BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 44 (1966), pp. 233-245

13. *Response Analysis of Tall Buildings to Strong Earthquake Motions. Part 2. Comparison with Strong Motion Accelerograms (1).*

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(Read June 22, 1965.—Received Dec. 28, 1965.)

Abstract

Comparison is made between computed and recorded accelerations at the top of reinforced concrete buildings in a longitudinal direction caused by strong earthquakes. The computed accelerations are obtained using response analysis technique for a multi-mass vibratory system which is considered to represent each building. Good agreement is seen between computed and recorded accelerations in every building.

1. Introduction

The use of earthquake response analysis of buildings is becoming common in the field of earthquake engineering and many papers relating to this problem have been published. However, most papers are concerned with theoretical investigations and the theoretical results have not yet been systematically compared with earthquake records except the work by Kanai and Yoshizawa.[1]

It is intended in this paper to compare accelerations at the top of the buildings, computed by means of earthquake response analysis, with those recorded by SMAC or DC type strong motion accelerographs. The computation is made in such a way that the building is reduced to a multi-mass vibratory system and the acceleration recorded at the base of the building is applied to this system as an input.

In this first trial of the comparative study only the longitudinal direction of the building is considered so that the building can be represented by the relatively simple vibratory system without consideration of the effect of rocking vibration.

1) K. KANAI and S. YOSHIZAWA, "Some New Problems of Seismic Vibrations of a Structure. Part 1," *Bull. Earthq. Res. Inst.*, **41** (1963), 825-833.

2. Outline of the buildings and earthquake records

The outlines of the three buildings considered in this study are as follows.

Akita Prefectural Building: Fig. 1 shows a general plan and a longitudinal section of the building. It is a six-story reinforced concrete office building having a basement and a three-story penthouse. The light

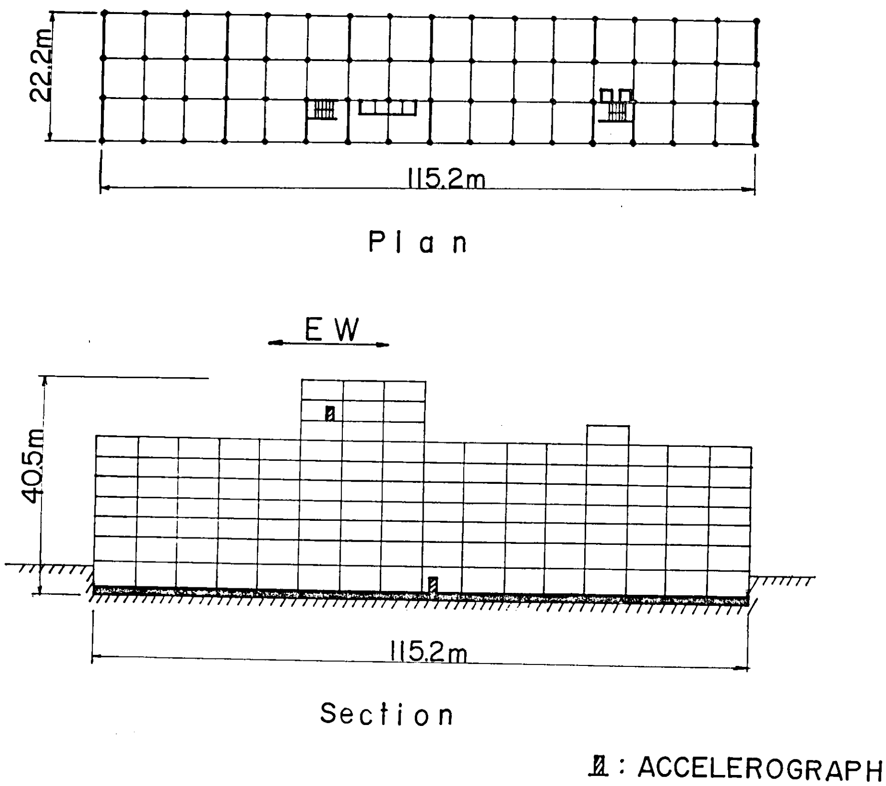


Fig. 1. Plan and section of the Akita Prefectural Building.

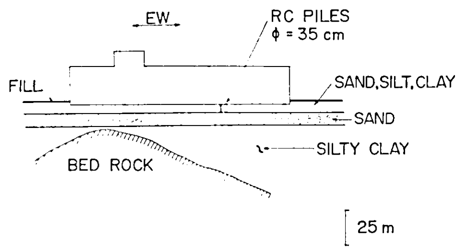


Fig. 2. Foundation and soil condition of the Akita Prefectural Building.

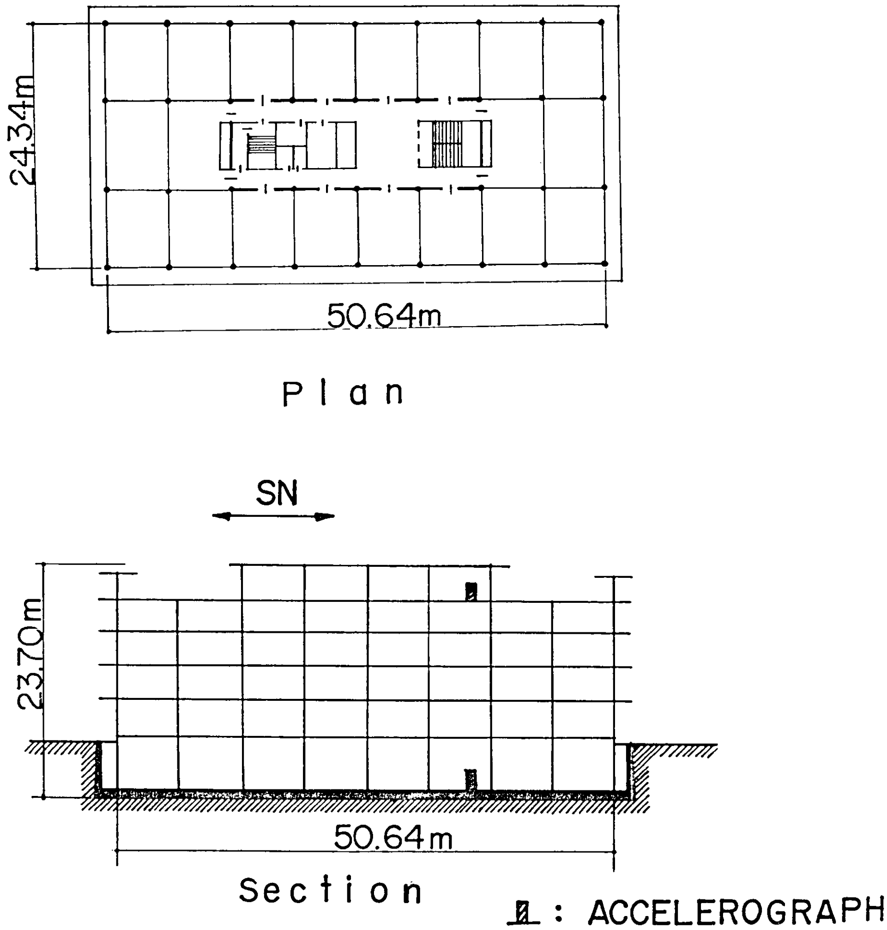


Fig. 3. Plan and section of the Shizuoka Administration Building.

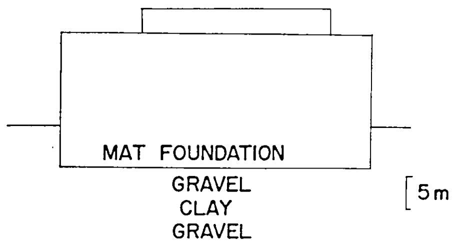


Fig. 4. Foundation and soil condition of the Shizuoka Administration Building.

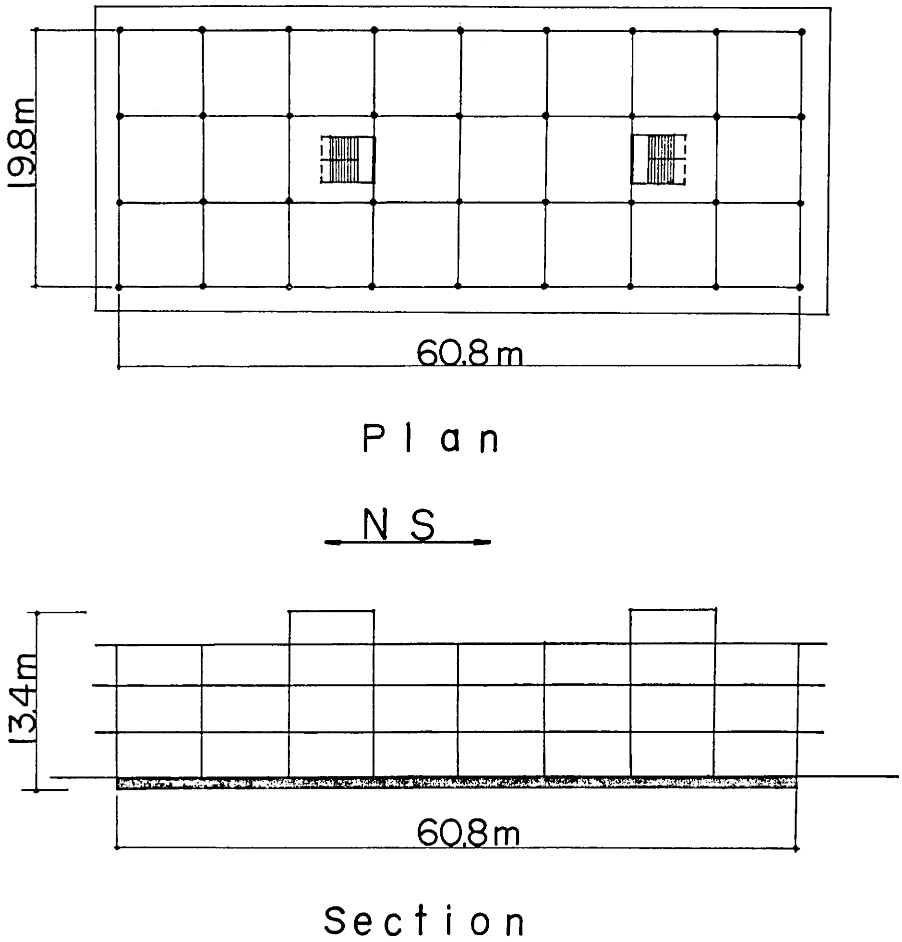


Fig. 5. Plan and section of the Maibara Administration Building.

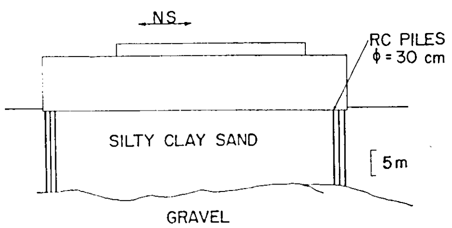


Fig. 6. Foundation and soil condition of the Maibara Administration Building.

weight aggregates are used as the concrete materials above the second floor level. The whole building is supported by reinforced concrete piles as shown in Fig. 2.

Shizuoka Administration Building, Japan National Railways: Fig. 3. shows a general plan and a longitudinal section of the building. It is a five-story reinforced concrete office building having a basement, and it rests on a gravel layer with mat foundation (see Fig. 4).

Maibara Administration Building, Japan National Railways: Fig. 5 shows a general plan and a longitudinal section of the building. It is a three-story reinforced concrete office building having a penthouse. Reinforced concrete piles are used as shown in Fig. 6.

Earthquake records used in this study are the accelerograms at the top and bottom of each building obtained with SMAC and DC type strong motion acceleragraphs. The data related to the earthquake records are listed in Table 1.

Table 1. Data of the earthquakes and earthquake records

Earthquake	Building	Epicentral distance (km)	Orientation	Position	Maximum acceleration (gal)
Mar. 27, 1963 35.8N 135.8E h=20 km M=6.9	M	75	NS	RF	50
				1F	30
			EW	RF	90
				1F	45
Jun. 16, 1964 (Niigata Earthq.) 38.4N 139.2E h=40 km M=7.7	A	135	NS	P2	300
				B1	100
			EW	P2	225
				B1	95
Apr. 20, 1965 34.9N 184.2E h=40 km M=6.2	S	45	NS	5F	120
				B1	100
			EW	5F	175
				B1	70

3. Outline of the computation

In the computation of the earthquake response of each building, a

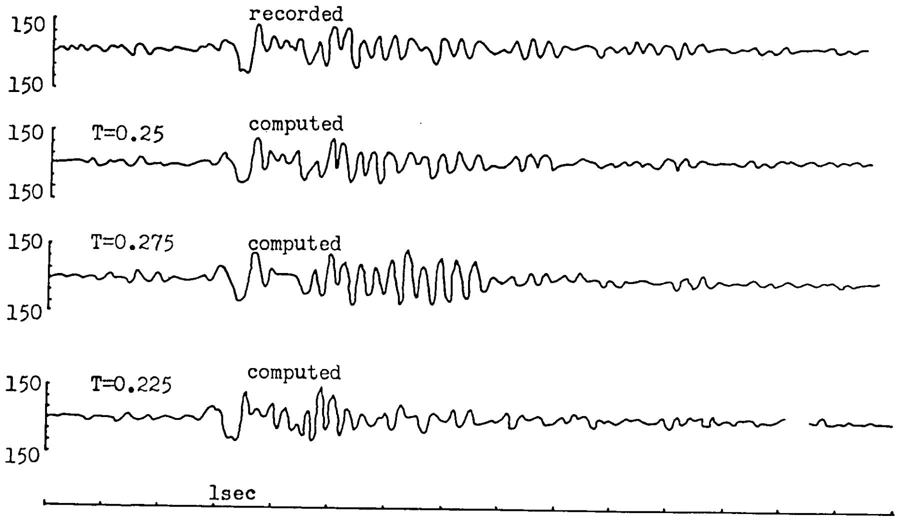


Fig. 7. Comparison of a recorded acceleration and the computed accelerations for the system having various fundamental periods illustrated for the case of the Shizuoka Administration Building.

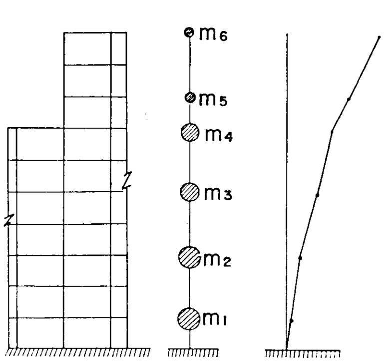
whole building is reduced to a multi-degree of freedom system having masses and spring constants and it is assumed to have no rocking motion.

The masses of the vibratory system are determined from dead loads and about one half of the design live loads.

As it is difficult to estimate the spring constants purely from the size of the structural members shown in the drawings without any actually measured data, the determination of the spring constants is made by the aid of the response analysis. First, the fundamental natural period of the system is determined so that the computed response to recorded ground motion becomes similar to the corresponding recorded acceleration changing the natural period by 0.025 sec interval. Fig. 7 illustrates this procedure in the case of the Shizuoka Administration building. As the spring constants calculated from the lateral rigidity of the structural elements of the building are always too small to satisfy the fundamental period obtained above, the "additional" regidities other than those of main structural frames are considered. These additional rigidities are of concrete block partition walls, reinforced concrete stairways, etc., and it is ascertained that the amount of additional rigidities are not unreal. The fraction of the critical damping is assumed to be 0.05 in all cases.

Outline of the computation of each building is as follows.

Akita Prefectural Building: A six mass shear type vibratory system is considered. The location and value of the mass, first mode shape and the spring constants are shown in Fig. 8. The spring constants due to the rigidity of frames and walls are calculated by means of Muto's *D*-method[2] considering the effect of finishings and reinforcing bars, *T*-beam effect on beam rigidity, end rigid zone at the joint of the frame, shearing and bending deformation in wall analysis, etc. The "additional" rigidities in this building are those of the concrete block partition walls and are ascertained to be reasonable. The fundamental natural period of the system is 0.5 sec.



N	MASS ton·sec²/cm	K total ton/cm	K frame ton/cm	K wall ton/cm	K block ton/cm
6	.51	250	100	150	
5	.45	600	200	400	
4	3.80	4000	1900	900	1200
3	3.30	4800	2300	1100	1400
2	3.50	5600	2500	1500	1600
1	4.50	8000	3400	2900	1700

Fig. 8. Masses rigidities and first modal shape of the reduced system for the Akita Prefectural Building.

The constants used in the analysis are as follows.

Young's modulus of concrete $Ec=210\ \mathrm{t/cm^2}$
Young's modulus of light weight concrete $Ec'=80\ \mathrm{t/cm^2}$
Shear modulus of concrete $Gc=Ec/2.3$
Shear modulus of light weight concrete $Gc'=Ec'/2.3$
Young's modulus of steel $Es=2100\ \mathrm{t/cm^2}$.

The equation of vibration for multi-mass shear type vibratory system with viscous damping is generally expressed as

$$m_i \ddot{Y}_i + C_i(\dot{Y}_i - \dot{Y}_{i-1}) + C_{i+1}(\dot{Y}_i - \ddot{Y}_{i+1}) + K_i(Y_i - Y_{i-1}) + K_{i+1}(Y_i - Y_{i+1}) = -m_i \ddot{y}_0 \,. \tag{1}$$

Where

2) K. Muto, "Seismic Analysis of Reinforced Concrete Buildings," *Proceedings of World Conference on Earthquake Engineering* (1956).

Y_i=displacement of i-th mass relative to the base

y_0=earthquake ground motion

m_i=mass of i-th mass point

C_i=damping coefficient of i-th story

K_i=spring constant of i-th story .

Analog computer "SERAC"[3] is used to solve equation (1). The block diagram for this computation is shown in Fig. 9.

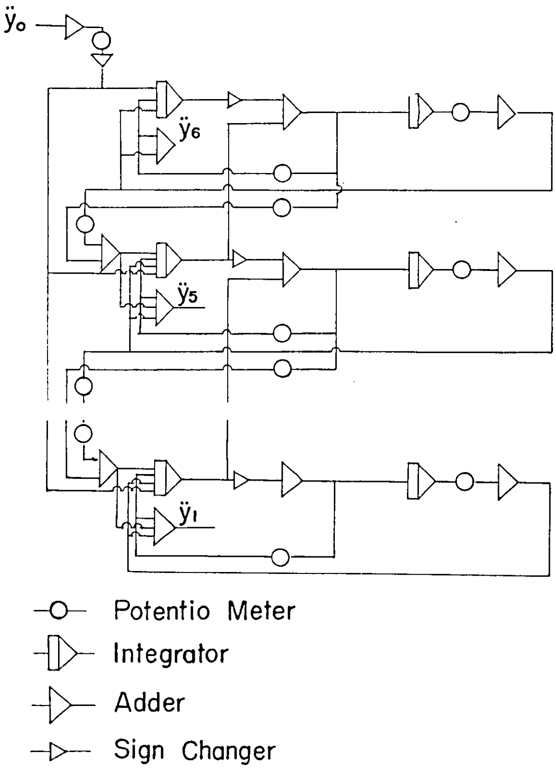
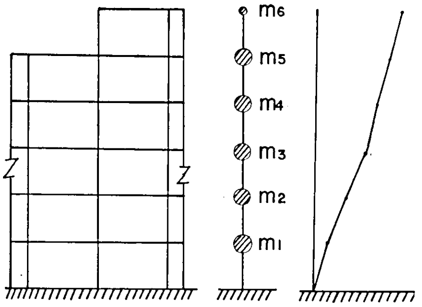


Fig. 9. Block diagram for analog computation.

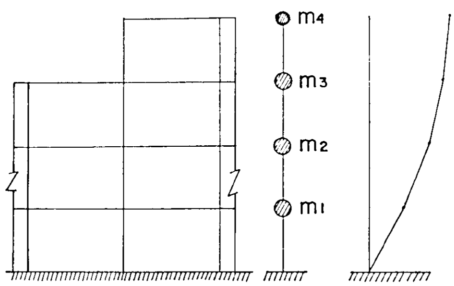
Shizuoka Administration Building, Japan National Railways: *A* six mass shear type vibratory system is considered. The various data of the system are shown in Fig. 10. The rigidities of the main structural elements, open frames and core walls, are calculated in a similar way to the above. Again "additional" rigidities are considered as K (other)

3) Strong Earthquake Response Analysis Committee "SERAC Report No. 1, 2," 1962.



N	MASS $\frac{\text{ton-sec}^2}{\text{cm}}$	K total $\frac{\text{ton}}{\text{cm}}$	K frame $\frac{\text{ton}}{\text{cm}}$	K core $\frac{\text{ton}}{\text{cm}}$	K other $\frac{\text{ton}}{\text{cm}}$
6	0.6	2600	600	1600	400
5	1.2	8500	1000	6300	1200
4	1.2	9300	1100	6900	1300
3	1.2	10200	1300	7100	1800
2	1.2	10100	800	7500	1800
1	1.3	16200	900	12400	2800

Fig. 10. Masses, rigidities and first model shape of the reduced system for the Shizuoka Administration Building.



N	MASS $\frac{\text{ton-sec}^2}{\text{cm}}$	K total $\frac{\text{ton}}{\text{cm}}$
4	0.2	1400
3	1.2	3800
2	1.2	4100
1	1.3	4300

Fig. 11. Masses, rigidities and first model shape of the reduced system for the Maibara Administration Building.

which represents the rigidity of partition walls in this case. The fundamental natural period of the system is 0.25 sec. The computation is also made by SERAC computer.

Maibara Administration Building, Japan National Railways: A four mass shear type vibratory system is considered. The various data of the system are shown in Fig. 11. As the main structural element is a frame with spandrel beams which consists of reinforced concrete beams and concrete block walls, the effect of the concrete block is considered as an end rigid zone of the columns and the increase of the rigidity of the beam. By determining the length of the rigid zone properly, it is not necessary to consider the "additional" rigidity in this case. The fundamental natural period of the system is 0.25 sec.

4. Comparison of the computed and recorded accelerations

The wave forms of the computed and recorded accelerations are shown

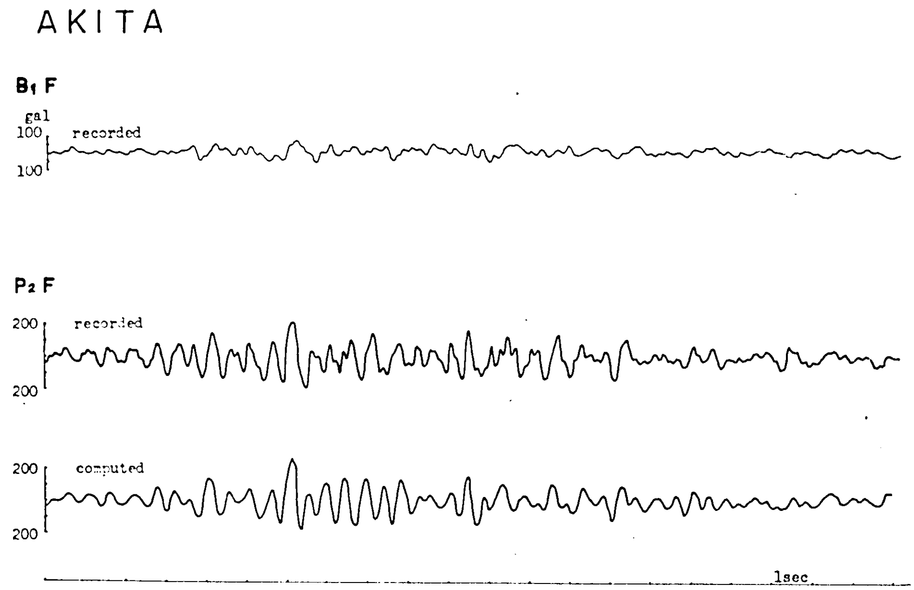


Fig. 12. Comparison of the computed and recorded accelerations, Akita Prefectural Building.

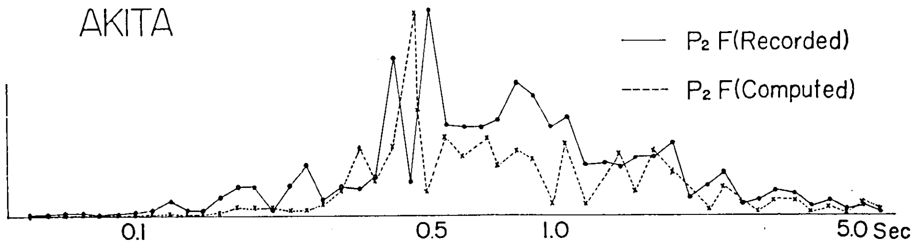


Fig. 13. Fourier spectrum for the computed and recorded accelerations, Akita Prefectural Building.

in Figs. 12, 14 and 16. In each figure the first curve represents the recorded acceleration at the base of the building and the second and third ones represent the recorded and computed accelerations at the top of the building, respectively. Fourier spectra of these curves are also shown in Figs. 13, 15 and 17.

It can be said from these figures that the computed accelerations coincide well with the recorded ones.

5. Conclusions

Although the method of computation employed in this investigation

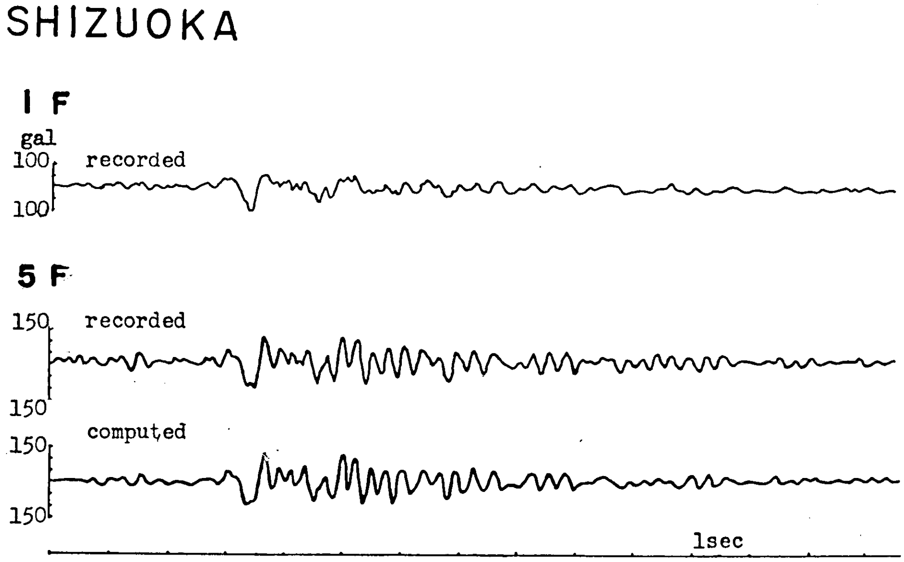


Fig. 14. Comparison of the computed and recorded accelerations, Shizuoka Administration Building.

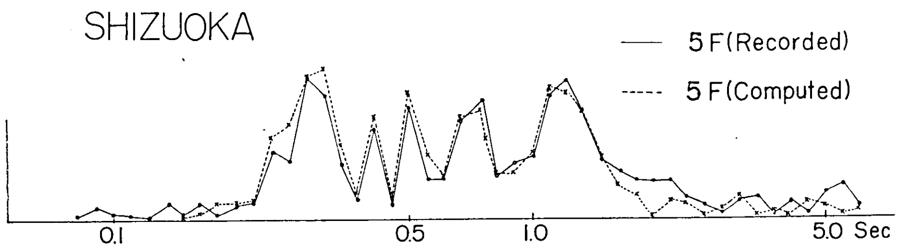


Fig. 15. Fourier spectrum for the computed and recorded accelerations, Shizuoka Administration Building.

is based on various assumptions, agreement of the computed and recorded accelerations for three buildings is unexpectedly good. This suggests that the earthquake response analysis of ordinary reinforced concrete buildings by a reduced multi-mass vibratory system will give results fairly close to the real behavior of buildings during earthquakes if the estimation of the lateral rigidity is properly made.

The present investigation is limited to the case in which the rocking vibration can be neglected. Further investigation must be made for the building with rocking vibration such as transverse vibration of the building considered herein.

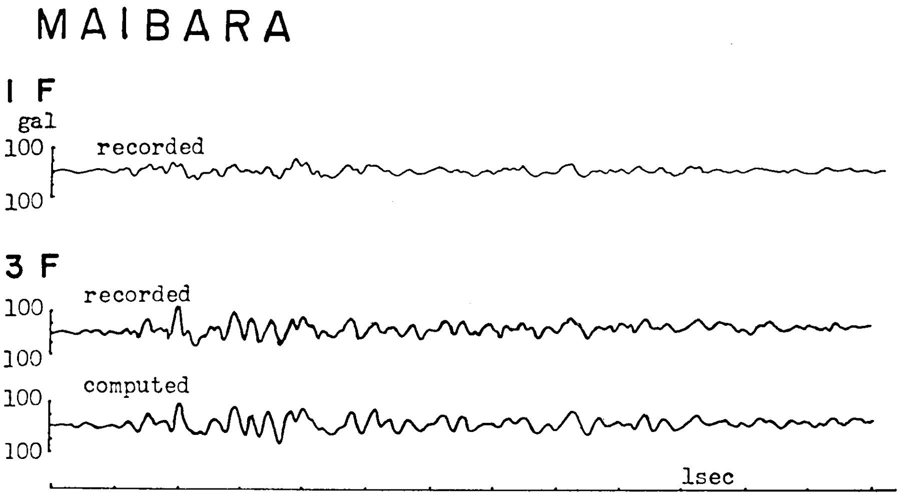


Fig. 16. Comparison of the computed and recorded accelerations, Maibara Administration Building.

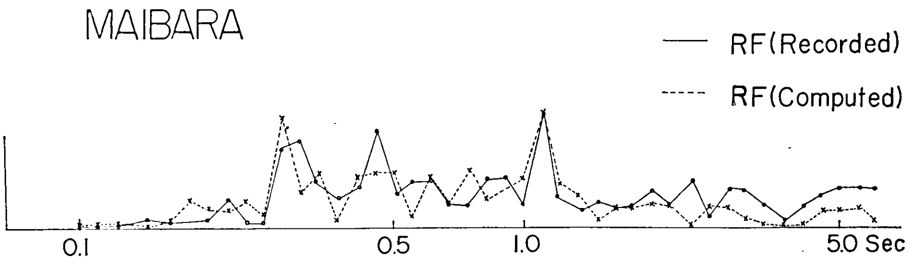


Fig. 17. Fourier spectrum for the computed and recorded accelerations, Maibara Administration Building.

Acknowledgment

The authors wish to express their sincere thanks to Professors K. Kanai and H. Umemura for their encouragement, and to Prof. Y. Satô for permission in making the computer program available. Their thanks are also due to the Japan National Railways and the Akita Prefectural Government for putting the data related to their buildings at the authors' disposal.

13. 高層建築物の強震応答解析に関する研究

第 2 報　強震計記録との比較 (1)

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村上雅也

強震計によつて地震時の上・下階の加速度が記録された 3 棟の鉄筋コンクリート造建築物について,その長辺方向を対象とし,多質点系置換により,建物基部の実測加速度を入力として与えて上部の加速度波形をアナログコンピューターにより計算し，その結果を実測加速度波形と比較した．結果は波形においても，フーリエスペクトルにおいてもよい一致を示した．この計算では建物の振動系モデルをせん断型多質点系としたが，そのバネ定数の算定にはラーメン，耐震壁などの主要骨組以外に間仕切壁，腰壁などの剛性も考慮に入れた．この結果により，主要骨組以外の剛性寄与も適当に考慮すれば，多質点系の振動モデルによる地震応答解析で地震時の建物のゆれ方が十分解明できることがわかつた．ただし建物の短辺方向では，ロッキングの影響が大きく入るものと考えられるので，別途検討中である．