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Aerodynamic Behaviour of the Cable Stayed Bridge Toyosato Ohhashi

Comportement aérodynamique du pont haubané de Toyosato Ohhashi

Aerodynamisches Verhalten der seilabgespannten Toyosato-Ohhashi-Brücke

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Abstract

This paper describes the aerodynamic behavior of a cable-stayed girder bridge. The wind tunnel experiment was conducted at relatively large Reynolds numbers by using a sectional model, which was 1/20 scale of a prototype.

The results show that the cable-stayed girder bridge with a trapezoidal closed cross section is always stable against a horizontal wind. However, some restricted motions could occur in an inclined wind to a horizontal direction with a comparatively low wind velocity and not so large amplitudes.

To make clear the aerodynamic behavior of the prototype in turbulent flow, the observation of atmospheric turbulences at the site where the prototype was constructed has been continued. By analyzing the structures in the atmospheric turbulence, it was recognized that the restricted motions, which had been observed in the wind tunnel experiment by using a smooth flow, would not occur in the prototype which was subjected to a natural wind fluctuating at random.

1 Introduction

The authers have been concerned about the response of flexible structures to a wind. Such structures as suspension bridges, tall stacks and cable-stayed girder bridges are known to be vulnerable to the effect of a wind. It has been known that a large number of bridges and stacks were damaged or destroyed by winds. Especially, the failure of the Tacoma Narrows Bridge which is a suspension bridge having a main span 853 meters long is known to be a remarkable accident. This bridge was destroyed by twisting vibrations which occurred at a relatively low wind speed of 19 m/s. After this accident, many treaties on aerodynamic behaviors of suspension bridges were presented.

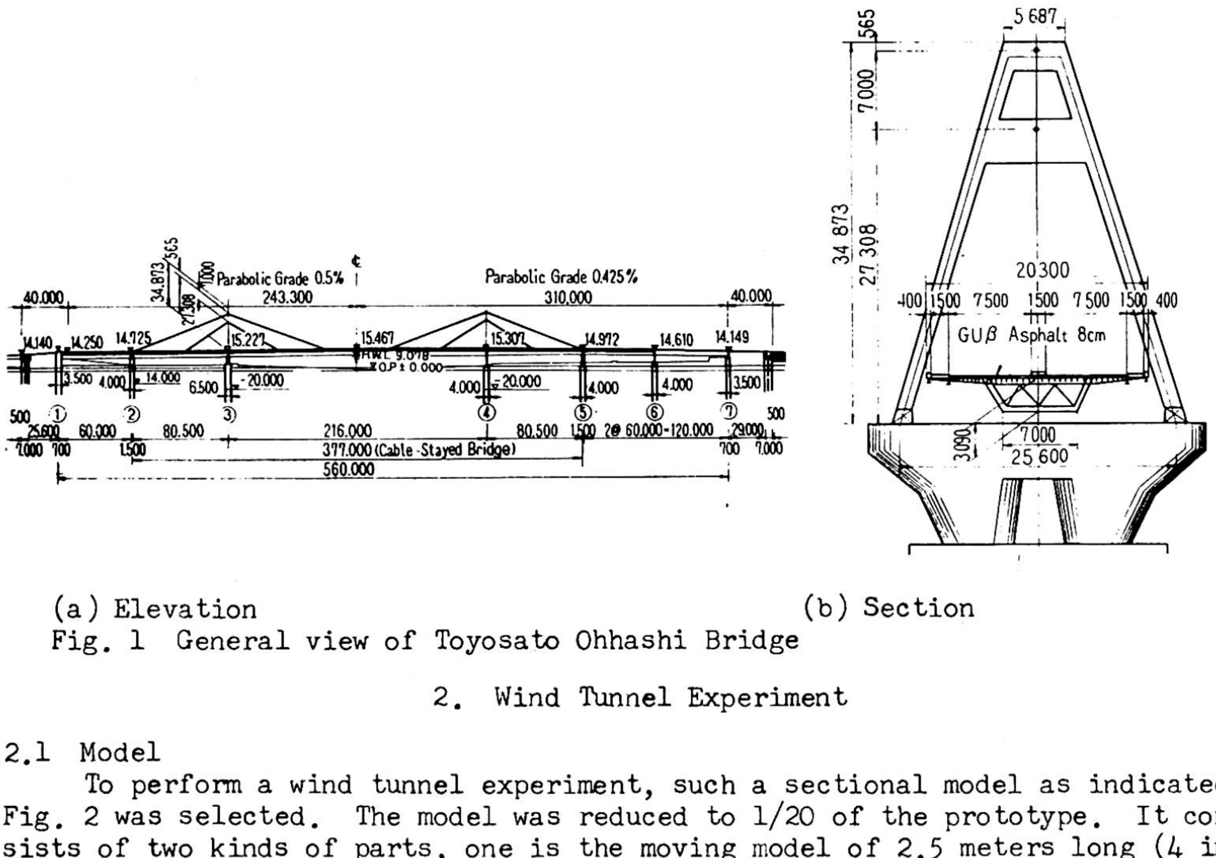
F. Bleich[1)] suggested that the aerodynamic instability of suspension bridges showed a flutter as experienced with the wings, and applied to the suspension bridges the general theory previously applied to an aeroplane by Theodorsen and others. Many studies have been done since Bleich presented his report. According to the fact that in most cases suspension bridges have complex cross sectional shapes compared with wings, experimental values can not agree well with the theoretical results.

Recently, G. V. Parkinson[2)] has suggested that a gallopping oscilation of a prismatic bar is to be considered as a nonlinear self-exited oscilation. And he stated that this theory well fit the experimental result for bluff cross section like The Tacoma Narrow Bridge.

The above-mentioned studies are mainly concerned with the aerodynamic stability of suspension bridges in a smooth flow. On the contrary, it has been pointed out that the effect of a turbulence of a natural wind must be considered. A. C. Davenport[3)] has applied a noise theory to determine the response of a suspension bridge in a turbulent flow.

The aerodynamic behavior of a bridge is different from each other, because it has different cross sectional shape, dimensions and dynamic characteristics. So, none can predict exactly its behavior without carrying out a wind tunnel experiment.

The authers conducted a wind tunnel experiment to investigate the aerodynamic stability of a cable-stayed girder bridge, Toyosato Ohhashi Bridge. (Fig. 1). Catastrophic motions and restricted motions were observed in this experiment. It was concluded that the formers appeared at so high wind velocities and the latters would not occur in a natural wind.



(a) Elevation (b) Section

Fig. 1 General view of Toyosato Ohhashi Bridge

2. Wind Tunnel Experiment

2.1 Model

To perform a wind tunnel experiment, such a sectional model as indicated in Fig. 2 was selected. The model was reduced to 1/20 of the prototype. It consists of two kinds of parts, one is the moving model of 2.5 meters long (4 in Fig. 2). It has a supporting shaft along the center axis of the model (2 in Fig. 2). The other parts are end plates and dummy models of 0.1 meter long (1 and 3 respectively in Fig. 2). The existence of the end plates and dummy models will be useful for eliminating three-dimensional effects of a wind stream.

The model was manufactured minutely so that it might resemble the prototype in detail, and its weight and moment of inatia were 68.8kg and 65.8kg.cm.sec. respectively.

2.2 Test Procedures

The model was supported horizontally in the wind tunnel by using eight coil springs so as to move vertically in the plane of the tunnel cross section and rotate about the supporting shaft and fixed by piano wires not to move windward. Natural frequency of the vertical vibration of the model was varied by changing a spring constant, and natural frequency of the rotational vibration was varied by changing a distance between the opposite springs. Structural damping of the model was varied by using magnet dumpers, changing an intencity of magnetic forces and a location of the dampers, and damping coefficients of the both of vertical and rotational vibration were controlled freely.

Accelerations and displacements of the vibrating model were measured by accelerometers of wire strain gauge type and linear transformers, respectively. Wind pressures were measured by an alcohl manometer.

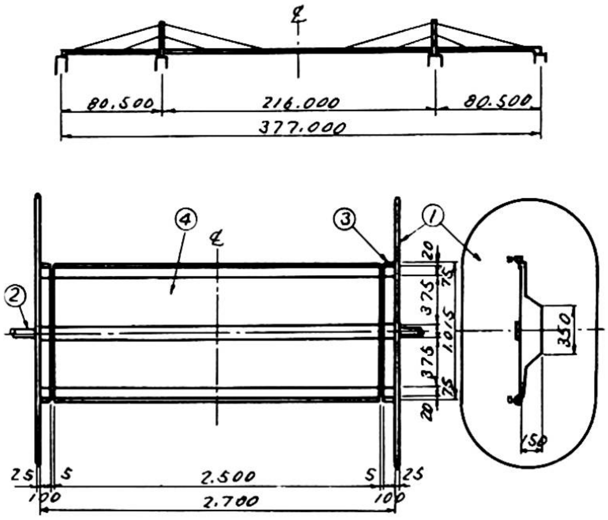


Fig.2 Prototype and its wind tunnel model.

The tests were conducted at Reynold's numbers of $1.0\times10^5/2.0\times10^6$, which were considerably higher than at ordinary dynamic tests.

Static tests were conducted at constant Reynold's numbers of 6.7×10^5 and 1.0×10^6.

The typical examples of the dynamic tests are shown in Table 1.

2.3 Test Results

(a) Static Tests

The drag, lift and moment coefficients of air forces were calculated with measured data. There are no significant differences among each coefficient which is obtained at the different Reynold's number. These coefficients of the air forces are compared with the other types of models, namely a truss type and a wing type as indicated in Fig. 3.

(b) Dynamic Tests

i) Catastrophic Vibrations

When an angle of attack for the model is zero degree, no catastrophic vibration can be observed in all the range of wind velocity, corresponding test numbers are A-1, 2, 3 in Table 1. When the angle of attack exists, catastrophic vibrations occur at relatively low wind velocities, corresponding test numbers are B-1, 2 and C-1, 2, 3, 4 in Table 1.

ii) Restricted Vibrations

When the model has a positive angle of attack, vibrations are observed at lower wind velocities than the velocity at which the catastrophic vibrations occur. These vibrations disappear when the wind velocity increases to some more high values. These phenomena are so cal-

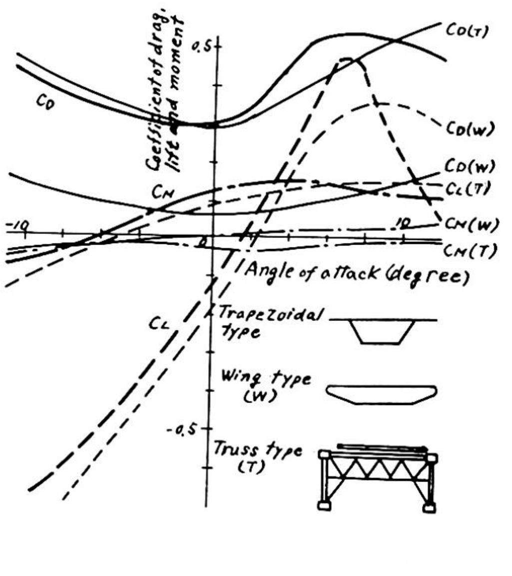


Fig.3 Coefficients of air forces compared with the other types of bridge sections.

led "restricted vibrations". Amplitude response curves of these phenomena are shown in Fig. 4 (a) and Fig. 4 (b).

Table 1. Summary of tests and results

Test number	α deg.	Nz c/s	Nθ c/s	Vc m/s	Vz m/s	Tz sec	Vθ m/s	Tθ sec	Sz	Sθ
A - 1	0	4.28	5.25	119	-	-	-	-	-	-
A - 2	0	3.08	3.82	108	-	-	-	-	-	-
A - 3	0	3.11	3.27	200	-	-	-	-	-	-
B - 1	3	4.25	5.25	67	4.3	480	24	100	0.18	0.17
B - 2	3	5.00	5.22	52	4.1	480	17	105	0.18	0.17
C - 1	5	1.30	2.66	72	4.6	169	30	55	0.11	0.15
C - 2	5	3.07	3.83	59	4.0	250	31	-	0.11	0.14
C - 3	5	3.08	3.16	46	4.1	244	38	51	0.11	0.15
C - 4	5	3.10	2.57	86	4.8	185	31	-	0.11	0.19

Note: Nz, Nθ : Frequency of model.
Vc : Critical Velocity for catastrophic vibration.
Vz, Vθ : Wind Velocity at which restricted vibration occur.
Tz, Tθ : Time during which amplitude of restricted vibration is growing.
Sz, Sθ : Strouhal number of model.
Suffixes z and θ indicate vertical and rotational vibrations respectively.

It is well known that in case of the catastrophic vibration, the amplitudes grow rapidly in a short time to catastrophic magnitude from a rest position. On the contrary, the restricted vibrations observed in these tests were mild. It took a very long time to attain to stationary amplitudes.

The vertical or rotational vibration appeared independently with proper natural frequency. In some cases the both vibrations were observed at the same time, each frequency of the both vibrations were near its natural frequency and not combined together.

The damping coefficients of the model were changed and the corresponding response curves are shown in Fig.4 (a). The amplitudes decrease as the damping coefficients increase, but no strong relation between the amplitudes and the damping coefficient can be found in these tests.

The wind velocity at which the restricted vibration attains its maximum stationary amplitude is different in each test which has a different natural frequency and angle of attack. If the Strouhal numbers of the vibrating model are defined as follows: $S=Nh/V$, where N is vertical or rotational natural frequency

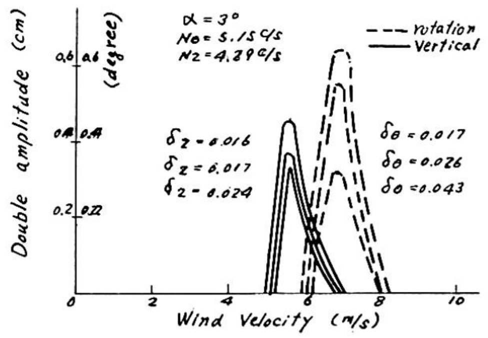


Fig.4 (a) Amplitude response curves

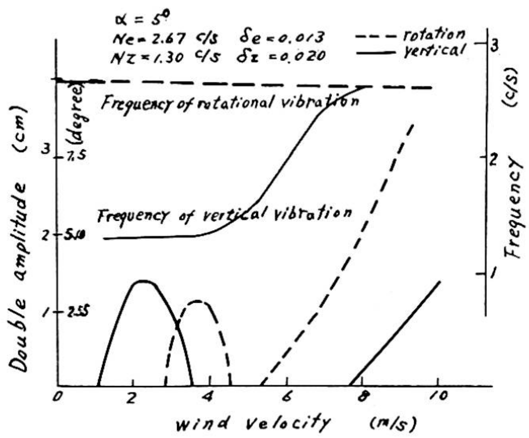


Fig.4 (b) Amplitude response curves

of the model, h shows horizontal projection of a height of the model and V is wind velocity at which the amplitude response attains the muximum value. In cases of angle of attack $\alpha=5^{\circ}$, corresponding test numbers are C-1, 2, 3, in Table 1, the Strouhal numbers are $S \doteqdot 0.17$ for the rotational vibrations and $S \doteqdot 0.11$ for the vertical vibrations respectively. In cases of angle of attack $\alpha=3^{\circ}$, corresponding test numbers are B-1, 2 in Table 1, the Strouhal numbers are $S \doteqdot 0.17$ for the both of the vertical and rotational vibrations.

K. Klöppel[4] and T. Yamaguchi[5] measured the Strouhal numbers of the models whose cross sectional shapes were similar to the model handled in this paper. They showed that the Strouhal numbers of the models were about S = 0.12. Their models were simply designed and made of wooden plates, on the contrary the model herein was closely resembled to a prototype having handrails, wheel guards, etc. According to the cross sectional shape of the models, the frequencies of wake voltices discharged from the models seem to be different from each other sensitively. Those of the model herein were slightly higher than those of their models, and the Strouhal numbers of the model herein were slightly enlarged.

3. Safety of Prototype

3.1 Critical Velocities for Catastrophic Vibrations

From the previous section the critical velocities at which the model caused catastrophic vibration were obtained. The models were arranged to satisfy the aerodynamic similarity, so the critical velocities of the model prototype could be calculated from those of the model. The critical velocities of the prototype are shown in Table 1. In cases of angle of attack $\alpha=0^{\circ}$, the critical velocities are very high. If a safety factor for the critical velocity of a catastrophic vibration is assumed as f = 1.2*), the allowable maximum wind velocity is estimated from the critical velocity in Table 1 to be $V_a=V_c/f=V_c/1.2$. In cases of angles of attack $\alpha=3^{\circ}$ and $\alpha=5^{\circ}$, the critical velocities are relatively low compared with a stormy wind velocity.

It will be necessary to examine if such critical velocities are dangerous for the prototype or not. It is useful to apply the relation[6] between angle of attack and velocity of a natural wind observed at the Severn Bridge in England and the Akashi Narrows Bridge in Japan to examin the above question. (Fig.5). According to the results of the above observations, the maximum wind velocity drops as the angle of attack increases, the maximum wind velocities are found to be 27 m/s and 10 m/s for the angles of attack of the wind $\alpha=3^{\circ}$ and 5° respectively, where the velocities are the average values during 30 seconds.

The prototype has been constructed at an open field, so that the abovementioned fact is applicable to this case. Namely, the prototype does not cause a catastrophic vibration corresponding to the model which has a positive angle of attack.

*) This value is specified at "Standard Specification for the design of the Honshu-Shikoku Renrakukyo (Long Span Suspension Bridge) against wind" 1967 (in Japanese).

3,2 Safety against restricted vibration

It has been studied that a restricted vibration appears at a very low wind velocity, for example a vertical vibration occurs at the wind velocity V = 4m/s if a natural wind flows having a positive angle of attack $\alpha=5^{\circ}$.

The amplitudes of restricted vibrations of the prototype were predicted from the experimental data, using the theory by F. B. Farquarson[7]. The theory is based on the following assumption that the aerodynamic damping in the wind of a given velocity can be expressed by a power series equation of amplitude. The amplitudes of the prototype predicted with the above theory are shown in

Table 2. In this calculation a vibration mode of the prototype was assumed to be of the first mode. In cases of vertical vibrations the amplitudes of the maximum fiber stresses are not so large, and in cases of rotational vibrations the amplitudes of the maximum shearing stresses are relatively large, however the corresponding wind velocities at which the amplitudes attain the maximum values are higher than those of the vertical vibrations.

Table 2. Maximum amplitudes and stresses of prototype due to restricted vibrations and corresponding wind velocities.

Test number	α deg	Vertical Vibration			Rotational Vibration		
		η max cm	σ max kg/cm^2	V m/s	θ max deg	τ max kg/cm^2	V m/s
B - 1	3	2.6	32	4.2	0.36	359	30
B - 2	3	5.1	62	4.6	0.28	244	30
C - 1	5	14.5	177	7.6	0.80	700	34
C - 2	5	13.9	170	8.3	-	-	40
C - 3	5	11.0	134	8.1	0.38	311	37
C - 4	5	11.6	141	8.5	0.52	455	30

As indicated above, the vertical restricted vibrations occur at very low wind velocities when the wind has an angle of attack. It is doubtful if the prototype actually vibrates in a natural wind as indicated in the next section, because the natural wind flows horisontally in average for time and space at an open field, and has an angle of attack fluctuating positively and negatively at random with a relatively high frequency. On the other hand, the restricted vibrations grow very slowly, it takes more than 100 seconds long to attain the maximum stationary amplitude from the rest position in the cases of the vertical vibrations.

4. Aerodynamic Behavior of Prototype in Turbulent Flow

To see whether the above assumption is true or not, the observations of natural wind have been made at the point where the prototype was constructed, and at the same time the behavior of the bridge due to wind has been observed.

No restricted vibration has been able to be observed so far. Vertical components of the wind were analyzed with the observed data. One of these is shown in Fig.6, in which the full lines show the theoretical values calculated from the power spectrum of vertical component of a wind proposed by H. A. Panofsky and R. A. McCormic[8]. This figure shows the maximum angle of attack of a wind as a function of time during which an angle of attack is averaged. In this case the mean wind velocity is about 10 m/s. The angle of attack of a wind decreases as the time increases.

It can be concluded that a wind does not continue to flow in the constant direction at negative or positive angle of attack for a long time,

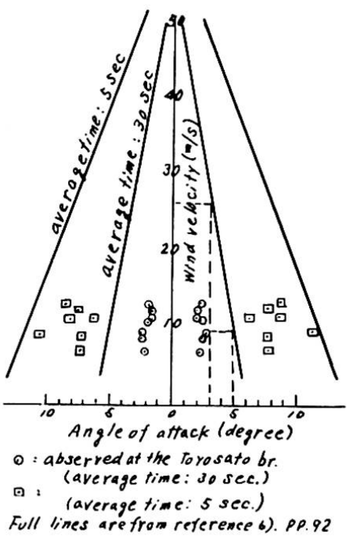


Fig.5. Wind velocity and angle of attack.

and such a wind can not develop a restricted vibration at all. That is to say, it is recognized that there is no natural wind which enables the prototype to cause the restricted vibration which was observed in the wind tunnel experiment.

5. Conclusions

The following results could be obtained from the wind tunnel experiment concerning to the cable-stayed girder bridge.

(1) When no angle of attack of a wind exists, this type of bridge is considerably stable in terms of an aerodynamic stability.

(2) When a positive angle of attack of stationary wind exists the model gives rise to the restricted vibrations at very low wind velocities.

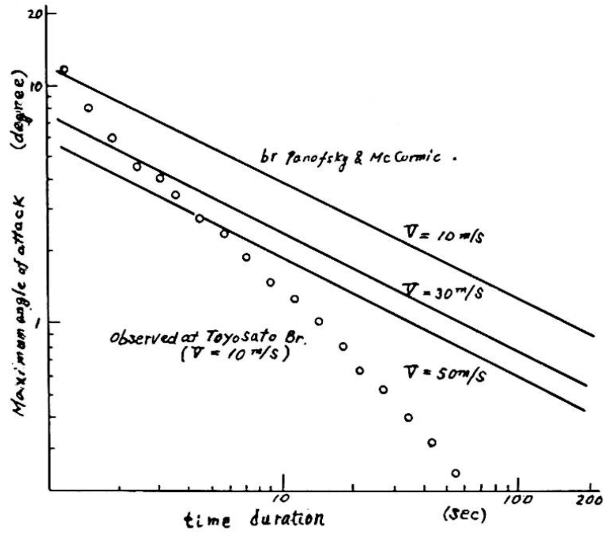


Fig.6 Maximum angle of attack of natural wind.

(3) Both vertical and rotational amplitudes of the restricted vibrations of the prototype in the stationary wind were predicted. As a result, it was found that these amplitudes would not grow to a significant quantity.

(4) It takes more than 100 seconds for the vibration to attain a maximum stationary amplitude from its rest position in case of vertical vibration of the prototype.

(5) From the field measurements, it was found that a natural wind could not cause the restricted vibrations. Besides, no vibration of the prototype has been observed up to now.

Acknowledgment

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Summary

Zu make clear the aerodynamic characteristics of a cable-stayed bridge (Toyosato Ohhashi Bridge) with trapezoidal cross section, the wind tunnel investigation has been carried out using two-dimensional model with linear scale of 1:20 in comparatively high Reynold's number.

The investigation has shown that the aerodynamic instability will not be induced in high wind which may be experienced at the site of actual bridge.

The small stationary amplitude vibrations, so-called restricted vibrations, grew up slowly in smooth airflow inclined upwards 5 degrees to horizontal. However, it is recognized from studying the three-dimensional effect of actual bridge that the restricted vibration may not be considered to occur in turbulent airflow such as natural wind which has been measured at the site.