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Summary

Wind Resistance is one of the most important themes in the design of super long-span bridges. To improve their wind resistance, a series of wind tunnel studies and analytical studies were conducted. According to the test results and analytical results, it was found that slot at the center of girder and cross hangers were effective to improve the aerodynamic stability. By reviewing the wind tunnel studies for the Akashi Kaikyo Bridge conducted at the Large Boundary Layer Wind Tunnel, wind resistant design methods for super long-span bridges are discussed and proposed.

1. Introduction

The Akashi Kaikyo Bridge has the world-longest span length of 1990m. In the world and in Japan, there are several plans or ideas to construct bridges longer than the Akashi Kaikyo Bridge. In the design of such super long-span bridges, wind resistance is one of the most important themes. The approaches to improve aerodynamic stability can be classified into structural one and aerodynamic one. In this paper described first is the study on improvement of wind resistance of super long-span bridges.

As was found from the full model wind tunnel studies for the Akashi Kaikyo Bridge, special cares should be taken when we predict wind-induced vibrations of super long-span bridges. In this paper follows discussion and proposal on the wind resistant design methods for super long-span bridges.

2. Improvement of Wind Resistance by Aerodynamic Approach

2.1 Flutter Characteristics of Slotted Box Girders

The effect of location and size of slot on aerodynamic characteristics was examined through section model wind tunnel tests [1]. Considering a super long-span bridge which has center span length of 3,000m with two side spans of 1,500m, the structural conditions were assumed. Reduced mass μ (=m/(ρB^2), m: mass per unit length, ρ : air density, B: girder width), reduced polar moment of inertia ν (=I/(ρB^4), I: polar moment of inertia per unit length), and natural frequency ratio ε (=f_θ/fz, f_θ : torsional natural frequency, fz: vertical bending natural frequency) were 16, 2.1, and 2.1, respectively. The cross section of the model is shown in Fig.1. From the test results, it was found that the slot at the center increased the flutter onset wind speed. It was also found that the flutter onset wind speed was increased with the width of slot at the center of the girder (Fig.2).

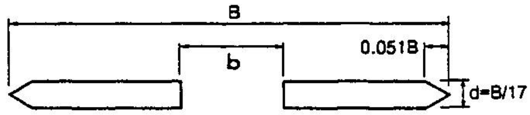

Fig.1 Cross section of girder

In order to understand the effect of slot at the center of girder, preliminary analysis was conducted. For the analysis, aerodynamic forces acting on the each box of the girder were calculated using the Theodorsen's function. The aerodynamic interference between the 2 boxes was neglected. Using these aerodynamic forces, two degree-of-freedom flutter analysis was conducted by U-g method [2]. The result of the flutter analysis (Fig.2) indicates that the flutter onset wind speed increases with size of slot. The differences between the analysis and the experiment seems to be caused by aerodynamic interference between the 2 boxes.

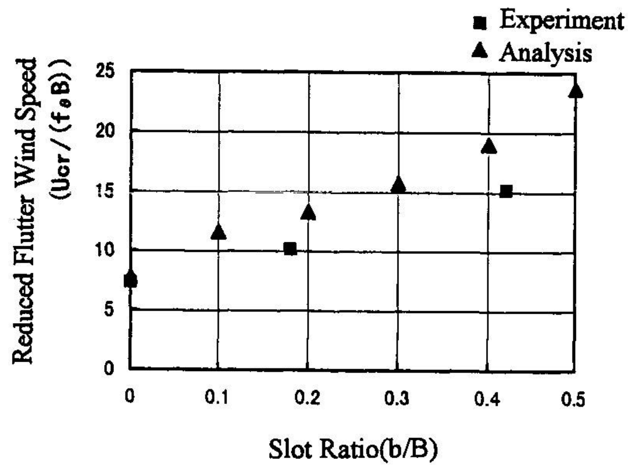

Fig.2 Flutter onset speed and slot ratio

Although wide slot at the center of the girder improves flutter characteristics, narrower slot would be preferable from the viewpoint of construction cost of towers and foundations. To improve aerodynamic characteristics, the effect of some devices was studied by section model tests [1]. The tested devices are illustrated in Fig.3. The results showed that the center barrier and guide vanes improved flutter characteristics very well. However, the flutter speed was not so high when angle of attack was -3 deg. It was found that the guard rails at the bottom deck increased the flutter speed considerably at this angle of attack.

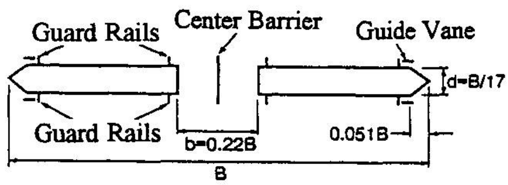

Fig.3 Slotted box girder with devices

2.2 Unsteady Aerodynamic Forces of Slotted Box Girders

In order to understand the aerodynamic characteristics of the slotted box girder more precisely, unsteady aerodynamic forces were measured for three models: model A (single box girder, b=0 in Fig.1), model B (slotted box girder, b=0.22B in Fig.1) and model C (slotted box girder with devices, Fig.3). The measurement was made by forced oscillation method [3]. Coefficients of the unsteady aerodynamic forces were defined as follows:

$$L=\pi\rho\{B^2[L_{ZR}\omega^2 z+L_{ZI}\omega z']+B^3[L_{\theta R}\omega^2\theta+L_{\theta I}\omega\theta']\} \quad (1.1)$$

$$M=\pi\rho\{B^3[M_{ZR}\omega^2 z+M_{ZI}\omega z']+B^4[M_{\theta R}\omega^2\theta+M_{\theta I}\omega\theta']\} \quad (1.2)$$

where, L: lift (upward positive), M: aerodynamic moment (head up positive), z: vertical displacement (upward positive), θ : torsional displacement (head up positive), ω : circular frequency, ( )': d( )/dt, L_{xx} or M_{xx}: coefficients of unsteady aerodynamic forces ($_R$: in phase with displacement, $_I$: in phase with velocity).

In general, it is difficult to predict coupled flutter characteristics directly from these coefficients. For 2-degrees of freedom system, Nakamura[4] showed approximate relationship between unsteady aerodynamic coefficients M_{ZI} , $M_{\theta I}$, $L_{\theta R}$ and $M_{\theta R}$ and some flutter properties as follows:

$$\delta a \fallingdotseq -\pi^2 M_{ZI} X/\nu - \pi^2 M_{\theta I}/\nu \quad (2.1)$$
$$X \equiv z_0/\theta_0/B \fallingdotseq \pi L_{\theta R}/(-1+(f_z/f_\theta)^2\sigma^2)/\mu \quad (2.2)$$
$$\sigma^2 \equiv (f_\theta/f)^2 \fallingdotseq 1+\pi M_{\theta R}/\nu \quad (2.3)$$

where, δ a: aerodynamic damping in logarithmic decrement. They were derived by assuming that absolute value of aerodynamic damping and phase angle are small, and that absolute value of the amplitude ratio X is small. As is shown here, $M_{\theta R}$ affects the frequency ratio σ. $L_{\theta R}$ and σ affect the amplitude ratio X. M_{ZI} , $M_{\theta I}$ and X affect the aerodynamic damping.

If onset of flutter is defined as $\delta a \leqq 0$, simpler inequality for onset of flutter can be derived from (2.1)-(2.3) as follows:

$$\alpha M_{ZI} L_{\theta R}/M_{\theta I} + \beta M_{\theta R} \geqq 1 \quad (3.1)$$
$$\alpha \equiv (\varepsilon^2/(\varepsilon^2-1))(\pi/\mu) \quad (3.2)$$
$$\beta \equiv (1/(\varepsilon^2-1))(\pi/\nu) \quad (3.3)$$

The left hand side of equation (3.1) was calculated for the Models A, B and C using measured unsteady aerodynamic forces, as well as for single plate and slotted plate using the Theodorsen's function. μ , ν and ε were assumed as 15, 2.0 and 2.0, respectively. The results are shown in Fig.4, where they are plotted with $f_\theta B/U$. The slotted box girders and slotted plate show higher flutter speed than the single box girder or single plate. Since the first term of the left hand side of equation (3.1) was much larger than the second term, it can be said that this higher flutter speed was caused mainly by property of $M_{ZI} L_{\theta R}/M_{\theta I}$. In Fig.4, flutter speed of slotted box girder with devices is higher than that without devices. When the left hand side of equation (3.1) was plotted with fB/U (where f is apparent frequency in wind) rather than $f_\theta B/U$, reduced flutter speed U/(fB) of slotted box girder with devices was almost identical with that of slotted box girder. It means that the effect of devices comes from small value of $M_{\theta R}$, which affects apparent frequency in wind.

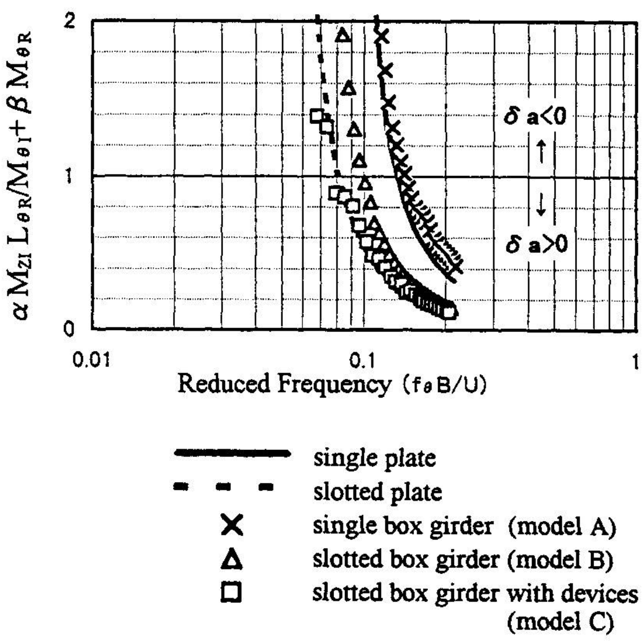

Fig.4 Prediction of flutter speed

2.3 Flutter Analysis for a Super Long-Span Bridge

Using all the measured coefficients of unsteady aerodynamic forces of model C, flutter analysis of a super long-span bridge was conducted. The main span length of the super long-span bridge was 2,500 m, and the side span was 1,250 m. μ , ν and ε were assumed as 14, 1.8, and 1.8, respectively. For comparison, flutter analysis was also conducted using unsteady aerodynamic forces of the single plate derived from Theodorsen's function. The structural conditions for both cases were same. Flutter speed for the slotted box girder was as high as about 80 m/s. On the other hand, the critical wind speed for single flat plate was as low as about 40 m/s.

3. Improvement of Wind Resistance by Structural Approach

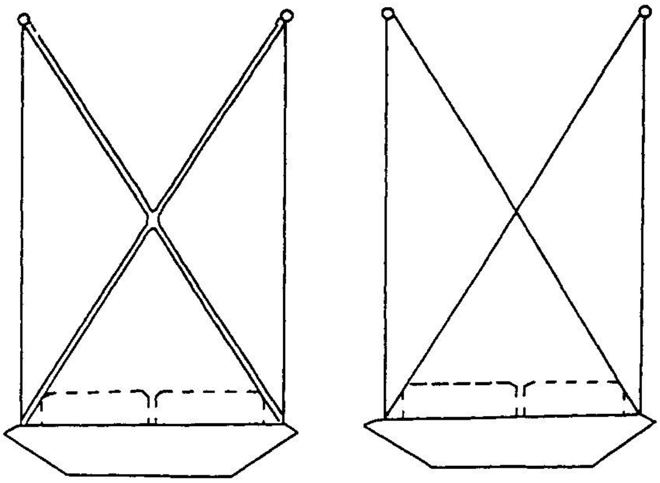

Fig.5 Cross hanger system

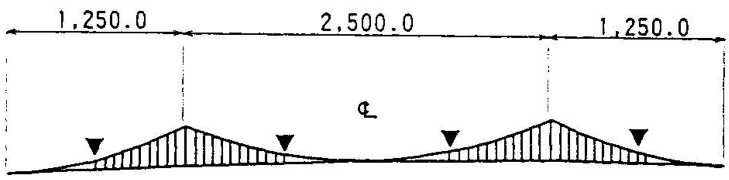

Fig.6 Locations cross hangers set (▼)

In order to improve aerodynamic stability of a super long-span bridge, cross hanger systems were examined. Cross hangers are hangers which connect main cables to stiffening girder crossing over the deck. Cross hanger systems changed natural frequencies, mode shapes and modal masses of the bridge. Natural frequencies, mode shapes and modal masses of the bridge have close relation with flutter onset wind speed of it. Two types of the system were tried, shown in fig.5. One was a system used cables as cross hangers. This system is not effective for compression force. The other is a system used steel members as cross hangers, effective for compression force. Four sets of cross hangers were used in a super long-span bridge, one set at the center of each side span and two sets in the center span (Fig.6). The main span of the bridge was 2,500m, and side spans were 1,250m each. μ, ν and ε were assumed as 21, 2.5, and 2.7, respectively. The type of stiffening girder was a box girder without slot. Flutter analysis of the bridge was conducted. From analysis results, the cable cross hanger system increased the flutter onset wind speed about 10 m/s from that of the bridge without the system, about 60 m/s. The steel member cross hanger system increased 20 m/s.

4. Wind Resistant Design Methods for Super Long-Span Bridges

4.1 Findings from the Wind Tunnel Study for the Akashi Kaikyo Bridge

Wind tunnel study for the Akashi Kaikyo Bridge was conducted at the Large Boundary Layer Wind Tunnel in Tsukuba using 1/100 full aeroelastic model. The model was designed so that the similarity requirements of shape, mass distribution and stiffness distribution might be satisfied. In the smooth flow test [5], remarkable static torsional displacement was observed. Coupled flutter was observed at the wind speed of 8.5m/s (85m/s for real bridge). The rotation center lay on the windward side at the midspan, on the leeward side at quarter point of center span, and on the windward side again at the middle of side spans. During the flutter, its vertical bending vibrational mode was not similar to any of natural modes, while its torsional vibrational mode was similar to the first symmetric natural mode. Therefore it does not seem that aerodynamic stability of super long-span suspension bridges can be predicted directly from spring-mounted rigid model test. From comparison between wind tunnel tests and flutter analyses, it was found that aerodynamic derivatives such as Drag due to Heaving motion, Drag due to Torsional motion, Lift due to Along-wind motion, and Pitching moment due to Along-wind motion should be included in addition to the conventional aerodynamic derivatives.

In the turbulent flow test [5], gust responses were observed, and the responses were compared with the calculated ones. As for vertical bending and torsional responses, the agreement was fairly good, however, the observed horizontal bending responses were much smaller than calculated ones. One of the causes of this discrepancy was thought to be the spatial correlation which was assumed as the exponential function of $fb\,|x_1-x_2|/B$. Since the measured spatial correlation of wind speed did not tend to unity as frequency became 0 when separation of measurement points were large, the calculation might lead to an overestimation as was pointed out in ref.[6] and [7]. Using the measured aerodynamic admittance and the spatial correlation based on the turbulent flow of the wind tunnel, gust responses were calculated again. Although there still remains some discrepancy, accuracy of the calculation has been improved.

4.2 Design Tools for Super Long-Span Bridges

In general, there are three kinds of tools for wind resistant design. They are:

a) Section model test (spring mounted rigid model test, measurement of aerodynamic forces, and so on),
b) Analysis based on aerodynamic forces measured from section model tests, and
c) Full aeroelastic model test.

Section model test is the simplest method. If aerodynamic instability of interest can be assumed as one-degree of freedom (eg. Vortex-induced vibration, galloping, and torsional flutter) or two-degree of freedom, and if torsional deformation of the bridge deck due to steady aerodynamic forces is negligibly small, we can predict critical wind speed of the instability directly from the section model test. As was shown in the experiment for the Akashi Kaikyo Bridge, however, we could not predict the critical wind speed of flutter directly from the section model test, because the torsional deformation was not negligibly small, and because flutter mode consisted of higher vibrational modes as well as fundamental modes. For the wind resistant design of super long-span bridges, therefore, we may well regard the section model test as a tool for eliminating aerodynamically unfavorable cross section of bridge deck or a tool for obtaining aerodynamic data that will be used in the detailed analysis.

As was demonstrated in the wind tunnel studies for the Akashi Kaikyo Bridge, and as was pointed out by Irwin [8], full aeroelastic models give important and unexpected insights into the bridge response. In the full aeroelastic model test, turbulence effects can be well simulated; three-dimensional and local topographical effects can be studied; and influences of various modes and mode shape can be included. Disadvantages of full aeroelastic models are greater cost and time for building and testing them.

If the accuracy of an analytical method is verified by comparing with a full aeroelastic model test, we can use the analytical method instead of the full aeroelastic model test. Comparison with a full model wind tunnel test suggests how to improve analytical methods. To predict flutter of the Akashi Kaikyo Bridge, for instance, the effect of the static torsional displacement and higher natural modes had to be considered, and several aerodynamic derivatives had to be included in addition to the conventional ones. To predict gust responses of the Akashi Kaikyo Bridge, more accurate spatial correlation model was required. Although the present analytical method has been improved by comparing with the full aeroelastic model tests of the Akashi Kaikyo Bridge, the verification of the method is necessary if the method is applied to super long-span bridges that have longer span, inexperienced bridge deck configuration or inexperienced cable system.

4.3 Design Procedures for Super Long-Span Bridges

The procedure of wind resistant design for super long-span bridges can be proposed as follows:

a) Selection of bridge deck cross section by section model tests
b) Prediction and evaluation of wind-induced deformation and vibration by the analytical method that is the most reliable at that time
c) Verification and improvement of the analytical method by comparing with a full aeroelastic model test
d) (in case of slight change of bridge design) Prediction and evaluation of wind-induced deformation and vibration by the verified analytical method
e) (if the accuracy of the analytical model is not enough) Verification of the finalized bridge design by a full aeroelastic model test

5. Concluding Remarks

(1) It was found that box girder with slot at the center had good flutter characteristics, and that it could be improved by some devices like center barrier and guide vane. It seems that the slotted box girder would be one of the possible stiffening girders for super long-span bridges. It was also found that cross-hangers were effective to increase flutter speed of super long-span bridges.

(2) Since super long-span bridges will have inexperienced span length, inexperienced bridge deck cross section or cable systems, full aeroelastic model tests will play an important roll in wind resistant design of super long-span bridges. To overcome its disadvantage, namely greater cost and time, section model tests can be used to select aerodynamically favorable cross section, and analytical methods verified by the full aeroelastic model tests can be applied to predict and evaluate wind-induced response.

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