0240

SIMULATION OF CONCRETE FRAME COLLAPSE DUE TO DYNAMIC LOADING

Motohiko HAKUNO[1]

SUMMARY

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) has been used to analyze the collapse of various structures composed of granular materials such as soil and rock. I made simulation studies related to the fracture of a structural foundation, cliff collapse, rock avalanches, debris flows, and liquefaction. Iwashita and Hakuno(1990) 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). The EDEM model proposed in the present study allows fracture separation to occur.

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.

[1] *Dept. of Civil and Environmental Engineering, Toyo University, Kawagoe, Saitama, Japan. Email:hakuno@eng.toyo.ac.jp*

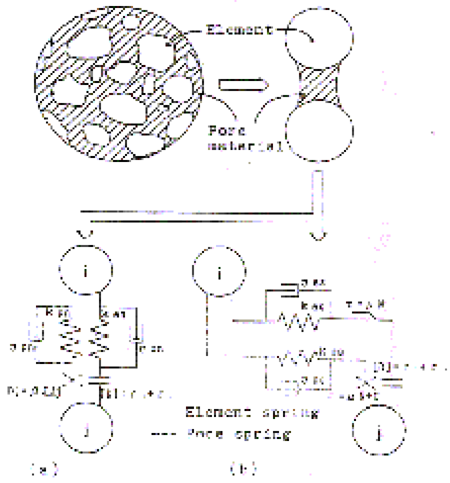


Figure 1: EDEM modeling of concrete: (a) Normal direction; (b)Tangential direction

Equation of Motion

$$m_i \ddot{\mathbf{u}} + \mathbf{C}_i \dot{\mathbf{u}} + \mathbf{F}_i = 0 \qquad (1)$$

$$\mathbf{I}_i \ddot{\psi} + \mathbf{D}_i \dot{\psi} + \mathbf{M}_i = 0 \qquad (2)$$

The motion of a particle elememt i having mass mi and moment of inertia Ii is

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 ψ = 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.

Pore Springs and Their Fracture Criteria

Establishment of Pore Spring

To account for the pore material in the EDEM model, we introduced additional mortar springs called pore springs between elements in both the normal and tangential directions (Fig.1). The establishment of the pore spring is shown between elements i and j. This takes place when the distance between these two elements is closer than a prescribed value.

The natural length of the pore spring, Lij is prescribed input data to the computer program and is the initial distance between elements i and j.

Fracture Criteria for Pore Spring

At first, the pore material is firm and stable and associated with the particles. But when an external force acts on the model the elements begin to move, and cracks are produced in the pore material by tensile and shear forces. The pore material will its tensile resistance and will resist only compressive and shear deformation between the particles. Therefore, we have divided the fracture process of the pore spring into 2 stages: In stage 1, the pore spring is normal. It resists not only compression but tension and shearing deformation when an external compressive or tensile force acts on it. In stage 2, cracks are present in the pore material. The effect of the pore spring remains only while the compressive force acts between elements. Because the pore spring has no tensile resistance, it resists compressive and shearing deformation only while the compressive force acts.

There are two conditions under which the pore spring changes from the first to the second stage as follows: (1) when the pore spring is fractured by tensile force in the normal direction; and (2) when the pore spring is fractured by shear force in the tangential direction.

During EDEM calculations, the particular condition for each crack in the pore spring is saved. when the pore springs were established, each was in the first stage, but the stage changes according to the following fracture criteria:

1. Fracture criteria in the normal direction: The pore spring changes from the first to the second stage when the strain on it at time t exceeds a prescribed critical strain β .

Although this criterion shows that a pore spring crack is produced by tensile strain in the normal direction, in both the normal and tangential directions, the pore springs are assumed to change from the first to the second stage. At the same time, the cause of pore-spring destruction is registered in the computer as the tensile strain in the normal direction.

Fracture criteria in the tangential direction; Coulomb's equation gives the fracture criteria for the pore spring in the tangential direction as

$$\tau = C + \mu N \qquad (3)$$

in which τ = maximum resistant shear force between particles in the tangential direction; C = cohesive constant force; μ = friction coefficient; and N = normal force acting between particles i and j.

When the tangential force acting on the pore spring is larger than τ , the state of pore spring in both the normal and tangential directions is assumed to change to stage 2. At that time, the cause of fracture is registered in the computer as the shearing force, and the force acting tangentially on this pore spring becomes τ .

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.

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 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.

Estimation of Time Increment Δt

The EDEM employs explicit step-by-step numerical integration. The stability of the analysis depends on the value of the time increment Δt and it is necessary to determine the proper value of Δt. We determined this time increment Δt as follows: In the EDEM, the forces that act on each element are calculated after taking into account all elements in contact and the pore material surrounding the elements. Reaction forces can not be estimated accurately if the stress wave moves over the contacting element during the time increment Δt. Therefore, a rough determination of Δt is

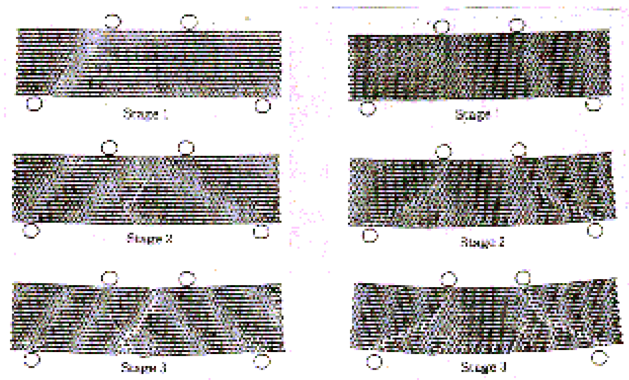
$$\Delta t < Dmin/Vp \qquad (4)$$

in which Vp = P-wave propagation velocity, and Dmin = minimum distance between the centers of two elements. This is what is known as an explicit time-step calculation.

NUMERICAL RESULTS

Case 1: Bending Fracture Test of Concrete Specimen

The EDEM was used to simulate a bending fracture test of the concrete specimen. The specimen was bent under a constant rate of deformation. The fracture process during bending is shown in Fig.2, 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 the Fig.2(a) 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. In the Fig.2(b) for the reinforced concrete specimen, the completely different fracture process is found. In this case, shear strain is predominant.



(a)Concrete specimen without reinforcement (b)Reinforced concrete specimen

Figure 2: 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.

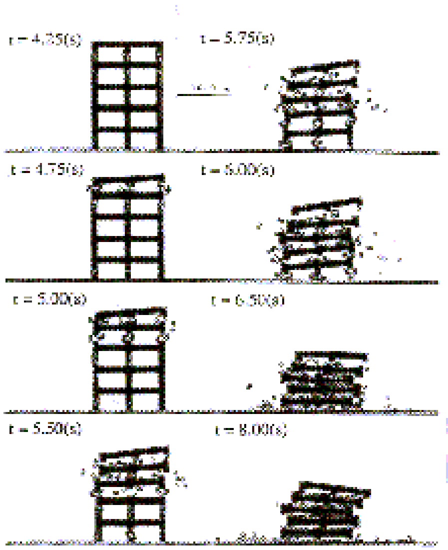


Figure 3: Upper-story fracture and pancake collapse of five-story building because of horizontal seismic loading (Element and pore spring distribution)

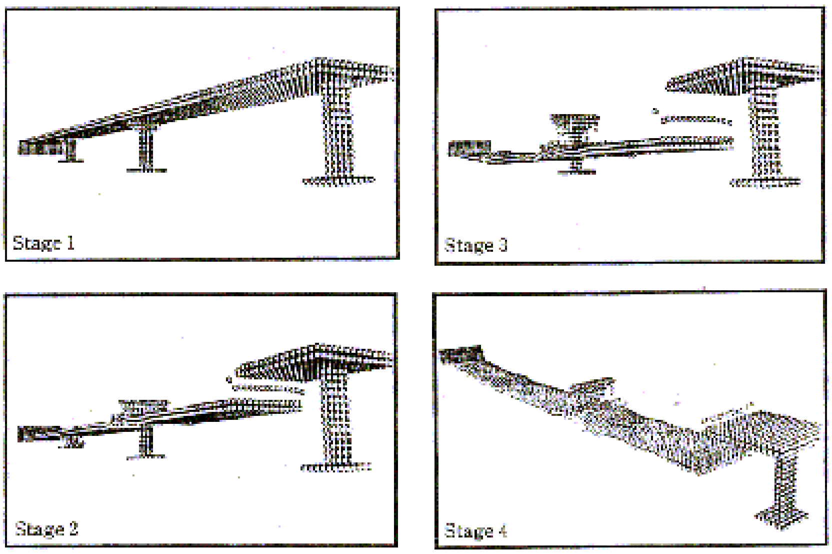


Figure 4: 3-D Collapse process simulation of a highway bridge

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. In this failure mode, particular cases in which columns taper towards the upper floor, as was often the case in the Mexico earthquake of 1985, are dealt with.The numerical results in Fig.3 show that the fracture begins in the columns on the upper floors because they are weaker. Normally, shearing fracture would have been the mode of fracture, but Fig.3 indicates a different mode, probably because too few elements were used. As future speed of computers increase, we will increase the number of elements and attempt to reproduce the mode of local fracture with higher fidelity.

CONCLUSION

Models of concrete frames were designed based on the assumption that the concrete aggregate can be modeled as circular 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 concrete frame and a 3-D highway bridge 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.

REFERENCES

Cundall, P. A. (1971). "A computer model for simulating progressive, large scale movement in blocky rock sys tem." Symp., ISRM. Nancy, France, Proc. 2, pp129-136.

Iwashita, K., and Hakuno, M. (1990). "Modified distinct element method simulation of dynamic cliff collapse." Structural Engineering /Earthquake Engineering, Proc. JSCE, Japan Society of Civil Engineers, Tokyo, Japan, 7(1), pp133s-142s.

Meguro, K., and Hakuno, M.(1989). "Fracture analyses of concrete structures by the modified distinct element method." Structural Engineering/Earthquake Engineering, Proc. JSCE, Japan Society of Civil Engineers, Tokyo, Japan, 6(2), pp283s-294s.