DYNAMIC CHARACTERISTICS AND EARTHQUAKE RESPONSE ANALYSIS OF THREE-SPAN CONTINUOUS STRESS RIBBON BRIDGE

Toshihiko ASO[1], Kiyoshi UNO[2], Yoshio FUJIMOTO[3], Hiroshi OKAZAKI[4] And Masakatsu WATANABE[5]

SUMMARY

This study aims to clarify the dynamic characteristics and earthquake responses of a three-span continuous stress ribbon bridge. Excitation test was performed to obtain natural frequencies, vibration modes and damping coefficient. It became clear from the test results that natural frequencies up to 10th mode are below 3.0 Hz and are very close to each other due to low flexibility of ribbon. This bridge has large sag, thus the coupling vibration between torsional and out-of-plane vibrations exists. Damping coefficient is about 0.3-0.5% for all modes. This damping is very small compared to other types of PC bridges. The eigen value of the bridge is computed using finite element method (FEM). Calculated values are close with test results. Earthquake response analysis by FEM was carried out using the test results and the model used in eigen value analysis. (Six different waves are used and four cases of input directions are considered; namely, the in-plane horizontal, the in-plane vertical, the out-of-plane and the simultaneous input of these three.) Results of the analysis revealed that vertical response displacement is large even in the case of horizontal seismic loading. Moreover, when the earthquake is directed to both horizontal and vertical directions at same time, the bending moment at the edge of ribbon becomes large.

INTRODUCTION

In recent years, many stress ribbon bridges has been constructed in Japan because of its fine spectacle. Most stress ribbon bridges are single-spanned but continuous bridges of two and three spans are also popular. It is expected that dynamic characteristics and earthquake responses of continuous stress ribbon bridges are different from single span stress ribbon bridges and other common types.

Vibration of stress ribbon bridges is easily occurred because of its low stiffness and low damping of girder. The vibration problems of stress ribbon bridges are very important for dynamic serviceability, aerodynamic stability and seismic safety. Some studies has been performed about dynamic characteristics and dynamic serviceability of stress ribbon bridges [Hiejima, 1993][Kajikawa, 1998][Kajikawa, 1999][Touge, 1997]. However, most of these studies are treated single span stress ribbon bridges and a few continuous stress ribbon bridges. Stress ribbon bridges with long length are expected to increase in the future, the dynamic characteristics of the bridge must be clarified for rational and safety design.

This paper describe the dynamic characteristics of a three span continuous stress ribbon bridge, the current longest bridge of this type in Japan, with length of 160m (47m+66m+47m), width of 3.8 m and sag of 1.9 m at the center span and 0.99 m at side spans. Dynamic characteristics were measured by exciting test and numerical analysis were also carried out. According to test results, natural frequencies, vibration modes and damping ratio became clear. The analytical results show cross agreement with test results. Using the analytical model which used in eigen value analysis, earthquake response analysis of the bridge was performed. Analytical results shows the dynamic behavior of three span continuous stress ribbon bridge under earthquake is complex due to its high flexibility and low damping of girder.

[1] *Department of Civil Engineering, Yamaguchi University, Ube, Japan Email: aso@sd1.civil.yamaguchi-u.ac.jp*
[2] *Department of Civil Engineering, Kyushu Kyoritsu University, Kitakyushu, Japan*
[3] *Fuji PS Co., Fukuoka, Japan*
[4] *Maeda Co., Fukuoka, Japan*
[5] *Kasuya town office, Fukuoka, Japan*

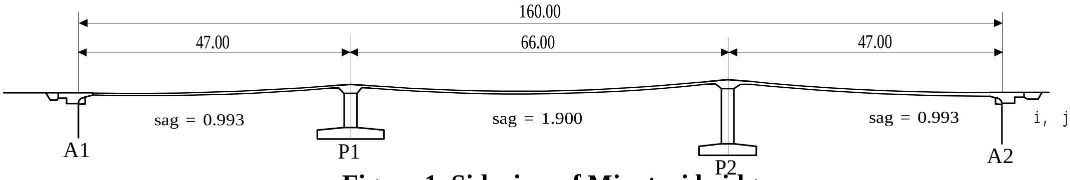


Figure 1 Sideview of Mizutori bridge

EXCITING TEST

Fig. 1 shows a sideview of Mizutori bridge. This bridge was constructed as footway bridge and is the longest three-span continuous stress ribbon bridge in Japan, whose length is 160 m (47 m+66 m+47 m), width is 3.8 m and sag is 1.9 m at center span and 0.99 m at side spans. The minimum thickness of girder is 0.2m at the center of center span and thickness is coming larger until 1.5m at the ends of side spans. Ground anchors were used at the ends of girder (at both abutments) to resist the horizontal force due to live load and dead load of superstructure. All foundations are spread foundation.

To clarify the dynamic characteristics of three span continuous stress ribbon bridge, exciting test was carried out. Forced vibration was created by jumping and running of a person. Oscillated points are set at the center point of all spans and quarter point of center span for measuring vertical vibrations. In order to observe torsional vibration, two or three people were made to run in the upstream side of center span. In all cases of tests, response vertical accelerations were measured at eleven points of girder.

Figure 2 shows time histories of measured acceleration during vertical vibration and torsional vibration. These accelerations were observed at the center of center span. In this figures, A/D sampling interval is 0.01 sec. Vertical vibration was caused by one person jumping at the center point of center span, and the maximum acceleration is found to be almost 60gal. Figure 3 indicate Fourier spectra of measured acceleration shown in Fig. 2. In the spectra, the peak frequencies are shown clearly. From the spectra of all observed points, most peaks are points below 3.0Hz. This tendency is caused by long span length and low stiffness of girder. The dynamic behavior of girder of stress ribbon bridge is similar to cable. An eigen value analysis was also carried out using three dimensional FEM model. Table 1 shows the natural frequencies obtained from exciting test and numerical analysis. Results of analysis are similar to test results in vertical vibration, but there are small difference in torsional vibration. Fifth vertical vibration appeared in the analysis, however it was not found in the spectra.

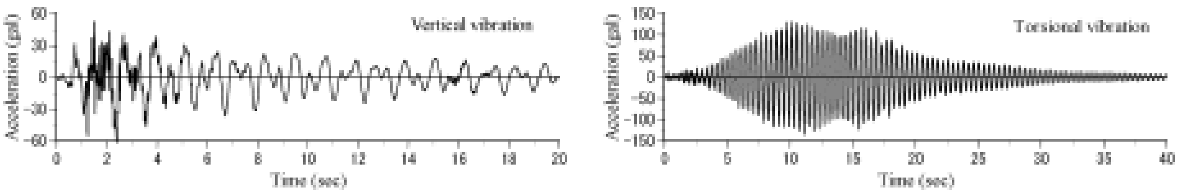


Figure 2 Time history of acceleration

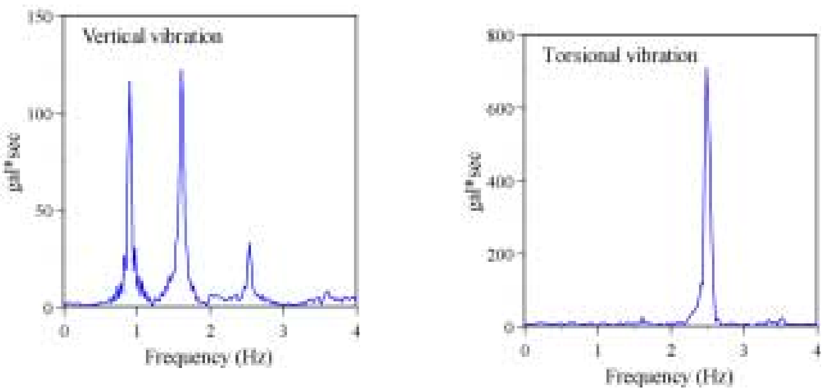


Figure 3 Fourier spectra

Table 1 Natural frequencies

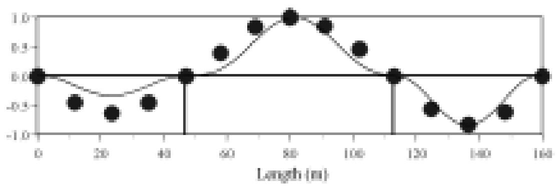
	Vertical vibration									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Test	0.901	1.074	1.270	1.611	-	1.810	2.002	2.542	3.076	3.222
Analysis	0.901	0.967	1.288	1.574	1.654	1.666	2.109	2.529	2.975	3.070

	Torisional vibration		
	1st	2nd	3rd
Test	2.490	3.003	3.076
Analysis	2.647	3.633	3.680

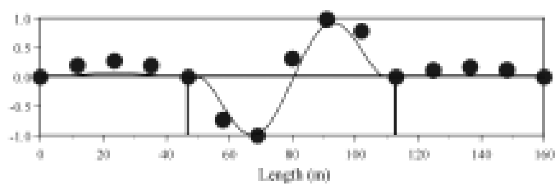
This is because, difference of natural frequencies of fourth and fifth vibration is too small to separate these vibration.

Fig. 4 indicate the two lowest vibration mode of this bridge, vertical direction and torsional vibration respectively. In these figures, circle marks indicate results of exciting test and solid line is results of eigen value analysis. These results are also similar. Until 4.0Hz, there are eleven natural vertical vibration modes and three torsional vibration modes with no longitudinal vibration mode. Out-of-plane vibrations are coupled with torsional mode. This is a typical phenomena for hanging structure, that have a sag. When designing stress ribbon bridges, these coupling vibration must be considered for aeronautical stability and dynamic serviceability.

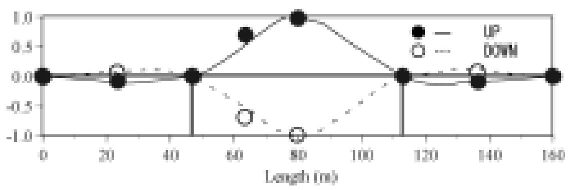
The bridge that have low bending stiffness, vibration amplitude will become large. When considering the response characteristics excited by earthquake, wind and traveler, it is very important to decide damping of structure. There are two ways to calculate damping coefficient from results of exciting test. One way is by calculating damping coefficient from time history of damping free vibration. The other method is by using resonance curve (power spectrum), i.e. half power method. Damping coefficients at each vibration mode, calculated by half power method, of this three span continuous stress ribbon bridge are shown in Table 2. In general, damping coefficient of girder type footway bridge is 0.5-1.5%, however in this bridge, damping is very



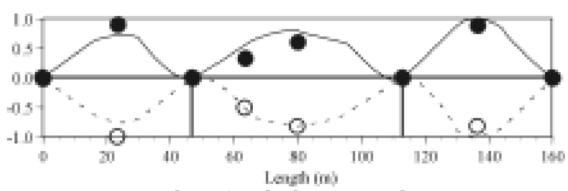
First vertical vibration mode



Second vertical vibration mode



First torsional vibration mode



Second torsional vibration mode

Figure 4 Vibration modes

Table 2 Damping coefficients

	Vertical vibration									
	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
Damping Coefficient (%)	0.479	0.315	0.333	0.291	-	0.500	0.453	0.398	0.451	0.397

	Torisional vibration		
	1st	2nd	3rd
Damping Coefficient (%)	0.421	0.403	0.247

small which is 0.25-0.5%. These values indicate the serious problem for dynamic serviceability and stability, where it is difficult to reduce vibration immediately.

As mentioned above, natural frequency, natural vibration mode and damping coefficient of Mizutori bridge were became clear. The dynamic characteristics of many single or two span continuous stress ribbon bridges were reported by Kajikawa [Kajikawa, 1997]. Figure 5 shows a relationship between span length and natural frequency of the lowest vertical vibration and torsional vibration. In this figure, eleven bridges are single span, two bridges are two span continuous and three bridges are three span continuous bridges, including Mizutori bridge. The range of sag-span ratio of these 16 bridges ranges from 1/30 to 1/50, thickness of standard cross section of girder in the region of 0.17m to 0.25m. It is remarkable that the natural frequency can be approximately estimated from span length. The natural frequencies of these vibration modes are related with span length as exponential function. Results of Mizutori bridge indicates same tendency with other stress ribbon bridges. Relationship between damping coefficient and span length is shown in Fig.6. It is appeared that damping coefficient of stress ribbon bridge is smaller than another type bridges. In the first torsional vibration,

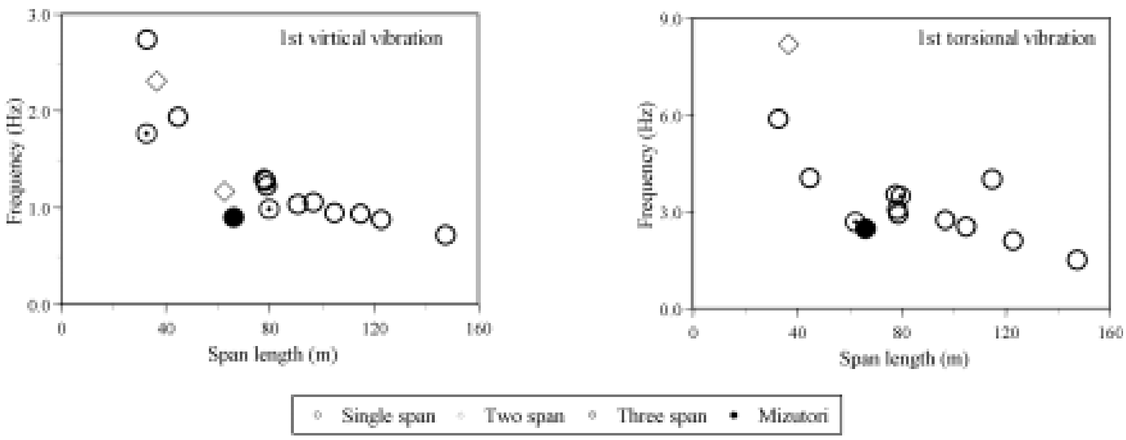


Figure 5 Relationship between span length and natural frequency

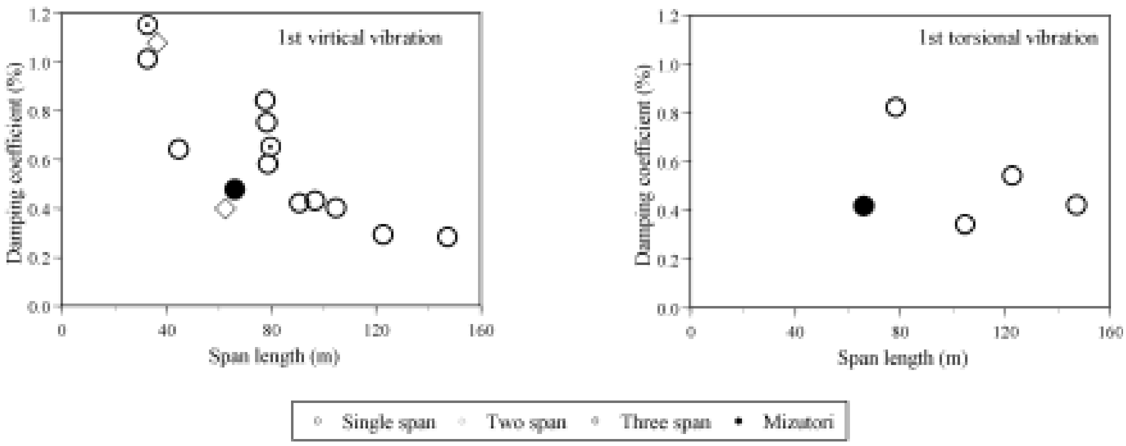


Figure 6 Relationship between span length and damping coefficient

only a few damping coefficients were reported, where it is difficult to compare damping coefficient of Mizutori bridge with that of another bridges.

EARTHQUAKE RESPONSE ANALYSIS

The seismic behavior of stress ribbon bridge is expected to be more complex than another type of bridges. However, there are few reports about dynamic behavior of stress ribbon bridge under earthquake. Therefor, earthquake response characteristics of three span continuous stress ribbon bridge was analyzed. In the analysis, three dimensional FEM model, that is same model used in eigen value analysis, was used. Considering the soil property of bridge site, two types of earthquake was used as input motion, each type include three seismic wave, i.e. dynamic analysis was carried out for six different seismic waves. Type 1 is seismic waves of interplate earthquake, with maximum acceleration of almost 320gal and resonance frequency of 0.5-1.0Hz. Type 2 is shallow earthquake, where duration time is shorter than Type 1 and resonance frequency is 1.5-2.0Hz . Table 3 shows details of these six seismic waves and time histories of Type1-1 and Type 2-1 are shown in Fig. 7. Sampling time of waves is 0.01s. Seismic response analysis was computed using Newmark's β method (β =0.25) of time step 0.01s. Damping of bridge was considered as Rayleigh damping.

Table 2 Details of seismic waves

Wave number	Name	Year	Max. acceleration (gal)
Type 1-1	Kaihoku bridge	1978	318.8
Type 1-2	Kaihoku bridge	1978	320.0
Type 1-3	Shichihoku Bridge	1993	322.7
Type 2-1	JMA Kobe observatory	1995	812.0
Type 2-2	JMA Kobe observatory	1995	765.9
Type 2-3	HEPC Inagawa	1995	780.0

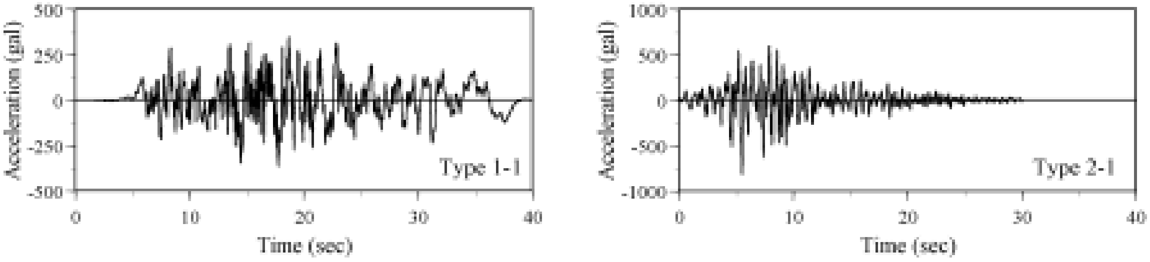


Figure 7 Examples of time history of seismic waves

From the results of analysis, maximum response displacements and accelerations were appeared at the center of span when seismic waves are inputted to axial direction. This is because, the stiffness of girder is lower than another type bridges and the effect of sag. Fig. 8 indicates the vertical and axial maximum response displacement at the center of each spans for each seismic waves. Even when oscillated to axial direction, large

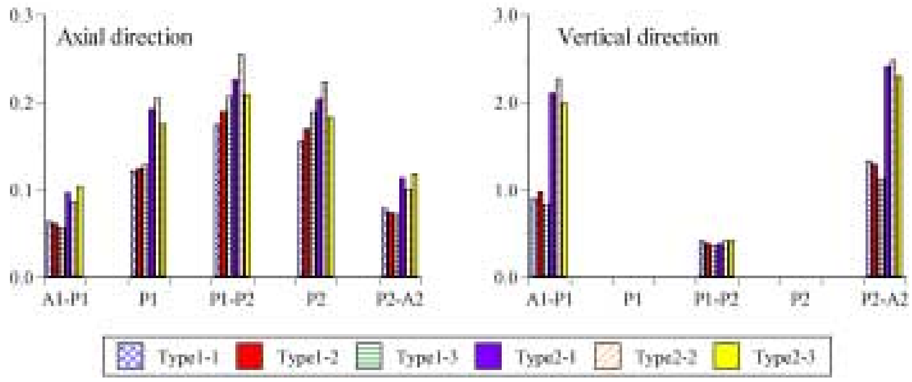


Figure 8 Comparison of response displacement

vertical displacements occurred at side spans. These vertical response displacements are larger in Type 2 waves than that of Type 1. However , axial displacements are not so different in both seismic waves. Response bending moment of girder is small due to high flexibility, maximum bending moments are observed t the bottom of piers, theses are almost 500-800 tfm. The results of one direction input analysis describe that the difference of seismic waves was more remarkable in the side spans. The differences in the center span and piers of three span continuous stress ribbon bridge are small because members with low stiffness vibrates irrespective to input seismic wave.

The axial seismic motion created large vertical response displacement of girder, this phenomena describes thatthe direction of input wave is very important for seismic analysis of stress ribbon bridge. The dynamic behaviors under multi direction inputting were computed. In this calculation, 5 cases were considered as shown in Table 3. Input seismic wave was observed at JMA Kobe observatory in 1995. The N-S component is inputted to axial direction with maximum acceleration of 812gal, E-W component to out-of-plane direction with 766gal, and the U-D component to vertical direction with 406gal. Figure 9 shows a response displacements of all of analytical cases. In these figures response displacements vary with combination of wave direction. For out-of-plane direction, response displacement of Case 3 is larger than that of Case 2. It is confirmed that axial oscillation affects to out-of-plane motion. Similarly, when considering the combination of vertical and axial wave, vertical displacement is large. In designing stress ribbon bridge, it is therefore safe to perform three dimensional seismic analysis with multi direction wave inputting must be carried out.

Table 3 Analysis cases

	Direction of inputting wave		
	Axial	Out-of-plane	Vertical
Case 1	o	-	-
Case 2	-	o	-
Case 3	o	o	-
Case 4	o	-	o
Case 5	-	o	o
Case 6	o	o	o

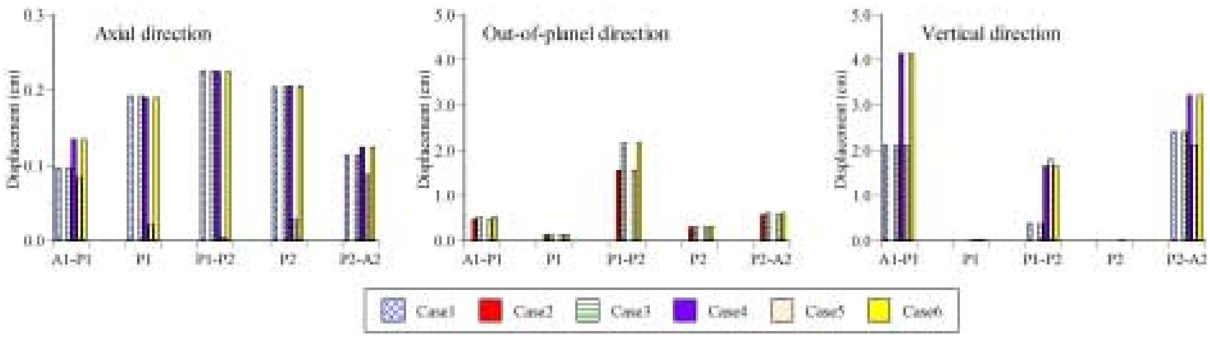


Figure 9 Comparison of response displacement with seismic wave direction

CONCLUSIONS

1. Dynamic characteristics of three span continuos stress ribbon bridge was clarified by exciting test and eigen value analysis. Results of three dimensional analysis are cross agreement to results of exciting test.

2. The natural frequencies of this bridge up to 10th mode are below 3.0 Hz and are very close to each other due to low flexibility of ribbon. Some modes clearly indicate that torsional vibration and out-of-plane vibration are coupled. These modes are must be considered in aeronautical stability.

3. The damping coefficients in each mode of this bridge vary from 0.25% to 0.5%, which are smaller than another type of bridges.

4. Seismic response analysis was carried out. Results of the analysis revealed that vertical response displacement is large even in the case of horizontal seismic loading. Moreover, when the earthquake is directed to both horizontal and vertical directions at same time, the response becomes large.

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