Sensitivity Analysis of Dynamic Characteristics of Steel Plate Composite Girder Bridge with Supported Cross Beam System

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Abstract: A steel plate composite girder bridge with support beam system was selected in the case study and the software of SAP2000 was adopted to build its refined seismic finite element model. A sensitivity analysis about the dynamic characteristics of the bridge was carried out and the design parameters included relative stiffness ratio of beam to slab, shear stiffness of shear nails and steel beam. The results show that: the stiffness ratio of beam to plate has little influence on the low-order modes of structure, but more significant influence on the high-order modes. Furthermore, in the high order modes, the effect of the stiffness of concrete slabs on the dynamic characteristics of high order modes of structures is greater than that of the stiffness of steel girders. Large reduction of the stiffness of shear nails significantly affects the natural vibration period, the order of mode shapes and the mass participation coefficient. Its influence on the vertical dynamic characteristics of bridge is significantly greater than the dynamic characteristics in the longitudinal direction and the in the horizontal direction. Steel beams have little influence on the dynamic characteristics of structures.

1. Introduction
Because of its many advantages, steel-concrete composite beams are more and more widely used in engineering construction, and their structural dynamic characteristics have attracted much attention of scholars in the field of bridge engineering.

Huang et al [1] put forward the equation of the dynamic characteristic of composite beams with partial shear connection which can be used to calculate the natural frequency and model shape of composite beams, the key parameters which affect the dynamic characteristic of bridge can also be determined the results. Chao Zegang et al [2] adopted the method of theoretical analysis and numerical simulation to study the dynamic characteristics of steel-concrete composite beams in the perspective of natural frequencies of composite beams. Experiments were carried out with six model beams by Hou Zhongming et al [3], to study the basic dynamic characteristics and damage identification of steel-concrete composite box girders. The influence of shear connectors on the natural vibration characteristics of composite beams was investigated in 2012. The results show that the dynamic stiffness of composite beams is directly related to the shear connectors, and the stiffness of composite beams cannot be calculated based on static theory [4]. In 2014, Xia He et al [5] deduced the basic dynamic equation of steel-concrete composite beams, which took the damping, the relative slip between steel beams and concrete slabs into consideration. The analytical solutions of natural frequencies and mode shapes of simple-supported composite beams were obtained. Through the comparative analysis of the results, it was found that the flexibility of connectors had some influence on the dynamic characteristics of composite beams. Zhang Yanling et al [6] designed three steel-concrete composite box girder tests to
study the basic dynamic characteristics and dynamic response of composite beams under forced vibration. The experimental results show that the vibration frequency of composite beams increases with the decrease of shear connectedness. Liu Huan [7] obtained the natural frequencies and modes of the test beams from the excitation tests of the test beams. It was found that the natural frequencies decrease with the decrease of the content of shear connection. Fang G et al [8] found that the bending vibration frequency can be reduced by 20% to 40% as the interface shear connection stiffness decreases through theoretical calculation.

At home and abroad, the influence factors of dynamic characteristics of steel plate composite beams are mainly concentrated on shear connectedness. At the same time, parameter analysis based on material strength and structure size has been carried out. However, many factors which affect affecting dynamic characteristics of composite beams have not yet been taken into consideration, especially for steel plate composite beam bridges with supporting beam system. Therefore, the sensitivity analysis about the dynamic characteristics of steel plate composite girder bridges with support beam system is carried out in this paper. The effect of design parameters such as beam-plate stiffness ratio, shear nail shear stiffness and steel beam was taken into consideration.

2. Engineering overview
This paper is based on Huaihe Bridge in Shouxian from Huainan to Hefei of Jinan-Qimen Expressway. Steel plate composite girder bridge with supporting cross beam system was highly adopted in the approach bridge. The main girder of the bridge is composed of two I-shaped steel plate composite beams with a full width of 26.5m. The girder is 1.75m high at the center line of the steel beam. The standard cross section and the cross section near bearing of the main girder are shown in Figure 1.

![Figure 1. The cross section of main girder](image)

The prefabacrted bridge deck is made up of bi-directional variable cross-section slab, which consists of prefabricated slab, longitudinal wet joint and transverse wet joint. The single beam section is divided into four prefabricated plates in transverse direction and one whole plate in longitudinal direction. C40 concrete slab is adopted in the bridge deck in the positive moment region while the negative moment section at the pier top is made of PVA fibre concrete slab. The cast-in-place wet joint is made of C40 micro-expansive concrete. The steel main girder adopts Q345D I-shaped straight web steel girder, while the steel main girder and the middle cross girder are connected with the concrete bridge deck by welding nails with a diameter of 22mm. The welding nail material is ML15. The transverse connection between the two main beams is strengthened by the middle cross beam, and the standard spacing of the middle cross beam is 5.0m.

3. Seismic Finite Element Model of Bridge Structures
In order to consider the influence of different important components on the dynamic characteristics of the structure, the structural and seismic characteristics of steel plate composite girder bridges with supporting cross beam system were taken into consideration in building the finite element model. The shell element is used to simulate the concrete deck. The frame element is used to simulate the steel main beam and the steel cross beam. The connection element with given corresponding stiffness in different directions is used to simulate the shear nail. The axial tensile strength of a single shear nail is taken in the axial direction, and the bi-linear constitutive model [9] proposed by OEHLELS is adopted in modeling the shear nail in the transverse and longitudinal directions of the bridge.
According to the Code for Design of Steel-concrete Composite Bridges (GB50917-2013)\cite{10}. The shear capacity of single shear nail is calculated as $P_{\text{max}}=99.8\text{kN}$. And the average shear stiffness $K_e=36\text{kN/mm}$ is calculated based on OEHLERS method. Shear nails are densely distributed in steel girders. Because the simulation of all shear nails not only increases the workload of modeling but also reduces the calculation efficiency, the shear nails are merged in the modeling. The stiffness reduction caused by group nails effect after merging is considered.

For the substructure, the bearing is simulated by link element. The frame beam element is adopted to model the pier and column. The pie and column are discretized according to the rule that the mass distribution should be uniform, and the pile foundation is simulated by the concentrated soil spring model of $6 \times 6$.

4. Sensitivity of Structural Dynamic Characteristics to Design Parameters

4.1. Stiffness ratio of beam to plate

The design stiffness of concrete slab and steel girder are $K_{\text{slab}}$ and $K_{\text{beam}}$ respectively, that is, Case 1. Then, the stiffness of concrete slab is changed to $0.5 K_{\text{slab}}$, $1.5 K_{\text{slab}}$ and $2.0 K_{\text{slab}}$ in turn, and the stiffness of steel girder is unchanged, corresponding to Case working 2 to 4. Finally, the stiffness of steel beam is changed to $0.5 K_{\text{beam}}$, $1.5 K_{\text{beam}}$ and $2.0 K_{\text{beam}}$ in turn, and the stiffness of concrete slab is unchanged, corresponding to Case 5 to 7. The information of different cases is shown in Table 1.

| Case name | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 |
|-----------|--------|--------|--------|--------|--------|--------|--------|
| Stiffness | $K_{\text{slab}}/K_{\text{beam}}$ | 0.5 $K_{\text{slab}}$ | 1.5 $K_{\text{slab}}$ | 2.0 $K_{\text{slab}}$ | 0.5 $K_{\text{beam}}$ | 1.5 $K_{\text{beam}}$ | 2.0 $K_{\text{beam}}$ |

(1) Changing the stiffness of concrete slabs

(2) Changing the stiffness of steel girders

Figure 4. Effect of stiffness ratio of beam to slab on mode mass participation factor in the longitudinal direction (X-direction)
According to Table 1, Figure 4 and Figure 5, the mass participation factor of the first mode of vibration is dominant in the longitudinal direction, reaching 82.71%. The stiffness of concrete slab or steel girder has little effect on the first mode of vibration. Although it affects the frequency and mass participation factor of the longitudinal high mode of vibration, but generally not more than 5%. Therefore, the stiffness ratio of beam to slab has little effect on the dynamic characteristics in the longitudinal direction. Similarly in the transverse direction, the mass participation factor of the second mode occupies the dominant position, reaching 80.54%. Changing the stiffness of concrete slabs or steel girders has little effect on the dynamic characteristics in the transverse direction.

According to Table 1 and Figure 6, it can be seen that in vertical direction as the stiffness of concrete slabs increases, the mass participation coefficient of the first-order modes with the most important contribution gradually increases, and the order of different mode shapes also changes. A relatively obvious high-mode effect even occurs. For example, in Case 3 and Case 4, the 16th mode has the largest vertical mass participation coefficient, while in Case 1 it is the 13th mode and in Case 2 it is the 15th mode. However the modes with the largest vertical mass participation coefficient have nearly same periods and mass participation coefficients. In higher modes (after the fiftieth order), mode shapes with mass participation coefficients of 16.55% and 15.77% appeared in the Case 3 and Case 4 respectively, while the other modes did not appear. Moreover, with the increase in the stiffness of steel beams, the variation vertical structural dynamic characteristics is similar to the condition when the concrete slab is changed.

4.2. Shear Stiffness of Shear Nails
The design value of shear stiffness of shear nails is taken as $K$, and the stiffness is reduced to 0.1 $K$, 0.01 $K$, 0.001 $K$ and 0.0001 $K$ in turn, as shown in Table 2.
According to Table 2 and Figure 7, it can be seen that as the reduction of shear stiffness of shear nails decreases, the period of mode shapes with large mass participation coefficients in the longitudinal and transverse directions continue to prolong, i.e. the first and second modes. The order of some higher modes also changes and the dynamic characteristics of structures is affected. In the vertical direction, as the shear stiffness of shear nails decrease, Case 1 to 5 with the largest mass participation coefficient appear in different order, and the corresponding mass participation coefficient decreases from 51.71% to 49.67%. Moreover, the order of vertical higher order modes and their mass participation coefficients are significantly changed.

Further analysis shows that when the shear stiffness of the shear nail is greater than 0.01 times the design stiffness, the stiffness of the shear nail has little influence on the dynamic characteristics of the structure. When the shear stiffness of shear nails is less than 0.01 times the design stiffness, the effect of shear stiffness reduction on the dynamic characteristics of the structure becomes significant.

4.3. Steel Cross Beam

For composite girder bridges with supporting beam system, besides end cross beams, the steel beams installed in each span can not only connect the main steel beams, but also function together with the prefabricated deck through shear nails. Therefore, the number of steel cross beams per span was selected as a parameter, and the information of different cases is shown in Table 3. Among them, Case 1 (6 steel beams per span) is the designed number of steel beams.
Table 3. Analysis of Steel Beams

| Case name | Case 1 | Case 2 | Case 3 | Case 4 |
|-----------|--------|--------|--------|--------|
| Number of steel beams | 6      | 3      | 1      | 0      |

(1) In the longitudinal direction (X direction)
(2) In the transverse direction (Y direction)
(3) In the vertical direction (Z direction)

Figure 8. Effect of steel beam on mode mass participation coefficient

Table 3 and Figure 8 show that the number of steel beams has little effect on the period, occurrence order and mass participation coefficient of the modes with significant mass participation coefficients in the longitudinal and transverse directions. The high-order modes (over 50 orders) varies within 5% when the number of steel beams changes. In the vertical direction, the number of steel beams has little effect on the mode shape with the largest mode mass participation coefficient, but it has great influence on the higher mode shapes with relatively larger contribution. It can change the period, the order of occurrence and the mass participation coefficient of the higher mode shapes, that is to say, it can change the vertical high mode effect and dynamic characteristics of the bridge in the vertical direction are affected.

5. Conclusion

In this paper, a refined finite element model of steel plate composite girder bridge with support beam system is built and the dynamic characteristics of bridge are investigated. The effects of the important design parameters, such as beam-plate stiffness ratio, shear stiffness of shear nail and steel beam, on the dynamic characteristics of steel plate composite girder bridge with support beam system are compared and analyzed. The conclusions are as follows:

(1) The stiffness ratio of beam to slab has less influence on the low-order modes of structure and greater influence on the high-order modes of structure; it has less influence on the longitudinal and transverse dynamic characteristics of structure, but greater impact on the dynamic characteristics in the vertical direction. In the lower modes, the effect of stiffness of steel girders on the dynamic characteristics of structure is larger than that of concrete slabs. In the higher modes, the effect of stiffness of concrete slabs on the dynamic characteristics of structure is larger than that of steel girders.
(2) The large reduction of the stiffness of shear nails has great influence on the dynamic characteristics of the structure, which significantly changes the natural vibration period, the order of mode shapes and the mass participation coefficient.

With the reduction of shear stiffness of shear nails, the period of mode shapes with significant longitudinal and transverse mass participation coefficients of bridges will be prolonged and the order of some higher modes will be changed. In vertical direction, the effect of shear stiffness reduction of shear nails on the dynamic characteristics of structures is significantly greater than that in the other two directions.

(3) Steel beams have a little influence on the dynamic characteristics of bridge in the longitudinal and transverse directions, and slight influence on the main vertical modes, but have great influence on the higher vertical modes. Generally speaking steel beams have little influence on the dynamic characteristics of structures.

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