https://doi.org/10.3311/PPci.20494

Periodica Polytechnica Civil Engineering, 66(4), pp. 1199–1206, 2022

Calculation of the Elastic Maximum Transverse Bending Moment of Trapezoidal Corrugated Web Girder

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Received: 09 June 2022, Accepted: 15 August 2022, Published online: 29 August 2022

Abstract

Trapezoidal corrugated web girder (TCWG) is widely used in many fields. The elastic transverse bending moment which exists in the flange influences the mechanical properties of TCWG. For the simply supported TCWG, the equivalent load method is proposed in this paper. And the transverse bending moment calculation model is established. The calculation formula of the elastic maximum transverse bending moment under the most unfavorable geometrical situation is deduced. The formula is consistent with the existing literature. ANSYS finite element method is used to calculate the elastic transverse bending moment of the flange. The calculation results of formula are in good agreement with the finite element analysis. The existence of transverse bending moment is verified by the experimental data. The physical significance of the transverse bending moment as the integral bearing performance index of the TCWG is revealed in this paper. This paper provides a reference for further analysis of transverse bending moment of simply supported TCWG.

Keywords

trapezoidal corrugated web girder, transverse bending moment in the flange, ANSYS finite element method, elastic stress, elastic bending strength

1 Introduction

Due to the reasonable force performance of corrugated webs, corrugated web steel girders are widely used in structural applications such as buildings and bridges [1–4]. For example, corrugated web steel girders are widely used in steel-concrete composite bridges [5]. Similar to open web steel joists (OWSJ) [6], corrugated web steel girders are also economical [7]. The corrugated web girders offer several advantages over those girders formed with flat webs. And in the future, they may replace the closely spaced transversely stiffened webs of the overhead crane carrying girders [8].

First used in France, the idea of replacing flat webs with corrugated webs dates back to the 1970s [9]. A corrugated web I-girder will twist out-of-plane simultaneously as it deflects in-plane under the action of in-plane loads [10]. The additional transverse bending moment comes from the shear force in the corrugated web and its value depends on the geometry of the corrugation profile [11]. The out-of-plane behavior can be analyzed as a flange transverse bending problem which was first observed in the 1990s [12]. The flange transverse bending stresses were investigated [13, 14].

The importance of the transverse bending stresses on the bending resistance is considered in the Eurocode [15] which contains rules for the design of corrugated web girders. The reduction factor is introduced in the calculation to consider the influence of the transverse bending moment on the bending moment resistance of the girder [15].

Corrugated web beams are girders made of thin-walled corrugated webs and plate flanges [16]. The trapezoidal corrugated web configuration and related geometric parameters are shown in Fig. 1.

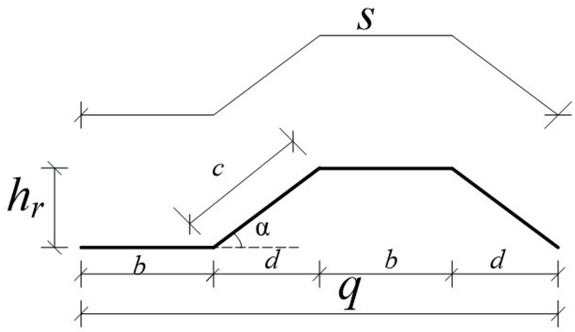

Fig. 1 Trapezoidal corrugated web configuration and geometric notation

Cite this article as: Luo, H. "Calculation of the Elastic Maximum Transverse Bending Moment of Trapezoidal Corrugated Web Girder", Periodica Polytechnica Civil Engineering, 66(4), pp. 1199–1206, 2022. https://doi.org/10.3311/PPci.20494

Under the action of shear force, the transverse bending moment arises in the flange of the trapezoidal corrugated web girder (TCWG). The theoretical total normal stresses in the bottom flange are determined by superposition of in-plane bending stresses and flange transverse bending stresses [10, 12]. ANSYS finite element method is used to analyze the influence of the transverse bending moment on the elastic bending strength of trapezoidal corrugated web steel girders, and the influence of parameters is discussed [17]. The transverse bending moment is important to TCWG and needs to be considered in the design [10]. Especially in elastic design, the influence of bending normal stress caused by transverse bending moment of flange cannot be ignored [18]. If the transverse bending moment in the flange is ignored, the calculation may be unsafe [19]. And no relationship was observed between the magnitude of the transverse bending moment and the plastic bending resistance of the flanges [18].

Closed form differential equation for flange transverse bending problem is derived for a web with a sinusoidal profile [10]. The "fictitious load method" was applied to analyze the transverse bending moment of TCWG [12]. The variation of flange transverse bending moments in a corrugated web I-girder is found to be directly related to an area function that depends exclusively on the geometry of the web profile. And a so called "C-factor method" is introduced to analyze flange transverse bending of corrugated web I-girders [14, 20].

Compared with a flat web, a corrugated web does not carry any significant axial (longitudinal) stress under axial loading [12]. And this is the so-called "accordion effect" [11]. It was suggested that the ultimate moment capacity of corrugated web beams could be calculated based on the flange yield stress, and the contribution of the web be negligible [7]. The web is subjected to a state of pure shear stress, and the shear stresses distribute evenly along the web height [21].

In view of the importance of the maximum transverse bending moment in the calculation, for the most unfavorable situation, Eq. (1) was proposed for calculating the possible maximum transverse bending moment of the flange and the finite element method could be used for accurate calculation of the transverse bending moment [11].

$$M_{z,\max} = \frac{Vh_r}{2h_w}(2b+d), \tag{1}$$

where V is the section shear force and h_w is the height of the web. The parameters h_r, b and d are shown in Fig. 1.

The number of previous investigations focusing on the bending moment of the trapezoidal corrugated web girders is relatively small [22].

Aiming at the case of simply supported TCWG under concentrated load, this paper proposes a new model for calculating the elastic maximum transverse bending moment in the flange. The corresponding formula is deduced and compared with the general finite element program ANSYS [23] and the experiment. This paper provides a new research idea for the analysis and calculation of elastic transverse bending moment of TCWG.

2 Equivalent load method and corresponding calculation model

A typical TCWG consists of two steel flanges welded to a trapezoidal corrugated steel web (Fig. 2). Considering the maximum transverse bending moment of the flange, the most unfavorable geometrical situation is that both the load and the reaction force act in the middle of the inclined web, and the distance between the action points is an integral multiple of the wavelength [11, 18]. The most unfavorable girder geometry and loading conditions are shown in Fig. 2. The TCWG is subjected to load F_z, and the load model is shown in Fig. 3.

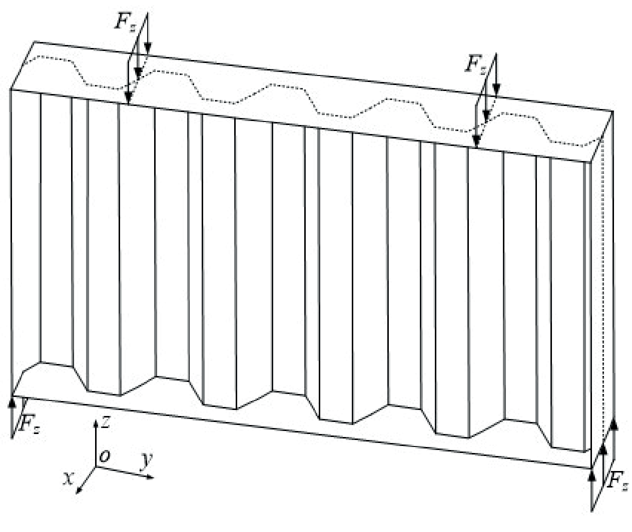

Fig. 2 Trapezoidal corrugated web steel girder

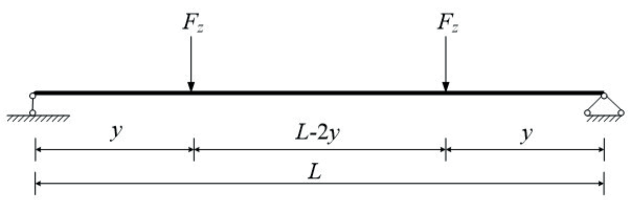

Fig. 3 Load model 1 of trapezoidal corrugated web steel girder

In the y length range of the left and right ends of the TCWG shown in Fig. 3, the steel girder is intercepted with the xoz plane, as shown in Fig. 4. According to Abbas et al. [10] the shear force V_x corresponding to the transverse bending moment M_z can be determined by Eq. (2).

$$V_x = \frac{2Ve}{h_w}, \tag{2}$$

where $e \leq h_r/2$.

It can be seen from Eq. (2) that V_x is not a constant value, and the magnitude of V_x is related to e. Substituting $e = h_r/2$ into Eq. (2) yields the maximum value of V_x, that is $V_{x,\max}$.

$$V_{x,\max} = Vh_r / h_w \tag{3}$$

According to Ref. [10] the relationship between the transverse bending moment M_z and shear force V_x is as shown in Eq. (4).

$$V_x = \frac{dM_z}{dy} \tag{4}$$

In order to calculate the maximum transverse bending moment $M_{z,\max}$, the upper or lower flange of the TCWG is considered as a separate member. A load equivalent to the load effect in the xoy plane is applied to the flange member and the flange member constraints are the same as that of the original structure. Under the action of equivalent load, the shear force V_x of the flange member is the same as that of the original structure. So, the maximum flange transverse moment $M_{z,\max}$ corresponding to the flange member is equal to that of the original TCWG based on Eq. (4). It reflects that the flange member can be used for the equivalent calculation of the original structure.

Take the TCWG shown in Fig. 2 as an example, the upper flange or the lower flange is analyzed as a separate component. Under the load shown in Fig. 3, the shear force V_x distribution is shown in Fig. 5 when $y = q$.

Under the action of the equivalent load in the xoy plane shown in Fig. 6, the shear force V_x distribution of the flange member is the same as that in Fig. 5.

Under the equivalent load shown in Fig. 6, the diagram of the bending moment M_z of the flange member is shown in Fig. 7, and the maximum transverse bending moment $M_{z,\max}$ is located 0.5 q away from the end of the component. The maximum transverse bending moment can be calculated by Eq. (5).

$$\begin{aligned} M_{z,\max} &= 0.5d(2V_{x,\max}/d)(b+0.75d) \\ &\quad -0.5d(2V_{x,\max}/d)\cdot 0.25d = V_{x,\max}(b+0.5d) \end{aligned} \tag{5}$$

In addition, according to the "equivalent" principle of $M_{z,\max}$ calculation, as long as the calculation value of $M_{z,\max}$ is equal to the original structure, it is not necessary

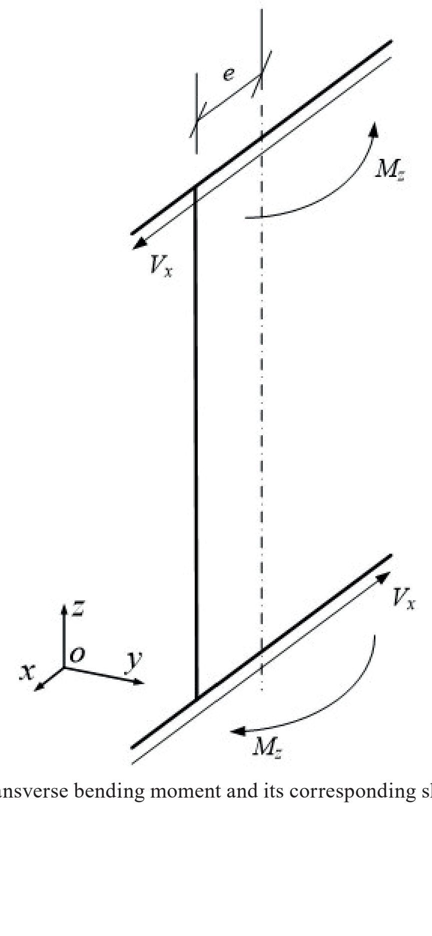

Fig. 4 Transverse bending moment and its corresponding shear force

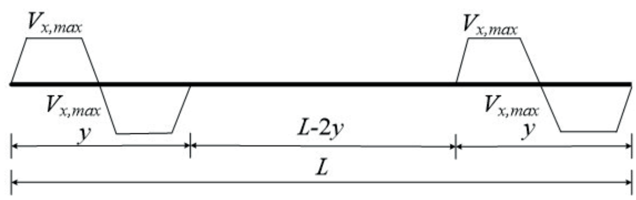

Fig. 5 Shear force distribution of flange member

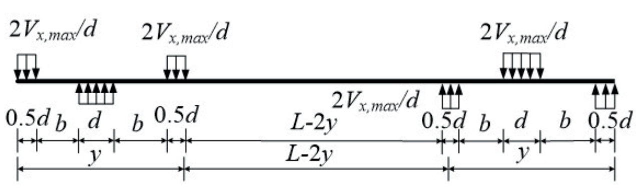

Fig. 6 Equivalent load diagram 1 of flange member

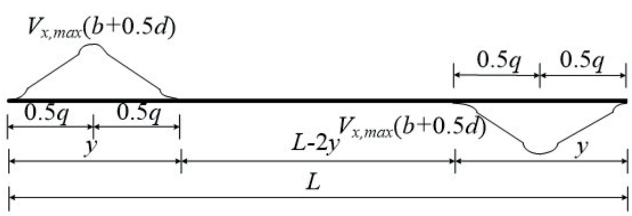

Fig. 7 Distribution diagram of transverse bending moment of flange member

to require that the shear force V_x of each section of the flange member be equal to that of the original structure. If the continuous load shown in Fig. 6 is replaced by concentrated load, then under the equivalent load shown in Fig. 8, the maximum transverse bending moment $M_{z,\max}$ of the flange member is located 0.5 q away from the end of the component.

$$\begin{aligned} M_{z,\max} &= V_{x,\max}(b+0.75d) - V_{x,\max} \cdot 0.25d \\ &= V_{x,\max}(b+0.5d) \end{aligned} \tag{6}$$

In Fig. 1, if $\alpha = \pi/2$, that is, $d = 0$, the trapezoidal corrugated web is rectangular corrugated web, and $M_{z,\max}$ can be calculated by Eq. (6). From this point of view, the computational model of Fig. 8 is more widely applicable than that of Fig. 6. It is worth noting that the "equivalent load" in this paper is similar to the "fictitious load method" in Abbas et al. [12]. Both methods share similarities in computational purpose, i.e., once the equivalent loads or the fictitious loads are determined, the flange transverse bending problem can be solved using conventional structural analysis. However, the two methods are different in specific calculation aspects such as calculation parameters. For example, the equivalent load method proposed in this paper selects the maximum transverse shear force $V_{x,\max}$ as the calculation parameter, while the fictitious load method in Abbas et al. [12] takes the transverse shear force V_x as the calculation parameter. Different calculation parameters not only lead to different calculation expressions, but also have differences in actual calculation applications. For example, for trapezoidal and rectangular corrugated webs, two different fictitious load distributions need to be considered, respectively in Abbas et al. [12], while the method proposed in this paper only needs to consider an equivalent load distribution as shown in Fig. 8 to solve the maximum transverse bending moment.

As the main purpose of this paper is to calculate the maximum transverse bending moment, the shear requirement for flange member section can be relaxed. As noted above, the shear V_x of each section of the flange member does not have to be equal to that of the original structure.

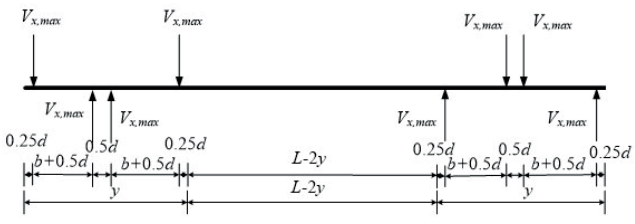

Fig. 8 Equivalent load diagram 2 of flange member

Therefore, the calculation model under the equivalent load in this paper is relatively simple, and the word "equivalent" directly shows the relationship between the flange member and the original structure.

The calculation result of Eq. (5) or Eq. (6) is the maximum transverse bending moment $M_{z,\max}$ of the TCWG. When Eq. (3) is substituted into Eq. (5) or Eq. (6), Eq. (1) is obtained.

3 Finite element calculation

Under the action of bending moment M_x and M_z, the y-direction normal stress σ_y of the end point of the upper and lower flange of the TCWG is shown in Fig. 9. The distribution of elastic normal stress on the flange of corrugated web girder confirms the existence of transverse bending moment [24].

According to Abbas et al. [10] the normal stress σ_y of the flange end point can be determined by Eq. (7).

$$\sigma_y = \frac{M_x h_w}{2I_x} + \frac{M_z B}{2I_z}, \tag{7}$$

where I_x is the section inertia moment about the x-axis and I_z is the section inertia moment of the single flange with respect to the z-axis. And B is the width of flange.

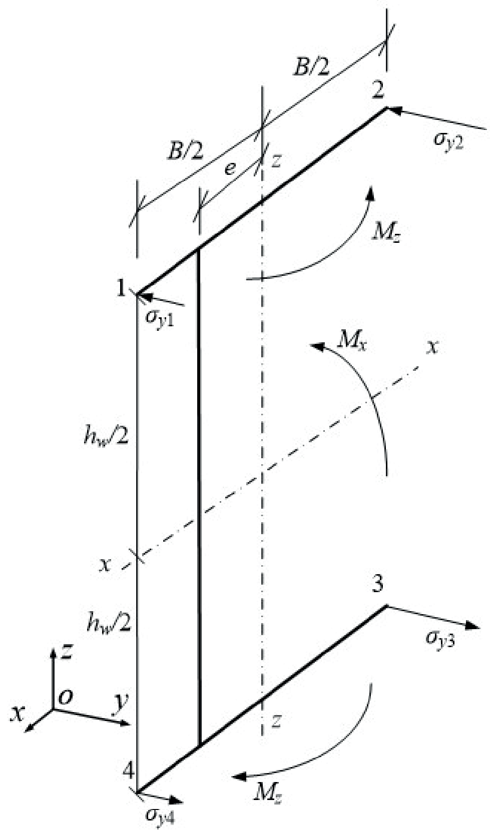

Fig. 9 Section bending moment and its corresponding normal stress

It can be seen from Fig. 9 that the normal stresses (the compressive stress is negative and the tensile stress is positive) are as follows:

$$\sigma_{y1} = -\frac{M_x h_w}{2I_x} + \frac{M_z B}{2I_z}, \tag{8}$$

$$\sigma_{y2} = -\frac{M_x h_w}{2I_x} - \frac{M_z B}{2I_z}, \tag{9}$$

$$\sigma_{y3} = \frac{M_x h_w}{2I_x} + \frac{M_z B}{2I_z}, \tag{10}$$

$$\sigma_{y4} = \frac{M_x h_w}{2I_x} - \frac{M_z B}{2I_z}. \tag{11}$$

For the upper flange, set

$$k = \frac{\sigma_{y1} - \sigma_{y2}}{2} = \frac{M_z B}{2I_z}. \tag{12}$$

For the lower flange, set

$$k = \frac{\sigma_{y4} - \sigma_{y3}}{2} = -\frac{M_z B}{2I_z}. \tag{13}$$

So, the transverse bending moment M_z can be obtained from Eq. (12) or Eq. (13).

In this paper, the waveform parameters of the TCWG are as follows: $h_r = 80$ mm, $d = 80$ mm, $b = 170$ mm. The remaining geometrical parameters of the steel girder are as follows: web height h_w = 1000 mm, the thickness of the web $t_w = 3$ mm, the thickness of the flange $t_f = 12$ mm, the width of the flange B = 250 mm, the span of the steel girder $L = 16\ q$.

A first-order linear elastic analysis is conducted using the general finite element program ANSYS [23]. The eight-node three-dimensional shell element (Shell93) is used to model the corrugated webs, flanges and stiffeners of the steel girders. Each node has six degrees of freedom, three translations in the x, y, and z directions of the node, and three rotations about the x, y, and z axes of the node, respectively. Fig. 10 shows the finite element (FE) mesh of the steel girder. For all members of the steel girders, a combination of mapping mesh and free mesh is used to generate quadrilateral elements with element edge of 0.2 b. Therefore, there are at least six elements along the flange width. The linear elastic material model is used in the calculation, in which the elastic modulus E is 210 GPa and Poisson's ratio v is 0.3. Simply supported girders are modeled and analyzed. The stiffeners are installed at the supports and the loading positions. The stiffener thickness is set as t = 15 mm.

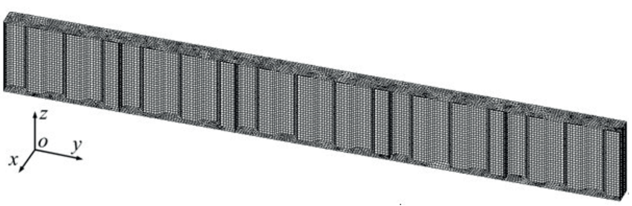

Fig. 10 FE model

In the post-processing, the section is divided by the definition path and the corresponding path command, and the stress value of the section point is extracted. As shown in Fig. 9, after obtaining σ_{y1}, σ_{y2}, σ_{y3} and σ_{y4} by the finite element method, the parameter k can be calculated from Eq. (12) or Eq. (13) to plot the distribution of k along the y-axis of the girder. Under the loading conditions shown in Fig. 11, part of the calculation parameters are as follows: $L = 16\ q$, $y = 3\ q$ and $F_z = 100\ N$.

Under the load conditions shown in Fig. 11, the distributions of upper and lower flange parameter k along the y-axis of the girder are shown in Fig. 12 and Fig. 13, respectively. The distance between adjacent calculation points along the y-axis of the girder is 25 mm.

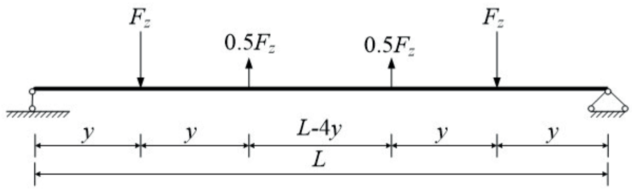

Fig. 11 Load model 2 of trapezoidal corrugated web steel girder

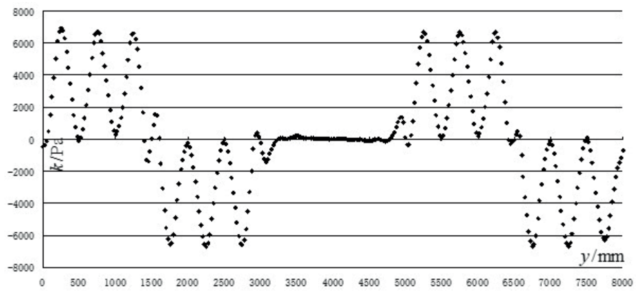

Fig. 12 Distribution diagram of parameter k along the y-axis of the upper flange of a TCWG

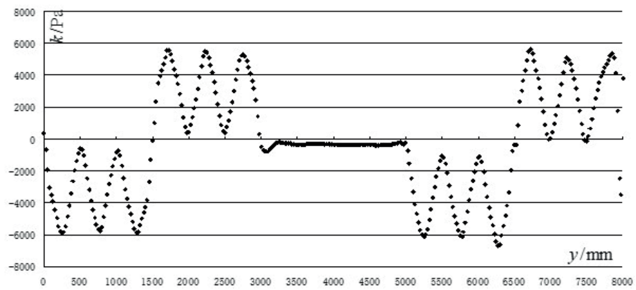

Fig. 13 Distribution diagram of parameter k along the y-axis of the lower flange of a TCWG

As shown in Fig. 12 and Fig. 13, the transverse bending moment M_z tends towards zero in the section where the shear $V = 0$. The absolute value of the shear V of other sections is 0.5 $F_z = 50$ N and the corresponding transverse bending moment M_z is distributed as waveform. For the trapezoidal corrugated web steel girder shown in Fig. 2, the maximum transverse bending moment is located at an odd multiple of half the wavelength from the end of the girder. In addition, as shown in Fig. 12 and Fig. 13, there is a double moment with a regular change in the non-zero shear section, which shows the existence of transverse bending moment. It should be pointed out that the transverse bending moment distribution shown in Fig. 12 and Fig. 13 is similar to that shown in Fig. 7.

4 Comparison and analysis

It can be seen from Fig. 12 that the maximum value of k is $k_{\max} = 6950$ Pa, and the calculation of $M_{z,\max}$ obtained by substituting $k_{\max}$ into Eq. (12) is as follows:

$$M_{z,\max} = 2I_z k_{\max}/B = 2\times\frac{1}{12}\times 0.012\times 0.25^3 \times 6950 \div 0.25 = 0.87\mathrm{N\cdot m}. \quad (14)$$

In addition, the calculated value of $M_{z,\max}$ can be obtained by Eq. (1).

$$M_{z,\max} = \frac{Vh_r}{2h_w}(2b+d) = \frac{50\times 0.08}{2\times 1}\times(2\times 0.17+0.08) = 0.84\mathrm{N\cdot m} \quad (15)$$

Therefore, the relative deviation between the formula and the finite element calculation is

$$\frac{0.84-0.87}{0.87}\times 100\% = -3.4\%. \quad (16)$$

So, the calculation results of the two methods are relatively close. In addition, for the three steel girders provided in Kövesdi et al. [11], Kövesdi et al. [18] and Abbas [25] the maximum transverse bending moments are calculated by using Eq. (1) and finite element method, respectively, as shown in Table 1. The parameters M_1 and M_F in Table 1 are the maximum transverse bending moments of steel girders calculated by Eq. (1) and finite element method, respectively. The parameters σ_1 and σ_F in Table 1 are the normal stresses at the ends of the flange corresponding to M_1 and M_F, respectively.

As can be seen from Table 1 that, in general, the calculation results of Eq. (1) are close to that of the finite element method. This shows that the formula is in good agreement with the finite element calculation. In addition, the finite element calculated values in this paper are in good agreement with those in literature. For example, the finite element calculation value M_F' in reference [11] is 3.5 kN·m, and the finite element calculation value MF in this paper is 3.6 kN·m. The ratio of the two is about 0.97. The theoretical formula can be verified by numerical calculation [26], and the calculation formula derived in this paper is the same as the existing one, so the numerical calculation and the method in this paper are mutually verified.

Experimental study on a simply supported corrugated web I-girder with a trapezoidal web profile was carried out [25]. The girder was loaded in four-point bending, with two loads and two reaction points. Detailed experimental details can be found in Abbas [25]. The value of $k_{\max}$ measured by the experiment is 106 MPa. According to Eq. (12), the $M_{z,\max}$ value corresponding to the value of $k_{\max}$ is 17.9 kN·m. As shown in Table 1, the finite element calculation value of in this paper is 22.5 kN·m. Therefore, the relative deviation between the finite element calculation value and the test value is

$$\frac{22.5-17.9}{17.9}\times 100\% = 25.7\%. \quad (17)$$

The calculated value of $M_{z,\max}$ from Eq. (1) is 24.5 kN·m which is shown in Table 1. Therefore, the relative deviation between the calculation formula and the test is

$$\frac{24.5-17.9}{17.9}\times 100\% = 36.9\%. \quad (18)$$

In the case of real structures, the transverse bending moment can be influenced by the support conditions and its value can be significantly smaller than the theoretically determined maximum value [18]. Considering, that

Table 1 Comparison of finite element method and formula calculation results

Source	b/mm	d/mm	B/mm	h_r/mm	h_w/mm	t_f/mm	t_w/mm	V/kN	σ_1/MPa	σ_F/MPa	M_1/kN·m	M_F/kN·m	M_F/M_1
Kövesdi et al. [18]	350	272	400	220	2500	30	10	1000	53.5	53.8	42.8	43	1
Kövesdi et al. [11]	210	165	225	133	500	20	6	50	23.1	21.3	3.9	3.6	0.93
Abbas [25]	300	200	225	150	1200	20	6	489	145.2	133.3	24.5	22.5	0.92

the actual supports of the steel girder used in the test are not ideal simple supports, the above calculation deviations are within a reasonable range. It should be pointed out that, compared with the test value, the results of calculation formula and the finite element analysis are both safe. And it verifies the existence of transverse bending moment from the experimental point of view.

As shown in Eqs. (1) and (7), under the condition that other parameters are unchanged, the maximum positive stress $\sigma_{y,\max}$ of the flange increases as V and $M_{z,\max}$ increase.

Due to the "accordion effect", the shear force of the trapezoidal corrugated web steel girder is mainly borne by the web, and the bending moment is mainly borne by the flange [2, 10, 27]. The transverse bending moment is related to the shear force of the web and the normal stress of the elastic bending moment of the flange. Therefore, in contrast to the "accordion effect", the transverse bending moment reflects the relationship between the shear strength of web and the flexural capacity of flange.

In summary, the maximum transverse bending moment $M_{z,\max}$ reflects the integrity and coordination of the flange and web of the TCWG in elastic bearing capacity.

5 Conclusions

In this paper, the calculation model of the maximum elastic transverse bending moment in the flange is established by using the equivalent load method for the simply supported TCWG under concentrated load. The formula of the maximum elastic transverse bending moment consistent with the existing literature is deduced. Comparisons among calculation formula, finite element analysis and test results show that the deviations are acceptable. The finite element method in this paper reveals that there is a certain amount of double moment in the model analyzed. It confirms the existence of transverse moment and helps to understand the mechanism of the transverse bending moment. In contrast to the "accordion effect", the transverse bending moment in the flange reflects the overall performance of the TCWG. The following conclusions can be drawn from this study:

1. The formula of the maximum elastic transverse bending moment has been derived from the equivalent load method.
2. The physical significance of the transverse bending moment as the integral bearing performance index of the trapezoidal corrugated web girder is revealed.

In view of the wide application of TCWG and the important significance of transverse bending moment for design, the research is helpful to promote the engineering application of TCWG.

Acknowledgement

This work is supported by a grant (No. 15A045) provided by the Scientific Research Project of Higher Education in Hunan Province and a grant (No. 15061) provided by the Talent research Foundation of Hunan Institute of Engineering.

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