Three-Dimensional Visualization of AE-SiGMA by VRML for Micro-Cracking in Concrete

Graduate School of Science and Technology, Kumamoto University, Student Member ○ Farid Uddin A.K.M.
Graduate School of Science and Technology, Kumamoto University, Member of JSCE Masayasu Ohtsu

1. Introduction

AE-SiGMA procedure is developed as a powerful technique for moment tensor analysis of acoustic emission (AE)[1]. Crack kinematics of locations, types and orientations are quantitatively determined[2]. Because these kinematical outcomes are obtained as three-dimensional (3-D) locations and vectors, virtual reality modelling language (VRML) is applied. Failure processes of concrete specimens are discussed by using 3-D visualisation of AE-SiGMA analysis.

2. Moment tensor analysis

By taking into account only P wave motion of the far field of Green's function in an infinite space, displacement Ui(x, t) of the first motion is obtained,

$$U_i(x,t)=-1/(4\pi\rho\upsilon_p^3)(r_i r_p r_q/R)(dS(t)/dt)M_{pq}. \quad (1)$$

Here, ρ is the density of the material and υ_p is the velocity of P wave. R is the distance between the source y and the observation point x, of which direction cosine is r = (r1, r2, r3). S(t) is the source-time function of crack motion. Considering the effect of reflection at the surface and neglecting the source-time function, amplitude A(x) of the first motion is represented,

$$A(x)=Cs/R\,Ref(\mathbf{s},\mathbf{r})r_p M_{pq}\, r_q, \quad (2)$$

where Cs is the calibration coefficient including material constants in Eq. 1. t is the direction of the sensor sensitivity as shown in Fig.1. Ref(**s**,**r**) is the reflection coefficient. Since the moment tensor is symmetric, the number of independent unknowns of M_{pq} is six. Thus, multi-channel observation of the first motions at more than six channels is required to determine the moment tensor components.

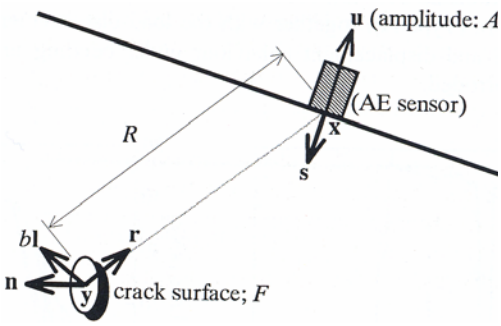

Fig.1 AE observation at AE sensor placed on a boundary surface.

3. Crack kinematics representation

In the case of an isotropic material, the moment tensor, M_{pq}, is defined as,

$$M_{pq}=(\lambda l_k n_l \delta_{pq}+\mu l_p n_q+\mu l_q n_p)\Delta V \quad (3)$$

where λ and μ are Lame's elastic constants. **l** is the unit direction vector and **n** is the unit normal vector to the crack surface as shown in Fig.2. ΔV is the crack volume. Then, the classification of a crack is performed by the eigenvalue analysis of the moment tensor. Setting the ratio of the maximum shear contribution as X, three eigenvalues for the shear crack become X, 0, -X. Likewise, the ratio of the maximum deviatric tensile component is set as Y and the isotropic tensile as Z. It is assumed that the principal axes of the shear crack are identical to those of the tensile crack. Then, the eigenvalues of the moment tensor for a general case are represented by the combination of the shear crack and the tensile crack. Because relative values are determined in AE-SiGMA, three eigenvalues are normalized and decomposed,

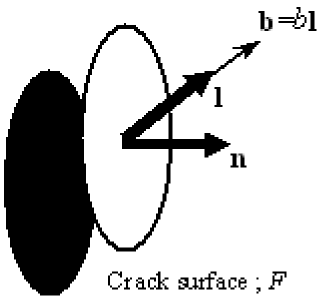

Fig.2 Modelling of a micro-crack.

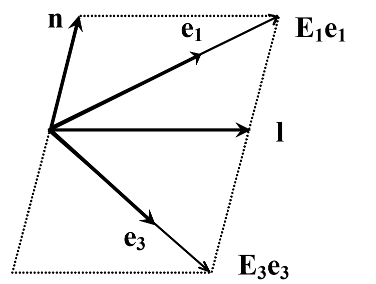

Fig.3 Crack nucleation by moment tensor analysis.

$$1.0=X+Y+Z, \qquad e_2/e_1=0-0.5Y+Z, \qquad \text{and} \qquad e_3/e_1=-X-0.5Y+Z, \quad (4)$$

where X, Y, and Z denote the shear ratio, the deviatric tensile ratio, and the isotropic tensile ratio, respectively. In AE-SiGMA analysis, AE sources of which the shear ratios $X < 0.4$ are classified into tensile cracks. Otherwise, the sources of $X > 0.6$ are classified into shear cracks. Sources of X are between 40% and 60% are referred to as mixed mode. Fig.3 shows the geometry among the unit eigenvectors, normal to crack surface **n** and crack motion direction **l**. Three eigenvectors are $\mathbf{e_1}=\mathbf{l}+\mathbf{n}$, $\mathbf{e_2}=\mathbf{l}\times\mathbf{n}$, and $\mathbf{e_3}=\mathbf{l}-\mathbf{n}$. The vectors **l** and **n** can be recovered from the following relations,

$$\mathbf{l} = [(2+2l_k n_k)^{1/2}\,\mathbf{e_1} + (2-2l_k n_k)^{1/2}\,\mathbf{e_3}]/2$$

$$\mathbf{n}=[(2+2l_k n_k)^{1/2}\mathbf{e_1}-(2-2l_k n_k)^{1/2}\mathbf{e_3}]/2. \quad (5)$$

Keywords: AE-SiGMA, micro-crack, virtual reality modelling language (VRML), concrete, moment tensor analysis
Address: Kumamoto University; Kurokami 2-39-1, Kumamoto 860-8555, Japan; TEL 096-342-3542 FAX 096-342-3507

Fig.4 VRML objects for tensile, shear, and mixed-mode cracks.

Table 1 Dimensions of the concrete specimens

Concrete specimen	Dimensions	Cover thickness in concrete	Remarks
A	25cm x 25cm x 15cm	4cm	with a pre-crack notch
B	25cm x 25cm x 10cm	2cm	with a pre-crack notch

4. Visualisation of micro-cracking

By AE-SiGMA procedure, classification of cracks is readily made, whereas crack orientation is not easily recognized. In this respect, VRML is introduced. Crack models of tensile, mixed-mode and shear are given in Fig.4. Here, an arrow vector indicates a crack motion vector, and a circular plate corresponds to a crack surface, which is perpendicular to a crack normal vector.

In experiments[3], due to expansion of corrosive products, cracks are nucleated in concrete. Initiation and propagation of cracks are studied experimentally. Figures 5 and 6 show results of AE-SiGMA analysis of two specimens, which were fractured by expansive pressure at the holes. Two types of concrete specimens were made and the dimensions of the specimens are given in Table 1. Here, it is confirmed that the surface crack is nucleated first in previous studies[3]. Consequently, a pre-crack was introduced at the cover in both cases. The difference of cracking patterns could correspond to the restriction effect of the cover thickness in concrete.

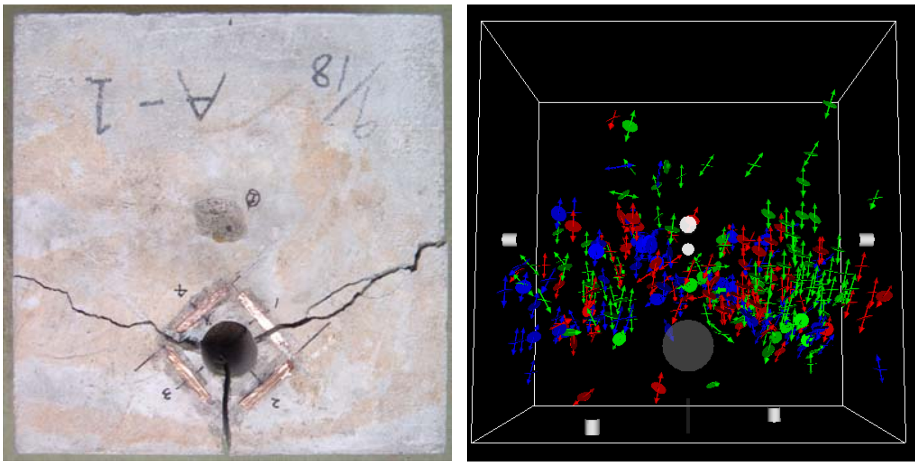
Fig.5 Photograph of crack propagation (left) and SiGMA analysis visualised results (right) of the specimen A.

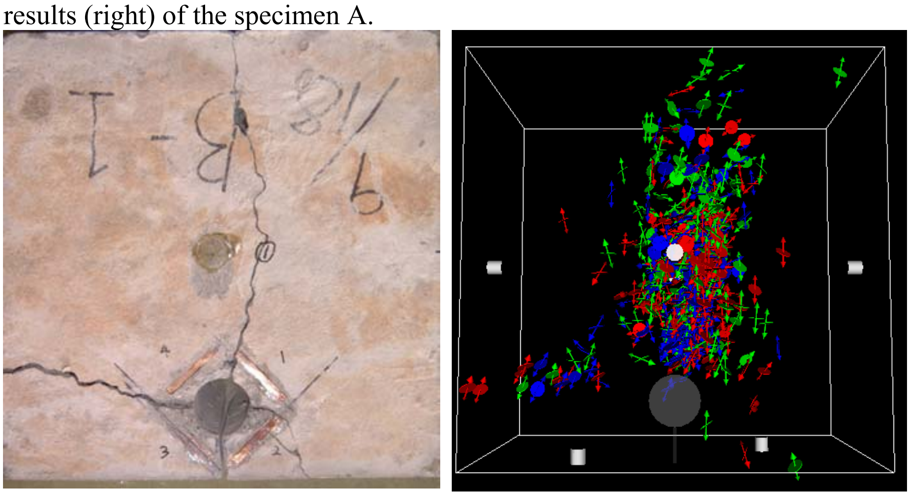
Fig.6 Photograph of crack propagation (left) and SiGMA analysis visualised results (right) of the specimen B.

5. Conclusion

Nucleation of cracks can be quantitatively analyzed by applying AE-SiGMA. Crack kinematics on locations, types and orientations are determined three-dimensionally. Three-dimensional visualization procedure for AE-SiGMA analysis is developed by using VRML. Failure processes of concrete specimens are successfully visualized. The difference of crack patterns is clarified. Also, it is found that cracking mechanisms due to expansion of hole (likely corrosive products) are mostly associated with the tensile-type of micro-cracking along with mixed-mode and in a few cases with the shear-type of micro-cracking.

References

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