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Determination of double-K fracture parameters using semi-circular bend test specimens

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ABSTRACT

The present research was conducted to evaluate the double-K fracture parameters using semi-circular bend test. Fracture tests were carried out on semi-circular bend specimens with three different diameters with a range from 200 mm to 500 mm and four different concrete strengths. The results indicated that double-K fracture parameters K_{Ic}^{ini} and K_{Ic}^{un} values for semi-circular bend specimens were size and strength dependent. All the fracture parameters such as critical effective crack length, critical crack mouth opening displacement and unstable fracture toughness increased as the specimen size increased; while, initial fracture toughness decreased with the increase of specimen size.

1. Introduction

Fracture toughness is an important property of any material in design application. It can be described as ability of a material, containing cracks, to resists fracture upon external loading. Griffith studied the behavior of cracks in brittle material which led to the concept of fracture toughness in fracture mechanics.

It is imperative to determine the fracture parameters in order to analyze a concrete structure with respect to fracture mechanics. The fracture parameters of concrete were first studied by Kaplan in 1961 [1]. The author used the classical principles of linear elastic fracture mechanics (LEFM) to propose unique parameter i.e. critical stress intensity (K_{Ic}) or critical strain energy release rate (G_{Ic}) in concrete fracture. The study further indicated that LEFM cannot be used in concrete because KIc and GIc depend on the size and geometry of specimens. It is worth noting that it is not only fracture parameters that depend on the size, but even simple and very used properties like compressive or tensile strength may be sensitive to the size of the specimen and the boundary conditions.

Later studies, on fracture mechanics of concrete, also showed that classic linear elastic fracture mechanics (LEFM) is not applicable for the determination of fracture parameters in quasi-brittle material such as concrete [2]. The failure of LEFM was due to presence of in-elastic zones (fracture process zones) in the front and around the tip of main cracks in the concrete. Large fracture process zones, ahead of initial crack tip, are responsible for the size effect behavior of unstable cracks due to aggregate interlocking. The non linear behavior in metallic structures is due to result of strain hardening and plasticity characteristics of material by the formation of dislocations. In case of quasi-brittle material like concrete, the non linear behavior is controlled by the fracture process zone originated by the formation and branching of micro-cracks.

To overcome this problem, many researchers have developed non linear fracture mechanics approaches to delineate the fracture dominated failure of concrete structures [3–7]. As a result many non linear fracture mechanics models and modified

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Nomenclature

a	crack length
a_0	initial crack length
a_c	critical crack length
C	compliance
C'	non-dimensional compliance
CMOD	crack mouth opening displacement
CMOD_c	critical crack mouth opening displacement
D	diameter of specimen
d_{max}	maximum aggregate size
E	Young modulus
K_{Ic}^{ini}	initial fracture toughness
K_{Ic}^{un}	unstable fracture toughness
P	applied load
P_{ini}	initial cracking load
P_{max}	maximum load
R	radius of SCB specimen
S	span of SCB specimen
T	thickness of SCB specimen
w/c	water–cement ratio
Y	non-dimensional stress intensity factor
ν	poisson's ratio
α	crack length/ radius

LEFM models have been formed to characterize fracture process zone. In this regard, fictitious crack model [3], crack bend model [4], two parameter model (TPM) [5], effective crack model [6], size effect model (SEM) [7] and the double-K model [8] has been evolved. To characterize the failure of concrete structures, at least two experimentally determined fracture parameters were required for these models, compared to LEFM. In double-K models two fracture parameters i.e. unstable fracture toughness K_{Ic}^{un} and initial cracking toughness K_{Ic}^{ini} are required for the characterization of failure of concrete structure.

Double-K model was proposed to respond to different states in concrete fracture. This model described the three important stages during crack propagation in concrete like crack initiation, stable crack propagation and unstable fracture [8]. The double-K fracture model depends on the two material parameters i.e. initial cracking toughness K_{Ic}^{ini} and unstable fracture toughness K_{Ic}^{un}, respectively. The initial toughness can be described as the material inherent toughness which resists the external load at crack development. At this stage material behaves elastically and micro cracks are established at small scale in the absence of main cracks. The initial cracking toughness K_{Ic}^{ini} is calculated directly from the initial crack load and initial notch length from the LEFM formula.

The unstable fracture toughness K_{Ic}^{un} is the total toughness at the critical condition i.e. at the onset of unstable crack propagation. The same LEFM formula can be used to determine this parameter by knowing the peak load and corresponding effective crack length. To find different stages of failure conditions in double-K model, the crack tip stress intensity factor K_I is compared with two material characteristics; K_{Ic}^{ini} and K_{Ic}^{un}. This criterion represented five stages of crack propagation i.e. (1) no crack development if $K_I < K_{Ic}^{ini}$ (2) onset of crack propagation if $K_I = K_{Ic}^{ini}$ (3) stable crack development if $K_{Ic}^{ini} < K_I < K_{Ic}^{un}$ (4) critical unstable crack propagation if $K_I = K_{Ic}^{un}$ and (5) unstable crack development if $K_I > K_{Ic}^{un}$.

The one of the advantage of double-K method is that it does not need close loop testing system in laboratory. The failure or unstable fracture of normal structure can be predicted under given loading or displacement conditions. However for special or important structures like concrete pressure vessel, high concrete dam and liquid retaining structures need accurate prediction for both failure and crack initiation.

Different specimens and geometries were being used in the past to perform stable fracture testing of concrete failure. The fracture behavior of concrete can directly be measured by the Uniaxial tensile test with controlled displacement. Due to difficulty in the direct test, indirect methods are generally used to measure the fracture parameters of different geometries. The indirect methods involved for the testing of various geometrical shapes are three-point bending test, compact tension test and wedge-splitting test. The three-point bending geometry is commonly used to measure the fracture parameters in different fracture models. The advantage of three-point bending test (TPBT), on the fracture testing of specimen, is that standard machines can be used for the test. Moreover, stable bending test on pre-cracked beams can easily be performed. RILEM technical committee 50-FMC [9] has proposed guidelines for the determination of fracture energy of cementitious materials by three-point test on notched beam. However, the use of fracture testing in the large structure is not recommended, possibly due to heavy weight of beam itself. Other problems are also faced during handling of large structure and an extra care is required for the fracture analysis. While on practical side, the test is difficult to be done on drilled specimen from construction sites or on existing structure. That is why compaction test (CT) and wedge-splitting tests (WST) have been followed by