

An Investigation on Wind-Resistance and Economic Improvements of Super Long Span Suspension Bridges Synoptic Report

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**Public Works Research Institute, Ministry of Construction, Japan
Honshu-Shikoku Bridge Authority
Public Works Research Center
Hitachi Zosen Corporation
Ishikawajima-harima Heavy Industries Co., Ltd.
Kawada Industries, Inc.
Kawasaki Heavy Industries, Ltd.
NKK Corporation
Mitsui Engineering and shipbuilding Co., Ltd.
Mitsubishi Heavy Industries, Ltd.
Sumitomo Heavy Industries, Ltd.**

I, Asahi, Tukuba-shi, Ibaraki-ken, 305-0804 Japan

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By

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Synopsis:

Objective of this three years research being started in 1995 was to develop basic schemes of a 6-lane 3-span suspension bridge, which have flutter onset wind speed higher than 80 m/s notwithstanding its main span length of 2500 m and its total length of 5000 m. The first step of the research was to determine the basic dimensions of the bridge. The research was actually divided into 3 approaches; in the first approach, emphasis was placed on introducing a new cable system rather than improving the aerodynamic characteristics of a mono-box deck; in the second approach, the improvement of the aerodynamic characteristics was aimed by refining the shape of a dual-box deck; and in the last approach, new concepts were developed. The research was conducted along three ways; that is improvements of aerodynamic characteristics, structural characteristics and combination of these.

Keywords: Super long-span suspension bridge, Wind tunnel test, Aerodynamic stability, Economic saving, Flutter

DIRECTORY OF JOINT RESEARCHERS:

Public Works Research Institute, Ministry of Construction, Japan

Koichi Yokoyama, Director, Structure and Bridge Department,

Yasuyuki Fujishiro, Director, Structure and Bridge Department

Michio Okahara, Director, Structure and Bridge Department

Hiroshi Sato, Head, Structure Division

Katsuya Ogihara, Senior Research Engineer, Structure Division

Shigeki Kusahara, Senior Research Engineer, Structure Division

Hideaki Matsuno, Research Engineer, Structure Division

Kenichi Ohgi, Research Engineer, Structure Division

Hiroteru Matsufuji, Research Engineer, Structure Division

Honshu-Shikoku Bridge Authority,

Atsushi Okukawa, General Manager, Design Department,

Haruki Akiyama, Manager, First Design Division,

Nobuaki Furuya, Manager, First Design Division,

Kazuya Ogawa, First Design Division,

Kazuhiko Furuya, First Design Division,

Ryuichi Toriumi, First Design Division,

Masahiro Takeguchi, First Design Division,

Chihiro Kawato, First Design Division,

Public Works Research Center

Shigetoshi Kobayashi, Executive Director

Isao Takatori, Public, General Manager, Planning Division

Tadayuki Shimada, Special Engineer

Shinji Kondo, Special Engineer

Hitachi Zosen Corporation

Nobumichi Yamamura, General Manager, Design Division

Toshio Ueda, General Manager, Research Institute

Hiroshi Tanaka, General Manager, Design Division

Yasuhiro Matsushita, Design Division

Yukifumi Matsuoka, Design Division

Eiji Yamaguchi, Research Institute

Ishikawajima Harima Heavy Industries Co., Ltd.
Shuuichi Hikami, General Manager, Research Institute
Kazutoshi Matsuda, Manager, Research Institute
Masafumi Tokushige, Research Institute
Masanao Suzuki, Planning Division
Shuusaku Uejima, Planning Division

Kawada Industries, Inc
Shigeru Echigo, Executive Director, Research and Developing Division
Masahiro Yoneda, Manager, Research and Developing Division
Kimio Kimura, Construction Division
Yasushi Uchiumi, Manager, Research and Developing Division
Katsunori Ohno, Research and Developing Division
Yoshihiko Tamaki, Research and Developing Division

Kawasaki Heavy Industries, Ltd.
Kazushi Ogawa, General Manager, Engineering Division
Hideki Shimodoi, Manager, Engineering Division
Toshio Saito, Engineering Division
Yasusato Hashimoto, Engineering Division
Chiaki Nogami, Engineering Division
Kusumi Odate, Engineering Division

NKK Corporation
Nobumitsu Fujisawa, General Manager, Research Institute
Katsuaki Takeda, General Manager, Research Institute
Takuya Murakami, Research Institute
Mikio Koizumi, General Manager, Planning Division
Atsunori Kawabata, Manager, Engineering Division
Michiaki Takao, Engineering Division

Mitsui Engineering and shipbuilding Co., Ltd.
Hiroo Inoue, General Manager, Engineering Division
Kazuyoshi Narita, General Manager, Engineering Division
Kenichi Sano, Engineering Division

Masakazu Sakai, Engineering Division
Ryuuichirou Ohmori, Design Division
Hiroyoshi Morishima, Engineering Division
Kenichi Hayashi, Engineering Division
Masayuki Akase, Engineering Division
Fumitaka Yoshizumi, Engineering Division

Mitsubishi Heavy Industries, Ltd.
Yujin Henmi, Manager, Design Division
Toru Saito, General Manager, Research Institute
Akihiro Honda, Manager, Research Institute
Shigeto Hirai, Research Institute
Shinsuke Tokoro, Research Institute
Nobuyuki Sasaki, Manager, Research Institute
Ichirou Masuda, Manager, Design Division

Sumitomo Heavy Industries, Ltd.
Masao Miyazaki, General Manager, Engineering Division
Miyuki Nakamura, Manager, Engineering Division
Yoshiaki Saito, Engineering Division
Kouji Kazama, Engineering Division
Hiroshi Kubota, Engineering Division

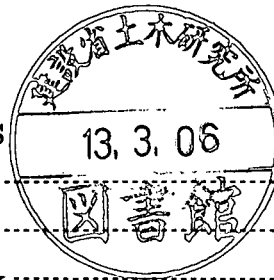


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Summary of a Three-Year Research

1. Outline of Research Results

Objective of this three year research being started in 1995 was to develop basic schemes of 6-lane 3-span suspension bridge, which have flutter onset wind speed higher than 80 m/s notwithstanding its main span length of 2500 m and its total length of 5000 m. The first step of the research was to determine the basic dimensions of the bridge. The research was actually divided into 3 approaches; in the first approach, emphasis was placed on introducing a new cable system rather than improving the aerodynamic characteristics of a mono-box deck; in the second approach, the improvement of the aerodynamic characteristics was aimed by refining the shape of a dual-box deck; and in the last approach, new concepts were developed. The research was conducted along three ways; that is improvements of aerodynamic characteristics, structural characteristics and combination of these.

In the investigation on the improvement of the aerodynamic characteristics, effects of fairing, air-gap, wind barrier, etc. were studied for the mono-box deck, and flutter wind speed up to approximately 80 m/s (i.e., the targeted value) was achieved. Furthermore, aerodynamic stability of the dual-box deck was remarkably improved by installing a vertical stabilizer, guide vanes, fairing, protruding plates under the girder, outside wind barrier and so on. In addition to the coupled flutter, studies were done for vortex-induced oscillation which appeared at relatively low wind speed and for 4-lane bridges which were aimed to reduce the construction cost. New cross sections were investigated such as oval shape, polygonal shape, diamond shape, hexagonal shape with air-gap, combined mono-box and dual-box and so on.

As for investigation on improvement of the structural characteristics, promising technologies developed here were cross stay, horizontal stay, diagonal stay and so on. Gravitational rigid frame was an example of the newly proposed structural idea.

Finally, as a combination of the aerodynamic improvement and structural improvement, the investigated ideas were the mono-box deck with 3 main cables and triangle stay system, dual-box with 4 main cables and cross hanger, combination of crossed main cables, cross stay and center wind barrier, and combination of suspension and cable-stayed bridge with combination of mono and dual boxes.

2. Investigation on Aerodynamic Improvement

2.1 Aerodynamic Characteristics of Mono-box Deck

At first aerodynamic characteristics of mono-box deck were investigated through section model test or 2 degree of freedom flutter analysis with measured aerodynamic derivatives. Secondly, aerodynamic stability was evaluated through 3-dimensional flutter analysis for some cross sections that showed good performance in the first step. The flutter analysis was performed with aerodynamic derivatives and measured 3-coefficients of air-flow force (drag, lift and moment). The basic scheme of investigated suspension bridges had 6 lanes, with sag ratio of 1/9. The allowable stress of the main cable was 1000

N/mm². The mass of the bridges was reduced to about 35 ton/m. Main conclusions of this investigation are as follows.

(1) Effect of fairing shape

1) Changing the fairing shape, the flutter onset wind speed was raised about 10 % compared with that of the prototype. In addition, the flutter speed was raised about 10 % with refinement of position of rails for movable inspection platform and shape of handrails (Fig.-2.1.1).

2) Change of fairing at the tip of the stiffening girder (Fig.-2.1.2) improved the flutter wind speed by about 10 %.

(2) Effect of center barrier

When the barrier was stuck out from the center of the stiffening girder to both upward and downward direction, the flutter wind speed was increased and vortex-induced oscillation in the bending mode was also significantly suppressed. Too larger height of the barrier, however, caused random oscillation in the bending mode, which meant that the selection of a suitable protruding height was important. Combination of the center barrier and appropriate shape of the girder-tip fairing (Fig.-2.1.2) raised the flutter wind speed by about 20 %.

(3) Effect of air-gap

1) As for the depth of the stiffening girder, 5 m and 3 m were relatively good among 3 different depths of 7 m, 5 m and 3 m.

2) When the girder depth was 5m and the width of air-gap was 3 m, improvement of the flutter wind speed was only about 20 %.

3) When the girder depth was 5 m, the air-gaps at the center and shoulders of the girder, increased the flutter wind speed at negative angle of attack, however it decreased the speed at positive angle of attack.

4) When the innermost 2 lanes and the median one were converted into open grating with solidity ratio of 50 % (Fig.-2.1.4), comparatively good flutter characteristics were obtained except for the positive angle of attack.

(4) Effect of wind barrier

1) When permeable wind barriers provided with horizontal vanes were equipped to the girder which had a depth of 5 m and air-gaps at both median and shoulders, the flutter characteristics at positive angle of attack were improved. In addition, installation of the center barrier showed best aerodynamic stability; the flutter wind speed reached near 80 m/s (i.e., the targeted value in Fig.-2.1.3).

2) Although conventional wind barrier provided at the deck-tips reduced the flutter wind speed, the barrier installed at the girder center raised the flutter wind speed. As for wind shielding effect to reduce wind speed, the barrier which had 3 m height and 66 % solidity ratio, was effective not only for on leeward lanes but also for on windward one lane. The barrier, however, increased the drag coefficient, so much attention should be paid in the design.

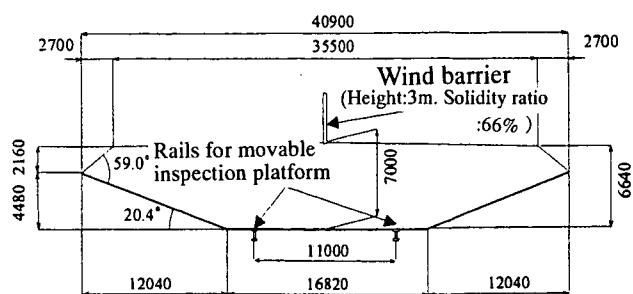


Figure-2.1.1 Fairing shape · rails for movable inspection platform · wind barrier

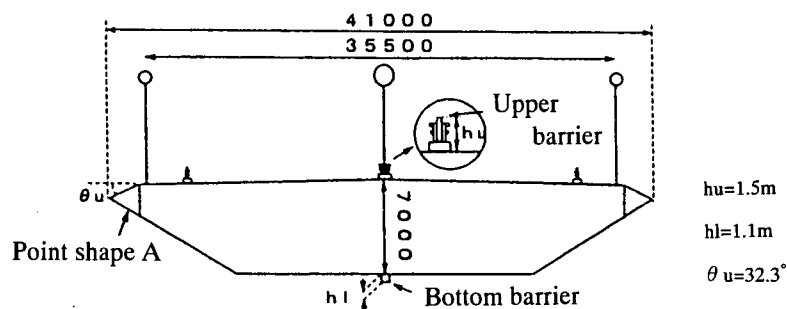


Figure-2.1.2 Girder-tip fairing · upper barrier · bottom barrier

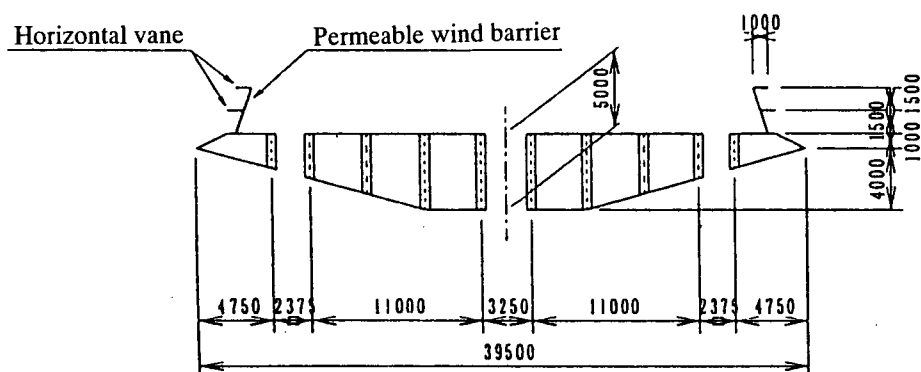


Figure-2.1.3 Horizontal vane · permeable wind barrier · center barrier with air-gap of girder

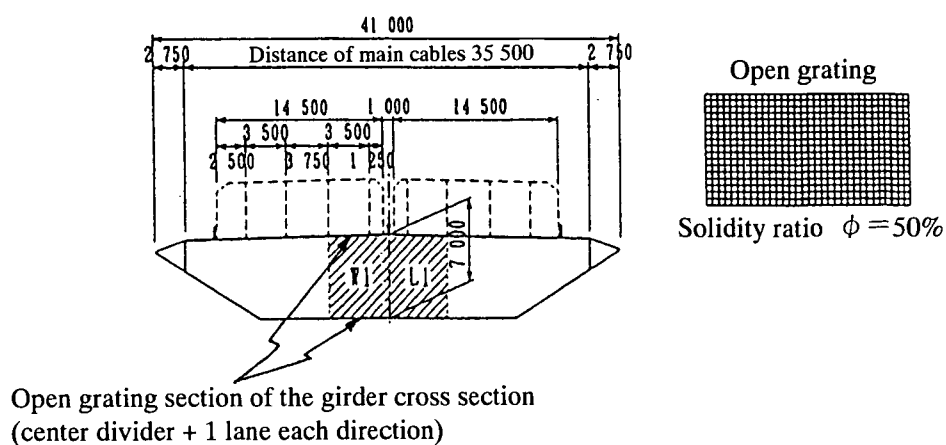


Figure-2.1.4 Open grating at center of girder

2.2 Aerodynamic Characteristics of Dual-Box Deck

Two flat box girders with center opening are called “dual-box deck” here.

Each institution proposed its newly elaborated dual-box deck referring to previously investigated cross sections, and improved the aerodynamic stability through section model tests. The applied structural scheme (e.g., the number of lanes : 6, the mass of the superstructure ≤ 40 ton/m) was the same as the mono-box deck. For the cross sections which showed relatively good aerodynamic stability, three dimensional flutter analysis were conducted.

Main conclusions obtained here are as follows:

(1) Effects of vertical stabilizer and guide vane

1) Aerodynamic stability was improved by providing center opening, and its effectivenesses were influenced by the shape of the basic cross section and width/depth ratio of the deck.

2) When a vertical stabilizer (i.e., a center barrier) was installed at the center opening of the dual-box deck (Fig.-2.2.2), the aerodynamic stability was improved. When the center opening was made the wider, its performance became the higher. The combination of 15.5 m center opening and two vertical stabilizers (Fig.-2.2.4) gave a good result.

3) When horizontal stabilizers (Fig.-2.2.1) or guide vanes (Figs.-2.2.2 or 2.2.3) were added to the vertical stabilizer, the aerodynamic stability was remarkably improved, and some cross sections successfully reached a flutter wind speed higher than 80 m/s.

4) The application of the open grating to both the innermost lanes as the passing ones contributed to keep good aerodynamic stability without widening the whole width of the deck (Fig.-2.2.3).

(2) Effect of fairing

It was found that fairings yielded a comparatively good result when the pointed angle of 60 or 70 degrees was used for the tip

(3) Effect of protuberant plate beneath stiffening girder

When fairings were symmetrical top and bottom, the flutter speed to install under-barriers (Fig.-2.2.2), vertical plates (Fig.-2.2.5) or rails for movable inspection plat forms (Fig.-2.2.5) beneath the girder could be increased. Because it reduced the aeroelastic moment, the negative deformation of torsion became small.

(4) Effect of shoulder-side wind barrier

When permeable wind barriers (solidity ratio = 30 or 50 %) were installed at shoulders or farther outside of the deck, the harmful effects on aerodynamic stability were very small (Fig.-2.2.3).

(5) Study on vortex-induced oscillation

When the intensity of turbulence became 5 to 10 % (generated by grid), vortex-induced oscillation, which occurred in smooth flow at low wind speed, was suppressed.

(6) Influence of the number of lanes

Although the above mentioned results were mainly obtained for the 6-lane bridge, almost same results were also obtained for the 4-lane bridge (Figs.-2.2.2 and 2.2.3).

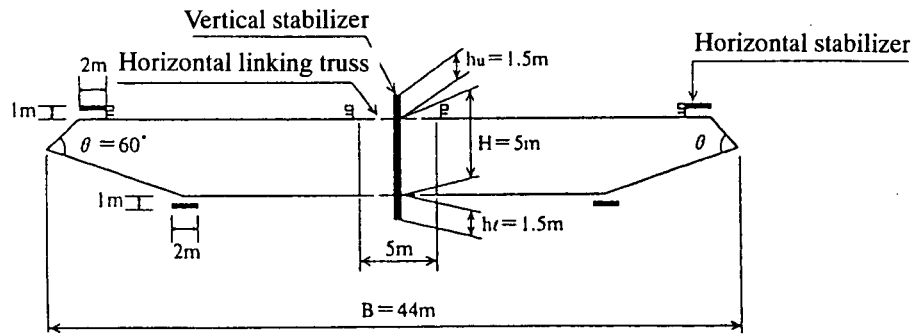


Figure-2.2.1 Vertical stabilizer · horizontal stabilizer

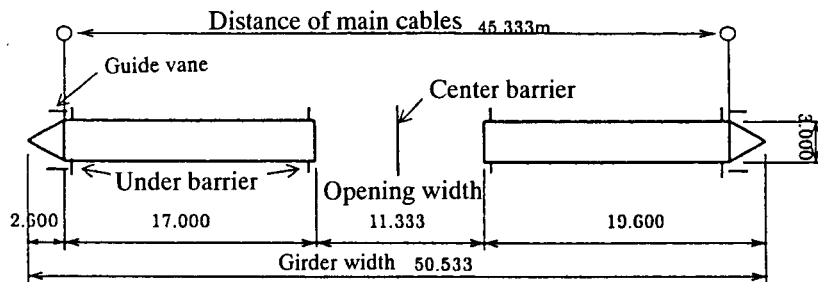


Figure-2.2.2 Center barrier · guide vane · under barrier

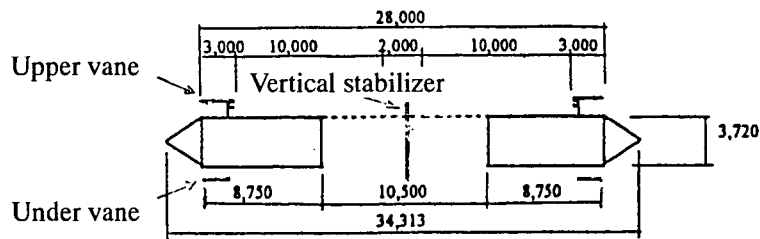


Figure-2.2.3 Vertical stabilizer · vanes

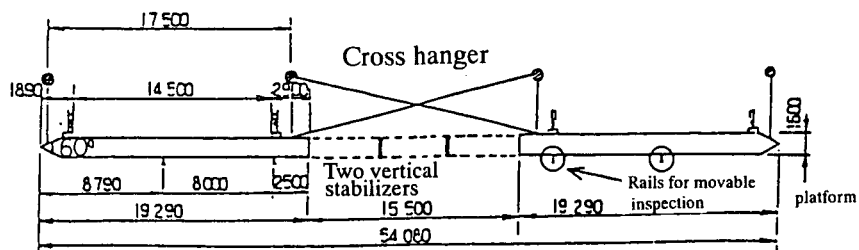


Figure-2.2.4 Two vertical stabilizers

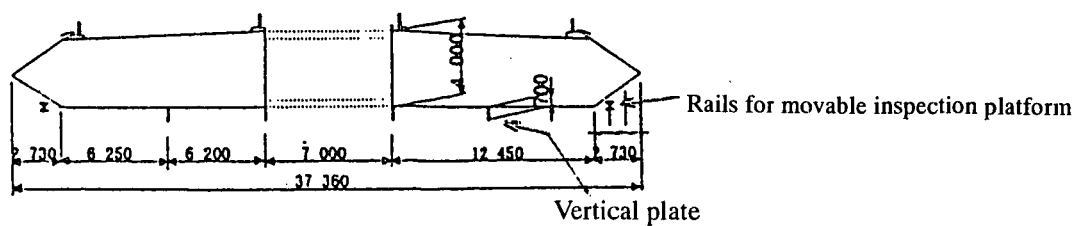


Figure-2.2.5 Vertical plate · rails for movable inspection platform

2.3 Aerodynamic Characteristics of Newly Proposed Cross Section

The main conclusions of this study are as follows:

(1) New cross sections other than mono-box deck and dual-box deck

1) Elliptic cross section and polygonal cross section

It was found that the aerodynamic characteristics of the elliptic cross section or the polygonal cross section (Fig.-2.3.1) were similar to those of the flat airfoil. Although it was difficult to find out better cross sections than the flat airfoil in the aerodynamic characteristics, these two sections were favorable because they have small magnitude of C_D (i.e., small drag force). By utilizing this concept, the flutter wind speed may be improved if torsional stiffness is increased by making the girder thick. On the other hand, it was found that dependence of the steady aerodynamic force on the wind speed was significant. Then the influence of Re number on the aerodynamic characteristics of such cross sections should be studied hereafter.

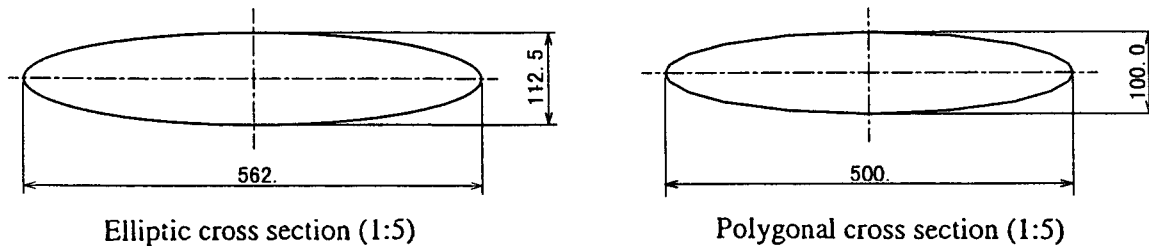


Figure-2.3.1 Elliptic cross section · polygonal cross section (model)

2) Rhombus cross section

Although it was failed to find any rhombus cross section (Fig.-2.3.2) having superior aerodynamic characteristics than the flat airfoil, its flutter wind speed was less dependent on the change of angle of attack and its drag coefficient was small. This small drag coefficient has a possibility to raise the flutter wind speed when torsional stiffness is increased.

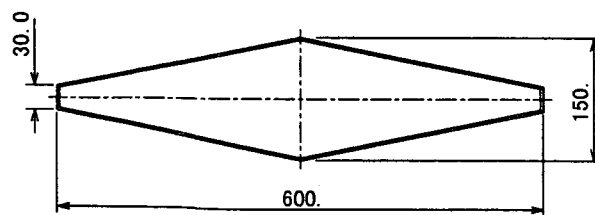


Figure-2.3.2 Rhombus cross section (model)

3) Hexagonal cross section with air-gap (Fig.-2.3.3)

Flutter wind speed can be improved by 60 % by the installation of the upper-outer barrier. In addition, the static deformation of the full bridge may be reduced if the configuration of fairings and the width of air-gap are properly organized.

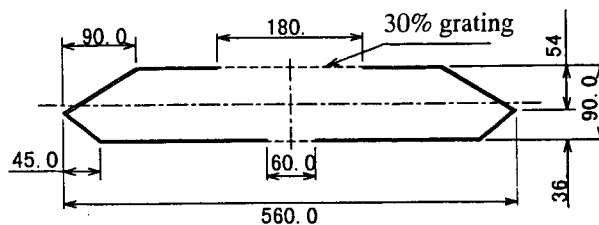


Figure-2.3.3 Hexagonal cross section (model)

(2) Combination of dual-box deck and mono-box deck (Fig.-2.3.4)

This idea was intended to increase both aerodynamic stability and economy of the bridge by using the dual-box deck to the mid-span portions which were needed to have good aerodynamic characteristics and by using the mono-box deck to the end portions of the span which was requested to have narrow width in order to avoid extra construction cost of the substructures. A main back ground of this idea was that the aerodynamic characteristics of the mid-span portions governed the flutter performance of the entire suspension bridge. The flutter wind speed higher than 80 m/s was achieved. In addition, the excessive static torsional deformation which had been an issue at an early stage of the research could be sufficiently reduced by the improvement of the cross section of the dual-box deck.

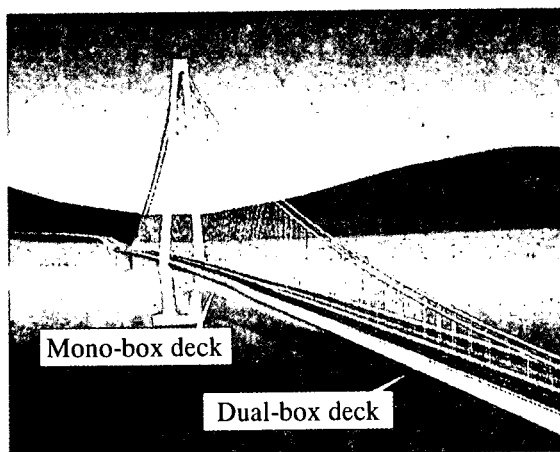


Figure-2.3.4 Combination of dual-box deck and mono-box deck

3. Investigation on Structural Improvement

3.1 Study of Cable-system

As for improvement of the aerodynamic stability by introducing cable-system, the following ideas are famous: an idea of main cables arranged over and beneath the suspended structure which was proposed during the study for the Messina Straits Crossing 2],3], an idea of decreasing the nominal span length of the main cables by arranging both inclined additional cables from the tower top and inclined struts from the tower base, which was considered for Gibraltar Straits Crossing 3] and so on. Introducing new cable-system and improving the aerodynamic characteristics are earnestly being investigated even today, and this approach can be divided into two groups: one is a cable arrangement over the entire bridge and the other is a partial cable arrangement. The former, systems are combined use of inclined stays 3], 8], 10], 19], mono-cable 4], 5], 8],10], mono-duo cables 3], 16] 17], change of cable center distance 12], 14], center-connected cable 15], storm cable 8], 10], and so on. As for the latter, cross stays 3], 4], 8], 9], 10], 13], horizontal stays 7], 11], 18] and rigid suspenders arranged at the span center 6] have been proposed. Among these, it is well known that cross stays (sometimes called as cross hangers) are very effective.

In this research, investigation of arrangement of the main cables and stays was made based on these previous study results. Main conclusions of this investigation are as follows:

(1) Arrangement of the main cables

1) Three cables (Fig.-3.1.4)

A part of the cross section of the main cables (previously two in number) was shifted along the bridge axis so that the number of the main cables became three and the polar inertia moment was thus reduced. However, this idea could not raise the flutter wind speed, which remained almost at the same speed as conventional structural system.

2) Crossing main cable (Fig.-3.1.1)

In this idea, main cable is crossing each other at the span center in order to raise the torsional stiffness of the main span. This effect can be also expected during direct lift-up operation of the deck blocks during erection. When this is applied to the mono-box deck, the flutter wind speed is increased by 20 %.

(2) Various stays

1) Cross stay

At first, optimum position of cross stays (diagonal stays) was studied, and the conclusion was that 0.3 L point for the main span and 0.5 Ls points for the side spans (L and Ls are each span length, Fig.-3.1.2) were recommended. When the cross stays were used for the mono-box girder, raise of the flutter wind speed was approximately 10 % for both cases of non-compressive stays (one sided effect) and compressive stays (dual sided effect). However, the latter had superior effect, and the best effect was obtained when the compressive stays were arranged in the main span only.

2) Combination of cross stay and other cable systems

The combination of the cross stays and the horizontal stays (Fig.-3.1.3) resulted in a large increase of the flutter wind speed . When the horizontal stays were placed over 12%-long portion of both main span and side span length in addition to the cross stays arranged at 0.26 L points of the main span and 0.44 Ls points of the side spans, the flutter wind speed reached more than 80 m/s; the target value. When the portion to which the horizontal stays were placed became longer, the flutter wind speed went upward furthermore. On the other hand, the flutter wind speed was rather low comparing with simple use of the cross stays when the other stays such as tower cross stays, tower top horizontal stays and so on were used with the cross stays. As for inclined cross stays, they were found to be effective in some cases, but the flutter wind speed obtained from flutter analysis using measured non-stationary aerodynamic derivatives was significantly small.

3) Triangle stay

Triangle stay, which is peculiar to the three main cable systems and is arranged between the center main cable and the tips of the deck, is intended to avoid visual confusion of the cross stays which were viewed as overlapping (Fig.-3.1.4). This stay had almost the same performance as the cross stay to raise the flutter wind speed, and there was a possibility to gain high flutter wind speed when it was used along with a flutter resistant deck, because flutter characteristics of the bridge with the stay seemed to be greatly influenced by the aerodynamic derivatives of the deck.

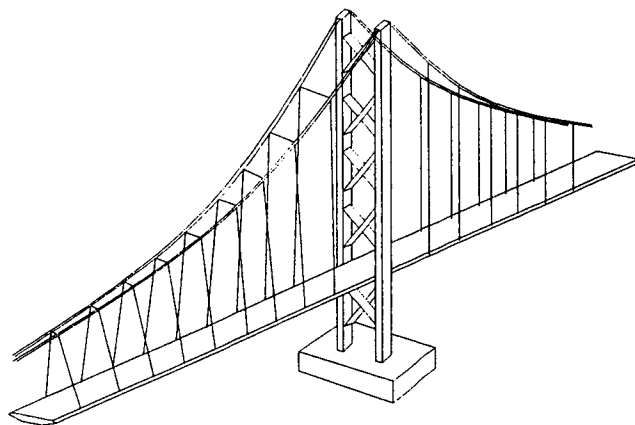


Figure-3.1.1 Crossing Main Cable

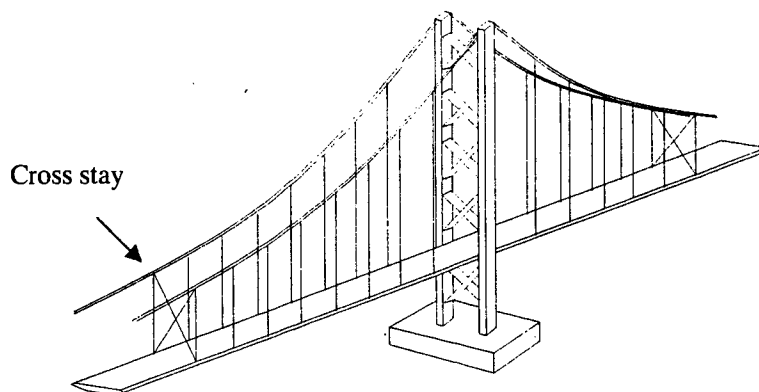


Figure-3.1.2 Cross stay

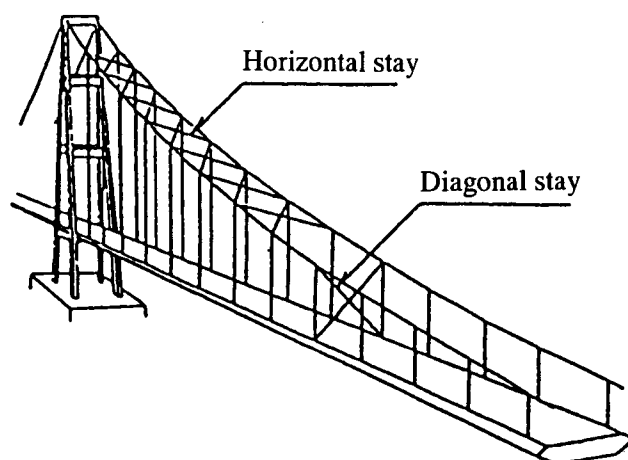
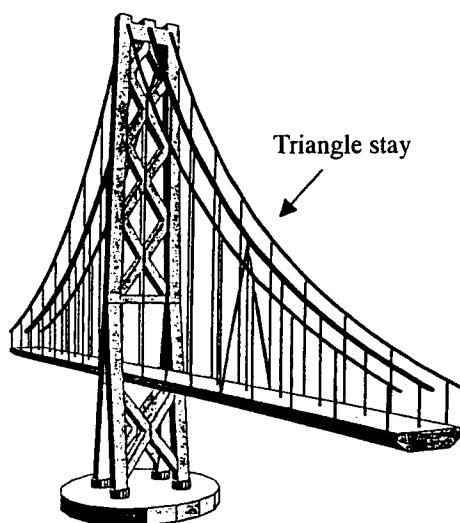


Figure-3.1.3 Combination of suspension and cable-stayed bridge with mono and dual-box deck



Triangle stay fixation points:
Center span side: $L/4$ point
Side span side: center point
(Total 4 points)

Figure-3.1.4 Triangle stay

4. Investigation on the Combination of Aerodynamic and Structural Improvement

(1) Combination of improved mono-box deck, three main cable system and triangle stays

This idea was intended to raise the flutter wind speed by a combination of the improved mono-box deck in Fig.-2.2.1 and the cable system shown in Fig.-3.1.4. It achieved to raise the flutter wind speed higher than 80 m/s.

(2) Combination of dual-box deck and four main cables

This idea which combines mono-box deck, four main cables and cross hangers (Fig.-3.2.4) also realized the flutter wind speed to be higher than 80 m/s.

(3) Combination of cross stays, crossed main cables and center barrier

In this idea, the mono-box deck installed with the center wind barrier (Fig.-2.1.4) and the crossed main cables (Fig.-3.1.1) or the cross stays (Fig.-3.1.2) are combined to obtain the flutter wind speed higher than 80 m/s for both cases.

(4) Combination of a suspension and a cable-stayed bridge with mono and dual-box deck (Fig.-4.1.1)

This new structural concept is a combination of mono-box deck and dual-box deck with straightly arranged stays to raise the torsional stiffness at the mono-box section. This new structure cleared the design target flutter wind speed of 80 m/s for both 6-lane bridge and 4-lane bridge.

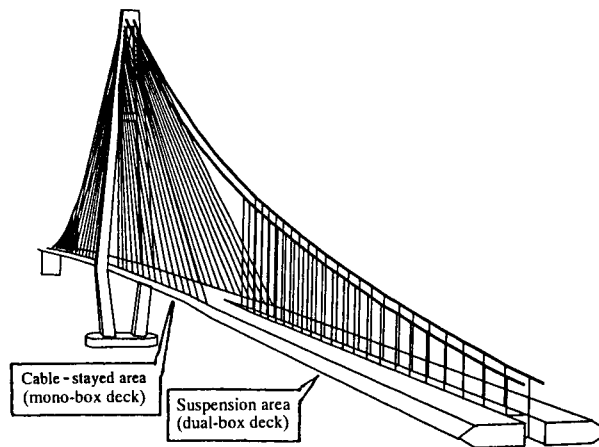


Figure-4.1.1 Combination of suspension and cable-stayed bridge with mono and dual-box deck

< References >

- 1). M. Yasuda, R. Nakagaki and T. Ueda. "Improvement of Flutter Characteristics for Super-Long Span Suspension Bridges." *Construction Institute's 42nd Annual Academic Lecture Meeting Outlines*, 1 - 341, October 1987.
- 2). I. Harasaki, "Messina Straight Bridge." *Road (Doro)*, January 1992.
- 3). C. Borri, M. Majowiecki and P. Spinelli. "The Aerodynamic Advantages of a Double-effect Large Span Suspension Bridge under Wind Loading." *J. of Wind Engineering and Industrial Aerodynamics*: 48 317-328, 1993.
- 4). M. Yoneda, K. Kimura, K. Ohno, S. Nakazaki, K. Nomura. "Comparison of Different Cable Systems on the Static and Coupled Flutter Characteristics of 3000m Class Suspension Bridge." *Journal of Structural Engineering*: Vol. 40A, 1994.
- 5). C. Otsubo, S. Ukai, H. Tanaka, M. Esaki, K. Ninomiya. "The Design and Construction of the Kamo Yurarinko Bridge." *Bridge and Foundation Engineering*: 95-3.
- 6). M. Suzuki, Y. Hikami, N. Uno. "Aerodynamic characteristics of super-long suspension bridges and new ideas for a bridge superstructure." *Proceedings of the 49th Annual Conference of the Japan Society of Civil Engineers*, 1-(B) (1994), 1098-1099 (in Japanese).
- 7). M. Arai, M. Miyazaki, H. Kubota. "The Effects of Horizontal Stay Cables on the Wind Resistance Designs of Super Long Large Suspension Bridges." *Construction Institute's 49th Annual Academic Lecture Meeting*, 1994.
- 8). H. Sato, R. Toriumi, M. Watanabe. "Evaluations of Super Long Large Bridge Cable Systems" *Construction Institute's 49th Annual Academic Lecture Meeting*, 1994.
- 9). S. Suzuki, M. Kitagawa. "Evaluations of the Wind Resistance Stability Constructions of Long Large Box Girder Suspension Bridges" *Construction Institute's 49th Annual Academic Lecture Meeting*, 1994.
- 10). H. Sato, R. Toriumi, M. Sekiya, M. Watanabe. "Fundamental Evaluations for Attaining Wind Resistance Stability on Super Long Large Bridges." *13th Proceedings of National Symposium on Wind Engineering*, 1994.
- 11). M. Arai, M. Miyazaki. "Research on Horizontal Stay Systems and Wind Resistance Designs of Super Long Large Suspension Bridges." *13th Proceedings of National Symposium on Wind Engineering*, 1994.
- 12). K. Ogawa, H. Shimodoi, G. Isoe, Y. Hashimoto. "Considerations regarding the Vibration Characteristics of New Types of Super Long Large Suspension Bridges." *Journal of wind Engineering*: Vol. 63, 1995.
- 13). Y. Otani, M. Kitagawa, T. Kanezaki, H. Katsuji. "Evaluations of the Improvement Effects of Cross Hangars on the Flutter Limit Wind Velocity of Long Large Suspension Bridges" *Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers*, 1995.
- 14). K. Ogawa, Y. Hashimoto, H. Shimodoi, G. Isoe. "Research on the Vibration Characteristic Improvement Measures of New Types of Super Long Large Suspension Bridges." *Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers*, 1995.
- 15). M. Sasaki, Y. Kubo, S. Kawamura, T. Sakata. "The Flutter Characteristics of Super Long Large Bridges Implementing the Center Connecting Cable Method." *Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers*, 1995.
- 16). H. Tahira, Y. Morizono, Y. Fujino, K. Maeda, M. Nagai. "The Wind Resistance Stability Measures and Static Construction Characteristics on Super Long Large Suspension Bridges with the MONO-DUO Method." *Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers*, 1995.
- 17). T. Hosaka, K. Maeda, Y. Fujino, Y. Morizono, M. Nagai. "The Wind Resistance Stability Measures and Torsional Vibration Characteristics on Super Long Large Suspension Bridges with the MONO-DUO Method." *Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers*, 1995.
- 18). M. Arai, M. Miyazaki, H. Kubota, Y. Suzuki. "Research on Wind Resistance Stability of Super Long Large

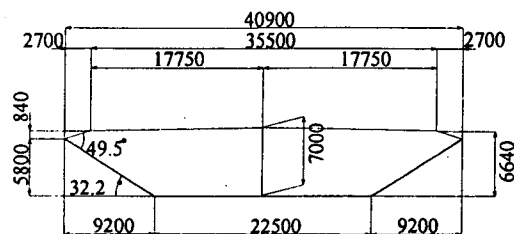
Suspension Bridges with the Cable Stay Method." Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers, 1995.

19). K. Nomura, S. Nakazaki, Y. Tamaki, N. Narita, K. Maeda. "Basic Research on the Wind Resistance Stability Characteristics of Super Long Large Cable Stayed Suspension Bridges." Proceedings of The 50th Annual Conference of The Japan Society of Civil Engineers, 1995.

1-box girder with modified fairing and center wind shield

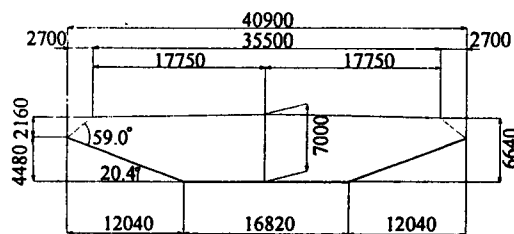
Mitsubishi Heavy Industries, Ltd.

Outline



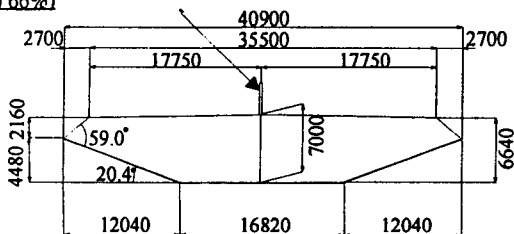
Cross section proposed in the past

Optimize the shape of the fairing



Modified cross section (1)

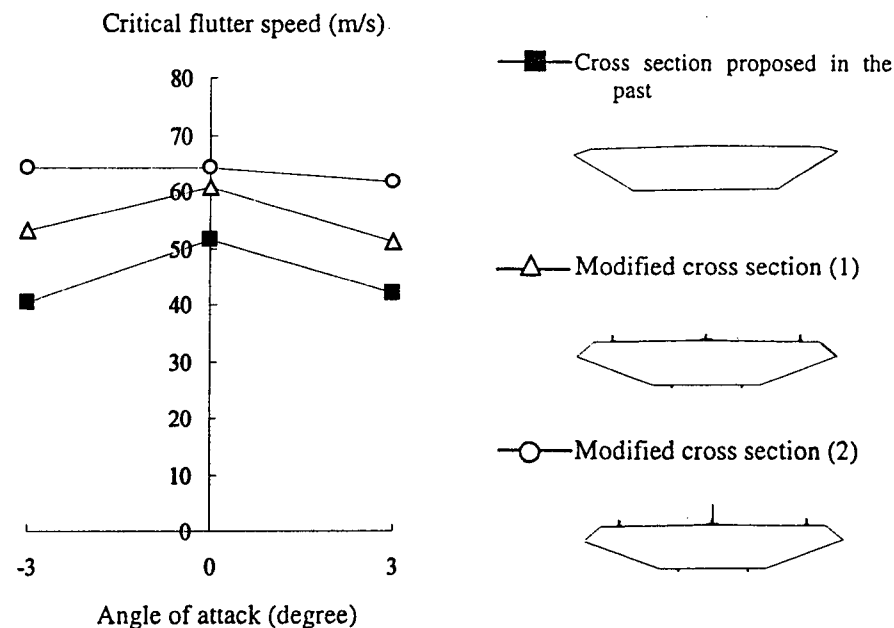
Center wind shield (height 3m, solidity ratio 66%)
Installation of center wind shields



Modified cross section (2)

Flutter resistance characteristics

Critical flutter speed (spring support test)



Figures within the brackets indicate the rate of improvement over the former cross section

		Girder cross section configuration		
		Cross section proposed in the past	Modified cross section (1)	Modified cross section (2)
Attack angle	+3°	42 m/s	51.2 m/s (21.9%)	61.7 m/s (46.9%)
	0°	51.5 m/s	60.6 m/s (21.7%)	64.3 m/s (30.5%)
	-3°	40.3 m/s	53.2 m/s (30.7%)	64.2 m/s (56.9%)

Static aerodynamic characteristics

Model name	Cross section proposed in the past	Modified cross section (1)	Modified cross-section (2)
Wind velocity	16.0 m/s	20.0 m/s	20.0 m/s
Outer surface area	0.1672 m ²	0.5559m ²	0.5559m ²
Projected area	0.1564m ²	0.5041m ²	0.5041m ²
Solidity ratio	93.6%	90.7%	90.7%
Model width	0.5467	2.70	2.70
(C _D) _{α=0}	0.631	0.599	0.836
(dC _L /dα) _{α=0}	6.817 (1/rad)	4.939 (1/rad)	3.270 (1/rad)
(dC _M /dα) _{α=0}	1.296 (1/rad)	1.201 (1/rad)	1.397 (1/rad)

- * With the modified cross section 1, the gradient of lift force is decreased compared to the cross section proposed in the past → characteristic favorable to the gust response of bending mode.
- * The resistance increases with the modified cross section 2, and the gradient of lift force changes depending on the angle of attack.

Characteristics and comments

- * The critical flutter speed can be increased substantially when compared with the cross sections proposed in the past, by optimizing the shape of the fairing.
- * Furthermore, it is confirmed the flutter limit wind velocity can be increased through the installation of center wind shields.
- * The static aerodynamic characteristics can also be improved by optimizing the shape of the fairing.
- * Not considering overdrive.

Wind resistance characteristic evaluation conditions

* Spring support response test conditions

Item	Unit (Model value)	Actual bridge	Small model	Large model
Scale	-	-	1/200	1/40
Total cable length	m	40.9	0.205	1.023
Girder weight	kN/m (N/model)	343	8.58 *	579 **
Polar moment of inertia	t · m (kg · m ² /model)	6769	4.17 × 10 ⁻³	7.20 **
Frequency (Bending)	Hz	0.0537	1.78	0.601
Frequency (Torsional)	Hz	0.1604	5.27	1.757
Frequency ratio	-	2.987	2.97	2.923
Structural damping (Logarithmic decrement)	-	0.02	0.02	0.02
Wind speed ratio (Bending)	-	-	6.03	3.57
Wind speed ratio (Torsional)	-	-	6.09	3.65

Model length 1m, **Model length 2.7m.

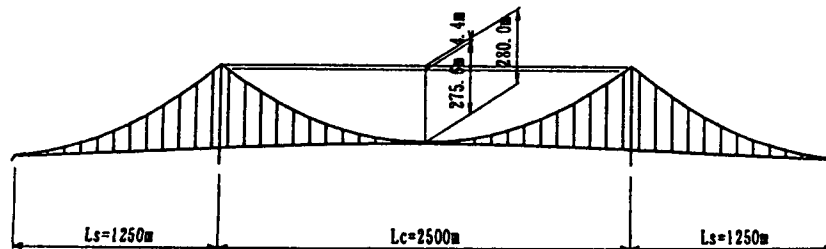
- * Cross sections proposed in the past: testing was conducted with a small, 1/200 scale model.
- * Modified cross sections 1 and 2: testing was conducted with a large, 1/40-scale model.

Modified 1-box girder with opening and fairings

Sumitomo Heavy Industries, Ltd.

Outline

Overall view

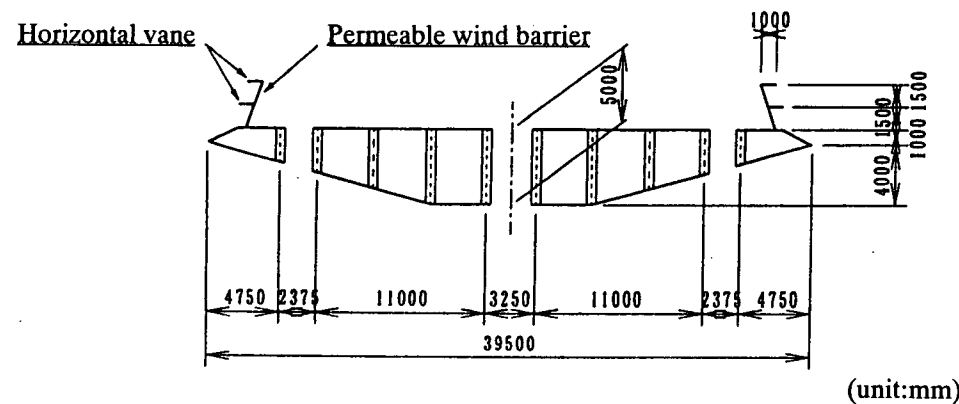


Structure type	3 span 2 hinge suspension bridge
Cable span length	1,250 m + 2,500 m + 1,250 m
Sag ratio	1 / 9
Girder configuration	Box girder (girder height 5m) with opening

Characteristics · Comments

- * The flutter resistance stability of negative angle of attack was improved when the air-gap was installed (at the shoulder and median of girder).
- * The stability of positive angle of attack was improved when a horizontal stabilizer was installed on the center barrier and permeable wind barrier with horizontal vane.
- * When the above 2 measures are combined, it was possible to obtain a flutter wind speed of over 75m/s with only girder aerodynamic modifications.

Girder cross section configuration



Wind resistance characteristic

* Spring support test results

Attack angle	-3°	0°	+3°
Flutter onset wind speed	80.5 m/s	87.0 m/s	77.2 m/s

* Flutter analysis results

- 88.4 m/s (When static deformation in wind condition is not considered)
- 79.1 m/s (When static deformation in wind condition is considered)

Wind resistance characteristic evaluation conditions

Various conditions of the analysis model

Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	35.5 m
	Effective cross sectional area	1.2 m ² / Br
	Allowable stress degree	980N/mm ²
Hanger	Hanger interval	100 mm
	Cross sectional area	0.024 m ² / Point
Stiffening girder	Cross sectional area	1.3 m ² / Br
	Vertical flexural stiffness	12.0 m ⁴ / Br
	Horizontal flexural stiffness	160.0 m ⁴ / Br
	Torsional strength	26.0 m ⁴ / Br
	Polar moment of inertia	3303 t·m / m / Br
Dead weight	Suspension structure	235 kN / m / Br
	Cable	108 kN / m / Br
	Total	343 kN / m / Br
Main tower	Tower height	TP + 380.0 m
Boundary condition	Support condition of girder end	Vertical : fix Transverse : fix Torsional : fix

Flutter analysis conditions

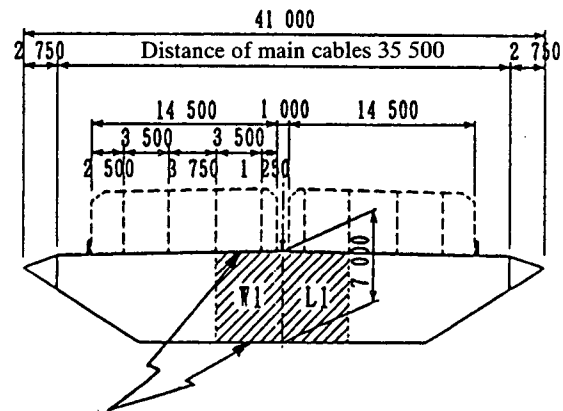
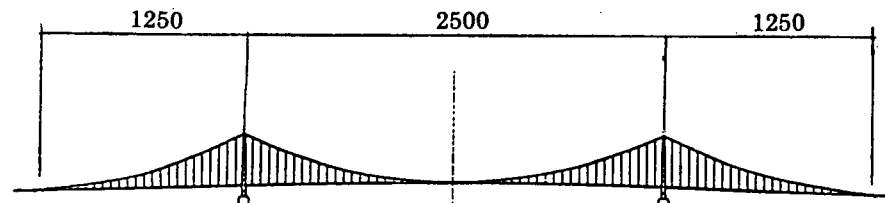
Item	Analytical condition				
Analytical method	Direct method				
Air density	1.23 kg/m ³				
Static deformation in wind condition	Considered				
	Not considered				
Structural damping	$\delta = 0$ During analysis				
	$\delta = 0.02$ At flutter onset wind speed				
Aerodynamic force coefficient	Aerodynamic force	Main girder			
			Vertical	Torsional	Horizontal
		Lift	○	○	△
		Moment	○	○	△
		Drag	○	○	△
○: Non-stationary aerodynamic force					
△: Quasi-steady aerodynamic force					
Cable, quasi-steady resistance, lift.					
Non-stationary aerodynamic force	Actual value				
Quasi-steady aerodynamic force	Main girder	$C_D = 0.75, A_n = 7.0 \text{ m}^2 / \text{m}$			
	Cable	$C_D = 0.7, A_n = 1.0 \text{ m}^2 / \text{m}$			
Other	Girder width	$B = 41 \text{ m}$			

1-box girder with open gratings

Kawada Industries, Inc.

Outline

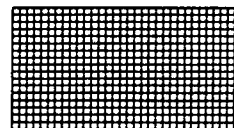
Overall view



(unit:mm)

Open grating section of the girder cross section (center divider + 1 lane each direction)

Open grating section



Solidity ratio $\phi = 50\%$

Structure type	3 span 2 hinge suspension bridge
Cable span length	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9

Characteristics · Comments

- * Type where 'open grating' was performed on the center section of the girder cross section (center divider + 1 lane each direction).
- * Open grating improved the overdrive characteristics.
- * When the solidity ratio of open grating is approximately $\phi = 50\%$, the flutter developing wind velocity will be of a similar level as when the opening is fully opened ($\phi = 0\%$).

Wind resistance characteristic

- * Maximum overdrive vibration amplitude (spring support testing (uniform flow $\delta = 0.02$))

Attack angle	Deflection overdrive	Torsional overdrive
-3°	Does not develop	Does not develop
0°	"	"
+3°	"	2.1 deg.

- * Flutter onset wind speed (spring support test (uniform flow $\delta = 0.02$))

Attack angle	Flutter onset wind speed
-3°	92.9 m/s
0°	81.4 m/s
+3°	48.8 m/s

Wind resistance characteristic evaluation conditions

Table Analytic model conditions

Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	35.5 m
	Effective cross sectional area	1.2 m ² / Br
	Number of cables	2 Cables / Br
	Horizontal tensile force	9.63 × 10 ⁵ kN / Br
	Allowable stress degree	980 N/mm ²
Stiffening girder	Cross section area	1.3 m ² / Br
	Vertical flexural stiffness	12.0 m ⁴ / Br
	Horizontal flexural stiffness	160 m ⁴ / Br
	Torsional strength	26 m ⁴ / Br
	Polar moment of inertia	3303 t · m/m/Br
Dead weight	Girder	235 kN / m / Br
	Cable	108 kN / m / Br
	Total	343 kN / m / Br
Main tower	Tower height	370.0 m
Girder width (representative width used for the analysis)		41 m

Table Spring support response test conditions (scale 1/71)

		Actual bridge	Model value
Weight		343 kN / m/ Br.	110 N /model
Polar moment of inertia		6769 t · m/Br.	0.432 kg · m ² /model
Frequency	Deflection	0.0537 Hz	1.235 Hz
	Torsional	0.1604 Hz	3.237 Hz
Frequency ratio		2.987	2.621
Structural hyperbolic logarithm damping factor	Deflection	-	0.02
	Torsional	-	0.02
Wind speed multiplying factor		-	3.585 *

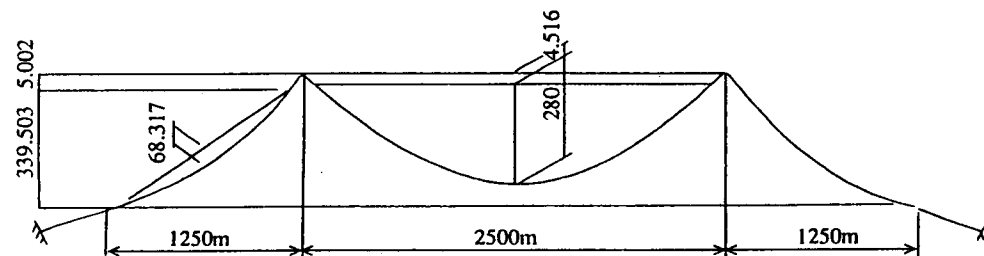
note). The wind speed multiplying factor when the frequency ratio difference was amended using the Selberg method.

2-box girder with vertical and horizontal stabilizers

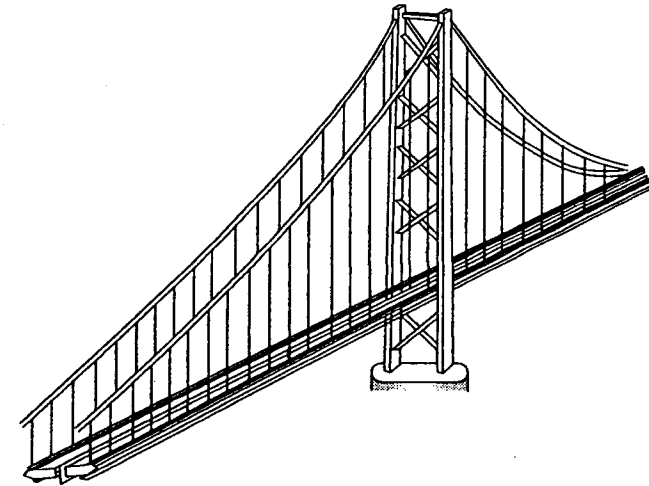
Hitachi Zosen Corporation

Outline

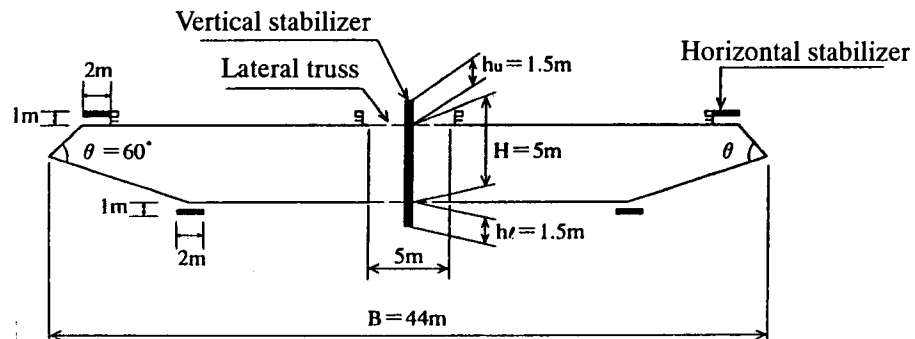
Overall view



Structure type: 3 span 2 hinge suspension bridge
 Cable span length: 1250m + 2500 m + 1250 m
 Sag ratio: 1 / 9
 Girder type : 2-box girder (6 lanes) using vertical and horizontal stabilizers.



Girder cross section configuration



Characteristics · Comments

- * A 2-box girder with improved wind resistance characteristics through the synergistic effect of vertical and horizontal stabilizers is used.
- * The width of the center slot is kept as small as possible, and so the cable interval and tower pillar interval are minimized.
- * The cable and hanger types are conventional.

Wind resistance characteristic

- * Flutter wind speed (attained through a 3 dimensional multi-mode flutter analysis incorporating of the static deformation under wind action) : 78m/s (attack angle 0°).
- * Vertical bending and torsional vortex-induced oscillation occur below 10m/s, but disappear when the open-grating is set in the center slot. And it vanishes also in the turbulent flow with 10% turbulence.

Wind resistance characteristic evaluation conditions

Items of analysis model

Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Cable span length	1250m + 2500m + 1250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	39 m
	Effective cross sectional area	1.4 m ² / Br
	Number of cables	2 Cables / Br
	Cable axial force	6.48 × 10 ⁵ kN / Cable
	Allowable stress degree	980 N/mm ²
Hanger	Cross sectional area	0.014 m ² / Point
Stiffening girder	Cross sectional area	1.4 m ² / Br
	Vertical flexural stiffness	6.5 m ⁴ / Br
	Horizontal flexural stiffness	208.0 m ⁴ / Br
	Simple torsional stiffness	15.2 m ⁴ / Br
	Flexural torsional stiffness	622.4 m ⁶ / Br
	Polar moment of inertia	3655 t·m / m / Br
Dead weight	Girder weight	249 kN / m / Br
	Cable weight	126 kN / m / Br
	Total weight	375 kN / m / Br
Main tower	Tower height	408.75 m
Modeling	Girder boundary condition	Modeling the tower link and wind shoe
	Girder center of gravity	3.95m above the bottom plate.
	Girder joint interval	50 m
Girder width (representative width used for the analysis)		44 m

Flutter analysis conditions

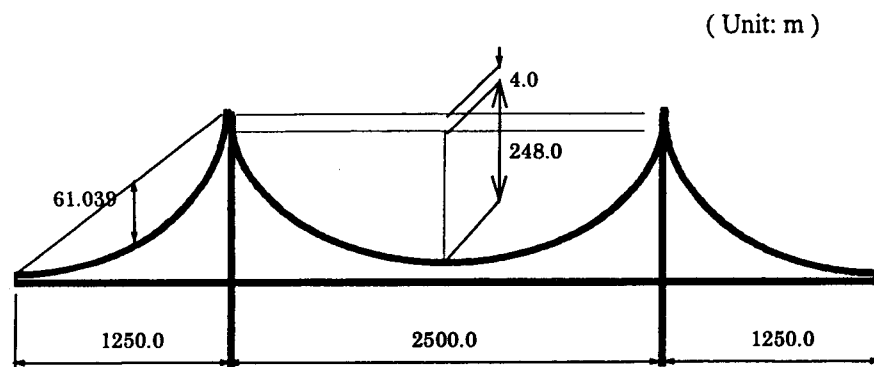
Item	Analytical condition			
Analytical method	The mode combination method including 20 modes under the static deformation due to wind action.			
Air density	1.23 kg/m ³			
Static deformation under wind action	Considered			
Structural damping	All modes $\delta = 0.02$			
Aerodynamic force coefficient	Main girder			
		Vertical	Torsional	Horizontal
	Lift	○	○	○
	Moment	○	○	○
	Drag	○	○	○
○: Measured flutter derivatives				
Cable: Quasi-steady drag, lift.				
Main tower: Quasi-steady drag				
Aerodynamic force coefficients	Measured value (forced oscillation method)			
Drag coefficient	Cable $C_D = 0.7$, $A_n = 1.1 \text{ m}^2 / \text{m} / \text{Br.}$ Main tower $C_D = 1.4$			

Slotted girder with center-barrier, guide-vane and under-barrier

Public Works Research Institute,
Ministry of Construction

Outline

Overall view



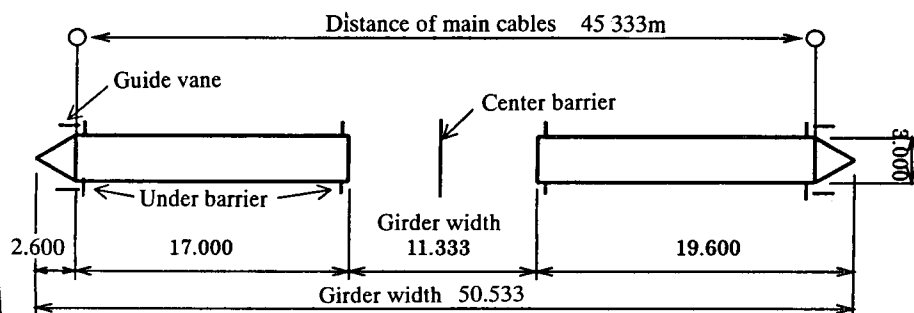
Structure type: 3 span 2 hinged suspension bridge
Cable span length: 1250 m + 2500 m + 1250 m
Sag ratio: 1 / 10

Characteristics · Comments

- * Slotted box girder was applied to improve the aerodynamic stability instead of the truss girder and mono-box girder. The size of slot is approximately 20% of the girder total width.

Girder cross section configuration

(unit:m)



Wind resistance characteristic

- * Flutter on-set wind speed (angle of attack = 0°)

85 m / s (Flutter analysis using measured aerodynamic)
35 m / s (Flutter analysis using Theodorsen's function)

Wind resistance characteristic evaluation conditions

Table Analytic model conditions

Item		Structural value
Type	Structure type	3 span 2 hinged suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 10
Main cable	Distance of main cables	45.333 m
	Cross sectional area	1.1 m ² / Br
	Horizontal component of tension	7.82 × 10 ⁵ kN/Br
	Allowable stress	980 N/mm ²
Hanger	Cross sectional area	0.0082 m ² / Point
Stiffening girder	Cross sectional area	1.54 m ⁴ / Br
	Vertical stiffness	2.17 m ⁴ / Br
	Horizontal bending stiffness	288.2 m ⁴ / Br
	Torsional strength	8.91 m ⁴ / Br
Dead load	Girder	252 kN / m / Br
	Cable	167 kN / m / Br
	Total	419kN / m / Br
Polar moment of inertia		1.44 × 10 ⁴ t · m ² /m
Main tower	Height	350 m
Modeling	Girder boundary condition	Correspond with the girder end fixation method
	Girder center of gravity	Same as the fixation point
	Girder joint interval	125 m
Girder width (representative width used for the analysis)		45.333 m

Table Flutter analysis conditions

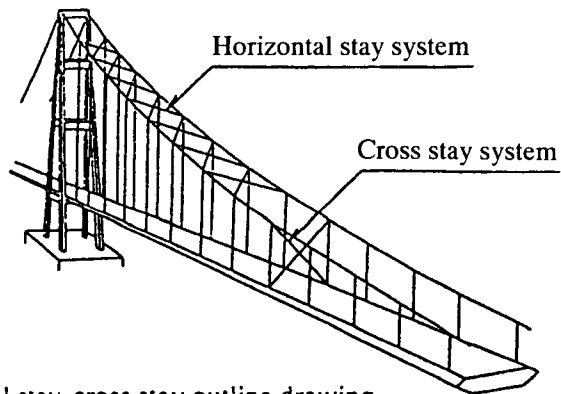
Item	Analytical condition			
Analytical method	Mode combination method. Using natural vibrational mode under non-windy conditions. Using lower 50 modes.			
Air density	1.23 kg/m ³			
Static distortion under windy conditions	Consideration			
Structural damping	All modes $\delta = 0.02$			
Aerodynamic force coefficient	Main girder			
		Vertical	Torsional	Horizontal
	Lift	○	○	○
	Moment	○	○	○
	Drag	○	○	○
	○: Unsteady aerodynamic force, △: Quasi-steady aerodynamic force, ×: not considered Cable: Quasi-steady drag force and lift force. Main tower: not considered			
Unsteady aerodynamic force coefficient	Experimental value (forced oscillation method, application range : angle of attack = ±3°)			

Combination effects of horizontal stay system and cross stay system

Sumitomo Heavy Industries, Ltd.

Outline

Overall view



Horizontal stay, cross stay outline drawing

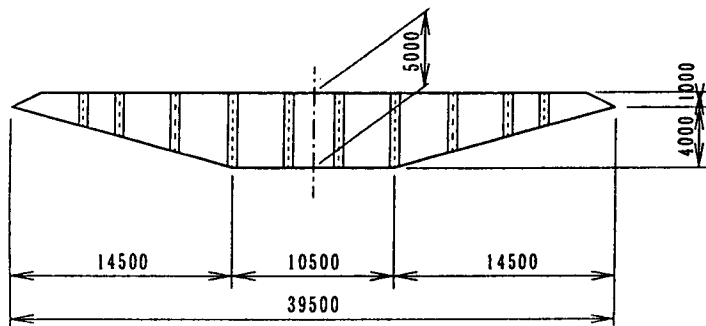
Structural type	3 span 2 hinge suspension bridge
Cable span length	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9

Characteristics · Comments

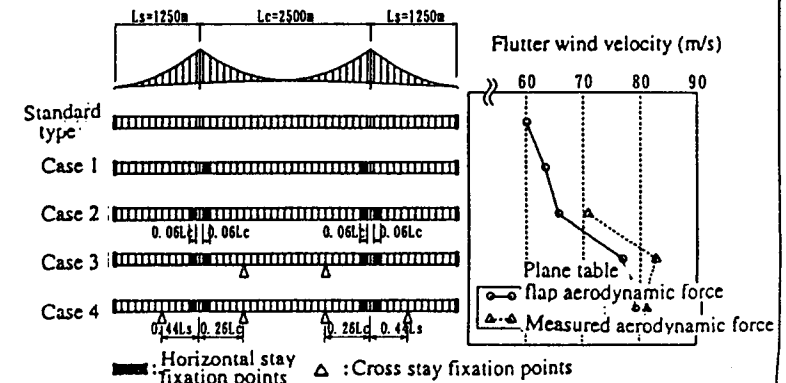
- * It's possible to improve the flutter resistance characteristics by using the cable systems.
- * By using both the horizontal stay system and the cross stay system, the flutter onset wind speed increased by 31%.
- * The effect of improvement is greater when the horizontal stay system is installed over a larger area.

Girder cross section configuration

(unit:mm)



Wind resistance characteristic



Wind resistance characteristic evaluation conditions

Various conditions of the analysis model

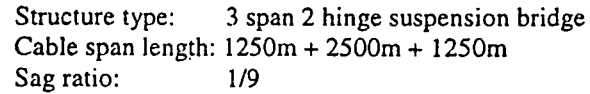
Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	35.5 m
	Effective cross sectional area	1.2 m ² / Br
	Allowable stress degree	980 N/mm ²
Hanger	Hanger interval	100 m
	Cross sectional area	0.024 m ² / Point
Stiffening girder	Cross sectional area	1.3 m ² / Br
	Vertical flexural stiffness	12.0 m ⁴ / Br
	Horizontal flexural stiffness	160.0 m ⁴ / Br
	Torsional strength	26.0 m ⁴ / Br
	Polar moment of inertia	3303 t·m/m/Br
Dead weight	Suspension structure	235 kN / m / Br
	Cable	108 kN / m / Br
	Total	343 kN / m / Br
Main tower	Tower height	TP + 380.0 m
Boundary condition	Support condition of girder end	Vertical : fix Transverse : fix Torsional : fix

Flutter analysis conditions

Item	Analytical condition																				
Analytical method	Direct method																				
Air density	1.23 kg/m ³																				
Static deformation in wind condition	Not considered																				
Structural damping	$\delta = 0$ (During analysis) $\delta = 0.02$ (At flutter developing wind velocity)																				
Aerodynamic force coefficient	Aerodynamic force <table><tr><th colspan="4">Main girder</th></tr><tr><th></th><th>Vertical</th><th>Torsional</th><th>Horizontal</th></tr><tr><td>Lift</td><td>○</td><td>○</td><td>△</td></tr><tr><td>Moment</td><td>○</td><td>○</td><td>△</td></tr><tr><td>Drag</td><td>○</td><td>○</td><td>△</td></tr></table> ○: Non-stationary aerodynamic force △: Quasi-steady aerodynamic force Cable, quasi-steady resistance, lift.	Main girder					Vertical	Torsional	Horizontal	Lift	○	○	△	Moment	○	○	△	Drag	○	○	△
Main girder																					
	Vertical	Torsional	Horizontal																		
Lift	○	○	△																		
Moment	○	○	△																		
Drag	○	○	△																		
Non-stationary aerodynamic force	Actual value, plane table flap aerodynamic force																				
Quasi-steady aerodynamic force	Main girder $C_D = 0.75$, $A_n = 7.0 \text{ m}^2 / \text{m}$ Cable $C_D = 0.7$, $A_n = 1.0 \text{ m}^2 / \text{m}$																				
Other	Girder width $B = 41 \text{ m}$																				

Honshu-Shikoku Bridge Authority

Overall view



- * A 2 box girder where the 4 overtaking lanes were grated.
- * Vertical stabilizers were installed on the grating sections, and guide vanes on the girder ends in order to improve wind resistance characteristics.
- * Conventional cables and hangers from the past were used.

Diagram illustrating the dimensions of a ship hull cross-section (rectangular hull form). The diagram shows a cross-section with a total length of 28,000 and a total width of 34,313. The dimensions are divided into segments: 3,000, 10,000, 2,000, 10,000, and 3,000 for the length, and 8,750, 10,500, and 8,750 for the width. A vertical dimension of 3,720 is indicated on the right side. A dashed line indicates a width of 4,000 at the center of the hull.

- * By implementing this girder type, the flutter onset wind speed was over twice that when compared with the Selberg method (2 dimensional wind tunnel testing).
- * The flutter onset wind speed (the results estimated using the Selberg method were amended with the wind tunnel test results) was approximately 70m/s.
- * Within the turbulence angle of inclination $\pm 3^\circ$, the influence of the attack angle on the flutter onset wind speed is small. The attack angle 0° characteristics are comparatively poor.

Wind resistance characteristic evaluation conditions

Various conditions of the analysis model

Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Cable span length	1250m + 2500m + 1250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	28 m
	Effective cross sectional area	0.40 m ² / cable
	Number of cables	2 Cables / Br.
	Cable maximum tensile force	Approximately 3.72×105 kN/ cable
	Allowable stress degree	980 N / mm ²
Stiffening girder	Cross section	1.03 m ² /Br
	Vertical flexural stiffness	2.64 m ⁴ /Br
	Horizontal flexural stiffness	14.08 m ⁴ / Br
	Simple torsional stiffness	5.30 m ⁴ /Br
	Polar moment of inertia	1,699ton · m ² / m
Dead weight	Girder	170 kN / m
	Cable	34 kN / m / cable
	Total	238 kN / m / Br.
Main tower	Tower height	370 m
Modeling	Girder boundary condition	No modeling of the link
	Girder center of gravity	Hanger fixation height and level
	Girder joint interval	125 m
Girder width (representative width used for the analysis)		34.313 m

Flutter developing wind velocity estimation method

Item	Analytical condition
Analytical method	The flutter onset wind speed was estimated using the following methods. 1. The characteristic frequency was attained using an analysis model. 2. The estimated flutter developing wind velocity was attained using the Selberg method. 3. The figure attained in 2 above is amended using the results of 2 dimensional spring supported wind tunnel tests, which is used as the estimated flutter onset wind speed value.
Air density	1.23 kg/m ³

Characteristic frequency

Mode	Characteristic frequency
Vertical flexure symmetrical first order	0.0540 Hz
Torsional strength	0.1375 Hz

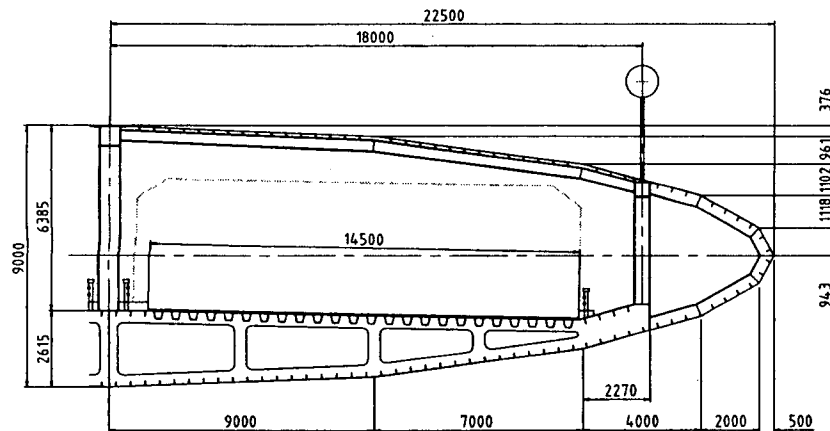
Polygonal cross section

Mitsui Engineering & Shipbuilding Co., Ltd.

Outline

Overall view

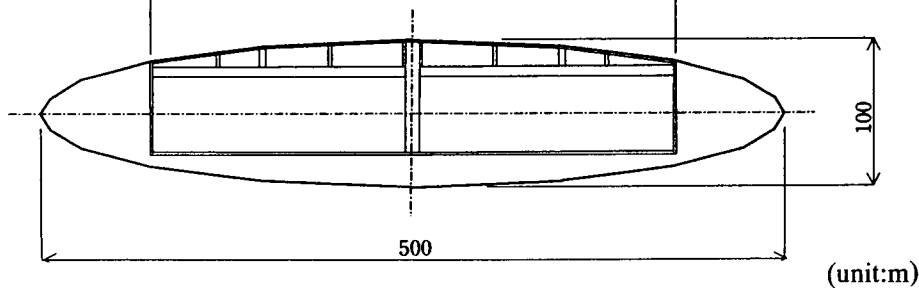
Intended for use on an actual bridge.



Girder cross section configuration

Area possible for opening.

Wind tunnel model



Characteristics · Comments

- * Seeking cross sections that did not exist in the past, hope was put of an elliptic cross section, and a polygonal (20 angles) cross section intended for actual bridge was taken up.
- * Inner girder traffic which is immune to close to traffic under windy conditions.
- * If the results are good, make a consideration the possibility of including lighting and exhaust through the ceiling section (upper surface).
- * The drag coefficient is small, and favorable to wind load.
- * The higher girder height increases stiffness characteristics compared to a flat cross section, and it is expending for a improvement in aerodynamic stability.

Wind resistance characteristic

Spring support test: uniform flow, attack angle $\alpha = 0.0\text{deg}$, $\delta = 0.02$

* Flutter onset wind speed

$\kappa = 0.99$ (Basic type)

Hard flutter

* Vortex induced oscillation

No observed (attack angle $\alpha = 0.0\text{deg}$)

Wind resistance characteristic evaluation conditions

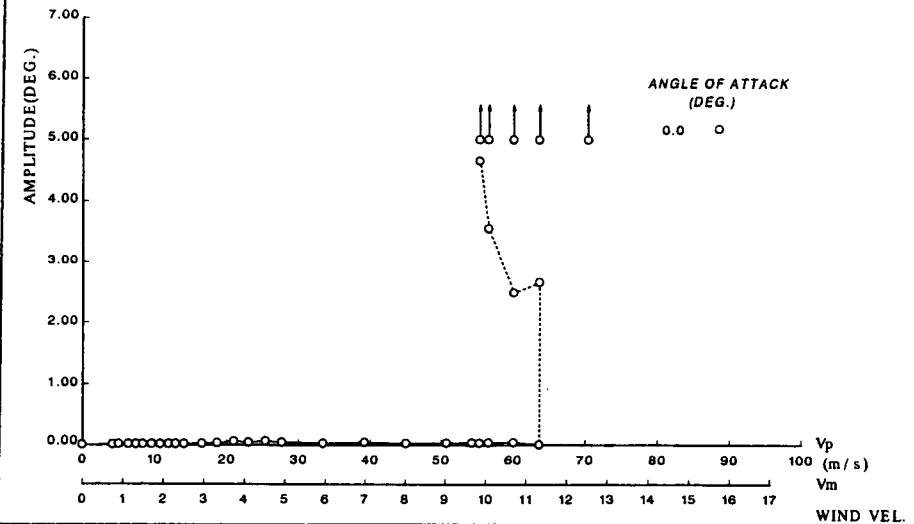
Table. Estimated Vibration Parameters (Polygonal Cross Section (P - 15))

		Intended for actual Designation B / D = 5	Required value on model	Experimental value
Name			P - 15	P - 15
Scale		-	1 / 90	1 / 90
Total width (Representative width) B		45.0 m	0.500 m	0.500 m
Girder height (representative height) D		9.0 m	0.100 m	0.100 m
Weight		392 kN/m	48.44 N/m	49.78 N/m
Polar moment of inertia		10000 t · m ² / m	0.152 kg · m ² /m	0.161 kg · m ² /m
Frequency	Deflection	0.050 Hz	0.900 Hz	1.051 Hz
	Torsional	0.150 Hz	2.700 Hz	2.404 Hz
Frequency ratio		3.00	3.00	2.29
Logarithmic decrement	Deflection	0.02	0.02	0.02
	Torsional	0.02	0.02	0.019
Wind speed ratio	Deflection	-	5.0	4.28
	Torsional	-	5.0	5.62

Note (1). These parameters were set through reference to (time when) the 2 box type proposed for the Akashi Straight Bridge (Based on a 6 lane bridge).

V-A characteristics

V-A θ characteristics drawing
(uniform flow: $\alpha = 0^\circ$)



Flutter analysis

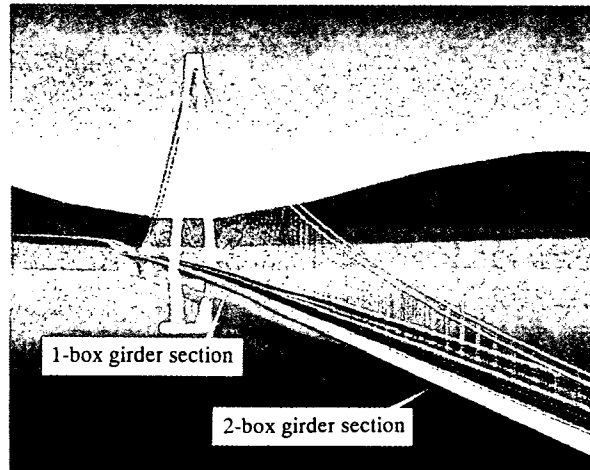
* The flutter analysis was not carried out, because a section form with high stability was not found.

Girder-system composed of 2-box and 1-box girder (6-lane type & 4-lane type)

Kawasaki Heavy Industries Ltd.

Outline

Overall view



2-box girder section is applied to the center part of $L_c/2$ in the main span

1-box girder section is applied near the tower

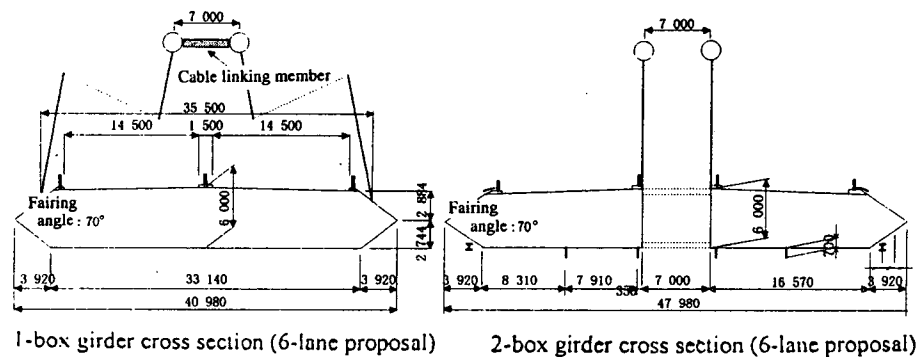
Structural type	3-span 2-hinge suspension bridge
Cable span	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9

Characteristics · Comments

- * While the 2-box girder is installed at the center part of the main span to improve wind resistant characteristics of the bridge, the 1-box girder is used near the tower in order to reduce the girder weight.
- * Cables are located according to the center opening width in the 2-box girder. The inclined hangers at the 1-box girder are expected to improve torsional stiffness and the vertical hangers at the 2-box girder are used to attain road vehicle spaces.
- * As the aerodynamic devices for the 2-box girder cross section, inspection car rails are installed on the bottom surface of the fairing and vertical plates are installed on the bottom flange of the box girder, in order to modify static aerodynamic moment characteristics and to improve flutter stability characteristics. (The flutter critical wind velocity is increased by over 20% in the 6-lane cross section)
- * The 4-lane cross section attains similar levels of flutter stability as the 6-lane cross section.

Girder cross section configuration

(unit:mm)



Wind resistance characteristic

Flutter onset wind speed (by multi-mode flutter analyses)

6-lane proposal : about 90 m/s (Angle of wind inclination : 0°)

4-lane proposal : about 90 m/s (Angle of wind inclination : 0°)

Maximum amplitude of vortex-induced vibration

by wind tunnel tests with the 6-lane proposal section model in uniform flow (structural damping : 0.02 in logarithmic decrement)

Attack angle	Vertical deflection	Torsional deformation
+ 3°	Does not occur	0.3 deg.
0°	Does not occur	Less than 0.1 degrees
- 3°	Does not occur	0.6 deg.

Wind resistant characteristic evaluation conditions

Various conditions of the analyzed model (6-lane proposal)

Item		Structural value
Type	Structure type	3-span 2-hinge suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	7.0 m
	Effective cross sectional area	1.370 m ² / Br
	Number of cables	2 cables / Br.
	Dead weight tensile force	1.18 × 10 ⁶ kN / Br
	Allowable stress degree	980 N / mm ²
Hanger	Cross section area	9.34 × 10 ⁻⁴ m ² / m / Br
Stiffening girder	Cross section area	1.516 (1.280) m ² / Br
	Vertical flexural stiffness	9.660 (9.524) m ⁴ / Br
	Horizontal flexural stiffness	263.3 (133.3) m ⁴ / Br
	Torsional strength	21.0 (19.8) m ⁴ / Br
	Polar moment of inertia	5.00 × 10 ⁴ (2.74 × 10 ⁴) t · m ² / m
Dead weight	Stiffening girder	274(231) kN / m / Br
	Cable	119 kN / m / Br
	Total	393(350) kN / m / Br
Main tower	Tower height	370 m
Attachment stay	-	None
Modeling	Girder boundary condition	Modeling the tower link and the wind shoe
	Girder center of gravity	3.0 m below the hanger fixation point on the girder
	Girder joint interval	98 m
Girder width (representative width used for the analysis)		47.98 (40.98) m

Flutter analysis conditions

Item	Analytical condition																
Analytical method	Multi-mode flutter analyses Natural vibration modes in no wind condition are used. The first 50 modes are considered																
Air density	1.18 kg/m ³																
Static deformation in wind condition	Yes (Considering the change in non-stationary aerodynamic forces due to torsional deformation of the girder)																
Structural damping	All modes $\delta = 0.02$																
Aerodynamic force coefficient	Main girder																
	<table><tr><td></td><td>Vertical</td><td>Torsional</td><td>Horizontal</td></tr><tr><td>Lift</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Moment</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Drag</td><td>△</td><td>△</td><td>△</td></tr></table>		Vertical	Torsional	Horizontal	Lift	○	○	×	Moment	○	○	×	Drag	△	△	△
		Vertical	Torsional	Horizontal													
	Lift	○	○	×													
Moment	○	○	×														
Drag	△	△	△														
○: Non-stationary aerodynamic force △: Quasi-steady aerodynamic force Cable: Quasi-steady drag and lift.																	
Non-stationary aerodynamic force	Measured values (by free oscillation method)																
Quasi-steady aerodynamic force (Values are for a 6-lane proposal)	Girder : Measured values of three-component stationary aerodynamic forces $C_D = 0.921$, $A_n = 6.00 \text{ m}^2 / \text{m} / \text{Br.}$ (2-box girder section, wind attack angle 0°) Cable : $C_D = 0.7$, $A_n = 2.08 \text{ m}^2 / \text{m} / \text{Br.}$																

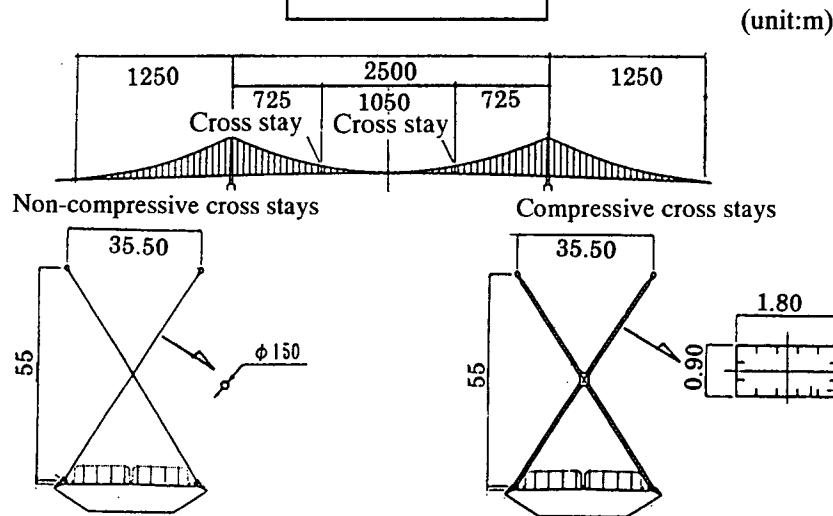
Note) The values in brackets indicate the values for the 1-box girder section.

Optimum position of vertical cross stays

Kawada Industries, Inc.

Outline

Overall view

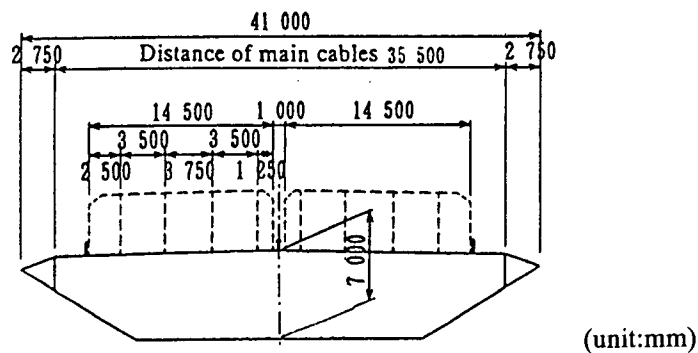


Structural type	3 span 2 hinge suspension bridge
Cable span	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9

Characteristics · Comments

- * This type uses compressive cross stays (dual sided effect) and non-compressive cross stays (one sided effect).
 - * Optimum position of the cross stays (using measured aerodynamic force).
- Compressive stays : only on the center span side near 0.3L (L: center span length). When compared with the base type without cross stays, the flutter developing wind velocity increased about 20 %.
- Non-compressive stays : near the center span side 0.3L + side span side 0.5Ls (Ls : side span length). When compared with the base type without cross stays, the flutter developing wind velocity increased by about 15%.

Girder cross section configuration



Wind resistance characteristic

- * Flutter onset wind speed (by flutter analysis)
- Pressure resistant : 70m/s (Center : 0.3L) → in consideration of distortion under windy conditions 68 m/s.
- Non pressure resistant: 66m/s (Center : 0.3L + Side : 0.5Ls)
- Base type (no cross stays): 57 m / s

Wind resistance characteristic evaluation conditions

Table Various conditions of the analysis model

Item		Structural value
Type	Structure type	3 span 2 hinge suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	35.5 m
	Effective cross sectional area	1.2 m ² / Br
	Number of cables	2 cables / Br.
	Horizontal tensile force	9.63 × 10 ⁵ kN / Br
	Allowable stress degree	980 N / mm ²
Hanger	Cross section area	0.03 m ² / 125 m / Cable
Stiffening girder	Cross section area	1.3 m ² / Br
	Vertical flexural stiffness	12.0 m ⁴ / Br
	Horizontal flexural stiffness	160 m ⁴ / Br
	Torsional strength	26 m ⁴ / Br
	Polar moment of inertia	3303 t · m ² / m
Dead weight	Girder	235 kN / m / Br
	Cable	108 kN / m / Br
	Total	343 kN / m / Br
Main tower	Tower height	370.0 m
Attachment stay	Crossed stay cross sectional area	0.01m ² / cross stay
Modeling	Girder boundary condition	No modeling the tower ring and wind shoe
	Girder center of gravity	Cable fixation point
	Girder joint interval	125 m
Girder width (representative width used for the analysis)		41 m

Table Flutter analysis conditions

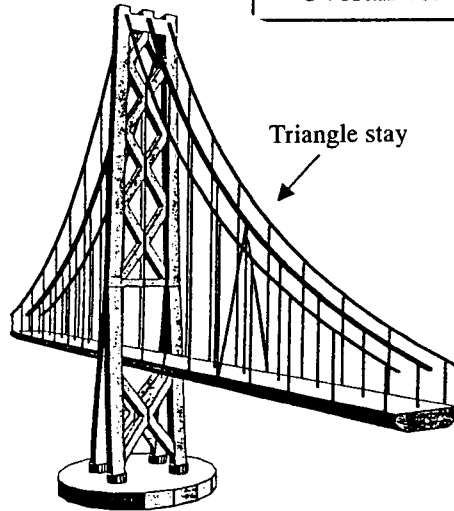
Item	KW1			
Analytical method	Direct method			
Air density	1.23 kg/m ³			
Static deformation in wind condition	Considered Not considered			
Structural damping	$\delta = 0$ (During analysis) $\delta = 0.02$ (At flutter developing wind velocity)			
Aerodynamic force coefficient	Main girder			
		Vertical	Torsional	Out-of-plane
	Lift	○	○	×
	Moment	○	○	×
	Drag	×	×	△
	○: Non-stationary aerodynamic force △: Quasi-steady aerodynamic force ×: Not considered Cable, quasi-steady resistance, lift.			
Non-stationary aerodynamic force	Actual value			
Quasi-steady aerodynamic force	Main girder $C_D = 0.75, A_n = 7.0 \text{ m}^2 / \text{m} / \text{Br.}$ Cable $C_D = 0.7, A_n = 2 \times 1.0 \text{ m}^2 / \text{m} / \text{Br.}$			
Other	Girder width B = 41 m			

Combination of three main cables with auxiliary triangle stay cables and mono-box deck with modified fairing and center-barrier

NKK Corporation

Outline

Overall view



Triangle stay

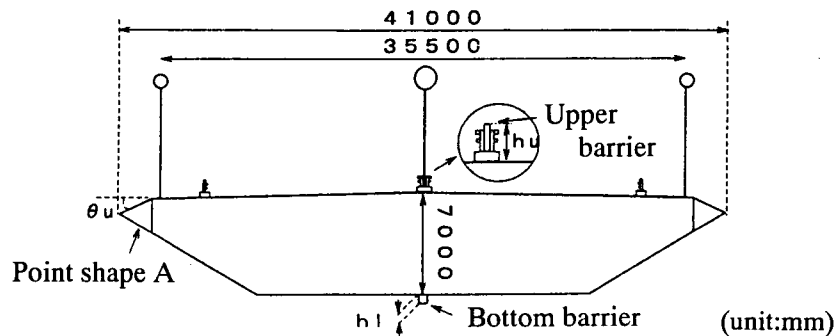
Triangle stay fixation point.
Center span side : L/4 point.
Side span side : center.
(Total 4 points).

Structural type	3 span 2 hinge suspension bridge
Cable span	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9
Main cable cross section ratio.	1 : 2 : 1 (The center is 2.)

Characteristics · Comments

- * This is a construction type which combines the 3 cable suspension bridge + triangle stay method with a modified mono-box deck.
- * The flutter onset velocity of the mono-box deck increased by over 20 percent, due to the installation of upper and bottom barriers, and changes to the shape of the girder-tip fairing.
- * The flutter onset velocity is higher than a 2 cable suspension bridge + cross stay method of the same cross section.

Girder cross section configuration



Wind resistance characteristic

- * Flutter onset wind speed (by flutter analysis) is 80m/s. (vertical skew angle of flow $\alpha = 0^\circ$)
- * Maximum amplitude of vortex-induced oscillation (spring mounted tests) (uniform flow, $\delta = 0.02$)

Attack angle	Bending	Torsional
+ 3°	Not occur	0.77 deg.
0°	Not occur	Not occur
- 3°	Not occur	0.52 deg.

Wind resistance characteristic evaluation conditions

Various conditions of the analysis model

Item		Structural value
Type	Structure type	3-span 2-hinge suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	35.5 m
	Effective cross sectional area	1.2 m ² / Br
	Number of cables	3 cables / Br.
	Horizontal tensile force	9.63 × 10 ⁵ kN / Br
	Allowable stress	980 N / mm ²
Hanger	Cross section	0.011 m ² / Point
Stiffening girder	Cross section	1.3 m ² / Br
	Vertical flexural stiffness	12.0 m ⁴ / Br
	Horizontal flexural stiffness	160 m ⁴ / Br
	Torsional rigidity	26 m ⁴ / Br
	Polar moment of inertia	3303 t·m/m
Dead weight	Girder	235 kN / m / Br
	Cable	108 kN / m / Br
	Total	343 kN / m / Br
Main tower	Tower height	370.0 m
Auxiliary stay	Triangle stay cross section	0.011 m ² / Point (effective on one side)
Modeling	Girder boundary condition	Modeling the tower link and wind bearing
	Girder center of gravity	3.5 m below the cable fixing point
	Girder hanger interval	70 m
Girder width (representative width used for the analysis)		41 m

Table Flutter analysis conditions

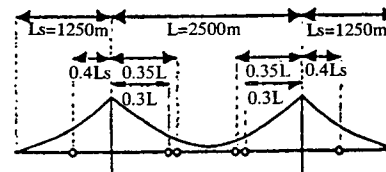
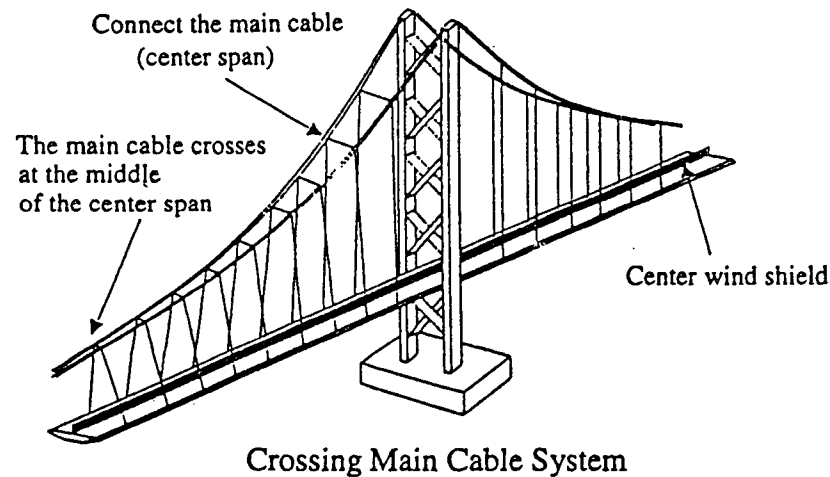
Item	Analytical condition																
Analytical method	Mode combination method. Use 100 eigen modes in windy conditions. (The eigen modes in wind velocity 80m / s is applied to all wind velocities).																
Air density	1.23 kg/m ³																
Static distortion under windy conditions	Considered																
Structural damping	All modes $\delta = 0.02$																
Aerodynamic force coefficient	Main girder<table><tr><td></td><td>Vertical</td><td>Torsional</td><td>Horizontal</td></tr><tr><td>Lift</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Moment</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Drag</td><td>×</td><td>×</td><td>△</td></tr></table> ○: Non-stationary aerodynamic derivatives △: Quasi-steady aerodynamic force ×: No consideration. Cable: Quasi-steady resistance Lift / Main tower: not considered		Vertical	Torsional	Horizontal	Lift	○	○	×	Moment	○	○	×	Drag	×	×	△
	Vertical	Torsional	Horizontal														
Lift	○	○	×														
Moment	○	○	×														
Drag	×	×	△														
Non-stationary aerodynamic derivatives	Measured value (forced oscillation method)																
Quasi-steady aerodynamic force	Main girder: use measured coefficients. $C_D = 0.75$ ($\alpha=0^\circ$) $A_n = 7.0 \text{ m}^2 / \text{m} / \text{Br.}$ Cable $C_D = 0.7$, $A_n = 2.0 \text{ m}^2 / \text{m} / \text{Br.}$																

Combination of 1-box girder with center wind shield and new cable system

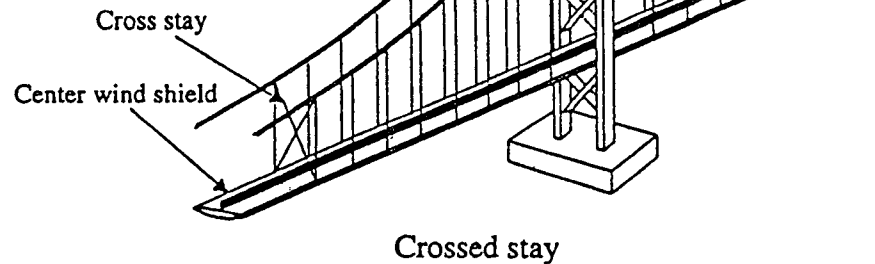
Mitsubishi Heavy Industries, Ltd.

Outline

Overall view

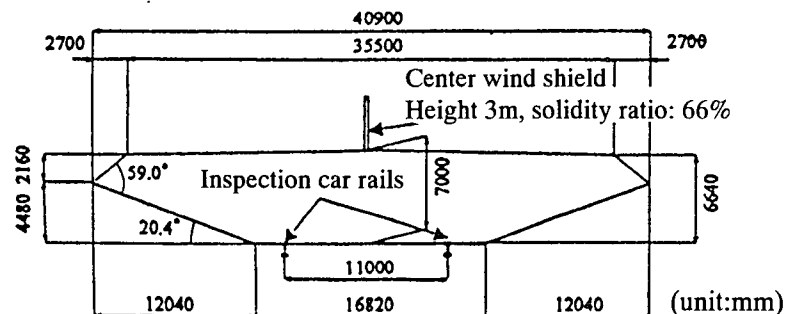


○ : Crossed stay fixation points



Girder cross section configuration

- * Optimize the shape of the fairing, and the inspection car rail fixation point
- * Installation of center wind shields



Characteristics · Comments

- * A one box girder cross section featuring a center wind shield effective for improving both the anti-flutter characteristics, as well as the safety of cars running under strong wind conditions is used.
- * As a new type, the Crossing Main Cable system, or the cross stay.

Wind resistance characteristic

- * Critical flutter speed (value attained by 3 dimensional flutter analysis: turbulence angle of inclination 0°)

	Crossing Main Cable System	Crossed stay (6 locations)
With center wind shield	82.8 m / s	96.3 m / s
No center wind shield	79.1 m / s	89.7 m / s

- * Not considering overdrive

Wind resistance characteristic evaluation conditions

Various conditions of the analysis model

Item		Structural value	
Type	Structure type	3 span 2 hinge suspension bridge	
	Span length	1,250m + 2,500m + 1,250m	
Main cable	Sag ratio	1 / 9	
	Distance of main cables	35.5 m	
	Effective cross sectional area	$2 \times 0.6 = 1.2 \text{ m}^2 / \text{Br}$	
	Young's modulus	200 kN/mm ²	
	Allowable stress degree	980 N / mm ²	
Hanger	Hanger interval	28 m	
	Cross sectional area	0.0056 m ²	
	Young's modulus	137 kN/mm ²	
Stiffening girder	Cross section	1.3 m ² /Br	
	Vertical flexural stiffness	12 m ⁴ /Br	
	Horizontal flexural stiffness	160 m ⁴ / Br	
	Torsional stiffness	26 m ⁴ /Br	
	Moment of inertia	3303 t · m ² /m/Br	
Dead load	Suspension structure	235 kN / m / Br	
	Cable	108 kN / m / Br	
	Total	343 kN / m / Br	
Tower	Theoretical cable vertex	TP + 380.0 m	
	Internal stiffness	200 m ⁴ / shaft	
	External stiffness	100 m ⁴ / shaft	
	Torsional strength	35 m ⁴ / shaft	
Modeling	G.B. C	Boundary condition	Modeling the tower ring and wind shoe
		Center of gravity	Same as the fixation point
		Horizontal member	None
		Tower pillar intervals.	45 m
Girder width (representative width used for the analysis)			40 m

Flutter analysis conditions

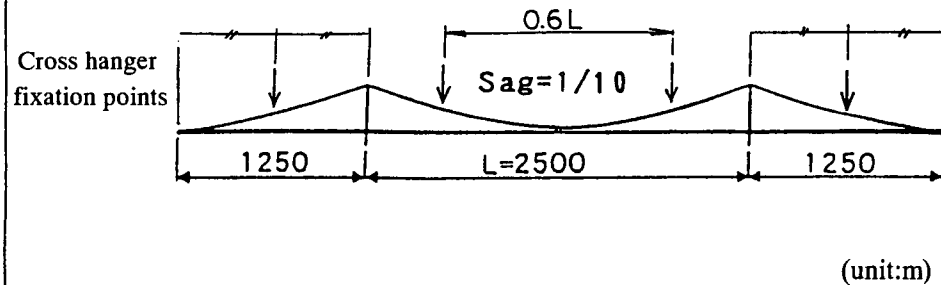
Item	Analytical condition																
Analytical method	Mode combination method. Use lower 50 modes. Use oscillation modes under no wind conditions.																
Air density	1.23 kg/m ³																
Static distortion under windy conditions	Not considered																
Structural damping	All modes $\delta = 0.02$																
Aerodynamic force coefficient	Main girder<table><tr><td></td><td>Vertical</td><td>Torsional</td><td>Horizontal</td></tr><tr><td>Lift</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Moment</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Drag</td><td>×</td><td>×</td><td>△</td></tr></table> ○: Unsteady aerodynamic force △: Quasi-steady aerodynamic force ×: No consideration. Cable: Quasi-steady drag, lift.		Vertical	Torsional	Horizontal	Lift	○	○	×	Moment	○	○	×	Drag	×	×	△
	Vertical	Torsional	Horizontal														
Lift	○	○	×														
Moment	○	○	×														
Drag	×	×	△														
Unsteady aerodynamic force coefficient	Measured value (forced vibration test)																
Quasi-steady aerodynamic force	Main girder: $C_D = 0.75$ ($\alpha=0^\circ$), $A_n = 7.0 \text{ m}^2 / \text{m} / \text{Br}$. Cable $C_D = 0.75$, $A_n = 2.0 \text{ m}^2 / \text{m} / \text{Br}$.																

2-box girder with four main cables, cross hangers for structural stiffening and double barriers for aerodynamic stabilization

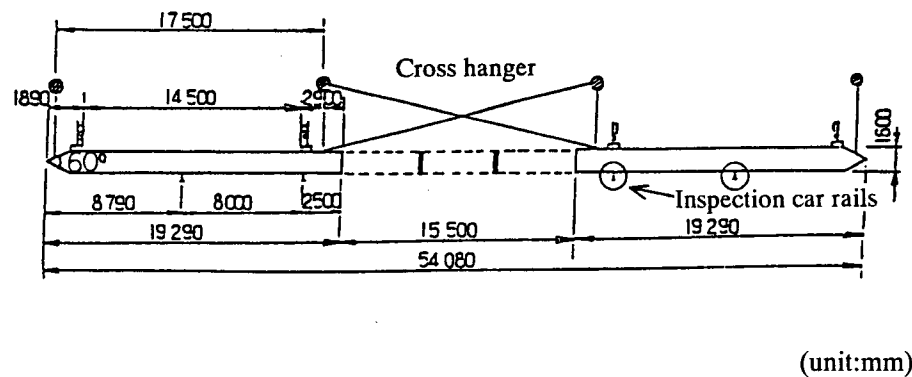
Ishikawajima-Harima Heavy Industries Co., Ltd.

Outline

Overall view



Girder cross section configuration



Characteristics · Comments

- * This bridge has excellent wind resistance, with a flutter wind speed above 90m/s at a pitch angle of 0° .
- * This bridge is very economic, with the total weight of cables and steel girder being 319 kN/m.
- * The twin-box cross-section, fitted with double barriers, dramatically increases the flutter wind speed at positive angles of attack (leading edge up) to over 97m/s between $+1^\circ$ and $+5^\circ$.
- * The inspection car rails were installed as shown in the lower drawing to maintain a high flutter wind speed at positive angles of attack while also providing a positive pitching moment at zero angle of attack.
- * The cross-hangers were positioned at locations that maximized the torsional stiffness of the deck, while maintaining a positive angle of attack under high winds.

Wind resistance characteristic

- * The predicted flutter wind speed was 90 m/s at zero angle of attack.

Wind resistance characteristic evaluation conditions

Item		Structural analysis/ model conditions
Type	Structure type	3 span 2 hinge suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Girder span length	1,226m + 2,480m + 1,226m
	Sag ratio	1 / 10
Main cable	Distance of main cables	37.5 m
	Cross section	0.385 m ² / cable
	Number of cables	4 cables
	Horizontal tensile force	2.48 × 10 ⁵ kN / cable
	Allowable stress degree	980 N / mm ²
Hanger	Cross section	0.04625 m ² / Point
Stiffening girder	Cross section	0.516 m ² / deck
	Vertical flexural stiffness	0.301 m ² / deck
	Horizontal flexural stiffness	11.39 m ⁴ / deck
	Torsional strength	0.7695 m ⁴ / deck
Dead weight	Girder + side beams	180 kN / m / Br
	Cable	139 kN / m / Br
	Total	319 kN / m / Br
Girder ultra moment of inertia		163.7 t·m ² /m/deck
Main tower	Tower height	342.5 m (Theoretical cable vertex)
cross hanger	Cross section	0.014 m ² / Point
Modeling	Girder boundary condition	Modeling the tower ring and wind shoe
	Girder center of gravity	0.8m below the cable fixation point
	Girder joint interval	125 m
Girder width (representative width used for the analysis)		19.29 m

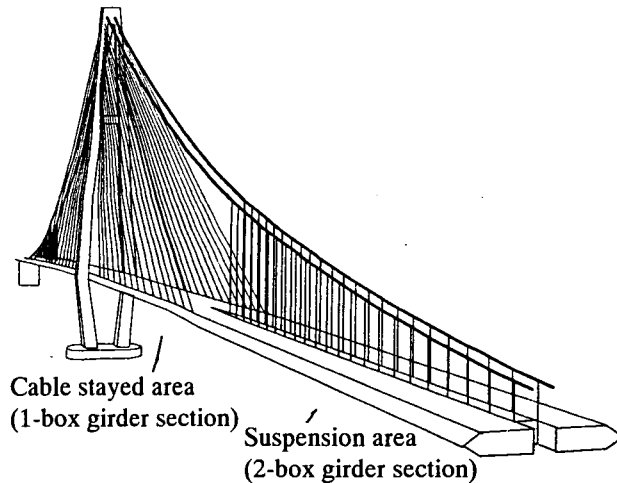
Item	Flutter analysis conditions			
Analytical method	Mode combination method. Use characteristic frequencies under windy conditions. Use low 50 modes.			
Air density	1.18 kg/m ³			
Static distortion under windy conditions	Considered			
Structural damping	All modes $\delta = 0.02$			
Aerodynamic force coefficient	Main girder			
		Vertical	Torsional	Horizontal
	Lift	○	○	△
	Moment	○	○	△
	Drag	○	○	△
○: Non-stationary aerodynamic force △: Quasi-steady aerodynamic force Cable: quasi-steady resistance Lift / Hanger: quasi-steady resistance				
Non-stationary aerodynamic force	Actual value (forced oscillation method)			
Quasi-steady aerodynamic force	Main girder: $C_D = 1.684$ (Attack angle = 0°) $A_n = 2.626 \text{ m}^2 / \text{m}$			
	Cable: $C_D = 0.7$, $A_n = 4 \times 0.783 \text{ m}^2 / \text{m} / \text{Br}$. Hanger: $C_D = 0.7$, $A_n = 1.25 \text{ m}^2 / \text{m} / \text{Point}$ (in the member axis direction)			

Combination of 2-box and 1-box combined girder and stay-cable system

Kawasaki Heavy Industries Ltd.

Outline

Overall view



The 2-box girder section is applied to the suspension areas which are the center part of $L_s/2$ in the main span and the bridge end part of $L_s/2$ in the side span.

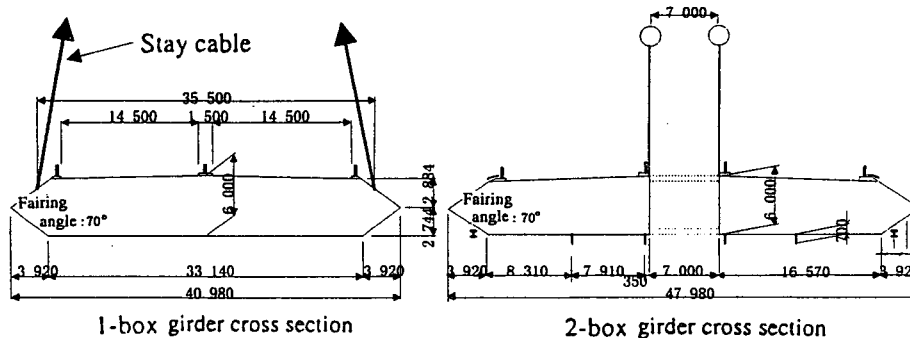
Structural type	3-span continuous cable-stayed suspension bridge
Cable span	1250 m + 2500 m + 1250 m
Sag ratio	1 / 9

Characteristics · Comments

- * While a 2-box girder is installed at the center part of the main span to improve wind resistant characteristics of the bridge, a 1-box girder is used near the tower in order to reduce the girder weight.
- * Cables are located according to the center opening width in the 2-box girder and the vertical hangers suspend the 2-box girder. The stay cables on the tower suspend the 1-box girder to reduce torsional deformation under wind load.
- * The flutter critical wind velocity is almost the same as the suspension bridge with 2-box and 1-box combined girder.
- * There is the possibility of lowering construction costs due to lowering cable weight (or cable force), while also a smaller anchorage scale.
- * There is the possibility of shortening erection time as the girder in the cable stayed area is erected while the cables are being installed.

Girder cross section configuration

(unit:mm)



Wind resistance characteristic

- * Flutter onset wind speed (by multi-mode flutter analyses) 6-lane proposal : over 85m/s (Angle of wind inclination : 0°).
- * Maximum amplitude of vortex-induced vibration by wind tunnel tests with the 6-lane proposal section model in uniform flow (structural damping : 0.02 in logarithmic decrement)

Attack angle	Vertical deflection	Torsional deformation
+ 3°	Does not occur	0.5 deg.
0°	Does not occur	Less than 0.1 degrees
- 3°	Does not occur	1.0 deg.

Wind resistant characteristic evaluation conditions

Various conditions of the analyzed model

Item		Structural value
Type	Structural type	3-span continuous cable-stayed suspension bridge
	Cable span length	1,250m + 2,500m + 1,250m
	Sag ratio	1 / 9
Main cable	Distance of main cables	7.0 m
	Effective cross sectional area	0.950 m ² / Br
	Number of cables	2 cables / Br
	Dead weight tensile force	8.43 × 10 ⁵ kN / Br
	Allowable stress degree	980 N / mm ²
Hanger	Cross section area	9.34 × 10 ⁻⁴ m ² / m / Br
Diagonal cable	Cross section area	1.02 ~ 2.58 × 10 ⁻³ m ² / m / Br
Stiffening girder	Cross section	1.516 (1.776) m ² / Br
	Vertical flexure stiffness	9.660 (13.278) m ⁴ / Br
	Horizontal flexural stiffness	263.3 (183.2) m ⁴ / Br
	Torsional strength	21.0 (31.0) m ⁴ / Br
	Polar moment of inertia	5.00 × 10 ⁴ (3.16 × 10 ⁴) t · m ² / m
Dead weight	Stiffening girder	274(302) kN / m / Br
	Cable	87(73) kN / m / Br
	Total	361(375) kN / m / Br
Main tower	Tower height	370 m
Modeling	Girder boundary condition	Modeling the tower link and wind shoe
	Girder center of gravity	3.0 m below the hanger fixation point on the girder
	Girder joint interval	98 m (Located densely around the 2 box / 1 box boundary area.)
Girder width (representative width used for the analysis)		47.98 m (40.98 m)

Note). The values in brackets indicate the values for the 1 box girder section.

Table Flutter analysis conditions

Item	Analytical condition																
Analytical method	Multi-mode flutter analyses. Characteristic vibration modes in no wind condition are used. The first 50 modes are considered.																
Air density	1.18 kg/m ³																
Static deformation in wind condition	Yes (Considering the change in non-stationary aerodynamic forces due to torsional deformation of the girder).																
Structural damping	All modes $\delta = 0.02$																
Aerodynamic force coefficient	Main girder																
	<table><tr><td></td><td>Vertical</td><td>Torsional</td><td>Horizontal</td></tr><tr><td>Lift</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Moment</td><td>○</td><td>○</td><td>×</td></tr><tr><td>Drag</td><td>△</td><td>△</td><td>△</td></tr></table>		Vertical	Torsional	Horizontal	Lift	○	○	×	Moment	○	○	×	Drag	△	△	△
		Vertical	Torsional	Horizontal													
	Lift	○	○	×													
	Moment	○	○	×													
Drag	△	△	△														
○: Non-stationary aerodynamic force																	
△: Quasi-steady aerodynamic force																	
Cable: Quasi-steady drag and lift.																	
Stay cable: not considered																	
Non-stationary aerodynamic force	Measured values (by free oscillation method)																
Quasi-steady aerodynamic force (Values are for a 6-lane proposal)	Girder: Measured values of three-component stationary aerodynamic forces $C_D = 0.921$, $A_n = 6.00 \text{ m}^2 / \text{m} / \text{Br}$ (2-box girder section, wind attack angle 0°) Cables: $C_D = 0.7$, $A_n = 1.74 \text{ m}^2 / \text{m} / \text{Br}$																

