Mechanical behavior evaluation of corrugated steel webs (CSWs) multi-cell PC box girders

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Abstract: In order to optimize the design of the girder bridge, based on the CSWs PC box girders bridge design parameter, the mechanical behavior of single-room girder boxes from the single cell to five cells under four different load combinations were analyzed by using the FEA. The mid-span displacement in the bottom flange, Von-mises shear stress in both corrugated web sides, normal warping stress and dead weight of the box girder were obtained. Calculation results have shown that multiplying cell numbers could increase the efficiency of prestressing and decrease the Von-mises shear stress in both corrugated web sides in some cases. However, with the cell numbers increasing, the normal warping stress under eccentric load and the dead weight of the girder increase dramatically. Finally, by utilizing the Simple Formula Method and Principal Component Analysis Method, the proper cell number for the box girder of the specified size is suggested.

1. Introduction

In 1986, corrugated steel webs PC box girder bridge was invented in France [1], which mechanical behaviors have been studied for thirty years. Based on the bending theory, its flexural bearing capacity equation that considered the effective width and the eccentric loads was promoted [2]. And its bending stress distribution of the flanges under the symmetric loads was disclosed [3].

However, the aforementioned researches mostly concentrated on the mechanical performances of the single-cell or double-cell girders. The comparison of the conclusions was also neglected. In this research, girders whose cells vary from one to five are analyzed by the FEA, and two comprehensive methods are used to suggest the proper cell numbers.

2. The parameters of the girder bridge

2.1 The design of the girder bridge

The details of the corrugated steel webs PC box girder bridge are as follows: the material of the top and bottom flanges is C50 concrete. The thickness of the Q345D CSWs is 0.16m. The prestressed reinforcements are made up of fifteen 1860Mpa strands whose diameter is 15.2mm, and 14 of the prestressed reinforcements distributed in the top flange, 4 of them are in the bottom flange. The span of the box girder is 6.755m which has 0.5m diaphragms on each side. The single-cell girder and CSW are shown in figure 1. Double-cell to quintuple-cell girders are accomplished by dividing the single box evenly along its longitudinal direction.
2.2 The parameters of the FEA models & loads

FEA model settings: The eight-node hexahedron solid element is used to simulate concrete, and CWS is simulated by the quadrilateral plate element, using the line element to analyze the prestressed reinforcement. To stimulate the geometric constraint of the rigid frame bridge, 6 DOFs in the bottom of the two diaphragms are restricted.

Loads conditions: Dead weight is calculated by the girder’s density and volume automatically. The prestress load of the reinforcements is 1395Mpa, and the second-stage load is 2kN/m. According to China national standard JTGB01-2014 [4] and JTG D60-2015 [5], equivalent vehicle load consists of two parts: 5.25kN/m uniform load and 164.11kN concentrated force.

3. Mechanical performance analysis among single boxes with different cell numbers

3.1 Mid-span middle point displacement in the bottom flange

Seen in figure 2, without the prestress load, dead weight results in the middle point displacements of the mid-span bottom flange downward, and the displacement of the single-cell girder achieves the maximum which is 0.16mm. However, once the prestress load is applied, the springing phenomenon can be observed dramatically. As expected, the second-stage load and vehicle load decrease the springing heights.
Figure 2. Mid-span middle point displacement (m) of the bottom flange of girders with different cell numbers

Displacement is effectively restrained by the cell partitions. But the restriction is limited, especially if the numbers of partitions are growing up to some level. When the cell numbers increase from one to three, the effect of the dead weight is weakened due to the constrained bottom flange, and it can be helpful to apply the prestress load. Regard to the girders with four cells and five cells, partitions give a considerable contribution to the dead weight and longitudinal stiffness, which induce the prestress and springing height loss.

3.2 Von-mises shear stress distribution in the outermost mid-span CSWs

Under the prestress load, the Von Mises shear stress distribution of the mid-span outermost webs is shown in figure 4. With the increase of the cell numbers, Von Mises shear stress decreases. Compared with the single-cell girder, the maximum Von Mises shear in the intersection of the top flange and the outermost webs of the double-cell to quintuple-cell girders incline 0.81%, 3.48%, 5.12%, 6.98%, respectively.

Figure 3. Von-mises shear stress distribution of boxes with different cell numbers under prestress load

Under the second-stage load and vehicle load, the Von Mises shear stress distributions share the same tendency with the former one. The variation of shear stress can be seen in table 1. Because the CSWs take responsibility for the shear stress, so multiplying the number of CSWs partition can effectively reduce the Von Mises shear stress of the outermost CSWs.
### Table 1. Maximum von-mises shear stress of boxes with different cell numbers under different load conditions

| Load                        | Single cell | Double cells | Triple cells | Quadruple cells | Quintuple cells |
|-----------------------------|-------------|--------------|--------------|-----------------|-----------------|
| Prestress loads (KPa)       | 89902.49    | 89170.56     | 86772.94     | 85302.80        | 83626.77        |
| Second-stage loads (KPa)    | 89797.40    | 89094.07     | 86696.09     | 85231.16        | 83562.44        |
| Vehicle loads (KPa)         | 89882.03    | 89363.49     | 86956.24     | 85478.98        | 83835.13        |

### 3.3 Nominal warping stress of the boxes in mid-span controlling spots

Bending stress and warping stress are generated simultaneously under the eccentric load. According to the load decomposition method [6], an eccentric load can be divided into the symmetric load and the antisymmetric load. To Make sure that bending stress is equal to the former one under the vehicle load, warping stress can be easily acquired by eccentric stress subtracts bending stress.

![Decomposition of eccentric loads](#)

The warping stress in the intersection of the mid-span top flange and the outermost CSWs is shown in table 2. AASHTO[7] has suggested that the ratio of warping stress to bending stress, namely $\frac{\sigma_{\text{w}}}{\sigma}$, should be controlled within 10%. From table 2, warping stress and $\frac{\sigma_{\text{w}}}{\sigma_{\text{M}}}$ are growing up with the increase of cell numbers. It should be cautious enough to multiply cell numbers.

### Table 2. Nominal warping stress of boxes with different cell numbers in the mid-span cross-section

| Parameters              | Single cell | Double cells | Triple cells | Quadruple cells | Quintuple cells |
|-------------------------|-------------|--------------|--------------|-----------------|-----------------|
| Nominal warping stress (KPa) | 195.73      | 473.25       | 696.36       | 839.32          | 913.71          |
| $\frac{\sigma_{\text{w}}}{\sigma_{\text{M}}} \times 100\%$ | 1.94        | 3.75         | 6.39         | 6.90            | 7.95            |

### 4. Comprehensive evaluation of the cell numbers

Above all, the proper cell number of this sort of girder is evaluated by the simple formula method (SFM) [8] and the principal constitution analysis method (PCAM) [9]. To ensure the accuracy of the evaluation, Dimensionless of the mid-span middle point displacements of the bottom flange, the maximum Von
mises shear stress of the outermost CSWs, the maximum warping stress under the vehicle loads, and the dead loads are carried out, \( x_i (i=1, 2, 3, 4) \) is the component index. The results are shown in table 3.

| Cell            | Index | \( x_1 \) | \( x_2 \) | \( x_3 \) | \( x_4 \) | SFM    | PCAM  |
|-----------------|-------|-----------|-----------|-----------|-----------|--------|-------|
| Single cell     |       | 0.99      | 1.00      | 0.21      | 0.73      | 2.93   | -0.49 |
| Double cells    |       | 0.76      | 0.99      | 0.52      | 0.80      | 3.07   | -0.17 |
| Triple cells    |       | 0.72      | 0.97      | 0.76      | 0.86      | 3.31   | 0.07  |
| Quadruple cells |       | 0.91      | 0.95      | 0.92      | 0.93      | 3.71   | 0.25  |
| Quintuple cells |       | 1.00      | 0.93      | 1.00      | 1.00      | 3.93   | 0.35  |

Parameters are negative in table 3, consequences from two methods indicate that the mechanical behaviors of the single-cell girder are better synthetically. The reason for the unsatisfactory performance of the multi-cell girders can be sorted into two aspects. First, too many cell partitions induce the increase of the dead weight of the girder. Moreover, as the cell numbers rise, the warping stress increases drastically at the same time, but the slight contribution to the Von Mises shear stress and displacement can be neglected. Generally, the single-cell box girder is suggested for girder in such size.

5. Conclusions

(i) By FEA analysis, it can be concluded that adding cell numbers increase the springing heights of the bottom flange under the prestress loads and decrease the Von Mises shear stress of the outermost CSWs.

(ii) As the cell numbers increase, warping stress under the eccentric loads and dead weight rise simultaneously.

(iii) Utilizing two comprehensive evaluation methods, the single-cell box girder in such size is suggested.

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