Wind-resistant design of cables for the Tatara bridge

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Summary

The stay-cables of the Tatara Bridge have a much lower natural frequency than those of other bridges because of their longer length. Wind tunnel tests were conducted to study their rain vibration characteristics in low frequency ranges as well as to examine the efficiency of vibration control methods using an aerodynamic measure. As a result, it was found that indenting the surfaces of cables improves the aerodynamic stability and has less drag force than that of cables with roughened surfaces. Finally, the aerodynamic measure was applied to the cables of the Tatara Bridge.

1. Introduction

The Tatara Bridge, with a center span of 890 meters, is the longest cable-stayed bridge in the world(Fig.-1) at the completion. It connects two islands, Ikuchijima and Ohmishima, on the Onomichi-Imabari route of the Honshu-Shikoku Bridge. This bridge employs a composite structure of steel and PC: the dead-load imbalance between the center span and the side spans, caused by the side spans being shorter than the center span, is compensated by PC girders installed at the end of the side spans. The cables are anchored in two planes of a fan-shaped arrangement. Each cable consists of galvanized steel wires and is coated with polyethylene (Table-1).

The typical vibrations of cable-stayed bridges caused by wind include rain vibration, wake galloping, and vortex-induced vibration. What bridges have shared in common regarding rain vibration was that they were located in relatively flat areas and that the surfaces of cables were smooth, for example, covered with polyethylene [1), 2)]. This suggested that the Tatara Bridge may also likely be subject to rain vibration. Besides, there were reports that rain vibrations could have large amplitudes, requiring additional damping, it appeared necessary to consider damping techniques adequately in advance. On the other hand, their multi-cable arrangement tends to increase the importance of reduction of the wind load of the cables. If this large wind load(the drag force) is capable of being decreased, it will be a great help in optimizing the whole configuration of the structure. In view of these circumstances, we studied the characteristics of rain vibration and discussed not only measures for vibration control but also for smaller drag force.

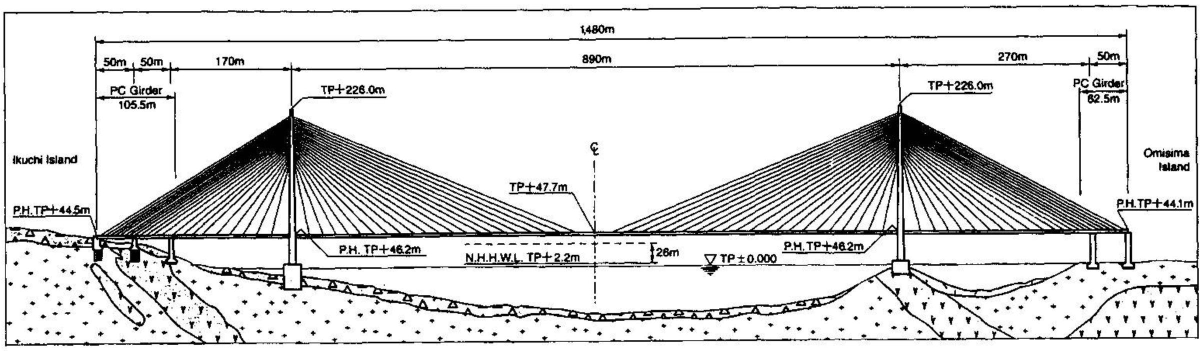

Fig.-1 General View of Tatara Bridge

Table-1 Dimension of Cables

Type	Multi-fan type (anchored in 2 planes)
Number of Cables	168 cables (21 levels)
Cable Construction	151～379 galvanized wires(ϕ 7mm)/cable
Corrosion Protection	Polyethylene coating
Cable Diameter	110～170 mm
Cable Length	108～462 m
Cable Weight	5～56 ton/cable (480～1, 194 N/m)
Frequency	0. 26～1. 05 Hz (when completed, first mode)

2. Investigations into Characteristics of Vibrations

2.1 Summary of Wind Tunnel Tests

The Tatara Bridge Cables are characterized by an extremely low natural frequency compared with those of conventional cable-stayed bridges, because of very long cable length resulting from the long span. The longest cable of this bridge was expected to have a natural frequency of about 0.26Hz while the lowest natural frequency was about 0.5 Hz in the case of other cable-stayed bridges. Thus, wind tunnel tests [3] were conducted for the primary purpose of clarifying the vibration characteristics in low frequency ranges, which was an unexplored field.

The cable model used for the wind tunnel test was a full size rigid body consisting of a 12-m long 155-mm diameter, covered by polyethylene in which a steel pipe was inserted, and both ends of which were supported by springs for the purpose of studying vibration characteristics. A full scale model was used, because it ensured similarity requirements such as adhesion characteristics of water to the cable surfaces and those of water rivulets. Rain was simulated by a spray nozzle at the exit cone of the wind tunnel and an auxiliary nozzle at the top end of the cable.

2.2 Vibration Characteristics of Tatara Bridge Cables

The wind tunnel test revealed the following characteristics (Fig.-2).
1)Rain vibration is generated even in a low frequency range (0.26 to 0.54 Hz).
2)Rain vibration occurs in the wind velocity range of about 6m/s and 12m/s, and it is generated at the lowest wind velocity when the relative angle is 45°.
3)Of the two velocity ranges, the vibration in the higher wind velocity range occurs with rivulets formed on both the upper and lower surfaces of the cable while the vibration in the

lower wind velocity is generated with rivulets formed only on the lower surface of the cable.
4)If the structural damping of the cable is 0.02 or so in terms of logarithmic decrement (δ), rain vibration is suppressed by local vibration.
5)Turbulent flow has some damping effect with respect to rain vibration.

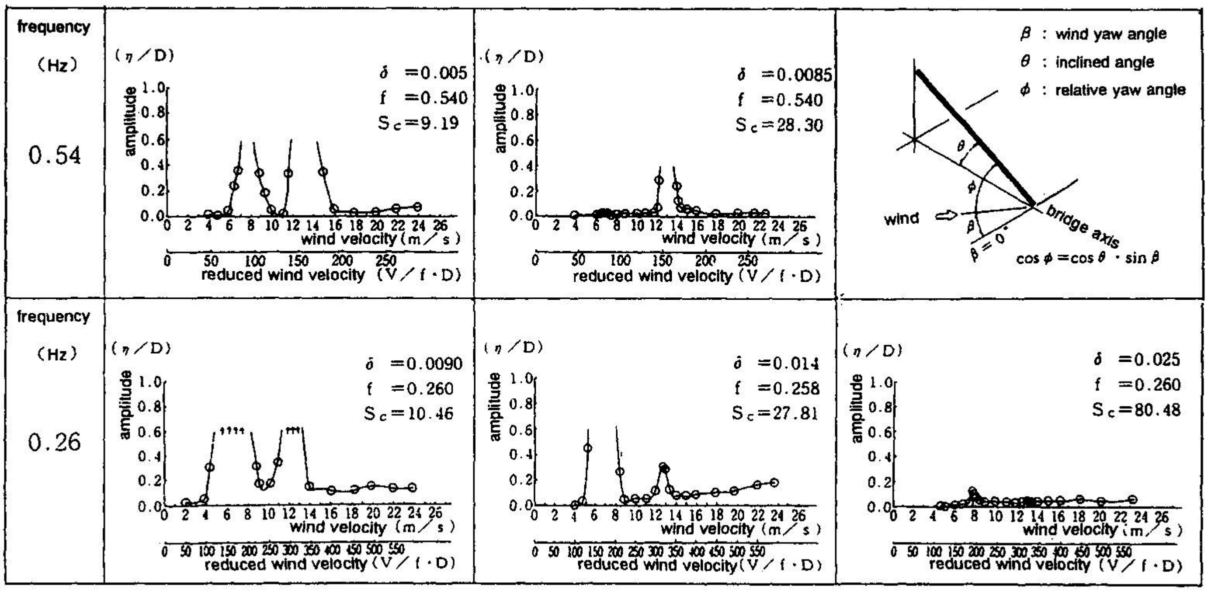

Fig.-2 Vibration Characteristics of Cable

3. Discussion of Vibration Control Measures

3.1 Application Problems of Vibration Control Measures to Tatara Bridge

As measures to control rain vibration, three methods are actually in use: tying the cables with wires, increasing structural damping of the cables by installing damping devices, and improving aerodynamic characteristics of cables by giving deformation on their surfaces. With the Tatara Bridge, an aerodynamic countermeasure was applied to the cables for the following reasons.

The tying-cable method is not effective on vibrations because wire connections form other mode shape nodes of the vibrations. Moreover, the method intended for all the high-order modes is not practical, because the countermeasure should be taken to the 11th mode for the longest cable. Regarding the installing damping device method, damping effects can be estimated by analytical calculation to a certain degree. In the case of the Tatara Bridge, the structure of the equipment and maintenance of mountings present problems, because the long cables make the size of the dampers larger and their mounting locations higher. Furthermore, this method is not desirable from an aesthetic point of view.

The aerodynamic method, which processes the surfaces of cladding material to directly suppress the exciting forces acting on the cables, does not require secondary equipment. Therefore, it is free of the problems posed by the structures of equipment, which are often encountered in the case of the tying-cable method and installing damping devices method. Various aerodynamic countermeasures have been proposed and already applied for a few bridges. In the East-Kobe Bridge [4], parallel protuberances were applied to the stay cables covered with polyethylene. Helical strakes were added on the surface of the stay cables in the Normandy Bridge. U shaped groovings were cut on the surface of the stay cables coated by polyethylene in the Yuge Bridge.

However, the Tatara Bridge had the following problems. Aerodynamic countermeasures were apt to cause a greater drag force at the design wind velocity than that of a smooth surface. For example, the drag coefficient of the cable with parallel protuberances is 1.2 at the design wind velocity, while 0.7 for a cable with a smooth surface. In the design of the Tatara Bridge, a smaller drag force is preferable, because wind load for cables with smooth surfaces comes up to about 30% of total wind load. If a cable having a larger drag force were applied to the Tatara Bridge, that would affect the structural design of the deck or the tower section. Therefore, it was quite necessary to investigate any aerodynamic countermeasure to develop a cable section with a smaller drag force and, at the same time, better vibration suppressing effects in a low frequency range.

3.2 Discussion of Aerodynamic Countermeasure

To investigate the effect of the surface configuration of cable on aerodynamic properties, three-component balance tests [5)] were carried out. The drag coefficient of a body with a circular section is a function of the Reynolds number, $Re=VD/\nu$, where V is the flow velocity; D is the representative length; ν is the kinematic viscosity. Fig.-3 shows the results of the experiment that compared drag characteristics between a cable surface having uniform roughness and that having discrete concave pattern (indented cable). In both cases, the roughness was 1% of the cable diameter. The indented cable (Photo.-1) showed a different trend from the cable with uniform roughness. Its drag coefficient (C_D) was 0.61 at a critical Reynolds number of 1×10^5. Within the range of measurements up to a Reynolds number (Re) of 5.5×10^5, equivalent to a wind velocity of about 55 m/s, the drag coefficient remained approximately constant, less than 0.7. This proved that if a cable surface is roughened discretely, drag characteristics almost equivalent to those of a smooth cable (with a circular cross section) can be obtained in the range of design wind velocity.

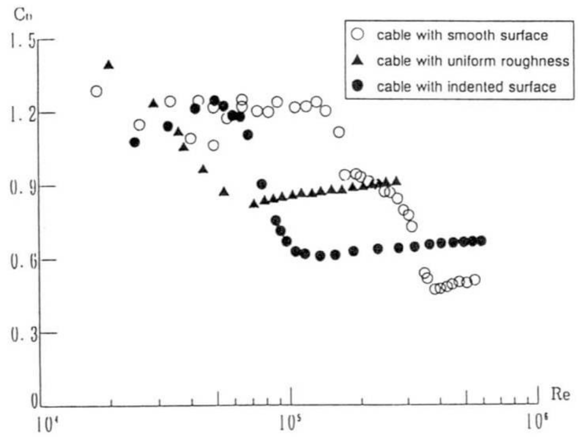

Fig.-3 Drag Characteristics

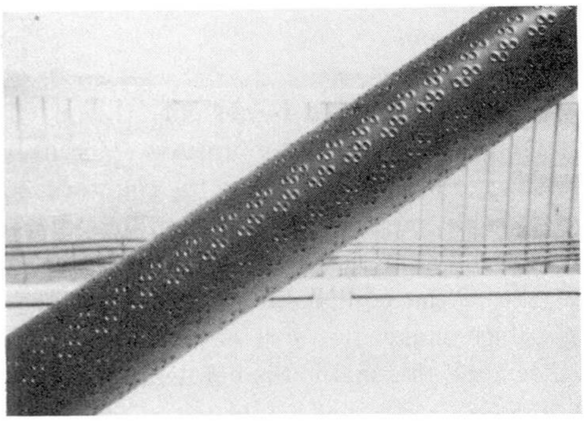

Photo.-1 Indented Cable

The characteristics of the cable having an indented pattern was analyzed through measurement of pressure distribution(Fig.-4). As for the cable with a smooth surface, in the subcritical range, the location of the separation point, θ, was about 80° for the Reynolds number (Re) of about 0.9×10^5, and the pressure coefficient on the rear surface was almost constant, showing that thorough flow separation takes place at the rear surface. In the supercritical range at a Re number of about 5.5×10^{5}, the separation point moved backward an angle θ of about 100°, and the static pressure on the rear surface was restored because of turbulence mixing, narrower wake width and so forth. On the other hand, with a cable having the indented pattern, almost no difference was noted in the pressure coefficient at Re number of 0.9×10^{5} and 5.3×10^{5}. The separation point (θ) was located at an angle of about 110°. This proves that the indented cable already reached a supercritical state at a wind velocity of about 10 m/s, which agreed well with the results of the drag coefficient measurement. With the indented cable, a negative pressure peak was observed at an angle θ of about 80° in the supercritical state. This negative pressure is estimated to suppress the formation of rivulets on the upper surface: such rivulets are one of the causes of rain vibration. This indicates that the indented cable is able to suppress rain vibration by increasing apparent Reynolds numbers.

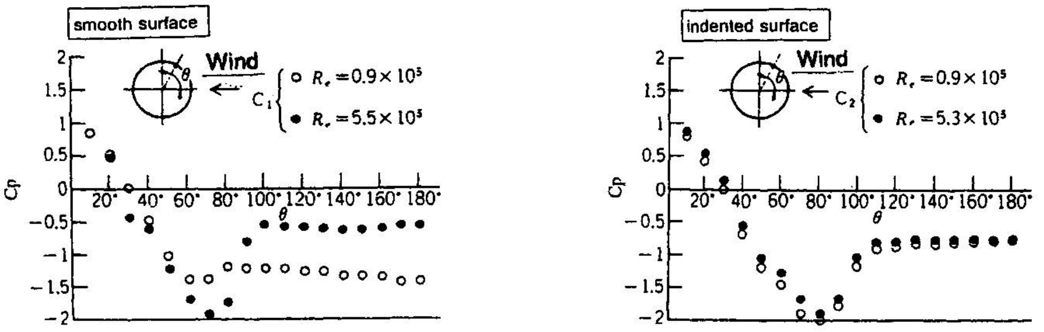

Fig.-4 Pressure Distribution of Cables

3.3 Results of Wind Tunnel Tests

As a measure to control rain vibration aerodynamically without increasing the drag coefficient, a cable surface having discrete concave roughness (indented cable) was considered. The drag coefficient of the indented cable was about 0.7, which was almost equal to the design drag coefficient of a cable with a smooth surface. In order to learn the rain vibration suppressing effects of the indented cable, vibration tests under simulated rainfall were carried out. The method used for the wind tunnel test was the same size as that indicated in 2.1. The results of tests are shown in Fig.-5. The aerodynamic characteristics of the cable are summarized as follows.

1) There was no evident vibration in a high wind velocity range in which vibration was observed with smooth cables. Some vibration was observed in a low wind velocity range, at a wind velocity of about 6 m/s.
2) Vibration in a low wind velocity range, which occurred under a limited wind velocity range, was able to be suppressed when the in-plane (vertical) structural damping (δ) of the cable was increased to 0.02 or so.
3) The vibration tended to be suppressed in turbulence flow, and the indented cable had more suppressing effects than those of smooth surfaces.
4) Frequency dependency was observed in the generation of vibration: rain vibration became less prone to occur in high frequency ranges and no evident vibration was observed in the frequency range above 1 Hz.

It is considered that the vibrations at a high wind velocity range were caused by the rivulets on upper surfaces of the cables and that suppression effects was observed as the location and the width of the rivulets changed. On the other hand, as the vibrations at a low wind velocity range were caused by the rivulets forming on the lower surfaces. It appears that the surface treatment alone was not sufficient in controlling vibration. Through rainfall experiments, it was confirmed that the indented cable had rain vibration suppressing effects in a high wind velocity range. It is considered that the indented pattern had effects on raising the apparent Reynolds number and making the flow separation point move backward. The vibration observed in a low wind velocity range around 6 m/s could be reduced negligibly to a low level in the actual bridge, considering the turbulent flow at the site. Besides, with indented cables, vibrations are limited to low-order modes below 1 Hz if they ever appear, making it easier to take installing damping measures than with cables having smooth surfaces.

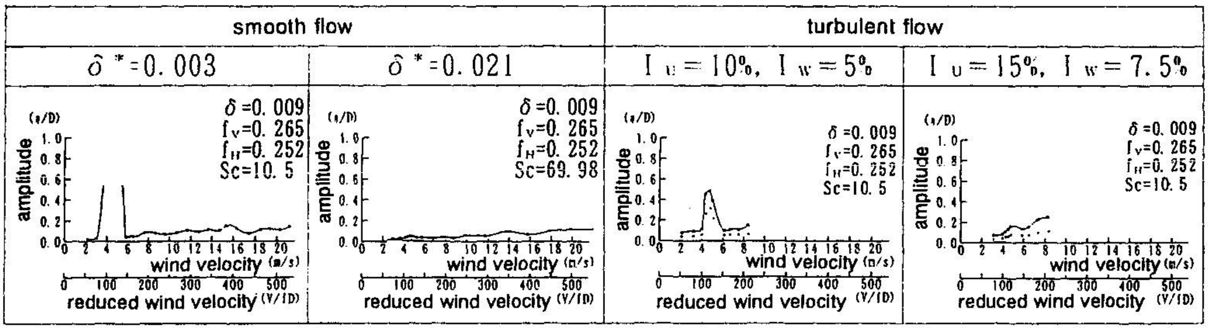

Fig.-5 Test Results of Indented Cable

4. Conclusions

In this study, vibration characteristics of the Tatara Bridge Cables were examined and wind-resistant designs using an aerodynamic countermeasure were discussed. The results obtained by the study are summarized as follows.

1) The indented cable was adopted for the Tatara Bridge as an aerodynamic measure to control rain vibration. It appears that indented cables have a sufficient suppressing effect on rain vibration, considering the turbulent flow at the site.

2) The indented cable has a drag coefficient almost equal to that of a cable with a smooth surface, resulting in decreased wind loading.

3) A structure has been employed that will allow installation of dampers, to prepare for the worst.

4) Finally, the behavior of the cables on the actual bridge has been watched since the construction phase. And no rain vibration has been noted up to now.

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