The CFRP repair performance in pre-cracked Reinforced concrete beams

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Repair of Pre-cracked RC Beams Using CFRP Laminates

The following paper addresses the effects of pre-existing cracks on the flexural behavior of reinforced concrete (RC) beams strengthened with carbon fiber reinforcing polymers (CFRP). A group of seventeen beams were used in the experimental study and tested in flexure. Eleven of the beams were cracked prior to the installation of the CFRP by vertically loading the beams in flexure until just past the cracking moment capacity to develop cracks in the bottom of the beam. CFRP laminates and U-shaped stirrups were then applied and allowed to cure before a final testing, loading each beam until ultimate failure. It was found that the load carrying capacity of a pre-cracked beam repaired with CFRP laminates was increased by a range of 12% to 109% when compared to an unstregthened un-cracked beam. Also, the use of U-wrapped CFRP laminate combined with straight soffit laminates proved to be effective in increasing the load capacity. It extended the desired behavior of strengthened beams and delayed delamination or debonding of the straight longitudinal laminate at the tension side.

Keywords: concrete, beams, repair, precracked, CFRP.

Introduction

The literature shows an abundant amount of experimental and analytical information about the effectiveness of FRP sheets/strips for strengthening or retrofitting reinforced concrete (RC) members and the behavior of strengthened structural elements. Most of the published experimental work that addresses external strengthening of concrete beams with composite materials is focused on specimens without pre-existing damage. This paper presents the results of an investigation into the effect of existence of cracks on the flexural behavior of RC beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) laminates. The experimental program consisted of testing 17 reinforced concrete (RC) beams under three point flexural loads. Different configurations of CFRP laminates, strengthening levels,and cracking conditions are studied. The paper presents the flexural behavior of the strengthened beams including load-deflection characteristics and mode of failure. The results indicate a significant gain of approximately 30% for the strengthened beam capacity than that for the control unstrengthened beam. The repair of pre-cracked beams with CFRP laminates restored their flexural capacity to reach a failure load similar to that of the control uncracked strengthened beams.

Using FRP systems add extra tensile strength to a concrete member and such level of tension provided by the FRP is limited by the FRP design tensile strength and the ability to transfer stresses into the substrate through bond. This technique can be used for flexural strengthening [1-3] and shear strengthening [4]. The short-term tensile strength of CFRP laminates for flexural strengthening of concrete beams was investigated by Okeil et al. [5] to demonstrate the size effect inherent in composite materials. The use of FRP strengthening of concrete beams under fatigue loading was also investigated experimentally [6] and analytically [7]. Previous research also indicates that externally bonded CFRP laminates can be used to increase the ultimate strength of steel girders and to restore the lost capacity and stiffness of damaged girders [8-10]. Since FRP materials have relatively lower modulus of elasticity compared to steel, large amounts of strengthening FRP are usually required to develop a significant increase of the elastic stiffness. The use of Carbon FRP (CFRP) for structural strengthening has so far been the preferred choice since the modulus of elasticity for GFRP is lower, which reduces the effectiveness of GFRP strengthening systems. Nevertheless, Okeil et al. [11] introduced an alternative technique for strengthening steel structures by stiffening buckling-prone thin plates using pultruded Glass FRP sections.

As can be seen from the summary review, FRP materials are a proven strengthening alternative for various structural components subjected to different loading conditions. The existing condition of the deficient structure has a great effect on the outcome of FRP strengthening. Few studies looked into the effect of pre-existing cracks on the effectiveness of FRP strengthening in flexure. For example, the behavior of FRP strengthened reinforced concrete beams that were initially preloaded up to 85% of their capacity was investigated experimentally. This paper focuses on strengthening precracked concrete beams in flexure using CFRP sheets. Experimental and analytical results are presented. Seventeen beam specimens were tested including control specimens. A fiber section analysis model is used to estimate the strength of the tested specimens.

Experimental Program

Specimen Description and Test Setup

An experimental program was devised to study the effect of preexisting cracks on the efficiency of CFRP strengthening of RC structures. Seventeen beams were included in the experimental program, which were tested in flexure. Eleven out ofthe seventeen beams were pre-cracked before installing the CFRP strips. The specimens were then tested after the adhesive cured by loading them to failure. The tested specimens included using multiple CFRP layers (strengthening level) and configurations (soffit-only and U-shaped). LVDTs were mounted at mid-span to measure deflections. A 100-kip [445 kN] displacement-controlled hydraulic actuator was used to apply static loading at mid-span. Automatic data acquisition system was used to record the loads and displacements. Continuous visual inspection was performed to determine any possible debonding or delamination between the CFRP membranes and the concrete.

Figures 1a, 1b, 1c and 1d showthe dimensionsof the two beams' sets. Beams of set #1 had dimensions of 5 inches x 9.65 inches x 5.5 feet [127 mm x 245 mm x 1676 mm], which allowed for an effective span of 5.33 ft [1524 mm]. Beams of set #2 had dimensions of 5 inches x 9.65 inches x 6 feet [127 mm x 245 mm x 1828.8 mm], which allowed for an effective span of 5 ft [1625.6 mm].

The longitudinal reinforcement was 2 # 4 [2M12] 60 ksi steel bars for flexure and # 3 [M10] 60 ksi steel stirrups spaced at 4 inches for shear. Two control beams (B1 and B2from set #1) and four beams(B-1,B-2,B-3 and B-4 from set # 2)were tested for flexural strength comparison. Bi-axial CFRP laminates were used for strengthening. This CFRP product offers a tensile strength of 65,900 psi [454 MPa], and an elastic modulus of 5.8 msi [39989 MPa]. These properties yield a per ply strength of 1430 pounds per inch [250 N/mm] of width, however, the manufacturer recommends a long term per ply strength of only 860 pounds per inch [151 N/mm] of width. A different product was used for set#2 that offers a tensile strength of 550,000 psi [3800MPa], and an elastic modulus of 33,000 ksi [270GPa],Tensile Modulus 430 kips/in/ply.

The beams were initially loaded beyond their cracking moment level using a single point load at mid-span. This was achieved using a 10-kip [45-KN] load applied in the initial stage to crack the beams. The applied load was then removed to perform the strengthening task by applying the epoxy on the tension side of the beams. The CFRP laminates were then bonded as per the configurations that can be seen in Figure 1. These configurations are used as opposed to full wrapping of the beam since it is believed that full wrapping might trap in moisture causing faster corrosion issues within the beam.

Pressure was applied to the first CFRP layer to minimize the existence of any voids between the CFRP laminate and concrete surface and obtain optimal adhesion with the concrete substrate. However, the preparation and application of CFRP to the concrete surface was actually performed in several steps. The first step was to remove all loose materials, depressions, and dust from the surface and deep clean with 2000 psi water pressure. Then, the surface was left to dry and measurements and mark placements of the CFRP overlays were done.

For the 1stset of beams, the base primer was mixed with the adhesive and applied to the marked surface using a ¼ - 3/8 in. paint roller. Adhesive was applied to small areas at a time, as this mixture will dry within a half hour. The previously applied mixture was allowed to become "tacky" (within about 15 minutes) before bonding the first layer of laminate by repeatedly applying pressure to the laminate while it was on the concrete surface to remove all trapped air. Low water pressure was sprayed to cover the entire first layer thoroughly and the remaining layers were applied similarly on top of it, up to a maximum of four layers. The total curing time is 60 minutes after the water application.

For the 2ndsetof beams,the base primer was mixed with the adhesive and applied to the marked surface using a ¼ - 3/8 in. paint roller. Adhesive was applied to small areas at a time, to minimize the elapsed time between mixing and application of the saturant to ensurethe material is applied to the fabric at least 15 minutes prior to any thickening orgelling. Twolayers of fabric were applied on the soffit of the beam,while a single layerwas used for the U shaped wraps.

Table 1
Summary of test results for set #1

Beam	**Failure Load** **lb [N]**	**Capacity Increase** **(%)**
B1	12,136 [53,981]	--
B2	15,609 [69,429]	28.6
B3	15,747 [70,043]	29.8
B4	16,356 [72,753]	34.8
B5	16,911 [75,223]	39.3

Summary of test results for set #2

Beam	**Failure Load** **lb [N]**	**Capacity Increase** **(%)**
B1	12,398 [55,172]	--
B2	24,270 [108,123]	95.7
B3	24,944 [111,274]	101.2
B4	19,461 [86,652]	57
B5	25,906 [115,28]	108.9
B6	24,045 [107,169]	93.9
B7	21,164 [87.324]	70.7
B8	19,551 [72,753]	57.7
B9	20,119 [89,532]	62.3
B10	18,856 [83,914]	52.1
B11	18,944 [84,312]	52.8
B12	16,647 [74,083]	34.3

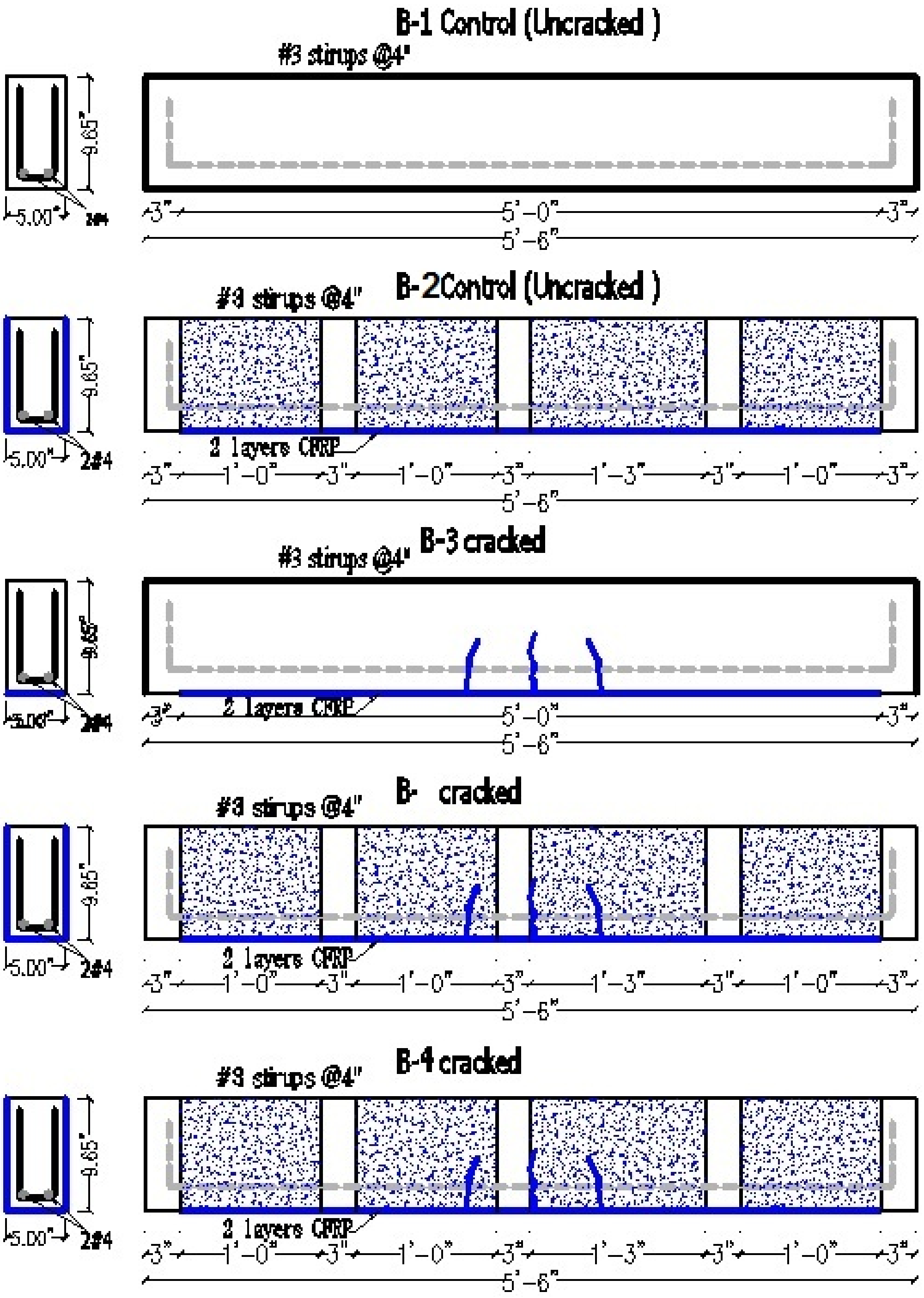


Fig. 1.a Set #1 Beam Details.[1 ft=304.8mm, 1 in=25.4mm]

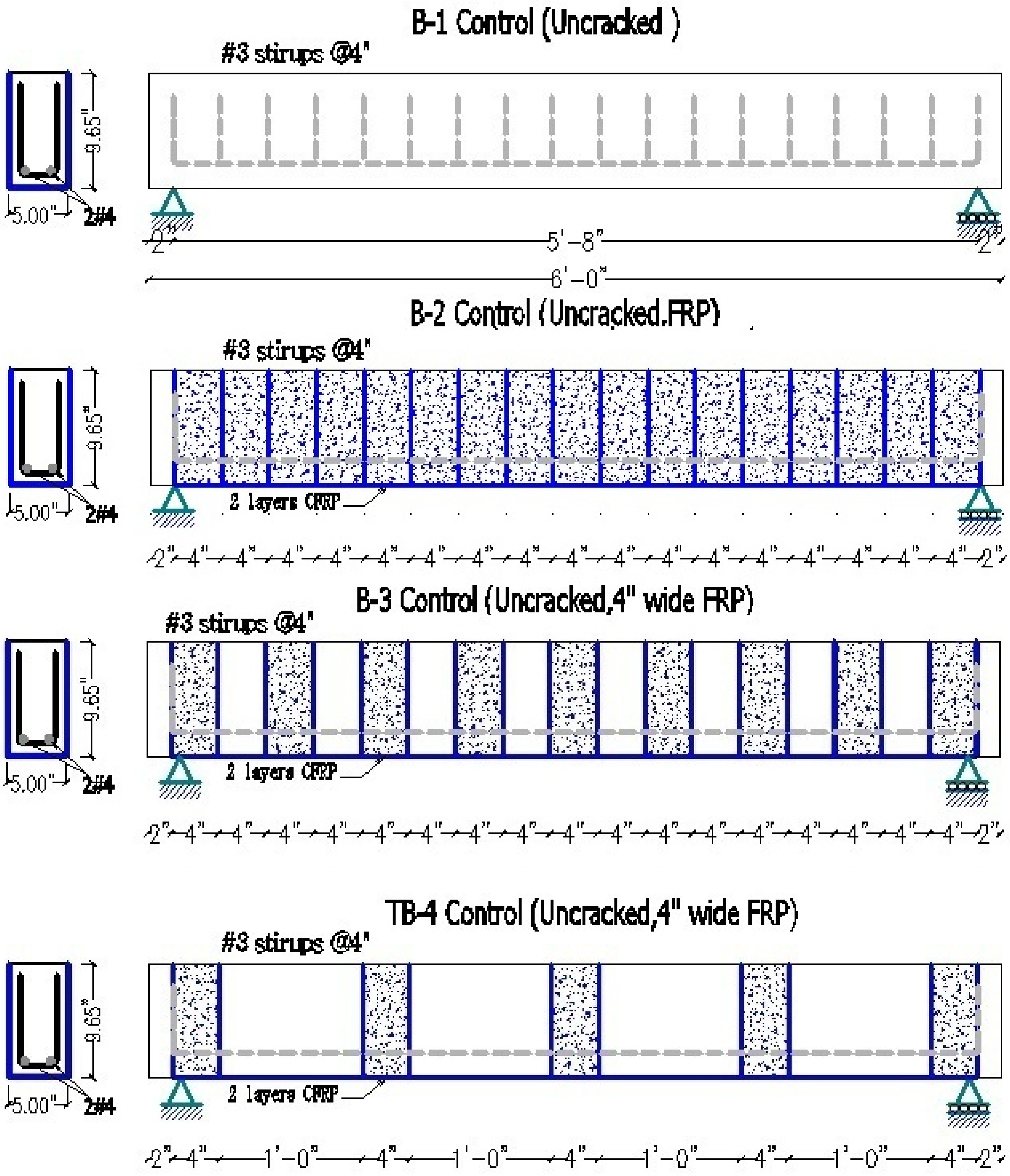


Fig. 1.b Set #2 Beam Details.[1 ft=304.8mm, 1 in=25.4mm]

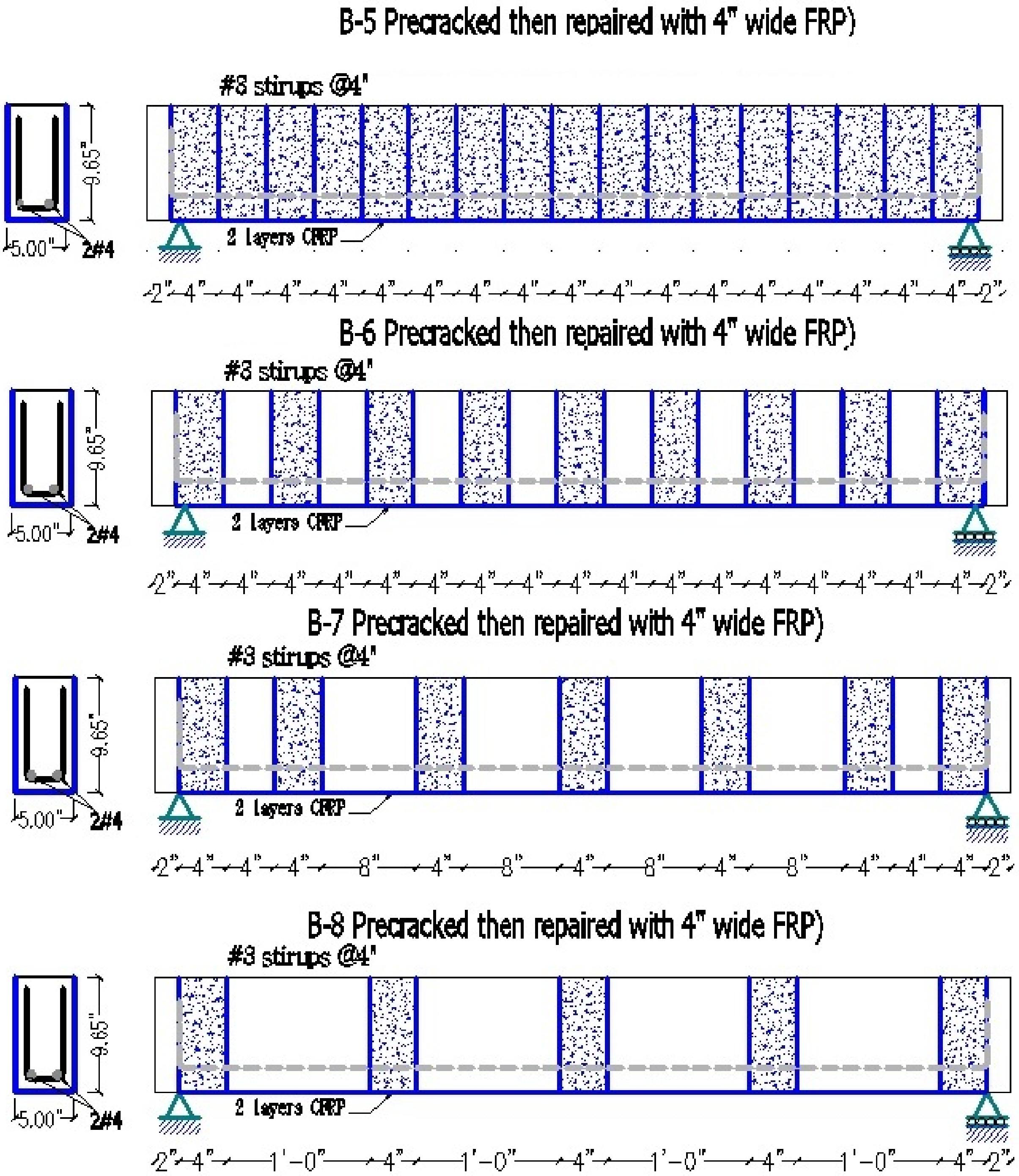


Fig. 1.c **Set #2 Beam Details.[1 ft=304.8mm, 1 in=25.4mm]**

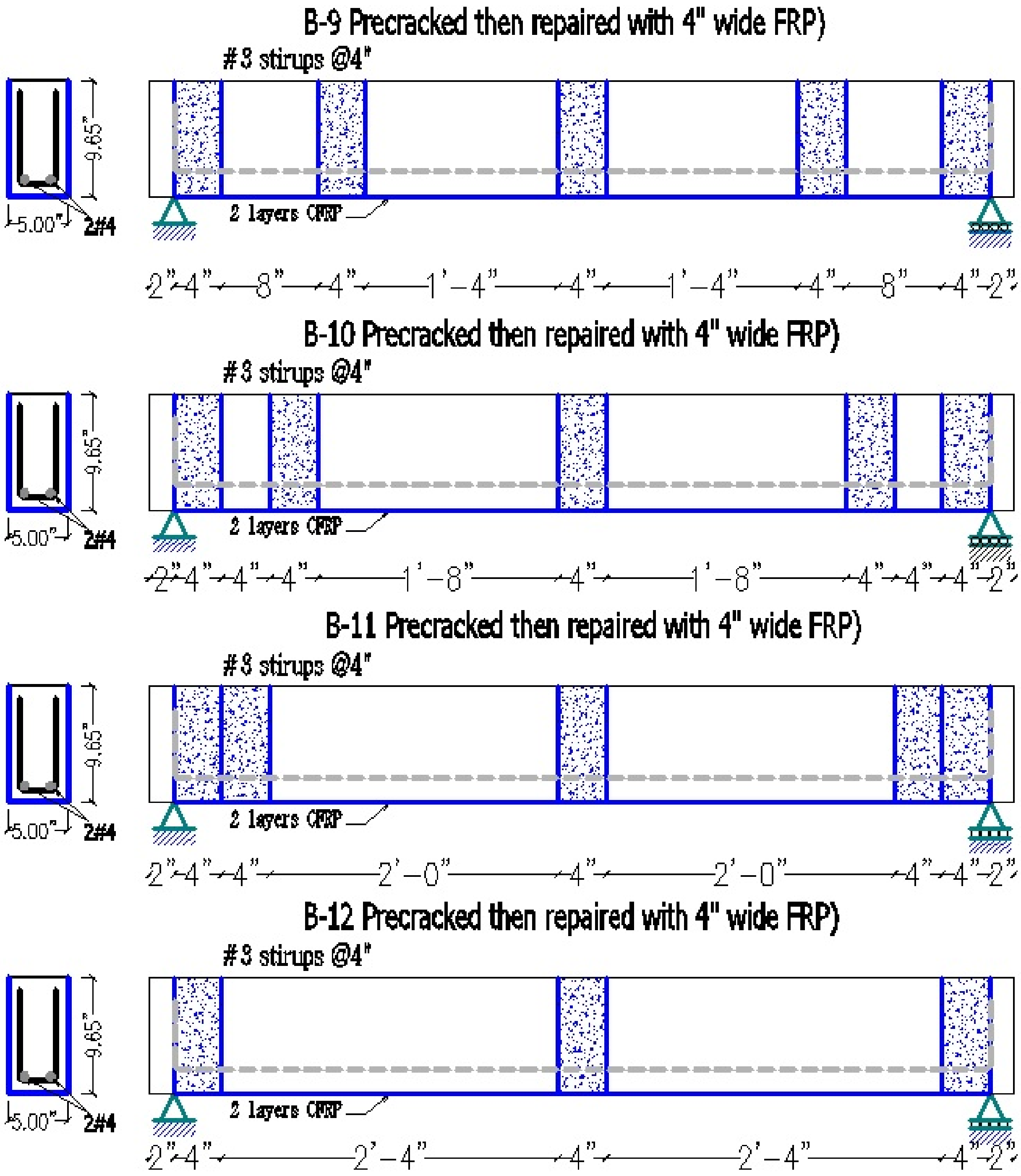


Fig. 1.d Set #2 Beam Details.[1 ft=304.8mm, 1 in=25.4mm]

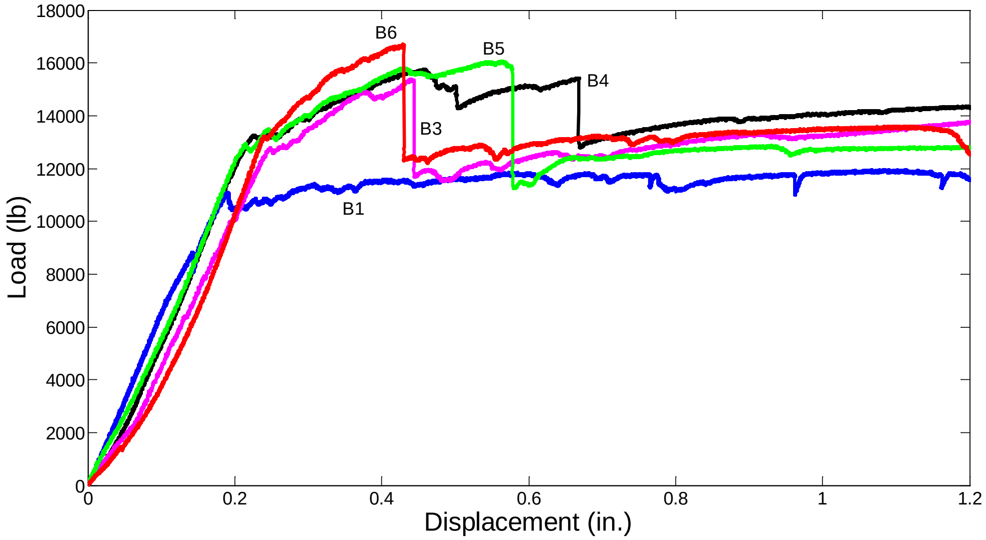


Fig. 2 Load – deflection curves for beams set#1 [1 pound=4.45N, 1in=25.4mm]

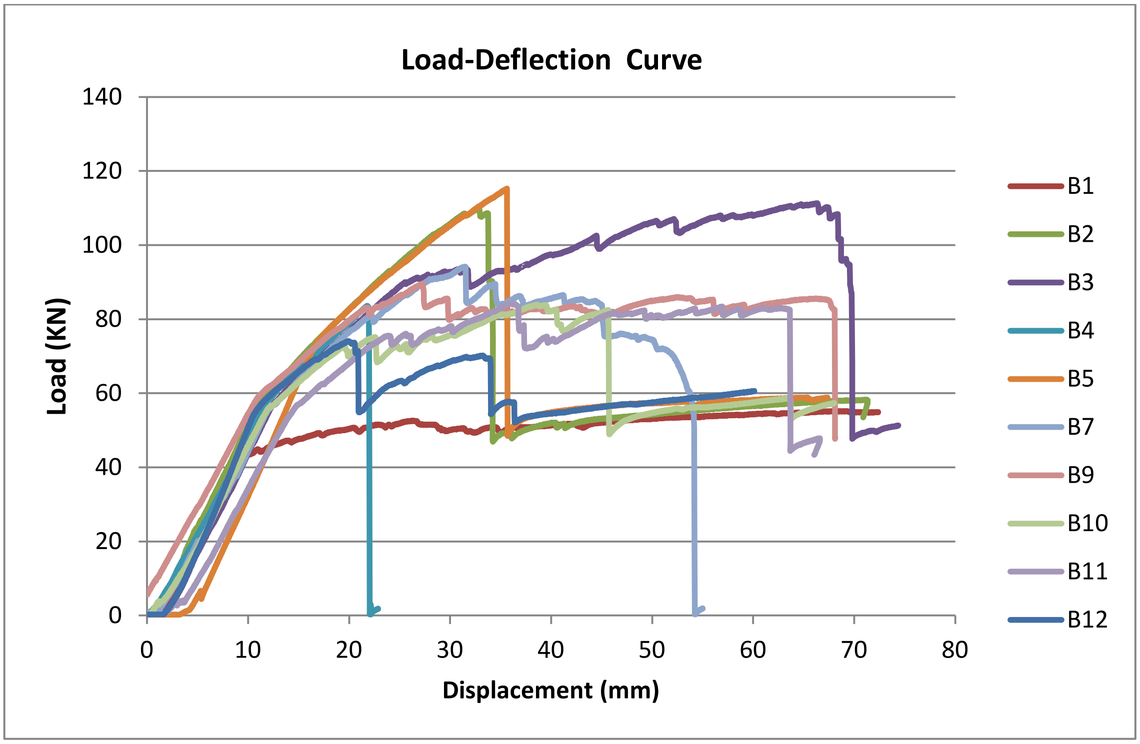
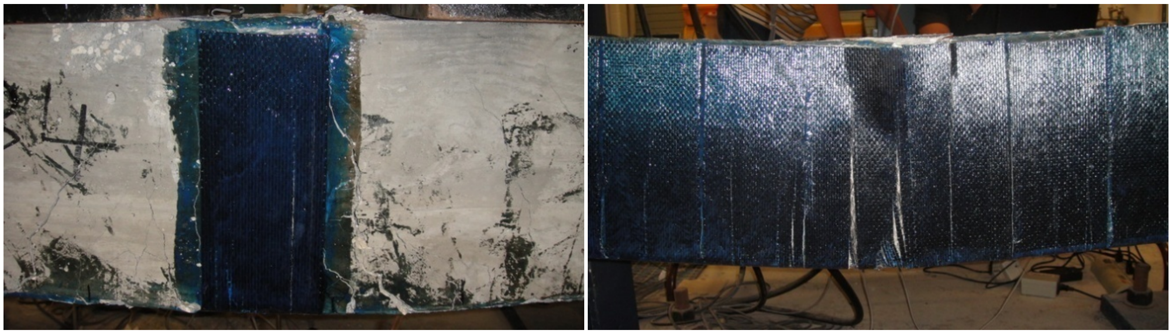


Fig. 2 Load – deflection curves for beams set#2 [1 pound=4.45N, 1in=25.4mm]

(a) Pre-cracking of Beam B5 and (b) FRP rupture of Beam B6

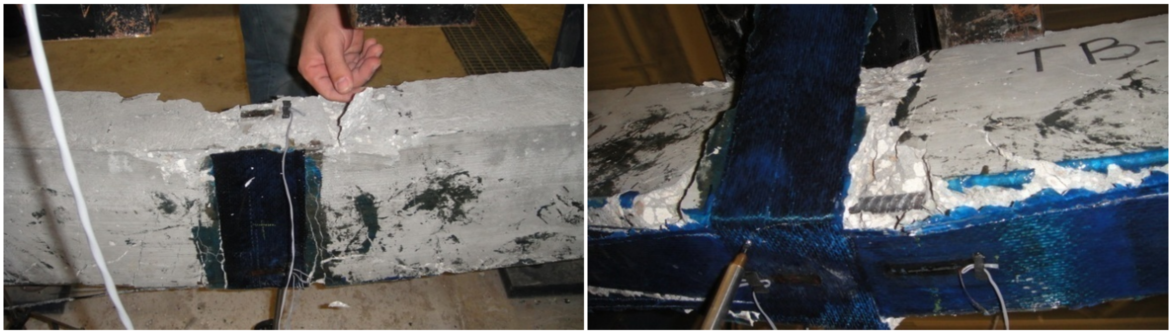
(c) CFRP debonding B2 set #2 (d)CFRP delamination B4set #2



(e) CFRP rapture B4 set #2 (f) CFRP rapture B5 set #2

(g) CFRP debonding B6 set #2 (d)CFRP delamination B9set #2

Fig.3 Beam failure modes



(h) concrete compression failure B-11 set#2　　(i)CFRP delamination and debonding B4set #2

Fig.3 Beam failure modes

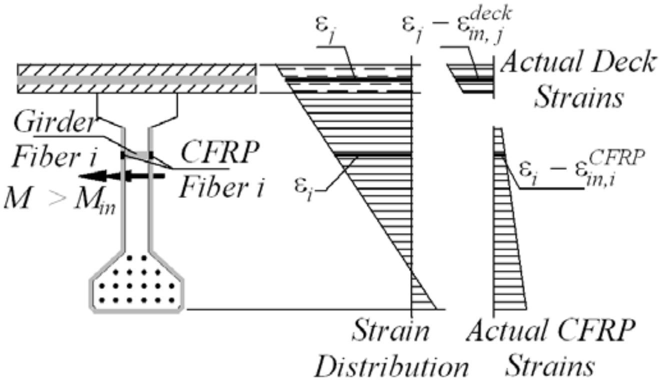


Fig. 4 Fiber section analysis model

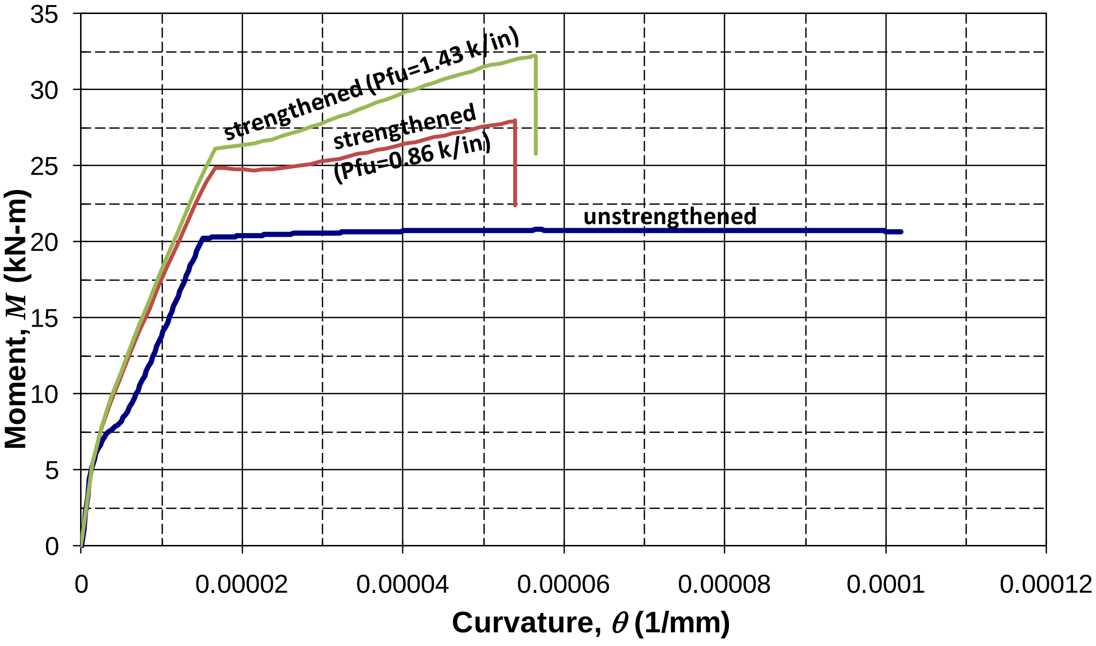


Fig. 5 Moment curvature relations for tested specimens

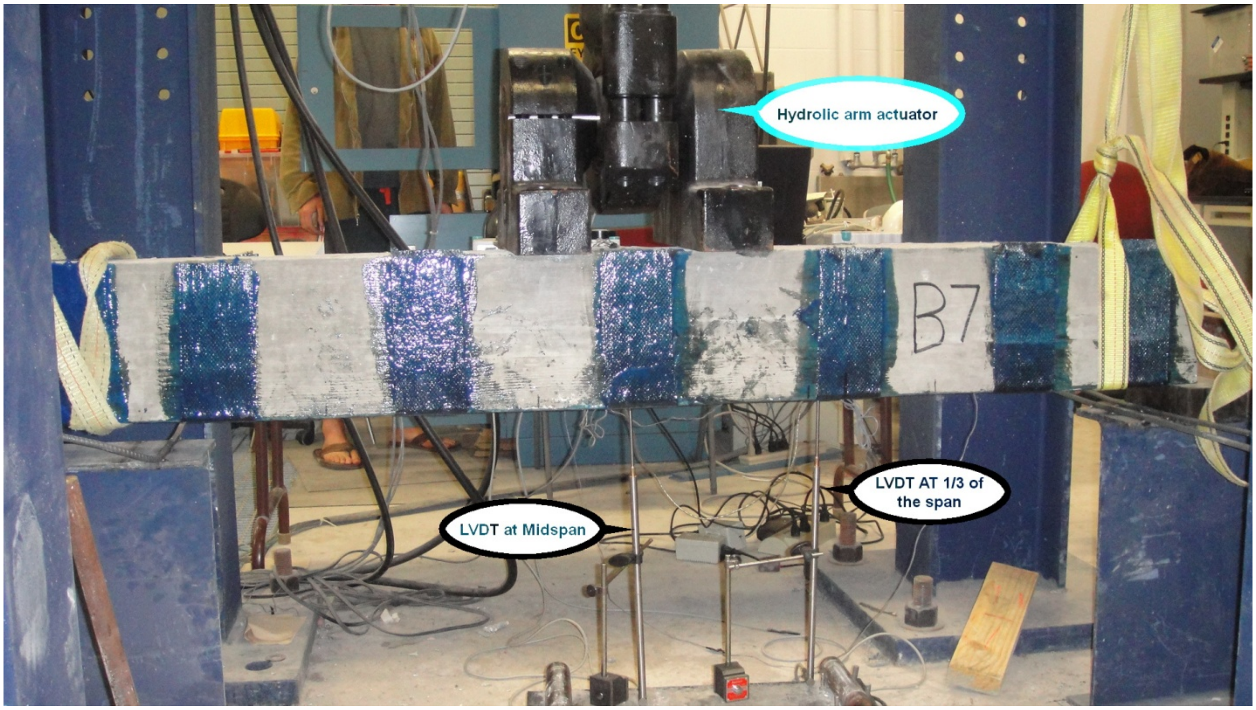


Fig. 6 Full test apparatus

Discussion of test results

The flexural behavior of the repaired beams was studied by analyzing the load-deflection characteristics and mode of failure. Control beams from set #1 (unstrengthenedB1 and strengthened B2) were tested to failure without pre-cracking.Also control beamsfrom set #2 (B-1 unstrengthened,B-2 B-3 and B-4 strengthened). Beams B3, B4, and B5 from set #1 were cracked before the application of the CFRP laminates. Also, B-5 to B12 from set #2 were pre-cracked then tested to failure.

Table 1 lists the failure loads for all tested specimens. A comparison between the failure load of Beam B1 (unstrengthened) and Beam B2 shows that CFRP strengthening enhanced the flexural capacity by 28.6% for set#1. Similarly, for set #2, an increase of 101.2% for B3 that was fully wrapped with U shaped CFRP when compared with B1 (unstrengthened)

An increase in the failure load of 29.8% was observed for the CFRP repaired pre-cracked beam B3 compared to the un-strengthened control beam B1 (93.9% increasing in flexural strength for the pre-cracked then repaired with CFRP soffit's laminates and u shaped wrapping B6 from set#2compared with B1). This is almost identical to the increase in flexural capacity for Beam B2(B3 also in set#2), which shows that pre-existing cracks do not affect the effectiveness of CFRP flexural strengthening. The results also show that U-shaped wrapping of CFRP laminates (pre-cracked beams B4 and B5 from set#1 and B5 ,B6 ,B7 ,B8 ,B9 ,B10,B11 and B12 from set#2) enhanced the flexural capacity further even if the U-wrapping was not continuous and its sole purpose is to prevent delamination of the continuous strips attached to the soffit. The increase in flexural strength for Beams B4 and B5 in comparison with Beam B2 was 4.8% and 8.3%, respectively(wide range for set#2). Figure 2 shows the load deflection curves of tested beams.

The modes of failure of the tested beams were also studied.

Set#1

Beam B2 experienced a mode of failure that was initiated by concrete flexural cracking and steel yielding, which were followed by CFRP failure. Similarly, the failure mode of repaired pre-cracked Beam B3 was flexural crack widening at 13,489 lb [60 kN] and then CFRP rupture at 15,747 lb [70 kN] followed by concrete crushing after excessive deflection. Repaired Beam B4experienced flexural cracking and yielding of steel. Afterwards, compression concrete was crushed while CFRP still did not rupture. Repaired Beam B5 experienced flexural cracking, yielding of steel, and then crushing of concrete in compression followed by rupture of CFRP laminates at beam's soffit or tension side. Figure 3 shows failure mode for Beams.

Set#2

Failure mode observed as following:

B2,B3, and B5 experienced a mode of failure that was initiated byCFRP failurefollowed by concrete flexural cracking and steel yielding.

B4 and B6experienced flexural cracking and yielding of steelaaccompanied with CFRP soffit laminate rupture. Afterwards, compression concrete was crushed while CFRP still did not rupture.

B7experienced a mode of failure that was initiated byconcrete flexural cracking and steel yieldingfollowed byCFRP debonding.

B8experienced flexural cracking and yielding of steel. Afterwards, large deflection happened while CFRP still did not rupture.

B9experienced flexural cracking and yielding of steel accompanied with CFRP soffit laminate rupture. Afterwards, compression concrete was crushed.

B10 and B11: experienced flexural cracking and yielding of steel a accompanied with CFRP soffit laminate rupture and U wrap debonding. Afterwards, compression concrete was crushed.

B11experienced a mode of failure that was initiated byconcrete flexural cracking and steel yieldingfollowed by the soffitCFRP laminatedebonding.

Analysis of Tested Specimens

A fiber section model was used to analyze the tested beams. The model dissects the section into layers (fibers) through its height as can be seen in Fig. 4. Each of the individual longitudinal layers represents a certain material (concrete, CFRP, or reinforcing steel) based on its geometric location and hence is assigned appropriate constitutive models based on uniaxial stress-strain relationships. The model is capable of accounting for material nonlinearities and the construction sequence; i.e. time of introducing a composite deck or applying FRP strengthening. This is achieved by adjusting the strain level in each fiber by the initial strain condition at the time of its introduction to the system. For example, strains in CFRP fiber '*i*', $\varepsilon_{CFRP,i}$, is determined using Eq. 1 where $\varepsilon_{in,i}^{CFRP}$ is the strain at fiber '*i*' at the time of bonding the FRP to the beam.

$$\varepsilon_{CFRP,i} = \varepsilon_i - \varepsilon_{in,i}^{CFRP} \tag{1}$$

Equilibrium of stress resultants and compatibility of strains in the cross-section are evaluated until convergence is achieved through an iterative process. Once the strain profile that maintains equilibrium is achieved, the bending moment is calculated using internal forces from the stresses in each fiber, σ_i, which is determined using the appropriate modulus of elasticity, E_i. Equation 2 gives the moment expression for a general case of a prestressed beam

$$\sum M = \sum_{i=1}^{m}\left(\sigma_{\mathrm{PS},i} A_{\mathrm{PS},i}\right)\left(d_{\mathrm{PS},i}\right) + \sum_{j=1}^{n}\left(\sigma_{c,j} A_{c,j}\right)\left(d_{c,j}\right) + \cdots$$

$$\sum_{k=1}^{p}\left(\sigma_{\mathrm{CFRP},k} A_{\mathrm{CFRP},k}\right)\left(d_{\mathrm{CFRP},k}\right) + \sum_{l=1}^{q}\left(\sigma_{\mathrm{s},l} A_{\mathrm{s},l}\right)\left(d_{s,l}\right) = 0.0 \tag{2}$$

where $d_{\mathrm{PS},i}$, $d_{c,j}$, $d_{\mathrm{CFRP},k}$, and $d_{s,l}$ are the distances from the girder top to the centroid of prestressed strand layer *i*, concrete fiber *j*, CFRP fiber *k*, and steel bar layer *l*, respectively. More details about the analysis model (BMACS) can be found elsewhere [13].

The moment curvature relations were obtained for the tested beam cross section using the analytical approach described above. Figure 5 shows the moment-curvature relationship obtained from the computer model for strengthened and unstrengthened sections. Two strengthened cases were analyzed. The first one utilized the expected tensile strength provided by the manufacturer of the FRP material (1430 pounds/ply/in), while the second reflects results obtained using the manufacturer recommended values (860 pounds/ply/in). The analytical values for the ultimate flexural capacity of the beams were calculated at 15.34 kip-ft [20.08 KN-m] for set#1 and 12.71kip-ft for set#2 without CFRP repair, while moment resistance of 23.79 kip-ft [32.25 KN-m] and 20.63 kip-ft [27.97 kN-m] were obtained for the CFRP strengthened beams using the expected and recommended tensile properties, respectively. The results show that the increase in flexural strength is estimated to be more than 50% if the expected value is used in design and 34% if the recommended value is used. In both cases, the FRP design strain, ε_{fd}, was limited to ACI 440.2R-08 [1] recommended value which is given by the expression given in Eq. 3

$$\varepsilon_{fd} = 0.083\sqrt{\frac{f_c^{'}}{nE_f t_f}} \le 0.90\varepsilon_{fu} \qquad \text{(inch-pound units)}$$

$$\tag{3}$$

$$\varepsilon_{fd} = 0.41\sqrt{\frac{f_c^{'}}{nE_f t_f}} \le 0.90\varepsilon_{fu} \qquad \text{(SI units)}$$

These results are different than the observed experimental ones, which showed an increase between 28.6% and 39.3%. The detected mode of failure was FRP debonding (soffit FRP fibers reaching ε_{fd}). As stated earlier, this is the same mode of failure that was observed experimentally. The discrepancy in results shows that estimating accurate FRP limit strain [5] is of utmost importance for obtaining reliable flexural strengths of FRP strengthened concrete beams.

Conclusions

The following conclusions are deduced from the analytical and experimental results:

- Repairing pre-cracked beam with either straight CFRP laminates or straight and U-shaped wrapping of CFRP laminates restored their flexural capacity to be similar to control CFRP strengthened beam.
- The capacity of the repaired pre-cracked beam using straight CFRP laminates was restored and enhanced recording a 29.8% from set#1 and 101.2% from set#2 increase in the failure load compared to the un-strengthened control beam.
- The load carrying capacity of repaired pre-cracked beams with CFRP laminates was increased than that for control un-strengthened RC beam with a range from 29.8% to 39.4%. for set#1 and 34.3% to 108.9% for set#2
- The use of U-wrapped CFRP laminate combined with straight laminates proved to be effective in increasing the load capacity. It extended the desired behaviour of strengthened beams and delayed delamination or debonding of the straight longitudinal laminate at the tension side.
- Accurate estimate of FRP rupture strain is extremely important for obtaining reliable estimates of flexural capacity of strengthened members.

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