Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, August 13-18, 1995

Analytical studies on impact penetration behavior of concrete structures by discrete element method

Sawamoto, Y., Tsubota, H., Kasai, Y., Koshika, N., Morikawa, H.
Kajima Corporation, Tokyo, Japan

ABSTRACT : The applicability of a Discrete Element Method (DEM) to the fracture behavior of concrete structures under impact loading has been verified by the authors. Firstly in this paper, appropriate material parameters are selected by simulating splitting tensile tests of cylindrical concrete specimens under various loading rates. Next the dependence of penetration depths on missile hardness is discussed based on analyses from a full-scale impact test .

1 INTRODUCTION

The need for a quantitative method of estimating the fracture behavior of concrete structures under impact loading has been increasing.

This behavior includes global and local behaviors. It has been particularly difficult to estimate local behaviors by numerical analysis, but recently fracture analysis methods have been tried. The authors verified the applicability of the DEM to the local failure problem [1]. They then determined the appropriate DEM parameters including dynamic increase factor (D.I.F.) (which is dependent on strain rate effect) by applying this method to simulate uni-axial compression tests of cylindrical concrete specimens under various loading rates [2]. They have thus shown that local damage can be quantitatively estimated by simulating impact tests of reinforced concrete panels subject to rigid and deformable missiles using the DEM [3].

This paper firstly describes how the DEM analysis is used to simulate splitting tensile tests (static and high-speed loading), which have a more complicated stress distribution than uni-axial compression tests. It indicates that the DEM parameters used here are more valid, and simulate a full-scale impact test conducted on a reinforced concrete panel struck by a deformable missile [4]. Next the relationship between missile rigidity and penetration depth is determined by the impact analysis of plain concrete panels using missile strength as an analytical parameter, and the local damage to concrete structures is estimated by the same DEM parameters.

2 BASIC CONCEPT OF DEM

DEM idealizes a structure as an assemblage of rigid circular elements connected to each other by non-linear springs and dashpots, each element having to satisfy equation of motion, and the dynamic characteristics of the whole body being expressed by forces transferred between elements during contact [1]. The equation of motion is solved by the explicit time integration method, applied to the elements in succession. The Mohr-Coulomb model, with a tension cutoff law, is applied to the discrete fracture model of concrete.

3 SIMULATION ANALYSIS OF CONCRETE SPLITTING TENSILE TEST

3.1 Splitting Tensile Test

The experiment was performed for two types of loading: static and high speed (deflection rate 100cm/sec) . The loading method is given in JIS A 1113. As show in Figure 1, a compressive fracture appeared right under the loading plate, but the final fracture was tensile.

3.2 Simulation Analysis

(1)Analytical Model
The analytical model is a plane strain model comprising a loading plate and a specimen (a 15cm-diameter cylinder with a thickness of 1cm). Both are assemblages of rigid circular elements whose radii are 0.25cm or 0.125cm. The loading plate has the same curvature as the specimen, and contact points between loading plate and specimen increase under loading. The analytical parameters are given in Table 1. They are the same as those used to simulate uni-axial compression tests [2].

(2)Analytical Results
In the static loading analysis, two values of radius (0.25cm and 0.125cm) were used. Figure 2 shows the final fracture state (solid lines express fracture section). The results clearly show that, regardless of the element radius, the final fracture state is tensile after going through a peak load. This is in good agreement with Figure 1.

Figure 3 shows the load-displacement relationship. The tensile strength of Ft = 22.5 kgf/cm^2 set up in the analysis was compared with the analytical peak calculated by the formula $2P/(\pi dl)$ (where P is load, d is diameter of specimen, l is length of specimen). For r=0.25cm, the analytical peak is 0.8 times the tensile strength, but for r=0.125cm, they are nearly equal.

In the high-speed loading analysis, a radius of 0.25cm was used for convenience of analysis. Figure 4 shows the final fracture state, and Figure 5 shows the load-displacement relationship. These show that in general the final fracture state is the same as the static loading state, without many cracks around the circumference, and that the experimental strength increase factor for the high-speed loading is 2.5 [5], and the analytical one is 2.8.

From these results, it was concluded that the proposed DEM parameters were more reasonable.

4 SIMULATION ANALYSIS OF LARGE-SCALE IMPACT TEST

4.1 Outline of experiment

In this test, a target square reinforced concrete panel of 7m side length and 160cm thickness were subjected to impact by steel deformable missiles of diameter 760mm and mass 1616kgf projected at 215m/sec perpendicular to the panel [4] .

4.2 Analytical Model

The analytical model is an axi-symmetric one of 4.0cm radius (missile model is 2.0cm radius). Reinforcement is modeled by assuming springs between elements to possess bi-linear elasto-plastic characteristics. The missile model is shown in Figure 6. The spring constants and strengths are determined such that these values are equal in axial stiffness and strength of the actual missile. The analytical parameters are shown in Table 2.

4.3 Analytical Result

Figure 7 compares the test and analytical results for the final fracture condition of the reinforced concrete panel. As shown, as soon as the deformable missile crashes into the panel, the front part of the missile buckles, and, after about 10 msec, the rear part buckles. The analytical penetration depth of 19.3cm is in good agreement with the experimental value of 21.0cm. After 10msec, a shear-cone crack is observed in the rear face of the panel. In the final fracture condition (t=20msec), both analytical values of diameter of circumferential crack and residual deformation, caused by the shear-cone produced in the rear face of panel, describe experimental values well. In particular, residual deformation is 12.5cm in the analysis and 13.5cm in the experiment.

Figure 8 shows the time response of impact force at the panel caused by the impact of the missile. Two peak values of impact force are observed: right after impact and about 7msec after impact, corresponding to the buckling of the front and rear parts of the missile. In practice, the impact force is zero at 11msec, indicating that the impact is finished at this time.

Figure 9 shows the time history of missile penetration depth. The missile penetrates rapidly to a depth of about 8cm right after crash, and then penetrates slowly after 7msec, finally reaching 19.3cm. There are two types of the penetration behavior. The first is the sinking of the missile into the concrete and the second is the added penetration caused by a push-out of a cone of concrete. Because no impact force is observed after 11msec, it is clear that the missile penetrates without resistance because of the push-out of concrete.

From these result, it was concluded that the DEM demonstrated the detailed penetration behavior, which was difficult to observe in the experiment, and that it could estimate the behavior quantitatively.

5 RELATIONSHIP BETWEEN MISSILE RIGIDITY AND PENETRATION DEPTH

In this chapter, the DEM parameters used above are applied to estimate analytically the dependence of penetration depth on missile rigidity. Missile strength is increased by changing the material yield strength of the missile (σ u). The analytical cases are shown in Table 3. The rigid missile shown in Case 5 has the same strength as that in Case 4, but has higher horizontal stiffness than that in Case 4 because it is solid.

Furthermore, concrete panel thickness is changed to 320cm, to estimate the penetration depth into solid concrete, that is to say, to exclude the added penetration depth caused by the push-out of concrete.

Figure 10 compares penetration depths obtained from response analysis. This indicates that, though an increments of penetration depths do not depend on missile strength right after impact, a missile with small strength, as in Case 1, immediately reaches a maximum depth and stops. Penetration depth generally increases with missile strength, but the responses for Case 3 and Case 4 are nearly equal. This reveais that, when missile strength exceeds that for Case 3, penetration depth remains constant.

The maximum penetration depth for Case 4 is smaller than that for Case 5, even though missile strengths are the same. It seems that the model of Case 4 deforms horizontally because of its smaller horizontal stiffness. By the way, the penetration depth of a rigid missile calculated by a modified NDRC ,for example, formula is 86.1cm. This is about twice that of Case 5: 43.3cm.

6 CONCLUSION

1) The validity of the DEM parameters was confirmed so that fractural mechanism of splitting tensile tests of concrete cylinders and the detailed penetration behavior for full-scale impact could be elucidated by the DEM.

2) Using the selected DEM parameters, it was demonstrated analytically that penetration depth varied greatly depending on missile strength.

3) A series of the DEM analyses using the identified DEM parameters was able to estimate quantitatively material tests, such as uni-axial compression tests and splitting tensile tests of cylindrical concrete specimens, and local damage to concrete structures such as reinforced concrete panels. It seems that ,after this, a quantitative estimation of impact behavior for various conditions such as missile shape, strength, and velocity, is possible using the DEM.

REFERENCES

[1] Morikawa, H. and Kobayashi, N.(1992) "Local Fracture Analyses of a Reinforced Concrete Structures by the Discrete Element Method", Proceedings SUSI 92, Second International Conference on Strucrures Under Shock and Impact in Southampton

[2] Koshika,N.,Kusano,N.,Morikawa,H.,Aoyagi,T.,Kobayashi,N.and Sawamoto,Y. (1992) Proceedings ISIE, International Symposium on Impact Engineering in Sendai

[3] Morikawa, H. ,Kusano,N. , Koshika,N. ,Aoyagi,T. ,Hagiwara,T. and Sawamoto,Y. (1993) "Estimations of Impact Strength on Reinforced Concrete Structures by the Discrete Element Method" Proceedings SMiRT 12 Conference

[4] Muto,K. ,Tachikawa,H. ,Sugano,T. ,Tsubota,H. ,Kobayashi,H., Koshika,N. , Tsujimoto,T. (1989) "Experimental Studies on Local Damage of Reinforced Concrete Structures by the Impact of Deformable Missiles" Proceedings SMiRT 10 Conference

[5] Saito, H. ,Imamura,M. , Okamoto,Y. ,Kasai,Y. ,Tsubota,H. and Yoshimura,M. (1993) "Loading Capacities and Failure Modes of Various Reinforced Concrete Slabs Subject to High-speed Loading" Proceedings SMiRT 12 Conference

Table 1 Imput Parameters

Name	Value
Particle radius r	0.25,0.125
Particle spring constant Kn	1.87×10^5
Particle spring constant Ks	0.37×10^5
Tensile strength Ft	22.5×2r
Cohesion C	37.0×2r
Compressive strength Fc	246.0×2r
Friction coefficient μ	0.2
Damping coefficent hn,hs	0.03

unit : kgf,cm

Table 2 Imput Parameters

Name	Concrete	Missile(Front)	Missile(Rear)
r	4.0	2.0	2.0
Kn	$1.65\times10^5\times2\pi b$	$9.84\times10^4\times2\pi b$	$9.84\times10^4\times2\pi b$
Ks	$0.55\times10^5\times2\pi b$	$1.97\times10^5\times2\pi b$	$1.97\times10^5\times2\pi b$
Ft	$167.2\times\times2\pi b$	$2696.25\times2\pi b$	$7190.0\times2\pi b$
C	$274.3\times\times2\pi b$	$2696.25\times2\pi b$	$7190.0\times2\pi b$
Fc	$1800.0\times2\pi b$	$5392.5\times2\pi b$	$14380.0\times2\pi b$
μ	0.20	0.0	0.0
hn,hs	0.03	0.03	0.03

unit : kgf,cm

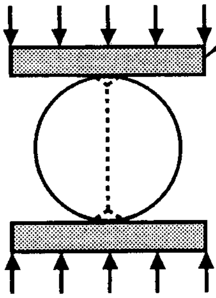


Figure 1 Fracture Mode

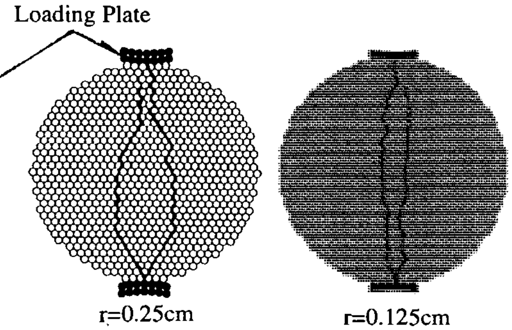


Figure 2 Fracture State under Static Loading

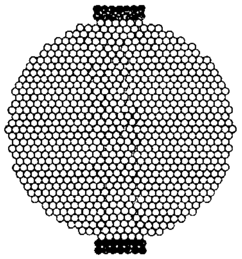


Figure 4 Fracture State under High-speed Loading

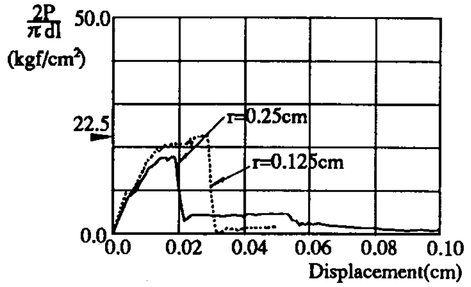


Figure 3 Load-Displacement Relationship under Static Loading

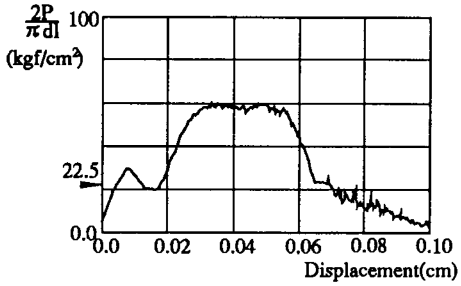
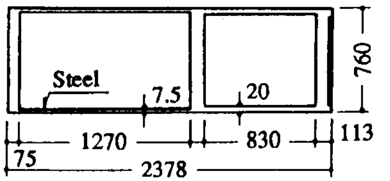
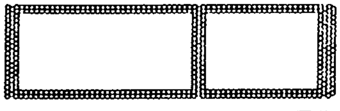


Figure 5 Load-Displacement Relationship under High-speed Loading



Deformable Missile

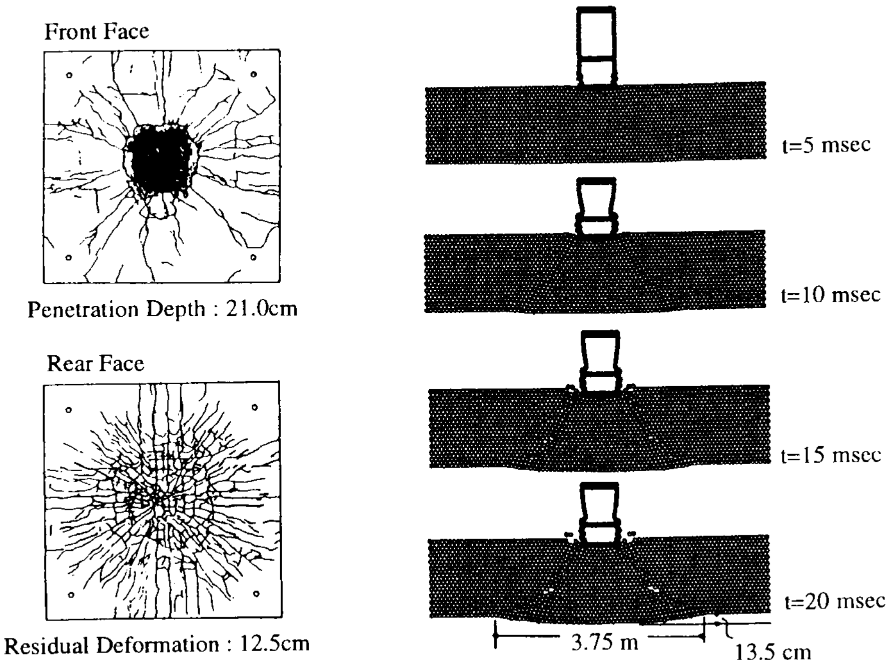


DEM Model

Figure 6 DEM Model

Table 3 Analytical Cases

Name	Type of Missile	Material Yield Strength of Missile
Case 1	Deformable	$1.0\times\sigma u$
Case 2	Deformable	$10.0\times\sigma u$
Case 3	Deformable	$25.0\times\sigma u$
Case 4	Deformable	$\infty\times\sigma u$
Case 5	Rigid	$\infty\times\sigma u$



Damage of Test Panel

Fracture Process

Figure 7 Damage Modes

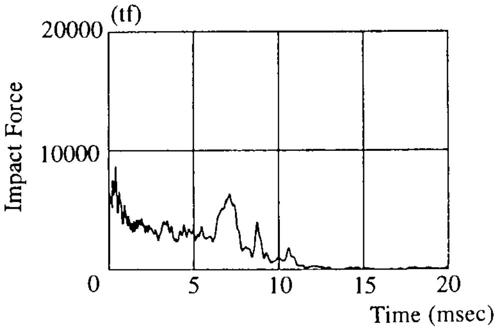


Figure 8 Impact Force of Missile

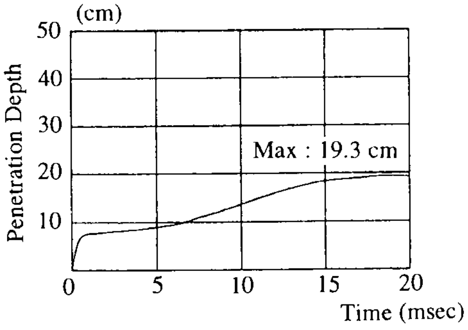


Figure 9 Penetration Depth of Missile

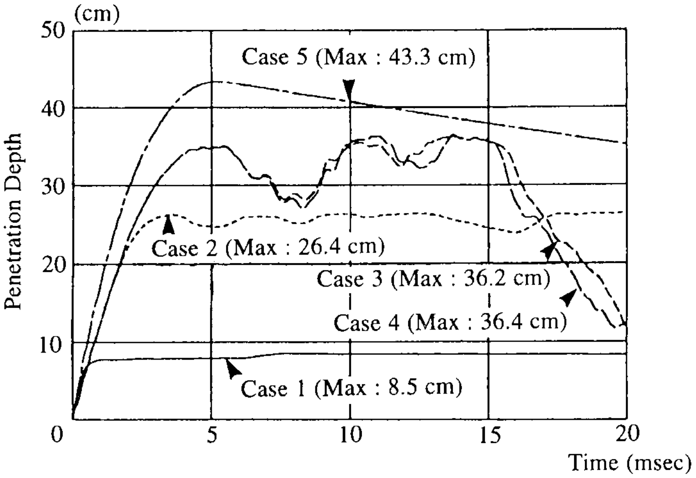


Figure 10 Comparison of Penetration Depths