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Flexural Response of CFRP-Prestressed Concrete Beams

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Abstract- ***This paper presents a numerical analysis investigation of the behavior of prstressed beams with carbon fiber strands (CFRP). Three dimensional finite element beam models are created on the finite element software ANSYS- 2013 to study the flexural response of the investigated models. The investigated models have two different types of prestressing cables, namely; steel and CFRP tendons. A parametric study was conducted to examine the effects of prestressing reinforcement ratio, concrete strength, and level of initial prestressing on the behavior of the studied prestressed concrete models. The results show that the CFRP cables can be as effective as steel cables.***

Index **— Prostheses concrete, FRP tendons, carbon fiber, Flexural Response**

I. INTRODUCTION

In many parts of the world, bridge decks and floor slabs of parking garages are subjected to repeated wetting and drying cycles in combination with chemical deicing salts which lead to corrosion of steel reinforcing bars embedded in the concrete. Given time, the structural integrity of the reinforced concrete element may be jeopardized, due to the steel corrosion. In recent years, numerous reinforced concrete bridges and parking garages have been constructed with little or no tensile steel reinforcement in favor of non-corrosive alternatives such as fiber-reinforced polymers (FRP). New applications for FRP in civil engineering are continually being developed as a result of their intrinsically superior electrochemical properties compared with conventional steel. Recently FRP reinforcements are introduced to the construction of reinforced and prestressed concrete structural elements. However, more research on the behavior of prestressed concrete tensioned with FRP cables is needed to fill the lack of knowledge on the subject to help code officials in developing the necessary guidelines for their design and construction [1, 4]. Experiments have been conducted on FRP strand relaxation. The relaxation of 3000 hours was investigated at 20, 40 and 60°C under initial stress level of 70% of ultimate stress (Ando et al., 1997) [2]. Creep and long term strength have been studied (Machida. 1997) [3], superior properties of CFRP materials are observed with long term residual strength after 100 years of more than 90 % of short term tensile strength. In spite of the limited tests on fatigue, fatigue strength of CFRP strands is Nolan G. Domenico (1995) [5] has studied bond of carbon cables (CFCC), He found that the transfer length and flexural bond length are proportional to the cross-sectional area of the CFCC cable, inversely proportional to the strand diameter and the transfer length is proportional to the prestress level while the transfer bond strength was not affected by the prestress level. Nabil F. Grace (2003) [6] found that for double tee beam prestressed with bonded and unbonded carbon fiber tendons, the ultimate load and the cracking load were, respectively, approximately 5.3 and 1.4 times the service load. Mary Beth D. Hueste (2003) [7] has recommended that design parameters in the AASHTO specifications need to be modified for use with high strength concrete because the current design equations in the AASHTO specifications for prestressed concrete members are based on mechanical properties of normal concrete strengths of 6000 psi or less. Nabil F. Grace (2004) [8] has found that beam prestressed using both pre tensioning and unbonded post-tensioning tendons had a 26 percent higher ultimate load capacity and 36 percent lower energy ratio than the beam with non-prestressed un bonded post-tensioning tendons, and level of pre tensioning forces in the bonded tendons affects the flexural load-versus-deflection response, ultimate load, and failure modes of the box beams and the effective pre tensioning force level of 40% in conjunction with post tensioning force level of 70% resulted in a maximum ultimate load-carrying capacity. Martin noel (2007) [9] has studied five full-scale slab bridge strips were tested up to failure in four-point bending, including a steel-RC control slab and four GFRP-RC slabs, the mid span deflections and flexural crack widths were 3 and 4 times those of the control slab respectively, and the mode of failure was changed from a ductile flexural failure to a brittle shear failure due to the low stiffness of the GFRP reinforcement. Weichen XUE (2009) [10] demonstrated that the remarkable reduce of crack width could be found in the concrete beams with combined reinforcements and the crack widths in the prestressed concrete beams reinforced with FRP reinforcements were larger than the corresponding values in prestressed concrete beams reinforced with steel reinforcements for a given load level. However, more researches on the behavior of prestressed concrete tensioned with FRP cables are needed to fill the lack of knowledge on the subject to help code officials in developing guidelines for design and construction. The main objective of this research program is to study the flexural response of prestressed concrete beams with CFRP prestressed strands. The investigation employs the non-linear finite element analysis to evaluate the influence of significant structural parameters on the structural performance of CFRP-prestressed concrete in comparison with that of steel-prestressed concrete.

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II. NONLINEAR FINITE ELEMENT ANALYSIS

In this paper ANSYS finite element program is used. The concrete damaged plasticity model in ANSYS provides a general capability for modeling concrete in all types of structures using concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete. The Solid65 element was used to model the concrete. This element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions (Figure1). Beam 188 is suitable for modeling steel and fiber reinforcement (Figure 2). Link8 element was used to model FRP tendons. This element is a 3D spar element and it has two nodes with three degrees of freedom – translations in the nodal x, y, and z directions (Figure 3).

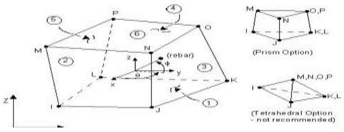
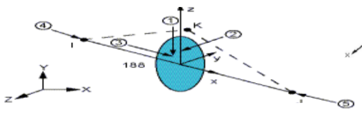


Fig. 1 Solid65 element



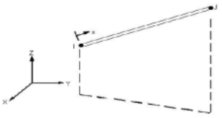


Fig. 2 Beam 188 element **Fig. 3 Link 8**

III. VERIFICATION OF THE NONLINEAR FINITE ELEMENT MODELING

To verify the nonlinear finite element modeling constructed by the use of the nonlinear finite element analysis program ANSYS in the analysis of four models identical to those tested experimentally by Martin Noel (2007) [9] and Nolan Domenico (1995) [5] are prepared and constructed by the use of this program, their results are compared to those obtained experimentally. The comparison between both the experimental and finite element results is considered the base in checking the validity of the finite element modeling. This comparison was carried out through the failure load. Model 1 is a slab strip with cross section and length 600mm×300mm, and 5000 mm respectively, clear span in loading was 4500 mm, with shear span 1750 mm, the top mat and transverse bottom reinforcements were glass fiber bars (GFRP) 13 mm @150mm . top and bottom clear cover were kept 30mm , bottom longitudinal direction consist of 6 steel bars 15mm @ 100mm. Model 2 has the same properties of model 1 but bottom longitudinal reinforcement consist of 6 GFRP bars 16 mm @ 100mm. Model 3 is a T- Section beam with total depth 320 mm , width of flange 300 mm, thickness of flange 80 mm and thickness of web 100 mm. This model was also post-tensioned with 1 CFRP 15.2 mm tendon at a depth of 260 mm, clear span in loading was 2800 mm with shear span 1200 mm. Model 4 has the same properties of model 3 but with shear span 700 mm. Deflections and load capacities (Δu and Pu respectively) of experimental models versus FE models with differences in percentage were shown at Figure 4 and Table (1), it is seen that the FEM models provided good predictions against the experimental data, including average errors of 7.3%, and 17.5% for the ultimate loads and the maximum deflection, respectively.

Table (1) Deflections and load capacities of experimental versus FEM

Model	Exp. results		FEM results		Difference %	
	P_u kN	Δ_u mm	P_u kN	Δ_u mm	Load %	Defl. %
Model 1	167	176	154.7	193	7.3	9.6
Model 2	166	110	170	91	2.4	17.5
Model 3	95	28.4	96	28.4	1.05	0.0
Model 4	164	29	155	24.7	5.4	13.7

The effects of prestressing reinforcement ratio (ρ), concrete compressive strength (fcu) and the prestressing force level (P) on the flexural behavior of prestressed concrete beams with steel and CFRP tendons are investigated. The specimens C1 and S1 have ρ values of 0.63 %, while specimens C2 and S2 have ρ values of 0.494% are investigated to highlight the effects of ρ on specimens response. Their concrete compressive strength, fcu=35 MPa and tensile strength, ft = 2.6 MPa, and the prestressing force level, P = 70% of the strand strength f_{ult}.

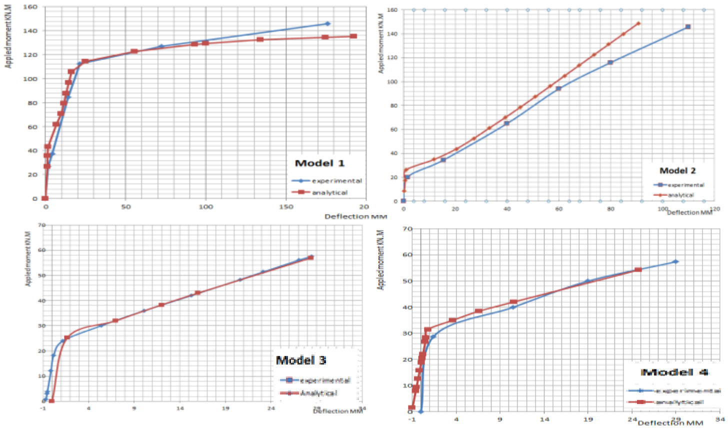


Fig. 4 Experimental versus FEM load-deformation

IV. PARAMETRIC STUDY

In this investigation the same models and loading setup of the above discussion were used. All CFRP and steel tendons have ultimate strength (fult) equal 1860 MPa, CFRP modulus of elasticity (Ec) equal 165 GPa, steel tendons have modulus of elasticity (Es) equal 200 GPa. Table 2 shows the mechanical properties of different types of FRP tendons adopted from reference [11]. Figure (5) and table (3) show the details of test specimens. CFRP-prestressed specimens assigned the symbols C1 to C5, and steel-prestressed specimens assigned the symbols S1 to S5.

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Table (2) tensile properties of prestressed tendons according to (CAN/CSA-S806-02) [11]

Mechanical properties	Prestressing steel	CFRP Tendons
Yield stress MPa	1034-1396	N/A
Tensile strength MPa	1397-1862	1650-2410
Elastic modulus GPa	186-200	152-165
Yield strain %	1.4-2.5	N/A
Rupture strain %	More than 4	1-1.5
Density Kg/m^3	7900	1500-1600

The behavior of another two groups of specimens (C3 and S3) and (C4 and S4) with f_{cu} of 45 MPa and 60 MPa respectively, are studied to clarify the effects of fcu on specimens' performance. Their reinforcement ratio, ρ =0.56% and their prestressing level, P = 70% of the strand strength. To study the prestressing level effects on the flexural response, two specimens of CFRP cable C5 and of steel cable S5 with concrete compressive strength equal 35 MPa and prestressing reinforcement ratio, ρ =0.63% at prestressed level, P = 50% of the strand strength were numerically analyzed. Full bond between the tendons and concrete face is assumed in analysis. Figure (6) shows the tested model finite element meshing; the boundary conditions.

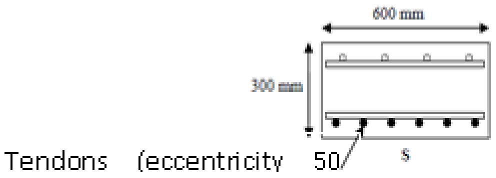

Fig. 5 Test specimen details

Table (3) Test specimen details

Beam	f_{cu} MPa	f_{ult} MPa	E MPa	ρ%	P%
C1	35	1860	165000	0.63	70
S1	35	1860	195000	0.63	70
C2	35	1860	165000	0.494	70
S2	35	1860	195000	0.494	70
C3	45	1860	165000	0.56	60
S3	45	1860	195000	0.56	60
C4	60	1860	165000	0.56	60
S4	60	1860	195000	0.56	60
C5	35	1860	165000	0.63	50
S5	35	1860	19500	0.63	50

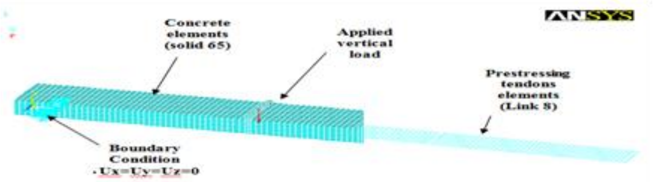

Fig. 6 Finite element model

The tensile strength and young's modulus of FRP reinforcements depend on mainly the type of fibers, the volumetric ratio of fibers (usually more than 60 percent), the angle between load carrying fibers, the longitudinal axis of reinforcement, the shape of the cross section of the rebar and diameter of the reinforcement. Compression failure is less violent and more desirable than tension failure, and is similar to that of an "over-reinforced" concrete beam with internal steel reinforcement. Because FRP tendons will generally exhibit larger deformations prior to compression failure than beams prestressed with steel tendons; therefore, the beams provide warning of failure in the form of large deformations.

V. RESULTS AND DISCUSSION

A. *Effect of prestressed reinforcement ratio (ρ)*

To study the effect of prestressing reinforcement ratio (ρ) on flexural response and failure mode of the different models, four models of two types of tendons with different prestressing reinforcement ratios in tension 0.00633 and 0.00494 were studied using ANSYS (C1, S1, C2 and S2) with constant other parameters such as fcu, ft, model dimensions, and level of prestressing, P = 70% of the strand strength. The results are shown in Table 4, where (Pcr , Δcr), (Pel , Δel), and (Pu , Δu), which are the coordinates of first cracking point, elastic limit point, and ultimate point, respectively are given. Using information gained from load-deflection relations, the ductility index (μΔ), the over strength factor (Ω), the initial un-cracked elastic stiffness (Ki), the plastic stiffness (Kp) and the energy absorption index (E.A.I = the ratio of total area under load-deflection curve to area under elastic part at the same curve) are listed in Table (5). They are calculated from the following equations. They are calculated from the following equations.

$\mu_{\Delta} = \Delta_u / \Delta_{el}$ ………. (1)

$\Omega = P_u / P_{el}$ ………. (2)

$K_i = P_{el} / \Delta_{el}$ …….. (3)

$K_p = (P_u \_ P_{el}) / (\Delta_{u} - \Delta_e)$ (4)

The increase of prestressed reinforcement ratios (ρ %) for both steel and CFRP has reduced mid span deflections while increased the strength at the cracking and ultimate loads. For prestressing steel and CFRP beams, the over strength factor (Ω) is slightly increased with increasing the prestressing reinforcement ratios (ρ %). The ductility index (μΔ) of the CFRP-prestressed beam is found to be lower than that of steel-prestressed beam by about 21% and 56 % for reinforcement ratios (ρ %) 0.63% and 0.494% respectively. The energy absorption index (E.A.I) of CFRP-prestressed beam is lower than of steel-prestressed beam, the (E.A.I)

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decreased by 20% and 50% for reinforcement ratios (ρ %) 0.63% and 0.494% respectively. CFRP-prestressed beam showed higher plastic stiffness (Kp) than that of steel-prestressed beam by about 1.5 times. In terms of ultimate performance it is interesting to note the failure modes of the various investigated beams (Table 5), all of the beams were tested with similar dimensions and concrete compressive strength; therefore any differences in the mode of failure of each specimen can be attributed to the effect of ρ %. The steel- prestressed beams, failed in flexure initiated by yielding of the steel reinforcement followed by eventual crushing of the concrete in compression, the CFRP-prestressed beams failed in compression and balanced failures for reinforcement ratios (ρ %) 0.63% and 0.494% respectively. It is clear from Figure 7 that CFRP-prestressed beam, the elastic stiffness is almost the same than that of steel-prestressed beam. The ultimate load capacity was reached for all beams, and the concrete strain attained its maximum value (0.003) except the specimen S2 due to the yielding of prestressing steel (Figure 8). Figure 9 shows that tendon capacity had fully consumed at all specimens except C1, so it can be said that all of them have economic design except C1.

Table (4) Loads and Deflections values at variable ρ

Beam	ρ%	P_{cr} kN	Δ_{cr} mm	P_{el} kN	Δ_{el} mm	P_u kN	Δ_u mm
C1	0.63	127.6	3.7	145	6	233	34.6
S1	0.63	128.5	4.0	143.5	6	218	44.0
C2	0.494	107.2	3.5	130	7.7	208	53.10
S2	0.494	105	2.7	120	4	188	64.0

Table (5) Computed data at variable ρ

beam	ρ%	Ω	μ_Δ	E.A.I	K_i	K_p	K_P/K_i	Failure mode
C1	0.63	1.61	5.76	9.46	16111	3081	0.19	Compression
S1	0.63	1.52	7.35	11.78	16124	1955	0.12	Tension
C2	0.494	1.60	6.88	12.66	12871	1721	0.135	Balanced
S2	0.494	1.57	15.98	25.40	19048	1135	0.06	Tension

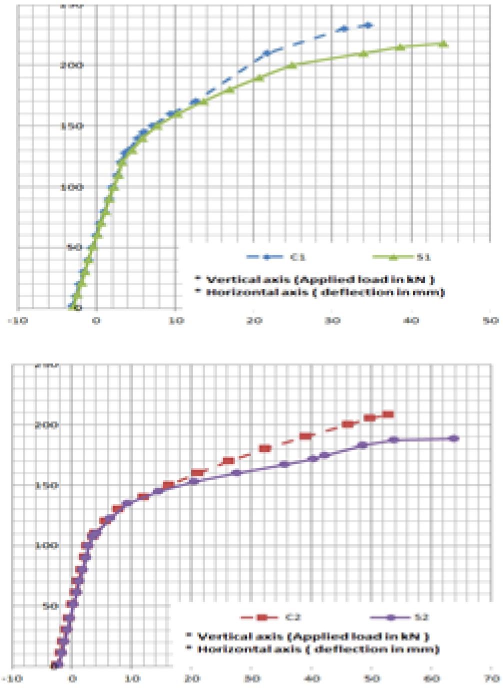


Fig. 7 Load versus deflection

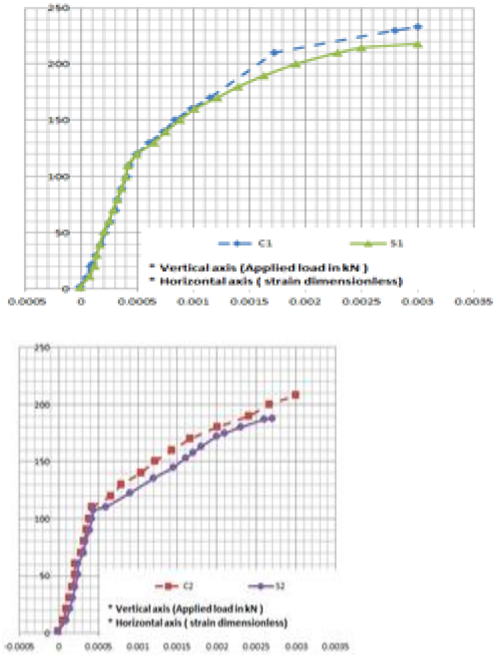


Fig. 8 Load versus Concrete strain

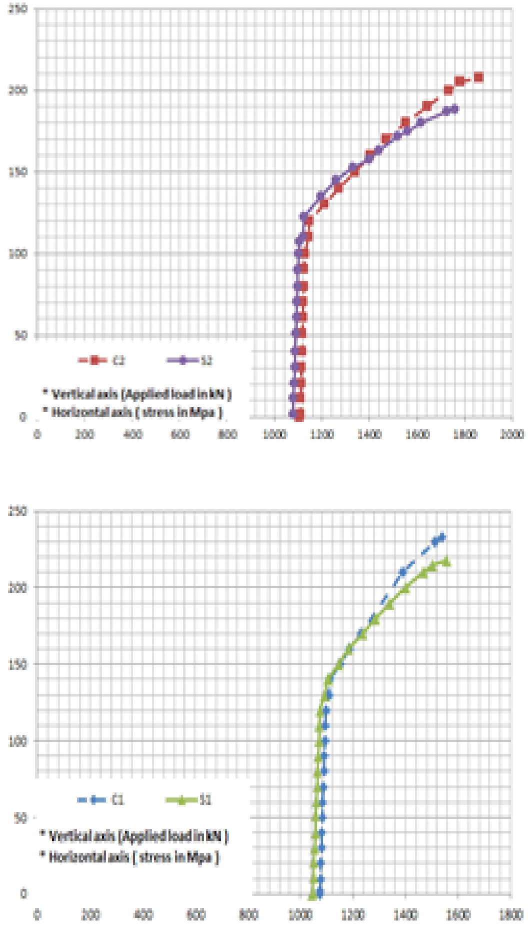


Fig. 9 Load versus Tendon Stress

A. *Effect of Concrete Compressive Strength (fcu)*

In this discussion the effect of concrete compressive strength (f_{cu}) on flexural response and failure mode is investigated. Four models of two types of tendons with different concrete compressive strength 45 and 60 MPa were studied C3, S3, C4 and S4. Other parameters are constants for all models. The first crack point, elastic limit point, and ultimate point, are listed in Table 6. Ductility index μ_Δ, over strength factor Ω, initial elastic stiffness K_i, plastic stiffness K_p and energy absorption index E.A.I are listed in Table 7. Specimen's load-deflection behavior, Load concrete strain, and Load versus Tendon Stress are presented in Figure 10, Figure 11, and Figure 12 respectively, which show that as concrete strength increase, the deformation capacity of CFRP- prestressed beam as well as its ultimate load capacity is slightly decreased (by about 7%). However, for steel-prestressed beam, the deformation capacity is slightly decreased (by about 7%), and its ultimate load capacity slightly increased (by about 8%) as the concrete strength increased. The Influence of concrete strength on ductility; table 7 shows ductility index μ_Δ and energy absorption index E.A.I as a function of concrete strength for the beams tested in this program. It may be seen that μ_Δ and E.A.I decreases with increasing f_{cu}.

beam	f_{cu} MPa	P_{cr} kN	Δ_{cr} mm	P_{el} kN	Δ_{el} mm	P_u kN	Δ_u mm
C3	45	112	3.3	130	6.2	235	60.5
S3	45	105	2.0	120	4.0	212	59.6
C4	60	118	3.3	145	8.7	250	62.4
S4	60	108	4.0	120	6.5	230	55.6

Table (6) Loads and Deflections values at variable f_{cu}

beam	f_{cu} MPa	Ω	μ_Δ	E.A.I	K_i	K_p	K_P/K_i	Failure mode
C3	45	1.81	9.76	19.37	15663	1933	0.12	Comp.
S3	45	1.77	14.9	39.45	30000	1654	0.06	Tension
C4	60	1.72	7.17	14.80	13679	1955	0.14	Tension
S4	60	1.92	8.55	18.36	14545	2240	0.15	Tension

Table (7) Computed data at variable f_{cu}

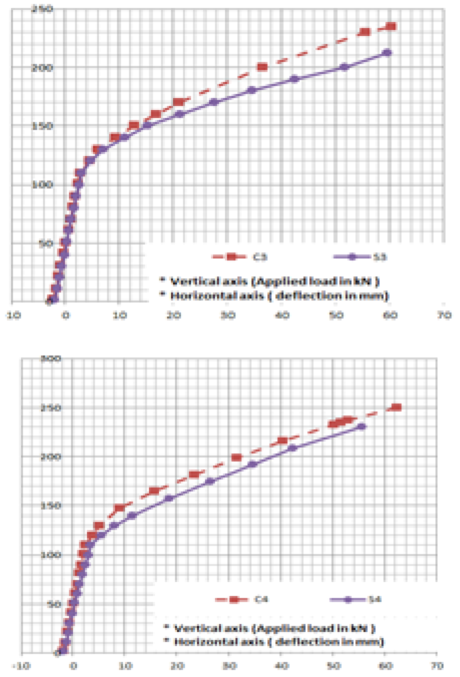


Fig. 10 Load versus deflection

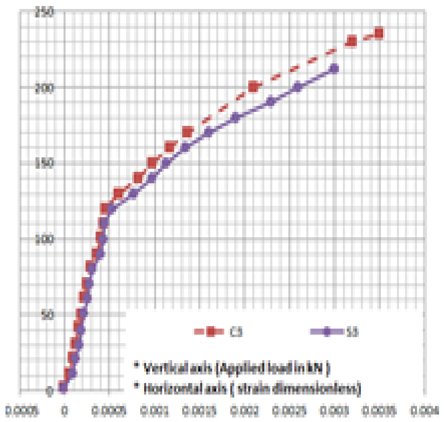
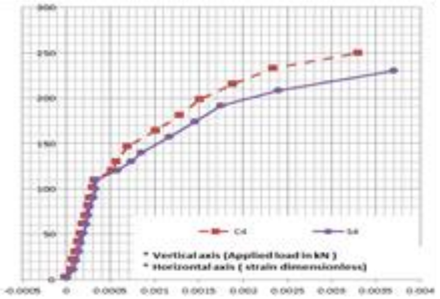


Fig. 11 Load concrete strain



Cont. of Fig. 11

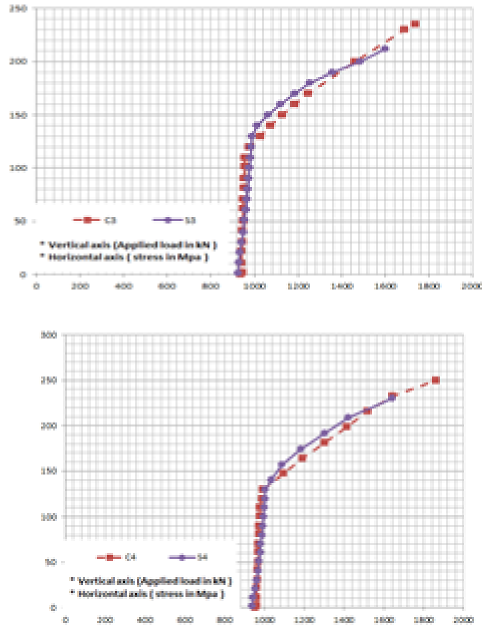


Fig. 12 Load versus Tendon Stress

B. *Effect of Level of Prestressed*

In this discussion the effect of prestressing force level on flexural response and failure mode of beams C1, S1, C5 and S5 is undertaken. Two prestressing force levels are used; namely 70% and 50%. Other parameters such as prestressing reinforcement ratio and concrete compressive strength are constant for all models. The analysis results are presented Tables 8 and 9, also the load-deflection relations and load versus Tendon Stress are shown in Figure 13 and Figure 15 respectively. The prestressing levels of CFRP cables have significantly affected the load-deflection responses, as shown in Tables 8, 9 and Figure 13. From results it is observed that, deformation capacity is higher for lower prestressing level; (67% for CFRP and 40% for steel cables), while ultimate load capacity slightly increases by increasing prestressing level. For the CFRP beams, the values of E.A.I and μ_Δ are almost doubled by reducing prestressing level from 70% to 50% (Table 9). While for steel, the μ_Δ is increased by 45% and the E.A.I is decreased by 15%. Figure 14 shows typical strain development in the concrete for both prestressed CFRP and steel beams. No significant strain changes were observed in the prestressed concrete until the initial cracking load of the beams; however, the strain increment in the concrete beyond the cracking load was considerably influenced by the level of prestressed in the CFRP and steel. The level of prestressed in the CFRP and steel beams did not significantly affect the stiffness of the beams; however, stiffness of CFRP beams was considerably higher than that of steel beams.

Table (8) Loads and Deflections values at variable P

Beam	P%	P_{cr} kN	Δ_{cr} mm	P_{el} kN	Δ_{el} mm	P_u kN	Δ_u mm
C5	70	127.6	3.7	145	6	233	34.6
S5	70	128.5	4.0	143.5	6	218	44.0
C6	50	107.6	3.4	120	5.2	215	58
S6	50	109	3.8	99	5.8	188	62

Table (9) Computed data at variable P

Beam	P%	Ω	μ_Δ	E.A.I	K_i	K_p	K_P/K_i	Failure mode
C5	70	1.61	5.76	9.46	16111	3081	0.19	Comp.
S5	70	1.52	7.35	11.78	16124	1955	0.12	tension
C6	50	1.79	11.15	20.40	15789	1799	0.11	tension
S6	50	1.90	10.70	9.95	15440	1584	0.10	tension

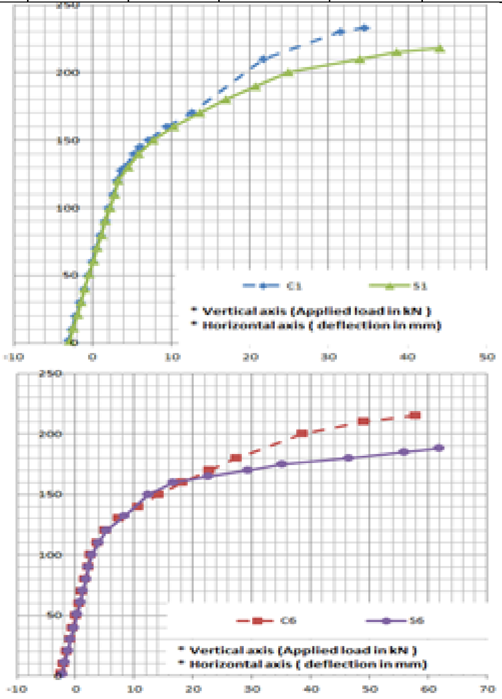


Fig. 13 Load versus Deflection

For the specimens GFRP (G5, G6, G7, G8), the failure mode is similar to the specimens of AFRP. Using of high concrete compressive strength (50-60) Mpa leads to significant

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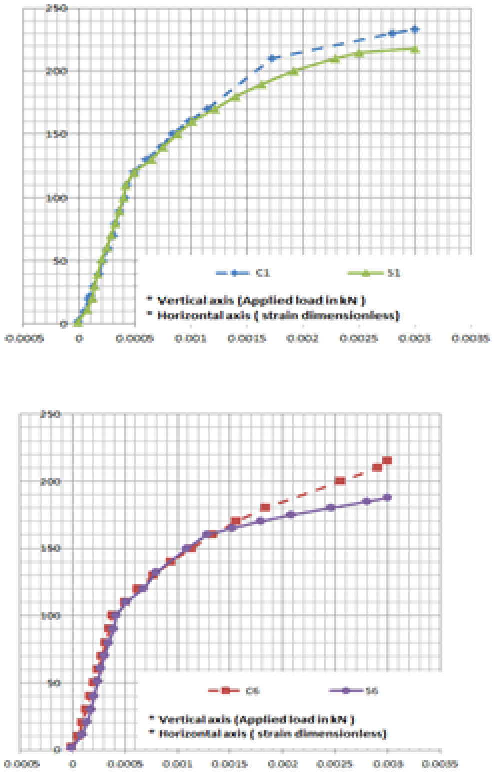

Fig. 14 Load versus Concrete strain

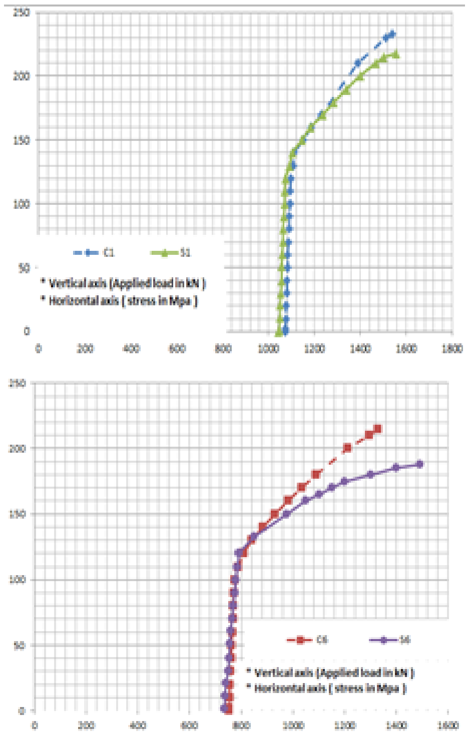

Fig. 15 Load versus Tendon Stress

VI. CONCLUSIONS

This paper presents the effects of prestressed reinforcement ratio, concrete compressive strength, and level of initial prestressing force on the behavior of CFRP-prestressed and steel-prestressed concrete beams. Nonlinear 3-D FEM models were developed and analyzed to predict the flexural behavior of the prestressed beams, including the load-deflection responses, concrete strain, elastic and plastic properties, and failure mode predictions. Several conclusions were made from this study:

1- The increase of prestressed reinforcement ratios ρ for both steel and CFRP beams reduces the midspan deflection capacity, while increases the strength at the cracking and ultimate load capacity, with little impact on failure mode.

2- The ductility index (μΔ) of CFRP-prestressed and steel-prestressed beams with decrease as prestressing reinforcement ratios ρ increases.

3- The plastic stiffness (Kp) of the prestressed beam with CFRP and steel increased as prestressing reinforcement ratios ρ increases.

4- For CFRP-prestressing beams, the increase of concrete strength increases the deformation capacity, but slightly decreases the ultimate load capacity.

5- For steel-prestressed beams, the increase of concrete strength slightly decreases the deformation capacity, and slightly increases the ultimate load capacity.

6- The μΔ and E.A.I decrease with the increase in concrete strength for both steel and CFRP-prestressed concrete.

7- The ultimate deformation capacity increases for the lower prestressing level; (67% for CFRP and 40% for steel cables). On the other hand the ultimate load capacity slightly increases by increasing prestressing level.

8- For the CFRP beams, the values of E.A.I and μΔ are almost doubled by reducing prestressing level from 70% to 50%. While for steel, the μΔ is increased by 45% and the E.A.I is decreased by 15%.

9- The level of prestressing in CFRP and steel beams did not significantly affect the stiffness of the beams; however, the stiffness of the CFRP-prestressed beams was higher than that of the prestressing steel.

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