Study on the application of ambient vibration tests to evaluate the effectiveness of seismic retrofitting

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Abstract. In recent years, earthquakes have occurred frequently, and the seismic performance of existing school buildings has become particularly important. The main method for improving the seismic resistance of existing buildings is reinforcement. However, there are few effective methods to evaluate the effect of reinforcement. Ambient vibration measurement experiments were conducted before and after seismic retrofitting using wireless measurement system and the changes of vibration characteristics were compared. The changes of acceleration response spectrum, natural periods and vibration modes indicate that the wireless vibration measurement system can be effectively applied to evaluate the effect of seismic retrofitting. The method can evaluate the effect of seismic retrofitting qualitatively, it is difficult to evaluate the effect of seismic retrofitting quantitatively at this stage.

1. Introduction
In recent years, massive earthquakes have occurred frequently around the world. Especially in Japan, the earthquake-prone country, the safety of human’s lives and property is under the threat of earthquake constantly. As learning places and refuge, the significance and urgency are self-evident to grasp and improve the seismic performance of school buildings. After The East Japan Earthquake (2011), the Japanese government expanded the scope for seismic implementation, brought into the “Buildings surround emergency transportation roads” and improved the seismic implementation rate index on the basis of current seismic code [1].

From the perspective of environmental protection and cultural inheritance, Japan has been the transition from “economic priority” to “circular development”, so it is mostly to improve the seismic performance of existing buildings by reinforcement [2]. However, it can only be evaluated and determined by the change of design index (Is: comprehensive seismic index; Ctu·SD: intensity index) [3] for the rationality of the reinforcement design and the accuracy of the reinforcement construction project. Nevertheless, the seismic retrofitting of existing buildings is supposed to be built on the situation of construction for selecting reasonable reinforcement approaches. Therefore, there are some disadvantages to evaluate the seismic effectiveness depend on design source or man-made evaluation absolutely. In 2005, there was a most influenced event about anti-seismic camouflage in Japan [4], which raised the question of the current method for relying on the design data of reinforcement or the experience of professional artisans solely.
With the rapid development of sensing technology, its effective application has been penetrated in various fields. Most researchers are committed to using sensing technology to determine and analyze the vibration characteristics of buildings. But, most of the research results still remain in the analysis of the vibration characteristics of the individual buildings. There are few studies on the effective application of the eigenvalue. This study used wireless vibration measurement system to carry out ambient test for school buildings before and after the seismic retrofitting construction. Then, it can establish an effective evaluation method for seismic retrofitting by comparing and analyzing the change of vibration characteristics. This paper discusses the rationality of the wireless measurement system and the effectiveness of the research method in the case of a high school building in Hiroshima, Japan. So far, most of the researches detect and assess the safety of existing buildings based on the change of natural periods, but due to the small deformation, it is important to grasp the surrounding environment in the vibration test. This research carries on integrated evaluation by means of comparing the vibration modes and the deformation before and after seismic retrofitting, and finally establishes an objective and effective evaluation method.

2. Description of the experiment

2.1. Test equipment
The test equipment used in this study is a wireless vibration measurement system that developed by Hiroshima University and institute of research. It is composed of commercial servo-type acceleration sensors and wireless transmitting units which were developed. In consideration of the constraints of on-site vibration test and the multifarious status, the system can greatly save time and labour. Besides that, it can avoid the wiring error for on-site test owing to omit the wiring. The 3-axis acceleration sensor has high sensitivity, which is suitable for ambient test. Figure 1 is the general situation of the wireless measurement system. The accelerometers have a wide frequency and acceleration range (DC to 1000 Hz and ±3 g, respectively) and the wireless signal units provide signal conditioning, 24-bit A/D conversion, and time synchronization of multiple sensors (maximum 7).

The time used in the vibration test for this school building is 1 hours (layout for the sensor and system debugging and vibration test). Since the vibration test proceeded during the period of students’ noon break, it is verified that the labour saving of wireless measurement system and the rationality.

2.2. Sensor placement
In this experiment, ambient vibration tests were applied to this school building before and after the seismic retrofitting construction in 2013. In order to obtain the vibration characteristics and confirm the effectiveness of the seismic retrofitting works, acceleration sensors were placed in the central part of the school building and the staircase as shown in Figure 2.

2.3. Outline of the building and seismic retrofitting
The objective school building is located in Hiroshima City, Japan. It is a three-story, nearly rectangular, reinforced concrete building, with one of its dimensions being considerably longer than the other one (54 m × 10 m). The direction of the length side is the frame structure and the direction of short side is the frame shear wall structure. Because it is built before the year of 1981 (the period of practicing old seismic standards in Japan), the seismic identification results indicated that the seismic performance of the school building was low, and the risk of the great earthquake damage was extremely high. To strengthen the school building, the retrofitting construction was conducted in 2013. Figure 2 shows the survey of the objective building and seismic retrofitting construction.

The seismic retrofitting construction of the school building was carried out in 2013 in order to satisfy the target value. To strength the building, additional framed steel braces were built in the longitudinal direction. To improve the ductility of columns, structural slits were constructed in the staircases. In the transversal direction, additional earthquake resistant walls were constructed in the first floor. Due to the larger opening of floors in staircases, the transmission efficiency of seismic force in the transversal direction was weak. So, additional slabs were built in the staircases.

3. Results of the experiment

Figure 3 shows the time-history curves of ambient vibration. This result is the acceleration response spectrum of the centre of the 3rd floor and the 1st floor of the building before and after seismic retrofitting construction. As shown in this figure, the acceleration response of the 3rd floor that after the retrofitting is weaker than before, while the change of the 1st floor has no obvious. The implementation of the seismic retrofitting construction has influenced the vibration response of the upper structure in the building. Therefore, this paper analyses and compares the changes of vibration characteristics that based on the acceleration waveform measured by ambient vibration.

3.1. The change of natural period

Take the waveform of surface as the input wave, the acceleration responses of the upper structure as the output signal to get the natural periods based on the Fourier analysis method. In order to verify the accuracy of the change rate of natural periods before and after the seismic retrofitting, eigenvalue of the building is calculated based on design data. The structure is simplified by ignoring the effect of filling walls on the rigidity of the whole structure. The change of natural periods before and after seismic retrofitting is shown in Table 1.
The probability of estimating the
acceleration waveform based on the
natural frequency ± 0.1 Hz). Using Band-pass filter to
deal with acceleration waveform, in this paper the bandwidth takes 0.2 Hz (natural frequency ±0.1 Hz). The wireless measurement system can automatically generate the vibration modes of the selected frequency according to the input of coordinate and the setting of analytic condition.

### Table 1. Natural periods of the objective building before and after seismic retrofitting.

| Direction   | Result of ambient vibration | Result of eigenvalue analysis |
|-------------|-----------------------------|------------------------------|
|             | Before                      | After                        | Change rate | Before | After | Change rate |
| Longitudinal| 0.293 sec.                 | 0.269 sec.                  | 1.25        | 0.257 sec. | 0.215 sec. | 1.20 |
| Transversal | 0.186 sec.                 | 0.165sec.                   | 1.33        | 0.121 sec. | 0.116 sec. | 1.04 |

As shown in table 1, after seismic retrofitting of the objective school building, the natural period in the longitudinal direction changed from 0.293s to 0.269s, the natural period in the transversal direction changed from 0.186s to 0.165s. Strengthening methods and reinforcement engineering improved the stiffness of the school building. The natural period of the longitudinal direction is longer than the transversal direction. By comparing the results of the ambient measurement and eigenvalue analysis, the period calculated by eigenvalue analysis is smaller than the former. The reason is that eigenvalue analysis model ignored the influence of stiffness of the filler wall and so on. Comparing the change rate of the two, natural period in the longitudinal direction is roughly equal, while the deviation in the transversal direction is larger. Due to the method of establishing eigenvalue analysis model, especially there are some errors during simplification of the short-limb shear walls and filler walls in the transversal direction. However, the table shows ambient result can reasonably reflect the effectiveness of seismic retrofitting, especially by comparing the change rate.

#### 3.2. The change of amplification ratio

Figure 4 shows the change of amplification ratio. The acceleration amplification rate in the longitudinal direction after the seismic retrofitting is about a third of before. While, there is less variation in the transversal direction. A huge number of steel supports have been added in every floor in the longitudinal direction to improve the strength. In the transversal direction, it is strengthened partially on the 1st floor only, and the change is not obvious. But, it can be seen from the distribution curves: the distribution curve of amplification ratio in the longitudinal direction before and after seismic retrofitting is in a straight line; due to the uneven arrangement of the shear walls, change of distribution curve in the transversal direction is irregular. Because the reinforcement is only conducted in the 1st floor, the change of acceleration response indicates a significantly reduced trend which is relative to other floors in the transversal direction. The probability of estimating the seismic retrofitting is verified by the change of vibration characteristics.

#### 3.3. The change of vibration modes

This study uses the method which has been presented for analysing vibration modes [8]. The method is based on the natural vibration frequency determined by the transfer function. Using Band-pass filter to deal with acceleration waveform, in this paper the bandwidth takes 0.2 Hz (natural frequency ±0.1 Hz). The wireless measurement system can automatically generate the vibration modes of the selected frequency according to the input of coordinate and the setting of analytic condition.

![Figure 4. The change of amplification ratio before and after seismic retrofitting](image)
Figure 5 shows the first vibration mode before and after seismic retrofitting. The 1st mode of the longitudinal direction is translational motion. Stiffness in the central of the transversal direction is greater, so the 1st mode shows torsion deformation. After the seismic retrofitting, the setting of steel supports has greatly reduced the acceleration response of each floor in the longitudinal direction. As mentioned earlier, the acceleration response almost has no change due to concrete walls were added only on the 1st floor. Therefore, if the part of structure that strengthened has little effect on the stiffness of the whole building, it is difficult to evaluate the effect of seismic retrofitting from the change of the first vibration mode.

3.4. Evaluation of the reinforcement of slabs
In order to improve the overall resistant deformation of the school building in great earthquakes, the seismic retrofitting thickened the slabs in staircases as shown in Figure 2. The reinforcement method is in order to reduce the difference of deformation between overall building and staircase in the transversal direction. Figure 6 shows the comparison of displacement before and after the seismic retrofitting construction. Displacements in the centre of the building and the staircase are selected.

Difference of displacement between the staircases and the central part of the school building is larger before thickened the slabs. While, after the seismic retrofitting construction, the difference is smaller. Moreover, it is in good agreement with the results of the first vibration mode that reverse deformation is shown before the seismic retrofitting. Therefore, the strengthening of the slabs enhances the integrity of the school building and improves the deformation difference of the building basically.
4. Conclusions

This study used the wireless measurement system to carry out ambient test before and after the seismic retrofitting construction of a school building. The efficiency and labour saving of the wireless measurement system were verified. It can be seen from the results of this paper:

(1) The changes of natural periods and amplification ratio are in good agreement with the method of the seismic retrofitting, which can be used to evaluate the effectiveness of the retrofitting construction and grasp the engineering quantity of retrofitting construction approximately.

(2) The change of the first vibration mode can evaluate the reinforcement effect intuitively and bring convenience to quality inspection. But the change of the first vibration mode is closely related to the reinforcement method and the reinforcement amount.

(3) It is verified to evaluate the effect of the seismic retrofitting which is based on ambient vibration. However, it is important to improve the accuracy of this method and study the correspondence with great earthquakes.

In order to improve the reliability of the evaluation method and establish quantitative method, more research examples need to be accumulated.

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