Experimental and Analytical Methods to Determine Fracture Parameters for Concrete

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Abstract

Fracture propagation in concrete is dominated by slow crack growth and the nonlinear process zone in front of the crack tip. As the size of this fracture process zone may be relatively large and dependent on aggregate-size and specimen-geometry, the standard method for determining K_{IC} for metallic materials cannot accurately predict fracture toughness without any modification. Experimental methods to account for slow crack growth and the effect of crack tip nonlinearity have been developed. A theoretical model to predict the extent of the nonlinear process zone and a method to include the effects of crack-tip nonlinearity in predicting fracture resistance of concrete are described. The model is simply an extension of linear elastic fracture mechanics where crack-tip stress field is assumed to be under pure Mode I crack opening. The uniaxial tensile behavior is employed in the model which is successfully used to predict the size of the nonlinear process zone for double cantilever beam, double torsion, and notched beam specimens. The size of the fracture process zone depended on the size of the specimen-geometry. The proposed model satisfactorily predicts the experimental data of other investigators.

1. Introduction

Fracture toughness of metallic materials in Mode I crack propagation under plane-strain conditions (K_{IC}) is usually determined by testing either compact tension specimens or notched-beam specimens (Fig. 1). The method of testing and the dimension of these two types of specimens are specified by relevant ASTM Standard specifications [1]. Among other things, these dimensions are specified to assure that: (1) the slow crack growth prior to attaining peak load is small compared to the initial notch length so that almost linear load-deflection relationship is obtained, and (2) the zone of nonlinearity around the crack tip (radius of plastic zone) is small compared to the length of the notch and that of the uncracked ligament. If these restrictions are met then one can obtain specimen-independent fracture toughness (K_{IC}) using the concepts of linear elastic fracture mechanics (LEMF) from the test results.

Crack propagation in concrete is widely recognized as associated with slow crack growth and nonlinear process zone around the crack tip. The extent of slow crack growth is clearly evidenced from the nonlinearity of the load - CMD curves prior to reaching the peak load (Fig. 2) [2]. The nonlinear process zone (also often termed microcracked zone or plastic zone) in concrete is believed to be relatively large due to its heterogeneity and large grain size and volume fraction of aggregates [3]. Thus, the straight forward extension of the formulae and methods developed for metals would lead to extremely large size specimens.

To predict fracture resistance of concrete, an alternate approach is proposed by modifying the concepts of linear elastic fracture mechanics to include the effects of slow crack growth and crack-tip nonlinearity due to the process zone [4-5]. A theoretical model based on the assumption of pure Mode I crack opening and on the observed uniaxial tensile behavior is developed to predict the extent of nonlinear process zone [6]. These attempts are briefly summarized in this paper.

2. Slow Crack Growth and Resistance Curve

The concept of R-curves (or resistance curves) has been used by many investigators [7-10] to characterize the fracture resistance during slow stable incremental crack growth for rocks, ceramics, asbestos cement, mortar and concrete. R-curve can be obtained by plotting strain energy release rate with crack growth. The value of the strain energy release at first increases with crack extension during slow crack growth and reaches a steady state value as approaching unstable crack propagation. To accurately measure the energy absorbed during crack growth, the specimen must be loaded at constant rate of crack mouth displacement, load must be stopped at frequent interval to measure crack growth and unloading-reloading technique should be used to determine the unloading compliance (C_R) and the corresponding permanent deformation (δ_p) at every observed crack growth.

The strain energy absorbed during each crack extension can then be determined from the modified strain energy release rate (G_R) which includes the inelastic energy absorbed during crack growth as [4,5].

$$G_R = \frac{P_1 P_2}{2t} \left[\frac{dC_R}{da} + \frac{(P_1 + P_2)}{P_1\ P_2} \quad \frac{d\delta_p}{da} \right] \qquad (1)$$

where P_1, P_2 are two consecutive neighboring loads in the loading sequence, t is thickness in the crack plane and a is crack growth. The value of G_R is physically the area under load-deformation curve between two unloading lines. R-curve is simply a relationship between the calculated G_R and the measured crack extension (Fig. 4).

3. Theoretical Model for Fracture Process Zone

Fracture process zone in concrete results from microcracking and aggregate-interlock around the crack tip. The size of this process zone is likely to depend on the size of aggregates, the debonding characteristics of aggregates as well as specimen geometry. To include the effect of this nonlinearity in predicting fracture resistance of concrete, a crack and the process zone can be modeled as follows [6].

A crack in Mode I opening is shown in Fig. 5b. An actual length of crack can be represented by: a traction free length - $\underline{a}$, and a nonlinear zone - ℓ_p where crack closing traction exists across the crack. If the crack closing stress is known and if the crack-tip stress field is assumed to be under Mode I opening, then the actual crack can be replaced with an effective crack - a_{eff} (= $a + \ell$). Under a given load, crack is assumed to initiate when crack surface displacement at the tip of the traction free crack - $\underline{a}$ reaches a critical value of η_{max} (the maximum crack surface displacement in the descending branch of the uniaxial tensile test at zero tensile stresses - see Fib. 5a).

Since crack closing pressure in the process zone is a function of crack surface displacement - η which in turn depends on the applied load, specimen geometry, length of the process zone and the crack closing pressure, an iterative procedure is needed to predict the size of the process zone. This was done by first assuming an initial crack growth vs. crack surface displacement relationship. Knowing the crack surface displacement, the crack closing pressure can then be determined from the uniaxial "tensile stress-displacement" relationship (Fig. 5a). With the nonlinear zone being replaced by a crack extension and a traction zone, the load-line deformation and crack-tip displacement can be calculated for a given applied load using the concepts of linear elastic fracture mechanics. The crack tip displacement is to be checked with the initiation criteria ($\eta = \eta_{max}$) while load-line deformation is compared with the measured data. Due to difference in specimen configurations (double cantilever beam, double torsion and notched-beam specimens), different approximate procedures were used to determine crack face displacements but they were all based on the same crack tip model. Details of the calculation and testing procedure were discussed in References [4-6].

4. Fracture Process Zone

Fracture process zone depends on geometry of specimen and the type and size of microstructure. It was found that the size of the process zone for double cantilever beam was about 75mm (3 in.) whereas it was only 25mm (1 in.) for double torsion specimen (Fig. 6). For notched beam specimen, this zone varied from 25 - 75mm (1 - 3 in.) and was found to be varied with the size of the specimen uncracked ligament (W-a). A regression relationship for this variation was given as:

$$\ell_p = \left[\frac{W - a}{2}\right] - 5.342 \times 10^{-3} \left[\frac{W - a}{2}\right] \qquad (2)$$

where ℓ_p is the size of fracture process zone in inches, W is the depth of the beam and a is notch depth, both W and a are given in inches.

The length of the process zone in mortar specimens (Mix 1:2:0.5 - C:S:W) was found to be about 25 - 75mm (1 - 3 in.); 30mm for asbestos cement [7] and of the order of 40 x 10^{-3}mm for PMMA [11]. These large differences must, among other things, be related to the size of microstructure.

5. Fracture Resistance

To characterize fracture resistance of concrete, not only the inelastic energy absorbed during slow crack growth that has to be included in the form of modified strain energy release rate - G_R, but also the effect of nonlinear process zone (ℓ_p) which tends to increase the length of the effective crack growth, must be taken into account.

In conclusion, the modified R-curve, which is a plot of modified strain energy release rate - G_R vs. effective crack growth - a_{eff} ($= a + \ell_p$), seems to be a promising method to predict fracture toughness of concrete. Using the model developed here, it was possible to satisfactorily predict experimental results of other investigators as illustrated in Fig. 7 [12].

6. Further Research

Theoretical and experimental investigation currently in progress at Northwestern University include determination of nonlinear process zone for rocks of varying grain size, effects of strain rate on process zone and prediction of fracture toughness of fiber reinforced concrete using some of the concepts outlined above.

Acknowledgment

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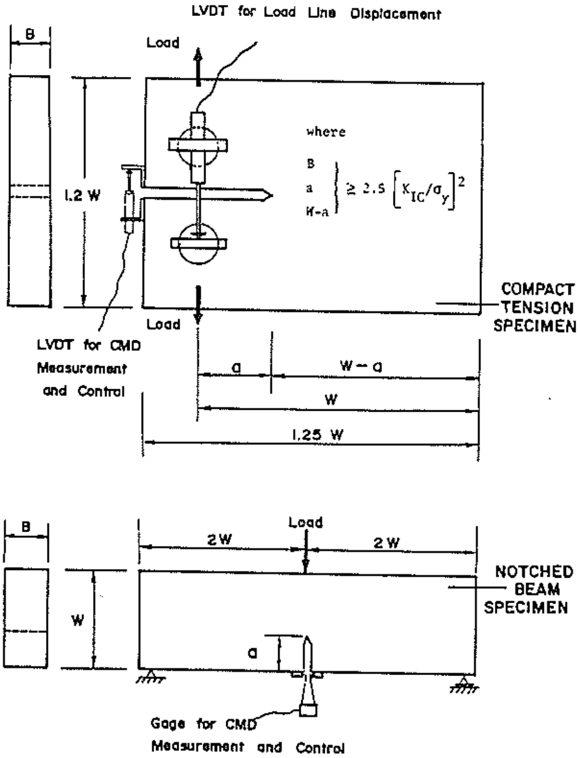


Fig. 1 - ASTM - Standard Test Specimens

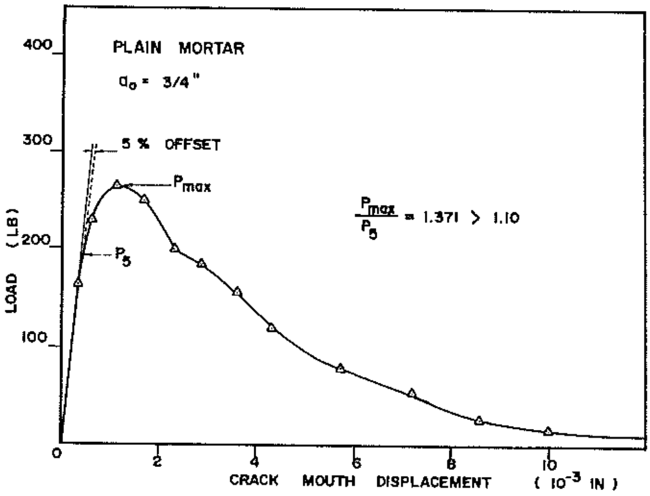


Fig. 2 - Evidence of Slow Crack Growth in Mortar

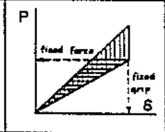
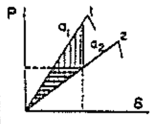
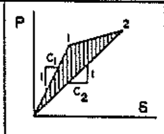
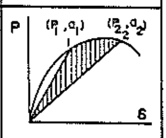
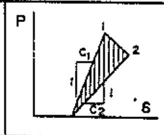
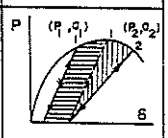
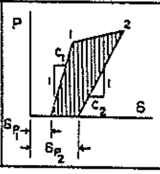
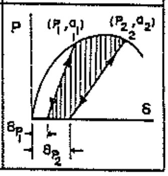
STRAIN ENERGY RELEASE RATE, G_R	STRAIGHT LINE MODELS	ACTUAL CURVE
A) UNSTABLE LINEAR ELASTIC BRITTLE BEHAVIOR $G_R = \frac{P^2}{2}\cdot\frac{dC}{dA}$		
B) STABLE WITHOUT PLASTIC DEFORMATION. IRREVERSIBLE WORK AREA METHOD. $G_R = \frac{P_1P_2}{2}\cdot\frac{dC_s}{dA}$		
C) RELOADING AND UNLOADING METHOD. $G_R = \frac{P_1P_2}{2}\cdot\frac{dC_R}{dA}$		
D) STABLE WITH PLASTIC DEFORMATION. $G_R = \frac{P_1P_2}{2}\left[\frac{dC_R}{dA} + \left(\frac{P_1+P_2}{P_1P_2}\right)\frac{d\delta_p}{dA}\right]$		

FIG. 3

Schematic Models for Different Fracture Behavior and Corresponding Strain Energy Release Rates

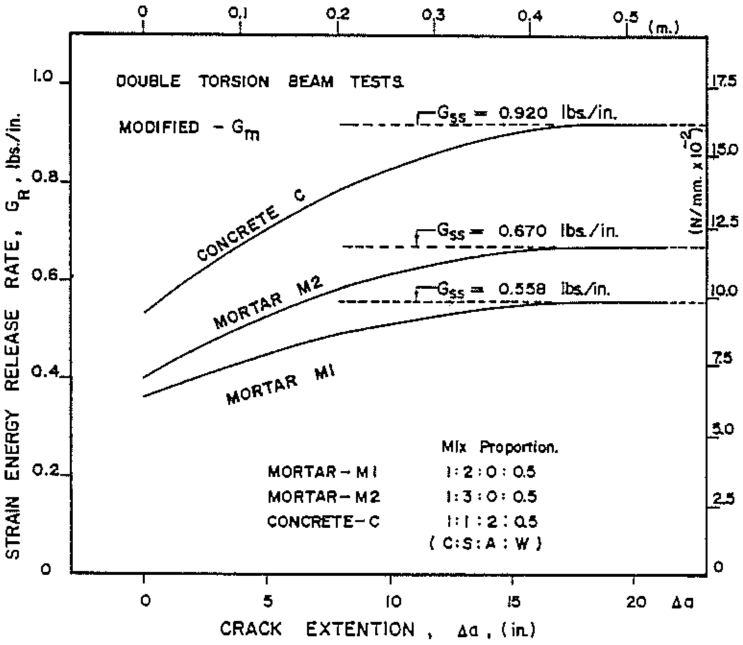


Fig. 4 - Resistance (R) Curves for Mortar and Concrete

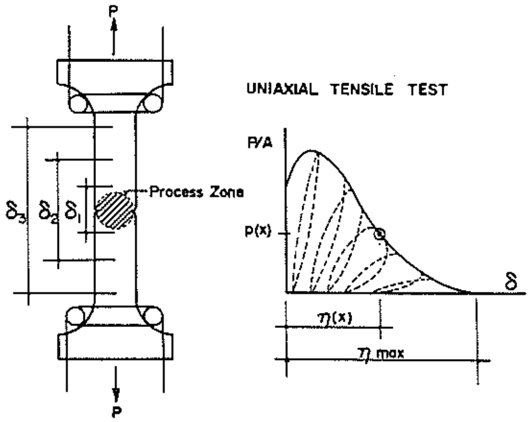


Fig. 5a - Test-Method to Determine the Relationship between p(x) and η(x)

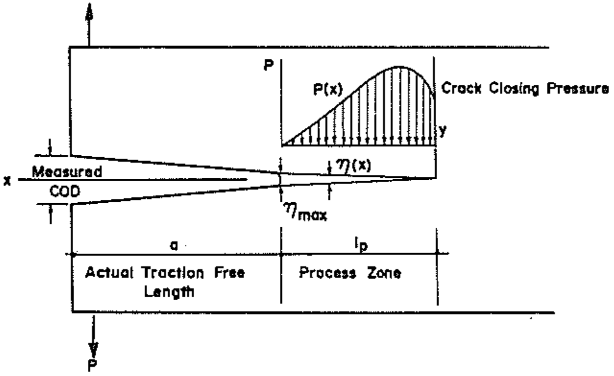


Fig. 5b - Idealized Representation of the Process Zone for Compact-Tension Specimen of Mortar and Concrete

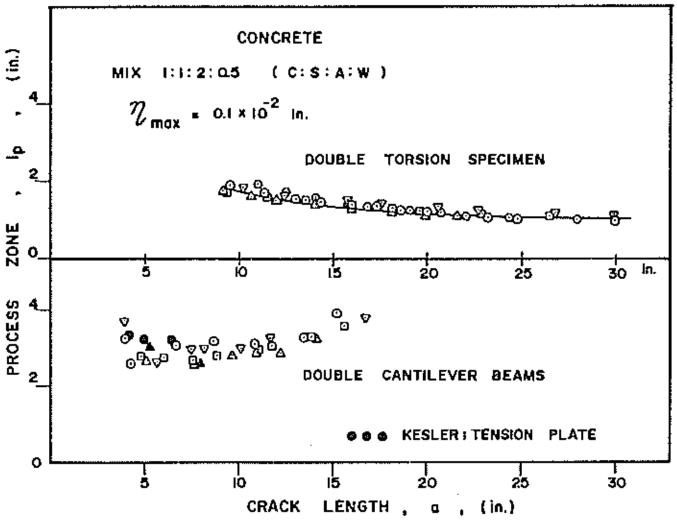


Fig. 6 - Effect of Specimen Geometry on the Size of the Process Zone

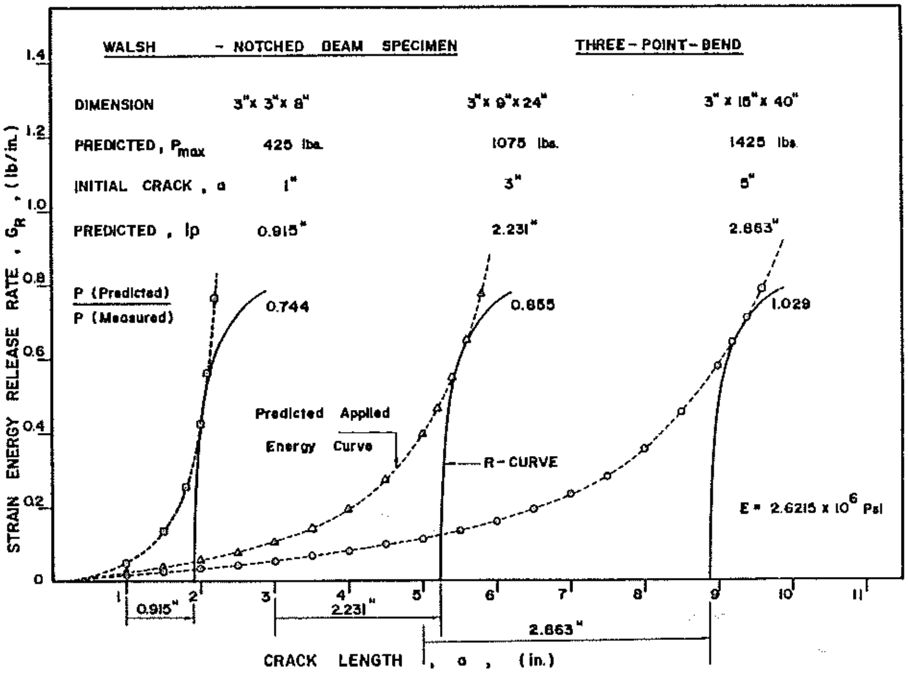


Fig. 7 - Prediction of Test Results on Notched Beam Specimens Using Concept of Modified R-Curve