Evaluation of Fudai floodgate bridge damaged by tsunami

Shinichiro Mori [1] and Ratna Prasad Twayana[2]

[1] Professor, Faculty of Engineering, Ehime University
(3 Bunkyo-cho, Matsuyama 790-8577 Japan)
E-mail: mori@ehime-u.ac.jp
[2] Student member, Faculty of Engineering, Ehime University
(3 Bunkyo-cho, Matsuyama 790-8577 Japan)
E-mail: twayana.ratna.prasad10@cee.ehime-u.ac.jp

In this paper, the vibration measurement of Fudai floodgate bridge was conducted to evaluate the level of damages caused by tsunami triggered by Great East Japan Earthquake. Among the four spans of this bridge, two spans (span 1 and span 2) were totally collapsed while other two spans (span 3 and span 4) were suffered from severe structural damages. Massive tsunami struck this bridge leaving residual vertical deflection of 30 cm on span 3 and 7 cm on span 4. Comparsion between the frequencies of this bridge before and after damages were made. FEM model was adopted to evaluate to the frequency of undamaged state. It was found that there was about 27% decrease in frequency after the damages caused by tsunami. This study also demonstrates the application of impact hammering method to evaluate the vibration characteristics of bridge.

Key Words : *frequency, impact, damages, floodgate*

1. Background

The M9.0 Great East Japan Earthquake struck the north east region of Japan on 11 March 2011. It was the largest earthquake ever recorded in Japan. This gigantic earthquake triggered powerful tsunami and caused catastrophic damages of infrastructures, life-lines, tsunami protection walls and floodgates. Tsunami protection walls and floodgates are the first components to be affected by this tsunami. The overtopping of these walls induced the submergence of several meters of coastal low lands. Most of tsunami protection wall such as Kamaishi Tsunami Protection Breakwater, tsunami wall of Ryoishi village were severely damaged. However, the Fudai floodgate was able to withstand the massive tsunami protecting the Fudai-mura town. This floodgate played a vital role to cause minimum damages in this town.

2. Introduction

Fudai floodgate which is 15.5 m high is located about 300 m from the seashore of the Fudai River. Its construction began on 1972 and was completed in 1984. This floodgate comprises main four panels with vertical lift gates, floodgate's tower and floodgate's bridges. In this paper, our study confine to the evaluation of existing condition of floodgate bridge after tsunami. The overall dimension of this floodgate is 100.50 m in length and 5.50 m in width. It is four-span bridge having span length of 24.95 m each as in Fig.1. Fig.2 shows the condition of this bridge after tsunami hit. The first and second spans (S1 and S2) were totally collapsed while third span (S3) and fourth span (S4) suffered from severe structural damages with residual vertical deflection of 30 cm and 7 cm respectively. Numerous flexural cracks were observed on the main girders. This bridge consists of three precast T-shaped post-tensioned girders on each span and these girders were named as G1, G2 and G3 for convenience. Girder G1 is at downstream of the river while G3 is at upstream of the river.

3. Vibration measurement procedure

Vibration measurement of heavily damaged span 3 and span 4 were done before their demolition. This measurement mainly consists of GEODAS which is 24 channels data acquisition system including

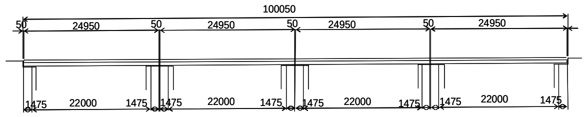

Fig.1 Side view of Fudai floodgate bridge.
(Note: All dimensions are in mm)

Fig.2 Fudai floodgate bridge after tsunami.
S1(span 1): Totally collapsed
S2 (span 2): Totally collapsed
S3 (span 3): Severely damaged with residual vertical deflection of 30 cm
S4 (span 4): Severely damaged with residual vertical deflection of 7 cm

amplifier, AD converter and recorder. Velocimeter CR4.5-2S were connected to GEODAS in order to record the vibration of the bridge. Sensor CR4.5-2S is three components (one vertical and two horizontal directions) moving-coil type velocimeter. It consists of spring type pendulum having the natural frequency of 0.5 Hz electrically with modification of gain to be flat in between 0.5 Hz and 23 Hz. Vibration measurements were conducted by using six velocimeters. These velocimeters were arranged over the main girders (G1, G2 and G3) of span 3 as shown in Fig.3 and similar type of sensor configuration was also adopted in the case of span 4 too. In this figure, the grid points were named with three digits where first digit, second digit, third digit refer to span number, girder number of respective span and point on the bridge respectively. The excitations for the vibration measurement were provided by impact generated by wooden hammer. The impacts were given on the different grid points by dropping the wooden hammer of 2.5 Kilograms at the interval of 20 seconds. The free vibration of bridge was recorded for 180 seconds with the sampling frequency of 200 Hz. The preliminary test on the bridge indicated the impulses generated by dropping wooden hammer were sufficient to excite the several modes of bridge vibration.

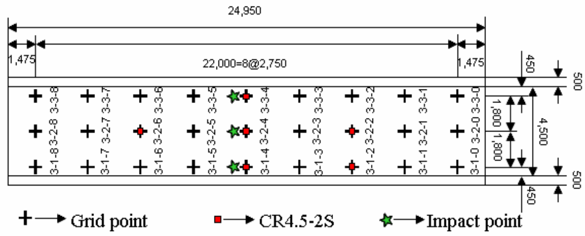

Fig.3 Plan view of sensor configuration and impact location on span 3 of Fudai floodgate bridge.
(Note: All dimensions are in mm)

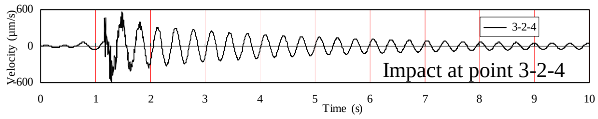

Fig.4 Velocity time histories of free vibration of span 3 recorded by velocimeter at point 3-2-4 due to impact at point 3-2-4.

4. Data analysis

Velocity time histories were drawn from recorded raw data after doing drift correction. A segment of 4096 data was extracted from entire velocity time histories and extracted segment was transformed into frequency domain by using Fast Fourier Transformation. Finally, the predominant frequencies were determined by using peak picking method.

5. Results

The velocity time histories of free vibration of span 3 recorded by the velocimeter at point 3-2-4 due to impact at point 3-2-4 is illustrated in Fig.4. The recorded waveform has the maximum amplitude of around 600 μm and vibration become steady after eight seconds. Fig.5 shows the Fourier spectra of span 3 of Fudai floodgate bridge. These spectra were recorded by velocimeter at points 3-1-4 and 3-2-4 due to impact at point 3-2-4. There is clear appearance of peaks around 3.08 Hz and 27.93 Hz in both spectra. The point 3-2-4 is central mid point of the bridge. When impact is given at mid point (3-2-4), first bending mode and third bending mode of bridge vibration are easily excited. Thus 3.08 Hz and 27.93 Hz are first bending and third bending mode of bridge vibration.

Fourier spectra recorded by velocimeter at points 3-1-4 and 3-2-4 due to impact at point 3-1-4 is shown in Fig. 6. The point 3-1-4 is the central downstream edge of the bridge. When the impact was given at this point (3-1-4), some difference can be seen in the Fourier spectra. There was clear appearance of

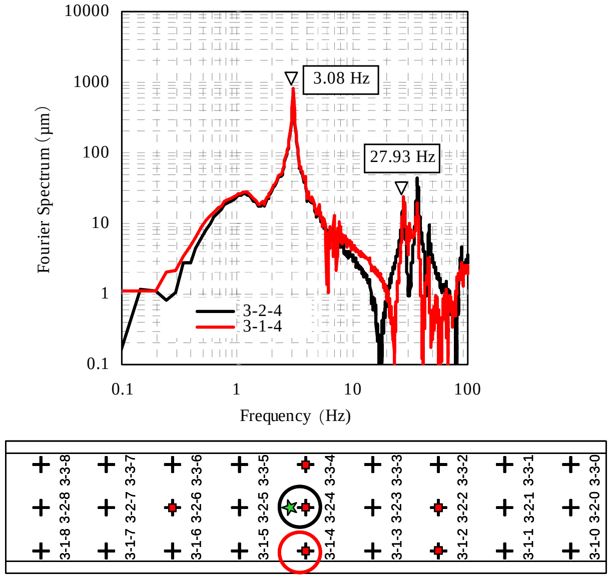

Fig.5 Fourier spectra of span 3 recorded by velocimeter at points 3-1-4 and 3-2-4 due to impact at point 3-2-4.

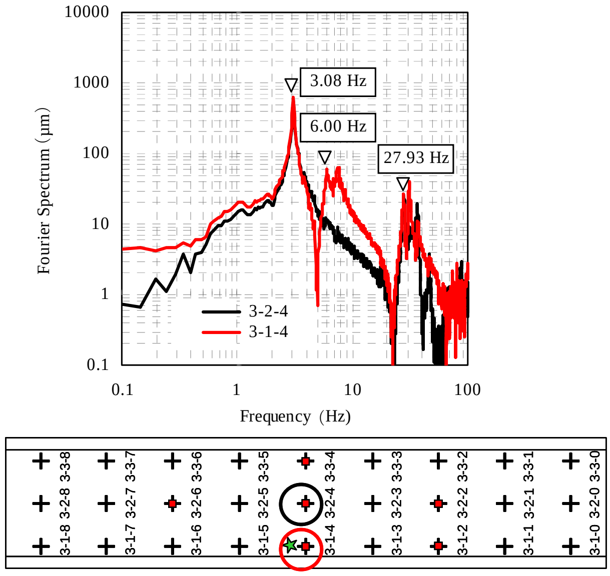

Fig.6 Fourier spectra of span 3 recorded by velocimeter at points 3-1-4 and 3-2-4 due to impact at point 3-1-4.

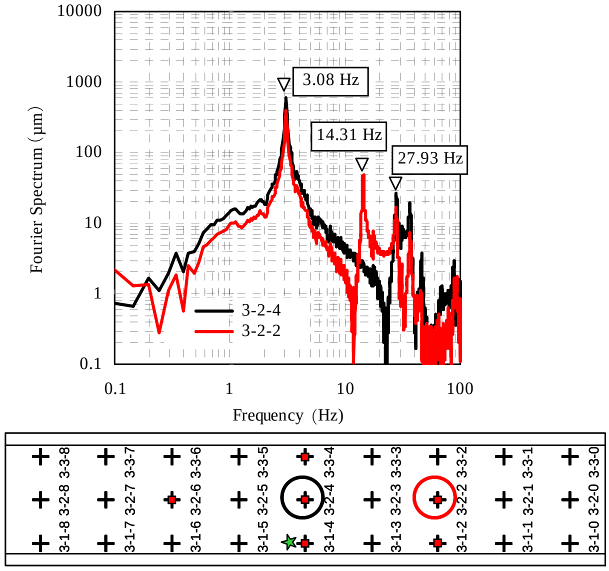

Fig.7 Fourier spectra of span 3 recorded by velocimeter at points 3-2-2 and 3-2-4 due to impact at point 3-1-4.

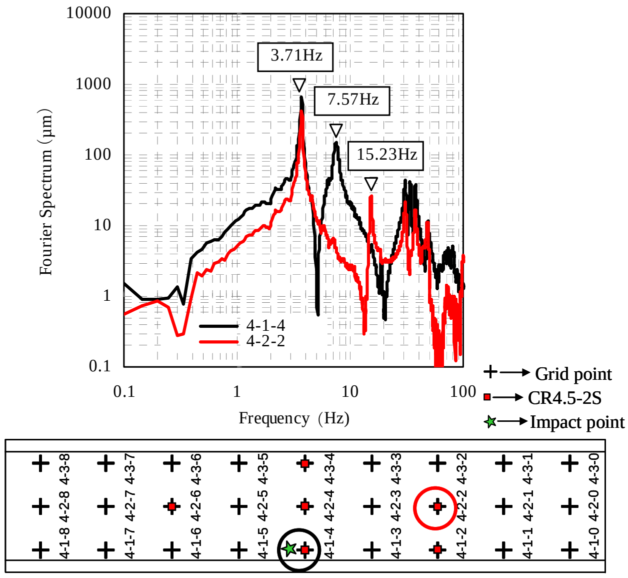

Fig.8 Fourier spectra of span 4 recorded by velocimeter at points 4-1-4 and 4-2-2 due to impact at point 4-1-4.

second peak around 6.00 Hz in the Fourier spectra recorded by velocimeter at point 3-1-4 while there was no peak around 6.00 Hz in the Fourier spectra recorded by velocimeter at point 3-2-4. When the point 3-1-4 is impacted, torsional mode is easily excited. Thus 6.00 Hz is corresponds to the first torsional mode of bridge vibration. For the first torsional mode, point 3-2-4 acts as a node point resulting no peak around 6.00 Hz.

Fig.7 shows the Fourier spectra recorded by velocimeters at points 3-2-2 and 3-2-4 due to impact at point 3-1-4. In these spectra, there is no appearance peak around 6.00 Hz as the both points are node points in the case of torsional mode of vibration. A clear peak can be seen around 14.31 Hz in the spectra recorded by the velocimeter at point 3-2-2 while there is no peak around 14.31 Hz in the spectra recorded by velocimeter at point 3-2-4 although impacted point is same. So, it can be said that 14.31 Hz corresponds to the second bending mode of vibration. In second bending mode, quarter span is easily excited while mid span acts as node point.

The typical Fourier spectra of span 4 of Fudai floodgate bridge is shown in Fig.8. These are the spectra recorded by the velocimeter at points 4-1-4 and 4-2-2 due to impact at point 4-1-4. The first bending, first torsional and second bending modes were found to be 3.71 Hz, 7.57 Hz and 15.23 Hz respectively.

6. Discussion

The first bending mode of span 3 and span 4 were found to be 3.08 Hz and 3.71 Hz respectively. Although the span lengths of both spans are same, obtained frequencies are very different. This difference in frequency may be due to difference in level of damages caused by tsunami in these spans. From this figures, it can be said that level of damages in span 3 was higher than that in span 4. The residual static deflection of span 3 was found to be 30 cm while that of span 4 was found to be 7 cm only as shown in Fig.9. Since the frequency is proportional to the square root of flexural stiffness, the flexural stiffness of span 3 was found to be about 30% less than that of span 4.

Finite Element Model (FEM) of this bridge was generated to know the frequencies of undamaged state. This bridge was model as simply supported beam with rubber bearing as shown in Fig.10. The first bending and second bending modes of undamaged state were found to be 4.22 Hz and 16.88 Hz respectively. The summary of frequencies obtained from FEM model and actual measurement were listed in the Table 1. By comparing the frequency of undamaged and damaged state, it was found the measured frequency was 27% less than FEM frequency (undamaged state) in the case of span 3 while it was 12% less than FEM frequency (undamaged state) in the case of span 4 with regards to first mode of vibration. In the span 3, the maximum reduction in frequency was found to about 27 % which is the case of first bending mode. However, In the span 4, the maximum reduction in frequency was found to be about 19 % which is the case of third bending mode. From this results, it can be also concluded that not only first mode, higher modes of vibration are also sensitive to the level of damages in the girders.

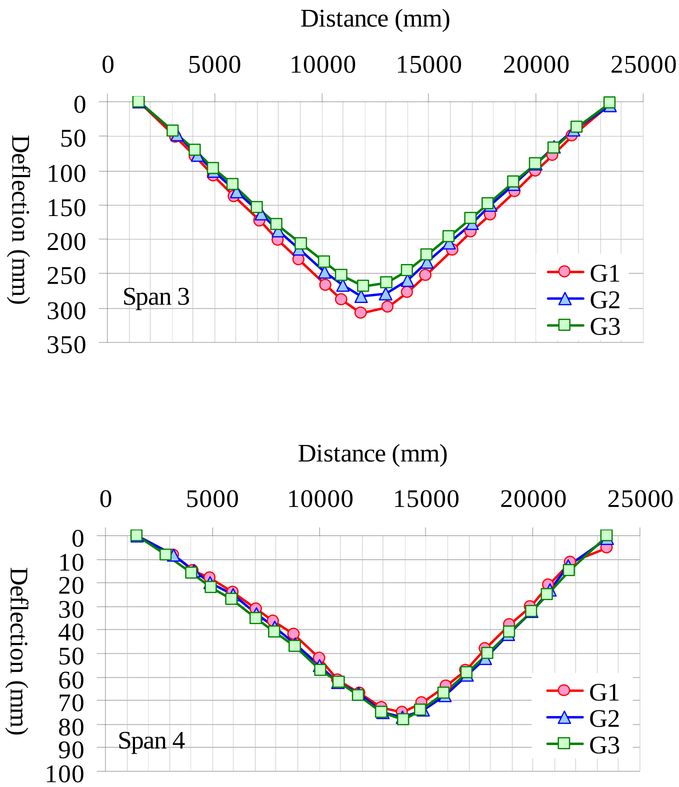

Fig.9 Residual deflection profile of girders of span 3 and span 4 of Fudai floodgate bridge after tsunami. (Source: CAESAR, PWRI)

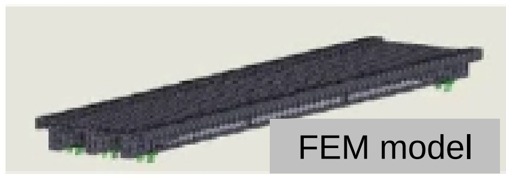

Fig.10 FEM model analysis of Fudai floodgate bridge. (Source: CASER, PWRI)

Table 1 Summary of frequencies of span 3 and span 4 of Fudai floodgate bridge.

Modes	FEM model frequency (Undamaged state)	Span 3		Span 4	
		Measured frequency (Damaged state)	Reduction in frequency	Measured frequency (Damaged state)	Reduction in frequency
First bending mode	4.22 Hz	3.08 Hz	27.01%	3.71 Hz	12.08%
First torsional mode	-	6.00 Hz	-	7.57 Hz	-
Second bending mode	16.88 Hz	14.31 Hz	15.22%	15.23 Hz	9.77%
Third bending mode	37.98 Hz	27.93 Hz	26.46%	30.86 Hz	18.74%

7. Conclusions

There was significant reduction in the frequencies of span 3 and span 4 of Fudai floodgate bridge due to the damages caused by the tsunami triggered by Great East Japan Earthquake. The level of damages on span 3 was higher than that on span 4 which was also reflected in their frequencies. Thus, the amount of reduction of frequency is proportional to the level of damages in the girders. It is also found that not only first mode, higher modes of bridge vibration are also equally sensitive to the level of damages in the girders.

8. Acknowledge

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