

## **Effective flange width for composite box girder with corrugated steel webs**

\*Ruijuan Jiang<sup>1)</sup>, Tianhua Xu<sup>2)</sup> and Qiming Wu<sup>3)</sup>

<sup>1)</sup> *School of Civil Engineering, Shandong University, Jinan, Shandong Province, China  
Research Center, Shenzhen Municipal Design & Research Institute Co., Ltd,  
Shenzhen, Guangdong Province, China*

<sup>2)</sup> *Research Center, Shenzhen Municipal Design & Research Institute Co., Ltd,  
Shenzhen, Guangdong Province, China  
Department of Civil and Environmental Engineering, The Hong Kong University of  
Science and Technology, Hong Kong, China*

<sup>3)</sup> *Research Center, Shenzhen Municipal Design & Research Institute Co., Ltd,  
Shenzhen, Guangdong Province, China*

<sup>1)</sup> *jiangrj@szmedi.com.cn*

### **ABSTRACT**

In the design of box girder bridges, the effective flange width is commonly used to calculate the normal stresses under bending to consider the influence of the shear-lag effect. As composite box girder bridges with corrugated steel webs are getting popular around the world, it is important that a rational concept of the effective flange width can be adopted for such bridges to ensure their safety. This paper proposes a new method to calculate the effective flange width for the composite box girders with corrugated steel webs. It takes into account the non-uniform distribution of the normal stresses on the flange cross-section as well as the influence of the varying thickness of the flange along the transverse direction. Comparison is carried out between the proposed and two traditional definitions of the effective flange widths on the basis of the 3D finite element simulation for a continuous bridge with a span arrangement of (88+156+88) m under the self-weight. The coefficients of effective flange widths are first calculated according to the three definitions. Then the normal stresses are calculated following the elementary beam theory with the adoption of the three definitions and then compared with the simulated stresses. The comparative study shows that the proposed definition of the effective flange width in this paper can the most accurately predict the peak stress, and to some extent reduce the cost of the bridge construction. Therefore, the proposed definition of the effective flange width in this paper is suggested for the design of composite box girder with corrugated steel webs.

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<sup>1)</sup> Professor

<sup>2)</sup> PhD

<sup>3)</sup> Senior engineer

## **1. INTRODUCTION**

Composite box girder bridges with corrugated steel webs is getting popular in China and around the world in recent years. With the use of the corrugated steel webs, the self-weight of this type of bridge is greatly reduced, and the mechanical performance is strongly enhanced. Moreover, the construction of this kind of bridge is relatively simple and inexpensive. The basic mechanical behavior, such as the bending, shearing and torsional behaviors, of composite box girders with corrugated steel webs have been intensively investigated (Jiang 2015).

When a box girder is subjected to bending, the normal stress is not uniformly distributed along the transverse direction of the flange due to the non-uniform distribution of the shear strain of the flange, which is called "the shear-lag effect". The safety of a bridge cannot be assured until the shear-lag effect is properly considered in the bridge design. However, the research on the shear-lag effect of composite box girders with corrugated steel webs is rather limited. Accordingly, how to consider the influence of the shear-lag effect in the design of this kind of bridge is debatable.

In the current engineering practice, the effective flange width is usually used to calculate the cross-sectional normal stress, so that the shear-lag effect can be somehow considered. Generally speaking, two traditional methods (termed as Methods 1 and 2, respectively) are usually used to calculate the effective flange width for box girders. In Method 1, the normal stress on the outer boundary of the flange cross-section is first integrated over the width of the flange and then divided by the maximum normal stress (e.g. Lin 2011). This method does not consider the non-uniformity of the stress along the thickness of the flange. In Method 2, the normal stress is first integrated over the whole flange cross-section, and then divided by the product of the maximum normal stress and the thickness of the flange (e.g. Ahn 2004). It is only applicable to the flange with a uniform thickness. Due to the limitations of these traditional methods, they cannot be directly applied to the flanges with varying thickness. However, the box girders with corrugated steel webs usually have flanges with varying thickness.

Therefore, in this paper, a new method is first proposed to calculate the effective flange width of flanges with varying thickness. Then based on this method, the effective flange width of the composite box girders with corrugated steel webs is numerically studied based on a three-span continuous box girder bridge with a span arrangement of (88+156+88) m. The example bridge is modeled using solid and shell elements in ANSYS so that the accordion effect of the corrugated steel webs can be appropriately taken into account.

## **2. CALCULATION OF EFFECTIVE FLANGE WIDTHS**

### **2.1 Effective flange width**

It is assumed that within the range of the effective flange width, the normal stresses are uniformly distributed, and their magnitude is equal to the maximum normal stress on the actual cross-section. The integral of the assumed stresses should be

equal to the actual axial force at the same cross-section. As shown in Fig. 1,  $b_i$  and  $t_i$  ( $i = 1, 2, 3$ ) are the width and thickness of the flange, respectively;  $b_{ei}$  is the effective flange width;  $A_i$  is the cross-sectional area of the flange;  $\sigma_x$  is the actual normal stress;  $\sigma_{x,max}$  is the maximum value of  $\sigma_x$ . The definition of the effective flange width can be expressed as:

$$\sigma_{x,max} b_{ei} t_i = \iint_{A_i} \sigma_x dA \quad (1)$$

In design, the coefficient of effective flange width,  $\rho$ , which is defined as  $\rho = b_{ei}/b$  is usually used to take the shear-lag effect into account.

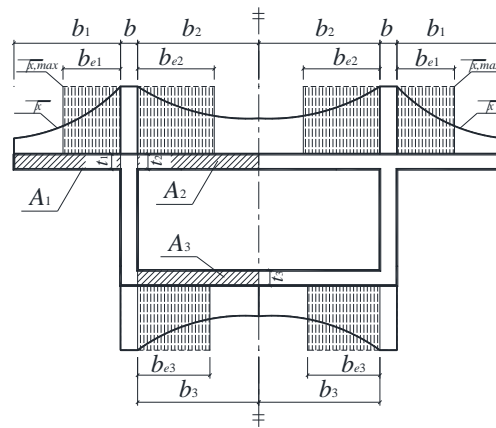


Fig. 1 Schematic diagram of effective flange width

## 2.2 Proposed method for effective flange width calculation

In practice, the thickness of the flange in a composite box girder with corrugated steel webs usually varies along the transverse direction, as shown in Fig. 2. Meanwhile, the normal stresses are not uniformly distributed along both the width and the thickness of the flange. A rational calculation method of the effective flange width should be able to take into account the influence of these two factors.

In this research, a new equation is used to calculate the effective flange width of a composite box girder with corrugated steel webs, as given in Eq. (2):

$$\rho_i = \frac{\iint_{A_i} \sigma_x(y, z) dA}{b_i \int_{t_{ai}} \sigma_x(y_{bi}, z) ds} \quad (i=1,2,3) \quad (2)$$

where  $\sigma_x$  is the normal stress on the flange cross-section;  $y$  and  $z$  are the transverse and vertical directions of the same flange cross-section;  $t_{ai}$  ( $i = 1, 2, 3$ ) is the average thickness, which can be calculated by  $t_{ai} = A_i/b_i$ ;  $y_{bi}$  is the  $y$ -coordinate of the intersection point of the flange and the web. All the variables are shown in Fig. 2. In the denominator of the right-hand-side term in Eq. (2), the normal stress is integrated along

the average depth of the flange,  $t_{ai}$ . In this way, the proposed method can be applied to flanges with varying thickness. If  $\rho_i > 1$ , the effective flange width is larger than the actual width of the flange, which means the shear-lag effect is negative, and vice versa. The value of  $\rho_i$  represents the degree of the influence of the shear-lag effect.

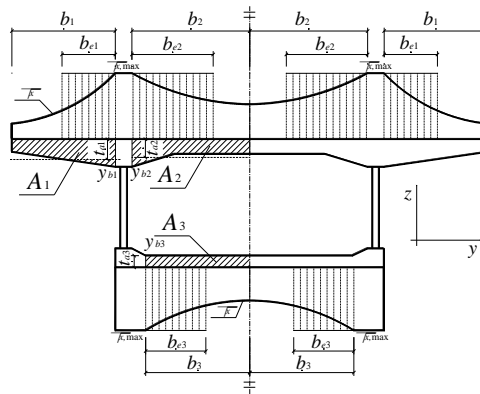


Fig. 2 Schematic diagram of the proposed calculation method

### 2.3 Traditional methods for effective flange width calculation

The two traditional methods, termed as Methods 1 and 2, mentioned in Section 1 for the calculation of the effective flange widths of box girders are expressed as Eq.(3) and (4), respectively.

$$\rho_i = \frac{\int_{b_i} \sigma_{x0}(y) dA}{b_i \sigma_{x,\max}} \quad (i=1,2,3) \quad (3)$$

where  $\sigma_{x0}$  represents the normal stress along the outer boundary of a cross-section.

$$\rho_i = \frac{\iint_{A_i} \sigma_x(y, z) dA}{b_i t_i \sigma_{x,\max}} \quad (i=1,2,3) \quad (4)$$

where  $t_i$  is the thickness of the flange.

## 3. COMPARATIVE STUDY

To study the applicability of the proposed calculation method for the effect flange width, 3D finite element simulation is performed for a three-span continuous composite box girder bridge with corrugated steel web subjected to its self-weight. The coefficients of effective flange width are calculated using the proposed method and Methods 1 and 2 (Eqs. (3) (4)), and then used to calculate the normal stresses on the bridge cross-sections based on the elementary beam theory. The results based on these three methods are compared with each other.

### 3.1 Example bridge and finite element model

In this research, a three-span continuous composite box girder with corrugated steel webs is studied as an example bridge. The length of the main span is 156 m, and the length of each side span is 88 m. The typical cross-sections of the bridge are shown in Fig. 3. The width of the top flange is 16.25 m. The height of the girder is 8.3 m at the intermediate support location, and 3.5 m at the mid-point of the main span. The height of girder varies following a parabolic curve with a power of 1.6 from the intermediate support location to the mid-point of the main span.

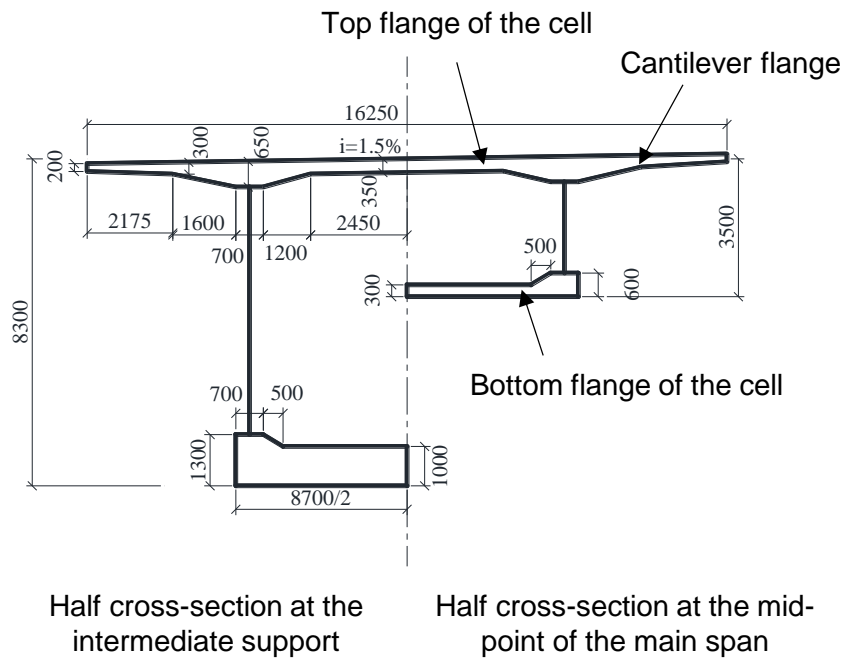


Fig. 3 Cross-sections of the example bridge

The finite element model is developed in ANSYS, which is shown in Fig. 4. The concrete flanges and the corrugated steel webs are modeled using SOLID45 and SHEEL63 elements, respectively. They are connected through the same nodes shared by the flange and web elements. The vertical displacements of the nodes at the bearing locations are restraint. Only half of the bridge is modeled considering the symmetry along the length of the bridge, thus the longitudinal displacements of the nodes at the mid-point of the main span are set to zero. In the finite element model, both the concrete and the steel are modeled as linear elastic materials. The material properties are summarized in Table 1. The finite element model consists of 225758 elements and 317490 nodes.

Table 1 Material properties in the finite element model

| Materials | Density (kg/m <sup>3</sup> ) | Young's modulus (MPa) | Poisson's ratio |
|-----------|------------------------------|-----------------------|-----------------|
| Concrete  | 2600                         | $3.45 \times 10^4$    | 0.20            |
| Steel     | 7850                         | $2.01 \times 10^5$    | 0.30            |

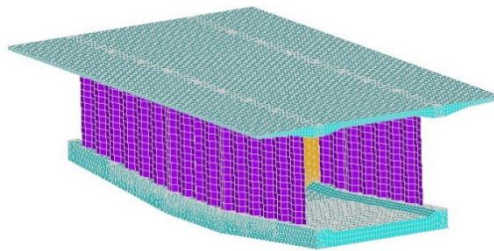


Fig. 4 Part of the finite element model of the example bridge

### 3.2 Effective flange widths under self-weight

Because the self-weight takes up about 80% of all the loads of a bridge, the case in which the bridge is subjected to its self-weight is considered in this research. The self-weight is applied to the finite element model by inputting the density and applying the gravity to the model. Fig. 5 shows the distribution of the normal stress on the cross-section at  $x = 91$  m ( $x$  is the longitudinal coordinate with its origin at one end of the example bridge). This cross-section is located at the intermediate support location and on the mid-span side of the diaphragm. The maximum negative bending moment occurs at this cross-section, generating a maximum tensile stress of more than 14.6 MPa in the top flange.

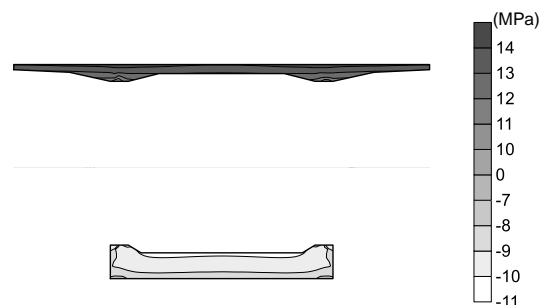


Fig. 5 Normal stress distribution at  $x = 91$  m under self-weight

The coefficients of effective flange width calculated by the proposed and two traditional methods are shown in Fig. 6. The results for the cantilever flange, the top and the bottom flange of the cell are shown separately. According to the figure, for the cantilever flange and the top flange of the cell, the coefficients of effective flange width obtained using the proposed method are similar to those estimated based on Method 1. Method 2 gives far smaller results in these two cases. This is because the maximum stress on a cross-section is used in the denominator of Method 2, which will lead to conservative results. If the coefficients of effective flange width calculated using Method 2 are adopted for the bridge design, the cost of the bridge construction may increase. On the other hand, for the bottom flange of the cell, the proposed method and Method 2 give similar results. However, the results calculated by Method 2 are still smaller, which shows again this method is conservative. The results obtained using Method 1 seems irrational because this method cannot consider the influence of the non-uniform distribution of the normal stresses along the thickness of the flange. The longitudinal

distribution of the coefficients of effective flange width presented in Fig. 6 also shows that the influence of the shear-lag effect is more severe in the part where positive bending moment occurs. Some singular points can be observed at the location where the bending moment is nearly zero and at the mid-point of the main span because the stress is close to zero or the influence of the boundary conditions.

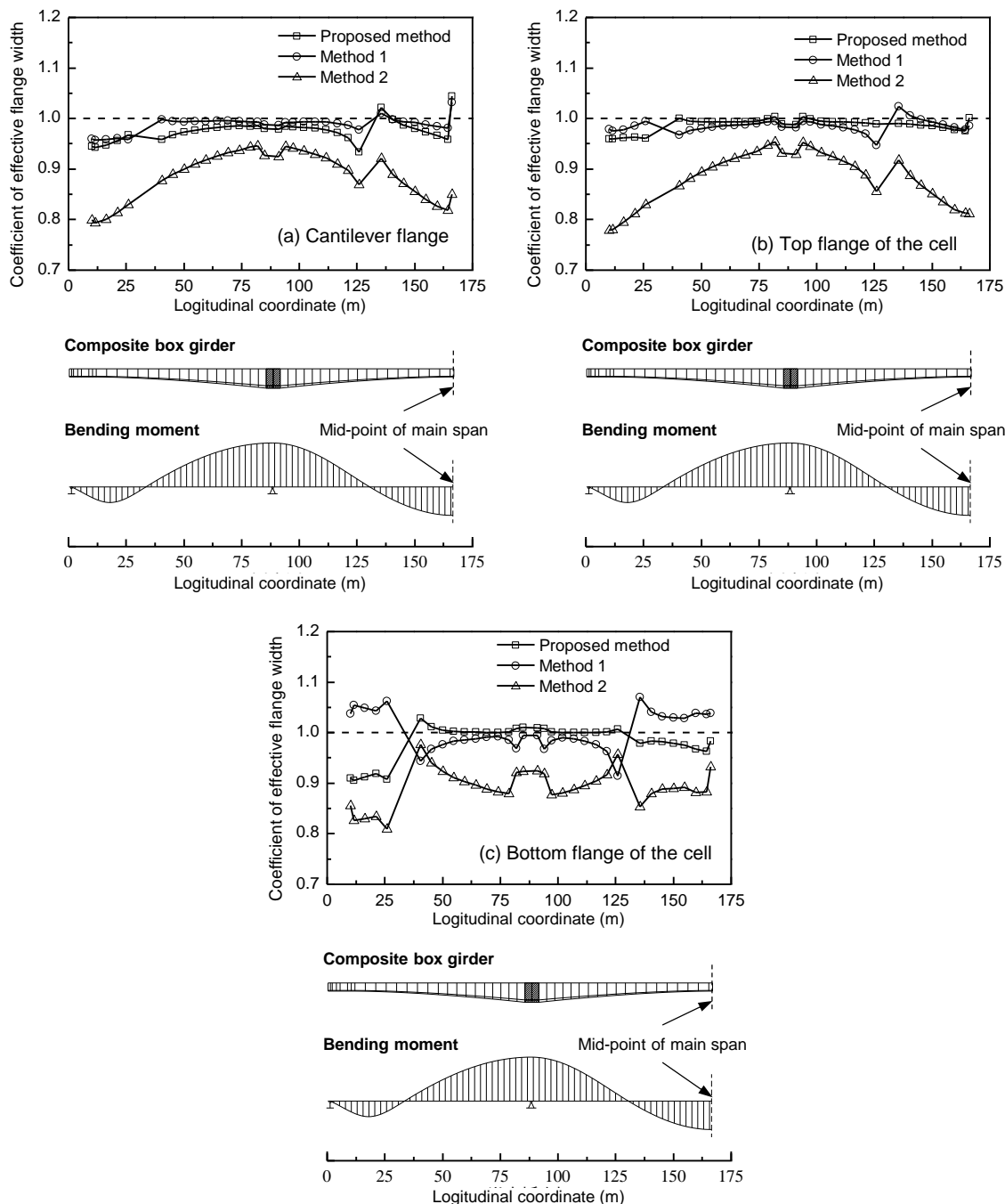


Fig. 6 Coefficients of effective flange width calculated using different methods under self-weight



### 3.3 Verification based on the elementary-beam theory

The proposed method is further verified based on the elementary beam theory. To be more specific, first the moment of inertia is calculated for each cross-section by replacing the actual flange width with the corresponding effective flange width. The effective flange widths are the product of the coefficients of effective flange width (as shown in Fig. 6) and the actual flange width. Afterwards, the calculated moment of inertia is used to calculate the normal stress following the elementary beam theory. Let  $\eta$  represents the ratio between the normal stress obtained using the elementary beam theory,  $\sigma_0$ , and the maximum normal stress on the corresponding cross-section in the finite element model,  $\sigma_{max}^*$  (i.e.  $\eta = \sigma_0 / \sigma_{max}^*$ ). The distributions of  $\eta$  along the longitudinal direction of the bridge are shown in Fig. 7. The values for the top and the bottom of the cross-section are shown separately. If the  $\eta$  value is close to 1.0,  $\sigma_0$  is almost equal to  $\sigma_{max}^*$ , which indicates the adopted effective flange width is accurate. As shown in Fig. 7, the normal stresses calculated using the proposed effective flange width agree well with the simulated value in both cases. Method 2 leads to the most conservative results, as the corresponding  $\eta$  values are larger than those obtained by other methods. For the top of the cross-sections, the results obtained using Method 1 are similar to those obtained using the proposed method. However, for the bottom of the cross-sections, the two methods deviate from each other.

Further define the cumulative deviation,  $\Delta$ , as

$$\Delta = \sum (\eta - 1)^2 \quad (5)$$

The values of  $\Delta$  for different cases are listed in Table 2. It can be observed that the cumulative deviation of the proposed method is the smallest. Therefore, the proposed method is the most accurate one among these methods, and it is suggested to be used in the design of composite box girder bridges with corrugated steel webs.

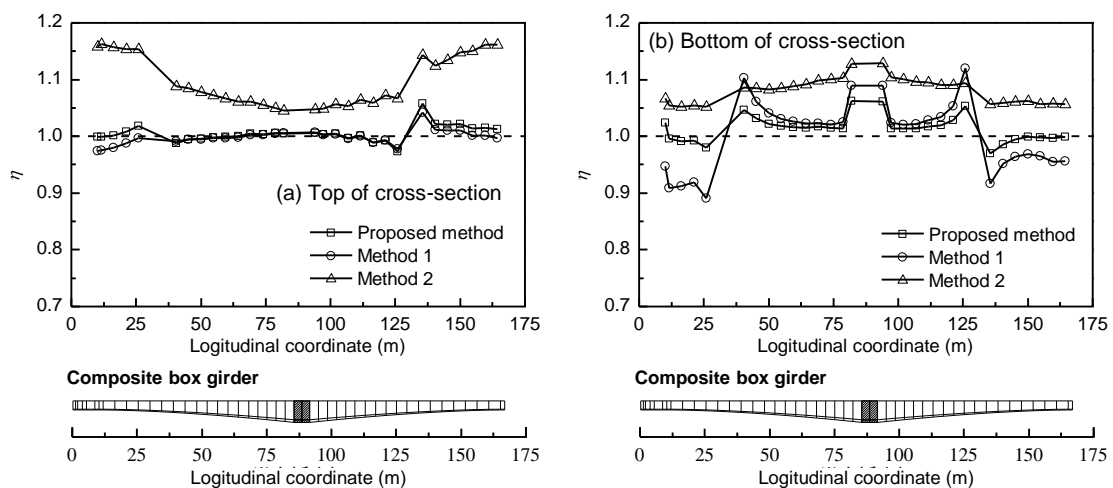


Fig. 7 Distribution of  $\eta$  based on the elementary beam theory under self-weight



Table 2 Cumulative deviation of different methods

|                         | Proposed method | Method 1 | Method 2 |
|-------------------------|-----------------|----------|----------|
| Top of cross-section    | 0.008           | 0.009    | 0.269    |
| Bottom of cross-section | 0.114           | 0.275    | 0.123    |

#### 4. CONCLUSIONS

In this paper, a new method for the calculation of the effective flange width is proposed for the composite box girder with corrugated steel webs. The main conclusions are as follows.

(1) The influences of the non-uniform distribution of the normal stresses and the varying flange thickness are properly considered in the proposed method.

(2) Based on the finite element simulation results of an example bridge subjected to its self-weight, the coefficients of effective flange width calculated using three methods are compared. It shows that the effective flange width coefficient calculated using the proposed method is the most rational one, which can ensure the bridge safety and at the same time save the cost of bridge construction to some extent.

(3) When used to calculate the normal stresses of an example bridge subjected to bending, the coefficients of effective flange width obtained using the proposed method yields the least cumulative deviation.

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