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AERODYNAMIC STABILITY OF LONG-SPAN BOX GIRDER BRIDGES AND ANTI-VIBRATION DESIGN CONSIDERATIONS

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As structures tend to be large-sized these days, box girder bridges are steadily getting to be long-spanned, the maximum span length of some box girder bridges being beyond 250 m nowadays (Higaki *et al*. 1989). These long-span box girder bridges differ from the bridges suspended by cables such as cable-suspension bridges and cable-stayed bridges in that the box girder bridges support all their loads with only their girders. Thus, the depth of girder becomes more in order to achieve rigidity, which leads to a blunt girder cross-section. Therefore, the aerodynamic stability of box girder bridges is often inferior to that of cable-suspension bridges and cable-stayed bridges. Moreover, a large-scale countermeasure against the vibration is required to improve the aerodynamic stability, so a careful investigation for the aerodynamic stability is necessary at the stage of preliminary design. This paper attempts to systematize a series of wind tunnel tests on the general aerodynamic characteristics and the countermeasures against the vibration for long-span box girder bridges, and describes the comparison between test results and field measurements. Furthermore, the points which require special attention in the design of such bridges and in the countermeasures against the vibration are mentioned.

1. INTRODUCTION

STRUCTURES TEND TO BE LARGE-SIZED THESE DAY as a result of industrialization, economic growth, increase in transport volume, and development of scientific techniques such as computers.

Similarly, box-girder bridges are getting to be long-spanned. Nowadays the maximum span of some box-girder bridges is beyond 250 m. The bridges are more flexible as they become longer spanned, and this tendency leads to an increase in the number of bridges that are liable to vibration. The cross-sections of these box-girder bridges should be bluff in order to achieve rigidity. Therefore, a careful investigation of aerodynamic stability is necessary.

Figures 1 and 2 show the relation between the maximum span length and B/D ratio (where B is the width of the deck, and D is the depth of the deck) of the cross-section at the mid-point of the center span, for one-box and two-box girder bridges, respectively (Bridge & Offshore Engineering Association 1995).

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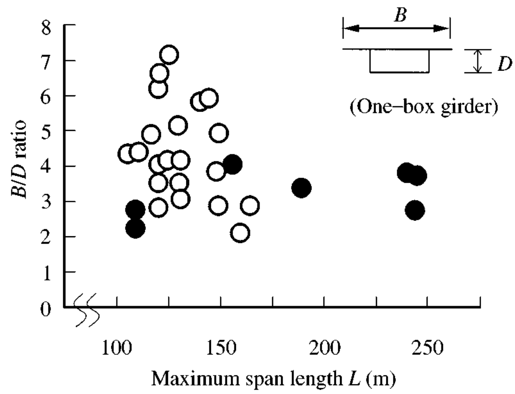


Figure 1. Relationship between maximum span length and B/D ratio (one-box girder); filled data points; results of wind tunnel tests.

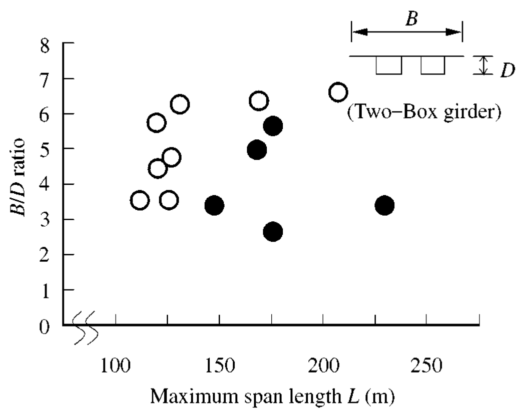


Figure 2. Relationship between maximum span length and B/D ratio (two-box girder).

It is found that the B/D ratio of the cross-section is getting lower and that the number of box girder bridges with blunt cross-section is increasing as the span length gets longer. In a comparison between one-box and two-box girder bridges, it is found that the B/D ratio of two-box girder bridges is generally larger. In long-span box girder bridges with span length beyond 150 m, there is a trend that more bridges have blunt cross-section with B/D ratio less than 4·0 which is obvious especially in one-box girder bridges. As is well known, these blunt structures suffer from the aerodynamic vibration such as galloping and vortex-induced vibration.

In considering aerodynamic vibration of a long-span box girder bridge, it is necessary to pay attention to the following aerodynamic characteristics:

(i) reduced wind speed in long-span box girder bridge in natural win is as low as 50, where quasi-steady theory cannot be applied; (ii) the Scruton number (Sc) of long-span box girder bridge ranges from 10 to 20, where vortex-induced vibration and galloping occur simultaneously (Scruton 1963); [$\mathrm{Sc} = 2M\,\delta/(\rho D^2)$, where M is mass per unit length, δ is logarithmic damping decrement, ρ is air density, and D is depth of cross-section]; (iii) in long-span box girder bridges, the girder depth (B/D ratio) changes along the bridge axis; therefore, its aerodynamic characteristics are strongly effected by three-dimensionality

This paper deals with galloping and vortex-induced vibration that occurs in long-span box girder bridges. It takes into account structural features of long-span box girder bridges mentioned above, and describes the methods for predicting their aerodynamic response characteristics and the countermeasures against vibration.

2. AERODYNAMIC STABILITY OF LONG-SPAN BRIDGES

2.1. Influence of B/D Ratio in Girder Cross-section

Figures 3 and 4 show the results of wind tunnel tests for box girder cross-sections with various B/D ratios (Saito & Honda 1990).

It is generally considered that the value of 4·0 for B/D is a boundary that classifies aerodynamic characteristics of the cross-section as shown in Figures 3 and 4. (In a strict sense, the characteristics change according to he length of the bracket.)

In a box girder cross-section, it would be generally accepted that vortex-induced vibration occurs at low wind speed, and galloping occurs at higher wind speed. The value of 4·0 for B/D is considered to correspond to the boundary value that determines whether galloping occurs or not. This is endorsed by the fact that the slope of the lift force against the angle of attack (see Figures 3 and 4) changes from positive to negative around the value of $B/D = 4{\cdot}0$.

Figures 5 and 6 show the results of a wind tunnel test employing a spring-mounted sectional model (Sakamoto *et al.* 1986). Figures 5 and 6 show the characteristics of amplitude of vortex-induced vibration and critical wind speed for galloping against the change of logarithmic decrement, respectively. Moreover, Figure 7 shows an example of aerodynamic response characteristics.

Concerning the characteristics of aerodynamic vibration of these structures, it is generally considered that vortex-induced vibration can easily be controlled by countermeasures, and this vibration does not lead to a fatal problem for structures. This is because the amplitude of the vibration is limited even if it occurs, and it can be reduced by additional structural damping.

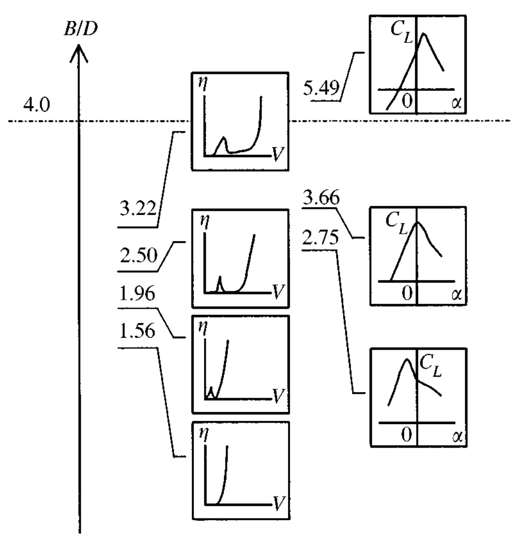


Figure 3. Variety of aerodynamic characteristics versus B/D ratio (one box-girder).

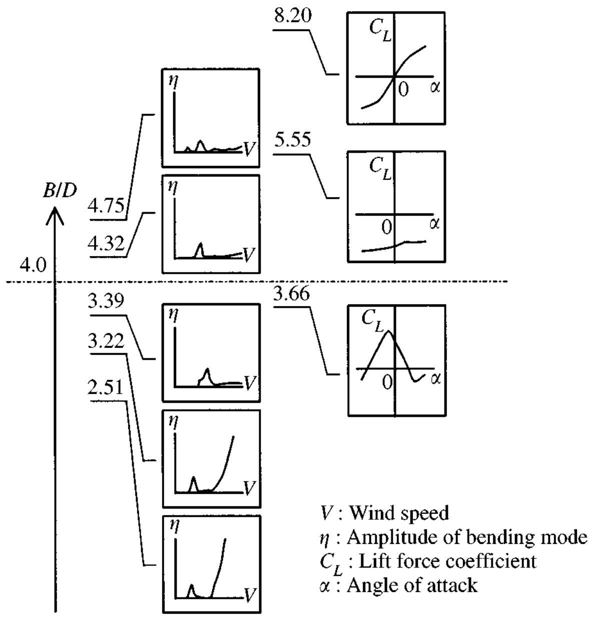


Figure 4. Variety of aerodynamic characteristics versus B/D ratio (two-box girder).

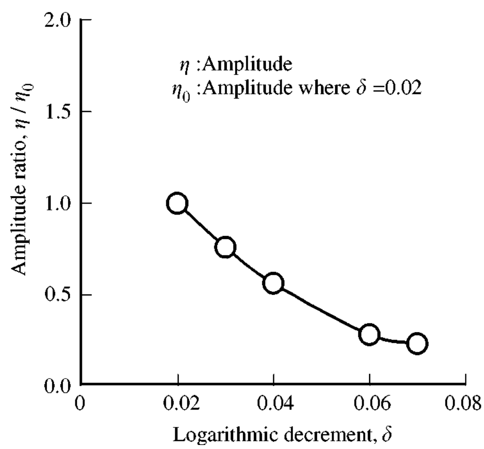


Figure 5. Relationship between amplitude of vortex-induced vibration and logarithmic decrement.

However, it is considered to be difficult to control galloping by additional structural damping, because the amplitude is unlimited and the critical wind speed is little affected by additional structural damping. Therefore, it is necessary to develop an aerodynamic improvement, to prevent galloping.

As the wind speed increases, there is a continuous change from vortex-induced vibration to galloping, and the critical wind speed of galloping corresponds to the onset wind speed of the so-called 'Karman-type vortex-induced vibration' (Scruton 1969).

The formula estimating the critical wind speed for galloping of box girder bridges could be obtained from the formula for the critical wind speed of the so-called Karman-type

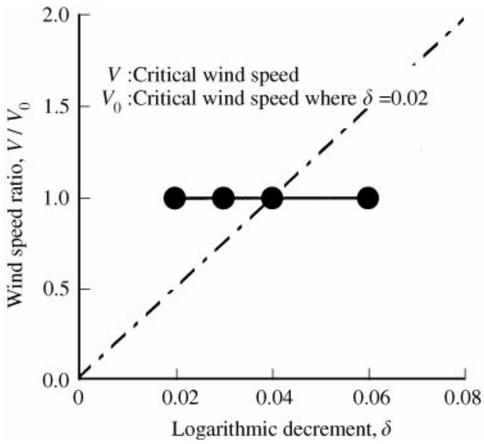


Figure 6. Relationship between critical wind speed for galloping and logarithmic decrement based on quasi-steady theory.

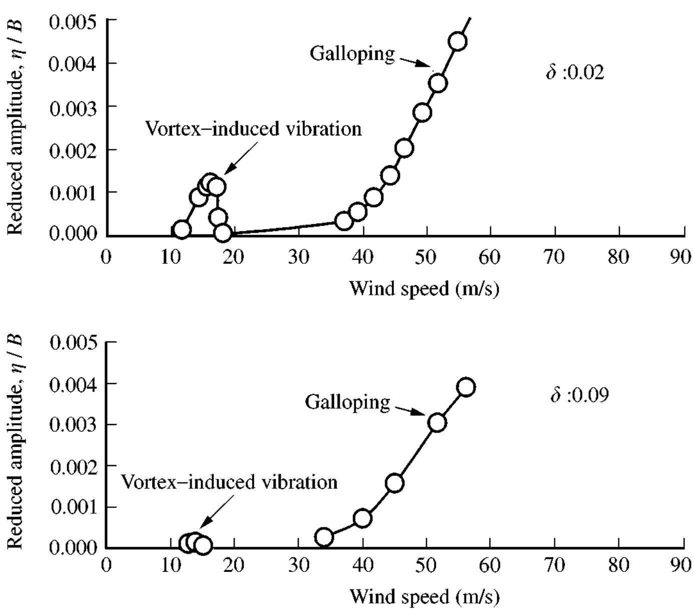


Figure 7. Examples of aerodynamic response characteristics for a box girder bridge.

vortex-induced vibration (Shiraishi & Matsumoto 1981),

$$\frac{V_c}{fD} = 0{\cdot}845 \exp(B/D) + 3{\cdot}255, \tag{1}$$

where V_C is the critical wind speed for galloping, and f is the natural frequency

Fig. 8 shows the comparison of the reduced critical wind speeds obtained from the sectional model wind tunnel tests of some box girder bridges with the characteristics estimated from equation (1) (Saito & Honda 1990; Sakata & Tanaka 1970).

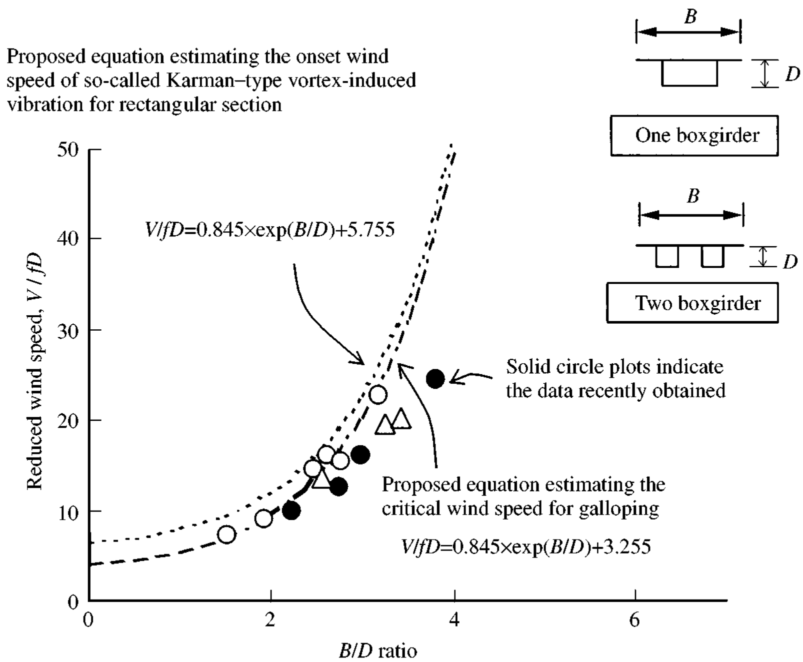


Figure 8. Relationship between critical wind speed for galloping and B/D ratio.

As shown in Figure 8, the critical wind speed estimated from equation (1) is in good agreement with the results of wind tunnel tests both in one-box and in two-box girder bridges.

Moreover, equation (1) gives a quite high reduced critical wind speed of approximately 50 at $B/D = 4{\cdot}0$, which lends support to the contention that the value of 4·0 for B/D is a boundary value that determines whether galloping occurs or not.

As to vibration in the torsional mode the aerodynamic problem is left out of consideration in most box girder bridges, because of their torsional rigidity and the high torsional frequency.

2.2. Difference in Aerodynamic Stability between One- and Two-box Girder Bridges

As to the dynamic response characteristics previously discussed for horizontal wind, one-box and two-box girder bridges have almost the same characteristics. This section describes the effect of the angle of attack as an example of the differences between them. Figure 9 shows the gradient of lift coefficient where the angle of attack equals zero, obtained by wind tunnel tests employing a sectional model.

As shown in Figure 9, an angle of attack between 0 and 3° makes very little difference in the characteristics of two-box girder bridges. However, it makes some difference in the case of one-box girder bridge.

In two-box girder bridges, the gradient of lift force is almost the same both for 0 and 3° angle of attack, and turns to positive when the B/D ratio is beyond 6·0. This suggests galloping can be suppressed by making the B/D ratio larger. On the other hand, for a one-box girder bridge, the gradient of lift force is different for zero and 3° angle of attack. Therefore, it would be difficult to stabilize galloping by changing the B/D ratio.

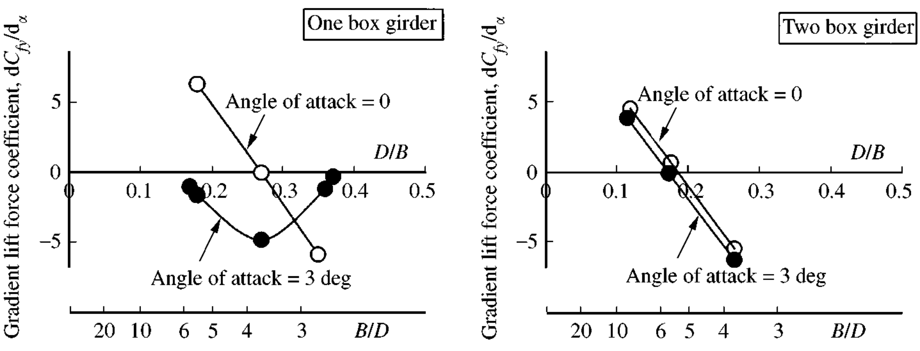


Figure 9. Aerodynamic characteristics of box girder bridges against the change of angle of attack.

It tends to be accepted that the aerodynamic stability of two-box girder bridges is superior to that of one-box girder bridges. This is because two-box girder bridges usually have shallower cross-sections, as shown in Figures 3 and 4. However, in the cases of a cross-section with $B/D > 4{\cdot}0$, the gradient of lift force is negative both in one-box and two-box girder bridges, which means that there is little difference between them in galloping instability, as shown in Figure 8.

2.3. Effect of Turbulence

A lot of tests for vortex-induced vibration in uniform flow have been carried out in the past (Shiraishi & Matsumoto 1981). However, natural wind differs from uniform flow generated in a wind tunnel in that natural wind includes turbulence. In this section, the effect of turbulnce for vortex-induced vibration is discussed.

Figure 10 shows the ratio of amplitue of vortex-induced vibration in turbulent flow to that in uniform flow with respect to turbulence characteristics.

As shown in Figure 10, there is a trend that the amplitude ratio approaches the value of 1·0, as the length scale of turbulence becomes larger and turbulence intensity becomes lower. On the other hand, the vortex-induced vibration scarcely occurs as the length scale of turbulence becomes smaller and turbulence intensity becomes higher (Saito & Honda 1990). Thus, the vortex-induced vibration can scarcely occur in the case of a turbulence intensity (I_w) beyond 10%, when length scales of turbulence are smaller than the width of the girder.

Therefore, in bridges with low deck level or bridges at an inland site, the vortex-induced vibration can scarcely occur. On the other hand, in bridges with high deck level or bridges at a sea site, it is considered that the amplitude of vortex-induced vibration becomes as large as that in wind tunnel tests in uniform flow.

2.4. Effect of Three-Dimensionality (Effect of Girder Depth Changing along Bridge Axis)

Generally, the girder depth of box girder bridges changes along the bridge axis. Therefore, the cross-sections of most box girder bridges are blunt at supporting shoes, even if they are shallow at the mid-point of the center span.

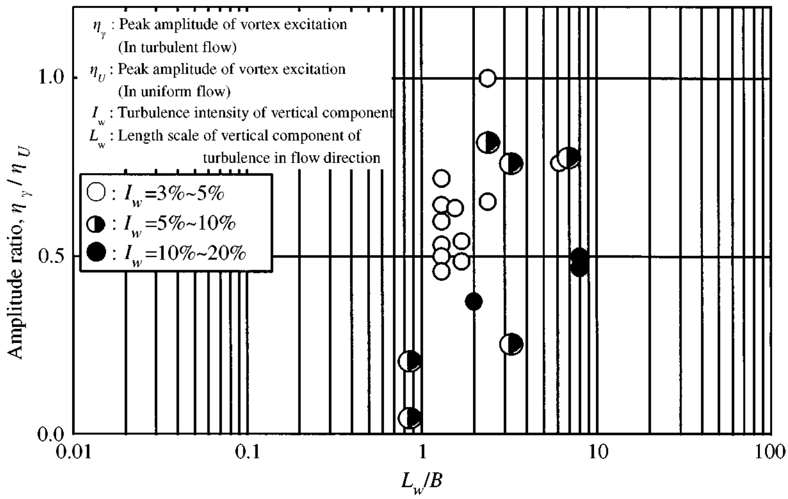


Figure 10. Reduction of amplitude for vortex-induced vibration in turbulent flow.

Strip theory can be applied to evaluate aerodynamic stability for the entire bridge of which the cross-section changes along the birdge axis. Aerodynamic damping of the entire bridge, for amplitude at the mid-point of η_0 and wind speed V, can be calculated by the following equation by means of strip theory:

$$\delta_{3\mathrm{D}}(\eta_\theta, V) = \frac{\displaystyle\int_{x=0}^{l} m(x)\cdot\delta_{2\mathrm{D}}[\eta(x), V]\cdot\phi^2(x)\,\mathrm{d}x}{\displaystyle\int_{x=0}^{l} m(x)\cdot\phi^2(x)\,\mathrm{d}x}, \quad \eta(x) = \eta_0\phi(x), \tag{2}$$

where $\delta_{3\mathrm{D}}(\eta_0, V)$ is the aerodynamic damping of the entire bridge (a function of amplitude η_0 and wind speed V), x is the coordinate along bridge axis, $m(x)$ the mass at the point x, $\phi(x)$ the modal function of the objective mode for calculation, and $\delta_{2\mathrm{D}}[\eta(x), V]$ is the aerodynamic damping of the cross-section at point x (function of amplitude $\eta(x)$, and V). Therefore, the steady-state amplitude of the entire bridge can be calculated where equation (2) gives a value which equals the negative value of structural damping.

Table 1 gives a comparison between the result calculated by strip theory, employing the data from the sectional model wind tunnel test, with that of the entire bridge model wind tunnel test (Sakamoto *et al.* 1986); see Figures 11 and 12.

As shown in Figures 11 and 12 and Table 1, the aerodynamic characteristics of the entire bridge almost correspond to that of the cross-section at the $L/6$ point of the center span, rather than that estimated from the integration of the characteristics of each cross-section applying strip theory (Saito & Honda 1990). It is considered that this is caused by the effect of three-dimensionality of the flow that occurs due to girder depth changing along the bridge axis.

Therefore, in the case of box girder bridges with girder depth changing along the bridge axis, a further investigation is required to determine whether the entire bridge is stable or not, even if the cross-section at the mid-point is aerodynamically stable.

Table 1

Comparison between the result of calculation employing "strip theory" and the result of the entire bridge model wind tunnel test

		Maximum single amplitude of first bending mode (Vortex-induced vibration)		Critical wind speed for galloping	
Angle of attack		0° (mm)	3° (mm)	0° (m/s)	3° (m/s)
Calculation applying "strip theory" with the parameters estimated from the sectional model wind tunnel test		230	360	>90	>90
Wind tunnel test (Entire bridge model)	Wind from sea	346	426	63	59
	Wind from land	488	450	65	65

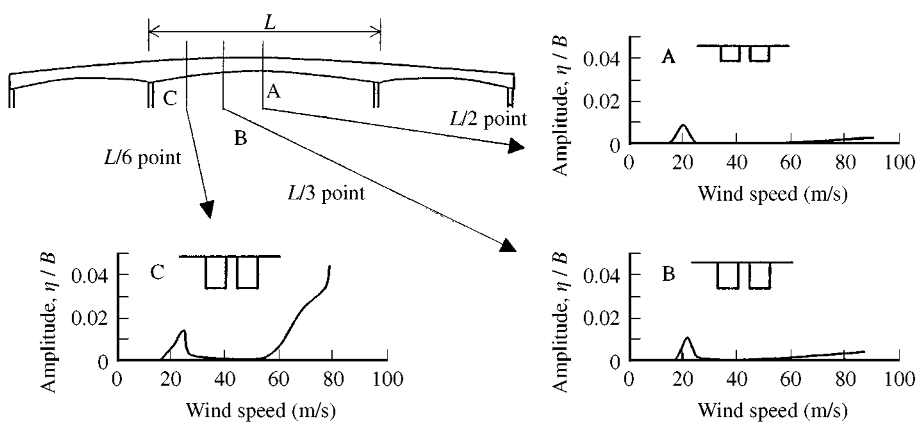


Figure 11. Aerodynamic characteristics of girder bridge (result of the wind tunnel test employing the sectional model).

3. COUNTERMEASURES AGAINST VIBRATION OF LONG-SPAN BOX GIRDER BRIDGES

3.1. Counter Measures against Galloping

As mentioned in Section 2.1, the response characteristics of galloping for box girder bridges cannot be improved by additional structural damping. Therefore, a horizontal plate (the small plate attached to the web a little above the bottom edge) has been developed in wind tunnel tests as an effective aerodynamic improvement.

An example of the aerodynamic improvement is shown in Figure 13. It indicates the results of tests employing three different entire bridge models (Saito 1990).

As to galloping, it is possible to completely suppress the oscillation by a horizontal plate for both one-box and two box-girder bridges, as shown in Figure 13. However, containing vortex-induced vibration, the horizontal plate has little effect, or tends to amplify the vibration a little.

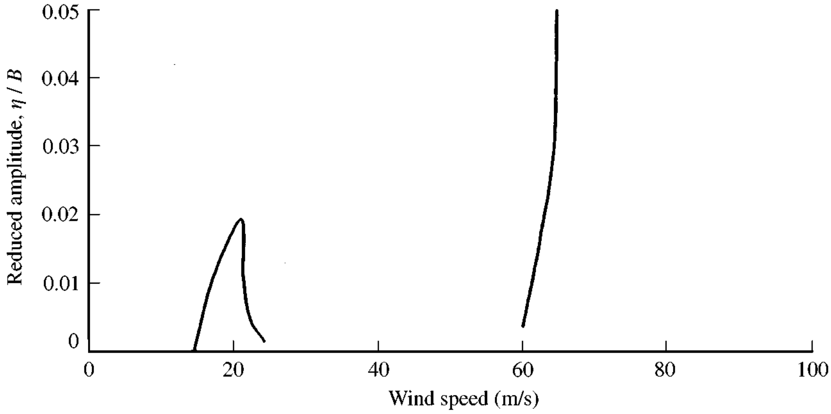


Figure 12. Aerodynamic characteristics of a box girder bridge (results of wind tunnel test employing the entire bridge model).

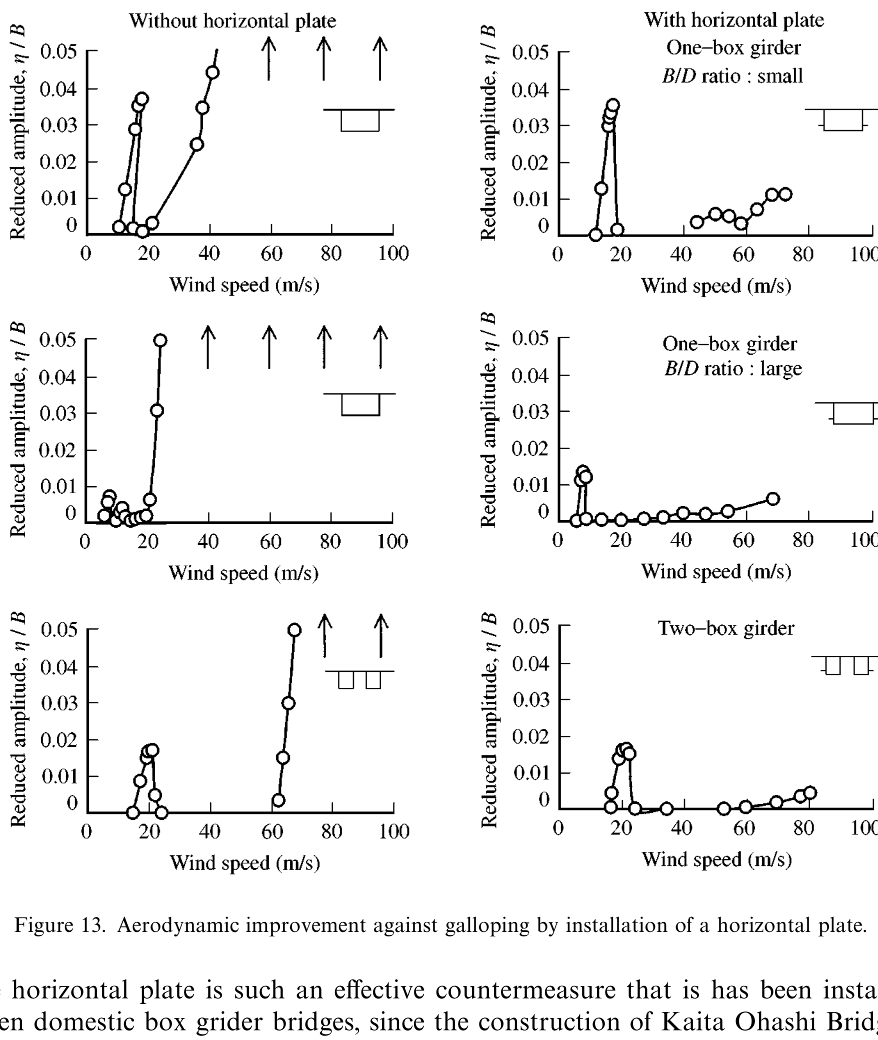


Figure 13. Aerodynamic improvement against galloping by installation of a horizontal plate.

The horizontal plate is such an effective countermeasure that is has been installed in over ten domestic box grider bridges, since the construction of Kaita Ohashi Bridge (see Figure 14. Japan Association of steel Bridge Construction 1994).

Figure 14. Kaita Ohashi Bridge with horizontal plate installed; (Japan Association of Steel Bridge Construction 1994)

3.2. Mechanism of the Effect of Horizontal Plate

Figure 15 shows the effect of a horizontal plate on the wind force characteristics, which was obtained by sectional model wind tunnel tests for the cross-section with and without a horizontal plate. It is found that the gradient of the lift coefficient of the cross-sections turns positive at an angle of attack around 0° by attaching the horizontal plate, as shown in Figure 15.

This result corresponds to the change in aerodynamic characteristics that the galloping is suppressed by the horizontal plate, as shown in Figure 13.

Wind load merely acts on the leeward plate, but has a large effect on the windward plate. This characteristic of the windward plate corresponds to the wind force characteristics of the entire bridge. Because of these points, it is considered that the change of gradient of the lift coefficient, or the effect on vibration, is owed mainly to the windward plate.

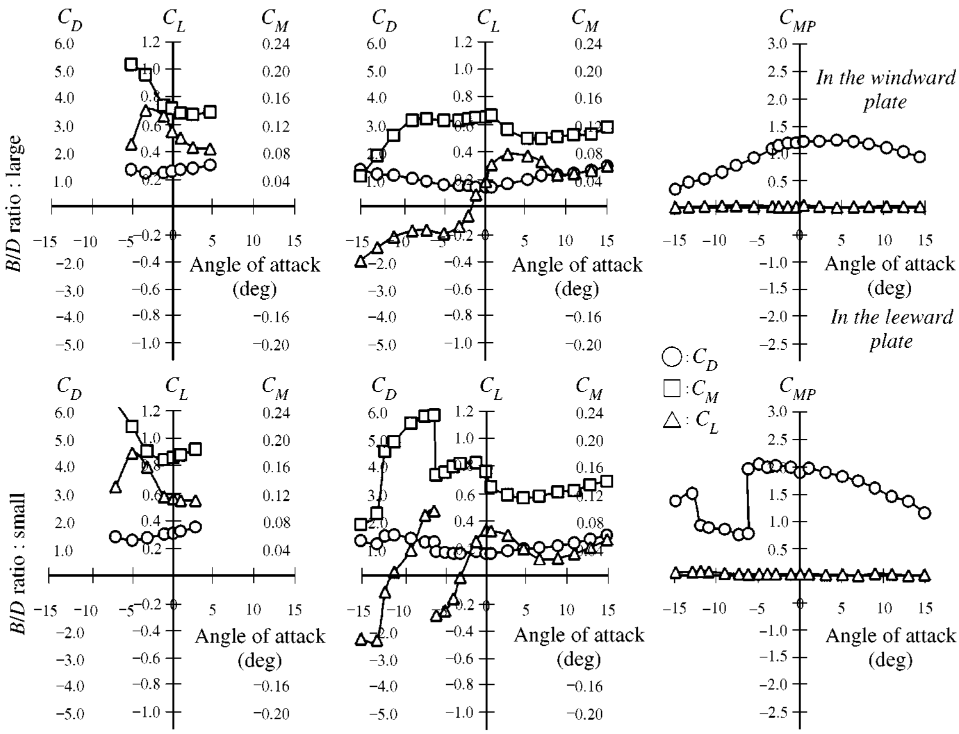
These effects are caused by the phenomenon that a horizontal plate decreases the separation from the bottom of the girder and prompts the reattachment of the separated flow onto the girder itself, as shown in the flow pattern around the cross-section in Figure 16.

Therefore, a horizontal plate leads to a reduction by half in the drag force coefficient (from 1·5 to 0·7) because of the narrower wake, as shown in Figure 16, as well as to an improvement in the gradient of the lift coefficient.

As mentioned above, a horizontal plate is extremely effective not only for aerodynamic improvement, but also for the reductioon of wind load.

3.3. Countermeasures against Vortex-Induced Vibration

As stated in the foregoing, vortex-induced vibration might be suppressed when the structural damping or the turbulence intensity at the bridge site is high. Even if it occurs, it is possible to suppress it by increasing the structural damping, by employing a countermeasure such as a Tuned Mass Damper (TMD). The principles of these devices are as follows (Egusa *et al.* 1988).

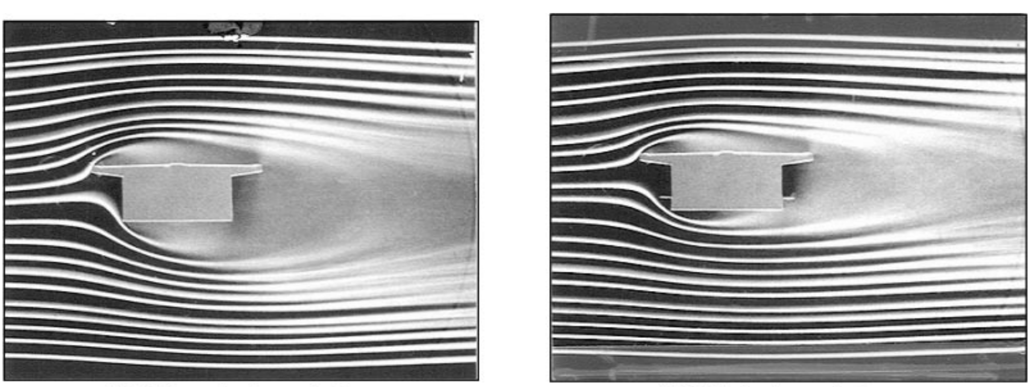


Wind force characteristics (without horizontal plate)

Wind force characteristics (with horizontal plate)

Moment acting on the bottom of the hotizontal plate

Figure 15. Effect of the horizontal plate on wind force characteristics.



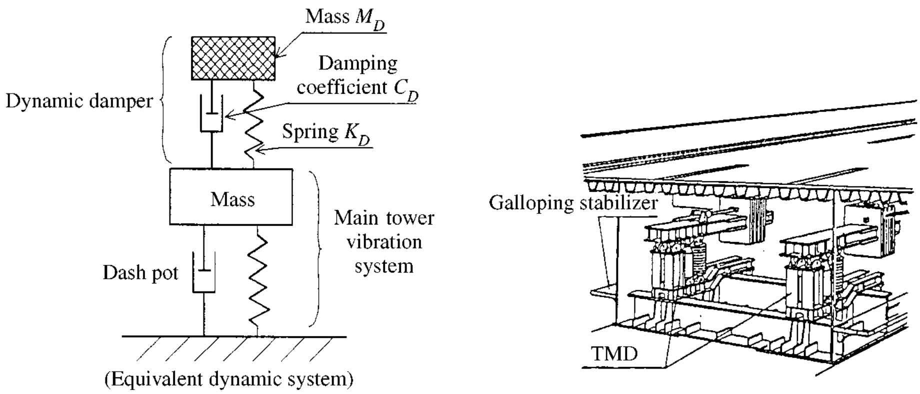
(a) Without horizontal plate

(b) With horizontal plate

Figure 16. Flow pattern around the cross-section (effect of the horizontal plate). (a) without horizontal plate (b) with horizontal plate.

The secondary vibration system is designed to have the same natural frequency as that of the main vibration system. When the main vibration system starts to oscillate, the secondary vibration system acts as a stabilizer, because its damping force acts on the main vibration system. Figure 17 shows the outline of TMD.

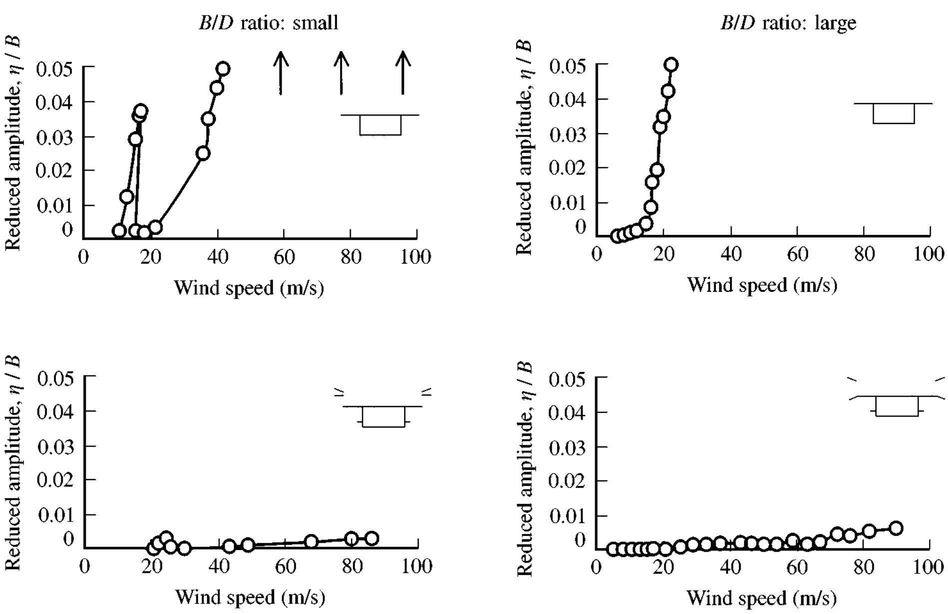
However, in bridges with not enough room for such dampers, the attachments as shown in Figure 18 (doubled-flap, flap and skirt) are effective as aerodynamic countermeasures



Dynamic model of TMD

TMD installed inside box girder (Honda *et al.* 1993)

Figure 17. Outline of tuned mass damper TMD, and the TMD as installed.



Doubled-flaps and horizontal plate

Flap, skirt and horizontal plate

Figure 18. Examples of aerodynamic improvements for vortex-induced oscillation.

against the vibration. It is considered that these attachments remove the vortex by turning accelerated flow towards the surface of the bridge. Moreover, they themselves bring turbulence to the surface of the bridge, and keep the air-flow close to the cross-section.

3.4. Effect of Reynolds Number

The response characteristics may depend upon the Reynolds number, namely the effect of air viscosity, where the aerodynamic stability is improved by he horizontal plate.

TABLE 2

Reynolds number where aerodynamic vibrations occur

	Reynolds number	
Scale of models	Voretx-induced vibration	Galloping
1/30	$4{\cdot}4\times10^{4}$	$1{\cdot}2\times10^{5}$
1/90	$8{\cdot}5\times10^{3}$	$2{\cdot}3\times10^{4}$
1/170	$4{\cdot}2\times10^{3}$	$1{\cdot}4\times10^{4}$

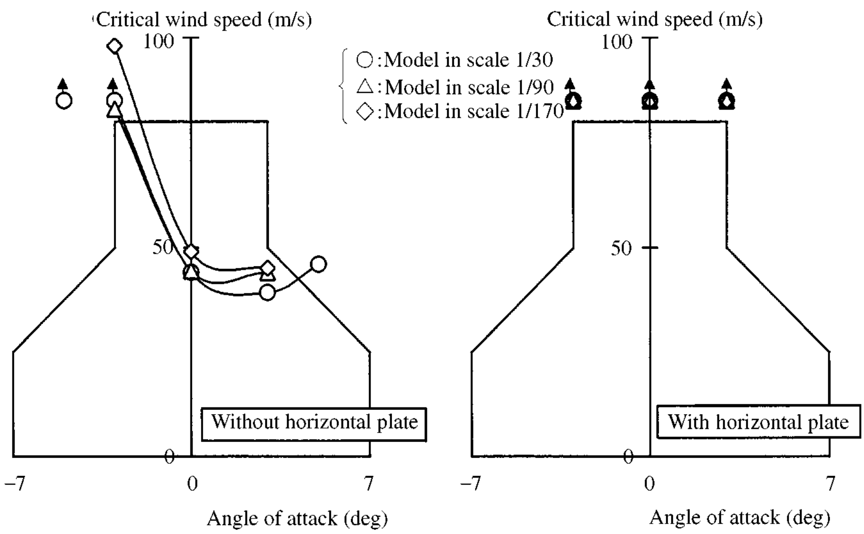


Figure 19. Characteristics of critical wind speed for galloping versus angle of attack.

This section describes the results of spring-supported tests for a box girder bridge employing three types of sectional model in scale of $\frac{1}{170}$, $\frac{1}{90}$ and $\frac{1}{30}$. These tests aim to examine the change in the response characteristics with Reynolds number, both for the cross-section with and without the horizontal plate. Table 2 shows the Reynolds number range in each test.

Figures 19 and 20 show the results of wind tunnel tests, for the cross-section with a horizontal plate and for the original cross-section in each Reynolds number range, of the three types of cross-sections mentioned above, for galloping and vortex-induced vibration, respectively.

As shown in Figure 19, the results of the tests in the three different Reynolds number ranges indicate good agreement, both for the cross-sections with and without the horizontal plate. Thus, it is considered that galloping is insensitive to Reynolds number in the range investigated here.

As to vortex-induced vibration, a little change in the maximum amplitude is found in the cross-sections with a horizontal plate where the angle of attack is negative, as shown in Figure 20. However, drastic changes in the response characteristics of the type observed in corner-cut rectangular cylinder (Okajima *et al.* 1991) are not observed.

Though it is quite difficult to discuss the aerodynamic stability for the vibration of prototype bridges only with this result because of the larger Reynolds number in the full

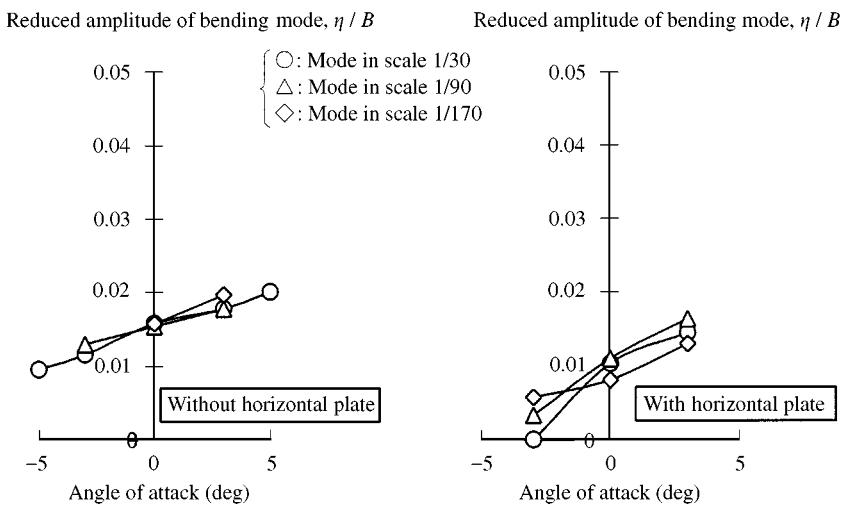


Figure 20. Characteristics of amplitude for vortex-induced vibration versus angle of attack

sizes, it is expected that the horizontal plate would be an effective improvement for prototype bridges also.

4. ARRAYED BOX GIRDER BRIDGES

Recently, in urban areas, there are many cases where a bridge is newly constructed next to an existing bridge. Aerodynamic stability of these tandem bridges largely differs from that of a single bridge, because the bridges have an aerodynamic effect on each other.

Figure 21 shows one of the results of wind tunnel tests in uniform flow, employing the aeroelastic model of tandem box girder bridges (Tokoro *et al.* 1998). The existing bridge is called Bridge B (B/D ratio $= 7{\cdot}0$), and the newly constructed bridge is called Bridge A (B/D ratio $= 3{\cdot}1$) in Figure 21.

As shown in Figure 21, Bridge A, which is supposed to be more aerodynamically unstable because of its blunt cross-section, is likely to cause catastrophic vibration even to Bridge B, which is supposed to be stable as a result of its shallow cross-section, and never showed any vibration by itself.

In this case, it is difficult to attach the countermeasure on the existing Bridge A thus, the horizontal plate was installed on the windward side of the newly constructed Bridge B. Finally as shown in Figure 22, the aerodynamic stability of both bridges was secured.

Moreover, in the bridges arrayed in a triple parallel arrangement, galloping is suppressed also with the horizontal plate, and vortex-induced vibration is reduced employing TMDs (Honda *et al.* 1993).

5. COMPARISON WITH FIELD MEASUREMENTS FOR PROTOTYPE BRIDGE

After completion of a bridge, a field measurement of the prototype bridge in natural wind has been increasingly carried out, in order to improve the accuracy and the reliability in estimating the response characteristics of the wind tunnel tests (Honda *et al.* 1993; Katsuura *et al.* 1997).

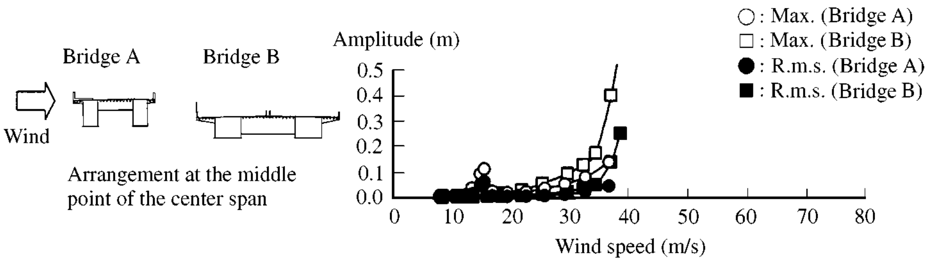


Figure 21. Aerodynamic characteristics of the twin-box girder bridges (original cross-section).

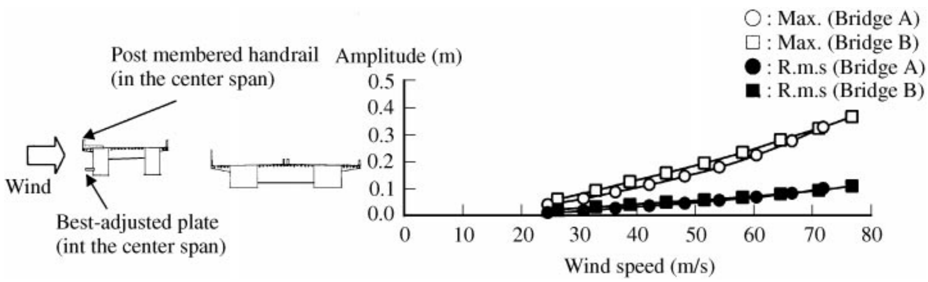


Figure 22. Aerodynamic characteristics of the twin-box girder bridges (improved cross-section).

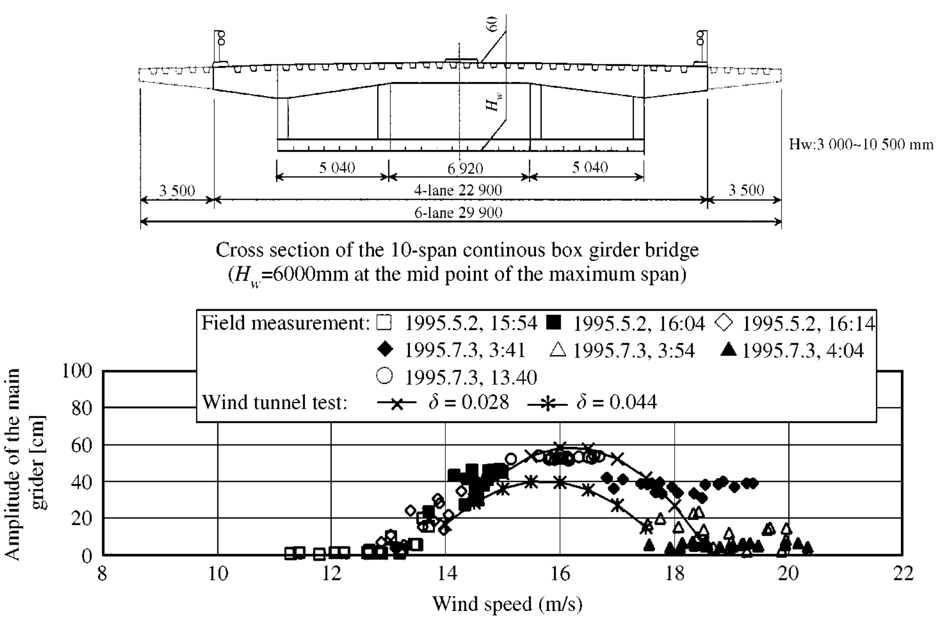


Figure 23. Comparison of field measurements with wind tunnel test results; dimensions in mm.

Figure 23 shows the comparison of field measurements for the prototype bridge with result of the wind tunnel test in the case of a 10-span continuous box girder bridge.

The logarithmic decrement of the prototype bridge in the first bending mode varies between 0·028 and 0·044, according to the results of forced vibration tests for the prototype bridge. Furthermore, it is considered that the wind acting on the bridge has little turbulence, because the bridge is constructed over the sea. By comparing these field measurements with results of wind tunnel tests in uniform flow with the same logarithmic decrement, it is proved that they indicate good agreement with each other.

In this case, the vibration occurred during construction, as estimated in the wind tunnel test. Therefore, the vibration was suppressed by installing TMDs as planned at the design stage.

6. CONCLUDING REMARKS

In this paper, an outline of the aerodynamic stability of long-span box girder bridges is described, and some countermeasures against vibration are suggested. However, the main subject of this paper is the consideration of aerodynamic stability, from the point of view of the aerodynamic characteristics of the girder cross-section. Therefore, further investigation of structural characteristics and natural wind characteristics at bridge sites would be required. Several investigations on estimating the structural characteristics and the natural wind characteristics at bridge sites have been carried out already (Hirai *et al.* 1993). Some of these studies have been employed in the practical design of bridges, so further progress would be expected.

A lot of long-span box girder bridges will be constructed in the future, because they are structurally simple. The cross-sections of these box girder bridges will likely be blunter, while the span will become longer. Therefore, a careful consideration of aerodynamic stability would be increasingly necessary at the preliminary design stage. The author would be pleased if this paper contributes to the process of a safe and sound design.

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