Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Torsional vibration and in-plane floor vibration of a long-in-plan building

K.Ohami & M.Murakami
Chiba University, Japan

H.Nemoto
Kajima Corporation, Japan

ABSTRACT: In long-in-plan buildings, the torsional-vibration mode arises even if little eccentricity in the transverse direction, and the in-plane floor vibration mode also does during earthquakes. The purpose of this paper is to investigate the effects of these two vibrational modes and the causes of the torsional-vibration mode, based on the long-term earthquake observations of an existing building. Results are as follows. In some earthquake records, each of these two vibrational modes accounts for more than 40% of the peak acceleration of the records observed at the ends of the top floor. The main causes of the torsional vibration are the torsional input motion due to its long foundation slab and/or the torsional coupling due to the eccentricity in the longitudinal direction which seems to be usually overlooked in considering the dynamic characteristics of this type of buildings.

1 INTRODUCTION

In long-in-plan buildings, the torsional-vibration mode arises even if little eccentricity in the transverse direction during earthquakes. The in-plane floor vibration mode such as arch-shaped floor vibration mode also arises during earthquakes. However these observational data are not enough at present.

The causes of the torsional vibration are thought as follows: in this type of buildings, input motion to the long-footing slab has a possibility to contain the torsional component, which is a cause of the torsional vibration. The torsional coupling due to the eccentricity in both directions is also a cause of the torsional vibration. It arises surely when the eccentricity in the transverse direction is large. However, even if the eccentricity is small, it is well-known that the strong torsional coupling also arises when the natural frequencies of the translational mode and the torsional mode approach closely each other. In this type of this buildings, the eccentricity in the transverse direction is small in general, since sufficient attention is usually paid on the eccentricity to prevent the torsional vibration in the structural planning. On the other hand the eccentricity in the longitudinal direction results often from necessity of architectural planning and/or from insufficiency of attention on the eccentricity in the structural planning, but it is also small as a necessity from the configuration of the floor plan.

The cause of the in-plane floor vibration is thought that the in-plane bending stiffness of floor slabs in this type of buildings are small.

The authors have carried out a long-term earthquake observations in an existing building and its surrounding subsoil since 1970 (Murakami et al. 1973, Ohami et al. 1980, 1984). This building is a typical one in this type of buildings, which has the floor plan of about 11 in terms of aspect ratio. It has small eccentricity in the longitudinal direction but little eccentricity in the transverse direction.

The main purposes of this observations are firstly to know the dynamic behavior of this building and its surrounding subsoil during earthquakes, secondly to establish an appropriate analytical model for soil-structure system and finally to check the structural soundness of this building under sever earthquakes.

As a part of these purposes, this paper investigates the following items by using the observed records:

1. the degree of effects of the torsional vibration and the in-plane-floor vibration on the earthquake responses.
2. the verification of 3 causes of the torsional vibration and the degree of effects of each cause of the torsional vibration.

2 BUILDING AND EARTHQUAKE OBSERVATIONS

2.1 Building

The building for investigations is an existing 11-story apartment house supported by piles as

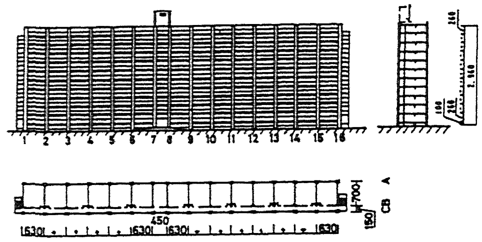

Fig.1 Outline of building

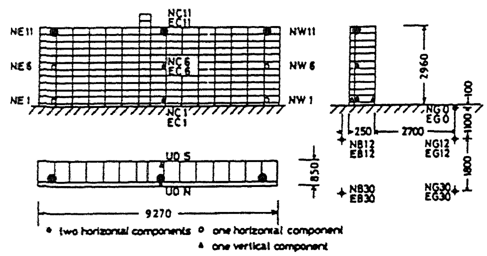

Fig.2 Location of accelerometers

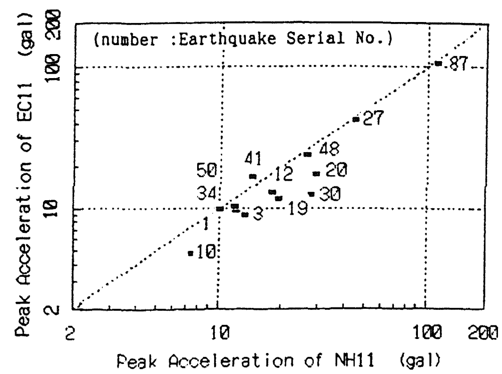

Fig.3 Peak accelerations at the 11th floor

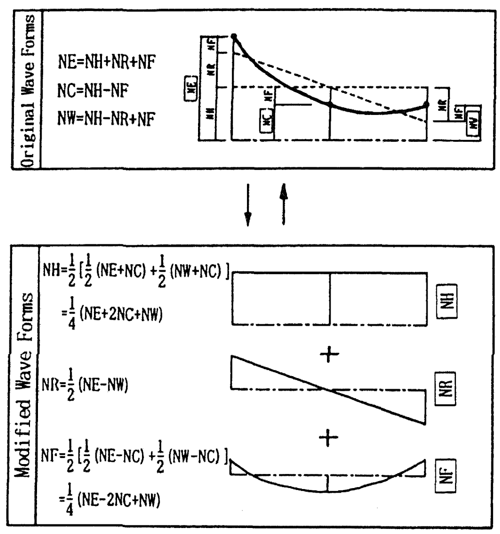

Fig.4 Definition of 3 modified wave forms

shown in Fig.1. This building is a typical one in this type of buildings, since the floor plan is 8.5m x 92.7m and its aspect ratio is about 11. The building has little eccentricity in the transverse direction but small eccentricity in the longitudinal direction, which result from the location of walls as shown in Fig.1. This fact is confirmed by the results of the natural mode of floor slabs in the forced vibration tests.

2.2 Earthquake observations

Fig.2 shows locations and directions of the accelerometers. The components in the transverse direction are observed at 3 points of the center (NC11) and both ends (NE11 and NW11) in the 11th floor. The component (EC11) in the longitudinal direction is observed at the center in the 11th floor. 4 components (NC1, NE1, NW1 and EC1) are observed also at the same points in the 1st floor. 13 sets of earthquake records are investigated in this paper. The ordinance in Fig.3 shows the peak accelerations observed in the longitudinal direction of the 11th floor. The numbers in this figure denote the serial number of earthquakes.

3 OBSERVATIONAL STUDIES ON EFFECTS ON RESPONSES

3.1 Methods

3 modified wave forms (NH11, NR11 and NF11) are produced from 3 original wave forms (NE11, NC11 and NW11) according to the definition shown in Fig.4. These modified wave forms are the translational, the torsional and the arch-shaped components, respectively, of the original wave forms (NE11 and NW11) at the ends of the 11th floor.

The first objective to investigate the effects of the torsional vibration and the arch-shaped vibration on the earthquake responses is carried out by comparing 6 modified and original wave forms one another.

3.2 Results

To investigate the average effects during each earthquake, Fig.5 shows the relation among the peak values of Fourier amplitude spectra of 3 modified wave forms (NH11, NR11 and NF11) in terms of the ratios of NR11 and NF11 to NH11. The ratios (the ordinate) of NR11 to NH11 are 0.2-0.9 and the ratios (the abscissa) of NF11

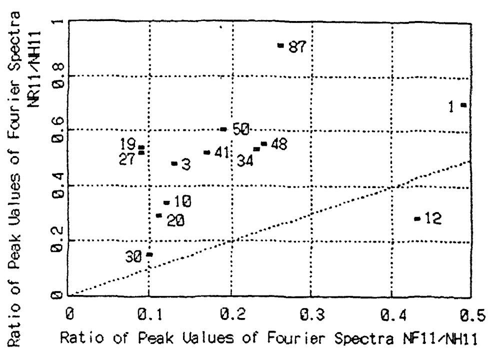

Fig.5 Ratios of peak values of Fourier *amplitude spectra NR11/NH11 and NF11/NH11*

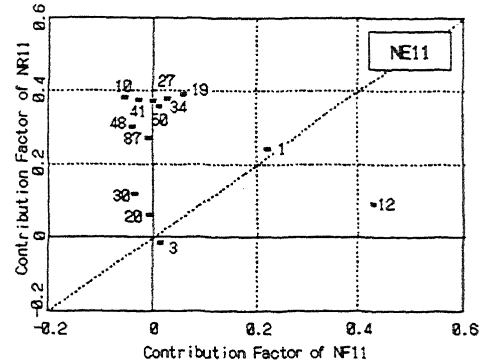

Fig.6 Contribution factors to the peak acceleration NE11

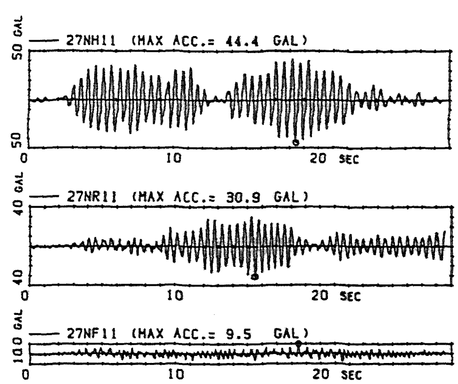

Fig.7 Acceleration waves of NH11, NR11 and *NF11*

to NH11 are 0.1-0.5. To investigate the effects at the time when the peak acceleration of the original wave forms (NE11) arises, Fig.6 shows the contribution factors of NR11 and NF11 to the peak accelerations of NE11. Although the result of NW11 is not shown, the contribution factor of NR11 to NE11 and NW11 is -0.2-0.5 and those of NF11 is -0.1-0.4. The negative sign means that NR11 and NF11 act to reduce the peak acceleration of NE11 or NW11. *Fig.7 shows 3 modified wave forms of the* earthquake records (No.27) in which the large effect of the torsional vibration appears and shows that the contribution factor of NR11 varies with the passage of time.

The followings are pointed out from all the results. The degree of effects of the torsional vibration and the arch-shaped vibration on earthquake responses varies not only with earthquake records but also with the passage of time during each earthquake. In some earthquake records, the torsional vibration and the arch-shaped vibration account for about 50%, 40%, respectively, of the peak acceleration of the original wave forms (NE11 and NW11) at the ends of the 11th floor.

4 OBSERVATIONAL STUDIES ON CAUSES OF TORSIONAL VIBRATIONS

4.1 Methods

The causes of the torsional vibration are thought to be the following ones:

1. the torsional input motion
2. the torsional coupling between the translational mode and the torsional mode due to the eccentricity in the longitudinal direction (abbreviated to "the longitudinal coupling")
3. the torsional coupling between the translational mode and the torsional mode due to the eccentricity in the transverse direction (abbreviated to "the transverse coupling")

The second objective to investigate the causes of the torsional vibration is carried out by evaluating the contribution factor of each of 3 causes to the torsional vibration.

The coherence between NR1 and NR11 is calculated to investigate the contribution of the torsional input motion. NR1 is not the real torsional input motion, because it contains in part the component of the torsional response due to the dynamic soil-structure interaction, but it is assumed to be the torsional input motion, because the sway ratio of the 11th floor in the transverse direction is small (about 0.1) according to the results of the forced vibration tests.

The longitudinal coupling is investigated firstly by the degree of approach of the natural frequency of the longitudinal translational mode to that of the torsional mode. These natural frequencies are determined conveniently by the predominant frequencies which are estimated by the Fourier spectra of EC11 and NR11. The longitudinal coupling is investigated secondly by the contribution factor of EC11 to NR11 which is evaluated by the coherence between these wave forms. When the torsional vibration is generated by the strong longitudinal coupling, NR11 contains large amount of the component of the longitu-

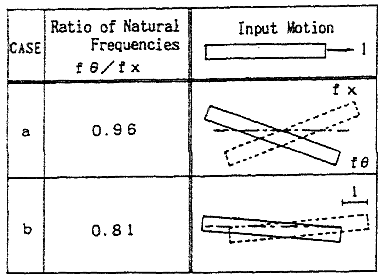

Fig.8 An example of participation functions (a single story analytical model)

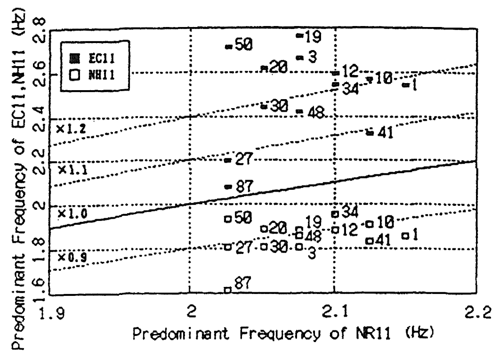

Fig.9 Predominant frequencies of NH11, NR11 and EC11

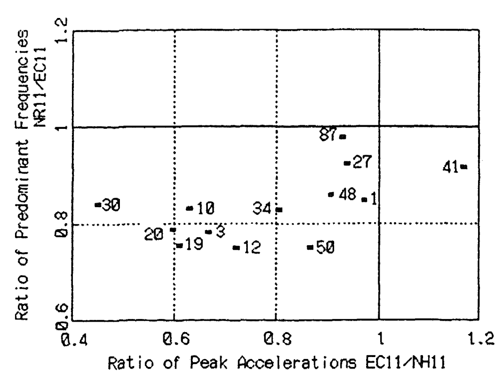

Fig.10 Ratios of predominant frequencies and ratios of peak accelerations

dinal translational mode which is also contained surely in EC11. The stronger longitudinal coupling, the larger coherence between EC11 and NR11.

The transverse coupling is also investigated in the same manner.

4.2 Features of the long-in-plan building

The basis of the method for the investigation of the longitudinal and transverse couplings are explained as follows, as an example of the longitudinal coupling.

Since the eccentricity in the longitudinal direction can not become large and the radius of gyration is large, the eccentricity factor defined in terms of the ratio of these two values is generally small in this type of buildings. Even though the eccentricity factor is small, the strong torsional coupling appears when the natural frequencies of the longitudinal translation mode and the torsional mode approach closely each other. For example, the CASE-a in Fig.8 shows the participation functions in a case where the analytical model is a single story with small eccentricity in the longitudinal direction and is subjected to excitation of the longitudinal input motion.

Although the CASE-b in Fig.8 has the same eccentricity factor as the CASE-a, the torsional coupling scarcely appears because these two natural frequencies become distant each other. The natural frequency of a building is supposed to change due to nonlinearity of stiffness which depends on the response amplitude levels during earthquakes. Therefore, if the rates of stiffness reductions in both directions are different from each other, the difference between these two natural frequencies changes.

4.3 Results and discussions

The results concerning earthquake records in which the large torsional vibration appears are discussed in the following.

Fig.9 shows the predominant frequencies of EC11 and NH11 in the ordinate and the predominant frequency of NR11 in the abscissa. The predominant frequencies of NH11 are smaller than those of NR11. The difference between them in the transverse direction is generally smaller than that in the longitudinal direction and is almost constant regardless of earthquake records.

On the other hand, the predominant frequencies of EC11 are larger than those of NR11. In comparison with the differences in the transverse direction, the difference in the longitudinal direction varies largely with earthquake records. The earthquake records of the small difference between EC11 and NR11 are No.87, No.27, No.41, No.48, No.1 and so on. In these earthquake records, the amplitude level in the longitudinal direction approaches more closely to that in the transverse direction than in the other earthquake records as shown in Fig.3. The relation between the ratio of EC11 to NH11 in the peak accelerations is shown in the abscissa and the ratio of NR11 to EC11 in the predominant frequencies is shown in the ordinate of Fig.10. As the amplitude level of EC11 approaches to that of NH11, the predominant frequency of EC11 approaches to that of NR11. This fact confirms the supposition for change of natural frequencies in 4.2.

The coherence concerning the transverse

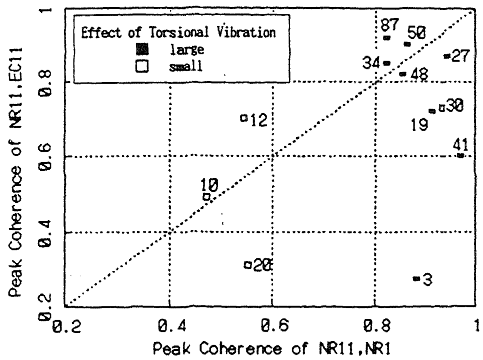

Fig.11 Peak values of coherence

coupling, not shown in the figure, are very smaller than that concerning the other two causes, although in the transverse direction the degree of approach of these two predominant frequencies is large as mentioned above.

Fig.11 shows the peak coherence concerning the torsional input motion and the peak coherence concerning the longitudinal coupling. The peak coherence concerning the torsional input motion is very large in all earthquake records. In comparison with them, the peak coherence concerning the longitudinal coupling varies largely with earthquake records. Fig.12 shows that in almost earthquake records (No.87, No.27, No.48 and No.34) of the small difference between the predominant frequencies of EC11 and NR11, the peak coherence concerning the longitudinal coupling are large. The torsional coupling do not appear, however, in the earthquake records (No.41) although the building has the dynamic characteristics of the strong torsional coupling, that is, the small difference between the predominant frequencies EC11 and NR11. The reason is that the longitudinal input motion has little component of the natural frequencies of the longitudinal translational mode and the torsional mode.

The followings are pointed out from all the results. In such earthquakes that the large torsional vibration arises, the torsional input motion is one of main causes of torsional vibration. In some of these earthquakes, the longitudinal coupling is another main cause. On the other hand, the effect of the transverse coupling is very small. The reason why the longitudinal coupling becomes one of main cause is not because of large amount of eccentricity but because of small difference between the natural frequencies of the longitudinal translational mode and the torsional mode. The degree of the torsional coupling varies with earthquake records and the passage of time during each earthquake, because the difference between these two natural frequencies varies due to nonlinearity of stiffness depending on large response amplitude level.

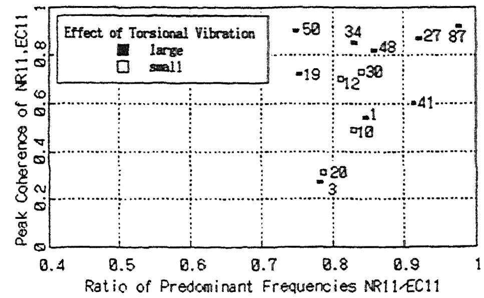

Fig.12 Ratios of predominant frequencies and peak coherence

5 ANALYTICAL STUDIES ON CAUSES OF TORSIONAL VIBRATIONS

5.1 Methods

The second objective to investigate the causes of the torsional vibration is carried out quantitatively through earthquake response analyses. The analytical model consists of the superstructural one having 11 rigid floor slabs with eccentricities in both directions and the substructural one having rocking but no sway at the basement. Stiffness is assumed linear on the response analyses.

3 responses (NR11(E), NR11(H) and NR11(R)) corresponding to NR11 to each excitation of EC1, NH1 and NR1, respectively, are calculated, where NR11(E) and NR11(H) are the torsional vibration caused by the longitudinal coupling and the transverse coupling, respectively, and NR11(R) is the torsional vibration caused by the torsional input motion. Each effect of 3 causes on the torsional vibration is evaluated by comparing the amplitude levels of these 3 responses one another. Before these earthquake response analyses, the stiffness and damping of the model are determined by the response to simultaneous excitation of EC1, NH1 and NR1 so that the response wave forms of EC11, NH11 and NR11 is consistent with the observed ones in a range of the large response amplitude level. 3 earthquake records (No.19, No.27 and No.87) are investigated.

5.2 Results

Fig.13 shows the relation among the peak acceleration values of the 3 responses to each excitation. These results support the results of the observational study in 4.3 as follows. In such earthquake records that the large torsional vibration arises, the torsional input motion is one of the main causes of the torsional vibration. In some (No.27 and No.87) of these earthquake records, the longitudinal coupling is another main cause. The effect of the transverse coupling is very small and is not a main cause in all earthquake records.

In earthquake records (No.27 and No.87)

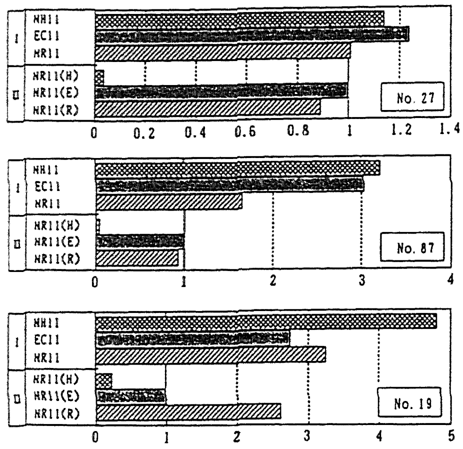

Fig.13 Ratio of peak accelerations under simultaneous (I) and each (II) excitations

which have two causes of the torsional input motion and the longitudinal coupling, both of these effects (NR11(R) and NR11(E)) are almost the same degree as shown in Fig.13. However there is the large difference between these two earthquake records as for the ratio of the peak accelerations of NR11 to NR11(E) and NR11(R). By comparing NR11(R) and NR11(E) in Fig.14, it is confirmed that this ratio is large in the earthquake (No.87) in which the amplitude levels of these two wave become large at close time.

6 CONCLUSIONS

In some earthquake records, each of the torsional vibration and the arch-shaped vibration accounts for more than 40% of the peak acceleration of the observed records at the ends of the 11th floor. Therefore both of these two vibrations have large influence on seismic capacity of this building. They are also supposed to have influence on seismic capacities of machines and equipments if settled, because this building has more various and higher natural frequencies than the ordinary buildings do.

The causes of such large torsional vibration are the torsional input motion and/or the torsional coupling in the longitudinal direction. It is explained by considering the strong torsional coupling due to the close approach of the natural frequencies of the longitudinal translational mode and the torsional mode, why the torsional coupling in the longitudinal direction becomes large and is one of main causes of the torsional vibration in spite of the small eccentricity in the longitudinal direction. Moreover it is attributable to the feature of nonlinearity of stiffness in long-in-plan buildings that the

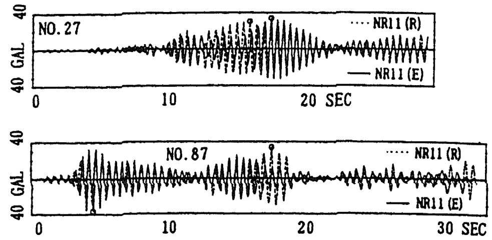

Fig.14 Torsional responses NR11(E) and NR11(R)

degree of the approach of these two natural frequencies changes relatively large.

With respect to the torsional coupling in both directions in this type of buildings, following three cautions should be paid:

1. The effect of the torsional coupling in the longitudinal direction has a possibility to become large in the large response amplitude level, even if it is small in the small response amplitude level.
2. The torsional coupling in the longitudinal direction seems to be usually overlooked as a cause of the torsional vibration in this type of buildings, in comparison with the other two causes. Because the eccentricity in the longitudinal direction is generally small and the torsional vibration has little influence on the response in this direction of a long-in-plan.
3. The torsional coupling in the transverse direction do not become a main cause when buildings have little eccentricity in this direction as well as the building investigated in this paper. However if there is relatively large eccentricity in the transverse direction, the torsional coupling is supposed to become a main cause in this direction where the natural frequencies of the transverse translational mode and the torsional mode approach closely each other in general in this type of buildings.

REFERENCES

Murakami M., Tamura R., Tanaka Y., Ohami K., Osawa Y. and Umemura H. 1973. Earthquake resistance of a steel frame apartment house with precast concrete panel. Proc. of the 5th World Conference of Earthquake Engineering, Vol.2, Rome:2688-2697.

Ohami K. and Murakami M. 1980. Earthquake observation in and around a steel frame apartment house with precast concrete panel. Proc. of the 7th World Conference of Earthquake Engineering, Vol.4, Istanbul:561-568.

Ohami K. and Murakami M. 1984. Observational Studies on Dynamic Characteristics of Existing Soil-Structure System. Proc. of the 8th World Conference of Earthquake Engineering, Vol.3, San Francisco:793-800.