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Improvement of aerodynamic stability of simplified suspension-bridge girder structure

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ABSTRACT

Wind-tunnel study on the improvement of aerodynamic stability of simplified suspension-bridge girder structures was conducted with using a 1/40-scaled section model. Objective of the study is the development of an economically superior suspension bridge with 500-1,000m center span length. The wind-tunnel test showed that an edge-girder type cross section exhibited large amplitude torsional vortex-induced vibration as well as torsional flutter at a low wind speed. Accordingly, open grating deck, triangular faring, center stay and diagonal bracing as well as mass effect were tried to improve the aerodynamic stability. Finally, feasibility of the best combination to a full-scale bridge was examined by structural analysis.

1. INTRODUCTION

Suspension bridge is the most suitable form for super long-span bridges with a more than 1,000m center span. It is also superior and competitive for less than 1,000m span bridges even though recently cable-stayed bridge is very likely to be selected for such span length. From the viewpoint of aerodynamic stability, a truss or closed box girder is mostly adopted for long-span bridges. However, even box girder has a limit for realizing lower manufacturing cost due to complicated welding, and many vertical and lateral ribs.

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In this study, aiming at the development of a simplified girder structure with adequate aerodynamic stability and economical efficiency for suspension bridge, model suspension bridges were designed and their aerodynamic stability were examined by section-model wind-tunnel tests. Then, the feasibility for such a simplified suspension bridge girder structure was discussed by structural analysis.

A simpler girder structure proposed in this study is the so-called edge girder structure in which main girders are arranged on the both outsides and a composite deck slab is placed between the two girders, as shown in Fig.1. However, it is well known that this edge-beam girder is inferior to aerodynamic stability as reported, for example, in cases of Tacoma Narrows Bridge and Alex Frazer Bridge. Authors also conducted a wind-tunnel test for such an edge girder structure of a suspension bridge (Katsuchi, et al. 2013). In this study, in order to improve the aerodynamic stability of the edge girder structure of a suspension bridge, some aerodynamic countermeasures of a steel grating, faring, cable stay and diagonal bracing were tested. In addition, mass effect was investigated. Finally, the feasibility of the aerodynamically best and simplified girder structure to a full-scale bridge was examined by structural analysis.

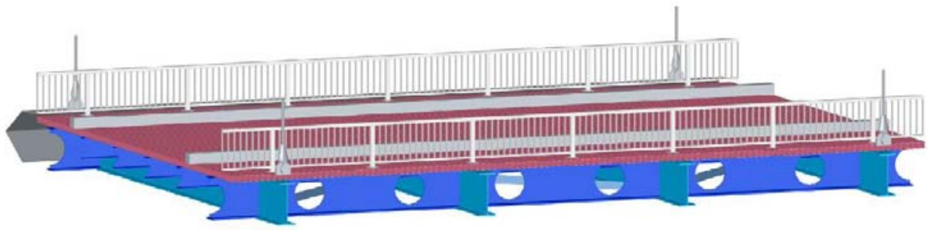


Fig. 1 Edge girder structure

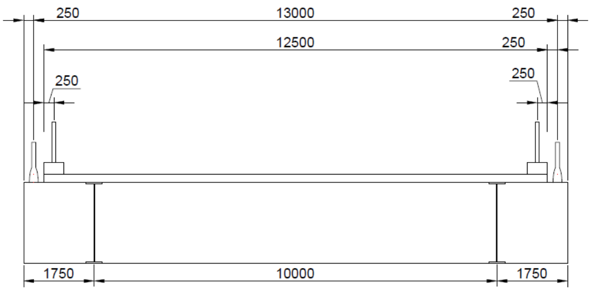
2. MODELING OF SUSPENSION BRIDGES WITH SIMPLIFIED GIRDER STRUCTURE

2.1 Model bridge design

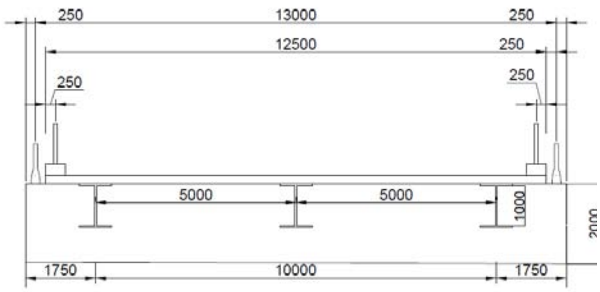
Suspension bridges with simplified girder structures studied here are designed. Model bridges are single span suspension bridges with the center span of 540m and the sag ratio of 1/10. The 13.5m wide and 1.0m high bridge girder accommodates two traffic lanes. A simplified girder structure consists of two edge girders and a deck slab. Three types of the deck slab are adopted: RC deck, I-beam grid RC deck and steel grating deck. In order to investigate structural efficiency of the deck slab, three types of girders are adopted: two, three and six girders, as shown in Fig. 2. In addition, hanger interval in the longitudinal direction is varied at 10, 15 and 20m. Asphalt pavement of 70mm thickness is placed on the RC decks. Main cables are designed assuming the tensile strength of 1,800 MPa with the safety factor of 3.

Table 1 shows weight of suspended structures for model suspension bridges to be studied. Suspended structure weight varies from 15 to 20t/m except for the steel grating deck type. Larger hanger interval tends to yield a heavier structure. Two edge-girder type also yields a heavier structure. On the other hand, steel grating deck girder is considerably light. Fig. 3 shows the total weight of superstructures including towers and cables for models with the hanger interval of 15m.

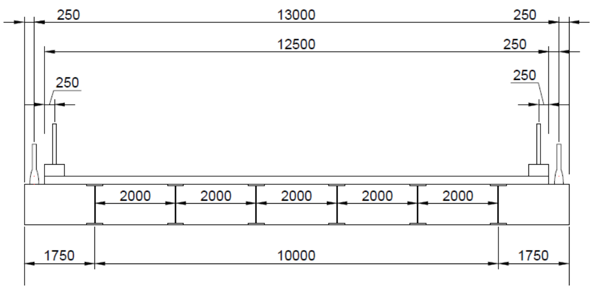
Based on the model bridge design, a multiple girder structure rather than two edge girder one is advantageous with respect to the total weight. However, construction cost of a bridge must be evaluated by not only total weight (material cost) but also simplification of structures (fabrication cost). In addition, a steel grating deck girder is quite advantageous with respect to structural simplification as well as the total weight. However, it should be noted that a suspension bridge requires weight effect to some extent for aerodynamic stability. This will be examined by a wind-tunnel test described later.



(a) Two edge girder structure



(b) Three girder structure



(c) Six girder structure

Fig. 2 Cross section of girder

Table 1 Weight of model suspension bridges

Hanger interval (m)	No. of girder beam	Deck type	Girder weight (kN/m)	Tension of main cables (kN)	Area of main cable (m^2)	Unit weight of suspended structure (kN/m)
10	2	I-beam grid RC	122.7	1.83×10^5	0.155	147.1
	3	RC	165.3	2.18×10^5	0.185	194.5
		I-beam grid RC	132.8	1.91×10^5	0.160	158.1
	6	RC	171.5	2.24×10^5	0.190	202.2
		I-beam grid RC	118.9	1.81×10^5	0.155	143.4
		Steel grating	39.4	1.15×10^5	0.100	55.2
15	2	I-beam grid RC	123.9	1.84×10^5	0.155	148.4
	3	RC	164.0	2.18×10^5	0.185	193.3
		I-beam grid RC	139.0	1.97×10^5	0.165	165.1
	6	RC	172.1	2.24×10^5	0.190	202.1
		I-beam grid RC	127.7	1.88×10^5	0.160	152.9
		Steel grating	40.7	1.16×10^5	0.100	56.5
20	2	I-beam grid RC	127.7	1.88×10^5	0.160	152.9
	3	RC	166.5	2.19×10^5	0.185	195.8
		I-beam grid RC	144.0	2.01×10^5	0.170	170.9
	6	RC	177.7	2.29×10^5	0.195	208.5
		I-beam grid RC	133.9	1.93×10^5	0.165	160.0
		Steel grating	49.4	1.23×10^5	0.105	66.0

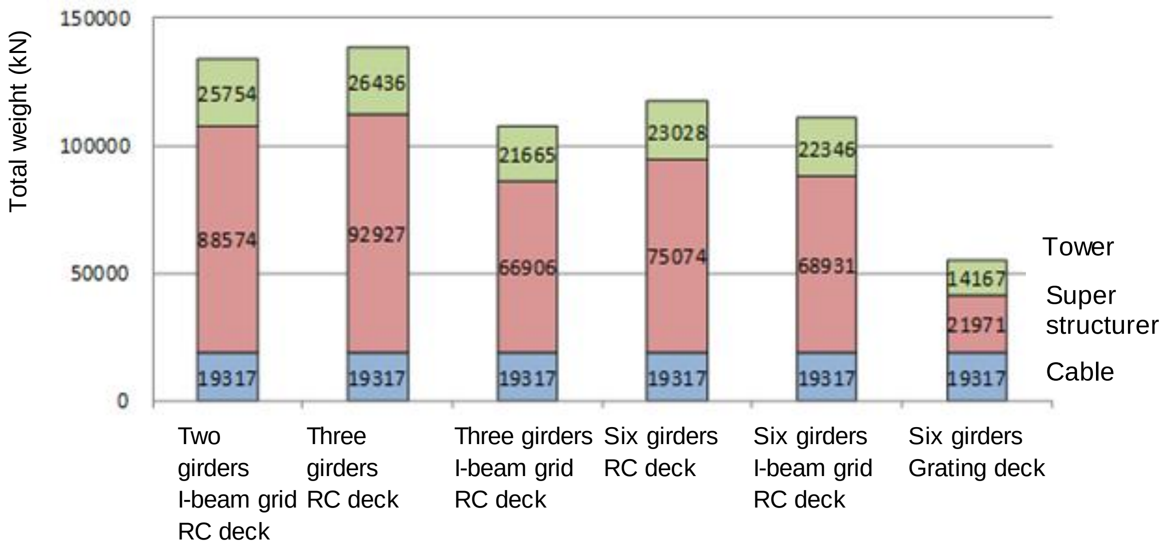


Fig. 3 Comparison of total weight (Hanger interval of 15m)

2.2 Natural frequency

In order to obtain fundamental dynamic characteristics of the model suspension bridges, natural frequencies are analyzed with 3D finite element models. These are also used for wind-tunnel test conditions. Table 2 shows natural frequencies for four fundamental modes: first symmetric vertical (1SV), first asymmetric vertical (1AV), first symmetric torsion (1ST) and first asymmetric torsion (1AT). Fig. 4 shows vibration mode shapes for case No.11. Since the weight of suspended structures except for a steel grating deck type varies by only 20%, torsional frequency also varies by only 10%. On the other hand, a steel grating deck type yields much larger torsional frequencies.

Table 2 Natural frequencies of fundamental modes

No.	Type of model (Hanger interval - Girder number - Deck type)	1SV (Hz)	1AV (Hz)	1ST (Hz)	1AT (Hz)
1	10 - 3 - RC	0.229	0.172	0.413	0.309
2	10 – 6 - RC	0.226	0.169	0.412	0.314
3	10 – 2 - I	0.258	0.197	0.435	0.331
4	10 – 3 - I	0.250	0.190	0.432	0.324
5	10 – 6 - I	0.261	0.199	0.443	0.332
6	10 - 6 - G	0.362	0.288	0.650	0.497
7	15 – 3 - RC	0.233	0.189	0.414	0.339
8	15 – 6 - RC	0.229	0.185	0.409	0.337
9	15 – 2 - I	0.258	0.214	0.436	0.361
10	15 – 3 - I	0.246	0.203	0.423	0.346
11	15 – 6 - I	0.253	0.210	0.431	0.351
12	15 – 6 - G	0.381	0.339	0.643	0.541
13	20 – 3 - RC	0.242	0.175	0.428	0.322
14	20 – 6 - RC	0.239	0.171	0.415	0.317
15	20 – 2 - I	0.266	0.196	0.434	0.334
16	20 – 3 - I	0.251	0.185	0.426	0.317
17	20 – 6 - I	0.256	0.190	0.429	0.319
18	20 – 6 - G	0.362	0.288	0.608	0.465

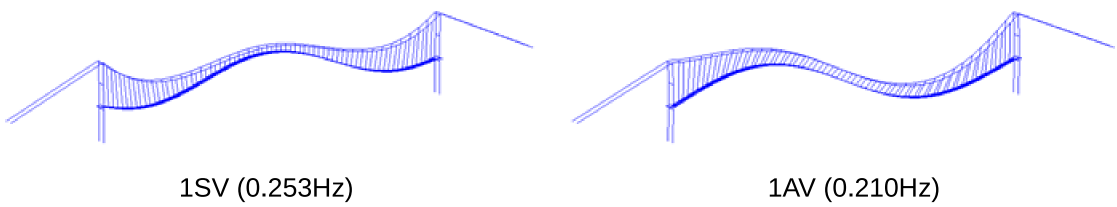
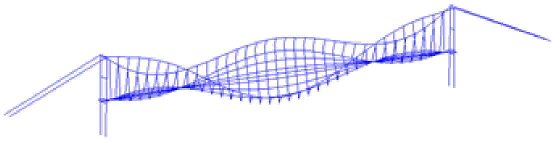
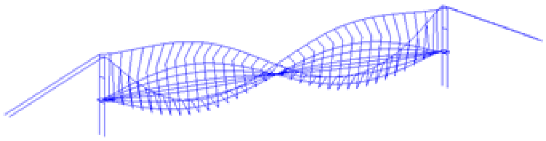


Fig. 4 Vibration mode shapes (No.11: 15-6-I)



1ST (0.431Hz)



1AT (0.351Hz)

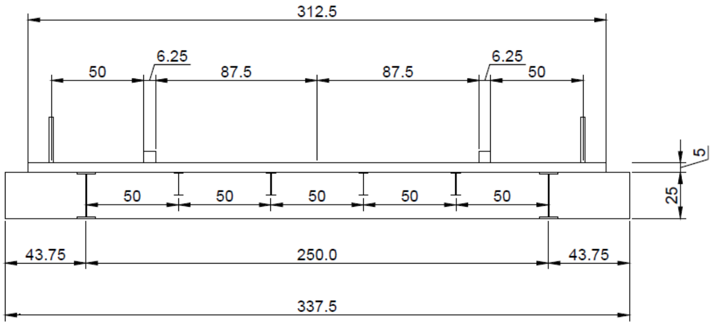
Fig. 4 (cont.) Vibration mode shapes (No.11: 15-6-I)

3. INVESTIGATION OF AERODYNAMIC STABILITY

3.1 Test cases and conditons

In order to investigate the aerodynamic feasibility of the simplified girder structure of suspension bridge, a section-model wind-tunnel test was conducted. A two-edge-girder with steel grating deck structure was originally intended to realize the simplification of a suspension bridge girder. The section model was fabricated for such geometry, as shown in Fig. 5. A steel grating deck was modeled as shown in Fig. 5(b). When a solid deck like a RC deck is tested, a cover plate was attached on the grating deck. Some aerodynamic countermeasures of faring were prepared to improve the aerodynamic stability, as shown in Fig. 6.

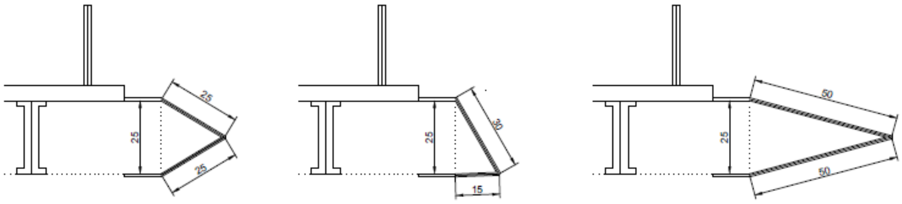
Table 3 shows test cases. Twenty cases in total were conducted where three different mass conditions were considered to investigated the mass effect. Table 4 shows test conditions. The section model was fabricated as a 1/40 scaled model. It was given two degrees of freedom in the wind tunnel. Structural damping was adjusted by electro-magnetic dampers to logarithmic decrement of 0.02, however torsional damping could not be adjusted.



(a) Cross section

(b) Grating deck

Fig. 5 Section model of wind-tunnel test



(a) Faring A (b) Faring B (c) Faring C

Fig. 6 Types of aerodynamic countermeasure

Table 3 Test cases

No.	Unit weight of suspended structure (kN/m)	Deck	Faring
1	62.5	Grating	None
2			Faring A
3			Faring B
4		Solid	None
5			Faring A
6			Faring B
7			Faring C
8	125.1	Grating	None
9			Faring A
10			Faring B
11		Solid	None
12			Faring A
13			Faring B
14			Faring C
15	187.6	Grating	None
16			Faring A
17			Faring C
18		Solid	None
19			Faring A
20			Faring C

Table 4 Test conditions

			Proto type	Model
Deck width *B* (m)			13.5	0.3375
Girder height *D* (m)			1.0	0.025
Mass *m* (kg/m)		Cases 1-7	6.38×10^3	3.99
		Cases 8-14	12.76×10^3	7.98
		Cases 15-20	19.14×10^3	11.96
Polar moment of inertia *I* (kg m^2/m)		Cases 1-7	113.4×10^3	0.0443
		Cases 8-14	226.8×10^3	0.0886
		Cases 15-20	340.2×10^3	0.1329
Natural frequency *f* (Hz)	Vertical	Cases 1-7	0.325	2.01
		Cases 8-14	0.231	1.48
		Cases 15-20	0.189	1.26
	Torsion	Cases 1-7	0.493	4.02
		Cases 8-14	0.350	3.50
		Cases 15-20	0.289	2.81
Structural damping δ	Vertical		0.02 in log.	0.020 - 0.021
	Torsion		0.02 in log.	0.010 - 0.012

3.2 Test results of aerodynamic stability

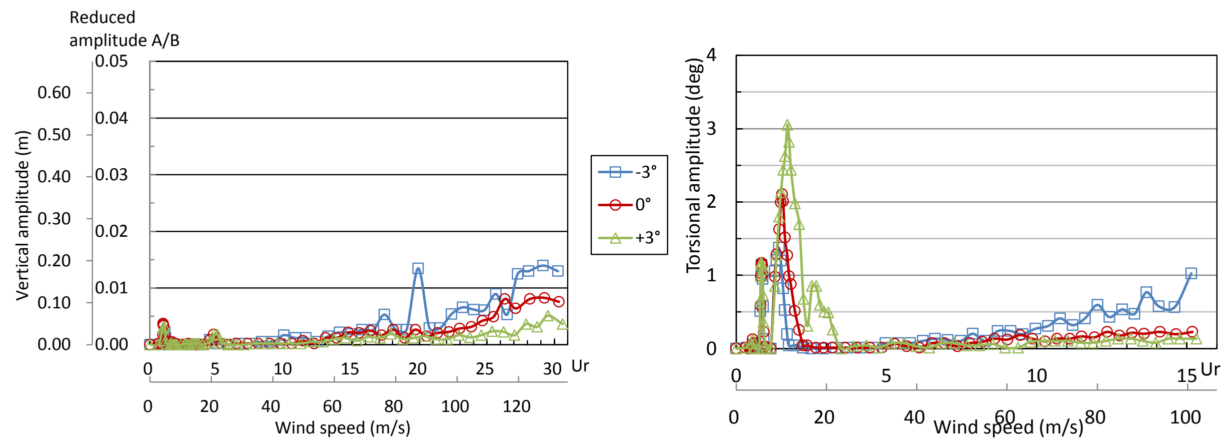
Due to the limitation of space, some characteristic results of the wind-tunnel test are shown in Figs. 7-12. The result is presented in the non-dimensional values and prototype dimensions by quantities in Table 4.

Fig. 7 shows wind-induced vibration response in vertical and torsion for Case 1 (Grating deck, no faring, lowest mass). There is only small amplitude vortex-induced vibration in the vertical direction while there is quite large amplitude one in the torsion. On the other hand, no flutter was observed up to very high wind speed. This result is similar to previous studies (Sadashima, et al. 2000 and Watanabe, et al. 2000). In this study, three types of faring were prepared, however none of those could suppress this large amplitude torsional vortex-induced vibration. There is only one possible solution for the steel grating deck structure. Largest mass case (Case 15) showed an almost satisfactory result, as shown in Fig. 8. Maximum amplitude of 1 degree was observed in +3 degree angle of attack. It may be suppressed by additional damping and/or turbulence. However, large mass condition will spoil the advantage of light weight of steel grating deck.

Fig. 9 shows wind-induced vibration response in vertical and torsion for Case 4 (Solid deck, no faring, lowest mass). Vortex-induced vibration in both vertical and torsion was observed. In addition, flutter occurred at low wind speeds. This is due to aerodynamically unstable cross section of a two-edge-girder structure. After trying to improve the aerodynamic stability of this cross section, it was found that Faring C was the most effective as shown in Fig. 10 (Case 7). Vortex-induced vibration was completely suppressed and flutter onset wind speed was increased to almost twice. However, it seems to be still short for the requirement of a 500m-class suspension bridge.

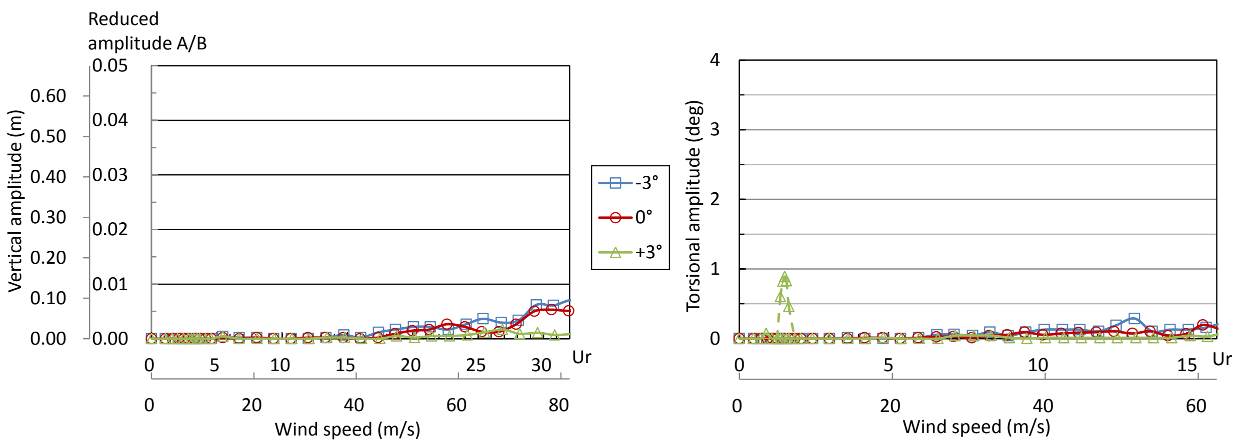
Fig. 11 shows wind-induced vibration response in vertical and torsion for Case 14 (Solid deck, faring C, middle mass). This case is a twice mass case of Case 7. The result shows the mass effect. Flutter onset wind speed was increased by the mass effect. However, mass effect also decreased natural frequencies so that a converted wind speed in the prototype bridge decreased to the level lower than that of the lighter case, on the contrary.

Fig. 12 shows wind-induced vibration response in vertical and torsion for Case 20 (Solid deck, faring C, largest mass). This case is a triple mass case of Case 7. Mass effect was observed much more than in Case 14. Mass effect to increase flutter onset wind speed surpassed the reduction effect of natural frequency. However, it also seems to be still short for the requirement of a 500m-class suspension bridge.



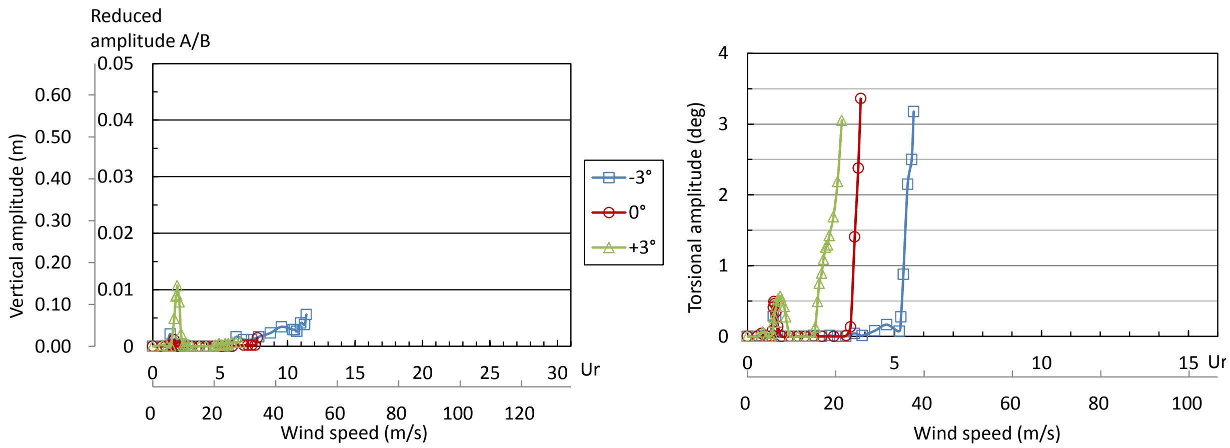
(a) Vertical (b) Torsion

Fig. 7 Vibration amplitude vs. wind speed (Case 1)



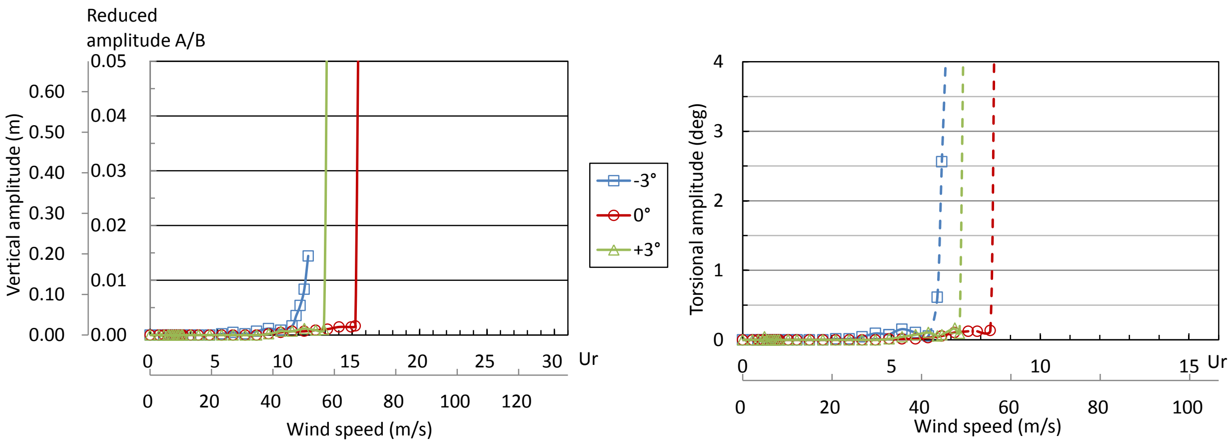
(a) Vertical (b) Torsion

Fig. 8 Vibration amplitude vs. wind speed (Case 15)



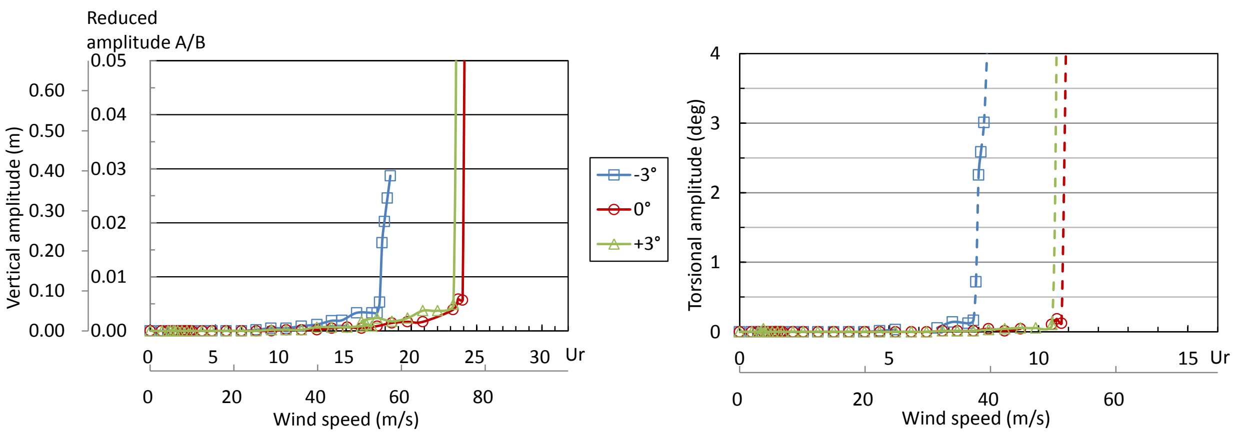
(a) Vertical (b) Torsion

Fig. 9 Vibration amplitude vs. wind speed (Case 4)



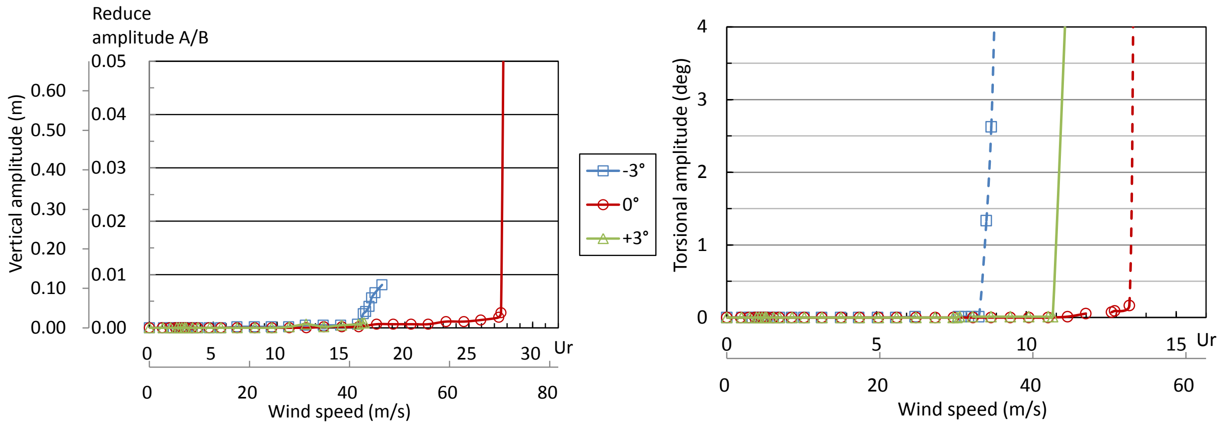
(a) Vertical (b) Torsion

Fig. 10 Vibration amplitude vs. wind speed (Case 7)



(a) Vertical (b) Torsion

Fig. 11 Vibration amplitude vs. wind speed (Case 14)



(a) Vertical (b) Torsion

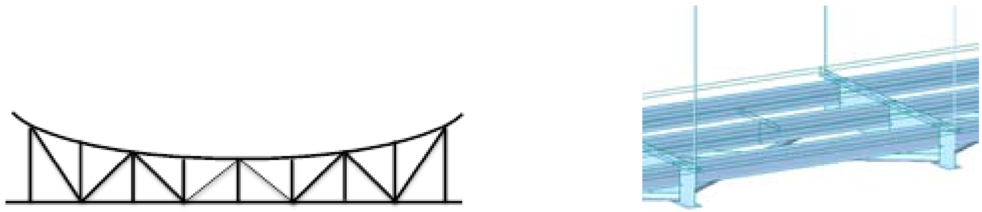
Fig. 12 Vibration amplitude vs. wind speed (Case 20)

3.3 Structural countermeasures to improve aerodynamic stability

As a result of the wind-tunnel test, it was found that some simplified girder structures (e.g., solid deck with faring C and heavy steel grating deck) have possible feasibility. In order to further investigate and improve the aerodynamic stability of those cases, structural countermeasures to increase torsional frequency were investigated.

Cable stays connecting main cables and girder at the span center, and diagonal bracing below the deck were applied to the original bridge models, as shown in Fig. 13. Then, torsional natural frequency was calculated. Effect of the increase in flutter wind speed was examined by multiplying the wind-tunnel test result by the frequency ratio.

Since Case 20 (Solid deck, faring C and largest weight) showed possible feasibility of aerodynamic stability, the corresponding bridge model was recalculated with the same weight as that in the wind-tunnel test. In addition, cable stays and diagonal bracing were put to the recalculated model. Then, the increase effect in torsional natural frequencies were applied to the wind-tunnel test result to obtain flutter onset wind speed for structural countermeasures. Fig. 14 shows flutter onset wind speed for structural countermeasures based on the wind-tunnel test result. Putting diagonal bracings below the girder (solid deck, faring C and largest weight) increased the flutter onset wind speed to more than 50m/s and 80m/s at -3 and 0 degree angle of attack, respectively. This will make the girder structure aerodynamically feasible for mild wind condition areas.



(a) Cable stays (8 stays) (b) Diagonal bracing

Fig. 13 Structural countermeasures

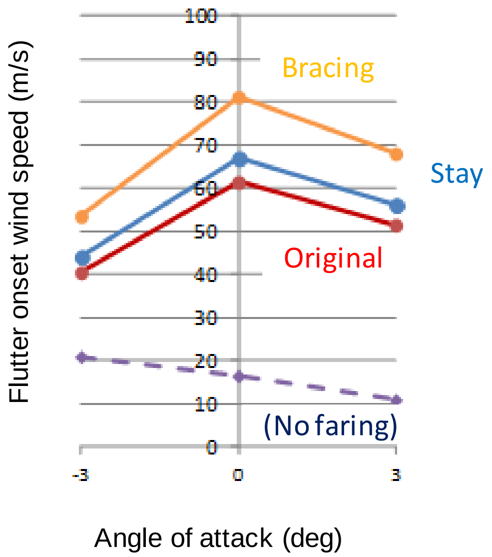


Fig. 14 Flutter onset wind speed for structural countermeasures

4. CONCLUSIONS

Feasibility and improvement of aerodynamic stability of simplified suspension-bridge girder structures for 500-1,00m span was studied by structural analysis and wind-tunnel test. The wind-tunnel test showed that a solid deck supported by two edge girder structure with triangular-shape faring provided the possible feasibility of flutter onset wind speed. On the other hand, a steel grating deck structure exhibited large amplitude torsional vortex-induced vibration. Further improvement of flutter onset wind speed of the solid deck structure was realized by cable stays or diagonal bracings. Flutter onset wind speed with diagonal bracings increased to more than 50m/s and 80m/s at -3 and 0 degree angle of attack, respectively. This will make the simplified girder structure proposed in this study aerodynamically feasible for mild wind condition areas.

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