Journal of Southeast University (English Edition) Vol. 25, No. 3, pp. 372 – 375 Sept. 2009 ISSN 1003—7985

Spatial structural analysis of main saddle for single tower spatial cable self-anchored suspension bridge

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Abstract: Based on the engineering background of the Jiangxinzhou Bridge in Nanjing, issues related to the spatial main saddle of the self-anchored suspension bridge are studied. The refinement finite element model is established by the secondary development technology based on the platform of the general finite element program, and a reasonable load pattern is used in its spatial structural analysis, by which its path of force transference and stress distribution are obtained. Matched with the spatial main cable, the tangency point correction method is also discussed. The results show that the lateral wall stress of the saddle groove is higher than the stress within the wall due to the role of lateral forces in the finished bridge state; the horizontal volume force of the main cable can generate a gradient distributed vertical extrusion pressure on the saddle clamping device and the main saddle body; the geometric nonlinear effect of the self-anchored suspension bridge cable system in the construction process is significant, which can be reflected in the spatial tangent point position of the main cable with the main saddle changes a lot from free cable to finished cable.

Key words: self-anchored suspension bridge; finite element; main saddle; spatial cable; structural design

In recent years, self-anchored suspension bridges have been attracting extreme attention due to their elegant and economic characterstics. In China, self-anchored suspension bridges that have been completed and opened to traffic include Pingsheng Bridge[1], Sancaji Bridge[2] and Wanxin Bridge[3], etc. In addition, some spatial cable system self-anchored suspension bridges have also appeared, such as Yongzhong Bridge[4] in Korea, Tianjing Fuming Bridge[5] in China, etc. The spatial cable system can greatly enhance the lateral rigidity and the horizontal bearing capacity of suspension bridges, without affecting the vertical bearing capacity. But, meanwhile, the spatial cable shape also brings a number of difficulties to the structural design, calculation, analysis, and construction control. Some issues related to the main saddles should be paid attention to, such as the structure design of the main saddle to accommodate spatial cable curves, spatial loading models, spatial structural analyses, and position corrections of the main cable to the spatial main saddle. Regarding background of the Jiangxinzhou Bridge in Nanjing, issues related to the spatial main saddle are studied, which offer references for the structural design and analysis of similar structures.

Received 2008-12-16.

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Foundation items: The National High Technology Research and Development Program of China (863 Program) (No. 2006AA04Z416), the National Science Fund for Distinguished Young Scholars (No. 50725828).

Citation: Li Jianhui, Li Aiqun, Yuan Huihui, et al. Spatial structural analysis of main saddle for single tower spatial cable self-anchored suspension bridge [J]. Journal of Southeast University (English Edition), 2009, 25(3): 372 – 375.

1 Engineering Background

1.1 Bridge descriptions

The Jiangxinzhou Bridge in Nanjing is a single-column-tower and spatial-cable self-anchored suspension bridge, with a span arrangement of (35 + 77 + 60 + 248 + 35) m. The general layout of the Jiangxingzhou self-anchored suspension bridge is shown in Fig. 1.

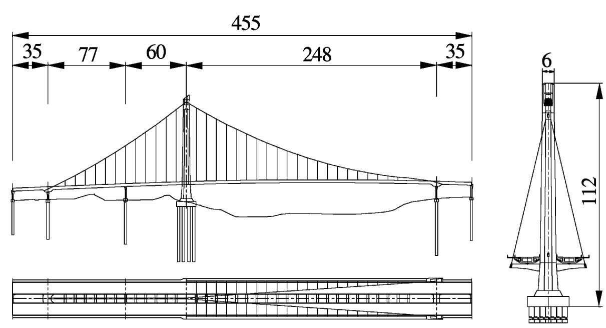

Fig. 1 General layout of the Jiangxingzhou self-anchored suspension bridge (unit: m)

1.2 Structural design of spatial main saddle

Main saddles are important bearing components of suspension bridges to support and fix main cables in order to change their directions smoothly. Its design principle is that the curves of main saddle and cable under finished bridge conditions match each other. As the Jiangxinzhou Bridge has a unique structure, and a relatively complex structural design of the main saddle is used, which has a 7.334° deflecting transition between two saddle slots. The whole structure is in the structural form of rib-delivering-force, with a lateral rib thickness of 60 mm, a longitudinal rib thickness of 250 mm and a saddle slot side thickness of 100 mm. In order to increase the friction between the main cables and the saddle slots, vertical separators are set in the saddle slots. Main cables are positioned into saddle slots stream by stream. After all the cables are positioned and adjusted, the tops are filled with zinc blocks, onto which clamping devices are then installed. The main saddle structure is shown in Fig. 2.

2 Finite Element Analysis

2.1 Load value

2.1.1 Vertical force

According to the motorway suspension bridge design standard (in approval), the centripetal pressure and the pressure intensity of each cable stream are

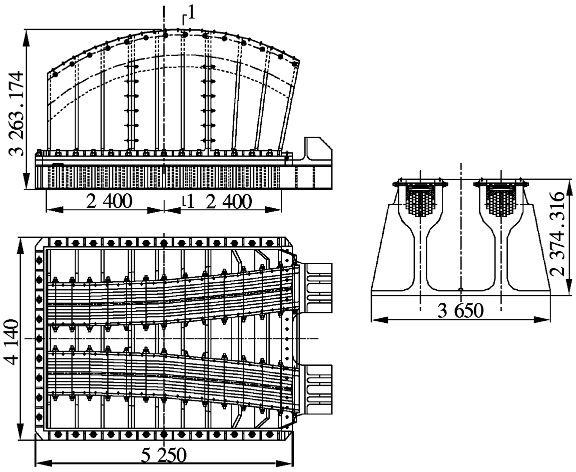

Fig. 2 General layout of the main saddle (unit: mm)

$$f_{sr} = \frac{F_c n}{n_s r_v}, \quad f_{srp} = \frac{f_{sr}}{b} \tag{1}$$

where F_c is the maximum force of a single cable, being the maximum of the side span cable force or the main span cable force; n is the number of streams in one column; n_s is the number of streams of the center column; r_v is the arc radius of the bottom of the slot supporting cables; b is the width of the slot road supporting cables.

2.1.2 Horizontal force

1) The side pressure, produced by the vertical load from the highest top of a cable stream to the calculation height h, is

$$f_h(h) = \frac{f_v b(1 - e^{-(2\mu h)/(3b)})}{2\mu} = 21.595 \times (1 - e^{-0.001\,667h}) \tag{2}$$

$$f_v = \frac{F_c n_{sc}}{r_v n_s b H} \tag{3}$$

where μ is the friction coefficient; f_v is the vertical force per unit volume of center cable streams; n_{sc} is the number of center cable streams; H is the total height of center cable streams.

2) The lateral force of the spatial cable system has not yet been specified definitely in highway suspension bridge design standards (under approval). This paper uses Eq. (4) to calculate the lateral pressure and the pressure intensity affected by the spatial cable system onto the saddle, with reference to calculation of the vertical force.

$$f_{sh} = \frac{F_c n_h}{n_s r_h}, \quad f_{shp} = \frac{f_{sh}}{b_h} \tag{4}$$

where F_c is the maximum force of a single cable pulling force; n_h is the number of cable streams in this line; r_h is the arc radius of the bottom plane of slot supporting cables; and b_h is the vertical width of a single stream.

3) The tie lever force of a saddle slot along unit arc, n_{tra}, can be calculated by

$$n_{tra} = \frac{N_{sb} n_{sb}}{l_{sa}} \tag{5}$$

where N_{sb} is the single tie lever force; n_{sb} is the number of jib levers; and l_{sa} is the side wall arc length of a saddle slot in the center of jib levers.

2.2 Simulation calculation and analysis

The general finite element software, Ansys, is selected for calculation. The elastic block element is used to simulate the main saddle. The elastic modulus of the saddle body $E = 202$ GPa and the Poisson ratio $\mu = 0.3$. Under relative boundary conditions and the most unfavorable combination, spatial finite element analyses and calculations are preformed based on the loading model described in section 2.1.

From the calculation nephogram, it can be found that all the high stresses take place in the places where lateral stiffeners cross longitudinal ones, and the maximum Von Mises stress is 117.8 MPa. Here the saddle material adopts ZG310-570 with a yield strength of 310 MPa and a safety coefficient $K = 2.63$. Since having a symmetrical structure, two half saddle cross sections are selected as typical sections to verify stress distribution status. See Fig. 3 for Von Mises stress distribution map of the typical cross section and Tab. 1 for the label of Von Mises stress distribution map.

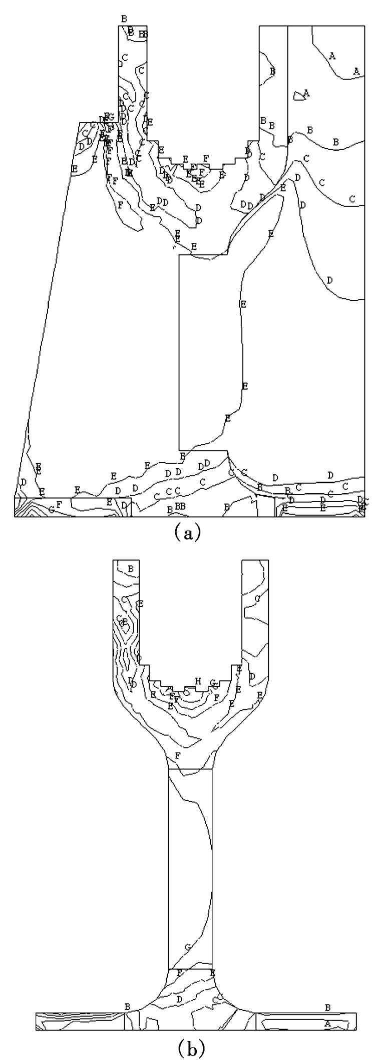

Fig. 3 Von Mises stress distribution map of the typical cross section

Tab. 1 Label for Von Mises stress distribution map MPa

Label	A	B	C	D	E	F	G	H	I
Section 1	5. 75	13. 7	21. 7	29. 6	37. 6	45. 5	53. 5	61. 4	69. 4
Section 2	7. 24	12. 8	18. 4	23. 9	29. 5	35. 1	40. 6	46. 2	51. 7

3 Calculation Method of Spatial Cable

The main saddle which has special geometric features to support the main cable smooth change in the direction is an important bearing component of suspension bridges, so the precise calculation method of spatial cables is also a key issue in main saddle design and analysis. A precise calculation method of spatial curve cables is briefly introduced for single-tower self-anchored suspension bridges. Unlike conventional suspension bridges, for the self-anchored bridges, stiffening girders and the tower can bear huge axial forces under the condition of finished bridge, which results in compression deformation. Therefore, it is necessary to consider accurately the deformation caused by compression. The key point in calculating cable curve is to combine theoretical cable processes with the nonlinear finite elements, then repeatedly iterate and correct the anchoring location of the main cable resulting from compression. The calculation process is as follows:

1) Analyze the initial equilibrium and accurate conditions of the main cable, and output F_i of the cable system into the tower beam finite element program;

2) Put compression Δ_i into the cable program system to update anchoring location coordinates;

3) Re-output F_{i+1}, and stop iterating and correcting if ABS ($F_i - F_{i+1}$) is less than or equal to the tolerance value;

4) Correct the saddle according to geometric compatibility conditions, and output unstressed cable lengths and cable shapes under the state of the finished bridge;

5) Output free cable curve, cable clamp location and pre-displacement of main tower saddle according to conditions of compatible deformation and equilibrium;

6) Output the displacement of the main cable and hangers on the anchoring crossbeam, pre-camber of the main saddle under the state of a free cable.

Based on the above theory and the calculating method, a program is compiled for the calculation of the spatial cable system, as a program package SASB. According to computations for the main cable system of the Jiangxingzhou Bridge, from free cable to finished bridge conditions, the maximum displacements of the main cable are 1. 78 m vertically and 3. 85 m horizontally.

4 Approaches of Correcting Main Saddle Position

It is believed that the theoretical top point should be the intersection of two side main cables' clutch points along the suspended cable line under the basic designed temperature and finished bridge condition, so the calculation of the main cable shape and of the saddle position can be separated[6]. The spatial main saddle is adopted in the Jiangxinzhou Bridge, to which the separate calculation method does not fit very well, so some simplified measures are taken. Using the successful experiences of Ref. [7], in this paper the saddle is simplified as being in one plane (the saddle plane). Because the ratio of the lateral distance to the horizontal distance of the two terminals of a single spatial cable equals that of the lateral force to the horizontal force, after such simplifying, it can be naturally ensured that the main cable plane will be approximately tangent with the saddle in the horizontal plane as long as that in the vertical plane is ensured. The calculation shows that as long as the saddle is set properly, the angle on the tangent point will be very small between the main cable tangent line and the saddle plane, which can meet the accuracy specified in engineering and, at the same time, the plane separate method can be used to project the saddle onto the vertical plane. Based on the above mentioned ideas, tangency points of the saddle position of the Jiangxinzhou Bridge are computed. The results are listed in Tab. 2.

Tab. 2 Tangency points of the main cable with spatial saddle m

Status	Tangent point in side span	Tangent point in main span	Circle center
Free cable	(7 768. 089, 0. 700, 103. 503)	(7 771. 974, 0. 829, 103. 177)	(7 769. 720, 0. 754, 99. 632)
Finished cable	(7 767. 596, 0. 700, 102. 369)	(7 772. 552, 1. 037, 102. 690)	(7 770. 292, 0. 884, 99. 149)

5 Conclusions

Related issues of the spatial main saddle are discussed and analyzed. Some conclusions can be given as follows:

1) The stress in the saddle slot external wall is bigger than that of the inside wall under finished bridge conditions. Different thicknesses of the saddle slot can be considered in saddle structural design.

2) A lateral loading model on the spatial saddle can be adopted by referring to the longitudinal loading model, and a lateral volume force can produce a vertical pressure which has a gradient distribution on the saddle slot, and its contributing model needs to be further studied.

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独柱塔空间缆索自锚式悬索桥主鞍座空间受力分析

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摘要:以南京江心洲大桥为工程背景,对空间缆索自锚式悬索桥主鞍座的相关问题进行研究. 以大型通用有限元程序为平台,采用二次开发技术,建立精细化有限元模型,在此基础上采用合理的加载模式对其进行空间受力分析,并阐述与空间主鞍座相匹配的主缆切点简化修正方法. 结果表明:空间主缆在成桥状态对主鞍座横向力的作用会造成鞍槽外侧壁应力大于内侧壁的应力;主缆横向体积力会对主鞍座压紧装置和鞍体产生梯度分布的竖向挤压力;自锚式悬索桥体系转换过程中缆索的几何非线性效应显著,体现在空缆到成桥状态主缆与主鞍座空间切点位置会有较大的变化.

关键词:自锚式悬索桥;有限元;主鞍座;空间缆索;结构设计

中图分类号:U448. 25;U443. 38