THE NEED FOR STANDARD TEST METHODS

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Abstract

A Workshop on Standards for Measurement of Mode I Fracture Properties of Concrete was held July 20-21, 1995 at the University of Wales, Cardiff. This paper summarizes the results of this workshop. Consensus agreement was reached on the following points: a testing standard is needed; the standard should be directed to the measurement of a minimum of two fracture parameters; a simple test (level 1) and a more advanced test (level 2) should be specified; and the testing geometry should be prismatic beams (rectangular and circular in section) subjected to bending.

1 Introduction

Some thirty years ago attempts were made to apply the concepts of Linear Elastic Fracture Mechanics (LEFM) to analyze plain and reinforced concrete structures. The non-objectivity of the measured values of parameters such as fracture toughness, e.g., variation in specimen size or notch depth, led to abandonment of using only LEFM and explicit consideration of non-linear effects caused by a process zone preceding the open crack front. The application of the fictitious crack model led to a proposed test now called the work of fracture test, RILEM (1985). Other non-linear models resulted in more proposed tests, e.g., the two-parameter model, RILEM (1990a) and the size-effect model, RILEM (1990b).

While researchers active in fracture mechanics studies on concrete structures are well aware of the need for such an approach to characterize structural behavior in terms of size effects and brittleness, acceptance by the practicing engineer has not been forthcoming. It is felt that this may be due, in part, to the lack of available testing standards. This was a major motivating factor in bringing together--to the extent possible--the individuals most actively involved in devising testing procedures for measuring fracture mechanics properties of concrete in an attempt to reach agreement on developing testing standards.

2 Background of the workshop

In June 1993 the American Concrete Institute (ACI) Committee 446 Fracture Mechanics and the Society for Experimental Mechanics (SEM) Subdivision on Fracture of Concrete and Rock agreed to form an ACI-SEM Task Group on Test Standards for Measurement of Fracture Properties of Concrete. In an independent action, in December 1993, Committee C-9 of the American Society for Testing and Materials (ASTM) formed a Task Group on Concrete Fracture Mechanics. This group agreed in July 1994 to interact with the ACI-SEM Task Group.

An initial proposal prepared by the ACI-SEM Task Group was to adopt the three RILEM proposed tests, RILEM (1985, 1990a, 1990b) into one test standard with two levels of testing. This two-level idea was modeled after the test standard adopted by the International Society for Rock Mechanics (ISRM) for fracture mechanics testing of rock, ISRM (1988). Following formal discussions within the task groups and other informal discussions among persons interested in seeing the development of a testing standard it was decided to hold a workshop on this topic in July 1995 at Cardiff. The location was chosen with a view of providing an environment which would enhance interaction between researchers and engineers from the U.S. and other countries. The objective of the workshop was to obtain consensus agreement on basic standard test components: properties to be measured, type of test(s), type of specimen(s). The following persons attended the workshop: B. I. G. Barr,

Z. P. Bazant, M. Elices, V. S. Gopalaratnam, W. H. Gerstle, R. Gettu, N. M. Hawkins, A. R. Ingraffea, A. D. Jefferson, B. Karihaloo, H. Mihashi, B. Mobasher, C. Ouyang, P. C. Perdikaris, J. Planas, K. Rokugo, S. P. Shah, L. S. Struble, S. E. Swartz, T. Tang, M. A. Taşdemir, and Y. Uchida. A number of other people participated in the work but were not able to attend.

2.1 Technical organization of the workshop

The workshop was organized into five working groups charged with the preparation of position papers to be written in advance and distributed to the participants prior to the workshop. These groups were: I. Test Standardization-Fundamental Issues; II. Test Standardization-Testing and Other Practical Issues; III. Influence of Specimen/Structural Size on Test Parameters; IV. Correlation of Test Parameters with Parameters from Popular Models; V. Practical Applications-Design and Numerical Examples.

3 Summaries of working group position papers

3.1 Group I. test standardization-fundamental issues

Professor Elices presented this paper which was co-authored with J. Planas. The stated purpose of this contribution was to set the stage for discussing test standardization to determine parameters for Mode I fracture properties of concrete. The need for a reference frame and common language were emphasized. Such a reference frame which classifies the fracture models starting with LEFM is shown in Fig. 1.

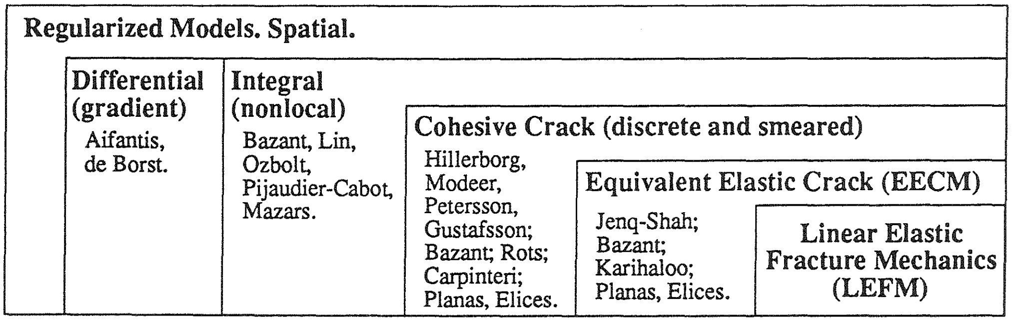

Fig. 1. Classification of macroscopic fracture models for concrete.

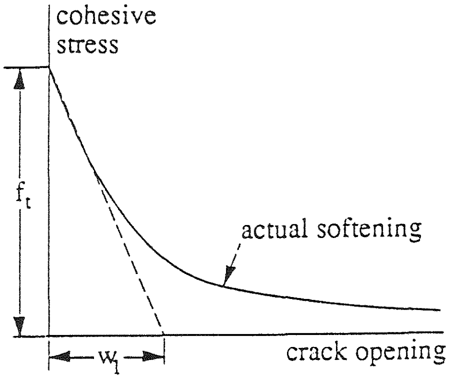

Fig. 2. Softening curve and its initial linear portion.

A major emphasis in the paper was the need to have at least two fracture parameters in order to predict maximum loads in normal size, plain concrete beams in three point bending. It was also noted that two parameters are needed to characterize concrete behavior using the fictitious crack model and equivalent elastic crack models. As an example, the two parameters associated with the fictitious crack model are tensile strength f_t and initial slope of the stress-softening curve (or equivalently w_1) as shown in Fig. 2--see Planas, et al. (1994).

It was stated that from a practical point of view it is probably better to devise test procedures from which parameters of the various models could be reliably extracted. In fact, by using only results of peak loads from two different tests it is possible to determine the parameters of all two-parameter models.

3.2 Group II. test standardization-testing and other practical issues

The issues this group were to address included test stability and its relation to test parameters, closed-loop versus open-loop testing, material and geometric limitations of the test standard(s), inter- and intra-laboratory variability in test results. The paper was presented by Professor Barr. It was suggested that the three competing RILEM recommendations for fracture tests have delayed the introduction of the basic ideas of fracture mechanics into Codes and Standards. The paper focused strongly on the idea that the essential features of a proposed test procedure, which will be acceptable to both the research community and to practicing engineers, are that the test should be simple in concept, technically sound, readily carried out and proven to give reproducible results. It was pointed out that the "end-user" community includes not only researchers but also structural engineers and contractors. The standard test geometry should be based on specimen configurations already in use for other standard tests and should require equipment no different from that already in use for other standard tests. The simpler the test, the fewer will be the errors. The type of specimen and loading configuration should be such that the method is not sensitive to minor operator errors and does not require considerable "setting-up" skill or time.

It was noted that the most common concrete specimens are cylindrical (cast or cores). While these are typically used for compression and split-tension tests, they could also be used for fracture tests. On the other hand, the rectangular beam specimen is often used for modulus of rupture tests. All three RILEM test proposals recommend the use of notched, rectangular beam specimens. It was also noted that the work of fracture test, RILEM (1985) which gives G_F can be readily adapted to include the determination of the elastic modulus and the tensile strength as well as the strain-softening response of the material.

In conclusion, the following "points to ponder" were given. Is it not possible to have more than one recommended test geometry? It is important to have a well defined testing procedure (which may be suitable for more than one geometry). Perhaps the energy values can be obtained using P-CMOD curves instead of P-LPD curves (the former being relatively insensitive to support settlement, errors in geometry and alignment, etc.)

3.3 Group III. influence of specimen/structural size on test parameters

This paper was presented by Professor Bazant who stated that the size effect on nominal strength of structures is the most important practical consequence of the global energy release associated with large fractures. The measured values of the parameters characterizing material properties must be independent of the specimen or structure size, or else they would not represent properties of the material alone but also properties of the structure.

The size effect impacts the problem of choice of a standardized test in two ways: the material fracture parameters must be independent of the specimen size (and geometry) when geometrically similar specimens of different sizes are tested; the fracture parameters can be determined from size effect measurements. The method of test described in RILEM (1990b) requires a minimum of three different sizes of beams be tested but only the maximum load needs to be measured. A new test proposal in which only one size of beam needs to be tested was presented--see also Bazant and Li (1995). From two beam tests, one notched and one un-notched, and for which only the maximum load is measured, it is possible to obtain the fracture parameters G_f (the fracture energy for an infinite-size specimen) and c_f defined as the distance from the notch tip to the tip of the equivalent LEFM crack in a specimen extrapolated (mathematically) to infinite size.

3.4 Group IV. correlation of test parameters with parameters from popular models

This paper was presented by Professor Shah who started by re-emphasizing the problems encountered by early researchers in trying to apply LEFM to concrete. Again, this stems from the presence of a process zone of significant size when compared to the crack length or structure size. By considering the strain energy release rate to be made up of two parts--material surface energy and energy to overcome the cohesive pressures generated in separating the surfaces--it is clear that at least two parameters are needed to describe the fracture process.In the different models, these are K_{IC}^{S} , $CTOD_C$--RILEM (1990a); and G_f, c_f - RILEM (1990b). Equivalences between all these parameters were presented. In particular $K_{IC}^{S} = \sqrt{G_f E}$ and an equation relating c_f and $CTOD_c$ was given. In the discussion, Gettu and Gopalaratnam presented data that extended this to include $K_{IC}^{S} = \sqrt{G_f^1 E}$ (also $G_F^1 = G_f$ where G_F^1 is ½ f_t w_1 in Fig. 2) and $CTOD_c = w_1 = \delta_c$. In this, δ_c is the effective crack-tip-opening-displacement according to the size effect method. Finally, Professor Shah proposed a simple test using only peak load measurements to determine these parameters--Tang. et al. (1995).

3.5 Group V. practical applications--design and numerical examples

This paper was presented by Dr. Gopalaratnam and summarized recent work of ACI 446 (1995) in using fracture parameters in the design of reinforced concrete structures. Specific design applications included: pull-out failure of anchors, minimum reinforcement in beams, crack width and spacing, shear failure of reinforced concrete beams and slabs, beam and ring failures of unreinforced pipes, and concrete dams. He also discussed the need to characterize high strength materials using fracture mechanics because of the brittle nature of such materials. The effectiveness of toughening mechanisms for such materials can be evaluated through use of fracture mechanics. The use of brittleness numbers in assessing structural ductility and energy absorbing capacity associated with dynamic events was presented.

3.6 Presentation by Rokugo and Uchida

The importance of the softening diagram and how it might be modeled in a convenient way was presented. This information is given elsewhere in this FRAMCOS Proceedings--see Uchida, et. al. (1995).

4 Concrete results from the workshop

The following actions were agreed upon unanimously.

- Two parameters (as a minimum) should be determined.
- Two levels of testing:
  Level 1, two different types of specimen, measure the maximum load
  Level 2, measure load-deformation to get additional information.
- The proposed standard will (initially) use rectangular prismatic beams in three-point-bending (TPB).
- A procedure for testing will be prepared which will be suitable for geometries in addition to rectangular prismatic beams in TPB.
- A task group will be formed to evaluate cylindrical specimens. If this work is completed by a set date, the cylindrical specimen will be included in the proposed standard. If not, it will form the basis for a follow-on specification or a revision thereof.
- The same specimen will be used for the level 1 and level 2 test.
- The test procedure will be based on the existing RILEM recommendations, ASTM standards where applicable and modified as needed.
- Two Task Groups were formed:
  Task Group I on developing the proposed standard with or without cylindrical specimens (Gopalaratnam, Chair)
  Task Group II on preparing a recommendation to the standard for use of cylindrical specimens (Ingraffea, Chair).
- Deadlines: December 1995 for task group drafts; March 1996 draft of entire standard prepared and reviewed by workshop participants and other interested persons (this will be followed subsequently by review by other organizations); presentation to ASTM Symposium (C9) in December 1996.

Acknowledgements

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