SOUNDNESS EVALUATION OF PRESTRESSED CONCRETE STRUCTURES BY VIBRATION MEASUREMENT

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Abstract

Prestressed concrete (PC) structures are advantageous in terms of durability. However, even they deteriorate as they age. We conducted a study of soundness evaluation by vibration measurement for existing PC bridges demolished due to obsolescence, remarkable defects or other reasons.

This paper describes the result of vibration measurement of an existing PC bridges. The levels of damage that engineers want to evaluate by vibration measurement vary depending on maintenance levels. Therefore, we conducted vibration measurement and examined possibility of anomaly detection as to various damage cases of PC bridges. From the result, when subjected to significant damage, it was found that the frequency is reduced by about 30% relative to healthy values.

Introduction

Since prestressed concrete (PC) structure can control cracking by the use of prestressing, it is advantageous in respect of durability. However, even these PC structures deteriorate throughout in-service years. As shown in Figure 1, deterioration has been seen in some PC bridges at stages earlier than their service life due to defective grout filling or other reasons. Therefore, effective estimation of remaining strength of a deteriorated PC structures would be the challenge in the maintenance of PC bridges.

Figure1. Corroded and Broken Cables in Precast Segment Box Girder Bridge

Based on the above-mentioned background, "Public Works Research Institute" and "Japan Prestressed Concrete Contractors Association" have been jointly conducting clinical studies by using demolished bridges to enhance the evaluation technology for PC bridges. Measurement of the vibration characteristics of a PC bridge before its demolition was performed as part of the clinical study. Since vibration measurement has the advantage that it is a nondestructive testing and simple approach, whether it can be applicable for the estimation of the remaining strength of the deteriorated existing PC bridges is evaluated.

The PC bridge which greatly suffered the dynamic damage

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Fudai floodgate maintenance bridge suffered severe damage due to the attack of gigantic tsunamis generated by the 2011 Great East Japan Earthquake.

As shown in Figure 2 ,two spans of the bridge collapsed totally due to failure at their mid span and another two spans survived with large vertical residual deflections. Especially in the 3rd. span, maximum deflection of 300mm and bending cracks with the maximum width of 5mm were observed. Therefore, it was considered that the span might collapse anytime. On the other hand, in the 4th. span, the maximum deflection was 80mm.

Figure 2. Fudai floodgate maintenance bridge (after Tsunami)

As shown in Figure 3, we have measured the vibration by excitation in the weight falling method with nine accelerometers evenly spaced between end crossbeams.

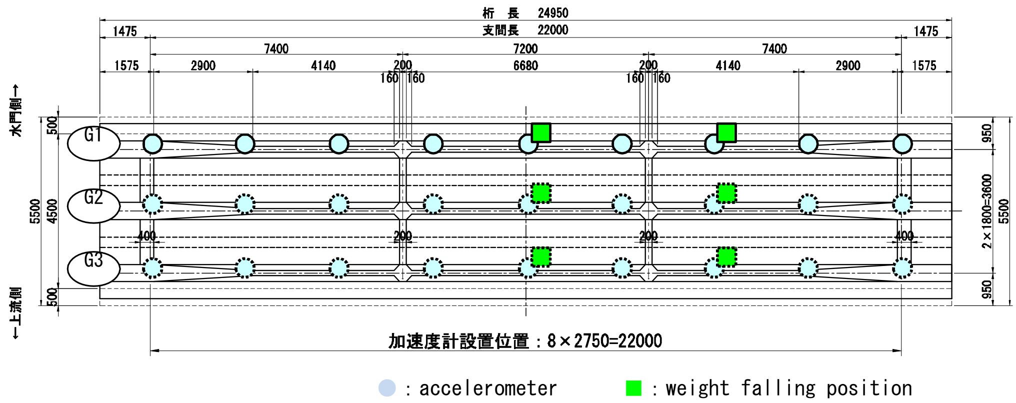
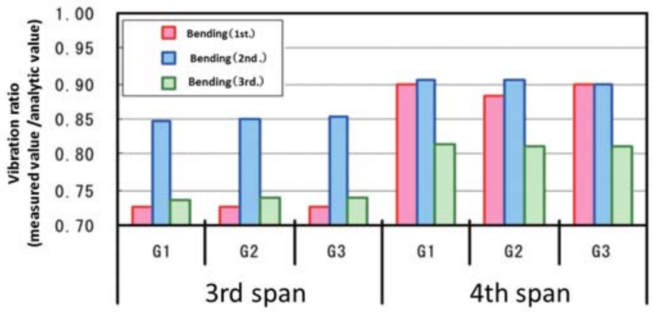


Figure 3. Measurement position and excitation position

Figure 4 shows the result of measurement. A slight difference was observed in each of the main girder vibration frequency. Compared with the analysis result of intact model, frequencies of 3rd. span are 20 to 30 percent lower and those of 4th. span are 10 to 20 percent lower than that of intact state. Tendency of reduction of vibration frequencies was consistent with extent of damage. It was confirmed that it is possible to detect the load-bearing performance degradation by measuring the vibration of the member, if the PC member is subjected to large



(analytic value : 1st. 4.22Hz ,2nd. 16.88Hz , 3rd. 37.98Hz)

Figure 4. Vibration frequency ratio for the analytic value

mechanical damage. Reduction rate of the second bending mode in the 3rd. span was small compared to the first bending mode and the third bending mode. The reason of this difference is that the portion of the maximum amplitude of the 1st and 3rd modes coincides with the severely damaged portion of the girders as shown in figure 5. Moreover, in the 4th. span, reduction of vibration frequency of higher mode was remarkable.

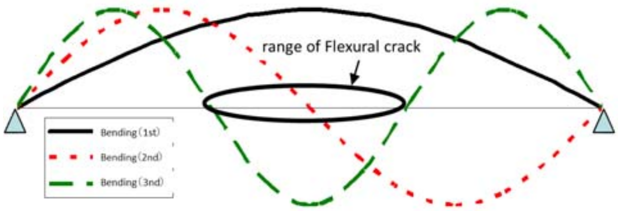


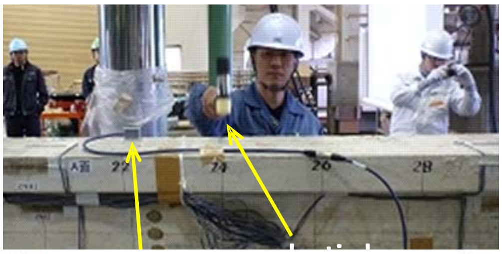
Figure 5. Bending vibration mode of the simple

Transition of vibration characteristics during loading tests

The transition of vibration characteristics was investigated during loading tests of the decommissioned girders. These investigations were conducted during two different loading cases. The investigation during the bending loading test and the shear loading test assumed the damage of whole girder and the damage of a part of the girder respectively.

Transition of vibration characteristics during bending load tests

Bending load tests were conducted on the girders sampled from decommissioned bridges. One was a pre-tensioned girder from Nakagawa Bridge and another was a post-tensioned girder from Aimigawa Bridge. Vibration measurements were conducted as follows. Velocimeters or accelerometers were set on the upper surface of PC girder as shown in Figure 6. After reaching each loading step, we unloaded to zero and we gave excitation by a plastic hammer (impact excitation method) and measured the dominant vibration frequencies.



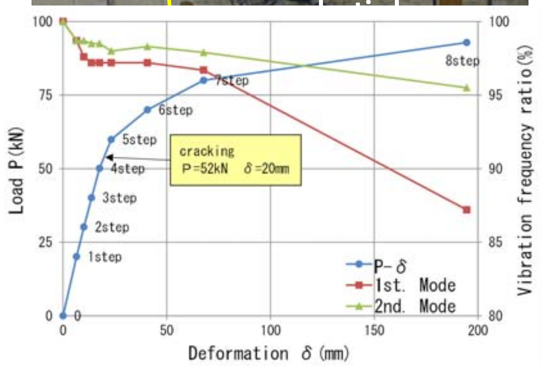


Figure 7. Transition of vibration frequency(pre-tensioned girder)

The result of vibration measurement of the pre-tensioned girder is shown in Figure 7. The decreasing ratio of the frequencies of the first and second modes are plotted in the figure. The deformation was measured at the maximum deflection point, not at the measurement points of vibration. Before the bending cracks appeared (loading step 4), decrease of frequencies was observed for the first and second modes. But they did not change very much after the appearance of the bending cracks. And finally at step 8 at which applied load was higher than the design bending strength of 80kN and the girder considerably deformed, decrease of the frequencies reached approximately 13% and 5% for the first and second modes respectively.

The result of vibration measurement of the post-tensioned girder is shown in Figure 8. The steps at which the girder was unloaded and the vibration measurement was conducted were set after the appearance of the bending cracks. From the figure, it was found that the frequencies did not decrease much between the appearance of cracks and the yield of steel members, although that of the first mode decreased significantly between the beginning of the loading and the appearance of the cracks.

On the other hand, the decrease of the frequency was approximately 30 % at the primary bending mode and approximately 20 % at the secondary bending mode in Step 4 which is the final point of the member after reaching the maximum load.

It can be considered that one reason of the decreasing of the frequency in the early loading stage is that the supports were not stable enough at the beginning of the loading. From the above, it was verified on both pre-tensioned and post-tensioned girder that the frequency decrease significantly when the member is close to the ultimate state, while the frequency did not change remarkably around the load level of the appearance of the flexural cracks or that of the yield of members. This reason can be conceived that on PC members, the cracks closed by the restoring force after unloading and the stiffness of member was recuperated.

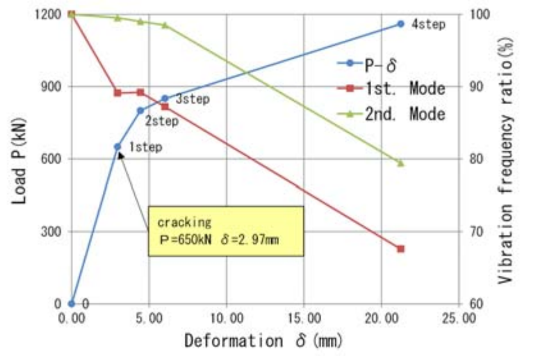


Figure 8. Transition of vibration frequency(post-tensioned girder)

<u>Transition of vibration characteristics during shear loading tests</u>

A shear loading test was conducted at the post-tensioned girder (Aimigawa Bridge). The vibration measurement was conducted before and after loading tests. In the test, the girder was loaded until the yield of the steel members. The latter vibration measurement was conducted in unloaded condition. The impact excitation method by a sandbag and the ambient vibration method were adopted.

Table 1 represents the result of the vibration measurement. Regarding the ambient vibration measurement method, the higher-order-mode of vibration could not be measured but some decreasing of the frequency could be found in each dominant vibration mode. Regarding the impact excitation method, the frequency tended to decrease when the order of mode was high. This is because, for the third bending, the partial damage near the shear loading point corresponds with the antinode of vibration

Table 1. Result of the vibration measurement during shear loading tests

mode	Loading test	natural frequency (Hz) ambient vibration method	natural frequency (Hz) impact excitation method
bending (1st.)	before	6.694	6.378
	after	6.458	6.353
	ratio	0.95	1.00
bending (2nd.)	before	21.301	21.276
	after	21.130	21.047
	ratio	0.99	0.99
bending (3rd.)	before	Undeterminable	57.363
	after	Undeterminable	52.953
	ratio	—	0.92

mode. Which coincides with the previous studies.

Vibration characteristic of deteriorated bridge

The PC bridge at which the vibration measurement was performed is shown in Figure 9. The structural type is a five-span simple PC T-section girder bridge. It was constructed in 1967 and served more than 40 years. Since the bridge was constructed on the coast of Japan Sea and therefore severely damaged by chloride attack, repairs had been performed more than once as damages of concrete or corrosion of steel were identified. However, because of confirmation of re-deterioration due to corrosion and breakage of PC wires as shown in Figure 10, rebuilding of the bridge was planned, and its service was terminated in September, 2010. Before its demolition, the vibration test was performed by vehicle falling method, weight falling method, and ambient vibration method as shown in Table 2. Excitations were applied at 1/2 and 1/4 points of the span on the G3 girder, and measurements were performed at points that divide the G1 and G5 girders equally into 8 segments. (Shown in Figure 11) The measurement condition is shown in Figure 12. Examples of spectra obtained in the vibration test performed by using vehicle falling method, weight falling method, and ambient vibration method are shown in Figure 13.

Figure 9. PC bridge

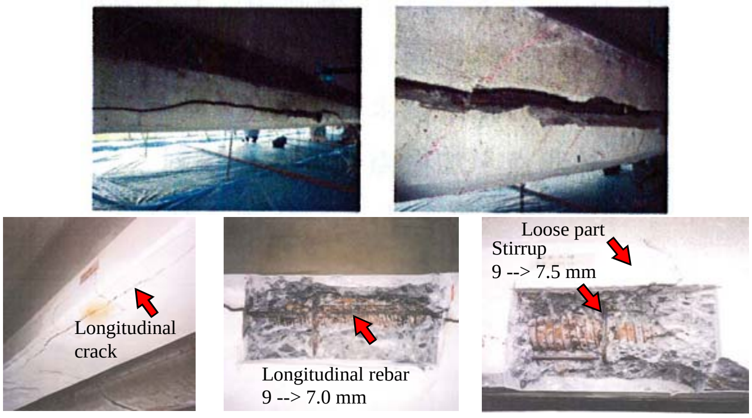


Figure 10. Deterioration of PC bridge

Table 2. Methods of excitation

	Vehicle drop method	Weight drop method	Ambient vibration method
Excitation method	4 rear wheels of a vehicle of 111 kN weight are dropped from a step of 130 mm high to provide forced excitation to the bridge.	A weight of 0.245 kN mass is dropped by free fall from a height of 1.0 m to provide forced excitation to the bridge. The shock excitation force is about 30 kN.	The ambient vibration during a calm period when there is no traffic on the adjacent temporary bridge is measured. * Because microtremor exists around the bridge due to natural and artificial causes, the bridge is continuously subject to random and micro vibration.
Advantages	No special excitation equipment other than testing vehicle is required. Relatively large excitation force can be obtained.	When a small size weight is used, vibration can be applied by human power. Relatively constant excitation force can be applied.	No excitation needs to be applied, and measurement can be performed easily even for a bridge which is currently in-service.
Disadvantages	The weight of vehicle sometimes cannot be negligible as an added mass. Also, the characteristic vibration of the vehicle (e.g. 3 Hz for a damp truck) can sometimes dominate as an excitation force.	Depending upon the mass of weight, there can be cases that adequate excitation force cannot be obtained.	A vibration measurement equipment with high precision is necessary. It may sometimes be influenced by noise, etc. and/or the process method because of small amplitude.

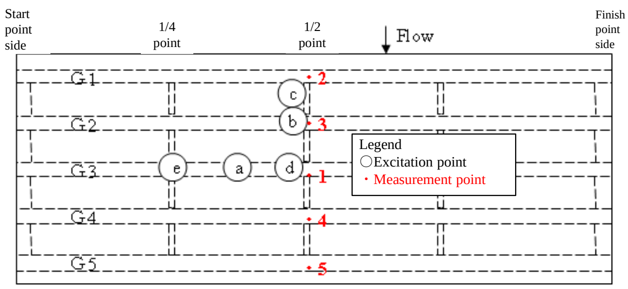


Figure 11. Excitation point and the measurement point

Vehicle falling method

Weight falling method

Figure 12. Excitation methods

The Figure shows results obtained in the 1st. span with excitation point located at 1/4 point of the span and measurement at 1/2 point of the G3 girder span. Dominant frequencies have been concentrated near 4Hz in the all method. Additionally, dominant frequencies in the range of 20 Hz ~ 40 Hz were found in the weight falling method. Also, for the weight falling method in which the third through fifth dominant frequencies (20 Hz ~ 40 Hz) were

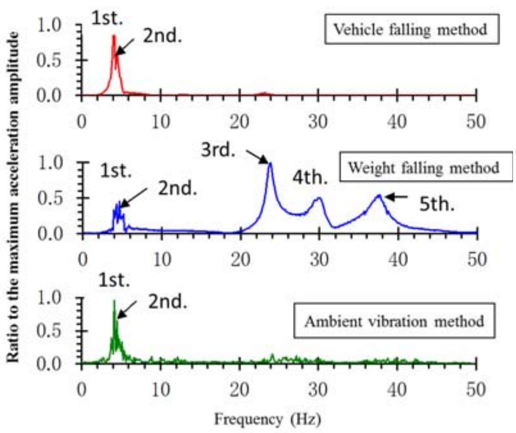


Figure 13. Measured spectra

found, dominant frequencies of the 1st. span, where damage was severe, and the 2nd. span, where damage was minor, were shown in Table 3. According to the inspection data of the past, section loss of concrete and breakage of PC cable by chloride attack has been found in the 1st. span. Deterioration of the 1st. span was severe while that of the 2nd. span was comparatively minor. For higher modes, frequencies of the 1st. span were much smaller than those of the 2nd. span. As mentioned in the shear loading test, it may be possible to grasp the deterioration by measuring the high-order vibration modes.

In this bridge, it was possible to find a difference of the frequencies because

Table 3. Comparison of frequency (1st. Span1, Span 2)

Mode number	Dominant frequency(Hz)		f1/f2	Mode of vibration
	Span 1	Span 2		
	f1	f2		
First	4.3	4.3	1.00	First bending
Third	23.7	25.2	0.94	Unknown
Fourth	30.2	31.5	0.96	Third bending
Fifth	37.1	40.8	0.91	Unknown

the deterioration levels of each span differs. However, this method may not be applied to the most of the bridges. For the general cases, it is better to measure the value when intact state and compared it when the bridge deteriorates.

CONCLUSION

From the result of this study, the following conclusions can be drawn:

(1)When the PC Bridge suffered severe damage, there is possibility of detecting deterioration by vibration measurement.

(2) For PC members, reduction of vibration frequency is small because of the restoring force induced by the prestress.

(3) It may be possible to detect the damage of PC bridges comparing the vibration characteristics in sound state and those in current state.

Acknowledgments

CAESAR’s research activity utilizing decommissioned bridges was able to be conducted using demolished bridges provided from municipalities along with cooperation agreement with the Japan Prestressed Concrete Contractors Association (JPCCA). We thank them for their corporation.