Development of Three - Layer Composite Steel - Concrete - Steel Beam Element with Applications

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Abstract

In this study, a general linear one-dimensional finite element beam model is developed for the analysis of the three layer composite steel- concrete- steel beams which are a special case of the multi-layer

Connectors, concrete layer thickness, plate thickness, type of loading and concrete compressive strength composite beams. The model is based on partial interaction theory of composite beams where the flexibility of shear connectors is allowed. A program is constructed using VISUAL BASIC language to analyze this type of beams.

Numerical applications are presented to demonstrate the validity and applicability of the present method. A parametric study is carried out to demonstrate the effect of some parameters including the variation of shear stiffness of shear on the behaviour of three-layer composite beams. The results of the proposed programmed model shows a good agreement with those obtained by finite elements method using ANSYS program (Release 11, 2007. The models used in ANSYS program are shell element, brick element and combine element to simulate the behaviour of steel plates, concrete part and shear connectors respectively.

Keywords: Composite SCSS beams, Finite elements, Partial interaction, parametric study, ANSYS

تطوير عنصر عتبة مركبة من ثلاث طبقات فولاذ – خرسانة – فولاذ مع تطبيقات

الخلاصة

في هذه الدراسة تم تطوير نموذج عام خطي ذو بعد واحد بطريقة العناصر المحددة لتحليل العتبات المركبة ثلاثية الطبقة فولاذ – خرسانة – فولاذ وهي حالة خاصة من العتبات المركبة متعددة الطبقات . إن النموذج المقترح قد تم بناؤه على أساس نظرية الربط الجزئي للعتبات المركبة حيث تتصرف روابط القص بصورة مرنة. لقد تم بناء برنامج باستخدام لغة (VISUAL BASIC) لتحليل العتبات من هذا النوع. ولاختبار صحة ودقة الطريقة المقترحة تم تطبيقها على عدد من الأمثلة, كما تم إجراء دراسة لتحديد تأثير بعض العوامل على تصرف هذا النوع من العتبات , وقد شملت الدراسة تأثير كل من الجساءة العمودية لروابط القص ،سمك طبقة الخرسانة ، سمك صفائح الحديد، نوع الأحمال، ومقاومة الانضغاط للخرسانة. وقد أظهرت النتائج توافقا جيدا مع التي تم الحصول عليها باستخدام طريقة العناصر المحددة من برنامج ANSYS. (الإصدار الحادي عشر، 2007)

Introduction

The aim of using or selecting any material in construction is to make full use of its properties in order to get best performance for the structure being constructed keeping

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in mind the availability, strength, workability, durability of the material and economy of construction [1]

The most important and frequently encountered combination of construction materials is that of steel and concrete applied for buildings as well as bridges. Although very different in nature , these two materials complement one another:

- Concrete is efficient in compression and steel reinforcement in tension.
- Steel components are relatively thin and prone to buckling, concrete can restrain these against buckling.
- Concrete also gives protection against corrosion and provides thermal insulation at high temperature.
- Steel brings ductility into the structure

Steel-concrete-steel sandwiched (SCSS) construction or double skin (DSC) construction is a special case of multi-layer composite constructions. It is a relatively new and innovative form of construction consisting of a layer of plain concrete, sandwiched between two layers of relatively thin steel plates, connected to the concrete by shear connectors. SCSS construction was originally considered as an alternative form of construction for immersed tube tunnels as shown in Figure (1).

It has been used for a variety of offshore and onshore applications including oil production and storage vessels, caissons, core shear walls in tall building and blast and impact resistant structures [2].

The system was originally devised for use in submerged tube tunnels by a team of local constructions in Cardiff, UK (Messrs Tomlinson and partners in conjunction with Sir Alexander Gibb and partners) [3]

The important advantages of the system are that the external steel plates act as both primary reinforcement and permanent formwork, and also as impermeable, and blast and impact resistant membrane.

The full or partial depth shear connectors are used which transfer normal and shearing forces between the concrete and the steel plates, and also act as transverse shear reinforcement .[4]

In this study a three-layer composite element is developed. The element is used to analyze the steel-concrete-steel sandwiched (SCSS) beams with partial composite action. The Finite Element Method has been used to derive the stiffness matrix of the one dimensional composite element with 9 degrees of freedom per node.

A computer program is established using **BASIC** language to analyze this type of beams. The results of the program are compared with those obtained by **ANSYS** computer program and show a good agreement.

2. Finite Element Formulation

2.1 Basic Assumptions

In the analysis of three-layer composite beams by the finite element method, the following assumptions are introduced:

1. The shear connection between the three components of a composite beam is continuous along the length, i.e. discrete deformable connectors are assumed to be replaced by a medium of

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negligible thickness having normal and tangential modulus, as shown in Figure (2)

2. For each layer, Euler-Bernoulli assumption of plane sections normal to neutral plane (or axis of the beam) before bending remain plane and normal to the deflected axis after bending. This implies that distribution of strain is linear over the depth of each layer. Hence, no transverse shear deformation in layers is assumed.
3. Only longitudinal normal strain, slip (connector shear strain) and uplift (separation between layers) are taken into account.
4. The constitutive relations, including the stress-strain relations for layers and the load-slip relation for shear connectors are assumed linear.
5. The deformation in the structure is assumed small such that nonlinearity due to geometry is negligible.
6. Friction and bond effect between layers are neglected(slip is allowed).
7. No shear lag is present in the layer section, i.e. no variation of the layers strain or stress across the width of the concrete section is allowed.
8. The load is applied in short terms so that the effects of long term loading (creep and shrinkage) are neglected.

2.2 Derivation of the Stiffness Matrix

The derivation of the stiffness matrix can be achieved either by using the minimum total potential energy principle or by using the principle of virtual displacements. Here, for simplicity the principle of minimum total potential energy is used. The total potential energy is equal to the strain energy stored in the body minus the losses in potential due to applied loads.

$$\Pi = U - V \quad \text{———} (1)$$

Where: Π = total potential energy., U = strain energy. , V =losses in potential energy due to applied loads.

To get the equilibrium equations:

$$\frac{\partial \Pi}{\partial e_i} = 0 \quad \text{———} (2)$$

Where e_i is any degree of freedom?

According to the degrees of freedom shown in Figure (2) and the deformation shown in Figure (3) the displacements and strains at interface are as follows:

In component 1 (top layer element):-

$$u^{(1)} = u_0^{(1)} - \frac{dw^{(1)}}{dx}.z^{(1)} \quad ,$$

$$e^{(1)} = \frac{du_0^{(1)}}{dx} - \frac{d^2w^{(1)}}{dx^2}.z^{(1)} = e_0^{(1)} - \frac{d^2w^{(1)}}{dx^2}.z^{(1)}$$

In component 2 (intermediate layer element):-

$$u^{(2)} = u_0^{(2)} - \frac{dw^{(2)}}{dx}.z^{(2)}$$

$$e^{(2)} = \frac{du_0^{(2)}}{dx} - \frac{d^2w^{(2)}}{dx^2}.z^{(2)} = e_0^{(2)} - \frac{d^2w^{(2)}}{dx^2}..z^{(2)}$$

In component 3 (bottom layer element):-

$$u^{(3)} = u_0^{(3)} - \frac{dw^{(3)}}{dx}.z^{(3)} \quad ,$$

$$e^{(3)} = \frac{du_0^{(3)}}{dx} - \frac{d^2w^{(3)}}{dx^2}.z^{(3)} = e_0^{(3)} - \frac{d^2w^{(3)}}{dx^2}..z^{(3)}$$

Slip at interfaces

Slip between top layer element and intermediate layer element

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$$s_{12} = u^{(1)}(bottom face) - u^{(2)}(top face) = u^{(1)}(z = -d^{(1)}_{bot}) - u^{(2)}(z = d^{(2)}_{top})$$

$$s_{12} = (u_0^{(1)} + \frac{dw^{(1)}}{dx}.d^{(1)}_{bot}) - (u_0^{(2)} - \frac{dw^{(2)}}{dx}.d^{(2)}_{top}) \quad ---(3)$$

Slip between intermediate layer and bottom layer is:

$$s_{23} = u^{(2)}(bottom\ face) - u^{(3)}(top\ face)$$

$$s_{23} = (u_0^{(2)} + \frac{dw^{(2)}}{dx}.d^{(2)}_{bot}) - (u_0^{(3)} - \frac{dw^{(3)}}{dx}.d^{(3)}_{top}) \quad ---(4)$$

The shear flow at interface:

$$f_{(interface)} = \frac{k_s.n}{p}.s$$

(per unit length(smeared model))

Where k_s = shear stiffness of one connector(force/unit slip)
n = no. of connectors in one row
p = spacing (or pitch) of connector along the beam

Separation at interface

a- Between the top and bottom layers

$$w_{(separation)} = w^{(2)} - w^{(1)} \quad ------------(5)$$

b- Between the intermediate and bottom layers

$$w_{(separation)} = w^{(3)} - w^{(2)} \quad ------------(6)$$

The normal force at interface:

$$q_{(interface)} = \frac{k_n.n}{p}.w_{(seperation)}$$

$k_n = normal\ \ stiffness\ of\ one\ connector$
(Force/unit separation)

Derivation

$$u_o^{(1)} = N_1 u_{01}^{(1)} + N_2 u_{02}^{(1)}$$

$$u_o^{(2)} = N_1 u_{01}^{(2)} + N_2 u_{02}^{(2)}$$

$(axial deformation component 1)$

$(axial deformation component 2)$

For 2-nodes

$$u_o^{(3)} = N_1 u_{01}^{(3)} + N_2 u_{02}^{(3)}$$

$(axial deformation component 3)$

$The shape functions are:$

$$N_1 = \frac{1-x}{L} \quad and \quad N_2 = \frac{x}{L}$$

$$w^{(1)} = N_3 w_1^{(1)} + N_4 q_1^{(1)} + N_5 w_2^{(1)} + N_6 q_2^{(1)}$$

Also :

$$w^{(2)} = N_3 w_1^{(2)} + N_4 q_1^{(2)} + N_5 w_2^{(2)} + N_6 q_2^{(2)}$$

And :

$$w^{(3)} = N_3 w_1^{(3)} + N_4 q_1^{(3)} + N_5 w_2^{(3)} + N_6 q_2^{(3)}$$

where:

$$N_3 = 1 - \frac{3x^2}{L^2} + \frac{2x^3}{L^3} \qquad N_4 = x - \frac{2x^2}{L} + \frac{x^3}{L^2}$$

$$N_5 = \frac{3x^2}{L^2} - \frac{2x^3}{L^3} \qquad N_6 = \frac{x^3}{L^2} - \frac{x^2}{L}$$

The principle of minimum potential energy is used to derive the stiffness matrix (18x18) and nodal forces vector (18x1).

[illegible]

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To get the stiffness matrix (and the nodal force vector), the following is used:

$$\frac{\partial\Pi}{\partial u_{o1}^{(1)}}=0,\ \frac{\partial\Pi}{\partial u_{o1}^{(2)}}=0,\ \frac{\partial\Pi}{\partial u_{o1}^{(3)}}=0,\ \frac{\partial\Pi}{\partial w_{1}^{(1)}}=0,\ \frac{\partial\Pi}{\partial q_{1}^{(1)}}=0,\ \frac{\partial\Pi}{\partial w_{1}^{(2)}}=0$$

And so on.

3. Material Modelling

3.1 Concrete

For the linear proposed model, only modulus of elasticity(E_c) is needed to define the concrete model. According to ACI- code[5] :

$$E_c = 4700\sqrt{f_c'} \quad ------------(7)$$

Where f_c' is the cylinder compressive strength of concrete in MPa and E_c is the modulus of elasticity of concrete in MPa.

While for **ANSYS** computer program, the uniaxial stress-strain relationship for concrete in compression is defined according to (Desayi and Krishnan) [6] as follows:

$$f=\frac{E_c\,\varepsilon}{1+\left(\frac{\varepsilon}{\varepsilon_o}\right)^2}\ ---(8)\ ,\quad \varepsilon_o=\frac{2f_c'}{E_c}----(9)\ ,\quad E_c=\frac{f}{\varepsilon}----(10)$$

where: f = stress at any strain e , N/mm^2. , e = strain at stress f .

$E_c =$ Initial modulus of elasticity for concrete (equation 7)

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

3.2 Steel

For the linear proposed model, only modulus of elasticity (E_s) is needed to define the steel model. According to ACI- code[5] :

$$E_s = 200000\ MPa \quad ------------(11)$$

For **ANSYS** computer program, Steel is a much simpler material to represent compared to concrete. Its strain-stress behavior can be assumed to be identical in tension and compression. A typical uniaxial stress-strain curve for a steel specimen loaded monotonically in tension is shown in Figure (5). The stress-strain diagram may be made for simplicity to consist of two branches: A first branch starts from the origin with a slope equal to E_s, up to yield stress f_y. A second branch is horizontal (perfectly plastic) or, for practical use of computers, is assumed to have a very small slope(strain hardening) such as $10^{-4}E_s$ and this last case is limited to the strain 0.01 according to EC4 [7].

3.3 Shear Connectors

For the proposed model, the properties needed are the tangential stiffness of the connector layer (K_s), and the normal stiffness of the connector

layer (K_n).

The tangential stiffness (K_s) is calculated from:

$$K_s=\frac{k_s\,n}{p} \quad ---------------(12)$$

where k_s = shear stiffness of one connectors (force/unit slip)= 100 kN/mm (AZIZ(8))

n = no. of connectors in one row

p = spacing (or pitch) of connector along the beam

The normal stiffness (K_n) is calculated from:

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$$K_n = \frac{k_n.n}{p} \quad ----------(13)$$

k_n =Normal stiffness of one connector (force/unit separation)= 1 kN/mm (in tension)= 10 kN/mm (in compression)

While for **ANSYS** program, only the shear and normal stiffnesses k_s and k_n are needed.

In this study, the relation between force and displacement for the shear connectors is modelled as linear for the proposed and **ANSYS** model, the shear and normal stiffnesses are defined using the experimental results carried out by AZIZ[8].

4. Numerical Applications

To check the validity and accuracy of the finite element model, two examples are carried out, the first presents the analysis of three layered composite simply supported beam under mid-span concentrated load while the second concerns the analysis of the same beam under uniform load. Due to symmetry one half of beam is considered in the analysis. The analyzed beam is of 6000 mm length(center to center) and 200 mm width, consists of (figure 6):

- Concrete part of 200mm depth sandwiched between two steel plates.
- Two steel plates, each of 10mm depth, one at the top of the beam and the other is at the bottom of beam.
- Shear connectors between the concrete and the two steel plates. The shear connectors are of stud type with 13 mm diameter.

4.1 Proposed Model Analysis

For the proposed model, the value of $f'_c = 25\,MPa$ is adopted, thus from equation (7) the modulus of elasticity equals to 23500MPa. According to the tests carried out by AZIZ[8] the value of the shear stiffness of head stud connectors at 50% of ultimate strength ranges from 106 kN/mm for (13mm) diameter to 203 kN/mm for (19mm) diameter. If the value of k_s =100 kN/mm is adopted, two rows of shear connectors at 200mm spacing are used then $K_s = k_s.n/p$ = 1 kN/mm^2, While the normal stiffness of the connector layer $K_n = k_n.n/p$. Since this example is used for comparing results then, $K_n = K_s$ = 1 kN/mm^2 in tension (separation) and K_n = 10 kN/mm^2 in compression (contact) is adopted.

4.2 ANSYS Model

The shell43 element is used to model the top and bottom steel plates while solid65 brick concrete element is used to model the concrete sandwiched between the steel plates. Combine39 is used to model shear connectors, two types of this element are used ,one exhibits displacement in x-direction only to simulate the resistance to horizontal shear while the other exhibits displacement in y-direction only to simulate the resistance to normal force[9]. The two types of this element can be extinguished using KEYOP3 Command, then selecting (UX) for the first type and (UY) for the second.

4.3 Load data

The beam is analyzed under central point and uniform load. Since the analysis using the proposed model is linearly elastic, while the nonlinear material properties are considered when the analysis is carried out by ANSYS program, the load is taken

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nearly half of the failure load. The failure load is found by ANSYS program and it is equal to 120 kN and 40 kN/m for concentrated and uniform load respectively. Thus the analysis is carried out using a concentrated and uniform load equal to 60 kN and 20 kN/m respectively. Since one half of the beam is considered, then the concentrated load is taken 30 kN.

4.4 Results

Figures (7) to (9) show the values of deflection, lower interface slip and upper interface slip along the beam under concentrated and uniform loads. Tables (1) to (3) show the difference of maximum deflection, maximum lower interface slip and maximum upper interface slip between the present study and ANSYS which are equal to 9.6%, 5.3% and 8% respectively.

4.5 Parametric study

In addition to the results above, a parametric study is carried out to demonstrate the effects of the following factors on the behavior of this type of beams:

1. Shear stiffness of connectors: Figures (10.a), (10.b) and (10.c) show the effect of this factor on the behavior of the beam (deflection, slip at lower and upper interfaces). The reference value of the stiffness is taken (1000 N/mm^2) which is considered (100%). The other values are (500 N/mm^2 = 50%) and (2000 N/mm^2=200%)

2. Normal stiffness of connectors: To investigate the effect of the this factor on the behavior of the beams (deflection, slip, separation), three values of tensile normal stiffness are considered, KN=1000 N/mm^2=100%, KN=500 N/mm^2=50%, and KN=2000 N/mm^2=200%. From the results it was found that the effect of this parameter is very small and can be neglected.

3. Concrete layer thickness: Figures (11.a), (11.b) and (11.c) show the effect of this factor on the behavior of the beam (deflection, slip at lower and upper interfaces). The reference value of thickness is taken (200mm), which is considered (100%). The other values are (300mm = 150%) and (400 mm=200%).

4. Steel plates thickness: Figures (12.a), (12.b) and (12.c) show the effect of this factor on the behavior of the beam (deflection, slip at lower and upper interfaces). The reference value of thickness is taken (10mm), which is considered (100%). The other values are (15mm = 150%) and (20 mm=200%).

5. Concrete compressive strength: Figures (13.a), (13.b) and (13.c) show the effect of this factor on the behavior of the beam (deflection, slip at lower and upper interfaces). Three types of concrete strength are taken in to consideration, $f_c' = 20, 30,$ and 40 MPa.

5. Conclusions

Based on the results obtained in this investigation, the following can be concluded:

1. The proposed method of the finite element analysis with the developed composite beam element appears to be valid and powerful for the elastic analysis of the three layered composite beams.
2. Comparison of the results of the present study with that of

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ANSYS program, show that the maximum difference in deflection is 9.6%. which are considered reasonable values.

3. The significant factor which affects the stiffness of the three layered beam is the shear stiffness of the connectors.
4. The normal stiffness of shear connectors in tension has a negligible effect on the behavior of the three layered composite beams.
5. The lower interface slip is much greater than the upper interface slip. This is due to the restraint of the lower layer in the horizontal direction and due to the tensile stress developed in concrete at lower interface while the stress developed at top interface is of compression type.
6. Increasing the concrete thickness decreases the deflection and slip. The effect of this parameter on the upper interface slip is more than that on the lower interface slip.
7. Increasing the steel plate thickness decreases the deflection and lower interface slip, while it increases the upper interface slip.
8. The increase in the compressive concrete strength will decrease the deflection and slip. Generally the rate of increase is small.

6. References

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TABLES

Table (1): Maximum deflection for central point load

Type of Analysis	Present Analysis	ANSYS	Difference
Maximum Deflection(mm)	16.16	17.87	9.6%

Table (2): Maximum lower interface slip for central point load

Type of Analysis	Present Analysis	ANSYS	Difference
Maximum Slip(mm)	0.4	0.38	5.3%

Table (3): Maximum Upper interface slip for central point load

Type of Analysis	Present Analysis	ANSYS	Difference
Maximum Slip(mm)	0.13	0.141	8%

FIGURES

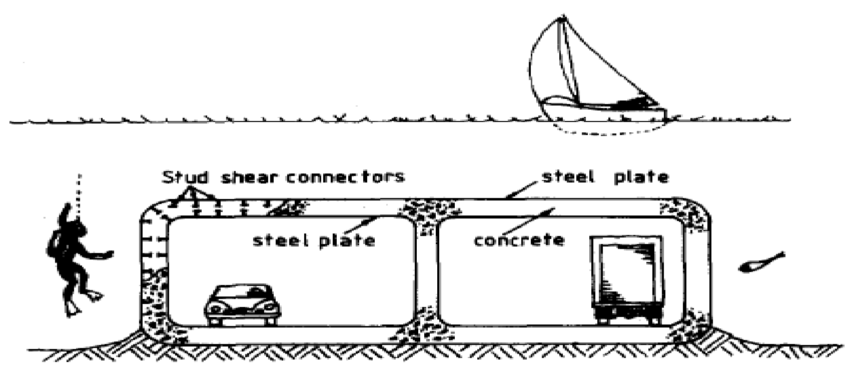

Figure (1) DSC construction in a submerged tube structure [2]

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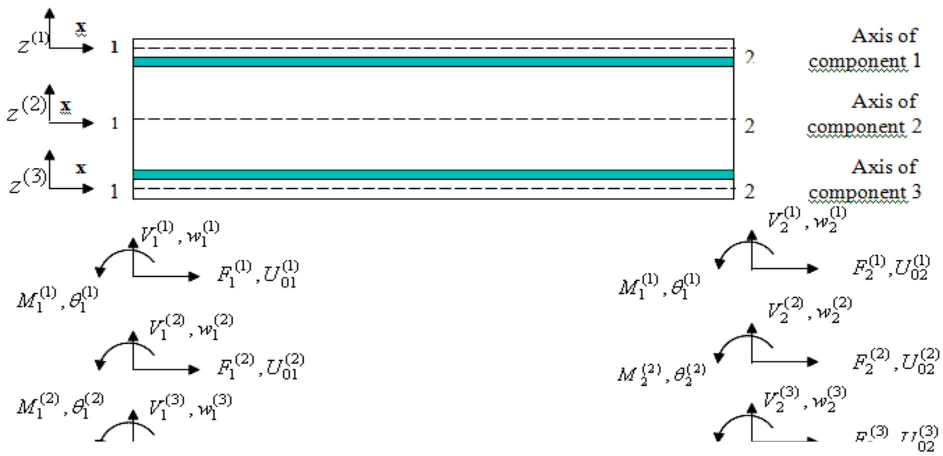

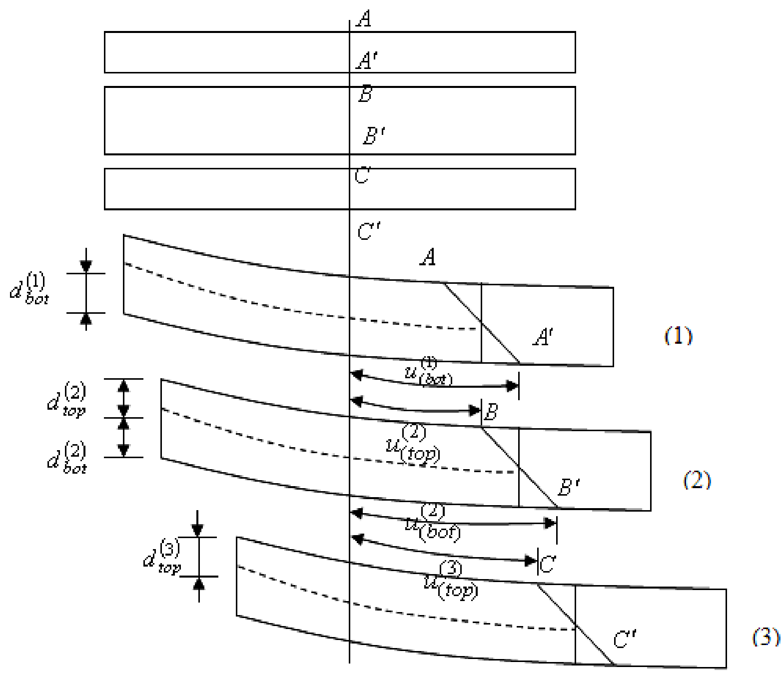

Figure (3) Deformation of the three-layer composite beam

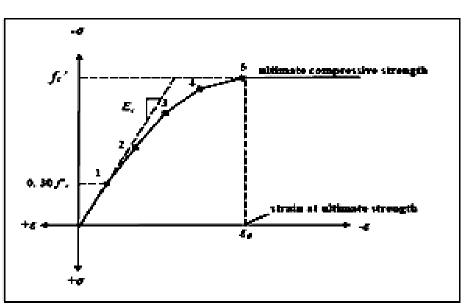

Figure (4) Simplified compressive uniaxial stress-strain curve for concrete [6].

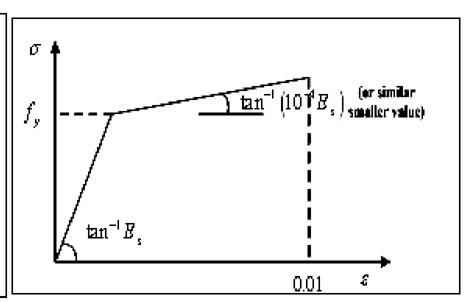

Figure (5) Idealization of steel stress-strain for computer calculations [7].

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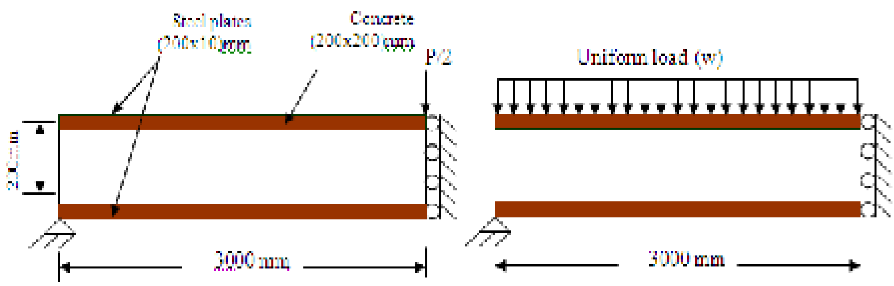
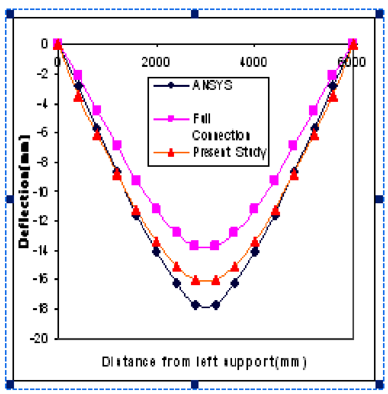
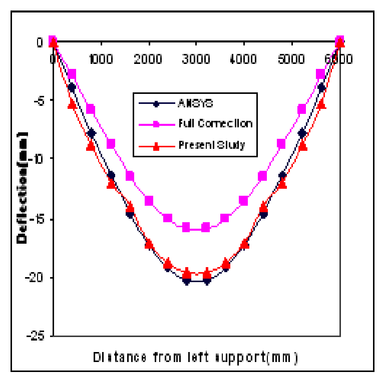


Figure (6) One half of the beam



Figure(7.a) Deflection along the beam under concentrated load



Figure(7.b) Deflection along the beam under uniform load

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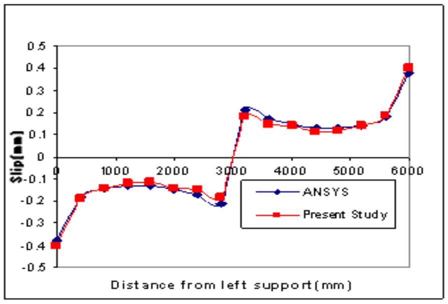
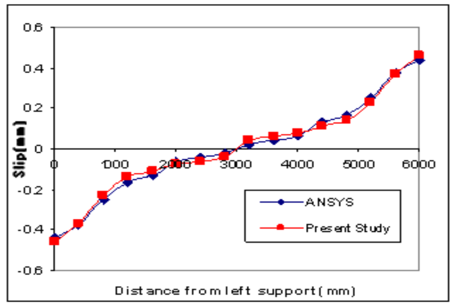
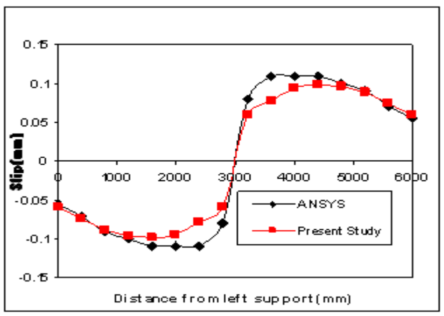


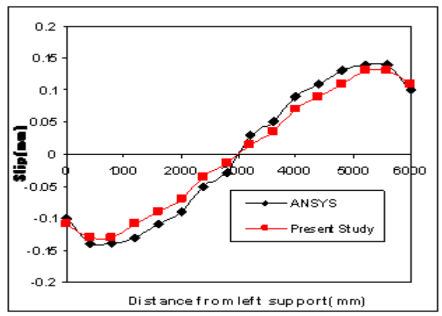
Figure(8.a) Lower interface slip along the beam under concentrated load



Figure(8.b) Lower interface slip along the beam under uniform load



Figure(9.a) Upper interface slip along the beam under concentrated load



Figure(9.b) Upper interface slip along the beam under uniform load

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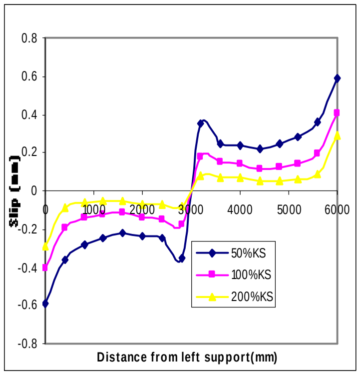

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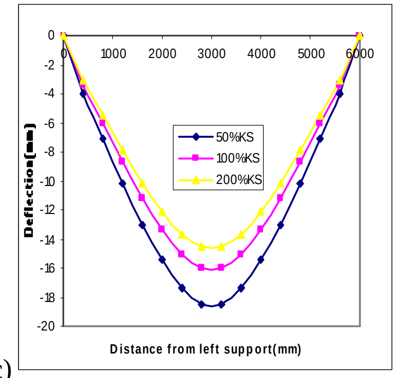

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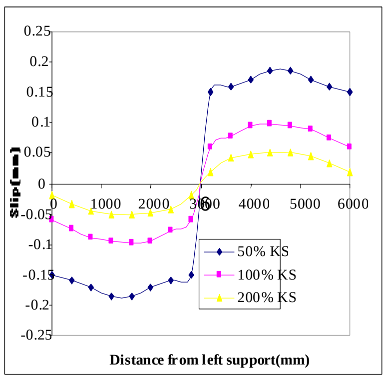

(b)

Figurer (10.a) Variation of deflection

Figure (10.b) Variation of lower inter-face slip for different values (KS)

Figure (10.c) Variation of upper inter-face slip for different values (KS)

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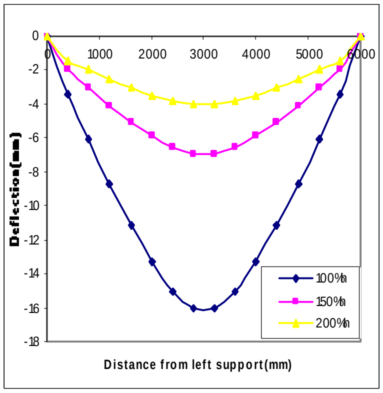
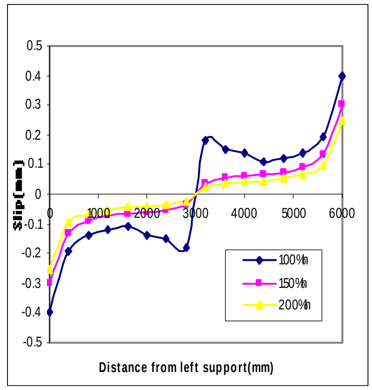


(a)



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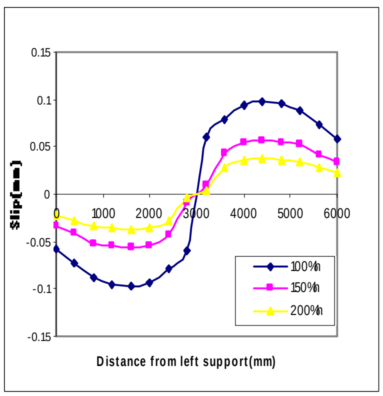

(b)

Figure (11.a) Variation of deflection for different values of concrete thickness

Figure(11.b)Variation of lower slip for different values of concrete thickness

Figure (11.c)Variation of lower slipfor different values of concrete thickness

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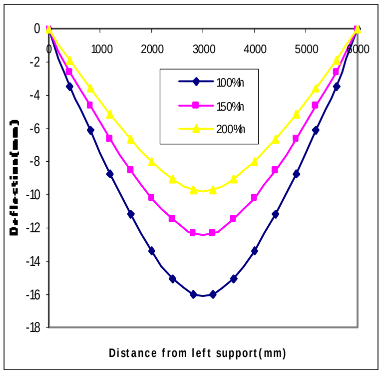
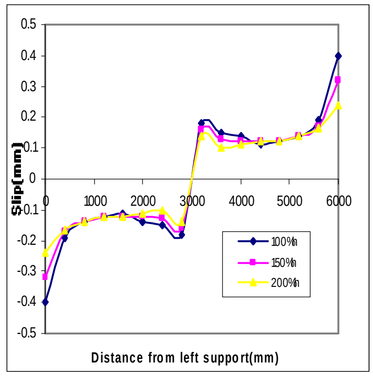


(a)



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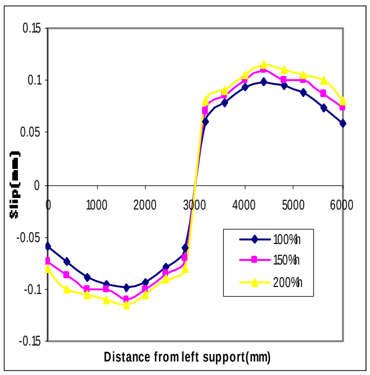

(b)

Figure (12.a) Variation of deflection for different values of plate thickness

Figure (12.b) Variation of lower slip for different values of plate thickness

Figure (12.c) Variation of lower slipfor different values of plate thickness

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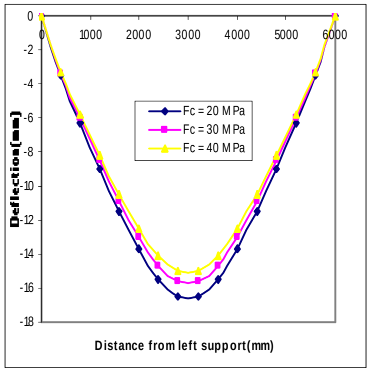
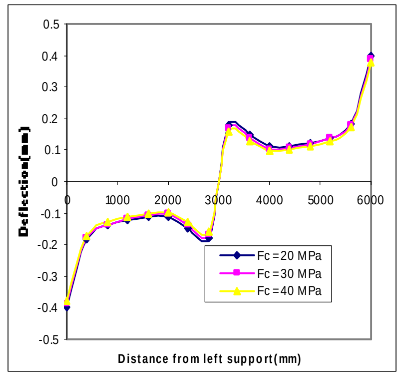


(a)



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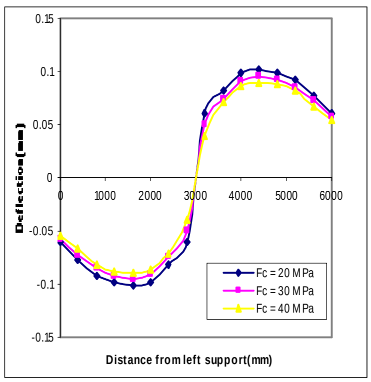

(b)

Figure(13.a)Variation of deflection for different values of concrete compressive thickness

Figure(13.b)Variation of lower slip for different values of concrete compressive thickness

Figure(13.c)Variation of upper slip for different values of concrete compressive thickness

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