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Theoretical and experimental study on shear lag effect of partially cable-stayed bridge

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Abstract: In order to resolve the traffic congestion problem, many cable-stayed bridges are designed with a large width to span ratio. This results in significant shear lag effect to cause nonuniform stress distribution along the flanges of the beam of bridge. This paper reports study on the shear lag effect of the Lanzhou Xiaoxihu Yellow River Bridge. A 3D finite element model of the bridge was developed and finite element analysis (FEA) was done to obtain the theoretical results. To evaluate the theoretical results, a scaled model was made to conduct static test in laboratory. The experiment results accorded with the results obtained by FEA. It is proved that FEA is an effective method to predict shear lag effect of bridges of this type.

Key words: Cable-stayed bridge, FEA, Experimental, Shear lag effect
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INTRODUCTION

The Lanzhou Xiaoxihu Yellow River Bridge is one of few partially cable-stayed bridges. It is considered a partially cable-stayed bridge because beams are under both axial loads and flexure loads. The cables are arranged in semi-fan configuration in a single plane so that they can be easily anchored to the tower. The cable-stayed portion is a 136 m center span with two 81.2 m side spans. The width of box girder's top flange is 27.5 m, and the bottom flange's width is 15.4 m. The ratio of span to width is about 5. The main beam is a 4 m three-cell box girder fixed to the tower with the height of 17 m.

Since the beam of this bridge is a thin-walled box girder, under both bending and axial loads, stresses do not distribute uniformly along the top and bottom flanges. This phenomenon is called "shear lag". Shear lag effect would become more significant with increase of the ratio of width to span and ratio of width to depth of the cross section. Many studies (Reissner, 1946; Cheng and Luo, 1991; Tesar, 1996; Luo *et al*., 2002; Chang, 2004) were focused on simply supported beams or continuous beams under concentrated and uniform loads. Few studies have been conducted to analyze the shear lag effect on a three-dimensional model of a cable-stayed bridge.

In this project, FEA theoretical analysis and experimental investigation were conducted to study the shear lag effects of the box girder in cable-stayed bridges. The results of the finite element method (FEM) were verified by the physical 3D model under dead load. The construction of the Xiaoxihu Yellow River Bridge in Lanzhou, China, one of Lanzhou's key transportation projects was finished in June 2003. It proved that finite element method can help engineers to better understand the stress condition of cable-stayed bridges.

EXPERIMENTAL SETUP

The scaled bridge model was built in the laboratory by using plexiglass and steel strings. The beam, tower, and piers were made of plexiglass while the cables were made of steel wires. The scale factor S_l of the bridge's main body is 1/40, and the full length of the scaled model is 7.5 m.

The similarity ratio of the strain between the bridge and its model is $S_\varepsilon=1$. The similarity ratio of the modulus of plexiglass to that of concrete is $S_E=1/12$. Hence, the stress similarity ratio is $S_\sigma=S_E=1/12$. For the cables, since the material for the actual structure and experimental model is the same, the stress similarity ratio is 1. The similarity ratio of the cable area is $S_A = S_l^2 S_E$.

The superstructure's own weight and the superimposed dead load were considered in the experimental model. Both loads were simulated by applying sand bags to the model. The similarity equation of linear load intensity was $S_w=S_\sigma S_l$. The prestressing in the steel wires of the experimental model was determined by the equivalent stress conditions. The prestressing was applied simultaneously by hanging weights on all the strings.

STATIC LOAD EXPERIMENTS

Experimental scheme

To study the shear lag effect of the bridge, static experiments were conducted at the structural laboratory of Lanzhou Jiaotong University. In the static experiment, the distributions of the longitudinal and transverse flexural stresses of the main beam were measured to facilitate the evaluation of the shear lag effect of the bridge under dead loads.

Experimental load

Dead loads consist of two parts: dead loads and superimposed dead loads. Dead loads are the permanent loads placed on a structure before the concrete slab hardens and include concrete slab, tower, and cables, etc. Superimposed dead loads are permanent loads placed on the structure after the concrete hardens, and include bridge railing, sidewalks, and wearing surface, etc. No live loads are considered in this experiment. Two loading cases are analyzed: DL1 and DL1+DL2, where DL1 is dead load before the concrete slab hardens and DL2 is the superimposed dead load.

The dead loads (DL1) and the superimposed dead loads (DL2) were simulated by adding sand bags on the experimental model. The weight of the plexiglass itself was also considered in the experiment and analysis. The linear load intensity of the dead load (DL1) of the full-scale bridge is 621.3 kN/m and the superimposed dead load (DL2) is 82 kN/m, which yielded a combined load of 703.3 kN/m. According to the principle of similitude, the similarity ratio of linear total dead load intensity is $S_w=S_\sigma S_l=0.00205$. Therefore, the experimental load of the linear load intensity is 1.44 kN/m.

The average tension stress of the cables of the actual bridge is 828 MPa. Based on the principle of similitude, the tension on the strings is 361.8 N.

Layout of measurement locations

In order to evaluate the critical stresses and shear lag effects along the bridge in the experiment, seven locations were identified and shown in Fig.1. These locations were selected in the vicinity of each tower and the centerline of the bridge. At each of these locations, a total of 18 strain gages were placed at the top and bottom flanges of the box girder. The locations of the strain gages are shown in Fig.2, which represents a typical cross-section of the bridge.

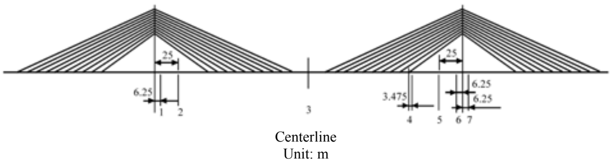

Fig.1 Locations of measurement points

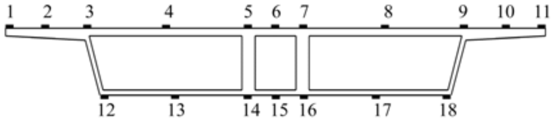

Fig.2 Location of strain gages along cross sections

Finite element analysis

The model creation and analysis were implemented by using commercial FEA software ANSYS, which is one of the most commonly used software in structural engineering. It is capable of performing a 3D static and dynamic analysis as well as various other applications. ANSYS version 7.0 was used since this version can handle prestressing issues.

The bridge is modelled with a combination of beam, shell, and link elements. The box girder is modelled by using both shell (Shell 63) and beam

(Beam 189) elements. Shell 63 is a 4-node element with both bending and membrane capabilities. Both in-plane and normal loads are permitted. The element has 6 degrees of freedom at each node. Beam 189 is based on Timoshenko beam theory. It is a quadratic 3D beam element with six or seven degrees of freedom at each node. In the 3D bridge model, the total number of beams is 152 with 311 joints while total number of shells is 75202 with a total of 71926 joints. The results showed that shell elements are more consistent with the experimental results than beam elements.

As far as the tower is concerned, Beam 44 is adopted since it allows users to define the changing dimensions of the tower. Beam 44 is a uniaxial element with tension, compression, torsion, and bending capabilities. The element has six degrees of freedom at each node.

The cable is modelled using Link 8 element and prestressing is considered in the analysis. Link 8 is a 3D uniaxial tension-compression element with three degrees of freedom at each node. Link 8 can be used to model trusses, sagging cables, links, springs, etc. The static finite element model is shown in Fig.3.

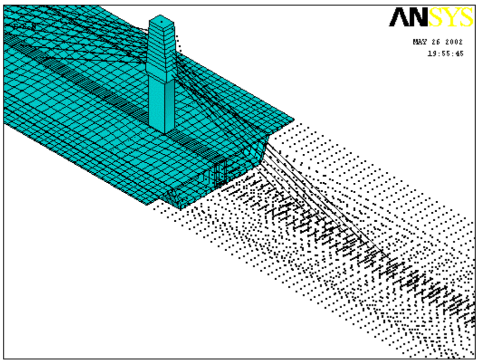

Fig.3 The static FEA model

Comparison of the results between experimental analysis and FEA

Under dead load conditions, the shear lag effects were analyzed in all sections. The most significant locations are at the bottom of the bridge towers. Section 1 and Section 7 are both located near the towers. The maximum shear lag coefficient, the ratio of maximum stress to the average stress, is 1.26, which appeared on the top plate of Section 7. The stress distributions of Section 7 are shown in Fig.4, where, vertical axis represents stress with unit of kPa and horizontal axis is the transverse direction of the bridge cross section. Both experiment and FEA results showed that the shear lag coefficients were larger on the top plates, and smaller on the bottom plates.

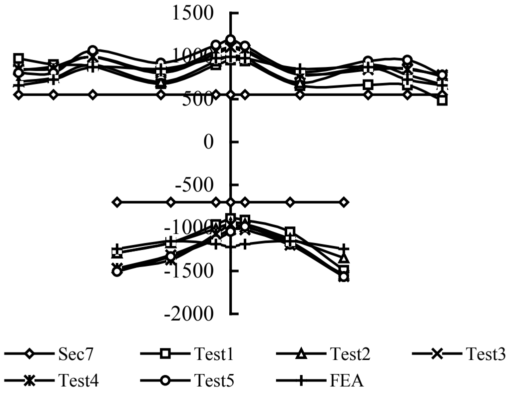

Fig.4 Stress distribution on Section 7

CONCLUSION

In this work, both FEA analysis and experimental tests were conducted to evaluate the shear lag effect of cable-stayed bridges. It is shown that shear lag coefficients vary in different locations along the longitudinal axis of the bridge. The closer to the tower, the more shear lag effects appear. The shear lag results predicted by FEA were consistent with the experimental results under different dead load cases. It was shown that FEA could be an effective method for analyzing the 3D cable-stayed bridges. The finite element analysis proved to be a strong analysis tool for designers of cable-stayed bridges.

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