Fracture Mechanics of Concrete Structures
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MODELLING AND VERIFICATION OF MICROCRACK PROPAGATION IN CONCRETE

R. Arai
Shibaura Institute of Technology, Tokyo, Japan
T. Shibata, H. Hayano, K. Kohno, H. Mori, and T. Okamoto
Central Research Institute, Nihon Cement Co., Ltd, Tokyo, Japan

Abstract
In this study a model of microcrack occurred during the fracture process of mortar or concrete is presented and verified using Rigid Bodies Spring Model (RBSM), which is characterise by tensile and shear springs. A model of mortar or concrete specimen under compressive and tensile actual loading was considered. Based on the Moment Tensor Analysis of Acoustic Emission, information about crack location and crack type are obtained. Also cracks are classified into tensile cracks or shear cracks. Consequently, there is good agreement between analysed results and experimental results. Thus RBSM could be suggest being useful for the calculation of fracture basic criteria of concrete.
Key words: Rigid Bodies Spring Model , microcrack, Acoustic Emission

1 Introduction

Rigid-Bodies Spring Model (RBSM) is one of the Discrete Analysis for Rigid-

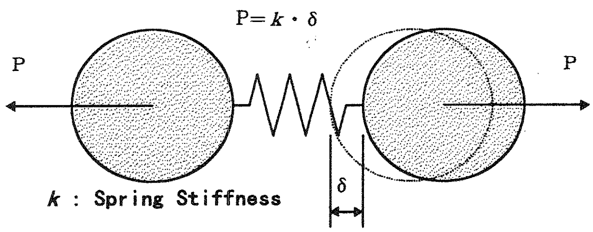


Fig.1 Rigid Bodies-Spring System

Bodies Spring Model (RBSM) is one of the Discrete Analysis for limit analysis. Fig. 1 shows that two rigid bodies are connected by a spring, when it is forced by tensile alone. In the system, it is assumed that rigid bodies are not deformed by tensile. In exchange the spring stretches, and stores the energy. Extending this concept and introducing springs which resist tensile and shear force, into the model creates RBSM (Takeuchi, N. et al., 1994). In this way, RBSM can easily express cracking and slipping to show their influence on the failure of concrete structure (Shibata, T. et al.,1996). In this paper, RBSM is applied for compression test of mortar and concrete, and compared with the experimental result.

2 Abstract of RBSM

Table 1. simply summarises the difference between finite element method (FEM) and RBSM, and the details follows.

1. Element Shape : Analysing Plane-Strain Problem by RBSM, analysis region needs to be meshed like FEM. Triangle and squares are used as element in FEM. However RBSM does not have any limit, because it is assumed that rigid body is not deformed. Voronoi Polygons is used to divide the body.

Table 1. Difference of FEM and RBSM

	FEM	RBSM
Element Shape	Triangle	Arbitrary Polygon
Degree of Freedom	2 ; (u, v)	3 ; (u, v, θ)
Position of Degree of Freedom	the Apex of a triangle	Arbitrary Point Inside Element (Center of gravity etc)
Stress	Inside Element (σx, σy, τ)	On the Boundary of Element (σn, τ)

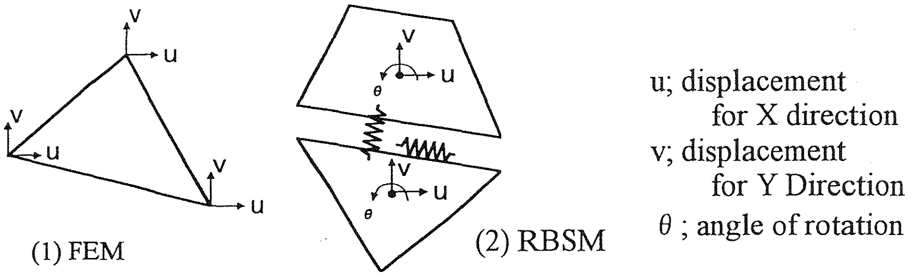


Fig.2 Degree of Freedom and the location

2. Degree of freedom and the location : As in Fig.2, element of FEM has two degree of freedom (u, v) on each node. In contrast, element of RBSM has three degree of freedom, u, v, and θ , on arbitrary point.
3. Stress : In element of FEM, stresses (σ x, σ y, σ xy) of respective elements are calculated from displacement of each node. In RBSM, we calculate two forces per unit of area (σ n, σ) on boundary line of element (see Fig.2).

3 Fracture Analysis Method Using RBSM

3.1 Fracture Condition of Spring

The springs are assumed to satisfy the following conditions, and they should be broken when tensile stress or shear stress becomes bigger than material parameter.

Constitutive Equation $\sigma = E \varepsilon$ (1)

Fracture Condition $\sigma = ft$ (2)

Coulomb's Equation $\tau = c + \sigma tan$ (3)

Where σ = normal stress, τ = shear stress, E = Young's Modulus

This analysis takes into account only shear and tensile fracture beause it was assumed that material does not break by compress. Table2 shows material parameters, which are used as spring stiffness, on element's boundary. These parameters are dicided by Literature Neville, A.M. (1973) and experimental results (Table 4) . But coarse aggregate are not defined, because it is assumed that coarse aggregate can not be deformed

Table2. Material Parameters

	E GPa)	υ	ft(MPa)	c(MPa)	ϕ (°)
(1)mortar-mortar	27.0	0.2	2.0	4.0	35.0
(2)mortar- coarse aggregate	20.0	0.2	1.5	2.5	35.0

ε = strain , ft = tensile stress , c =shear strength , ϕ= Angle of internal friction

or broken. In analysis of mortar it is assumed to be homogeneity material. However row (2) are also used for between coarse aggregates, because it is assumed that mortar exists between them.

3.2 Voronoi Tessellate

In this study, Voronoi Tessellate is used for meshing to reduce the effect of element shape on result of analysis. Voronoi Polygons are arbitrary polygons, which are formed by the perpendicular bisectors of each line of triangles formed by panel points generated by random-number. Fig.3 shows the meshing in this study. The meshing of both mortar and concrete are. The elements, indicated by bold line in Fig.4, are distributed as a coarse aggregate in concrete. Rate of coarse aggregate area is decided as 30 %. Table 3 shows condition of element in this analysis.

Table 3. Condition

①Type of Element	Plane Strain Problem	④Number of Panel Point	796
②Friction after Failure	Ignored	⑤Number of Element	429
③Friction of Loaded Surface	Exist	⑥Number of Spring	1118

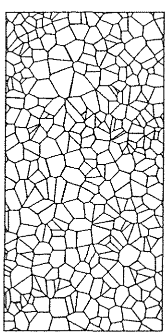


Fig.3 Voronoi Tessellate

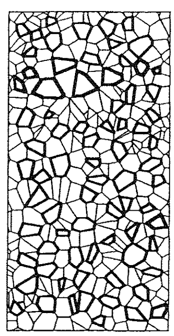


Fig.4 Placing Aggregate Element

4 Measurement of crack type by experiment

After compressing mortar and concrete, AE waveform is measured. From the measurement, these information of cracks in specimen are obtained ①Points of generation ②Pattern of generation ③Type.

Materials used for the experiment are Ordinary Portland Cement (specific gravity =3.15), crushed sand (specific gravity = 2.59) and crushed stone (specific gravity = 2.64, maximum size= 20mm). Axial compression test is carried out by cylindrical (ϕ 10×20cm) specimens, which are made of mortar or concrete. The water-cement ratio of them is 50 %. The volume ratio of coarse aggregate is 40 %. Mortar, in which coarse aggregate is removed, is used. Table4 shows mechanical character of mortar and concrete.

Fig.5 shows location of AE sensor when AE waveform was measured. AE waveform recorder can simultaneously records six AE waveforms. It carries out Moment Tensor Analysis by using recorded AE waveform (Ohtsu, M.,et al., 1993) . Finally , location and crack information are obtained.

Table 4. Mechanical Character of Mortar and Concrete

Type	Strength (MPa)		Young's Modulus (GPa)
	Compression	Tension	
Mortar	41.8	2.05	27.0
Concrete	40.5	2.30	29.4

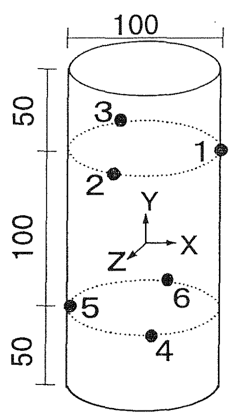


Fig.5 Location of AE Senser

5 Result and Discussion

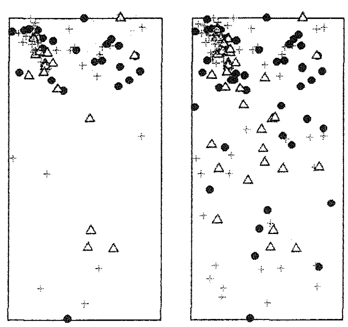
5.1 Result of experiment

Fig.6 and Fig.7 show the state of the micro-crack development in mortar and concrete at the middle of the test and the end of the test, which were obtained from AE waveform data. They show XY plane of Fig. 5,

In Fig. 6, many cracks are on upper part of the specimen. The reason is that the upper part becomes comparatively weak due to bleeding. The bleeding happen because fresh mortar is considered to be a little bit softly. In concrete, at the first level of load, cracks are in uniformly. It is proposed that at the end of fracture both tensile and shear cracks is uniform as a whole.

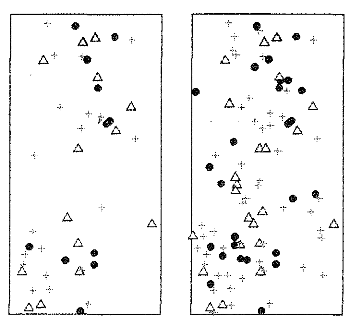
Comparing mortar with concrete, shear cracks ratio is more than one of tensile cracks. That is to say, ratio of shear crack to tensile cracks is almost 1:1 in mortar but about 2:1 in concrete. The cause is many shear slidings happen on boundary line of between coarse aggregate and mortar-matrix. Therefore it is considered that the slips are introduced by shear cracks.

Fig.8 shows the relationships between AE hit counts and compressive load of mortar. Until the load level is 90 percent, AE hits are gradually generated. However, once it reaches over the percent, AE hit are rapidly produced. Therefore, the result of AE method shows that the microcrack



(a)at the middle of test (b)at the end of test

Fig. 6 State of the Crack Development (Motar)



(a)at the middle of test (b)at the end of test

Fig.7 State of the Crack Development (Concrete)

● : Tensile Crack: Crack contains tensile components above 60 %

+ : Shear Crack: Crack contains shear components above 60 %t

△ : Mixed Crack: Crack contains tensile and shear components

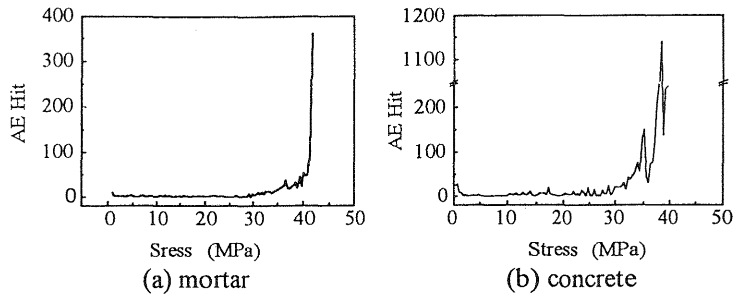


Fig.8 Relationship between the number of AE hit and stress

occurs gradually before the fracture, then rapid occurrence of the microcrack affect the fracture of mortar and concrete.

5.2 The comparison of analytical and experimental result

Fig. 9 shows stress-strain curve obtained by RBSM in compression test. Solid line expresses the result of analysis and the dotted line shows experimental result. Also, circles in the figures express the fracture point of spring showed in Fig. 10 and 11. Through this study, compressive fracture is not taken into account as a fracture condition, and we just set the condition of shear and tensile.

However, the stress-strain curve from the analysis shows same fashion with experimental curve. The strength of mortar from analysis is 20 % lower than the one by experiment, but the values of Young's Modulus from both analysis and experiment are same. The reason why the Strength shows lower value in analysis is that friction after cracking is not taken into account, although friction exists in reality.

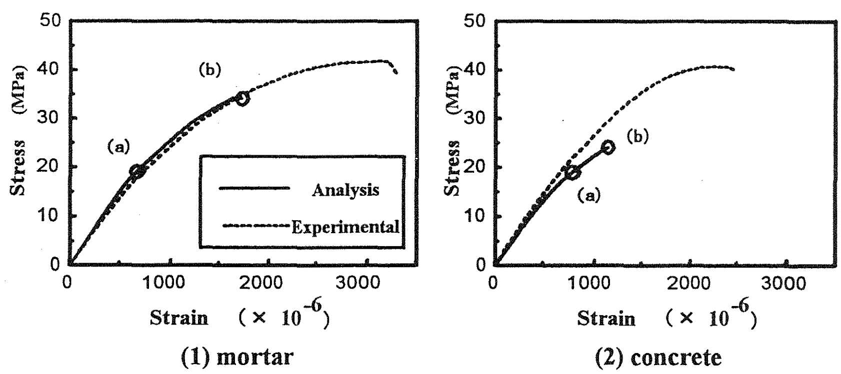
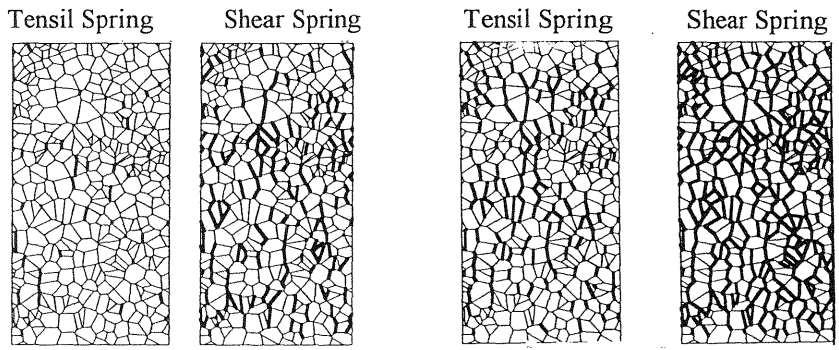


Fig. 9 Stress Strain Curve Analysis Experimental

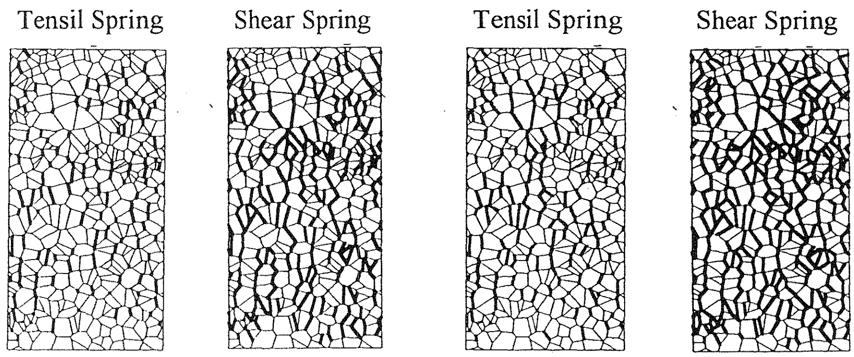
In concrete, both values of Young's Modulus and strength from analysis are lower than one by experiment. It is because that the mechanical behavior of materials is expressed by springs connecting the rigid-body elements in RBSM. Young's Modulus and strength of coarse aggregate are not take into account in analysis, but only bond of mortar-aggregate interface. Consequently analysis results show lower value.

Fig. 10 and 11 show fractures situation of springs in RBSM when load is 19MPa and break point. Comparing mortar and concrete at 19MPa shows that the many of tensile springs on boundary and coarse aggregate in axial direction are broken in concrete, while tensile springs in mortar are not much broken.



(a)At 19Mpa (b)Break Point

Fig.10 Fracture Situation of Spring(Mortar)



(a)At 19Mpa (b)Break Point

Fig.11 Fracture Situation of Spring(Concrete)

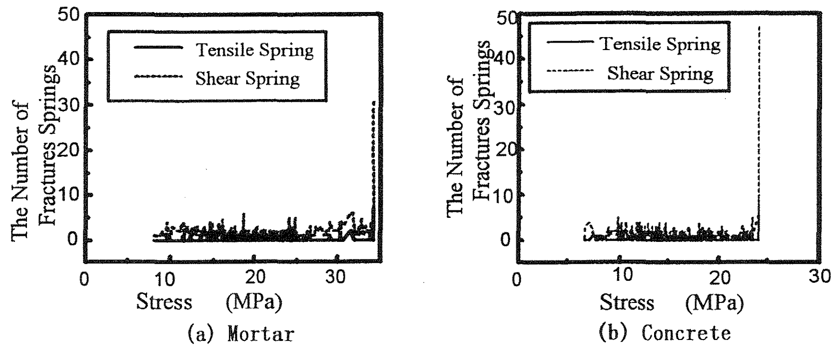


Fig.12 the curve of stress vs. the number of fractured springs

Shear springs are broken as a same fashion in both concrete and mortar, but the fracture ratio in concrete is a little bit bigger. At the fracture, although it is not obvious the differences between these two materials, the vertical cracks, which can be seen in real compression test, are generated. Furthermore, since loading surface has effect of friction, cracks exist less than the other parts. However, triangle cracks, which are generated at fracture on the end of specimen in real test, cannot be seen through this analysis.

By comparing fracture situation of springs (Fig. 6 and 7) and figures of cracks obtained by experiment (Fig. 10 and 11), it could be said that analytical results shows almost same distribution of cracks in specimen, although crack distribution is localised due to the materials' non-homogeneity.

Fig. 12 shows the curve of stress vs. the number of fractured springs. Both shear and tensile springs are gradually broken from the beginning and suddenly most of the springs are broken, then the specimen itself is failure. It can be considered that this is almost same development of AE obtained by experimental results. Therefore, the fact is one of the items to support the idea that the phenomenon of generation of cracks can be expressed by fracture of springs in RBSM.

6 Conclusions

The results of the study are summarised as follows,

1. RBSM can be used to model development of microcrack in mortar and concrete.
2. It is proved that there is a relationship between shear/tensile springs by and shear/tensile cracks by Moment Tensor Analysis of AE.

3. RBSM well to simulate AE event development by the development of spring fracture
4. From 1.-3., RBSM can be suggested to be an useful for the calculation of fracture basic criteria of mortar and concrete.

In future we will apply RBSM to member of concrete under bending and reinforced concrete. Also we have tried improvement of RBSM's computer program due to simulate softening behavior of concrete.

7 References

Neville, A. M. (1973) Properties of Concrete, **Pitman Publishing**

Ohtsu, M., Shigeishi, M., Yuyama, S., Okamoto, T. (1993) SiGMA Produce for AE Moment Tensor Analysis, **Japanese Society of Non-Destructive Inspection (JSNDI),** Vol.42,No.10,570-575

Shibata, T., Okamoto, T., Ogawa, K., and Ymamoto, K. (1996) Ultimate Fracture Analysis of Cement Mortar by Rigid-Bodies Spring Model, **Proceedings of the Japan Concrete Institute**, Vol. 18, No.1, 627-632

Takeuchi, N., Ueda, M., Kitoh, H., Higuchi, H., Kanbayashi, A. (1994) Size Effect Analysis of Plain Concrete Beams by Using RBSM with Voronoi Element, **Journal of Structural Engineering**, Vol.40A, 519-27