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Nonlinear Behavior of Continuous Composite Steel Concrete Beam with External Prestress

Ali Hussein Qader, V. C. Agarwal, Amer M. Ibrahim

Abstract—This paper presentsa nonlinear finite-element analyses have been carried out to investigate the behavior up to failure of continuous composite steel-concrete beam with external Prestressing tendon, in which a concrete slab is connected together with steel I-beam by means of headed stud shear connectors, subjected to symmetrically static loading. ANSYS computer program (version 12.1) has been used to analyze the three dimensional model. This covers: load deflection behavior, strain in concrete, strain in steel beam and failure modes. The nonlinear material and geometrical analysis based on Incremental-Iterative load method, is adopted. One model had been analyzed to verify its capability and efficiency. The results obtained by finite element solutions have shown good agreement with experimental result.

Keywords— ANSYS. 12.1, externally Prestressing, Composite steel-concrete beam, Finite element.

I. INTRODUCTION

The use of external Prestressing as a means of strengthening or rehabilitating existing bridges has been used in many countries since the 1950s. It has been found to provide an efficient and economical solution for a wide range of bridge types and conditions. The technique is growing in popularity because of the speed of installation and the minimal disruption to traffic flow. The principle Prestressing, is the application of an axial load combined with a hogging bending moment to increase the flexural capacity of a beam and improve the cracking performance. It can also have a beneficial effect on shear capacity(Dally, 1997)[5]. Composite steel-concrete beams Prestressed with high strength external tendons have demonstrated many advantages as compared with plain composite beams: Increase in ultimate moment capacity of structure, Enlarge the range of elastic behavior before yielding for the structure with the introduction of internal stresses. The stresses can then oppose the moment generated by the loading.

The amount of structural steel used in construction, based on yield strength alone, can be significantly reduced by the use of high-strength tendons, thereby reducing the cost of construction.

A composite beam can be Prestressed, using a jack, by the tensioning high-strength tendons connected at both ends to brackets or anchorages that are fixed to the composite beam. Prestressing 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.

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Prestressing can be carried out for simple-span or continuous-span composite beams. In the positive moment region, the steel beam is usually Prestressed before the concrete is cast because the negative moment induced by Prestressing 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 Prestressed either separately or jointly along the top flange before or after casting of the deck Saadatmanesh[2] (1989).In this paper, a 3D nonlinear finite element model using the finite element program ANSYS version 12.1 has been developed to account for the non-linear behavior in continuous composite beam prestressed with external tendons. To examine the model verification was done using the experimental result of M. Safan, A. Kohoutkov[1](2001).Using this model, numerical analysis was performed and compared with the experimental result.

II. REVIEW OF LITERATURE

Saadatmensh, et al. [2] (1989) tested two prestressed composite steel-concrete beams. Beam (A) had prestressing bars along the bottom (tension) flange and was subjected to positive bending moment. Beam (B) had prestressing bars along the top (tension) flange and was subjected to negative bending moment.Ayyub, et al. [3] (1990) examined the behavior of prestressed composite steel-concrete beams under positive bending moment, and the benefits of different types of prestressing are compared. Safan and Kohoutkova[1](2001) investigated experimentally the behavior of a double-span steel composite beam externally prestressed by means of continuous tendons.Nie, et al. [7] (2007)investigated the behavior of simply supported prestressed steel-concrete composite beams through experimental and analytical studies.Previous research has been done on prestressed steel and concrete composite beams with external tendons such as byDall’Asta and Dezi[13] (1998),Dall’Asta and Zona[14] (2005),ZonaA.[11](2009) and Chen Sh. [12](2009).

III. OBJECTIVES OF THE STUDY

1) To investigate the structural behavior of composite beams external Prestressing in which a concrete beam is connected together with a steel I-beam by means of headed stud shear connectors.
2) To deal with the study of the theoretical analysis of beams by using nonlinear three dimensional finite element program, ANSYS 12.1.
3) To study the validity of the used methods of analysis by comparing their results with the experimental ones.

IV. ANALYTICAL MODEL

In this paper, prestressed continuous composite steel-concrete beam is analyzed; the dimensions and details of the beam are illustrated in Fig.1 and Fig.2 . A beam, (C-BEAM) was analyzed in this study to investigate the behavior of externally prestressed continuous composite steel-concrete beam, by developing a general analytical approach to predict the ultimate flexural response. The accuracy and validity of the finite element models is determined by ensuring that failure modes are correct, the ultimate load is reasonably predicted in comparison with the available experimental investigations. (C-BEAM) is tested by M. Safan, A. Kohoutkova[1]. The beam is continuous composite steel-concrete beam, having concrete slab, steel beam, and two draped prestressing tendons and which is subjected to positive bending moment as shown in Figure 9. The prestressing bars were anchored at the two ends of the beam.

A summary of the materials properties of the selected beams are listed in Table 1.

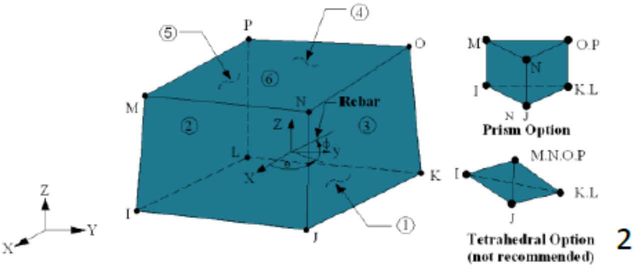


Fig. 1: Loading configuration & dimensions of the test specimen(all dimension in mm)

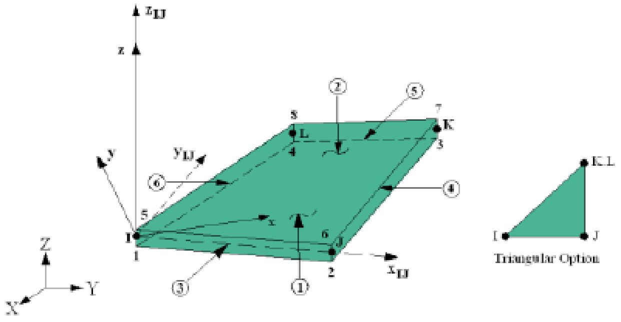


Fig. 2:Details of Beam (C-BEAM)
(all dimension in mm)

Table 1: Summary of Material properties

Beam	Prestressing Tendons			Fc' (MPa)	fy (MPa)
	fpe (MPa)	Ap (mm^2)	Fpy (MPa)		
C-BEAM	1497	141.57	1673	30	300

V. FINITE ELEMENT MODEL

The ANSYScomputer program is utilized for analyzing structural components encountered throughout the current study. Finite element representation and corresponding elements designation in ANSYSused in this study are discussed:-

A. Finite element model of concrete

Solid 65 element type has been used to model the infill cement concrete and its non-linearity for nonlinear analysis. It is used for 3-D modelling of solid with or without reinforcing bars. The solid element has eight nodes with three degrees of freedom at each node – translations in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing. The geometry and node locations for this element type are shown in Figure(3).

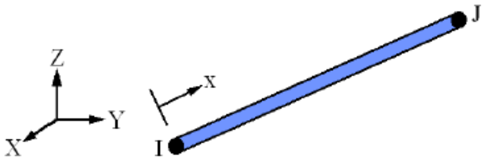


Fig.3: SOLID65 geometry

B. Finite element model of steel beam

To represent the steel beam in finite element, 4-node shell element is needed with three translations in x, y and z in each node to achieve the compatibility condition with translation in x, y and z in adjacent brick element to it. For this purpose, three-dimensional 4-node shell element, which is represented as (SHELL43 in ANSYS) is used, regardless of the rotations in each nodes. The element has plasticity, creep, stress stiffening, large deflection, and large strain capabilities. The geometry, node locations, and thecoordinate system for this element are shown in Figure 4.

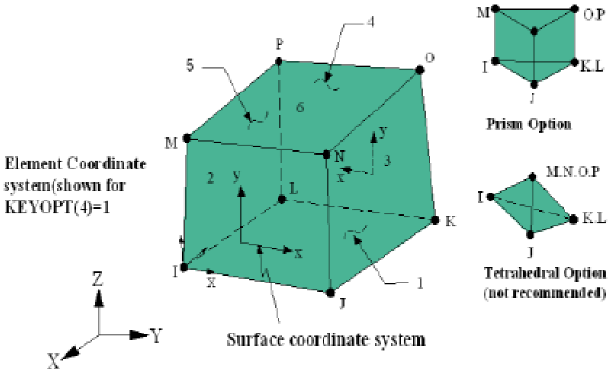


Fig.4: SHELL43 geometry

C. Finite element model of reinforcement

To model steel reinforcement in finite element. Three techniques exist these are discrete, embedded, and smeared. The discrete model (LINK8) is used in this study. The LINK8 is a spar (or truss) element. This element can be used to model trusses, sagging cables, links, springs, etc. The 3-D spar element is a uniaxial tension-compression element with three degrees of freedom at each node: translations of the nodes in x, y, and z-directions.

No bending of the element is considered. The geometry, node locations, and the coordinate system for this element are shown in Figure 3.

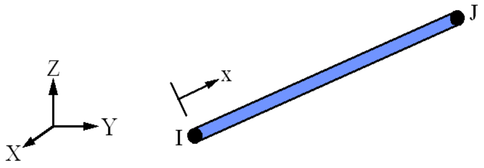


Fig.3: LINK8 geometry

D. Finite element model of external Prestressedtendon

Link8 as shown in Figure 5 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.

E. Finite element model of steel plates

Steel plates are added at the loading location to avoid stress concentration problems. This provides a more even stress distribution over the load area. The solid element (SOLID45 in program) was used for the steel plates. The element is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions as shown in Figure 4.

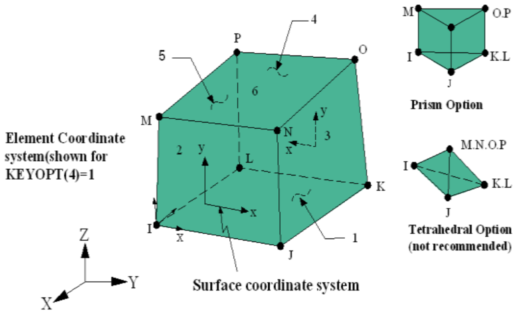


Fig.4: SOLID45 geometry

F. Finite element model of interface surface

A three-dimensional nonlinear surface-to-surface "contact-pair" element (CONTA-173& TARGE170) was used to model the nonlinear behavior of the interface surface between concrete and steel beam. The contact-pair consists of the contact between two boundaries, one of the boundaries represents contact, slid and deformable surface taken as contact surface (CONTA-173 in ANSYS) and the other represents rigid surface taken as a target surface (TARGE-170 in ANSYS). Figure 7 shows the geometry of (CONTA173& TARGE170).

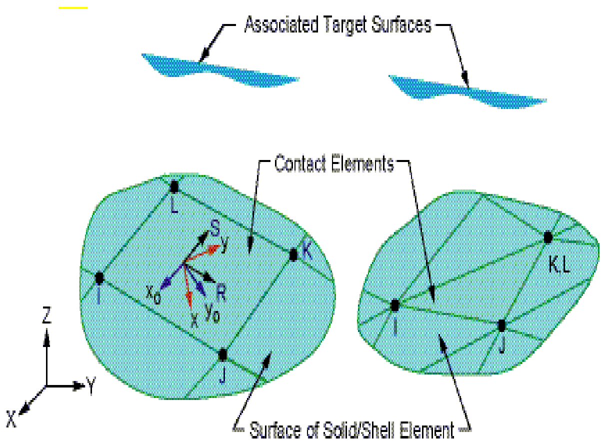
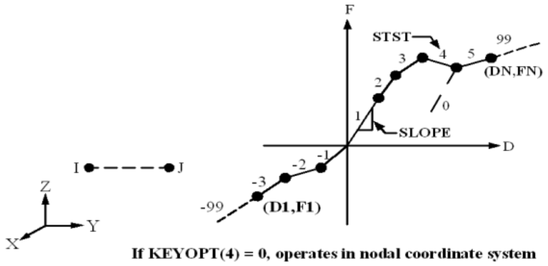


Fig. 4: Geometry of CONTA173 and TARGET170

G. Representation of shear connectors

A nonlinear spring element (COMBIN39 in ANSYS) and (Link8) are used to represent the shear connectors behavior. COMBIN39 is used to resist the normal force between the concrete and steel beam while Link8 works as stirrups in resisting the vertical shear at concrete layer. COMBIN39 is a unidirectional element (or nonlinear spring) with nonlinear generalized force-deflection capability that can be used in any analysis. The element has longitudinal or torsional capability in 1-D, 2-D, or 3-D applications. The geometry, node locations, and the coordinate system for this element are shown in Figure 8.



If KEYOPT(4) = 0, operates in nodal coordinate system

Fig.6: COMBIN39 geometry

VI. MATERIAL MODELING

In this study, the main components of prestressed composite section: concrete slab, steel beam, tendons, contact surface andshear connection are modeled with relevant ANSYSelements that are explained in sequel. A three dimensional element was used to representation the structure.

A. Modeling of concrete

The concrete is assumed to be homogeneous and initially isotropic. The adopted stress-strain relation is based on work done by Desayi and Krishnan[8]; as shown in Figure 9.

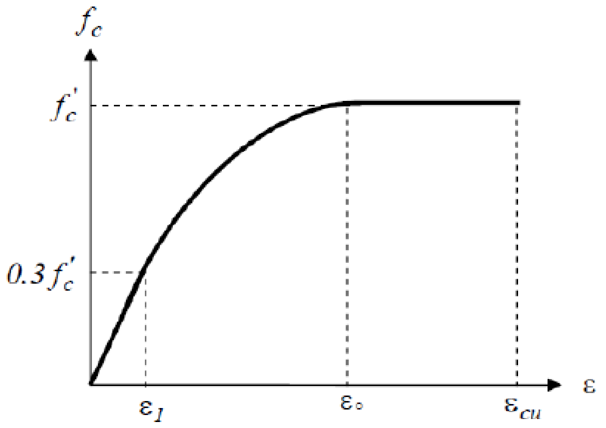


Fig. 7: Simplified compressive Uniaxial stress- strain curve for concrete

Compressive uniaxial stress-strain relationship for concrete model was obtained by using the following equations to compute the multilinearisotropic stress-strain curve for the concrete.

$$f_c = \varepsilon E_c for \quad 0 \le \varepsilon \le \varepsilon_1 \ldots\ldots..(1)$$

$$f_c = \frac{\varepsilon E_c}{1+\left(\frac{\varepsilon}{\varepsilon_\circ}\right)^2} for \quad \varepsilon_1 \le \varepsilon \le \varepsilon_\circ \ldots\ldots...(2)$$

$$f_c = f_c' for \; \varepsilon_\circ \le \varepsilon \le \varepsilon_{cu} \ldots\ldots...(3)$$

$$\varepsilon_1 = \frac{0.3 f_c'}{E_c} (\text{Hooke's law}) \ldots\ldots....(4)$$

$$\varepsilon_\circ = \frac{2 f_c'}{E_c} \ldots\ldots\ldots\ldots....(5)$$

Where:
ε_1=strain corresponding to ($0.3f_c'$), $\varepsilon_\circ$=strain at peck point, ε_{cu}= ultimate compressive strain.

B. Modeling of steel beam

In contrast to concrete, the mechanical properties of steel are well known, and it is a much simpler material to be represented. The strain-stress behavior can be assumed to be identical in tension and compression. The bilinear stress-strain relationship indicated in Figure 10 is used in this study[9].

In the present work, the strain hardening modulus (E_t) is assumed to be (0.03 Es). This value is selected to avoid convergence problems during iteration.

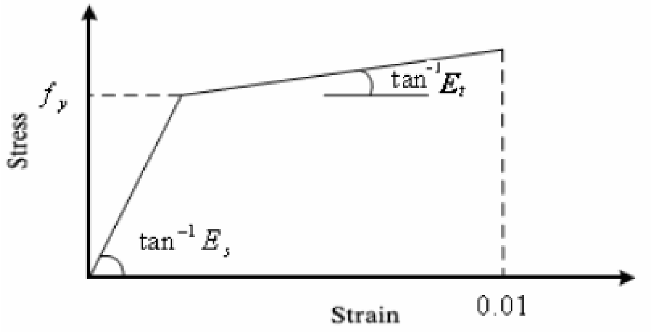


Fig. 8: Bilinear stress-strain relationship of steel beam

C. Modeling of reinforcement and prestressing bars

Since the ordinary steel bars and prestressing cable are slender, they can be assumed to transmit axial force only. Modeling of ordinary steel and prestressed steel in finite element is much simpler. The stress-strain relationship for ordinary reinforcing steel and prestressingtendons can be represented as shown in Figure 10.

D. Shear friction and contact modeling

In the basic Coulomb friction model, the two contacting surfaces can carry shearing stress up to a certain magnitude across their interface before they start sliding relative to each other; this state is known as contact (sticking). Once the shearing stress is exceeded, the two surfaces will slide relative to each other and this state is known as (sliding).In the present work, coefficient of friction with (μ=0.7) has been used.

E. Modeling of shear connector

The normal forces transmitted by the axial forces in the reinforcing bars are modeled by using a link element (LINK8 in ANSYS), while, the shear forces that are transmitted by

shearing and flexure of the reinforcing bars are modeled by using a nonlinear spring element (COMBIN39 in ANSYS). The equation used to modeling the behavior of shear connector is:

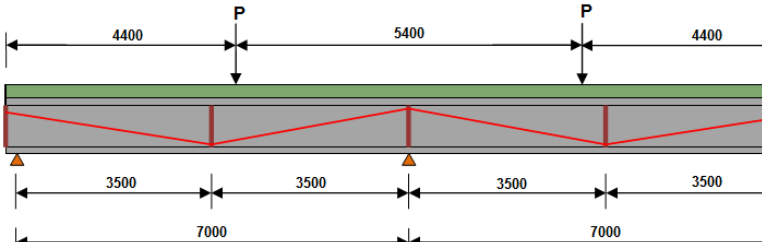
$$F_d = F_{du}\left(1 - \frac{1}{e^{\Delta U_s}}\right)^{0.558} \ldots\ldots\ldots\ldots\ldots(6)$$

F_d is the dowel forceWhere ΔUs= Tangential displacement (mm).F_{du}= Ultimate dowel force (Millard-Johnson Equation), given by:

$$F_{du} = 1.3\text{Ø}^2 \sqrt{1.2 f_c' f_y} \ldots\ldots\ldots\ldots\ldots(7)$$

VII. ANALYTICAL MODEL

In this paper, prestressed continuous composite steel-concrete beam is analyzed; the dimensions and details of the beam are illustrated in Fig.9 and Fig.10 . A beam, (C-BEAM) was analyzed in this study to investigate the behavior of externally prestressed continuous composite steel-concrete beam, by developing a general analytical approach to predict the ultimate flexural response. The accuracy and validity of the finite element models is determined by ensuring that failure modes are correct, the ultimate load is reasonably predicted in comparison with the available experimental investigations. (C-BEAM) is tested by M. Safan, A. Kohoutkova[1]. The beam is continuous composite steel-concrete beam, having concrete slab, steel beam, and two draped prestressing tendons and which is subjected to positive bending moment as shown in Figure 9. The prestressing bars were anchored at the two ends of the beam.



A summary of the materials properties of the selected beams are listed in Table 1.

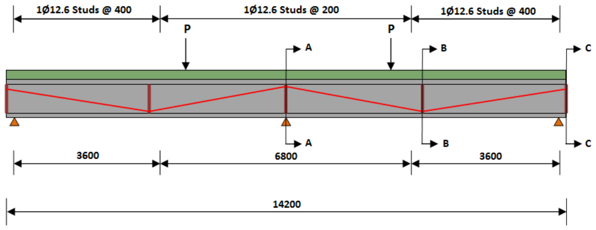
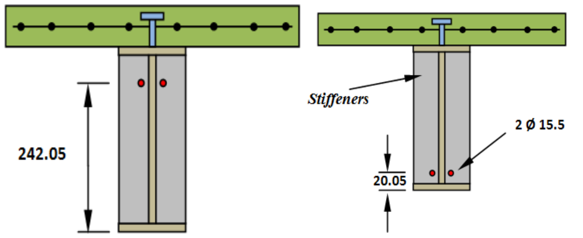
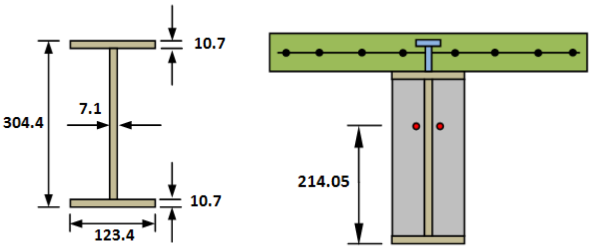


Fig.9: Loading configuration & dimensions of the test specimen(all dimension in mm)



Section (A-A) Section (B-B)

(a)Shear Connectors distribution



(b) Cross section and reinforcement

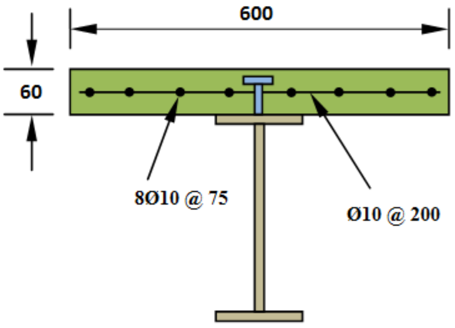


Fig. 10:Details of Beam (C-BEAM) (all dimension in mm)

A. Finite elements mesh

The model designed for the numerical analysis was defined by seven types of elements that form the concrete slab, steel reinforcements, steel beam, shear connectors,two draped prestressing tendons,stiffeners, steel plates and the pair of contact at the slab-beam interface .The Nodes one by one coupled on the interface surface between concrete and steel beam The finite element mesh developed for all elements followed the same methodology.Figure 11 show the finite element mesh for the components cited.

Table 1: Summary of Material properties

Beam	Prestressing Tendons			Fc' (MPa)	fy (MPa)
	fpe (MPa)	Ap (mm^2)	Fpy (MPa)		
C-BEAM	1497	141.57	1673	30	300

VIII. RESULTS AND DISCUSSIONS

A. Load-deflection curve

The load-midspan deflection curve of the prestressedcontinuouscomposite steel-concrete beam obtained from the finite element analysis using ANSYS computer program (version 12.1) was compared with corresponding experimental data as shown in Fig.(12) . In general, it can be noted from the load deflection curve that the finite element analyses is agree well with the experimental result throughout the entire range of behavior.

B. Ultimate load at failure

Table 2 shows the comparison between the ultimate loads of the experimental (tested) beam, $(Pu)_{EXP.}$, and the final load from the finite element model, $(Pu)_{FEM.}$. The final load for the finite element modelis the last applied load step before the solution starts to diverge due to numerous cracks and large deflection.

The numerical model predicts ultimate load of (307.23 kN) at each span, for beam (C-BEAM),and capture well the nonlinear load-deflection response of the beams up to failure as mentioned before. In comparison with the experimental value, the numerical model show (2.35%) increase in ultimate load for the beam (C-BEAM). As shown in Table (2), the ultimate load obtained from numerical model agree well with the corresponding value of the experimental (tested) beam.

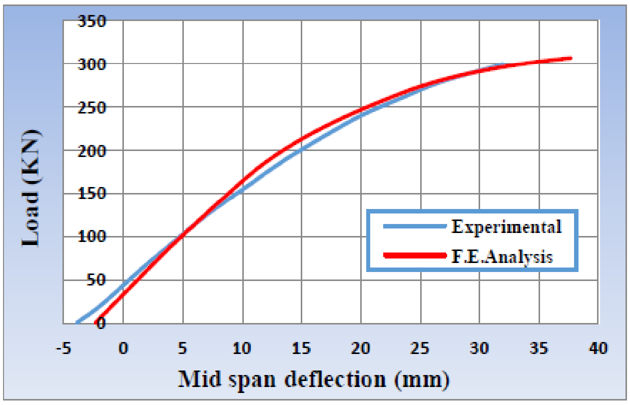


Fig. 11: Load-Deflection Curve for Beam (C-BEAM)

Analytic and test beam	Ultimate load (kN)		$\frac{(Pu)_{FEM}}{(Pu)_{EXP}}$	Difference Ratio
	$(Pu)_{FEM}$	$(Pu)_{EXP}$		
C-BEAM	307.23	300	1.024	2.35%

Table 2: Comparison of Experimental Results with Numerical Results for (C-BEAM)

C. Deflected shape

A deflected shape for two load step, camber arising from the effect ofprestressing force in the external tendon; and deflected shape due toexternally applied loads are shown in Fig. (13) and Fig. (14). Deflection (Vertical displacement) was measured at mid-span of each span of (C-BEAM) at the center of the bottom face of the beam, in y-direction (Uy).

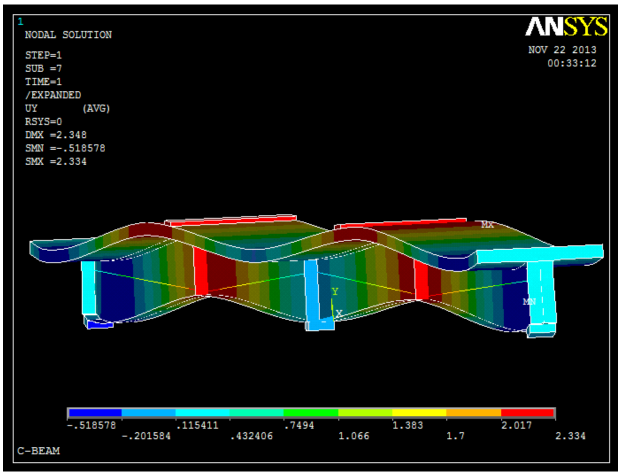


Fig. 12: Initial Camber of the Beam (C-BEAM) with no AppliedConcentrated Load

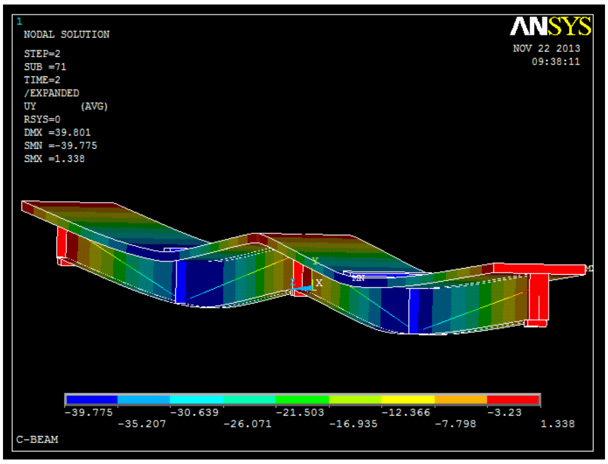


Fig. 13: Deflected Shape for Beam (C-BEAM) at Load = 307.23KN at each span

D. Load-strain curves

Figure (15) shows the load versus extreme compression fiber strain response of the concrete slab observed from analytical study (computer program) of (C-BEAM).

Figure (16) shows results that are obtained by ANSYS computer program for load versus strain in the prestressed bar. The strain in the bar was recorded up to yielding. The curve was offset from the origin of the coordinate system by the initial prestressing strains. This Figure shows the increase in strain in the prestressing tendons with loading. The tendon was pre-strained to an initial strain of 2700 micro-strain reaching a load of 44KN in each of the tendons. In Figures (17) and (18), the mid span top and bottom flange strains of the (C-BEAM) beam is shown. Higher strain values were recorded in the bottom flange than the top flange.

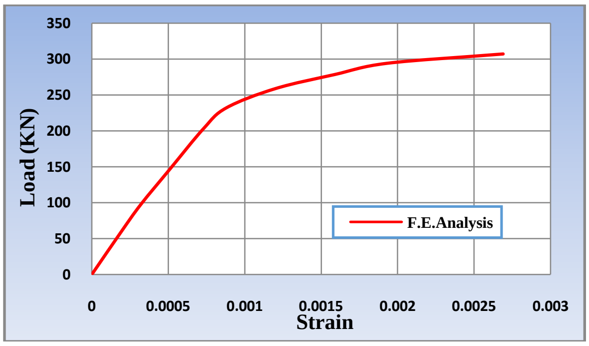


Fig.14: Load-Strain Curve for Extreme Compression Concrete Fiber of (C-BEAM)

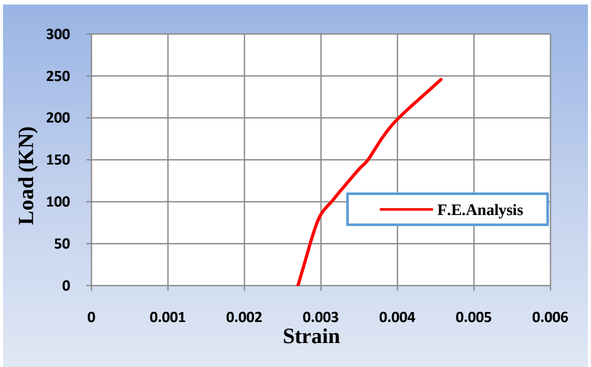


Fig. 15: Load-Strain Curve for Prestressed Bars for (C-BEAM)

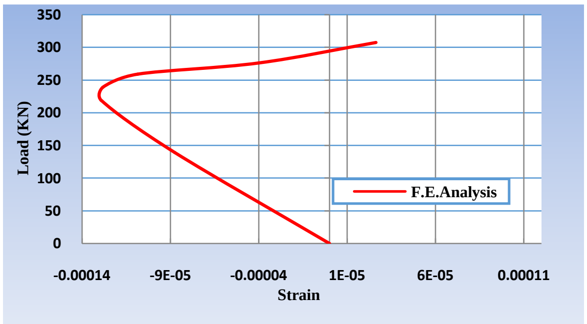


Fig. 16: Load-Strain Curve for Top Flange for (C-BEAM)

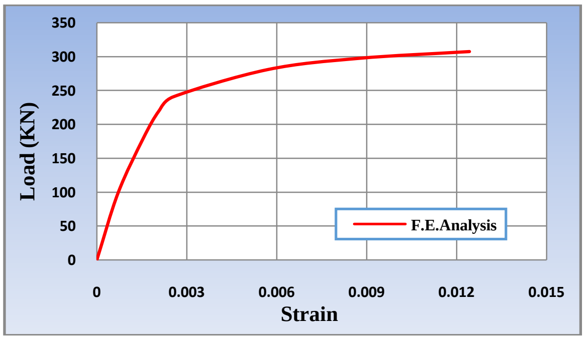


Fig. 18: Load-Strain Curve for Bottom Flange for (C-BEAM)

IX. CONCLUSIONS

The analysis is based on the finite element method by using ANSYScomputer program (version 12.1). A three – dimensional nonlinear finiteelement analysis is conducted to investigate the general behavior ofprestressedcontinuous composite steel-concrete beam.The analytical testcarried out for the onecase studied (draped) indicated that the load-deflection behavior and the ultimate loadis in good agreement with the published experimental result. The difference between the predicted numerical ultimate load to the experimental ultimate load has value of (2.35%) for prestressedcontinuous composite steel-concrete beam. Thisresult reveal the accuracy and efficiency of the developed computer program (ANSYS 12.1) in predicting the behavior and ultimate load of prestressedcontinuouscomposite steel-concrete beam.

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