

論文

[2147] TWO - DIMENSIONAL DYNAMIC NON - LINEAR FINITE
ELEMENT ANALYSIS OF RC SHEAR WALLSC. M. Song¹ and K. Maekawa²

1. INTRODUCTION

Nowadays the nonlinear dynamic behaviors of RC structures are mainly investigated by experiments, which are very expensive and, in some cases, difficult to perform. Therefore, it is advisable to develop general numerical analysis methods as substitutes for experiments. A numerical method is also helpful in interpreting experimental results. The objective of this study is to develop a general dynamic finite element analysis procedure for RC structures subjected to in-plane dynamic forces. At present, most of the researches on dynamic analysis of RC structures are concerned with frames, columns, beams and other structural elements. Complicated RC structures are usually simplified as frames or columns with lumped masses, because it is easier to find the restoring forces of those structural elements and to solve this kind of structural systems mathematically. The dynamic analysis of frames and other structural elements is based on the equations of motion of the system,

$$[M] \{\ddot{X}\} + [C] \{\dot{X}\} + [K] \{X\} = \{F\} \quad (1)$$

in which $[M]$, $[C]$, $[K]$ are mass matrix, viscous damping matrix and secant stiffness matrix. $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$, $\{F\}$ are acceleration vector, velocity vector, displacement vector and external force vector, respectively. $[M]$ and $\{F\}$ are easily obtained. $[K]$ can be found from the relations of restoring forces and displacements of structural members which are usually deduced from experiments or numerical static analyses, but several researches have found that the dynamic responses of reinforced concrete structures during severe earthquakes can not be obtained accurately by means of static load-displacement relations [1]. $[C]$, which is one of the most difficult point in such an analysis, is usually solved from damping factors given based mostly on experiences and some experiments.

In this paper, the general finite element method established for static analysis of RC structures [2] is extended to dynamic analysis. This method makes use of two dimensional smeared crack elements for members and discrete crack elements for member junctions. It gave results of RC structures under arbitrary static loading histories in very good agreement to experimental results. From the equilibrium equation of a structure and the path-dependent constitutive model of RC elements, the governing equation can be written as,

$$\{R\} = \{F\} - [M] \{\ddot{X}\} - \iiint_V [B]^T \{\sigma(\varepsilon, t)\} dV = 0 \quad (2)$$

¹Graduate Student, Department of Civil Engineering, University of Tokyo

²Associate Professor, Department of Civil Engineering, University of Tokyo

in which $\{\sigma(\varepsilon, t)\}$ is stress vector which depends on strain and time history, and can be obtained from the constitutive model of RC elements. If a model of RC element can include path-dependent and time-dependent effects, this approach can take into consideration of viscous damping, hysteretic damping and stiffness characteristics at the same time instead of making the cumbersome separation of them as stiffness matrix and viscous matrix. Unfortunately, there is no time-dependent model of RC elements available. The model used in this analysis is only path-dependent. Hence, viscous damping is neglected. $[R]$ is error vector, which should be zero provided a given displacement field is the solution of the problem. Its values is checked in every iteration. Iterating will be performed until the error vector is small enough to satisfy accuracy requirements. The stiffness matrix is used only in predicting displacement increments from error vector. Its accuracy will affect convergence speed of iterating but not the accuracy of final results. This approach is preferred when it is difficult to obtain accurate stiffness or the iteration of Newton-Raphson method may diverge. The accumulated error in solution can be restrained in this method because equilibrium is checked constantly. The numerical procedure used in solving Eq. 2 is explained in Ref.[4]

2. ANALYSIS OF A RC COLUMN WITH A CONCENTRATED MASS

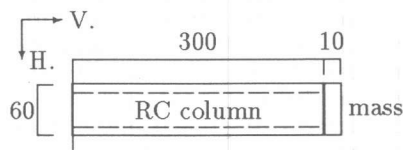


Figure 1: RC Column(cm)

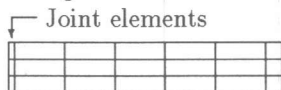


Figure 2: Element Mesh

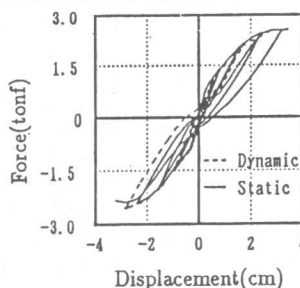


Figure 3: Force vs. Displacement

In order to verify the computer program and demonstrate the different dynamic response characteristics of different kinds of structures, a RC column with a concentrated mass (Fig.1) on its top was computed. Concrete strength is 30MPa. The density of concrete is assumed as zero for simplicity. The reinforcement ratio is 1.5%. The elastic modulus of concentrated mass is assumed to be 100 times of the initial elastic modulus of concrete. The density of the concentrated mass is $2 \times 10^{-4} \text{ kg/cm}^3$. This structure is divided into 3×6 8-node elements and 3 joint elements between the beam and foundation to idealize the pull-out of reinforcing bars from foundation. Total node number is 80(Fig.2). The ratio of width to length of this column is about 1/5 and the mass of the column is neglected. When a single degree of freedom system is subjected to horizontal ground motion \ddot{X}_g , its equation of motion Eq.(2) will be,

$$KX = -M(\ddot{X} + \ddot{X}_g) \quad (3)$$

where X and \ddot{X} are displacement and acceleration of the concentrated mass relative to foundation. $\ddot{X}_a = \ddot{X} + \ddot{X}_g$ is its absolute acceleration. K represents its restoring characteristics. From Eq.3 we can see that if the time-dependent effects of restoration force are neglected the static restoration force-displacement relation should be the same with dynamic one for a single degree of freedom systems. This column was analyzed under a static loading acting on its top and under a ground motion $\ddot{X}_g = 20 \sin\left(2\pi \frac{t}{0.72}\right) \text{ gal}$ by using the [WCOMD]. The relations between loads and displacements of concentrated mass are shown in Fig.3 with the solid and dash lines standing for static and dynamic analysis respectively. We can observe that it is close to the static one with only very small

discrepancy. This indicates that such a structure can be simplified as a single degree of freedom system, and that its static restoring force-displacement relation can be used in dynamic analyses and designs.

3. ANALYSIS OF A SINGLE STORY SHEAR WALL

The experiments of RC shear walls under earthquake loads are very difficult to control and very expensive. The seismic resistance ability of a RC shear wall is usually evaluated by static numerical analyses or experiments. It is doubtful whether the dynamic properties of such structures can be simulated correctly by static analyses. Using the above method and the path-dependent model of RC elements, the authors analyzed a single story reinforced concrete shear wall under reversed cyclic static load and a dynamic ground motion.

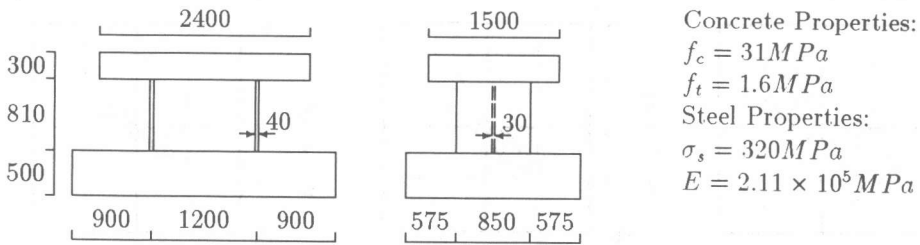


Figure 4: Single Story Shear Wall(mm)

Figure 4 shows the dimensions of the single story RC shear wall analyzed. Because the footing is much stiffer than the shear wall, it was omitted here for simplicity in computation. The junction deformation concerning the pull-out of reinforcing bars and shear slip was simulated by joint elements. The top slab is treated as a rigid body. Its weight is 17.5 tons. The density at both ends of the slab is 3 times of that in the middle part. Self-weight was imposed at first. Isotropically arranged reinforcement ratio of the shear wall is 1%. This shear wall was divided into 22 smeared crack RC elements and 16 joint elements on the connection surface of foundation, columns and wall. The total node number is 125. In the case of static analysis the force-displacement relation at the center of slab in x-direction is shown in Fig.5. The experimental result from Ref. [3] is shown in Fig. 6. The responses of this shear wall under a horizontal ground acceleration $\ddot{X}_{g1} = (100 + 80 \frac{t}{T}) \sin(2\pi \frac{t}{T}) \text{ gal}$, where $T=0.08\text{sec}$ is the period of input motion, were calculated. The time step used for Newmark's method is 0.002sec. Because the top slab is a rigid body, we can get the horizontal, vertical, rotational inertial forces by timing the mass or inertial moment of the top slab with corresponding accelerations. The relation between the horizontal inertial force of top slab and the relative displacement at the center of top slab is illustrated in Fig.7. It exhibits considerable difference with the static analysis(Fig.5). This can be explained by examining the inertial force histories obtained from analysis shown in Fig.8. Although only horizontal motion is inputted, vertical and rotational vibrations are also excited. The horizontal, vertical and rotational inertial forces in Fig.8 are in the same order after approximately 0.5sec. In the static analysis and experiment only horizontal forces are taken into consideration. The different loads caused the obvious discrepancy between Fig.5, or Fig.6 and Fig.7. This means that it is not proper to applied the static horizontal restoring force-displacement relation to dynamic analyses and designs.

4. ANALYSIS OF A THREE-STORY SHEAR WALL

In most of the studies on multi-story RC shear walls, each story is analyzed for

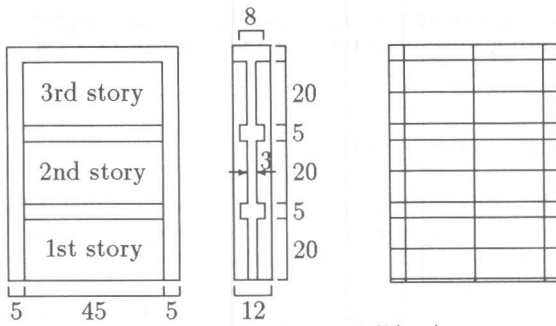


Figure 9: Three Story Shear Wall(cm) and Element Mesh

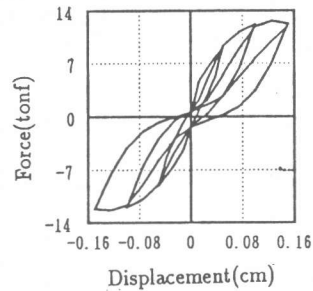


Figure 10: Force-Displacement Relation of Static Loading

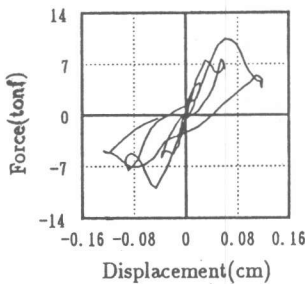


Figure 11: Force-Disp. Relation of 1st Story

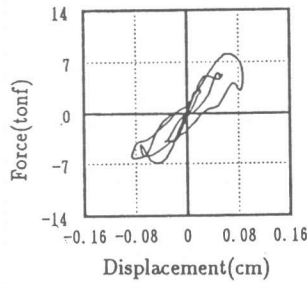


Figure 12: Force-Disp. Relation of 2nd Story

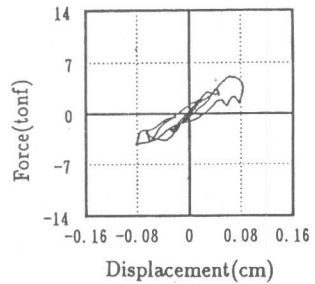


Figure 13: Force-Disp. Relation of 3rd Story

This three-story shear wall was divided into 36 8-node elements and 4 joint elements. Total nodal number is 144. The element mesh is shown in Fig.9.

Table 1. Material Properties		
Reinforcement layout:	Concrete strength:	Yielding stress of steel:
Column: 6-D6	$f_c=24\text{MPa}$	D6: $\sigma_y=470\text{MPa}$
Beam: 4-4 ϕ		4 ϕ : $\sigma_y=334\text{MPa}$
Wall: 1-2 ϕ 50@		2 ϕ : $\sigma_y=265\text{MPa}$

The response of this shear wall was calculated under a horizontal ground acceleration $\ddot{X}_g = 40 \frac{t}{T} \sin(2\pi \frac{t}{T}) \text{gal}$, where $T=0.16\text{sec}$ is the period of ground acceleration. Time step used in this analysis is 0.004sec , i.e., 40 steps in a period of input acceleration. In the static analysis of the first floor of the three-story shear wall, a reversed cyclic loading was applied at the center of the slab. The restoring force-displacement relation obtained is shown in Fig.10. The restoring force-displacement relations of the three shear walls obtained in the dynamic analysis are shown in Fig.11, Fig.12 and Fig.13, respectively. Vertical axis is the sum of inertial forces of the slabs above the corresponding story. Horizontal axis is the differences of the displacements at the centers of corresponding top slabs and bottom slabs. When subjected to horizontal ground motions, not only horizontal displacements but also rotation and vertical responses of the slabs are expected for the three-story shear wall. Since the height to width ratios of the shear walls are $\frac{4}{9}$, the stress distributions of the shear walls will be affected by the slabs and by each other. Comparing the four figures illustrating the restoring force-displacement relations (Fig.10-Fig.13), we can find that they are quite different with each other. The behavior of a three-story shear wall under dynamic loading is very complicated, which can not be fully represented by a restoring force-displacement relation obtained from static loads.

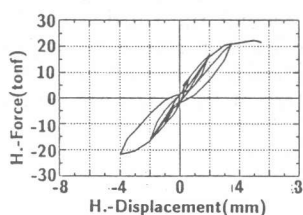


Figure 5: Force-Disp. Relation(Static)

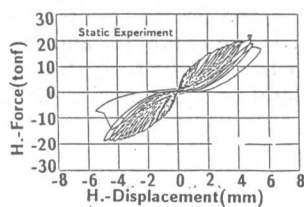


Figure 6: Force-Disp. Relation(Experimental)[3]

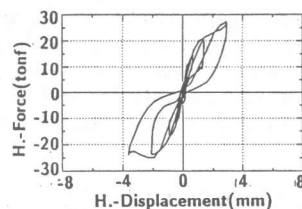


Figure 7: Force-Disp. Relation(Dynamic)

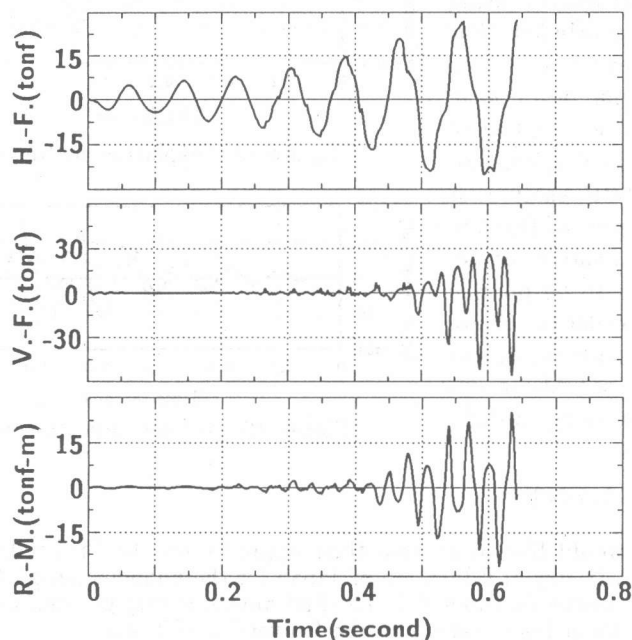


Figure 8: Inertial Force Histories

restoring force-displacement relation as a separated structure under static loads. Then, the relations are used for dynamic analysis. Because the stress distributions and crack patterns would be quite different among each story of a multi-story shear wall, and also not the same with those of a single story RC shear wall, generally, a restoring force-displacement relation obtained in such a way does not represent the dynamic characteristics of a multi-story shear wall adequately. In order to obtain accurate results it is necessary to analyze multi-story shear wall as it is, but few such studies have been done.

A three-story RC shear wall was targeted. The dimensions of the shear wall are shown in Fig.9. The three slabs are treated as elastic elements, with the elastic module as $2. \times 10^5$ MPa, which will not crack. The mass of this structure is concentrated on the three slabs with the mass of each slab being 13200kgf. The other material coefficients are given in Table 1. Here we completed two computations using the program [WCOMD]. One is on the three-story shear wall as a whole structure, and external load is a ground motion. The other one is on the lowest story of the three-story shear wall under a horizontal static reversed cyclic load. In these two analyses the element mesh of the lowest story used are the same. The restoring force-displacement relations obtained are compared.

The three curves in Fig.14 are the displacement responses at the centers of the three slabs, respectively. S1, S2 and S3 stand for the results of first, second and third story. In Fig.15 input ground acceleration is the curve S0, and the acceleration responses at the centers of slabs 1, 2, 3, are given by curves S1, S2, S3, respectively. It can be observed that the amplitudes of the acceleration responses at the centers of the slabs are larger than that of input acceleration.

5. CONCLUSIONS

From the above results in this primary stage of nonlinear dynamic analysis of RC structures using FEM, it can be concluded that under severe dynamic forces some nonlinear phenomena of in-plane responses, such as the coupling of different vibration modes, can not be found out by static analysis or simplified single degree of freedom model. A general analysis procedure of FEM seems to be promising in this field. In order to achieve good accuracy a time-dependent constitutive model suitable to dynamic analysis is urgently needed.

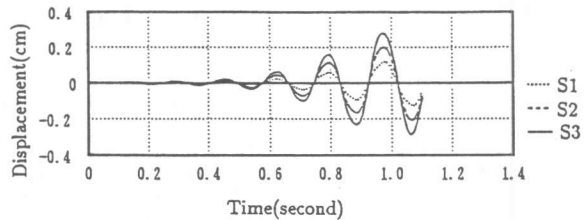


Figure 18: Displacement Response

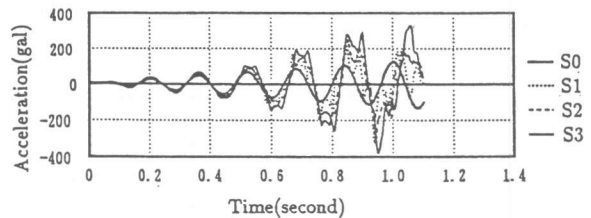


Figure 19: Acceleration Response

ACKNOWLEDGMENTS

The authors would like to express their appreciations to Prof. Okamura for his advises and to the Ministry of Education of Japan for the financial support of Grand-in-Aid for Scientific Research No.01420034. The first author is very grateful to the Japanese Government for its financing his study in the University of Tokyo.

REFERENCES

- [1] Mutsuyoshi, H., Machida, A. and Tsuruta, K. "Dynamic Nonlinear Earthquake Response of Reinforced Concrete Structures Based on Strain Rate Effect", Concrete Library of JSCE, No.8, Dec. 1986, pp.101-115.
- [2] Okamura, H., Shin, H. and Maekawa, K. "Development of Analytical Models for Reinforced Concrete", Structural Design, Analysis & Testing Proceedings, Structures Congress'89, ASCE, May 1-5, 1989, pp.49-58.
- [3] Murata, M., et al. "Model Test for Evaluation of the Seismic Behavior of Reactor Building, Part-5, Damping Characteristic Test(Static Test)", Summaries of Technical Papers of Annual Meeting of Architectural Institute of Japan, Structure I, 1989, pp.1059-1060.
- [4] Song, C.M. and Maekawa, k., "Nonlinear Dynamic Finite Element Analysis of RC Shear Walls Subjected to Seismic Excitations", 2nd Intl. Conf. on Computer Aided Analysis and Design of Concrete Structures, Austria, April, 1990, pp.1213-1224