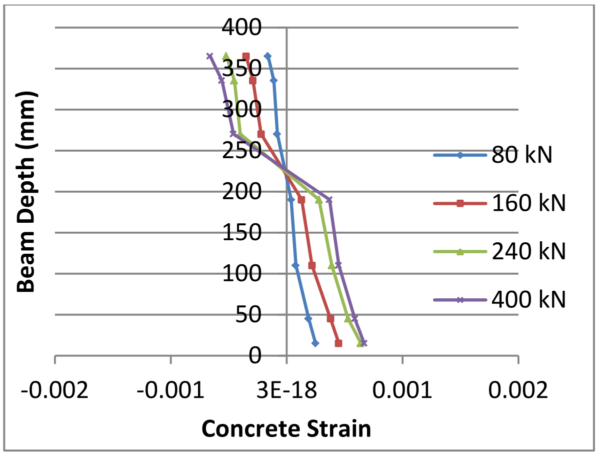

Figure 14: Concrete strain distribution for deep beam N.C.M.2

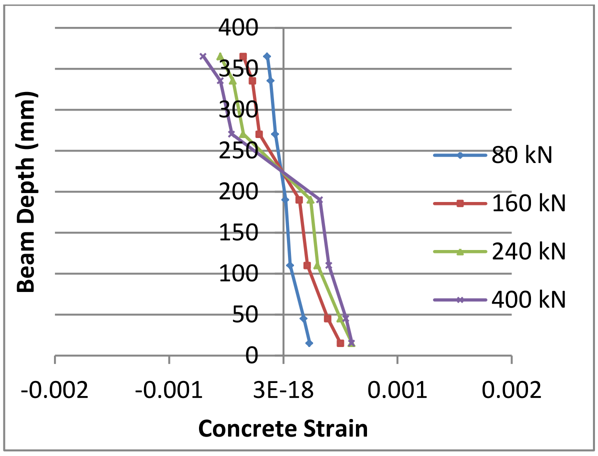

Figure 15: Concrete strain distribution for deep beam N.C.M.3

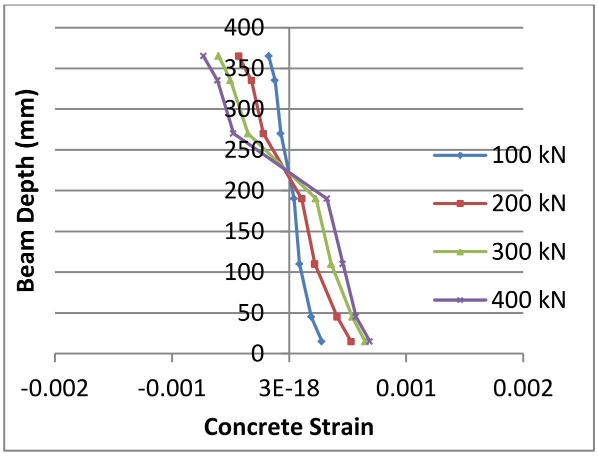

Figure 16: Concrete strain distribution for deep beam N.C.M.4

Conclusions

Based on the results obtained from the experimental work for the externally strengthened reinforced concrete beams with CFRP laminates under different monotonic and cyclic loading, the following conclusions are presented:-

1) The experimental test results confirm that the strengthening technique of CFRP system is applicable and can increase the shear capacity for strengthened of RC beams. In this study, for normal concrete the ultimate load capacity of the strengthened beams ranged between 38% to 18% under monotonic load and between 11% to 26% under cyclic load over the ultimate load capacity of the reference (unstrengthened) beam.
2) According to the observations through the beams test, the presence of external CFRP laminates on the surface of the tested beams. The presence of strengthening was delayed and restrained cracking propagation which caused increase in load carrying capacities prior to and beyond the first cracking and the initial shear cracks appear at higher loads in case of strengthened beams.
3) The use of CFRP is significantly influenced by the spacing of the strips. For example in two identical beams(**N.C.M.1** and **N.C.M.4**, including CFRP changing the spacing of the strips from 50mm to 20mm respectively, increased the strength of the beam by 17%.
4) Astiffer load-deflection response is observed for reinforced concrete deep beams strengthened with CFRP strips as compared with response of control deep beam.
5) The inclined CFRP strips give better results than the vertical CFRP strips in ultimate load, deflection and crack width.
6) For beams subjected to cyclic load the mode failure is nearly the same as that of beams subjected to monotonic load and the cyclic loading produced somewhat less brittle behavior in beam under cyclic loading, over their identical beams under monotonic load.
7) In general, cyclic loading was found to increase the total deflection at failure when compared with beams subjected to monotonic loading.

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