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FRACTURE TESTS OF MASONRY CONCRETE ELEMENTS BY GRANULAR ASSEMBLY SIMULATION

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SUMMARY

A number of fracture analyses of concrete structures have been made; but, none have been reported in which concrete has been considered a noncontinuous material. In 1971, Cundall introduced the Distinct Element Method (DEM), a numerical simulation by which rock behavior can be analyzed. It is based on the assumption that each individual rock element satisfies the equation of motion. We have developed a modified DEM in which the gravel and mortar present in concrete are idealized respectively as circular particle elements and nonlinear springs. With it, we analyzed the fracture behaviors of concrete structures. Our numerical results agree well with observations recorded for past earthquake damage.

INTRODUCTION

Various fracture analyses of concrete have been made by using the Finite Element Method (FEM). But, no numerical fracture analyses in which concrete has been considered a noncontinuous material have been reported.

The idea of handling sand analytically as a granular assembly was introduced by T. Mogami(Ref. 1) in 1965. Then in 1971, Cundall introduced the Distinct Element Method (DEM)(Ref. 2), a numerical simulation that can be used to analyze the behavior of rock. It is based on the assumption that each individual rock element satisfies the equation of motion. In 1973, independent of Cundall, Hakuno and Hirao also made a granular assembly simulation of circular particles in their investigation of the static deformation of sand (Ref. 3). Concrete consists of a mixture of gravel and mortar, and we have now developed a modified DEM in which the gravel and mortar are idealized respectively as circular particle elements and nonlinear springs between them. (Fig.1)

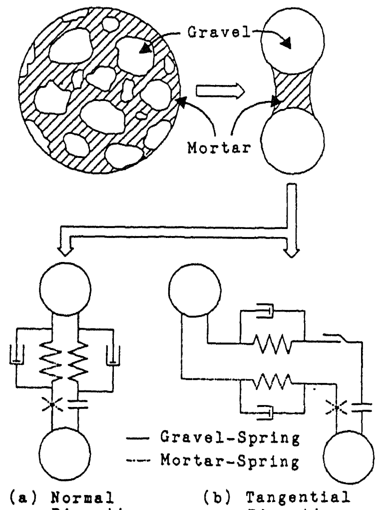


Fig.1 Modeling of Concerte to a Mass-Spring System

All the equations of motion for each particle were solved step-by-step in the time domain.

METHOD OF ANALYSIS

Distinct Element Method

Cundall's(1971) Distinct Element Method (DEM) is based on the assumption that every element satisfies the equation of motion and that the transmission of force between elements follows the law of action and reaction. This method presented a new way by which to analyze the dynamic behavior of granular assemblies numerically. In the early application of his method, Cundall (1971) assumed that the rock medium is an assembly of polygonal elements. Computation took a long time because of the complicated judgement needed about the contact between such polygonal particles. Therefore, the total number of elements that could be used for simulation was restricted by the limitation of CPU time. Later, Cundall replaced the polygonal elements with circular ones (Cundall et al.,1979). With these latter elements, each need be specified only by its radius. It is therefore easy to judge the contacts between elements; Consequently, the computing time is reduced.

In our reseach on concrete fracture, we have considered in idealizing mortar additional springs in the normal and tangential directions between particles.

The motion of a particle having the mass, m_i , and the moment of inertia, I_i , is

$$m_i \frac{d^2 u}{dt^2} + C_i \frac{du}{dt} + F_i = 0 \tag{1}$$

$$I_i \frac{d^2 \varphi}{dt^2} + D_i \frac{d\varphi}{dt} + M_i = 0 \tag{2}$$

in which F_i is the sum of all the forces acting on the particle,
M_i the sum of all the moments acting on it,
C_i and D_i the damping coefficients,
u the displacement vector and φ the angular displacement.

The time histories of u and φ can be obtained by step-by-step numerical integration of these equations. The force exerted on one particle by another was estimated from the deformation of the spring between them. The elastic constant of the spring was estimated from the propagation velocity of the P wave for the normal spring and the S wave for the tangential spring.

The time interval for the integral calculation was decided roughly from equation(3).

$$\Delta t < \frac{\mathrm{Dmin}}{Vp} \tag{3}$$

in which Dmin is the minimum diameter of a particle element, and Vp is the propagation velocity of the P wave.

Equation(3) shows that the forces F_i and M_i in eqs.(1) and (2) are obtainable from the deformation of the springs of the neighboring particles alone. That is because the particle i moves owing only to the effect of neighboring particles, the stress wave should not travel beyond these neighboring particles during the interval, Δt.

The fracture criteria for the tangential mortar spring can be expressed as

$$\tau = c + \sigma \cdot \mu \tag{4}$$

in which τ is the maximum resistant force between particles in the tangential direction, c the cohesive constant force, σ the normal force and μ the friction coefficient.

NUMERICAL RESULTS

Compression Test on a Concrete Specimen

Numerical simulation of the compression test was done with our modified DEM.(Fig.2). The specimen was compressed vertically under constant deformation during each time step. During stage 1, no crack occurred in either the particle or the spring location. If a crack were to occur, the spring at the corresponding place would disappear; therefore, the development of a crack and its position can be determined from the spring location figure. Stage 2, shows the incidence of shear crack at the spring location. In stages 4 and 5 pieces of concrete separate from the main body of the specimen and fall off. Such separation of a concrete block can not be analyzed by traditional methods such as the FEM. The numerical results obtained agree with results of past laboratory tests.

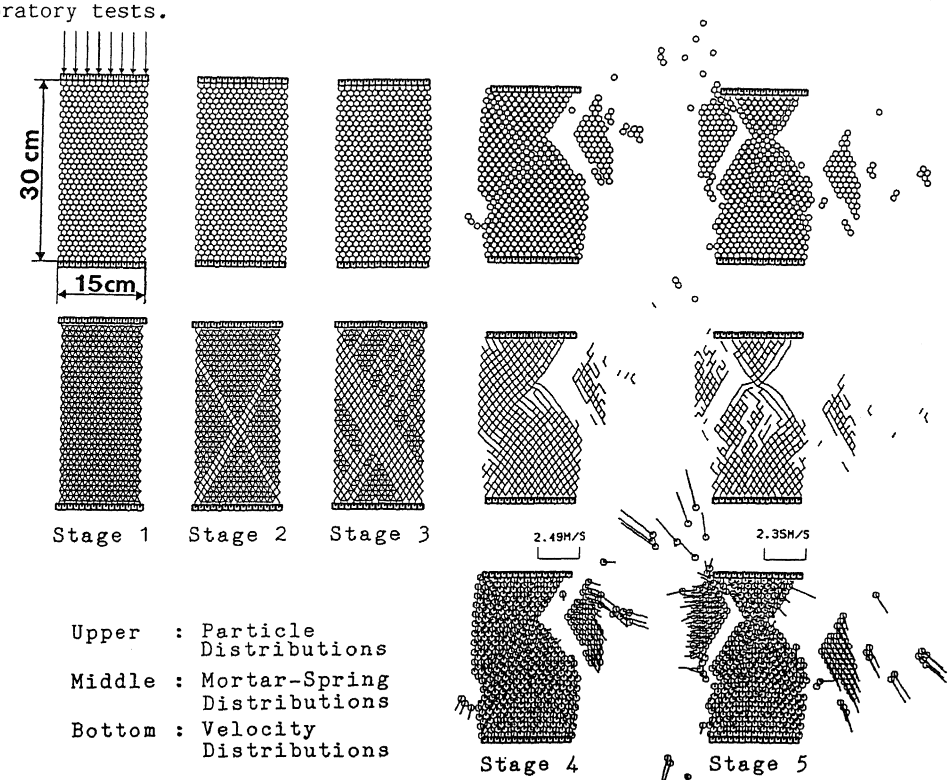


Fig.2 Fracture Process during a Compression Test of a Concerte Specimen under a Vertical, Constant-rate Deformation

Impulsive Fracture of a Masonry Concrete Frame

The fracture behavior of a masonry concrete frame subjected to a horizontal increasing force is shown in Fig.3. In stage 2, shear cracks are present at the foot of the frame. In stage 4 in the spring location, the cracks that are present at the corners of the frame seem to be produced by concentrated stress.

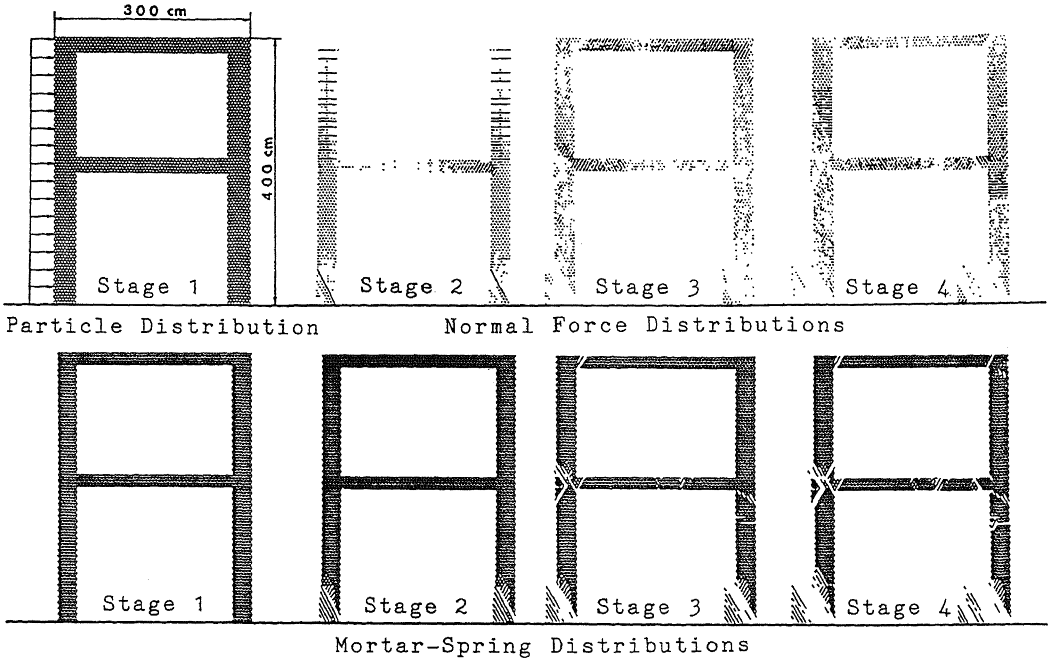


Fig.3 Fracture Process in a Concrete Frame under Horizontal Impulsing Loading

<u>Dynamic Fracture of a Masonry Wall</u>

The progressive cracking of a masonry concrete wall subjected to a sinusoidal, horizontal force with the period of 0.2 s is shown in Fig.4. At first shear cracks were produced, then when the applied force was exerted in the reverse direction, new cracks crossing the original ones were produced. This pattern of crossing shear cracks on walls has frequently been seen after earthquakes.

The fracture pattern for a wall surrounded by a strong concrete frame is given in Fig.5. This pattern is similar to the one in Fig.4.

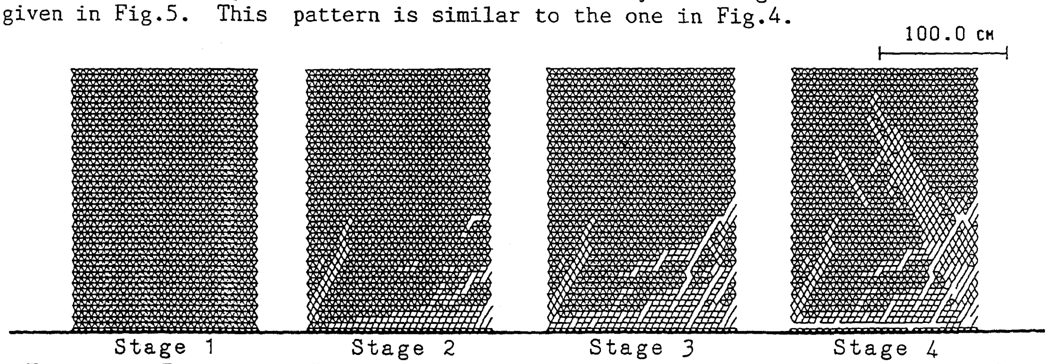
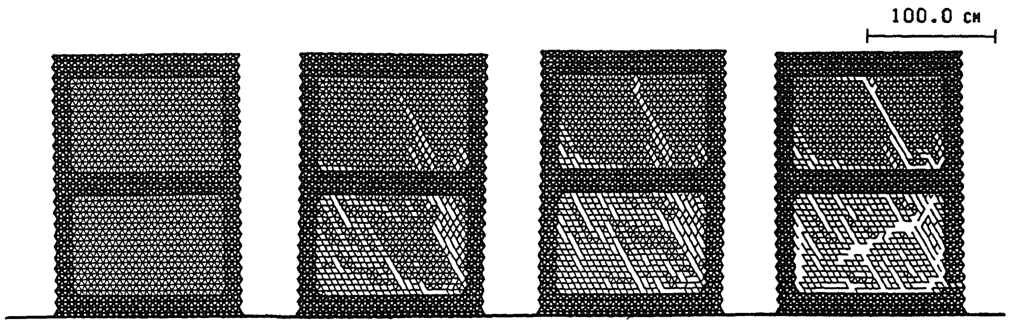


Fig.4 Fracture Process in a Masonry Concrete Wall under Sinusoidal Loading (Mortar-Spring Distributions)



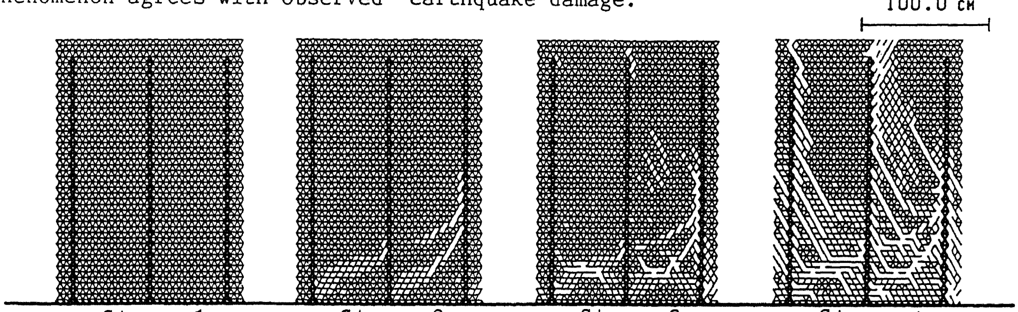
Stage 1 Stage 2 Stage 3 Stage 4

Fig.5 Fracture Process in a Masonry Concrete Wall with a Frame under Sinusoidal Loading (Mortar-Spring Distributions)

Dynamic Fracture of a Reinforced Concrete Wall

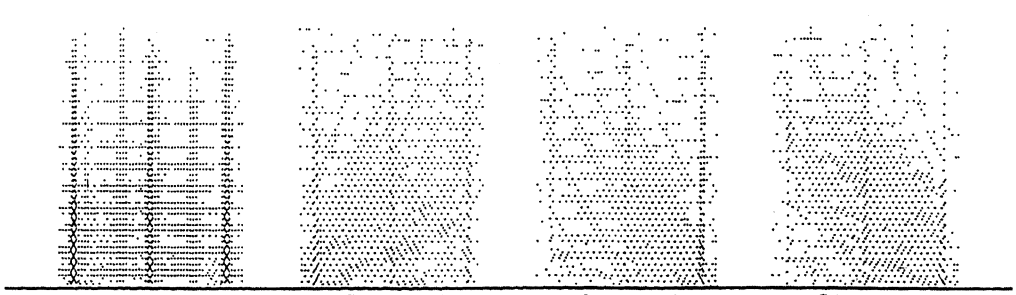
The progressive cracking of a reinforced concrete (RC) wall subjected to a sinusoidal horizontal force is shown in Fig.6. The figure shows that a crack, which was not continuous, jumped the reinforcing steel bar during stage 2 . The bottom examples in Fig.6 show that the normal force distributions and the normal force clearly are concentrated around the reinforcing bar.

The crack pattern obtained when the reinforcing steel bar covered only half the height of the wall is shown in Fig.7. In this case, an additional horizontal crack appeared at approximately the top of the reinforcing bar.This phenomenon agrees with observed earthquake damage.



Stage 1 Stage 2 Stage 3 Stage 4

(a) Mortar-Spring Distributions



Stage 1 Stage 2 Stage 3 Stage 4

(b) Normal Force Distributions

Fig.6 Fracture Process in an RC Wall under Sinusoidal Loading

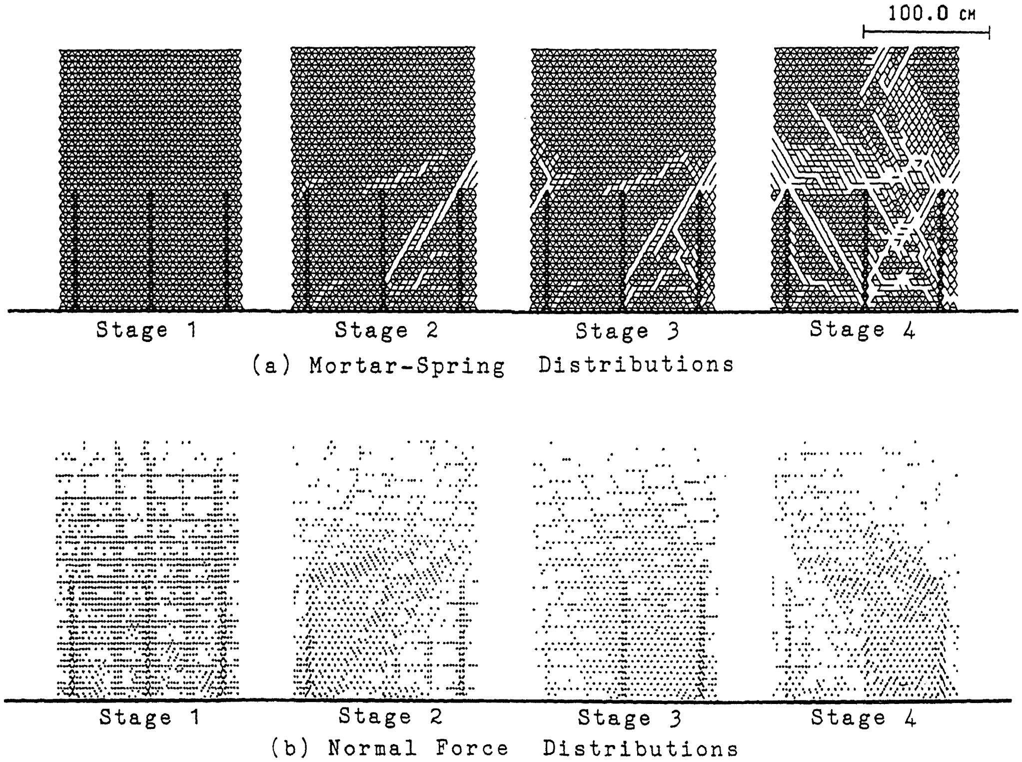


Fig.7 Fracture Process in an RC Wall Reinforced with a Short Steel Bar

CONCLUSION

The results of our study clearly show that the modified DEM can be used to make fracture analyses of concrete structures that are under dynamic loading.

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