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Determination of residual fracture parameters of post-fire normal strength concrete Up to 600 °C using an energy approach

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HIGHLIGHTS

- Determine the residual fracture parameters of normal-strength post-fire concrete using an energy approach.
- Describe the influence of temperature on the fracture energy release rate in the post-fire concrete.
- Verify the equivalence between stress intensity factors and energy parameters.

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ABSTRACT

According to the double-G fracture model (G means energy release rate), the residual fracture behavior of post-fire normal strength concrete is described. The initial fracture energy release rate and the unstable fracture energy release rate are termed to distinguish the different crack propagation stages. The difference between the two energy release rates, named as the cohesive energy release rate, is to be induced by taking into account the aggregate bridging interlock. In total ten temperatures and fifty specimens are considered. The double-G fracture parameters are then experimentally determined. Based on the assumed relationship among the three energy release rates, the calculated unstable fracture energy release rate is obtained. Finally the feasibility of the double-G fracture model is verified.

1. Introduction

The energy dissipation phenomenon due to aggregate bridging stress or cohesive stress distributing across the crack face in fracture process zone (FPZ) has limited the direct application of linear elastic fracture mechanics (LEFM) concept in quasi-brittle materials like concrete. As a result, several nonlinear fracture models, e.g. cohesive crack model or fictitious crack model [1–6], crack band model [7], two parameter fracture model [8,9], size-effect model [10,11], effective crack model [12], double-K fracture model [13–16], and the K_R-curve approach based on cohesive stress distribution [13,17] have been proposed. The cohesive crack model and the crack band model are based on the finite element or the boundary element methods while the other fracture models are based on the modified linear elastic fracture mechanics concepts by taking into account the effect of material nonlinear behavior due to the existence of the fracture process zone. Unlike the two parameter fracture model, the size-effect model and the effective crack model, Xu and Reinhardt [13] raised the double-K (K means fracture toughness) fracture model which including the initial fracture toughness and unstable fracture toughness, presenting three stages of crack propagation in concrete: crack initiation, stable crack propagation and unstable crack propagation. The different stages of crack propagation can be described by using the double-K fracture parameters: the initial cracking toughness K_{Ic}^{ini} and the unstable fracture toughness K_{Ic}^{un}. K_{Ic}^{un} is defined as the ability to resist the maximum external load at critical fracture condition, whereas K_{Ic}^{ini} provides the information of the external load at which the crack will begin to advance in a stable manner. The difference between K_{Ic}^{ini} and K_{Ic}^{un} , termed as cohesive toughness K_{Ic}^{c}, is determined according to the cohesive distribution on the fictitious process zone.

The modified linear elastic fracture models (including the double-K fracture model) are based on the stress intensity factor. In theory, there should be an equivalent energy solution to the double-K fracture model. Therefore, recently, Xu and Zhang [18] proposed the double-G fracture criterion using the concept of energy release rate. Two governing parameters, i.e. the initiation fracture energy release rate G_{Ic}^{ini} and the unstable fracture energy release rate G_{Ic}^{un}, are introduced in this model to predict at which stage the crack

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Nomenclature

a	equivalent elastic crack length (m)	a_0	initial notch depth of the specimen (m)
a_s	effective crack length corresponding to w_s (m)	C	compliance of specimens
B	specimen thickness (m)	COD	crack opening displacement (mm)
C_i	initial compliance of specimens (mm/kN)	$CMOD_c$	critical crack mouth opening displacement (mm)
$CMOD$	crack mouth opening displacement (mm)	$CTOD_c$	critical crack tip opening displacement (mm)
$CTOD$	crack tip opening displacement (mm)	d_{max}	maximum size of coarse aggregates (mm)
d	distance between roller axis and precast notch (mm)	f	height of concrete above the precast notch (m)
E	residual Young's modulus (MPa)	G	energy release rate (N/m)
f_t	tensile strength (MPa)	G_{Ic}^{un}	unstable fracture energy release rate (N/m)
G_F	fracture energy (N/m)	$G_{Ic}^{un\text{-}e}$	measured unstable fracture energy release rate (N/m)
$G_{Ic}^{un\text{-}c}$	calculated unstable fracture energy release rate (N/m)	G_{Ic}^{c}	critical cohesive breaking energy release rate (N/m)
G_{Ic}^{ini}	initial fracture energy release rate (N/m)	H_0	thickness of the clip gauge holder (m)
$G_{I\text{-}coh}$	average value of cohesive breaking energy per unit length (N/m)	K_{Ic}^{un}	unstable fracture toughness (MN/m$^{1.5}$)
H	height of wedge-splitting specimens (m)	$\overline{K_{Ic}^{un}}$	effective unstable fracture toughness (MN/m$^{1.5}$)
K_{Ic}^{ini}	initial fracture toughness (MN/m$^{1.5}$)	$\sigma(w_x)$	cohesive stress at crack opening displacement w_x (MPa)
$\overline{K_{Ic}^{ini}}$	effective initial fracture toughness (MN/m$^{1.5}$)	P_u	maximum load (kN)
$\sigma(s)$	cohesive stress at breaking point (MPa)	w	crack opening displacement at the tip of initial notch (mm)
P_{ini}	initial cracking load (kN)	w_x	crack opening displacement corresponding to the crack extension length x (mm)
T_m	heating temperature (°C)	w_u	weight loss of the post-fire specimens (g)
w_s	crack width at break point of softening curve (mm)	α	deformation coefficient of concrete
w_0	crack width at stress-free point (mm)	$\Pi(x)$	total energy dissipation at any value of crack extension (N)
W_S	wedge-splitting		
$\Gamma(x)$	local cohesive breaking energy at location x (N/m)		
a_c	critical notch depth of the specimen (m)		

propagation is occurring. In addition, energy consumption due to the aggregate cohesive resistance is linked to the proposed two fracture parameters. The difference between G_{Ic}^{ini} and G_{Ic}^{un} is termed as the cohesive toughness G_{Ic}^{c} and these three parameters have the same relationship as the double-K fracture model. Kumar and Barai [19] presented the influence of size-effect on the double-G and the double-K fracture parameters and investigated the equivalent relationship between the two fracture models. The influence of the softening function on both fracture criteria is also reported.

The influence of temperature on the fracture parameters was considered by several researchers, mainly on the fracture energy and material brittleness [20–24], but not many reports on the fracture toughness [25,26]. Most experimental results showed that the residual fracture energy held an increase–decrease tendency with temperatures, while the residual fracture toughness decreased monotonously due to the thermal damage induced by high temperatures. For the post-fire concrete, the double-K fracture model has proved its validation which means that the three stages of crack propagation also exist in post-fire concrete [27]. Correspondingly, there should be an equivalent energy solution to the double-K fracture model for the post-fire concrete, i.e. the double-G fracture model.

The main objects of present paper are to investigate the influence of temperature on the double-G fracture parameters and to prove its applicability to the post-fire concrete. The equivalent relationship between the residual double-G and double-K fracture parameters also needs to be verified. Hence, the present investigation covers three parts. The first part reviews the fundamental conception and theoretical calculation procedures of the residual double-G fracture model controlling parameters G_{Ic}^{ini} and G_{Ic}^{un} for wedge-splitting geometries [18]. Secondly, experimental investigations are performed on the post-fire wedge-splitting specimens. The residual double-G fracture parameters can then be examined using the obtained experimental data. Finally, the equivalent relationship between the residual double-G fracture parameters and the residual double-K fracture parameters is discussed.

2. Softening traction-separation law of post-fire concrete

The softening traction-separation law is a prerequisite to determine the double-G fracture parameters. Many expressions have been proposed based on the direct tensile tests or numerical analysis [2,28–35] at room temperature. Based on numerical studies, simplified bilinear expressions for the softening traction-separation law were suggested by Petersson in 1981 [2], Hilsdorft and Brameshuber in 1991 [30], and Phillips and Zhang in 1993 (illustrated in Fig. 1). The area under the softening curve is defined as the fracture energy G_F by Hillerborg et al. in 1976 [1]. Therefore, one can get the following equation:

$$G_F = \frac{1}{2}(f_t w_s + \sigma_s w_0) \quad (1)$$

As a consequence, a general form of the simplified bilinear expression of the softening traction-separation law is given as follows:

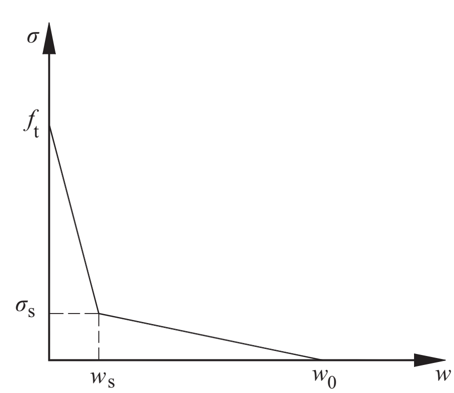

Fig. 1. The bilinear softening traction-separation law.