CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216
DOI: 10.3303/CET1762164

Study on Shear Lag Effect of Composite Box Girder Bridge with Corrugated Steel Webs

Xu Dong
Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China
xuxudong@126.com

The corrugated steel webs composite box girder bridge is a new bridge structure with corrugated concrete webs with fold effects, which can replace traditional concrete webs. Compared with traditional concrete web box girder, the application of steel webs greatly reduces the weight of the bridge. At the same time, the utilization of steel web has significantly improved the shear capacity of the web, reducing the occurrence of inclined cracks which is conducive to the full use of materials. Due to the shear lag effect, normal stress distribution of the box girder at bending moment is not uniform. However, the web of corrugated steel web is overall corrugated and the transverse contact width between the web, the roof and the bottom plate is large, which can effectively reduce the shear lag effect of the box girder. In this paper, the energy variation method in calculating the shear lag coefficients of the box girder with corrugated steel webs was first introduced. Then the modeling of the box girder with corrugated steel webs was constructed by using finite element analysis software ANSYS while the energy variation method was used to verify the results. The results show that the finite element method can be better used to simulate the shear lag effect of the composite box girder bridge with corrugated steel webs, and the variation regularity of the transverse and longitudinal shear lag coefficients of the composite box girder bridge with corrugated steel webs was also explored.

1. Introduction

In elementary beam theory, the magnitude of stress at the same height from the neutral axis of the main beam subjected to bending moment should be equal. However, both the theoretical analysis and the experimental results have shown that the stress on the fiber layer is not equal in magnitude due to the influence of the web. The stress at the junction of the web and the flange is greater (or less) than that at distance from the web. This phenomenon is known as "stress diffusion" or "shear lag". Shear lag effect is usually expressed by the shear lag coefficient, which is the ratio of the stress at the junction of the flange plate with the web and the stress calculated by elementary beam theory. If the stress at the junction of the flange plate and the web is greater than that calculated by elementary beam theory, the effect is called positive shear lag, otherwise is called negative shear lag.

Many scholars at home and abroad have done a lot of research on shear lag effect (Lin et al., 2015; Zhou, 2008; Ding, 2009; Wang, 2012; Li et al., 2009; He, 2005; Nie et al., 2011; Wu, 2002; Zhao, 2016; Luo, 2009). By selecting the reasonable warping displacement function of double box girder and using the energy established differential equation analysis of shear lag effect on box girder method, Zhang et al. (2012) analyzed the equilibrium condition of axial shear lag warping stress corresponding to the moment and product of inertia geometric characteristics of the shear lag warping. At present, the majority of scholars in the field of box girder shear lag mainly focuses on ordinary box girder, and is less involved in corrugated steel web composite box girder. Since the composite box girder with corrugated steel web has being widely used due to its superior mechanical properties and economic performance, this paper studying its shear lag effect is very necessary. In this paper, the analytical tool is ANSYS finite element software.

Please cite this article as: Xu Dong, 2017, Study on shear lag effect of composite box girder bridge with corrugated steel webs, Chemical Engineering Transactions, 62, 979-984 DOI:10.3303/CET1762164

2. Energy variation method

The energy variation method is one of the most popular methods to analyze the shear lag effect. It is not only clear and easy to derive the concept, but also feasible to calculate the deflection of the beam and qualitatively analyze the influence of various parameters and supporting conditions. The object of this paper is the uniform box girder with corrugated steel webs. With the energy variation method, the exact calculation formula for the shear lag coefficient of the selected section can be obtained by solving the shear lag problems of composite box girder with corrugated steel webs. Therefore, this paper uses the energy variation method to analyze the shear lag effects. The basis of deduction of energy variation formula is the virtual work principles. When the existence of the strain energy function is confirmed, it is assumed that the principle of virtual work will lead to the establishment of the principle of minimum potential energy when the external force remains unchanged during the displacement change. The energy variation method first needs to introduce two generalized displacements, namely the vertical deflection ω(x) and the longitudinal displacement u (x, y) of the beam. Then the basic differential equation of shear lag effect is solved by using the principle of minimum potential energy and variation method. Finally, the stress in the flange plate can be obtained after applying the boundary conditions; the illustration is shown in Figure 1.

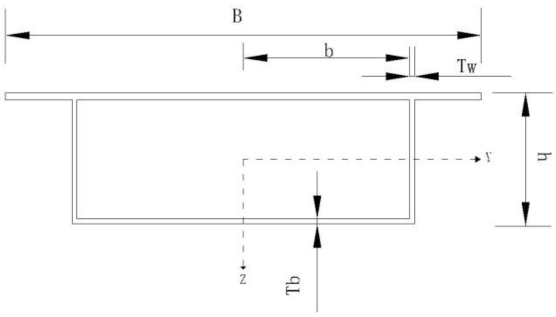

Figure 1: Derivation Diagram

$$\omega = \omega(x) \tag{1}$$

$$u(x,y) = h_i[\frac{d\omega}{dx} + (1 - \frac{y^3}{b^3})u(x)] \tag{2}$$

In the formula: u(x) - The maximum difference of shear angle between top and bottom plate and web;
h_i - The vertical Z coordinate of the beam height.
From the principle of minimum potential energy, the total energy variation should be zero, So:

$$\delta\pi = \delta(\bar{V} - \bar{\omega}) = 0 \tag{3}$$

Among them:

$$\begin{aligned} \pi &= \int M(x)\frac{d^2\omega}{dx^2} \cdot dx + \frac{1}{2}\int EI_{\omega}(\frac{d^2\omega}{\partial x^2})^2 dx \\ &+ \frac{1}{2}I_s\int \{E[(\omega'')^2 + \frac{3}{2}\omega'' u' + \frac{9}{14}(u')^2] + \frac{9Gu^2}{5b^2}\}dx \end{aligned} \tag{4}$$

The above equation is divided into zero. You can get the basic differential equation of shear lag effect. For the top and bottom, you can use:

$$\omega'' = -(\frac{M(x)}{EI} + \frac{3I_s}{4I}u') = -\frac{1}{EI}(M(x) + M_F) \tag{5}$$

$$M_F = \frac{3}{4}EI_s u' \tag{6}$$

M_F stands for the additional bending moment caused by the shear lag effect, which makes the stress, curvature, etc. of the box girder different from the results calculated by the simple beam theory. The additional bending moment is proportional to the bending stiffness of the top and bottom plates.
For the simply supported beam in the span under the concentrated load, the normal stress could be calculated by using elementary beam theory as follows:

$$\sigma_{l/2} = \frac{Plh_i}{4I} \tag{7}$$

While the energy calculated in variation method of the cross-normal stress is:

$$\sigma_{l/2} = \frac{Plh_i}{4I} - \frac{7nPh_i}{12kI}(1-\frac{y^3}{b^3}-\frac{3I_s}{4I})th\frac{kl}{2} \tag{8}$$

Shear lag coefficient obtained by (8) and (9) is:

$$\lambda = 1-\frac{7n}{3kl}(1-\frac{y^3}{b^3}-\frac{3I_s}{4I})th\frac{kl}{2} \tag{9}$$

3. Finite element analysis

The finite element model of simply supported composite box girder with corrugated steel web under concentrated load is established by using finite element analysis software ANSYS. The longitudinal stress of the top and bottom slabs under the load condition is analyzed. Then, the results obtained by finite element analysis are compared with the theoretical results derived by energy variation method to verify the correctness of the finite element model.

3.1 Model unit type selection

In this model, the top and bottom panels are modeled by using 8-node solid elements, solid185. Because the web is thin, a 4-node elastic shell element, shelll81, is used for simulation. In modeling, in order to ensure that the top and bottom plate and the web between the nodes coincide, the model of the bottom floor and the corrugation of corrugated steel web corrugated line should completely coincide. Diaphragm using 8 node entity solid185 simulation is thick, and the connection between the diaphragm and the top plate coincide at the same time. There is no restricting relationship between the diaphragm and the corrugated steel web, and the pre-stressed steel bar is simulated by link8 element.

3.2 Model properties

In this model, the corrugated steel web uses Q235, A3 steel, and the elastic modulus is 210GPa while the Poisson ratio 0.3. The top floor adopts C50 concrete, the elastic modulus is 34.5GPa while the Poisson's ratio 0.167.
The calculated span of the model beam is 30m and the height is 0.6m. The top and bottom plates of the box girder are 1.4m and 0.6m in width repectively, and the thickness are all 0.06m. Besides, the length of the cantilever on both sides is 0.4m. The specific dimensions of the cross section of the corrugated steel webs and the box girder are shown in Figure 2 and Figure 3.

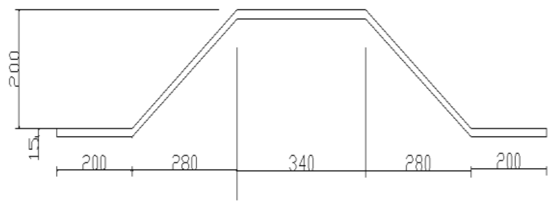

Figure 2: Shape of Corrugated Steel Web (unit: mm)

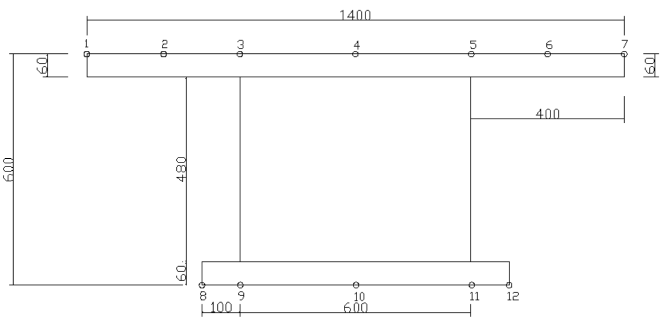

Figure 3: Cross-sectional Dimension of the Box Girder with Corrugated Steel Web and the Location of Measuring Points (Unit: mm)

In order to study the shear lag effect at different positions in the cross-section of the model, the cross-section of the box girder bridge with corrugated steel webs in this paper is arranged up to 12 measuring points, which are the edge of the upper flange plate, the junction point of upper flange plate and web, the midpoint of the roof, the edge of the lower flange plate, the junction point of the lower flange plate and web and the midpoint of the floor. The concrete finite element model is shown in Figure 4

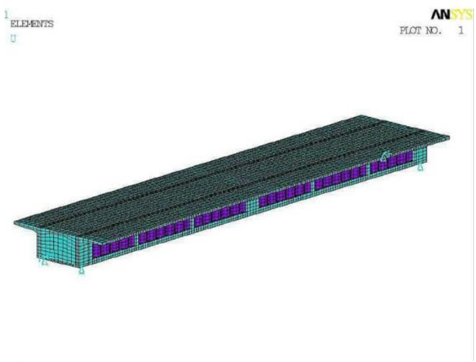

Figure 4: Finite Element Model of Composite Box Girder with Corrugated Steel Webs

3.3 Comparison of shear lag coefficient obtained by two methods

Because the shear lag effect is most prominent at the junction point of flange plate and web and the shear lag coefficient becomes the largest in the cross-section, the shear lag coefficient at the junction of flange plate and web should be compared. At the same time, in order to make the shear lag effect more prominent, the concentrated load and uniform load are symmetrically loaded at the intersection of upper flange plate and web. In the concentrated and uniform load under the effect of finite element and energy variation method, the obtained cross-section shear lag coefficient is shown in Table 1.

Table 1: Comparison of Shear Lag Coefficient of Span Section of Simple Beam

Cross-sectional position	Load form	Finite element calculation results	Energy variation method results	Error (%)
Across	Concentrated load	1.37	1.28	6.569
Across	Uniform load	1.15	1.09	5.217

As can be seen from Table 1:

1) The shear lag coefficients obtained by the two methods are similar. Under the action of concentrated load, the shear lag coefficients of the cross-section calculated by the two methods are less than 6.6%. Under the action of uniform load, the coefficients calculated differ by about 5.2% which can be neglected.

2) The coefficient under concentrated load is larger than that under uniformly distributed load, and the error of the two methods under concentrated load is more than that under uniform load.

3) The calculation results by finite element method is larger than that of energy variation method, namely, the

shear lag effect is more obvious. Thus it is safer by using finite element method to calculate the shear lag coefficient. Tht is to say that using finite element method to analyze the shear lag effect of box girder with corrugated steel webs is safer and more accurate.

4. Shear lag effect of transverse and longitudinal directions of composite box girder bridges with corrugated steel webs

In this paper, the variation law of the shear lag coefficient at the critical position of the transversal mid-span roof and floor is analyzed, and the shear lag coefficient of the load section along the longitudinal direction of the bridge is also calculated. Besides, the shear lag effect of composite box girder with corrugated steel web is obtained.

4.1 The variation law of the shear lag coefficient across the mid-span

Both the concentrated load and the uniformly distributed load are symmetrically acted on the web of both sides of the middle section of the simply supported beam, and the shear lag coefficient along the transverse key plate of the cross-section is calculated. The variation law of the calculated shear lag coefficient is shown in Figure 5 and Figure 6. On the top plate, point 4 in the center of the section is the origin and the coordinate is 0 while the coordinates of the remaining 6 points are shown in Figure 5. At the bottom of the floor, in the center of the cross-section, 10 points are the origin and the coordinate is 0 while the coordinates of the remaining four points are shown in Figure 6.

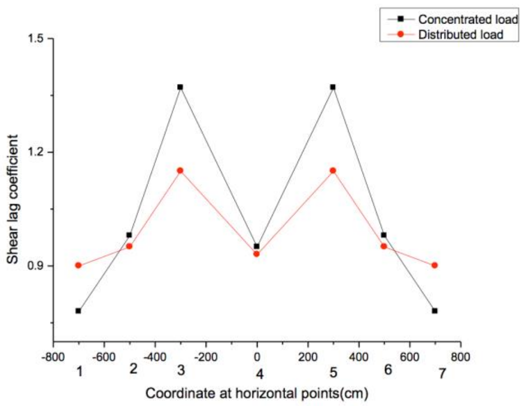

Figure 5: The Law of the Shear Lag Coefficient of the Key Points of the Roof

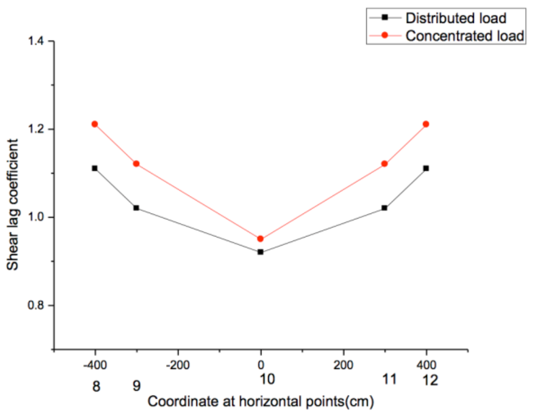

Figure 6: Law of Shear Lag Coefficient for Key Points of Floor

As can be seen from Figure 5:

1) On the top plate, the shear lag coefficient at the interface of upper flange plate and web is greater than 1 under both concentrated load and uniform load, which is positive shear lag effect. When the coefficient reaches the maximum value here, shear lag effect is more prominent.

2) On the top plate, the coefficient at the edge of upper flange plate is less than 1 under both concentrated load and uniform load, which is negative shear lag effect. When the coefficient reaches the minimum value here, shear lag effect is more prominent.
3) On the top plate, the coefficient of the mid-point of roof is less than 1 under both concentrated load and uniform load, which is negative shear lag effect.
4) On the top plate, the coefficient curve under the uniformly distributed load is gentler than that under the concentrated load, which indicates that the shear lag effect is more prominent under the concentrated load.
As can be seen from Figure 6:
1) On the bottom plate, the coefficient at the edge of concrete lower flange plate is greater than 1 under both concentrated load and uniform load, which is positive shear lag effect where the coefficient reaches the maximum.
2) The coefficient at the mid-point of concrete slab is less than 1 under both concentrated load and uniform load, which is negative shear lag effect where the coefficient reaches the minimum.
3) The coefficient at the interface between lower flange plate and web is not the maximum, which is different from that of upper flange plate, showing the influence of shear flow on the interface between the lower flange plate and the web.
4) On the base plate, the coefficient curve under the uniformly distributed load is gentler than that under the concentrated load, which indicates that the shear lag effect is more prominent under the concentrated load.

5. Conclusion

In this paper, finite element model of composite box girder bridge with corrugated steel web with 30m span is established by using finite element analysis software ANSYS. The shear lag coefficient is calculated and the variation law of the shear lag coefficient along the longitudinal and transverse directions is analyzed. Finally, the following conclusions can be drawn from the calculation and analysis:
1) The shear lag coefficient of the roof is larger than that of the bottom plate under both concentrated load and uniform load, in which the shear lag effect is more serious.
2) The results show that the maximum shear lag coefficient is between the upper flange plate and the web under both concentrated load and uniform load, and the maximum shear lag coefficient of the bottom plate is at the edge of the lower flange plate.
3) Although the shear lag coefficient at the mid-span is smaller than that at the fulcrum, the stress value of the former is much larger than that of the latter, meaning that the maximum stress value should be in the cross-section.
4) When the shear lag coefficient is calculated, the shear lag coefficient of the top plate should be used for safety.

Reference

Ding W.L., 2009, Analysis of shear lag effect of long span prestressed concrete continuous box girder bridge, Central South University.

Fu X.F., Zhao P.L., 2016, Shear lag effect analysis of long span continuous rigid frame bridge box, Shanxi building, 24, 35-31.

He G.Y., 2005, Box girder shear lag effect and influence factor analysis, Nanjing water conservancy research institute.

Li L.F., Peng K., Wang W., 2009, Theoretical and Experimental Research on girder with corrugated steel webs of the box, Technology of highway and transport, 26(4), 78-83.

Lin Z., Fang W.B., Yang Z.Z., Sun L.X., Ji W., 2015, Study on shear lag effect of box girder bridge under prestress, Chinese Journal of highway and transport, 05.

Luo J.S., 2009, Shear lag effect of cantilever box girder bridge, Chang'an University.

Nie J.G., Li F.X., Fan J.S., Cai Q., 2011, Practical design method of steel concrete composite beam considering shear lag effect, Engineering mechanics, 28(11), 45-51.

Wang Y.J., 2012, Analysis and Research on shear lag effect of box section beam, Chongqing University.

Wu W.Q., 2002, Shear lag effect of corrugated steel webs composite box girder, Southeast University.

Zhang Y.H., Lin L.X., Liu Y., 2012, Influence of shear lag effect on deflection of box girder, Chinese Journal of Computational Mechanics, 29(4), 625-630.

Zhou S.J., 2008, Shear lag effect analysis of box girder, Engineering Mechanics, 1-5.