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An Experimental-Numerical Study for Determination of Concrete Fracture Physical Parameters in DEM

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Abstract

A computer program is developed using Distinct Element for Fracture Analysis (DEFA) of structural media under the dynamic loads. The program has been used for different real failure cases of concrete structures and it is found that more investigation should be done for determination of fracture physical parameters. In this research one-plane shear specimens have been tested and the physical parameters including cohesion and friction coefficient are determined. The obtained parameters from the tests and the analytical relations are used in the simulations. The failure mode and crack pattern are very similar in experiments and simulation. The shear strengths obtained from the simulation are well agreed with those from the experiments. Also the distribution of forces and displacements from the numerical analysis are in well agreement with those from the photo-elasticity patterns for such a shear test.

Key words: Concrete, Fracture, Physical parameters, Experiment, DEM

1 Introduction

After introduction of DEM by Cundall et al. (1979), it has been widely used for discontinuous and granular media. There is an interest for using

DEM for fracture analysis of continuous media, Meguro & Hakuno (1989), Morikawa et al. (1995), Lorig & Cundall (1978), Takada & Hassani (1996a). However, there are some shortcomings in this method such as need for large memory and very fast computers and some unreliability about the numerical results, Takada & Hassani (1996b). We have already developed a new computer program based on the main concepts of DEM, Takada & Hassani (1996a, b, c).

For increasing the ability of the program for doing more accurate and quicker analysis with the usual computers we have already developed some new concepts for determining the visco elastic parameters, Takada & Hassani (1996b), suitable time-step, Takada & Hassani (1996c), periodical updating for possible new contacts, modeling the reinforcement in structures, Takada & Hassani (1997a, b), introducing physical randomness instead of geometrical one, Takada & Hassani (1997c) and symmetrical analysis, Takada & Hassani (1997d). In this study for getting more rigorous idea about the reliability of the program for fracture analysis of concrete a series of tests have been done on one-plane shear test specimen. The physical properties such as Young's modulus, Poisson's ratio, compressive strength, cohesion and internal friction coefficient are obtained through the tests. These parameters have been used as input data. The results from the program are compared with those of experiments.

2 Numerical simulation of failure in structural media

In the developed numerical simulation in this paper, the medium is modeled as an assembly of circular (disk) particles, Cundall et al. (1979) which are connected to each other through two types of springs and dash pots (Voigt-Kelvin visco-elastic model). The force is transferring due to direct contact and /or through the pore medium between those elements that are within a specified distance from each other. The latter type was introduced by Iwashita, Meguro & Hakuno (1989) as the winkler types springs for modeling the cohesion in the granular media. There is also a mathematical type of damping known as global damping, Cundall et al. (1979), for stabilizing the central finite difference scheme which is used for solving the equation of motion of the elements. The model which is used in this program is shown in Fig. 1.

This model is used for developing the program on the following bases:

- Newton double integration scheme for tracing the movement of elements.
- Computing the interelements forces due to the visco-elasticity theory.
- Crack modeling by breakage in pore connection between the elements.

- A modified Coulomb criterion for shear failure.
- Tension cut-off for tension failure in pore medium.
- Periodical contact detection between the elements for new contacts.

The loaded elements will move due to the external loads and transfer forces to the other elements. The total forces acting on one element result to an unbalanced force which make the elements move to a new position. Before next time-step the failure of the springs are judged. For the next time-step, the relative displacement between the neighboring elements exert incremental forces on the and this computation cycle is repeated. The general flow of the program is shown in Fig. 2.

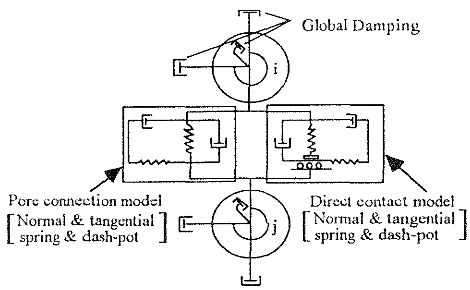


Fig. 1. Contact and pore medium models

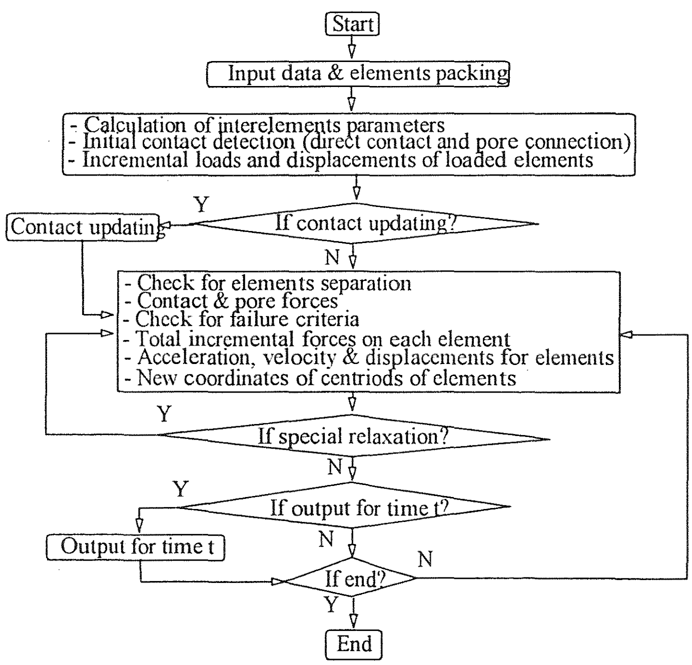


Fig. 2. Flow of fracture analysis and failure monitoring with DEM

3 Failure criteria for concrete

In the brittle type material such as concrete there are three types of failure as shear, tension and compression failure

In the case of dry granular there is no cohesion in the criterion and the shear failure is the shear-compression and there is not shear-tension one. In cohesive granular and continuous media there are both shear-compression and shear-tension failure. In this case the cohesion factor is involved in Coulomb criterion.

For the pure tension failure mostly a cut-off type failure is applied, because of its convenience in computation (to avoid from hysteric computation for tension failure).

The failure criteria for the developed program are briefly explained here. The main criteria for failure in pore medium are summarized in Table 1 where Fn, Fs, μ and C are the normal, tangential force, friction coefficient and the cohesion between the elements, respectively. L0 is the initial distance, Lt, the distance in time t and Lut is the separation distance between two elements. The reinforcement yields by reaching to the yield point and will be broken by passing the ultimate tensile strain.

There is no failure in compression without shear, while a cut-off failure is considered in pure tension between the elements in pore medium.

Table 1. Failure criteria for pore media

Pore condition	Direction			
	Normal		Tangential	
	Mode	Condition	Mode	Condition
Before failure	Compression	$Fn>0$	Active	$Fs \leq C+\mu Fn$
			Crack-slide	$Fs>C+\mu Fn \rightarrow Fs=\mu Fn$
	Tension	$Fn<0$	Active (No friction)	$Fs \leq C$
			Crack (separation)	$Fs>C \rightarrow Fn=0$, $Fs=0$
After failure	Compression	$Fn>0$, $L_0<L_t<L_{ut}$	Active (only friction)	$Fs \leq \mu Fn$
			Slide	$Fs> \mu Fn \rightarrow Fs= \mu Fn$
	Separation	$L_t > L_{ut}$	Crack Separation	$Fn=0$, $Fs=0$

Since in concrete the compressive strength is a well-known parameter, the other strength parameters are given as a function of it . The selected empirical formulation for model parameters of concrete, Lorig & Cundall (1978), Hassani (1997) in this research are summarized as follows:

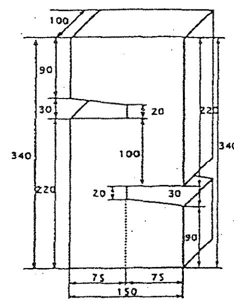
1. Tensile strength

a) Direct tension (Eq. 1, less than $0.1f'c$,which is used in this research)
b) Splitting test (Eq. 2, approximately between $0.1f'c$ $0.15f'c$)
c) Modulus of rapture from 3 points bending test (Eq. 3, about $0.15f'c$)
2. Cohesion (Eq. 4)

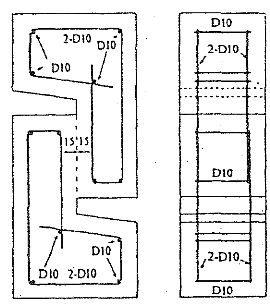
$$f_t = 0.22 f_c^{0.84} \tag{1}$$
$$f_t = 1.73\sqrt{f_c} \tag{2}$$
$$f_t = 3\sqrt{f_c} \tag{3}$$
$$c = 0.5\sqrt{f_t . f_c} \tag{4}$$

4 Method of experiment

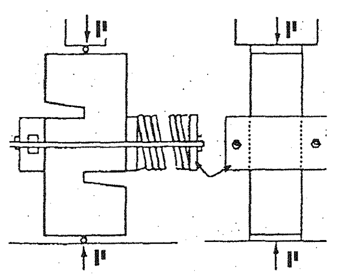
The general details of the specimen are depicted in Fig. 3. For getting the compression strength, Young's modulus and Poisson's ratio, many tests have been done on cylindrical specimens for both mortar and relevant concrete with water to cement ratio of 0.6 and 0.9, Akahori (1997). To obtain the cohesion and friction coefficient for using in the simulation, the one-plane shear test has been done as shown in Fig. 3.



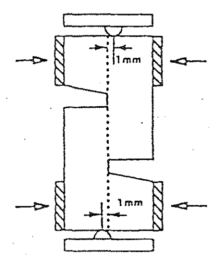
(a) Dimensions



(b) Reinforcement



(c) Lateral force for measuring friction



(d) Prestressing for crack prevention

Fig. 3 The general scheme and information of the test specimen

Considering the shear strength in the shear plane which is compound of cohesion and friction, two types of tests have been done. The strain gages were attached in the middle of the shear part of the specimen.

In one series of the tests there are no lateral compression forces on the middle part of the specimen . In this case, the obtained shear strength is equal with the cohesion. In the other series of the tests there were lateral compression on the middle part (Fig. 3-c) and by calculating the normal pressure and cohesion in the shear plane, the friction angle and coefficient were determined.

In the preliminary tests which were done without reinforcement, the force was not transferred to the shear plane and the failure was monitored in the upper and lower parts of the specimens. After using the reinforcement in the specimen, still some cracks happened under the load and support. For this reason we decided to prestress the upper and lower parts by post-tensioning using plates and bolts as shown in Fig. 3-d. An eccentricity of 1mm is used to decrease bending effect on the shear plane.

5 DEM simulation

A 2-D model of the specimen has been prepared for analysis by DEFA program based on the distinct element algorithm. As shown in Fig. 4, the model is an assembly of circular elements. The reinforcement are also simulated in the model by using the double-pore concept, Hassani (1997). The average compressive strength for concrete with w/c=0.6 and 0.9 are 32.39 and 22.07 N/mm^2, respectively. The ultimate tensile strength for the reinforcement is about 500.0 N/mm^2. The main other parameters for analysis are in Table 2.

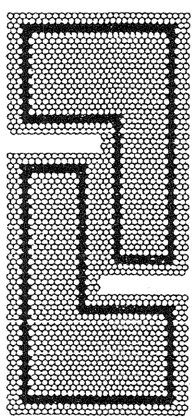


Fig. 4. The DEM model for one-plane shear test used in analysis

Table 2. The main Input data used in analysis

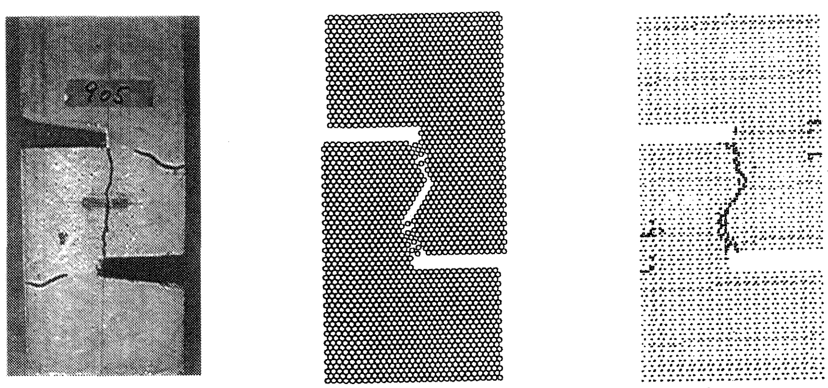
Item	Young's Mudulus ($\times 10^4 N/mm^2$)	Poisson's Ratio	Cohesion (N/mm^2)	Friction Coefficient	Tensile Strength ($N/mm2$)	Tensile strain $\times 10^{-6}$
Experiment (w/c=0.6)	2.55	0.15	5.40 (4.75)	0.43	2.65 (2.80)	400.0
Experiment (w/c=0.9)	1.76	0.15	4.10 (3.35)	0.57	2.17 (2.05)	400.0

Inside the parenthesis are from the Eqs. 1 and 4.

6 Comparison of the experimental and numerical results

The general failure mode and crack pattern in the experiment are shown in Fig. 5-a which are very similar with those from the analysis in Fig. 5-b, c. Both in the test and analysis, the bending cracks in the both side of the specimen are monitored before the cracking in the shear plane. The distribution of the forces and displacements including their directions are depicted in Fig. 6 and Fig. 7. For getting more reliability about the distribution of the strains, the one obtained from the analysis is compared with another one from photoelasticity experiment , Asai (1992) in Fig. 8 which are very similar to each other.

The relation between shear stress and strain in the shear plane for two types of the tested concrete (w/c=0.6 and 0.9) are given in Fig. 9. There two curves from analysis compared with the test result which are in a good agreement. As shown in Table 2, the data used in one analysis are directly from the test and in another analysis some of the data are changed with those from Eqs. 1-4 which are depicted in the parenthesis in the Table.



(a) General failure mode (test) (b) Failure mode(analysis) (c) Crack pattern(analysis)

Fig. 5. Failure modes and crack patterns

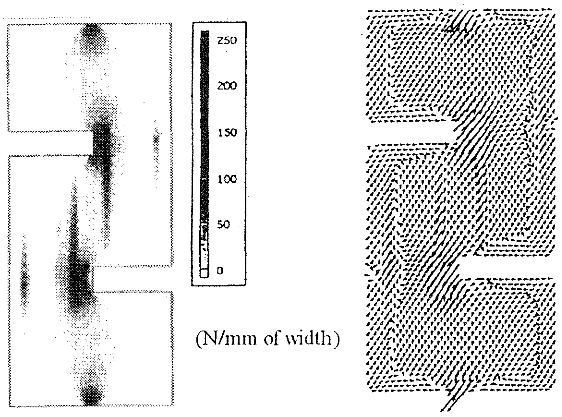


Fig. 6. Force distribution and direction (from the analysis)

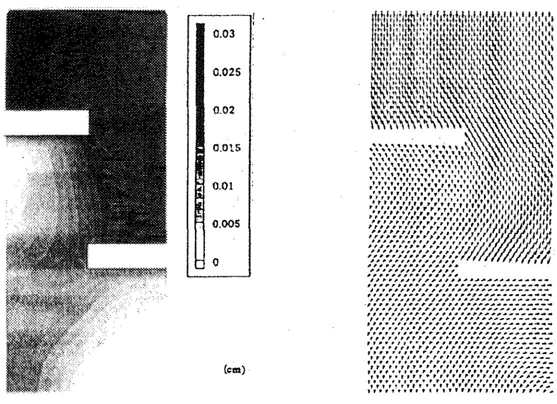


Fig. 7. Displacement distribution and direction (from the analysis)

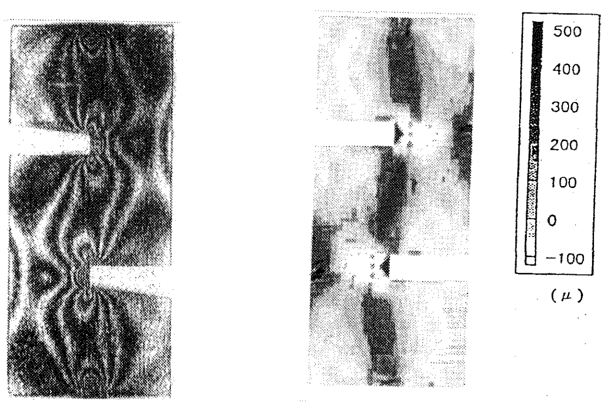


Fig. 8. Strain distribution from the photoelasticity test and the analysis

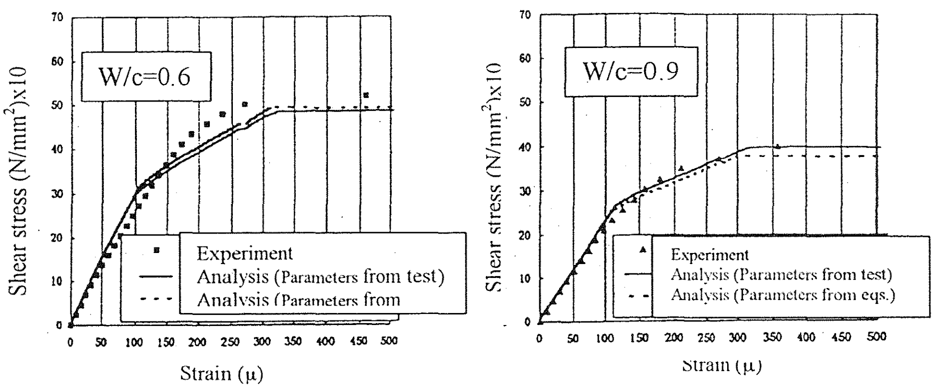


Fig. 9. Shear stress and strain relation

7 Discussion

The problems during the experiment showed that this type of specimen can not give the complete and pure shear behavior. Therefore, some other types should also be investigated for more accuracy. There is the bending effect in the test which was monitored both in the experiment and the analysis which prevents the pure shear failure in the specimen (Fig. 5). However from the comparison point of view, the obtained results from the analysis are in a good agreement with the experiments. The results in Figs. 5-8 show the ability of the program for complete fracture analysis of concrete. One important problem in analysis by DEM is the size effect which is under investigation by the authors. The quantitative results in Fig. 9 show that the tension and cohesion strength calculated from the given equations are reliable for using in analysis.

8 Conclusions

In this research a series of tests are done on one-plane shear specimen to obtain the fracture parameters of concrete such as tensile strength, cohesion and friction coefficient. The obtained parameters from the tests and empirical formulation were used in DEFA program (DEM analysis). The obtained qualitative and quantitative results from the analysis are compared with those from the experiment. The main conclusions are:

1- More sophisticated specimen is necessary for pure shear test and omitting the effect of bending on the shear behavior of the test specimen.

2- The computer simulation of the test by DEFA program came to a good agreement both in qualitative and quantitative results with the experiment.
3- The tensile and cohesion strength calculated from the empirical formulation gave acceptable results in DEM analysis.
4- More investigation is necessary on the effect of the element size on the results of the program.
5- Friction coefficient of the concrete needs more sophisticated study and formulation for using in the DEM analysis.

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