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Effect of size and cohesive assumptions on the double-K fracture parameters of concrete

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ABSTRACT

This paper studies the effect of size and cohesive assumptions on the double-K parameters in concrete fracture. These two parameters are the fracture toughnesses K_{Ic}^{ini} and K_{Ic}^{un}, related with the crack initiation and the limit of the stable crack propagation, respectively, which are calculated using data from a load-crack mouth opening curve, P-w_M (Xu and Reinhardt, 2000). The study starts from three-point bending tests with three different beam sizes, whose results calibrate a numerical model, used to produce additional P-w_M curves from a wider beam-size range, with beam depths from 13 to 1300 mm. The paper presents a simplification to obtain K_{Ic}^{ini} experimentally based on the loss of linearity in the P-w_M curve, which allows avoiding the use of strain gauges to measure the crack initiation load. The evolution of K_{Ic}^{un} and K_{Ic}^{ini} shows size dependence. The calculated values of K_{Ic}^{un} increase slightly with the beam size whereas those of K_{Ic}^{ini} remain constant but below the experimental range and, later, they diminish for large beam sizes. This points out that K_{Ic}^{ini} calculation procedure is not correct, especially for sizes out of the usual experimental range. These shortcomings can be overcome by an appropriate selection of the initial stretch of the cohesive law, which leads to a proposal for improving the procedure to calculate K_{Ic}^{ini}. The analysis includes the calculation of the complete toughness-crack length curves (K_{Ic}-a), which are also dependent on the specimen size.

1. Introduction

An initial approach to fracture consists in using Linear Elastic Fracture Mechanics (LEFM), which assumes that a crack grows once the factor proportional to the intensity of the stresses around its tip reaches a critical value, the fracture toughness. LEFM is easy to use and admits the superposition principle, which is key to most structural design methodologies. However, cracks in concrete do not behave in this way, since the intense stresses at the tip of them or around defects generate a gradual deterioration process that extends in a zone whose size is commensurate to the dimensions of normal structural elements (fracture process zone or FPZ). This phenomenon makes concrete behave in an inelastic way, so LEFM is not directly applicable. In order to solve this problem, two main different non-linear approaches were developed, the cohesive crack model by Hillerborg et al. [1] and the crack band model by Bažant and Oh [2], although they require of numerical methods to be used.

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Nomenclature

a	crack length
a_0	notch length
a_c	critical crack length, corresponding to the maximum load
c_i	initial compliance of the linear ascending part of the load-CMOD curve
f_c	compressive strength
f_t	tensile strength
h	height of a cylindrical specimen
ℓ_{ch}	characteristic length
w	crack width
w_0	critical crack opening in the Reinhardt's softening law
w_1	intercept with the x-axis of the tangent to the softening curve for $w = 0$
w_c	critical crack opening in a softening law
w_{ch}	characteristic crack width
w_G	position of the center of gravity of the softening curve
w_k	crack opening at the kink of the bilinear softening law
w_M	crack mouth opening
w_{max}	intercept with the x-axis of the parallel to the linear ascending part of the load-CMOD curve that crosses at its peak point
w_{Mc}	critical crack mouth opening, corresponding to the maximum load
w_{Tc}	critical crack opening at the tip of the notch, corresponding to the maximum load
x_e	acting position along a crack of the resultant of cohesive stresses
B	thickness of the specimen
D	specimen size, specimen depth
E	elastic modulus
E_{SEN}	elastic modulus from a three-point bending test
F_1	geometric function
G_F	fracture energy
H_0	thickness of a clip gauge holder
K	stress intensity factor at the tip of an elastic crack
K_{Ic}	fracture toughness in opening mode I
K_{Ic}^c	cohesive toughness
K_{Ic}^{ini}	initial fracture toughness
$K_{Ic,m}^{ini}$	initial fracture toughness from a measured value of the crack initiation load
K_{Ic}^{un}	unstable fracture toughness
L	length of a beam specimen
P	load
P_c	maximum load
P_e	resultant of cohesive stresses on a crack
P^{ini}	measured initial cracking load
R	crack extension resistance
S	span in a three-point bending test
U	relative position along a crack
U_e	relative acting position of the resultant of cohesive stresses on a crack
V_0	parameter that relates the notch length to the specimen size
V_c	parameter that relates the critical crack length to the specimen size
V_h	parameter that relates the notch length to the specimen size considering the presence of a clip gauge holder
Z	calibration function
β_c	non-dimensional stress at the tip of the notch
ϕ	diameter of a cylindrical specimen
σ	stress
σ_N	nominal stress at the center of the span in bending
σ_{Nc}	critical nominal stress
CMOD	Crack Mouth Opening Displacement
FPZ	Fracture Process Zone
LEFM	Linear Elastic Fracture Mechanics

Alternatively, simplified calculation methods based on elastic equivalences were also proposed [3,4]. They consist in considering a specimen geometrically identical to the concrete one but behaving elastically so that LEFM is applicable. The virtual elastic specimen is enforced to give the same mechanical output as the actual concrete one in any two parameters