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

Effect of Diaphragms on Shear Lag in Steel Box Girders

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***Abstract*—*This paper reports a study of the effects of steel plate diaphragms on shear lag in steel box girders within the elastic range of material property and without including the effect of plate buckling. STAAD.Pro program had been utilized to evaluate and determine top flange stress distribution and the actual effective flanges width in steel box girders with or without diaphragms. Shell elements had been used to model the flanges, webs, and diaphragms. Different numbers, thickness and types for the plate diaphragms have been used to determine their effects on the shear lag in the flange. Using diaphragms had affected slightly shear lag. The diaphragms number affected obviously the shear lag in the top flange, especially the magnitude of maximum top flange longitudinal stresses.*

***Keywords*— *Diaphragms, effective width, shear lag, steel box girder.*

I. INTRODUCTION

A box girder is a beam with a hollow cross-section. The box girder normally comprises either reinforced concrete, structural steel, prestressed concrete, or a composite of steel and reinforced concrete. The box is typically rectangular or trapezoidal in cross-section. The use of thin walled steel box girders as main load carrying members in bridge structures has gained considerable popularity (Al-Sherrawi and Fadhil, 2012).

Box girder bridges are commonly used for highway flyovers and for modern elevated structures of light rail transport. Although normally the box girder bridge is a form of Beam Bridge, box girders may also be used on cable-stayed bridges and other forms. It is considered as “The box is typically rectangular or trapezoidal in cross-section” (Yas and Dilip, 2017).

When a box girder is subjected to a bending moment, the stress distribution differs somewhat from that given by the ordinary theory of bending. The reason for these differences, denoted by the term "shear-lag action", lies in the fact that the cover sheet suffers appreciable shear deformations, particularly after it buckles into diagonal-tension fields [Kuhn, 1938].

The effect of shear lag causes the longitudinal stress at flange/web connection to be higher than the mean stress across the flange. Therefore, the effect of shear lag has to be catered for in the design of box-girder bridges, especially for those with wide flanges.

Many researchers had been studied shear lag. Reissner (1946) studied shear lag in box girders. An analytical procedure using stiffener-sheet solution had been suggested by Malcolm and Redwood (1970). By means of the finite element method of analysis, Moffatt and Dowling (1975) studied the shear lag phenomenon in steel box girder bridges. Kuzmanovic’ and Graham (1981) found the minimum potential energy principle was a suitable approach to evaluate the shear lag in box girders. Foutch and Chang (1982) investigated the effects of shear lag and shear deformation on the static and dynamic response of tapered thin-walled box beams.. Chang and Zheng (1987) analyzed shear lag and negative shear lag effect in cantilever box girders through variation approach and finite element techniques. The sub-structuring analysis method for shear lag stress using the conditions of compatibility and equilibrium was introduced by Fafitis and Rong (1996), and Lee and Wu (2000) improved the inefficiency of traditional finite element analysis using uniform meshes in the solution of shear lag stress. Wang (1997) derived an energy equation for the lateral buckling of thin-walled members with openings considering shear lag phenomenon. Also, Luo et al. (2001) studied the negative shear lag in box girder with varying depth. However, these studies recognized that the complicated equations by many investigators were not so practical for the design of steel box girders. Luo et al. (2002) carried out experimental study on the shear lag effect of box girder with varying depth. Lin and Zhao (2011) used an energy-based variation analysis to evaluate the AASHTO provisions for effective flange width. Al-Sherrawi and Fadhil (2012) studied the effects of stiffeners on shear lag in steel box girders with stiffened flanges. Lin and Zhao (2012) developed a least-work based method for modeling inelastic shear lag behavior. An effective modulus was formulated and the Poisson’s ratio following the theory of plasticity was used in the inelastic shear lag model. Al-Sherrawi and Mohammed (2014) employed a nonlinear three-dimensional finite element analysis to study the shear lag effects and determine the actual effective slab width of the composite steel concrete beam. The theoretical solution method for the shear lag effect of cantilever box girder is solved by Zhou (2014) through exerting the principle of minimum potential energy and combining the variation method. Vlašić and Mujkanović (2017) performed a parametric study using stability evidence for six different types of stiffeners in a steel box girder. The reduction due to shear lag from the bending moment was dependent on the effective length, plate width, and stiffener to plate area ratio (stiffener contribution). Al-Sherrawi and Mohammed (2018) carried out parametric studies to investigate the effect of some important parameters on shear lag in a beam under concentrated load. Yao et al. (2018) investigated the dynamic response of the steel box girder under internal blast loads through experiments and numerical study. The diaphragm affected the propagation of the internal shock waves.

II. Diaphragms

Diaphragm – A vertically oriented solid-web transverse member connecting adjacent longitudinal flexural members, or placed inside of a closed-box or tub section to transfer and distribute vertical and lateral loads, to provide stability to the compression flanges, and to limit the cross-section distortion to acceptable levels.

Diaphragms are structural members that resist lateral forces and transfer loads to supports. The main functions of the diaphragms are [Al-Sherrawi, 1995]:

- Preserving the cross-section shape of the box girder against large distortion.
- Providing good resistance to torsion through shear flow.
- Preventing local buckling of the flanges due to compression.
- Supporting concentrated loads.
- Transmitting vertical forces from webs to the supports.

The main types of steel plate diaphragms that are usually used in steel box girders are shown in Fig. 1. Another type is steel cross frame diaphragms [Watheej and Al-Sherrawi, 2009]. Also, diaphragms classified according to its position as support diaphragms and intermediate diaphragms.

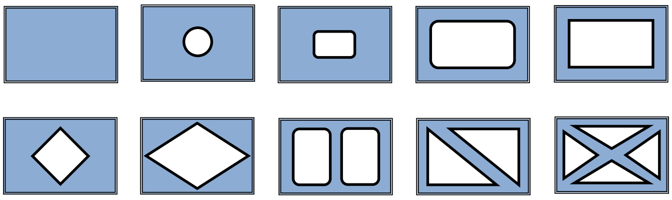


Fig. 1. Different types of steel diaphragms.

The main goal of the present work is to investigate the effect of the introducing diaphragms on the top flange longitudinal stress distribution in a steel box girder by using finite element method.

III. Shear Lag in Box Beam

The general methods for calculating the shear lag effect in a box beam have the following kinds: (1) energy variation method: By using the principle of minimum potential energy and combining the variation method.; (2) the tuning function method, based on the theory of the elastic orthotropic plate method and the theory of folded plate method; (3) based on the numerical method of finite element method, the finite difference method and finite segment method; (4) analogy bar method; (5) test methods [Wang and Qiu, 2014].

IV. Effective Width

The effective flange width is the width of a hypothetical flange that compresses uniformly across its width by the same amount as the loaded edge of the real flange under the same edge shear forces. Alternatively, the effective width can be thought of as the width of theoretical flange which carries a compression force with uniform stress of magnitude equal to the peak stress at the edge of the prototype wide flange when carrying the same total compression force (Hambly, 1991).

The effective width of a girder flange varies along the span and depends significantly on the load distribution, cross-sectional properties, and boundary conditions, as well as the plan dimensional of the girder (Moffatt and Dowling, 1975).

Effective width may be defined in a variety of ways depending on which design parameter is deemed more significant. It is generally obtained by integrating the rigorously calculated longitudinal stress in the flange, and dividing by the peak value of stress. And therefore $\bar{b}$ is calculated here by considering flange stress and is given by (Al-Sherrawi and Mohammed, 2014):

$$\bar{b} = \frac{\int_0^b \sigma_x \, dy}{(\sigma_x)_{max.}} \qquad (1)$$

where $\bar{b}$ is one-side effective flange width, b is half flange width, σ_x represent the normal stress in the longitudinal direction, and $(\sigma_x)_{max.}$ is the maximum normal stress between $0 \le z \le b$.

V. Finite Element Modeling

STAAD.Pro program has been used to generate a three dimensional finite element model for the steel box girder. Three-dimensional four-node isoparametric shell elements were used to model the steel plates, while the stiffeners were modeled by beam elements. The steel model used for all components in the girder model was linear/elastic.

The steel box girder used as a reference throughout this paper is simply supported girder has a width equals 144 in., a depth equals 72 in., and a length equals 720 in. The thickness of the steel plates equals 0.5 in. To ensure no flange buckling, stiffeners for each flange were used (4.5 in. ×1 in. @ 9 in. c/c) (Al-Sherrawi and Fadhil, 2012).

The three-dimensional finite element mesh for the reference steel box girder, which has been used in STAAD.Pro program, is shown in Fig. 2-a.

VI. Parametric Study

The influence of the variation in some parameters on the shear lag and the distribution of normal flange stresses in steel box girders have been investigated. These parameters were diaphragms number, diaphragms thickness and diaphragms types.

A. *Diaphragms Number*

There are few existing guidelines for the determination of diaphragm number. By using the box girder shown in Fig. 2 with different number of equally spaced diaphragms, some results are obtained from which qualitative conclusions can readily be drawn. The cases examined are: no diaphragm at all, diaphragms at the supports only, and additional diaphragms at l/2, l/3, 1/4, l/5 and 1/6 of the span lengths, respectively. All diaphragms are 0.5 in. thick, which can be almost, considered as rigid.

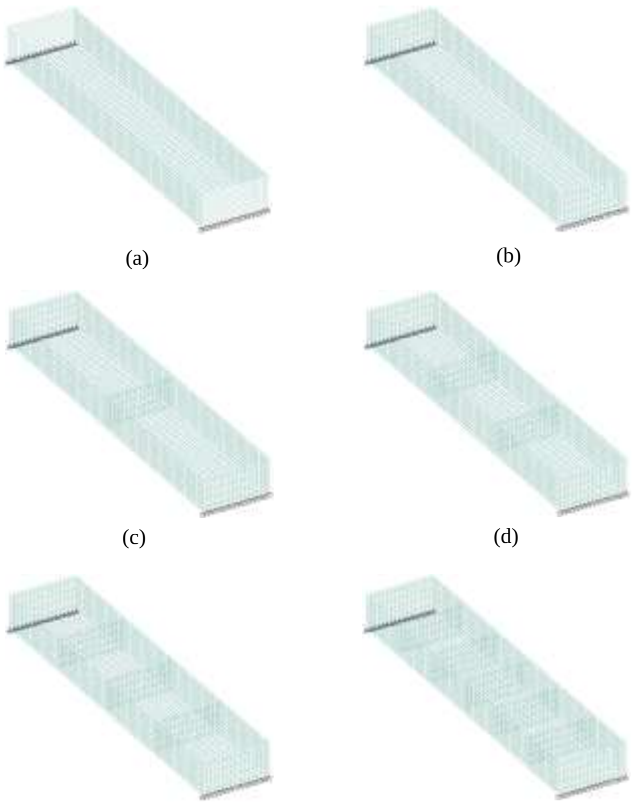


Fig. 2. Finite element modeling of the steel girder, (a) without diaphragms, (b) with two diaphragms, (c) with three diaphragms, (d) with four diaphragms, (e) with five diaphragms, (f) with seven diaphragms.

The distributions of the top flange stresses for different numbers of diaphragms are shown in Figs. 3-5. While the stress contours in the top flange of the steel girder for different numbers of diaphragms are shown in Fig. 6.

Adding a mid-span diaphragm caused an increase in the maximum top flange stress. This increasing reaches about 70%. The variation in the stress contours in the top flange of the steel girder, especially in mid-span, is due to stresses redistribution as a result from adding diaphragms.

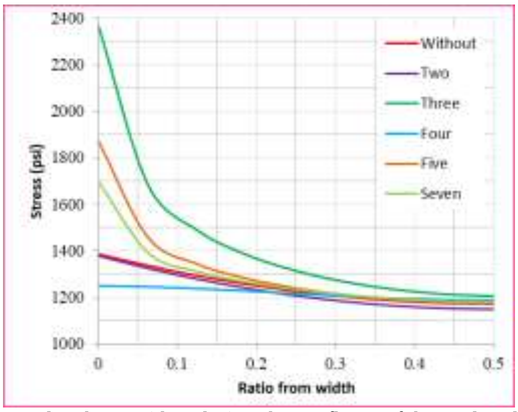


Fig. 3. Stress distribution (shear lag) in the top flange of the steel girder due to changing number of diaphragms.

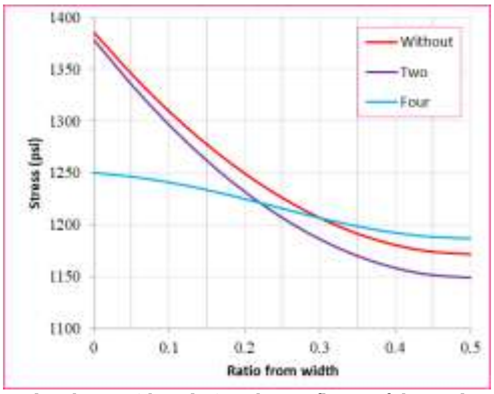


Fig. 4. Stress distribution (shear lag) in the top flange of the steel girder due to using 0, 2 and 4 diaphragms.

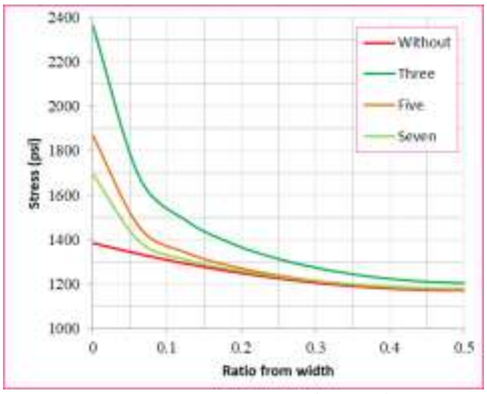


Fig. 5. Stress distribution (shear lag) in the top flange of the steel girder due to using 0, 3, 5 and 7 diaphragms.

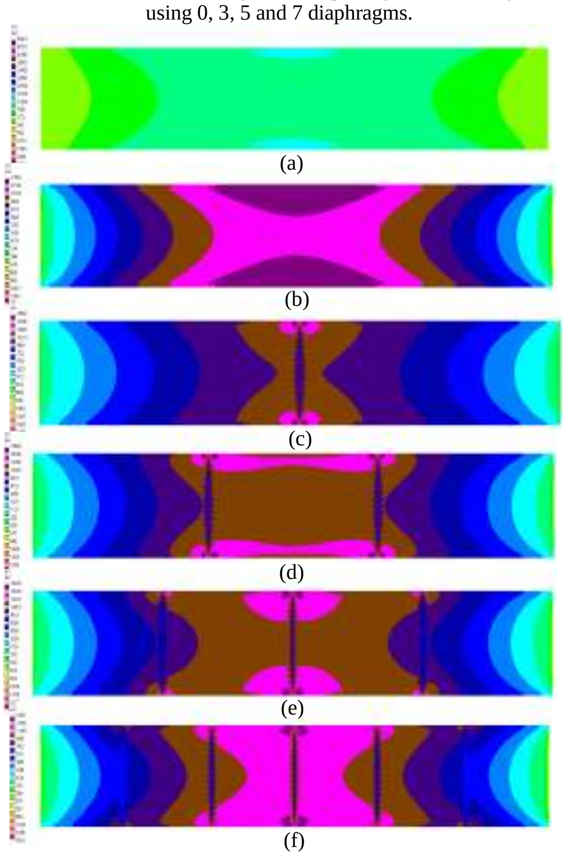
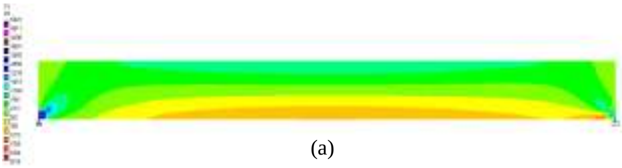


Fig. 6. Stress contours in the top flange of the steel girder, (a) without diaphragms, (b) with two diaphragms, (c) with three diaphragms, (d) with four diaphragms, (e) with five diaphragms, (f) with seven diaphragms.

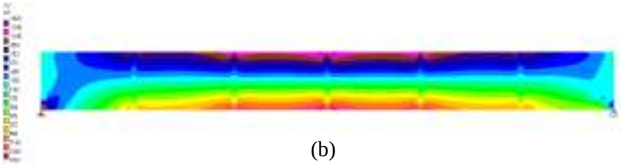
It must be pointed out that diaphragm spacing has noticeable effect on shear lag in steel box girders.

Diaphragms with even number in a steel box girder affected slightly the shear lag in the top flange, and it reduced the magnitude of maximum top flange longitudinal stresses. While diaphragms with odd number affected obviously the shear lag in the top flange, especially the magnitude of maximum top flange longitudinal stresses.

Fig. 7 shows the stress contours in the web of the steel girder for the cases without diaphragms and with seven diaphragms.

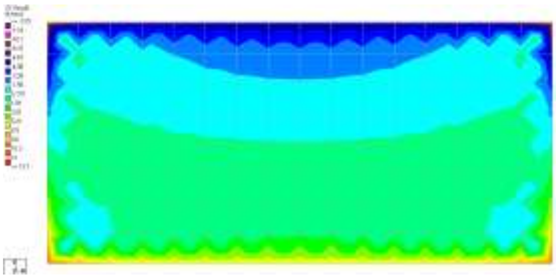


(a)

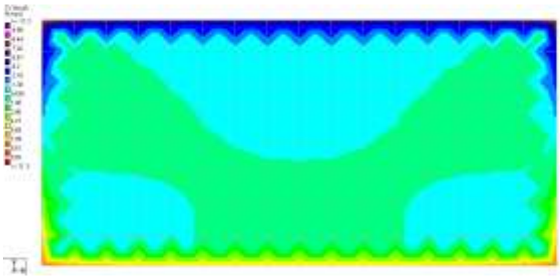


(b)

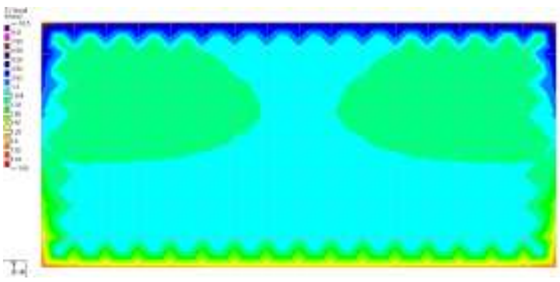
Fig. 7. Stress contours in the web of the steel girder, (a) without diaphragms, (b) with seven diaphragms.



(a)



(b)



(c)

Fig. 8. Stress contours in the mid-span diaphragm of the steel girder, (a) with three diaphragms, (b) with five diaphragms (c) with seven diaphragms.

Fig. 8 shows the stress contours in the mid-span diaphragm of the steel girder for the cases with three, five and seven diaphragms.

The deflections are almost the same when there are numerous numbers of diaphragms in the steel girder, as shown in Table I.

TABLE I. Maximum deflection of the steel girder.

No. of Diaphragms	Deflection (in.)
Without	0.99950
Two	0.08722
Three	0.09175
Four	0.08894
Five	0.09030
Seven	0.09010

B. *Diaphragms Thickness*

Changing the thickness of the diaphragms from 0.2 in. to 0.8 in. had no effect on the distribution of normal stresses in the top flange of the steel girder.

C. *Diaphragms Shape*

Figs. 9 and 10 show the variation in the stress distribution (shear lag) in the top flange of the steel girder due to use diaphragms with single rectangular open (access hole) and two rectangular opens, respectively. While Fig. 11 shows the variation in the stress distribution (shear lag) in the top flange of the steel girder due to use diaphragms like cross.

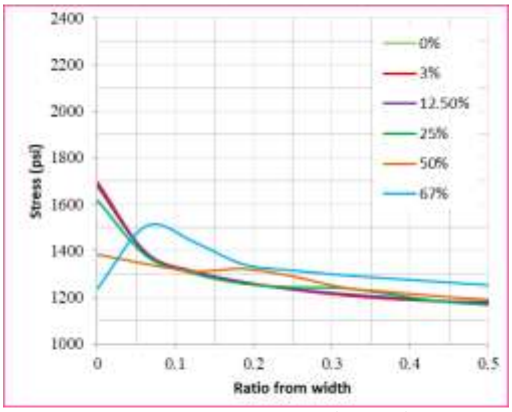


Fig. 9. Stress distribution (shear lag) in the top flange of the steel girder with single rectangular open.

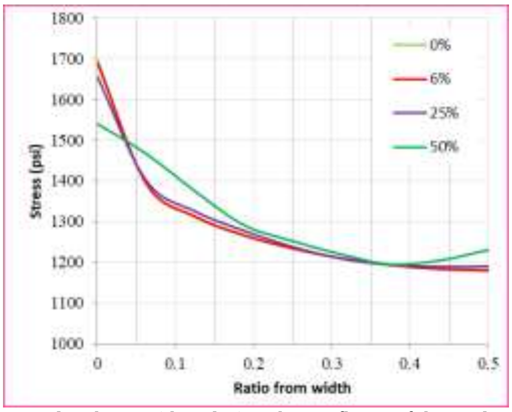


Fig. 10. Stress distribution (shear lag) in the top flange of the steel girder with two rectangular opens.

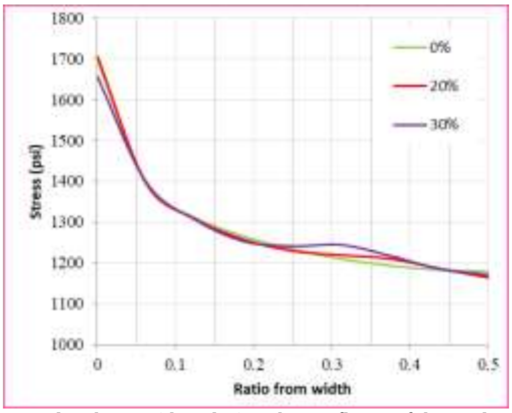


Fig. 11. Stress distribution (shear lag) in the top flange of the steel girder with diaphragms like cross.

VII. Conclusions

1) Using even number of diaphragms in a steel box girder affected slightly the shear lag in the top flange, and it reduced the magnitude of maximum top flange longitudinal stresses.
2) Using odd number of diaphragms in a steel box girder affected obviously the shear lag in the top flange, especially the magnitude of maximum top flange longitudinal stresses.
3) Changing the thickness of the diaphragms had no effect on the distribution of normal stresses in the top flange of the steel girder.
4) Using diaphragms with access holes in a steel box girder affected gradually the shear lag in the top flange with the increase of the area of the holes.

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