Aerodynamic Investigation of Cable-stayed Bridge with 2-edge Girder

Takuya Murakami*, Katsuaki Takeda**, Michiaki Takao*** and Rokusui Yui****

* Senior Research Engineer, Civil & Building Research Dept. Applied Technology Research Center
** Chief, Civil & Building Research Dept. Applied Technology Research Center
*** Manager, Technology Development Sec. Bridge Design Section
**** Researcher, Civil & Building Research Dept. Applied Technology Research Center

This paper investigates aerodynamic countermeasures using 2-edge girder sections for a cable-stayed bridge. Wind tunnel tests were conducted to confirm the performance of the new countermeasures. Additional structural countermeasures based on increasing the rigidity of the bridge were also investigated. This study concluded that the addition of a horizontal member at the top of the tower is the most effective method for increasing the flutter onset velocity. These aerodynamic countermeasures were also found to be economical.

1. Introduction

From the economical viewpoint, cable-stayed bridges with a 2-edge girder section (edge girder) have recently been the focus of attention in Japan. This type of bridge has been already adopted in other parts of the world, especially in North America. In Japan, however, mono-box girder sections have usually been used to date because of their good aerodynamic performance. The aerodynamic disadvantages of the edge girder need to be improved.

Aerodynamic countermeasures that use additional members have been developed. For example, the overhanging deck and edge plate are used in the Alex-Fraser bridge[1)], fairings in the Longs Creek Bridge[2)], baffle plates in the Quincy Bridge[3)] and so on. However, recognition during the initial design stage of practical uses of these additional members is desirable to make the structure more economical. On the other hand, structural countermeasures have also been developed to improve flutter performance by increasing the total torsional rigidity of cable-stayed bridges. For example, a high, rigid A-type (or diamond-shaped) tower and an additional middle pier in the side span are used in the Yangpu Bridge[4)]. However, the aerodynamic effectiveness of these features has not been investigated in detail.

This paper evaluates aerodynamic and structural countermeasures for 2-edge girder sections without an overhanging deck that are more economical than a similar structure with an overhanging deck. Wind tunnel tests were conducted first to confirm the performance of a new countermeasure that uses rectangular corner members, which are assumed to be essential attachments, such as maintenance passages or lifeline boxes. Next, structural countermeasures that increase bridge rigidity were investigated to find effective countermeasures against flutter. Finally, the applicable span length for the cable-stayed bridge was investigated, focusing on the flutter performance of the 2-edge girder section without an overhanging deck.

2. Outline of assumed bridge

The assumed bridge is shown in **Fig.1**. This bridge is a 760m long, double plane, 3-span, continuous, cable-stayed bridge with a 400m center span and 180m side spans (side span ratio of 0.45). The tower is an H-shape, and a floating system is used between the girder and tower. Two 2-edge, girder sections without an overhanging deck were selected for their economy: an I-shaped girder section (section A) and a box-shaped girder section (section B). The 2-edge box-shaped girder section is common in long-span cable-stayed bridges. The sections have a width of 22m, height of 2m, cross beam height of 1.5m and spacing of 3m, and stringers with a height of 0.5m and spacing of 4.0m. A blocked, central guard fence is installed for aerodynamics and economy.

3. Aerodynamic investigation

3.1 Experimental apparatus

Spring-supported tests were conducted in a wind tunnel with a test section 2m wide by 3m high. This study tested angles of attack $\alpha=0°$ and $\pm 3°$ with smooth flow conditions. The 1.59m long section models were 1:50 geometrical scale. The aerodynamic performance of the original 2-edge, I-shaped girder section (**Fig.1**(c)) with 0.5m

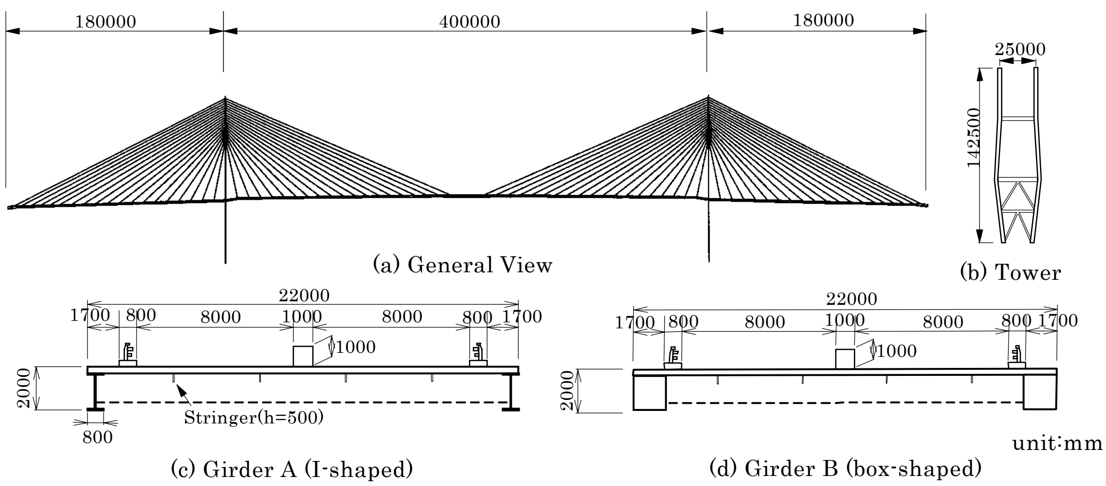


Fig.1 Cable-stayed bridge for investigation

stringer height (section A2) was compared to a model with 1.5m stringer height (section A1). The properties of the section models, which are shown in **Table 1**, were determined based on a cable-stayed bridge with a 400m center span. The concept of the new countermeasures evaluated in this study is shown in **Fig.2**. The figure shows 1m wide rectangular members protruding from the inside of the I-shaped main girders to approach the good performance of corner cut-off sections. In the box-shaped girder, the rectangular members are installed on the deck and at the bottom of the box-shaped main girders. The Pa of the protruded depth and the XU and XL distances from the edge of the girder section were investigated in this study.

Table 1 Properties of bridge section model

Property	Prototype (assumed)	Model (scale 1:50)
Width	22.0m	0.44m
Depth	2.0m	0.04m
Mass	25.23t/m	16.05kg/model
Inertia	1548t･m^2/m	0.394kgm^2/model
Damping(δ)	–	0.020
Bending freq.	0.27Hz	2.10Hz
Torsional freq.	0.54Hz	4.20Hz

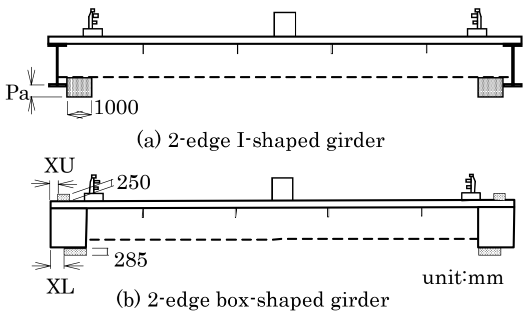


Fig.2 Concept of new countermeasure

3.2 Results

The torsional flutter onset velocity and the maximum amplitude of vortex-induced vibration were measured in every test case. The amplitude of vortex-induced vibration was transformed into an acceleration, and the torsional amplitude was expressed as an acceleration at the edge of the girder section in order to compare the results to the 100gal serviceability criterion in the Wind-Proof Design Specifications for Highway Bridges[5]. A bending amplitude of 35cm (η /B=0.016) and a torsional amplitude of 0.45°. in the prototype corresponds to 100gal. The flutter onset velocity criterion is assumed to be 60m/s. This is based on standard conditions for cable-stayed bridges in Japan: the girder is located in a coastal area, at an elevation of 60m and with a basic wind velocity of 35m/s.

3.2.1 2-edge I-shaped girder section

The results are shown in **Fig.3**. In these figures, the criterion is shown as a double line, and Pa = w/o means the case without rectangular members.

(1) Stringer height

Considering stringer height, the aerodynamic performance of A1 was better than A2. The flutter onset velocity of A1 exceeds that of A2 by more than 10m/s, while the bending and torsional acceleration of vortex-induced vibration of A1 is smaller. This demonstrates that higher stringers improve the flutter performance, which is similar to the effect of baffle plates.

(2) Aerodynamic performance of original section

For the case without rectangular members (Pa = w/o), the flutter onset velocity of section A1 exceeded 60m/s for all angles of attack studied. On the other hand, section A2 had a lower flutter onset velocity of 45m/s for the angle of attack of α = –3° and 50m/s at α = 0°. In addition, the maximum acceleration of torsional vortex-induced vibration exceeded 100gal at α = –3° for both sections. Therefore, some countermeasures against vortex-induced vibration must be taken for both sections, while additional countermeasures against flutter are needed for section A2.

(3) Effectiveness of countermeasure

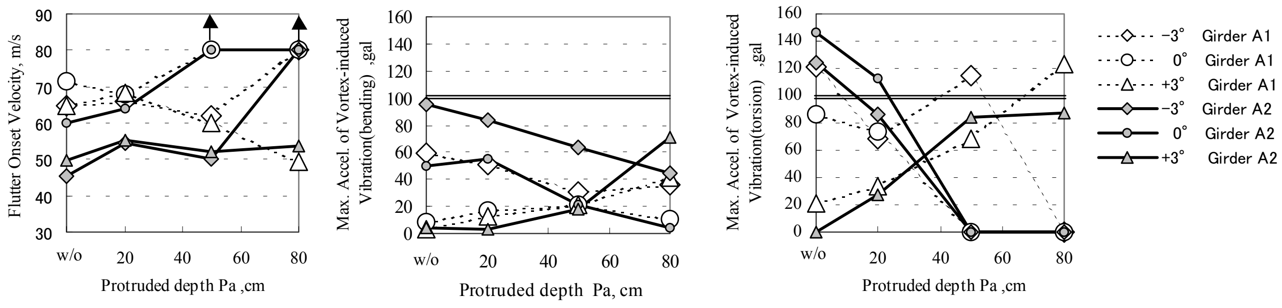
In section A1, increasing Pa degrades the aerodynamic performance at α = +3°. For Pa=80cm, the flutter onset velocity was about 50m/s, and the acceleration of torsional vortex-induced vibration reached about 120gal. On the other hand, at α = –3°, the torsional vortex-induced vibration performance improved for the cases of Pa=20 and 80cm. Thus, in section A1, the case of Pa=20cm has the best aerodynamic performance with a flutter onset velocity that is the same as the original section A1 (Pa = w/o) and a vortex-induced vibration that is reduced to 70gal.

In section A2, the cases of Pa=50 and 80cm had better vortex-induced vibration performance at attack angles of α =0° and –3°, with remarkably reduced accelerations. In addition, the maximum acceleration of vortex-induced vibration at α = +3° did not exceed 100gal for any case, although increasing Pa increased the vortex-induced vibration acceleration similarly to section A1. However, the flutter onset velocity was about 50m/s in all cases. For section A2, the case of Pa=80cm has the best aerodynamic performance, with flutter performance exceeding that of the original section A2 (Pa = w/o) and vortex-induced vibration below 100gal. However, the flutter onset velocity remained about 55m/s, so an additional countermeasure against flutter may be necessary.

In conclusion, the new countermeasure has protruding rectangular members on the inside of I-shaped main girders that can be used for public attachments and that are effective for reducing vortex-induced vibration. However, the optimum depth of the protrusion is different than the stringer height.

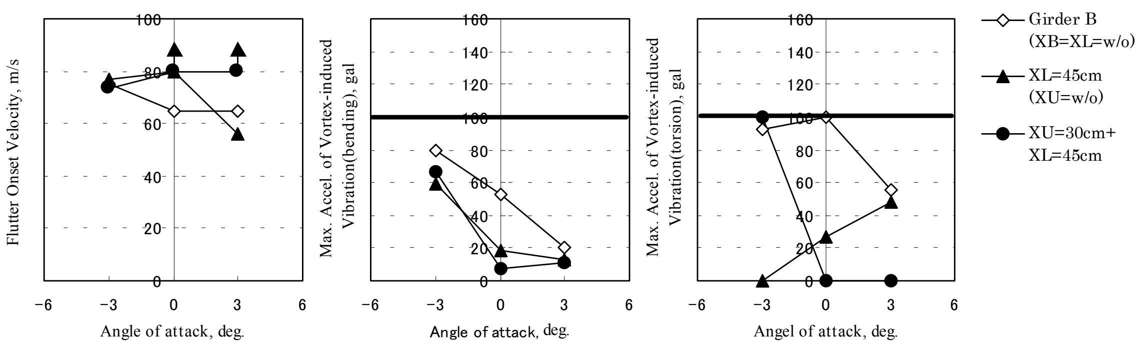
3.2.2 2-edge box-shaped girder section

Fig.4 shows representative test results for the original section B (XU=XL=w/o), the modified section B1 (XL=45cm and XU=w/o), and the modified section B2 (XU=30cm and XL=45cm). The flutter onset velocity of section B was about 65m/s, which is 50% higher than that of the 2-edge I-shaped girder section (A2). In addition, the acceleration of vortex-induced vibration was nearly 100 gal, although it was less than that of section A2. Therefore, the aerodynamic performance of the 2-edge, box-shaped girder section is better than that of the 2-edge I-shaped girder section. In section B1, the maximum acceleration was reduced, but the flutter performance was worse at the angle of attack of α = +3°. On the other hand, the flutter onset velocity for section B2 exceeded 74m/s at angles of α = 0 and ±3°, which is 15% higher than that of the



(a) Flutter (b) Vertical vortex-induced vibration (c) Torsional vortex-induced vibration

Fig.3 Investigation on new countermeasure (2-edge I-shaped girder)



(a) Flutter (b) Vertical vortex-induced vibration (c) Torsional vortex-induced vibration

Fig.4 Investigation on new countermeasure (2-edge box-shaped girder)

original section B. Vortex-induced vibration did not occur at $\alpha = 0°$, which is the normal wind condition, even though the maximum acceleration of bending and torsional vortex-induced vibration at $\alpha = -3°$ was about the same as for section B. Therefore, suitable values of XU and XL improve the flutter performance, so this countermeasure may be effective for long span, cable-stayed bridges.

4. Structural investigation

Two degrees of freedom flutter analyses were conducted to investigate the effectiveness of structural countermeasures in which additional members are installed to increase the overall bridge rigidity. The first mode of bending and torsional frequency was determined by eigenvalue analysis. Flutter analyses were then conducted using the results of the eigenvalue analyses and the measured flutter derivatives of section A1 without protruding rectangular members (Pa=w/o). The concept of the investigated structural countermeasure is shown in **Fig.5**, and the properties of the analytical model, which are different from **Table 1**, are shown in **Table 2**. Additional piers were installed in the side span in **Fig.5**(a) and the tower cable were used in **Fig.5**(b). The additional horizontal members

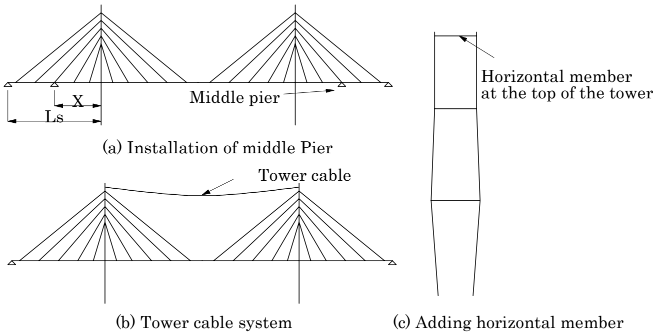


Fig.5 Concept of structural countermeasures

placed at the top of the tower are shown in **Fig.5**(c). Two cases were conducted for locations in the tower cable with different sectional areas. The properties of the additional horizontal member were assumed to be the same as those of the upper horizontal member.

The results are summarized in **Table 3**. The torsional frequency increased in all cases, but the additional middle piers and the tower cable systems do not effectively increase the flutter speed. On the other hand, adding a horizontal member at the top of the tower not only increases the torsional frequency effectively, but also increases the flutter speed by 16%. Therefore, the addition of horizontal members at the top of the tower is the most effective measure evaluated in this study. The analysis shows that the frequency ratio is a more important parameter than torsional frequency for cable-stayed bridges with a 2-edge, I-shaped girder configuration like section A.

In this application, we have to pay attention to increasing the acceleration of vortex-induced vibration. For example, when the countermeasure is applied to section B with Pa=80cm, the flutter onset velocity increases to 65m/s from 55m/s (using the same 16% increase), as shown in **Fig.3**. On the other hand, the acceleration of vortex-induced vibration, which is calculated by an increase of 13% in this result, remains less than the criterion of 100gal. Therefore, this countermeasure can be effective in combination with some girder sections.

Table 2 Properties of analytical model

Girder	Outline	Shape	2-edge I-shaped girder
		Width	22m
	Mass	Mass	23t/m
		Moment of inetia	2400t・m^2
	Stiffness	Area	1.05m^2
		Vertical	0.8m^4
		Horizontal	160m^4
		Bending - Torsional	85m^6
Tower	Stiffness	Out - Plane	11～20m^4
		In - Plane	6～8m^4
		Torsional	15～21m^4
	Horizontal member	Out - Plane	6m^4（U）, 11m^4（L）*1)
		In - Plane	5m^4（U）, 7m^4（L）
		Torsional	8m^4（U）, 15m^4（L）

(Remarks) *1) U : Upper member L : Lower member

Table 3 Effectiveness of structural countermeasures

Analytical condition			Frequency (Hz)			Flutter onset velocity	The rate of increase		
Girder	Countermeasure		Vertical sym. 1st	Torsional sym. 1st	Ratio		Torsional sym. 1st	Ratio of frequency	Flutter
2-edge I-shaped	Nothing (basic)		0.2711 Hz	0.4605 Hz	1.70	63 m/s	1.00	1.00	1.00
	Additional pier	X= Ls/4	0.4041 Hz	0.5246 Hz	1.30	66 m/s	1.14	0.76	1.05
		X= Ls/2	0.4014 Hz	0.5317 Hz	1.32	66 m/s	1.15	0.78	1.05
		X= 3Ls/4	0.3303 Hz	0.4895 Hz	1.48	64 m/s	1.06	0.87	1.02
	Adding horizontal member		0.2711 Hz	0.5207 Hz	1.92	73 m/s	1.13	1.13	1.16
	Tower cable system	Area 1	0.3230 Hz	0.4934 Hz	1.53	65 m/s	1.07	0.90	1.03
		Area 10 1)	0.4825 Hz	0.5226 Hz	1.08	52 m/s	1.13	0.64	0.83

(Remarks) 1) Area 10 shows that the sectional area of tower cable is ten times as large as that of inclined cables

5. Applicable span length investigation

The maximum span length of 2-edge girder sections without an overhanging deck was investigated. A preliminary design for cable-stayed bridges with a main span of 200-600m was first conducted. The flutter onset velocity was then calculated using the same procedure as in the structural investigation. The flutter derivatives of the basic girder sections (sections A2 and B) and the modified girder sections (Pa=80cm and XU=30cm, XL=45cm) were used in two degrees of freedom flutter analyses. The results are summarized in **Fig.6**. This figure depicts the relation between the span length and the flutter onset velocity and shows minimum values for attack angles of 0°, –3° and 3°. Some countermeasures may be required for cable-stayed bridges with main spans over 300m that use the basic I-shaped girder section without an overhanging deck. The use of the modified girder section (Pa=80cm) countermeasure and the addition of a horizontal tower with the 2-edge I-shaped girder section without an overhanging deck extends the applicable main span length of a cable-stayed bridge to over 400m. The use of the 2-edge box-shaped girder section along with the countermeasures investigated here can permit a cable-stayed bridge with main span lengths of over 600m.

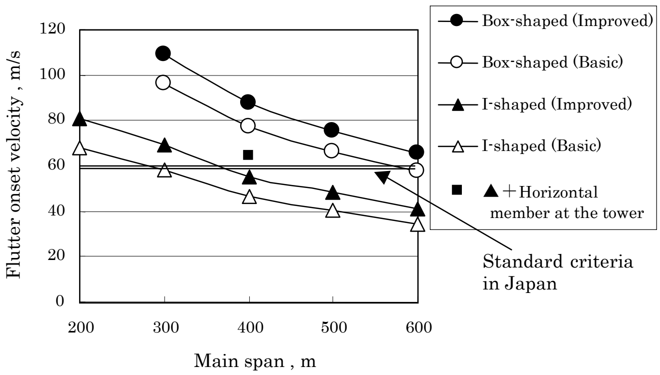


Fig.6 Relation between main span and flutter onset velocity

6. Conclusions

This paper investigates aerodynamic and structural countermeasures for cable-stayed bridges with 2-edge girder sections without an overhanging deck. The conclusions are as follows:

(1) Higher stringers in a 2-edge, I-shaped girder improve the flutter performance of the girder section.

(2) Protruding rectangular members on the inside of I-shaped main girders can be an effective countermeasure for vortex-induced vibration, as well as being used for public attachments. However, the most suitable protrusion depth of the rectangular members is different than the stringer height.

(3) The aerodynamic performance of the 2-edge, box-shaped girder section is better than that of the 2-edge, I-shaped girder section.

(4) The installation of rectangular members on the deck and at the bottom of the box girder can be an effective countermeasure for flutter. Therefore, this measure can permit a longer span for cable-stayed bridges.

(5) The installation of horizontal members at the top of the tower was the most effective measure for increasing the flutter onset velocity of those evaluated in this study. Adding a middle pier in the side span and tower cable system cannot effectively increase the flutter onset velocity, even though it increases the torsional frequency.

(6) Countermeasures are necessary to improve the flutter performance of 2-edge, I-shaped girder sections without an overhanging deck for cable-stayed bridges with a main span of over 300m. By using the proposed countermeasures, however, the 2-edge, I-shaped girder section without an overhanging deck can be used for cable-stayed bridges with main spans over 400m. The main span of a cable-stayed bridge with a 2-edge, box-shaped girder section can be extended to over 600m using the countermeasures investigated here.

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<Please refer to>
Takuya Murakami
Civil & Building Research Dept., Applied Technology Research Center
Tel : (81) 44-322-6337
E-mail : tmurakam@lab.keihin.nkk.co.jp