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Analysis of Wind Stability of Cable-stayed Bridge with Single Cable Plane

***Abstract**. Taking Lanqi SongHua River Bridge as an example, this paper has made an analysis of the dynamic character, wind-resistant stability and flutter instability are analyzed, especially the analysis of the flutter stability at maximum double cantilever stage during construction phase. This paper analyzes the dynamic characters of the FE model of the whole bridge through response spectrum method to reap the natural frequency, the vibration modes and other parameters, and then checks the flutter stability. The results show that the bridge is very safe. The analysis method provides bases and references for the wind-resistant of Lanqi SongHua River Bridge.*

***Streszczenie.** W artykule zaprezentowano wykorzystanie metody element skończonego do analizy właściwości dynamicznych mostu wiszącego na rzece Langi SongHua. Analizowano stabilność drgań, naturalną częstotliwość drań, wibracje odporność na porywy wiatru. (**Analiza odporności na wiatr mostu wiszącego na rzece Langi SongHua**)*

Keywords: cable-stayed bridges, dynamic mechanical analysis, stability.
Słowa kluczowe: most wiszący linowy, właściwości dynamiczne

Introduction

The first cable-stayed bridge appeared in 1956, since then, the study of its dynamic performance has been being under the universal concern of the civil engineering field of bridge, which is due to people's attention to the dynamic characteristics and aerodynamic performance of suspension bridge. With an increase in both the number and the span of the cable-stayed bridge, its wind-resistant and seismic stability has drawn more and more attention [1-3].

As to cable-stayed bridge with double cable planes of general arrangements, when the width-span ratio is not too little, the torsional frequency is two times bigger than the vertical bending frequency because of the powerful anti-twists ability provided by the cable. Thus lateral-torsional coupling flutter is hard to come into being, so the flutter modality of cable-stayed bridge with double cable planes is purely torsional flutter and the critical wind velocity is quite big. When it comes to cable-stayed bridge with single plane, its vertical dynamic characteristics are almost the same as that of the cable-stayed bridge with double cable planes. But because the cable no longer provides anti-twists ability, it causes the sharp decrease of torsional frequency which is close to the vertical bending frequency or much smaller. In view of this, the flutter modality is mainly lateral-torsional coupling flutter [4-6].

Lanqi Songhua River Bridge is a concrete cable-stayed bridge with double towers and a single cable plane. The dynamic character, the wind-resistant stability and the flutter instability are analyzed in this paper, especially the analysis of the flutter stability at the maximum double cantilever stage during construction phase.

Project Overview

Lanqi Songhua River Bridge is located in the southeast ring of Jilin orbital highway on Changchun to Hunchun of the National Trunk Highway .The ground of this bridge belongs to II site, the basic earthquake intensity of the situation of this bridge is VII, and the fortification intensity is VIII.

The layout （Figure 1） of the bridge is 102.5m+240m+102.5m, and the total length is 625m.The main bridge is a concrete cable-stayed bridge with double towers and a single cable plane of which the main span is 240m and the side span is 102.5m. The approach bridge is cast-in-situ prestressed concrete box-section continuous beam with a single box and tow rooms and its span is 30m. The main girder is prestressed concrete box girder, and the standard cross section is one box and three rooms structure with the beam height of 2.5m and width of 27.3m. The upper section of the bridge tower is a hollow rectangular cross section and its standard size at longitudinal direction is 4.0m and lateral direction is 7.0m. And the lower section of the bridge tower is solid, which is 2.95m(lateral) and 7.0m (longitudinal). The tower's height over the bridge is 69.91m. The body of main pier is thin-walled box structure, whose breadth is 7.2m (longitudinal) and 17.0m(lateral), the pier's height is 13.98m and wall thickness is 13.98m and 1.2m respectively. The body pier uses C40 concrete.

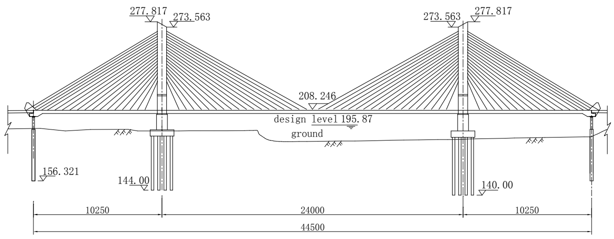


Fig.1. The Layout of Lanqi Songhua River Bridge [cm]

Dynamic Characteristics Calculation

The model analysis of the bridge structure is basis on the structure seismic response analysis, which mainly includes calculation of natural frequency and analysis of main vibration mode [1].

Natural vibration characteristics of bridge structure are important parameters of dynamic characteristics calculation, which mainly include natural frequency、vibration mode、damping ratio and so on. What's more, it reflects the stiffness index of the bridge. Natural vibration characteristics depend on composition system, stiffness index, weight distribution, supporting condition and so on. It has an important meaning for the deeper understanding of response spectrum analysis and seismic time-history response analysis of the bridge. According to Figure 1,we use spatial FE model of the whole bridge to make the model analysis of this long-span cable-stayed bridge, then obtain the vibration mode serial number、frequencies、cycles and vibration mode characteristics at the completion state of the former eight orders, which are particularly shown in table 1, and the former 8 orders vibration shape diagrams are neglected[7-8].

Table 1 Natural frequency at the completion state

Vibration Mode	Frequency （Hz）	Vibration mode characteristics
1	0.25989	Main tower 1 order symmetrical lateral vibration

2	0.30341	Main tower 1 order anti-symmetric lateral vibration
3	0.48981	Main girder 1 order symmetrical vertical bending
4	0.55566	Main girder 1 order anti-symmetric vertical bending
5	0.71182	Main girder 1 order symmetrical lateral bending
6	1.008	Main girder 2 order symmetrical vertical bending
7	1.048	Main girder 2 order anti-symmetric vertical bending
8	1.1107	Main girder 1 order symmetrical torsion

It is generally recognized that about the dynamic characteristics calculation of the conventional cable-stayed bridge, the most concerned 3 vibration modes are as follows: ① anti-symmetric floating vibration mode, ②1 order symmetrical vertical bending vibration mode, ③ 1 order symmetrical torsion vibration mode as the main vibration mode. The first two vibration modes are very important to seismic response; the latter two vibration modes are the main vibration modes about wind vibration, and the first vibration mode is the basic vibration mode to vehicle vibration response. We can see that the natural vibration characteristics of the bridge have the following features due to table 1:

(1) The fundamental frequency of this two-tower cable-stayed bridge with a single plane is 0.25989Hz, the fundamental period is 3.847782s, the stiffness index is relatively larger, so the issues of dynamics in the design of this bridge should be emphasized.

(2) The first and the second vibration modes are the symmetrical and anti-symmetric lateral vibration of the main tower, which contribute most to the lateral seismic response of the tower. The earlier appearance of the two vibration accord with the characteristics of cable-stayed bridge with a single plane.

(3) The cycle of the main girder 1 order symmetrical vertical bending is 2.041608s, which has a huge effect on the seismic response and wind-resistant stability of cable-stayed bridge.

(4) The ratio of the first torsional frequency and the first flexural frequency is 2.268, which is relatively great and advantageous to wind-resistant stability.

The Flutter Stability Analysis

When evaluating the aerodynamic stability of structure, the flutter characteristics and galloping characteristics should be analyzed. Due to the actual situation of the bridge, the aerodynamic stability analysis of structure is mainly about the critical wind velocity and the flutter tested wind velocity, and the galloping doesn't need further research [9-12].

Dynamic Characteristics Calculation

Basic wind velocity

According to << Meteorological Data of Jilin Orbital Highway Lanqi Songhua River Bridge >> and<< Wind-resistant Design Specification for Highway Bridges >> [13]: the basic wind velocity of this area is regarded as $V_{10}=$ 19.525 m/s.

Design basic velocity

The land surface roughness of the bridge site is kind II. According to literature [13], V_d = $K_1 V_{10}$ .The correction coefficient $K_1=$1.04, then $V_d=$20.306m/s. Therefore the Design basic velocity of construction stage is $V_{sd}=$0.84,V_g $=$17.06m/s.

Flutter tested wind velocity

According to literature [8], the flutter tested wind velocity $[V_{cr}]=1.2\mu_f U_d$, the correction coefficient μ_f is 1.31, then $[V_{cr}]=$31.92m/s.

The Flutter Stability Checking Calculation

Calculate different kinds of parameters: $\varepsilon=\omega_t/\omega_b=$2.2676, ω_t is the torsional frequency which is regarded as eighth order; ω_b is the bending frequency which is regarded as third order. $\rho=1.225\text{kg/m}^3$, $\mu=m/(\pi\rho b^2)=75.29$, $r=(I_m/m)^{0.5}=6.31m$, $r/b=6.31/13.65=0.462$

The flutter critical wind velocity of the lateral-torsional coupling is calculated due to VanDerput approximate formula, which is shown below:

$$V_{co}=[1+(\varepsilon-0.5)\sqrt{\left(\frac{r}{b}\right)\times 0.72\mu}]\omega_b b=431.61m/s$$

The separated flow flutter critical wind velocity is calculated due to Herzog formula, which is shown below:

$$V_{co}=T_{h0}^{-1}f_t B$$ where $T_{h0}^{-1}=2.5(\mu r/b)^{0.5}=14.75$, $V_{co}=T_{h0}^{-1}f_t B=447.25m/s$.

After comparison, $V_{co}=$413.61m/s .

The reduction coefficient of interface shape is relative to the flat critical wind velocity $\eta_s=0.62$; the reduction coefficient of wind incidence angle effect $\eta_\alpha=1.0$, therefore the flutter critical wind velocity above the bridge deck

$$V_{cr}=\eta_s\eta_\alpha V_{co}=0.62\times1.0\times413.61=256.44m/s.$$

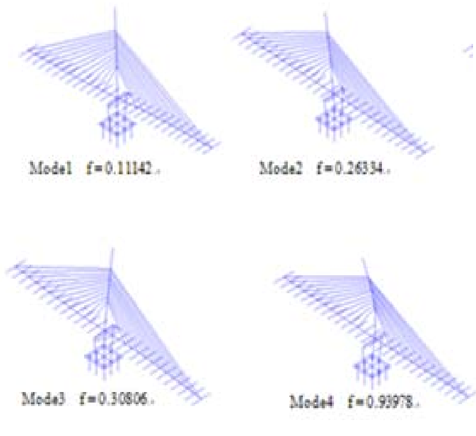
As $[V_{cr}]=31.92m/s\ll V_{cr}=320.19m/s$, the structure is very safe and the wind tunnel test is not needed.

The Flutter Stability Checking Calculation at the Maximum Double Cantilever Stage

The maximum double cantilever stage of the long-span cable-stayed bridge is always the most unfavorable state for the wind-resistant; therefore the stability checking calculation is needed to ensure the security of the bridge.

Dynamic Characteristics Calculation

The former eight—order vibration modes are shown in figure 2,and the natural frequencies、cycles and vibration mode characteristics are shown in table 2.



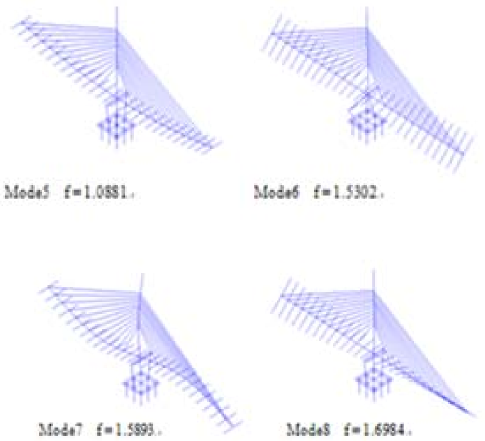


Fig.2 Vibration Mode charts at the maximum double cantilever stage

Table 2 Natural Frequency at the maximum double cantilever stage

Vibration Mode	Frequency（Hz）	Vibration mode characteristics
1	0.11142	Main girder vertical vibration
2	0.26334	Main tower 1 order lateral vibration
3	0.30806	Main tower vertical vibration
4	0.93987	Main tower1 order lateral bending
5	1.0881	Main girder1 order symmetrical vertical bending
6	1.5302	Main girder symmetrical torsion
7	1.5893	Main girder1 order anti-symmetric lateral bending
8	1.6984	Main girder anti-symmetric bending

Stability Checking Calculation

Calculate different kinds of parameters: $\varepsilon = \omega_t / \omega_b = 1.406$ ， ω_t is the torsional frequency which is regarded as the sixth order; ω_b is the bending frequency which is regarded as the fifth order.

The bending-torsional coupling flutter critical wind velocity is calculated due to VanDerput approximate formula, which is shown below:

$$V_{co} = [1 + (\varepsilon - 0.5)\sqrt{\left(\frac{r}{b}\right) \times 0.72\mu}]\omega_b b = 516.44 m/s$$

The separated flow flutter critical wind velocity is calculated due to Herzog formula, which is shown below:

$$V_{co} = T_{h0}^{-1} f_t B = 616.17 m/s .$$

After comparison

$$V_{co} = 516.44 m/s$$

The flutter critical wind velocity on the bridge deck is shown below:

$$V_{cr} = \eta_s \eta_\alpha V_{co} = 0.62 \times 1.0 \times 516.44 = 320.19 m/s$$

And because of $[V_{cr}] = 31.92 m/s \ll V_{cr} = 320.19 m/s$, the bridge is very safe at the maximum double cantilever stage.

Through comparison of the flutter stability checking calculation both at the maximum double cantilever stage and the completion state, it can be drawn that the critical wind velocity at the maximum double cantilever stage is higher than that at completion state. But because both of them are much higher than the flutter tested wind speed, the bridge is very safe both at construction state and completion state.

Conclusions

(1) By the analysis and research of the flutter stability in the completion state and the maximum double cantilever stage, we can see that the maximum double cantilever stage is the control state of the construction of cable-stayed bridge, which should be given adequate attention.

(2) The flutter analysis results indicate that as long as the flutter tested wind speed $[V_{cr}]$ is smaller than the critical wind velocity V_{cr} no matter it`s in the completion state or in the maximum double cantilever stage, the cable-stayed bridge can meet the requirements of the flutter stability and doesn’t need Wind Tunnel Test. Furthermore, the smaller the $[V_{cr}]$ is than V_{cr} , the more surplus、enough wind-resistant and flutter stability it has.

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