3D Simulation of Concrete-Frame Collapse due to Dynamic Loading

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ABSTRACT

The extended distinct-element method (EDEM) is used to construct models of multi-degrees of freedom systems for particles of concrete frames and to conduct a series of numerical simulations in which the particles collapsed due to seismic forces. When a concrete frame collapses, it is reduced to a pile of debris. If the debris is rejoined to form the concrete frame, the original shape is restored; i.e., the frame prior to collapse is considered to be an assembled body of concrete debris. The EDEM is a method for analyzing discontinuous bodies, but here we report on an analysis in which concrete debris is considered to contain the elements of a discontinuous body. For convenience, we assumed that the particle shape in the debris is circular and that the parts are connected by springs that satisfy the Mohr-Coulomb yield conditions. The results of our simulations are in good agreement with records of damage done by past earthquakes.

INTRODUCTION

The distinct element method (DEM) proposed by Cundall (Cundall 1971)[1] has been used to analyze the collapse of various structures composed of granular materials such as soil and rock. Examples include the fracture of a structural foundation (Uemura and Hakuno 1987)[2], cliff collapse (Iwashita and Hakuno 1990)[3], rock avalanches (Uchida and Hakuno 1990)[4], debris flows (Hakuno and Uchida 1991)[5] and liquefaction (Hakuno and Tarumi 1988)[6]. Iwashita and Hakuno(1990)[3] proposed the extended distinct element method (EDEM) as a modification of Cundall's distinct element method by adding pore springs to such pore material as clay between particles, and Meguro and Hakuno proposed that an aggregate of circular elements and mortar constituent pore springs would satisfy the conditions of fracture (Meguro and Hakuno 1989)[7]. Under these assumptions, we established a model for concrete by setting these pore springs among elements and then followed the fracture process (Meguro and Hakuno 1989)[7].

The EDEM, however, has a serious drawback in that it requires an enormous amount of calculation time because explicit numerical integration is unstable unless the time step used is very short. Therefore, should this EDEM method be applied to concrete structures, an analysis of the fracture of the whole structure would be prohibitive. Therefore, we analyze only the fracture of the structural members composed of few elements.

To simulate the fracture analysis of a whole structure, we reduced the number of elements as much as possible. For example, for a column, two circular elements for two dimensional analysis, four spherical ones for three dimensional analysis, are arranged through the member cross section because at least two or four elements are required to resist bending moment in the column. But, when the number of elements is drastically reduced, the model becomes oversimplified. The structure model may show a very different mode of fracture than that occurring when an actual structure fractures.

We assume that a result that tells whether the structural component in question has broken down or has not broken down is satisfactory for purposes of studying fracture of the structure as a whole. Detailed information on the mode of local fracture of a particular part is sacrificed. When the number of elements is greatly reduced, the model resembles a multi-degree-of –freedom (MDOF) model common to earthquake-response analyses. The EDEM model proposed in the present study allows fracture separation to occur. Conditions in which elements become separated from one another after fracture are not allowed in analyses with MDOF models.

EXTENDED DISTINCT ELEMENT METHOD

Although the conventional distinct element method used in geotechnical engineering has proven very useful, there has been few reports of the DEM being applied to other media. We have extended the use of DEM to the analysis of the fracture of concrete structures, usually analyzed only by continuous material method (FEM). We have developed an extended distinct element method, and a computer program has been written that can be used both for geotechnical engineering and with various other media as well. This method maintains continuity of the circular elements because it includes the pore material springs. Fig.1 shows how concrete is modeled using the EDEM.

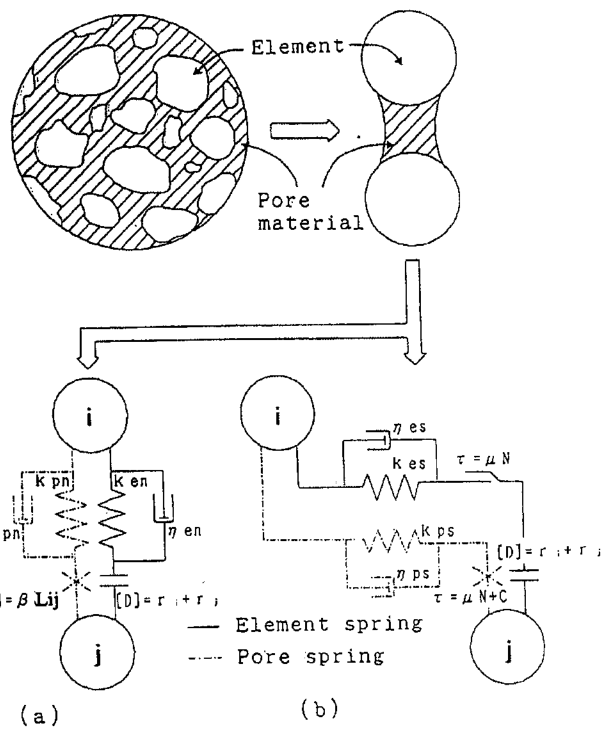

Fig.1. EDEM Modeling of Concrete: (a) Normal Direction; (b)Tangential Direction

Equation of Motion

The motion of a particle elememt i having mass m_i and moment of inertia I_i is

$$m_i\ddot{u} + Ci\dot{u} + Fi = 0 \qquad (1)$$

$$Ii\ddot{\phi} + Di\dot{\phi} + Mi = 0 \qquad (2)$$

in which **Fi** = sum of all the forces acting on the particle; **Mi** = sum of all the moments acting on the particle;

Ci and Di = damping coefficients; **u** = displacement vector; and ϕ = angular displacement.

The dynamic response of the structure can be obtained in the time domain by step-by-step numerical integration of the equation of motion.

Estimation of Material Parameters of EDEM

Although the material parameters for EDEM analysis should be determined experimentally, it is impossible to do so in certain cases. Therefore, we proposed a simple method to determine these parameters that takes in to account the physical significance of the individual parameters.

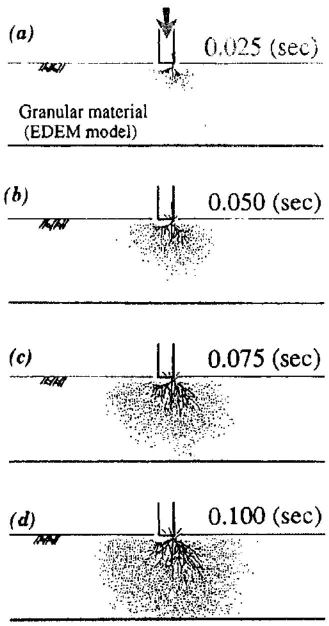

Fig.2. Propagation of Wave in EDEM Model

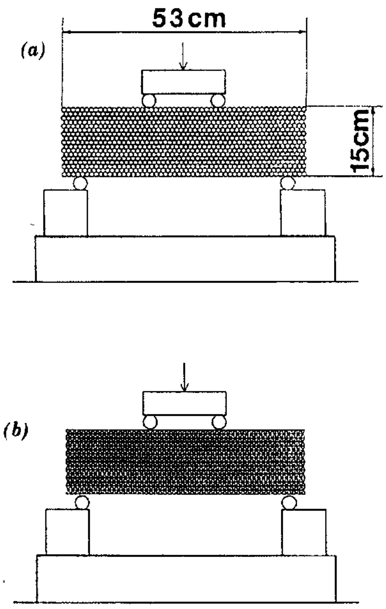

Fig.3. Model of Concrete Specimen: (a) Particle Distribution; (b) Mortar Spring Distribution

Estimation of Elastic Constants of Element Spring and Pore Spring

The spring constants of the elements and pore material springs can be determined from the wave velocity in the objective medium. The propagation velocities of the P- and S- waves, Vp and Vs, respectively, depend on Young's modulus, Poisson's ratio and mass density. We assume that the elastic constant of the normal spring is estimated by Vp, which is obtained from the impulsive numerical experiment (Fig. 2) and that of the tangential spring by Vs. The composite elastic constant of an element and the pore material spring are obtained in both directions. The elastic constants of the element and pore material in both directions can be calculated from these composite values.

NUMERICAL RESULTS

Case 1: Bending Fracture Test of Concrete Specimen

The EDEM was used to simulate a bending fracture test of the concrete specimen modeled in Fig.3. The specimen was bent under a constant rate of deformation. The fracture process during bending is shown in Fig.4, which also shows the mortar spring distribution and the position of the intact mortar. During stage 1, no cracks occur in the spring locations. Should a crack occur, the mortar spring at the corresponding site would be eliminated. The cracks in Fig.4 are all tensile cracks. Although the test system is completely symmetric, the crack produced is not symmetric. We believe this is because of accumulated computational error due to canceling for no initial imperfections were prescribed for the pore springs.

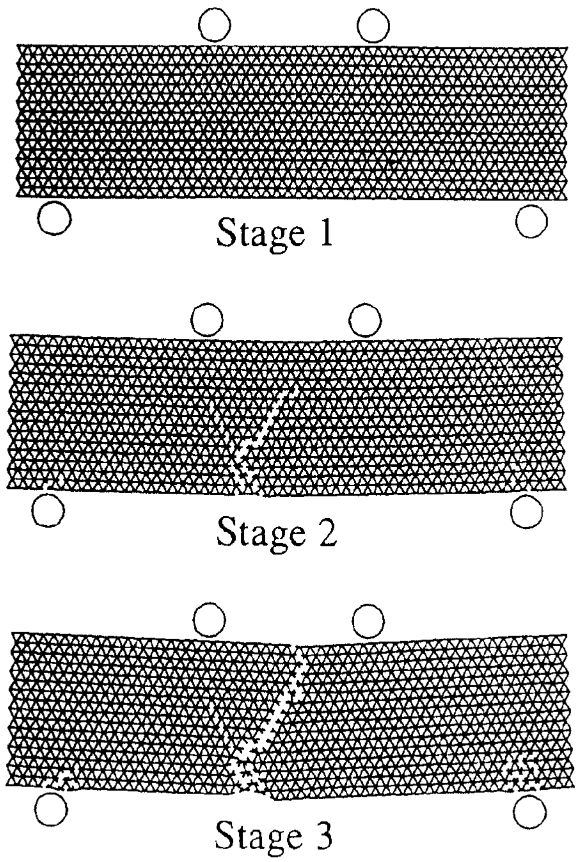

Fig.4. EDEM Simulation of Bending Test under Vertical, Constant-Rate Deformation (Mortar Spring Distribution)

Case 2: Collapse Simulation of Concrete Frames by Horizontal Seismic Oscillation

Because this simulation deals with the fracture of a whole structure and because aggregate particles are modeled by elements and mortar modeled by springs, the number of elements would be enormous, making numerical analysis prohibitive. We nevertheless simulated the collapse process by sacrificing accuracy of the local fracture mode prediction in favor of global mode prediction, by using models in which the number of elements was minimized. Two elements were arranged in the cross sections of the columns and beams. The input seismic waves for the model frame are simulated to excite resonance of the model.

1. Simulation of a pancake-type collapse; This type of collapse is apt to occur when columns and walls are weak, as when they are composed of brick masonry. (Fig.5,6,7,8)

Fig.5. Pancake-Type Collapse of Building in Athens Earthquake, Greece, 1999

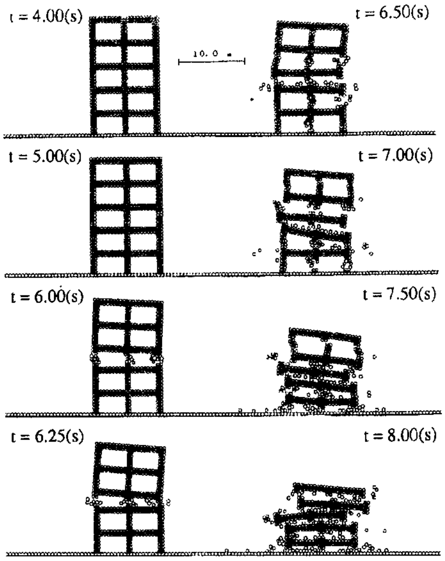

Fig.6. Pancake Collapse of Five-Story Building due to Horizontal Seismic Loading (Element and Pore Spring)

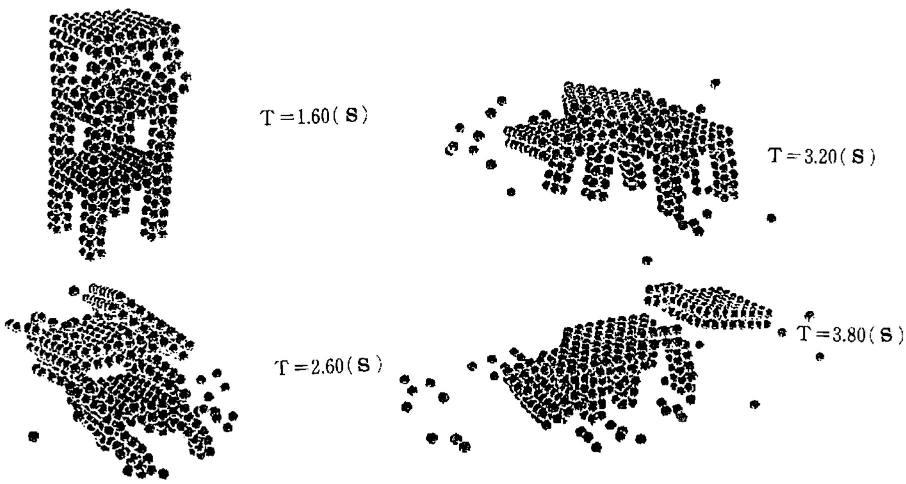

Fig.7. 3D Pancake Collapse of Three-Story Building because of Horizontal Seismic Loading (Element Distrib.)

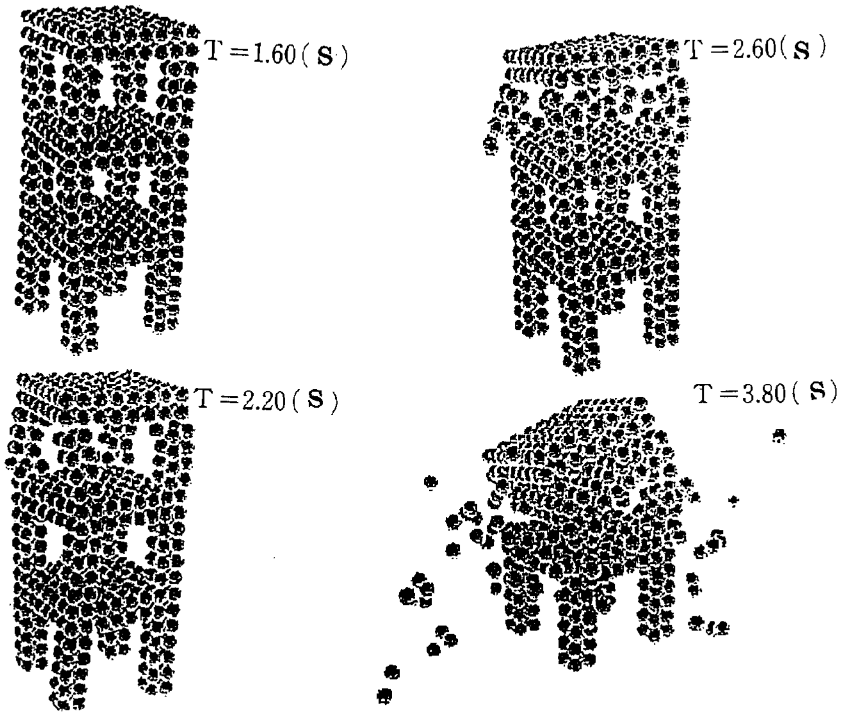

Fig.8. Pancake Collapse of Three-Story Building because of Twisting and Horizontal Seismic Loading (Element and Pore Spring Distribution)

2. Fig.9 shows the damage done on a highway bridge in Northridge Earthquake,USA, 1994.
   Fig.10 shows the collapse simulation of it.

Fig.9. Complicated Collapse of a Highway Bridge in Northridge Earthquake, USA, 1994 (Photo. By EERC, University of California at Berkeley)

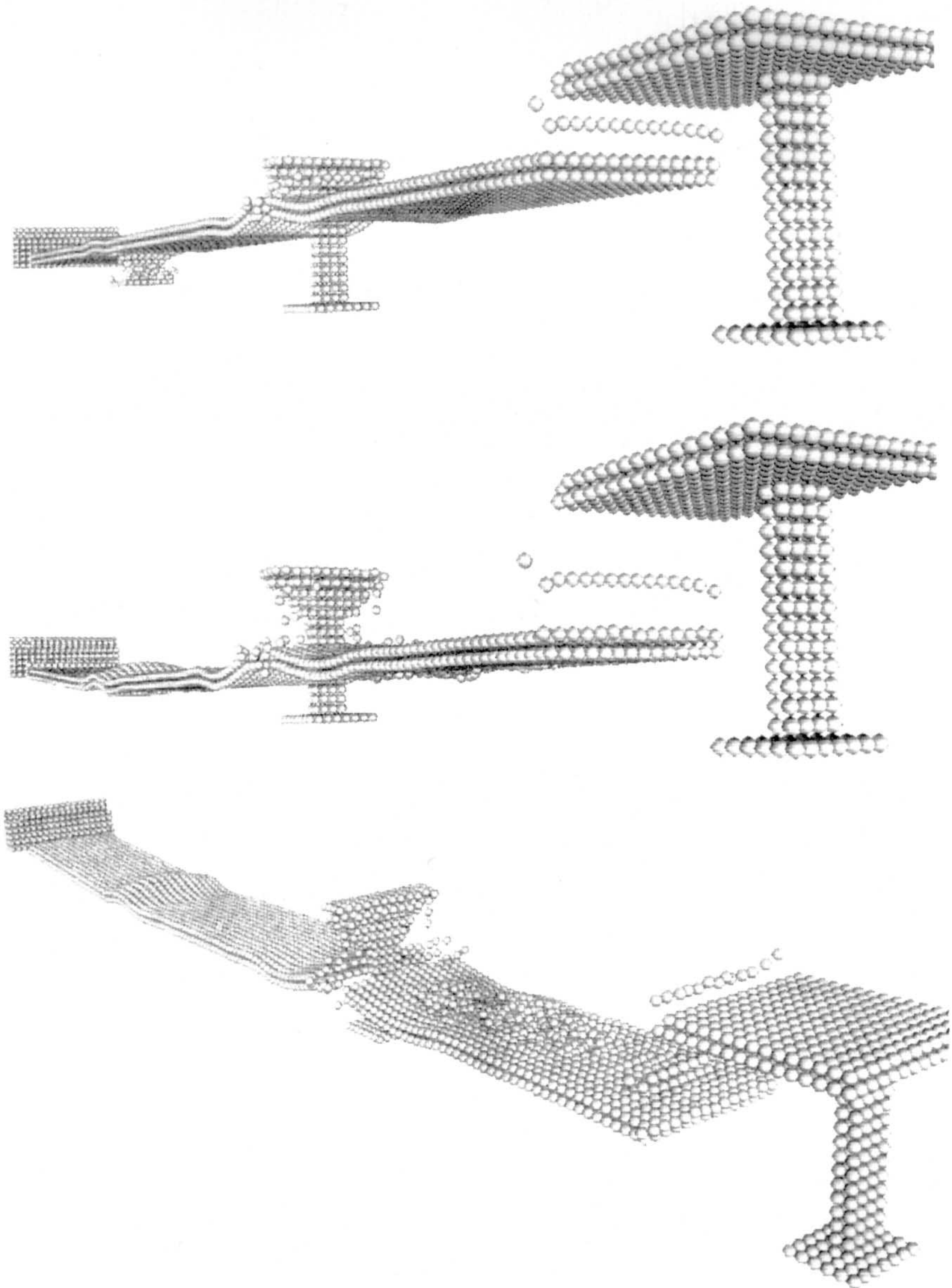

Fig.10. 3D Collapse Process Simulation of a Highway Bridge (Element Distribution)

CONCLUSION

Models of concrete frames were designed based on the assumption that the concrete aggregate can be modeled as circular or spherical elements and that mortar that binds the aggregate can be represented by springs. The bending fracture of a beam and collapse processes of a 2-D and a 3-D concrete frame were simulated. Although in some cases this approach does not accurately represent the model of local fracture, the results for the fracture of a structure as a whole such as pancake-type collapse, generally replicate observed earthquake damage. We believe that when the improvements of the speed of computers are made, the EDEM will be a powerful means of analyzing the fracture of a structure.

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