Acta Technica *62* No. 1A/2017, 247–258

Natural frequency of PC composite simple supported beam with corrugated steel webs

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Abstract. The prestressed corrugated sheet steel exhibits a good performance and has been widely used in the construction of bridges and other similar structures. But the performance of the prestressed corrugated sheet metal is easily affected by external conditions, especially if its frequency of self-oscillation decreases the life span. So this paper presents a combination of corrugated steel web PC simply-supported box girder, the natural frequency of vibration research of corrugated steel belly PC combination of simply supported box girder structure natural frequency and dynamic characteristics analysis of corrugated steel web PC combination simply supported box beam shear lag effect of corrugated steel web PC combination of simply supported box girder shear effect and the coupling effect of the two is the influence of three important factors, which greatly influenced by the shear effect, prestress tension and steel anchor beam position is affected, a greater influence on the steel beam section.

Key words. Corrugated steel web, PC composite, simply supported box girder, natural frequency.

1. Introduction

With the development of economy and society, the prestressed concrete box girder has been widely used because of its strong anti-bending and twisting performance. At the same time, because of the increasing span of prestressed concrete box girder, the proportion of the beam's self-weight load increases, which makes the prestressing force consume most of the internal forces generated by the self-weight of the load beam, resulting in its economy becoming lower and lower. Therefore, in order to reduce the weight of prestressed concrete box girder, both in the choice of materials or structural design have been a high degree of attention. The simple composite box girder with corrugated steel web can optimize the web structure while reducing the dead weight of the girder, and it replaces the internal prestressing with the external prestressing force, so as to achieve the purpose of reducing the weight of the

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structure. However, due to the influence and limitation of the external environment, the mechanical properties of simply supported PC box girder with corrugated steel webs will affect its performance. Therefore, the mechanical properties of simply supported PC box girder with corrugated steel webs have become the research focus and direction of researchers at home and abroad in recent years. Some scholars have studied the mechanical behavior of trapezoidal corrugated steel web girders under fatigue loading, which provides a reliable basis for judging the fatigue life of corrugated steel web girder [1]. Later, some scholars have put forward the research on the seismic performance and torsional resistance of corrugated steel web girders, and some results are obtained [2]. Some scholars have combined the characteristics of the steel beam with corrugated steel web, and considered the effect of shear deformation. The formulas for calculating the deflection of steel web with corrugated steel web under the action of concentrated force are given. This has been helpful for subsequent in-depth studies [3]. In order to optimize the structure of corrugated steel web girders and to reduce the weight of the steel girders, some scholars have studied the effect of prestressed steel web girder accordion, and concluded that the accordion effect can help the corrugated steel web steel [4].With the research on the mechanical properties of steel webs with corrugated steel webs, many scholars have shifted their research points from static mechanics to the study of the dynamic properties of steel webs with corrugated steel webs. Some scholars have proposed the study of natural frequencies of steel webs with corrugated steel webs, this reduces the external influences of corrugated steel webs and improves their overall performance [5].Some scholars have put forward the in vitro dynamic factors of the natural frequency of steel webs with corrugated steel webs, which provides a new research direction for the study of steel webs with corrugated steel webs. Because the study of corrugated steel web steel girder is relatively late in China, the main research is focused on the study of static mechanics, and the research of dynamics is still in need of further study.

Based on the current research and development of PC composite simply supported box girders with corrugated steel webs, this paper will study the natural frequency of simply supported PC box girder with corrugated steel webs.In the second part, the development and future prospect of PC combined simple box girder with corrugated steel web will be summarized.In the third part, the structure and advantages of simply supported PC box girder with corrugated steel web are expounded, and the factors affecting the natural frequency of simply supported PC box girder with corrugated steel webs are discussed. In the fourth part, the experimental data of the factors affecting the natural frequency of simply supported PC box girder with corrugated steel web are analyzed. Finally, the process and results of the study on natural frequency of simply supported PC box girder with corrugated steel web are summarized in the fifth part.

2. State of the art

The prestressed concrete box girder has been widely used in the construction of bridges and other structures before the concrete composite box girders with corrugated steel webs are widely used. However, due to the shortcomings of the longer the weight of the beams, it makes a lot of scholars to improve the research of concrete box girder. A French engineer in the initial study of concrete box girder proposed the use of flat steel plate instead of the idea of concrete webs. As a result of the high stress of the steel plate, the prestress in the concrete slab will be consumed, and the web will need to be thickened to prevent the web from bending. The final result is not ideal [6]. French company Campenon Bernard proposed a further idea that the using corrugated steel plate replaces flat steel. In this scenario, the corrugated steel plate replaces the original flat steel plate and can be extended along the bridge, resulting in a more reasonable structure of the corrugated PC composite bridge. Its concrete definition is that the corrugated web panel PC composite box beam is a thin steel plate to replace the traditional concrete box beam thicker web, and the steel plate is bent into a certain corrugated shape, forming a new, structural force. A more reasonable box girder structure greatly improves the bridge's ability to leap [7]. Then the Japanese introduced the technology, and carried out a lot of research. With the application of PC box girder with corrugated web, the researchers have found that external factors affect its mechanical characteristics and even affect the safety and service life of corrugated PC composite box girder. Therefore, the mechanics characteristics of PC box girder with corrugated webs are studied and some achievements have been obtained. However, there are still few researches on the dynamics of PC composite box girders with corrugated steel webs, which requires further study. Figure 1 is the corrugated steel web PC composite simple box girder bridge construction site map.

3. Methodology

3.1. Structure and advantages of PC composite simply supported box beam with corrugated steel web

The corrugated web panel PC structure is a simple box beam structure in the concrete between the upper and lower plate by the steel web instead of concrete thick web, and the steel web in the bridge is a vertical fold shape, which is the accordion effect [8]. Although this form is simple, it does not substantially bear the axial forces, which avoids the problem of prestress loss due to web restraints when using flat steel plates, and it does not have to be otherwise thickened to avoid the thickness of the steel web buckling deformation of steel plate. In addition, the interaction between the corrugated steel web and concrete roof and floor is the combination of the two. Its main function is to resist the longitudinal shear force between the corrugated steel web and concrete roof and floor [9]. The connection between corrugated steel web and concrete roof and floor is usually made by shear connectors. The design of connection key is directly related to the bearing capacity of the whole structure and its safety. Prefabrication of corrugated webs is usually done by means of high-strength bolts or by field welding [10]. The connection between the corrugated steel web and the concrete roof and floor is usually of two kinds. One is a non-embedded connection, that is, welding the steel plate at the upper and lower ends of the corrugated steel plate, and the steel plate is provided with welding shear nails to help the corrugated steel plate and the concrete plate to be joined together. The second connection is an in-line connection, which involves perforating the corrugated steel plate through the rebar and then welding the longitudinal reinforcement at the upper and lower ends of the steel plate and finally into the concrete [11]. In addition, it was also derived from other connection methods. Here is not a repeat. As shown in Figure 2 is a wave plate and concrete plate connected to the common schematic.

Fig. 1. Two snaps of a bridge constructed with simply supported PC beams with corrugated steel webs

The merits of the structure of the box-girder structure with the corrugated web-shaped PC simply embodying the box girder are firstly manifested in the condition that the weight of the box girder is reduced to a great extent and the load proportion of the bridge girder is reduced. The prestress loss is greatly reduced. Secondly, the effect of prestressing force on the concrete box girder and concrete box girder with plane steel web is improved significantly by its organ effect, and the efficiency of prestressed concrete box girder with prestressed concrete box girders is significantly improved, which greatly increased the span capacity of the bridge. And it makes the corrugated rigid web PC combination simply box beam has more extensive application fields [12].

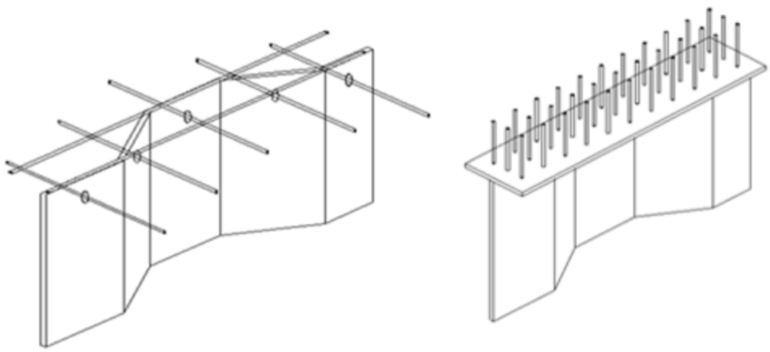

Fig. 2. Schematic diagram of common connections for corrugated steel plates and concrete slabs

3.2. Free vibration equation of PC box girder with corrugated steel webs

The free vibration equation of the PC box girder with corrugated steel webs is based on the structural and mechanical properties of the PC box girder with corrugated steel webs. It is also based on the basic assumptions of the energy law. First of all, because of the special structure of corrugated steel PC box girder, its bending resistance in the longitudinal direction of the bridge is almost negligible, and the cross section of the PC box girder of the corrugated steel web is subject to the "pseudo-section assumption" [13]. Second, Fig. 3 is a corrugated steel box PC box girder diagram. The symbols b, ζb and b_1 in the figure are, respectively, 1/2 of the width of the box girder of the corrugated steel PC box girder, the width of the cantilever plate and the width of the flat section of the vane in the box. Symbols hu, h_{b} are the distances from the center of the upper wing and the lower wing to the mandrel. When calculating the strain energy of the upper and lower wings, only the longitudinal strain of the concrete wing plate εx and the shear strain of the cross-section plane γ_{xy} are taken into account, and the vertical strain, lateral strain and shear strain outside the plate plane are neglected, that is to say, $\varepsilon_y = \varepsilon_z = \gamma_{xz} = \gamma_{yz} = 0$. Finally, the corrugated steel web PC box girder and the concrete vane are connected tightly, without slip condition. When the PC box girder bridge with corrugated steel webs is subjected to free bending vibration, the vertical and horizontal dynamic displacement functions can be introduced to describe the displacement mode because of the influence of shear lag effect:

$$W = W\left(x, t\right) \ , \tag{1}$$

$$U\left(x, y, z, t\right) = h_{\mathrm{i}}\left[\varphi\left(x, t\right) + \left(1 - y^{-3}\right)\xi\left(x, t\right)\right] \ , \tag{2}$$

$$\bar{Y} = \begin{cases} y/b, 0 \leq y \leq b\,, \\ \left(b + \zeta b - y\right)/\zeta b, b \leq y \leq b + \zeta b\,. \end{cases} \tag{3}$$

In the formula, $\varphi\left(x, t\right)$ and $\xi\left(x, t\right)$ are the angular displacement and the maximum longitudinal displacement difference function of the box girder section due to bending deformation when the PC box girder bridge with free corrugated steel web is vibrated. Then the natural frequency of the PC box girder with corrugated steel web is obtained by using the eigenvalue equation of the free bending vibration equation of the PC web girder with corrugated steel webs according to the actual boundary condition.

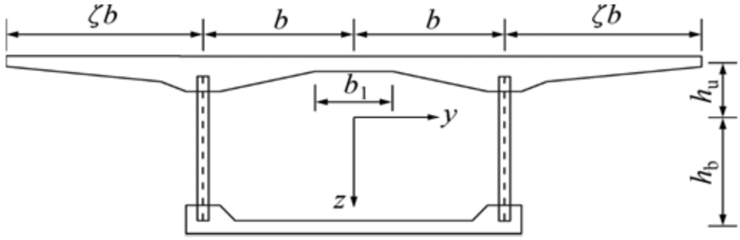

Fig. 3. Sectional view of the PC box girder with corrugated steel webs

3.3. Influencing factors of natural frequency of PC composite simple supported beam with corrugated steel webs

Corrugated steel web PC composite simple box girder is mainly used in the construction of bridges. In the course of the use of the bridge, the dynamic load and wind force of the vehicle, the ground motion of the earthquake, and the individual dynamic loads of the individual population arise because the bridge structure will vibrate because of the influence of external forces.And this vibration can increase the internal forces calculated in accordance with the static force and the possibility of causing local structural fatigue damage. Seriously, it would even destroy the bridge completely [14]. Therefore, the structural vibration of the bridge is an important factor affecting the safety of the bridge. The vibration of bridge structure is a cyclical process in which the deformation energy and kinetic energy of the structural system are transformed with each other due to the input of external force and the friction loss. How much structural system by external force input is the sensitivity of the system and its inherent natural frequency and the frequency of the input effect, that is, the degree of resonance is closely related. So it is necessary to understand and determine the natural frequency and dynamic characteristics of PC simply supported box girder with corrugated steel webs.

The solution of the bending vibration equation of PC simply supported box girder with corrugated steel web can be obtained by the governing differential equations and natural boundary conditions for bending vibration are obtained from equations (1–3) above. The shear lag effect of simply supported PC box girder with corrugated steel web can be seen. The shear effect and the coupling effect of PC composite simple box girder with corrugated steel webs are the three important factors affecting the natural frequency of simply supported PC box girder with corrugated steel webs. And in the process of solving the low-order bending vibration frequency solution, the influence coefficient of the shear lag is much smaller than 1, and the influence coefficient of the coupling effect is also very small. Therefore, the influence of the two factors on the natural frequency of PC composite simple box girder with corrugated steel web is small, and the effect of shearing effect of corrugated steel web PC composite simple box girder is not negligible, otherwise it will cause wrong result. Besides prestressed concrete box girder structure with corrugated steel web, the external prestressing influences the natural frequency of simply supported PC box girder with corrugated steel webs, and its dynamic characteristics are more significant than that of prestressed concrete box girder [15]. Therefore, the study on the natural frequency of PC simple box girder with corrugated steel web is carried out by external prestressing. The prestressed external prestressed concrete box girder with corrugated steel web is PC - type. Both ends of the prestressing force exert a pair of prestressing force, the eccentricity is e. According to the natural vibration equation of corrugated steel web PC combined simple box girder, the bending differential equation of PC simply supported box girder with corrugated steel web under external prestressing force can be obtained as:

$$EI\frac{\partial^4 y}{\partial x^4}+\frac{\partial^2\left(N_1 y\right)}{\partial x^2}-\frac{\partial^2 M}{\partial x^2}+m\frac{\partial^2 y}{\partial t^2}=0\,. \tag{4}$$

In the formula, y is the vibration displacement, EI is the bending rigidity of the beam, m is the mass per unit length of the beam, M is the bending moment of the external prestressing force to the beam. Beam bending moment caused by external prestress $M = N_1 e + N - 2x$, among them, N_1 and N_2 are the components in the horizontal and vertical directions of the predecessor N_p. That is, $N_1 = N_\mathrm{p}\cos\theta$ and $N_2 = N_\mathrm{p}\sin\theta$. According to the vibration of the beam in the process, the external prestressing is constantly changing, so we can put

$$N_1 = N_\mathrm{p}^0 + \Delta N_1\,, \tag{5}$$

$$N_2 = N_\mathrm{p}^0 + \Delta N_2\,, \tag{6}$$

$$M = N_1 e + N_2 x = (N_1^0 + \Delta N_1)e + (N_2^0 + \Delta N_2)x\,. \tag{7}$$

Substituting equations (5–7) into equation (4), we obtain

$$EI\frac{\partial^4 y}{\partial x^4} + \frac{\partial^2}{\partial x^2}\left[(N_1^0 + \Delta N_1)y\right] -$$

$$-\frac{\partial^2}{\partial x^2}\left[(N_1^0 + \Delta N_1)e + (N_2^0 + \Delta N_2)x\right] + m\frac{\partial^2 y}{\partial t^2} = 0\,. \tag{8}$$

Due to vibration displacement $y \le e$, so $\Delta N_1 y \le \Delta N_1 e$. Thus, $\Delta N_1 y$ can be ignored and also, since N_{p}^0 is the effective prestress of external prestressing tendons, the value is constant. So its second derivative with respect to x is equal to 0, which provides

$$EI\frac{\partial^4 y}{\partial x^4} + N_1^0\frac{\partial^2 y}{\partial x^2} - e\frac{\partial^2 \Delta N_1}{\partial x^2} - \frac{\partial^2 \Delta N_2}{\partial x^2}x + m\frac{\partial^2 y}{\partial t^2} = 0\,. \tag{9}$$

The influence of external prestressing on the natural frequency of PC composite simple box girder with corrugated steel web is mainly manifested in three aspects: prestressed beam tension, anchorage position of steel beam, steel cross-sectional area. After that, the three aspects of corrugated steel web PC combined simple box girder are compared.

4. Result analysis and discussion

In this paper, the experimental data of prestressed beam tension, anchorage position of steel beam and cross section of steel beam are analyzed for three factors affecting the natural frequency of PC combined simple box girder with corrugated steel web. Table 1 presents is the impact of prestressed beam tension on the natural frequency of pc composite simple supported beam with corrugated steel webs. In the experiment, the anchorage position of the prestressed steel beam is $6h/12$ (h being the beam section height), the cross-sectional area of the prestressed steel beam being $A = 1.4 \times 10^{-4}\,\mathrm{m}^2$. It can be seen from the data in the table that the prestress of prestressed PC simply supported box girder with prestressed corrugated steel web is slightly increased.This is in accordance with the results of theoretical calculation and finite element experimental results of the natural frequencies of the simply supported PC box girder with corrugated steel webs under different prestressing tendons. This also shows that prestressed beam tension on the corrugated steel web PC composite simple box girder of the natural frequency of the impact is relatively small.

Table 1. Impact of pre-stressed beam tension on the natural frequency of PCcomposite simple supported beam with corrugated steel webs

Prestressed beam tension (kN)	Theoretical value (Hz)	Finite element value (Hz)	Error (%)
50	31.8471	32.0841	0.73
80	31.8495	32.0843	0.72
110	31.8519	32.0845	0.71
140	31.8542	32.0847	0.71

Table 2 shows the influence of anchorage location of steel beam on natural frequency of PC composite simply supported box girder with corrugated steel webs. In the experiment, the prestressing force of prestressed steel beam of prestressed steel box with corrugated steel PC composite simple box girder is $F = 50\,\mathrm{kN}$, the cross - sectional area being $A = 1.4 \times 10^{-4}\,\mathrm{m}^2$. It can be seen from the experimental data in the table that the natural frequency of prestressed PC steel box girder with corrugated steel web is reduced with the increase of anchorage position. And the theoretical calculated values of the box girder at different prestressed anchor positions are in accordance with the calculated values of the finite element method. That is to say, the anchoring position of the steel beam has little effect on the natural frequency of the PC combined simple box girder with corrugated steel webs.

Table 2. Effect of anchorage location of steel beam on natural frequency of simply supported PC box girder with corrugated steel webs

Anchorage position of steel	Theoretical value (Hz)	Finite element value (Hz)	Error (%)
$3h/12$	31.8481	32.0935	0.72
$4h/12$	31.8445	32.0902	0.71
$5h/12$	31.8503	32.0871	0.73
$6h/12$	31.8570	32.0841	0.73

Table 3 presents the influence of cross sectional area of steel bundle on natural frequency of pc composite simple supported box girder with corrugated steel webs. In the experiment, the tensile force of the prestressed steel beam is $F = 50\,\mathrm{kN}$, the anchoring position is $6h/12$, $A = 1.4 \times 10^{-4}\,\mathrm{m}^2$. It can be seen from the experimental data in the table that the natural frequency of prestressed steel PC composite simple box girder with the corrugated steel web will increase with the increase of the cross-sectional area of prestressing beam. The theoretical value of the natural frequency of the box girder with different cross-sectional area of the prestressed steel beam is in accordance with the calculated value of the finite element experimentally. This also shows that the steel beam cross-sectional area of the corrugated steel web PC composite simple-support box girder self-oscillation frequency has a certain impact.

Table 2. Influence of cross-sectional area of steel beam on natural frequency of simply supported PC box girder with corrugated steel webs

Sectional area of steel	Theoretical value (Hz)	Finite element value (Hz)	Error (%)
A	31.8473	32.0843	0.75
$2A$	31.9435	32.2060	0.83
$3A$	32.0363	32.3049	0.84
$4A$	32.1263	32.3843	0.81

5. Conclusion

Prestressed wave steel plate PC combined with simply supported box girder is better than concrete box girder in structure and material weight. It has been widely used in bridge and other construction. However, due to the structural characteristics of corrugated steel belly PC combined with simply supported box girder and the influence of external conditions, the safety of its use is reduced and its service life is affected. The mechanical properties of simply supported box girder with corrugated steel belly PC are studied. This paper presents a study on the natural frequency of simply supported PC box girder with corrugated steel sheet. In this paper, the development and advantages of corrugated steel sheet abutment PC combined box girder are expounded, and the influence factors of the natural frequency of bellows composite box girder with corrugated steel plate are studied. The experimental results show that the effect of shearing effect on the natural frequency of the PC box girder with corrugated steel plate is more significant. In the external stress, the prestressing force and the anchoring position of the steel beam have little effect on the natural frequency of composite pc box girder with corrugated steel plate. The influence of the steel beam cross section on the natural frequency of the composite box girder with corrugated steel sheet is greater, and the natural frequency of the composite box girder increases with the increase of the sectional area.

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Received May 22, 2017