Committee Report : JCI- TC111A

Technical Committee on Evaluation Method of Crack Propagation of Concrete Structures

Hikaru NAKAMURA, Keiichi IMAMOTO, Kohei NAGAI, Takeshi WATANABE, Ippei MARUYAMA, Toshihide SAKA and Yoshihito YAMAMOTO

Abstract

With a focus on crack propagation in concrete, this Committee concentrated on the morphology of cracking and investigated the current state and future development of the evaluation of crack propagation, while inventorying test and analysis techniques currently available and examining their scope and potential. The topics included testing techniques capable of evaluating crack propagation (digital image processing, etc.), analysis techniques for evaluating crack propagation (FEM, RBSM, etc.), and methods of evaluating crack propagation in deterioration cases due to various causes (drying shrinkage cracking, corrosion cracking, etc.).

Keywords: crack propagation, deteriorative factor, measurement technique, numerical analysis, performance evaluation

1. Introduction

Evaluation of cracks in concrete structures resulting from various causes has recently been attracting attention from the aspects of maintenance and service life extension. Suppression of temperature and shrinkage cracking, for instance, is required for newly built structures. Clarification of the causes of cracking and prediction of crack propagation are required for existing structures. Conventional studies have tended to focus on conditions to suppress the occurrence of cracking, accurately grasping the state of observed cracking, and assessment of its impact. Structural analysis techniques have also tended to focus on each crack, scarcely covering the propagation behavior of a crack after its initiation. Accurate evaluation of crack propagation behavior, if possible, will greatly contribute to the sophistication of technology for crack suppression and control.

Therefore, the present Committee experimentally and analytically reviewed the current techniques for evaluating crack propagation in concrete structures, investigated the methods of their application to deterioration cases, and recapitulated their serviceability and potential.

Table 1: Committee Members

Chairperson	Hikaru NAKAMURA	Nagoya University
Vice Chairperson	Keiichi IMAMOTO	Tokyo University of Science
Secretary General	Kohei NAGAI	University of Tokyo
Experiment WG		
Convener	Takeshi WATANABE	Tokushima University
Vice Convener	Ippei MARUYAMA	Nagoya University
Members	Keiichi IMAMOTO	Tokyo University of Science
	Yuichiro KAWABATA	Port and Airport Research Institute
	Takatsune KIKUTA	Tohoku University
	Ichizou KISHIMOTO	Kinki University
	Mitsuo KOYANAGI	Obayashi Corporation
	Shigehiko SAITO	University of Yamanashi
	Haruhiko SUWADA	National Institute for Land and Infrastructure Management
	Masaki TAMURA	Kogakuin University
	Naoko TSUCHIYA	Building Research Institute
	Masanori TSUZUKI	Obayashi Corporation
	Akira HOSODA	Yokohama National University
	Hiroshi MATSUDA	Nagasaki University
	Ken WATANABE	Railway Technical Research Institute
Observer	Akira DEMIZU	Nagasaki University
Analysis WG		
Convener	Kohei NAGAI	University of Tokyo
Vice Convener	Toshihide SAKA	Kajima Technical Research Institute
Members	Hikaru NAKAMURA	Nagoya University
	Shingo ASAMOTO	Saitama University
	Hideki OHSHITA	Chuo University
	Hiroki OGURA	SHIMIZU Corporation
	Noriyuki TAKAHASHI	University of Tokyo
	Nobuhiro CHIJIWA	Tokyo Institute of Technology
	Shigeharu NAKAMURA	Osaka Institute of Technology
	Tomohiro MIKI	Kobe University
	Yoshihito YAMAMOTO	National Defense Academy of Japan

Table 1 lists the members of the Committee. They were organized into the Experiment WG to survey the latest findings of crack measurement and the Analysis WG for numerical analysis, and reorganized accordingly for their mutual relations and round-robin tests to be described later.

Part of the committee activities will be reported in the following chapters. This chapter introduces the committee activities as a whole in line with the full version of the Committee Report. The Report begins with a survey of findings from the committee activities related to crack propagation. After mentioning the concept of crack propagation, it summarizes the relationship between the physical quantities constituting crack propagation and performance (**Fig. 1**). This includes the physical quantities associated with the initiation, mechanical data, propagation, and boundary conditions of cracks and the performance evaluation based on these quantities. Crack propagation phenomena induced by each deteriorative factor are also explained and compared. Treatment and remedial measures for cracking from a practical aspect are also summarized as engineering evaluation methods.

As to the progress and current state of the crack measurement technology, the Experiment WG then reviews the measurement accuracy and application examples of crack scales, digital imaging, digital image correlation, electronic speckle pattern interferometry, resin impregnation, ultrasonic flaw detection, impact elastic wave testing, acoustic emission (AE), and techniques using radioactive ray imaging.

As to numerical analysis expressing crack propagation, the Analysis WG reviews models necessary for expressing cracks for each phenomenon and systematizes representative analysis techniques and their features. Application cases are presented in regard to in-section equilibrium, member deformation, finite element analysis (FEM), and rigid body-spring modeling (RBSM) to recapitulate the latest findings related to analysis of crack propagation due to material deterioration and external forces.

Also, the Report describes the Committee’s own round-robin tests and numerical analysis. In the round-robin tests, crack propagation was measured by AE, image analysis, etc. on the material and structural levels to examine the serviceability of the methods. In the round-robin analysis, drying shrinkage and shear and flexural failure of beams were analyzed using test data in the literature by FEM and RBSM to compare the results.

Finally, the current state and future expectation for the evaluation of crack propagation are summarized through discussions held during the term of the Committee.

This summarizes the Committee Report. The following chapters report on the progress and current state of crack measurement technology (Experiment WG, Chapter **2**), numerical analysis expressing crack propagation (Analysis WG, Chapter **3**), and round-robin tests and analysis (Chapter **4**).

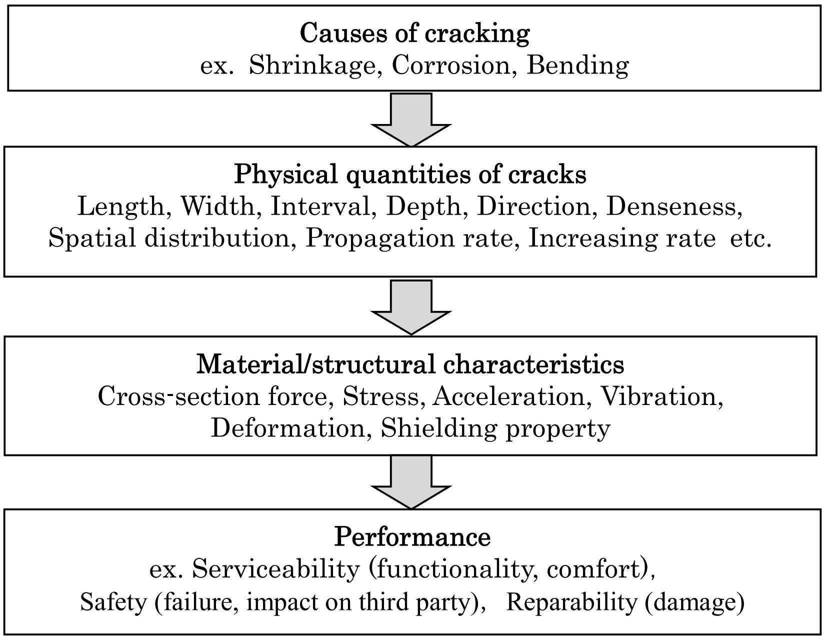

Fig. 1: Performance evaluation flow starting from the causes of cracking

2. Development and current state of crack measurement techniques (Experiment WG)

2.1 Activities

The Experiment WG surveyed techniques and methods of measuring crack propagation. For measuring crack propagation, it is essential to three-dimensionally grasp the shapes of cracks and measure their changes on a time axis. This WG decided to inventory those measurement techniques from the angles of “physical quantities of cracks and measurement techniques” and “causes of cracking and examples of measuring crack propagation”, pursuing what each measurement technique can provide in regard to cracking. The Committee Report is partially presented in the following Sections:

2.2 Physical quantities of cracks and measurement techniques

Techniques for measuring and evaluating cracks were surveyed as measurement techniques for crack propagation and physical quantities. **Figure 2** shows an example of measurement results using a measurement system by digital image correlation[1)].

The methods of evaluating crack propagation currently in use may enable quantitative evaluation but can lead to qualitative evaluation depending on the physical quantity to be measured, applications of measurement, and interpretation of the measurement results. Care should therefore be exercised. Some techniques are difficult to apply in the field. These should be used in the laboratories.

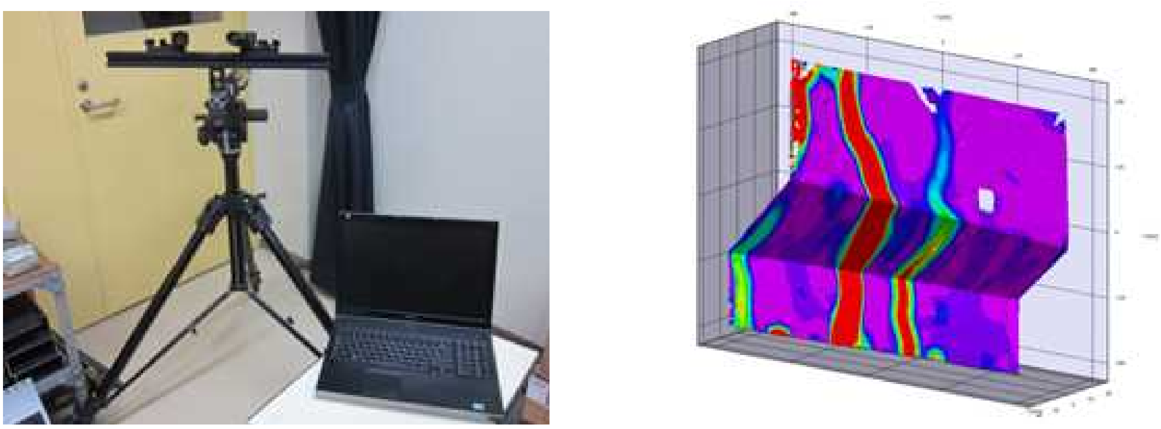

Fig. 2: A system and result (maximum principal strain distribution) of measurement by image correlation[1)]

Table 2 gives the intended evaluation items of crack measurement techniques and methods of converting data for evaluation of cracks. The measurement methods ultimately present some of the quantities or qualitative indices of cracks. However, they do not directly measure the quantities of cracks but are normally designed to convert the data or read the data in a different way. These are summarized in the table. Note that this table does not cover all techniques and conversions.

When measuring crack propagation using these techniques, measurement continuous in time is carried out. For such phenomena as dynamic failure, which proceeds very quickly, the measurement results are strongly affected by the temporal resolution of the technique. On the other hand, continuous measurement may not be possible using the same specimen by, for instance, resin impregnation.

2.3 Causes of cracking and examples of crack propagation measurement

Examples of actual crack propagation measurement carried out using the measurement techniques shown in **Table 2** were systematized according to the causes of cracking. The WG recapitulated the results of literature survey by classifying the causes into three categories: shrinkage cracking (drying, temperature), cracking due to external forces (fatigue, static, dynamic/seismic), and deterioration cracking (reinforcement corrosion, alkali-aggregate reaction, frost damage)

Table 2: Relationship between crack measurement techniques and cracking

Measurement technique	Evaluation item	Conversion to cracks/quantification technique
Visual observation (incl. crack scales/tape measures	Length, width	
Displacement meters (π gauges, etc.)	Displacement (strain)	
Digital imaging (cameras, scanners)	Analysis of pixels in images taken	Detect cracking from image analysis and determine the length and width of cracks from the relationship of the scanned area and pixel size.
Digital image correlation	Analysis of pixels in images taken	Calculate the travel of given points to determine the size and direction of displacement
Resin impregnation	Optical recognition of the presence of resin	Optically detect the presence of resin
Infrared thermography	Analysis of pixels in images taken	Determine the width of cracks from the relationship of scanned area and pixel size.
Elastic wave (ultrasonic/impact elastic waves)	Temporal waveform, arrival time of elastic wave	- Grasp the increase in the width of fine cracks by relative dynamic modulus. - Evaluate the crack depth by propagation rate and propagation time difference.
Acoustic emission (AE)	Temporal waveform and waveform parameters of elastic wave generated at the time of crack initiation	- Locate the source of crack initiation by multiple sensors. - Identify cracks and evaluate the initiation conditions, growth properties, or degree of damage to the structure by analyzing the occurrence history, frequency, correlations, and patterns of cracking.
X-ray	Transmitted and dispersed x-ray fluxes to the incident flux	Determine the length and width of cracks from the relationship of scanned area and pixel size.

3. Numerical analysis to express crack propagation (Analysis WG)

3.1 Activities

The Analysis WG reviewed the latest information on techniques for analyzing crack propagation and crack models. In order to analyze crack propagation through concrete materials and members, it is essential to model the materials and members and select the analysis technique in accordance with the cracking phenomenon under analysis. This WG decided to review the basic concepts of analysis techniques to track crack propagation, the method of handling the cracks by each technique, and latest examples of analysis. The Committee Report is partially introduced in the following Sections:

3.2 Basic concept of crack propagation analysis

Figure 3 shows a typical flow of crack propagation analysis. For this analysis, it is necessary to begin with the reproduction of cracking and tensile stress causing cracking. In other words, it is necessary to model the drive principles/driving forces of tensile stress.

In the case of the reinforced concrete structure given in **Fig. 3**, the drive principles/driving forces are classified into two: internal and external factors. Models of internal factors include mechanical models, such as those for volume changes, strength development, and elastic modulus development to express the concrete materials and models of reinforcing materials, such as steel bars and fibers. Models of external factors also include models of restraining members, ground conditions, and loading conditions serving as causes of mechanical behavior and environmental factors including temperature and humidity changes.

When reproducing cracking, it is necessary to select a crack initiation criterion and cracking model. A number of models including smeared models and discrete models have been proposed as crack models. Models for reproducing cracking should be selected from among these in accordance with the intended phenomena and physical quantities (length, width, location, etc.) to be investigated.

Reproduction of crack propagation requires selection of a post-cracking softening model and bond model to express interaction with reinforcement. Bilinear models and curve models, depending on the tensile energy, are predominant for the post-cracking softening model. A large number of bond models are also available. This should be selected in accordance with the intended phenomenon.

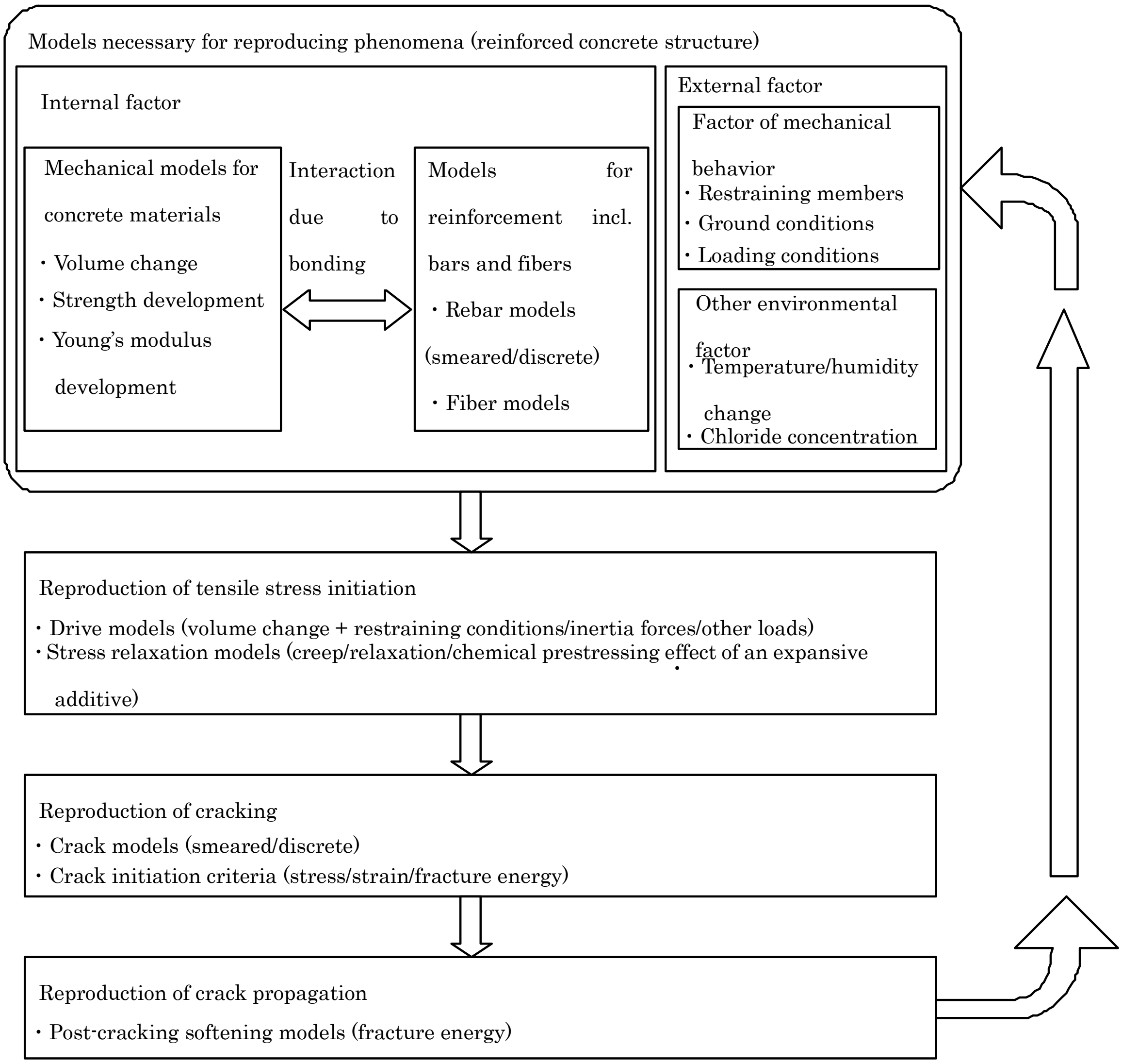

Fig. 3: Basic flow of crack propagation analysis

Table 3: Representative crack propagation analysis techniques

Category	Representative technique
In-section equilibrium	Tensile limit strain criteria[2], tensile stress criteria[3], tensile softening law criteria[4]
Member deformation	Member deformation
Techniques based on continuum modeling	Finite element method (FEM), generalized finite element method (X-FEM), etc.
Techniques based on discontinuum modeling	Rigid body-spring modeling (RBSM)[9], distinct element modeling (DEM)

3.3 Crack propagation analysis techniques and latest analysis cases

The present WG surveyed the handling of cracking and latest analysis cases in regard to analysis techniques given in **Table 3**.

The in-section equilibrium method is a method in which the crack initiation criterion is applied to the equilibrium between the forces acting on a section, which change over time, and the deformation of the section to evaluate the crack initiation and propagation (crack width). It is applicable to shrinkage and flexural cracking of uniaxial members affected by drying shrinkage. For analysis, the crack width is modeled by focusing on the bond slip between concrete and reinforcement, and the external forces and shrinkage strain are modeled into stress and strain acting on the section of the member. The equilibrium formulas of the stress and strain of concrete and reinforcement within the section are thus formulated.

The member deformation method deals with flexural cracks and shear cracks occurring in columns and beams, which are often modeled into lines, mainly due to earthquake motions. The analysis technique comprises a crack width evaluation model[5)], crack length evaluation model[6)], and crack width-length relationship evaluation model[5)]. This has been investigated to evaluate increases in the width and length of flexural cracks, flexural shear cracks, and shear cracks from the member deformation by applying experimental formulas to a simple analysis technique.

Techniques based on a continuum assume a concrete member to be a continuum and cracking is modeled as anisotropy. These techniques, which are represented by the finite element analysis method (FEM), are mostly formulated by sophisticating the constitutive laws of stress-strain relationship. Recent studies include those that explicitly model cracking using generalized FEM (see a review of past studies[7)] for details). These techniques cover a wide range of phenomena from shrinkage cracking to stress cracking, with many analysis models being proposed. A system has recently been developed whereby both microscopic material properties and macroscopic structural stress can be analyzed in an integrated manner, thereby allowing tracking of time-dependent changes in stress conditions and cracking behavior from the placement of concrete to the end of its service[8)].

Techniques based on a discontinuum are useful for expressing discontinuous displacement due to cracking. Rigid body-spring models (RBSM)[9)] and the distinct element method are included in this type. Rigid-body spring models can be formulated by relatively simple constitutive laws and are characterized by their capability of directly evaluating crack width as the amount of the tensile deformation of vertical springs. Softening models incorporating tensile failure energy are generally used for constitutive models of vertical springs. These are also used for mezzo-level analysis of concrete in which the nodes for aggregate and reinforcement are explicitly modeled[10), 11)]. Similarly to FEM, these models are applied to a wide range of members and structures.

4. Round-robin tests and analysis

4.1 Tests on the material level

(1) Experiment overview

As material level tests, specimens having slits as shown in **Fig. 4** were fabricated referring to past studies[12), 13), 14)], and the state of crack propagation under uniaxial compressive loading was simultaneously measured by image correlation and acoustic emission (AE). **Photo 1** shows the measurement setup. Gypsum, mortar, and concrete specimens were prepared, with the slit angles being 0, 45, and 90 degrees.

Two high-speed cameras with a resolution of 1 million pixels were used for measurement by image correlation. For AE measurement, resonance sensors of a 150 kHz type were used. Sensor channels on each specimen totaled 6, 4 on the sides and 2 near the sensors.

(2) Test results

As examples of the test results, this section describes the measurement results of mortar specimens with a slit angle of 45°. **Figures 5** and **6** show the distribution of the maximum principal strain by image correlation and the results of source location by AE, respectively.

Figure 5 reveals that the distribution of the maximum principal strain nearly agrees with the locations of macroscopic cracks visually confirmed. Also, **Fig. 6** reveals that the AE sources are distributed at locations of large strain in **Fig. 5**, suggesting that fine cracks occurred and propagated into large cracks. Also, comparison between the results by both methods with respect to the loading level reveals that AE tends to be detected at a loading level lower than that at which an increase in the strain is confirmed by image analysis.

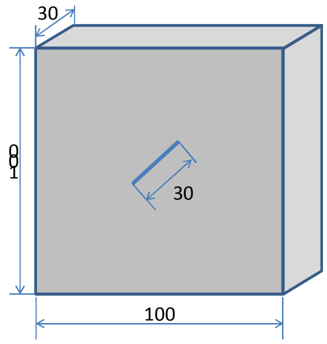

Fig. 4: Outline of specimen

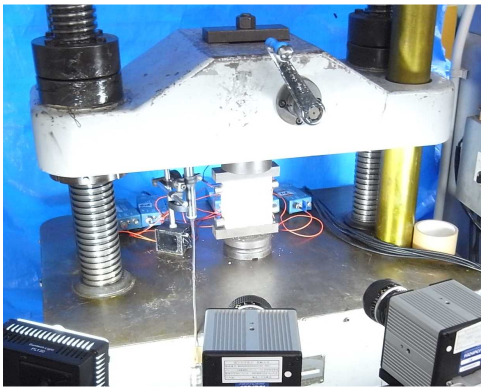

Photo 1: Measurement setup

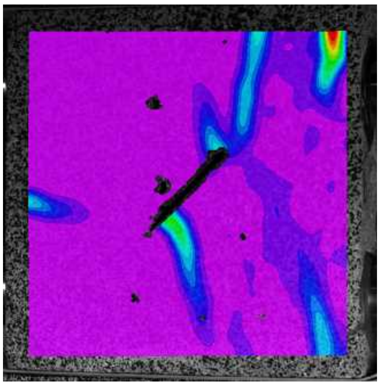

Fig. 5: Maximum principal strain distribution by image correlation

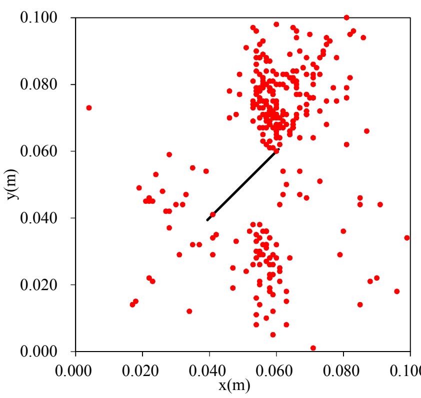

Fig. 6: Results of source location by AE

Acknowledgment:

The authors express their gratitude to the Faculty of Engineering of Nagasaki University for allowing us to use their experiment facilities and to Dr. Kentaro Ohno of the Tokyo Metropolitan University for his cooperation in the analysis of AE measurement results.

4.2 Round-robin analysis

(1) Analysis overview

Round-robin analyses of reinforced concrete and short fiber-reinforced concrete members were conducted under various conditions by the in-section equilibrium method, member deformation method, FEM, and RBSM as reported in Section **3.3** to grasp the current state of technology for the prediction of crack propagation. As an example, this Section describes analysis by 3D FEM and 3D RBSM using reinforced concrete subjected to shear failure.

The tests under analysis are those conducted by Watanabe et al.[15)], who precisely measure the cracking properties at each loading stage using image analysis techniques.

Tension-softening models based on fracture energy were used in both 3D FEM[16), 17)] and 3D RBSM[18), 19)] analyses. Also, reinforcement was discretely modeled, and the bond slip behavior between reinforcement and concrete was modeled. An element size of around 20 mm was selected so that the crack intervals observed in the tests would be sufficiently reproduced.

(2) Comparison with test results

Figure 7 shows the load-displacement responses obtained from the tests and analysis. Though the analysis overevaluates the rigidity obtained by the tests, the maximum load is adequately reproduced by both techniques.

Figure 8 shows the state of crack propagation at different loading steps obtained from the tests and analysis. **Figures 7 (a)** and **7 (b)** show the principal strain distribution and crack width, respectively. The dotted lines in the figure represent the cracks observed in the tests. Both 3D FEM and 3D RSBM are found to roughly reproduce the crack intervals and crack propagation angles observed in the tests.

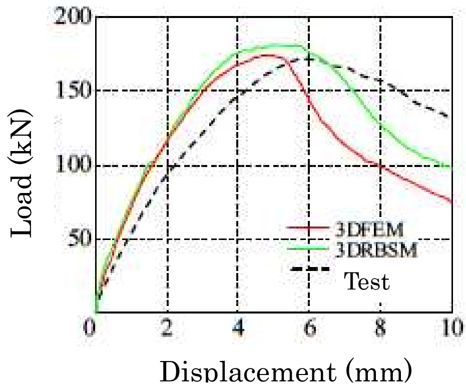

Fig. 7: Load-displacement relationship

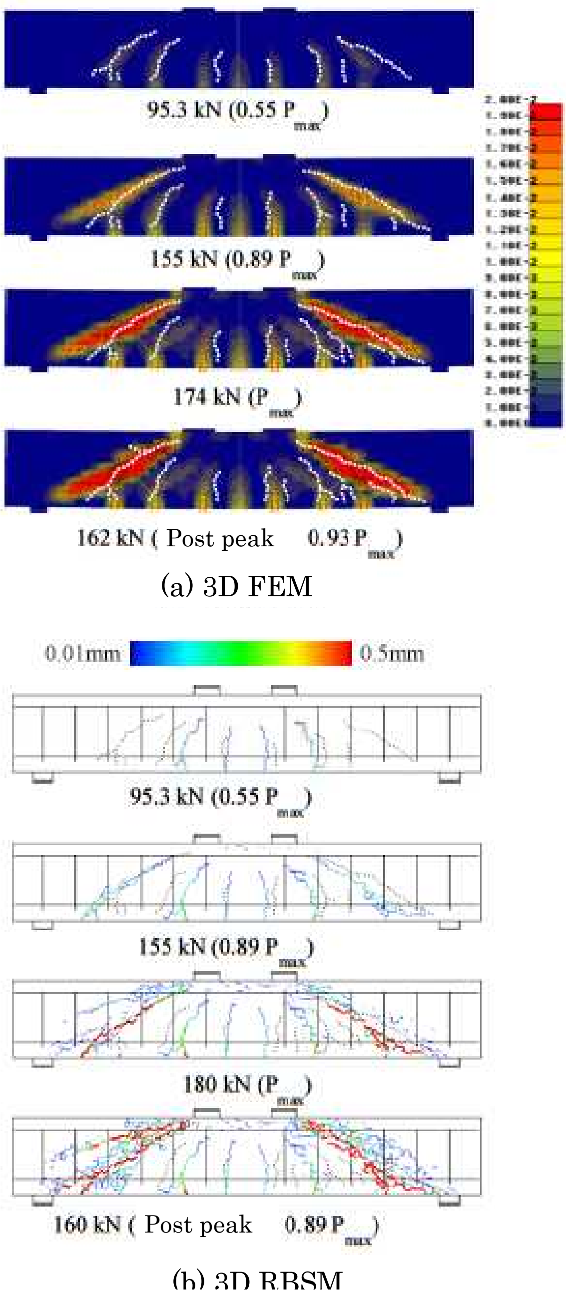

Fig. 8: Stages of crack propagation

(3) Summary

Within the range of tests under analysis, it was confirmed that the crack intervals and crack propagation angles can be adequately reproduced by current analysis techniques. However, there have not been sufficient studies that focus on the reproducibility of the detailed crack information as verified in this Section, while active studies have been conducted using nonlinear numerical analysis techniques, focusing on the reproducibility of macroscopic load-displacement response or spatial distribution of strain. A sufficiently small element size is required for reproducing detailed information of cracking. Further verification should be carried out regarding the correspondence between the element size and the averaging scale of mechanical behavior on which conventional constitutive models are premised. This WG also verified the effects of various analysis conditions on the results, including bond-slip models between reinforcement and concrete and first cracking due to dying shrinkage. Refer to the Committee Report for details.

5. Afterword

This Technical Committee reviewed crack propagation and its evaluation methods cross-sectorally from measurement and analysis aspects and academic and practical aspects in regard to a variety of factors. At present, organic linkage between measurement and numerical analysis of crack propagation including internal concrete has yet to be fully achieved, not being incorporated into a quantitative evaluation method or explicitly reflected on design. However, measurement technology and numerical analysis techniques have been increasing in variety and improving in precision, showing promise for further development. Findings of crack propagation, if systematized in the future, will be utilized for suppressing crack propagation. For instance, fibers for reinforcing concrete, which bridge cracks to suppress further opening, can be used more actively for the purpose of crack control in accordance with the external force conditions and deteriorative factors.

References

1) Demizu, A., Matusda, H., Ito, Y and Kimura, Y. : Displacement, strain, and crack measurement at loading test on removal PCT girder bridge by DICM, Proceedings of the Japan Concrete Institute, Vol.34, No.2, pp.1411-1416, 2012. (in Japanese)

2) Koyanagi, M., Masuda, Y., Nakane, S. : A study on prediction analysis of cracking widths due to shrinkage in reinforced concrete walls, Concrete Research and Technology, Vol.2, No.2, pp.59-68, 1991. (in Japanese)

3) Seo,T., Nakagawa,T., Ohno,Y. : Shrinkage Crack Width and Interval in Reinforced Concrete Wall, Proceedings of the Japan Concrete Institute, Vol.28, No.1, pp.557-562, 2006. (in Japanese)

4) Ujike,I., Sato,R., Xu,M., Anzai,S. : A Numerical Creep Analysis of Reinforced Concrete Members in Consideration of Tension Softening, Proceedings of the Japan Concrete Institute, Vol.20, No.3, pp.133-138, 1998. (in Japanese)

5) Takahashi, N., Takahashi, E., Nakano, Y. : Demonstration of the evaluation method for quantity of cracks in RC members, Proceedings of the Japan Concrete Institute, Vol.31, No.2, pp.859-864, 2009. (in Japanese)

6) Takahashi, N., Ito, Y., et al. : Simple estimation method for seismic crack-length of RC beam: Parts 1 and 2, Summaries of Technical Papers of Annual Meeting of Architectural Institute of Japan, C-2, pp.249-252, 2012. (in Japanese)

7) Applied Mechanics Committee, Computational Mechanics Subcommittee : Recent advances in computational mechanics for civil engineering, Journal of Japan Society of Civil Engineers, Ser. A2 (Applied Mechanics (AM)), Vol.68, No.1, 31-50, 2012. (in Japanese)

8) Maekawa, K., Ishida, T., and Kishi, T.: Multi-Scale Modeling of Structural Concrete, Taylor and Francis, 2008.

9) Kawai, T. : New Element Models in Discrete Structure Analysis, Journal of the Society of Naval Architects of Japan, 141, 174-180, 1977.

10) Nagai, K., Sato, Y., Ueda, T. : Mesoscopic Simulation of Failure of Mortar and Concrete by 2D RBSM, Journal of Advanced Concrete Technology, Vol.2, No.3, pp.359-374 2004.

11) Muto, S., Nakamura, H., Tanabe, T., Srisoros, W., Lee, S. : Analysis of bond characteristics between concrete and deformed bar by meso-scale analysis, Journal of Applied Mechanics: JSCE, Vol.7, pp.767-774, 2004. (in Japanese)

12) Shigeishi, M. and Ohtsu, M. : Acoustic Emission Waveform Analysis in Two-Dimensional Models, Japan Society of Materials Science, Vol.45, No.9, pp.1055-1060, 1996. (in Japanese)

13) Genki Maeda et al.: Visualization of crack propagation in concrete material by DICM, Proceedings of the 67th Annual Conference of the Japan Society of Civil Engineers, pp.1007-1008, 2012. (in Japanese)

14) Sugiyama, T. et al.: Evaluation of crack propagation from slit in gypsum specimen by DICM, Proceedings of the 67th Annual Conference of the Japan Society of Civil Engineers, pp.1009-1010, 2012. (in Japanese)

15) Watanabe, K., Higashi, H., Miki, T., Niwa, J. : Real-time image analyzing system for loading tests of structural concrete, Doboku Gakkai Ronbunshuu E, Vol.66, No.1, pp. 94-106, 2010. (in Japanese)

16) Morikawa, H., Koiso, T., Fukuda, R. : Nonlinear finite element analysis of reinforced concrete structures under cyclic loading, Annual Report of Kajima Technical Research Institute, Vol.54, pp.57-62, 2006.

17) Morikawa, H. : Improvement of 3D FEM for RC beam-column joints using blind analyses, Annual Report of Kajima Technical Research Institute, Vol.60, pp.79-84, 2012.

18) Yamamoto, Y., Nakamura, H., Kuroda, I., Furuya, N. : Analysis of uniaxial compression failure of confined concrete by three dimensional rigid body spring model, Doboku Gakkai Ronbunshuu E, Vol. 66, No. 4, pp.433-451, 2010. (in Japanese)

19) Gedik, Y. H., Nakamura, H., Yamamoto, Y., Kunieda, M. : Evaluation of Three-Dimensional Effects in Short Deep Beams Using a Rigid-Body-Spring-Model, Cement and Concrete Composites, Volume 33, Issue 9, pp.978-991, 2011.