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A comparative study on three approaches to investigate the size independent fracture energy of concrete

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ABSTRACT

This paper deals with investigation of size-independent fracture energy (G_F) of concrete. The study involves numerical modeling of three point bend concrete beams that are geometrically similar having constant length to depth ratio with varying notch to depth ratios. RILEM fracture energy (G_f) values evaluated numerically and experimentally are found to be in reasonable agreement. G_F is estimated from developed relationship of fracture energy release rate and through bilinear model by G_f values. G_f values have been utilized to develop a simple methodology for estimation of G_F. Comparative analysis of G_F from three different methodologies has been carried out.

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1. Introduction

Concrete, due to its excellent shielding capability, fire rating, long service life under normal and accidental conditions and ease in construction with relatively lower cost, is used extensively in building most of the civil engineering structures. In-spite of such salient features, the concrete structures generally consist of numerous micro-cracks that might result in fracture of the concrete structures under service loads, accidental load and/or exposure to regular environmental conditions. Thus a micro-crack in concrete may become a potential source of crack propagation leading to a probable catastrophic failure. In order to prevent such accidents, it is necessary to predict the failure mechanisms of structures, so that the safety of concrete structures throughout the service life can be assured. The failure mechanism can be studied by quantifying the energy consumed in crack propagation and formation of new crack surfaces. In a concrete structure, the crack growth requires a certain amount of energy that can only be studied through an energy based propagation criterion, which provides a fundamental basis for understanding the phenomenon of concrete fracture mechanism. Concrete despite predominantly elastic material response, exhibits a stable non-linear fracture response in tension loading, when tested under displacement control. The reason for the non-linearity is the development of a fracture process zone (FPZ) ahead of the crack tip. In a quasi brittle material like concrete the energy dissipated for the formation of FPZ ahead of the crack tip, is termed as fracture energy. The concrete fracture energy characterizing the failure process is still under extensive research. The various finite element studies [1–3], incorporating the concrete strain based softening model, showed the dependency on mesh size. The fracture energy based concrete softening model yields the consistent finite element results independent of mesh size. The size-independent fracture energy is the most useful parameter in the analysis of cracked concrete structure.

Hu and Wittmann [4] proposed the bilinear function so that size-independent fracture energy G_F can be estimated from the fracture energy data measured on laboratory-size specimens. The study by Elices and Planas [5] compared the theoretical

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Nomenclature

g_f	local fracture energy at crack tip
G_f	RILEM fracture energy
G_F	size independent fracture energy
w	crack opening displacement
w_c	maximum widening of the crack separation displacement (terminal point where cohesive stress equals to zero)
$\alpha = a/W$	notch to depth ratio of three point bend beam
σ	cohesive stress

background and experimental aspect of various concrete fracture models like cohesive crack model, the equivalent elastic crack model, or models based on two parameters such as Bazant's and Jenq-Shah's [1]. The fictitious crack method is applied to determine the load–deflection diagrams of notched plain concrete beams under three-point bending using various forms of strain softening in the stress–deformation relationship and the results indicated that there is a need to determine a more realistic relationship [6]. The study by Luigi and Gianluca [7] deals with the identification of concrete fracture parameters through the size effect curves, associated with certain specimen geometry, to identify the tensile strength and the initial fracture energy, which are typically used to characterize the peak and the initial post-peak slope of the cohesive crack. Acoustic emission technique [8] on three point bend specimen is used to estimate the FPZ size. In the work of Karihaloo et al. [9], 26 test data sets from literature have been re-evaluated to assess the validity of obtaining the size-independent fracture energy of concrete by testing three point bend specimen. The fracture test on geometrically similar (constant length to depth ratio) three point bend (TPB) plain concrete beam specimens, made of aggregates, sand, cement and water, were performed by Raghu Prasad [10].

Concrete structures due to their unique material characteristics often need the application of quasi-brittle fracture mechanics. The investigation undertaken so far involved limited concrete fracture tests on laboratory size concrete specimens. The precise definition and test method for estimation of the fracture energy has been a subject of debate among researchers. Based on the fracture test results, a basic understanding of the fracture processes can be developed, but the exact quantification of size-independent fracture energy remains still elusive. Although some progress has been achieved but altogether detailed study on size independent fracture energy is not readily available. The present study investigates this aspect.

The present work involves the numerical modeling of fracture tests of geometrically similar TPB beams having constant length to depth ratio [10]. The displacement controlled test on the universal TPB specimens was conducted for varying a/W ratio = 0.05, 0.25 and 0.33 to estimate the fracture energy [10]. The simulation of TPB specimen performed by the finite element analysis incorporating the concrete softening behavior, predicts the load–load line displacement curves. The numerically and experimentally observed maximum load, vertical displacement at maximum load is found to be in excellent agreement. The RILEM fracture energy (G_f) of concrete is estimated from the numerically predicted and experimentally observed load–load line displacement curves. The RILEM fracture energy values have been averaged out at various a/W for geometrically similar beams and the coefficient of variance is estimated. This is how a methodology is developed to investigate the size-independent fracture energy (G_F) of concrete utilizing the values of G_f. Also G_F values are estimated from the other two methodologies based on Hu and Wittmann bi-linear model and fracture energy release rate.

The size-independent fracture energy of concrete is the most useful parameter in the analysis of cracked concrete structure. The present study investigates an easy and robust technique for the determination of the size independent fracture energy of concrete. To accurately analyze the concrete fracture phenomenon, the study involves the comparative analysis of size independent fracture energy by the three methodologies based on Hu and Wittmann bi-linear model, fracture energy release rate and presently proposed model based on G_f averaging for geometrically similar beams. The comparison of fracture energy values evaluated by these different methods has not been carried out before in the open literature. Thus the present study invokes a primary approach based on concrete fracture mechanics that helps to understand the failure mechanisms and load bearing capacity of concrete structures.

2. Theoretical background

The fracture energy of concrete is the most important parameter in the fracture behavior of concrete that describes the mechanism of cracking. The commonly used method for measuring the fracture energy is the work-of-fracture method recommended by RILEM [11]. The local fracture energy model [4] and the energy release rate are the other methods for measuring the size-independent fracture energy of concrete. The method developed in this paper and other two popular methods to estimate the size independent fracture energy are described below.

2.1. Proposed methodology using RILEM fracture test

RILEM technical committee recommended the guidelines for determination of fracture energy of cementitious materials by conducting TPB test on notched beam [11,12] as shown in Fig. 1. In order to obtain a complete load and load point

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