Fracture Mechanics of Concrete Structures
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FRACTURE AND SOFTENING ANALYSIS OF CONCRETE WITH PARTICLE MODEL

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Abstract
In this paper, the particle model of concrete developed by Jirasek & Bazant is applied to mortar and concrete specimens to analyze a correlation between microscopic and macroscopic fracture nature. First, the particle model of three-component material is formulated and microscopic mortar parameters are determined by some numerical identification. Next, concrete prisms and notched beam specimens having each differing parameters are analyzed. Numerical examples show good agreement with test results and also explain an effect of aggregate size used. Finally, fracture simulation of concrete under compression is conducted to show a limitation of the present particle model.
Key words: Distinct element method, particle model, concrete fracture

1 Introduction

In recent years, the applications of microscopic analytical models to concrete are becoming feasible due to advances of computer technologies. Especially, studies on the particle model developed by Jirasek & Bazant (1994/1995, 1995) and the lattice model by Schlangen & van Mier (1992) attract a great deal of attention because of their realistic numerical simulations of concrete fracture with simple microscopic material models. However, both encountered several difficulties in their early attempts on the discrete element approaches. For instance, more considerations seem to be still needed for a correlation between micro and macro fracture nature and for a fracture simulation of concrete subjected to compressive stress.

The objective of this study is to develop a particle model which can simulate the fracture phenomenon affected by aggregates or some ingredients of cementitious material. Firstly, the particle model is formulated to better represent multiple material characteristics of concrete. Next, fundamental micro-macro fracture characteristics of the model are examined by using the numerical results on fracture analysis of mortar and concrete specimens subjected to tensile stress. Finally, fracture analysis of concrete subjected to compressive stress is conducted to show the intrinsic limitation of the 2-dimennsional particle model presented.

2 Particle model

A particle model in this study is basically based on the model by Jirasek & Bazant (1994/1995, 1995). The basic formulation of the model is summarized as follows.

1. A lattice network is constructed with link elements which transmits only axial force.
2. Nonlinear stress-strain relation including tension softening behavior is assigned to each link (Fig.1).
3. To solve nonlinear equations, the method of inelastic forces (MIF) which is combined with the event-controlled step size algorithm is applied to provide an effective incremental analysis. A distinctive feature of the MIF is no need to reconstruct the tangential stiffness matrix in each incremental step.

In previous works on the particle model by Jirasek & Bazant, random lattice approach was adopted to take into account the heterogeneity of concrete without consideration of multiple-material properties. That is to say, microscopic material property of concrete was characterized by only a micro-macro relation of fracture energy, so-called the size effect method.

In this study, multiple-material properties of concrete are taken into account to characterize the macroscopic response influenced by the aggregate size. The discretization procedure of the particle model including the multiple-material properties are described, as follows. First,

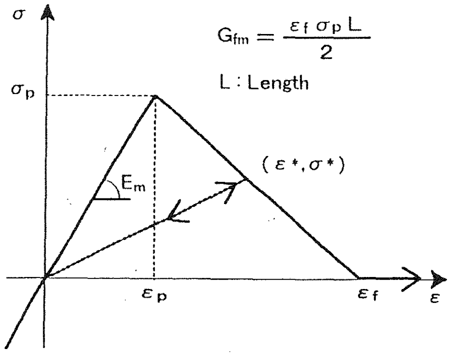


Fig.1 Microscopic stress-strain relation

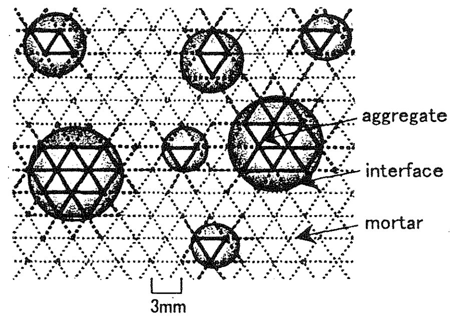


Fig.2 Particle model of three-component material

a regular triangular lattice network is constructed by using link elements. Here, the length of each link is set to 3mm. Because any regular lattice system inevitably results in directional bias in its fracture mode, the choice of random particle system would be better to avoid this problem. The implementation of material heterogeneity in a lattice system is another solution. Although it is realized that the latter is not always effective, this approach was chosen to clarify the influence of material heterogeneity qualitatively. Next, various sizes of circular aggregate are assumed, classified and randomly mapped on to the regular lattice network. Finally, mortar, coarse aggregate and interface links are separated and assigned their microscopic material characteristics (Fig.2). In the following section, microscopic material properties of mortar link are identified. It is assumed that fracture of concrete just occurs in mortar links. Consequently, heterogeneity of the present particle model is introduced by aggregate distribution.

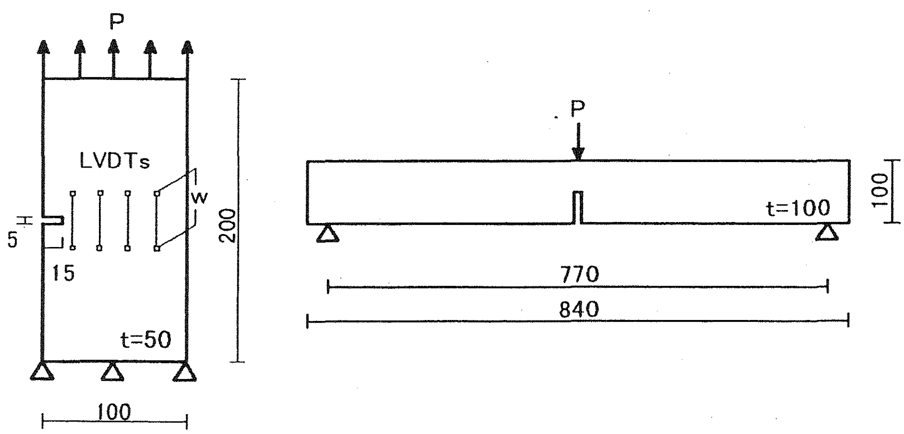
3 Fracture analysis of concrete subjected to tensile stress

3.1 Microscopic material parameters of mortar

A parametric study is conducted to determine the microscopic parameters of mortar link as micro-strength and micro-fracture energy. The shape of the model used is shown in Fig. 3 (a). Microscopic strength (σ_p) and fracture energy were varied, ranging from 2.0 to 5.0N/mm^2 and from 0.02 to 0.05N/mm, respectively. Calculated results are plotted in Figs. 4 and 5. A linear relation between G_f and G_{fm} is found in Fig. 4. Where, G_f is the macroscopic fracture energy defined as the area under the tensile strain-softening curve of concrete and G_{fm} is defined in Fig. 1. In the case of equal G_{fm}, G_f is not sensitive to variation of micro-strength. The relation is derived and shown in Fig. 4 as Eq. 1. On the other hand, Fig. 5 shows a relation between macroscopic strength (f_t) and microscopic parameters

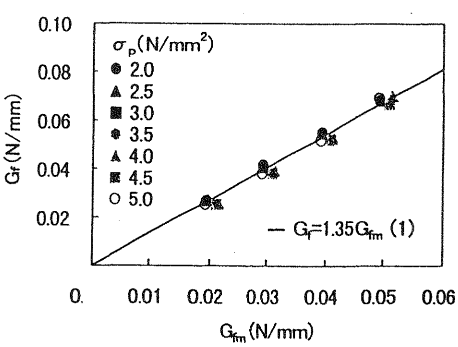
(σ_p, ε_f). The regression equation Eq. (2) is also obtained in the figure. It leads to a quadratic equation in terms of σ_p if the relation $\varepsilon_f = 2G_{fm}/(\sigma_p L)$ in Fig.1 is assumed. Therefore, if the macroscopic parameters (f_t and G_f) are given, the microscopic parameters are automatically obtained by solving Eq. (2). Note that this procedure is applicable only when a regular triangular lattice is set to 3mm length in each link.

Figs. 6 and 7 show numerical results of mortar specimens shown in Fig. 3 (a) by Schrangen & van Mier (1992) and Fig. 3 (b) by Mihashi (1995), respectively. In these analyses, microscopic parameters were determined by the above-mentioned method. These numerical results show a good agreement with test results and the validity of the proposed method is confirmed.



(a) Prism (b) Notched beam

Fig.3 Specimen geometry (unit:mm)



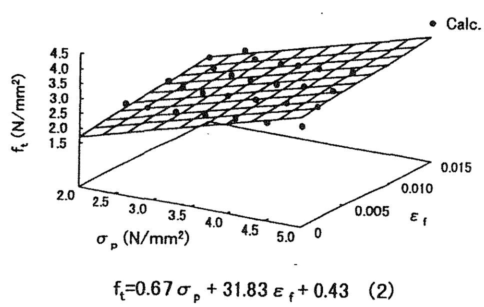
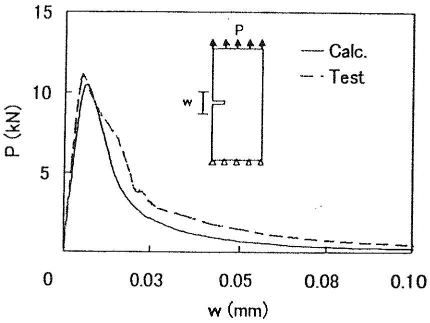


Fig.4 G_f - G_{fm} relation

Fig.5 Microscopic parameters(σ_p, ε_f) -macroscopic tensile strength(f_t) relation



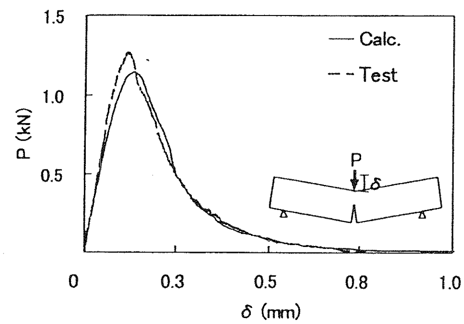


Fig.6 Load(P)-CMOD(w) curves Fig.7 Load(P)-displacement(δ) curves

3.2 Multiple-material modeling of concrete

Particle models including mortar, aggregate and interface links are examined from the prescribed definition of mortar parameters. Note that the distribution of aggregate in 2-D was assumed by the recommendation of aggregate weight ratios by the Japanese Architectural Standard Specification (JASS).

Fig. 8 compares a test result of a notched concrete prism specimen by Schlangen & van Mier (1992) with some calculated results. Where, microscopic limit strain (ε_f) of interface element was varied. The case of 1.0 ε_f shows steeper decline curve than the test or other calculated results. This indicates that the 2-dimensional particle model in this study is so unrealistic for modeling concrete fracture that microscopic crack propagetes around the 3-dimensional aggregate. This leads to underestimation of G_f. On the other hand, the case of 2.0 ε_f fairly good agreement in the softening branch. Based on these numerical results, the microscopic limit strain 2.0 ε_f for interface link is adopted in the following study.

Results of notched concrete beam specimens (Fig. 3 (b) by Mihashi (1995)) with different maximum aggregate size (d_a=5 and 25mm) are shown in Fig. 9. Results of 4 different aggregate distributions are also plotted. In the case of d_a =25mm, scattering on the peak load and the descending branch is found so that some improvements should be needed in the 2-dimensional modeling of aggregate distribution. The average response seems to be reasonably simulated in Figs. 9 (a) and (b). A relation between macroscopic fracture energy (G_f) and the maximum aggregate size (d_a) is plotted in Fig. 10. Estimation by CEB-FIP MODEL CODE is also drawn in the figure. Calculated results somewhat underestimate G_f values, although the increasing tendency of G_f values is predicted with the increase in d_a. Fig. 11 illustrates damage distributions in the case w=1.0mm. Fracture propagation of concrete can be seen in the simulation by the particle model. As the dominating crack propagates in the specimen, surrounding micro-cracks are beginning to close and the fracture is localized in a narrow zone. This process could be virtually obtained because of the model including a microscopic softening relation.

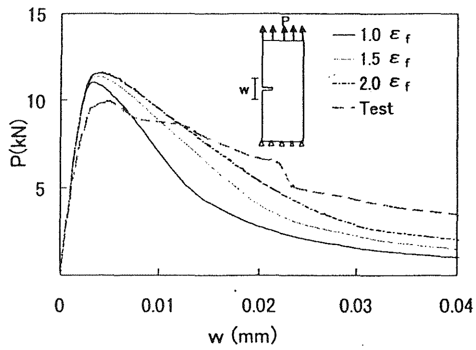


Fig.8 Load(P)-CMOD(w) curves

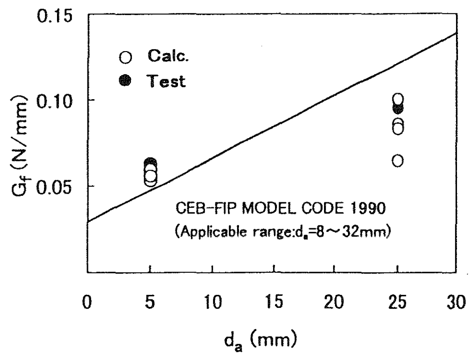


Fig.10 d_a-G_f relation

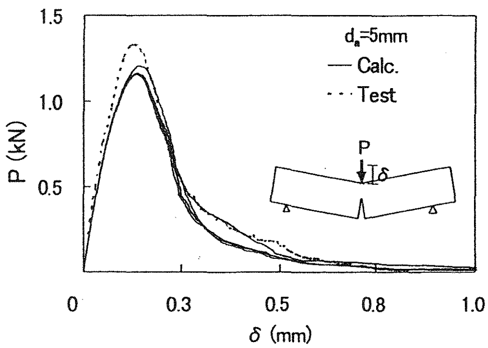
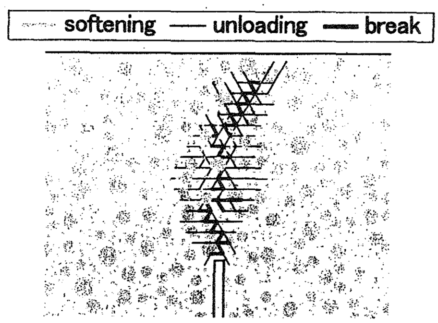


Fig.9(a) Load(P)-displacement(δ) curves



(a) d_a=5mm

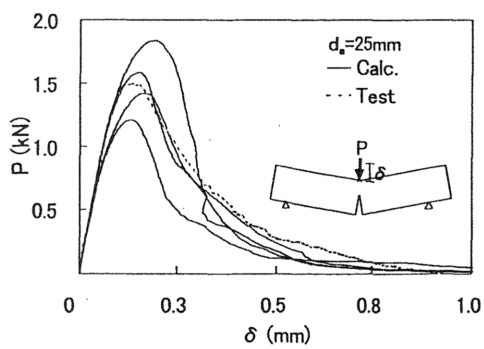
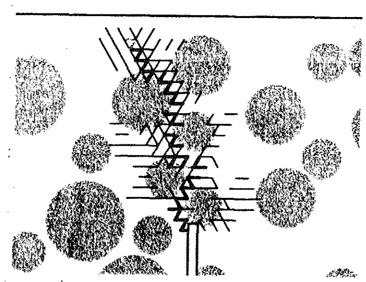


Fig.9(b) Load(P)-displacement(δ) curves



(b) d_a=25mm

Fig.11 Damage distribution

4 Discussion on compressive fracture nature

Fracture simulations of concrete subjected to compressive stress is conducted to show the limitation of the present particle model. A particle model with links which transmit only axial force shows macrospically Poisson's ratio ν=1/3. This value is not applicable to the macroscopic compressive response for general concrete, because the model leads to unexpected fracture in early loading stage. In order to compensate this drawback, an additional 2-D triangular finite element is superimposed to a triangular lattice network. In this study, for simplicity, only Poisson's effect is considered in the 2-D triangular finite element so that the perpendicular and shear stiffnesses are neglected in each element. Fig. 12 shows the test result by van Vliet & van Mier (1995) and calculated results with ν'= -0.3, -0.15 and 0; where ν' means Poisson's ratio adopted in the superimposed finite element. Calculated results indicate that improvement in macroscopic Poisson's effect may hold the key to the solution of the realistic compressive fracture analysis. However, more effective solutions are still needed from the observed results. Fig. 13 illustrates damage distribution when ν'= -0.3. The figure shows the perfectly broken state as soon as reaching the post peak region. The directional bias of fracture is more clearly appeared in the present study than those in the previous tensile stress state analysis. For gradual brittle response, a modeling shear friction in a link element would be required for future work.

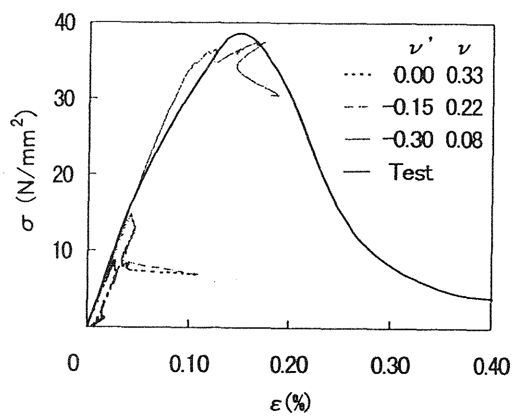


Fig.12 Stress(σ)-strain(ε) curves

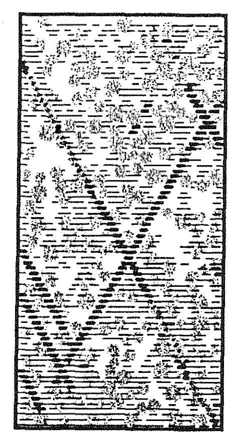


Fig.13 Damage distribution

5 Conclusions

A particle model was applied to simulate fracture of notched prisms and notched beams, introducing model parameters. Several conclusions can be made :

1. Microscopic mortar parameters in a particle model can be determined from macroscopic response observed in mortar specimen. Calculated microscopic parameters are applicable to fracture analysis of concrete.
2. A particle model for concrete can simulate a macroscopic response, taken into account the effect of the maximum aggregate size, although the model needs more considerations for 2-D aggregate distribution.
3. For compressive response in a particle model, macroscopic Poisson's ratio must be corrected to 0.2 for general concrete. In addition, to simulate a compressive softening behavior, modeling shear stiffness in a link element would be required.

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6 References

Jirasek, M. and Bazant, Z.P. (1995) Particle model for quasibrittle fracture and application to sea ice, **Journal of Engineering Mechanics**, 1016-1025.

Jirasek, M. and Bazant, Z.P. (1994/1995) Macroscopic fracture characteristics of random particle systems, **International Journal of Fracture**, Vol.69, 201-228.

Mihashi, H. (1995) Influence of strength properties of concrete on fracture mechanics parameters (Japanese), **Concrete Research and Technology**, Vol. 6, No.1. 81-88.

Schlangen, E. and van Mier, J.G.M. (1992) Experimental and numerical analysis of micromechanisms of fracture of cement-based composites, **Cement and Concrete Composites**, Vol.6, 81-88.

van Vliet, M.R.A. and van Mier, J.G.M. (1995) Softening behavior of concrete under uniaxial compression, **Proc. of FRAMCOS-2** (edit. Wittmann, H.), AEDIFICATIO Pub.