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BEHAVIOR OF PRESTRESSED SIMPLE AND CONTINUOUS PARTIALLY COMPOSITE STEEL-CONCRETE BEAMS

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Abstract: In this paper, a non-linear finite element analysis (FEA) has been done to analyze the internal stresses and strains under static load up to failure for the concrete slab and steel beam sections for simple and continuous composite beams with external prestressing. The concrete slab is partially connected with steel I-beam section by headed stud (shear connectors). ANSYS computer program (version 15) has been used to analyze the three-dimensional model. The nonlinear material and geometrical analysis based on Incremental –Iteration load method, is adopted. The reliability of the model was demonstrated by comparison with experimental results of simple prestressed composite beam carried out by another author. The results wash obtained by FEA solutions have shown good agreement with experimental results. The analysis for continuous prestressed composite beam covers: load deflection behavior, strain and stress in concrete slab and steel beam, force in shear connector, slipping between concrete and steel, and failure modes.
Keywords: Composite steel-concrete beams, finite element analysis (FEA), external prestressing, shear connection, slipping, uplift

INTRODUCTION

Use of Composite Construction has become increasingly popular due to the economy and speed in construction. The modern era of Composite Systems using steel and concrete for columns began with the work of the late Dr Fazlur Khan in 1966 [1]. Concrete filled steel tubular (CFST) structures have been increasingly used recently owing to good structural performances by their high load-bearing capacity and energy dissipation ability [2]. Leng et al. [3] investigated the structural performance of steel-concrete-steel sandwich beams inter connected by channel connectors with large interval.

Strengthening of existing buildings especially bridges is most important so, the use of external pre-stressing has been used from sixty five years ago because of its perfect and economical solution for many types and circumstances of bridges. This system has been widely spread due to speed and traffic crashes in less time. Continuous steel-concrete composite beams are widely used in buildings and bridges for higher span/depth ratios and less deflection etc., which results in superior economic performance compared with simply supported composite beams [4]

The principle pre-stressing is the application of axial load along with shear bending moment to increase the ability to improve the performance of cracking. It also could have a beneficial effect on shear capacity [5].

Pre-stressed composite beams (concrete- steel) with high strength external tendons have showed many advantages comparing with plain composite beams. These advantages as: expand the elastic behavior prior to yielding for the structures with internal stresses, increasing in capacity of ultimate moment of structures, use the high- strength tendons reduces the yield strength so, then reduces the amount of structural steel used in construction, tends to reduce the cost of construction.

A composite beam (concrete-steel) can be pre-stressed, using a jack, by the tensioning high-strength tendons connected at both ends to brackets or anchorages that are fixed to the composite beam. Pre-stressing a composite beam can introduce internal stresses into the member cross sections that can be defined for different purposes. Such induced stresses can then counteract the external loads applied on the structure. Pre-stressing can be carried out for simple-span or continuous-span composite beams. In the positive moment region, the steel beam is usually pre-stressed before the concrete is cast because the negative moment induced by pre-stressing may be used to counteract the positive moments caused by the concrete's self-

weight. In the negative moment region, the steel beam and concrete deck can also be pre-stressed either separately or jointly along the top flange before or after casting of the deck Saadatmanesh [6] Also Saadatmanesh [7], Ayyub [8], Nie J. [9], Zona A. [10], and Chen Sh. [11] researches have been done on pre-stressed steel and concrete composite beams with external tendons.

The behavior of the composite girders (concrete slab-steel girder) has been the subject of several researches all over the world [12].

It is widely known that laboratory tests require a great amount of time and, in some cases, can even be impractical [13]. The finite element method (FEM) can be used as a very useful tool in predicting the failure load of composite concrete-steel beams and can allow very detailed information for the distribution of stresses and strains in composite beams [14-16]. Ibrahim et al. [17] used a finite element model to study the behavior of simple prestressed composite beams by means of a developed computer program (ANSYS 12) and compared the numerical results to the experimental results. The numerical results showed that the behavior in the concrete slab and steel beam responded well with the experimental results. Patil and Shaikh [18] presented 3D numerical models of steel-concrete composite beams to simulate their structural behavior with emphasis on the beam-slab interface. Simulations were made using version 14.0 of the ANSYS code, based on the FEM. The results were compared with those provided either by standards, experimental work, or found in the literature, and such comparisons demonstrated that the numerical approach followed is a valid tool in analyzing steel-concrete composite beams.

A detailed literature review showed that the studies mostly focused on the behavior of simple prestressed composite beams. Also the review showed that little information was available on the structural analysis of composite continuous beams with external prestressing taking into consideration the effect of slipping and uplift in between concrete slab and steel beam section.

Therefore, the present study is concerned with the behavior of this type of structure (partially composite section), taking into consideration the slipping and uplift between concrete slab and steel beam section. The model using FEM version 15.0 of the ANSYS code.

FINITE ELEMENT MODEL

The analysis of simple and continuous composite beams with external prestressing was performed using ANSYS computer program (version 15). Model components encountered throughout the current study, corresponding finite element representation and corresponding elements designation in ANSYS are presented as follows:

Element type selection

The three-dimensional element SOLID 186 is adopted to discretize the concrete slab, which is able to simulate cracking behavior of the concrete under tension (in three orthogonal directions), crushing in compression and evaluate the material non-linearity and enable the coverage of reinforcement (reinforcement bars scattered in the concrete region). The steel section is modeled using the SHELL 43 element, which facilitates non-linearity of the material and shows linear deformation in the plane in which it is present. The modeling of the shear connectors is done by the BEAM 189 element, which allows the configuration of the cross-section enables consideration of the non-linearity of the material and includes bending stresses. The TARGE 170 and CONTA 173 elements are used to represent the contact slab-beam interface. These elements can simulate the existence of pressure between them in the case of contact and separation between them in the case of no contact. The slab-beam contact materials also take into account slipping and uplift between the parties. The prestressing stress was taken as the initial value and equal to the effective stress. It appears in the analysis as initial strain in link element. Link 8 is used to represent the external cable. Since the cable is located outside the steel section and the prestressing force is transferred to composite beam through end anchorages and stiffeners, the cable is connected to beam only at the anchorage or stiffeners.

MATERIAL MODELING

In this study, the main components of the composite section are modeled with relevant ANSYS elements as follows:

Modeling of concrete

The concrete is considered to be homogeneous and initially isotropic. The adopted stress-strain (fc-$\square$) relation is based on work done by Desayi and Krishnan [17] as shown in Figure 1.
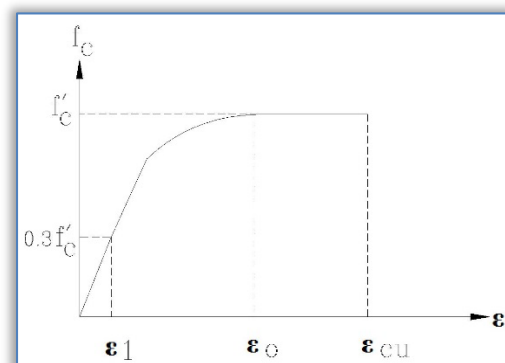

Figure 1. Compressive stress-strain curve for concrete used in ANSYS model

A compressive uniaxial stress-strain relationship for the concrete model was obtained by using Eqs. (1~4) to compute the multilinear isotropic stress-strain curve for concrete.

$$f_c = \varepsilon E_c \quad \text{for} \quad 0 \le \varepsilon \le \varepsilon_1 \qquad (1)$$

$$f_c = \frac{\varepsilon E_c}{1+(\frac{\varepsilon}{\varepsilon_o})^2} \quad \text{for} \quad \varepsilon_1 \le \varepsilon \le \varepsilon_o \qquad (2)$$

$$f_c = f_c^{'} \quad \text{for} \quad \varepsilon_o \le \varepsilon \le \varepsilon_{cu} \qquad (3)$$

$$\varepsilon_1 = \frac{0.3 f_c^{'}}{E_c} \quad \text{(Hooke's law)} \qquad (4)$$

$$\varepsilon_o = \frac{2 f_c^{'}}{E_c}$$

where, ε_1 = strain corresponding to (0.3f_c'); ε_o = strain at peak point; ε_{cu} = ultimate compressive strain.

Modeling of steel girder

The bilinear stress-strain relationship indicated in Figure 2 is used in this study [18]. The strain hardening modulus (E_t) is assumed to be (0.03 E_s). This value is selected to avoid convergence problems during iteration.
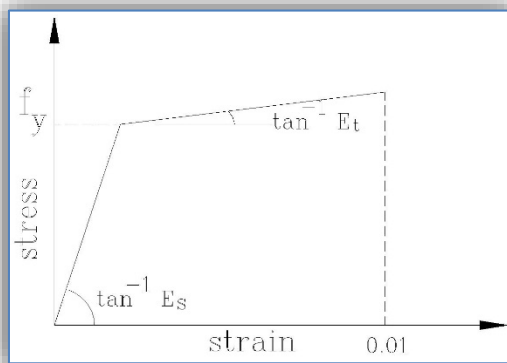

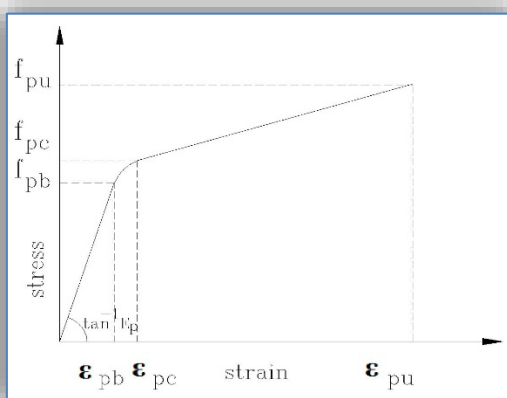Figure 2. Stress-strain curve for steel girder used in ANSYS model

Figure 3. Stress-strain curve for prestressing cable used in ANSYS model

Modeling of prestressing bars

The prestressing cable is slender, they can be assumed to transmit axial force only. Modeling of prestressed steel in F.E. is much simpler; the stress-strain relationship for prestressing tendons can be represented as shown in Figure 3.

Modeling of shear connectors

The qualitative behaviour of shear connectors in respect of: slipping, uplift, and repeated loading.
The push-out, and pull-out curves are shown in Figures 3 and 4 [13].
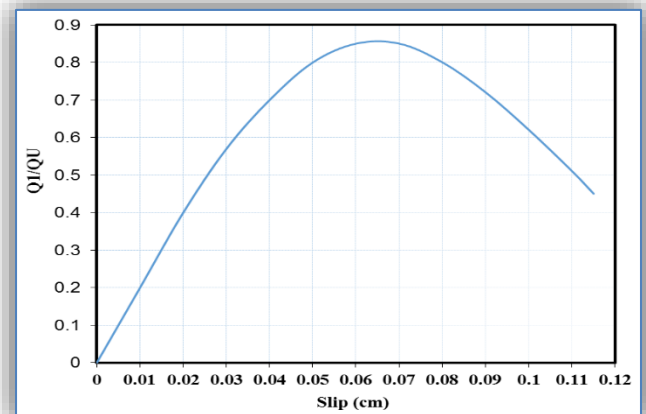

Figure 4. Load-slip curve from push-out test used in ANSYS model
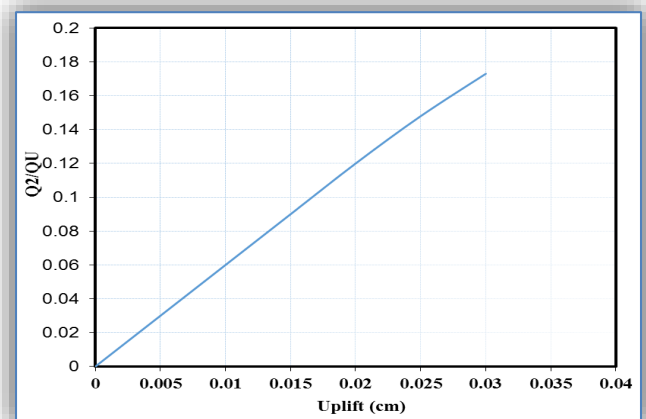

Figure 5. Load-uplift curve from pull-out test used in ANSYS model

The equation for push-out curve [13] is:

$$Q_{1\gamma} = Q_u (1 - e^{-c_1\gamma})^{c_2} \qquad (5)$$

where, $Q_{1\gamma}$ = horizontal force taken by the connector; Q_u = ultimate horizontal force taken by the connector; γ = relative slip between concrete slab and steel beam; C_1, C_2 = constants depend on the kind of connector.
and the equation for pull-out curve is:

$$Q_{2\Delta_a\gamma} = R_\Delta.\Delta_t \qquad (6)$$

where, $Q_{2\Delta a}$ = vertical force taken by the connector; R_Δ = equivalent secant rigidity of

connector for uplift; Δ_t = uplift between concrete slab and steel beam.

Geometrical modeling and finite element meshing

The numerically modeled beams are typically composed of simple and continuous beams with external prestressing are previously discussed. The model is defined by four types of elements that form the concrete slab with added reinforcements, steel girder, shear connectors and external prestressing. The elements are established separately, but the nodes are coupled one by one on the interface between concrete slab and steel beam. The finite element mesh developed followed the same methodology and degree of refinement presented in Figure 6.
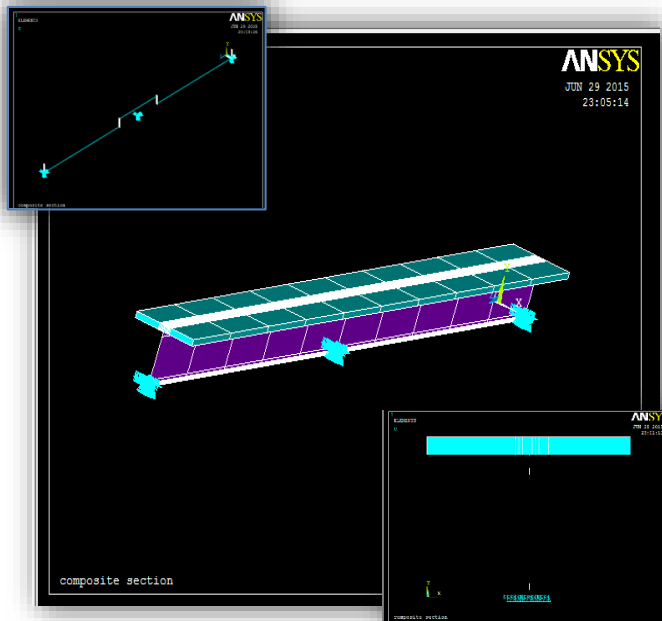
Figure 6 . Finite element model

THE VALIDATION OF THE MODEL

The validation of the model FEA was examined by comparison with experimental results for simple composite beams with external prestressing in the steel section by Ayyub [8]. Also, the results of the theoretical model described by Ayyub [8] are shown in the same graphs for the purpose of comparison.

Two beams (B1 and B2), shown in Figure 7, were tested to failure under positive bending moment, in which the beams were loaded in increments to near the ultimate load. Beams B1 and B2 were tested to study the differences in the structural behaviour when high-strength bars or strands are used as prestressing tendons.

Beam B2 is the counterpart of beam B1 with the same design details except the tendon type. The beam was prestressed with two 15 mm diameter, low-relaxation seven-wire strands, running the full beam length 30 mm above the bottom (tension) flange.
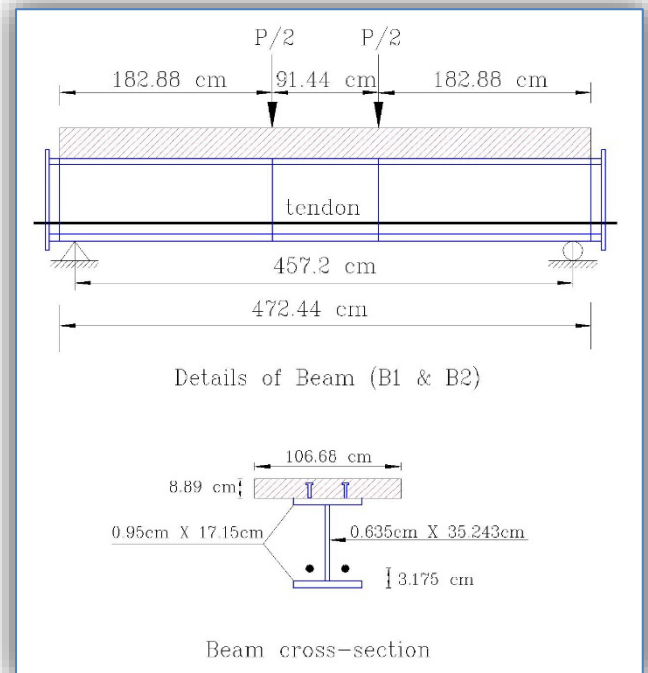

Figure 7. Composite beam (B1 and B2)

The parameters and material properties of the simple prestressed composite beam are shown in Tables 1 and 2.

Table 1. Positive moment specimens for external prestressing tendons for beam (B1 and B2)

Beam	Steel section type	Prestressing type	Tendon area (mm²)	Tendon force (KN)
B1	W 360*45	Bar	361	267.03
B2	W 360*45	Strand	279	289.00

Table 2. Mechanical properties of materials for beam (B1 and B2)

Element	Mode	Mean value of Yield strength (Mpa)	Mean value of Ultimate strength (Mpa)
Steel beam	Tension	420	576
Prestressing bars 15 mm	Tension	933	1112
Strand	Tension	1651	2056
Concrete	Compression	N.A.	41

N.A. is either not available or not applicable

Ayyub [8] assumed in the theoretical model that there is no slipping or uplift between concrete slab and steel beam (full composite section).

Figures 8-15 shows Load deflection, Load-strain for extreme concrete slab, and steel beam, Load-strain for prestressing bars for B1, and Load-increase in strand force for beam, B2
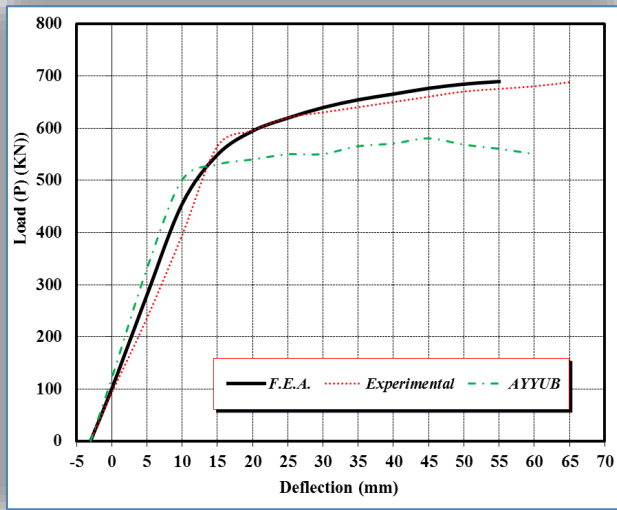
Figure 8. Load deflection results for beam, B1
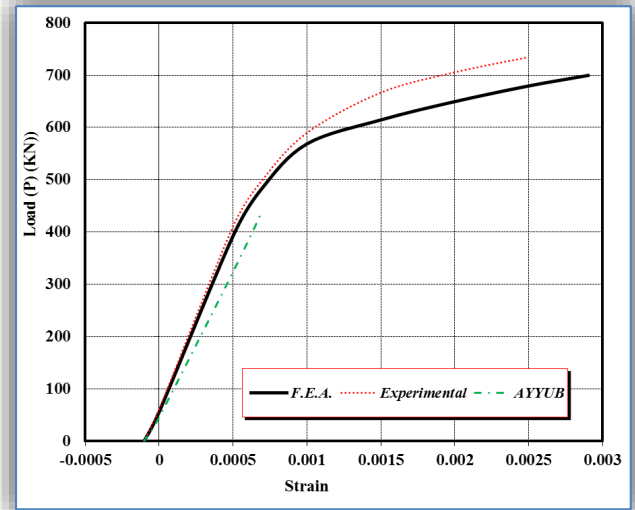

Figure 11. Load-strain curve at top of
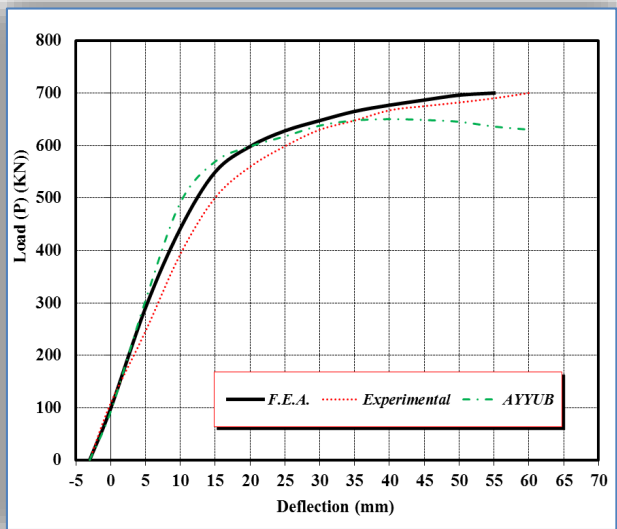the concrete slab surface for beam, B2

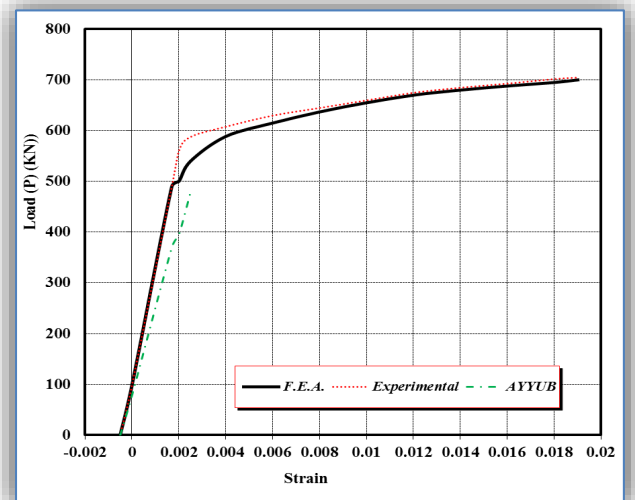Figure 9. Load deflection results for beam, B2

Figure 12. Load-strain curve at bottom fiber
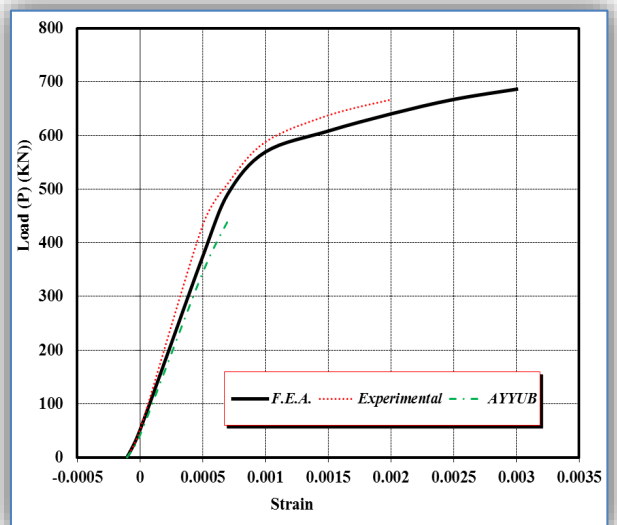of steel beam, B1

Figure 10. Load-strain curve at top of
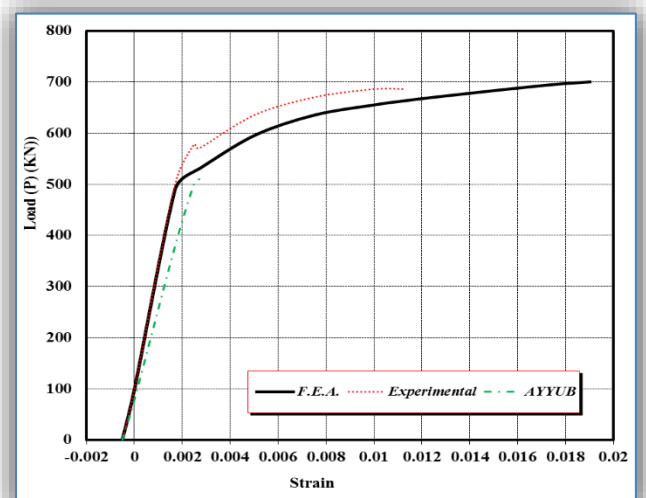the concrete slab surface for beam, B1

Figure 13. Load-strain curve at bottom fiber
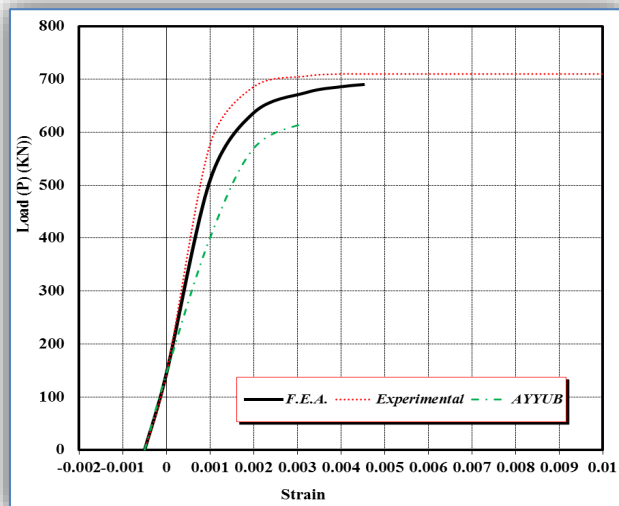of steel beam, B2

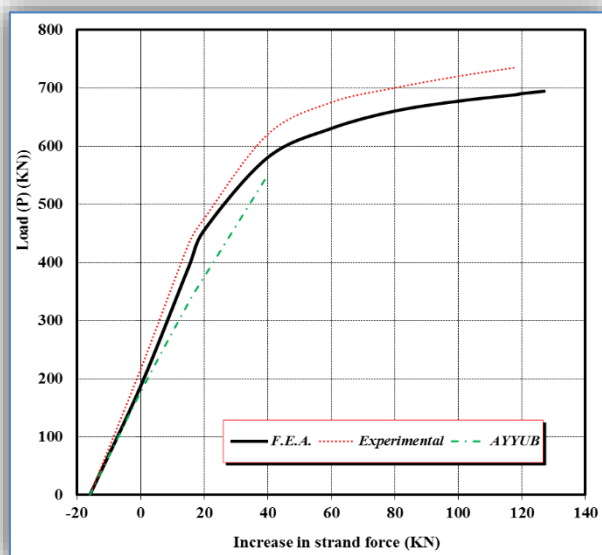Figure 14. Load-strain curve for prestressing bars for beam, B1

Figure 15. Load-increase in strand force for beam, B2

Discussion of results for beam B1

1- The load-deflection curves for beam B1 are shown in Figure 8. The behaviour of load-deflection curve was initially linear and elastic and become progressively nonlinear when the tension (bottom) flange and prestressing bars began to yield at a load about 588.6 KN (the curve showed a plateau because of reduced beam stiffness duo to the yielding of the steel beam and prestressing bars).the maximum calculated deflection from FEA is about 56 mm at the ultimate load, 692.8 KN, compared to 65 mm measured ultimate deflection.

2- The tested and predicted load versus strain in the top fiber of the concrete slab at mid-span section are shown in Figure 10. The initial behaviour was linear and elastic. After the tension flange yielded, the beam stiffness reduced with nonlinear behaviour until concrete crushed locally at strain of 0.003. The premature crushing of concrete occurred due to high localized stresses near the loading points. The predicted concrete strain for the top concrete surface, agree reasonably with the test results within the elastic range. In the plastic range, the small deviation between the measured and predicted strains may be attributed the differences between the idealized material models and the actual material behavior and/or material strengths.

3- Similarly, the tested load versus strain in the extreme fiber of the bottom (tension) flange of the steel beam were plotted and compared with the analytical results. These curves are shown in Figure 12.

4- The tested load versus strain in the prestressing bars is shown in Figure 14. The strain in the bars increased linearly with an increase in the applied load in the elastic rang. After the bars yielded at a load about 588.6 KN, the slope of the curve slightly reduced, and yielding progressed until the ultimate load was reached.

Discussion of results for beam B2

5- The load-deflection curves for beam B2 are shown in Figure 9. The behaviour of beam B2 was very similar to that of beam B1. It was initially linear and elastic and after the tension flange yielded at a load of 588.6 KN, the stiffness reduced and the behaviour of the beam become nonlinear until failure was reached by concrete crushing. The measured ultimate load for this beam is 693.96 KN slightly larger than the calculated beam B1. The difference can be attributed to the strain hardening of the steel section. The calculated mid-span deflection was 54 mm which is slightly smaller than that of measured value 56 mm.

6- Figure 11 shows the load versus strain in the top fibers (compression) of the concrete slab. The load-versus-strain in the bottom fibers flanges of steel beam are shown in Figure13. Figure 15 shows the load versus increase in the strand force.

7- The force in the cable increased linearly with applied load until the tension flange yielded. Thereafter, the behavior become nonlinear until failure is reached.

Comparison of FEA and experimental results for beams B1 and B2

The prestressing of conventional composite beam can significantly increase the load at which first yielding occurs and the ultimate capacity of the beams. The use of strands as prestressing tendons is preferable to bars duo to their higher strength-to-weight-ratio.

For the two beams B1 and B2, it is shown from the graphs that the present model gives more reliable results than those of Ayyub's [8] theoretical model. Moreover, the present model gives results up to failure.

CONTINUOUS PRESTRESSED COMPOSITE BEAM B3

The study is concerned with non-prestressed and prestressed continuous composite beam with two equal spans (L=20 m), subjected to uniformly distributed load (42.92 KN) Figure 16.
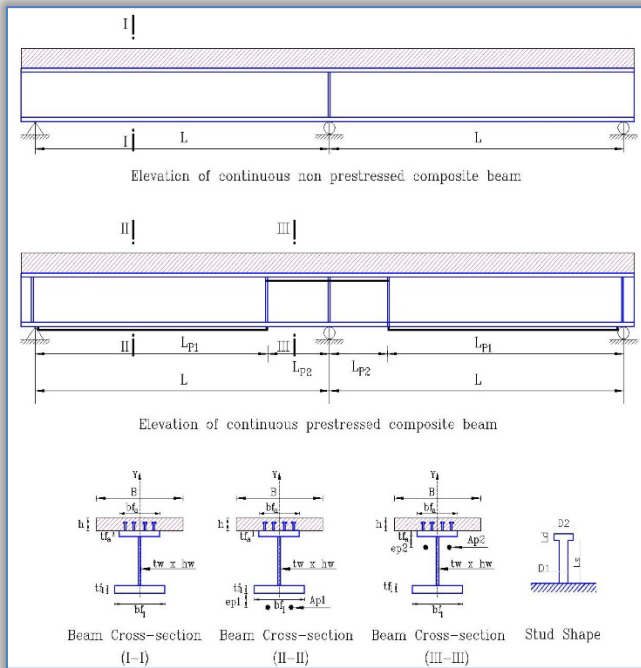

Figure 16. Continuous (two span) Composite beam without and with prestressing subjected to uniform load

The mechanical properties, and section for concrete slab, and steel beam are summarized in tables 3 to 4. Also the distances from bottom and top steel flange and force in cable is show in table 5.

Table (3) Material properties, and dimension of concrete slab cross-section

Material properties		Dimension			
E_c (GPa)	f_c' (MPa)	B_c (cm)	h_c (cm)	Top Mesh Reinf.	Bottom Mesh Reinf.
34.30	30.00	230.0	20.0	(6 Φ 12/m)	(6 Φ 16/m)

Table (4) Material properties, and dimension of steel beam cross-section

Material properties		Dimension					
E_s (GPa)	f_y (MPa)	t_1 (mm)	b_1 (mm)	t_2 (mm)	b_2 (mm)	t_w (mm)	h_w (mm)
214.00	370.00	20.0	300.0	30.0	450.0	15.0	1550.0

Table (5) Distances from bottom and top steel flange and force in cable

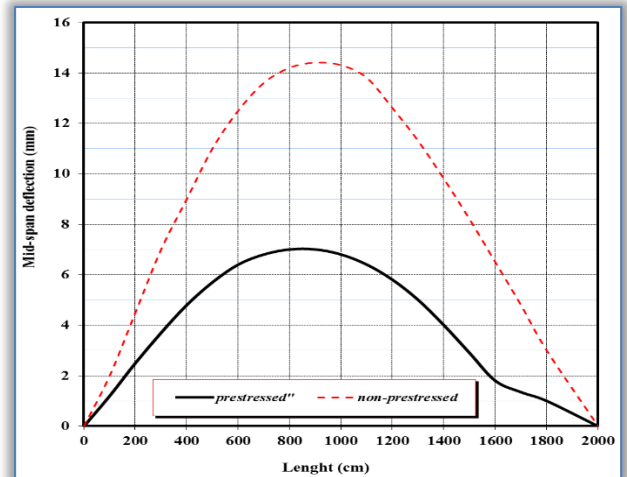| Prestressing			
ep_1(mm)	Fp_1(KN)	ep_2(mm)	Fp_2(KN)
86.45	919.1	157.0	1218.7

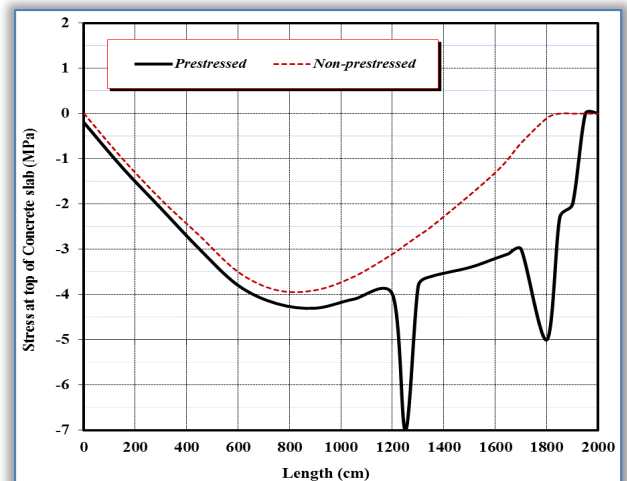Figure 17. Variation of Mid-span deflection with span length

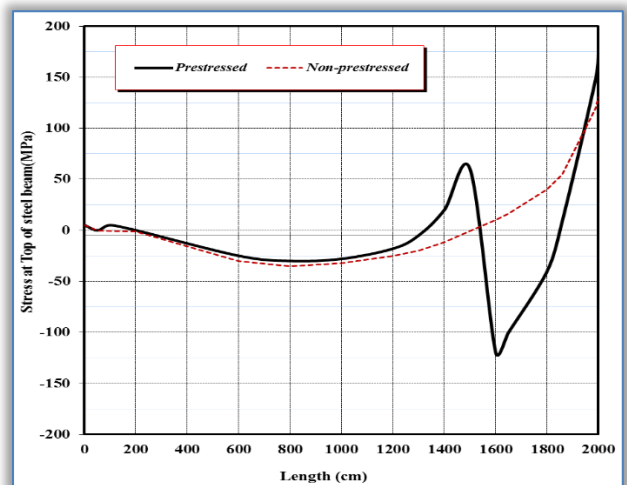Figure 18. Variation of Stress at top of concrete slab with span length

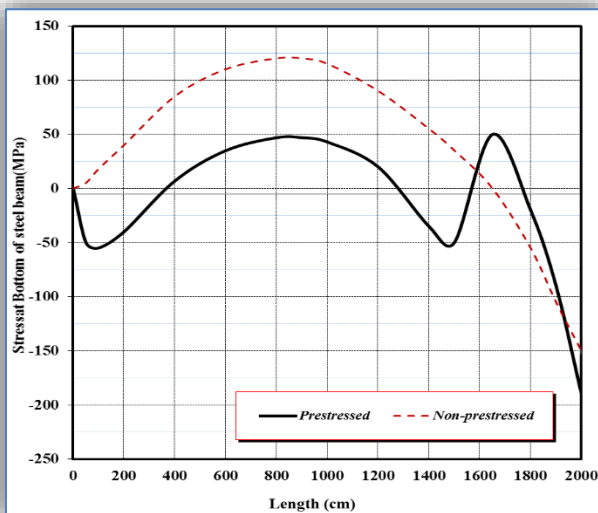Figure 19. Variation of Stress at top of steel beam with span length

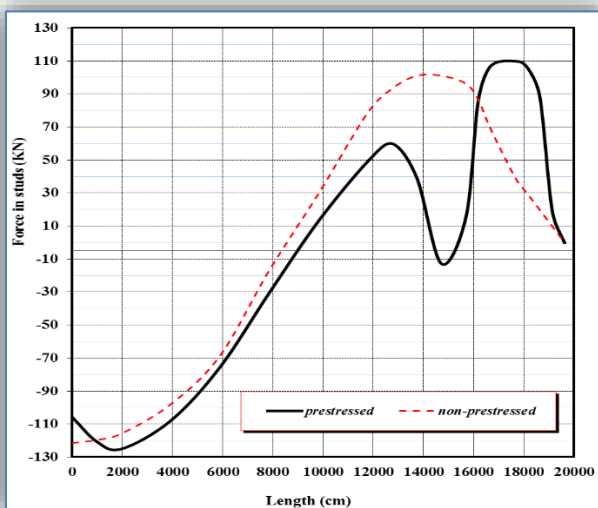Figure 20. Variation of Stress at bottom of steel beam with span length

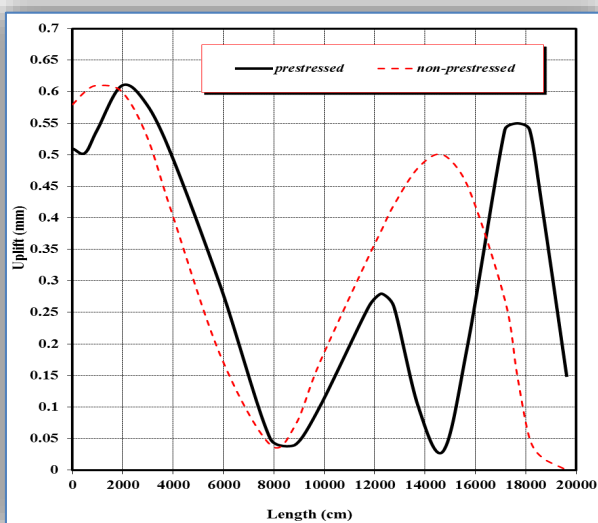Figure 21. Variation of Force at in studs with span length

Figure 22. Variation of Uplift between concrete slab and steel beam with span length

Figures 17 to 22 shows typical profiles for two-span continuous beam B3. The profiles are shown for one span only.

Discussion of results for beam B3

1. The load-deflection curves for beam B3 is shown in Figure 17. The prestressing reduced the maximum deflection by about 48%.
2. The compression stress in the top fiber of the concrete slab is shown in Figure 18. The prestressing increase it nearly the intermediate support by about 375%.
3. The stress in the top and bottom fibers of the steel beam are shows in Figure 19 and 20. The prestressing change the tension stress to a compression stresses, and the compression stress to a tension stresses at ends of prestressing cables which nearly at intermediate support (distance Lp2). But the prestressing reduced the bottom stresses by about 75% at the distance Lp1.
4. The Force in studs is shown in Figure 21. It redistribution at the distance Lp2 only since decrease near intermediate support and increase at intermediate support.
5. The uplift between concrete slab and steel beam is shown in Figure 22. It redistribution at the distance Lp2 only since decrease near intermediate support and increase at intermediate support.

CONCLISIONS

1. The computer program (ANSYS 15) used in this paper is able to simulate the behaviour and ultimate load of external prestressed composite steel-concrete beams.
2. The analytical tests carried out for the different cases (high-strength bars or strands are used as prestressing tendons) indicated that the load-deflection, the strain in the top fiber of the concrete slab, the strain in the bottom (tension) flange of the steel beam, the strain in the prestressing bars, and strand force are in good agreement with the experimental results.
3. The prestressing reduced the maximum deflection for continuous beam by about 48%.
4. The prestressing increase the stress in the top fiber of the concrete slab nearly the intermediate support by about 375%.
5. The prestressing change the stress from tension to a compression and the opposite nearly at intermediate support. But the prestressing reduced the bottom stresses by about 75% at the distance Lp1.
6. The prestressing redistribution the force in studs, and the uplift between concrete slab and steel beam near intermediate support, and at intermediate support.

References

[1.] Trilok Gupta and Ravi K. Sharma "Steel Concrete composite structures: state of art", International Journal of Latest Research in Science and Technology March-April (2015), Volume 4, Issue 2: Page No149-153,

[2.] Vu, T. D., Lee, S. Y., Chaudhary, S., & Kim, D. "Effects of tendon damage on static and dynamic behavior of CFTA girder" (2013). Steel and Composite Structures (2013). Volume 15 , Issue 5, Page 567-583

[3.] Leng, Y. B., Song, X. B., Chu, M., & Ge, H. H. "Experimental Study and Theoretical Analysis of Resistance of Steel-Concrete-Steel Sandwich Beams". Journal of Structural Engineering (2014)

[4.] Jianguo Nie; Muxuan Tao; C. S. Cai; and Shaojing Li "Deformation Analysis of Pre-stressed Continuous Steel-Concrete Composite Beams" Journal of Structural Engineering, November (2009), Volume 135, Issue 11.

[5.] Daly F. Witarnawan W., "Strengthening of bridges using external post- tensioning", Conference of eastern Asia society for transpotation studies, Seoul, Korea (1997).

[6.] Saadatmanesh H., Albrecht P., and Ayyub B., , "Guidelines for flexural design of pre-stressed composite beams", journal of structural engineering, ASCE (1989), Volume 115, Issue 11, Page 2944-2961

[7.] Saadatmanesh H., Albrecht P., and Ayyub B., "Experimental study of pre-stressed composite beams, ASCE, Journal of structural engineering (1989), Volume 115, Issue 9, Page 2348-2363

[8.] Ayyub B., Sohn Y., and Saadatmanesh H., "pre-stressed composite girders under positive moment, ASCE, Journal of structural engineering (1990), Volume 116, Issue 11. Page 2931-2951

[9.] Nile J., Cai C., Zhou T., and Li Y.,"Experimental and analytical study of pre-stressed steel-concrete composite beams considering slip effect", ASCE, Journal of structural engineering (2007), Volume 1233, Issue 4, Page 530-540.

[10.] Zona A., Ragni L., and Dall'asta A.," A simplified method for the analysis of externally pre-stressed steel-concrete composite beams". Journal of constructional steel research (2009), Volume 65, Page 308-313.

[11.] Chen Sh., Wang X., and Jia Y., "A comparative study of continuous steel-concrete composite beams pre-stressed with external tendons: Experimental investigation", Journal of constructional steel research (2009),, Volume 65, Page 1480-1489.

[12.] Darehshouri, S.F., Shanmugam, N.E., and Osman, S.A.,"Collapse behavior of composite plate girders loaded in shear", Journal Structural Engineering, (2012); Volume 138, Issue 3: Page 318–326.

[13.] Queiroz, F.D., Vellascob, P.C.G.S., and Nethercot, D.A., "Finite element modeling of composite beams with full and partial shear connection" Journal of Constructional Steel Research (2007); Volume 63: Page 505–521.

[14.] Alessandro, Z., "Finite element response sensitivity analysis of continuous steel-concrete composite girders", Steel and Composite Structures (2006); Volume 6(3): Page 183-202.

[15.] Ibrahim, M.A., Mohsen, S.K., and Ahmed, Q.W. "Finite element modeling of composite steel-concrete beam with external prestressing", International Journal of Civil and Structural Engineering (2012); Volume 3, Issue 1: Page 101-116.

[16.] Patil, P.S., and Shaikh, M.G. "A study of shear connector in composite beam in combined bending and shear by ANSYS", International Journal of Innovative Technology and Exploring Engineering (IJITEE), (2014); ISSN: 2278-3075, Volume 3, Issue-3.

[17.] Desayi, P., and Krishnan, S., "Equation for the stress-strain curve of concrete", Journal of the American Concrete Institute (1964); Volume 61: Page 345-350.

[18.] [18]. European Committee for Standardization (CEB), Eurocode 3, Design of Steel Structures, Part 1.1: General Rules and Rules for Buildings, DD ENV, 1993-1-1, EC3.