Aerodynamic stabilisation for super long-span suspension bridges

Aerodynamic Stabilisation for Super Long-Span Suspension Bridges

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Summary

As the post projects of the Akashi-Kaikyo Bridge, some new projects have been planned to cross straits in Japan by the application of super-long-span suspension bridges. Their center spans will be far above 2000m and a streamlined box deck is thought to be proper for its economy.
In this paper the aerodynamic stabilization of the suspension bridges with streamlined box deck is discussed and it is realized by using the configurations of so called flat box deck (i.e. shallow box deck) with vertical and horizontal stabilizers. The assessment is conducted by the wind tunnel tests and the three dimensional multi-mode flutter analysis. The vertical stabilizer is installed in the center slot of the deck and the horizontal stabilizers are also attached on both upper, lower of leading and rear edges of the deck. Then the deck is aerodynamically stable up to the proposed design wind speed at the deck height (i.e.,80m/s).

1. Introduction

Generally speaking bridge decks are classified into two types; truss and streamlined box ones. Since the well known collapse of the Original Tacoma Narrows Bridge in 1940, the truss decks have been applied to almost suspension bridges mainly in the United States and Japan. On the contrary, the streamlined box decks have been prevailed in England and so on. In Japan these two choices have been assessed in feasible studies in almost cases executing wind tunnel tests. Akashi-Kaikyo Bridge was determined to have the truss deck with a vertical-stabilizer installed at the center of the deck in the center span. Thus the bridge is stable in Akashi-Straits where the locations are susceptible to typhoon winds and the design wind speed (i.e.,V_{10}=43m/s) is relatively higher in Japan. The application of a streamlined box deck was also examined however an appropriate one could not be found to reach the design speed without any aeronautical problems (e.g., flutter, buffeting and vortex induced vibrations).

For the post Akashi-Kaikyo Bridge project, super-long-span suspension bridges are being proposed and their center span will be longer than about 2,250m. The application of streamlined box decks is predominant to these projects for their economy: the labor cost of workers and the financial condition of the government compel this choice.

This paper presents the aerodynamic stabilization for super-long-span suspension bridges by using vertical and horizontal stabilizers. The research was carried out by the wind tunnel experiments and the multi-mode flutter analysis.

2. Application of Stabilizers

A vertical stabilizer (i.e., V.S.) is the effective device to enhance the flutter speed. Therefore Akashi-Kaikyo Bridge has installed it in the center span as shown in Fig.1. The stabilizing mechanism of the vertical stabilizer for the truss deck is as follows[1]:

1) According to the flow visualization and the pressure distribution measurement around the deck at rest, the separated flow at the leading edge of the deck re-separates at the bottom edge of the V.S. and the upward flow is increased by the existence of the V.S. As a result of them, the negative pressure becomes large at the deck in the downstream. The pressure recovery is also observed at the trailing edge of the top surface of the deck in the

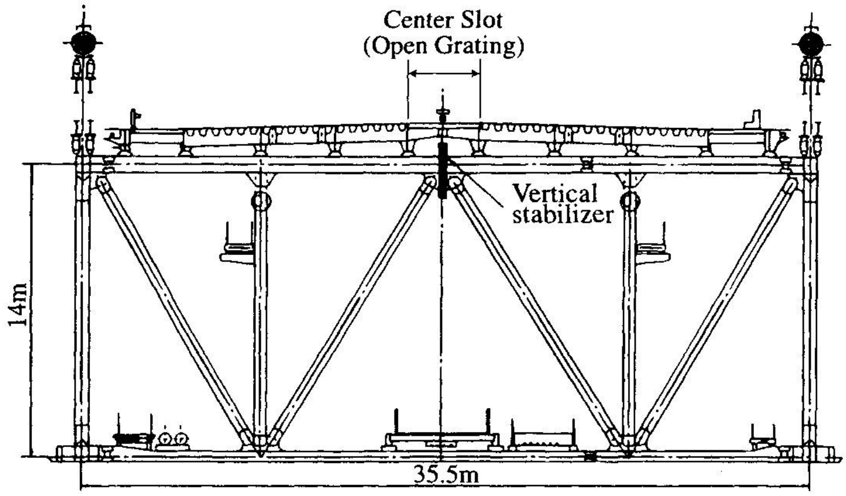

Fig. 1 The Vertical Stabilizer of the Akashi-Kaikyo Bridge in the center span

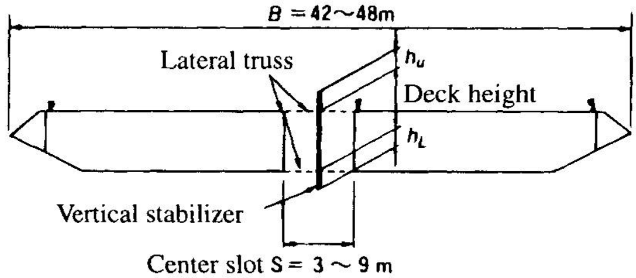

Fig. 2 Investigeted flat box girder

downstream. These phenomena become the stronger as the angle of attack becomes the larger. The absolute values of the lift coefficient with the V.S. become smaller than those without the V.S.

2) According to the flow visualization and the pressure distribution measurement around the deck in motion, the flow under the deck re-separates at the bottom edge of the V.S. and the upward flow is increased in the center slot at the middle of the deck. Then the damping force is created at the bottom surface in the downstream.
3) It is emphasized that the center slot in the middle of the deck plays the significant role for the improvement of the aerodynamic stability.

The authors proposed the application of the V.S. for a tapered box deck [2]. The center slot was made in the middle of the deck and the V.S. and lateral truss were installed there. The lateral truss retains the torsional rigidity of the deck (Fig.2). This method has been extended for the aerodynamic stabilization of the proposed super-long-span suspension bridge in this study.

3. Aerodynamic Stabilization

3.1 Objected Models

The proposed super-long-span suspension bridges namely the objects of this study are shown in Fig.3. The dynamic properties of the objected suspension bridges are shown in Table 1 and they were used for the section model tests.

3.2 Test Results

As the preliminary tests, deck height of 3, 5 and 7m were examined with changing a center slot

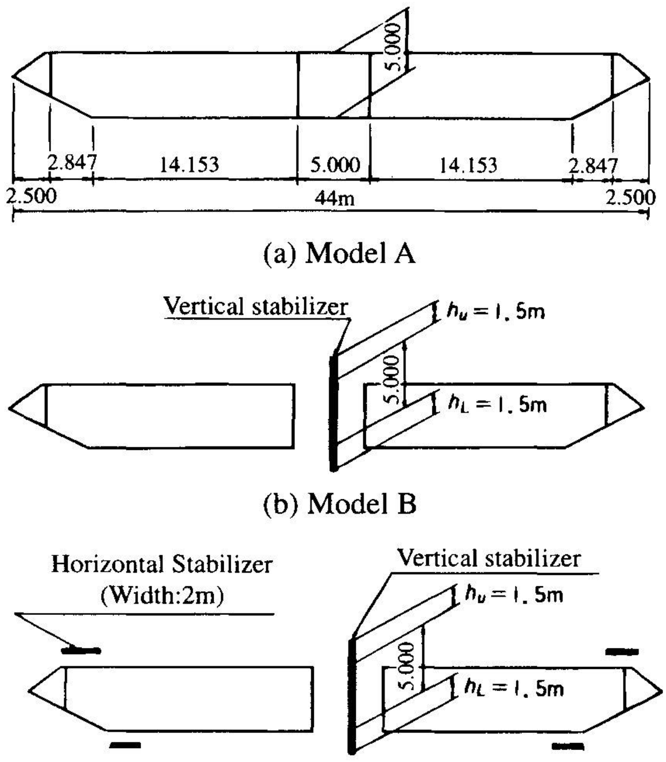

Fig. 3 Flat box girder with 5m depth and 5m center slot width

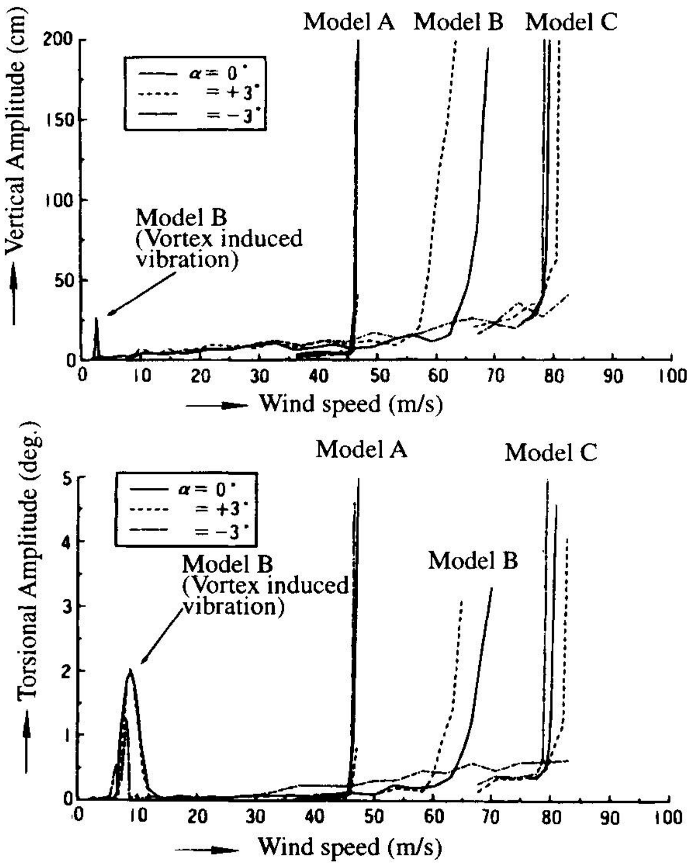

Fig. 4 Comparison of aerodynamic responses among model A, B and C

width from 3 to 5,7,9m. At the same time the height of h_U and h_L shown in Fig.2 were changed. It was found that the model B is the most aerodynamically stable when the deck height of 5m with a center slot width 5m and the V.S.(h_U = h_L=1.5m) in Fig.3 The aerodynamic responses of the model B is shown in Fig.4 where the coupled flutter speeds of α (i.e., angle of attack) = 0 and 3 degree are 66 and 62m/s respectively. The flutter did not occurred below the wind speed of 82.5 m/s at α = -3 degree. Though the vortex induced vibrations occurred at 2~3 m/s in vertical bending vibration and at 7~9 m/s in torsional one in the laminar flow tests, they disappeared in the turbulent flow with the 10% intensity of turbulence. These vibrations seem to be due to the existence of the V.S. however the test result indicates that the amplitudes of them will be very small in natural winds.

Table.1 Dynamic Properties of the Studied Suspension Bridges

The objected bridges		The objected suspension bridge (1250m+2500m +1250m)	The proposed suspenson bridges for Akashi-kaikyo project (960m+1,990m+960m)		
Deck Types		Flat box deck (44m×5m)	Truss deck	Flat box deck	
Dimensions			33.5m×14m	46m×7m	46m×5m
Mass(tf/m) (Cable+hanger+deck)		38.2	43.5	44.7	42.8
Mass moment(tf.m.s^2/m) (Cable+hanger+deck)		869	1,199	1,128	1,103
Frequency (Hz)	Vertical freq.	0.0523	0.0606	0.0608	0.0606
	Torsional freq.	0.133	0.152	0.176	0.150
Frequecy ratio		2.55	2.51	2.90	2.48

3.3 Application of Horizontal Stabilizer

The flat plate corner vane which we call "horizontal stabilizer" was introduced in addition to the vertical stabilizer to enhance the flutter speed as shown in Fig.3 (Model C). This device was originally invented by Sato et.al [3]. However the simultaneous application of vertical and horizontal stabilizers was the first trial and the results of the section model tests seem to be almost satisfactory as shown in Fig.4: The flutter speeds are almost 80m/s at α = -3, 0, +3 degree respectively without vortex induced vibrations.

3.4 Multi-Mode Coupled Flutter Analysis

The result of the section model tests does not always guarantee the aerodynamic stability of the long-span bridges. Therefore the multi-mode coupled flutter analysis is indispensable to its assessment[4]. In applying this analysis, the position shift of the bridge axis (i.e., bridge camber) was considered because under strong winds the bridge axis of long span bridges will have relatively large lateral displacements and torsional ones in the deck and cables. These incidents change not only the natural frequency but also the angle of attack to winds. These shifts were named "camber change" here and were taken into account for the flutter analysis. The derivatives which are defined as the following Eq.1 were measured and used for the analysis in accordance with the angle of attack by the camber change.

$$\left.\begin{aligned} L &= 1/2\,\rho\, V^2 B\,[k\cdot H_0^*\cdot \dot{s}/V + k\cdot H_1^*\cdot \dot{h}/V + k\cdot H_2^*\cdot B\cdot \dot{\alpha}/V + k^2\cdot H_3^*\cdot \alpha + k^2\cdot H_4^*\cdot h/B + k^2\cdot H_5^*\cdot s/B] \\ M &= 1/2\,\rho\, V^2 B^2\,[k\cdot A_0^*\cdot \dot{s}/V + k\cdot H_1^*\cdot \dot{h}/V + k\cdot A_2^*\cdot B\cdot \dot{\alpha}/V + k^2\cdot A_3^*\cdot \alpha + k^2\cdot A_4^*\cdot h/B + k^2\cdot A_5^*\cdot s/B] \\ D &= 1/2\,\rho\, V^2 A\,[k\cdot P_0^*\cdot \dot{h}/V + k\cdot P_1^*\cdot \dot{s}/V + k\cdot P_2^*\cdot B\cdot \dot{\alpha}/V + k^2\cdot P_3^*\cdot \alpha + k^2\cdot P_4^*\cdot h/B + k^2\cdot P_5^*\cdot s/B] \end{aligned}\right\}\ \cdot\cdot(1)$$

Where,

L, M, D : Unsteady lift, moment and drag force
ρ : Air density
V : Wind velocity, $k = 2\pi f B/V$
B : Deck width
f : Frequency of forced vibration
$h\cdot\alpha\cdot s$: Amplitude of heave, rotation and sway motion in forced vibration

The forced vibration method was applied to measure the above-mentioned eighteen flutter derivatives by using a newly devised machine. The examples of the measured flutter derivatives are compared with the ones expressed by Theodorsen's function in Fig.5. The Model A in Fig.3 has no center slot (i.e., the closed section) and the flutter derivatives are resemble to those obtained by the Theodorsen's function as shown in Fig.5. Fig.6 shows the result of the analysis with/without the camber change. Though these differences between with/without the camber change were not large among both cases, the flutter speeds of Model C are almost 80m/s and

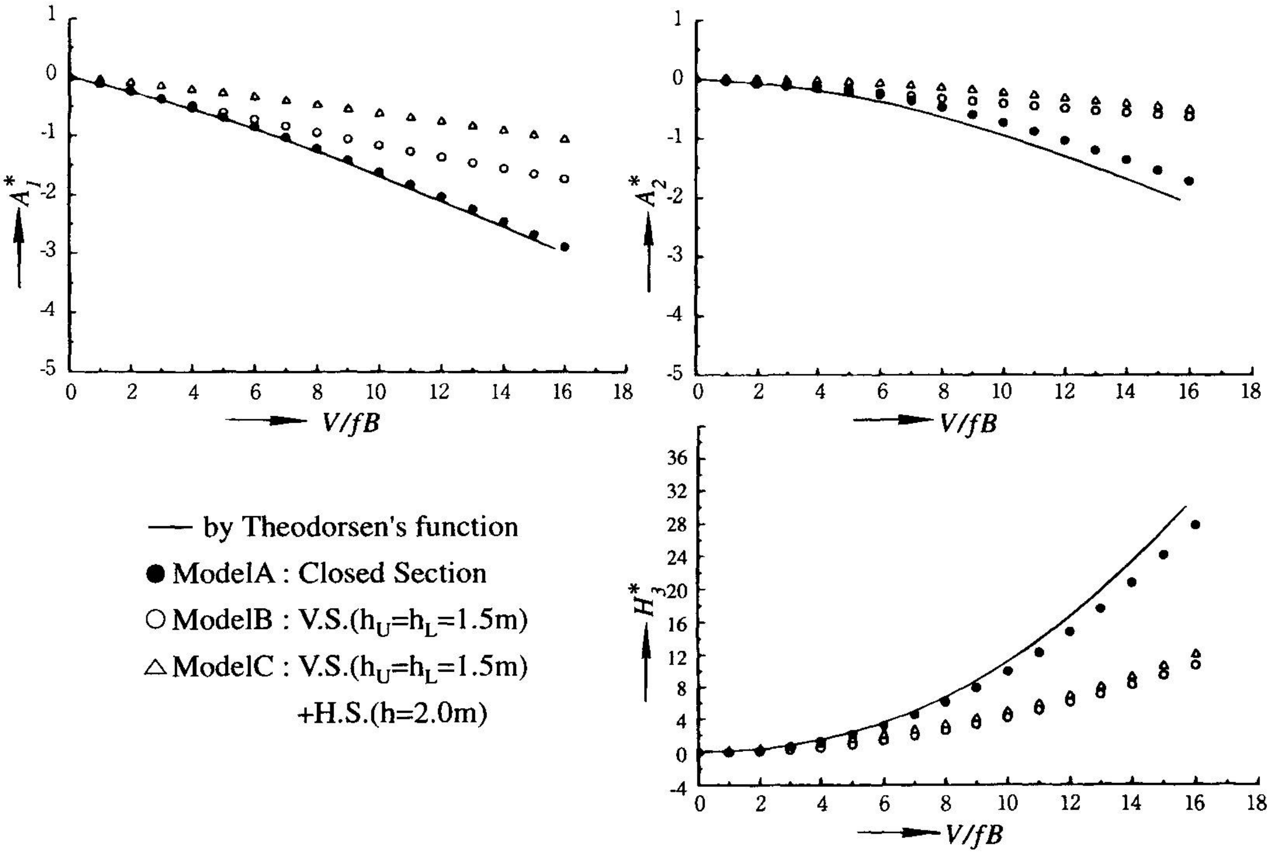

Fig. 5 Examples of Flutter Derivatives (Model A, B, C)

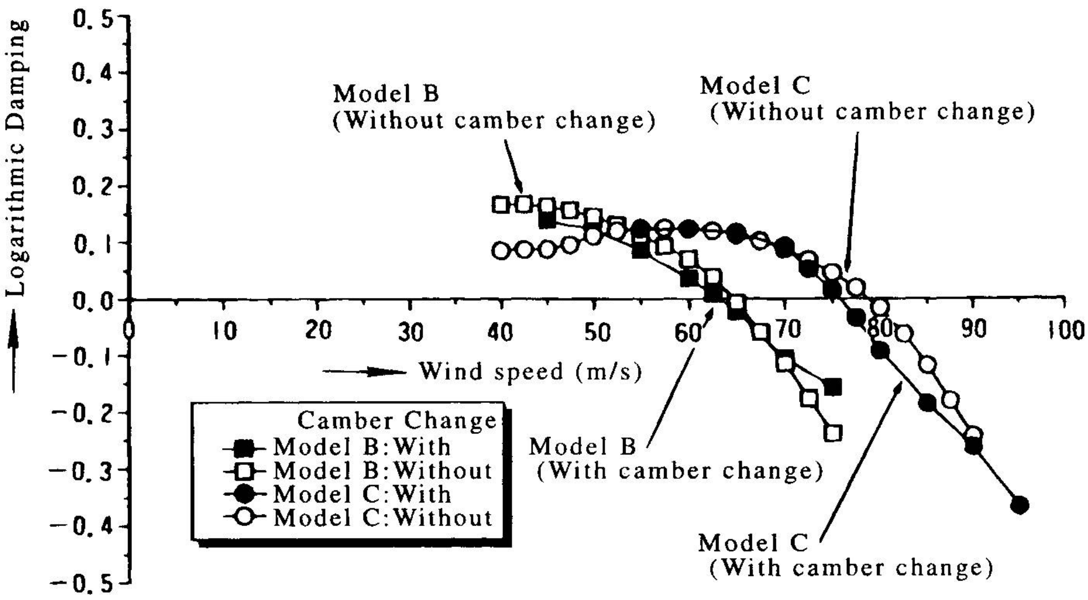

Fig. 6 3-D multi-mode coupled flutter analysis in case of section B and C

fulfill the design goal.

4. Conclusions

The aerodynamic stability of the super-long-span suspension bridges with the center span of 2,500m were assessed. The configuration of the deck is the flat box with six traffic lanes. The installation of the vertical stabilizer in the center slot and that of the horizontal stabilizer on both upper, lower leading and rear edges of the deck are very effective to enhance the flutter speed. It is ensured by the wind tunnel tests and multi-mode coupled flutter analysis.

This study was conducted as the cooperative research for the committee of "Joint Research on Development of Wind-Resistant and Economical Design of Super-Long-Span Bridges." Authors express their sincere appreciations to the members of the committee for their valuable discussions.

References

[1] Ueda, T., Yasuda, M. and Nakagaki, R., "Mechanism of Aerodynamic Stabilization for Long-Span Suspension Bridge with Stiffening Truss-Girder, " *J. of Wind Engineering*, No.37, JWE, pp.477-484, October 1988

[2] Tanaka, H., Yamamura, N. and Ueda,T., "Design of Super-Long-Span Suspension Bridge Based on Aerodynamics," *Bridges into the 21st Century*, October 1995, Hong Kong

[3] Sato, H., Toriumi, R. and Kusakabe, T. et al., "Flutter Characteristics of Box Decks with Slot Holes," *No. 50th Annual Convention of JSCE*, I-681, September 1995

[4] Tanaka, H., Yamamura, N. and Shiraishi, N., "Multi-Mode Flutter Analysis and Two & Three Dimensional Model Tests on Bridge with Non-Analogous Modal Shapes," *J. Struct. Mech. Earthquake Eng.*, No.471/I-24, JSCE, pp.71-82, July 1993