International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

Influence of Flange Breadth on the Effective Width of Composite Beams

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***Abstract*—*A composite beam is made up of a reinforced concrete slab connected to a steel beam by means of shear connectors. If the slab was wide and the composite beam is under positive bending moment, it is evident that the simple beam theory does not strictly apply because the longitudinal stress in the concrete flange will vary with distance from the beam web, the flange being more highly stressed over the web than in the extremities. In this paper a three-dimensional linear finite element analysis, using ANSYS program, is done 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.*

The stresses of concrete and steel are compared with stresses obtained from T-beam theory for variable breadths of concrete slab. Effective width for composite beams with different breadth under various loads has been drawn.

Keywords*—*Breadth, **c**omposite beam, effective width, finite elements, shear lag.

I. Introduction

A composite steel-concrete beam is used widely in modern bridges and buildings construction. A composite beam composed of rolled or built-up structural steel shape or HSS and structural concrete acting together, and a steel beam supporting a reinforced concrete slab so interconnected that the beam and the slab act together to resist bending.

It should be obvious that if the steel beams in a composite bridge deck are spaced quite apart from each other, as shown in Fig. 1, the entire concrete slab will not be effective as a compression flange in the composite action of the bridge deck (Al-Sherrawi, 2000) [1].

Fig. 1. Composite bridge deck.

It is well known that the uneven deformation of the wider top flange (concrete) can produce an uneven distribution of the longitudinal stresses under symmetrical bending. The shear lag effect can result in the obvious increase of longitudinal stress near the edge of the flange and cause stress concentration. (Haigen and Weichao, 2015) [2].

The effect of shear lag, in T-beam under positive bending moment, causes the longitudinal stress at flange/web connection to be higher than the mean stress across the concrete flange. Therefore, the effect of shear lag has to be catered for in the design of composite bridges, especially for those with beams have wide flanges. Effective width may be defined in a variety of ways depending on which design parameter is deemed more significant (Al-Sherrawi and Edaan, 2018) [3].

In normal composite construction, a relatively thin concrete floor slab acts as the compression flange of the composite beam. The longitudinal compressive bending stresses in the slab cause shear stresses in the plane of the slab. The shear stresses cause shear strains in the plane of the slab. One effect of these shear strains is that the areas of slab furthest from the steel beams are not as effective at resisting longitudinal bending stresses as the areas close to the steel beams. This effect is called *shear lag*. As a result, the longitudinal bending stress across the width of the slab is not constant, as shown in Fig. 2. The longitudinal stress tends to be a maximum over the web of the steel section, and reduces non-uniformly away from the center-line of the beam.

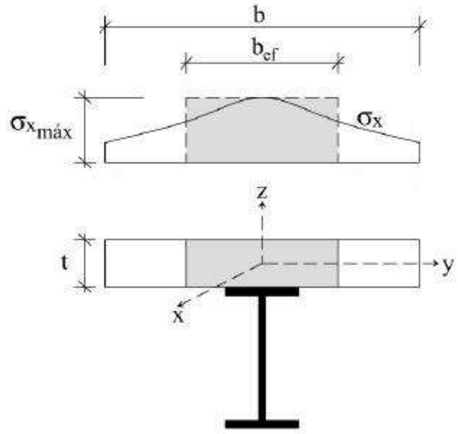


Fig. 2. Shear lag and effective width in a composite beam.

In order that simple "engineers" bending theory may be applied (i.e., plane sections remain plane in bending), the effective width concept is introduced. The section properties are calculated using the effective width (b_{ef}) which is assumed to carry a uniform stress across the width b_{ef}. The value of the stress in the concrete calculated using these effective section properties is equal to the maximum stress resulting from the effects of shear lag in the actual slab.

The effective flange width is a concept proposed by various codes and specifications to simplify the computation of stress distribution across the width of a flanged beam.

According to ANSI/AISC 360-16 (Section I3.1a.) [4], the effective width of the concrete slab in a composite steel-concrete beam shall be the sum of the effective widths for each side of the beam centerline, each of which shall not exceed:

(1) One-eighth of the beam span, center-to-center of supports;

(2) One-half the distance to the centerline of the adjacent beam; or

(3) The distance to the edge of the slab.

In order to estimate the flexural rigidity of a composite steel concrete beam, it is necessary to study the shear lag phenomenon, which plays an important role in the calculation of the effective width and the distribution of the normal bending stresses at the concrete slab of the composite beam (Al-Sherrawi and Mohammed, 2018) [5].

With the increasing use of steel-concrete composite beams in bridges and buildings more investigations related to this topic are necessary to fill the needs and improve the subject.

Previous research, based on elastic theory, has shown that the effective width in a composite steel concrete beam depends in a complex way on:

• The ratio of the flange breadth to the beam span.
• The type of loading.
• The boundary conditions at the supports.
• The degree of interaction.
• The thickness of concrete.
• Other variables.

The main objective of this work is to investigate the effect of the ratio of width of the slab to span length of the beam (b/L) on the effective slab width and stress distribution across the slab width (shear lag) of composite steel-concrete beams.

II. Previous Studies

There are many laboratory tests and analytical and numerical studies in the published literature dealing with shear lag in composite beams. The consensus of published literature generally is that the behavior of a composite beam depends primarily on the behavior of the connection between the slab and beam.

Moffatt and Dowling (1978) [6] describe the concept of *effective slab width* to simplify the analysis and design of the composite section. Effective slab width can be thought of as a reduced slab width with a constant stress distribution that is used to replace the actual slab width in a simplified analysis based on beam theory _“line girder analysis”_. This concept was adopted in different codes of practice nationally and internationally for analysis and design of composite sections in both buildings and bridges.

In the simply supported T-beam with a central concentrated load shown in Fig. 3-a, the shear flow distribution in the slab is linear, and this produces warping displacements or complementary displacements in the longitudinal direction that the parabolic in the transverse direction. In the left hand side of the beam, the shear is positive and the warping displacements are as shown in Fig. 3-b. On the other hand, the right hand side of the beam is subjected to negative shear, resulting in the warping displacements also shown in Fig. 3-b. In order for geometric compatibility to be maintained at mid span, changes are required in the bending stress distribution as well as in the shear stress distribution. These changes in stress result in the shear lag effect (Oehlers and Bradford, 1999) [7].

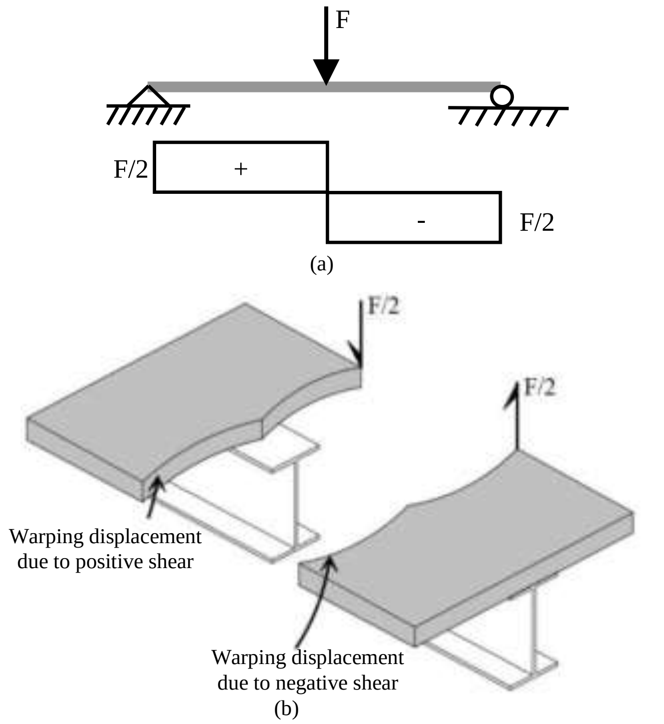


Fig. 3. Incompatible warping displacements at a shear discontinuity, (a) beam and shear force diagram, (b) warping displacement calculated from conventional theory (Oehlers and Bradford, 1999) [7].

Aref et al. (2007) [8] 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.

Gara et al. (2011) [9] presented a numerical model, capable of capturing the structural response produced by shear-lag effects, for the analysis of composite steel-concrete beams with partial interaction to account for the deformability of the shear connection.

In a composite beam, the ratio b/L is an important parameter affecting the shear lag phenomena and this parameter is not taken into account in the simple elastic analysis (Gupta et al., 2013) [10].

Al-Sherrawi and Mohammed (2014) [11] used nonlinear finite element analysis to execute a parametric study in examining the effect of some parameters on the effective width of a composite beam under different load conditions.

Zhu et al. (2015) [12] conducted a static load test on a wide composite twin-girder beam, which has significant shear-lag responses.

Henriques et al. (2015) [13] presented a computationally efficient generalized beam theory based beam finite element, specifically developed for capturing the materially non-linear behavior of wide-flange steel-concrete composite beams.

To study dynamic characteristics of steel concrete composite box beams, Wangbao et al. (2015) [14] established a longitudinal warping function of a beam section by considering self-balancing of axial forces.

Slab shear lag effect and partial connection at slab-girder interface have been included by Zhu et al. (2017) [15] 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) [16] carried out 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.

Taig and Ranzi (2017) [17] presented a generalized beam theory formulation to study the partial interaction behavior of two-layered prismatic steel–concrete composite beams.

Zhu and Su (2017) [18] proposed a new solution method to solve the one-dimensional analytical model of composite beams which is able to simulate the effects of interface slippage, and shear-lag and time-dependent effects.

Gara et al. (2018) [19] derived of a finite element formulation for the analysis of composite decks accounting for partial interaction theory and shear-lag effects.

Silva and Dias (2018) [20] verified 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.

Dawood and Al-Sherrawi (2018) [21] performed a parametric study to inspect the effect of the degree of interaction on the effective slab width in a composite steel-concrete beam.

Dawood and Al-Sherrawi (2018) [22] performed a three-dimensional linearly elastic finite element analysis to study the variation of shear lag due to loading type in a composite steel concrete beam.

III. T-Beam Theory

When the interface slip can be neglected, the cross section remains plane and then the strains vary linearly along the section depth. The stress diagram is also linear if the concrete stress is multiplied by the modular ratio $n = E_s / E_s$ between the elastic modulus E_s and E_c of the steel and concrete, respectively. As further assumptions, the concrete tensile strength is neglected, as it is the presence of reinforcement placed in the concrete compressive area in view of its modest contribution. The theory of transformed sections can be used, i.e., the composite section is replaced by an equivalent all-steel section, the flange of which has a width equal to b_{eff} / n. The translation equilibrium of the section requires the centroidal axis (Cosenzo and Zandonini, 1999) [23].

$$S = \frac{1}{n}\frac{b_{\text{eff}} \cdot x_e^2}{2} - A_s \cdot \left(\frac{h_s}{2} + h_c - x_e\right) = 0$$

That is quadratic in the unknown X_e (which is the distance of elastic neutral axis to the top fiber of concrete slab). Once the value of X_e is calculated, the second moment of area of the transformed cross-section can be evaluated by the following expression:

$$I = \frac{1}{n}\frac{b_{\text{eff}} \cdot x_e^3}{3} + I_s + A_s \cdot \left(\frac{h_s}{2} + h_c - x_e\right)^2$$

The same procedure is used if the whole cross-section is effective, i.e., if the elastic neutral axis lies in the steel profile. In this case the results:

$$x_e = d_s + \frac{h_c}{2}$$

where

$$d_s = \frac{A_s}{A_s + b_{\text{eff}} \cdot h_c / n} \cdot \frac{h_c + h_s}{2}$$

where d_s is the distance between the centroid of the slab and the centroid of the transformed section;

$$I = I_s + \frac{1}{n}\frac{b_{\text{eff}} \cdot h_c^3}{12} + A^* \cdot \frac{(h_s + h_c)^2}{4}$$

where

$$A^* = \frac{A_s \cdot b_{\text{eff}} \cdot h_c / n}{A_s + b_{\text{eff}} \cdot h_c / n}$$

IV. Parametric Study

This work is part of a continuous research line, which focuses on shear lag in a composite beam.

The simply supported steel-concrete composite beam, which investigated by Dawood and Al-Sherrawi (2018) [21], has been selected to carry out the parametric study in this study. A three-dimensional linear finite element analysis, using ANSYS program, is adopted in this work.

To study the effect of concrete slab breadth on the effective width of composite steel-concrete beam, three different ratios of width of the slab/span length ratio (b/L) have been adopted in this research (0.222, 0.272 and 0.364). The depth of the composite beam has been kept constant while varying the breadth of the concrete slab. The beam span was 5486 mm.

In this work, a total static load equals 100 kN has been assumed and three types of loading cases have been inspected:

a. A concentrated load (CL = 100 kN at midpoint of concrete slab top surface).
b. A line load (LL = 18.228 kN/m on the centerline of concrete slab top surface).
c. A uniformly distributed load (UDL 100 kN on the overall concrete slab top surface).

The three-dimensional finite element mesh for these three beams and their boundary conditions are shown in Fig. 4.

In this analysis the symmetry has been used by using half span of the three composite beams. The boundary conditions of these beams are shown in Fig. 4. The roller support is obtained by constrained displacement in y-axis, and at mid span the symmetry condition is used, the symmetry condition is obtained by constrained displacement in x-axis for all nodes and rotations in z-axis for shell elements.

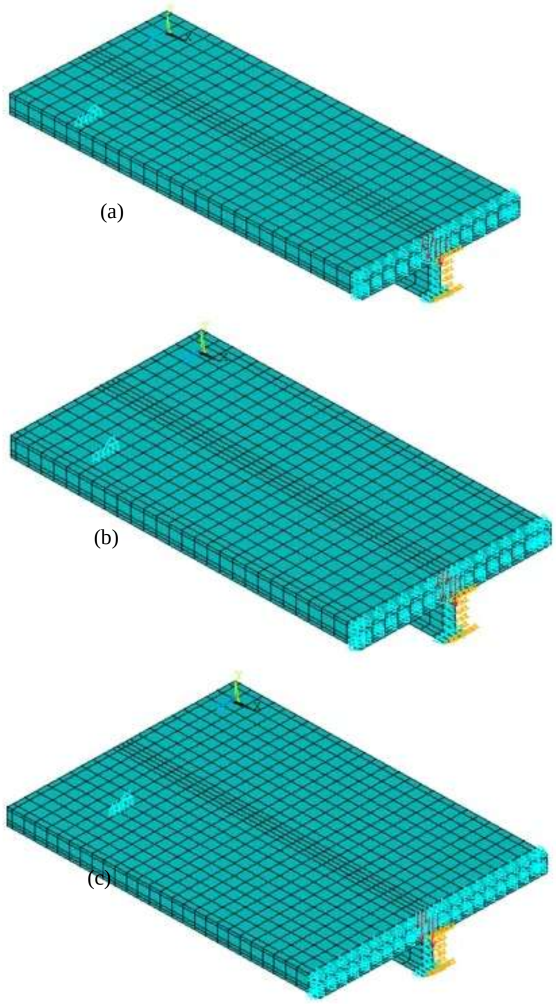


Fig. 4. Three dimensional finite element mesh for composite beam with different slab breadth, (a) b/L = 0.111, (b) b/L = 0.272, (c) b/L = 0.364.

Table 1 lists the effect of the variation in panel proportion (b/L) on the effective slab width ratio (b_{ef}/b) in a composite beam, which calculated by T-beam theory and finite element method. Fig. 5 shows a summary of this table.

TABLE 1. Effect of panel proportion (b/L) on the effective slab width ratio in composite beam

b/L	T-beam theory		finite element analysis b_{ef}/b		
	b_{ef}	b_{ef}/b	CL	LL	UDL
0.222	**b**	**1**	**0.649**	**0.940**	**0.996**
0.272	**L/4**	**0.914**	**0.607**	**0.927**	**0.994**
0.364	**L/4**	**0.685**	**0.544**	**0.902**	**0.989**

Under concentrated load, effective width ratio is reduced to the value of 0.544 in panel proportion equals 0.364. Also, under concentrated load, b_{ef}/b ratio from the finite element result shows a clear deviation from T-beam result for all b/L ratios. While b_{ef}/b ratio from the analysis of the composite beam under line load and uniformly distributed load deviates only when b/L equals 0.364. Also, the results of the effective width distribution for composite steel-concrete beams analyzed by finite element method under the case of line load are approximately the same results for the case of uniformly distributed load.

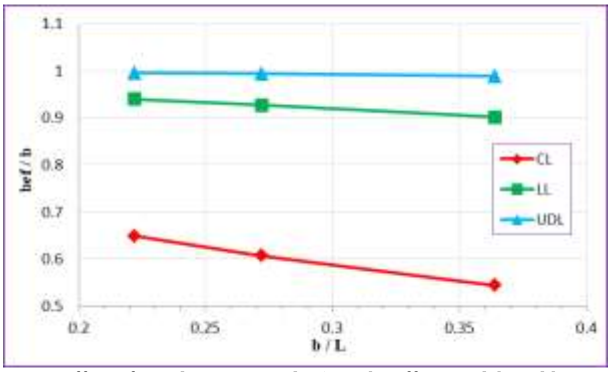


Fig. 5. Effect of panel proportion (b/L) on the effective slab width ratio.

Tables 2 and 3 list the ratio of maximum concrete slab and bottom flange steel beam stress calculated from T-beam theory and finite element analysis at midspan due to the three types of loading.

TABLE 2. Ratio of maximum concrete slab stress calculated from T-beam theory and finite element analysis at midspan

b/L	T-beam theory b_{ef}/b	CL		LL		UDL	
		b_{ef}/b	σ_c/σ_{ca}	b_{ef}/b	σ_c/σ_{ca}	b_{ef}/b	σ_c/σ_{ca}
0.222	**1**	**0.649**	**0.538**	**0.940**	**0.897**	**0.996**	**0.96**
0.272	**0.914**	**0.607**	**0.549**	**0.927**	**0.917**	**0.994**	**0.997**
0.364	**0.685**	**0.544**	**0.561**	**0.902**	**1.032**	**0.989**	**1.154**

TABLE 3. Ratio of maximum steel beam stress calculated from T-beam theory and finite element analysis at midspan

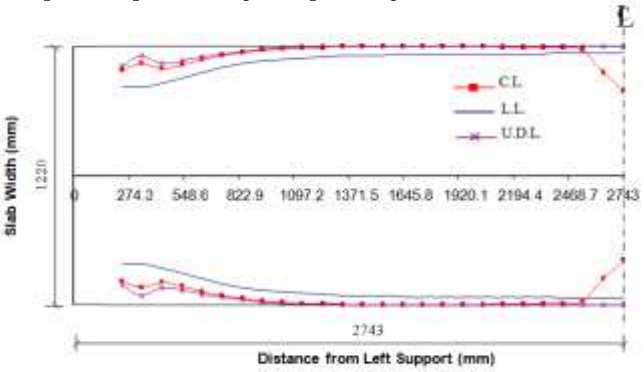
b/L	T-beam theory b_{ef}/b	CL		LL		UDL	
		b_{ef}/b	σ_c/σ_{ca}	b_{ef}/b	σ_c/σ_{ca}	b_{ef}/b	σ_c/σ_{ca}
0.222	**1**	**0.649**	**1.143**	**0.940**	**1.075**	**0.996**	**1.073**
0.272	**0.914**	**0.607**	**1.168**	**0.927**	**1.097**	**0.994**	**1.093**
0.364	**0.685**	**0.544**	**1.242**	**0.902**	**1.167**	**0.989**	**1.160**

From the results obtained, it can be concluded that the effective slab width and the maximum stress for both concrete slab and steel beam decreases as the ratio (b/L) increases, as shown in Tables 2 and 3, respectively.

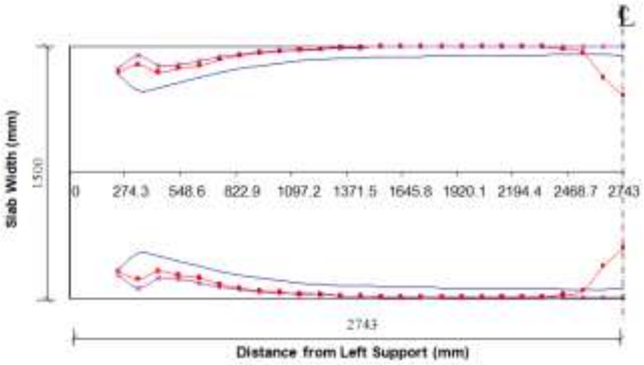
Stresses in the bottom flange of the steel beam calculated according to the T- beam theory are conservative, even when the mid span value of effective width is used along the entire span.

For a uniformly distributed load on the slab, simple T-beam theory always predicted a safe maximum stress in the steel beam, even when the effective slab width was taken as full width of slab. However, the longitudinal stress distribution in the slab was markedly different from the uniform distribution assumed in T- beam theory, nevertheless, with b_{ef}/b equals 1, the exact peak stress was only slightly greater than the T- beam stress.

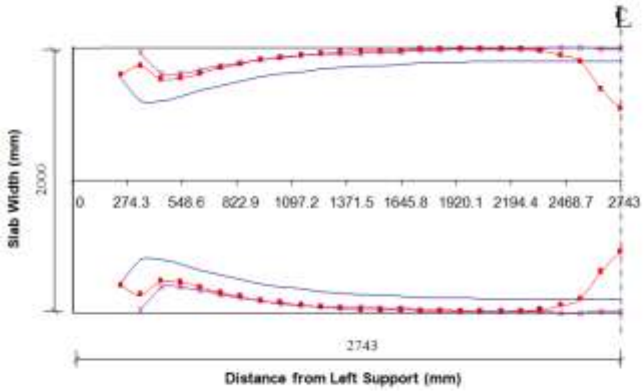
The distribution of the effective slab widths based on the normal stresses calculated at the top surface of the concrete flange for the three composite steel-concrete beams with respect to the three types of loading is shown in Fig. 6. It can be seen from results obtained that the effective width varies from point to point along the span length.



(a)



(b)

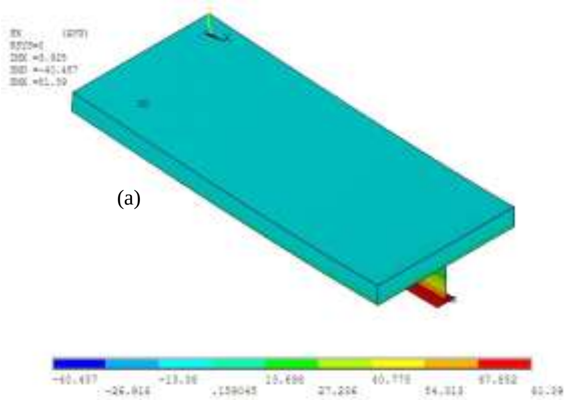


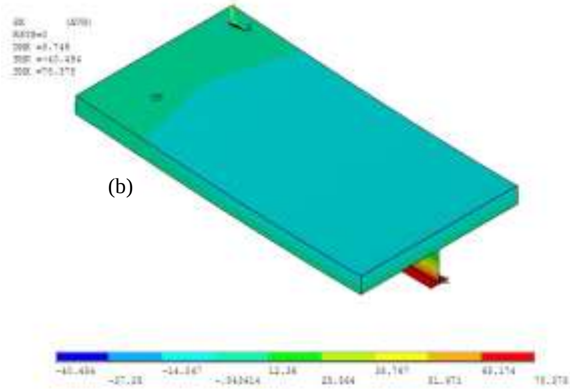
(c)

Fig. 6. Effective width for various loads, (a) b/L = 0.222, (b) b/L = 0.272, (c) b/L = 0.364.

It's clear that the variation in the breadth of the concrete flange in a composite steel-concrete beam under positive moment affects obviously the magnitude of the effective width and shear lag in the beam.

Fig. 7 shows contour plots for the longitudinal stress distribution in the three composite beams under concentrated load.





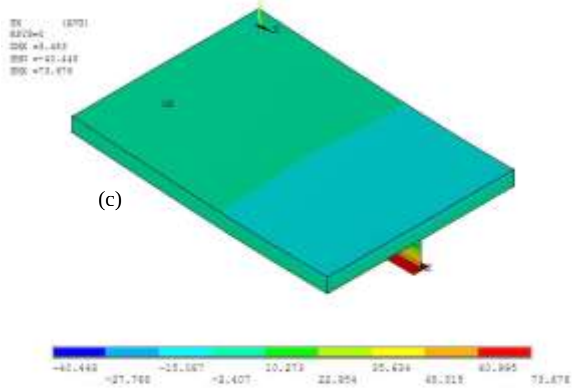


Fig. 7. Contour plots for the longitudinal stress for for composite beam with different slab breadth, (a) b/L = 0.222, (b) b/L = 0.272, (c) b/L = 0.364.

V. Conclusions

The linear finite element analysis has been used to investigate the simply supported composite steel-concrete beams with different breadth, and to provide data on accurate distribution slab normal stresses along the beam span. The principal conclusions of the investigation are:

1. Effective slab width calculated from finite element analysis depends strongly on slab panel proportion (b/L) and type of loading.
2. As b/L is reduced, the effective slab width tends to reach the full slab width, more rapidly at mid span than at the support.
3. Stress levels in the lower flange of the steel beam approach the rigorously calculated values as panel proportions are reduced.

International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

4. Effective width in composite beam clearly influences by the flange breadth.

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