SIMULATION OF COLLAPSE PROCESS OF A SCALED RC BUILDING SUBJECTED TO BASE EXCITATION

Hatem TAGEL-DIN[1] and Kimiro MEGURO[2]

[1] Member of JSCE, Ph.D., Visiting Researcher, Institute of Industrial Science, The University of Tokyo (4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan)
[2] Member of JSCE, Dr. Eng., Associate Professor, International Center for Disaster-Mitigation Engineering (INCEDE) Institute of Industrial Science, The University of Tokyo (4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan)

Simulation of collapse process of a small-scale reinforced concrete (RC) structure is carried out and compared with the results obtained by shaking table experiments. The experiment was performed using eleven storied RC building model subjected to series of base excitations whose shapes are same but different amplitudes. The numerical simulation is performed with two-dimensional Applied Element Method (AEM). The simulated structural response showed good agreement with experimental results. Due to the limitations of capacity of the shaking table used, the experiment was performed only up to the start of collapse. However, the analysis using the AEM was extended to simulate the detailed collapse behavior under magnified base excitations and realistic results were obtained.

***Key words**: Applied Element Method, AEM, reinforced concrete, collapse, computer simulation*

1. INTRODUCTION

Applied Element Method (AEM) is a newly developed method for structural analysis. The main advantage of the method is that it can follow the structural behavior from elastic range, crack initiation and propagation, separation of structural elements to total collapse in reasonable CPU time with reliable accuracy. The applicability and accuracy of the AEM in various fields were discussed in many publications[1)-6)]. It was proved that the method can follow nonlinear load-deformation before failure in Ref. (1). The complicated process of initiation and propagation, and opening and closure of cracks could be simulated[1)]. It was proved also that the location of crack initiation and propagation direction does not depend on the shape and/or arrangement of elements used[2)]. Even the effects of Poisson's ratio, which is normally neglected in the discrete type modeling, can be considred[3)]. The rigid body motion of failed structural elements can be simulated accurately[4)]. In addition, it was proved that the method can follow buckling load, and mode, and post-buckling behavior in reasonable CPU time and reliable accuracy[5)]. Collision and recontact problems[6)] are essential in many cases. For example, "What is the effect of collision between falling structural elements and neighbor structures?", What happens if structures having different dynamic characteristics collide during earthquakes?", "If a structure collapse, where and how do they undergo collapse?" and "What is the time of duration of collapse?". These questions can not be answered unless the numerical technique considers the recontact effects.

Although, these effects are very important from the viewpoint of safety and/or security of users, only few numerical techniques can deal with these problems. Many analyses of collision problems were performed using the EDEM[7), 8)], however, as the simulation using the EDEM needs long CPU time and it is less accurate than the proposed method in small deformation range. Other methods like Discontinuous Deformation Analysis, (DDA)[9)] were applied mainly to large deformation of rocks. The applicability of the DDA is still limited to simulation of behavior of rocks or bricks. In addition, the method requires long CPU time and many experiences to perform the simulation and in many cases, algorithm is not stable[9)].

2. OUTLINE OF EXPERIMENT

Recently, the size of scaled model specimens for structural tests tends to become larger and larger. A large scaled model test enables us to obtain data similar to real structures. However, since it requires large size testing facilities and large amount of research funds, it makes difficult to execute parametric tests. This paper introduces the simulation results of a scaled RC building model (1/15) subjected to magnified base excitation. The test structure was an eleven-storied building model[10),11)]. A general view of the model and sections are shown in Fig. 1. For more details about the structure shape or applied load, refer to Refs. (10) and (11). A series of base excitations were applied to the structure in order from small to large amplitudes. The shape of these excitations is same, namely, their frequency characteristics are same while amplitudes are different, from 40 Gal to 800 Gal, as shown in Fig. 2. The excitation G800 was applied twice to the structure, with normal (G800-1) and doubled (G800-2) time scale, respectively. This makes the numerical analysis more complicated because cumulative damage to the structural elements affects the response.

3. NUMERICAL MODEL AND RESULTS

The structure is modelled using 1,232 square-shaped elements. The comparison between the measured and simulated response of different floors is shown in detail in Ref. (12). The following factors are considered in the simulation using the AEM:

1. Stress-strain relation of concrete under cyclic loading[13)].
2. Stress-strain relation of reinforcement under cyclic loading[14)].
3. Additional bending moments because of load eccentricities at columns during tests[5)].
4. Large deformation, separation and rigid body motion of structural members during failure[4)].
5. Collision of structural members with each other and with the ground[6)].

The natural periods and modes, shown in Fig. 3, could be calculated using eigen value analysis. Different mode shapes and natural periods could be obtained easily. This indicates that the analysis can be performed in frequency domain as well as in time domain. Very good agreement could be obtained even when strong excitations are applied to the structure. Because of limitations of space, selected samples of the results are introduced in this paper. The calculated and measured responses of the roof

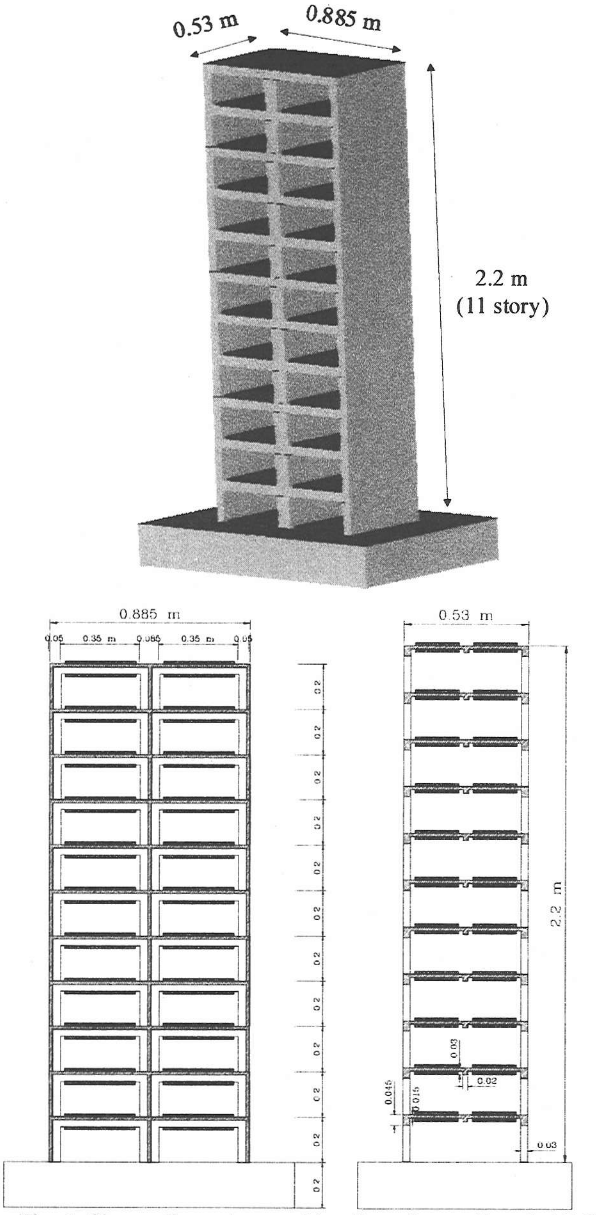

Fig. 1 Shape, dimensions and loading of a small-scaled RC building model under lateral excitation

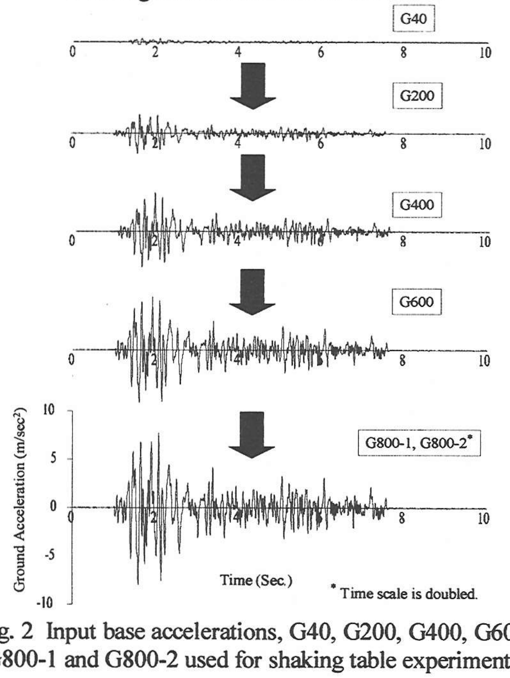

Fig. 2 Input base accelerations, G40, G200, G400, G600, G800-1 and G800-2 used for shaking table experiments.

in case of G600 and G800 are shown in Figs. 4 and 5, respectively. Although the structural behavior is highly nonlinear, with cracking, yield of reinforcement and crushing of concrete, excellent agreement between calculated and measured displacement responses could be obtained. Moreover, it is clear that the effects of cumulative damage during the applications of G40, G200 and G400 are considered automatically.

Most of experiments of RC structures are performed till failure but before complete collapse, where geometrical changes are generally small. It is very difficult to extend the experiments to follow the collapse process of structures. Difficulty arises from the fact that capacities of shaking tables are limited. As it is not easy to guess the collapse patterns before experiment, it is not safe to perform such kind of experiments, especially for full-sized structures. It may also result in damage of shaking table or surrounding area due to large collision forces.

The experiment was performed up to the G800-2 with doubled time scale, where the structure failed from the structural viewpoint, but it did not collapse. Therefore, numerical results of the same building subjected to a destructive excitation are also introduced. The amplitude of the base excitation of G800 is multiplied by 1.5 and its time scale is doubled. This destructive acceleration is applied to the same structure and the structural response during the process of failure including complete collapse is studied. As the collapse process is very complicated and it can not be represented accurately using two-dimensional model, relatively simple models for concrete crushing and reinforcement cut are adopted[6]. The analysis is performed using time increment of 0.0025 and 0.0005 seconds before and after recontact between elements occurs, respectively. The collapse history, shown in Fig. 6, can be summarized as follows:

1. Failure starts by excessive cracking, yield and cut of reinforcement at base floors.
2. Columns and beams of lower floors suffered complete damage while the upper floors suffered almost no damage but it moves together in rigid body motion and rotates around the failed structural elements till they collide with the ground.

4. CONCLUSIONS

Experimental results of a small-scaled RC building model subjected to a shaking table loading are compared with the results obtained by the new method, AEM. It can be concluded that:

1. The AEM can be applied for studying the nonlinear dynamic behavior of structures. Effects of cracking, concrete crushing, yield of reinforcement can be considered.
2. The rigid body motion and collision of structural elements during collapse can be followed with reliable accuracy.
3. No previous knowledge about the collapse process is needed before the analysis.
4. For future study of detailed collapse mechanism of structures, additional effects like buckling of reinforcement bars and sapling of concrete cover, etc. are needed to be modeled which are not taken into account in the AEM yet.

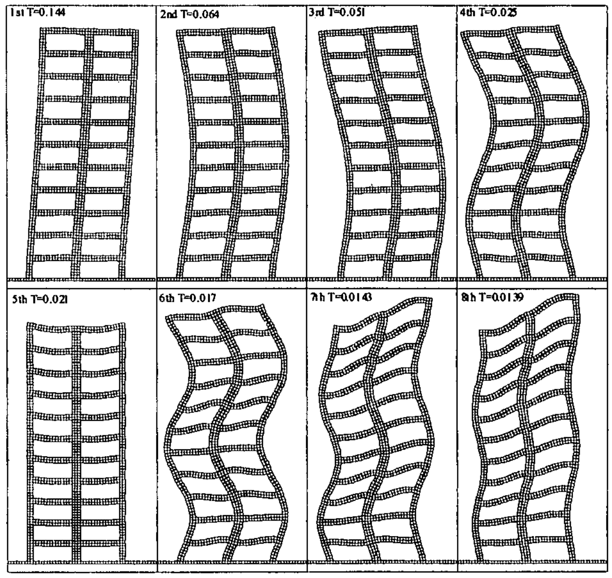

Fig. 3 Eigen values and modes of the building model.

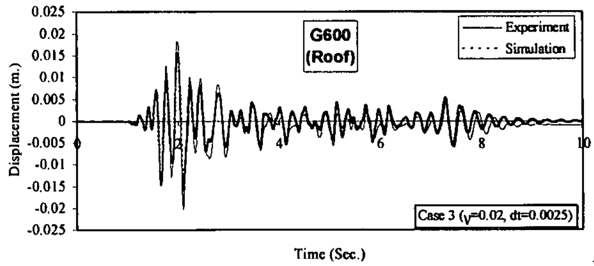

Fig. 4 Displacement response at the roof for G600 (damping ratio=0.02, simulation time increment=0.0025)

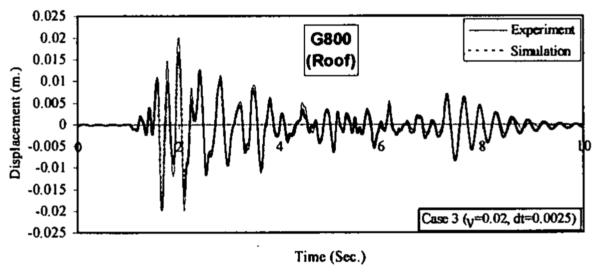

Fig. 5 Displacement response at the roof for G800-1 (damping ratio=0.02, simulation time increment=0.0025)

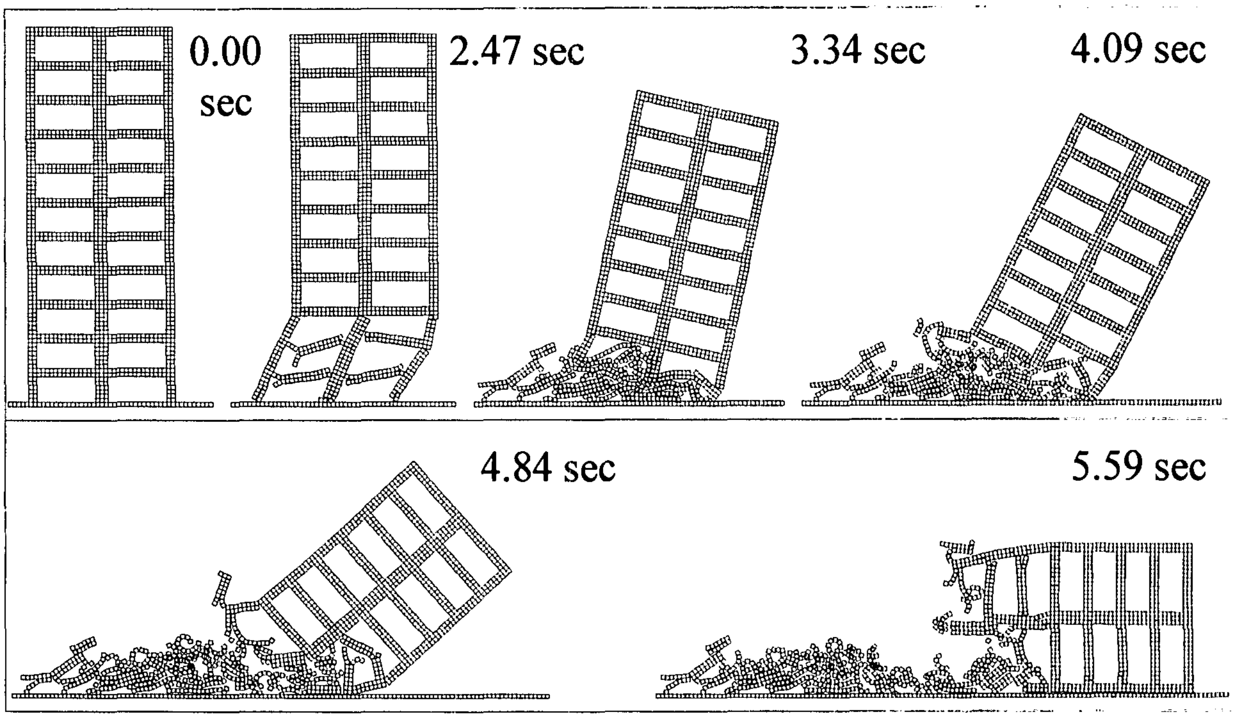

Fig. 6 Simulation of collapse process (Amplitude: 1200 Gal, Time scale: double)
(In the experiment, this case could not be performed because of limitation of shaking table capacity.)

5. It is very difficult, or impossible, to follow such behavior using methods that assumes continuum material, like FEM and BEM, where failure analysis is still restricted to cases where crack locations are known before the analysis.
6. The EDEM is one of the few models that can simulate such collapse behavior. The main advantage of the AEM compared to the EDEM is that the time increment can be enlarged before collision starts. In EDEM, the time increment is restricted to a certain small value, which is function of the material type and element size. It can not be enlarged even before collision starts. In the AEM, longer time increment can be used before collision and it makes the CPU time required shorter.

REFERENCES

1. Meguro K. and Tagel-Din H.: A new efficient technique for fracture analysis of structures, Bulletin of Earthquake Resistant Structure, No. 30, pp. 103-116, 1997.
2. Meguro K. and Tagel-Din H.: A new simplified and efficient technique for fracture behavior analysis of concrete structures, Proceedings of the Third International Conference on Fracture Mechanics of Concrete and Concrete Structures (FRAMCOS-3), Gifu, Japan, Oct. 1998.
3. Tagel-Din H. and Meguro K.: Consideration of Poisson's ratio effect in structural analysis using elements with three degrees of freedom, Bulletin of Earthquake Resistant Structure, No. 31, pp. 41-50, 1998.
4. Meguro K. and Tagel-Din H.: A new simple and accurate technique for failure analysis of structures, Bulletin of Earthquake Resistant Structure, No. 31, pp. 51-61, 1998.
5. Meguro K. and Tagel-Din H.: Simulation of buckling and post-buckling behavior of structures using applied element method, Bulletin of Earthquake Resistant Structure, No. 32, 1999.
6. Tagel-Din H. and Meguro K.: Applied element simulation for collapse analysis of structures, Bulletin of Earthquake Resistant Structure Research center No. 32, March, 1999.
7. Meguro K., Iwashita K. and Hakuno M.: Fracture analysis of media composed of irregularly shaped regions by the extended distinct element method, Structural Eng./Earthquake Eng., Vol. 8, No. 3, pp. 131s~142s, Japan Society of Civil Engineers, 1991.
8. Kusano N., Aoyagi T., Aizawa J.,Ueno H., Morikawa H. and Kobayashi N.: Impulsive local damage analysis of concrete structures by the distinct element method, J. of Nuclear Engineering and Design, No. 138, 1992.
9. Amadei B., Lin C. and Dwyer J.: Recent extensions to the DDA method, Proc. of 1st Int. Forum on Discontinuous Deformation Analysis (DDA), Berkley, California, Ed. Salami & Banks, 1996.
10. Okada T., Kumazawa F., Horiuchi S., Yamamoto M., Fujioka A., Shinozaki K. and Nakano Y.: Shaking table tests of reinforced concrete small scale model structure, Bulletin of Earthquake Resistant Structure, IIS, University of Tokyo, No. 22, pp. 13-40, 1989.
11. Kumazawa F. and Okada T.: Shaking table tests of reinforced concrete small scale model structure (Part 2), Bulletin of Earthquake Resistant Structure, IIS, University of Tokyo, No. 25, pp. 25-37, 1992.
12. Tagel-Din H.: A new efficient method for nonlinear, large deformation and collapse analysis of structures, Ph.D. thesis, Civil Eng. Dept., The University of Tokyo, Sept. 1998.
13. Okamura H. and Maekawa K.: Nonlinear analysis and constitutive models of reinforced concrete, Gihodo Co. Ltd., Tokyo, 1991.
14. Ristic D., Yamada Y., and Iemura H.: Stress-strain based modeling of hystertic structures under earthquake induced bending and varying axial loads, Research report, No. 86-ST-01, School of Civil Engineering, Kyoto University, March, 1986.