Behaviour of Composite Slim Floor Beam with Partial Interaction

Dr. Eyad K. S. Al-hachamee* **Mustafa K. Al-heety****

Received on: 13/3/2006
Accepted on: 8/4/2007

Abstract

This research includes a theoretical investigation about the behaviour of simply supported composite slim floor beams with partial interaction. For the purpose of analysis, the slim floor slab system is simplified to a multi-layered composite beam. The slim floor beam is embedded in concrete. Therefore, the layers of the slim floor are connected together by natural shear bond generated between the steel and concrete and distributed uniformly along the interface without using shear connectors. Linear behaviour with one degree of freedom of the slim floor (slip only) without separation is studied according to Johnson and May approach using different material properties and different types of loading.

Equilibrium and compatibility are satisfied for the forces and displacements at an assumed element to arrive at two differential equations of second-order in terms of slip and axial force. The equations are solved numerically using the finite difference method. A computer program is written in Visual Basic language to solve the problem.

The current model is applied to three typical simply supported slim floor beams tested experimentally by "Corus Construction Center". The model showed close prediction with the observed results.

Keywords: Slim Floor, Partial Interaction, Shear Bond, Composite Action, Embedded beam**.**

تصرف عتبات السقوف النحيفة المركبة ذات الارتباط الجزئي

الخلاصة

يتضمن البحث دراسة نظرية لتصرف عتبات السقوف النحيفة المركبة ذات الاسناد البسيط مستخدماً نظرية الترابط الجزئي. لغرض عملية تحليل السقوف النحيفة تم تبسيطها وتمثيلها على شكل عتبة مركبة ذات مقطع متعدد الطبقات. كون العتبات المستخدمة في السقوف النحيفة مغمورة ومغطاة بالخرسانة فإن الطبقات المكونة للسقوف النحيفة (الخرسانة والفولاذ) تـرتبط مع بعضها بواسطة قوة ربط طبيعية متولدة بين الخرسانة والفـولاذ تـدعى (قـوى التـرابط القصية) بذلك تم الاستغناء عن طريقة الربط القديمة بواسطة (الروابط القصية). تمت دراسة تصرف عتبات السقوف النحيفة الخطي والاخذ بنظر الاعتبار السماح بدرجـة حريـة مفـردة (انزلاق فقط) لسطح التماس بين الخرسانة والفولاذ دون اعتبار الانفصال الذي قد يحصل عند سطح التماس خاضعا بذلك إلى نظرية الباحث (جونسون) في الترابط الجزئي ولمختلف انواع التحميل.

تم تحقيق شرطي التوازن والتوافق للقوى والعزوم المقترحة على مقطع عرضـي نمـوذجي وكذلك الازاحات لعتبات السقوف النحيفة وتم التوصل الى نموذج رياضـي يشـمل معـادلتين تفاضليتين متزامنتين من الدرجة الثانية بدلالة المتغير الاول (الانزلاق) واخرى بدلالة (القوى

https://doi.org/10.30684/etj.25.3.20
2412-0758/University of Technology-Iraq, Baghdad, Iraq

المحورية). تم حل المعادلات التفاضلية بأستخدام طريقة الفروقات المحددة. تمت كتابة برنامج حاسبة بأستخدام لغة (فيجوال بيسك) لحل المعادلات التفاضلية المتزامنة.
تم تطبيق النموذج المقترح لعتبات السقوف النحيفة ذات الاسناد البسيط على نماذج تم فحصها سابقاً وقد اظهرت النتائج تقارباً مقبولاً مع النتائج المستخرجة سابقاً.

Notations

d_1	The distance between the centroids of first concrete and steel layer
d_2	The distance between the centroids of second concrete and steel layer
E_s	Modulus of elasticity of the steel layer
F	Axial force
F_{c1}	Axial force of first concrete layer
F_{c2}	Axial force of the second concrete layer
f_{cu}	Measured concrete cube strength
f_{sb}	Shear bond strength
f_{sb1}	Shear bond strength of the first interface
f_{sb2}	Shear bond strength of the second interface
f_{sbm}	Measured shear bond strength
g_c	Partial factor for concrete according to BS 8110
I_o	Constant as defined[7]
M	Moment
M_t	Total moment of typical section
N	Total vertical shear force at distance x from the support
P	Contacting perimeter of the beam with concrete
q	Shear flow per unit length
U	Interface slip
U_1	Slip at the first interface
U_2	Slip at the second interface
W	Deflection of the layers
$l_1 - l_8$	Constants as defined[7]
Δx	Distance between two successive nodes
dx	Increment of typical section of slim floor

1. Introduction.

The aim of using or selecting any material in construction is to make full use of its properties in order to get the best performance and durability of the structure being constructed, keeping in mind the availability, strength, stiffness, workability and durability of the material and economy of construction. Composite slabs and beams of concrete and steel are now used extensively in the construction of buildings and bridges.

Methods of improving material utilization can be classified into two categories. The first is to select appropriate materials to form a new product with desired properties, thus resulting in a composite material. Alternatively different materials can be arranged in an optimum geometric configuration. The structure is then known as a composite structure, and the relevant method of building is known as composite construction [1].

The main variable that affects the behaviour of composite structures is the slip, which can be defined as a differential longitudinal movement between the two components of the composite element. Slip has been proven to exist at the interface along the beam no matter how large is the number of shear connectors provided at the interface [2, 3]. Therefore, partial interaction rather than full interaction theories are essential to be developed in order to visualize the accurate behaviour of composite elements. However, codes of practice usually permit full interaction consideration in ultimate state design without referring to slip calculation, however the slip will affect the stress distribution across the composite section in the elastic range.

2. Slim Floor Constructions.

A new technology for floor systems is under development in Europe. This new floor system is called "slim floor" construction. In this system, steel beams are integrated into the concrete or composite slabs [4]. So, the floor system has a small depth with high stiffness and strength and therefore, besides architecture it is also interesting in view of economy. The original slim floor beam used in UK consisted of a Universal Column (UC) section with a plate welded to its bottom flange. The plate supports the floor slab directly, so that the plate is the only part of the section that is exposed.

Slim floor fabricated beams are partially or fully encased in concrete and achieve considerable composite action at the serviceability limit state, when elastic condition holds. Furthermore, at the fire limit state, when the beam is subjected to large deformations there is sufficient interlock between the steel section and the concrete to develop full composite action. Slim floor construction provides a steel floor system of minimum depth which competes directly with reinforced concrete flat slabs. Generally, the conventional steel-concrete composite beam is well established for longer spans (> 9m), but the slim floor beam creates more opportunities for steel in spans of (5-9 m) [5]. It also achieves a slab depth of 300mm or so, which is much less than that of the conventional steel construction. This issue increases the competitiveness of composite slim floor construction with the concrete flat slab system. On the other hand, compared with the conventional composite frame system that has a primary-secondary beam system, the new slim floor frame has a rather precise structural form. In slim floor construction, the slab is supported directly by the primary beam, and forms a part of composite beam to work together with steel beam. Between the rows of the single frame, tie members are employed to link them together and maintain the out-of plane stability of the frame.

3. Shear Bond.

Bond stress is the name assigned to unit shear force per unit area acting parallel to the beam surface on the interface between the beam and the concrete. This shear stress (bond stress) modifies the steel stress in the beam, either increasing or decreasing it, when transferring from concrete to steel beam. Bond stress could be measured by the rate of change of steel stress in the beam; there can be no bond stress unless the beam stress changes.

Bond strength is the resistance to slipping of the steel beam, or separation of concrete around the beam which is embedded in the concrete. This property is of great significance in structural design of flexural members. Moreover, the transferring of stresses between concrete and steel has a great influence in limiting the space and the width of cracks. Effective bond strength creates the composite action of steel with concrete. The design value of shear bond strength is obtained from an approximate relationship based on the results of slim floor tests according to the British Code (BS 8110) as shown below:

$$\text{Measured Shear Bond Strength } (f_{sbm}) = \frac{\text{Design Shear Bond Strength}}{\left(\frac{1}{g_c}\right)\times\left(\frac{30}{f_{cu}}\right)^{0.5}} \quad \dots (1)$$

where:

g_c is the partial factor for concrete (=1.5 in BS 8110).

f_{cu} is the measured concrete cube strength(characteristic compressive strength)

Shear bond at the interface is,

$$f_{sb} = P \cdot f \qquad -------- (2)$$

where:

P: is the contacting perimeter of the beam with concrete

f_{sbm} : measured shear bond strength

The shear bond strength has a design value of 0.6 N/mm^2 as justified by full-scale test for ASB sections with their raised pattern rolled into the top flange. The principles of partial shear connection showed that the bond resistance of the composite section may be predicted by using the shear bond strength of 1.1 to 1.3 N/mm^2 [1], acting around the web and flanges of the section.

4. Behaviour of Composite Slim Floor Beam.

Slim floor composite beam system is used as a type of composite construction and has the same behaviour, which has a slip and separation at the interface according to the theory of partial interaction. The slim floor beam system is simplified to a multi-layer beam system which has three layers, two of concrete and the other of steel; thereby the system has two interfaces generated due to the three layers. The used approach is Johnson's [6] approach that supposes that there is no significant vertical movement (separation) occurring at the interface of the connection but slip occurs whenever the connection being large in stiffness.

4.1 Slip.

An element of a composite slim floor beam, of length (dx) is considered. The slim floor beam consists of three layers denoted by (Concrete1), (Steel) and (Concrete2) respectively, joined together by a medium of negligible thickness but have finite tangential stiffness. The three materials are subjected to moment (M), shear force (V) and axial force (F), while (q) denotes the shear per unit length (shear flow) at the interface, fig (1).

By using equilibrium and compatibility, two simultaneous differential equations are derived to find the slip at the two interfaces as [7].

$$\left.U_1,xx - l_1 U_1 - l_2 U_2 + \frac{N \cdot d_1}{E_s \cdot I_o} = 0 \right\} \text{-- } (3)$$

$$U_2,xx - l_3 U_2 - l_4 U_1 + \frac{N \cdot d_2}{E_s \cdot I_o} = 0$$

For definition of symbols, refer to notations at the end of this research.

To get the complete solution; the above equations must be solved for each type of loading after substituting the boundary conditions. The solution of the equations will give the values of the interface slip along the beam span. The exact solution of such differential equations is complicated, so a numerical solution "finite difference method" is used to solve the equations.

4.2 Axial Force, Deflection.

To get the basic differential equations in terms of axial force, the applied external moment (Mt) is made equal to the sum of the individual moments that each element can carry together with the composite couple, so:

$$\left.\begin{aligned} Fc_1,xx - l_5 Fc_1 - l_6 Fc_2 &= -\frac{d_1 \cdot fsb_1}{E_s . I_o} M_t \\ Fc_2,xx - l_7 Fc_2 - l_8 Fc_1 &= -\frac{d_2 \cdot fsb_2}{E_s . I_o} M_t \end{aligned}\right\} \quad (4)$$

In Johnson's [6] approach the layers deflect by the same amount therefore; one equation for the three layers is needed:

$$W_i , xx = \frac{M_i}{E_i . I_i} \quad \text{Where i = any node}$$

$$W,xx = \frac{M_t - Fc_1 . d_1 - Fc_2 . d_2}{E_s . I_O} \quad \text{--- (5)}$$

This equation can be expressed by finite differences and solved numerically to get the value of deflection along the length of the beam:

5. Numerical Solution.

Equations (3) and (4) can be solved numerically by using the finite difference representation of various derivatives. This method will save time and effort as a personal computer can be used to apply the final solution to different loading conditions.

Equations (3) and (4) contain derivatives of second order in terms of slip (U) and axial force (F), respectively, which can be expressed in finite (central) difference form, using three nodes, as given below:

$$U_{i,xx} = \frac{U_{i-1} - 2U_i + U_{i+1}}{(\Delta x)^2} \quad \text{.... (6)}$$

in which, (Δx) is the node division, (U) is the dependent variable, (i) is the number of nodes. After substituting the above form of finite difference, into equations (3), the main finite difference expression is obtained [7].

6. Numerical Examples.

6.1 Asymmetric Slim Floor Beam (300 ASB) (First Example).

In this example using (300ASB), the connection between the concrete slab and the steel beam was provided by shear bond strength only without using headed studs. This shear bond was proved that it can replace shear connectors as long as the behaviour of the beam is still linear. Because the three layers are bonded in the system of the slim floor, two shear bond strengths (fsb) are generated. The first shear bond is (207.1 kN/cm) in the first interface, and the second is (1060 kN/cm) in the second interface.

Partial or full interaction between concrete slab and steel beam depends on the degree of shear connection; therefore, first interface has a behaviour of partial interaction, while the steel with the second layer of concrete has a behaviour close to full interaction Table (1) shows a comparison between the numerical solutions suggested for different number of nodes in the present model and the experimental test made by "Corus Construction Center"[5]. At 45 nodes and more, the value of slip becomes stable. This shows that using larger than this number of nodes gives the same value of slip. These values are reasonably close to the observed by experiments.

6.2 The UC 254 x 254 x 143 Steel Beam (Second Example).

In the second example a different steel beam is used with the properties listed in table (2). Other properties of the beam are shown in Figure (3).

In table (3) another convergence study of the present model was made to show the maximum deflection at mid-span of the second example. It can be shown that the value of deflection is (15.537mm) obtained by numerical solution while the value of deflection is about (16.1 mm) in experimental test. The difference between the two values is (3.5%). This difference is acceptable because the numerical solution doesn't take the whole conditions of the experimental test and it is within the range of permitted deflection (span/360) [2].

6.3 Asymmetric Slim Floor Beam (280 ASB) (Third Example).

In the first and second examples, the behaviour of the system was partial interaction, while the third example is assumed to have full interaction behaviour which is ideal case. Partial shear connection exists when there is insufficient longitudinal shear bond to develop the plastic bending resistance of the composite section [5].Table (4) shows the properties of the beam. Other Properties are shown in Figure (4)**,**

The design strength of the shear connector is (69.5 kN). Table (5) shows that the maximum value of slip at the end of beam is (0.0003 mm) that is closed to zero. The experimental test showed that no perceptible end slip occurred between the concrete and steel [5]. This value is due to the effect of adding shear connectors that cause a behaviour of full connection. In numerical solution the connection was by shear bond only without shear connectors. This proves that there is no need for using the shear connectors on the system of slim floor beam if the interface area is adequate for shear bond strength. The same example illustrates the convergence of deflection obtained from numerical solution of the present study and the deflection obtained from experimental test.

Figures (5) and (6) show some of the results obtained by numerical solutions of present study for the previous examples in the first and second interfaces.

7. Parametric Study.

7.1 Thickness.

Four different thicknesses of upper concrete layer are used (½ hc1, hc1, 1.5hc1, 2hc1,), to show their effect on interface slip, deflection and axial force along the beam, as illustrated in Figure (7). As the thickness of upper concrete layer increases, the lever arm of the couple increases. This causes an increase in amount of moment which increases the resistant axial force (fig. 7.c), and in turn causes an increase in slip (fig.7.a). The deflection decreases due to the increasing of the total second moment of area of the section (fig.7.b).

7.2 Effect of Loading.

A typical composite slim floor beam used in the convergence study is considered herein to study the effect of loading condition upon the general behaviour of the beam. The concentrated load is taken as (225 kN) (the same total load for uniformly distributed loading of (30 kN/m)) and applied at mid- span, at quarter and at three quarters of the beam span. Therefore the beam behaviour remained within the elastic range. The effects of the loading are illustrated in Figure (8). The slip is increased as the applied load increased (fig. 8.a). Generally, the slip distribution for concentrated load (fig.8.b) is similar to that of uniformly distributed load (fig.8.a) but the slip value of concentrated load is greater due to the high vertical shear force in this case. Figure (8.c) shows that the value of maximum axial force is more in the location of half beam span from the other quarters and is more critical than that of uniform loading. The same conclusion is drawn for the deflection, figure (8.d).

7.3 Effect of Shear Bond.

There are two ways of bonding the layers of the slim floor, one of these bonds is called shear bond which is explained earlier. In this study the layers of the slim floor are bonded by shear bond strength only, for purpose of comparison the shear bond value can be changed by taking more than one section of beam, this will change the perimeter contacting the steel with the concrete layer. The effects of the shear bond are illustrated in Figure (9). Many sections are used to show the effect of shear bond on the value of slip (fig.9.a). The slip value is decreased when the value of shear bond (section perimeter) increased. The distribution of the slip at interface 2 is very close for all sections due to the large contacting perimeter for all sections which generates large values of shear bond.

Figures (9.b), (9.c) and (9.d) show the effect of using different values for the stiffness of shear connectors placed at the top flange, (fig.4) on slip, axial force and deflection respectively. The resistant axial force increases while the slip decreases with the increasing value of shear connectors' stiffness. This effect is greater at interface 1 than interface 2 due to the contribution of the shear connectors' stiffness to the stiffness of upper concrete layer encased it.

8-Conclusions.

Based on the results obtained in this research, the followings can be concluded.

1-Slim floor is complex structure for the purpose of the study; therefore, it can be simplified to a multi- layered composite beam to obtain the behavioure and strength of slim floor.

2-In spite of the high stiffness of slim floor, the slip at the contacting interfaces is found and should not be neglected.

3-The numerical solution (finite difference method) can be used with acceptable tolerance to solve the basic differential equations.

4-The results of current model are compared with those of three slim floor beams tested experimentally in previous researches and they show good agreement.

5-As the upper concrete layer increases, both slip and axial force increase, while deflection decreases.

6-The slip decreases with the increasing of shear bond by using larger section or by adding shear connectors at the top flange.

7-Axial force, slip and deflection are more critical for the point load located at mid-span rather than that for other locations and that of uniform loading.

References

(1) Abrishami, H.H., and Mitchell, D., "Simulation of Uniform Bond Stress", ACI Mat. January, 1992, 89(2), pp. 161-168.

(2) Balakrishnan, S., "The Behaviour of Steel and Concrete Beams with Welded Stud Shear Connectors", Thesis Presented to the University of London, 1963, in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy.

(3) Gogoi, S., "Interaction Phenomena in Composite Beams and Plates", Thesis Presented to the University of London, 1964, in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy.

(4) Mullet, D. L., "Slim Floor Design and Construction", The Steel Construction Institute, 1992

(5) Website: www.corusconstruction.com , Corus Construction Center.

(6) (6) Johnson, R.P. and May, I. M., "Partial Interaction Design of Composite Beams", The Structural Engineer, Vol. 53, No. 8, Aug. 1975, pp. 305-311.

(7) (7). Al-Heety M. K. "Behaviour of Composite Slim Floor Beam with Partial Interaction" M.Sc. Thesis, University of Technology, Baghdad, 2005. PP.104.

(8) Goodman, J. R. and Popov, E. P., "Layered Beam System with Interlayer Slip", Journal of the Structural Division, Vo. 94, No. ST 11, Nov. 1968, pp. 2535-2547

(9) British Standards Institution, BS 5950: "The Structural Use of Steelworks in Buildings", part 3: design in composite construction, Section 3.1, Code of Practice for Design of Simple and Continuous Composite Beams, BSI, 1994.

Table (1) comparison between numerical solution and experimental test of 300 Asymmetric slim floor beam (Partial interaction).

Numerical solution (Present study)					Experimental test (mm) [5]
Slip at the end of span (mm)	Total number of nodes				0.25
	25	35	45	100	
	0.230	0.232	0.233	0.233	

Table (2) Properties of the (UC 254 x 254 x 143) steel beam [5]

Steel	The UC 254 x 254 x 143 beam	Section area	182.3 cm^2
		Moment of Inertia	22410.4 cm^4
		Modulus of elasticity	20000 kN/cm^2
		Depth of the steel beam	26.4 cm

Table (3) comparison between numerical solution and experimental results of the (UC 254*254*143) slim floor beam.

Numerical solution (Present study)		Experimental test (mm) [5]
Deflection at mid-span (mm)	At 100 nodes	16.1
	15.537	

Table (4) Properties of the 280 Asymmetric Slim Floor Beam for third example[5]

The 280 Asymmetric Slim Floor Beam	Section area	173.7 cm^2
	Moment of Inertia	22.16 cm^4
	Modulus of elasticity	20000 kN/cm^2
	Depth of the steel beam	28.8 cm
Shear Studs	Diameter (mm) * height (mm)	6 * 24
	Spacing (mm)	240
	No. of rows	1

Table (5) comparison between numerical solution and experimental test of 280 Asymmetric slim floor beam (Full interaction).

	Numerical solution (Present study)				Experimental test [5] (mm)
	Total number of nodes				
	25	35	45	100	
Slip at the end of span (mm)	0.0003	0.0003	0.0003	0.0003	0
Deflection at mid-span (mm)	1.0587				0.9

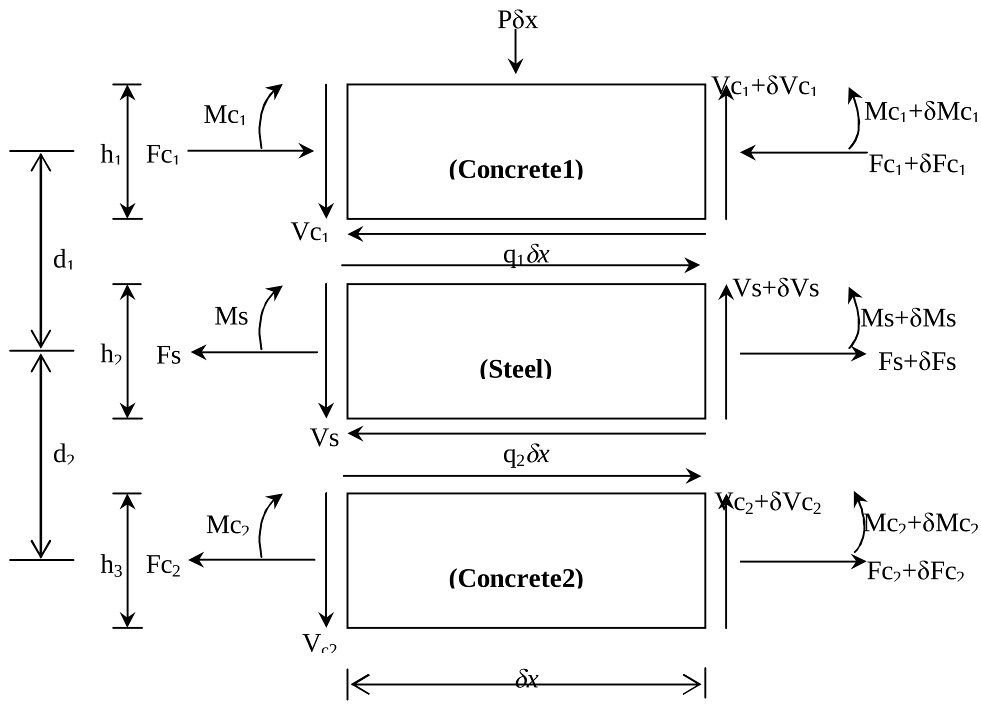


Figure (1). Elements of slim floor composite beam.

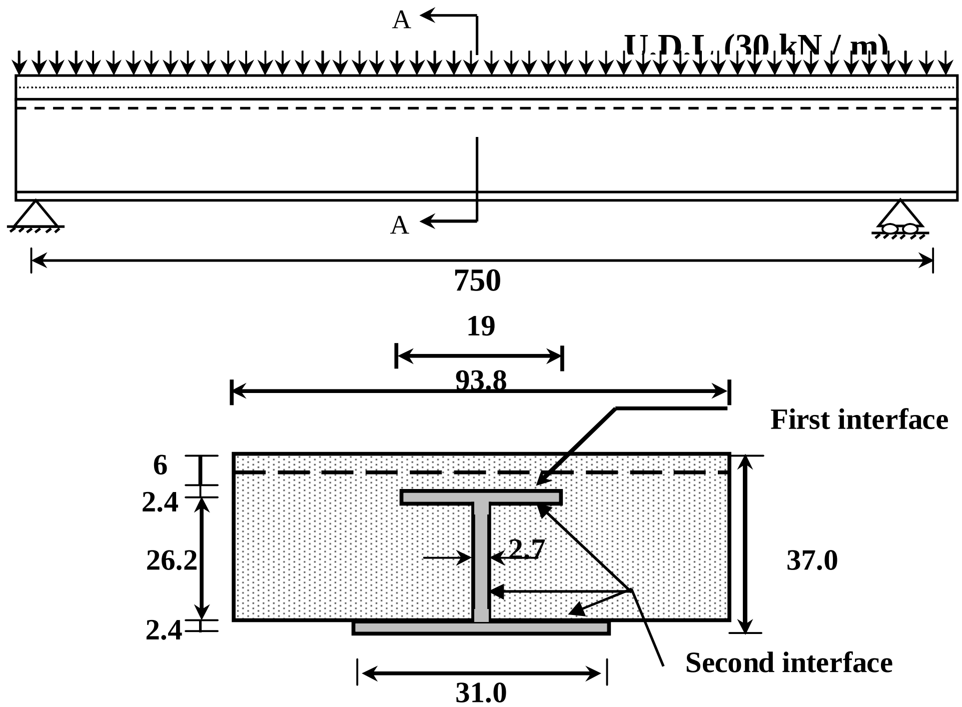


Figure (2) Typical section of composite slim floor with the 300 Asymmetric Slim Floor Beam All dimensions are in (cm)

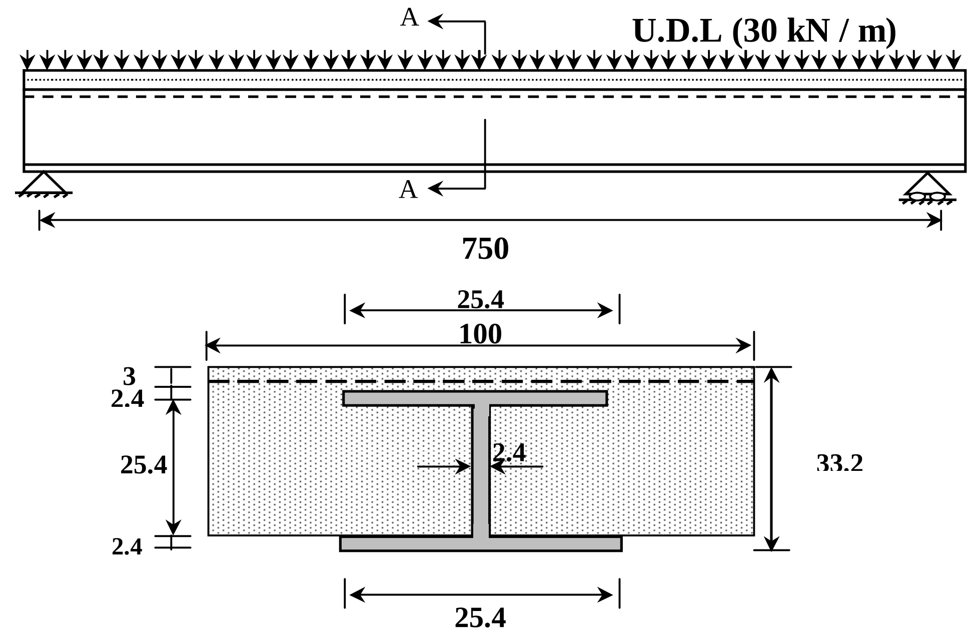


Figure (3) Typical section of composite slim floor with the (UC 254 x 254 x 143) Steel Beam All dimensions are in (cm)

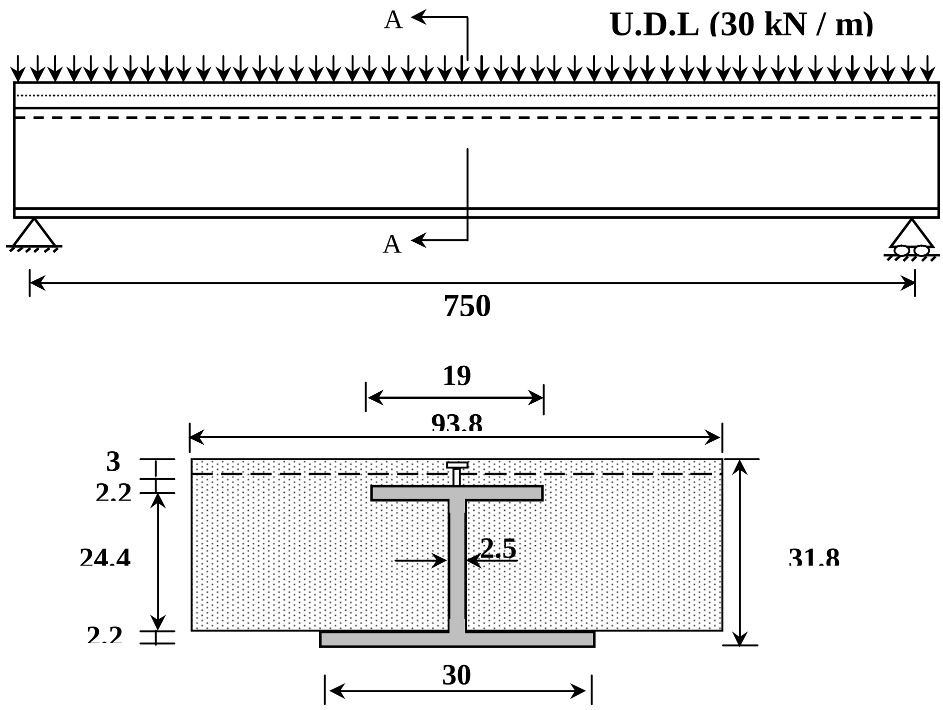
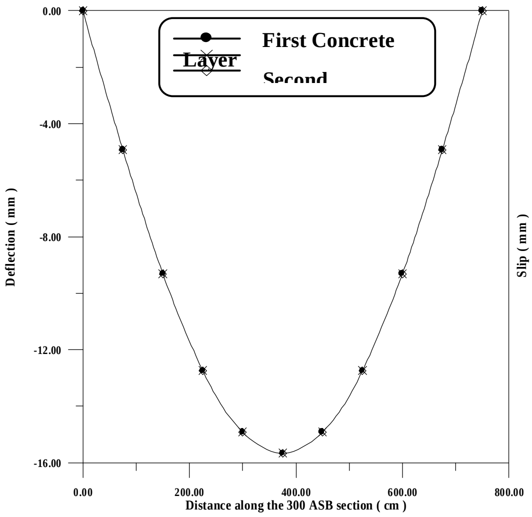
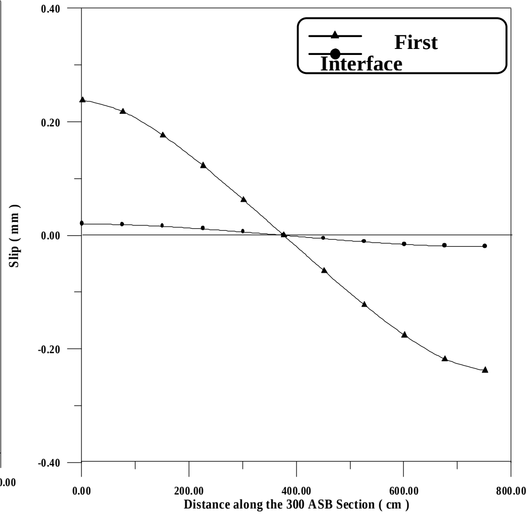


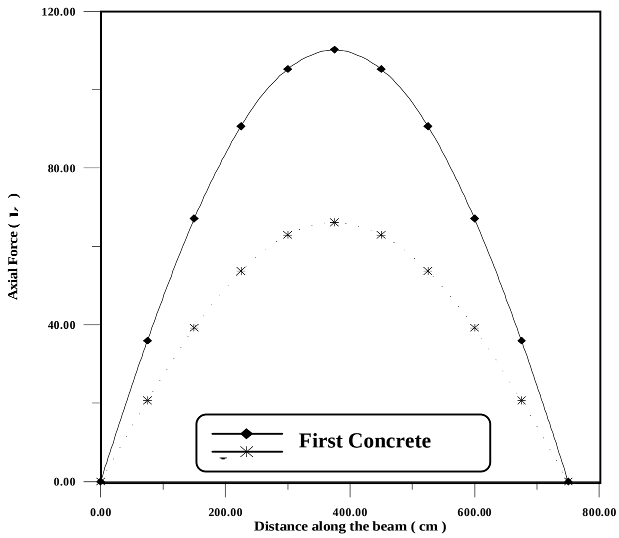
Figure (4) Typical section of composite slim floor with the 280 Asymmetric Slim Floor Beam All dimensions are in (cm)



(b)



(a)



(c)

Figure (5) (a) Distribution of the slip along the 300 ASB
(b) Distribution of the deflection along the (UC 254 x 254 x 143)
(c) Distribution of the axial force along the 300 ASB

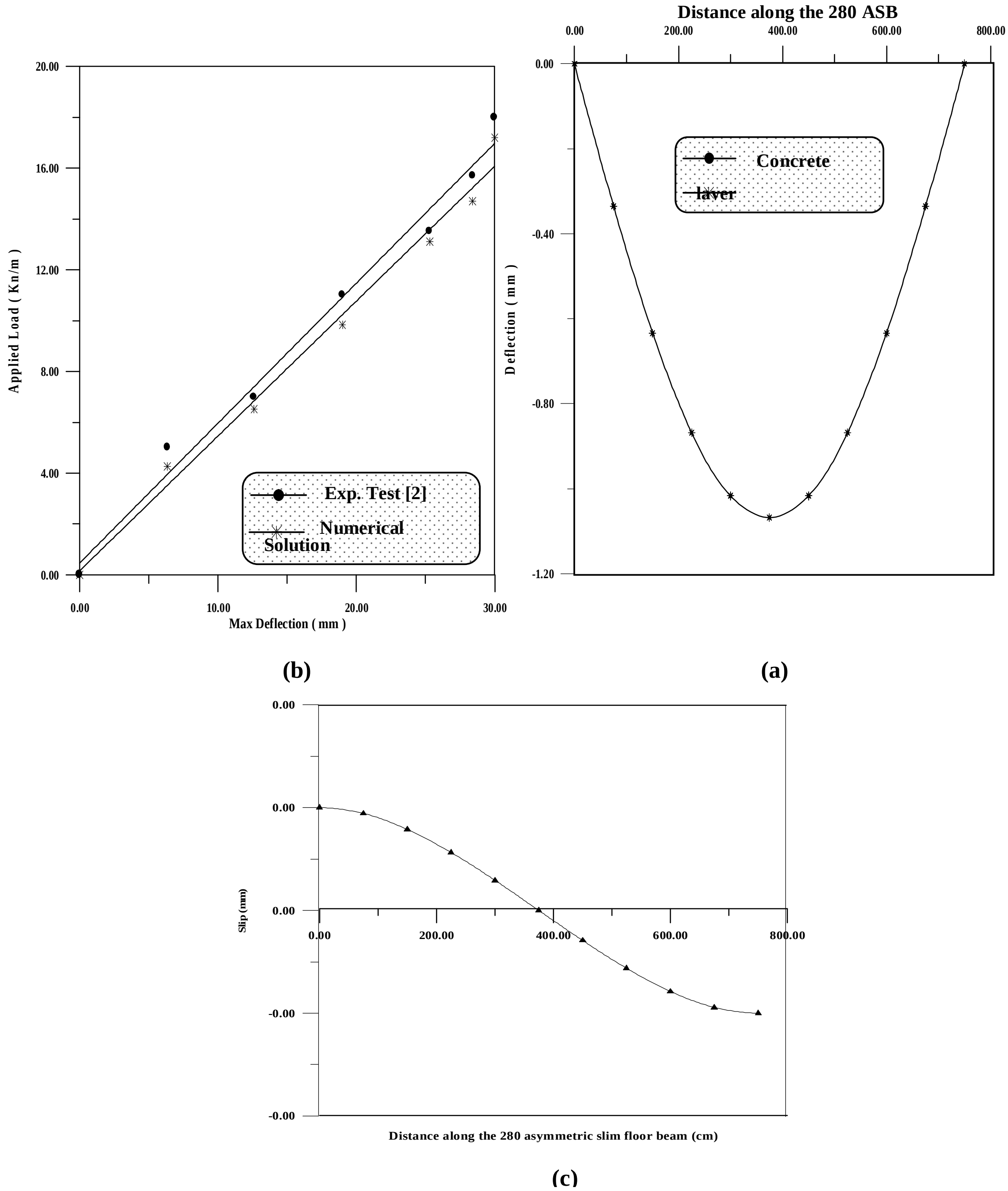
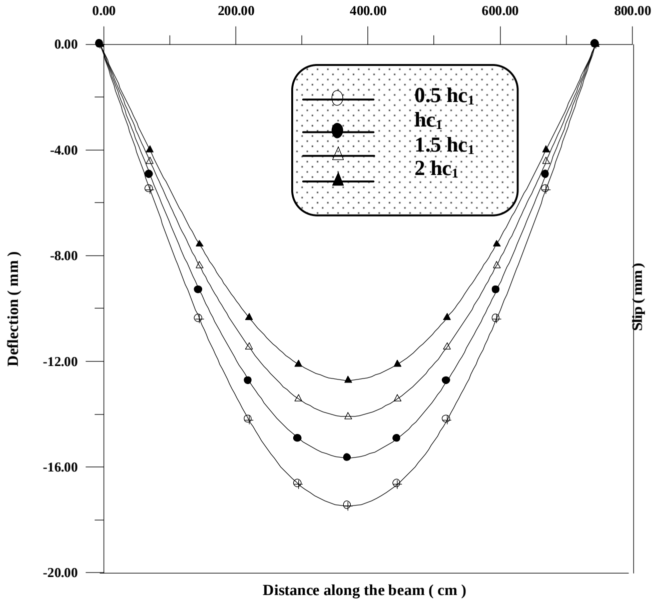
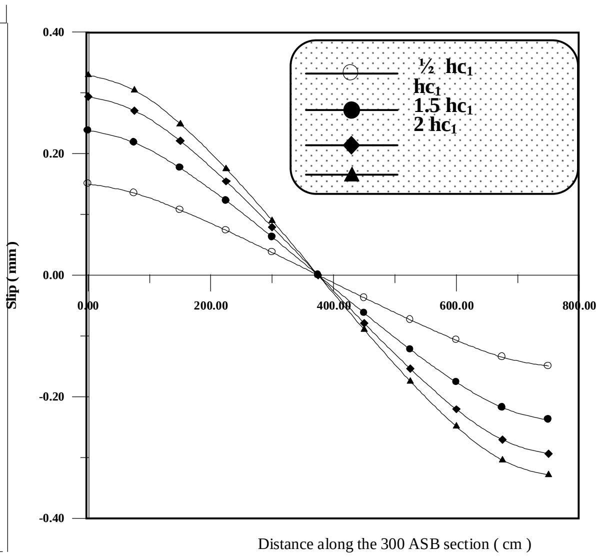


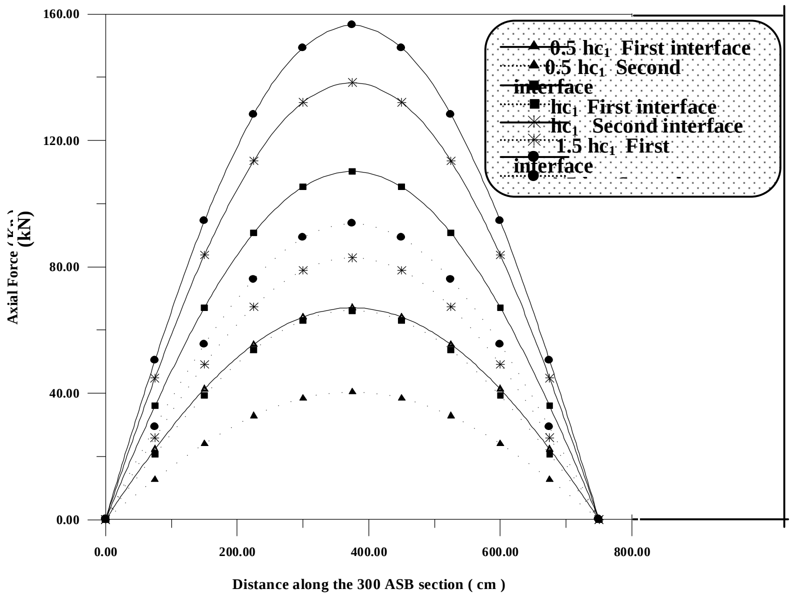
Figure (6) (a) Distribution of the deflection for the 280 ASB
(b) Values of Max deflection for different loading
(c) Distribution of the slip along the 280 ASB



(b)



a)



(c)

Figure (7) (a) Distribution of the slip along the 300 ASB for different thicknesses of top concrete layer
(b) Distribution of the deflection along the beam for different thicknesses of top concrete layer
(c) Distribution of the axial force along the 300 ASB for different thicknesses of top concrete layer

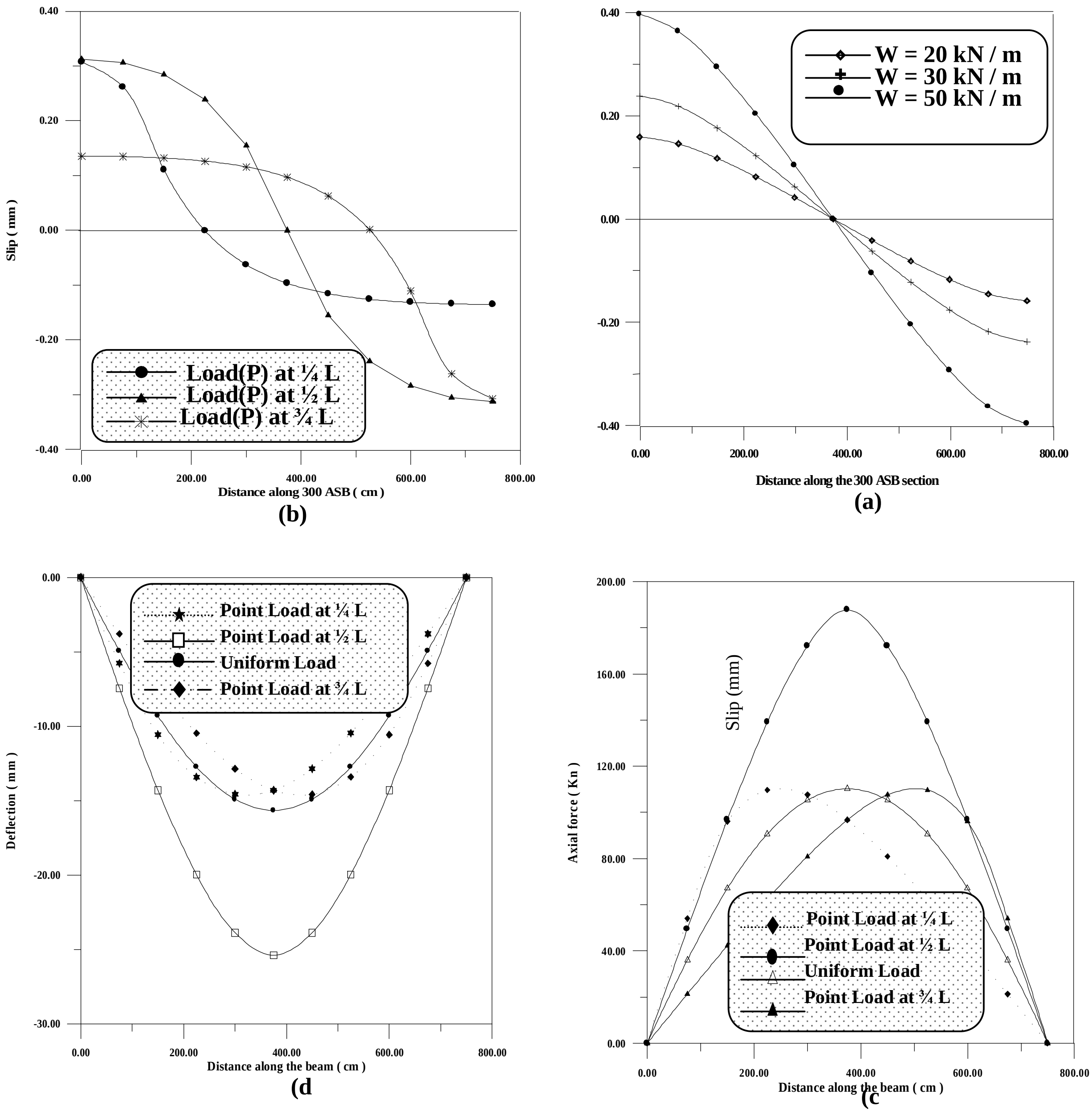


Figure (8) (a) Distribution of the slip along the beam for different values of loading
(b) Distribution of the slip along the beam for different locations of point load
(c) Distribution of the axial force along the beam for different locations of point load
(d) Distribution of the deflection along the beam for different locations of point load

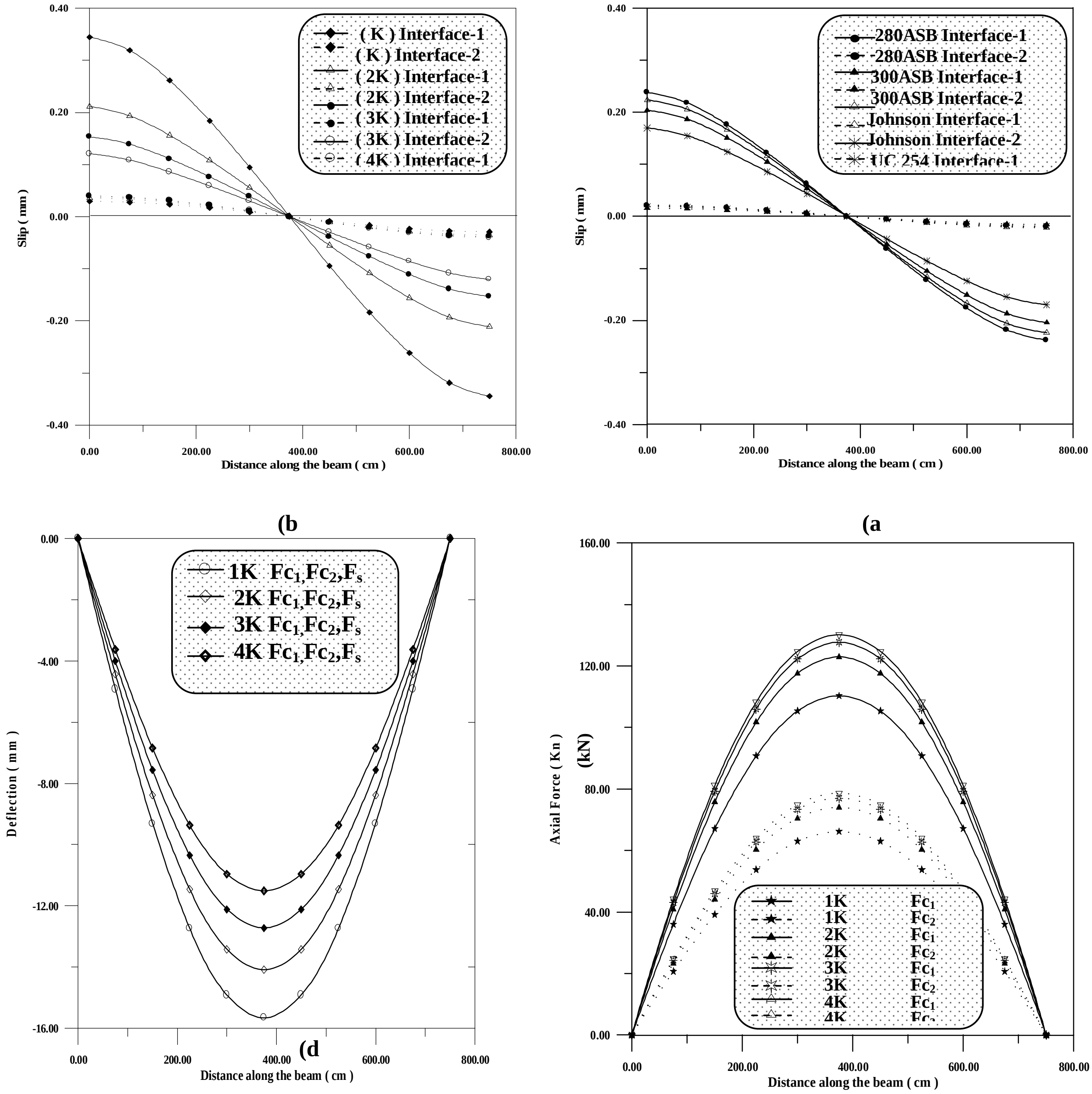


Figure (9) (a) Distribution of the slip along the beam for different values of shear bond
(b) Distribution of the slip along the beam for different values of shear Stiffness (K1)
(c) Distribution of the Axial Force along the beam for different values of shear Stiffness (K1)
(d) Distribution of the Deflection along the beam for different values of shear Stiffness (K1)