STUDY ON TORSIONAL MOTION OF STRUCTURE

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SUMMARY

To know the behaviour of a structure at the severe earthquake, we should obtain a dynamic characteristic, natural frequency, transverse and rotational motion characteristics of it, etc. These characteristics can be obtained with more accurately for an existing building by using some methods, not only numerical analysis but also an earthquake observation, a forced vibration experiment and microtremor measurement, which is as easier one. When the earthquake strengthening in the existing building is examined, it is most important to understand the three-dimensional dynamical behaviour of the structure especially torsional motion. However, it is difficult to get good information of a building where the repair was especially piled up and of a structure with complex shape only by analyses. In this paper, the method of understanding the property of three-dimensional motion in the building clearly and accurately by using the microtremor measurement result is shown. And this report mentions an experimental example of a building before and after earthquake-proof strengthened work. And dynamic characteristics obtained from measurement result are compared with that of analytical result.

INTRODUCTION

When the necessity of the reinforcement of an existing building is attempted, it is one of very important examination items to identify the vibrational characteristics of it with high possibility to damage the building at the earthquake. When the vibration properties becomes clear, it becomes possible to make plans which structural members have to be strengthened, how to reinforce them and to where additional members must be arranged. To understand a dynamic characteristic in an existing building, it can be achieved by the frame analysis and by the waveform analysing method using waves experimentally measured in the building. The vibration measurement testing method in building, microtremor (ambient vibration) measurement methods, forced vibration testing with shaking equipment and earthquake observations. When the earthquake observation is chosen, it is necessary to have set up an expensive device, compared with other methods, for a long period of one year or more. The vibration measurement in which the microtremor is used is a method that is the easiest and is possible to do very quickly, and is comparatively high accuracy even if compared with earthquake observation. The method of accurately understanding properties of the vibration of the structure by applying microtremor measurement is examined continuously in our laboratory.

To obtain the dynamical characteristic in the building from the microtremor measurement results, the spectrum was first analysed by Fast Fourier Transform (FFT) method as a first step. We obtained amplitude information on a superior each frequency by obtaining the amplitude spectrum in the same direction of each point of measurement on the building. And the amplitude distribution maps of vertical direction and of horizontal direction of the building were obtained from the Fourier amplitude values, and these were considered to be mode shapes.

However, because almost of actual structures have three-dimensional and complex shape, it was impossible to express the character accurately in this method. Especially, when the object had the twist characteristic, it was

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difficult to find that property from the chart. Then as a next step, the sensor of 2 or 3 was measured by arranging in the same direction on flush (on the same floor), and horizontal mode shapes were made by using amplitude distribution of each peak frequencies of spectra obtained by FFT analyses. The feature, which contained the rotation element of each frequency of the floor, could be shown by this method. In addition, with three microtremor sensors, the dynamic properties with a superior twist motion could be shown, if the assumption that floor slab has had considerable rigidity was permitted. There is another method of using not only spectrum amplitude information but also phase information in this case, too. However, as mentioned above, it is not constant but each vibration mode of the building never always appears on the microtremor measurement's result. Moreover, a spectrum chart is invaded frequent by the noise, which originates in some turbulence. Phase information of Fourier spectrum shows the result it is not easy to understand. In each single spectrum, the phase information shows not same results according to the range of the selection of the wave, which should be analysed. Then, we usually use only amplitude information on the average spectrum, obtained on a lot of spectra calculate from a huge digital wave-form data, rather than adopt phase information. A Fourier spectrum is calculated with FFT for a digital wave-form data of 10-20 seconds long, after the data window such as hanninng-window is multiplied to avoid unexpected side-lobe. Therefore, this is a result with the mean (value) of Fourier amplitudes of the array of spectra calculated from record of a few minutes length, and the result of doing another processing too. In this thesis, we assumed that this mean (value) showed the ratio of the amplitude distribution of each frequency, and adopted this. Moreover, it was judged that it might be able to eliminated the influence of the noise by introducing the average spectrum, using a assumption that the reproducibility of the noise in a specific frequency was few compared with that of the signal which showed peculiar dynamic characteristics in the building. In this case, each spectrum phase information becomes not significant at all. However, when the building was not a simple plane frame, it was not enough for us that these methods showed properties of major movement, because we could not obtain any information on the direction of each movement in the building. We assumed that all movement of the whole structure at natural frequencies were kinds of rotational motion if the structure had rigid slabs on each floor even if the structure was not well shaped. And, the method we present now by showing a centre position of the rotational movement at each superior frequencies on the plane of the building makes more clear to distinguish each characteristics of motion.

2. Measurement method and analysis process

In this method, first, we select at least 3 points and put two mutually orthogonal sensors at each point, and record all waves at the same time for 3-5minutes.Next, the resultant wave-form of some directions are calculated from the measured mutually orthogonal waves. And, by using FFT, we can obtain spectra array of each direction components. Then we can get average spectra of each direction. We usually calculate a wavy element of every ten-degree and are obtaining their spectra. Because the upper bound within the range of the frequency, which should consider on structure, may be 1-10Hz, we are using sampling rate as 100Hz usually. We adopt 10 seconds or 20 seconds for analytical span of each spectrum analysis. And 1/2 or 1/4 of analysis span is selected as intervals of the analysis of each spectrum, because of the adoption of hanning-window. When the FFT analysis span is assumed to be 20 seconds, and an analytical interval is assumed to be 1/2 analysis span, 28 spectra are obtained for the recorded data for five minutes, and 17 lines for 3 minutes data. By using spectra array, we obtain total 18 average spectra of each direction elements. Contour line spectra chart is made by assembling average spectrum of all direction elements at a certain reference point after the spectrum of the element for everyone is obtained. Amplitudes of each spectrum can observe as height of mountain in the chart. Then one peak of a mountain of the contour chart may suggest the direction of the main movement for the superior frequency. This is assumed to be a direction of the movement, which can be put on the frequency in the respect. In addition, the centre of the movement is sure to exist at the position of the right angle for this direction when thinking that the amplitude is very small compared with the size in the building. Then, if the direction of movement at certain frequency of 2 reference point, at least, orthogonal lines against direction of each point are obtained. And, when the intersection can be obtained, the point means the centre of the rotational motion of a specific frequency. In addition, verifying the accuracy of this method becomes possible by examining the intersection of them for the movement axis of each excellence frequency of a lot of points. When the microtremor is measured in a building, it is better to do measuring at midnight with low noise level the activity of man in the building. However, the measurement in the state, which the building uses, is often compelled in many cases. In these cases, various noises are included in the wave. Moreover, the appearance of the vibration characteristic is not constant in the structure with a seemingly symmetrical plane plan. In many cases, it is common two or more peaks appear alternately with time at same measurement point. You can observe this phenomenon on running shape of spectrum on measurement equipment such as FFT analyser if you want. Moreover, the vibration element of the ground in the building is included in the wave of the upper part floor of the building. It is thought that this element means the input to the building. To remove this factor, the upper part floor than ground is occasionally requested the spectrum ratio between the input floors if necessary. Authors usually record an effective shape of waves for three minutes or more to avoid the influence of other noises not anticipated as much as possible.

3. EXAMPLE

Microtremor measurements in an existing building are executed, and the result of applying this method is shown as follows. The building the examination was done is a department store in the downtown of Tokyo. The scale of this building is the eighth floor on the ground, and the sixth floor in the underground. We will show a plan of 3rd floor in Fig.1. This building is near a big intersection, and one of the walls, which are very long faces, the main street. Moreover, another one short walls which also faced another street of the intersection. Two main facades were covered with pre-cast concrete curtain-wall panels. The other two sides, faced to adjacent buildings, have huge rigid shear walls. After the Great Hanshin Earthquake in 1995, a lot of commercial buildings were reviewed of seismic capacity, and the examination was also done for this building. As a result, there was no trouble. But to increase the earthquake performance further, some quake resisting concrete walls and the steel frame braces were added. At the same time, curtain-walls on the facades were exchanged entirely to lightweight new frames made of aluminium. Reinforcement was done only to all upper-ground floors and was done no change for underground floors. We measured the microtremor two times in the building, the first was before reinforcing and the second after all working had done at nighttime after all shops in this store closed. In this microtremor measurement experiments, we used 16 moving-coil type velocity sensors in an appropriate place according to the purpose. And, waveform of about five minutes in 16 places was recorded simultaneously and measured six times in total in each experiment. Some results of these experiments is shown in Fig.2 and Table 1. The measurement point is somewhat different between before and after reinforcement. We examined the distribution of the displacement of all floors, which included all underground floors in the measurement before reinforced. However, when at the second measuring, the ground floor was emphatically measured because the first measurement result shows it seems to be no problem at underground floors (Fig.3). We chiefly measured ambient vibration in any case at three stairs shafts in the building.

To obtain the ratio of amplitude among each floor in each specified frequency, we first measured at the each floor of the stairs shaft at two contrasted positions, Southwest end and Northeast end. Next, for the purpose to get a horizontal plane movement information, we put the sensor respectively in the direction of two right angles each other at three point at rooftop floor and three points of the fifth floor, and arranged the sensor of six each floor. These two results are shown in Fig.4. When the rigidity in plane on the floor is assumed to be infinity, the result of two or more sensors put on one line in the direction of the measurement is sure to become the same. This has already been confirmed from the measurement testing result of other buildings. When this is made assumption, the movement properties of not only three points but also nine points in total can be obtained with six sensors installed on the same floor. It is difficult to find the frequency element from a contour spectrum chart because the amplitude is small when the rotation centre is near the measurement point respectively. However, we come to be able to presume the point with a centre axis of the rotation by using this method by obtaining the movement properties of a virtual point that the sensor is not put. Results of this method are shown in Fig.4 and Fig.5. The number 1,2,3 in Fig.4 shows the point putting sensors and other point are virtual point have used the measurement waveform result of the other measured point.

Every distinguished frequency after reinforcement rises by about 10% compared with before one (Table 1). Especially, the direction of the movement axis of each point is almost going side by side in the lowest frequency (the first frequency). This result suggests that it is in the place where the rotation centre parts from the building very much. It is thought that transverse element of motion is superior in this frequency compared with the rotation element. The intersection obtained from each movement axis is not mutually corresponding since the secondary frequency or higher natural frequency. However, the position of each intersection does not shift so large, and the gathering tendencies are seen within the narrow range. As for the position of the rotation centre of each frequency before and after reinforcement, the change is hardly seen contrast to a change in the frequency among the results from the first natural frequency to the third one. This shows that the rotation centre moved slightly and improved, distance between frame and intersections increased in every natural frequency.

Next, to verify accuracy at the rotation centre which had been obtained by this method, we compared this result with the result of a three-dimensional frame analyses in this building. The software, which we used for the analysis, is ETABS. The value of first frequency between of analysis and of experimental result has adjusted by changing weight value of each floor of the building for the calculation, so that value of first natural frequency of the calculation result and the measurement result may almost become the same. Afterwards, the values of presumption of the rotation centre and a higher number of vibrations and the rotation centre positions of calculation models were obtained. In this case, the floor slab is assumed completely hard and then the transformation in plane is made assumption, which not is. Therefore, the intersection of each movement axis becomes one point completely. The change in the rotation centre before and after reinforcement was not admitted just like the experiment result. Fig.6 is shown results of before strengthening numerical model and Fig.7 means results of after reinforcement model.

There are the following features when those analytical results are compared with the result of obtaining from the measurement. The position of the rotation centre is different in the first mode from the experiment result, and the result in which the rotation centre is near the building is shown in an analytical result. This shows that a lot of rotation elements are included compared with the experiment result in an analytical result. Moreover, a greatly different result was shown in it the third though the second frequency of both was almost corresponding in the result from the comparison of order of frequency. However, both rotation centres of both results were corresponding to almost the same place. It seems that the difference in the frequencies of higher-order of this originates in the method of setting an analytical model like the method of evaluating the weight distribution and the material volume etc. It has been described that a lot of assumption is included in the method. We should verify these one by one in the future.

4. CONCLUSIONS

I think that the method of expressing the vibration properties by showing a centre position of the rotational motion in the building proposed here is effective, according to the above-mentioned examination results.
By using this method, It is convinced that it is possible to examine reinforcement of existing structure more easily whether and where it is necessary to arrange the added earthquake-proof element when reinforcement is examined.

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Table 1: Results of microtremor measurement and analyses of the example building

	Experimental			Analyses			
Natural frequency	Before reinforcement	Strengthened	(ratio)	Before reinforcement	Strengthened	(ratio)	(ratio)
	A (Hz)	B (Hz)	C (A/B)	D (Hz)	E (Hz)	F (D/A)	G (E/D)
1st	1.42	1.61	1.13	1.44	1.57	1.01	1.09
2nd	2.00	2.25	1.13	1.88	2.04	0.94	1.09
3rd	2.54	2.73	1.07	3.81	3.89	1.50	1.02

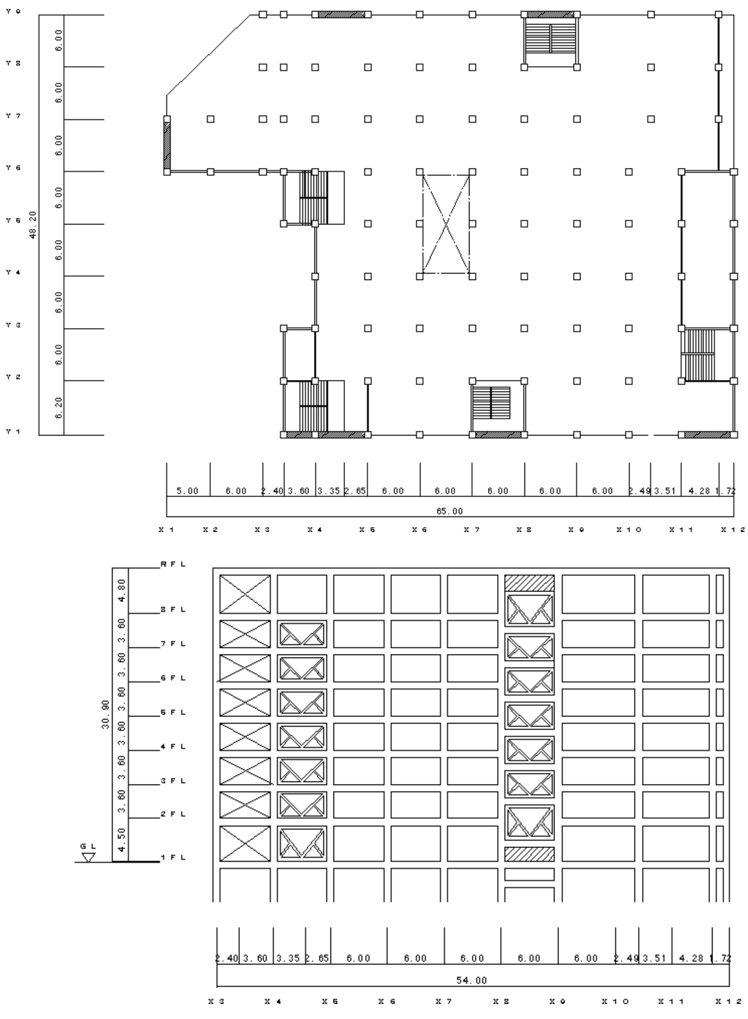

Figure 1: Typical Plan and west side frame(2 span were strengthened) of department store building

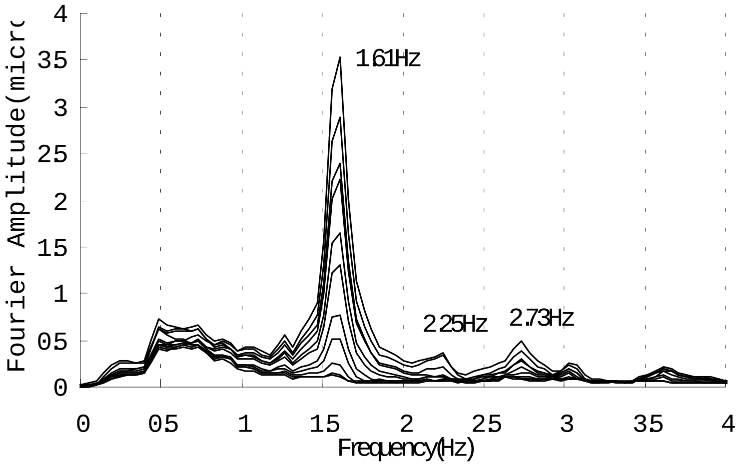

Figure 2: Typical Fourier average spectra on each floor level of the example building (South-east EW direction ,After strengthening)

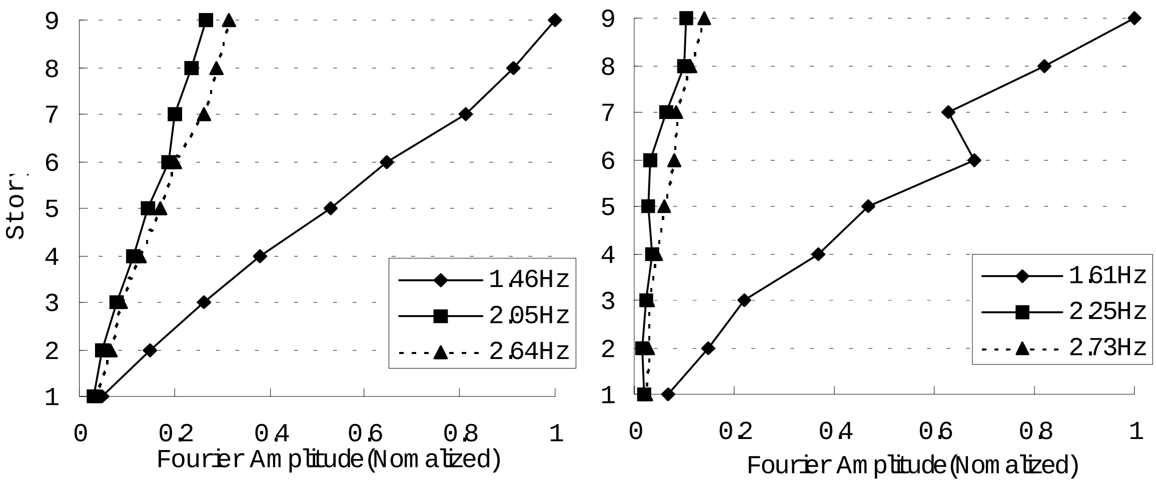

Figure 3: Vertical amplitude distribution of natural frequency; before and after strengthening

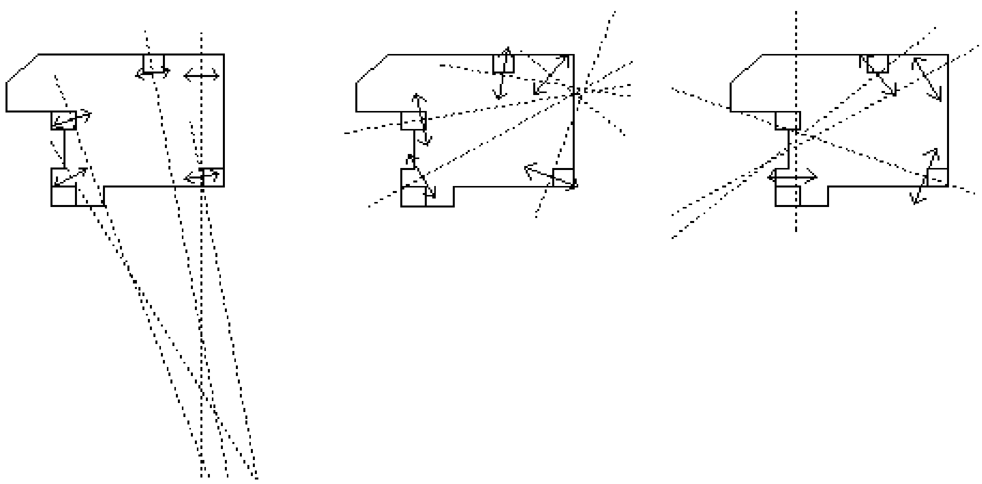

Figure 4: Motion on reference point of each natural frequency at the top floor (before strengthening, measured)

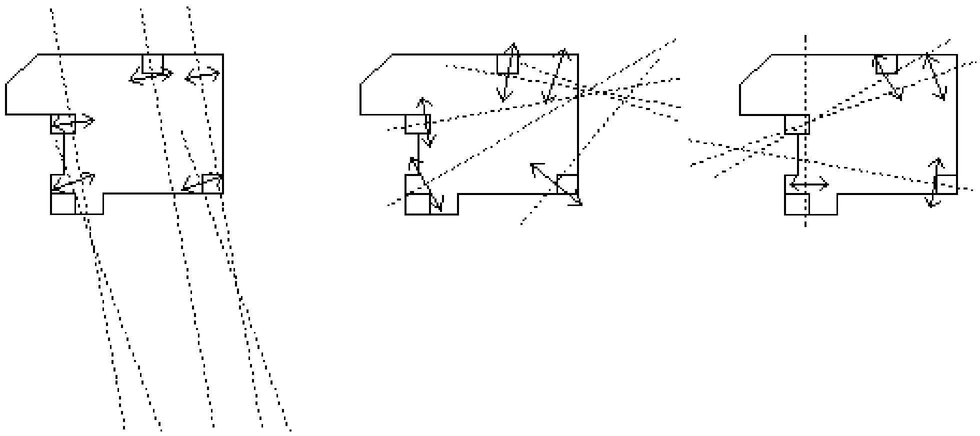

Figure 5: Motion on reference point of each natural frequency at the top floor (after strengthening, measured)

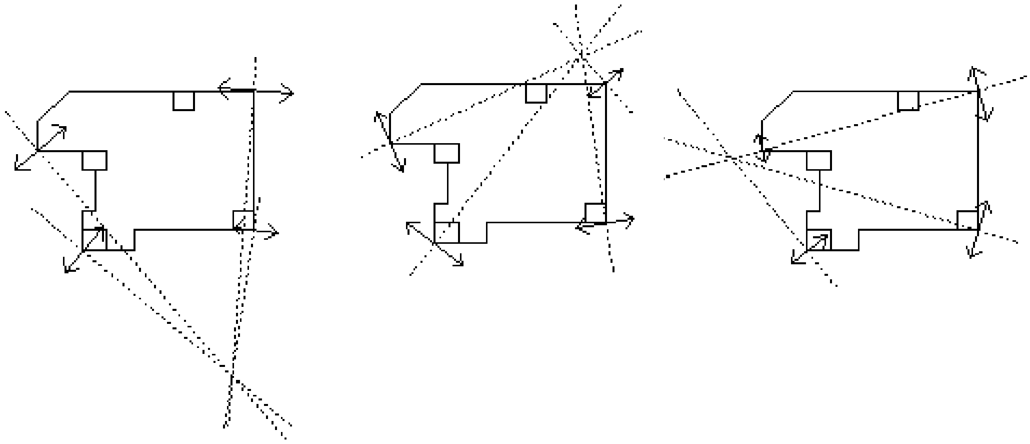

Figure 6: Motion on reference point of each natural frequency at the top floor (before strengthening, analysed)

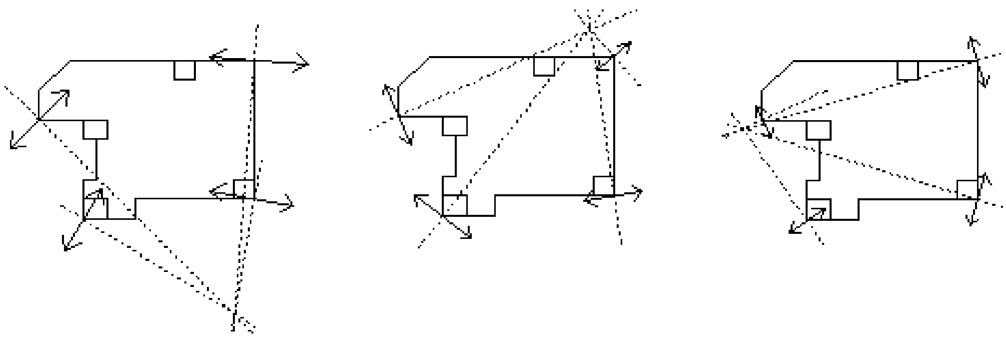

Figure 7: Motion on reference point of each natural frequency at the top floor (after strengthening, measured)