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Experimental Study on Flutter Performance of a 1700m Long Truss Girder Suspension Bridge

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ABSTRACT

Yang-Si-Gang Yangtze River Bridge of China is in detailed design stage, it is a steel truss girder suspension bridge with double highway decks, and the span is up to 1700m. Wind tunnel testing was conducted to study the wind resistance performance of the bridge, and a phenomenon called low-speed flutter or “soft” flutter was observed during section model tests. Comparing with classic flutter, there is no obvious divergence point in “soft” flutter, and the vibration amplitude increases slowly with the increase of wind speed, which is also harmful to the structural safety. To improve the flutter stability, varieties of countermeasures were tested, and some effective measures were found.

1. INTRODUCTION

As for the advantage in stiffness and crossing ability of steel truss girder, a number of world famous truss girder long span suspension bridges have been constructed widely. George Washington Bridge which was completed in 1931 and reformed in 1962 became the first double-deck highway bridge with main span over 1000m in that time. In 1937, the Golden Gate Bridge was once the world's largest suspension bridge. Afterwards in 1964 another double-deck truss girder suspension bridge named Verrazano Narrows Bridge (1298.5m-long) was completed and it still plays a great impact in the world today. In 1940, the bridge engineering community was greatly shocked by the wind-induced destroyed event of Tacoma Narrow Bridge, which fundamentally changed the design concept of long span bridges (Farquharson 1949). For the safety of wind resistant structure, the Golden Gate Bridge was strengthened in 1950, and the flutter critical wind speed of the bridge was increased. In 1960, in the design of lower deck of George Washington Bridge and the construction of Verrazano Narrows Bridge, the wind load and wind-induced vibration were one of main concerns and investigated in detail, which provided the basis for the wind resistant design of those structures. In 1970's and the beginning of this century, a large number of vibration monitoring in site was carried out on the Golden Gate Bridge and Verrazano Narrows Bridge for evaluating their comfortability. In 1998, the longest steel truss-stiffened suspension bridge (Akashi Kaikyo Bridge) with the span of 1991m was completed in Japan. In order to ensure the wind resistance safety and serviceability of the bridge, an extreme large boundary layer wind tunnel (width: 41m, height: 4m, length: 30m) was built to study the wind loading and wind-induced vibration in detail (Miyata 1992). And its flutter performance of truss girder was improved by using vertical and horizontal stabilizers (Miyata 1993).

Yang-Si-Gang Yangtze River Bridge which is in detailed design stage is located in Wuhan, Hubei Province of China. It is a double-deck truss girder suspension bridge with a span of 1700m. After competition it will become the second longest suspension bridge in the world (see Table.1). In addition to the larger span, the aerodynamic interference exists between the upper and the lower decks. Compared with highway and railway double-deck truss bridge, the lighter mass, weaker stiffness and lower damping make the structure sensitive to the effects of wind. With the action of wind, large deformation may be caused, and the problem such as flutter and aerostatic instability may affect the structural safety. Besides, vortex-induced vibration (VIV) and buffeting may affect the comfort of users (Simiu 1986). Therefore, the wind resistance performance of the bridge must be investigated, although the design wind speed of bridge is not very high. A series of wind tunnel tests were conducted at Research Center for Wind Engineering of Southwest Jiaotong University. The section model tests for flutter performance are mainly discussed in this paper.

Table 1 The Ranking of suspension bridge in the world

Ranking	Name	Country	Completion Year	Man Span (m)	Girder
1	Akashi Kaikyo Bridge	Japan	1994	1991	Truss
2	Yang-Si-Gang Yangtze River Bridge	China	——	1700	Truss
3	Nizhou Channel Bridge (The 2nd Humen Bridge)	China	——	1688	Box
4	Xi Hou Men Bridge	China	2009	1650	Box
5	Great Belt Bridge	Denmark	1998	1624	Box
6	İzmit Bay Bridge	Turkey	——	1550	Box
7	Yi Sun-Sin Bridge	Korea	2012	1545	Box
8	Run-Yang Yangtze River Bridge	China	2005	1490	Box
9	The 2nd Dongting Lake Bridge	China	——	1480	Truss
10	The 4th Nanjing Yangtze River Bridge	China	2012	1418	Box

2. ENGINEERING BACKGROUND

The mentioned bridge is a single span truss-stiffened suspension bridge with double highway decks. The span of this bridge is 1700m, and the higher tower is 244.0m high. The truss girder is 28.0m wide, 10m high. Fig.1 and Fig. 2 give the details of the bridge. The design wind speed is 32.6m/s, and the flutter checking wind speed is 47.7m/s.

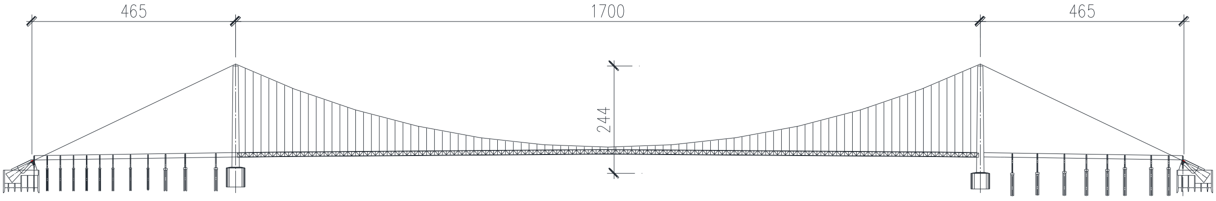

Fig.1 The layout of bridge (Unit: m)

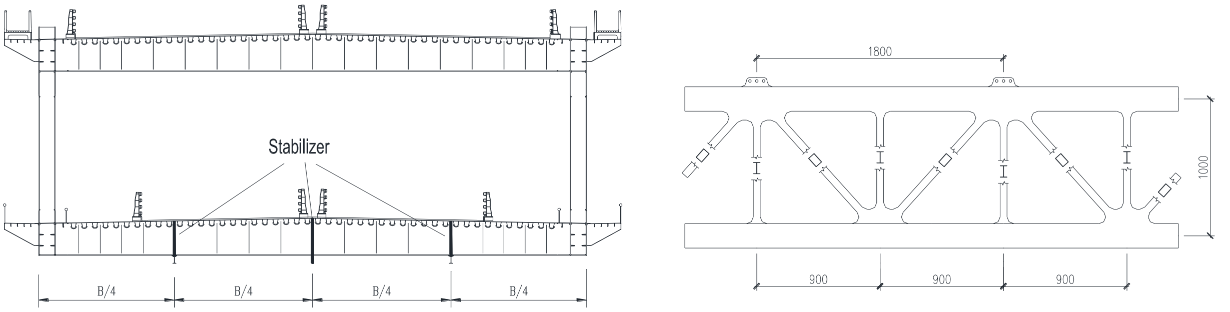

Fig.2 General view of the trussed girder (Unit: m)

3. THE SECTION MODEL TESTS

The wind tunnel (Type: XNJD-1) of Southwest Jiaotong University, a closed circuit wind tunnel with two tandem closed test sections, was used to carry out the investigation. The dimension of the test section is 2.4m×2.0m×16.0m (W×H×L), with wind velocity 0.5~45.0m/s (turbulent intensity<0.5%). A test set-up, which was specially designed to carry out dynamic test of bridge deck section and mounted on the outside walls of wind tunnel, was used in the testing. The model was suspended by 4 pairs of linear springs and could vibrate vertically and torsionally only. Fig. 3 shows that the section model was set in wind tunnel.

A geometric scale 1:52.67 was chosen to design and manufacture the section model. The length of the model (L) is 2.095m, the width (B) is 0.532m and the depth (H) is 0.190m. The model frame consists of wooden plates on both sides and four aluminum beams, and the remaining parts of model were carved by plastic according to design drawings (see Fig.4). In addition to keep the similarity of geometric shape, the section model is required to assure the similarity of mass, stiffness, and damping of structure, etc. These physical properties can be usually summarized into four dimensionless quantities: Reynolds number, Froude number, Cauchy number and critical damping ratio. Similar to the most wind tunnel tests, it is impracticable for this assignment to satisfy Reynolds number similitude. As vortex-induced resonance may occur at very low wind speed for this model scale, stiff similitude is usually replaced by Strouhal number in the modeling to increase the onset wind speed of VIV, which should be compatible with the stable operating wind speed of wind tunnel. The other three parameters have to be employed for section modeling. Those parameters can be expressed as:

Elastic parameter: $\frac{U}{f_h B}$ $\frac{U}{f_\alpha B}$ Mass parameter: $\frac{m}{\rho B^2}$ $\frac{I_m}{\rho B^4}$ Structural damping: ζ_h ζ_α

where, *U* is the wind speed; *B* is the width of bridge deck; f_h and f_a are vertical and torsional frequency respectively; *m* and I_m are mass and mass moment of inertia per unit length respectively; ζ_h and ζ_a are damping ratios (DA) of structures. The design parameters of the model representing the bridge are given in Table 2.

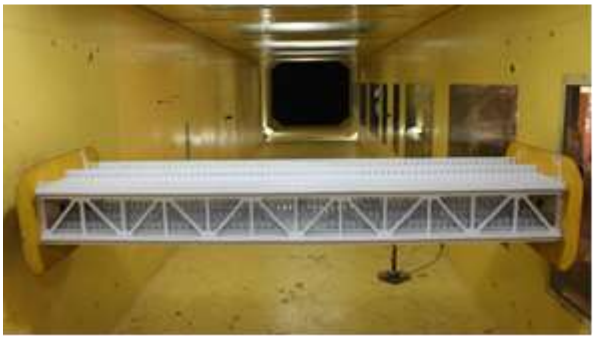

Fig. 3 Section model in XNJD-1 wind tunnel

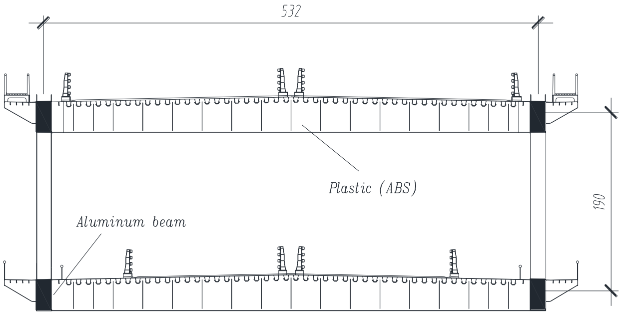

Fig. 4 The sketch of section model

Table 2 Parameters of the section model wind tunnel tests

Property	Unit	Scale	Prototype	Model needed	Model reached
H	m	1/52.67	10	0.190	0.190
B	m	1/52.67	28	0.532	0.532
m	kg/m	$1/52.67^2$	53072	19.130	19.141
I_m	kg·m^2/m	$1/52.67^4$	7465823	0.970	0.979
r	m	1/52.67	11.86	0.225	0.224
f_h	*Hz*	——	0.1168	——	1.695
ζ_h	%	1	0.50	0.50	0.38
f_α	*Hz*	——	0.2831	——	4.095
ζ_α	%	1	0.50	0.50	0.37
ε	—	1	2.423	2.423	2.392

4. TEST RESULTS

The objectives of the tests are to assess the flutter instability of the bridge by measuring the flutter critical wind speed directly, and mitigation countermeasure should be proposed if necessary. The section model was tested under three attack angles 0°, +3°, -3° in smooth oncoming flow, and the test was also conducted in a higher damping level (0.52%), which is proposed by Chinese Code.

In the test, a phenomenon called low-speed flutter or “soft” flutter was observed during section model tests. Comparing with classic flutter, there is no obvious divergence point in “soft” flutter, and the vibration amplitude increases slowly with the increase of wind speed. The torsional movement plays a dominant role in the vibration process. According to Chinese code, for the flutter phenomena that there is no obvious amplitude divergence point, the wind speed will be selected as the flutter critical wind speed when the torsional vibration amplitude (RMS) reaches 0.5°. Table 3 shows the testing results of the flutter critical wind speed at different attack angles. The flutter critical wind speed at +3° is only 32.8m/s, and is much lower than the flutter checking wind speed. It's also found that the amplitude is affected by the test system damping ratio for torsional dominated flutter (see Fig.5), and with the increase of damping ratio the critical wind speed will increase.

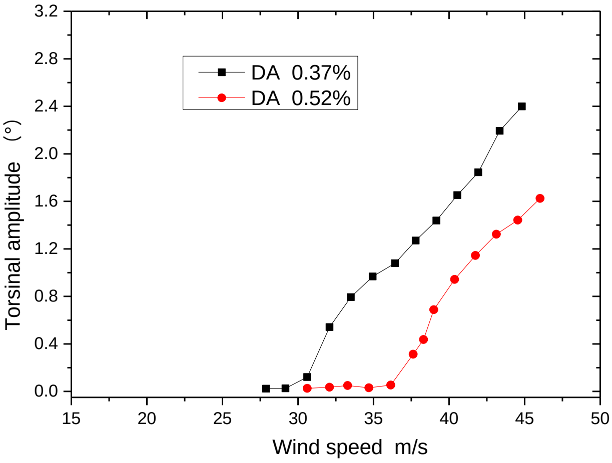

Fig. 5 The flutter amplitude at different damping ratio (+3°)

Table 3 Flutter critical wind speed at different angles

Attack angle (°)	U_{cr} (m/s)		$[U_{cr}]$ (m/s)
	Original girder	Measure	
-3	>60.0	>61.2	47.7
0	40.8	49.6	
+3	32.8/37.7 (DA: 0.52%)	44.2/49.6 (DA: 0.52%)	

Although the amplitude of the girder did not diverge suddenly according to the sectional model test result, it should be noted that the flutter critical wind speed of the bridge is quite low. Hence the mitigation countermeasures are definitely required to improve flutter instability of the bridge.

A variety of measures to increase the critical wind speed of flutter of bridge were tested in wind tunnels, including installing a vertical stabilizer in the center of the upper and lower decks, mounting horizontal winglets on both sides, as well as hanging vertical stabilizers under the lower deck. Some of these measures are effective for flutter stability. The reasonable and effective measure is to install three vertical stabilizers under the lower deck as shown in Fig.6. The flutter critical wind speed at lower damping is 44.2m/s, and in higher damping level the critical wind speed can reach to 49.6m/s (Table 3).

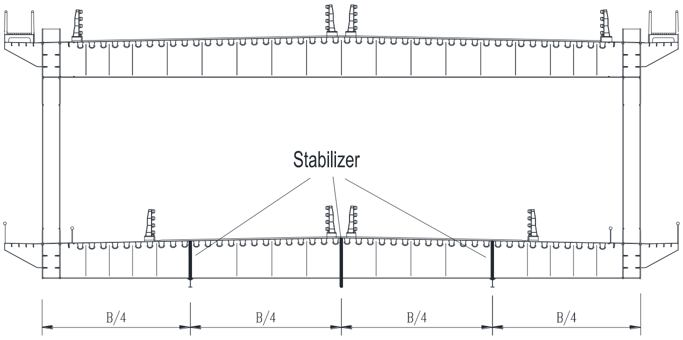

Fig. 6 The arrangement of mitigation countermeasure

5 CONCLUSIONS

The section model wind tunnel tests of the 1700m truss girder suspension bridge were conducted to verify the flutter stability and VIV performance, and several effective mitigation countermeasures were proposed based on current research. To install three vertical stabilizers under the lower deck is a relatively reasonable countermeasure. The truss girder of the long span bridge is in the design stage, the optimal mitigation measures for improving the aerodynamic stability of the bridge should be determined by section model tests and full bridge aeroelastic model tests. Besides, it is necessary to coordinate with several relevant departments, including the clients, designer, constructor, as well as the land and waterway transportation etc.

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