Analysis on mechanical properties of I-girder with 2000 corrugated steel webs

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Abstract. In order to meet the needs of the construction of larger span bridges in engineering, the large-sized corrugated steel web with 2000 corrugated steel webs were studied. The numerical model of I-girder with 2000 corrugated steel webs is established by finite element software. The effects of bending angle, web thickness and web height on deflection and shear buckling on the basis of this are studied. The research conclusions can provide reference for the design calculation and engineering use of I-girder with corrugated steel webs in the future.

1. Introduction

At present, the span of the prestressed concrete composite girder bridge with corrugated steel webs is increasing, and the original corrugated steel web geometry can not meet the requirements. It is urgent to study the mechanical properties of large-sized beam with corrugated steel webs.

Since the 1990s, scholars from various countries have conducted research on beam with corrugated steel webs. The shear buckling strength of corrugated steel webs is greatly affected by its geometric parameters[1]. Compared with conventional box girders with concrete webs, the influence of shear deformation may be not ignored in its deflection calculation[2]. Robert G Driver suggested using the Interactive buckling formula proposed by Lindner and Aschinger in the calculation of shear buckling strength[3]. The finite element method can effectively predict the bearing capacity and failure mode of I-girder with corrugated steel webs[4]. And the shear strength of corrugated steel webs is affected by the geometric parameters of the web[5]. The Interactive shear buckling failure mode of corrugated steel web close to local shear buckling maintains higher bearing capacity after buckling than the overall shear buckling failure mode[6]. The local shear buckling of corrugated steel webs is considered as a series of buckling of four-sided simply supported steel strips supported along the long sides and supported on the flanges with short sides[7-8]. The shear deformation of corrugated steel web has a significant influence on the deformation of the main beam[9]. The design formula of the shear strength of corrugated steel webs is mostly given in the form of a relationship between the normalized shear strength and the shear buckling ratio[10]. The Interactive buckling of corrugated steel webs cannot be simply viewed as a result of the interaction between local buckling and global buckling, but should be considered as a form of buckling from local buckling to global buckling transition[11]. With the development of large-span concrete composite box girder bridges with corrugated steel webs, it is urgent to further develop larger-sized corrugated steel webs[12].

In order to meet the needs of construction, this paper studies the main influencing factors of
mechanical properties of 2000 corrugated steel webs. This paper establishes a numerical model of I-girder with 2000 corrugated steel webs by ANSYS19.0. It ignores the effects of residual stress, nonlinear conditions, and geometric initial defects. The effects of parameters such as bending angle, web thickness and web height on deflection and shear buckling were studied. Changing the bending angle to explore the deflection of I-girder with the corrugated steel webs. Changing the height and thickness of the web to explore the shear buckling of the web.

2. Calculation of elastic shear buckling strength of corrugated steel webs
There are three main types of shear buckling of corrugated steel webs: local shear buckling, global shear buckling and interactive shear buckling. (more details could be revised in Reference[12])

2.1 local shear buckling
Local shear buckling occurs when the corrugated steel web corrugations are sparse. It is generally considered as buckling of rectangular plates supported by four sides. According to the theory of elastic stability of thin plates, four-sided support plate is subjected to uniform shear stress along the edge. Its calculation formula of local shear buckling strength is as follows:

$$\tau_{cr,l}^e = k_1 \times \frac{\pi^2 E}{12(1-\mu^2)} \left(\frac{t_w}{a}\right)^2$$

(1)

where $E$ is Elastic Modulus; $\mu$ is the Poisson’s ratio; $a$ is the maximum fold width (maximum of flat panel width $b$ and inclined panel width $c$); $t_w$ is the web thickness; and $k_1$ is the local shear buckling coefficient which is related to the board's boundary conditions and aspect ratio.

2.2 Global shear buckling
global shear buckling occurs when the corrugated steel web corrugations are dense. According to the theory of elastic stability of thin plates, Reissner and Bergmann made the corrugated steel web equal to the orthotropic plate, and proposed the calculation formula of the global shear buckling strength:

$$\tau_{cr,g}^e = 4\lambda \frac{(D_x)^{1/4}(D_y)^{3/4}}{h_w^2 f_w}$$

(2)

Where $D_x$ is the transverse bending stiffness per unit length of the corrugated web; $D_y$ is the longitudinal bending stiffness per unit length of the corrugated web; under the simple boundary condition $\lambda$ is 8.

2.3 Interactive shear buckling
Interactive shear buckling is generally considered to be a form of buckling in which local shear buckling interacts with global shear buckling. The design expression is based on experience. This paper uses a calculation formula that given by the Swedish specification:

$$\frac{1}{\tau_{cr,i}} = \frac{1}{\tau_{cr,l}^e} + \frac{1}{\tau_{cr,g}^e}$$

(3)

Where $\tau_{cr,i}$ is shear buckling strength.

3. Influence of bending angle on deflection
With the change of the bending angle of the corrugated steel web, the mechanical properties of I-girder with 2000 type corrugated steel webs will be affected. Therefore, this section conducts finite element analysis of bending angle changes on the mechanical effects.

3.1 Model introduction
The I-girder with corrugated steel webs is made of Q345 steel, elastic modulus is $2.06 \times 10^5$ MPa,
Poisson's ratio is 0.3, the upper wing width is 0.6 m, the lower wing width is 0.8 m, and the calculated span is 25 m. The web has a height of 1.6 m and a thickness of 30 mm. The geometric parameters of the 2000 type corrugated steel web are shown in Figure 1, and the dimensions are listed in Table 1.

![Figure 1. The geometry of corrugated steel webs](image)

| Type  | Geometric size (mm) | Bending angle(°) |
|-------|---------------------|------------------|
|       | l       | a₁       | a₂       | a₃       | d       | θ       |
| Type 2000 | 2000   | 530      | 470      | 527      | 240     | 27      |

3.2 Model establishment
The upper and lower flange and corrugated steel webs of the finite element model are simulated by shell element shell181. Boundary condition definition: the translational freedom of the three directions of the constraint joint at the fixed hinge support, and the translational freedom of the X and Y directions is constrained by the movable hinge support. Model as can be seen in Figure 2.

![Figure 2. Finite element model of I-girder](image)

3.3 The variation regular pattern of the influence of web bending angle on deflection
Table 2 shows the values of the corrugated height when the bending angles of 2000 corrugated steel webs are 25°, 27°, 30°, 35°, 40°, and 45°.

| Bending angle (°) | 25   | 27   | 30   | 35   | 40   | 45   |
|-------------------|------|------|------|------|------|------|
| d (mm)            | 220  | 240  | 271  | 329  | 394  | 470  |

Under the load of highway I-class lane, the mid-span deflection of the lower flange at different bending angles of the web is shown in Figure 3. It can be seen from Figure 3 that the bending angle is increased from 25° to 45°, the mid-span deflection value increased from 74.54 mm to 77.61 mm. Although the mid-span deflection has increased, but the increase is not large. It shows that the bending angle change has little effect on the deflection of I-girder with 2000 type corrugated steel webs. Reference to the industry standard "Corrugated steel webs in composite structure bridges" (JT/T 784-2010). The type 1000, 1200, and 1600 corrugated steel web geometries are recommended in this.
standard. The length of the straight section of the corrugated steel web is approximately equal to the length of the inclined section. Therefore, according to the length relationship between the straight section and the inclined section, the recommended angle of choice is 27°. Thus the subsequent parameter analysis of this paper is based on the selection of corrugated steel webs with a bending angle of 27° (shown in Figure 3 and Table 2 for specific parameters).

![Figure 3. Mid-span deflection varies with bending angle](image)

4. Analysis of beam height influence
With the change of the height of corrugated steel web, it will affect the mechanical properties of I-girder with 2000 corrugated steel webs. Therefore, this section analyzes the mechanical effects of corrugated steel web height on finite element analysis.

4.1 Finite element model
This section mainly analyzes the buckling performance of corrugated steel webs, thus the role of the upper and lower flange is not considered. Using four-sided simple boundary conditions. The finite element model of corrugated steel web is shown in Figure 4. In order to ensure shear buckling failure mode of corrugated steel web, uniform shear load is applied on the BC side to simulate the pure shear stress state of the corrugated steel web.

![Figure 4. Finite element model of corrugated steel web](image)
4.2 Model state change
The web height varies from 1m to 8m. The thickness of the web is 30mm. Eight finite element model of corrugated steel webs is established, and part of the buckling mode is shown in Figure 5.

![Buckling modal diagram of corrugated steel webs with different heights](image)

Figure 5. Buckling modal diagram of corrugated steel webs with different heights

It can be seen from Figure 5 that the change in web height has an effect on the shear buckling strength of the corrugated steel web. In a model with a web height of 1 m, most of the deformation is only on a piece of folding plate. It does not span adjacent multiple web areas. In a model with a web height of 8 m, the deformation runs through multiple wavelengths. When the web height changes between 1 m and 8 m, the deformation gradually increases. As the height of the web increases, the maximum shear stress of the corrugated steel web decreases from 19.7 MPa to 3.3 MPa. The buckling stress is reduced from 2663.4 MPa to 755.7 MPa. The specific values are shown in Table 3, where the theoretical formula uses the formula listed in Section 1.

| Web height(m) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Finite element calculation of buckling stress(MPa) | 2663.4 | 1742.8 | 1521.4 | 1365.3 | 1294.4 | 1253.4 | 987.5 | 755.7 |
| Local buckling calculation(MPa) | 3849.3 | 3348.1 | 2893.5 | 3222.9 | 3205.8 | 3200.5 | 3196.8 | 3187.8 |
| Global buckling calculation(MPa) | 19340 | 4835.2 | 2149 | 1208.8 | 773.6 | 538.0 | 394.7 | 302.2 |
| Interactive buckling calculation(MPa) | 3210.4 | 1978.3 | 1233.1 | 879.1 | 623.2 | 460.6 | 351.3 | 276  |

It can be seen from Table 3 that under the same web thickness, the web height is increased, and the calculated values of the three shear buckling stress theoretical formulas of the corrugated steel web are reduced. The reduction of local shear buckling stress is small, and global shear buckling stress and Interactive shear buckling stress decrease greatly. When the web height is 1~2 m, the finite element value of shear buckling stress is less than the theoretical formula. It shows that there is no buckling of the web at this time, only minor deformation occurs. When the web height is 3 m, the finite element value is greater than the Interactive buckling theory formula, but less than the local buckling and the overall buckling formula. This indicates that the composite buckling occurs at this time. When the web height is 3~8 m, the finite element value is larger than Interactive buckling and global buckling theory formula, which is less than the local buckling formula. It is shown that as the web height increases, the corrugated steel web changes from Interactive buckling to global buckling pattern.

5. Analysis of web thickness influence
According to the previous study on the influence of bending angle and corrugated web height, this paper fixed I-girder with 2000 corrugated steel webs with a bending angle of 27° and web height is 6m. Under this premise, eigenvalue buckling analysis of finite element models of four corrugated steel
webs with web thickness variation ranging from 10 to 40 mm are established. Part of the buckling mode is shown in Figure 6.

Figure 6. Buckling modal diagram of corrugated steel webs with different thicknesses

It can be seen from Figure 6 that the thickness variation of the web has a great influence on the shear buckling strength of the corrugated steel web. In a model with web thickness of 10 mm, deformation occurs on several boards and within a certain height range. In a model with web thickness of 40 mm, the deformation spans multiple wavelengths. Constantly increase the thickness of the web, the deformation has a tendency to gradually expand. Specific stress changes are shown in Table 4.

| Web height (m) | 10   | 20   | 30   | 40   |
|----------------|------|------|------|------|
| Finite element calculation of buckling stress (MPa) | 282.2 | 705.6 | 1253.4 | 1521.6 |
| Local buckling calculation (MPa) | 346.3 | 1422.2 | 3200.8 | 5690.3 |
| Global buckling calculation (MPa) | 310.0 | 414.5 | 538.0 | 622.6 |
| Interactive buckling calculation (MPa) | 163.6 | 321.0 | 460.6 | 561.2 |

It can be seen from Table 4 that under the same web height, the calculated values of the three shear buckling theoretical formulas of the corrugated steel web increase with the increase of the web thickness. Among them, the local buckling stress increases greatly, and the global buckling and Interactive buckling stress increase is small. When the web thickness is 10 mm, the finite element value is greater than the calculated value of the interactive buckling theory formula and less than local buckling and calculation of the overall buckling theory formula. It indicates that the corrugated steel web is undergoing interactive buckling. When the web thickness is between 20 mm and 40 mm, the finite element value is larger than the interactive buckling and the global buckling theory formula, which is less than the calculated value of the local buckling theory formula. It is shown that as the thickness of the web increases, the corrugated steel web changes from the interactive buckling to the global buckling pattern.

6. Comprehensive impact analysis

In this section, the eigenvalue buckling analysis of the finite element model is carried out by changing the height and thickness of the 2000 corrugated steel web. The web height varies from 1 m to 8 m, and the thickness of the web varies from 10 mm to 40 mm.

According to the results of finite element analysis, the deformation occurs on several daughter boards when the height and thickness of the corrugated steel web are small. When the height and thickness of the corrugated steel web are large, the deformation spans multiple wavelengths. The height and thickness of the web are continuously increased, and the deformation is gradually enlarged.

The 2000 type corrugated steel webs of different heights and thicknesses are classified according to the three types of shear buckling, as shown in Table 5.
Table 5. Variation range of thickness of 2000 corrugated steel webs during different buckling (unit: mm)

| Web height (m) | Local buckling (mm) | Global buckling (mm) | Interactive buckling (mm) |
|----------------|---------------------|----------------------|---------------------------|
| 1              | 10~12               | 14~18                | 32~40                     |
| 2              | 10~16               | 10~40                | 24~40                     |
| 3              | 10~40               | 10~40                | 20~40                     |
| 4              | 10~40               | 10~40                |                            |
| 5              | 10~40               | 10~40                |                            |
| 6              | 10~40               | 10~40                |                            |
| 7              | 10~40               | 10~40                |                            |
| 8              | 10~40               | 10~40                |                            |

It can be seen from Table 5 that for the 2000 corrugated steel web, when the height is small, if the thickness is small, local buckling is likely to occur. If the thickness is large, it is easy to occur that the global buckling. When the height is large, if the thickness of the web is small, it is easy to occur the Interactive buckling. If the thickness of the web is large, the global buckling is likely to occur.

7. Conclusion
The main conclusions of this paper are as follows:

- When the bending angle of the 2000 corrugated steel web is 25°, 27°, 30°, 35°, 40°, 45°, the deflection of the I-beam is not much different. According to the length relationship between the straight section and the inclined section, the recommended angle can be directly defined as 27°.

- The eigenvalue buckling analysis of the corrugated steel web was carried out by changing the height and thickness of the web. The results show that with the increase of web height, the corrugated steel web has a tendency to transform from interactive buckling to global buckling. And the results show that with the increase of web height, the corrugated steel web has a tendency to transform from interactive buckling to global buckling.

- By changing the height and thickness of the corrugated steel web at the same time, the eigenvalue buckling analysis of the finite element model is carried out to study the influence of geometric parameters on the shear buckling mode of the corrugated steel web. The results show that for the 2000 corrugated steel web, when the height is small, if the thickness is small, the local buckling is more likely to occur. If the thickness is larger, the interactive buckling is more likely to occur. And when the height is large, if the thickness of the web is small, it is more likely to be Interactive buckling. If the thickness of the web is large, the global buckling is more likely to occur.

References
[1] Luo R Edlund B. Shear capacity of plate girders with trapezoidally corrugated webs[J]. Thin-walled Structures, 1996, 26(1): 19-44.
[2] Li Hongjiang, Ye Jianshu, Wan Shui, et al. Influence of shear deformation on deflection of box girder with corrugated steel webs [J]. Journal of Traffic and Transportation Engineering, 2002, 2(4): 17-20.
[3] Driver R G, ABBAS H H, SAUSE R. Shear behavior of corrugated web bridge girders [J]. ASCE Journal of Structural Engineering, 2006, 132(2): 195-203.
[4] Li Guoqian, Zhang Zhe, Sun Feifei. Shear Strength of H-beam with Corrugated Webs [J]. Journal of Tongji University (Natural Science), 2009, 37(6): 709-714.
[5] Eldib M. Shear buckling strength and design of curved corrugated steel webs for bridges [J]. Journal of Constructional Steel Research. 2009, 65(12): 2129-2139.
[6] Jianguo N. Shear strength of trapezoidal corrugated steel webs [J]. China Civil Engineering Journal, 2013, 67(2): 223-236.
[7] Sause R, Braxtan T N. Shear strength of trapezoidal corrugated steel webs [J]. Journal Of Constructional Steel Research, 2011, 67(2): 223-236.
[8] Hassanein M F, Kharoob O F. Behavior of bridge girders with corrugated webs: (I) Real boundary condition at the juncture of the web and flanges [J]. Engineering Structures, 2013, 57(2): 554-564.
[9] Nie Jianguo, Li Faxiong. Theory model of corrugated steel web girder considering web shear behavior [J]. China Journal of Highways and Transport, 2011, 24(6): 40-48.
[10] Zhu Li, Cai Jianjun, Nie Jianguo. Elastic shear buckling strength of trapezoidal corrugated steel web [J]. Engineering mechanics, 2013, 30(7): 40-46, 54.

[11] Li Minghong. Study on Shear Properties of Corrugated Steel Web Beams [D]. Nanjing: Southeast University, 2014.

[12] Wang Yong. Analysis and Experimental Study on Shear Performance of Corrugated Steel Web Beams [D]. Nanjing: Southeast University, 2017.