ON THE WIND RESISTANT DESIGN METHODS FOR SUPER LONG-SPAN BRIDGES

by

Hiroshi SATO[1)], Katsuya OGIHARA[2)], Haruki AKIYAMA[3)] and Ryuichi TORIUMI[4)]

ABSTRACT

In Japan and in the world, there are several plans or ideas to construct bridges longer than the Akashi Kaikyo (strait) Bridge. In the design of such super long-span bridges, aerodynamic stability is one of the most important themes. By reviewing the wind tunnel studies for the Akashi Kaikyo Bridge and the Tatara Bridge conducted at the Large Boundary Layer Wind Tunnel, wind resistant design methods for super long-span bridges are discussed and proposed.

KEYWORDS

Wind resistant design method, Super long-span bridge, Flutter, Gust response, Analysis, Full aeroelastic model, Wind tunnel study

1. INTRODUCTION

The Akashi Kaikyo Bridge, which is now under construction in Japan, will have the main span length of 1990m. In Japan and in the world, there are several plans or ideas to construct bridges longer than the Akashi Kaikyo Bridge. In the design of such super long-span bridges, aerodynamic stability is one of the most important themes. Aerodynamic characteristics of slotted box girders were studied and proposed as one of the possible girders for super long-span bridges [1].

In Japan, the safety of proposed design of long-span bridges to wind-induced instabilities has been confirmed mainly by spring-mounted rigid sectional model test in smooth flow. Since the span length of the Akashi Kaikyo Bridge is much longer than the existent longest bridge in the world, it was thought that the wind-induced instabilities should be confirmed by more accurate wind tunnel study, namely full aeroelastic model study.

The Tatara Bridge, which is also under construction in Japan, will have the main span length of 890m. The bridge will be the world's longest cable-stayed bridge. In addition, the Tatara bridge will be surrounded by islands. Some of the islands have high mountains up to 400m above the sea level. Therefore, it was thought that the aerodynamic behavior should be confirmed through full aeroelastic model test with topographical model.

The wind tunnel studies for these bridges were conducted at the Large Boundary Layer Wind Tunnel, whose test section is 41m wide, 4m high and 30m long. Through the wind tunnel studies, the safety of these bridges were confirmed. In addition, some unexpected insights into flutter and gust response of super long-span bridges were found [2].

Considering the findings from the wind tunnel studies for the Akashi Kaikyo Bridge and the Tatara Bridge, wind resistant design methods for super long-span bridges are discussed and proposed in this paper.

2. EXISTING WIND RESISTANT DESIGN METHODS FOR LONG-SPAN BRIDGES IN JAPAN [3]

The wind resistant design of long-span bridges in Japan has been mostly based on the Wind Resistant Design Criteria for Honshu- Shikoku Bridges (hereinafter referred as to 'the Criteria'). The Criteria was originally formulated in 1967 and revised in 1976 by the ad hoc committee in the Japan Society of Civil Engineers. The Criteria prescribes the design wind load including the effect of gust and the evaluation method of wind-induced vibrations based on wind tunnel testing.

In the Criteria, the wind-induced vibrations of the bridge deck shall be estimated through spring-

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1) Head, Structure Division, Structure and Bridge Department, Public Works Research Institute, Ministry of Construction
2) Senior Research Engineer, Structure Division, ditto
3) Manager, First Design Division, Design Department, Honshu-Shikoku Bridge Authority
4) Deputy Manager, First Design Division, ditto

mounted rigid model test in smooth flow. The critical wind speed Vcr for flutter and galloping at attack angles from -3 deg. to 3 deg. shall be higher than the following reference wind speed Vr.

$$Vcr > Vr = 1.2V_D$$

The standard method for wind tunnel testing is described in the Guideline of Wind Tunnel Testing for Honshu-Shikoku Bridges.

3. FINDINGS FROM THE WIND TUNNEL STUDY FOR THE AKASHI KAIKYO BRIDGE [4]

The 1/100 full aeroelastic model of the Akashi Kaikyo Bridge was designed so that the similarity of shape, mass distribution and stiffness distribution might be satisfied (Photo 1). The stiffening truss was modeled without stiffening spine at the center of cross section. The bending stiffness in the plane of tower was simulated as well as the bending stiffness in the plane of bridge and torsional stiffness about the axis of tower. In modeling of the cables, mass, drag force and axial stiffness were simulated, and aerodynamic interaction with stiffening truss was considered.

3.1 EXPERIMENTS IN SMOOTH FLOW

In the smooth flow test, remarkable static torsional displacement was observed (Fig.1). It was caused mainly by aerodynamic drag force acting to the stiffening truss. In case of ordinary suspension bridges, which have center span of about 1,000 m, static torsional displacement is negligibly small. It was found in the full aeroelastic model test of the Akashi Kaikyo Bridge, however, that relative angle of attack cased by the static displacement was not negligibly small, and that it varied along the bridge axis. Since angle of attack affects flutter characteristics, the effects of torsional displacement on the aerodynamic stability must be considered in case of super long-span bridges, which have center span of 2,000 m or over.

Coupled flutter was observed at the wind speed of 8.5m/s (85m/s for real bridge) (Fig.2). 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 (Fig.3). During the flutter, its vertical bending vibrational mode was not similar to any of natural mode, while its torsional vibrational mode was similar to the first symmetric natural mode (Fig.4). Therefore it does not seem that aerodynamic stability of super long-span suspension bridges can be predicted directly from spring-mounted rigid model test.

In order to predict flutter of super long-span bridges analytically, the effect of the static torsional displacement should be considered, and higher natural modes as well as the first natural mode should be included. Besides, 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 following conventional aerodynamic derivatives.

Drag due to Along-wind motion
Lift due to Heaving motion
Lift due to Torsional motion
Pitching moment due to Heaving motion
Pitching moment due to Torsional motion

3.2 EXPERIMENTS IN TURBULENT FLOW

In the turbulent flow test, gust responses were observed in horizontal bending, vertical bending and torsional mode. As wind speed increased, the vibration of torsional 1st mode became dominant, and apparent damping became smaller. This seems to be the effect of flutter. Apparent damping in the turbulent flow was compared with that in the smooth flow. It was found that the effect of turbulence on flutter was small for this bridge model.

The observed gust responses were compared with the calculated ones. In the calculation, the following aerodynamic admittance and spatial correlation were applied.

i) aerodynamic admittance for drag [5]

$$Xu^2(fd)=2[kfd-1+\exp(-kfd)]/(kfd)^2$$

ii) aerodynamic admittance for lift and moment [6]

$$Xw^2(fb)=(a+\pi fb) / [a+(\pi a+1)\pi fb+2\pi(\pi fb)^2]$$

iii) spatial correlation [7]

$$R(fb)=\exp(-kfb\,|\,x1-x2\,|\,/B)$$

where,

a : constant (=0.1811)
B : width of stiffening truss
D : depth of stiffening truss
f : frequency
fb=fB/U
fd=fD/U

k : decay factor (assumed to be 8)
U : mean wind speed
x1, x2 : coordinate along bridge axis

As for vertical bending and torsional responses, the agreement was fairly good, however, the observed horizontal bending responses were much smaller than calculated ones (Table 1).

One of the causes of this discrepancy was thought to be the spatial correlation which was assumed as the exponential function of fb | x1-x2 | /B. Since the measured spatial correlation of wind speed (root co-coherence function, Fig.5) 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.[8] and [9].

Using the measured aerodynamic admittance and the spatial correlation based on the turbulent flow of the wind tunnel, gust responses were calculated again. The result is shown in Table 1. Although there still remains some discrepancy, accuracy of the calculation has been improved.

4. FINDINGS FROM THE STUDY FOR THE TATARA BRIDGE

4.1 EXPERIMENT IN SMOOTH FLOW [10]

The aerodynamic stability of the Tatara bridge was investigated in smooth flow. No divergent vibration such as flutter was observed. This means the Tatara bridge is aerodynamically stable. The only wind induced vibration observed was vortex-induced vibration with small amplitude.

4.2 EXPERIMENT WITH ISLAND MODEL [11]

Wind characteristics at the site are very complicated (Fig.6). For example, in the case of wind direction of NNW and SSE, a topographical effect is hardly recognizable. In other words, wind speed and turbulence intensity were scarcely changed by the topography. On the contrary, in the case of wind direction such as NE and W, wind characteristics were changed significantly by the topography. Particularly, in the case of NE direction, the turbulence intensity was considerably increased by the topography, but the wind speed was not remarkably decreased. In the design of the long-span bridge, these wind characteristics were thought to be critical.

Wind tunnel experiments were carried out for three cases of wind direction, namely 18, 36 and 180 degrees (Photo 2, Fig.7). Wind direction was defined clockwise from the north direction normal to bridge axis. When wind direction was 18 and 180 degrees, the topographical effect was hardly recognizable. On the other hand, in the case of 36 degrees, the topography increased the gust response significantly.

According to the quasi-steady theory, aerodynamic force due to approaching turbulence increases with square of mean wind speed and turbulence intensity. Fig. 8 shows the wind characteristics along the bridge axis in the three wind directions. In the case of 36 degrees, a significant increase in turbulence intensity along the bridge axis was recognized. However, the increase in turbulence intensity was associated with decrease in mean wind speed.

Another factor that influences the gust response of long-span bridges is correlation of fluctuating wind speed at different places. Table 2 shows turbulence intensity and integral scale of turbulence at the mid-point of the center span in case of 36 degree. It can be seen that the integral scale as well as intensity was increased very much by the topographical model. Fig.9 shows co-coherence of fluctuating wind speed at two places on the bridge axis. It can be seen that the correlation was much higher in case of 36 degree than in case of 180 degree.

From these measurements, it seems that the large gust response in case of wind direction 36 degree was caused by high turbulence intensity and high space-wise correlation of the turbulent flow generated by the topographical model.

5. WIND RESISTANT DESIGN METHODS FOR SUPER LONG-SPAN BRIDGES

5.1 DESIGN TOOLS

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 the Tatara Bridge, and as was pointed out by Irwin [12], 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. When we apply an analytical method, we have to consider the limitation of the method. 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 the super long-span bridges that have longer span, inexperienced bridge deck configuration or inexperienced cable system.

5.2 DESIGN PROCEDURE

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

6. CONCLUDING REMARKS

Full aeroelastic model tests give important and unexpected insights into the bridge response. This advantage was demonstrated in the wind tunnel studies for the Akashi Kaikyo Bridge and the Tatara Bridge. 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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Table 1 Gust Responses

	Horizontal (mm)	Vertical (mm)	Torsional (deg)
Measured	20	12	1.4
Calculated (Conventional calculation)	83	13	2.9
Calculated (Improved calculation)	38	11	1.5

Table 2 Turbulence Intensity and Integral Scale of Turbulence

Wind Characteristics (Center of center span)	with topographical model $\beta = 36°$	without topographical model $\beta = 36°$
Turburence Intensity		
Iu (%)	15.6	9.3
Iw (%)	8.7	5.8
Integral Scale of Turbulence		
Lxu (m)	1.21(242)	0.58(116)
Lxw (m)	0.25(50)	0.31(62)
( ):converted real scale		

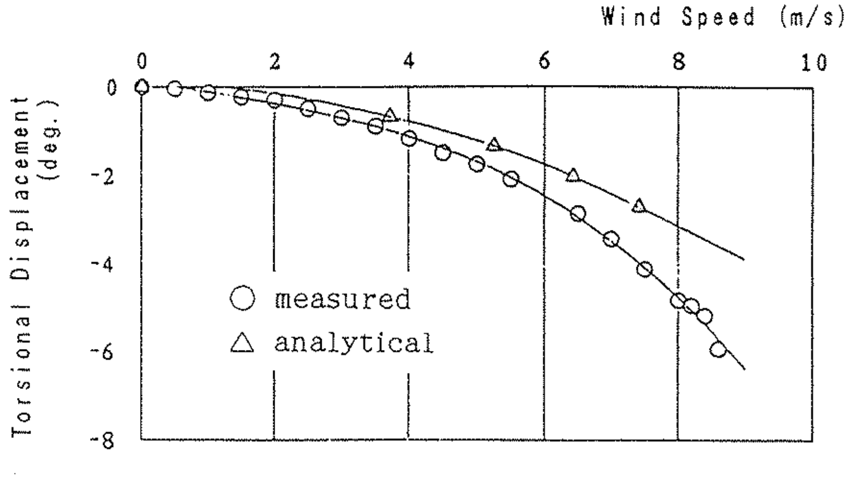


Fig.1 Torsional dispalcement by wind (midspan)

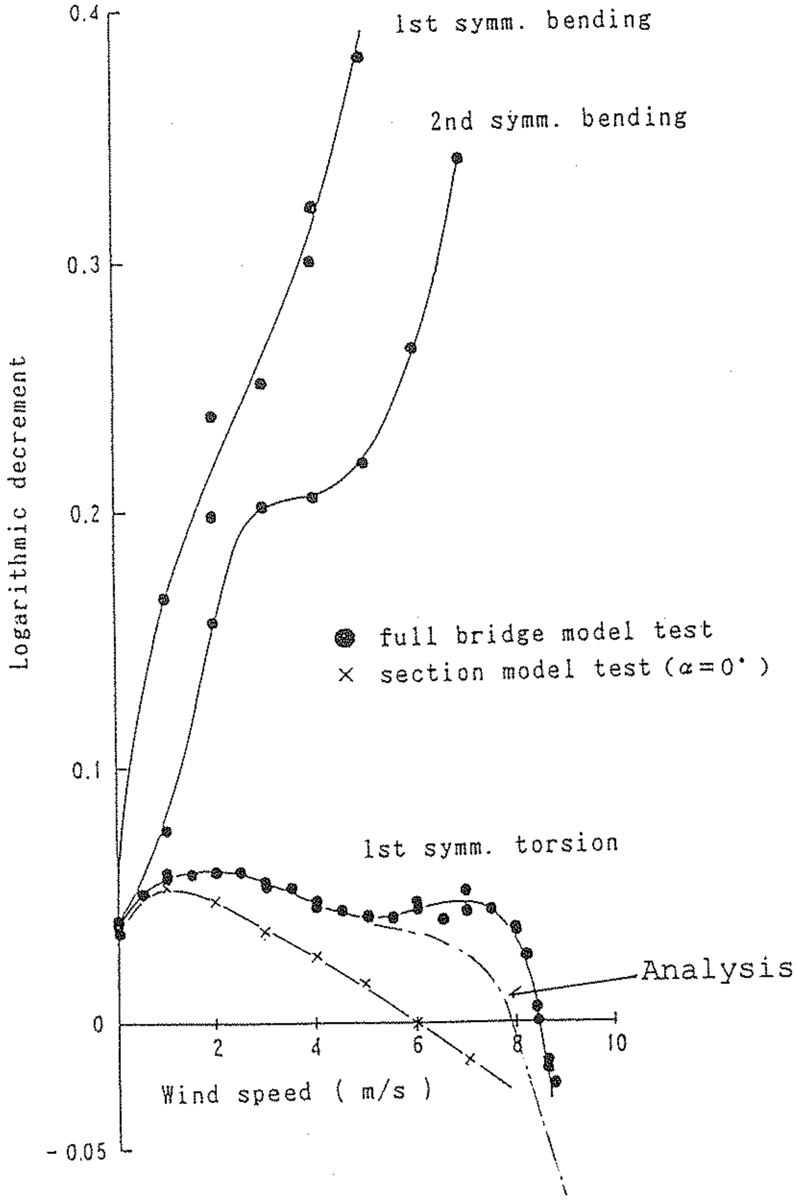


Fig.2 Change of aerodynamic damping

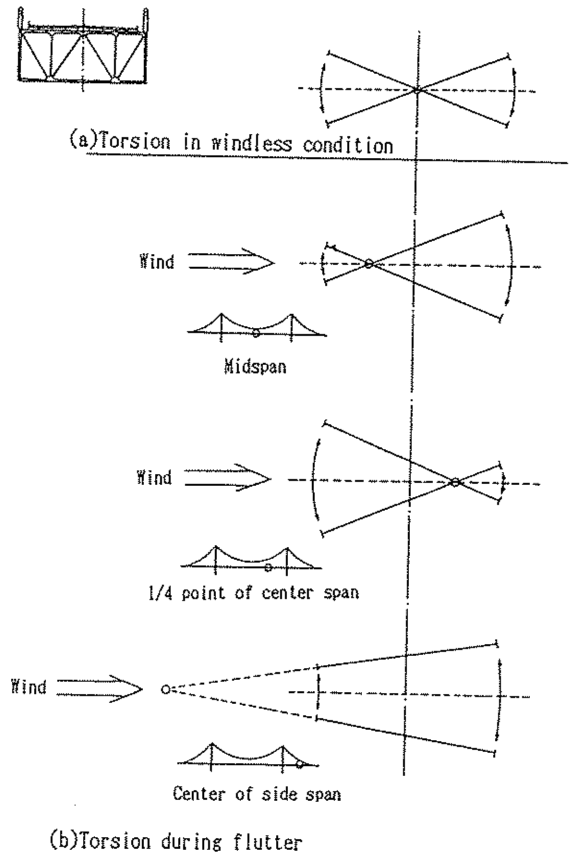


Fig.3 Movement of rotation center

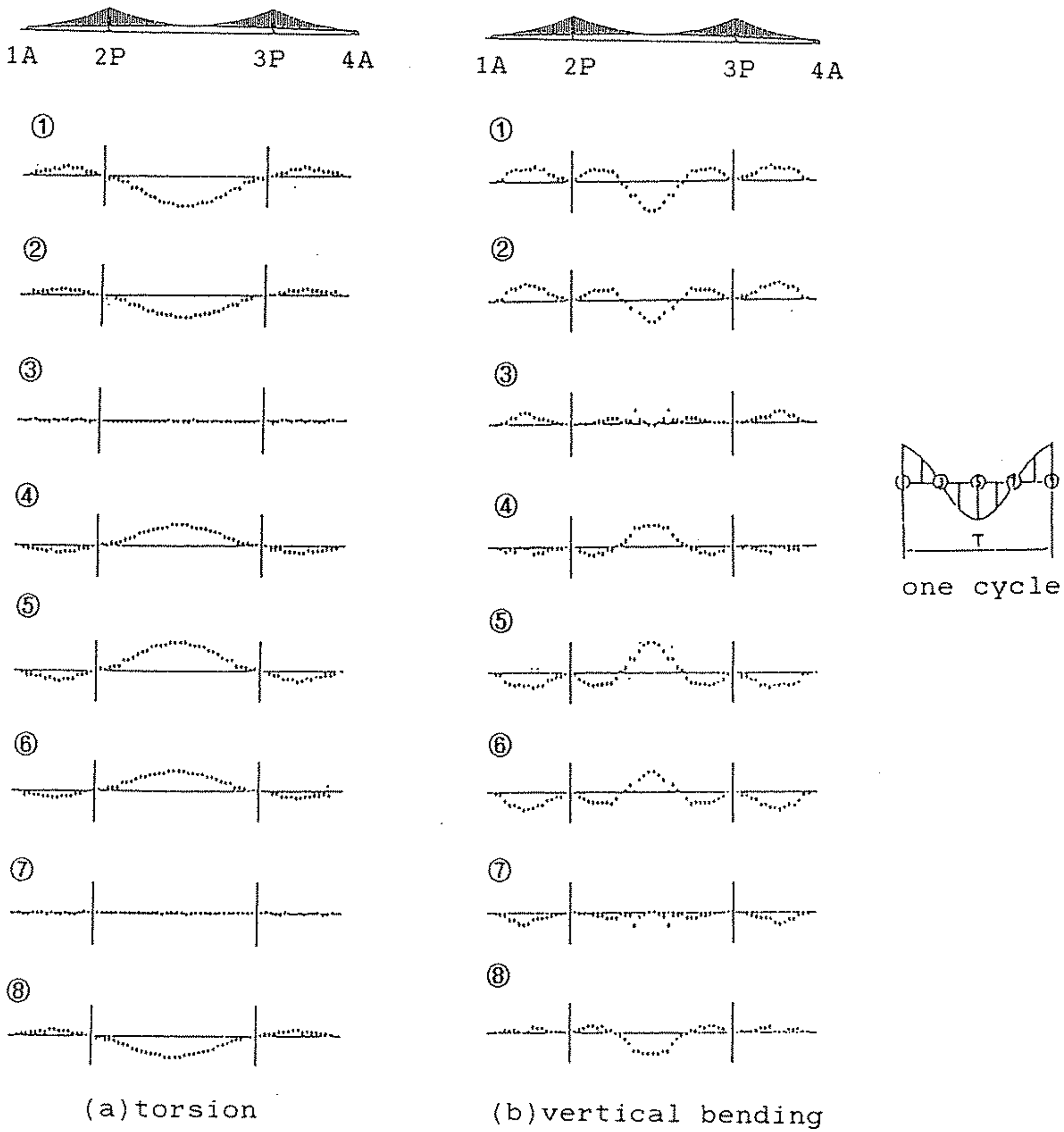


Fig.4 Response of girder cycle during flutter

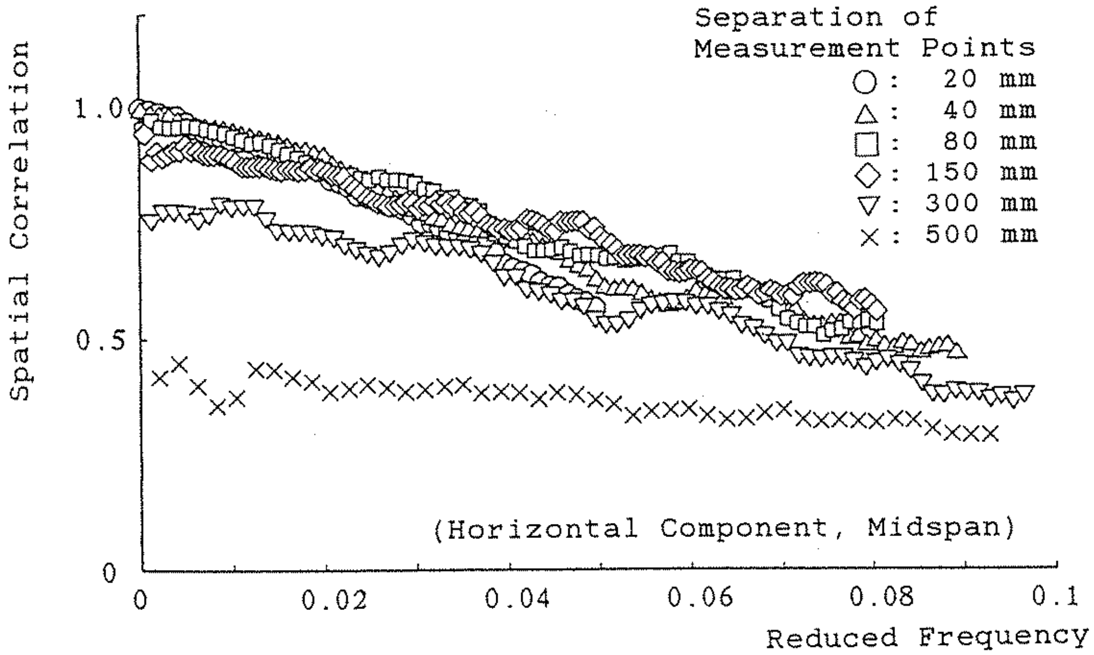


Fig.5 Spectral correlation of wind speed

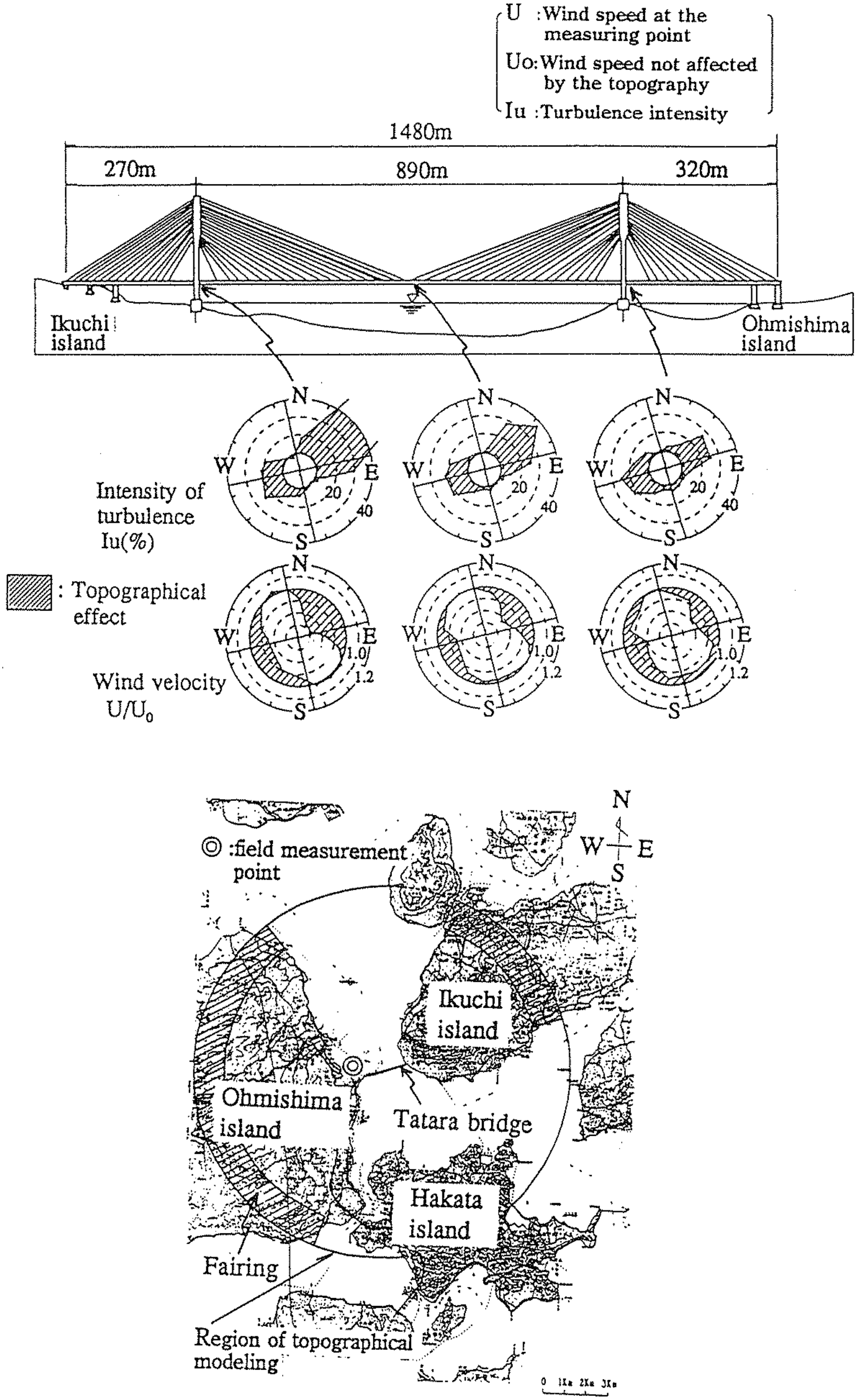


Fig.6 Wind flow pattern at the Tatara Bridge construction site

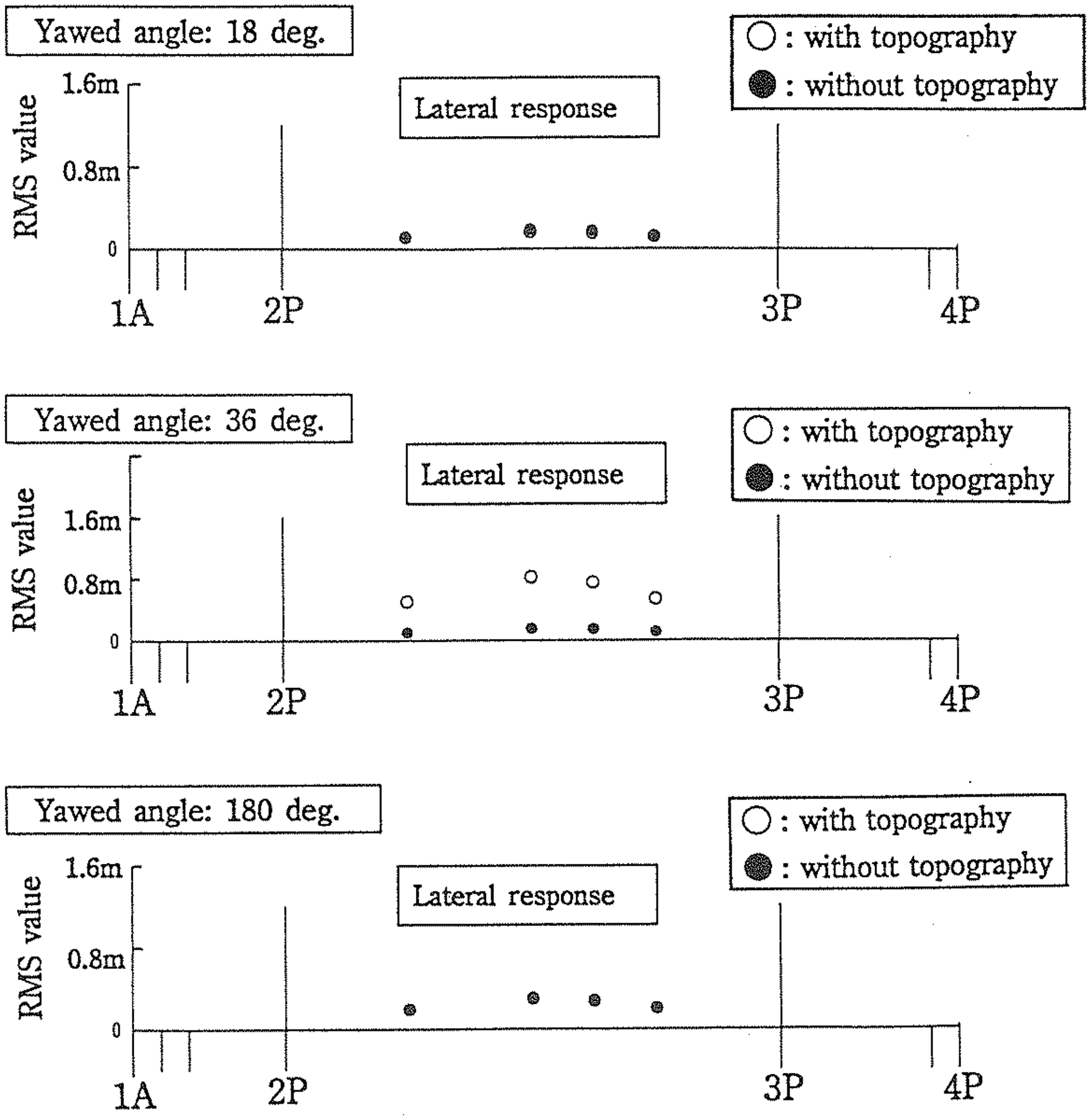


Fig.7 RMS value of girder's gust response

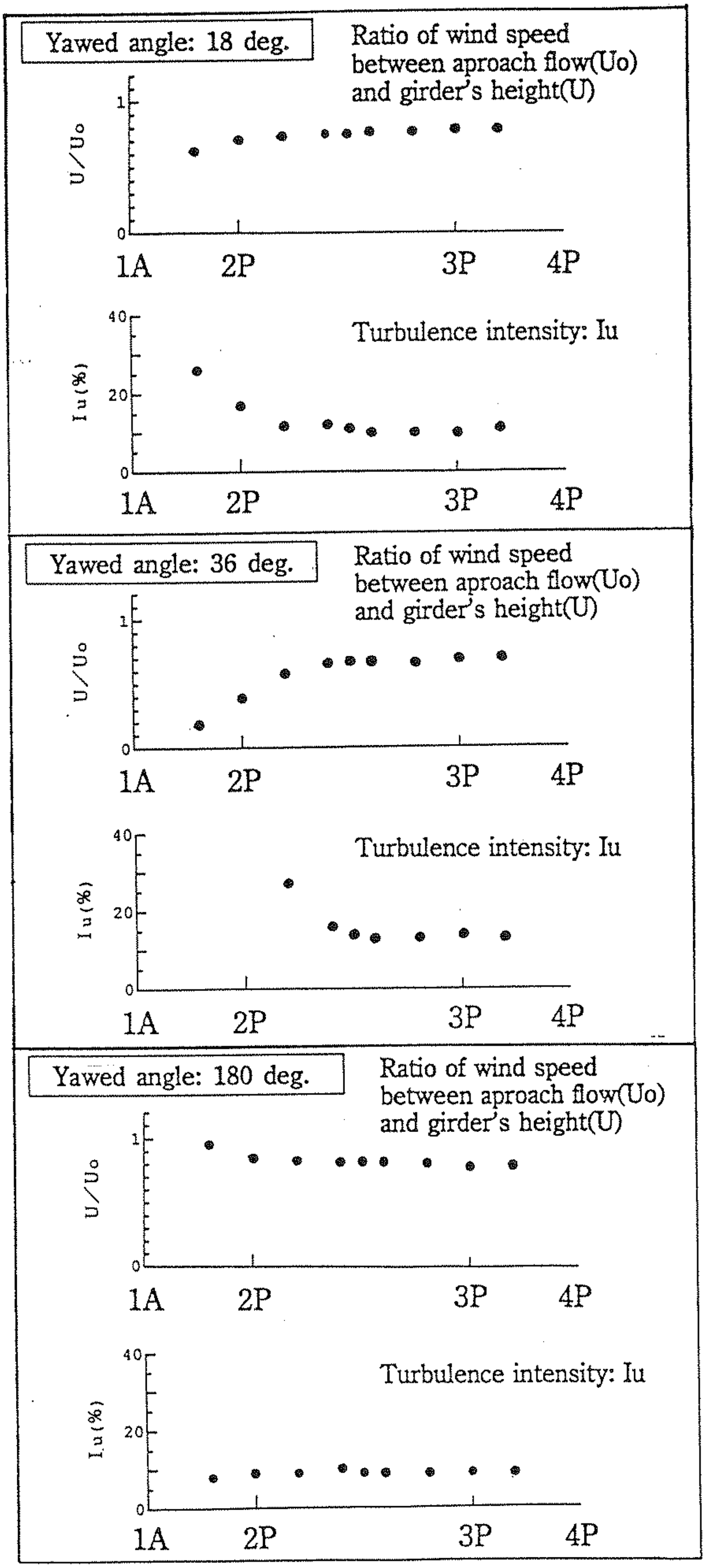
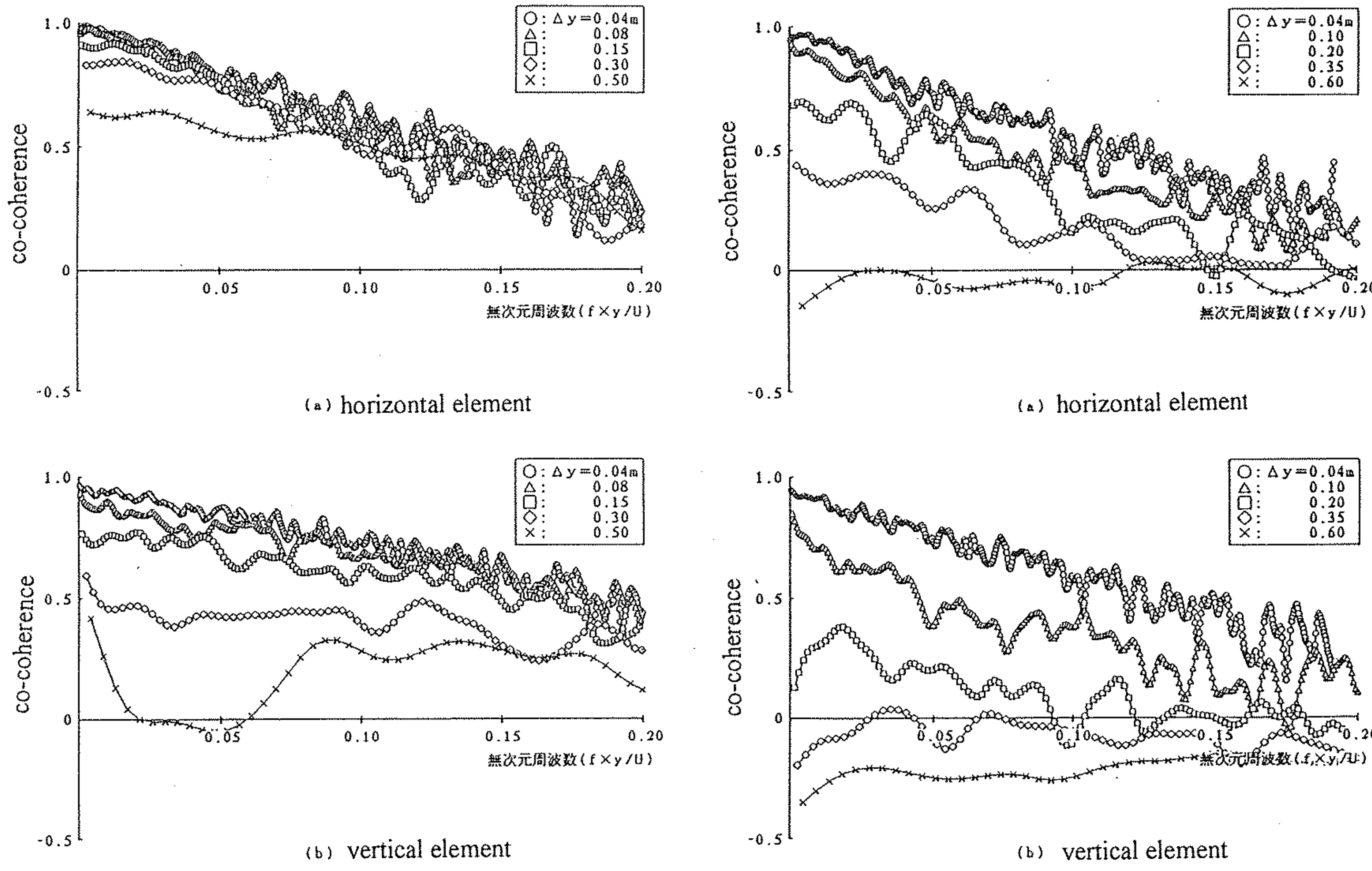


Fig.8 Wind characteristics along bridge axis



(a) horizontal element

(b) vertical element

(1) $\beta=36^\circ$

(a) horizontal element

(b) vertical element

(2) $\beta=180^\circ$

△ y:distanse from the center of center span,direction is from the center of center span to 2P tower

Fig.9 Co-coherence of fluctuating wind speed at two places

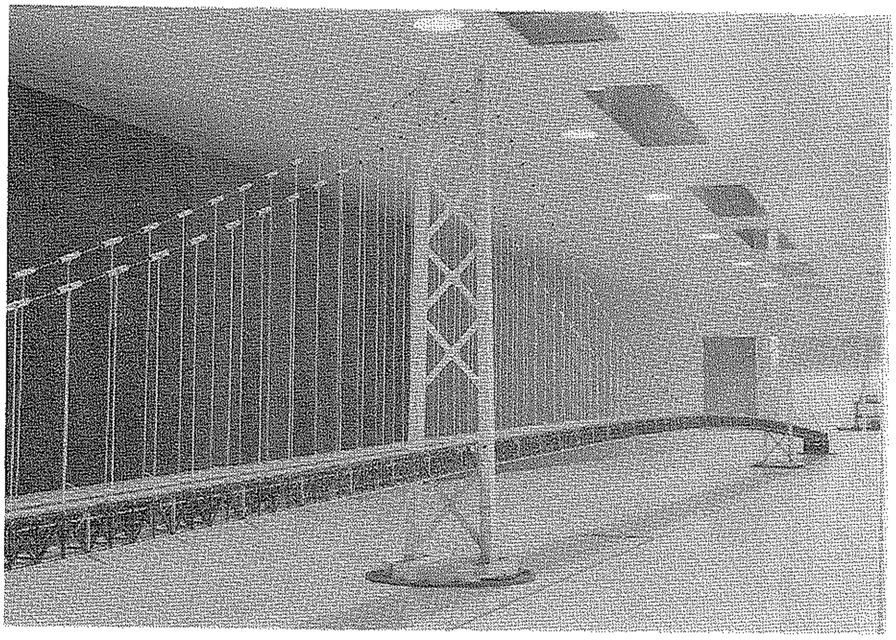


Photo 1 Full model test of the Akashi-Kaikyo Bridge

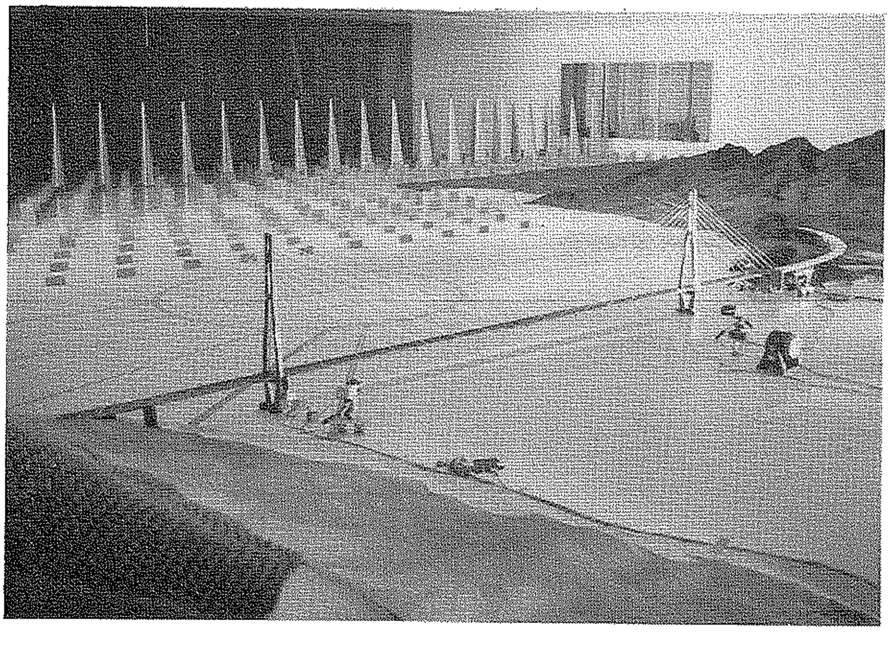


Photo 2 Model of the Tatara Bridge for the wind tunnel study in turbulent flow