EXPERIMENTAL FEASIBILITY STUDY FOR SLIGHT DAMAGE DETECTION AND LONG-TERM DEFORMATION MONITORING OF STRUCTURES BY AMBIENT VIBRATION

Sumitomo Mitsui Construction Co., Ltd., Regular Member ○Hoang Trong Khuyen
Sumitomo Mitsui Construction Co., Ltd., Regular Member Hiroyuki Uchibori
Sumitomo Mitsui Construction Co., Ltd., Regular Member Hiroo Shinozaki
Sumitomo Mitsui Construction Co., Ltd., Regular Member Naoki Nagamoto

1. INTRODUCTION

One of the critical judgments for structural monitoring is whether structure still useable or not after such events as earthquakes. Priestley et al. (1996) defines serviceability limit state as which bridges would be serviceable immediately after an earthquake and should not need repair right away. By this limit, damage level is slight, (no spalling of concrete, residual crack width less than 1mm), the bridges don't need to repair immediately, but damages should be detected to repair later for strengthening the durability of structures. In seismic countries, during the bridge life cycle, several moderate earthquakes could be occurred, causing slight damages. Severe damages are obviously detectable; however, the slight crack may be difficult to detect because of less stiffness reduction. In this paper, an experiment of a full-size prestressed bridge girder was carried to study the feasibility of detecting slight damages using ambient vibration.

Furthermore, integral of ambient vibration acceleration gives limited accuracy for residual displacement. However, tilts of accelerometers are sensitive to the deformed inclination of structures. That means using accelerometers is possible to estimate the residual deformation of structures, especially long-term deformation due to creep of concrete, foundation settlements which are essential for maintenance but hard to measure in practice. In this paper, an algorithm was developed to estimate the deformed shape of structures. An experimental displacement record was investigated to verify the feasibility of using accelerometers for long term deformation monitoring.

2.EXPERIMENTAL STUDY

An experiment of a full-size concrete pre-tensioned girder was carried out to verify slight crack's effect on natural frequency as well as feasibility of estimating deformation from sensing tilts. The girder is made of concrete with 155.5MPa compressive strength, 55.6GPa Young's modulus, and 7.57MPa tensile strength at age of 13 days. The girder is reinforced by 13 sets of 3ϕ7.4 pre-tensioned strands of aramid FRP rods. A set of 4 accelerometers were set up on top of the girder to measure ambient vibration as shown in Fig. 1. The girder was loaded until about 85% of maximum loading to induce slight cracks with residual width about 0.1-0.3mm. Then loading jack was removed out to maintain the same restrain condition with intact state. The girder ambient vibration, which induced by random excitation as people walking on ground, movement of testing equipment or white noise, was measured to identify structural properties such as natural frequencies, mode shapes, and damping. The modal natural frequencies were observed to clarify the effect of cracks on the structures. Furthermore, the girder deformation during the experiment was also measured in order to compare with estimated deformation calculated by tilted angles of accelerometers.

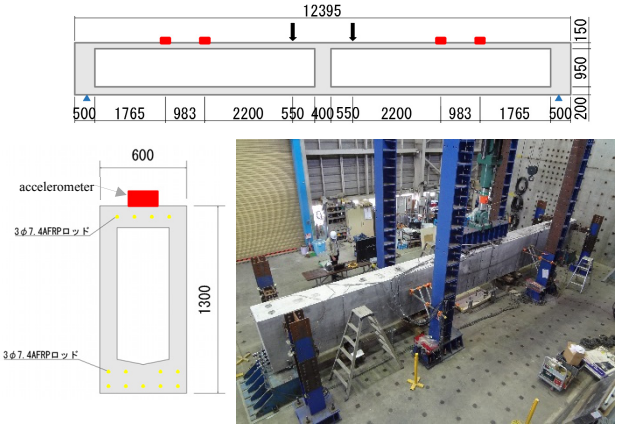

Fig. 1 Experimental setup of full-size pre-tensioned girder

3. ANALYSIS METHOD

The structural dynamic characteristics such as natural frequencies, mode shapes are functions of structural weight and stiffness. Consequently, there is a possibility of damage detection by tracking deviation of modal properties. Structural identification (estimate natural frequencies, mode shapes, etc.,) was proceeded by the output-only method. The ambient vibration acceleration data was transformed into a spectrum using a fast Fourier transform. Natural frequencies were estimated by peak picking method with an original algorithm as presented more details in Khuyen et al. (2020) to improve accuracy so that modal characteristics can be estimated event with a very low amplitude of ambient vibration.

Acceleration vector has a trigonometry relationship with gravity vector, that allows defining tilt angle of accelerometers. Once structure deforms due to concrete creep, foundation settlement, etc., the structural inclination would be changed. During ambient vibration, depending on the recording sample rate, the tilted angles may vary within a range. However, the mean variation can represent the long-term inclination variation of structures. In this paper, a procedure as in Fig.2 was employed to estimate the deformation of structures. Several accelerometers are installed at critical sections to measure the slope of

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Contact address: 2-1-6 Tsukuda, Chuo-ku, Tokyo, 104-0051, Japan, Tel: +81-3-4582-3121

deformed beam θ_i, then deformation shape is the integral of inclination function which comes from curve fitting of measured location.

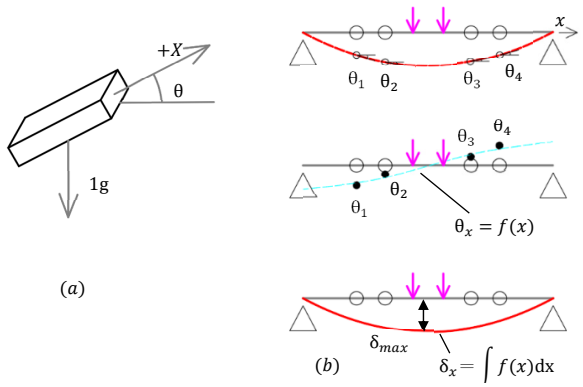

Fig. 2 (a) sensing tilt; (b) deform estimation algorithm

4. RESULT AND DISCUSSION

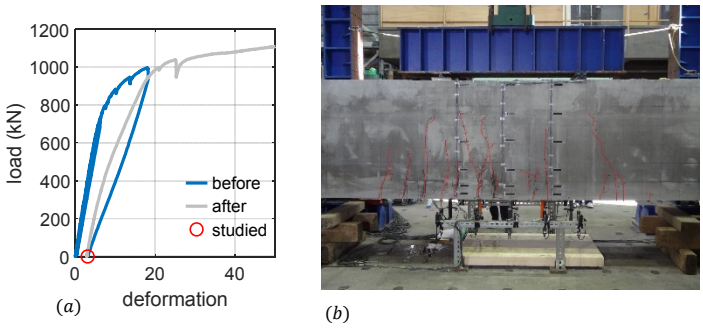

Fig. 3 (a) Loading cycles; (b) cracks at targeted condition

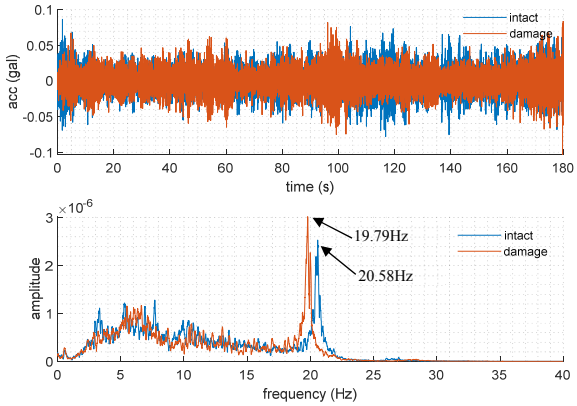

Fig. 4 Ambient acceleration and spectrum

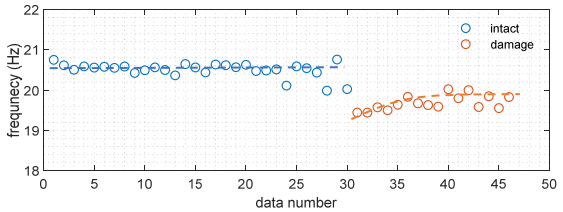

Fig. 5 First vertical frequency derivative

The girder was loaded until approximately 85% maximum loading to initiate slight cracks as load cycles in Fig.3(a). After loading jack was removed for ambient vibration measurement, the crack condition is as shown in Fig.3(b). Cracks at this studied condition extended 2/3 of girder height with residual crack width about 0.1-0.3mm. The number of cracks was the same, and only the crack length was extended as load increment at this condition. There was a little nonlinear behavior in P-δ curve was seen during loading. As shown in Fig.4, despite of very low ambient vibration amplitude of approximately 0.1 gal, the first vertical mode natural frequency can be identified. The natural frequency decreased due to cracks as shown in Fig. 5. The reduction of frequency is detectable, for example by statistic model in Khuyen et al. (2020), so that the slight crack, as in this case, is able to detect. However, it also found that natural frequency is gradually increasing by time due to the closure of cracks by pre-tensioned stress. Furthermore, using the algorithm in Fig. 2(b), the deformation of structures was estimated using 5-second average of ambient acceleration. Fig.6 shows a good agreement with measured deformation by displacement gauge. This confirmed the feasibility of using the accelerometer to monitor long-term deformation of structures such as creep deformation, foundation settlements or any deformation that make the inclination of structures change. This study confirmed the displacement estimated using tilts in accelerometers gives an error of less than 1mm. Accuracy also depends on how accurate the slope function of structures is fitted which derived by the number of accelerometers and fitting order.

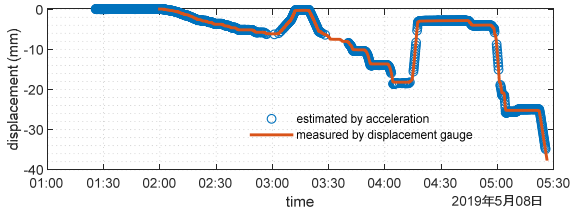

Fig. 6 Comparison of maximum deformation

5. CONCLUSION

This paper presented an experimental feasibility study for slight damage detection and monitoring of long-term deformation using ambient vibration. Results confirmed that the slight damage, which is cracks with residual width about 0.1-0.3mm as in the experiment, is detectable. In prestressed structures, cracks would be gradually closed due to prestress, and modal natural frequencies would recover partially, making more difficult to detect them. Furthermore, an algorithm was developed to estimate the long-term deformation using tilts of accelerometers. Results show that the estimated deformation has a good agreement with the experimental displacement record. This technique may be applicable in monitoring long term deformation due to foundation settlement, concrete creep or any geometry inclination change in structures.

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