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Research on the calculation model of shear key of adjacent precast concrete box beam bridge

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Abstract. In this paper, experimental study and finite strip method were used to analyze the lateral shearing performance of adjacent precast concrete box beam bridge shear key. According to the structural style and the load characteristics, the finite strip computational theory was introduced to derive the finite strip computational determinant of the adjacent precast concrete box beam bridge, study the computational method of the shearing performance of the shear key, and develop the corresponding computing program. Based on the field test of the adjacent precast concrete box beam bridge, the relative displacement difference of the shear key was proposed to judge the shearing performance and the lateral force transmission performance. The field test and numerical calculation results indicate that the relative displacement difference of the shear key can better evaluate the lateral shearing performance of the shear key and accurately distinguish the merits and demerits of the force transmission performance of the shear key. Compared with the commercial software which could not be used individually to deal with the shear key, the finite strip computational theory can use fewer elements to analyze the lateral shearing performance of the shear key with high computational efficiency. The comparison between calculating results with the experimental data verifies the accuracy and reliability of the computational theory and the computing program. The experimental and numerical analysis methods proposed in this paper can be used as the guidance for practical engineering.

Introduction

The vertical shear between the slabs of the adjacent precast concrete box beam bridge is transferred through the shear key, and hereby the traffic load is horizontal transferred and distributed. When the slab connection strength cannot resist the vertical shear, the filler concrete between the beams will crack under the traffic load[1]. Moreover, because of the torsion which is generated by the vertical shear of the box-beam, the cracking of the filler concrete could propagate. In addition, the interaction of the poor bridge deck drainage, the long-term overweight loading and other unfavorable factors aggravate these diseases[2-3]. In recent years, the longitudinal crack, pit and collapse along the tongue and groove between slabs in this type of bridge, and the concrete near shear key tattered or fallen, and leakage over large areas cause failing transverse contact and single plate bearing. As an ultimate result, driving safety and traffic capacity of the whole highway are imperiled. Therefore, how to accurately and effectively evaluate the lateral shearing performance of the shear key of the adjacent precast concrete box beam bridge is of great importance. However, the existing literatures were generally aimed at the adjacent precast concrete box beam bridge which had diseases in the shear key, analyzing the specific causes of the diseases and designing the corresponding reinforcement methods. The diseases are often limited to the visual defects, such as shear key concrete cracking, falling, etc. For the internal diseases of the shear key concrete, such as internal crack of the concrete, compaction degree of the grout, etc., cannot forecast, so the lateral shearing performance of the shear key cannot be accurately evaluated[4]. The spatial calculation analysis of the lateral shearing performance of the shear key is basically relied on the commercial finite element software, such as ANSYS and MIDAS[5-6]. Although, the geometry of the box-beam and the shear key are quite different, the fabricated box-beam is regarded as an integral slab with finite strip meshing. The shear key is not separately considered, but directly meshed together with the box-beam. Obviously, this approach cannot analyze the lateral shearing performance of the shear key, and now little of the research results are found in this area.

Therefore, in this paper, experimental study and finite strip method were used to analyze the lateral shearing performance of the shear key of the adjacent precast concrete box beam bridge. Based on the field test of the adjacent precast concrete box beam bridge, the relative displacement difference of the shear key was proposed. Then according to the structural style and the load characteristics, the finite strip computational theory was used to simulate the box-beam and the shear key, providing an effective numerical analysis method for the lateral shearing performance of the shear key.

Finite strip method and equation

The adjacent precast concrete box beam bridge is a typical strip structure in the longitudinal direction. It is suitable to use finite strip method [7]. In rectangular coordinate system, the relationship between strain and displacement of the finite strip:

$$\begin{gathered} e_x = \frac{\partial u}{\partial x},\ e_y = \frac{\partial v}{\partial x},\ g_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \\ \mathrm{X}_x = -\frac{\partial^2 w}{\partial x^2},\ \mathrm{X}_y = -\frac{\partial^2 w}{\partial y^2},\ \mathrm{X}_{xy} = 2\frac{\partial^2 w}{\partial x \partial y} \end{gathered} \tag{1}$$

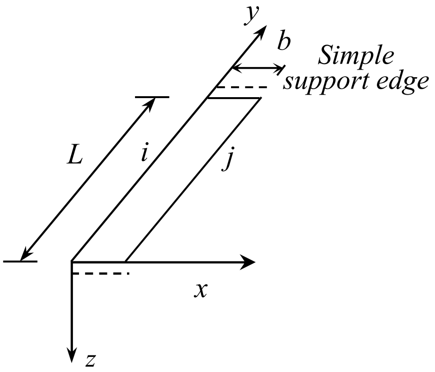

Figure 1 The finite strip element

Finite strip displacement interpolation function (Figure 1):

$$f = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \sum_{m=1}^{r} \begin{Bmatrix} u_m \\ v_m \\ w_m \end{Bmatrix} = \sum_{m=1}^{r} \mathbf{N}_m \boldsymbol{\delta}_m \tag{2}$$

where u_m、 v_m、 w_m are the displacements in the direction of x、 y、 z when the series number is m. $\mathbf{N}_m$ is the function of orthogonal function basement $\left\{\sin\frac{mp}{L}y\right\}$ and $\left\{\cos\frac{mp}{L}y\right\}$, L is the longitudinal length of adjacent precast concrete box beam bridge, and b is the width of strip.

The stiffness matrix of finite strip element is:

$$\begin{aligned} \mathbf{K}_e &= \int_V \mathbf{B}^T \mathbf{D} \mathbf{B} dV = \int_V [\mathbf{B}_1\ \mathbf{B}_2\ \mathbf{L}\ \mathbf{B}_r]^T \mathbf{D} [\mathbf{B}_1\ \mathbf{B}_2\ \mathbf{L}\ \mathbf{B}_r] dV \\ &= \int_V \begin{bmatrix} \mathbf{B}_1^T\mathbf{D}\mathbf{B}_1 & \mathbf{B}_1^T\mathbf{D}\mathbf{B}_2\ \mathbf{L}\ \mathbf{B}_1^T\mathbf{D}\mathbf{B}_r \\ \mathbf{B}_2^T\mathbf{D}\mathbf{B}_1 & \mathbf{B}_2^T\mathbf{D}\mathbf{B}_2\ \mathbf{L}\ \mathbf{B}_2^T\mathbf{D}\mathbf{B}_r \\ \mathbf{L} & \\ \mathbf{B}_r^T\mathbf{D}\mathbf{B}_1 & \mathbf{B}_r^T\mathbf{D}\mathbf{B}_2\ \mathbf{L}\ \mathbf{B}_r^T\mathbf{D}\mathbf{B}_r \end{bmatrix} dV = \begin{bmatrix} \mathbf{K}_{e11} & \mathbf{K}_{e12}\ \mathbf{L}\ \mathbf{K}_{e1r} \\ \mathbf{K}_{e21} & \mathbf{K}_{e22}\ \mathbf{L}\ \mathbf{K}_{e2r} \\ \mathbf{L} & \\ \mathbf{K}_{er1} & \mathbf{K}_{er2}\ \mathbf{L}\ \mathbf{K}_{err} \end{bmatrix} \end{aligned} \tag{3}$$

Where $\mathbf{D}$ is the elasticity matrix. The strain matrix $\mathbf{B}$ can be obtained by substituting Eq. (2) into Eq. (1). Eq. (3) could be changed as

$$\mathbf{K}_{e\,mn} = \int_V \mathbf{B}_m^T \mathbf{D} \mathbf{B}_n dV \tag{4}$$

Accordinmg to the orthogonality of $Y_m = \sin K_m y$ harmonic functions, Eq. (3) could be regarded as principal diagonal block array

$$\mathbf{K}_e = diag[\mathbf{K}_{e11}\quad \mathbf{K}_{e22}\ \mathbf{L}\ \mathbf{K}_{err}] \tag{5}$$

Then the first finite strip governing equation for the item m of the adjacent precast concrete box beam bridge is

$$\mathbf{K}_{mm}\mathbf{U}_m = \mathbf{R}_m \tag{6}$$

Where $\mathbf{K}_{mm} = \sum_e \mathbf{T}^T \mathbf{K}_{e\,mm} \mathbf{T}$, $\mathbf{T}$ is the rotation matrix from the global coordinate system to the local coordinate system. $\mathbf{U}_m$ and $\mathbf{R}_m$ are the full pitch displacement array and quarter line load array for the item m of the adjacent precast concrete box beam bridge, respectively. The displacement array of the adjacent precast concrete box beam bridge can be obtained from serial summation of peak displacement array.

$$\mathbf{U} = \sum_{m=1}^{r} \mathbf{P}_m \mathbf{U}_m \tag{7}$$

$\mathbf{P}_m$ is the displacement interpolation matrix of the item m and it is matrix function of the function of orthogonal function basement $\left\{\sin \frac{mp}{L} y\right\}$ and $\left\{\cos \frac{mp}{L} y\right\}$.

Numerical simulation and real bridge test of the adjacent precast concrete box beam bridge

The test selected one of the spans from a new 3 × 20 m prefabricated prestressed concrete hollow girder bridge of an expressway in Anhui Province. The test bridge has a calculated span of 19.3 m and a bridge width of 13.5 m. It consists of nine intermediate plates and two side plates in transverse direction with a total of ten shear keys, with a box-beam width of 1.17 m and a height of 0.9 m (Figure 2). The girder concrete is C40.

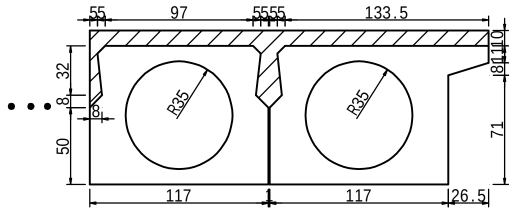

Figure 2 The test bridge hollow plate and hinge size [cm]

The test was carried out using two loading vehicles. The 1# vehicle has a total weight of 30.86t with a 3.36 t single load on the front axle and a 5.96t single load on the middle and rear axle. The 2# vehicle has a total weight of 29.24t with a 3.13t single load on the front axle and a 5.775t single load on the middle and rear axle.

The test was carried out under two load conditions and the corresponding size of the loading vehicles and of the loading position are shown in Figure 3 and Figure 4.

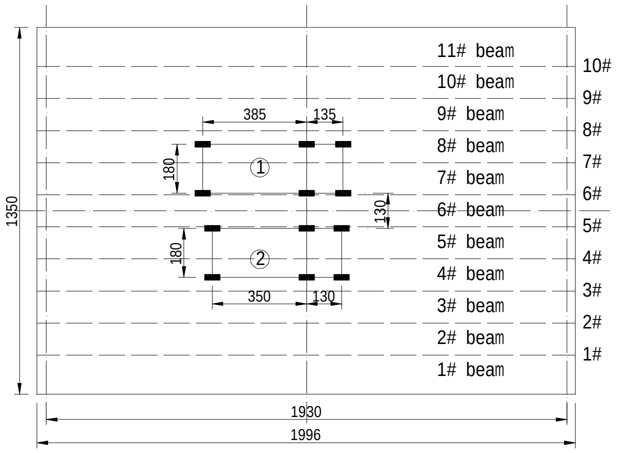

Figure 3 Load conditions 1 [cm]

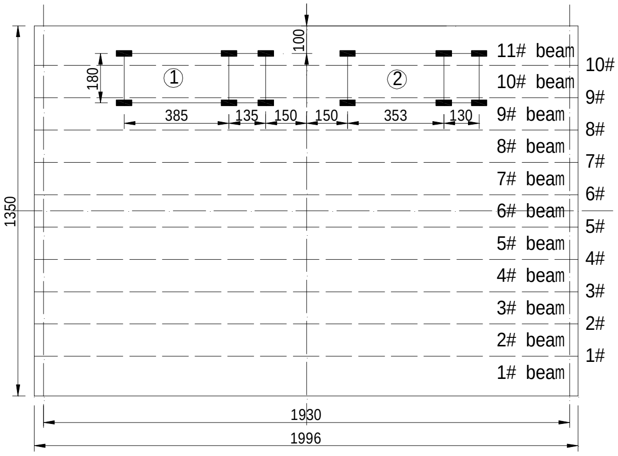

Figure 4 Load conditions 2 [cm]

In this paper, a finite strip calculation program is programmed according to the finite strip governing equation. The adjacent precast concrete box beam bridge is a typical strip structure in the longitudinal direction. According to the geometrical dimensions and material properties of the box-beam and shear keys of the experimental bridge, it is divided into 21 strips horizontally, of which there are 11 box-beams and 10 shear keys.

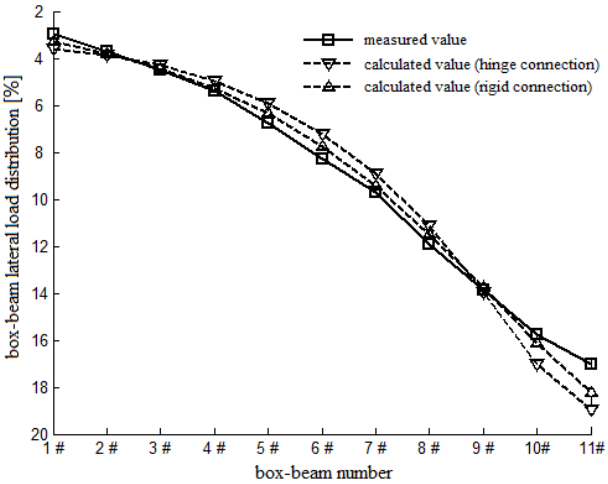

Figure 5 box-beam lateral load distribution comparison

When using beam method to deal with multi-beam bridge, the beam connection (shear keys) can only be simplified into two categories: hinge and rigid connection. Here taking the 2 partial load condition as an example. The horizontal distribution in load test is slightly different from the horizontal distribution coefficient used in the design. Assuming that the deflection of the mid-point of each plate in the crosswise direction is 100% and taking the ratio of deflection for each panel to total deflection as a transverse load distribution, Figure 5 shows the comparison between the calculated values of the transverse load distribution using the space beam lattice model and the measured ones.

It can be seen from Fig. 5 that the lateral distribution coefficient calculated by the space beam lattice model is in good agreement with the measured value, which can reflect the force of the main girder. However, the beam-shaped beam (shear key) has little effect on the transverse distribution of the beam load by the hinged and just-connected beams. The main problem with the Grillage method is that lateral joints (joints) can only be simplified to articulations and joints, making it difficult to consider the joint as a separate unit. Therefore, it is very difficult to directly evaluate the load-bearing capacity of the main girder, and it is also difficult to simulate the local stress in the shear key by the space beam lattice model.

The relative displacement of the shear keys obtained by calculation, the measuring values from bridge load test are shown in Table 1 for comparison. In the table, the relative displacement difference of each hinge is the vertical displacement of the minor board side minus the vertical displacement of the major board side, that is, the relative displacement sign represents the transmission direction of the shear force, and the "+" represents the minor board direction number Large plate delivery while the "-" does the contrary.

Table 1 Bridge 1 hinge relative displacement difference

Load conditions 1						Load conditions 2					
Hinge number	Relative displacement /10^{-3}mm		Hinge number	Relative displacement /10^{-3}mm		Hinge number	Relative displacement /10^{-3}mm		Hinge number	Relative displacement /10^{-3}mm	
	Caculated	Measured		Caculated	Measured		Caculated	Measured		Caculated	Measured
1#	-5	-19	6#	3	5	1#	-5	-7	6#	-9	-20
2#	-6	-15	7#	5	-	2#	-5	-6	7#	-10	-
3#	-6	-28	8#	6	21	3#	-6	-6	8#	-10	-24
4#	-5	-13	9#	6	17	4#	-7	-15	9#	-10	-20
5#	-3	-5	10#	5	20	5#	-8	-12	10#	-11	-20

It can be seen from Table 1 that, the relative displacement difference of shear key calculated by finite strip program is in the order of 10^{-3} ~ 10^{-2} mm. The deformation difference of this order of magnitude can be measured by existing test instruments (dial indicator, dial indicator, etc.) of. The actual bridge load test shows that the magnitude of the measured value is consistent with the calculated value. The finite strip method used in this paper, the shear key as an independent unit, its properties include cross-sectional properties and material properties, therefore, can simulate different shear keys. If the measured value of the relative displacement of the joint is taken as the target value, the damage degree of the joint can be identified by using the optimization method to correct the properties of the joint. The relevant procedure needs further study and preparation. When ANSYS, MIDAS and other commercial finite element software are used to analyze hollow girder bridge by bulk unit, the size of shear key is often too small compared with the main girder, resulting in poor grid division or excessive units, which affects the calculation efficiency. In this paper, the finite strip theory is in good agreement with the strip characteristics of the prefabricated hollow girder bridge. With fewer elements, the transverse shear resistance of box-beam joints can be analyzed and the computational efficiency is high.

Conclusions

In this paper, experimental study and finite strip method were used to analyze the lateral shearing performance of the shear key of The adjacent precast concrete box beam bridge. The field test and numerical calculation results indicate that the relative displacement difference of the shear key can better evaluate the lateral shearing performance of the shear key and accurately distinguish the merits and demerits of the force transmission performance of the shear key. When the relative displacement difference of the shear key is in the order of 10^{-2} mm magnitude, the force transmission performance is fine. If not, the shear key has diseases. Compared with the commercial software which could not be used individually to deal with the shear key, the finite strip computational theory can correctly and effectively analyze the lateral shearing performance of the shear key. The computing theory and the program are correct and reliable, and can be the guidance for the practical engineering.

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