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BLUFF BODY AERODYNAMICS APPLICATION IN CHALLENGING BRIDGE SPAN LENGTH

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1 INTRODUCTION

With the rapid increase of bridge span length, bridge structures are becoming more flexible, which requires bluff body aerodynamics studies related to bridge deck flutter instability and vortex induced vibration, as well as stay cable vibration. Aerodynamic stabilization of several suspension bridges recently built in China is introduced hereafter, and followed by aerodynamic feasibility study of a 5000m-span suspension bridge. Since cable-stayed bridges intrinsically have quite good aerodynamic stability against flutter oscillation, rain-wind induced vibration and mitigation are discussed as a main concern in most long-span cable-stayed bridges. Compared to suspension bridges and cable-stayed bridges, the arch bridge has relatively shorter span, but higher stiffness so that long-span arch bridges may not have wind-induced problem except for Shanghai Lupu Bridge that suffers vortex-induced vibration.

2 AERODYNAMIC STABILIZATION OF SUSPENSION BRIDGES

Ten longest-span suspension bridges in the world are listed in Table 1, which provides not only general figures about span, year of completion and location, but also specific information related to wind resistance performance. The top four suspension bridges suffered wind-induced problems, and some control measures have been adopted in practice.

Span Order	Bridge Name	Main Span	Girder Type	Wind-Induced Problem	Control Measure	Country	Year Built
1	Akashi Kaikyo	1991m	Truss	Flutter	Slot/Stabilizer	Japan	1998
2	Zhejiang Xihoumen	1650m	Box	Flutter	Slot	China	2008
3	Great Belt	1624m	Box	Vortex	Guide vane	Denmark	1998
4	Jiangsu Runyang	1490m	Box	Flutter	Stabilizer	China	2005
5	Humber	1410m	Box	None	None	U.K.	1981
6	Jiangsu Jiangyin	1385m	Box	None	None	China	1999
7	Hong Kong Tsing Ma	1377m	Box	Flutter	Slot	China	1997
8	Verrazano	1298m	Truss	None	None	U.S.A.	1964
9	Golden Gate	1280m	Truss	None	None	U.S.A.	1937
10	Hubei Yangluo	1280m	Box	None	None	China	2007

Table 1: Ten longest span suspension bridges in the world

2.1 Central Stabilizer

Among the top four suspension bridges, Jiangsu Runyang Bridge was designed as a typical three-span suspension bridge with span arrangement of 510m + 1490m + 510m and a traditional closed steel box, 36.3m wide and 3m deep. It was found in the first phase of the sectional model testing that the original structure could not meet the requirement of flutter speed of 54m/s. With a stabilizer on the central deck, further sectional model testing was conducted, and the confirmation wind tunnel tests with the full aeroelastic model were also performed. Both experimental results show good agreement with each other and the central stabilizer of 0.88 m height in Figure 1 can raise the critical flutter speed over the required value [1].

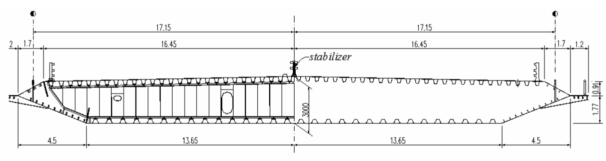


Figure 1: Jiangsu Runyang Bridge (Unit: m)

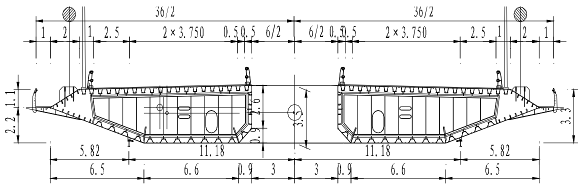


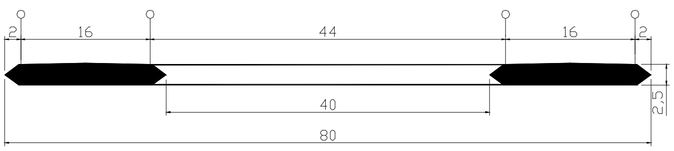
Figure 2: Zhejiang Xihoumen Bridge (Unit: m)

2.2 Twin Box Girder

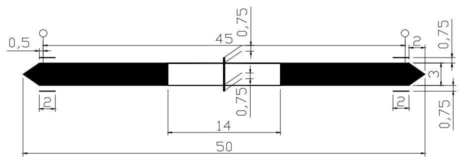
Zhejiang Xihoumen Bridge is designed as a two-span suspended suspension bridge with the main span of 1650m. Based on the experience gained from the 1490 m Runyang Bridge with flutter speed of 51 m/s and the 1624 m Great Belt Bridge with 65 m/s flutter speed, Xihoumen Bridge may cause problems of aerodynamic instability for suspension bridges, even with the stricter stability requirement of 78.4 m/s. Four alternative configurations of box girders were proposed and were investigated through wind tunnel tests. Apart from the traditional single box, the other three deck sections, including the single box with a central stabilizer of 2.2m and the twin box decks with a central slot of 6 m or 10.6 m, can satisfy the flutter stability requirement, and the 6 m slotted twin-box girder in Figure 2 was adopted [2].

2.3 Stabilization for Super-Long Span

With the emphasis on aerodynamic stabilization for longer span length, a typical three-span suspension bridge with a 5,000m central span and two 1,600m side spans is considered as the limitation of span length with the consideration of aerodynamic challenges. In order to push up the aerodynamic stability limit, two kinds of generic deck sections, namely a widely slotted deck (WS) (Figure 3a) and a narrowly slotted deck with vertical and horizontal stabilizers (NS) (Figure 3b), were investigated [3]. The minimum critical wind speeds for the WS and NS sections are numerically determined to be 82.9 m/s and 74.7 m/s, respectively [4].



(a) WS Cross section



(b) NS Cross section

Figure 3: Geometry of deck sections of WS and NS (Unit: m)

3 RAIN-WIND INDUCED VIBRATION OF STAY CABLES

Table 2 lists ten longest-span cable-stayed bridges in the world. Except for the Fujian Qingzhou Bridge, almost all other cable-stayed bridges listed in Table 2 suffered stay cable vibration induced by wind and rain condition, and adopted control measures, including dimples or spiral wires on cable surface, and mechanical dampers at the low ends of cables.

Span Order	Bridge Name	Main Span	Girder Type	Wind-Induced Problem	Control Measure	Country	Year Built
1	Jiangsu Sutong	1088m	Box	Stay cables	Dimples	China	2008
2	Tatara	890m	Box	Stay cables	Dimples	Japan	1999
3	Normandy	856m	Box	Stay cables	Spiral-wires	France	1995
4	3rd Jiangsu Nanjing	648m	Box	Stay cables	Dimples	China	2005
5	2nd Jiangsu Nanjing	628m	Box	Stay cables	Spiral-wires	China	2001
6	Zhejiang Jintang	620m	Box	Stay cables	Spiral-wires	China	2008
7	Hubei Baishazhou	618m	Box	Stay cables	Dimples	China	2000
8	Fujian Qingzhou	605m	Πgirder	Flutter	Guide vane	China	2003
9	Shanghai Yangpu	602m	Πgirder	Stay cables	Damper	China	1993
10	Shanghai Xupu	590m	Box	None	Damper	China	1997

Table 2: Ten longest span cable-stayed bridges in the world

The wind tunnel testing of prototype cable sections was carried out in dry-wind and rain-wind situations, as for example in Sutong Bridge with the outer diameters of 139mm (the most popular cables) and 158mm (the largest cables). As a result, cable vibration is much more severe under the rain-wind condition than under the dry-wind condition for both cable sections, and the maximum amplitudes of these two cables exceed the allowable value of length/1700. It can be concluded that the most unfavourable condition is under the inclined angle of $\alpha = 30°$ and the yaw angle of $\beta = 35°$ with the wind speed of about 7m/s to 11m/s, but the rain-wind induced cable vibration can be effectively controlled with a damping ratio up to 0.30% [5]. The other effective way to ease rain-wind vibration is to prevent cable surface from forming rivulets, which are known as the main effect to generate cable vibration. Two kinds of aerodynamic countermeasures including spiral wires and dimples against rivulets on cable surface were tested and were proven to be sufficient to reduce vibration amplitude to comply with the requirement [5].

4 VORTEX-SHEDDING VIBRATION IN ARCH BRIDGES

Ten longest-span arch bridges in the world are shown in Table 3, and only one of them, namely Shanghai Lupu Bridge, suffered wind-induced vibration problem, vortex-shedding oscillation due to bluff cross sections of arch ribs.

Span Order	Bridge Name	Main Span	Girder Type	Wind-Induced Problem	Control Measure	Country	Year Built
1	Ch.Q. Caotianmen	552m	Truss	None	None	China	2008
2	Shanghai Lupu	550m	Box	Vortex	Cover plate	China	2003
3	New River Gorge	518m	Truss	None	None	USA	1977
4	Bayonne	504m	Truss	None	None	USA	1931
5	Sydney Harbor	503m	Truss	None	None	Australia	1932
6	Sichuan Wushan	460m	Tube	None	None	China	2005
7	G.D. Xinguang	428m	Truss	None	None	China	2008
8	Sichuan Wanxian	420m	Box	None	None	China	2001
9	Chongqin Caiyuanba	420m	Box	None	None	China	2008
10	4th Hunan Xiantan	400m	Tube	None	None	China	2007

Table 3: Ten longest span arch bridges in the world

Shanghai Lupu Bridge over Huangpu River is a half-through arch bridge with two side spans of 100m and the central span of 550m, the longest span of arch bridges in the world. The two inclined arch ribs are 100m high from the bottom to the crown, and each has the cross section of a modified rectangular steel box with 5m width and depth of 6m at the crown and 9m at the rib bases as shown in Figure 4, a configuration for which vortex-induced vibration could occur in vertical and lateral bending modes of arch ribs.

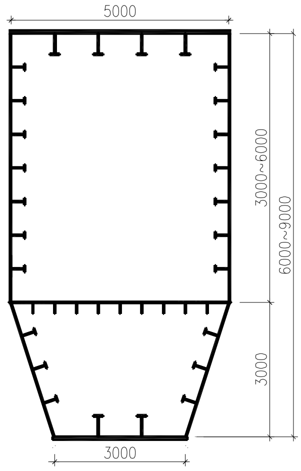


Figure 4: Lupu Bridge (Unit: mm)

With the CFD method developed in Tongji University, it was found that severe VIV happens with the amplitude of 0.028H (rib depth) at the Strouhal number (reduced frequency) St = 0.156 and the best solution among proposed seven control measures is the scheme of the full cover plate, which can reduce the amplitude to only about 40% of that in the original configuration [6]. The numerical results were confirmed by 1:100 aeroelastic full bridge model testing with or without preventive measures under different angles of attack and different yaw angles. Two schemes of aerodynamic preventive measures were experimentally investigated, including the full cover plate between two arch ribs (scheme A) and the partial cover plate with 30% air vent (scheme B). It can be concluded that scheme A or B effectively makes it possible to reduce VIV amplitudes effectively [7].

5 CONCLUSIONS AND PROSPECTS

- The intrinsic limit of span length due to aerodynamic stability is about 1,500m for a traditional suspension bridge. Beyond or even approaching this limit, designers should be prepared to improve aerodynamic stability of a bridge by adopting some countermeasures for girder, including stabilizer and slotted deck.
- Long-span cable-stayed bridges with spatial cable plane and steel box girder have high enough critical flutter speed and the main aerodynamic concern is rain-wind induced vibration of long stay cables. It seems that there is still room to enlarge main span length of cable-stayed bridges in the aspect of aerodynamic stability.
- Based on the evidence that only one out of ten longest-span arch bridges suffered in vortex-induced problem, the enlargement of span length of arch bridges should not be influenced by aerodynamic requirement.

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