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Shear Lag in a Continuous Composite Steel-Concrete Beam

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Abstract— *A composite steel-concrete beam is constructed from a concrete slab casted on a steel beam and joined together. Under positive or negative bending moment, the slab will behave as the top flange of the composite beam resisting the compressive or tensile stresses. To study the effect of the variation in degree of partial interaction between concrete and steel on shear lag in a continuous composite beam under different types of loadings, a three-dimensional linear finite element analysis is used.*

A comparison with an experimental test has been performed to validate the finite element analysis results. In general, good agreement between the finite element solution and the experimental result has been obtained. The maximum difference in the deflection was about (3.8%).

A parametric study has been carried out to investigate the effect of the partial interaction on the shear lag, effective with and maximum concrete and steel stress. It was found that the partial interaction in a composite steel-concrete beam has a minor effect on the effective slab width.

Keywords— *Continuous composite beam, Effective width, Partial interaction, Shear connector, Shear lag.*

I. INTRODUCTION

Composite construction consists of using two materials together in one structural member and using each material to its best use. The number of combinations is almost endless; steel and concrete, timber and concrete, timber and steel, precast and cast-in-place concrete, etc… (Al-Sherrawi, 2000) [1].

The most important and most frequently encountered combination of construction materials is that of steel and concrete, with applications in multi-story commercial buildings and factories, as well as in bridges. These materials can be used in mixed structural systems, for example concrete cores encircled by steel tubes, as well as in composite structures where members consisting of steel and concrete act together compositely.

These essentially different materials are completely compatible and complementary to each other; they have almost the same thermal expansion; they have an ideal combination of strengths with the concrete efficient in compression and the steel in tension; concrete also gives corrosion protection and thermal insulation to the steel at elevated temperatures and additionally can restrain slender steel sections from local or lateral-torsional buckling.

In multi-story buildings, structural steelwork is typically used together with concrete; for example, steel beams with concrete floor slabs. The same applies to road bridges, where concrete decks are normally preferred. The extent to which the components or parts of a building structure should embody all steel construction, be constructed entirely in reinforced concrete, or be of composite construction depends on the circumstances. It is a fact, however, that engineers are increasingly designing composite and mixed building systems of structural steel and reinforced concrete to produce more efficient structures when compared to designs using either material alone.

Composite steel-concrete beam, subject chiefly to bending, consists of a steel section acting compositely with a reinforced concrete flange. The two materials are interconnected by means of mechanical shear connectors (mainly headed studs) as shown in Fig. (1). The functions of these connectors are to transfer horizontal and normal forces between the two components, thus sustaining the composite action.

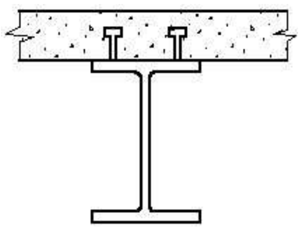

Fig. 1. Typical composite steel-concrete beam.

There are several composite beam cross-sections in which the wet concrete has been cast in situ on timber shuttering. For single span beams, sagging bending moments, due to applied vertical loads, cause tensile forces in the steel section and compression in the concrete deck thereby making optimum use of each material. Therefore, composite beams, even with small steel sections, have high stiffness and can carry heavy loads on long spans.

Many composite beams in buildings and bridges are, from the point of view of the static calculation, continuous beams over simple supports. The concrete slabs are also usually continuous since they are cast without joints. Continuous beams in comparison with single span beams, therefore, have the following advantages:

- greater load resistance due to the redistribution of bending moments
- greater stiffness
- smaller steel section to withstand the same loading.

On the other hand, the continuity can complicate the design, particularly in regard to lateral-torsional and local buckling in negative moment regions. Local buckling of steel can reduce the bending resistance of the section below the plastic moment, unless certain limitations to the breadth/thickness ratios of the elements making up the section are met. Based on these ratios steel sections are grouped in

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Classes 1 to 4: Class 1 sections allow for global plastic analysis, using moment redistribution, which gives a very economic design; Class 2 sections allow for plastic calculation of the moment of resistance but do not permit redistribution. Hot rolled sections conform to Class 1 or 2 in most cases and when they are used local buckling is not, therefore, a problem.

Adequately proportioned anti-crack reinforcement should be provided in the concrete slab over interior supports where joints are not present. If the reinforcing bars have enough ductility they will increase the bending resistance substantially in these hogging moment regions.

Garcia (1971) [2] presented a theoretical procedure for analyzing the negative moment region of continuous composite steel-concrete bridge beams which have no shear connectors between the steel beam and slab for a certain length over the internal supports as permitted by AASHO. Yam and Chapman (1972) [3] studied the elastic-plastic behavior of two-span composite beams numerically and with reference to experimental results. Shear lag has long been of interest to researches. Adekola (1974a) [4] formulated and solved constitutive equations, which relate partial interaction with shear lag by series solutions for deflections and in-plane stress in the slab to satisfy all the known boundary conditions. Adekola (1974b) [5] presented analysis for the interaction between non-prismatic beams and an orthotropic concrete plate, based upon the linear theories of the bending and stretching of thin plates, and it was shown that an exponential representation for the steel beam profiles provided a suitable basis for studying interaction in continuous non prismatic beams. In 1983, Ansourian [6] analyzed the behavior of continuous composite system consisting of steel girder and a concrete slab attached by shear connectors.

In 1990, Song and Scordelis [7], based on some rational assumptions, developed a harmonic shear-lag analysis using plane stress elasticity for the stresses in flanges of simple or continuous beams with I-, T- and box cross sections. Three types of structures-simply supported, cantilever, and continuous box girders-under various loading conditions were considered by Luo et al. (2001) [8] in a study on negative shear lag effects in box girders with varying depth using a modified finite element segment method. Sun and Bursi (2005) [9] proposed displacement-based and two-filed mixed beam elements for the linear analysis of steel–concrete composite beams with shear lag and deformable shear connection.

Husain et al. (2006) [10] developed a general nonlinear one-dimensional finite element beam model based on the partial interaction theory of composite beams where the flexibility of shear connectors is allowed for the analysis of composite beams. Okui and Nagai (2007) [11] presented a time-dependent (creep and shrinkage) finite-element analysis of a two I-girder composite bridge with a concrete slab. Aref et al. (2007) [12] introduced a robust effective slab width definition for the negative moment section to account for both the strain variation through the slab thickness and the mechanism that redistributes load from concrete to steel reinforcement after cracking. In 2007, Chen et al. [13] presented a parametric study, on simple span and multiple span continuous bridges, based on finite element analysis of bridges selected by a statistical method-namely, design of experiment concepts.

Kostić et al. (2011) [14] compared and evaluated results obtained by different methods proposed by EC4 with attention to effects relevant for continuous composite steel-concrete beam design, such as cracking of concrete in area of hogging moments, shear lag effect and concrete viscous deformations. Al-Sherrawi and Mohammed (2014) [15] used nonlinear finite element method to achieve a parametric study in investigate the effect of some important parameters on the effective width of simply supported composite beams under different load conditions. Haigen and Weichao (2015) [16] established a differential equation of longitudinal forces at transverse section flange and cantilever flange according to the strain compatibility and the force equilibrium conditions about a composite T-girder. In order to investigate dynamic characteristics of steel-concrete composite box beams, Wangbao et al. (2015) [17] established a longitudinal warping function of beam section considering self-balancing of axial forces.

Zhu et al. (2017) [18] included slab shear lag effect and partial connection at slab-girder interface in their new one-dimensional analytical model of composite twin-girder decks by introducing some new variations about cross-sectional properties of steel girder. Kalibhat and Upadhyay (2017) [19] carried a parametric study by considering various design parameters, such as, the span length, the degree of shear connection, cross section geometry of the steel beam and the concrete slab. Al-Sherrawi and Mohammed (2018) [20] investigated the shear lag phenomenon and determined the effective slab width in a composite steel-concrete beam under a concentrated load. Different parameters related to beams geometry and concrete slab material were considered in the study of Lasheen et al. (2018) [21] to evaluate the effective slab widths at service and ultimate loads.

Silva and Dias (2018) [22] verify the influence of the partial interaction in the evaluation of the effective width of composite beams formed by a concrete slab connected to a steel beam with deformable connection.

Reginato et al. (2018) [23] presented a finite element-based approach to study the effective width variation in non-pre-stressed steel-concrete beams under the serviceability stage, including time dependent effects such as concrete creep, shrinkage and cracking. Dawood and Al-Sherrawi (2018a) [24] presented a parametric study inspecting the effect of the degree of interaction on the effective slab width in composite steel-concrete beams. Dawood and Al-Sherrawi (2018b) [25] performed a three-dimensional linearly elastic finite element analysis to examine the variation of shear lag due to type of loading in composite steel-concrete beams. Al-Sherrawi and Dawood (2019) [26] used a three-dimensional linear finite element analysis to study the effect of the breadth of the slab on the effective slab width and stress distribution across the slab width (shear lag) of composite steel-concrete beams.

This study is part of a continuous research line that focuses on shear lag in composite steel-concrete beams. A three-

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dimensional linear finite element analysis, using ANSYS program, is adopted in this study.

II. Finite Element Verifications

The verification of the finite element modelling can be accomplished and comparing the results generated by ANSYS program to those obtained from the experimental test. In this work, Ansourian (1981) [27] continuous composite steel-concrete beam (CTB6) is used to verify the precision and the performance of the finite element models used in this work.

The beam CTB6 is one in a series of tested beams. The continuous composite steel-concrete beam consisted of two spans. The concentrated load was applied at center of each span. The dimensions and reinforcement details of this beam are shown in Fig. (2).

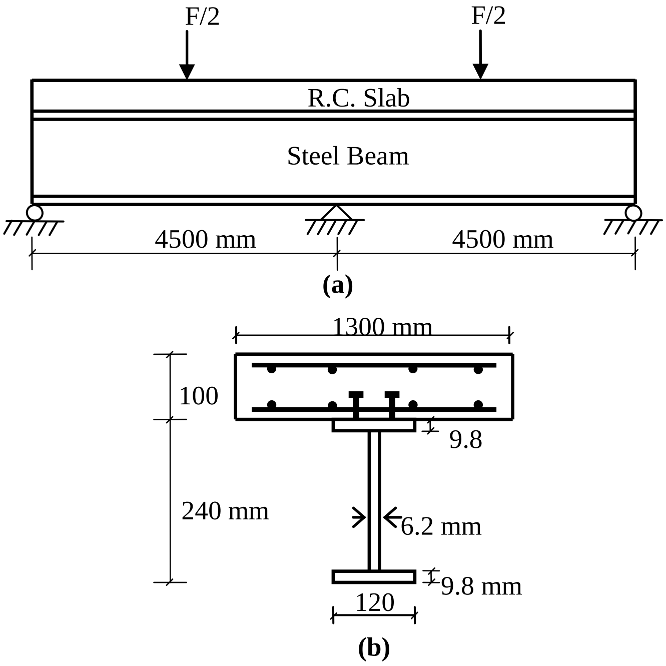

Fig. 2. Ansourian continuous composite steel-concrete beam (CTB6)
(a) Dimensions and loading arrangement (b) Cross section [Ansourian 1981].

A. Finite element idealization

Fig. (3) shows the three-dimensional finite element model for one span of the beam, which has been idealized by using (ANSYS V10) computer program. The concrete slab has been idealized by using (2304) eight nodded brick elements (SOLID45), and the steel beam has been idealized by using (384) four nodded shell elements (SHELL63). The reinforcements have been idealized by using (776) link elements (LINK8). The interface between the concrete slab and the steel beam (sticking and friction) has been idealized by (165) two nodded contact elements (CONTAC52). The shear connectors have been idealized by (90) link elements (LINK8) to resist uplift separation. The effect of dowel action of the shear connectors through the interface between top flange of the steel beam and the concrete slab has been modelled by (30) combine element (COMBIN14) to resist slip. The total number of nodes resulting from the above idealization was (3564) nodes, and the total number of elements was (3749) elements.

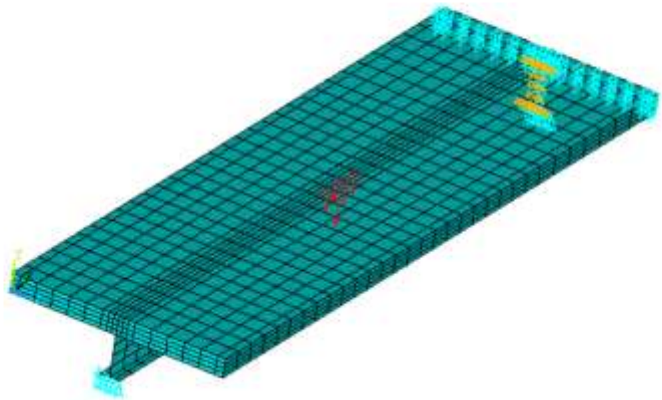

Fig. 3. Three-dimensional finite element mesh for Ansourian continuous composite steel-concrete beam (CTB6).

B. Material properties

Material properties of the Ansourian composite beam are summarized in Tables I and II. In this analysis, the symmetry has been adopted by using one span of the beam. The boundary condition of this beam is shown in Figure (3), the roller support is obtained by constrained displacement in y-axis, and at internal support the symmetry condition is used, the symmetry condition is obtained by constrained displacement in x-axis for all nodes and y-axis in the bottom flange of the steel beam (shell elements) in addition to rotations in z-axis for shell elements. The value of the load is chosen to avoid cracks in the concrete in the negative moment region (8 kN).

TABLE I. Description of Ansourian test beam.

Beam		CTB6
Span (m)		4.5×4.5
Slab	Thickness (mm)	100
	Width (mm)	1300
Steel Beam	Section	IPE 240×30.7 kg
	Area (mm^2)	3910
	Flange (mm)	9.8×120
	Web (mm)	6.2
Shear Connection (Number of 19×75 mm Nelson Studs)		60
Initial stiffness (kN/mm)		240
Percentage Shear Connection	Sagging	110
	Hogging	95
Longitudinal Reinforcement (mm^2)	Hog Top	1260
	Hog Bottom	767
	Sag Top	380
	Sag Bottom	160
Transverse Reinforcement		φ 10 @100 mm at bottom of slab

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TABLE III. Material properties of Ansourian test beam.

Beam		CTB6
Compressive strength N/mm^2		41
Density of concrete kg/m^3		2300
Lower yield stress N/mm^2	Flange	292
	Web	310
	Reinforcement	430
Ultimate tensile stress N/mm^2	Flange	462
	Web	450
	Reinforcement	533
Strain at strain-hardening ε_{sh}		0.014
Initial strain-hardening modulus E_{sh}, N/mm^2		3800

C. Finite element results

In this section, the results obtained using the linear finite element analysis carried out for the chosen beam (CTB6) are presented and compared with the experimental data, as shown in Table III. The experimental and analytical load-deflection curves are shown in Fig. (4).

TABLE IIIII. Comparison between the experimental and analytical results of Ansourian beam.

Load (kN)	Deflection (mm)		Error (%)
	Experimental	Analytical	
50	0.9696	0.9713	0.1
100	1.9696	1.9429	1
200	3.7878	3.8533	1.7
300	6.0606	5.8283	3.8

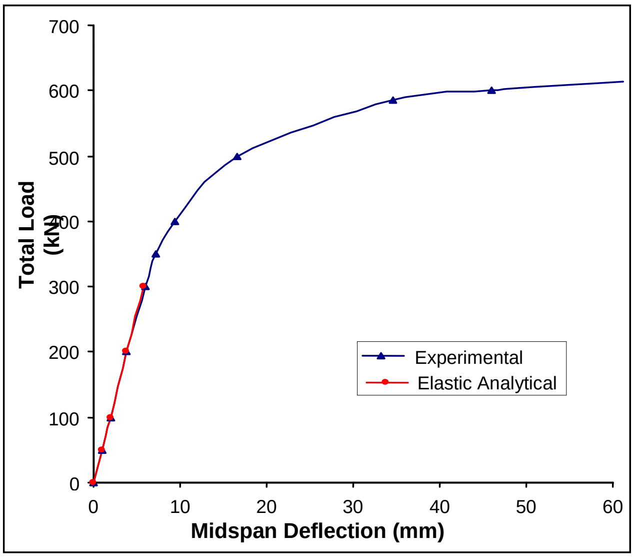

Fig. 4. Experimental and elastic analytical load-deflection curves for Ansourian continuous composite beam.

From results obtained, it can be concluded that the elements, which have been used to model the composite steel-concrete beams in the linear analysis of composite beams are adequate.

III. PARAMETRIC STUDY

The effect of partial interaction on Ansourian continuous composite beam has been inspected. To get full interaction, a large value for the stiffness of the stud shear connectors that used by Ansourian experimentally has been used by multiplying the stiffness value by 106. While for partial interaction, the stiffness of the shear connectors used by Ansourian experimentally has been reduced as a percentage from the stiffness of studs that has been used experimentally.

In this study, three types of loading have been investigated:

a. Concentrated load (CL) (8 kN) (at mid-span).

b. Line load (LL) (0.889 kN/m) (on the longitudinal web axis).

c. Uniformly distributed load (UDL) (0.683 kN/m^2) (on the overall slab).

The effect of partial interaction on the effective slab width with various degrees of interaction for three types of loading are shown in Figs. (5-7), it can be seen from results obtained the effective width various along the span.

The effect of the degree of interaction on the longitudinal compressive stress distribution at midspan and internal support for Ansourian composite steel-concrete beam (CTB6) for the three types of loading is shown in Figs. (8 and 9).

Effect of the degree of interaction on the effective slab width ratio and maximum stress at midspan and internal support for the same beam for three types of loading are listed in Tables IV - VI respectively. From the results obtained, it is seen that the effect of the degree of interaction has relatively minor effect on the effective width of the concrete slab, even for the wide range of the degree of interaction that considered. The maximum effect occurs under uniformly distributed load situation, when the degree of interaction decreases from full to 50% the effective width increases only by 5%. Also, the effect of the degree of interaction on the maximum stress is relatively minor, even for the wide range of degrees of interaction is considered. The maximum effect occurs under uniformly distributed load situation, when the degree of interaction decreases from full to 50%, the maximum slab top surface stress increases only by 10%, while the maximum steel beam bottom flange stress increases only by 3% under concentrated load.

TABLE IV. Effect of degree of interaction on the effective slab width ratio.

Degree of Interaction %	Stiffness of Single Stud kN/mm	Effective Slab Width Ratio $\bar{b}/b$					
		CL (8 kN)		*LL* (0.889 kN/m)		*UDL* (0.683 kN/m^2)	
		Midspan	Internal support	Midspan	Internal support	Midspan	Internal support
Full	240*10^6	0.655	0.743	0.871	0.697	0.991	0.676
Used	240	0.676	0.767	0.882	0.721	0.994	0.700
75	180	0.681	0.772	0.885	0.726	0.995	0.704
50	120	0.688	0.779	0.89	0.732	0.994	0.711

TABLE V. Effect of degree of interaction on the maximum slab stress.

Degree of Interaction %	Stiffness of Single Stud kN/mm	Maximum Slab Stress Ratio					
		CL (8 kN)		*LL* (0.889 kN/m)		*UDL* (0.683 kN/m^2)	
		σ_c/σ_{ca}	σ_s/σ_{sa}	σ_c/σ_{ca}	σ_s/σ_{sa}	σ_c/σ_{ca}	σ_s/σ_{sa}
Full	240*10^6	0.708	0.762	1.047	0.732	1.237	0.686
Used	240	0.681	0.73	0.99	0.706	1.157	0.663
75	180	0.673	0.723	0.973	0.701	1.145	0.658
50	120	0.664	0.712	0.956	0.691	1.111	0.65

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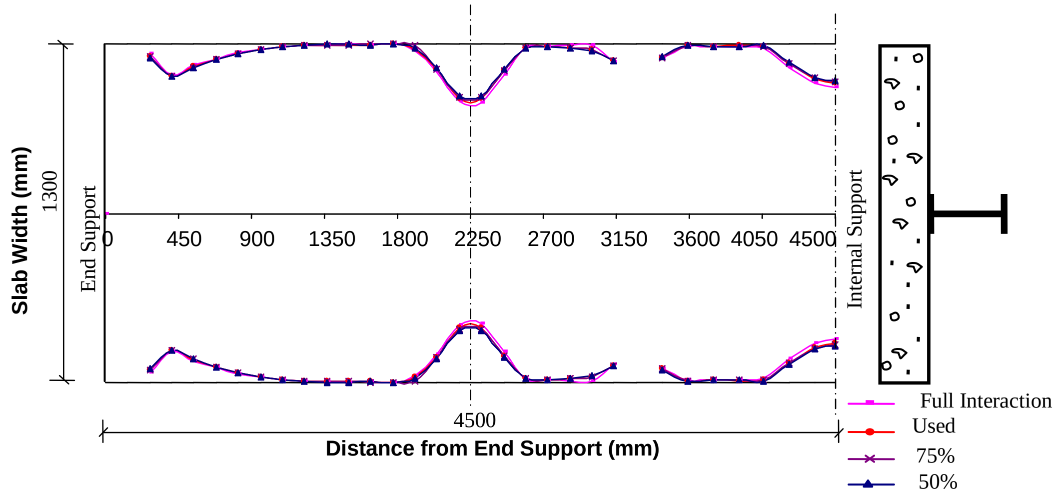

Fig. 5. Effective width for CL (8 kN) for various degrees of interaction.

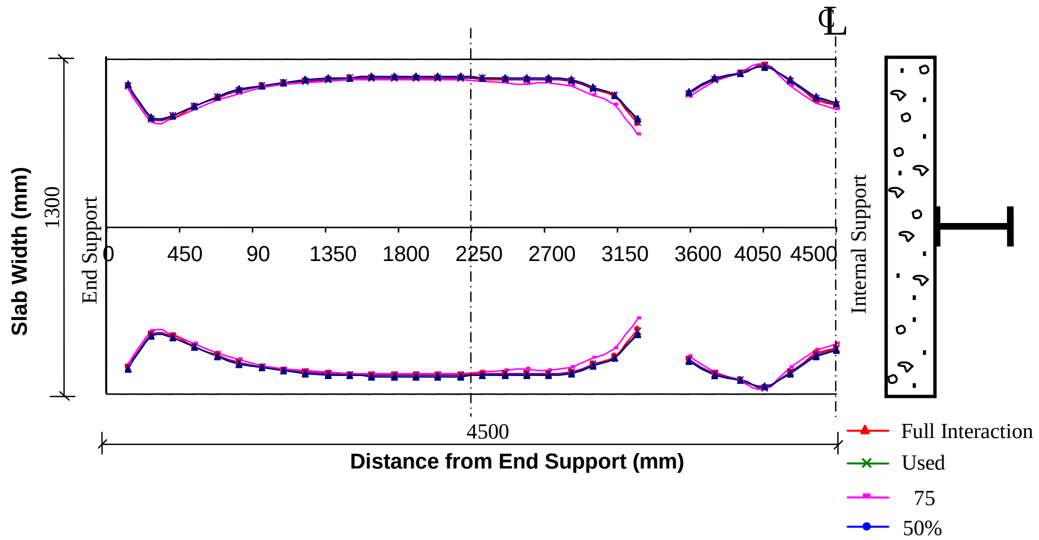

Fig. 6. Effective width for LL (0.889 kN/m) for various degrees of interaction.

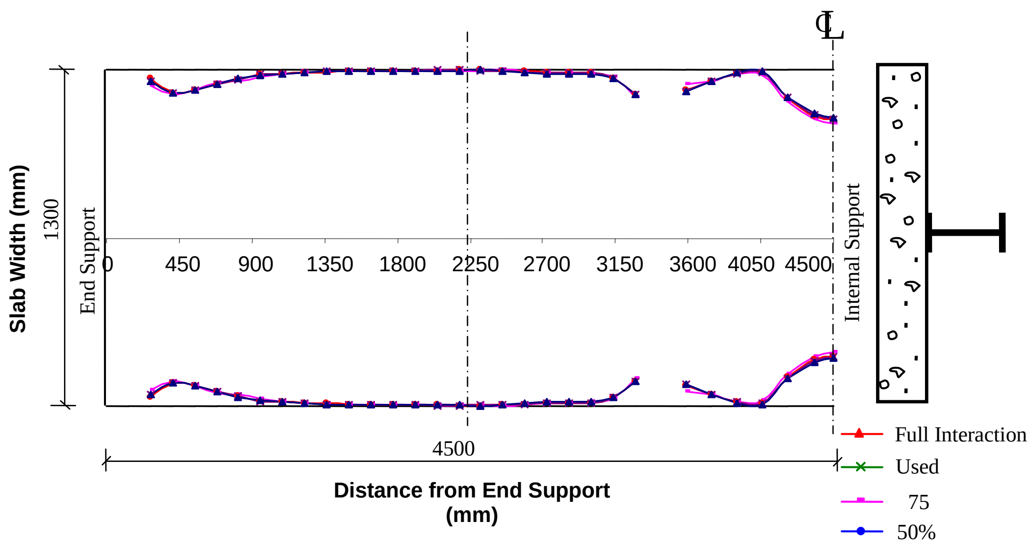

Fig. 7. Effective width for UDL (0.683 kN/m^2) for various degrees of interaction.

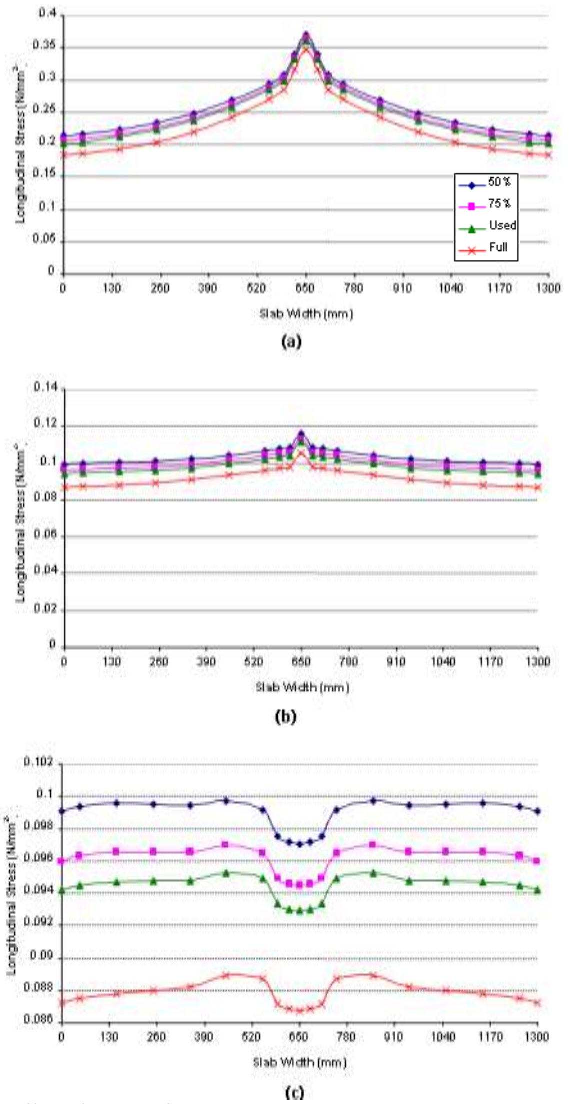

Fig. 8. Effect of degree of interaction on the stress distribution at midspan for Ansourian beam, (a) CL (b) LL (c) UDL.

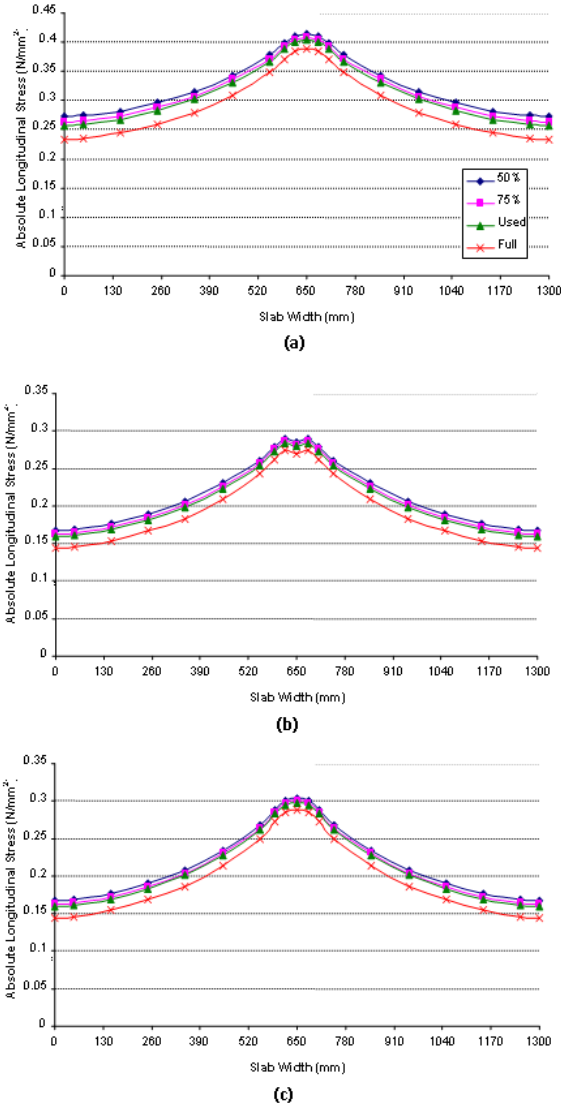

Fig. 9. Effect of degree of interaction on the stress distribution at internal support for Ansourian beam, (a) CL (b) LL (c) UDL.

TABLE VI. Effect degree of interaction on the maximum steel beam stress.

Degree of Interaction %	Stiffness of Single Stud kN/mm	Maximum Steel Beam Stress Ratio					
		CL (8 kN)		*LL* (0.889 kN/m)		*UDL* (0.683 kN/m²)	
		σ_c/σ_{ca}	σ_s/σ_{sa}	σ_c/σ_{ca}	σ_s/σ_{sa}	σ_c/σ_{ca}	σ_s/σ_{sa}
Full	$240*10^6$	1.315	1.358	1.285	1.396	1.285	1.395
Used	240	1.289	1.38	1.262	1.41	1.262	1.41
75	180	1.284	1.386	1.257	1.416	1.257	1.415
50	120	1.276	1.394	1.248	1.424	1.248	1.423

IV. CONCLUSION

The following conclusions can be drawn:

1. The effective slab width does not depend on the degree of interaction in a continuous composite steel-concrete beam.
2. Stresses in the steel beam calculated from the T-beam theory are conservative.
3. For a uniform distributed load on the slab, simple T-beam theory always predicted a safe maximum stress in the beam. However, the longitudinal stress distribution in the concrete slab was markedly different from the uniform distribution assumed in T-beam theory.
4. The results for the case of line load are approximately the same results for the case of uniformly distributed load.

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