Nonlinear finite element analysis of simply supported composite beams stiffened with steel channel

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***Abstract*: A composite beam is an accumulation of different materials so as to form a single unit to exploit the prominent quality of these materials according to their position within the cross-section of the composite beam. The present study investigates the structural behavior of six simply supported composite beams, in which a reinforced concrete T-beam is connected together with a steel channel located at the bottom of a T-beam by means of headed stud shear connectors. The used degrees of shear connection are (100%, 75%, 50%, and 38%). Three dimensional nonlinear finite element analysis has been used to conduct the numerical investigation for the general behavior of beams which are subjected to central point load. ANSYS 12.1 program code was used to estimate the ultimate loads, deflections, stresses, strains, end slip. Concrete was modeled by brick element (SOLID65), while the steel channel was modeled as brick element (SOLID45). Two-node discrete elements (LINK8) are used to represent the steel reinforcement and shear connectors. Perfect bond between the reinforcing rebars and the concrete was assumed. The load on beams was applied monotonically in increments up to failure. The reduction of the degree of shear connection from 100% to 38% causes increasing of strain, mid span deflection and end slip with an average of 3.95%, 13%, and 111% respectively, while the ultimate load decreases with an average of 7.3%. In order to observe the efficiency of the 3-D model, a comparison was made with available experimental work. Good agreement was obtained throughout this work between the finite element and available test results.**

I. INTRODUCTION

Steel-concrete composite beams have been extensively used in building and bridge construction. Composite action is achieved by using mechanical shear connectors. The shear connectors are usually welded to the top flange of a steel beam to resist longitudinal slip and vertical separation between the concrete part and the steel section. Economy can be obtained by the adoption of composite action when compared with the conventional design. In multi-storey buildings there will be, however, a considerable reduction in both weight and cost of steel work, if used compositely. A further and real advantage to the steel work designers is that the adoption of composite action for beams reduces the deflection criterion, as the stiffness of the composite section is many times greater that of the steel beam required to carry the same load, reduction of overall structural depth, and reduction of construction time.

Chapman and Balakrishnan 1964[1], studied the behavior of seventeen simply supported composite T-beams under static concentrated and distributed loads. The amount of shear connectors (welded studs) was varied within the range which might be contemplated for design purposes and the effect of interface slip on elastic and ultimate behavior was observed. It was found that the use of ultimate load design for a composite section may lead to working stresses approaching the yield stress, because of the large shape factor. They suggested that the shear connection should be designed to carry the horizontal shear force existing in the beam at ultimate load. For this purpose it was recommended that 80 percent of the experimentally determined capacity of shear connectors should be used. In the case of uniformly loaded beams, a uniform spacing of shear connectors was proved to be satisfactory, notwithstanding the triangular distribution of external shear force.

Mallick and Ghattopadhyay 1975[2], discussed the general behavior of sixteen continuous beams tested to failure under different arrangements of spans and concentrated loads. Reference was made to shear connection, slip, up-lift, flexural mode of action, stiffness and contribution of longitudinal reinforcement in the zones of negative moment. A very high degree of adaptation has been noticed in the tests, and the maximum theoretical loads were observed to have been carried within nine percent. In these tests an exploration was also made for the possibility of ultimate strength design of continuous beams in which the first hinges are formed at the loaded sections with the neutral axes located within the depth of the slab at failure.

II. MATERIALS IDEALIZATION

A. Idealization of Concrete

Three dimensional brick element SOLID65[3] was used to model the concrete with or without reinforcing rebars. The element is defined by eight nodes having three degrees of freedom at each node: translations of the nodes in x, y, and z-directions. Up to three different rebars specifications may be defined. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep. The rebars are capable of tension and compression, but not shear, they are also capable of plastic deformation and creep, figure (1).

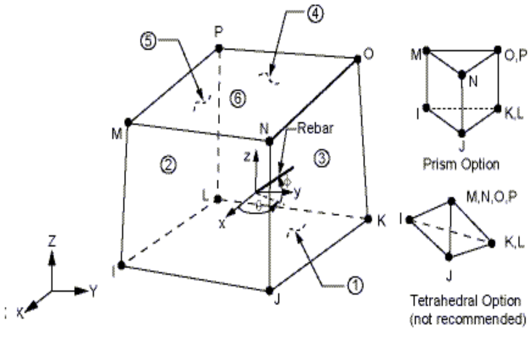


Figure (1) SOLID65 3D- Concrete element. Ref.[3]

B. Idealization of Reinforcing Bar and Shear Connectors

LINK8[3] element is used to model discrete representation of steel reinforcing rebars, which include tensile, compressive, stirrups, transverse reinforcement and stud shear connectors. LINK8 is spar (or truss) element which may be used in variety engineering applications. This element can be used to model trusses, sagging cables, links, spring, etc. The three dimensional spar elements is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z-directions, figure (2).

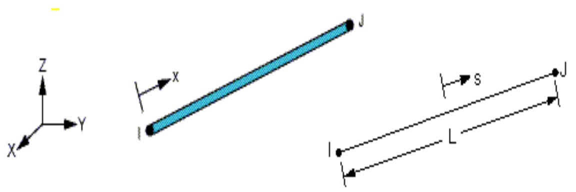


Figure (2) Local and global coordinates of LINK8 element. Ref.[3]

C. Idealization of Steel Channel

Three dimensional brick element SOLID45[3] was used to model the steel channel. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z-directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. The geometry, node locations, and the coordinate system for this element are shown in Figure (3).

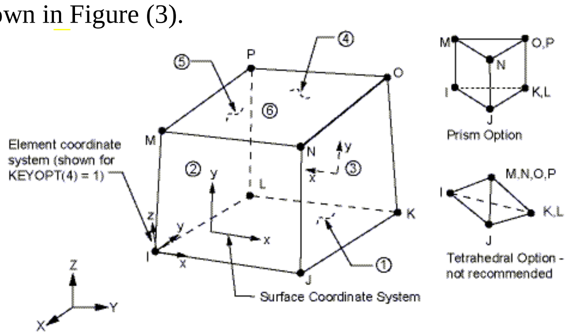


Figure (3) SOLID45 3D- Structural solid element. Ref.[3]

III. MATERIALS PROPERTIES

A. Concrete

The element SOLID65 requires linear isotropic and multilinear isotropic material properties to properly model concrete. From the ultimate uniaxial compressive strength $\grave{f}_c$, Table (1)[4], the elastic modulus of concrete (E_c) for each beam model was calculated according to ACI 318-08[5] by using Eq. (1).

$$E_c = 4700\sqrt{\grave{f}_c} \qquad (1)$$

Where: E_c, $\grave{f}_c$ are in (N/mm^2)

Poisson's ratio 0.3 for all composite reinforced concrete beam [6].

The compressive uniaxial stress-strain relationship for concrete model was obtained by using the following equations to compute the multilinear isotropic stress-strain curve for the concrete [5].

$$f = E_c.\varepsilon/(1+(\varepsilon/\varepsilon_o))^2 \qquad (2)$$

$$\varepsilon_\circ = 2.\grave{f}_c/E_c \qquad (3)$$

$$E_c = \sigma/\varepsilon \qquad (4)$$

Where:

f = stress at any strain ε (N/mm^2).

ε =strain at stress f.

$\varepsilon_\circ$=strain at the ultimate compressive strength $\grave{f}_c$.

Figure (4) shows the simplified compressive uniaxial stress-strain relationship that was used in this study.

The simplified stress-strain curve for concrete model is constructed from six points connected by straight lines. The curve starts at zero stress and strain. Point number 1, at 0.30 $\acute{f}_c$ is calculated for the stress-strain relationship of the concrete in the linear range (Eq. 4). Points number 2, 3, and 4 are obtained from (Eq. 2), in which $\varepsilon_\circ$ is calculated from (Eq. 3). Point number 5 is at $\varepsilon_\circ$and $\grave{f}_c$

TABLE 1. CONCRETE PROPERTIES[4]

Beam Item	Compressive strength $\grave{f}_c$ (MPa)/ 28 days
CB1-100	20.314
CB2-100	23.412
CB3-100	20.839
CB4-100	24.839
CB5-100	25.849
CB6-100	23.471

B. Steel Reinforcement, Shear Connectors and Steel Channel

In the present work the stress-strain curve of reinforcing bar is idealized as a bilinear curve, representing elastic-plastic behavior with strain hardening. This curve is assumed to be identical in tension and compression as shown in Figure (5)[7]. Material properties for the steel reinforcement, shear connector and steel channel are shown in Table (2)[4]. Poisson's ratio is assumed to be 0.3 for all beams[5].

V. GENERAL NONLINEAR SOLUTION

The use of the finite element method in nonlinear structural problems results simultaneous equations of the form [8]

[K].{a}={f } ------------------------------ (5)

In a simple elastic problem the solution for these equations can be obtained directly. This cannot be achieved when the nonlinearity presented in the stiffness matrix [K], which depends on the displacement level {f } = [K] {a}, and therefore cannot be exactly calculated before determination of the unknown nodal displacements {a}. The solution of nonlinear problems is usually attempted by combined Incremental-Iterative Techniques.

The incremental-iterative technique has been widely used in the nonlinear analysis of reinforced concrete structure. There are different methods used in connection with the incremental-iterative techniques.

TABLE 2. PHYSICAL PROPERTIES OF STEEL[4]

Item	Actual dimensions (mm)	Cross-sectional area (mm^2)	Yield stress (N/mm^2)	Modulus of elasticity (N/mm^2)
Channel	160x64.4x7.2	0.02342	312.45	201251
ϕ 10 mm	10	78.5	455.49	195793
ϕ 12 mm	12	0.0113	529.74	197845
ϕ 16 mm	16	0.0201	479.54	202099
Stud	19x100	283.5	460.00	205000

VI. CONVERGENCE CRITERION

The ANSYS program gives a number of choices when designating a convergence criterion. Convergence checking can be based on forces, moments, displacements, or rotations, or on any combination of these items.

Additionally, each item can have a different convergence tolerance value. For multiple degree of freedom problems, it also has a choice of convergence norms. It should almost always employ a force-based convergence tolerance. Displacement-based convergence checking can be added (and, when applicable, moment-based, rotation-based convergence checking can be added), if desired, but should not usually be used alone.

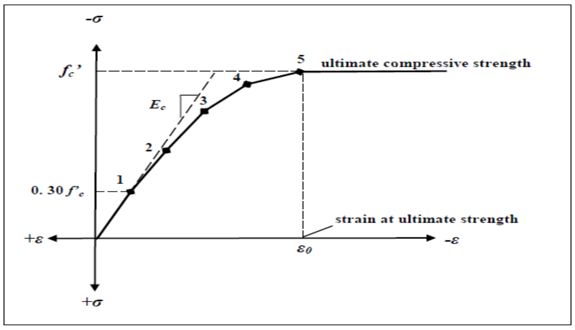


Figure (4) Simplified compressive uniaxial stress-strain curve for concrete. Ref.[5]

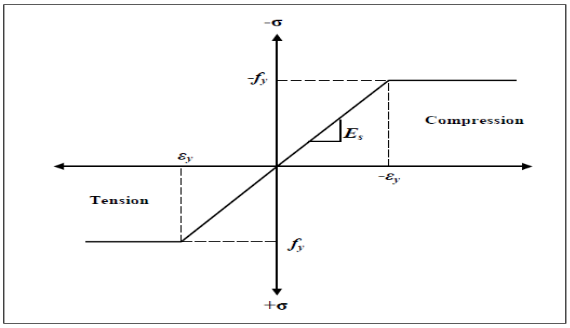


Figure (5) Stress-strain curve for steel reinforcement. Ref.[7]

VII. DETAILS OF BEAMS

In the present study, the structural behavior of simply supported composite concrete T-beam connected with steel channel by means of headed stud shear connectors are simulated depending on available experimental work[4], which are designed by using Taylor method.

Six groups of composite beams of 3 m effective length subjected to central point load were examined, major variables that characterized the beams are:

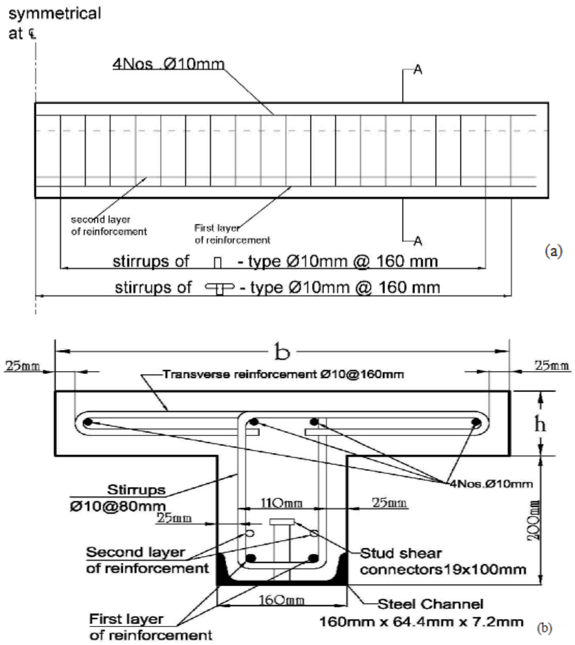
1-width of flange, 2- depth of flange, 3- amount of longitudinal reinforcement

Details of beams are given in Appendix, while longitudinal and transverse reinforcement are shown in Figure (6).

VII. REPRESENTATION OF LOADS AND BOUNDARY CONDITIONS

To get a unique solution, the model should be constrained by using displacement restrictions. For full-size of simply supported beam, the boundary conditions were modeled for roller support as (Uy=0 and Ux=0), while the hinge support was modeled as (Uy=0, Ux=0 and Uz=0).

In the experimental work, and to avoid premature local bearing failure of concrete, it is necessary to provide bearing plates under loading and reactions points. In present work, and for this reason, the load was distributed equally among the nodes under the loading plate. For one-half beam, Figure (7), the nodes at the cut area were restricted in direction normal to the cutting area (Uz=0), the load is also distributed at the nodes adjacent to the cutting area.



a) Reinforcement of concrete T-beam b) Section A-A
Figure (6) Details of beams. Ref.[6]

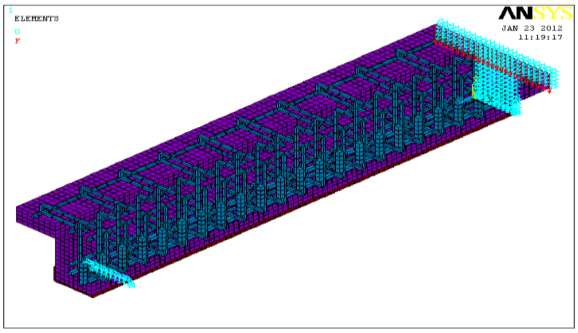


Figure (7) Representation of boundary conditions and applied loads (half span)

IV RESULTS OF BEAMS ANALYSIS

To illustrate the validity of the proposed numerical solution, the beams were analyzed by using the ANSYS computer program, as mentioned previously. The analysis of the composite beam required to transform its material configuration into a mathematical modeling, and insert the input data into the ANSYS program to simulate the actual behavior of the beams, as presented in chapter three.

A. Ultimate Load

The ultimate loads for each beam as calculated by using the finite element method are shown in Tables (4) and (5) for ordinary reinforced concrete T-beams and for composite beams respectively.

A comparison between the ultimate loads obtained from the finite element simulations ($P_{Num.}$) with the ultimate loads of the available experimental work (P_{Exp})[6] are shown in Table (6). The three-dimensional finite element model is found to give ultimate loads closer to the available experimental values, the ratios of the available experimental to numerical values of the ultimate load are 0.95 to 1.022 with an average of 0.999. The maximum difference between the experimental and theoretical ultimate load is less than 5.3%.

The reduction of the degree of shear connection from 100% to 38% causes decreasing ultimate load with an average of 7.3%. The ultimate loads for the finite element models are computed as the last applied load steps before the solution diverges due to numerous cracks and large deformations. It is clear that the ultimate theoretical loads obtained from the finite element analysis agree well with the corresponding values of the ultimate past experimental ones.

TABLE (4) NUMERICAL VALUES OF ULTIMATE LOADS FOR ORDINARY REINFORCED CONCRETE T-BEAMS

Beam item	Ultimate load ($P_{Num.}$) kN
TB1	175.750
TB2	199.000
TB3	176.000
TB4	206.718
TB5	210.910
TB6	217.480

TABLE (5) NUMERICAL VALUES OF ULTIMATE LOADS FOR COMPOSITE BEAMS

Beam item	Ultimate load ($P_{Num.}$) kN	Beam item	Ultimate load ($P_{Num.}$) kN
CB1-100	236.800	CB4-100	296.894
CB1-75	232.718	CB4-75	294.160
CB1-50	229.820	CB4-50	290.819
CB1-38	225.136	CB4-38	282.720
CB2-100	281.960	CB5-100	314.520
CB2-75	280.295	CB5-75	296.530
CB2-50	272.829	CB5-50	290.486
CB2-38	266.506	CB5-38	283.210
CB3-100	267.038	CB6-100	304.641
CB3-75	245.840	CB6-75	298.920
CB3-50	240.950	CB6-50	292.256
CB3-38	234.003	CB6-38	286.370

TABLE (6) ULTIMATE LOADS OF EXPERIMENTAL AND NUMERICAL ULTIMATE LOADS FOR COMPOSITE BEAMS

Beam item	Ultimate load (kN)		$P_{Exp.}$ / $P_{Num.}$	(($P_{Exp.}$-$P_{Num.}$) /$P_{Exp.}$) (%)
	$P_{Exp.}$	$P_{Num.}$		
CB1-100	241.620	236.800	1.020	2.0
CB2-100	288.022	281.960	1.022	2.2
CB3-100	253.687	267.038	0.950	5.3
CB4-100	299.597	296.894	1.009	0.9
CB5-100	308.230	314.520	0.980	2.0
CB6-100	309.211	304.641	1.015	1.5
Average			0.999	2.3

B. Deflection

The load-deflection curves obtained from the experimental test results for composite beams[6] are shown in Figure (8). While Figures (9) to (12) shows the load-deflection relationships obtained numerically for groups of six composite beams, each group have the same degree of shear connection of 100%, 75%, 50%, and 38%, respectively. The reduction of the degree of shear connection from 100% to 38% causes increasing of mid span deflection with an average of 13%. Good agreement is obtained between the predicted finite element results with experimental work. Figure (13) shows the deflection contours along half span for all beams at ultimate load.

C. End Slip

The variation of the end slip between the reinforced concrete T-beam and steel channel with load for degrees of shear connection 100%, 75%, 50%, and 38%, are shown in Figure (14), respectively. While Figures (15) to (16) shows the variation of end slip with load for the interested degrees of shear connection for beams CB1, CB2, CB2, CB4, CB5, and CB6 respectively. From the above figures, it can be seen that, the effect of shear connection degree on the end slip embodies through that, when the degree of composite action increases from 38% to 100%, the end slip decreases considerably by an average of 111%. The maximum values of end slip for all the considered beams are less than 2.5mm, which is recommended as failure value for shear connection.

D. Stresses and Strains

As the applied load increases, the strains are increasing continuously due to the effect of stresses redistribution at the cracked elements. Figure (17) shows the contours of the stresses distribution along half beam span at ultimate load, maximum stresses are ranged between 574.563 N/mm^2 to 787.521 N/mm^2 with an average of 683.318 N/mm^2. Figure (18) shows contours of the strains distribution along half span for beams at ultimate load, maximum strains are varied from 0.002784 to 0.003825 with an average of 0.003324. The lower values of ultimate load obtained theoretically may be attributed to the maximum compressive strain for concrete (0.0035), which is permitted by the code[9], this value governs the failure of beams in sagging bending. The reduction of the degree of shear connection from 100 % to 38% causes an increasing of the stresses and strains about 2.26% and 3.59%, respectively.

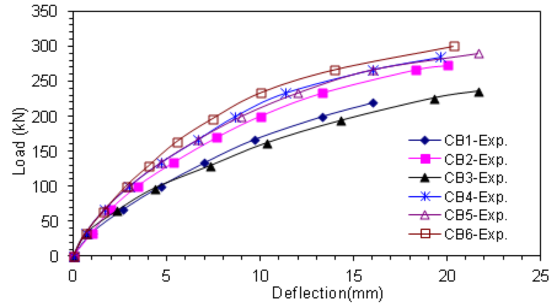


Figure (8) Variation of mid-span deflection with load (Experimental work). Ref.[6]

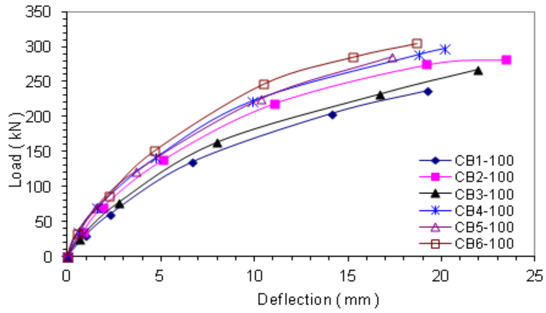


Figure (9) Variation of mid-span deflection with load (100% degree of shear connection)

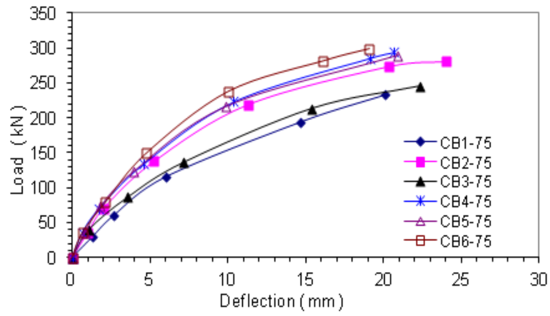


Figure (10) Variation of mid-span deflection with load (75% degree of shear connection)

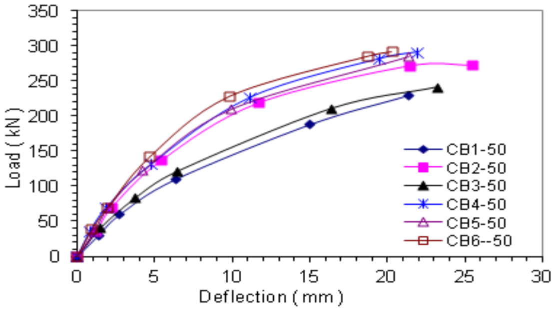


Figure (11)Variation of mid-span deflection with load (50% degree of shear connection)

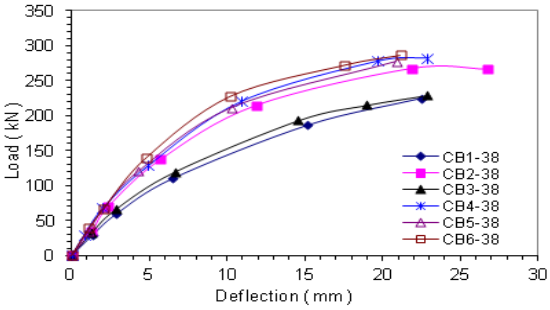


Figure (12)Variation of mid-span deflection with load (38% degree of shear connection)

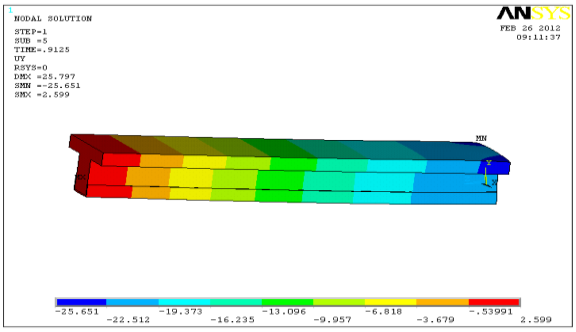


Figure (13) Deflection distribution along half span for beam CB1-38 at ultimate load

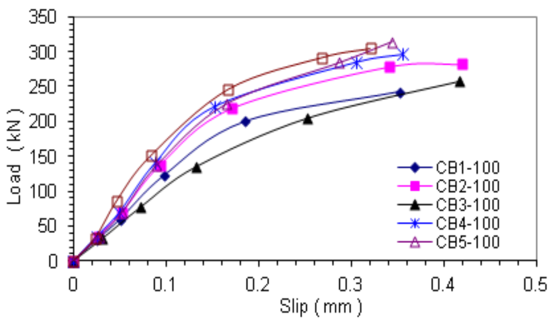


Figure (14) Variation of end-slip with load (100% degree of shear connection)

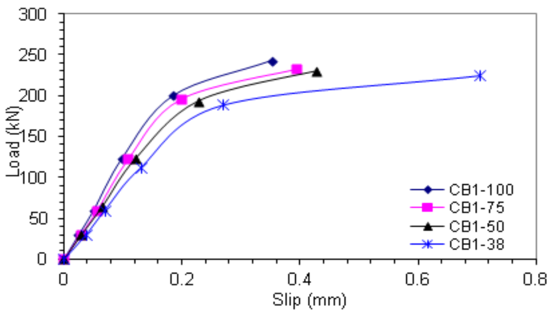


Figure (15) Variation of end-slip with load for beams CB1

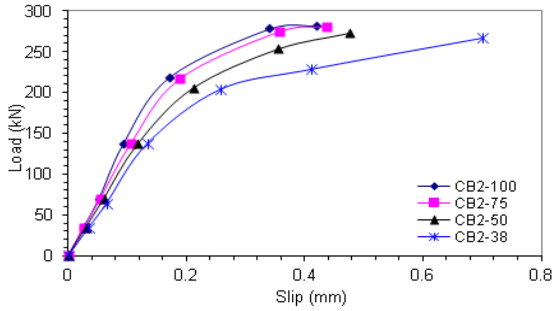


Figure (16) Variation of end-slip with load for beams CB2

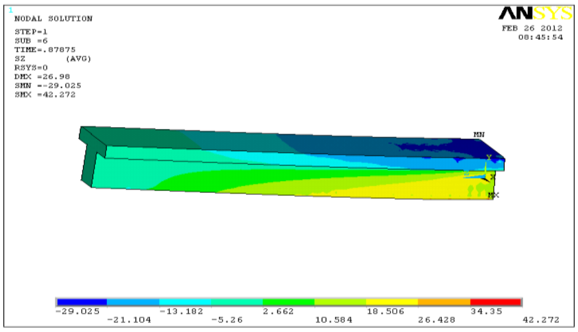


Figure (17) Stress variation in Z-direction along half span for beam TB1 at ultimate load

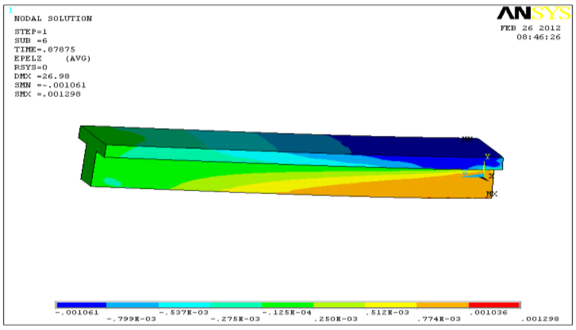


Figure (18) Strain variation in Z-direction along half span for beam TB1 at ultimate load

XII. CONCLUSIONS

The main concluding remarks that have been achieved from the finite element analysis may be summarized as:

1- The three–dimensional finite element model used in the present study is able to simulate the composite beams. The ultimate loads predicted are very close to that measured during the available experimental work.
2- The maximum difference between the experimental and the theoretical ultimate load is less than 5.3%. Composite action increases the ultimate load as compared with ordinary reinforced concrete beam, the average of increasing the ultimate load is about 44%.
3- As the degree of shear connection decreases from 100% to 38% The ultimate load decreases with an average of 7.3%. Mid span deflection obtained from the finite element is agrees well with the available experimental results.
4- The reduction of the degree of shear connection from 100% to 38% causes increasing mid span deflection with an average of 13%. The end slip between the reinforced concrete T-beam and steel channel increases when degree of shear connection decreased from 100% to 38% with an average of 111%.

5- The reduction of the degree of shear connection from 100% to 38% causes increasing of the stresses and strains about 2.26% and 3.59%, respectively.

IX. APPENDIX

Beam Item	Overall Depth (mm)	Flange dimensions		Internal tension reinforcement		Shear connectors	
		Width (mm)	Depth (mm)	Bottom layer	Top layer	Total No. per beam	Degree of Shear connection
CB1-100	270	420	70	2 ϕ12 mm	2 ϕ12 mm	43	100
CB1-75						32	75
CB1-50						21	50
CB1-38						16	38
CB2-100	300	420	100	2 ϕ12 mm	-------	43	100
CB2-75						32	75
CB2-50						21	50
CB2-38						16	38
CB3-100	270	460	70	2 ϕ16 mm	2 ϕ12 mm	43	100
CB3-75						32	75
CB3-50						21	50
CB3-38						16	38
CB4-100	300	460	100	2 ϕ10 mm	2 ϕ10 mm	43	100
CB4-75						32	75
CB4-50						21	50
CB4-38						16	38
CB5-100	270	500	70	2 ϕ16 mm	2 ϕ16 mm	43	100
CB5-75						32	75
CB5-50						21	50
CB5-38						16	38
CB6-100	300	500	100	2 ϕ16 mm	-------	43	100
CB6-75						32	75
CB6-50						21	50
CB6-38						16	38

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