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DYNAMIC RESPONSE ANALYSIS OF THE SECOND SAIKAI BRIDGE –A CONCRETE FILLED TUBULAR (CFT) ARCH BRIDGE-

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Abstract. *Concrete-filled steel tubular (CFT) arch bridges have been rapidly developing in China since 1990. Research has focused on the static behavior, thermal stress and erection technique, however, and there has been very little research of natural vibrations and dynamic responses of these bridges. Japan's first CFT arch bridge, the Second Saikai Bridge, is now under construction in Nagasaki Prefecture. Furthermore, this bridge has a pedestrian bridge that is suspended under the girder, which is rare. Therefore, the natural vibration properties are examined, and the influence of pedestrian bridge structure on the natural vibration of main bridge is discussed first. Response analysis under a moving vehicle and pedestrian is carried out, and the response characteristics and response level are clarified. The natural vibrations and responses are compared to those of CFT arch bridges that have been constructed in China. Results show the fine performance of both main bridge and pedestrian bridge of the Second Saikai Bridge.*

1 INTRODUCTION

In arch bridges, it may be practical to use concrete filled steel tubes (CFT) for the arch ribs in which the compression axial force is predominant. The infilled concrete delays local buckling of the steel tube, and the steel tube reinforces the concrete against tension, bending moment, and shear force. The tube also serves as a formwork for the concrete during construction of the bridge, thus saving a major construction cost[i,ii]. Moreover, the composite structural action between the infilled concrete and the steel tube improves the member's load-carrying capacity. As a result of these advantages, CFT construction for bridges has become widespread in recent decades[iii,iv]. More than one hundred CFT arch bridges have been constructed since 1990[v,vi,vii] in China, and a CFT arch bridge with the span length of over 400m is now being constructed[viii]. The Second Saikai Bridge, the first CFT arch bridge in Japan, is under construction in Nagasaki Prefecture.

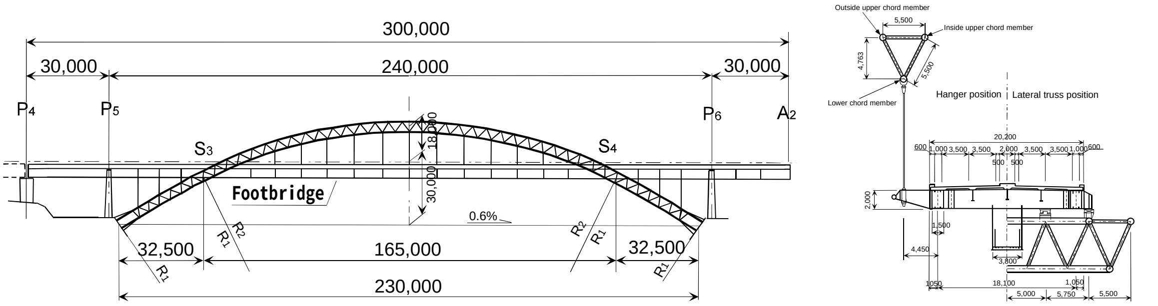
Research into CFT arch bridges has focused on the static behavior, thermal stress and erection technique [vii]. However, there has been very little research into vibrations and seismic responses of CFT arch bridges. The dynamic properties of CFT arch bridges have not been examined in detail. Therefore, it is necessary to evaluate the characteristics of the natural vibration, the dynamic response under traffic loading and the nonlinear seismic response of the actual Second Saikai Bridge. This paper focuses on the in-plane vibrations and discusses the properties of the natural vibration and the traffic-induced vibration. The nonlinear seismic analysis of this bridge will be discussed in a separate paper[ix].

This bridge has a pedestrian bridge under the girder. The pedestrian bridge allows pedestrians to cross the Second Saikai Bridge and visit a nearby public park. There is no other example in a highway bridge with such a structure suspended under the girder so it is necessary to understand the dynamic response characteristics of the pedestrian bridge. In particular, the response levels of the pedestrian bridge when a vehicle passes over the girder or when a pedestrian walks on the pedestrian bridge must be understood.

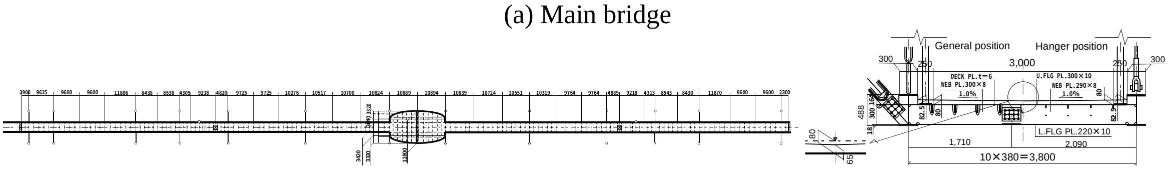
In this paper, the in-plane natural vibration properties of the bridge and the pedestrian bridge are examined, and the influence of the pedestrian bridge structure on the natural vibration of the bridge is discussed first. A response analysis induced by a moving vehicle is carried out, and the response characteristics of the bridge and the pedestrian bridge are clarified. The natural vibrations and responses are compared to those of CFT arch bridges that have been constructed in China. Finally, the response induced by a pedestrian walking on the pedestrian bridge is evaluated.

2 A BRIEF DESCRIPTION OF THE SECOND SAIKAI BRIDGE

The Second Saikai Bridge (tentative name) is a highway bridge on the Nishisonogi Region Expressway. The bridge crosses the Harioseto channel, connecting the Sasebo urban area and the Nagasaki urban area. The bridge is scheduled to be completed in 2005. As shown in Figure 1(a), the main span is 240m in length and the side spans are 30m in length. The bridge is 20.2m in width. The landscape of the site, the need to harmonize the design with that of the present Saikai Bridge (a deck type steel arch bridge with a span of 216m, completed in 1955) and the need to reduce the bridge's construction costs together lead the selection of the half-



(a) Main bridge



(b) Pedestrian bridge

Figure 1: General view of the Second Saikai Bridge (unit: mm)

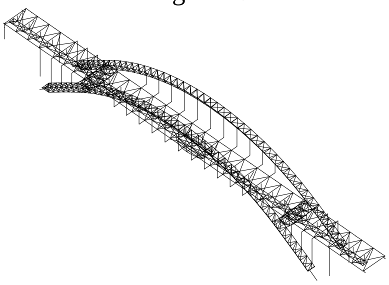


Figure 2: Integrated bridge model

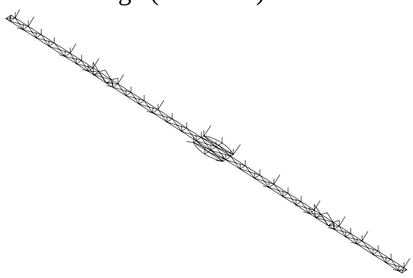


Figure 3: Separate Pedestrian bridge model

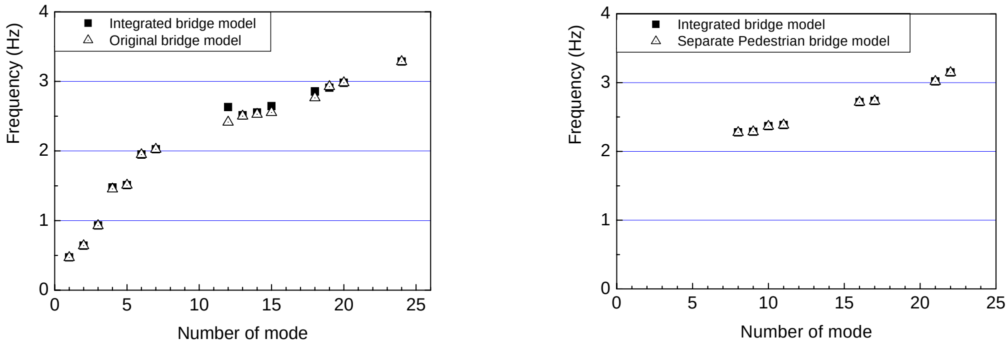
though braced-rib CFT arch bridge design for the main span. The bridge has two parallel arch ribs, each of which has a triangular cross-section consisting of three steel tubes. High fluidity concrete fills the three steel tubes. The three steel tubes have an outer diameter of 812.8mm and a thickness that differs depending upon the position of the arch rib. The deck system consists of I-beams arranged longitudinally, upon which a concrete slab is placed.

There is a pedestrian bridge under the bridge that allows pedestrians to cross the Second Saikai Bridge and visit the public park. This pedestrian bridge is 293.225m long and 3m wide. The pedestrian bridge itself has a girder made of two H-beam steel plates. This girder hangs by strand rope and steel tube from the lateral beams of the bridge. A general view of the pedestrian bridge is shown in Figure 1(b). The center of the pedestrian bridge has been widened to allow visitors to enjoy the view from the Second Saikai Bridge.

3 ANALYTICAL MODEL

3.1 Integrated bridge model

Figure 2 shows a model of the integrated bridge. This model takes into account the rigidity and mass of the pedestrian bridge. The arch rib, stiffening girder, lateral bracing, and pier are all modeled using three-dimensional beam elements based on actual cross-sectional properties. The column and hanger are modeled using three-dimensional truss elements. The lump mass



(a) Natural vibrations of the main bridge (b) Natural vibrations of the pedestrian bridge

Figure 4: In-plane natural frequencies

Table 1: Natural frequencies of CFT arch bridges and steel arch bridge

Bridge name	Span (m)	Type	Natural frequencies of in-plane modes (Hz)			
			1st antisymmetric	1st symmetric	2nd antisymmetric	2nd symmetric
Second Saikai Bridge	230	CFT	0.639	0.929	1.509	1.474
Jianghan Wuqiao Bridge [10)]	240	CFT	0.724	1.229	1.878	2.041
Saikai Bridge [11)]	216	Steel	1.153	1.507	2.805	2.306

matrix is adopted for this analysis.

On the pedestrian bridge, the girder and lateral beams of the pedestrian bridge are modeled using three-dimensional beam elements. The strand ropes and steel tubes are modeled using three-dimensional truss elements. The girder of the pedestrian bridge takes into account the stiffness of the floor system of pedestrian bridge.

Regarding boundary conditions, the springing position of the arch rib and the pier bases are fixed in all degrees of freedom. The earthquake shear force distribution rubber bearings are installed in the joints between the stiffening girder and the piers (P4, P5 and P6), the joints between the stiffening girder and abutment A2, and the joints between the stiffening girder and the lateral beams (S3 and S4). The model uses linear springs to simulate these bearings. The points linking the suspension members of the pedestrian bridge and the stiffening girder of the bridge have the same longitudinal, vertical and out-of-plane displacements as the stiffness girder of the main bridge. The vertical displacements in the origin points and the end points of the pedestrian bridge are restrained, as are the out-of-plane displacements in the lateral bracing of the pedestrian bridge.

3.2 Original bridge model and separate pedestrian bridge model

In order to examine the influence of the pedestrian bridge on the natural vibrations of the bridge, the original bridge model and a separate pedestrian bridge model are used in addition to the integrated bridge model.

In the original bridge model, the rigidities of the pedestrian bridge are not taken into account, and the masses of the pedestrian bridge are included with those of the girder. This original bridge model is adopted for the nonlinear seismic analysis of the main bridge.

The separate pedestrian bridge model is shown in Figure 3. In this model, only the pedestrian bridge's structure is considered. Regarding the boundary condition of the pedestrian bridge model, the points that link the hangers of the pedestrian bridge and the stiffening girder of the bridge are fixed in the longitudinal, vertical and out-of-plane degrees of freedom.

4 NATURAL VIBRATION CHARACTERISTICS

The natural vibration analysis is carried out using the integrated bridge model, and the natural vibration characteristics are examined. In this paper, the natural vibrations of the bridge except for the local oscillation of the pedestrian bridge are called the 'natural vibrations of the main bridge', and the local natural vibrations of the pedestrian bridge are called the 'natural vibrations of the pedestrian bridge'.

4.1 Natural vibration characteristics of main bridge

The first in-plane natural vibration, which has a frequency of 0.472Hz, corresponds to the floating mode, as it does with cable-stayed bridges. This is due to the rubber bearings installed in the longitudinal direction of the bridge that distribute earthquake shear forces. The second in-plane natural vibration has a frequency of 0.639Hz, which corresponds to the unique antisymmetric mode of arch bridges.

Furthermore, there are in-plane natural vibration modes in which the vibrations of the side spans are predominant. They have natural frequencies of 2.553Hz and 2.644Hz.

4.2 Natural vibration characteristics of pedestrian bridge

The lowest in-plane natural frequency of the pedestrian bridge natural vibration is 2.276Hz, which is much higher than the lowest in-plane natural frequency of the natural vibration of the main bridge.

4.3 Influence of natural vibrations of pedestrian bridge on main bridge

The weight of the pedestrian bridge on the Second Saikai Bridge is 8% of the steel weight of the integrated bridge. Therefore, in the model of the integrated bridge, the original bridge and the pedestrian bridge are treated as a monolithic structure. However, the original bridge is used for the seismic analysis of the main bridge[ix] and the separate pedestrian bridge model is used for the natural vibration analysis of the pedestrian bridge itself. In other words, it is assumed that the effect of the rigidity of the pedestrian bridge on the vibration of the main bridge is negligible. The influence of the natural vibrations of the pedestrian bridge on the natural vibrations of the integrated bridge is considered using the integrated bridge, original bridge, and independent pedestrian bridge models in order to analyze the validity of the assumption.

The in-plane natural frequencies of the main bridge vibrations using the integrated bridge model and the original bridge model are plotted in Figure 4(a). There are some differences in the natural modes near the natural frequency of 2.5Hz-2.8Hz, though the results using the original bridge model coincide with those using the whole bridge model. The vertical displacements in the origin points and the end points of the pedestrian bridge in the integrated bridge model are restrained, but these boundary conditions are not applied to the original bridge model. In other words, the differences in the natural frequencies are due to the different boundary conditions. The natural frequency of the original bridge model is about 8% lower than that of the integrated bridge model. Therefore, the influence of the natural vibrations of the pedestrian bridge on the natural vibration of the main bridge is small.

Figure 4(b) shows the natural vibrations of the pedestrian bridge for the integrated bridge model and for the separate pedestrian bridge model. The natural frequencies of the separate pedestrian bridge model agree well with those for the integrated bridge model. Therefore, the effect of the rigidity of the pedestrian bridge on the vibration of the main bridge is negligible. Moreover, the natural vibrations of the pedestrian bridge can be evaluated using the separate pedestrian bridge model.

However, when a moving vehicle passes by the girder of the main bridge, the dynamic analysis of the pedestrian bridge must use the integrated bridge model.

4.4 Comparison of CFT arch bridge and steel arch bridge

The Jianghan Wuqiao Bridge (240m, CFT, China)[x] and the Saikai Bridge (216m, steel, Japan)[xi], which have almost the same span length as the Second Saikai Bridge, are used to compare the natural vibration properties of CFT arch bridges with those of steel arch bridges. The in-plane natural frequencies of those three bridges are summarized in Table 3. It is known that the in-plane natural frequencies of CFT arch bridges are lower than those of the steel arch bridge.

5 RESPONSE CHARACTERISTICS UNDER A MOVING VEHICLE

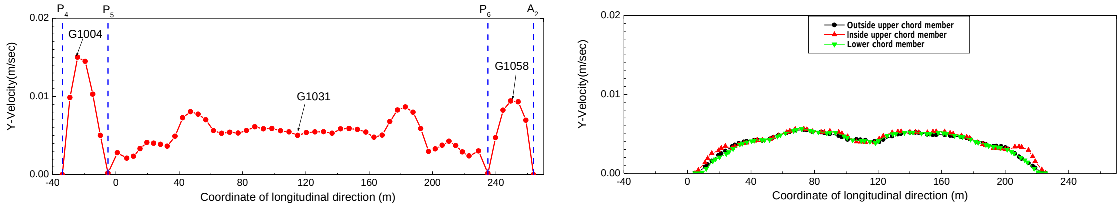
In this section, the vibrations of the Second Saikai Bridge under traffic loading are examined using the bridge-vehicle-road surface model based on Ref.[xii]. A two-degree-of-freedom vehicle is used as shown in Figure 5. The power spectral density of the road surface roughness is determined using Ref.[xii] The Rayleigh damping is used and the damping constant is assumed to be 0.01.

5.1 Response characteristics of girder

Figure 8 shows the maximum velocities of the girder and arch rib when a vehicle passes by the girder of the main bridge at a speed of 80km/h. The vertical axis corresponds to the maximum velocities and the horizontal axis corresponds to the coordinate in the longitudinal direction of the bridge.

On the main span, the maximum velocity of the girder of the main span is about 0.8cm/sec.

There is an investigation for the response level of a CFT arch bridge built in China[xiii]. The Shitanxi Bridge is a half-through CFT arch with a span length of 136m. The bridge has two parallel arch ribs, each of which has a rectangular cross-section consisting of four steel tubes. The response level of this bridge under the vehicle loading is investigated in 2000. The maximum velocity of the girder in the Shitanxi Bridge is about 5.7cm/sec.



(a) Girder (b) Arch rib

Figure 5: Maximum velocities under moving vehicle

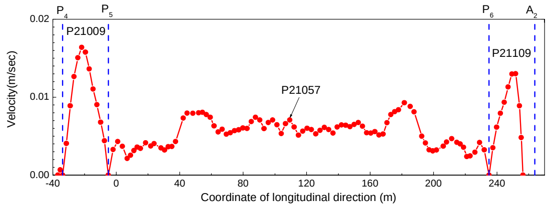


Figure 6: Maximum accelerations of pedestrian bridge under moving vehicle

Comparing the maximum velocity of the Second Saikai Bridge with that of the Shitanxi Bridge, the vibration level in the girder of the main span of the Second Saikai Bridge under traffic loading is smaller than that of the Shitanxi Bridge.

The maximum velocity in the arch rib of the Second Saikai Bridge is less than 0.5cm/sec as shown in Figure 5(b), while that of the Shitanxi Bridge is about 3.9cm/sec. Therefore, the vibration level in the arch rib of the Second Saikai Bridge is smaller than that of the Shitanxi Bridge.

However, a vibration with a maximum velocity of 1.5cm/sec is generated in the side spans, which have a span length of 30m. It is found that the girder in the main span generates small displacements even if the displacement of the side span is predominant..

5.2 Response characteristics of pedestrian bridge

Figure 6 shows the maximum velocities of the pedestrian bridge when a vehicle passes by the girder of the main bridge at a speed of 80km/h. The maximum velocity of the main span is about 0.8cm/sec and that of side spans is about 1.8cm/sec, which are the same values as those of the girder of the main bridge.

5.3 Response level

The ergonomic evaluation method developed by Kobori and Kajikawa[xiv] is used to appraise the vibration sensibility of the traffic-induced vibration on the Second Saikai Bridge. The relationship between the category and the lower limit of the VG for pedestrians is shown in Table 2.

Table 3 shows the maximum velocities and corresponding VG of the Second Saikai Bridge. Regarding the main span, both the maximum velocity of the girder and that of the pedestrian bridge are about 0.014m/sec, which is equal to VG=0.73. From the viewpoint of vibration sensation, its VG is in the category of ‘definitely perceptible’, and the vibration of the main span under traffic loading is small.

Table 2: Category and lower limit of VG for pedestrian

No.	Content of category	VG
1	Slightly perceptible	0.32
2	Definitely perceptible	0.61
3	Lightly hard to walk	1.12
4	Extremely hard to walk	1.48

Table 3: Response level of the Second Saikai Bridge

	Vmax (m/sec)	VG	Category
Girder N1004	0.01449	**0.73**	Definitely perceptible
N1031	0.00502	0.25	
N1058	0.00942	0.48	Slightly perceptible
Pedestrian bridge N21009	0.01577	**0.80**	Definitely perceptible
N21057	0.00707	0.36	Slightly perceptible
N21109	0.01297	**0.66**	Definitely perceptible

In the side spans, the maximum velocity of the girder of the main bridge and that of the pedestrian bridge are about 0.016m/sec and 0.013m/sec, which are equal to VG=0.80 and VG=0.66, respectively. These VG are in the category of ‘definitely perceptible’. Therefore, the vibration of the side spans under traffic loading is small, too.

6 RESPONSE CHARACTERISTICS UNDER PEDESTRIAN TRAFFIC

The lowest natural frequency of the pedestrian bridge is 2.276Hz. This is close to 2.0 steps/sec, which is the pace of an adult walking down a street[xv]. There is some apprehension about the resonance induced by a pedestrian walking on the pedestrian bridge when the predominant frequency of the pedestrian bridge is near the pace of the pedestrian. Therefore, the dynamic response characteristics of the pedestrian bridge induced by pedestrian traffic are examined.

The walking load, which takes into account the dead load of a pedestrian[xv], is used to examine the dynamic response characteristics that are induced by a pedestrian walking on the pedestrian bridge. The weight of the pedestrian and is set to 0.588kN (60kgf).

Regarding the response level induced by a pedestrian walking on the pedestrian bridge, the maximum velocity of the pedestrian bridge induced by a walking pedestrian is less than 0.008m/sec (VG=0.39), which is in the category of ‘Slightly perceptible’. Therefore, the responses induced by a pedestrian walking on the pedestrian bridge are small.

7 CONCLUSIONS

This paper examined the natural vibrations, vehicle-induced vibrations and pedestrian-induced vibrations of the Second Saikai Bridge, which is the first CFT arch bridge in Japan.

The main findings are as follows:

- The floating mode and the unique antisymmetric mode of the arch bridge are the first two in-plane vibrations of the main bridge, and the first natural frequency of the pedestrian bridge is higher than the lower frequencies of the main bridge.
- The influence of the rigidity of the pedestrian bridge on the main bridge is small. The independent pedestrian bridge model can be used to evaluate the natural vibrations of the pedestrian bridge, since the natural frequencies the pedestrian bridge are separate from those of the main bridge.
- The vehicle-induced responses of the main span are small, while the responses in the side spans are larger than those of the main span. The maximum acceleration of the side span is about 1.8cm/sec.
- The dynamic response induced by a pedestrian walking on the pedestrian bridge increases when the predominant frequencies of the pedestrian bridge are close to the pace of the pedestrian. However, the response level of the pedestrian bridge is small.

REFERENCES

[i] C.W. Roeder, B. Cameron and C.B. Brown, Composite action in concrete filled tubes, Journal of Structural Engineering, ASCE, Vol.125, No.5, 477-484 (1999)

[ii] A.H. Varma, J.M. Ricles, R. Sause and L.W. Lu, Experimental behavior of high strength square concrete-filled steel tube beam-columns, Journal of Structural Engineering, ASCE, Vol.128, No.3, 309-318 (2002)

[iii] W.C. Clawson, Bridge Applications of Composite Construction in the U.S., Structural Engineering in the 21st Century, Proceedings of the 1999 Structures Congress, 544-547, (1999)

[iv] S. Nakamura, New structural forms for steel/concrete composite bridges, Structural Engineering International 1, Journal of the International Association for Bridge and Structural Engineering (IABSE), 45-50 (2000)

[v] Z. Zhen, B. Chen and Q. Wu, Recent Development of CFST Arch Bridge in China, Proceeding of 6th ASCCS Conference, pp.205-212 (2000)

[vi] Y. Liu, B. Chen and H. Hikosaka, Recent developments in concrete-filled tubular arch bridge and horizontal swing erection method in China, Bridge and Foundation Engineering, Vol.33, No.2, 41-44 (1999) (in Japanese)

[vii] Q. Wu, B. Chen, K. Takahashi and S. Nakamura, Construction and technical subjects of concrete filled steel tubular arch bridges in China, Bridge and Foundation Engineering, Vol.35, No.10, 40-45 (2001) (in Japanese)

[viii] D. Peng, Q. Wu, K. Takahashi and S. Nakamura, Recent construction and development of long-span bridges in China, Bridge and Foundation Engineering, Vol.37, No.2, 43-49 (2003) (in Japanese)

[ix] H. Fujita, Q. Wu, M. Yoshimura, K. Takahashi, S. Nakamura and K. Furukawa, Nonlinear seismic analysis of the Second Saikai Bridge-concrete filled tubular (CFT) arch bridge-, Arch 04.

[x] Q. Wu, K. Takahashi, H. Matsuzaka, B. Chen and S. Nakamura, Study on natural vibrations and nonlinear seismic response of CFT arch bridge constructed in China, Journal of Constructional Steel 11 (2003) 177-184 (in Japanese)

[xi] Q. Wu, K. Takahashi, H. Kobayashi and S. Nakamura, Natural vibration properties and nonlinear seismic responses of the Saikai Bridge, Journal of Constructional Steel 11 (2003) 185-192 (in Japanese).

[xii] Q. Wu, K. Takahashi, T. Okabayashi and S. Nakamura, Response characteristics of local vibrations in stay cables on an existing cable-stayed bridge, Journal of Sound and Vibration 261(3) (2003) 403-420.

[xiii] M. Okatani, B. Chen, Q. Wu and T. Okabayashi, Dynamic behavior of a concrete filled steel tubular arch bridge under traffic road, Proceedings of Annual Conference of the Japan Society of Civil Engineers 56(1), 2001, pp.288-289, (in Japanese).

[xiv] T. Kobori and Y. Kajikawa, Ergonomic evaluation methods for bridge vibrations, Journal of Structural Mechanics and Earthquake Engineering, JSCE 230 (1974) 23-31 (in Japanese)

[xv] M. Yoneda, Dynamic response characteristics of the stress ribbon pedestrian bridges due to a walking human and a simplified method for evaluating maximum amplitude of this type of bridges, Journal of Structural Engineering 47A (2001) 351-362 (in Japanese)