SIMULATION OF COLLAPSE PROCESS OF ELEVATED EXPRESSWAY BRIDGES DUE TO THE 1995 KOBE EARTHQUAKE

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ABSTRACT

At 5:46 a.m. (local time) on January 17, 1995, the Great Hanshin (Hyogoken-nambu or Kobe) earthquake hit the Hanshin-Awaji area, Japan. The damage due to this earthquake was the worst earthquake disaster in Japan since the 1923 Great Kanto earthquake Over 100,000 houses and buildings collapsed and many modern civil infrastructures such as elevated bridges of highways and railways, and port facilities, etc. were also heavily damaged. In addition, fires broke out razing many houses after the quake. The death toll was more than 6,400 including deaths due to various problems following the earthquake. Unfortunately, most deaths were caused due to collapse of structures. To mitigate casualties due to earthquakes, it is important to study the mechanism of collapse of structures during earthquakes. In this study, using the Extended Distinct Element Method (EDEM), which is applicable to both a composite and continuous medium, and a perfect discrete one, the collapse mechanism of structures during the 1995 Great Hanshin earthquake is studied. Although the phenomena treated in this study were difficult to be simulated by the conventional methods such as the finite element method, the numerical results obtained agree well with the actual earthquake damage.

1. INTRODUCTION

To mitigate casualties due to earthquakes, it is important to study the mechanism of collapse of structures during earthquakes. The Great Hanshin earthquake of 17 January 1995 caused over 100,000 collapsed houses and buildings, many heavily damaged civil infrastructures, and more than 6,400 deaths. Most of the deaths were due to collapse of structures.

To assure the safety of the general public in the event of future earthquakes, it is vital to analyze the collapse of structures. The process which is used in analyzing the behavior of structures in a collapse, addressing the problems such as, "Where and how do they undergo collapse?", "Is the time of collapse short or long?", "How far would the fragments of structural members fly and/or move in the process of collapse?", and "Would the collapse of structures be partial or overall?", is expected to greatly reduce the domains of structure collapse behavioral uncertainties. It is hoped that the knowledge of engineering concerned with collapse of structures will pave way in bringing forth approaches which could clarify these uncertainties. For example, we may undertake such architectural designs which allow partial structural collapse but prevent complete collapse. The means of such an analysis at present is the Extended (or Modified) Distinct Element Method (EDEM, MDEM) (Iwashita and Hakuno, 1990, Meguro et al., 1988, Meguro et al., 1991) which were developed from the distinct element method (Cundall, 1971).

In this study, using the EDEM, the mechanism of collapse of structures during the 1995 Great Hanshin earthquake is studied by simulating various modes of collapse process of structures, especially, elevated expressway bridges, reported after the quake.

2. EXTENDED DISTINCT ELEMENT METHOD

Although the conventional distinct element method (DEM) used in geotechnical engineering has proved very useful, only a few applications are heard in other media (Meguro and Hakuno. 1989a, Meguro and Hakuno, 1992, Meguro and Hakuno, 1994). The use of DEM was extended to the fracture analysis of structures, usually analyzed only by the methods based on continuum equations such as the FEM. The EDEM was originally developed by the research group including the first author of the paper. A computer algorithm has been written which can be used both for geotechnical engineering and for various other media as well. This method maintains continuity of the elements because it includes the additional spring called pore-spring or joint-spring which represents the effects of the material surrounding the elements. Figure 1 shows the EDE modelling.

The equations of motion of an element. i, having the mass, mi, and the moment of inertia, Ii, are

$$mi \bullet d^2u/dt^2 + Ci \bullet du/dt + Fi = 0 \tag{1}$$

$$Ii \bullet d^2\phi/dt^2 + Di \bullet d\phi/dt + Mi = 0 \tag{2}$$

in which Fi is the sum of all the forces acting on the element; Mi the sum of all the moments acting on it; Ci and Di the damping coefficients; u the displacement vector; and ϕ the rotational displacement.

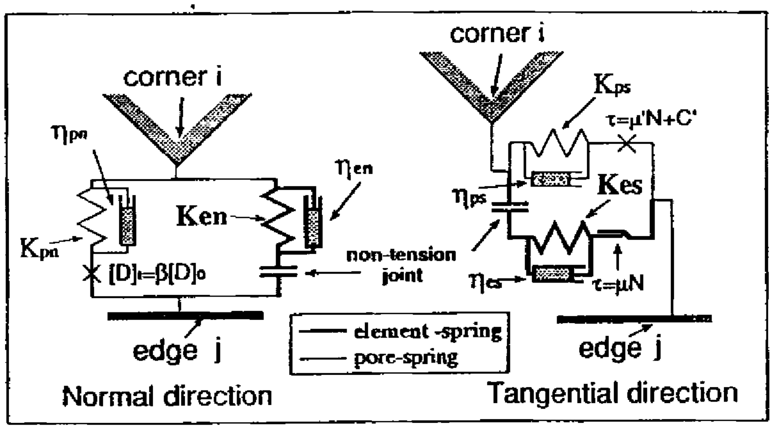

Figure 1. EDE modelling

The time histories of u and ϕ are obtained step-by-step in the time domain by the explicit numerical integration of equations (1) and (2).

The forces acting on an element are of two kinds, Fi and Mi which can be expressed as

$$Fi = Fie + Fip + mi\,(g+\alpha) \quad (3)$$

$$Mi = Mie + Mip \quad (4)$$

where Fie is the sum of forces from all the elements in contact; and Fip, from all the material surrounding it. Mie and Mip are the sums of all the moments from all the elements in contact and from all the material surrounding it respectively. These forces are obtained from the deformations of the element and pore-springs (joint-springs) set in the normal and tangential directions. In equation (3), g is the acceleration due to gravity and α is the external acceleration acting on it. As the fracture criterion of the pore-spring, a critical tensile strain (β) is specified in the normal direction, and Coulomb's equation is used in the tangential direction.

A new concept regarding the application of the EDEM is also proposed in this study: the EDEM can be taken as an extended lumped mass system, the field of application of which is extended to the discontinuous media, unlike the standard lumped mass system which is applicable only to the continuous media.

The EDEM is a conceptual model realized with a unique idea incorporated, wherein elements are each recognized as a unitary element of motion, a key to solve the equation of motion, and an interaction among elements is regarded as a spring action. In another aspect, the EDEM is taken as a lumped mass system, a subsystem of the composite, multi-degree-of-freedom (MDOF) system. Reference will now be made to "What is the most outstanding difference between the lumped mass system branched off from the MDOF system which is generally applied as a means for the dynamic response analysis, and the EDEM system?" The difference lies between the respective system configurations, the former being characterized in that only continuous bodies can be analyzed while the latter, featuring its configuration, enables behavioral tracking over such a scope from a continuous body to a discontinuous body. Taking note of this system configuration, the EDEM system may be grasped as a means for the response analysis (extended MDOF) following the MDOF system characterized by an extended scope of application.

Depending upon the material characteristics of the medium concerned and the scales of the structures to be modeled by the EDEM, it is impractical and beyond the operational capability of present computers to have models in which the elements have one-to-one correspondence with those in the real medium. For example, in the case where basic vibration and subsequent collapse modes, both of which hold significance in engineering, are required to be clarified, there is no need to model at the material level involving a large number of elements. In such a case, it is useful to consider the EDEM as an extended MDOF system, which can be applied to the collapse behavior of structure.

The dynamic response analysis by the conventional MDOF system is very difficult when analyzing the dynamic behavior in the stage of structural collapse initiation or in the process wherein structural collapse is progressing. However, the dynamic response analysis following the EDEM system allows us to simulate the collapse behavior of structures from a sound state to a complete collapse. Therefore, with the EDEM system dynamic response analysis, the structural vibration characteristics can vary with the outbreak of collapse, and keeping pace with the progress of collapse can phenomenally be illustrated in a state of spontaneity.

Examples of the EDE simulation are shown in Figures 2 to 5 (Meguro and Hakuno, 1989b). These are the analyses of dynamic behavior of the slender structures due to excitation. In case of the simulation using the model of case 1, cracks appear at the left and/or right beam-column connections of the 2nd and 3rd floors at 7.75 sec (Figure 3 (a)). The effects of appearance and slips between the cracks can be seen in the velocity response at the joint corners. Because of the damage due to cracks, dynamic properties of the structure system are changed. Its natural period become longer as shown in Figure 3 (b).

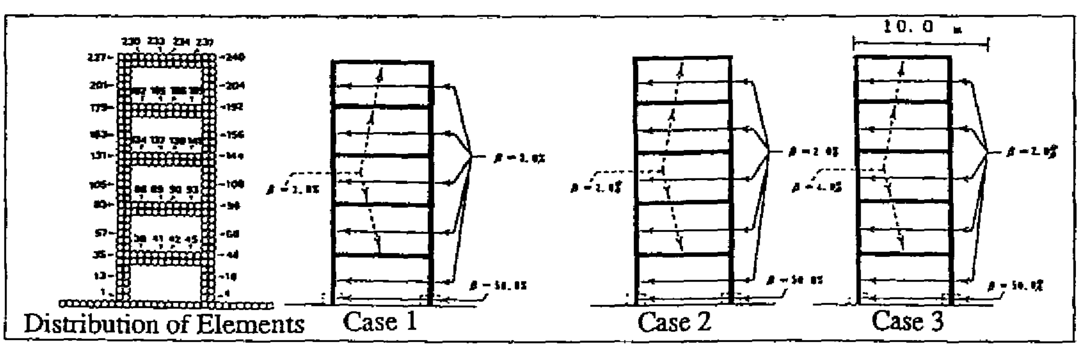

Figure 2. Building models

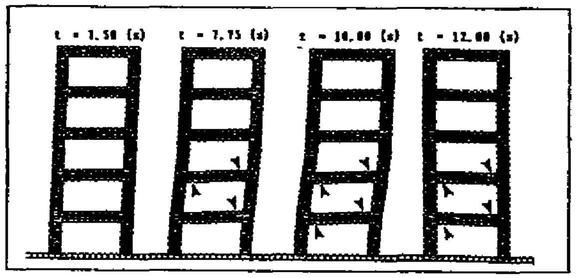

Figure 3(a). Seismic response analysis of a slender building (Case1: Example of earthquake damage to weak-beam-type buildings)

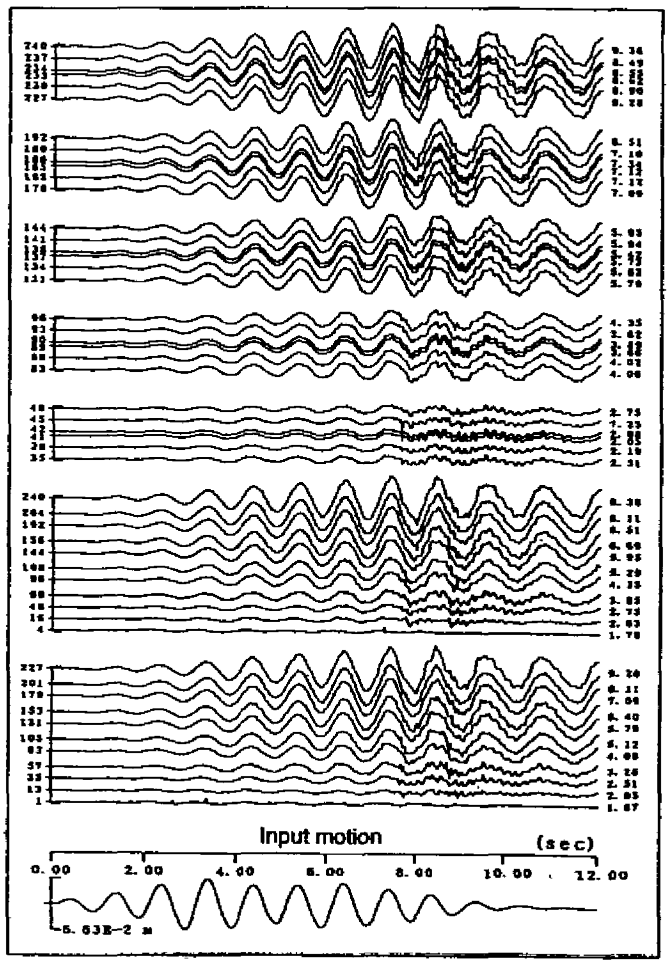

Figure 3(b) Time-history of response velocity (Horizontal comp. with Case 1)