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Flexural Behavior Of Reinforced Concrete Beams With Post-Tensioned CFRP Cables

E.M. Anter 1, A.M. Hilal 2, A. G. Asran 3

1 Graduate student, Department of Structural Engineering, Al Azhar University, Cairo, Egypt
2 Professor, Department of Structural Engineering, Al Azhar University, Cairo, Egypt
3 Professor, Department of Structural Engineering, Al Azhar University, Cairo, Egypt

الملخص العربى :

التقدم في دراسة علوم المواد يمكن المهندسين من تطوير سلوك المنشأت الخرسانية .الطبيعي استخدام كابلات الحديد في الكمرات سابقة الاجهاد في الكباري ولكن مع تعرض كابلات الحديد للعوامل البيئية يحدث صدأ لحديد التسليح هذا الصدأ يودي الي فقد في قوة الكابلات ومع الوقت يودي الي انهيار المنشأ . يهدف هذا البحث الي دراسة سلوك الكمرات الخرسانية المسلحة سابقة الاجهاد في الانحناء المدعمة بكابلات من الفولاذ وكابلات من الكربون فيبر من خلال عدد من التجارب العملية مع دراسة تأثير اضافه فيبر من الحديد وتاثير تغيير في الاجهاد للخرسانة وفي نهاية هذا البحث تم عرض اهم النتائج.

Abstract:

Advancement in the study of material science enables engineers to improve the behavior of the concrete structure. It is normal for prestressed concrete beams of bridges to use steel cables, but with the exposure of steel to environmental factors, corrosion occurs. This corrosion leads to a loss of strength of the prestressed steel cables and, in the long term, the collapse of the concrete structure, Hence, other non-corrosive materials can be used instead. Carbon fibers reinforced polymers (CFRP)-bars are one good option, use of as the prestressed reinforcement. The advantages of using CFRP materials are high strength to weight ratio, low relaxation and excellent fatigue strength. This study investigates the effect of two types of prestressed concrete cables one of them is steel cable (ST) and carbon fiber reinforced polymers cable (CFRP), on flexural behavior of reinforced concrete (T-section) beams. Also, the effect of adding steel fibers and changes in concrete strength were also investigated. A total of ten full scale beams were tested in the experiments. Test results showed that the flexural strength and stiffness of prestressed beams were found to increase significantly after being prestressed with carbon fiber reinforced polymer cable (CFRP), adding steel fiber resulted in higher value of flexural strength, and controlled the concrete cracking behavior.

Keywords: Prestressed concrete, posttensioned, CFRP,steel fiber, strands anchor system

1.Introduction

Since 1951, the research on prestressed reinforced concrete for highway bridges is still in progress, [1]. Most of the highway bridges in the United States are constructed of prestressed reinforced concrete. One of the problems occurring in prestressed beams using prestressed steel cables is corrosion (Figure 1). Prestressing a steel cable with a small cross-sectional area under environmental effects can lead to corrosion of the steel cables, resulting in brittle fracture of the beams. These facts made nonmetallic tendons as an attractive option [2-3]. Several types of tendons have been introduced such as Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP) and Aramid Fiber Reinforced Polymer (AFRP). The price of CFRP is higher than GFRP and AFRP. CFRP has high tensile strength compared to other FRPS [4]. CFRP is used in abundance as a construction material in the industrial construction field. An example of the use of CFRP in industrial construction is CFRP strands in prestressed reinforced concrete for bridges, especially in corrosive environmental conditions [5,6]. The advantages of CFRP material are stiffness relating to the light weight and high tensile strength [6,7].

Figure (1). corrosion of the prestressing steel [1]

2.Previous research

Danying Gao, et al. 2020 [8] studied the flexural behavior of reinforced concrete one-way slabs strengthened with external posttensioned FRP tendons. Six simply supported RC one-way slabs were tested. Five slabs were strengthened by external posttensioned GFRP tendons while the sixth slab had no strengthening tendons. The results showed that strengthening slabs with external FRP tendons improves the first-cracking moment, the moment at CFRP bar yield and the ultimate moment, as well as the stiffness of the slab reduces the tensile stresses in both the concrete and the bonded reinforcement led to making the cracks thinner and denser.

Ahmed Elrefai a, et al.2012 [9] studied externally bonding of CFRP tendons to strengthened post-tensioned beams. Five unstrengthened beams and 13 strengthened beams, were tested under various fatigue load ranges until failure. Usage of CFRP increased the fatigue life of the beams and the stress decrease in reinforcing bars due to post tension.

Ahmad Saudi Abdul-Zaher, et al.2016 [10] studied the behavior of fiber in shear reinforced concrete beams. The parameters were the type and the percentage of fibers volume and the presence of value of shear strength. The results showed that the ultimate load increased with increasing of percentage of fibers and increased the stiffness, hence reducing the deflection at the same load.

Ezzeldin Y. Sayed-Ahmed and Nigel G. Shrive. 1998 [11] studied a new steel anchorage system for CFRP tendons for posttension. CFRP cables have very poor lateral and shear strength. The anchor system for steel cables cannot be used with CFRP cables, so they designed anchor system by merging concepts from split wedge. four wedges made with rounded edge to reduce the stresses connection on the tendon and with angle 2°. This requirement to distribute the pressure on CFRP cables.

3.Objectives

The objectives of the current study were to; (1) study the behavior of prestressed beams with a different types of cable steel cable (ST) and carbon fiber reinforced polymers (CFRP) under static loadings, (2) study the effect of steel fiber on enhancement of beam capacity and (3) study the change of concrete strength value.

4.Experimental Program

A total of ten simply supported post-tensioned beams (T-sections) were tested under static load up to failure. All beams had the same overall dimensions, with an overall length of 2000mm and a support span of 1800mm. All beams had the same cross-sectional dimensions, 150*300mm for the web and 750mm*100mm for the flange, respectively, as shown in Figure 2 and Figure 3.

All specimens had the same bottom and top longitudinal reinforcement of 2Ø12 (fy=360 MPa). Five of the tested specimens had steel cables as prestressed tendons. Five of the tested specimens has CFRP cables as prestressed tendons. Four of beams with fibrous reinforced concrete with different type of cable and percentage of fiber, while six of them were of normal reinforced concrete with different type of cable and different compressive strength. Properties of prestressed steel cables and prestressed CFRP cable summarized in Table 1.

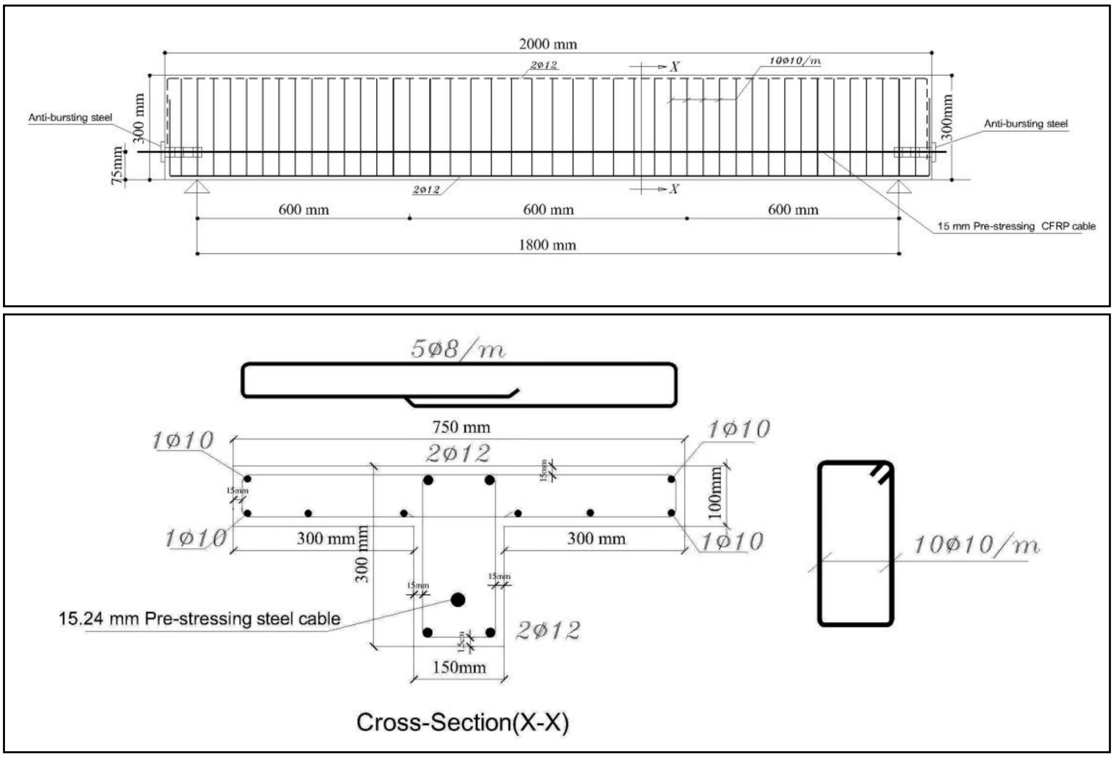

Table 1. Properties of prestressed steel cables and prestressed CFRP cable.

Property	ST cable	CFRP cable
Diameter [mm]	15.24	15
Length [mm]	2600	2600
Cross-Section Area [mm^2]	140	176.6
Yield Strength [MPa]	360	400
Tensile Strength [MPa]	1860	2400
Total Elongation [%]	7	1.7
Elastic Modulus [GPa]	204	160
Poisson’s ratio	0.3	0.27

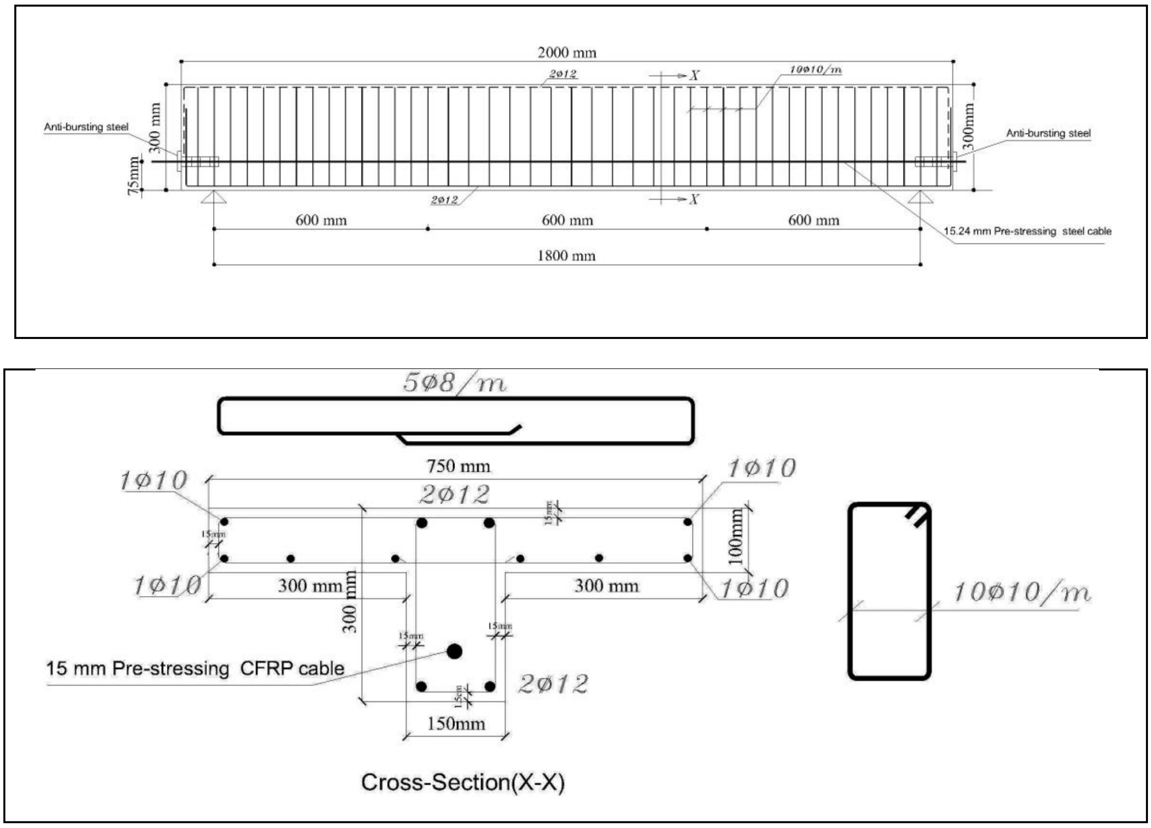

Figure (3). Reinforcement details of tested specimen's with CFRP cable

The tested specimens were divided into four groups of beams as follows. The beams code is given as the beam number, followed by the following: 35, 45 or 55 Mpa, which refers to concrete compressive strength, and percentage of steel fiber 0,1.0% ,1.5% from the volume of concrete. The strand profile remains the same for all beams. The web stirrups in all beams consisted of 2 vertical branches of 10 mm diameter bars that were horizontally spaced at 100 mm, to prevent shear failure occurrence prior to the flexural failure. The pre-stressing strands with nominal diameters of 15.24 mm comprised 7-wires for steel cable, diameter 15 mm for CFRP cable and anchor system to CFRP cable were design [11]. The beam schemes are summarized in Table 2. Table 3. represents the different design mixing used in this program.

Table 2. Experimental program for the beams.

Group	Specimen	fc,Mpa	volume of fiber%	flexural RFT	shear RFT
One	B1-35-ST-0	35	0	2ϕ12	10ϕ 10
	B4-35-ST-1	35	1	2ϕ12	10ϕ 10
	B7-35-ST-1.5	35	1.5	2ϕ12	10ϕ 10
two	B1-35-ST-0	35	0	2ϕ12	10ϕ 10
	B10-45-ST-0	45	0	2ϕ12	10ϕ 10
	B13-55-ST-0	55	0	2ϕ12	10ϕ 10
three	B2-35-CFRP-0	35	0	2ϕ12	10ϕ 10
	B6-35-CFRP-1	35	1	2ϕ12	10ϕ 10
	B9-35-CFRP-1.5	35	1.5	2ϕ12	10ϕ 10
four	B2-35-CFRP-0	35	0	2ϕ12	10ϕ 10
	B12-45-CFRP-0	45	0	2ϕ12	10ϕ 10
	B15-55-CFRP-0	55	0	2ϕ12	10ϕ 10

Table 3. The concrete mix design used for the test specimens of this experimental program.

component / Fcu (Mpa)	Cement (kg/m3)	water (l/m3)	Fine aggregate (kg/m3)	Coarse aggregate (kg/m3)	Sikament 163-m (kg/m3)
35	385	218.5	700	1408	0
45	450	232	700	1408	5
55	500	215	700	1408	7.5

Test Setup

The beams were tested under four-point load flexural loading. The applied load was measured with a calibrated load cell attached to the hydraulic jack as shown in Figure 4. LVDTs were used to measure the deflection (100mm). The tests were carried out in concrete lab, Faculty of Engineering, Al-Azhar University.

Figure (4). Test setup for flexural testing

5.Discussion of The Experimental Results

From the observed behavior of the tested beams the following remarks were concluded:

5.1. Failure Modes and Crack Distributions

Group1:

The type of failure was compression failure in all specimen in this Group and increasing the steel fiber percentage are more gradual crack distribution and smaller number of cracks and width. The cracking loads and failure loads for beams B1-35-ST-0, B4-35- ST-1 and B7-35- ST-1.5 were 50 kN, 62 kN, 68 kN as shows in figure (5) and 210 kN, 228 kN, 250 kN as shows in figure (6) respectively. Increasing the percentage of steel fiber increased the cracking load by 16.7% and 26.4%, and increased the failure load by 8% and 16% respectively. Figure (7) shows the cracks pattern of failure load in group 1.

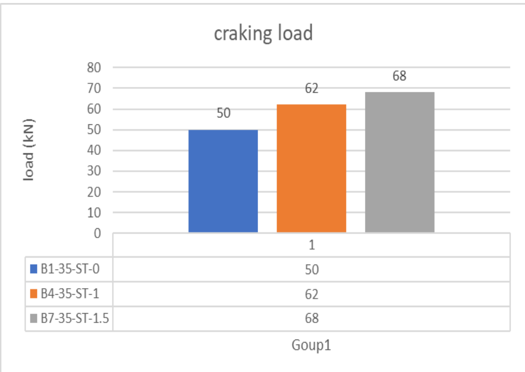

Figure (5). Cracking load for Group1

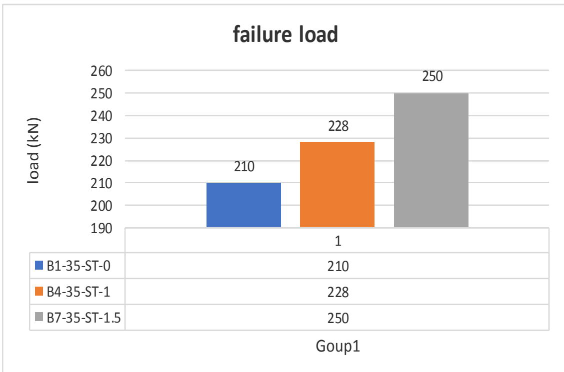

Figure (6). Failure load for Group 1

Figure (7). Cracks pattern of beams in Group 1

Figure (8) shows applied load versus mid-span deflection responses of tested beams in Group 1. For beam B7-35- ST-1.5 the mid span deflection decreased by 2.3% at failure load with increasing percentage of steel fiber content.

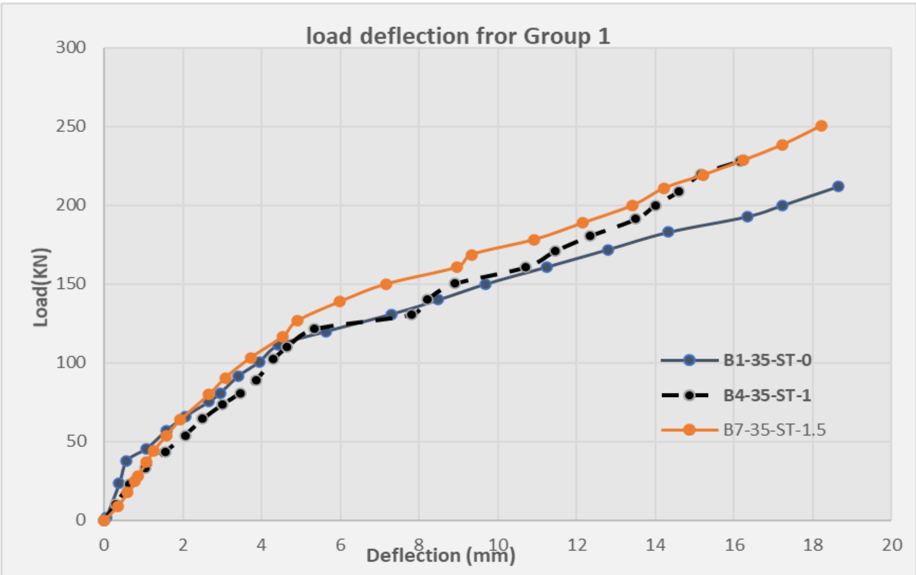

Figure (8). Applied load versus mid-span deflection for Group 1

Group2:

The type of failure was compression failure in all specimen in this Group. Increasing the strength without steel fiber content showed a more gradual crack distribution and smaller number of cracks. The cracking loads and failure loads for beams B1-35-ST-0, B10-45-ST-0 and B13-55-ST-0 were 50 kN, 60 kN, 70 kN as shows in figure (9) and 210 kN, 227 kN, 290 kN as shows in figure (10) respectively. Increasing the strength increased the cracking load by 16.6% and 28.5%, and increased the failure load by 7.5% and 27.5% respectively. Figure (11) shows the cracks pattern of failure load in group 2.

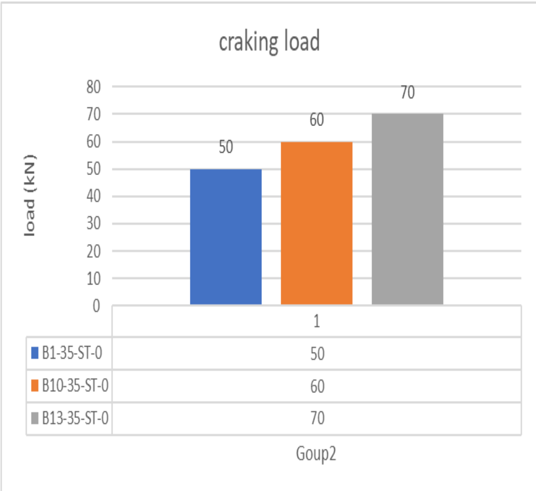

Figure (9). Cracking load for Group2

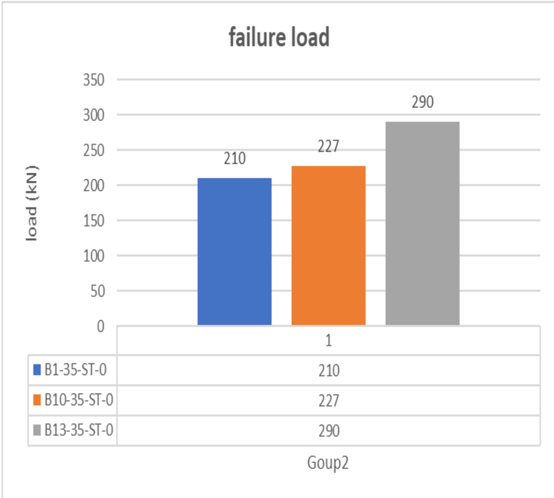

Figure (10). Failure load for Group 2

Figure (11). Cracks pattern of beams in Group2

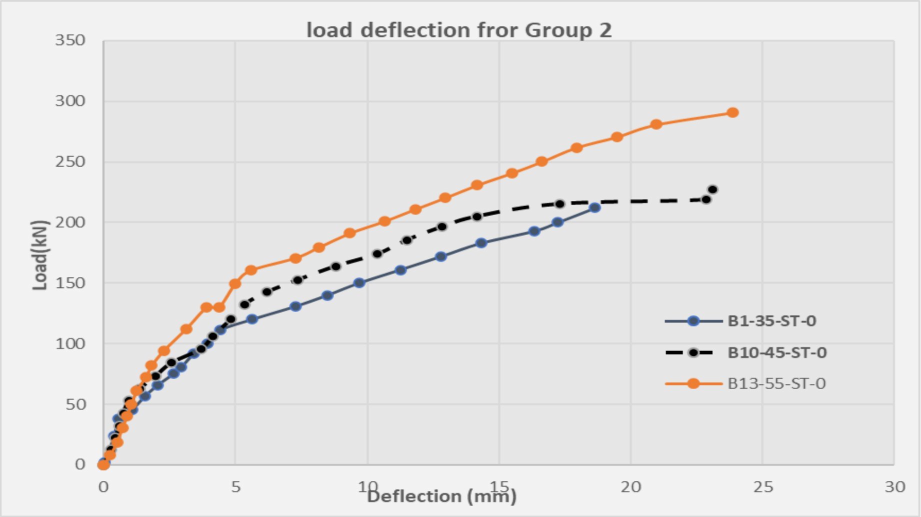

Figure (12). Applied load versus mid-span deflection for Group 2

Figure (12) shows applied load versus mid-span deflection responses of tested beams in Group 1. For beam B10-45- ST-0 and beam B13-55- ST-0 the mid span deflection increased by 18.9% and 21.8 % at failure load without steel fiber content. But in same point of failure load to beam B1-ST-35-0 (212kN) the mid span deflection decreases by 38% for beam B10-45-ST-0 and decreased 70% for beam B13-55-ST-0.

Group3:

The type of failure was compression failure in all specimen in this Group and increasing the steel fiber percentage a more gradual crack distribution and smaller number of cracks and width. The cracking loads and failure loads for beams B3-35- CFRP -0, B6-35- CFRP -1 and B9-35- CFRP -1.5 were 62 kN, 66 kN, 86.3 kN as shows in figure (13) and 213 kN, 233 kN, 263 kN as shows in figure (14) respectively. Increasing the percentage of steel fiber increased the cracking load by 6 % and 30.4%, increased the failure load by 8.5% and 19% respectively. Figure (15) shows the cracks pattern of failure load in group 3.

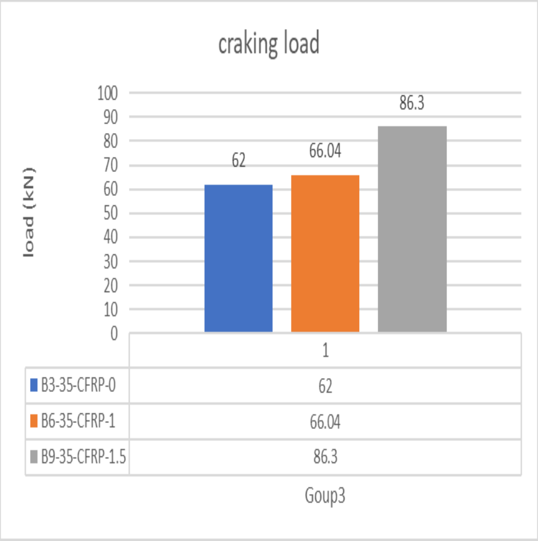

Figure (13). Cracking load for Group3

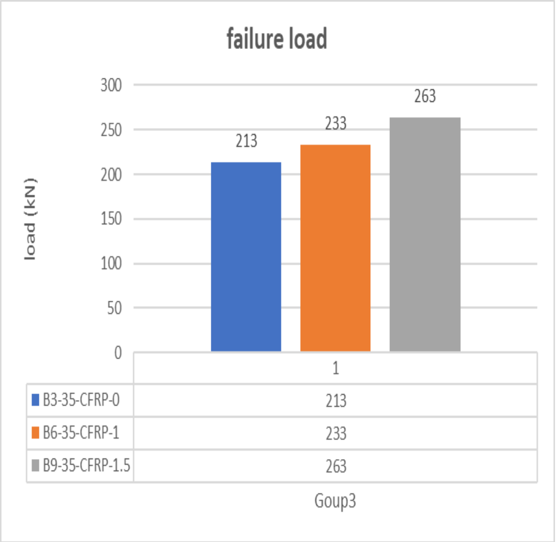

Figure (14). Failure load for Group 3

Figure (15). Cracks pattern of beam in Group3

Figure (16) shows applied load versus mid-span deflection responses of tested beams in Group 3. For beam B6-35- CFRP-1 and beam B9-35-CFRP-1.5 the mid span deflection decreased by 16.75% and 17.9 % at failure load without change in strength.

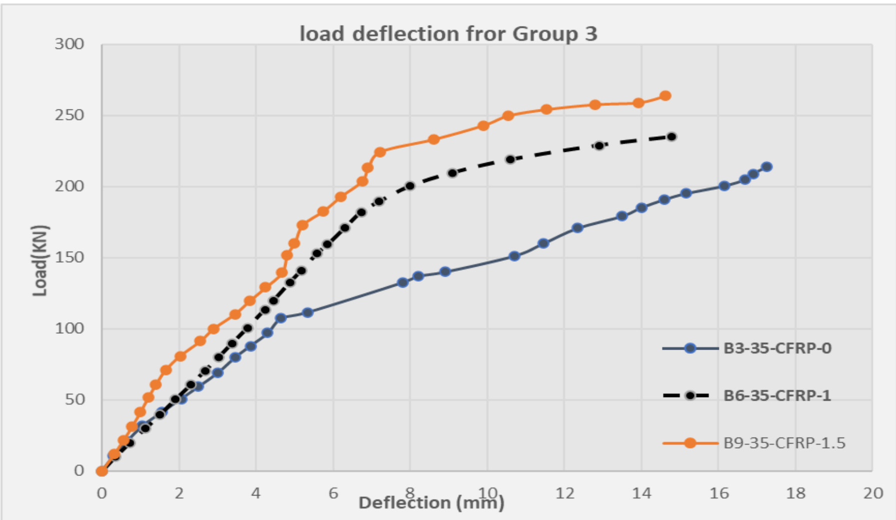

Figure (16). Applied load versus mid-span deflection for Group3

Group4:

The type of failure was compression failure in all specimen in this Group. Increasing the strength, a more gradual crack distribution and smaller number of cracks and width. The cracking loads and failure loads for beams B3-35- CFRP -0, B12-45- CFRP-0 and B15-55-CFRP-0 were 62 kN, 71.1 kN, 72 kN as shows in figure (17) and 213 kN, 234 kN, 321 kN as shows in figure (18) respectively. Increasing the strength increased the cracking load by 12.8 % and 13.9 %, and increased the failure load by 8.9% and 33.6% respectively. Figure (19) shows the cracks pattern of failure load in group 4.

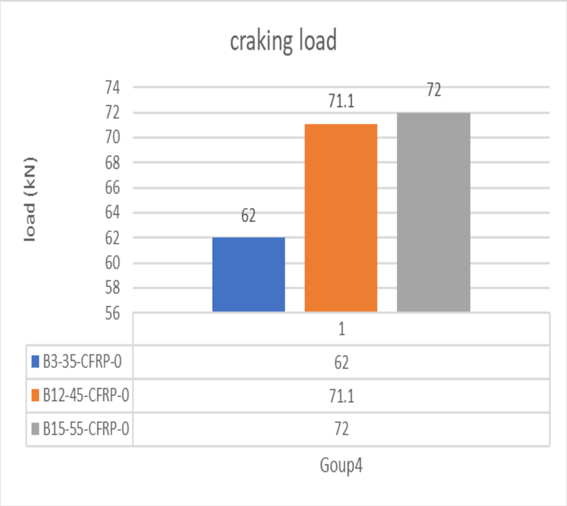

Figure (17). Cracking load for Group4

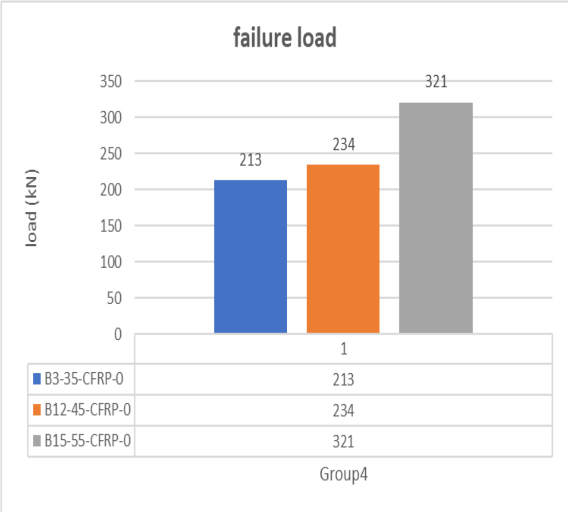

Figure (18). Failure load for Group4

Figure (19). Cracks pattern of beam in Group4

Figure (20) shows applied load versus mid-span deflection responses of tested beams in Group 4. For beam B15-55-CFRP-0 the mid span deflection slight decreased by 10.17% at failure load without adding steel fiber.

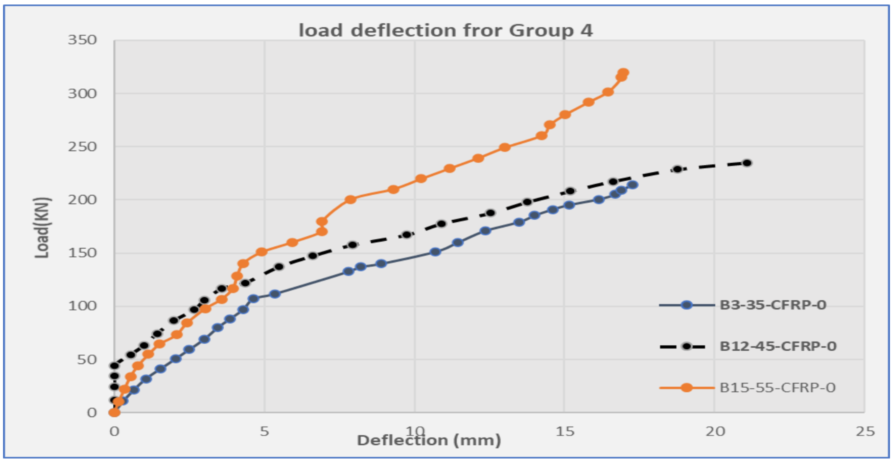

Figure (20). Applied load versus mid-span deflection for Group4

5.2. Steel strain

The total applied load versus the tensile steel strain of the flexural non-prestressed steel bars at the mid-span sections for all prestressed beams tested was obtained from electrical strain gauges. Figures 21-24 show the loaded steel strain curves, from the load history of all groups.

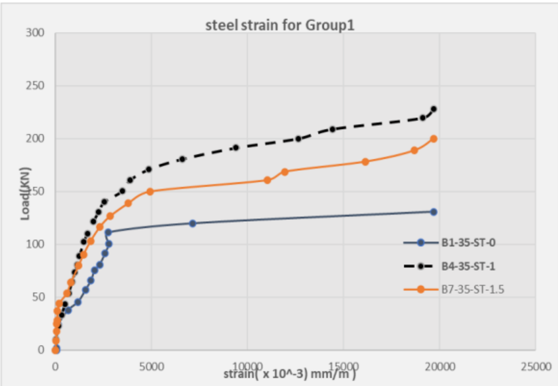

Figure (21). Total load versus the tensile steel strain for tested beams in the Group 1

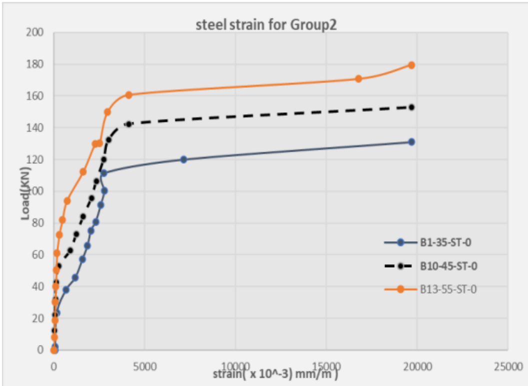

Figure (22). Total load versus the tensile steel strain for tested beams in the Group 2

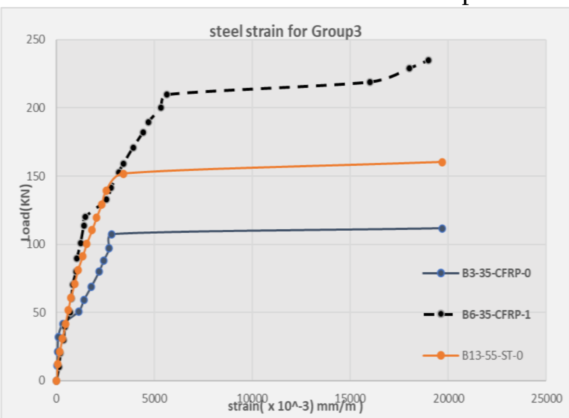

Figure (23). Total load versus the tensile steel strain for tested beams in the Group 3

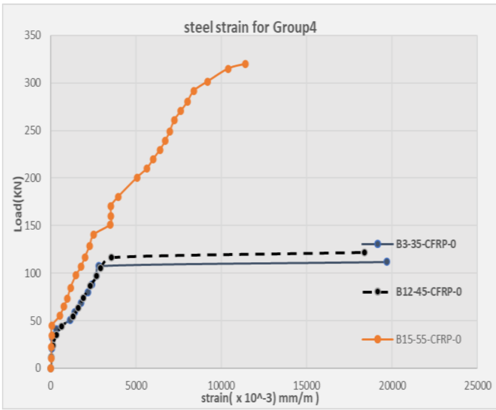

Figure (24). Total load versus the tensile steel strain for tested beams in the Group 4

6.Conclusion

It can be concluded from experimental results that the use of CFRP material is one of the most powerful techniques for strengthening concrete structural reinforced members.

The following could by summarized from the experimental program:

1- The use of CFRP cables increase the load capacity of beams compared to beam stressed with steel cables. Stiffness is also noted.

2- The use of CFRP cables reduces the number of cracks and shows a more gradual crack pattern and increases the cracking load.

3- The use of steel fiber with strength 35 MPa increasing cracking load in beams stressed with steel cables by26.7%and 16.7%, increasing failure load by 8%and 16% and decreased deflection by 2.3%.

4- Increasing strength in beams stressed with steel cables by increasing cracking load by16.6%and 28.5%, increasing failure load by 7.5% and 27.5% and increased deflection by 18.9 % and 21.8%.

5- The use of steel fiber with strength 35 MPa increasing cracking load in beams stressed with CFRP cables by 6% and 30.4%, increasing failure load by 8%and 8.5%and 19% and decreased deflection by 16.75%.

6- Increasing strength in beams stressed with CFRP cables by increasing cracking load by 13.9% and 12.8 %, increasing failure load by 8.9% and 33.6% and decreased deflection by 10.17.

7- For comparison between beams stressed with steel cables and CFRP cables: the use of CFRP cables increase failure load by 1.4% with no steel fiber and strength 35 Mpa, increasing failure load by 2.1% with 1% steel fiber and strength 35 Mpa, increasing failure load by 4.9 % with 1.5 % steel fiber and strength 35 Mpa, increasing failure load by 9.6 % with no steel fiber and strength 45 Mpa and increasing failure load by 3 % with no steel fiber and strength 55 Mpa.

8- For comparison between beams stressed with steel cables and CFRP cables: the use of CFRP cables decrease, deflection load by 7.9 % with no steel fiber and strength 35 Mpa, decreasing failure load by 46.2% with 1% steel fiber and strength 35 Mpa, decreasing failure load by 24.5 % with 1.5 % steel fiber and strength 35 Mpa, decreasing failure load by 9.5 % with no steel fiber and strength 45 Mpa and decreasing failure load by 40.8 % with no steel fiber and strength 55 Mpa.

9- The use of steel fibers increases the cracking load and ultimate load because the fibers increase the tensile strength of the concrete.

10- The addition of fiber increased stiffness and hence reduce the deflection.

7.Reference

1. J. A. Belarbi, M. Reda, P. Poudel, H. Tahsiri, M. Dawood, and B. Gencturk, "Prestressing Concrete with CFRP Composites for Sustainability and Corrosion-Free Applications", (2018).

2. Sang Yeol Park, "Shear Behavior of Concrete Beams Prestressed with FRP Tendons", (1999),74-85.

3. W. Podolny Jr, "Corrosion of Prestressing Steels and Its Mitigation", (1992) 37(5), pp (34-55).

4. Richard E Weyers, "Concrete bridges in aggressive environments", (1994), 151.

5. Xiong Yang, "Use of Fiber Reinforced Polymer Composite Cable for Post-tensioning Application", (2015).

6. Kenichi Ushijima, Tsuyoshi Enomoto, Noriaki Kose, and Yoshiaki Yamamoto, "Field deployment of carbon-fiber-reinforced polymer in bridge applications", (2016),61, pp (29-36).

7. J.J. Myers, T. Viswanath, Structures Congress 2006: "Structural Engineering and Public Safety", (2006) pp (1-8).

8. Danying Gao, Dong Fanga, Peibo Youa, Gang Chenb and Jiyu Tang"Flexural behavior of reinforced concrete one-way slabs strengthened via external post-tensioned FRP tendons", (2020).216

9. Ahmed Elrefai a, Jeffrey West b and Khaled Soudki, "Fatigue of reinforced concrete beams strengthened with externally post-tensioned CFRP tendon", (2012), 29 pp (246-256).

10. Ahmad Saudi Abdul-Zaher, Laila Mahmoud Abdul-Hafez, Yasser Rifat Tawfic and Osama Hammed, "Shear Behavior of Fiber Reinforced Concrete Beams", (2016),44, pp (132-144).
11. Ezzeldin Y. Sayed-Ahmed and Nigel G. Shrive, "A new steel anchorage system for post-tensioning applications using carbon fibre reinforced plastic tendons", (1996)