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An Efficient Finite Element Analysis Method for Shear Resistance and Stability of Corrugated Steel Web Bridges

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Abstract. An efficient finite element analysis method for shear resistance and stability of corrugated steel web bridges are proposed. By calculating the shear stress of the corrugated steel web at the key sections of the box girder, the shear strength of the corrugated steel web at each section is checked. The local buckling, global buckling and combined buckling critical shear stresses of corrugated steel webs are calculated, and the stability checking of corrugated steel webs in each section is carried out. The results show that the design of the corrugated steel web of the bridge meets the requirements of shear strength and buckling stability.

Keywords: Corrugated steel web; Composite box girder; Finite element analysis; Shear resistance and stability.

1. Introduction

Corrugated steel webs are used in place of the conventional concrete webs in a box girder, as indicated by the phrase "box girder with corrugated steel webs." We can minimize the thickness of the web and avoid stiffener reinforcement by employing corrugated steel webs, which has a positive impact on the economy and increases service life [1]. Additionally, due to the weight and the necessity for space for the tendons within the bridge deck, traditional bridges with prestressed concrete beams have a restricted span length that can be increased by using bridges with box girders made of steel-concrete composites with reduced static load (dead load). However, in conventional composite box girders bridges with flat steel webs, the webs will perceive a high proportion of pre-stress, amounting to 20-25%. The prestressed concrete composite box girder bridges with corrugated steel webs are an effective improvement over both conventional PC girder bridges and the classical steel concrete composite girder bridges by replacing concrete webs and reinforced flat steel webs with corrugated steel webs, respectively [2]. The benefits of external prestressing and corrugated steel webs for box or I-girder composite systems in bridge building were acknowledged by Campenon Bernard, France, in 1982. The Cognac Bridge, constructed in France as a test bridge in 1986, was the first highway bridge to use corrugated webs [3].

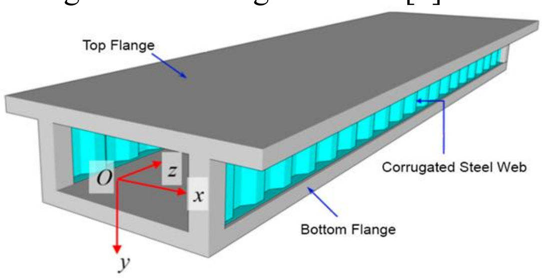

Figure.1 Structural diagram of a PC composite box girder with corrugated steel webs.

In comparison with a flat steel web, a corrugated steel web has higher out-of-plane flexural stiffness and resistance to shear buckling even without additional stiffeners, which significantly reduces the material and labor costs for the manufacture of superstructures; In 2017, A set of stocky

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trapezoidal corrugated web steel beams were tested by Moussa Leblouba [4] to examine how they responded to shear force. The stress distribution along the corrugated webs, which is impossible to get from field tests, has been examined using nonlinear finite element analysis. In 2019, On the shear performance of a tapered beam with trapezoidally corrugated steel webs, Man Zhou [5] performed experimental and numerical analyses. They found that the top concrete flange's shear bearing ratio is quite low, with an average proportion of less than 15%, and that the slanted bottom concrete flange significantly reduces the shear force acting on the support sections. In 2022, The shear performance of corrugated steel plate shear wall systems (CoSPSW) with inelastic buckling of infilled plates subjected to lateral stresses was studied by Qiang Cao [6-10]. A simplified analysis model for the CoSPSWs with inelastic buckling modes was also evaluated, along with geometric characteristics, failure modes, modes of resisting lateral loads, and stiffness requirement of surrounding columns.

2. Project Overview

At present, the PC continuous box girder bridges with corrugated steel webs built and under construction in Jiangsu Province are: Chuhe Bridge, Xuhong River Bridge, Xuyi Huaihe River Bridge, Beijing-Hangzhou Grand Canal Bridge(Xuzhou Eastern Bypass Expressway) and so on.

(a) Chuhe Bridge

(b) Xuhong River Bridge

(c) Xuyi Huaihe River Bridge

(d) Beijing-Hangzhou Grand Canal Bridge (Xuzhou Eastern Bypass Expressway)

Fig. 2. PC continuous box girder bridges in Jiangsu Province

This paper takes a PC composite continuous box girder bridge with corrugated steel webs as the engineering background. The total length of the bridge is 764.28m. The span combination is 2×(4×30)+(30+30+26)+(60+100+60)+(3×30)+(4×30) m. The main span is a pre-stressed concrete continuous girder (60+100+60) m with corrugated steel webs, designed as fully pre-stressed components in the longitudinal direction. The approaching bridges are all prefabricated small box girder bridges. The main pier of main bridge is a solid pier, the transition pier has a column pier, and the foundation of the entire bridge is drilled cast-in-place pile foundations.

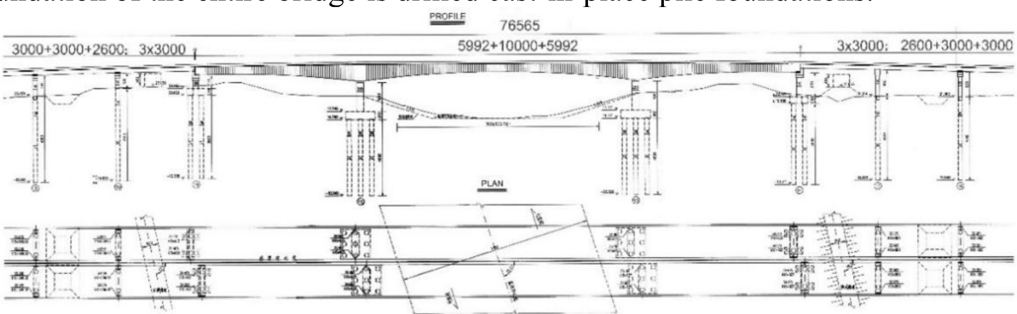

Figure.3 Bridge scheme, Plan and Profile (unit: cm)

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The structure of the main bridge is a variable cross-section continuous box girder, as shown in Figure 3: the main bridge girder height at mid support is 6.1m, solid concrete cross section with the upper flange width is 12.75m and the lower is 7m; the middle of mid span girder height is 3.0m, the PC composite box girder with corrugated steel webs; the box girder bridge is constructed by method of three-dimensional prestressed joint and balanced cantilever.

3. Analysis of Shear Resistance of Corrugated Steel Web Bridge

3.1 Finite Element Modeling

In this chapter, a prestressed concrete composite box-girder with corrugated steel webs for a continuous span bridge is modeled by using MIDAS Civil software to provide theoretical basis and technical support for the construction and monitoring of the bridge.

According to relevant study findings from throughout the globe, corrugated steel webs are mainly researched when the Prestressed Concrete composite box girder bridges with corrugated steel web are examined. The shear checking calculation of the PC composite box girder with corrugated steel web can be carried out by checking the shear stress intensity of the corrugated steel web. It generally includes three check contents: shear strength, buckling strength and shear connector bearing strength. This report uses the shear stress calculation theory to check the shear strength of the corrugated steel web under ultimate limit state as well as serviceability limit state.

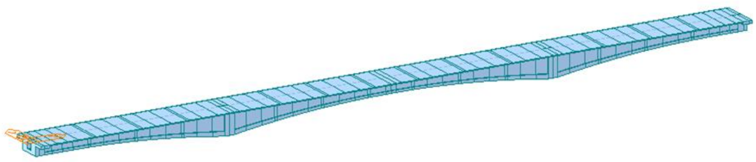

Figure.4 The bridge superstructure model

3.2 Shear Stress Checking for Corrugated Steel Web Under Ultimate Limit State

Schematic diagram of the shape of corrugated steel web is shown in Figure 5.

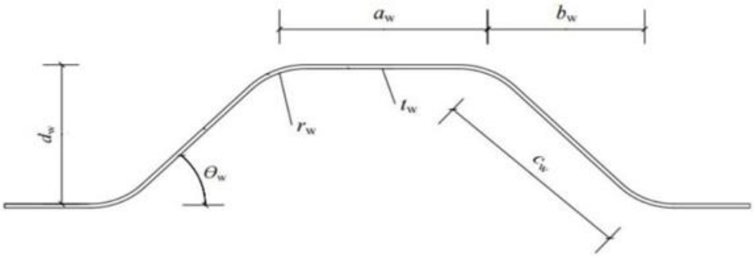

Figure.5 Schematic diagram of the shape of corrugated steel web

The ultimate shear strength of the corrugated steel web shall comply with the requirements of equations (1) - (2):

$$\gamma_0(\tau_{md} + \tau_{td}) \le f_v. \tag{1}$$

$$\tau_{md} = \frac{V_d - V_p}{t_w h_w}. \tag{2}$$

Where: γ_0 - Structural importance coefficient;

τ_{md} - Design value of shear stress generated by the vertical component of shear force and prestress;

τ_{td} - Design value of shear stress generated by torque;

f_v- Design value of shear strength;

V_d - Design value of shear force for a single corrugated steel web plate under the fundamental combination of actions;

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V_p - The vertical shear force generated by the prestressing force on a single corrugated steel web of the calculated section under the fundamental combination of actions;

t_w - Thickness of corrugated steel web;

h_w - Height of corrugated steel web.

Shear checking sections of the main girder can be seen in Figure 5. A total of 51 key sections will be checked for shear stress.

The shear safety factor of corrugated steel web under ultimate limit state is shown in Figure 6. It can be seen from the table that under ultimate limit state, the value of the shear stress at each section is smaller than the design value of the shear strength at the corresponding sections. Therefore, shear strength of corrugated steel web meets the requirements.

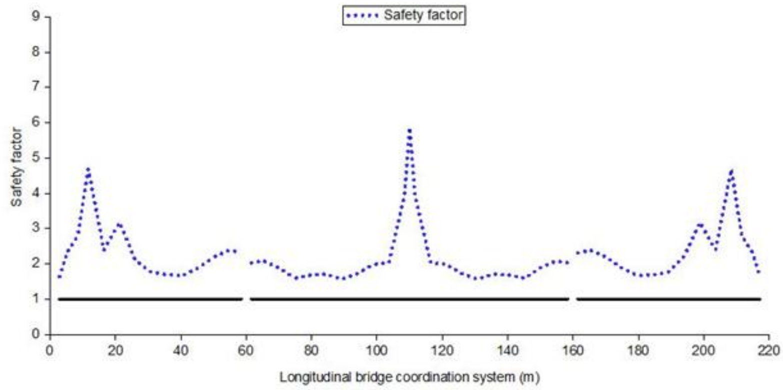

Figure.6 Shear safety factor of corrugated steel web under ultimate limit state

3.3 Shear Stress Checking for Corrugated Steel Web Under Serviceability Limit State

The standard combination of actions should be used for checking the shear stress of the corrugated steel web under serviceability limit state. The shear stress of the corrugated steel web under serviceability limit state shall comply with the requirements of equations （3） and （4）.

$$\tau_{md} + \tau_{td} \leq 0.625 f_{yv}. \quad (3)$$

$$\tau_{md} = \frac{V_k - V_p}{t_w h_w}. \quad (4)$$

In the equation:

τ_{mk} - Design value of shear stress generated by the vertical direction of shear force and pre-stress;

τ_{td} - Design value of shear stress generated by torque;

f_{yv} - Standard value of shear yield strength of corrugated steel web, taken as $1/\sqrt{3}$ of buckling strength;

V_k- Design value of shear force for a single corrugated steel web in the calculated section under the standard combination of actions;

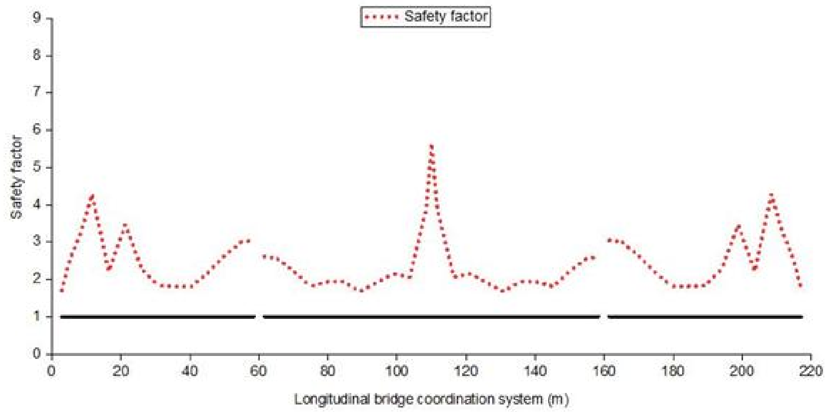

Figure 7 Shear safety factor of corrugated steel web under serviceability limit state

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It can be seen that under serviceability limit state, the design values of shear stress at each section are less than the design values of the corresponding section shear strength, which meets the requirements of the specification. Shear safety factor of corrugated steel web under serviceability limit state is shown in Figure 7.

4. Analysis of Stability of Corrugated Steel Web Bridge

Critical shear stress τ_(cr,L) (τ_(cr,G)) for local (global) buckling of corrugated steel web is calculated according to equations (5) ~ (7):

$$f(x)=\begin{cases}\tau_{cr,L}(\tau_{cr,G})=f_v & \lambda_s\le 0.6\\ \tau_{cr.L}(\tau_{cr,G})=[1-0.614\cdot(\lambda_s-0.6)]\cdot f_v & 0.6<\lambda_s\le\sqrt{2}\\ \tau_{cr,L}(\tau_{cr,G})=\frac{f_v}{\lambda_s^2}\sqrt{2}<\lambda_s\end{cases}. \tag{5}$$

$$\lambda_s=\sqrt{f_v/\tau_{cr.L}^e}. \tag{6}$$

$$\text{or } \lambda_s=\sqrt{f_v/\tau_{cr.G}^e}. \tag{7}$$

In the equation:

τ_{cr} – Functions for calculating the critical shear stress for combined buckling of corrugated steel webs;

$\tau_{cr,L}$– Critical shear stress for local buckling of corrugated steel web ;

$\tau_{cr,G}$– Critical shear stress for global buckling of the corrugated steel web;

λ_s- Shear buckling parameter;

f_v – Shear yielding strength of the web material;

$\tau_{cr.L}^e$–The elastic local buckling strength of the corrugated steel webs is calculated according to formula (8) ~ (9):

$$\tau_{cr.L}^e=\frac{k\pi^2E}{12(1-v^2)}\left(\frac{t_w}{h_w}\right)^2 \tag{8}$$

$$k=4+5.34\left(\frac{h_w}{a_w}\right)^2 \tag{9}$$

$\tau_{cr.G}^e$–The elastic global buckling strength of the corrugated steel webs is calculated according to equations (10) ~ (12):

$$\tau_{cr.G}^e=\frac{36\beta(EI_y)^{\frac{1}{4}}(EI_x)^{\frac{3}{4}}}{h_w^2t_w} \tag{10}$$

$$I_x=t_w^3(\delta^2+1)/(6\eta) \tag{11}$$

$$I_y=\frac{t_w^3}{12(1-v^2)} \tag{12}$$

In the equations:

k – Local buckling coefficient of corrugated steel web plate;

β – Global buckling factor, taken as 1.0;

I_y – Bending stiffness of corrugated steel web plate in the height direction per unit length;

I_x – Bending stiffness of corrugated steel web plate in the bridge direction per unit length;

δ – The ratio of wave height to thickness of corrugated steel web plate, $\delta=d_w/t_w$, d_w is the wave height of corrugated steel web, and t_w is the thickness of corrugated steel web;

η – Shape coefficient, the ratio of the axial length of corrugated steel web along the bridge to the unfolded length, $\eta=(a_w+b_w)/(a_w+c_w)$;

ν – Poisson's ratio of steel, ν =0.3.

Checking calculation for combined buckling bearing capacity of corrugated steel webs under ultimate limit state

The combined buckling shall meet the requirements of equations (11) ～ (12).

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It can be seen from Figure 8, under ultimate limit state, the combined buckling critical shear stress of each section (bearing capacity) is greater than the design value of shear stress of corresponding section, meeting the requirements.

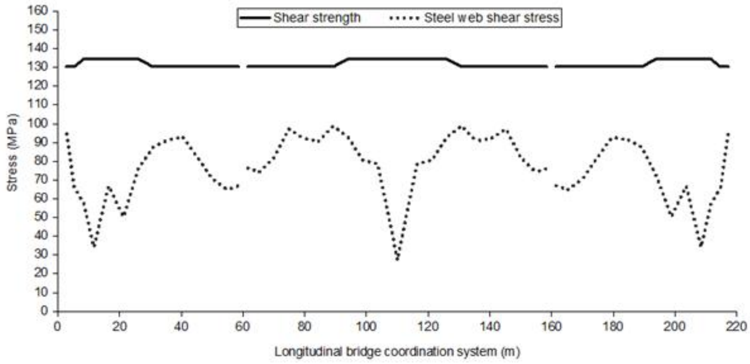

Figure 8 Shear stress checking results of corrugated steel webs under ultimate limit state

5. Conclusion

This chapter conducts static analysis of the structure of a bridge, calculates the internal force and stress values of the box girder under different working conditions, conducts shear strength and buckling stability checks on corrugated steel webs. The results are as follows:

(1) The shear resistance checking for corrugated steel webs and shear connectors meet requirements of both the ultimate limit state and serviceability limit state.

(2) Combined buckling resistance verification also qualified specification requirements.

References

[1] F.T.K Au et al. On the determination of natural frequencies and mode shapes of cable stayed bridges. Applied mathematical modeling 25 (2001) 1099-1115.

[2] Jiho Moon, Ik-Hyun Sung, Hak-Eun Lee. Natural Frequency of a composite girder with corrugated steel web. Steel and Composite structures – January 2015.

[3] Mayer M. Melhem, Colin C. Caprani, Mark G. Stewart. Reliability updating of partial factors for empirical codes: Application to Super-T PSC girders designs at the ultimate limit state in bending. Structure 35 (2022) 233-242.

[4] Qiang Cao, Jingyu Huang, Liang Zhao, Zhihong Fang, Ziyang Zhang. Research on shear performance of corrugated steel plate shear walls with inelastic buckling of infilled plates under lateral loads. Journal of Building Engineering 52 (2022) 104406.

[5] Jun He, Yuqing Liu, Zhaofei Lin, Airong Chen, Teruhiko Yoda. Shear behavior of partially encased composite I-girder with corrugated steel web: Numerical study. Journal of Constructional Steel Research 79 (2012) 166–182.

[6] Kadotani T., Aoki K., Ashizuka K., et al. Shear buckling behavior of prestressed concrete girders with corrugated steel webs. 1st fib Congress, Session 5: Composite structures. Osaka, Japan, 2002: 269-276.

[7] Sayed-Ahmed Y. E. Design aspects of steel I-girder with corrugated steel webs[J]. J. Struct. Eng. 2007: 27-40.

[8] Man Zhoua, Huiyang Fua, Xiaolong Sua, Lin Anb. Shear performance analysis of a tapered beam with trapezoidally corrugated steel webs considering the Resal effect. Engineering Structures 196 (2019) 109295.

[9] Alejandro Giraldo Soto et al. Experimental behaviour of steel-concrete composite box girders subject bending, shear and torsion. Engineering Structure 206 (220) 110169.

[10] Wang F. M., Deng G. L., Dang X. Z., et al. Seismic characteristics study of six-pylon cable-stayed bridge with corrugated steel webs[C]. In: Proceedings of the 2014 International Conference on Energy, Environment and Green Building Materials. Guilin, Guangxi, China, 2014: 53