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Rodrigo Flores Álvarez
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VIBRATIONAL BEHAVIOURS OF VERY TALL BUILDINGS WHEN THEY ARE SUBJECTED TO LARGE EARTHQUAKE MOTIONS, STUDIED BY QUESTIONNAIRE SURVEY METHOD

SYUN'ITIRO OMOTE*

1. INTRODUCTION

Since the establishment of the International Association for Earthquake Engineering (IAEE) (see for example 1,2) in 1963, research activity in the field of earthquake engineering has made a wonderful jump up in development in a global scale. Such a wonderful development in the field earthquake engineering owes much in the rapidly increased international exchange of scientific and technological knowledge and experiences in this field and the beautiful friendship brought about among the persons who extended good contribution for the establishment of the new Association.

In spite of the wonderful achievement in the science and technology for mitigating the earthquake disasters, large earthquakes are taking place one after another on the earth and fairly large damage is seen taking place on every occasion.

Withing these recent few years, there took place 1989 Loma Prieta earthquake (3) in San Francisco area of USA., the Spitak earthquake in

*Dr. Sci. Former Acting Director at the International Institute of Seismology and Earthquake Engineering, Tokyo, Building Research Institute (1962-1971). Former President of the Kyushu Sangyo University (1977-1983).

Armenia, USSR, and the 1985 Michoacan, Mexico earthquake, which brought about large earthquake destructions to the capital city of Mexico. Examining the earthquake damage of these earthquakes and referring to other recent earthquake damage, it is noticed that there are existing two different types of earthquake damage. One is so to say an old type damage and the other is the new type damage. The latter is caused by the new development of the urban facilities or the enlarged and complicated urban system itself. In the case of the future large earthquakes, it is duly expected that the latter damage will be actualized more and more clearly.

From this point of view, in this paper, it is discussed the problem of the vibrational behaviour of tall buildings especially that appears in their higher floors, when they are shaken by large earthquake motions, because by our study (4) it has become clear that unexpectedly large earthquake damage will stand out quite in large scale as a new type of earthquake damage, provided pertinent countermeasures could not have been taken in advance.

The 1978 Off-Miyagi Prefecture Earthquake (Miyagi-Ken-Oki E) (5) (M 7.4), Japan, brought about considerable but not devastating damage to Sendai City. This earthquake, however, attracted grave concern among us because the damage to Sendai City was taken to represent a miniature of the new type urban seismic destruction of future large earthquakes. One of the most noteworthy damage was seen in the upper stories of tall buildings. Fairly large uneasiness and confusion were brought about among people who were staying in these upper stories, and another example was seen in the damage of computer machines installed in the 11th floor of the 12-story Prefectural Government Building lost their function because of the breakage of the machine caused by the collision of the machine frameworks slided on the floor. Both cases were just before panic status might takes place. Excited by this event, we made a study to make clear the vibrational behaviour of tall buildings during the time they were shaken by large earthquake motions.

2. Intensity distribution by floor determined from questionnaire responses

2.1. *On the effectiveness of the questionnaire method to investigate the vibrational behaviour of tall buildings subjected to large earthquake motions*

There are seen only a few data to be available for analysing the vibrational behaviour of tall or very tall buildings at the time they are shaken by large earthquake motions. Up to here it was used in the text the expressions that tall buildings and very tall buildings without definition. The reader is cordially asked to understand that the tall buildings in this paper means the buildings of about 14-15 stories, and the very tall buildings are high-rise buildings of which floor numbers are 30 to 60. It is only recently that some of the tall and very tall buildings newly constructed became to be equipped with strong motion seismographs at several different stories. But only a few strong motion records have been obtained as yet in the case of some of the recent large earthquakes (6). Unfortunately, however, these data are not only very few in number, but also the recorded accelerations are usually too small to be used for the analysis of the vibrational behaviour of these tall buildings.

The only means left to obtain useful data for analysing the vibration behaviour of tall buildings is to carry out questionnaire survey to the people who were in these tall buildings so that the useful data for the computer analysis on the vibrational behaviours of these buildings could be drawn out from the experiences they felt in the building at the time of the earthquake.

2.2. *Employed questionnaires in our survey*

In practicing the questionnaire survey, we used basically the same questionnaire originally explored by (7). This questionnaire is composed by 36 question items. Details of the version of each item can be seen in the reference (8). On the occasion of the 1985, Mexico earthquake, Kazuaki Masaki of the Aichi Institute of Technology, Japan, in cooperation with Dr. Javier Lermo S. of the Mexico University, made a thorough investigation on the damage distribution in the Mexico City, by the aid of the questionnaire survey method, in which case they used the same questionnaire sheet originally explored by Ohta, but written in the Spanish language. The Spanish version of the question item and selection answers will appear in the paper of (9) elsewhere in the near future. In our case, however, we made a slight change on the original questionnaire to remove such questions as: 1) construction type of the building, 2) structure of the ground, 3) age of the building, and instead new question items were added such as, to give the actual floor number on which the person experienced the earthquake, and the position of the person at the time of the earthquake (walking, standing, sitting on a chair or on the floor). The total number of items to be analysed by a computer was unchanged.

2.3. *Construction of the questionnaire used in our survey*

Here, it seems necessary to give the basic outline of the construction of our questionnaire. Our questionnaire is provided 36 question items in one sheet of paper, and each question item is prepared four or five answers to be selected by the person who experienced the earthquake, to express one's own feeling at the time of the earthquake. In practice, the following procedure was taken: 1) Firstly, the questionnaire sheet is handed over to the people who were in the tall building at the time of the earthquake, asking to give one check to the prepared answers with regard to each respective question item, in accordance with their experience at the time of the earthquake. 2) Secondly, then a few days later the distributed questionnaires are collected by floor of each surveyed tall buildings. Careful examination is made to the collected answer sheet whether the entry to the questionnaire is made correctly or not. After this examination the effective answer sheets are established, 3) Thirdly, the data-base of the questionnaire is worked out basing upon the collected effective answer sheets with regard to each question items. Using the data-base and assisted by Ohta's program (10) the seismic intensity is computed by computer machine for each question item, then averaging the intensities calculated from all 36 items, the seismic intensity of that questionnaire sheet is determined. Namely, one sheet of questionnaire gives one seismic intensity at that location at the time of an earthquake.

The arithmetical mean value of the intensities calculated from the effective answer sheets collected from the same floor of the tall building, is taken as the intensity of that floor at the time of the earthquake. In this way, we obtained the intensity distribution by floor for many tall and high-rise buildings in cases of several earthquakes.

The seismic intensity here used represents the seismic intensity by means of the Japan Meteorological Agency (JMA) seismic intensity scale. Therefore, for the convenience sake of the readers outside Japan, in the figure, the JMA scale and Modified Mercalli (MM) scale is shown side by side and in the text MM intensity is shown in a parenthesis, for example (such and such by MM).

3. TALL AND VERY TALL BUILDINGS INVESTIGATED BY QUESTIONNAIRE METHOD AND EARTHQUAKES ON WHICH CASE THE SURVEY WAS CARRIED OUT

Aiming at to make clear the intensity distribution along height of tall buildings, our research using the questionnaire method started on the occasion of the 1978 Off-Miyagi-Prefecture (Miyagi-Ken-Oki) earthquake (11). In this case, and in the cases of several other earthquakes that followed, the questionnaire survey was carried out with many different types of tall buildings. But in the present paper we would like to report the result of our investigation carried out with two types of tall buildings which gave clear characteristics on the vibrational behaviour of tall buildings. One is the 14-story seven apartment buildings located in the Kawaramachi housing estate in Kawasaki City, that adjacent to Tokyo to the south, and the other is the seven high-rise buildings in Tokyo. These are shown in Table 1.

Each building of the 14-story apartment is built to the same basic plan: a type of twin corridor. In particular, buildings 4, 6 and 8 have the same plan and structure; a typical inverse Y shape. The exception is building Nº 2 which is composed of three twin corridor buildings, 14-story and 9-story, then 14-story, connected by expansion joints. Details of the elements of these structures are given in Table 2-a (12). The main elements of the high-rise buildings investigated are shown in Table 2b (13,14).

4. Intensity distribution by floor of investigated buildings

4.1. *The 14-story buildings*

Each dwelling unit of these 14-story apartment buildings is 2DK or 3DK (NDF: number of rooms plus a dining-kitchen [DK] and the make up of each family unit usually is very simple; parents and a few children. Two questionnaires were given to each unit on the assumption that more than two persons were prsent who could inform us about their earthquake experiences. We distributed twenty to thirty questionnaires per floor for the cases of three eartquakes, the MKO-E, IZU-E and KYB-E.

The collection rate for our questionnaire was fairly high, but the MKO-E and IZU-E occurred in the evening, some housewives were in the supermarket or on nearby roads rather than at home. Therefore, although the collection rate was high, the number of useful answers were fewer than expected, there being only 2-3 pertinent answers given for some floors. In 1983 the KYB-E took place. The magnitude of this earthquake was M = 6.0, but Kawasaki City was located not far from its epicenter, the seismic intensity in Kawasaki was 4 on the IMA scale. To make a comparison with the other two surveys done at the 14-story apartment buildings, we again conducted a questionnaire survey, but only with four buildings; 1, 2, 13 and 15, because responses from these buildings gave fairly good results for the 1978 and 1980 earthquakes.

TABLE 1

EARTHQUAKES AS WELL AS 14-STORY BUILDINGS AND HIGH-RISE BUILDINGS WITH WHICH THE QUESTIONNAIRE SURVEYS WERE CARRIED OUT

Earthquake	Abbreviation	M	Epicentral distance	Intensity in Tokyo	Bdg. Nº of 14-Story Buildings	Name of High-rise Buildings*
Miyagi-ken-Oki 1978-6-12	MKO-E	7.4	360^{km}	4	1, 2, 4, 6, 8, 13, 14	SM1, SSU, YKK, KDD, KMS
Izuhanto-Toho-Oki 1980-6-29	IZU-E	6.7	85	4	1, 2, 4, 6, 8, 13, 14	—
Kanagawa-Yamanshi Border 1983-8-8	KYB-E	6.0	70	4	1, 2, 13	SS6, SSU, SMI, YKK, NSB, KMS
Nagano Ken Seibu 1984-9-14	NKS-E	6.8	200	3	—	SM1, SSU, NSB, YKK

*Abbreviations should be referred to Table 2-b

TABLE 2A

CHARACTERISTIC OF 14-STORY APARTMENT BUILDINGS AT THE KAWARAMACHI-DANCHI, A HOUSING ESTATE

Bdg. N° of 14-story buildings	Dwelling families	Type of dwelling unit	Height of building	Height with pent-house	Total floor area
1	408	3DK	40.0^m	46.6^m	26.650$^{m^2}$
2	550	3DK	40.0	47.1	34.300
4	280	3DK	41.0	50.0	17.000
6	252	3DK	41.0	50.0	15.400
8	280	3DK	41.6	51.0	17.000
13	253	3DK	43.2	51.0	24.000
14	264	3DK	43.2	51.0	24.000

TABLE 2B

NUMBER OF STORIES AND THE PERIOD OF THE PROPER OSCILLATION OF 1st ORDER MODE OF HIGH-RISE BUILDINGS WITH WHICH THE QUESTIONNAIRE SURVEY WAS CARRIED OUT

Name of building	Abbrevia-tion*	Number of stories		Proper oscillation period 1st order mode Sec.
		Above ground	Under ground	
Sunshine 60	SS6	60	3	X 5.94 Y 4.59
Shinjuku Mitsui	SMI	55	3	X 5.08 Y 5.18
Shinjuku Sumitomo	SSU	52	4	X 5.07 Y 5.07
YasudaKasai Kaijo	YKI	43	6	X 4.78 Y 4.51
Kokusai Den-den	KDD	32	3	X 4.31 Y 4.39
NS Bldg.	NSB	30	3	X 2.46 Y 2.00
Kasumigaseki	KMS	35	3	X 5.14 Y 5.04

X: shorter side.
Y: longer side.

In the case of the MKO-E, 2,500 questionnaires were distributed and 1,106 sheets returned, in the case of the IZU-E, 7,314 questionnaires were distributed and 5,282 came back, and in the KYB-E, three thousand questionnaires were distributed and 1,502 returned. Availing these answered sheets, a data base was worked out as was explained in Sections 2.3. From this data base, by use of the computer program of (7) the seismic intensity for each answer sheet is worked out. The intensity of the answer sheet that belongs to the same one floor i collected. The arithmetical mean value of the intensity that belongs to the same one floor is taken as the seismic intensity of that floor. This procedure was repeated for each floor of all buildings in the cases of three earthquakes. Results are shown in Figs. 1a, b, c. In the figures, though the result of only three buildings is reproduced, the other buildings also showed quite the similar intensity increase pattern (15, 16). We notice, however, that by the difference in the exciting earthquakes the intensity increasing pattern with height of floors shows a fairly different pattern.

4-2. *The high-rise buildings*

At the time of our first survey to the high-rise buildings (the MKO-E) (11), the distribution of the questionnaire could be carried out only through the permission of the Security Management Office of each high-rise building. In this case 20 sheets of questionnaires were distributed to each floor, expecting the collection rate of the returned answer will exceed 50%. In the case of following two earthquakes, the KYB-E (17) and NKS-E (18), we could obtain the cooperation of the Tokyo Fire Department, the distribution of the questionnaire was greatly assited. In these cases, referring to the experience we learned from the MKO-E, at least 30 sheets were distributed at each floor by which we could obtain a larger number of returned sheets than the case of the MKO-E.

With regard to these returned answer sheets, careful examination was carried out so that such answer sheet as made miss entry or as answered by the people who was not in the high-rise building at the time of the earthquake could be eliminated for the further computer calculation. In this way, in the case of the KYB-E, 6,000 sheets of questionnaires were distributed to 6 high-rise buildings and returned effective answers were 4,130 sheets (46%), and in the case of the NKS-E, 5,340 sheets were distributed and 1,929 effective answers were obtained.

Using these effective answer sheets and following the analysis procedure availing the same computer program explained in the above Section (4.1.), the intensity of every floor of the high-rise buildings were determi-

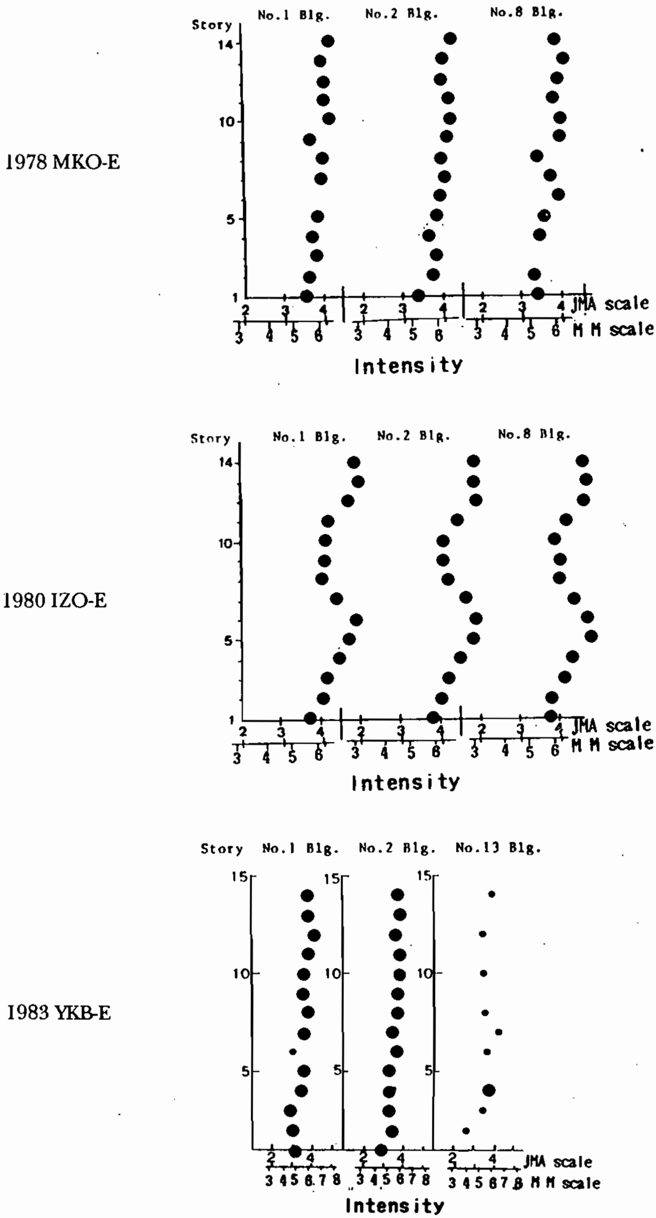


Fig. 1. Intensity distribution at each floor of Kawaramachi-danchi buildings 1,2 and 8,13, obtained from responses to the questionnaire survey for three different earthquakes.

ned. The result is reproduced in Figs. 2-a, b, c, with regard to each earthquake. In the figure a large black circle represents the intensity that was determined from more than 20 sheets of effective answers, a white large circle, the effective answers were 10-19 sheets, and a small white

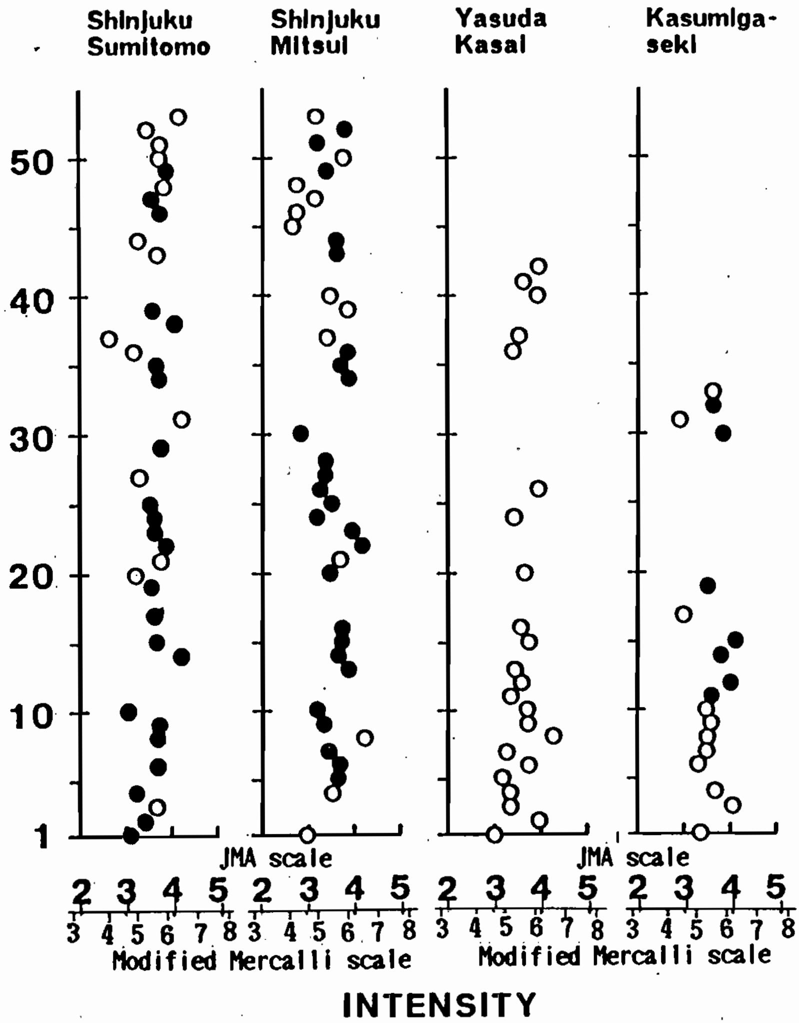


Fig. 2a. Intensity distributions by floor of high-rise buildings in the case of the MKO-E.

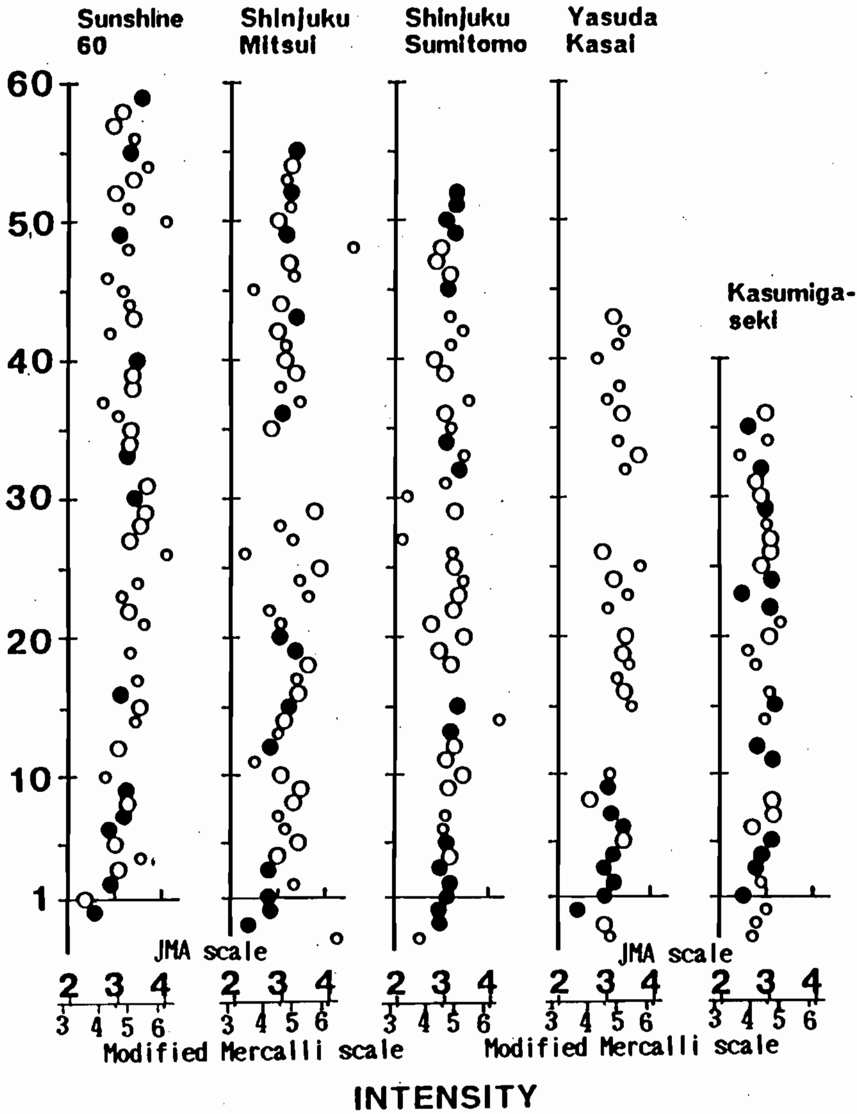


Fig. 2b. Intensity distributions by floor of high-rise buildings in the case of the KYB-E.

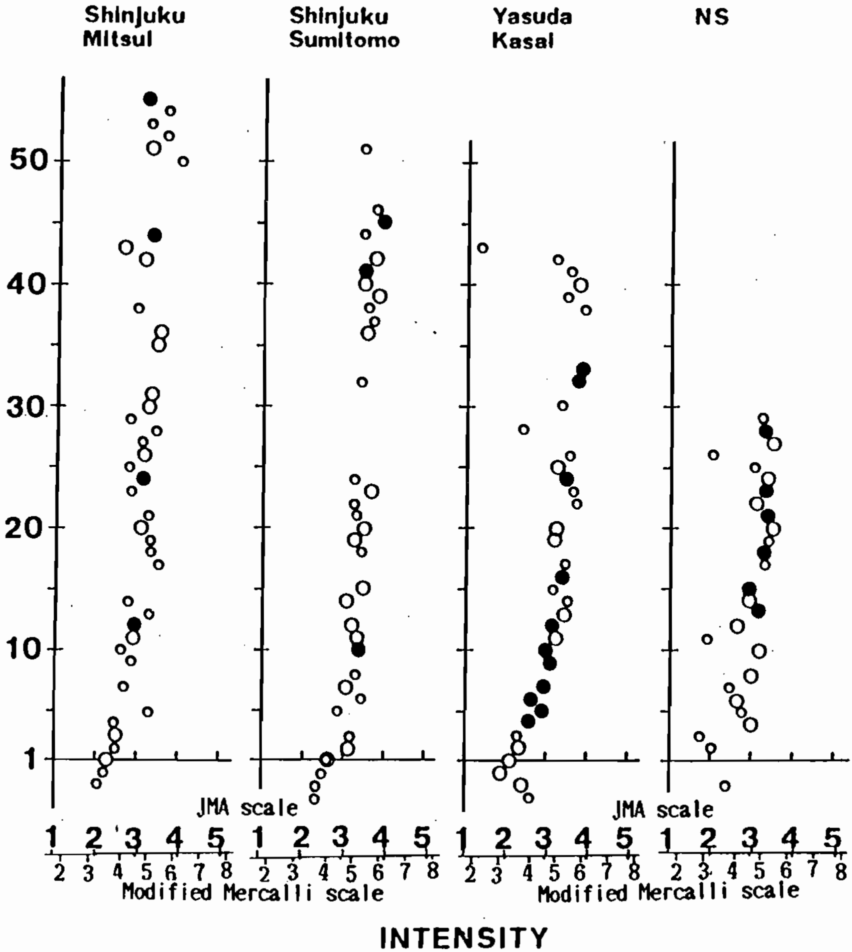


Fig. 2c. Intensity distributions by floor of high-rise buildings i the case of the NKS-E.

circle, effective answers were less than 9 sheets. The accuracy of the determined value of intensity naturally decreases with the decrease of the number of the sheets of effective answers. Especially, when the number of data sheets is less than a few sheets the determined intensity value shows sometimes deviates extremely. A few small white circles in Fig. 2b are showing a large deviation from the general trend of intensity distribution along height. Such a small white circle represents the intensity that was determined from extremely small number of answer sheets.

In the case of the MKO-E (Fig. 2a), a black circle represents the intensity determined more than 5 sheets, and white circle is less than 4 sheets, as in this case the distributed number of questionnaire sheets was much less than the cases of two other earthquakes.

5. THE CHARACTERISTIC NATURE ON THE INTENSITY DISTRIBUTION PATTERN ALONG HEIGHT OF TALL BUILDINGS WHEN THEY ARE SUBJECTED TO EARTHQUAKE MOTIONS

5.1. *14-story apartment building (19)*

i) Difference in the intensity value at the ground and top floors

As will be seen in Figs. 1a, b, c, the intensity increase with height of floors of the 14-story buildings shows quite a beautiful curve for all buildings for the cases of all earthquakes. From these pictures it can be considered that the intensity value determined by our questionnaire survey is giving fairly a reliable floor intensity of 14-story buildings when they are vibrated by large earthquake motions.

From this standpoint it can be pointed out some noteworthy evidences in these pictures. In this Section it is discussed the problem of the intensity difference between the ground and top floors. In the beginning the intensity of the ground floor determined by questionnaire responses will be considered. In the case of the MKO-E the intensity values obtained at the ground floor of the 14-story buildings were seen either 3.4 or 3.5 for all 14-story buildings which indicated that the questionnaire-derived intensity is highly accurate. In the case of the IZU-E, the mean ground floor intensity of 14-story buildings gave the value of 3.8, a value markedly larger than that of the MKO-E. Fluctuations of the respective intensity value from the mean value were very small, again proof that the observed intensity value derived from 10 or more questionnaires was greatly reliable. The questionnaire survey for the KYB-E was carried out with only 4 buildings at Kawasaki site (among 4 buildings one was a 12-story building). The ground floor intensity was rated at 3.0 showing only small fluctuations.

As to the second step, coming back to Figs. 1-a, b, c, again, the top floor intensity will be considered. From these figures, it can be clearly read out that the top floor intensity of every 14-story building is giving nearly the same value, but somewhat larger value than that of the ground floor, with regard to respective earthquake, though for the different earthquakes, of course, the top floor intensity is different respectively. In this way the ground and top floors intensity was determined so it is easy to show in Table 3 the difference in intensity value for the ground and top floors. Results are tabulated for all 14-story buildings at the time of three earthquakes.

Results in Table 3 show that:

1) when 14-story apartment buildings were subjected to large earthquake motion, the difference in intensity between the ground and top floors was exactly 1.0 grade on the JMA seismic intensity scale (about 1.5 grade by MM scale).
2) results were the same for all three earthquakes.
3) for 9-story buildings at the Kawaramachi-danchi (not discussed here), the difference in intensity between the ground and top floors is about 0.8, a value smaller than 1.0.

Although we made the general conclusion that there was an intensity difference of just 1.0 grade on the JMA scale between the ground and top floors of 14-story buildings, the actual ground surface intensities at the site for the three earthquakes were 3.3, 3.8 and 3.9 Strictly speaking, it must be noted that the above conclusion is valid only for an earthquake with an intensity of about 3.5. or so at ground surface.

ii) The specific character of the increase in intensity with floor height

The second topic we notice in Figs. 1a, b, c, is that when the same building is shaken by different earthquakes, very differently shaped curves appear

TABLE 3

DIFFERENCES IN INTENSITY VALUE BETWEEN THE GROUND AND THE TOP FLOORS OF ALL THE 14-STORY KAWARAMACHI BUILDINGS DURING THE THREE EARTHQUAKES

MKO-E	Blg.	Nº 1 0.9	Nº 2 1.0	Nº 8 1.0	Nº 14 0.95	Nº 15 1.0
IZU-E	Blg.	Nº 1 1.0	Nº 2 1.0	Nº 4 1.0	Nº 6 1.0	Nº 8 0.9
YKB-E	Blg.	Nº 1 1.0	Nº 2 1.0	Nº 13 1.1		

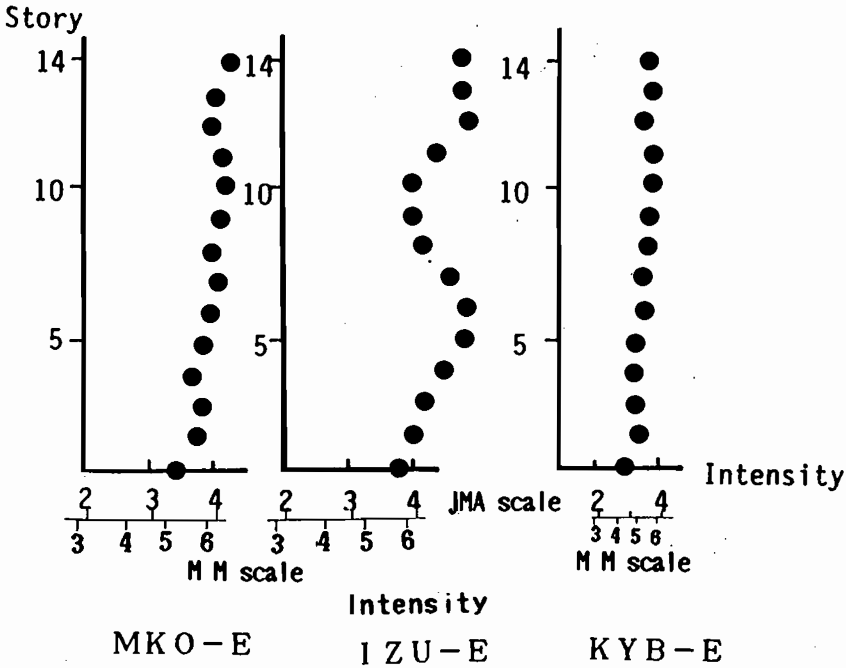


Fig. 3. The intensity distribution pattern by floor of the building N° 2 when it is shaken by different three earthquakes.

for the intensity increase patterns with floor height. As a typical example it is reproduced in Fig. 3 the intensity increase pattern of the building N° 2 when the building is excited by three different earthquakes. From this figure it is learned that in some cases the intensity distribution curve of a tall building may take a strange shape (centre, Fig. 3). Another example of a peculiar looking damage distribution curve along height of floors in a tall building is reproduced in Fig. 4. We notice at once that the damage percentage distribution curve in Fig. 4 shows quite a like form with the centre curve in Fig. 3. At the time of the 1985 Mexican earthquake, as one of the activities of international cooperation on the emergency reconstruction program for the earthquake destruction, the Damage Investigation Team form the Building Research Institute, the Ministry of Construction, Japan (20) made a detailed and thorough damage investigation of the 12-story building, Chapultepec 120, in Mexico City, and were able to work out the damage percentage with respect to each floor of this building. The definition of the damage percentage is given in refe-

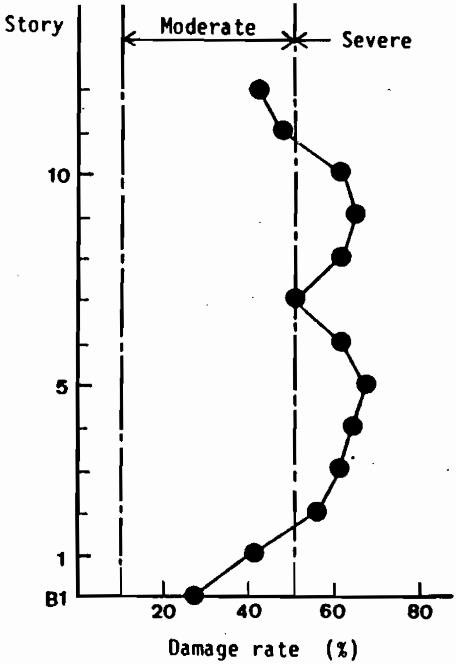


Fig. 4. Damage percentage for each floor of the Chapultepec 120 Building caused by the 1985 Mexico earthquake (Afeter Hirasishi *et al.* 1986).

rence (20). The shape of the curve showing the damage percentage is similar to that for the intensity distribution curves of building N° 2 for the IZU-E. In considering the measures to be taken for earthquake damage mitigation in tall buildings, the above phenomenon must be given careful attention.

Aiming at to give a theoretical explanation on the above evidence, we carried out the vibration analysis of these 14-story buildings (21) when they are excited by different earthquake motions that are having different frequency characteristics. The analytical calculation were carried out using as much available data as possible, and supported by reasonably allowable assumptions. Somewhat more detailed explanations on this procedure will appear in the next Section. As the result of this analysis, it was made clear that by the effect of the predominantly included higher frequency wave component in the earthquake motions of the IZU-E, such specific intensity distribution pattern as we see in the centre picture in Fig. 3 has come out.

5.2. *High-rise buildings (22).*

i) Difference in the intensity value at the ground and top floors in case of high-rise buildings

With regard to Figs. 2a, b, c, it can be pointed out two characteristic common nature on the pattern of intensity distribution along height of floors of all high-rise buildings. One is the pattern of intensity increase with height and the other is the scatter of intensity value with height. As to the former event, it can be seen in Figs. 2a, b, c, as a general tendency the intensity at the higher floor is larger than that of the ground floor but slightly. Observing somewhat more in detail, with every high-rise building we can say that from underground floor up to 5^{th} floor or so the intensity is incrasing with floor height monotonously, while after 5^{th} floor up to the top floor there are seen almost no change in the intensity value, though there are seen some ruggedness along height. As to the latter event, detailed discussions will be given in Section 5-2, ii.

In order to find out the difference in the intensity value between the ground and top floors, the first job to take is to read out the intensity value of the ground floor from the curves in Figs. 2a, b, c, that shows the intensity distribution along height for each building in the cases of three earthquakes. This job, however, is not so easy because of the scatter seen in the intensity distribution. Taking into considerations on this scatter, careful calculation was made so that the most reliable estimated mean intensity value of the ground floor could be worked out. The result is shown in Table 4 on the column "Ground floor intensity". Looking at this table, it is seen that ground floor intensity differs definitely with the diference of earthquakes, but with respect to each earthquake, the ground floor intensity of different high-rise buidings is seen almost the same as each other. This shows that the obtained ground floor intensity gives quite a reliable value.

In the former section (Section 5-1) we determined the ground floor intensity of the 14-story buildings by the same questionnaire survey method. In that case, the intensity of ground floor gave good accord with the intensity analysed from the questionnaire sheet collected from the people who were on the ground near to the 14-story apartment building. In the case of the high-rise building, however, the ground floor intensity in Table 4 shows definitely smaller value than that of the surrounding ground. This evidence shows clearly that when a high-rise building that has definitely longer proper oscillation period, is shaken by earthquake

TABLE 4

THE DIFFERENCE OF INTENSITY BETWEEN THE GROUND AND THE TOP FLOORS AS DETERMINED FROM THE QUESTIONNAIRE INTENSITY VALUES BY FLOOR OF HIGH-RISE BUILDINGS IN THE CASES OF THREE EARTHQUAKES

Name of building	MKO-E			KYB-E			NKS-E		
	Ground floor	Top floor	Difference	Ground floor	Top floor	Difference	Ground floor	Top floor	Difference
Sunshine 60	—	—	—	2.9	3.6	0.7	—	—	—
Shinjuku Mitsui	3.2	3.9	0.8	2.8	3.4	0.6	2.4	3.3	0.9
Shinjuku Sumitomo	3.1	4.0	0.9	2.8	3.3	0.5	2.5	3.4	0.9
Yasuda Kasai Kaijoo	3.3	4.1	0.8	2.8	3.3	0.5	2.3	3.3	1.0
Kasumigaseki	3.1	3.8	0.7	2.6	3.1	0.5	—	—	—
Kokusai Den-den	—	4.1	—	—	—	—	—	—	—
NS Blg.	—	—	—	2.8	3.4	0.6	2.5	3.4	0.9
Mean	3.2	4.0	0.8	2.8	3.4	0.6	2.4	3.3	0.9

motions, the maximum response acceleration of that building gives smaller value compared to that of an ordinary tall building, just as it is proved in the theory of dynamic analysis.

In like manner, the top floor intensity of each high-rise building was determined of which result is seen in Table 4 on the column of "Top floor intensity". In this way the intensities of the ground and top floors were determined, so it is easy to find the difference of intensity between the ground and top floors. Result is shown in the column of "Difference" in Table 4. From this table we notice firstly that the difference of rated intensity between the top and ground floors shows a different value with the different earthquakes. In the case of the KYB-E the difference is 0.6, while in the case of the MKO-E and the NKS-E the differences are 0.8 and 0.9 by JMA scale respectively. It may be considered that the latter two earthquakes represent an earthquake that took place at a location distant from Tokyo and having a larger magnitude compared to that of the KYB-E. Therefore, the moderately longer period component seismic waves might have been included somewhat predominantly compared to the case of the KYB-E. As the result of this effect, in the case of the MKO-E and NKS-E, somewhat larger vibration was induced in the high-rise buildings resulting that the difference of intensity at the ground and the top floor showed larger value that the case of the KYB-E. Secondly we notice that in our study of the 14-story buildings the difference of the intensity between the ground and the top floors was 1.0, the larger value compared to the case of the high-rise building. This event also shows clearly that as we learn in the theory of dynamic response analysis, the response vibration of the high-rise building due to earthquakes is smaller that the 14-story buildings because of the extremely long proper oscillation period of these high-rise buildings.

ii) On the scatter of the intensity values obtained from questionnaire responses

Again coming back to Figs. 2a, b, c, we notice that the arrangement of questionnaire-derived intensity values along height shows a scatter. This arrangement gives a strong contrast against the arrangement of the 14-story buildings in Fig. 1. In the latter case the arrangement of intensity values along height showed quite a regular form, showing no scatter.

In Section 6.3, detailed discussions are give to make clear the reason for which such a big difference comes to appear in the intensity distribution with height for the high-rise buildings and for the 14-story buildings.

6. The accuracy of tintensity value obtained from questionnaire response

6.1. *The standard deviation of the rated intensity values*

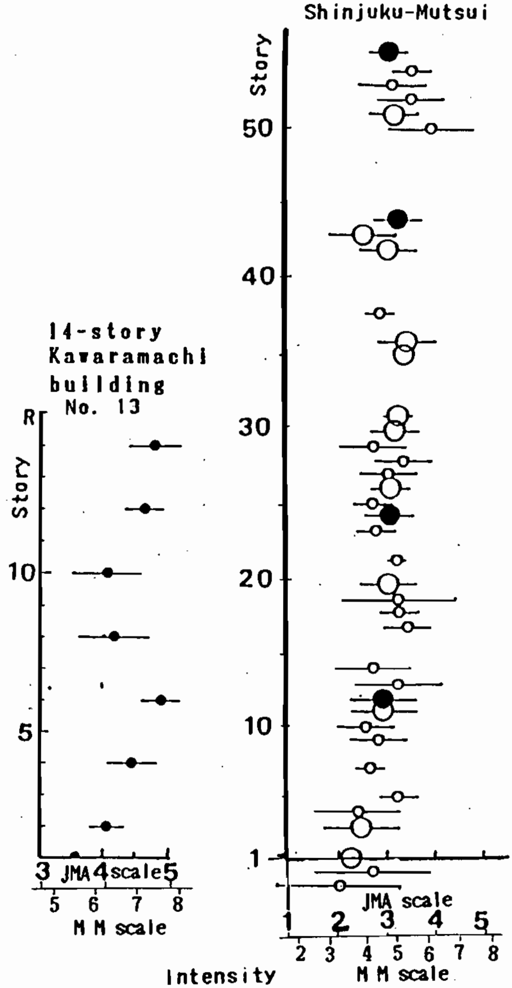
As an estimate to evaluate the accuracy or reliable extent of the rated intensity value by floor determined from the questionnaire response for the tall and the high-rise buildings the standard deviation was calculated for each intensity value of N° 13 14-story building and the Shinjuku Mitsui building (Fig. 5a, b). The length of a horizontal bar that is passing each circle indicates the largeness of the deviation. In these figures, it is noticed that the standard deviation for the case of the high-rise building is showing larger value. This also indicates that, the intensity value determined from the floor vibrations of high-rise building that are including longer period wave component predominantly, is giving lower accuracy.

6.2. *Comparison of the questionnaire-derived intensity with the maximum acceleration recorded on a strong motion seismograph installed on the same floor of high-rise buildings*

Many of these high-rise buildings are equipped with strong motion seismographs (SMAC) at several different floors of each building. In the Prompt Report of strong-motion Accelerograms (23, 24), the maximum accelerations recorded by these accelerographs at the time of the MKO-E and KYB-E were published. This maximum acceleration $\alpha_{máx}$ [gal] was converted into the value of intensity I by the equation $\alpha_{máx} = 0.253 \times 10^{0.5I}$ [gal] (25). In Figs. 6a, b these values of maximum acceleration are contrasted with the intensity value derived from questionnaire response for respective high-rise building in the case of the two earthquakes.

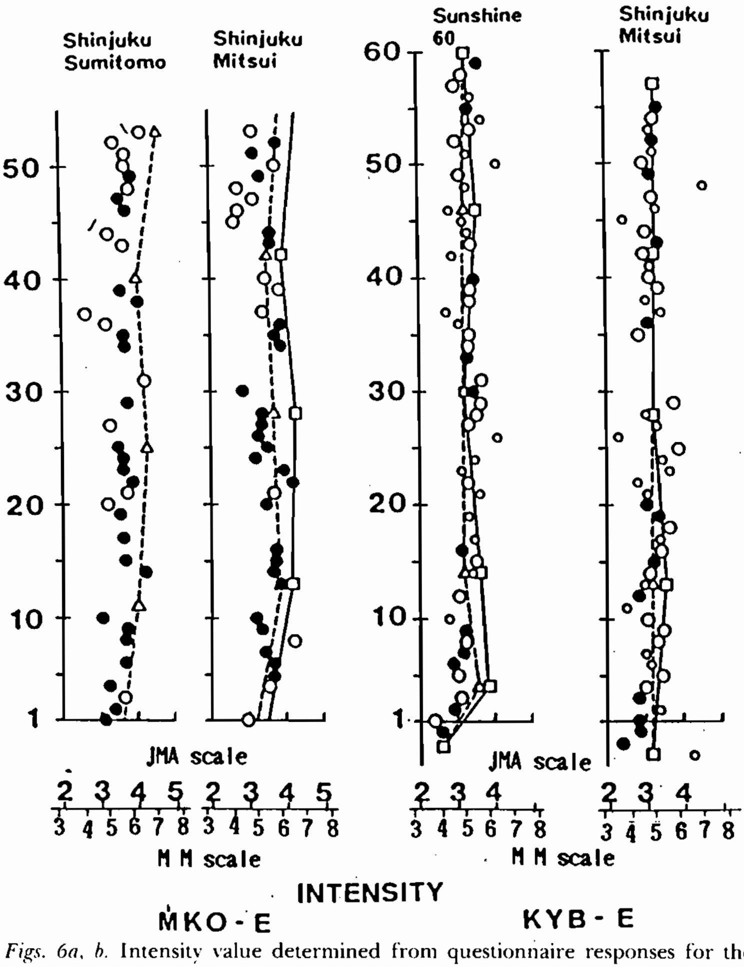
As it is already pointed out in Section 5.2., i, we can say that as a general tendency, the intensity distribution pattern in high-rise buildings is showing such a form that the intensity is slightly increasing monotonously from underground up to 5th floors or so, then after 5th floor up to the top floor there are almost no change in the rated intensity value. In this point, the agreement between the maximum acceleration recorded on the SMACS and questionnaire intensity is showing good harmony.

In Fig. 7 these maximum accelerations in Fig. 6 that appeared in the Prompt Report are directly contrasted with the questionnaire intensity value at the same floor. With regard to the SMAC records, the maximum acceleration of each floor is given by two ways, for E-W component and



Figs. 5a, b. Standard deviation of intensity value determined from the questionnaire responses. Length of a horizontal bar attached to each circle gives the largeness of the standard deviation, a is the 14-story Nº 13 building in the case of the IZU-E and b is the Shinjuku-Mitsui building in the case of the NKS-E.

N-S component. In Fig. 7, the larger acceleration value in these two components is plotted to represent the maximum acceleration of that floor. In Fig. 7 there is seen two oblique lines. The lower line represents the accelerations that give the bottom value of each intensity grade and



Figs. 6a, b. Intensity value determined from questionnaire responses for the high-rise buildings is contrasted with the maximum acceleration obtained from the SMAC records installed at the same floor. White quadrant and triangle represent the maximum accelerations in the direction of the longer and shorter spans of a building. The value of maximum acceleration is translated into intensity value by means of the usual method.

the upper line represents the acceleration that gives the middle value of each intensity grade. As will be seen in the figure, all the marks that relate to the questionnaire —derived intensity and the recorded SMAC maximum acceleration fall in between the two lines. Therefore, we can say the correspondence between the SMAC recorded maximum acceleration and

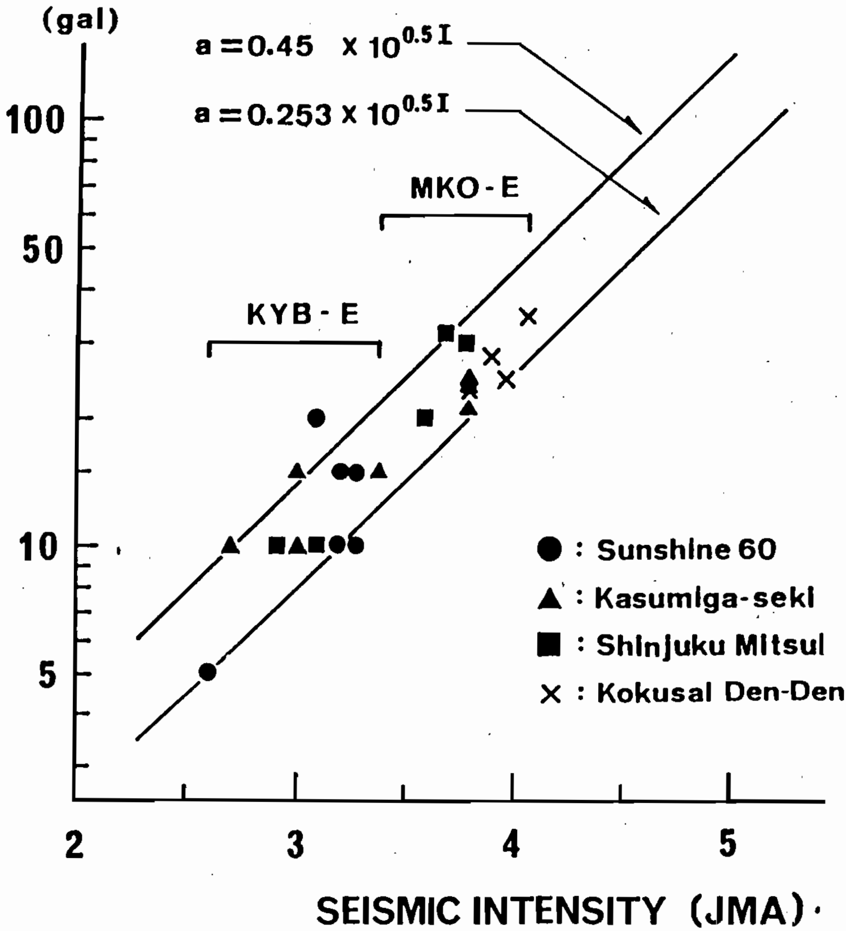


Fig. 7. The intensities obtained from questionnaire responses are compared with the maximum accelerations recorded by the SMAC strong motion seismograph installed on the same floor.

the questionnaire— derived intensity is showing good harmony, with regard to the both cases of the MKO-E and KYB-E.

A we have seen in Figs. 6 and 7, we could obtain a fairly satisfactory agreement between the maximum acceleration recorded by SMAC accelerographs and the questionnaire —derived intensity at the same floor. Therefore, it may be concluded that the intensity value by each floor derived from questionnaire responses is representing a reliable value to some extent, in spite of the scatter seen in the arrangements of questionnaire intensity along height.

6.3. *Maximum acceleration distribution by floor along height calculated from the dynamic response analysis with the modelled 14-story building using the observed strong motion records obtained at nearby stations was compared with the intensity distribution from the questionnaire survey (19)*

To assess the accuracy of the intensity values obtained from answer to our questionnaire surveys, we carried out the response analysis calculations for the buildings at the Kawaramachi site using the assumed input earthquake motions to the site derived from the records obtained at nearby strong motion observation station (26, 27 and 28), for the same earthquakes. The calculated maximum response analysis accelerations for each floor of a building were compared with the intensity values obtained by the questionnaire. A commonly used equation (25) for the conversion of the calculated acceleration to an intensity value was used. Although our response analysis calculations required a number of assumptions (29, 30), the calculated intensity was in most cases in good agreement with the value obtained from the questionnaire answers. This calculation provided good support to proof that the accuracy of the intensity values obtained from the questionnaire survey was fairly high.

6.4. *On the accuracy of the rate intensity value determined from the vibrations of high-rise buildings that contain very long period wave component predominantly*

As we have seen in Fig. 1, for the 14-story buildings the intensity distribution pattern shows quite a beautiful arrangement along height. While, when the same survey was carried out for the high-rise buildings we obtained a picture showing quite a different appearance (Fig. 2). The intensity distribution gave a pattern showing a scatter.

In order to give a reasonable explanation for the large difference in the distribution patterns of these two types of pictures, it must be pointed out the large difference existing in the period of the proper oscillation mode of the two types of buildings. The proper oscillation period of 14-story buildings is about 0.9 sec., while that of high-rise buildings is giving definitely longer proper oscillation period of about 4-5 seconds

(Table 2b). We notice that this extremely long proper oscillation period of high-rise buildings gave quite a different appearance.

Referring to the long history of defining the JMA seismic intensity scale (31), it seems that no detailed discussion has ever been extended to evaluate the intensity of the vibrations containing a very long period component, say 5 seconds or so (32). A few years ago, the JMA has established a special committee for defining the "Instrumental seismic intensity scale" expressed by the numerical value obtained from the instrumental observation of the ground vibration at the time of earthquake motions. As the result of this study a new proposal was brought about y the committee (33) to give reasonable and coordinatable intensity value with the existing intensity scale for the earthquake vibrations including many different periods. Even in this case, however, the period range of the "many different periods" covers in the range of 0.1 sec. to about 3 second (34). Therefore, the problem how to determine its intensity value for the ground vibration that are including such long periods as will be seen in the period of the 1 st oscillation mode of high-rise buildings (Table 2b), is not yet established even by JMA.

From our questionnaire survey, it was very clear that the people who were in the high-rise building at the time of an earthquake, they must have experienced the floor vibrations containing much longer than the vibrations that the people on the ground have experienced. Under these circumstances, it must be understood that it became a matter of great difficulty to assign to what grade of intensity value for the floor vibrations they experienced during earthquake when the floor vibrations were included long period vibration component, say as long as 5 seconds or so. At the same time, it must be confessed that the author has not yet encountered such situation as to determine the intensity of the very long period vibrations, it was not possible for us to prepare such question items in the questionnaire as can be drawn out effective answers from the people who were in high-rise buildings.

By means of above two reasons, we can say that the plot of the intensity value detemined from questionnaire response for the case of the high-rise buildinds gave the appearance of somewhat large scatter along height. However, in spite of these somewhat large scatter, assisted by other evidences such as in sections 2.3 and 2.4., we can say that the mean values of these intensities determined to each floor are showing fairly a reliable value.

5. Concluding remarks

As yet only few data were available to detect the knowledge on the vibrational behaviour of tall buildings, especially in their upper floors when they are shaken by large earthquake motions. The strong motion seismographs installed in the several different floors of some of the high-rise buildings so far gave only few available data.

In order to make clear the vibrational behaviour of tall and very tall buildings at the time of an earthquake, we introduced questionnaire survey method to two types of buildings: one is the 14-story reinforced concrete apartment buildings in Kawasaki City ant the other is the high-rise buildings in Tokyo. The questionnaire we used is so constructed as to give the value of intensity by JMA scale by means of computer calculation for every one sheet of effective answer. Calculating the arithmetical mean value of the intensities that belongs to the same one floor of one building, the mean intensity value of that floor can be determined. In this way the intensity of each floor of respective buildings at the time of several earthquakes was determined.

The accuracy of these rated intensities were examined by several means, as is described in detail in the text. According to our examination, the worked out intensity of each floor by means of questionnaire responses at the time of four different earthquakes, seems reliable fairly well.

By means of these studies, several new findigs were obtained. It was found firstly, for both type of buildings, at the time of an earthquake, the seimic intensity that appears in the upper floors is definitely larger than that of the ground floor. But with regard to the 14-story buildings, the difference of intensity between the ground and the top floors was in almost every case 1.0 grade by JMA intensity scale (about 1.5 grade by MM scale) for all three earthquakes investigated. On the contrary, in the case of high-rise buildings, the difference was rather smaller than the case of the 14-story buildings. This evidence claearly indicated that just as it was expected in the stage of designing of the high-rise building in accordance with the theory of dynamic analysis calculation of a high-rise building, when the building is shaken by earthquake motion, the response acceleration induced in the upper floors of this building must be rather small, because the proper oscillation period of the high-rise building is much longer than the ordinarily tall building, say in the order of 4.0-5.0 seconds.

The second is the problem of the scatter of the intensity increase pattern along the height of floors of the high-rise buildings. On the occasion of the 14-story building the intensity increase pattern gave a beautiful curve showing no scatter. Detailed examinations were made to find the reason why such a scatter is seen only in the case of the high-rise building. The conclusion we reached is that because of the extremely long proper oscillation period of these high-rise buildings, it is duly expected that the longer period components are predominantly included in the floor vibrations of the high-rise building in the case when they are shaken by earthquake motions. Because it is not experienced even by JMA, to determine the intensity of such vibrations as containing very long period component, it makes the matter greatly difficult to rate the intensity value of such floor vibrations as containing very long period components predominantly.

Thirdly, extending one step more above discussions, it may be able to draw out the following conclusions. If it is true to take that such longer period wave components are included predominantly in the earthquake induced floor vibrations og high-rise buildings, even if the response acceleration components of such floor vibration might be small indeed, it must be expected that displacement response amplitude might come out in a considerably large value, in the high-rise building vibrations, especially in their upper floors.

Taking into consideration all the above conclusions, it was made clear that for the tall buildings such as 14-story or so, and for the very tall high-rise buildings that have 50-60 stories, when they are shaken by earthquake motions, definitely larger intensity is observed in the upper floors than the ground floor. For the former buildings larger acceleration is predominating, while for the latter buildings displacement amplitude must become large valuer. These events, however, have not been recognized so clearly in the past studies. If this finding is true, in the case of large earthquakes, even though there may be no danger to take place the structural destructions of these buildings, another kind of severe seismic damage must appear in the higher floors of these tall buildings and the high-rise buildings, such as overturning and sliding around the floor of the cupboards, bulky chests of drawers, refrigerators, heavy bookshelves and other large pieces of furniture causing large scale confusión and turmoils for the people who were in such floors. In order to avoid this new-type damage and confusion, well organized training and education must be prepared in advance to these people. From the same reason the danger of fire in these higher floors will increase greatly. The problem of the danger of fire at the tall building and the high-rise building is not only limited to the enlargement of the fire to the upper floors, but also the swift diffusion of fire smoke into the upper floors causing serious trouble to evacuation. Well-prepared countermeasures should be established in advance to minimize these dangerous events.

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REFERENCES

1. Muto K. (1960). Preface of the Proc. 2nd World Conf. on Earthq. Eng. Tokyo, Kyoto, Vol. 1, p. 1.
2. Minami, J.K. *Report on IAEE matters by the Secretary-General*, (1965). Proc. 3rd WCEE, New Zealand, Vol. 1, pp. 102-104.

3. Plafker, G. and J.P. Galloway (1989). *Lessons learned from the Loma Prieta, California, Earthquake of October 17, 1989*, US Geological Survey Circular 1045.
4. Omote, S. (1988). *Earthquake disasters as seen from the viewpoint of urban disaster-proposal of a new viewpoint on the earthquake devastation*, Jour. Japan Soc. Natural Disaster Science, Vol. 7, N° 2, pp. 1-11 (in Japanese).
5. Japan Architectural Institute (1980). Report on the Miyagi-oki earthquake of 1978 (in Japanese).
6. Uchida, N., *et al.* (1981). *Seismic behaviour of the Sumitomo Sendai Bldg. during a strong earthquake*, N° 2 "Miyagi-ken Oki Earthquake" records June 12, 1978 and elastic plastic response analysis. Transactions of the Architectural Institute of Japan, N° 299, pp. 57-68.
7. Ohta, Y., N. Goto and H. Ohashi (1979). *A questionnaire survey for estimating seismic intensities*, Bull. Fac. Eng. Hokkaido Univ., N° 92, pp. 36-47 (in Japanese).
8. Kagami, H., S. Okada and Y. Ohta (1989). *Versatile application on dense and precise seismic intensity data based on an advanced questionnaire survey*, Proc., 9 WCEE 1988, Vol. 8, pp. 938-942.
9. Masaki, K. and Lermo, J. (1992). In preparation.
10. Ohta, Y., S. Okada, H. Ohashi and H. Kagami (1986). *A dense and precise survey of seismic intensity as an effective tool in engineering seismology*, Proc., 8 Europ. Conf. E.E. of 1986, pp. 48-55.
11. Omote, S. and N. Nakajima (1979). *Seismic intensity at each floor of tall apartment buildings at the Kawaramachi-danhi, Kawasaki City, Report:* Technical Committee for Investigating Measures for Earthquake Damage Mitigation in Kawasaki City (Kawasaki IMEDM), pp. 255-264 (in Japanese).
12. Kawasaki Municipal Office (1970). Report of the Construction Works on the Kawaramachi tall Apartment Housing Estate.
13. Miura, T. (1967). *On the high-rise building of Japan.* Building Letter, 67-1, p. 13. The Building Centre of Japan (in Japanese).
14. Hisada, T., K. Sakamoto and H. Tanaka (1981). *Data for designing tall buildings.* Data Book for earthquake-proof designing of buildings. Japan Architectural Institute, pp. 310-330 (in Japanese).
15. Omote, S. and H. Narahashi (1981). *Preliminary studies on the estimation of intensity distributions in tall buildings shaken by an earthquake*, Rep. Kawasaki IMEDM, pp. 53-63 (in Japanese).
16. Omote, S. and H. Narahashi (1984-a). *Questionnaire survey ant the result of the analysis of the data, on the occasion of the 1983 Nihonkai-Chu bu earthquake with the appendix of the intensity distribution of some of the Kawaramachi buildings at the time of the 1983 KYB-E.* Rep. Kawasaki IMDM, pp. 198-199 (in Japanese).
17. Omote, S., A. Sekizawa, S. Zama and H. Narahashi (1984-B). *Studies on the intensity distribution in high-rise buildings, with remarks on the problem of disaster prevention for the Yamanashi-Kanagawa Border earthquake.* Rep. Kawasaki IMEDM, pp. 201-218 (in Japanese).
18. Omote, S., A. Sekizawa, S. Zama and H. Narahashi (1985). *The estimation of vibrational behaviors of high-rise buildings at the time of an earthquake by means of*

questionnaire survey method and some comments for applying these results for disaster mitigation countermeasures for the case of the NKS-E. Rep. Kawasaki IMEDM, pp. 153-166 (in Japanese).

19. Omote, S. and H. Narahashi (1989). *Seismic intensity distribution in tall buildings determined from responses to questionnaire survey.* Jour Natural Disaster Sci., Vol. 11, pp. 1-25.
20. Hiraishi, H., *et al.* (1986). *Seismic capacity of a reinforced concreted building which suffered 1985 Mexico earthquake in Mexico City.* Parts 1 & 2 Twelve-story office building (1 & 2). Compiled Abstract, Technical Meeting of Japan Architectural Institute 1986, pp. 631-634 (in Japanese).
21. Omote, S. and Narahashi (1982). *The response analysis of tall apartment buildings used to verify the seismic intensity obtained form a questionnaire survey,* Rep. Kawasaki IMEDM, pp. 71-83, (in Japanese).
22. Omote, S., H. Narahashi, A. Sekizawa and S. Zama (1990). *Seismic intensity distribution in high-rise buildings determined from response to questionnaire survey when they are subjected to large earthquake motions* (in press).
23. NRCDP, 1978. Prompt Report on Strong-Motion Accelerograms, N° 15, June 12, 1978 Miyagi-Ken-Oki earthquake, pp. 1-15, National Res. Center for Disaster Prevention, Science and Technology Agency, Japan.
24. NRCDP, 1983. *Prompt Report on Strong-Motion Accelerograms,* N° 24, August 8, 1983 Kanagawa Yamanashi Kenkyo earthquake, pp. 1-0, National Res. Center for Disaster Prevention, Science ant Technology Agency, Japan.
25. Kawasumi, H. (1951). *Measures of earthquake danger and expectancy of maximum intensity throughout Japan as inferred from seismic activity in historical times,* Bull. Earthq. Res. Inst., 29, pp. 469-482.
26. Tsuchida, H., *et al.* (1967). *Site characteristics of strong motion earthquake stations in ports and harbours in Japan* (Part 1) Technical Note of Port Harbour Research Inst., Ministry of Transport, N° 34.
27. Kurata, E. *et al.* (1979). *Strong motion earthquake records on the 1978 Miyagi-Ken-Oki earthquake in port areas,* Technical Note of Port Harbour Research Inst., Ministry of Transport, Japan, N° 319.
28. Yokota, H. (1979). *Vertical array seismic observation in the soft ground around the Tokyo Bay area,* Bull. Res. Inst. of the Shimizu Construction Co. Ltd., Vol. 30, pp. 21-29.
29. Yamanaka, H., K. Seo, T. Samano, S. Midorikawa, E. Shima and M. Yanagisawa (1988). *On the seismic prospecting in the southwestern part of the Tokyo Metropolitan area* (3): analyses of explosion data in 1983 and 1984. Jour. Seis. Soc. Japan II, Vol. 41, pp. 527-539 (in Japanese).
30. Ohta, Y. and N. Goto (1976). *Estimation of S-wave velocity in terms of characteristic indices of soil, Butsuri-Tanko.* Geophisical Exploration. Vol. 29, Nº 4, pp. 31-41 (in Japanese).
31. Miura, T. (1964). *The historical development of the seismic intensity scale of Japan Meteorological Agency.* Sokko Jiho (JMA) Vol. 31, pp. 6-134-138.
32. Ichikawa, M. (1984). *Evaluation of seismic intensity of JMA using digital seismograms.* Jour. Meteorological Research Vol. 36, N° 6, pp. 1-31 (in Japanese)

33. SCEISI, 1988. *Report of the Special Committee for Evaluating the Instrumental Seismic Intensity*, JMA, pp. 1-21 (in Japanese).
34. HACHIMINE, T. (1989). *On the new instrumental observation of the seismic intensity.* Seismometrical Report of JMA. Vol. 52, pp. 43-68.