DYNAMIC ANALYSIS OF REINFORCED CONCRETE FRAMES WITH FRAMED SHEAR WALLS

by

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SYNOPSIS

Linear static and dynamic analysis of reinforced concrete frames with framed shear walls are carried out for various arrangements of framed shear walls. Analytical results indicate that dynamic response of such frames during an earthquake can be approximately evaluated by the static analysis.

INTRODUCTION

According to the current Japanese Building Standard Law for structures whose heights are not over 45 meters, lateral seismic force at each floor level is given by a product of seismic coefficient and weight located at the floor. Since the value of the seismic coefficient is mainly determined in accordance with the height above the ground to each floor level, lateral seismic forces in Japan are independant of the fundamental period of the whole structure. In evaluating the design earthquake forces on structures, the value and distribution of the lateral seismic force at each floor level should be determined on the basis of the results of dynamic response analysis, because lateral seismic forces are remarkably affected by the distribution of masses, rigidity of a whole structure, damping capacity, effects of building-foundation interaction, soil condition, earthquake excitation and so on.

Reinforced concrete frames with framed shear walls are frequently designed and constructed in Japan because they have effective resistance to lateral forces during strong earthquakes. Although these framed shear walls have considerably larger lateral load carring capacity than moment-resisting frames, many unknown factors still remain to be investigated such as rigidity, strength, ductility, load-deformation behavior and energy absorption capacity. There have been a number of studies on elastic structural analysis of reinforced concrete frames with framed shear walls, but in most of them, approximate methods of analysis or simplified modifications are used for evaluating the stiffness of framed shear walls because of its complexity [1][2][3]. Even if structures are not so tall, periods and modes of vibration of the whole structure are remarkably affected by their rigidities and the manner of arrangement of framed shear walls. Therefore, it is necessary to evaluate the rigidity of such framed shear walls as precise as possible.

In this paper, using the stiffness matrix of framed shear walls determined analytically, linear static and dynamic analysis of reinforced concrete frames with framed shear walls are carried out for various arrangements of shear walls in the frames. The main purpose of this analysis is [1] to investigate the effects of various patterns of arrangement of framed shear walls on dynamic response of the reinforced concrete frames, [2] to propose the approximate method for evaluating the value of the fundamental period of these frames and [3] to compare the results of dynamic analysis with those obtained from current design methods in order to evaluate the magnitude and distribution of the equivalent static lateral forces at each floor level.

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METHOD OF ANALYSIS

Analytical Models: Fig.1 shows schematic elevations of three-bay-six-story reinforced concrete frames used in the analysis. These specific examples of thirty-four frames with framed shear walls arranged apart can be classified into eight groups according to the manner of arrangement of the shear walls. And these classified groups are denoted by Type O, A, B, C, D, E, F and G, respectively as shown in Fig.1. Among these groups, framed shear walls are not provided in the frame of Type O. All story heights are 3.5 meters and distance from center to center of columns is 6.0 meters. Fig.2 shows detail of the framed shear wall used in the analysis. Cross-sectional dimensions of this framed shear wall are the same as those of the illustrative example in 1975 AIJ Standard for Structural Calculation of Reinforced Concrete Structures [4] and such a shear wall is frequently designed in Japan. Cross-sectional areas of all columns and beams are respectively the same as those of boundary frames of the framed shear walls in Fig.2 except that the depth of the footing beam is 1.0 meter. The vertical load used in the analysis is shown in Fig.3, assuming a uniformly-distributed dead plus live loads of 1.0 ton/m^2 on all stories.

Rigidity of Members and Framed Shear Walls: Stiffness matrices of beams and columns are determined by taking into account of the deformations caused by the normal force, shear force and bending moment. Effect of rigid-zone along the member is also taken into account [4]. Because the stiffness matrix of a whole structure with framed shear walls is remarkably affected by the rigidity of each framed shear wall, it is necessary to evaluate the rigidity of the framed shear wall as precise as possible. Herein, stiffness matrix determined analytically by using Airy's stress function [5] is used in order to evaluate the rigidity of the framed shear wall precisely. Since each framed shear wall as shown in Fig.2 has a total of four nodal points and each nodal point has a total of three nodal components for both forces and displacements, the order of the complete stiffness matrix of the framed shear wall is 12 × 12. This stiffness matrix proposed by M. Tomii and T. Yamakawa is, however, only applicable to the linear elastic analysis of reinforced concrete structures with framed shear walls arranged apart [5].

Static Analysis: According to the current Japanese Building Standard Law, lateral seismic force, f_i, at i'th floor level is given by a product of seismic coefficient, k_i, and weight, W_i, located at the floor. The value of k_i used in the analysis is shown in Fig.4. Distribution of k_i shown in Fig.4(a) is determined in accordance with the current Japanese Building Standard Law, while distribution shown in Fig.4(b) is similar to that specified by the Uniform Building Code in USA but has the same base-shear coefficient with that of Fig.4(a). Since weight distribution on each floor level is given in Fig.3, lateral seismic force at each floor level can be determined. For the given lateral forces, unknown displacements and internal forces of the members and framed shear walls are determined by means of the direct stiffness method [6].

Dynamic Analysis: The computations of dynamic response are performed by the normal mode method and the equations of motion are solved by the step-by-step integration method [7]. The modes of vibration which are higher than 6th mode are neglected. Damping ratios are assumed to be 0 and 5.0 per cent of critical damping in each mode of vibration. Earthquake accelerograms used in the analysis are El Centro 1940 NS and Taft 1952 EW which are modified so that the value of maximum acceleration is 0.2 g and both accelerations are given at one-thousand intervals of 0.01 second each. Characteristic values and vectors are calculated by means of the Q-R method [8].

RESULTS OF ANALYSIS AND DISCUSSIONS

Fundamental Period: Table 1 shows fundamental periods of vibration of all frames shown in Fig.1. It is seen from the table that the fundamental periods of those frames are remarkably affected by the manner of arrangement of framed shear walls. It is of interest to compare these values with the approximate solutions obtained by Geiger's equation. According to Geiger's equation, the fundamental period of vibration of a building frame is given by:

$$T_1' = \sqrt{\eta} / K \qquad (1)$$

where

T_1' = fundamental period of vibration of the building frame or structure in second in the direction under consideration,

η = horizontal deflection in centimeter at the top of the frame due to lateral static forces which are equal to the gravity loads at each floor level,

K = constant dependant upon the type or arrangement of resisting elements and structural form.

The value of η in Eq.(1) was calculated statically for all frames shown in Fig.1. Comparisons between the exact fundamental period, T_1, and the approximate solution, T_1', by Eq.(1) are shown in Fig.5 for all types of frames. The ordinate in Fig.5 denotes the ratio of T_1' / T_1. It is understood from Fig.5 that the values of fundamental period for Type 0, A, B, C and D can be well determined by Eq.(1) assuming that the value of K in Eq. (1) is equal to 5.6, while those for Type E, F and G, in which framed shear walls are not provided in the lower or intermediate stories, can be well determined assuming that K = 5.3.

Base Shear Coefficient: In Fig.6, maximum values of base shear coefficients occurred during the earthquakes are plotted against the corresponding fundamental periods of each frame. The results indicate that the base shear coefficients, ${}_DC_B$, are considerably affected by the manner of arrangement of framed shear walls.

Maximum Story Shears and Story Drifts: Maximum story shears occurred during the earthquakes were compared with the design shear forces which are specified by the current Japanese Building Standard Law. Typical of the results are shown in Fig.7. Solid and open circles in Fig.7 represent the ratios of ${}_DC_i / {}_SC_{Ri}$ and ${}_DC_i / {}_SC_{Ti}$, respectively, in which symbol, ${}_DC_i$, denotes the maximum value of the story shear coefficient at i'th story caused by the earthquake and symbols, ${}_SC_{Ri}$, and, ${}_SC_{Ti}$, denote the values computed from deviding the design shear forces at i'th story by the total weight above the i'th story. Subscripts, R, and, S, in ${}_SC_{Ri}$ and ${}_SC_{Ti}$ mean that ${}_SC_{Ri}$ and ${}_SC_{Ti}$ are calculated by using the seismic coefficients shown in Fig.4(a) and Fig. 4(b), respectively. In addition to these comparisons, maximum story drifts occurred during the earthquakes are also compared with the static story drifts caused by the design shear forces, and typical of their results are also shown in Fig.7. Solid lines and dashed ones in Fig.7 represent respectively the ratios of ${}_D\delta_i / {}_S\delta_{Ri}$ and ${}_D\delta_i / {}_S\delta_{Ti}$, in which symbol, δ, denotes the story drift which is the relative floor displacement between two adjacent floors and subscripts i, R and T to the symbol, δ, have the same means with those to the symbol, C. It is worthy of note that the ratios of ${}_DC_i / {}_SC_{Ri}$ and ${}_DC_i / {}_SC_{Ti}$ have good agreements with the ratios of ${}_D\delta_i / {}_S\delta_{Ri}$ and ${}_D\delta_i / {}_S\delta_{Ti}$, respectively. Furthermore, it is seen from the figure that the ratios of ${}_DC_i / {}_SC_{Ti}$ for Type 0, A, B, C and D and the ratios of ${}_DC_i / {}_SC_{Ri}$ for Type E and F are nearly constant through the height of the structures. This fact means that the distribution of the lateral seismic forces specified by the current Japanese Building Standard Law are reasonable for the frames such as Type E and F, in which framed shear walls are not provided in the lower stories, however, for the other type of frames, another distributions such as that specified by the Uniform Building Code are more reasonable than the current Japanese Building Standard Law. From the results of analysis as mentioned above, following approximate equations can be drawn:

$$ {}_D\delta_i \,/\, {}_S\delta_{Ti} \simeq {}_DC_i \,/\, {}_SC_{Ti} \simeq {}_DC_B \,/\, {}_SC_{TB} \quad \text{for Type 0, A, B, C and D} \qquad (2) $$

$$ {}_D\delta_i \,/\, {}_S\delta_{Ri} \simeq {}_DC_i \,/\, {}_SC_{Ri} \simeq {}_DC_B \,/\, {}_SC_{RB} \quad \text{for Type E and F} \qquad (3) $$

in which ${}_SC_{RB}$ and ${}_SC_{TB}$ denote the base shear coefficients which are determined from the distribution of the lateral seismic coefficients which are shown in Fig.4(a) and Fig.4(b), respectively. Eqs.(2) and (3) show that if the value of ${}_DC_B$ is given by the function of T_1, the maximum story shear coefficient, ${}_DC_i$, and the maximum story drift, ${}_D\delta_i$, caused by the earthquake can be evaluated from the results of static analysis.

CONCLUSIONS

Linear static and dynamic analysis of reinforced concrete frames with framed shear walls were carried out for various arrangements of framed shear walls. Summarizing the results of analysis;

1. Fundamental periods of the frames with framed shear walls arranged apart can be approximately evaluated by Geiger's equation.
2. Maximum base shears of these frames caused by the earthquake are remarkably affected by the manner of arrangement of framed shear walls.
3. Maximum story shears and maximum story drifts occurred during the earthquake can be approximately evaluated from the static analysis, assuming that the relation between the base shear coefficient and the fundamental period of vibration of those frames can be determined.

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REFERENCES

(1) K. Muto, "Aseismic Design Analysis of Building," Maruzen Company, Ltd., Tokyo, 1974.

(2) M. Yamada and H. Kawamura, "Aseismic Capacity of Reinforced Concrete Structures," —Medium or Low Rise Reinforced Concrete Rigid Frames with Shear Walls—, Trans. of AIJ, No. 190, Dec., 1971, in Japanese.

(3) Iain A. Macleod, "New Rectangular Finite Element for Shear Wall Analysis," Proc. of ASCE, Vol. 95, No. ST3, Mar., 1969.

(4) Architectural Institute of Japan (AIJ), "Standard for Structural Calculation for Reinforced Concrete Structures," 1975.

(5) M. Tomii, T. Yamakawa, "Relation between the Nodal External Forces and the Nodal Displacements on the Boundary Frames of Rectangular Elastic Framed Shear Walls," Part I~V Trans. of AIJ, No. 237~241, Nov., Dec., 1975, Jan., Feb., Mar., 1976.

(6) Harold C. Martin,"Introduction to Matrix Methods of Structural Analysis," McGraw-Hill, Inc., New York, 1966.

(7) J. Penzien, "Dynamic Response of Elasto Plastic Frames," Proc. of ASCE, Vol. 86, No. ST7, July, 1960.

(8) R. W. Clough, "Analysis of Structural Vibration and Dynamic Response," Japan-U.S. Seminar on Matrix Method of Structural Analysis and Design, Tokyo, 1969.

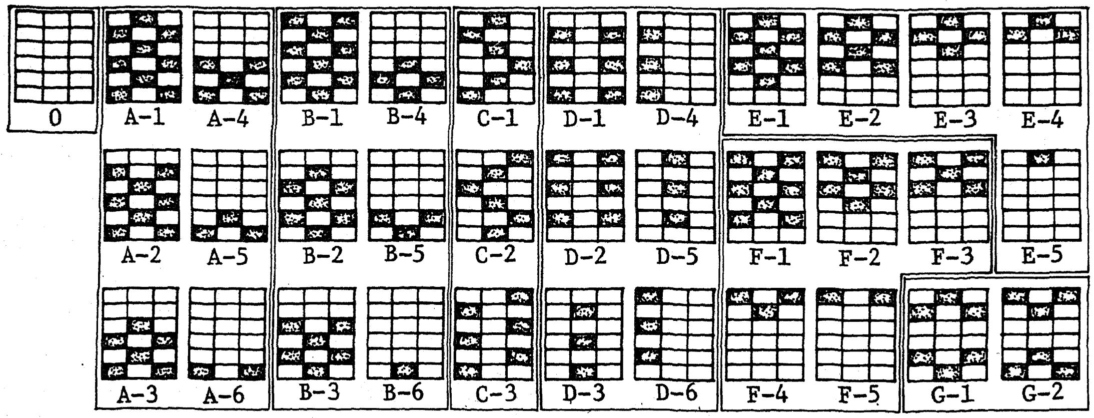


Fig.1 - Schematic elevation of frames

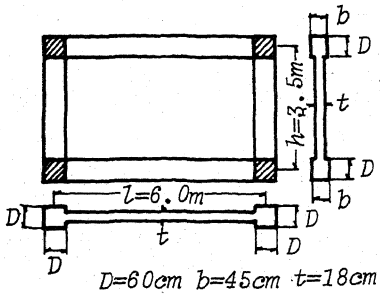


Fig.2 - Detail of the framed shear wall

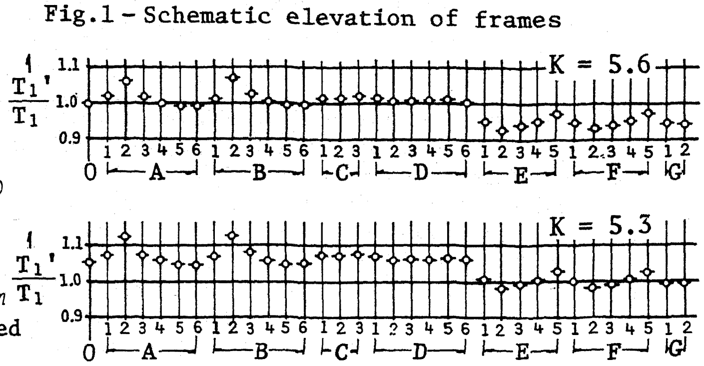


Fig.5 - Comparison between the fundamental periods by Geiger's equation and exact solutions

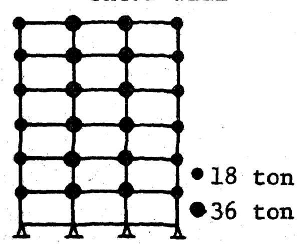


Fig.3 - Distribution of weights

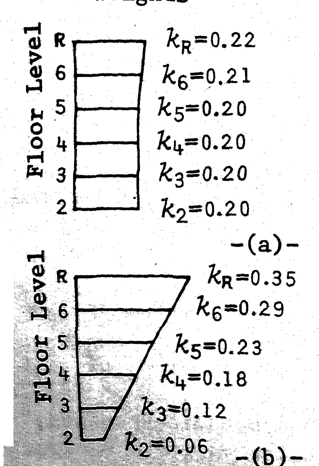


Fig.4 - Distribution of seismic coefficients

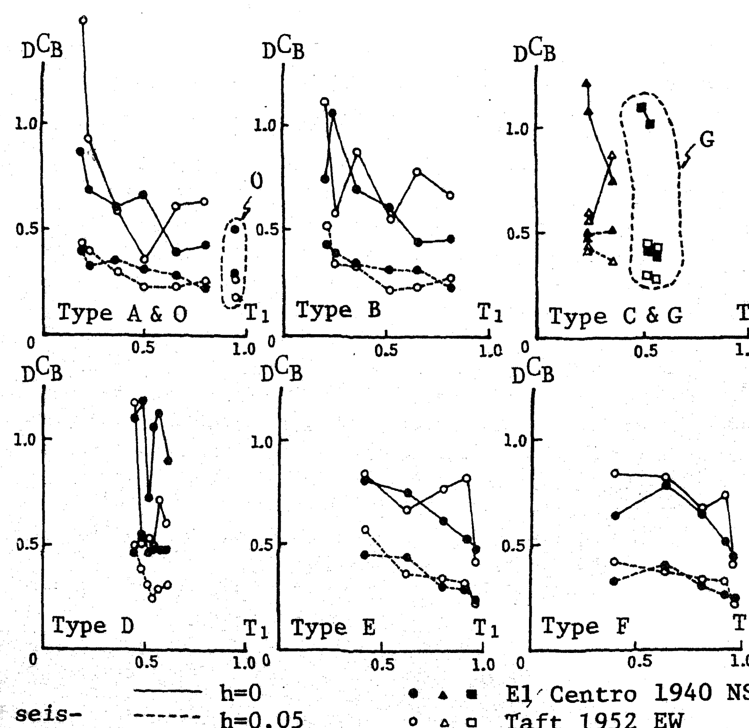
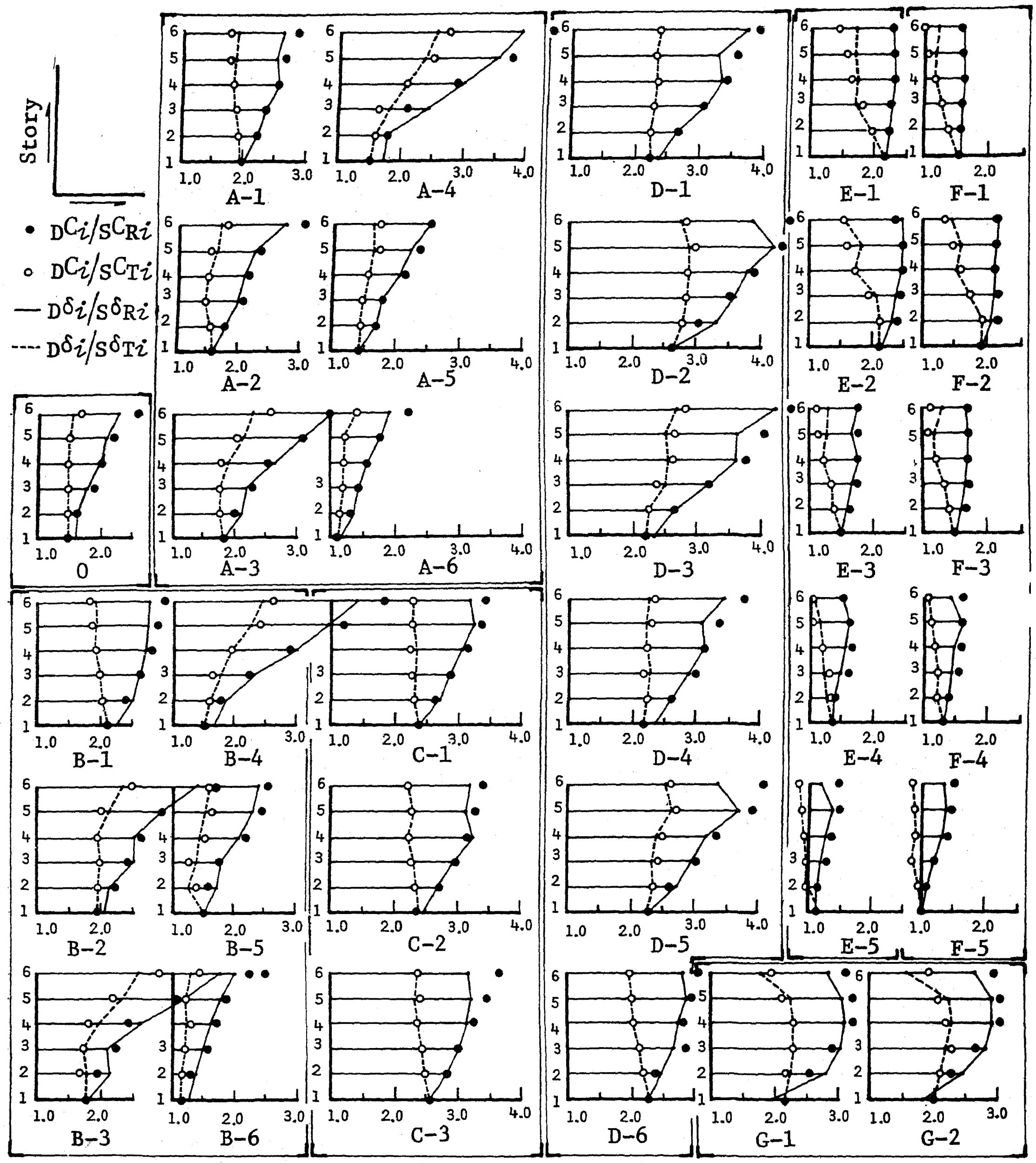


Fig.6 - Base shear coefficient



El Centro 1940 NS , h=0.05

Fig.7 - Variation of the maximum story shears and story drifts with height

Table 1 - Fundamental period of vibration (sec.)

Type	T_1												
		A-1	0.199	A-4	0.503	D-1	0.455	E-1	0.404	F-1	0.370
		A-2	0.233	A-5	0.666	D-2	0.498	E-2	0.613	F-2	0.637
0	0.955	A-3	0.371	A-6	0.806	D-3	0.524	E-3	0.719	F-3	0.777
B-1	0.207	B-4	0.518	C-1	0.254	D-4	0.542	E-4	0.877	F-4	0.884
B-2	0.251	B-5	0.656	C-2	0.255	D-5	0.563	E-5	0.933	F-5	0.933
B-3	0.359	B-6	0.820	C-3	0.369	D-6	0.582	G-1	0.510	G-2	0.543

DISCUSSION

A.K. Basak (India)

The effect of shear walls on overall stiffness formulation of any high rise structure will be predominant. The authors approach to this analysis are to be commended. The writer likes to point out a few points on this topic.

Type of construction of shear walls will be one effect which cannot be neglected. It means whether shear wall has to be constructed monolithically or by just dividing panelwise. Another point which is to be considered in the analysis before going to find the final displacements and forces is to analyze the structure three dimensional approach instead of doing a most conventional two dimensional procedure.

The writer wishes to know the authors views regarding the effect of shear walls placed between two parallel shear walls on overall structure behaviour when they are acting monolithically to that of parallel ones.

Author's Closure

With regard to the question of Mr. Basak, we wish to state that today (1977), since stiffness matrix of the framed shear wall is only determined analytically for one - bay - single - story shear walls (see Ref. 5), the behavior of frames with multistory shear walls are not examined in this paper. Now we are developing the stiffness matrix of the multi-story shear wall.

The main purpose of this analysis is to determine the exact solutions of the displacements, stresses and fundamental periods of the frames as well as to examine the structural behavior of the frames with framed shear walls arranged appart.These solutions will be able to be used to verify the validity of approximate solutions determined from the equivalent brace method for shear walls (See Ref.2). If the stiffness matrix of the multi-story shear walls mentioned above will be determined, three dimentional analyses of the whole building with such multi-story shear walls will be possible.