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Strengthening of Pre-stressed Steel–Concrete Composite Beams Using Carbon Fiber Tendons – A Parametric Study

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Abstract

Strengthening of structures using external pre-stressed Carbon fiber reinforced polymer systems have proven to be an effective process as system strengthen the structural capacity and decrease cracks and deformability. Three dimensions finite element model using ANSYS program is set up to study the impact of composite beams strengthened using externally pre-stressed Carbon fiber reinforced polymer tendons under flexural behavior. Studying parameters like pre-stress level, tendon material and tendon profile elevated from the bottom surface of steel beam flange considered under static loading. Consequences of the parametric study will give reasonable guidelines for the designers. The accuracy of the 3-D model is verified with the available experimental data. End from the finite element model and design suggestions are given.

Keywords: Composite; Post-tensioning; Finite element modelling; CFRP; ANSYS

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Introduction

Steel-concrete composite beams have been known as the economical structural systems for both multistory structures and steel bridges. Concrete slab due to its high stiffness can minimize shaking and deflections of the floor system and supply the demanded protection from the fire may occurs. Since both the steel and concrete are already existing in the structures, it is logical to relate them together to profit from their strength and stiffness [1-4].

Strengthening composite beam with externally post-tensioning have established a lot of advantages like increase the load carrying capacity, progress serviceability of existing structures like decrease tensile stresses and deflections. The most important zones in composite beams are flexure and shear zones [5,6]. Fiber Reinforced Polymer (FRP) technique utilize these zones become stronger by fortified them externally. FRPs materials are strong, with high resistance of rust, high strength to weight ratio and show the high tensile strength. FRPs are established to be the most functional for strengthening of existing structures because having the better properties and high tensile strength, more than traditional steel.

It is can used in the shape of tendons which are bonded externally to composite structural members. The major interest of utilizing pre-stressed CFRPs in the strengthening of composite beams are its low weight, high tensile strength, corrosion resistance, good resistance to degradation and creep, electromagnetic neutrality, quick and fast building, small relaxation losses, low labor costs and has an strength to adjust modulus of elasticity [7-9]. many concrete structures in Japan, UK, China, Europe and Canada have been strengthened using pre-stressed CFRP [10]. As Carbon-fiber-reinforced polymers are composite materials, it depend on matrix and reinforcement. The material properties depend on these two elements [11].

Experiments made the FRP tendon relaxation. Relaxation of 3000 hours was explored at 20°C, 40°C and 60°C under initial stress level of 70% of ultimate stress [12]. Creep and examined the long term strength [13], the advantages properties of CFRP materials are noticed with long term residual strength after 100 years of more than 90% of short term tensile strength. Although the limited tests on fatigue, conventional steel strands is mush lower than the fatigue strength of CFRP strands [14]. The present paper discusses strengthening steel–concrete composite beam with externally post-tensioning FRP tendons. The finite element software (ANSYS)[15] was used. Nonlinear material models for composite beam were utilized in the proposed three-dimensional model. The results of the model were verified with the available experimental outcomes. A parametric study is presented to inspect the impact of FRP tendons on strengthened composite beams. This includes: Carbon fiber, Glass fiber and Aramid fiber, pre-stress level and tendon profile elevated from the bottom surface of steel beam flange. The effective post-tensioned load is taken as an initial value that appears in the analysis as initial temperature in the beam elements applied to model the tendons.

Methodology

Finite element model

This study used the finite element program ANSYS version 15.0 [15] showing the conduct of the composite beam and the stud shear connectors. A three-dimensional finite element model is used for represent the material non-linear behavior of the composite beam. The steel I-beam was modeled utilizing an eight-node solid element with three degrees of freedom at each node. (SOLID 185) which has plasticity, stress stiffening, large deflection, and large strain capabilities is utilized for the three-dimensional modeling of solid structures. Three-dimensional spar elements were utilized to represent the reinforcement steel bars in the concrete in two directions. The concrete slab was modeled utilizing a three-dimensional concrete element (SOLID 65) that is able to crack in tension and crush in compression. In the suggested concrete material model, tensile stress, relaxation coefficient, shear transfer for open and closed cracks, and concrete crushing which took in consideration.

An eight-node solid element with three degrees of freedom at each node is used to represent the shear connector's conduct to withstand the normal and shear force between the steel beam and concrete slab. The external tendons are designed utilizing 3D spar elements. The LINK180 is a spar (or truss) element which used to simulate the external tendons.

The interface of the steel flange and the concrete slab was simulated by utilizing node-to-node contact element with three translational degrees of freedom at each node. The target of use the contact element between these connected surfaces is to prevent penetration and maintain physical separation between them as shown in **Figures 1 and 2**. For prevent stress concentration problems at the loading locations steel plates are inserted, this supplies a more even stress distribution on the load area.

Material modeling

Modeling is performed on ANSYS-15. The element damaged plasticity model in ANSYS provides a general capability for modeling all types of structures using concepts of isotropic damaged elasticity and isotropic tensile and compressive plasticity to represent the inelastic behavior of the composite steel- concrete beams. The choice of the suitable elements for the modeling of several composite beam portions needs to well understanding of the geometrical shape and material properties of each portion. Also, the Continuity of each element with the close elements must be considered. ANSYS [15] has an element which consider all requirements.

Modeling of concrete: The concrete is simulated to be homogeneous and initially isotropic. The uni-axial stress–strain curve for concrete in compression is required for ANSYS-15 as an input [15]. The simplified stress–strain curve for each beam model was developed from nine points attached by curved lines, as shown in **Figure 3**.

Modeling of steel I-beam: Steel mechanical properties are well known so the stress–strain conduct in tension and in compression can be supposed typical and identical Properties, i.e., elastic modulus and yield stress, for the steel I-beam used in this FEM case follow the design material properties utilized for the experimental investigation. The tri-linear stress-strain relationship indicated in **Figure 4** is used in this study.

Modeling of reinforcing steel bars and external pre-stressing steel tendons: As the reinforcing steel and post-tensioning tendons are long and relatively slender, they can generally be assumed to transfer axial forces only. This relation is supposed to be identical in tension.

Modeling of external pre-stressing FRP tendons: Pre-stressed FRPs have limited strain capacity and premature debonding failure may occur in the earlier stages [16]. The deformability index can be used as a major tool to avoid this phenomenon. By pre-stressing the FRP reinforcement, the stress in the internal

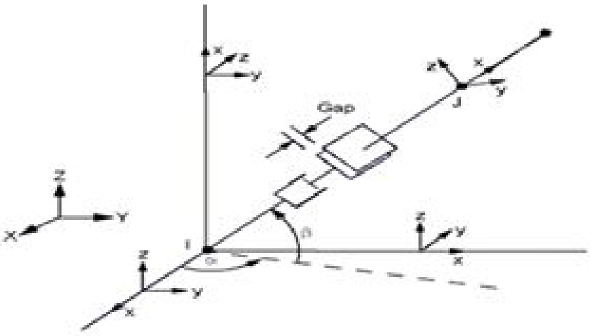


Figure 1 Contact element (178).

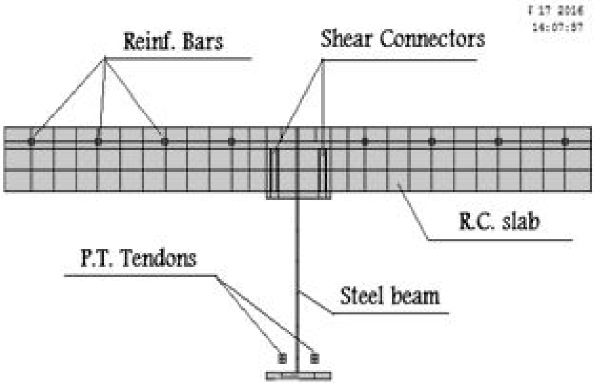


Figure 2 Composite beam cross-section.

reinforcing steel and deflections will decrease and there will be a higher utilization of the FRP materials. The tri-linear stress-strain relationship indicated in **Figure 5** is used in this study.

Real constants

The initial PT force is defined by an initial temperature which is calculated as given by equation (1)

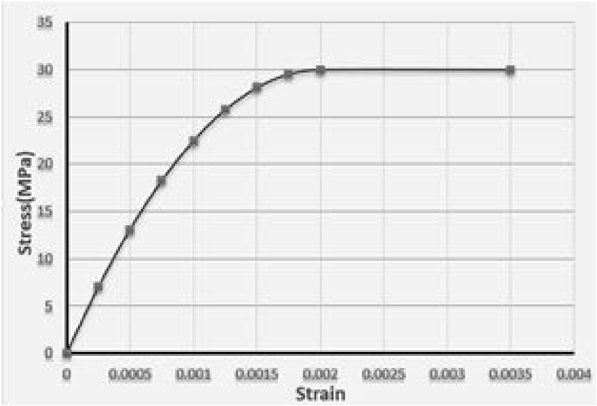


Figure 3 Stress-strain curve for concrete.

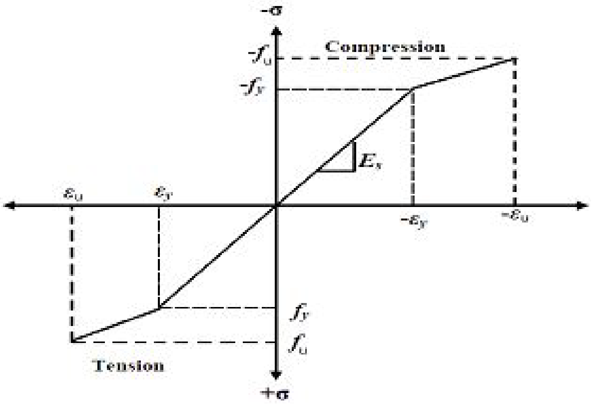


Figure 4 Stress-strain curve for steel.

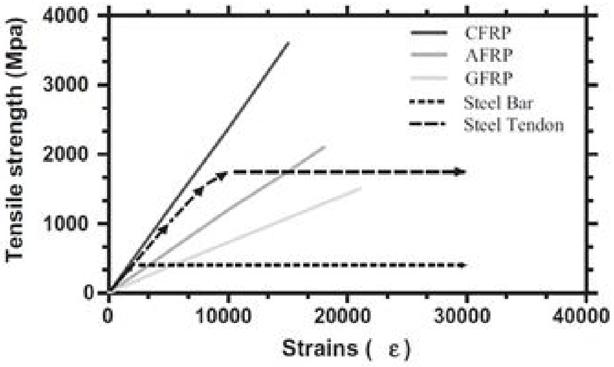


Figure 5 Stress–strain behavior of pre-stressed materials (tendons).

$$\text{initial temperature} = \frac{F}{\alpha E A p} \qquad (1)$$

where F is the initial PT force, E is the elastic modulus of the tendon, α is thermal expansion coefficient, and Ap is the tendon cross-sectional area.

Verification

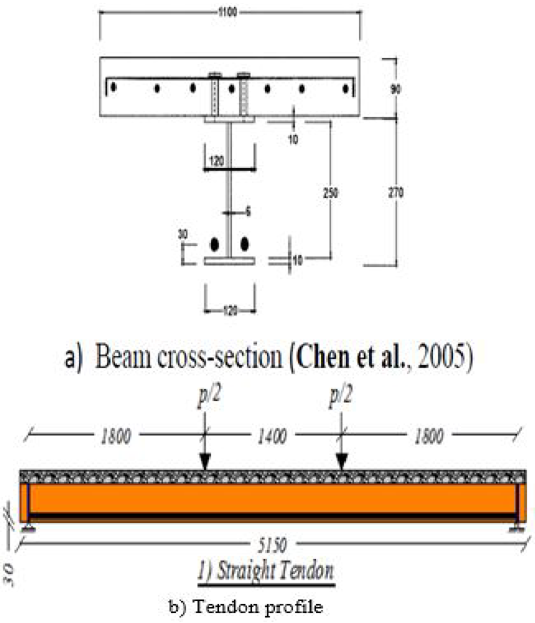
From literature was choosed Chen et al. [17]. The results were compared to varify the accuracy of the proposed FE model. The dimensions, details, and profiles of the pre-stressed tendons for the examined beams which clarified on **Figure 6**. The examined beams have a total length of 5150 mm and were propped on a 5000 mm simple span. Also, it`s loaded equaly on two points to get clearly bending. Two rows of 16 mm diameter by 65 mm length shear connector studs are attached to the top flange, with a transverse spacing of 76 mm symmetric to the centerline of the top flange and a linear distance of 200 mm. Full shear connection was accomplished with identity BS5400 Part 5. The concrete slabs were strengthened with ϕ8 deformed bars (8 mm in diameter) in two orthogonal directions.

Tendon profile was illustrated in **Figure 6**. The tendon profile was straight tendon which set at the two ends of the beam 30 mm over the bottom flange and expanded on the two ends of the web over the whole length of the beam.

The conclusion of the materials properties of the selected beam are listed on **Table 1**. The verification of the finite element model

Table 1 Summary of material properties.

Pressing Tendons					f_y (MPa)		f_u(MPa)	
f_y Mpa	f_u Mpa	A_P (mm^2)	F (KN)	f_c (MPa)	Web	Flange	Web	Flange
1680	1860	137.4	112.6	40	327.7	406.5	492.6	593.6



a) Beam cross-section (Chen et al., 2005)

1) Straight Tendon

b) Tendon profile

Figure 6 Details of studied beam (All dimensions in mm).

was achieved with accuracy 96% through comparison the FE model outcomes with experimental results created by Chen et al. [17]. The verification based on the maximum load carried by the model and also the deflection of the composite beam; as shown in **Figure 7**.

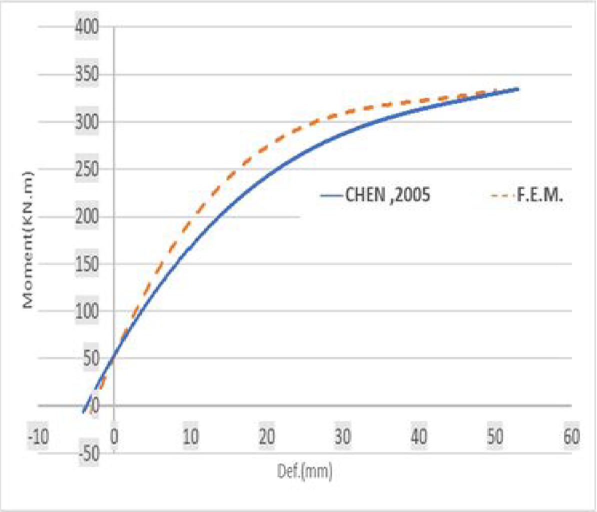


Figure 7 Moment–deflection curve.

Parametric study

Effect of draping frp tendons: Table 2 showed the typical tensile properties of various types of pre-stressed strengthening materials [18,19]. To explore the effectiveness of draping FRP tendons on the performance of the composite beam, a parametric study was accomplished on four new advanced models (ST, CT, AT, and GT) with several tendons material are tested. (ST) for steel tendon of 1860 MPa ultimate strength (fsu), and 200 Gpa modulus of elasticity (E), (CT) for CFRP tendon of 2410 MPa ultimate strength (fsu), and 165 Gpa modulus of elasticity (E), (AT) for AFRP tendon of 2068 MPa ultimate strength (fsu), and 70 Gpa modulus of elasticity (E), and (GT) for GFRP tendon of 1379 MPa ultimate strength (fsu), and 48 Gpa modulus of elasticity (E). The Total pre-stress force per bar P=112.6 KN. The geometrical advantages of the used models same as **Figure 6** and a summary of material and section properties for the verified and modeled composite beams are shown in **Tables 2 and 3**. **Figure 8** shows finite element mesh. For model (ST), the initial pre-stressing force in each tendon was 112.6 kN. The moment–deflection curve appeared nonlinear when the moment was 250 kN m, with a pre-stressing force of 150 kN in each tendon, while the deflection was 17 mm. The maximum moment was 333 kN m, while the deflection was 50 mm, and the ultimate pre-stressing force of the tendons was 223 kN.

Table 2 Tensile properties of pre-stressing tendons (CAN/CSA-S806-02).

Mechanical Properties	Prestressing Steel	AFRP Tendon	CFRP Tendon	GFRP Tendon
Nominal Yield Stress (MPa)	1034-1396	N/A	N/A	N/A
Tensile Strength (MPa)	1379-1862	1200-2068	1650-2410	1379-1724
Elastic Modulus (GPa)	186-200	50-74	152-165	48-62
Yield Strain (%)	1.4-2.5	N/A	N/A	N/A
Rupture strain (%)	>4	2-2.6	1-1.5	3-4.5
Density (kg/m^3)	7900	1250-1400	1500-1600	1250-2400

Table 3 Section properties of Models (ST, CT, AR, and GT).

Strand Strength (MPa)	Elastic Modulus (Gpa)	Tendon Material	Model	No.
1860	200	Steel	ST	1
2410	165	CFRP	CT	2
2068	70	AFRP	AT	3
1724	62	GFRP	GT	4

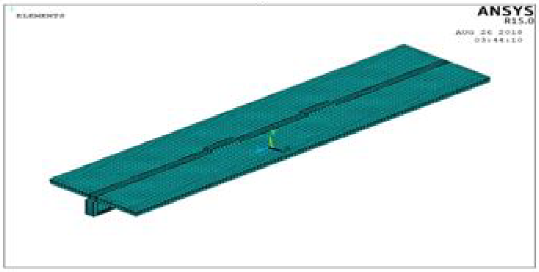


Figure 8 Finite element mesh.

Discussion

For model (CT), the initial pre-stressing force in each tendon was 112.6 kN. The moment–deflection curve appeared nonlinear when the moment was 270 kN m with a pre-stressing force of 300 kN in each tendon, while the deflection was 13 mm. The maximum moment was 370 kN m, while the deflection was 30 mm, and the ultimate pre-stressing force of the tendons was 331 kN.

For model (AT), the initial pre-stressing force in each tendon was 112.6 kN. The maximum moment was 279 kN m, while the deflection was 14 mm, and the ultimate pre-stressing force of the tendons was 284 kN.

For model (GT), the initial pre-stressing force in each tendon was 112.6 kN. The maximum moment was 234 kN m, while the deflection was 11 mm, and the ultimate pre-stressing force of the tendons was 234 kN.

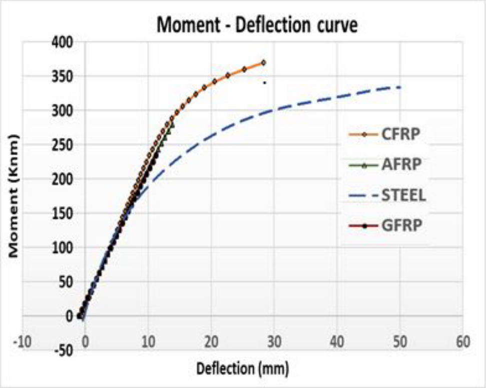


Figure 9 Moment–deflection curve for various materials of tendon.

Figure 9 clarifies the moment - deflection responses at the midspan for the composite beam with different types of external tendons. It is observed that CFRP tendon (model (CT)) had high strength with small deflection compared to others, steel tendon (model (ST)) had high strength compared to AFRP tendon (model (AT)) and GFRP tendon (model (GT)), steel tendon (model (ST)) had high deflection compared to others, and GFRP tendon (model (GT)) had small strength and small deflection compared to others.

Modes of failure

Two Modes of Failure occurred in the composite beam: concrete crushing and FRP rupture. For model (ST) the mode of failure was concrete crushing, while the maximum moment was 315 kN m due to long plates of ductility as shown in **Figure 9**. For model (CT) the mode of failure was CFRP rupture, while the maximum moment was 370 kN m. For model (AT) the mode of failure was AFRP rupture, while the maximum moment was 324 kN m. For model (GT) the mode of failure was GFRP rupture, while the maximum moment was 234 kN m.

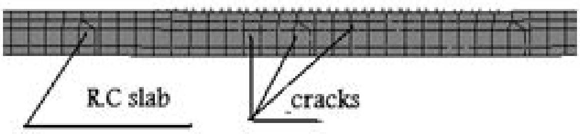


Figure 10 Concrete crushing failure.

Effect of pre-stress level

To explore the effectiveness of pre-stress Level on the performance of the composite beam strenghened with external pre-stressed CFRP tendon, a parametric study was accomplished on four advanced models (CT1, CT2, CT3,and CT4) with several pre-stress level are tested. (CT1) for CFRP tendon with pre-stress force per bar P=20% of its ultimate strength. (CT2) for CFRP tendon with pre-stress force per bar P=30% of its ultimate strength. (CT3) for CFRP tendon with pre-stress force per bar P=40% of its ultimate strength. (CT4) for CFRP tendon with pre-stress force per bar P=50% of its ultimate strength.

summary of tendon properties and pre-stress level of each model are shown in **Table 4**. **Figure 8** shows The geometrical of the used models.Results are shown in **Figure 11**.

Table 4 Properties of models (CT1, CT2, CT3, and CT4)

Prestress Level %	Strand strength (MPa)	Elastic Modulus (Gpa)	Tendon material	Model	No.
20	2410	165	CFRP	CT1	1
30	2410	165	CFRP	CT2	2
40	2410	165	CFRP	CT3	3
50	2410	165	CFRP	CT4	4

From **Figure 11** it is observed that :

Model (CT1) maximum moment was 385 kN m, while the deflection was 16.44 mm.

Model (CT2) maximum moment was 374 kN m, while the deflection was 15.33 mm.

Model (CT3) maximum moment was 363 kN m, while the deflection was 14.27 mm.

Model (CT4) maximum moment was 352 kN m, while the deflection was 13.27 mm.

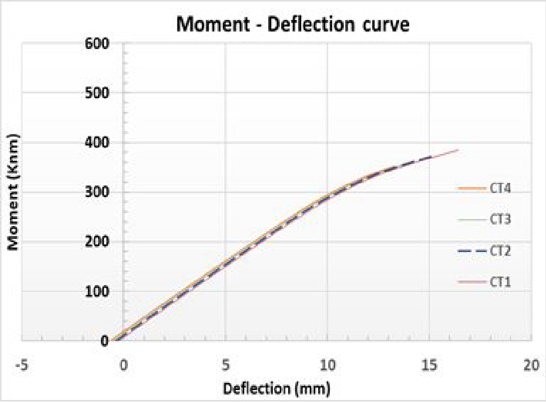


Figure 11 Moment–deflection curve for pre-stress level.

Figure 11 clarifies the moment - deflection responses at the midspan for the composite beam with different degree of pre-stress level.It is observed that model (CT1) had high strength with high deflection compared to others.

Effect of tendon profile elevated

To explore the effectiveness of tendon profile elevated from the bottom surface of steel beam flange on the performance of the composite beam strenghened with external pre-stressed CFRP tendon, a parametric study was accomplished on four advanced models (CH1, CH2,CH3, and CH4) with several straight CFRP tendon profile elevated from the bottom surface of steel beam flange he=10%,15%,20% and 25% of steel beam height respectively.

Table 5 Properties of models (CH1, CH2, CH3, and CH4).

he % of steel beam height	P.T Force (KN)	Model	No.
10	112.6	CH1	1
15	112.6	CH2	2
20	112.6	CH3	3
25	112.6	CH4	4

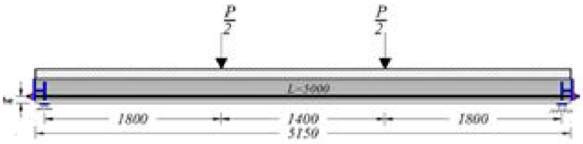


Figure 12 Geometrical of the used models (All dimensions in mm).

summary of tendon properties and tendon profile elevated of each model are shown in **Table 5**. **Figure 12** shows The geometrical of the used models.Results are shown in **Figure 13**.

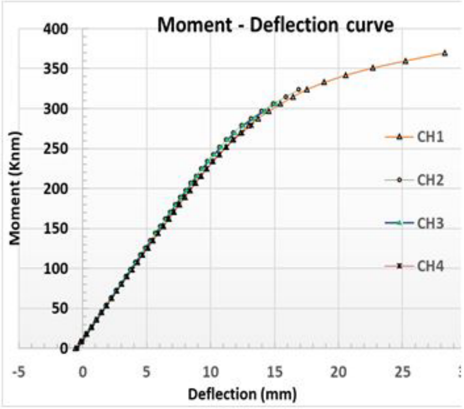


Figure 13 Moment–deflection curve for tendon profile elevated.

From **Figure 13** it is observed that :

Model (CH1), The maximum moment was 370 kN m, while the deflection was 30 mm.

Model (CH2), The maximum moment was 324 kN m, while the deflection was 16.9 mm.

Model (CH3), The maximum moment was 306 kN m, while the deflection was 15 mm.

Model (CH4), The maximum moment was 279 kN m, while the deflection was 13.2 mm.

Figure 13 clarifies the moment-deflection responses at the midspan for the composite beam with different tendon profile elevated from the bottom surface of steel beam flange.It is observed that model (CH1) had high strength compared to others.

Conclusion

In this research, a non-linear parametric analysis for composite beams externally post-tensioned with tendons has been evaluated. The FE model is validated using experimental results. And, a parametric study is accomplished to survey the various actions of strengthened beams with pre-stressed FRP tendons. The major conclusions are as follows:

1. Pre-stressed FRPs exhibited good potential and desirable structural properties including high flexural strength, enhance the ultimate load carrying capacity, reduce the deflections, high strength, high stiffness, and high energy absorptions than pre-stressed steel.

2. From all FRPs, CFRP is the best type, and, it was realized that pre-stressed CFRP increase the flexural strength and ductility of the composite beam. The other advantages of pre-stressed CFRPs are the low weight, high tensile strength, and low relaxation losses.

3. The major failure modes recognized under flexural loading in pre-stressed strengthened beams are concrete crushing for steel tendon, and FRP rupture for all FRPs tendon.

4. Increase pre-stress level of CFRP tendon decrease the flexural strength and deformability of pre-stressed composite beam with CFRP tendon.

5.Increase tendon profile elevated from the bottom surface of steel beam flange will decrease the ductility of the pre-stressed composite beam with CFRP tendon and decrease ultimate load capacity.

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