EVALUATION OF THE EFFECTS OF SEISMIC RETROFIT FOR REINFOECED CONCRETE SCHOOL BUILDINGS USING MICROTREMOR OBSERVATION

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SUMMARY

In Japan, earthquakes have been occurring frequently in recent years and the importance of seismic retrofit has been pointed out. In this study, the effect of seismic strengthening is investigated by two methods, microtremor observation and a numerical analysis, for retrofitted buildings. Two school buildings were strengthened by different construction methods, one using external braces and another adding a frame. The results of microtremor observation and numerical analysis show that the rigidity of these buildings have improved by implementing seismic strengthening. The microtremor observation shows a higher rate of rigidity improvement than that by the numerical analysis. The factors that are difficult to model, such as non-structural elements and construction accuracy, are taken into consideration in microtremor observation. We must avoid that the natural periods of ground and a building overlap by retrofit. Thus it is important to know change of the natural period of a building by retrofit. We suggest that microtremor observation is a useful tool to confirm the effect of seismic retrofit together with numerical analyses.

INTRODUCTION

In Japan, school buildings and gymnasia are often used as shelters after the occurrence of natural disasters, e.g. earthquakes. Therefore, buildings that may function as shelters should withstand earthquake forces. There are many existing buildings which were built based on old seismic codes and do not fulfill the present seismic code. Some of these old-coded buildings have suffered from damage in recent earthquakes. Based on past researches, it has been pointed out that some buildings built 25 or more years ago have brittle nature [1-2]. Therefore, seismic retrofit is necessary for such brittle buildings. As a method of seismic strengthening, addition of shear wall and reinforcement of columns have been employed frequently. However, in order to avoid problems to foundation by increasing the dead load, reinforcement by a steel brace became popular in recent years. Thus it is necessary to examine the effectiveness of this retrofit method to old-coded buildings. The seismic resistant capacity can be estimated by structural calculations for retrofitted buildings. However, the influence of construction performance cannot be taken into consideration in structural calculations. If it is possible to assess the seismic performance of buildings by an on-site observation, it may be quite useful information to evaluate the efficiency of seismic strengthening, together with the result from structural calculations.

In this study, the effect of seismic strengthening is evaluated from microtremor observation and a structural analysis for two retrofitted school buildings in Hiroshima Prefecture, Japan, especially from the viewpoint of the changes in the natural period of the buildings.

SEISMIC CAPACITY EVALUATION METHOD

The seismic safety of school buildings is investigated based on the seismic capacity evaluation method in Japanese standard [3]. In the method, the seismic capacity, I_S, is calculated by

$$I_S = E_0 S_D T \quad (1)$$

where E_0 is the basic structural index for each story in a given direction, S_D represents the shape index that is calculated from the plan of the building, and T is the age parameter estimated from the decrepit condition of the building. The basic structural index, E_0, is defined by

$$E_0 = CF\phi \quad (2)$$

where C and F are the structural strength and ductility index, respectively, and ϕ is the coefficient that converts the base shear force to the story shear force.

Seismic capacity evaluation has three levels depending on the complexity of the calculation. I_{S1} is used for the preliminary classification and is easiest to obtain. I_{S2} is used in seismic diagnoses for the most cases, particularly for school buildings in Japan. I_{S3} is used for actual retrofit works, and it is the most costly and time-consuming method for obtaining the necessary parameters. In the 1995 Hyogo-ken Nanbu (Kobe) earthquake, the I_{S2} index demonstrated a fair correlation between the seismic capacity of a building and the extent of damage. The buildings with I_{S2} values equal to or less than 0.3 sustained severe to moderate damages, and the buildings with I_{S2} values over 0.6 suffered from no to slight damages. Therefore, the I_{S2} index has been recognized and recommended as a measure for judging the seismic performance of buildings. However in these periods, the number of seismometers was not so large, and hence the estimated seismic motion to the buildings might be not so accurate. Note that I_{S3} is used in examining a strengthening design.

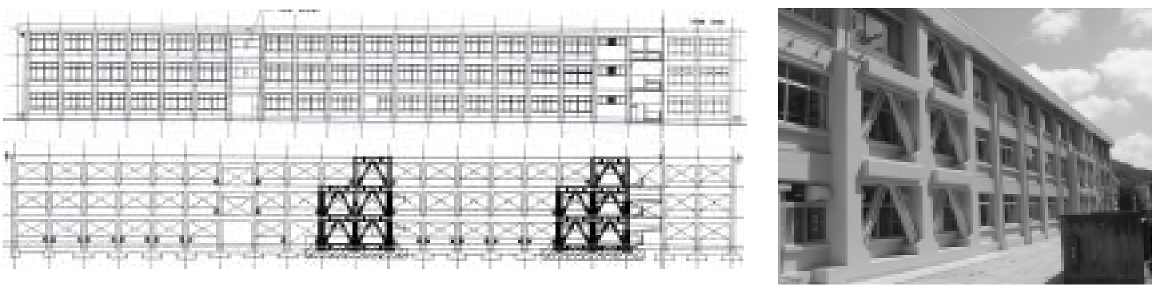
OUTLINE AND RETROFIT PLAN OF TWO SCHOOL BUILDINGS

The two buildings used in this study are located in Hiroshima Prefecture and named as buildings X and Y. The right photographs in Figure 1 show these buildings after retrofit. Building X is three-story, built in 1967 with the height of 10.92 m. It is a frame structure having shear walls to the transverse and longitudinal directions. The seismic capacity I_{S3} before the strengthening was less than the target value, 0.7, for the first and second stories in the longitudinal direction, and thus strengthening was carried out only to the longitudinal direction. The stiffness was enhanced by an external brace (see Fig. 1) and toughness was enhanced by adding slits, removing spandrel walls, and strengthening for columns.

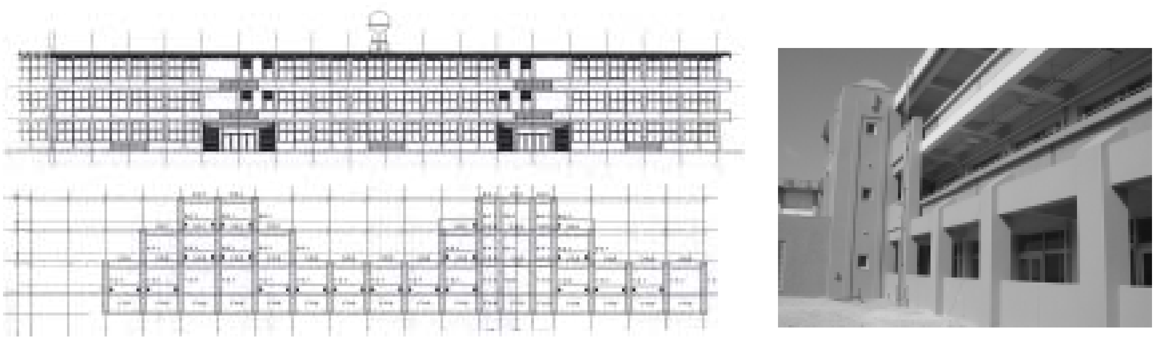
Building Y is also three-story, built in 1973 with the height of 11.11 m. It is a frame structure with shear walls to the transverse and longitudinal directions. The seismic capacity I_{S3} before strengthening was less than 0.7 for the first story in the longitudinal direction. The building was retrofitted by adding a reinforced-concrete frame from the exterior of the original building, as shown in Figure 1.

Figure 2 shows the improvement in seismic capacity by strengthening. It is pointed out that low seismic capacity of school buildings, in general, is responsible for the longitudinal direction, which has many windows. Therefore, strengthening was carried out to the longitudinal direction in the present examples. Although the two retrofit plans differ, the plans were made such that the value of I_S be increased about 50 % to the longitudinal direction.

For building X, the I_S value for each story to the transverse direction has decreased due to the removal of walls when the external brace for the third story was set up. However, there is enough seismic capacity for the third story comparing with other stories, and the decrease of I_S is in a permissible range. The reduction of I_S values are also seen for the first and second stories of building X and the second story of building Y, but they still have enough seismic capacity.

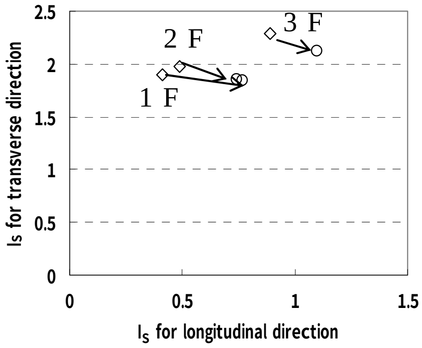


(a) Building X

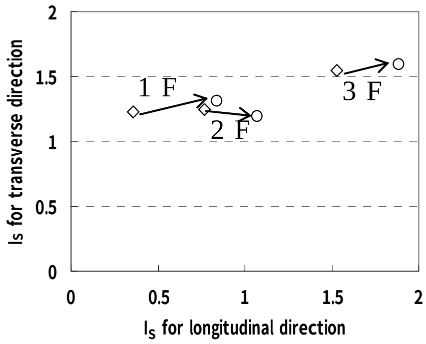


(b) Building Y

Figure 1. Elevation and added structural frame (left) and photographs after retrofit (right) of the two school buildings in Hiroshima Prefecture



(a) I_{S3} for building X



(b) I_{S3} for building Y

Figure 2. Seismic capacity of the buildings before and after seismic strengthening

ESTIMATION OF RETROFIT EFFECT

Verification of the strengthening effect by eigen value analysis

The effect of seismic strengthening was examined using a three-degrees-of-freedom (DOF) lumped mass model. The lumped mass models before and after strengthening were made from the data of seismic capacity evaluation and the strengthening plan. In order to model a building in a lumped mass system and to carry out an eigen value analysis, it is necessary to define the spring constant for each story. The shear rigidity was calculated from the formulae for the distribution coefficient of horizontal forces.

The horizontal spring constant, k, of each layer was calculated from the relationship between the relative story displacement, δ, and shear force, Q, of the layer:

$$Q = k\delta \tag{3}$$

If the relationship between the shear force and displacement is considered for one column of a frame, the slope deflection method is used to calculate the moments M_C for a column and M_B for a beam as follows:

$$\begin{aligned} M_C &= 2EK_0 k_C (3\theta - 3R) \\ M_B &= 2EK_0 k_B \cdot 3\theta \end{aligned} \tag{4}$$

where E is the Young's modulus, and K_0 is the standard rigidity, k_C and k_B are the rigidity for the column and for the beam, respectively. θ and R are the rotation angles for the beam and for the column, respectively. Equation 5 is derived from the moment of the column and the beam at a node.

$$\theta = \frac{k_C}{k_C + k_B} R \tag{5}$$

When $R = \delta / H$ (H: the story height) is substituted to Equation 5, the relationship between Q and δ can be expressed by Equation 6:

$$Q = \frac{\frac{k_B}{k_C}}{1 + \frac{k_B}{k_C}} \cdot k_C \cdot \left[\frac{12EK_0}{H^2} \right] \cdot \delta \qquad (6)$$

k_B in the equation is represented by the following average value when applying it to the entire structure.

$$k_B = \frac{k_{B1} + k_{B2} + k_{B3} + k_{B4}}{4} \qquad (7)$$

When Equation 7 is substituted to Equation 6, one gets

$$Q = ak_C \left[\frac{12EK_0}{H^2} \right] \delta$$
$$a = \frac{\bar{k}}{2 + \bar{k}}, \bar{k} = \frac{k_B + k_{B2} + k_{B3} + k_{B4}}{2k_C} \qquad (8)$$

For building X, the standard column section is 450 mm × 600 mm, the story height is 3,450 mm, and the rigidity calculation of a column shows that the concrete strength is 21 N/mm^2. Thus one gets

$$k = ak_C \left[\frac{12EK_0}{H^2} \right] = a \left[\frac{12EI}{H^3} \right] = 0.19 A_C \qquad (9)$$

where A_C is the section of the column and the values were set as E = 21,862 N/mm^2 [F_C = 21N/mm^2], I = 30,000A_C, H = 3,450 mm, a = 0.5 , k_C = 0.5 in this study.

Table 2. The natural period to the longitudinal direction obtained by the eigen value analysis

(a) Building X

	Story number	Mass (t)	Story Height (cm)	Rigidity (t/cm)	Natural period (s)
Before reinforcement	3	628.8	345	4761.0	0.18
	2	891.8	345	4761.0	
	1	895.8	345	4505.4	
After reinforcement	3	681.0	345	5174.2	0.17
	2	938.3	345	5380.8	
	1	962.1	345	5125.2	

(b) Building Y

	Story number	Mass (t)	Story Height (cm)	Rigidity (t/cm)	Natural period (s)
Before reinforcement	3	718.7	356	2734.2	0.25
	2	897.42	360	2517.3	
	1	1018.86	360	2517.3	
After reinforcement	3	729.12	356	3234.7	0.22
	2	1007.3	360	3264.4	
	1	1207.7	360	3739.9	

Similarly, when estimating the rigidity of shear walls and columns for buildings X and Y, the rigidity of each member was considered. Using the lumped mass models obtained, the natural periods of the two buildings to the longitudinal direction were computed as shown in Table 2. In the calculation, there is 1.11 times increase in stiffness for building X, and 1.31 times for building Y due to the strengthening.

Verification of strengthening effect using microtremor observation

Microtremor observation was carried out for the ground and the buildings at the two school sites. The instrument used for the microtremor observation is GEODAS (Buttan Service Co.). The obtained velocity records by the sensors were low-pass filtered and amplified and then converted to digital recording using 16 bits AD converter for storage in a laptop computer. For velocity measurement, sensitivity of the instrument is flat for period less than about 2 s. Sampling frequency of 100 Hz was used.

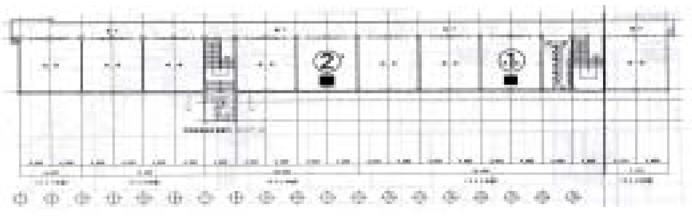
Figure 3 shows the location of the microtremor observations. These observing points are located on the third floor of each building. The obtained velocity records were converted from the time domain to the frequency domain to get the Fourier spectrum and it was smoothed by using a Parzen window of bandwidth 0.4 Hz.

The amplitude ratio of Fourier spectra for ground was calculated by H/V method proposed by Nakamura [4].

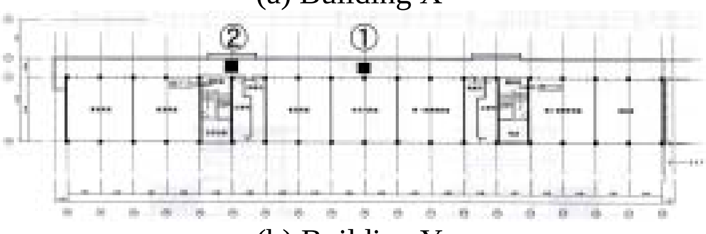
$$R_G^{NS}(T) = \frac{H_G^{NS}(T)}{V_G(T)} \qquad R_G^{EW}(T) = \frac{H_G^{EW}(T)}{V_G(T)} \tag{10}$$

where H_G and V_G are the Fourier amplitude spectra in the horizontal (NS and EW) and vertical directions and R_G is the H/V Fourier spectrum ratio of the ground. The predominant period of ground is determined by the peak period of the H/V ratio.

Figure 4 shows the H/V Fourier spectrum ratio of the two sites. For the ground near building X, no clear peak is observed in the H/V spectrum. The ground seems to be very

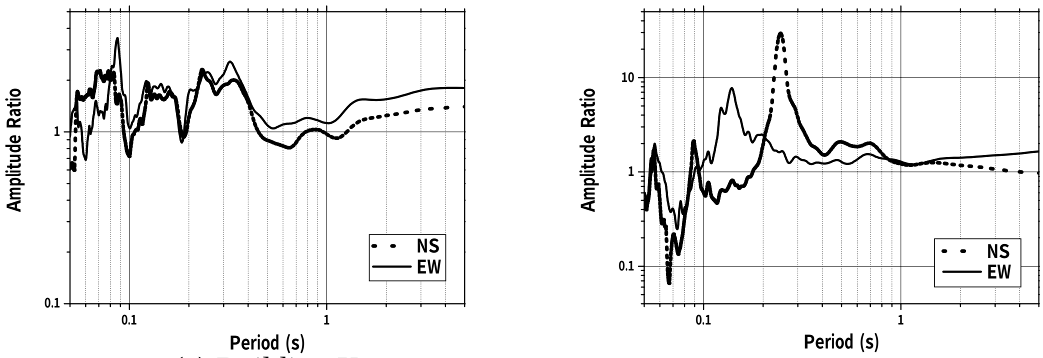


(a) Building X



(b) Building Y

Figure 3. Location of sensors in microtremor observation for the two building



(a) Building X (b) Building Y

Figure 4. Predominant periods of ground by microtremor observation

Table 3. Natural periods of the buildings by microtremor observation

		Before reinforcement(s)		After reinforcement(s)		Rate of periodic reduction	
Building	Story Number	L-direction	T-direction	L-direction	T-direction	L-direction	T-direction
X	3	0.23	0.13	0.20	0.11	0.86	0.84
Y	3	0.30	0.20	0.20	0.14	0.66	0.7

stiff at this site, located in a mountainous area. On the contrary, clear peaks were observed at the ground near Building Y, around 0.13s to the EW-direction and .022s to the NS direction. The reason for the discrepancy of the predominant period for the two directions is not so sure. Underground soil structure may be responsible.

The Fourier spectral ratio between the building and ground is calculated by

$$A^{LT}(T) = \frac{H_B^{LT}(T)}{H_G^{LT}(T)} \qquad A^{TR}(T) = \frac{H_B^{TR}(T)}{H_G^{TR}(T)} \tag{11}$$

where H_B and H_G are the Fourier amplitude spectra observed on the building floor and on the ground, respectively. The super script LT indicates the longitudinal direction and TR the transverse direction. The natural period of the building is determined by the peak period of the H/H ratio.

Table 3 shows the natural period of the buildings by microtremor observation. In this building, longitudinal direction is almost the same as EW direction, and it is necessary to be planned such that resonance may not occur by strengthening.

Due to seismic retrofit, the natural period of building X was reduced from 0.23s to 0.20s in the longitudinal direction and from 0.13s to 0.11s in the transverse direction. Similarly, for building Y, the natural period was reduced from 0.30s to 0.20s in the longitudinal direction and from 0.20s to 0.14s in the transverse direction. Thus the rigidity of building X increased 1.18 times in the longitudinal direction and 1.22 times in the transverse direction, and that of building Y increased 1.58 times in the longitudinal direction and 1.51 times in the transverse direction. It is noticed that although the seismic strengthening intended only to the longitudinal direction, the rigidity to the transverse direction has also increased.

Based on microtremor observation, the effectiveness of retrofit was confirmed, at least from the view point of stiffness increase. On the contrary, confirming the increase of shear resistance of the buildings directory, the main objectives of strengthening, is by no means easy from non-destructive measurement. We are planning to use Summit Hammer to examine the shear strength of concrete in seismic strengthening.

CONCLUSION

This research estimated the improvement effect of seismic strengthening of school buildings by paying attention to the change in the natural period. Two examples were studied in which retrofit was carried out with the main aim of increasing the shear resistance to the longitudinal direction. In the microtremor observation carried out before and after retrofit, a clear difference was observed in the natural period of the buildings. Based on the numerical analysis, there is 1.11 times increase in stiffness for building X, and 1.31 times for buildings Y. Microtremor observations suggested that there is 1.2 times increase in stiffness for building X, and 1.6 times for building Y. Because microtremor observation can measure the dynamic characteristics of a structure considering non-structural elements and soil-structure interaction, it is quite useful to confirm the effect of seismic strengthening of buildings.

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