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DYNAMIC BEHAVIOR CHANGE OF BUILDINGS BEFORE AND AFTER SEISMICALLY RETROFITTING

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SUMMARY

The dynamic characteristics of an existing middle-rise building are estimated by ambient vibration tests with a limited number of response sensors before and after seismic retrofitting. The analysis is done via the classical frequency domain analysis, Fourier and coherence spectra, as well as a finite element analysis. It is shown that the dynamic behavior of the building is estimated successfully and clarified to be improved by the retrofit with regard to its mode shapes as well as an increase in stiffness.

INTRODUCTION

Recently dynamic response characteristics of even complex structures can be easily estimated via dynamic analysis using a personal computer with much increase of computational capacity. The structure model for analyses, however, is usually based on initial drawings and specifications at the design stage. Therefore it is important to estimate the relationship between real structures and analysis models. Then, ambient vibration measurement is a useful tool to estimate the dynamic behavior of real structures in an elastic region, so a large number of measurements have been conducted especially for high-rise buildings to estimate the structural modes including their natural frequencies and damping coefficients [e.g. 1]. Aging characteristics of existing structures have also been estimated by many researchers especially before and after some severe earthquakes. Additionally, the dynamic properties of low- and medium-rise buildings are attracting more attention these days [e.g. 2, 3].

In this study, dynamic behavior of a building is estimated via ambient vibration tests before and after seismically retrofitted. By retrofit, not only improvement of seismic performance but also changes in dynamic behavior of structure are expected. When an ambient vibration test is conducted, it is better to increase the number of points for simultaneous vibration measurement as many as possible, so as to obtain a detailed structural behavior. For portability and economical efficiency, however, it is reasonable to estimate the structural behavior with a limited number of sensors when applied to ordinary existing buildings. The purpose of this study is to detect the change in dynamic properties including mode shapes and their natural frequencies before and after a seismic retrofit using frequency domain analyses, from a limited number of simultaneous measurement records of ambient vibration, say, less than ten.

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OUTLINE OF TARGET BUILDING AND PRELIMINARY ANALISYS

Outline of building under study

A target building of this study is a middle-rise school building located on a loamy layer, or Kanto loam, in Hongo Campus of the University of Tokyo, Japan. The location of the building is shown in Figure 0 and some photographs are shown in Figures 2 & 3. Peak ground velocity of 100 and 500 year return period are estimated 38m/s and 67m/s respectively at the site [4]. The building was constructed in 1965 and completed in 1967. It was designed before the two major revisions of Japanese seismic design code in 1971 and 1981, and therefore a seismic retrofit had been required.

It is an eight-story reinforced concrete building with two basement floors footing on footing foundation. The floor height is 3.5m (3.85m for the ground floor level). The plan of the upper floors is a slender rectangular shape of 80 meter long in longitudinal direction and 18 meter long in transverse direction as shown in Figure 3, as well as a three-story low-rise part connected to the center of the north elevation. The span between columns is 8 m and 9 m for longitudinal and transverse direction respectively. As shown in Figure 4, it has two pilotis, or an outdoor passage from south to north, at the west end (C1) on ground floor level and at the east end (C3) on basement level, respectively, which was considered a weak portion from a structural point of view and was

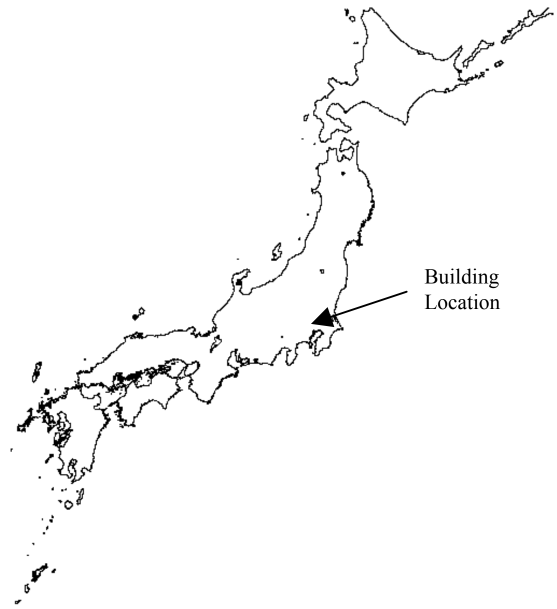


Figure 0 Location of the target building in Japan

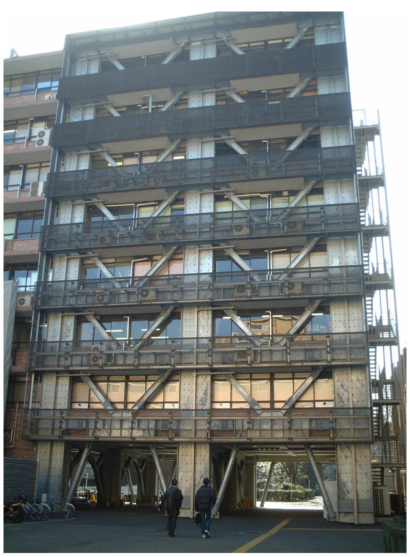


Figure 1 Piloti at east end in longitudinal direction on ground floor level after retrofit (view from north to south)

Figure 2 Dry area and flying beams on south elevation before retrofit (view from east to west)

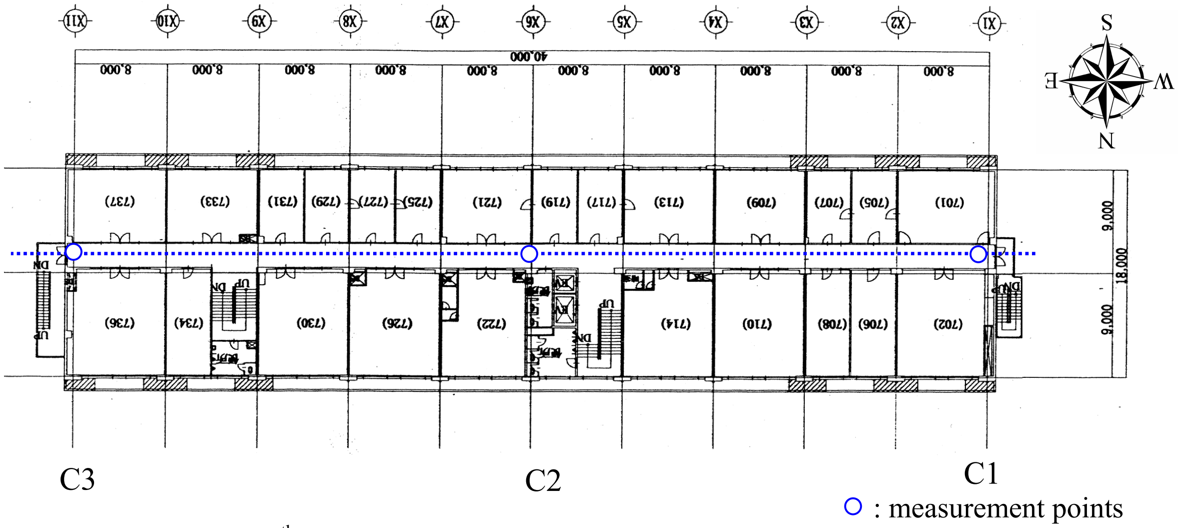


Figure 3 Plan of 7th floor and measurement points for ambient vibration test (below: north)

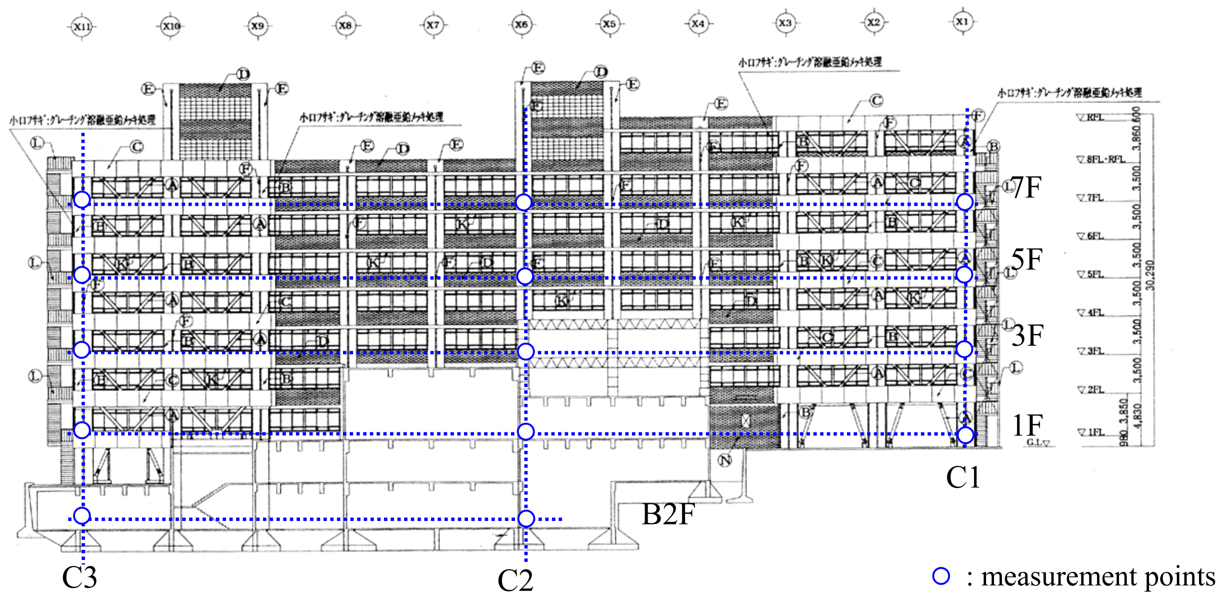


Figure 4 North elevation of the building after retrofit and measurement points for ambient vibration test

reinforced with braces as discussed later, part of which are observed in Figure 1. It has a dry area on south elevation along longitudinal direction and connected to a retaining wall with flying beams shown in Figure 2.

Additionally, it stands on the way of a moderate slope down from west to east. Considering all the aspects as pointed out above, its dynamic characteristic is considered complex, which should require densely arranged measurement points for microtremor sensors.

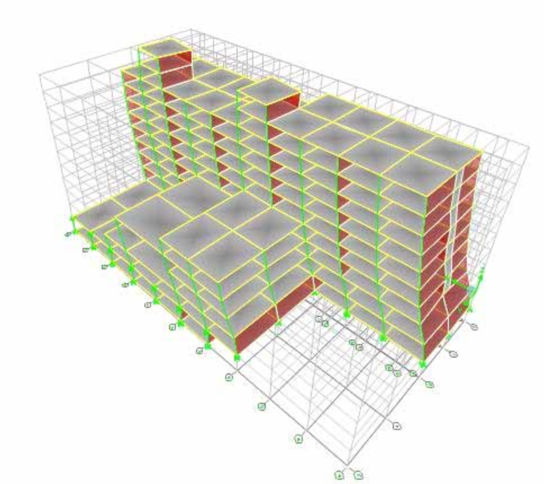
Preliminary analysis via finite element for structure before retrofitting

The building is supposed to have three dimensional vibration modes, as its structure is complex as described above. A three-dimensional finite element analysis is conducted for the structure before the retrofit, so as to have some structural information before an ambient vibration analysis. ETABS version 8.0 (Computers & Structures, Inc.) is used for the analysis. The building is extended and reinforced in 1963 and 1967 respectively, so the structural model for the finite element analysis is based on the drawings and calculation sheets both at construction, extension and past retrofitting. The following conditions are assumed in the analysis:

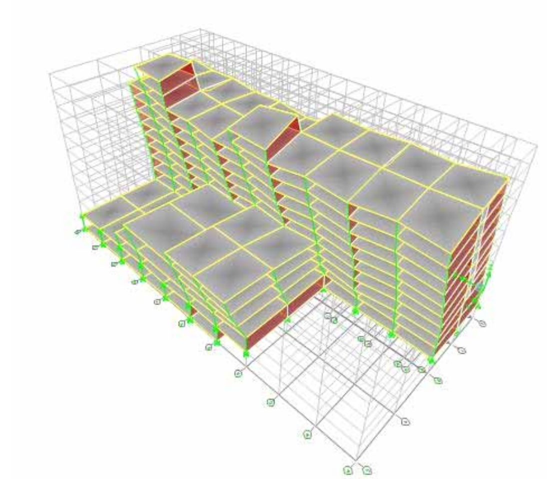
1) Effects of reinforcing bars on dynamic behavior are neglected.
2) Footing foundation is actually adopted but fixed ends are assumed in the finite element analysis.
3) Effects of nonstructural elements on the behavior are neglected for transverse direction and are taken into account for longitudinal direction.
4) Live load is assumed to be 100kgf/m^2 (0.98kN/m^2) according to the structural calculation sheets at the construction stage.

Mode shapes obtained are shown in Figure 5 up to the fourth mode, which are (a) a translational mode in longitudinal direction, (b) a translational mode in transverse direction, (c) a torsional mode and (d) a bent-up mode respectively. The natural frequencies are estimated 2.14Hz, 2.64Hz, 3.05Hz and 4.68Hz respectively.

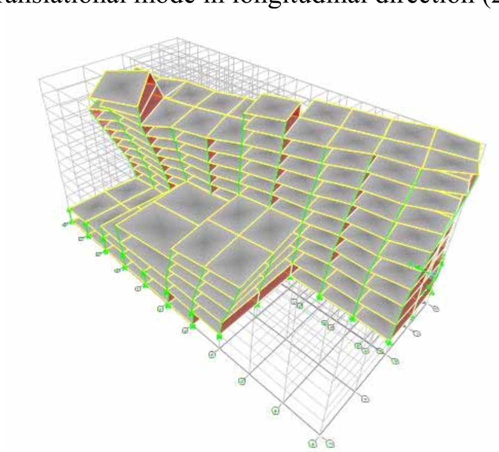
The natural frequencies of modes (a) (b) and (c) are mutually adjacent in frequency domain. The second mode of translation was obtained up to the fourth mode neither in longitudinal direction nor in transverse direction. Additionally, as shown in Figure 5 (a) (or (b)), a larger story deformation is observed near the piloti (right in the figures) and it is considered due to the lack of stiffness there.



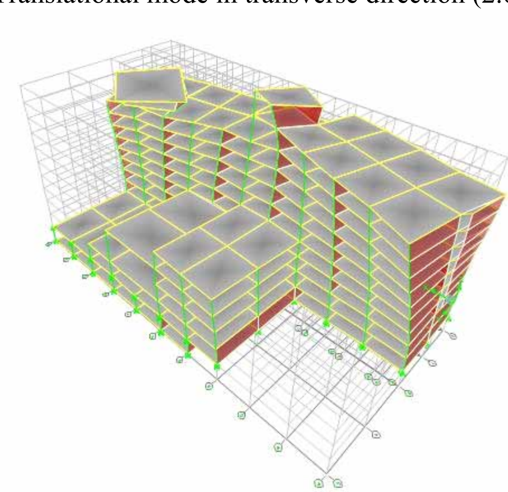
(a) Translational mode in longitudinal direction (2.1Hz)



(b) Translational mode in transverse direction (2.6Hz)

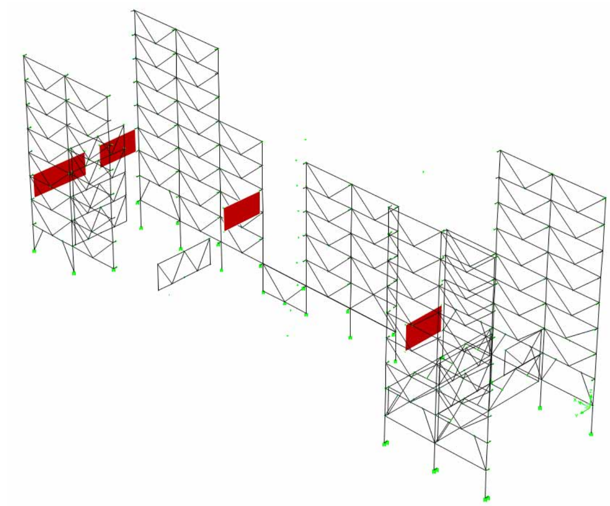


(c) Torsional mode (3.1Hz)



(d) Bent-up mode (4.7Hz)

Figure 5 Vibration modes of the target building via finite element analysis before seismic retrofit (air view from northwest)



Line: column, beam or brace   Solid rectangle: shear wall

Figure 6 Outline of the seismic retrofit (air view from northwest)

Outline of seismic retrofitting

The seismic retrofit work was conducted from 2002 to 2003. The menus of the seismic retrofit work are outlined as follows:

1) Two piloti zones were reinforced with additional steel frames and braces both in longitudinal and transverse directions.
2) Additional steel frames with braces were installed in longitudinal direction on north and south elevations.
3) Additional sheer walls were installed in transverse direction.

These menus are schematically illustrated in Figure 6. In the figure, a lot of frames are observed to have been installed in longitudinal direction, while the reinforcement in transverse direction seems to have been done with particularly emphasis on that of two pilotis.

AMBIENT VIBRATION MEASUREMENT

Outline of ambient vibration tests

Ambient vibration tests were conducted before and after the seismic retrofit. A portable ambient vibration monitoring system (Tokyo Sokushin, SPC-35) and velocity sensors (Tokyo Sokushin, VSE-15D) were used for the measurements. Frequency range of the sensor is 0.07~100Hz. Arrangement of measurement positions is shown in Figures 4 & 5. Responses were recorded simultaneously, respectively, either in a vertical line (C1~C3) or a horizontal line (B2F~7F) shown in the figures, since the number of velocity sensors was limited. Velocity responses were measured and its sampling time is 10 minutes and sampling frequency is 100Hz. Measurements were conducted in the daytime on Sunday in June 2002 and during the nighttime on Saturday in June 2003, respectively, before and after the retrofit.

For the analysis, each time series was divided into 14 records of 40.96-second duration for ensemble averaging. The results of frequency domain analysis for the 14 records, with the frequency resolution of 0.0244 Hz, were ensemble averaged to obtain sample coherence and phase spectra as well as sample Fourier spectra, transfer functions shown hereafter.

Dynamic characteristics of building

Vibration modes in transverse direction before retrofitting

In Figure 7, Fourier spectra of responses on the seventh floor (7F-C1~C3) in transverse direction before the retrofit are shown. Amplitudes of transfer functions, *or* ratio of Fourier spectra, of responses at both

longitudinal ends (7F-C1 & 7F-C3) to that in the center (7F-C2) are shown in Figure 8. These sets of time series were recorded simultaneously as noted above.
Firstly, Fourier spectra for responses both at C1 and C2, in Figure 7, have peaks at around 2.7 Hz, and spectrum for response at C3 seems to have a smaller peak at 2.7 Hz though it is almost hidden by the 'bell' shape around 3.2 Hz discussed later. Figure 8 shows transfer function of responses, 7F-C1/7F-C2 and 7F-C3/7F-C2, and 7F-C1/7F-C2 is larger than 7F-C3/7F-C2 at around 2.7 Hz. Figure 9 shows the cross-correlation between responses at both ends (C1 & C3). They are highly coherent around 2.7 Hz and phase spectrum around there is in the vicinity of zero, so they are considered to move in phase. Similarly, Figure 10 suggests that C1 and C2 move in phase as well. Therefore, this mode at 2.7 Hz is considered to be a translational mode. Amplitude of C1, however, is considered much larger than that of C3 shown in Figure 7, or a distorted translational mode, due to smaller stiffness of the piloti around C1 as discussed above. Besides, for this mode, the natural frequency obtained from the finite element analysis almost coincides with that from the ambient vibration test.
Secondly, spectra for responses at C1 and C3 have peaks at around 3.2 Hz, while that at C2 doesn't have a peak there. As shown in the transfer functions (7F-C1/7F-C2 & 7F-C3/7F-C2) in Figure 8, both of them have peaks around there. Additionally, to identify the mode, coherence analysis is conducted. It is suggested from Figure 9 that responses at both ends (C1 and C3) are highly coherent and move out of phase, while those at the west end and the center (C1 and C2) are mutually slightly coherent and seems to move out of phase as expected from Figure 10. Therefore, this mode is considered to be a torsional mode, whose center of rotation is located between C1 and C2. Finite element analysis also suggests that the natural frequency for the torsional mode is 3.1 Hz, which is quite close to this ambient vibration result.
Thirdly, all the spectra have peaks at 5.4Hz, where 7F-C1/7F-C2 and 7F-C3/7F-C2 are almost the same level in Figure 8. And also suggested in Figure 9 and Figure 10 is that both ends (C1 & C3) move in phase, while the center (C2) moves out of phase with both longitudinal ends. So it is supposed to be a bent-up mode. According to the finite element analysis, the natural frequency for a bent-up mode is 4.6 Hz, which is smaller than the ambient vibration result by 0.8 Hz.
Additionally, all the floors in height move in phase for all three modes discussed above, which is shown in the cross-correlation spectrum in Figures 12(a) and (b).
Finally, a small peak can be observed around 2.2 Hz in Figure 7, which may have a relation to a mode in longitudinal direction as discussed later. From the coherence and phase spectra in Figure 9, it is supposed that a translational mode in longitudinal direction is coupled with the torsional mode.

Vibration modes in transverse direction after retrofitting

The characteristics of dynamic behavior in transverse direction after the retrofit are discussed. All the figures from Figure 12 to Figure 16 are arranged in the similar manner as for those before the retrofit. In Figure 12, Fourier spectra of the seventh floor (7F-C1~C3) in transverse direction after the retrofit are shown.
In the Fourier spectra in Figure 12, all the spectra have peaks both at 2.8 Hz and 5.8 Hz. C1 and C3 have another peak at 3.4 Hz. At the peak at around 2.8Hz, amplitudes of response at C1 and C2 are almost the same, while that at C3 is about half of them. Compared with the similar mode before the retrofit, *or* the mode at 2.7 Hz in Figure 7, the natural frequency slightly increases. Similarly, the modes for 3.2 Hz and 5.4 Hz before the retrofit slightly increases to 3.4 Hz and 5.8 Hz respectively.
As discussed above, the mode at 2.7 Hz before the retrofit has the distorted translational mode. On the other hand, as shown in Figure 12, amplitudes of C1 and C2 are almost the same at the peaks around 2.8 Hz, while that of C3 is about half the height of them. The degree of distortion regarding translation seems to decrease due to the retrofit, though stiffness at the east part (C3) is considered slightly larger than the other two parts (C1 & C2). The translational mode before and after the retrofit are compared in detail. In Figure 17, the comparison of the mode shapes is shown. The figures are obtained using the peak values of Fourier spectra at specified frequency. The amplitudes are normalized by that at the center on the first floor (1F-C2) so as to compare the changes in the stiffness as well as that in the mode shape. From the

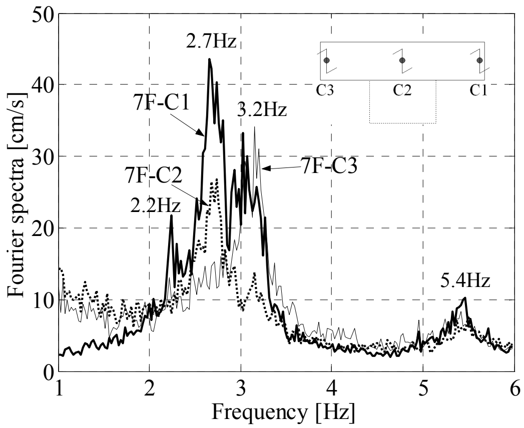


Figure 7 Fourier spectrum of responses on 7th floor in transverse direction before retrofit

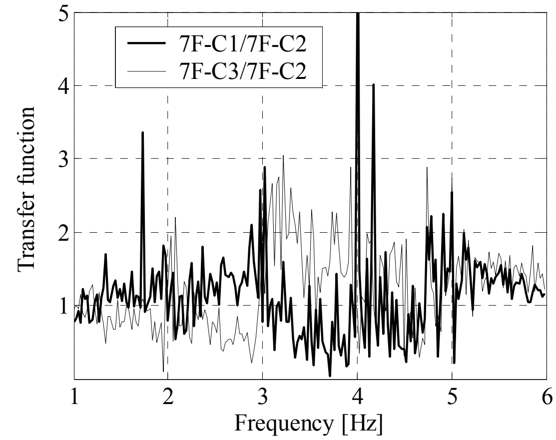
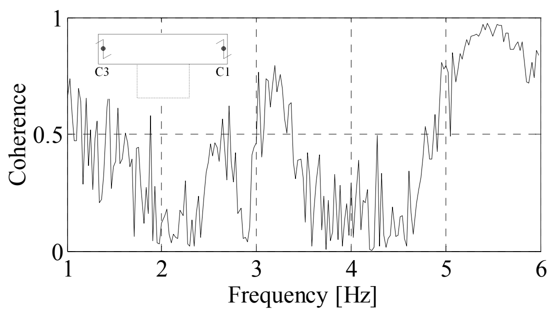
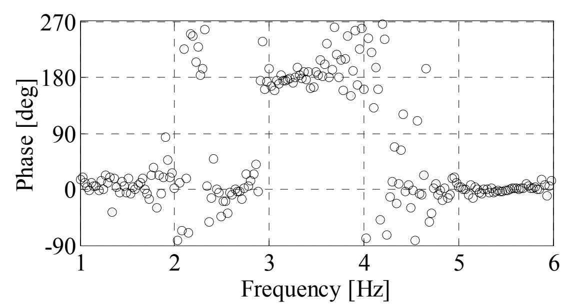


Figure 8 Transfer function of responses on 7th floor in transverse directions before retrofit

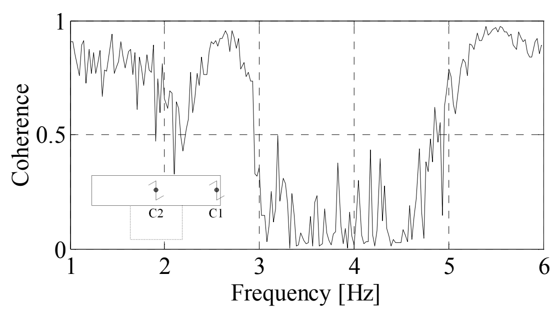


(a) Coherence spectrum

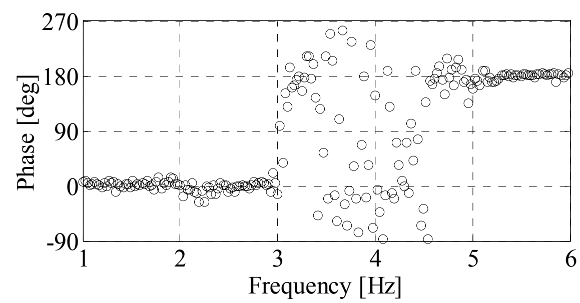


(b) Phase spectrum

Figure 9 Cross-correlation between responses at C1 and C3 on 7th floor (7F-C1 & 7F-C3) before retrofit

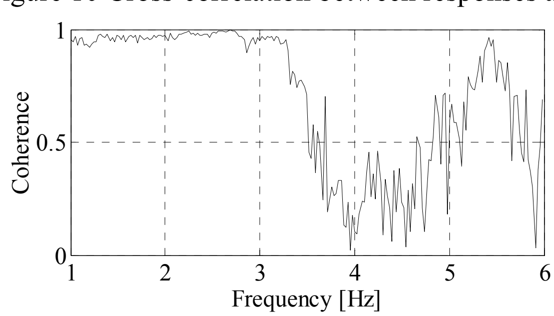


(a) Coherence spectrum

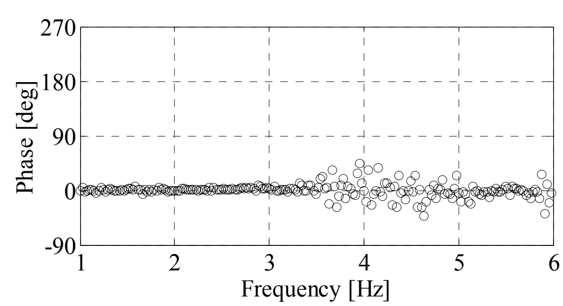


(b) Phase spectrum

Figure 10 Cross-correlation between responses at C1 and C2 on 7th floor (7F-C1 & 7F-C2) before retrofit



(a) Coherence spectrum



(c) Phase spectrum

Figure 11 Cross-correlation between responses at C1 on 7th & 3rd floors (7F-C1 &3F-C1) before retrofit

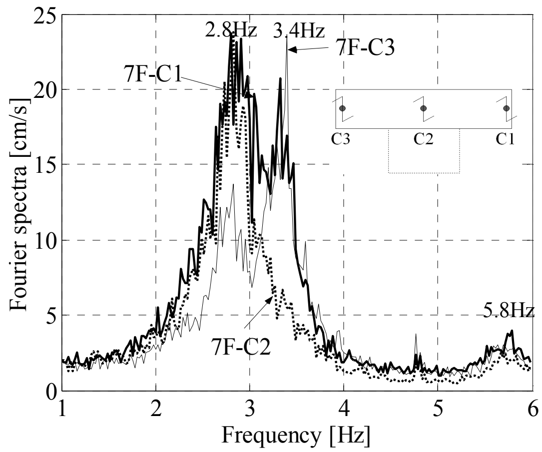


Figure 12 Fourier spectrum of responses on 7th floor in transverse direction after retrofit

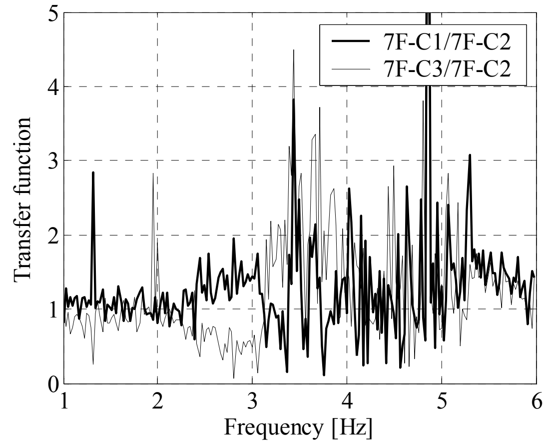
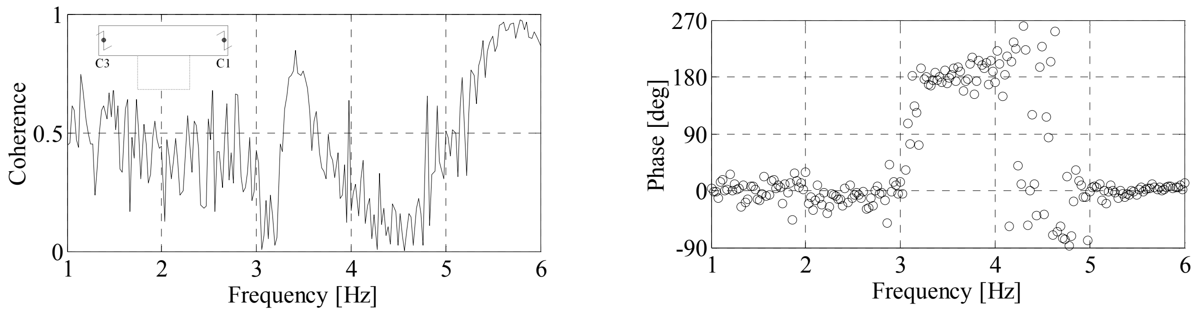
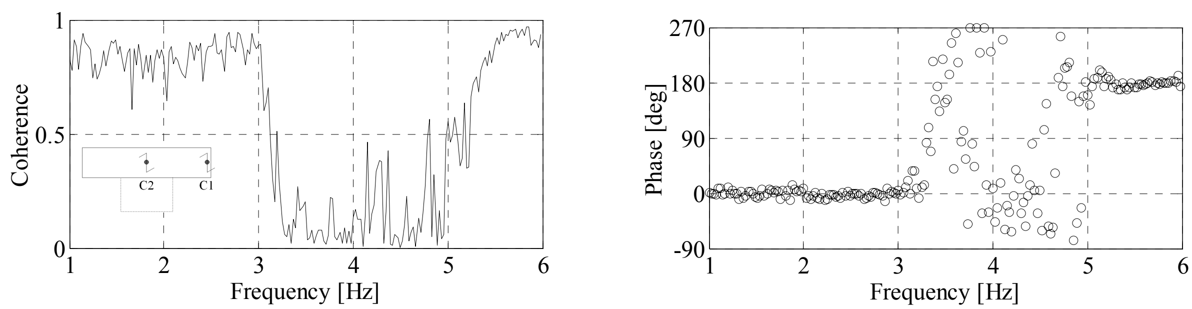


Figure 13 Transfer function of responses on 7th floor in transverse directions after retrofit



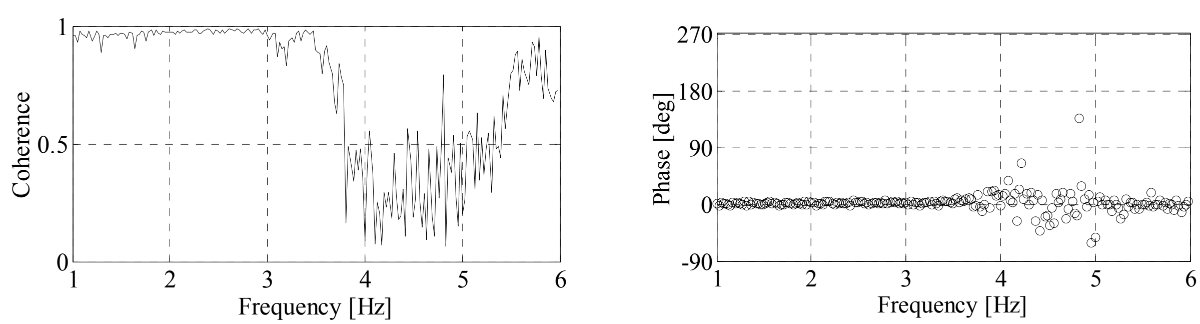
(a) Coherence spectrum (b) Phase spectrum

Figure 14 Cross-correlation between responses at C1 and C3 on 7th floor (7F-C1 & 7F-C3) after retrofit



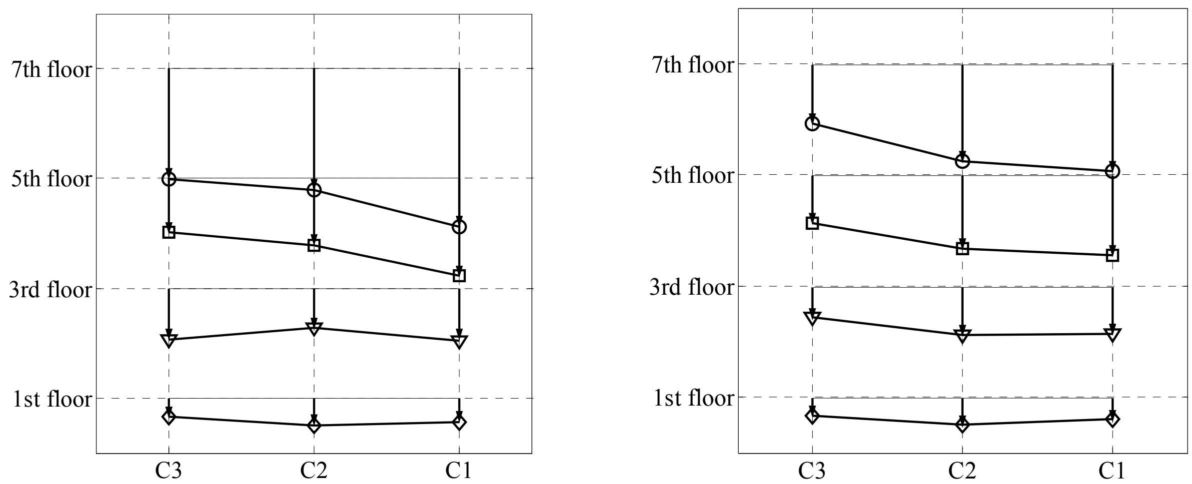
(a) Coherence spectrum (b) Phase spectrum

Figure 15 Cross-correlation between responses at C1 and C2 on 7th floor (7F-C1 & 7F-C2) after retrofit



(a) Coherence spectrum (c) Phase spectrum

Figure 16 Cross-correlation between responses of C1 on 7th & 3rd floors (7F-C1 &3F-C1) after retrofit



(a) Before seismic retrofit (c) After seismic retrofit

Figure 17 Estimated mode shape obtained from the peak of Fourier spectra for the translational mode in transverse direction (at 2.7 and 2.8 Hz before and after retrofit respectively)

Table 1 Comparison with regard to natural frequency before and after seismic retrofit for modes in transverse direction

	Before retrofit		After retrofit
	Finite element	Ambient vibaration	Ambient vibaration
Translational mode	2.6 Hz	2.7 Hz	2.8 Hz
Torsional mode	3.1 Hz	3.2 Hz	3.4 Hz
Bent-up mode	4.7 Hz	5.4 Hz	5.8 Hz

figures, it can be concluded that the stiffness in both ends increase, so that the deformations there decrease. Additionally, the degree of distortion of the translation mode decreases due to the reinforcement employed on the piloti zones in the transverse direction. It is, however, not be completely cured and it can be said that the stiffness at east end (C3) became a little larger than anticipated, compared with the other end (C1).

In Table 1, the changes in the natural frequencies of the modes are summarized for transverse direction before and after the seismic retrofit, as well as the comparison of the result of finite element analysis with the ambient vibration result before the retrofit. The result of finite element analysis is almost consistent with the ambient vibration result for the translational mode and the torsional mode, while the ambient vibration result gives larger frequency than those from the finite element analysis for the bent-up mode. The reason of this inconsistency may be considered due to either the effect of stiffness for partitioned wall and cladding or the effect of soil-structure interaction.

Vibration modes in longitudinal direction

In Figure 18, Fourier spectra for responses on the seventh floor are shown for the longitudinal direction as well. Those at three points (C1~C3) almost coincide with each other. And the natural frequency is estimated 2.2 Hz, which is almost as equal to the finite element result in Figure 5.

In Figure 19, Fourier spectra of responses after the retrofit at the same positions are shown, which suggest that the stiffness in longitudinal direction increases by about 20 percent, with the additional frames with braces installed in longitudinal direction.

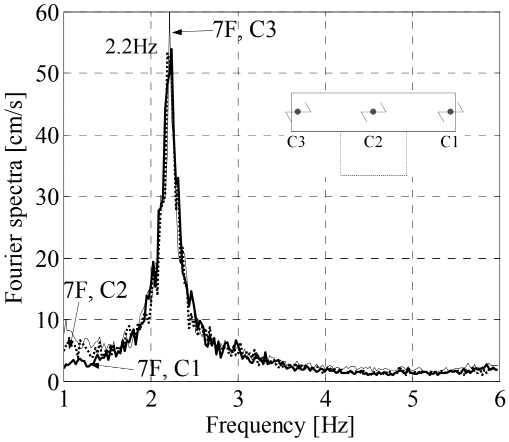


Figure 18 Fourier spectrum of responses on 7th floor in longitudinal direction before retrofit

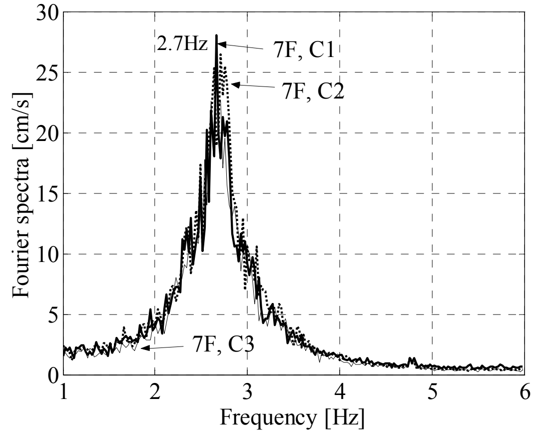


Figure 19 Fourier spectrum of responses on 7th floor in longitudinal direction after retrofit

CONCLUSIONS

The dynamic behaviors of the existing middle-rise school building were estimated before and after seismic retrofit via the frequency domain analysis, Fourier spectrum and coherence & phase spectra, as well as via the finite element analysis. The ambient vibration tests were conducted with a limited number of sensors, say less than ten and the detection of modal characteristics were demonstrated successfully. The results obtained via the ambient analysis with regard to the seismic retrofit for the building are as follows:

1) With the limited number of sensors, less than ten sensors, three dimensional mode shapes were detected to some extent from the classical frequency domain analysis.
2) The degree of distortion for the translational mode in transverse direction decreased due to the retrofit aimed to adjust irregularity, *or* the pilotis zones, though the distortion was not completely eliminated.
3) The natural frequencies of a translational mode in the longitudinal direction increased 20% after the retrofit.
4) The natural frequencies of the vibration modes from the finite element analysis coincide with that of ambient vibration test, except for the high-frequency bent-up mode.
5) It is difficult, however, to obtain more information, such as damping coefficient with the classical analysis, when the natural frequencies of two or more modes are closely located as in this case. Some system identical methodology may be required for that purpose.

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