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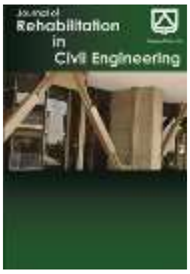

Flexural Strengthening of Deficient Reinforced Concrete Beams with Post-Tensioned Carbon Composites Using Finite Element Modelling

A. Hamzenezhadi[1] and M. K. Sharbatdar[2*]

1. PhD Candidate of Structural Engineering, Faculty of Civil Engineering, Semnan University, Semnan, Iran.
2. Associate Professor, Faculty of Civil Engineering, Semnan University, Semnan, Iran.

Corresponding author: *msharbatdar@semnan.ac.ir*

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ABSTRACT

The application of external post-tensioned steel bars as an effective way to strengthen an existing bridge has been so far used in many different countries. In recent decades, however, they have been replaced by bars made from Carbon Fiber Reinforced Polymer (CFRP), as a material with high tensile strength and corrosion resistance, to address several concerns with steel bars such as their application costs and difficulties, and also their durability. Post-tensioning these sheets can be a new efficient method in strengthening the beams and utilizing the high strength of these material.This study has focused on the flexural behavior of beams reinforced by Post-tensioned non-bonded CFRP sheets. 15 beams were categorized in 3 groups of 5m-, 10m-, and 15m-span in order to evaluate the effect of some parameters such as level of post-tensioning, sheet length, and beam span on its load capacity, failure mode, ductility, and cracks behavior. The results indicate that even though the increase in post-tensioning levels improves the effectiveness of the method, but this capacity improvement is much more for small span beams especially when CFRP sheets are 90% of the beam span, compared to long span beams. There has been a noticeable capacity increase around 50% in the beams when decreasing the sheet length from 90% to 45% of the beam span and also causing 11-14% increase in ductility in various conditions.

1. Introduction

Civil engineers are always engaged in providing new economic methods to for rehabilitation and strengthening of damaged concrete beams [1-3]. The main concern of structural engineers in doing so is the destruction of concrete bridges. This approach has been a topic in strengthening reinforced concrete bridges as one of the most important parts of roads and is of great importance because of rapid development of transportation systems [4-5]. There are various methods for strengthening a structure.

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In some of them, steel is utilized and in others Fiber Reinforced Plastic (FRP) is used. Most of existing research on FRP plate bonding for flexural strengthening has been carried out in the last decade. FRP strengthening systems has drawn a great attention as the need for structural strengthening is increasing while the cost is reduced when using FRP 6]. Sharif et.al in 1994, loaded reinforced concrete beams up to 85% of ultimate bending strength and then applied FRP plates to the bottom of beams. The results show that bending strength of the rehabilitated beams generally increases and plasticity of them is inversely proportional to the thickness of FRP plates [7]. Quantrill and Holloway performed experiments with four reinforced concrete beams strengthened with FRP plates and post tensioned up to 17.5 to 41.7% of their tensile strength and showed that post-tensioning CFRP plates prior to their adhesion is an effective way to improve performance and increasing bending capacity of strengthened beams [8]. Wang and Zho investigated the method of determination of nominal bending capacity of strengthened reinforced concrete beams using post tensioned FRP plates based on the traditional bending methods. However, the effect of FRP detachment is dismissed in their work [9]. Bastani et.al. compared the performance of structural steel beams retrofitted with Carbon FRP (CFRP) and Basalt FRP (BFRP) fabrics with finite element analysis. They concluded that the Basalt fabric offers a competitive and green alternative to the Carbon fabric [10]. Choobbor e.al. presented the bending performance of reinforced concrete beams strengthened with hybrid carbon and basalt fiber reinforced polymer (CFRP/BFRP) composite sheets. The proposed hybrid system is intended to improve the properties of the strengthening composite material, in which high strength CFRP sheets are combined with ductile BFRP sheets via epoxy adhesive. The models predicted the obtained load-carrying capacity and associated mid-span deflections at yield and ultimate loads, with a deviation that did not exceed 12% [11]. Siddika et.al. in a review research demonstrated that FRP composites can be used to recover the strength of damaged and corroded beams and exhibit good durability and insulation performance. It also provides a straightforward perspective of strengthening and retrofitting techniques for RC beams using FRP composites [12]. Lee et al. strengthened a reinforced concrete beam with a post-tension NSM system was fabricated, and a four-point loading experiment was performed. They proposed a finite element analysis model by simulating the bond behavior of FRP bars and the filler [13]. Gil et.al. compared the performances of beams with passive NSM laminate, and a third with post-tensioned NSM laminate. simple analytical equations based on the plane cross-section for pre-cracking and failure analysis were proposed, showing good agreement with the experimental results [14].

Although an integrated set of instructions and recommendations for concrete structures with external CFRP layers is provided by organizations such as ACI, CSA, ACE, ISIS and JSCE, a certain provision for bending strengthening of reinforced concrete beams using post tensioned FRP plates is not available in codes [15-19]. Fiber-reinforced polymer (FRP) composites are extensively used in advanced concrete technology given their superiority over traditional steel reinforcements [12].

2. Finite Element Models and Material Properties

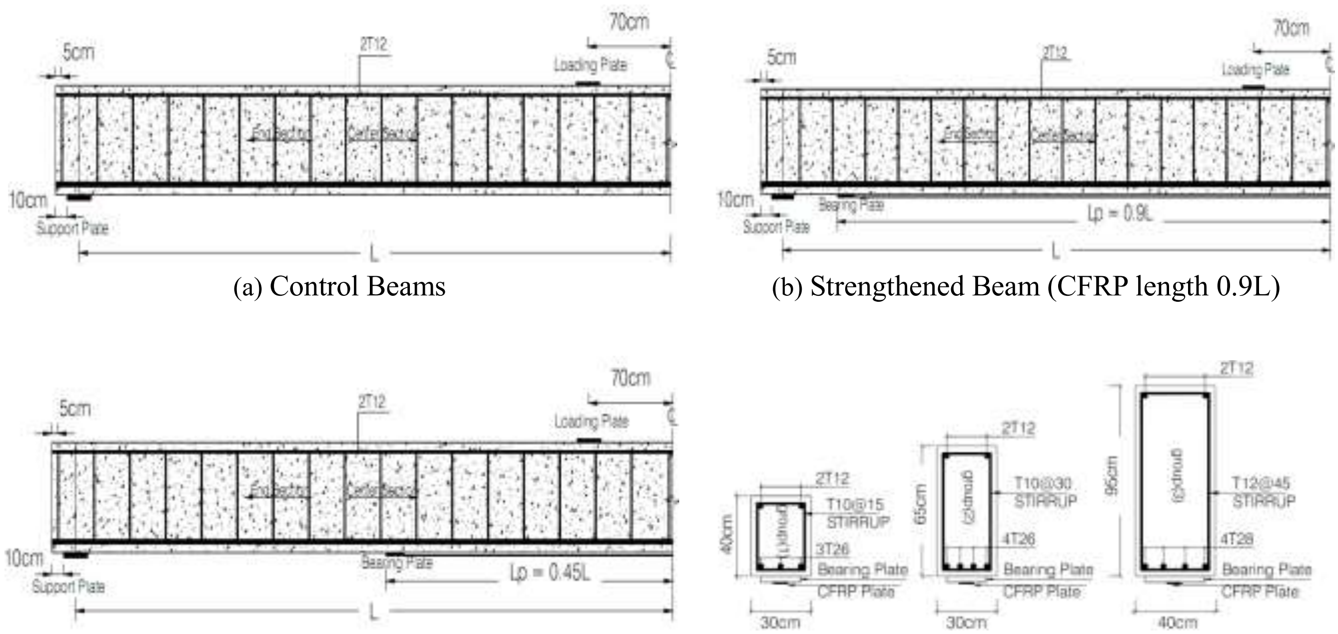
2.1. General

To study the effect of contributing parameters on flexural behavior of concrete beams strengthened with composite post-tensioned plates, finite element models are produced via ANSYS software [20]. In this software, concrete is modeled using solid65 element, longitudinal fittings and metal stirrups using link 8, supporting and loading plates using solid45 and CFRP plates using solid46 element. In this research, it is assumed that there is no slip in reinforcements and there is complete connection between anchors and FRP plate. Therefore, there will be no detachment or failure at anchores points.

2.2. Models

To evaluate the effects of this type of strengthening on concrete beams with different spans and the effects of plate length on flexural behavior of strengthened beams, 15 samples were modeled in 3 groups. First and second consisted of beams with 5 and 10m spans, and third group included beams with 15m span. Each group consisted of a control beam and three strengthened ones. In the third group, the length of the beams varied. In the first group, height, width and span of the beams were 400, 300 and 4800 mm, respectively. Based on the Iranian National Code for Design of RC Structures, a minimum height of L/16 should be provided for simply supported beams. To this aim, the height of the specimens has been considered in a way to satisfy this criterion [21].

In samples, 3φ26 as tensile longitudinal reinforcement with 1592 mm^2 cross section, 2φ12 with 226 mm^2 cross section as compressive longitudinal reinforcement and φ10 stirrups with 78.5 mm^2 with 150 mm distances were applied. In the second group, beams' height, width and span were 650, 300 and 9800 mm, respectively. Samples used 4φ26 as compressive longitudinal reinforcement and φ10 with 78.5 mm^2 with 300 mm distance were applied. Finally, the third group consisted of beams with height, width and span as much as 950, 400 and 14800 mm. All samples used 4φ28 as tensile longitudinal reinforcement with 2461.7 mm^2 cross section and 2φ12 with 2461.7 mm^2 as compressive longitudinal reinforcement and φ12 stirrups with 113 mm^2 cross section and 450 mm distance. In all samples, bending reinforcements were extended from each side as much as 100 mm. A schematic of dimensions, beams support positions, and post tensioned plates and reinforcements are shown in Fig. 1. Loading points distance in all models is 1400 mm. In Table 1, properties of fittings, used concrete and the post-tensioning amount of beam samples are presented.



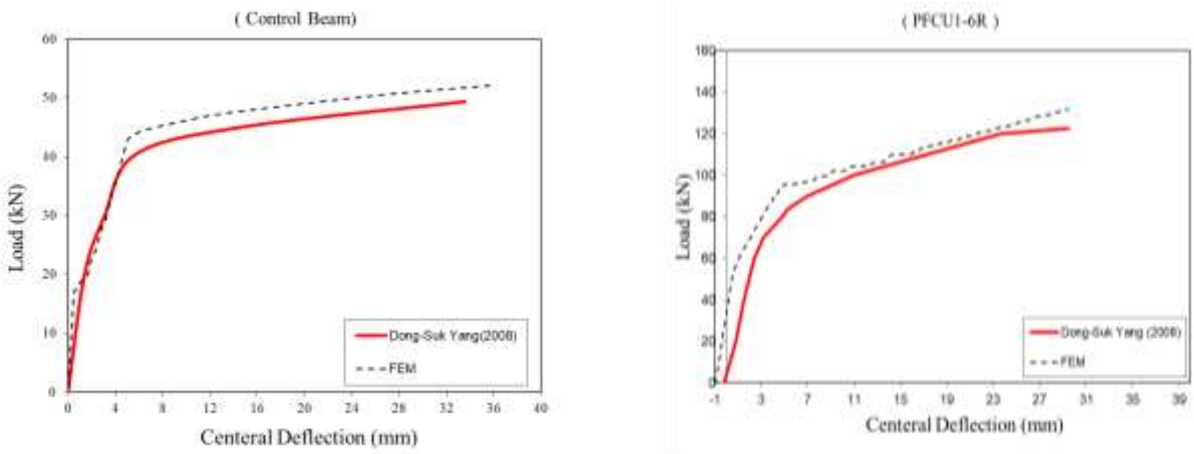
(a) Control Beams (b) Strengthened Beam (CFRP length 0.9L)

(c) Strengthened Beam (CFRP length 0.45L) (d) Section of Beam

Fig.1. Schematic of Beam Specimens

Table.1. Details of beam specimens

	BEAM	State	Compression bar	Tension bar	Stirrup	Compression Strength of Concrete (MPa)	(L_{FRP}/L_{beam})	Level of Post-Tensioning
Group1	BC1	Control	2 Ø 12	3 Ø 26	Ø10 @ 15	30	0.9	_
	BP125	Strengthened	2 Ø 12	3 Ø 26	Ø10 @ 15	30	0.9	25%
	BP150	Strengthened	2 Ø 12	3 Ø 26	Ø10 @ 15	30	0.9	50%
	BP170	Strengthened	2 Ø 12	3 Ø 26	Ø10 @ 15	30	0.9	70%
Group2	BC2	Control	2 Ø 12	4 Ø 26	Ø10 @ 30	30	0.9	_
	BC225	Strengthened	2 Ø 12	4Ø 26	Ø10 @ 30	30	0.9	25%
	BP250	Strengthened	2 Ø 12	4 Ø 26	Ø10 @ 30	30	0.9	50%
	BP270	Strengthened	2 Ø 12	4 Ø 26	Ø10 @ 30	30	0.9	70%
Group3	BC3	Control	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.9	_
	BP325	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.9	25%
	BP350	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.9	50%
	BP370	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.9	70%
Group3a	BP325-0.45L	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.45	25%
	BP350-0.45L	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.45	50%
	BP370-0.45L	Strengthened	2 Ø 12	4 Ø 28	Ø12 @ 45	30	0.45	70%



(a) Not Strengthened Beam

(b) Strengthened Beam

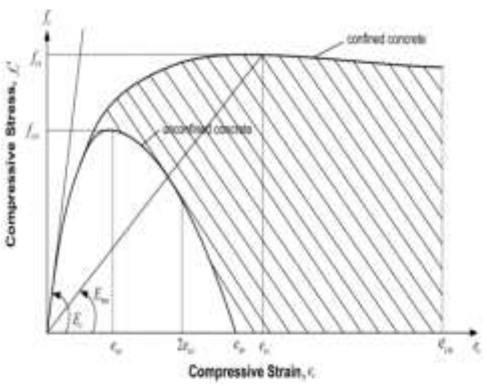
Fig.2. Load-deflection relation

2.3. Validation

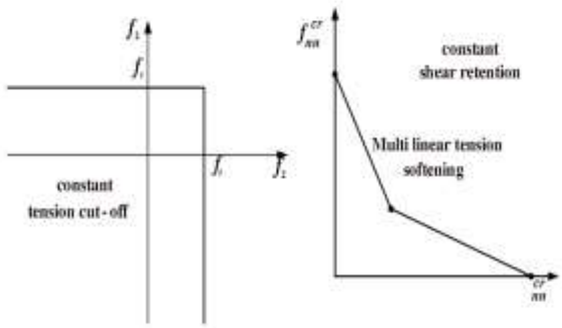
To control the validity of elements and supporting positions, two beams fabricated and tested by Dong Suk Yang et.al in 2008, were modeled and assessed [22] which includes a non-strengthened beam and another strengthened using composite plates having 60% post tensioning. A comparison of experimental and finite element results are shown in Fig. 2. As depicted in below diagrams, there is a little difference as much as 3-6% between experimental and finite element data. Several factors led to this difference including fine cracks propagated during concrete curing and shrinkage in all three directions which cannot be modeled in finite element model. On the other hand, assumption of complete connection between concrete and fitting does not apply in real situations. Upon slipping, the combined performance of concrete and steel is no longer available due to this little difference, our models, albeit the small difference, are valid.

2.4. Materials Modeling and their Properties

As shown in Fig. 3, the commonly used concrete analysis model consisted of the traditional plasticity model for the compression concrete, while the tensile behavior consisted of a smeared crack model, which assumes micro-cracking. As shown in Fig. 4a, the reinforcing bars had an elasto-plastic behavior, defined by their yield strength, with a typical elastic modulus of 205 GPa. A yield plateau, whose range depends on the class of steel, is followed by a strain-hardening behavior up to failure. In this model the reinforcing bars are modelled as steel layers of equivalent thickness. The CFRP plates have a very high unidirectional tensile strength, but with a stiffness close to that of steel. The behavior was essentially linearly elastic up to the tensile strength limit. Once the tensile strength has been reached, it is assumed to suddenly fail in a perfectly brittle mode, Fig. 4b. The material properties of the CFRP plate and Reinforcement used in the models are given in Table 2.

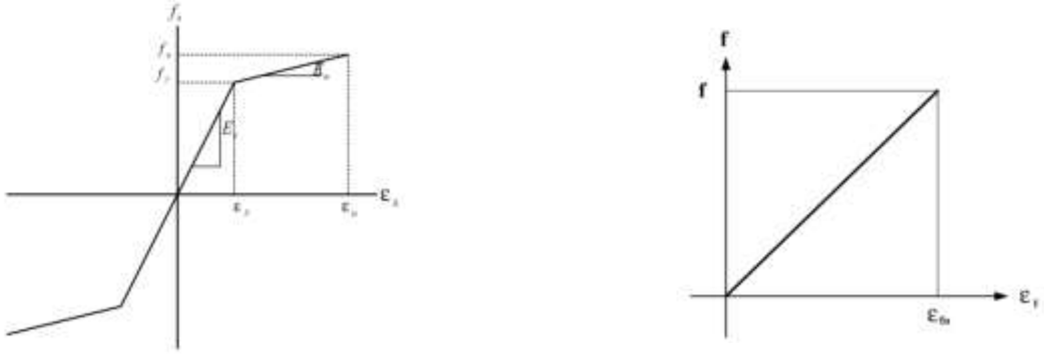


(a) Stress-strain curve under compression



(b) Smeared crack model under tension

Fig. 3. Concrete model for the finite element analysis.



(a) Reinforcement (b) CFRP plate

Fig. 4. Reinforcement and CFRP plate models for the finite element analysis.

Table.2. Material properties

Material	Properties
Steel	Modulus of Elasticity: 205 GPa
	Yield Strength: 300 MPa
CFRP Plates	Modulus of Elasticity: 173 GPa
	Tensile Strength: 2350 MPa
	Remarks: Width 7.5 cm, thickness 0.13 cm

3. Finite Element Analysis

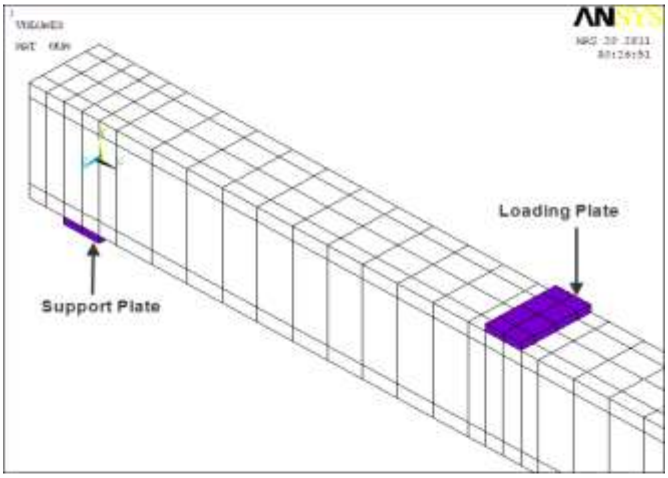
In this part, all aforementioned beams were modeled and meshed in ANSYS software. For example, Fig. 5. represents finite element model for control beams and beams having post tensioned CFRP. In order to post-tension the CFRP plates in strengthened beams they have to be stretched as much as δ, without any loading present, and as stated, according to desired post-tensioning cross section and since FRP is a material with linear behavior, we calculate required elongation of the plate to make such post tension:

$$\sigma = E.\varepsilon \quad (1)$$

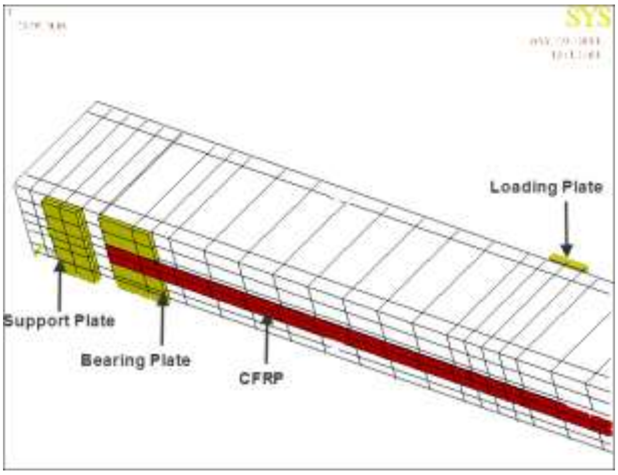
$$\varepsilon_{P\%} = 0.0P\,\varepsilon_U = 0.0P\frac{\sigma_U}{E} \quad (2)$$

$$\varepsilon_{P\%} = \frac{\delta}{L_{FRP}} \Rightarrow \delta \quad (3)$$

Where, P is post-tension value, ε_P is post-tension equivalent strain and ε_u and σ_u are ultimate strain and stress of the FRP plate, respectively. δ is the value of required elongation of CFRP plate to produce post-tension force. By stretching plate and attaching to anchor plates, required post-tension will be produced which is accompanied by a pressure in bottom and tension in upper surface. As can be seen in **Fig. 6**. an upward creep is produced in beam which causes the formation of cracks in upper surface of the beam and it can be claimed that this confirms the validity of the type of post-tensioning of the plate instead of making equivalent using linear elements.

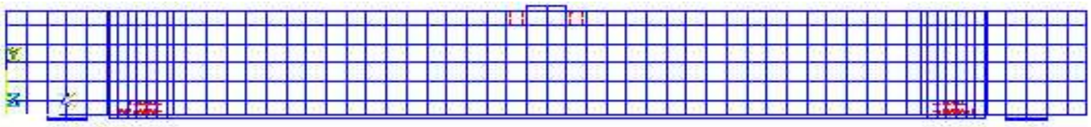


(a) FE Model of control specimens

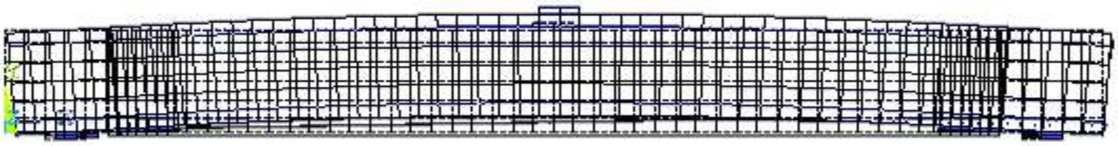


(b) FE Model of Strengthened specimens

Fig. 5. Models constructed in ANSYS.



(a) Cracks occurring in the upper surface of the beam due to post tensioning.



(b) Curved beam due to post tensioning.

Fig. 6. Post tensioned model in ANSYS.

4. Controlling Parameters of Structure Behavior

4.1. Ductility

Structure ductility in design of strengthened beams using post tensioned CFRP plates is important because CFRP has sudden and brittle failure. This concept can be defined as the capability of the structure to resist against loads beyond elastic limit without losing loading capacity up to the failure point. However, determination of ductility is still a challenging issue because there is no absolute definition for it. Various methods have been suggested To determine the plastic behavior of beams, each having their own pros and cons, including curvature ductility, as well as displacement, energy, and ductility change factor. Structures which are strengthened externally using CFRP plates must be designed carefully to achieve desired ductility to ensure that internally reinforcing steel bars yield before the fracture of CFRP plates. General parameters which affect ductility are reinforcement ratio, structure geometry, strengthening schematic, surroundings' conditions, time dependent behavior, compressive strength of the concrete, confinement and loading velocity. In this research, the general method of displacement ductility whose relationship is given below is selected to evaluate the ductility behavior of tested beams:

$$\mu_E = \frac{U_{ult}}{U_{yield}} \tag{4}$$

Where, U_{yield} and U_{ult} are yield and ultimate displacement, respectively.

4.2. Cracks Distribution

Structure life time is an important consideration. Presence of cracks in concrete structures especially in more humid regions or structures in contact with water such as beams of concrete bridges leads to a corrosion of reinforcements and concrete cancer. Moreover, it can cause a malfunction of concrete – reinforcement joint [11]. When a structure begins making cracks, the speed of propagation of material destruction is a function of crack width. Therefore, controlling crack width and propagation is necessary throughout the beams.

5. Results and Discussion

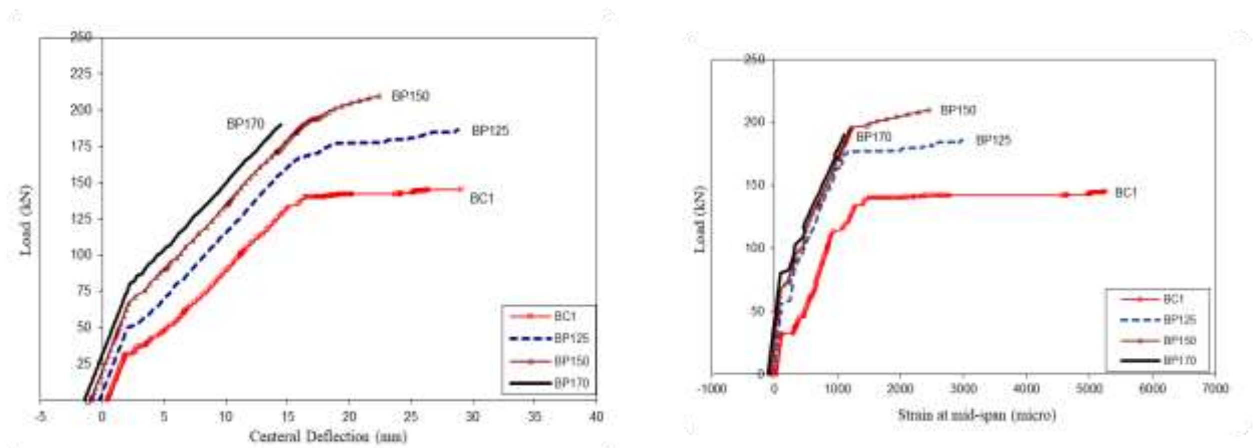
5.1. Effect of Post-Tensioning on Load Bearing Capacity

For this purpose, a set composed of 12 beams from group1, 2 and 3 were modeled and analyzed in finite element program and the effect of such beam strengthening system with various post-tensioning levels was assessed.

According to **Table 3**, which shows the result summary of group 1 beams' flexural behavior versus their load bearing capacity, The load – displacement curve of this group's beams using finite element analysis (FEA) is shown in **Fig. 7**. By increasing post-tensioning, the level of load corresponding to crack initiation in beams increases and this increase is approximately equal to the ratio of post-tension increase, so that this increase for beams BP125 is 56.7% (17.98kN) and for beam BP150 with twice post-tension is 124.3% (39.451kN). It means that there is about two times increase in crack initiation load in BP125 and for BP170, with 2.8 Times post tension, the value of crack initiation load in 158.7% (50.38kN). For this beam, a 2.8 times increase is shown and this can be used as an appropriate approximation for crack initiation load increase of beams strengthened by post-tensioning between above said post tensions and beams with short spans. Moreover, we can observe an increase in yielding and ultimate load in each of strengthened beams with increasing post tension. The level of this capacity improvement upon breaking in each of the BP125 and 150 beams with respect to control beam is about 41 and 64.9 kN which is equivalent to 28.3 and 44.7 percent increase. For BP170 beam, the amount of load bearing capacity increase due to failure mode by approaching ultimate tensile capacity and consequently plate rupture is only 45 kN (30%). In this beam, as can be seen in Fig. 7.diagrams, at the time of rupture, tensile reinforcements are not detached. According to Table 3, it can be inferred that the effect of post-tensioning on crack loading capacity, though relatively more than ultimate and yield strength of beam but the value of the increased load is independently more effective on the increase in beam's ultimate strength.

Table.3. Comparison of results for concrete beams strengthened with unbounded CFRP plates (group 1).

BEAM	Camber due to post-tensioning & weigh (mm)	Initial Cracking				Yielding				Ultimate							
		Load (kN)	Increasing of FEM Initial Cracking Load respect to BC1 Specimen(%)	Load bearing capacity Enhancement (kN)	Deflection (mm)	Load (kN)	Increasing of FEM Yielding Load respect to BC1 Specimen(%)	Load bearing capacity Enhancement(kN)	Deflection (mm)	Load (kN)	Increasing of FEM Ultimate Load respect to BC1 Specimen(%)	Load bearing capacity Enhancement (kN)	Deflection (mm)	FRP Stress (MPa)	Increasing of analytical Ultimate FRP stress respect to maximum(%)	FRP stress due to postztensioning (MPa)	Bearable stress Enhancement (MPa)
BC1	0.45	31.7	_	_	2.19	133.2	_	_	15	145.1	_	_	29.1	_	_	_	_
BP125	-0.23	49.7	56.7	18	2	167.2	25.5	34	15.94	186.3	28.3	41.1	28.77	1130	48	587.5	542.5
BP150	-0.9	71.2	124.3	39.4	2.66	193.5	45.2	60.2	16.92	210.0	44.7	64.9	22.41	1710	72.8	1175	535
BP170	-1.42	82.1	158.7	50.4	2.59	_	_	_	_	190.1	30	45	14.43	2350	100	1645	705



(a) Load–deflection relations (FEA) (b) Load-Tension Rebar Strain (FEA)

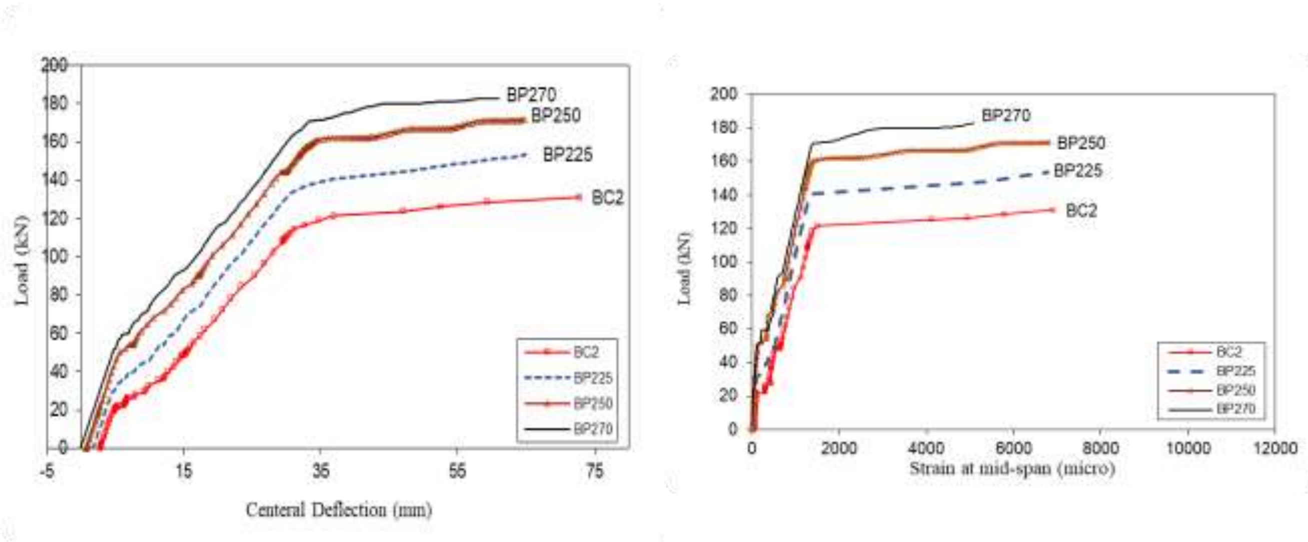
Fig. 7. Comparison of results for reinforced concrete beams strengthened with unbounded CFRP plates (group 1).

Strengthening of the beams of second group caused a 62.3% improvement of crack initiation capacity using 25% post tensioned plates and 146 and 171.9 percent for BP250 and 270, respectively compared to control beam. Results and curves of load bearing and strain of fittings of this group are presented in **Table 4** and **Fig. 8**. Increase in ultimate capacity resulted from bending strengthening of beam BP225 is about 23 kN (17.3%) and for beams BP250 and 270, this increase is as much as 40.6kN (31%) and 51.77kN (39.5%), respectively. As can be seen, in beams with average span length, all recorded load bearing capacities increases and results of **Table 5** and **Fig. 9** confirm this prediction for beam with long spans, so that crack load increase as much as 11.5kN by using 25% post tensions plates and crack initiation load in BP350 and 370 beams increased as much as 22.5kN and

31kN, respectively compared to control beams. Increase in ultimate load capacity due to bending strengthening in BP325 beam is about 13.9% of ultimate capacity of control beams and for BP350 and 370 beams, this increase is as much as 34.2 and 36.9%. for BP370, 7kN increase in load after tensile fitting yield, before collision of compressive concrete, caused CFRP plate achieve its ultimate capacity and rupture.

Table.4. Comparison of results for concrete beams strengthened with unbounded CFRP plates (group 2).

Bearable stress Enhancement (MPa)	FRP stress due to post-tensioning (MPa)	Ultimate						Yielding				Initial Cracking				Camber due to post-tensioning & weigh (mm)	BEAM
		Increasing of analytical Ultimate FRP stress respect to maximum(%)	FRP Stress (MPa)	Deflection (mm)	Load bearing capacity Enhancement (kN)	**Increasing of FEM Ultimate Load respect to BC2 Specimen(%)**	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	**Increasing of FEM Yielding Load respect to BC2 Specimen(%)**	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	**Increasing of FEM Initial Cracking Load respect to BC2 Specimen(%)**	Load (kN)		
–	–	–	–	72.84	–	–	131	31.03	–	–	114	4.53	–	–	19	2.8	BC2
482.5	587.5	45.5	1070	69.2	22.7	17.3	153.7	33.1	26.6	23.3	140.6	4.88	11.8	62.3	30.8	1.75	BP225
615	1175	76.2	1790	67.43	40.6	31	171.6	33.4	47.5	41.7	161.5	5.2	27.7	146.	46.6	0.73	BP250
705	1645	100	2350	61.32	51.8	39.5	1828	31.5	57	_	171	4.81	32.6	171.9	51.6	-0.1	BP270

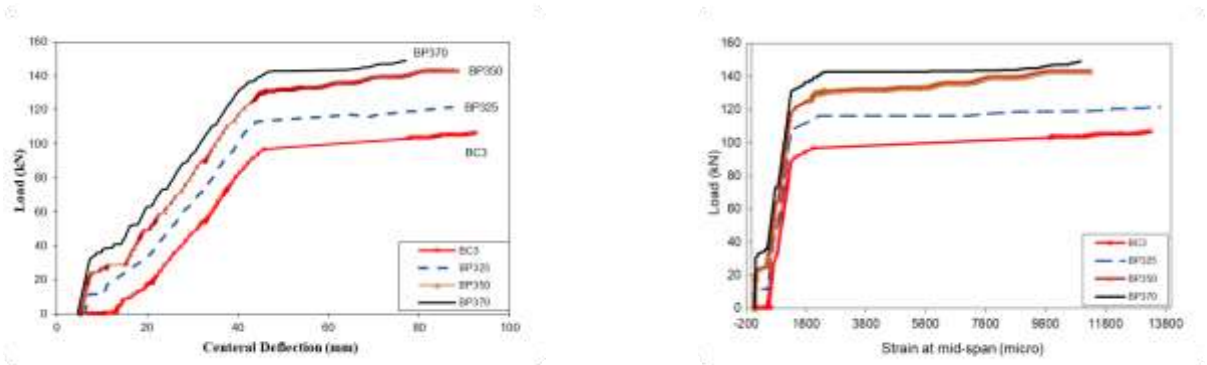


(a) Load−deflection relations(FEA)   (b) Load-Tension Rebar Strain (FEA)

Fig. 8. Comparison of results for reinforced concrete beams strengthened with unbounded CFRP plates (group 2).

Table.5. Comparison of results for concrete beams strengthened with unbounded CFRP plates (group 3).

Bearable stress Enhancement (MPa)	FRP stress due to post-tensioning (MPa)	Ultimate						Yielding				Initial Cracking			Camber due to post-tensioning & weigh (mm)	BEAM
		Increasing of analytical Ultimate FRP stress respect to maximum(%)	FRP Stress (MPa)	Deflection (mm)	Load bearing capacity Enhancement (kN)	**Increasing of FEM Ultimate Load respect to BC3 Specimen(%)**	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	**Increasing of FEM Yielding Load respect to BC3 Specimen(%)**	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	Load (kN)		
_	_	_	_	93.26	_	_	106.7	45.76	_	_	96.8	7.1	_	0.18	7.06	**BC3**
462.5	587.5	44.7	1050	87.85	14.9	13.9	121.6	44.17	15.1	15.6	111.9	7.15	11.5	11.6	6.15	**BP325**
625	1175	76.6	1800	88.59	36.5	34.2	143.2	47.85	34.6	35.8	131.4	7.18	22.5	22.7	5.25	**BP350**
705	1645	100	2350	77.06	42.3	39.6	149	46.51	45.5	47	142.2	7.15	31	31.2	4.57	**BP370**



(a) Load−deflection relations (FEA)

(b) Load-Tension Rebar Strain (FEA)

Fig. 9. Comparison of results for reinforced concrete beams strengthened with unbounded CFRP plates (group 3).

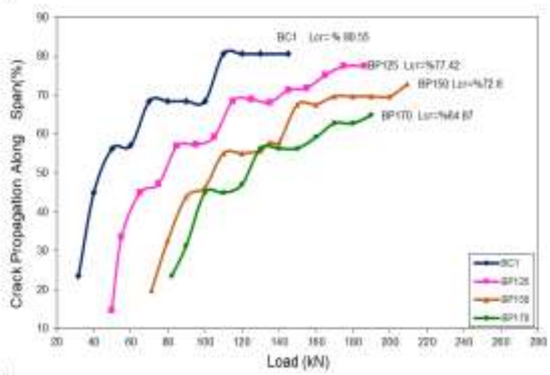
5.2. Effect of Post-Tensioning on Crack Distribution

Fig. 10. represents the crack development along beams. In all beams, increasing load will lead cracks depths to develop along compressive zone of the beam and causes beam collision due to compressive concrete rupture, while in sample with high post tension, upon failure, cracks won’t approach compressive zone of the beams and CFRP plate rupture is considered as the failure mode. Furthermore, strengthening, by increasing post-tension in ultimate load caused a decrease in the amount of developed cracks in the span, despite of higher applied load. That is, for BP 225, upon rupture, cracks were distributed in 77.23% of the span length and for BP250 and 270 beams, level of crack distribution at rupture load decreased as much as 65.56 and 65.21 percent, respectively.

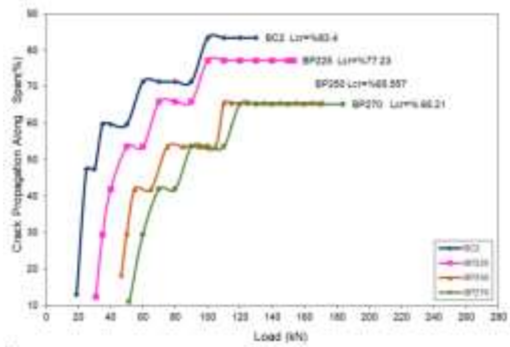
5.3. Effect of Span Length on Bending Behavior of Beams Strengthened with Unbounded CFRP Plates

According to above results, increasing post-tension in all beams with any span length, leads to an improvement in their load bearing at crack initiation, yielding of ultimate capacity. However, comparison of results obtained from finite element analysis to understand the effect of post-tension with change in span length is investigated in this section. Results obtained from finite element analysis to numerically analyze the effect of span length on strengthening and getting an appropriate result are presented in Table 6 and Fig. 11. According to diagrams, beam hardness before crack initiation and in two zones before and after yield independent of post tension, decreases with increasing span length. The amount of crack development capacity in BP125 beams with 25% post tensioned plates is 11.8kN and 11.5kN, respectively. Comparison of the value of crack initiation load for 25, 50 and 70 percent post-tension shows a decrease in crack load with span length increase.

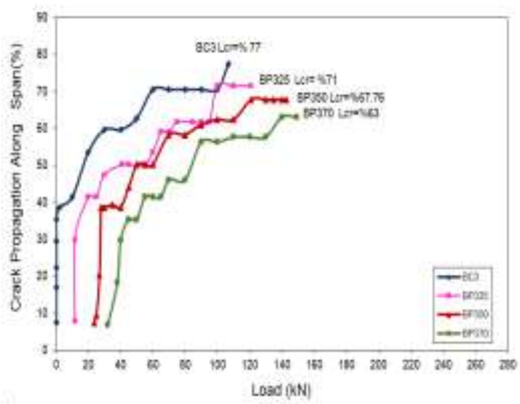
Comparison of load–strain in plates with different span lengths are shown in Fig. 12a. For all post-tension values, it shows that for same strain values in plates, level of capacity improvement in beams with 5m span lengths is considerably higher than beams with 10 and 15m span lengths. Therefore, the value of added yield and ultimate capacity of strengthened beams decreases with span increase. For instance, for BP125, according to Table 6, the value of increased ultimate capacity of the beams is 41.13kN and for BP225 and 325, there is 22.17 and 14.9kN decrease. Moreover, this decrease trend exists in BP150, 250 and 350 and the added ultimate load is 64.9, 40.6, and 36.5kN, respectively. Furthermore, changes in plate stress versus anchors location is shown as change in beam's curvature in Fig. 12b. As can be seen, slope of the diagram which gives the value of increased stress in anchor with increasing displacement, decreases with decreasing post-tension and increasing span length. This shows the decreasing effect of strengthening post tensioned plate with increasing span length in a certain post-tension value.



(a) Group (1) (FEA)

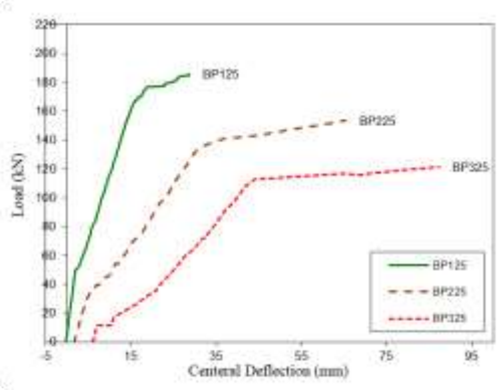


(b) Group (2) (FEA)

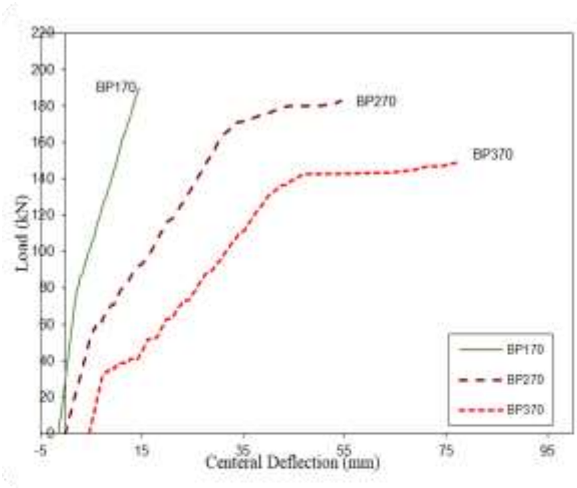


(c) Group (3) (FEA)

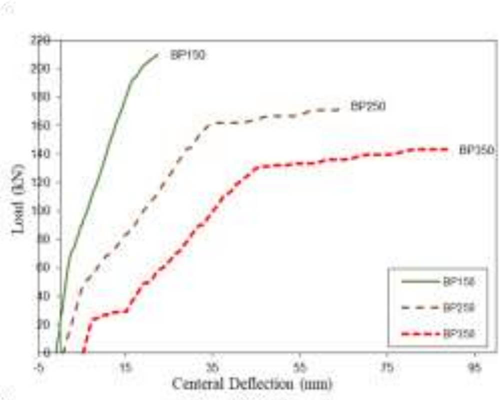
Fig. 10. Load-Crack Propagation along Span (%) Relation.



(a) 25% post tensioning(FEA)



(c)) 70% post tensioning(FEA)

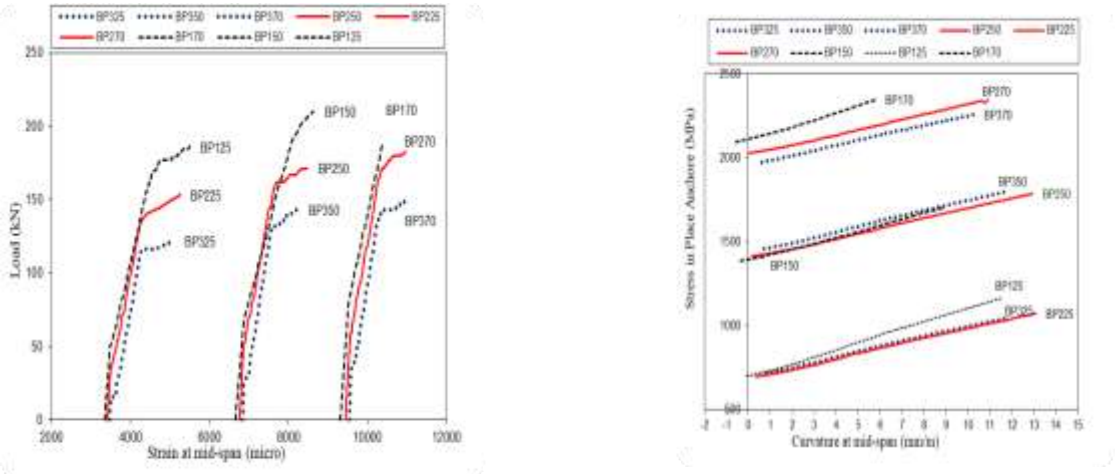


(b)) 50% post tensioning(FEA)

Fig. 11. Load−deflection relations for reinforced concrete beams strengthened with unbonded CFRP plates.

Table.6. Comparison of results for concrete beams strengthened with different span.

Ultimate			Yielding			Initial Cracking			
Deflection (mm)	Load bearing capacity Enhancement (kN)	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	Load (kN)	Deflection (mm)	Load bearing capacity Enhancement (kN)	Load (kN)	BEAM
29.1	_	145.14	15	_	133.25	2.19	_	31.749	**BC1**
72.84	_	131	31.03	_	114	4.53	_	18.96	**BC2**
93.265	_	106.73	45.76	_	96.78	7.1	_	0.18	**BC3**
28.77	41.13	186.27	15.94	33.98	167.23	2	17.981	49.73	**BP125**
65.43	22.7	153.7	35.1	26.6	140.6	4.88	11.81	30.77	**BP225**
87.85	14.888	121.62	44.17	15.14	111.92	7.15	11.47	11.65	**BP325**
22.41	64.88	210.02	16.92	60.25	193.5	2.66	39.451	71.2	**BP150**
64.72	40.6	171.6	35.4	47.53	161.53	5.2	27.677	46.637	**BP250**
88.59	36.473	143.21	47.85	34.63	131.41	7.18	22.48	22.66	**BP350**
14.43	44.99	190.13	_	_	_	2.59	50.381	82.13	**BP170**
54.62	51.77	182.77	33.5	57	171	4.81	32.6	51.56	**BP270**
77.06	42.308	149.04	46.508	45.471	142.25	7.15	30.98	31.16	**BP370**

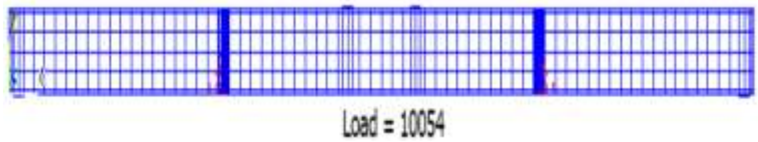


(a)Load-FRP Strain Relation(FEA) (b) Curvature -FRP Stress Relation(FEA)

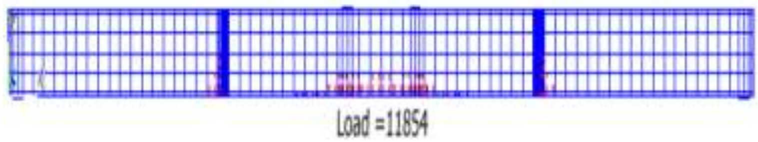
Fig. 12. Comparison of results for reinforced concrete beams strengthened with unbonded CFRP plate.

5.4. Effect of the Length of Strengthening Plate on Increased Capacity of Beams of Long Span

To study the effect of length of strengthening plate in third group beams having long spans, 3 beams with same post-tension properties were modeled and analyzed with the title of group 3a, by this exception that the length of plate decreased from 0.9 to 0.45 of span length. Important numerical results of finite element analysis of beams strengthened with plates of length 0.45L, 0.9L and post tensions as much as 25, 50 and 70% are presented in **Table 7**. Obtained results shows a decreasing crack initiation load in beams strengthened with shorter plates. In beams BP325, 350 and 370, required load to initiate cracks is 11.65, 22.66 and 31.16kN, respectively, by shortening strengthening plate, this load decreases and by increasing post tension, this load not only does not increase, but also decreases so that crack initiation load in Bp325- 0.54L decreases to 10kN and in Bp350 and 370, to 6.24 and 3.15kN, respectively. The reason for this decrease is the change in crack location. As can be seen in **Fig. 13**. for BP325-0.45L, by increasing load applied to the beam due to more effective post-tension force exerted on middle part of the beam as a result of more closer anchors to these anchors, first cracks developed in a point outside reinforcement zone. Therefore, although first crack is developed with lower load, decreasing crack numbers or taking it away from critical zone at the time of failure or yield can be a great strength in preventing deep crack in the middle of beam, because eliminating deep cracks in this region helps us utilize cross section capacity throughout the beam at the time of either reinforcement flow or their failure.



(a) Initial Cracking beside bearing plate



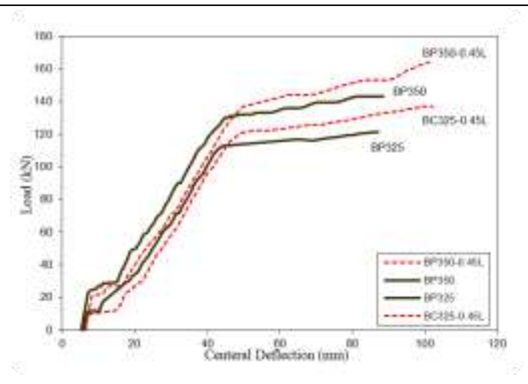
(b) Initial Cracking at mid span

Fig. 13. Schematic of initial crack for BP325-0.45L.

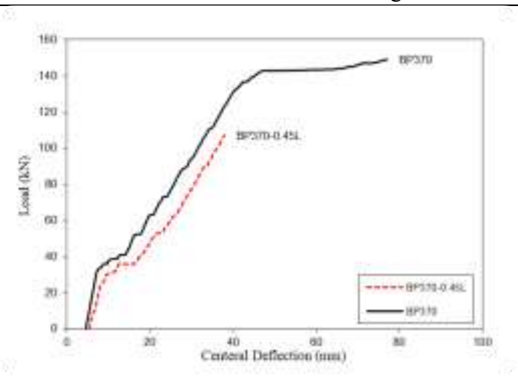
Table.7. Comparison of results for concrete beams (group 3) & (group 3a).

BEAM	Initial Cracking			Yielding				Ultimate						FRP stress due to post-tensioning (MPa)	bearable stress Enhancement(MPa)
	Load (kN)	Load bearing capacity Enhancement(kN)	Deflection (mm)	Load (kN)	**Increasing of FEM Yielding Load respect to BC3 Specimen(%)**	Load bearing capacity Enhancement (kN)	Deflection (mm)	Load (kN)	**Increasing of FEM Ultimate Load respect to BC3 Specimen(%)**	Load bearing capacity Enhancement (kN)	Deflection (mm)	FRP Stress (MPa)	**Increasing of analytical Ultimate FRP stress respect to maximum(%)**		
BC3	0.18	–	7.1	96.8	–	–	45.76	106.7	–	–	93.26	–	–	–	–
BP325	11.65	11.5	7.15	111.9	15.6	15.1	44.17	121.6	13.9	14.9	87.85	1050	44.7	587.5	462.5
BP325-0.45L	10.05*	9.9	7.78	120.8	24.8	24	49.3	137	28.4	30.3	102.2	1440	61.3		852.5
	11.85**	11.8	14.9												
BP350	22.66	22.5	7.18	131.4	35.8	34.6	47.85	143.2	34.2	36.5	88.59	1800	76.6	1175	625
BP350-0.45L	6.24*	6.1	6.4	137	41.6	40.2	50	164.2	53.9	57.5	101.22	2190	93.2		1015
	23.8**	23.6	11.7												
BP370	31.16	31	7.15	142.2	47	45.5	46.51	149	39.6	42.3	77.06	2350	100	1645	705
BP370-0.45L	3.151*	3	5.72	–	–	–	–	107.3	0.5	0.55	37.92	2350	100		705
	36**	35.9	12.44												

Initial Cracking load *
Cracking load at Mid Span**



(a) 25% & 50% post tensioning(FEA)



(b) 70% post tensioning(FEA)

Fig. 14. Load–deflection relations for reinforced concrete beams strengthened with unbonded CFRP plates.

In addition to this unusual decrease, crack load is only due to this fact that higher post-tension leads to higher tension in concrete at anchors location. As a result, load corresponding to first cracks in beams decreases with post-tension increase. But we must keep in mind that the magnitude of load necessary to initialize crack in the middle of beams increases for beams strengthened with decreasing plate's length and the amount of this increase is proportional to post-tension increase. This load, in BP325-0.45L whose overall crack distribution and initiation in the middle of beam is shown in **Fig. 14**b, is

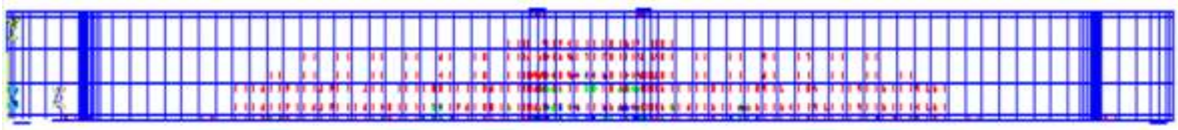
11.85kN and for beams BP350-0.45L and BP370-0.45L is 23.8 and 36kN, respectively. It means that we have about 0.2, 1.4 and 3kN increase compared to BP325, BP350 and BP370, respectively. Based on what is evident in diagrams of **Fig. 14**, for all values of post tension, the magnitude of the load necessary for reinforcement yield and ultimate load as well, increase when the length of strengthening plate decreases from 0.9L to 0.45L.

According to results presented in Table 7, the value of yield load increase in strengthened beam BP325 with respect to control beam is as much as 15.14kN and for BP325-0.45L, this increase is 24kN. This is about 1.5 times load increase compared to first strengthening. Using shorter CFRP plates caused an increase in added yield load compared to control beam with reinforcement with 50% post-tension from 34.6 to 40.2kN. But with strengthening having 70% post tension, plate achieves its ultimate tension capacity and its rupture occurs before fittings flow and this itself can be an indication of the more significant effect of plate in beam strengthening. The value of ultimate load has a considerable increase with decreasing plate's length, so that ultimate load increase in BP325-0.45L is 30.27kN which is about twice that of BP325 and for beam with 50% post tension, ultimate load increases from 36.47 to 57.47kN which is uniformly distributed along the beam.

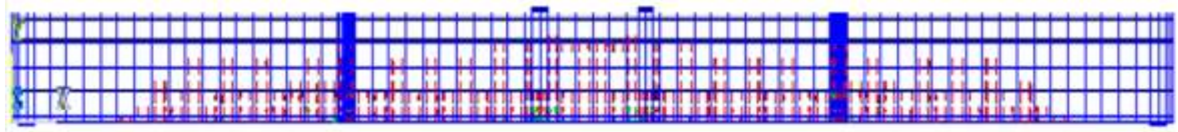
Fig. 15. Diagrams of **Fig. 16**. show that by shortening plate from 0.9L to 0.45L in beams with long spans, strain in strengthening plate has a greater growth after crack initiation, at the interval of crack loaf and after fittings' yield and for all post-tension values. This can be considered as more effectiveness of plate in exerted loads' bearing. As can be observed from diagrams of Fig. 14, the increase in reinforcements' strain is more and this can be attributed to the increase in applied load of FRP before yield. In beams with 25% post tension, the magnitude of strain increase after reinforcement yield in FRP plate with 0.9L length, is 18%, while for 0.45L length, this is 41% and for beams with 50% post tension, strain increase in plates increase from 8% to 23%. All available results point to the significant effect of post tensioned plates shortening on increasing structure load bearing capacities. Higher slopes of diagrams of Fig. 16. for all values of post-tension clearly shows more significant role of plate in second case and 390MPa increase in plate tension upon failure of the beam compared to first case, shown in Table 7, confirms above findings.

5.5. Ductility

In **Table 8**, values of ductility index for samples are shown. Results illustrate that this strengthening method leads to a decrease in ductility and increasing post-tension leads to even more decrease. Moreover, the amount of ductility in strengthened beams increases with span length and the magnitude of post-tension effect on ductility decrease, decreases with span length increase.

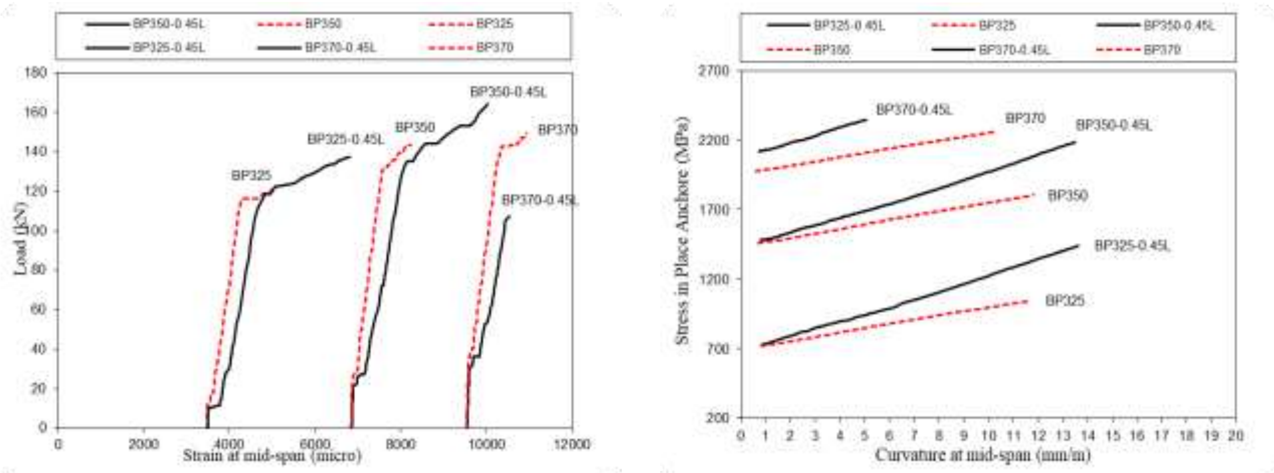


(a) BP350



(b) BP350-0.45L

Fig. 15. Schematic of cracking at Ultimate load.



(a) Load-FRP Strain Relation(FEA)

(b) Curvature -FRP Stress Relation(FEA)

Fig. 16. Comparison of results for reinforced concrete beams strengthened with unbonded CFRP plates.

For instance, the quantity of ductility decrease based on Tale 8 for BP150 is 31.7, but by increasing span length of beams BP250 and 350, the value of ductility index decreases as much as 22.1 and 9.2%, respectively compared to control beam.

Table. 8. Estimates of ductility

Ductility μE= (b)/(a)	(b) Ultimate (mm)	(a) yielding (mm)	BEAM
1.94	29.1	15	**BC1**
2.35	72.84	31.03	**BC2**
2.04	93.265	45.76	**BC3**
1.33	22.42	16.92	**BP150**
1.83	64.72	35.4	**BP250**
1.85	88.59	47.85	**BP350**
1.63	54.62	33.5	**BP270**
1.66	77.06	46.5	**BC370**
2.07	102.2	49.3	**BP325-0.45L**
2.02	101.22	50	**BP350-0.45L**

6. Conclusions

In this paper, flexural tests with a finite element method analysis, using the ANSYS program, were performed for reinforced concrete beams strengthened by post tensioned CFRP plates. The main conclusions drawn from the study were as follows:

- By increasing post tensioning, the magnitude of crack initiation load in beams increases significantly and this increase is more considerable in beams with shorter span length and approximately equal to post-tension increase ratio. For the beam with 25% of post tensioning, cracking load has been 57% increased, while by applying a 50% of post tensioning, cracking load has increased about 125%.
- Ductility of beams strengthened with span length always increases as in a beam with constant span length, ductility decreases, but the effect of post-tension on ductility decreases with span length increase. e.g. the reductions in ductility values for the specimens BP150, BP250 and BP350 have been around 31.7%, 22.1% and 9.2%, respectively.
- In all span lengths, capacity of beams strengthened with post-tension increase, improved, but the level of effect decreased with increasing span length. The decrement percentages have been about 34.3%, 29.26% and 29.23% for beams classes 1, 2 and 3, respectively. Shortening strengthening plate led to an increase in crack development in the middle of the beam and the magnitude of ultimate load showed a remarkable increase with shortening strengthening plates, that is ultimate load increased to twice of its original quantity.
- In beams with long span length, using non adhered and post tensioned CFRP plates having 0.45L length, led to a significant increase in load bearing capacities and a more

considerable decrease in ductility as a result of strengthening compared to ductility decrease using long post tensioned plates. The level of ductility compared to reference model has been increased in the range of 4-11%. Moreover, since FRP plates are expensive, using this method can be an economic option.

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