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Residual crack extension resistance of post-fire wedge-splitting normal strength concrete specimen based on the cohesive force function

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HIGHLIGHTS

- Determine the residual crack extension curves using the analytical and weight function method.
- Find the influence of temperature and softening curves on the residual crack extension resistance.
- Implement the stability analysis to judge the stability of crack propagation.
- Describe the influence of temperature on the crack tip opening displacement.

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ABSTRACT

A comparative study on determining the crack extension resistance curves (K_R-curves) for the complete fracture process associated with two functions of the cohesive stress distribution, i.e. Peterson's softening curve and CEB-FIP Model, 1990 softening curve using an analytical method and the weight function approach is presented in this paper. Fifty wedge-splitting normal strength concrete specimens were prepared to sustain ten different elevated temperatures up to 600 °C. The stress intensity factor curves (K-curves) were calculated from the load–displacement curves obtained on these post-fire specimens. At each temperature, the residual fracture toughness $K_R(\Delta a)$ increased with the crack extension length Δa, whereas the K_R-curves became lower and flatter with the increasing heating temperatures T_m. It was found that the K_R-curve calculated from the weight function method coincided well with the one from the analytical method, whereas different softening curves had observable effects on the K_R-curves. The stability of the K_R-curve and the influence of temperatures on the crack tip opening displacement–crack extension curves ($CTOD$–Δa curves) were also analyzed.

1. Introduction

The concrete fracture toughness symbolizes the crack resistance capacity of concrete. Xu and Reinhardt [21] proposed an analytical method to determine the crack extension resistance curve (KR-curve) based on the cohesive force in the fictitious crack zone which is expressed directly by the softening traction-separation law. The basic principle of the approach is that the crack extension resistance is composed of two parts. The first part is the inherent fracture toughness K_{Ic}^{ini}, which resists the initial propagation of an initial crack under loading. The second part is contributed by the cohesive force distributed along the fictitious crack during the crack propagation. Therefore, the KR-curve is a function of the cohesive force distribution $f(\sigma)$, the material tensile strength ft and the propagating crack length.

The K_R-curves for standard TPBT specimens were investigated numerically for different concrete strengths and specimen sizes [21]. It was observed that the K_R-curve became higher with the increasing crack length and concrete strength and had almost the same S-shape. The obtained K_R-curves were almost independent of the specimen sizes. However, some difference could be noticed on the obtained K_R-curves by using the different softening functions [5,19]. The influence of specimen geometry (TPBT and CT specimens) on the K_R-curves was considered by Shailendra Kumar [11], and it was found that specimen geometry had no obvious influence on the K_R-curves for the specified specimen sizes and the initial-crack length/depth ratios.

The analytical method for determining the K_R-curve [21] utilizes numerical integration technique, which requires special treatment because of singularity problems on the integral boundary conditions. Hence a weight function method was introduced [12,13] to calculate the values of the double-K fracture parameters which resulted in the closed form equations for calculating the

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Nomenclature

a	equivalent-elastic crack length, m
a_s	effective crack length corresponding to w_s, m
a_{w0}	effective crack length corresponding to zero stress of new fictitious fracture zone, m
b	specimen width, m
$CMOD_c$	critical crack mouth opening displacement, mm
$CTOD_c$	critical crack tip opening displacement, mm
E	residual Young's modulus, MPa
$f(\sigma)$	cohesive force distribution, MPa
G	self-weight of the specimens, N/m
h	height of wedge-splitting specimens, m
K	stress intensity factor, MN/m$^{1.5}$
K_{Ic}^{ini}/K_{Ic}^{un}	initial/unstable fracture toughness ratio
$m(x,a)$	weight function
P_{ini}	initial cracking load, kN
R_1,R_2	reaction force, kN
w	crack opening displacement at the tip of initial notch, mm
w_0	crack width at stress-free point, mm
Δa	crack extension length, m
$\sigma_s(w_s)$	cohesive stress at the break point of softening curve, MPa
θ	wedge angle of the loading system, °
a_c	critical notch depth of the specimen, m
a_{wc}	fully developed fictitious fracture zone length, m
a_0	initial notch depth of the specimen, m
$CMOD$	crack mouth opening displacement, mm
$CTOD$	crack tip opening displacement, mm
d	distance between roller axis and precast notch, mm
f	height of concrete above the precast notch, m
f_t	tensile strength, MPa
G_F	fracture energy, N/m
h_0	thickness of the clip gauge holder, m
$K_c(\Delta a)$	cohesive toughness, MN/m$^{1.5}$
K_R	crack extension resistance, MN/m$^{1.5}$
M_1 to M_4	parameters of weight function
P_u	maximum load, kN
T_m	heating temperatures, °C
w_s	crack width at break point of softening curve, mm
α	deformation coefficient of concrete
$\sigma(w)$	cohesive stress at the tip of initial notch, MPa
$\sigma(x)$	cohesive stress at equivalent-elastic crack length x, MPa

fracture parameters with acceptable errors compared with the analytical method. The same weight function with four parameters was applied to determine the K_R-curve based on the cohesive stress distribution in the fictitious zone [11]. It was concluded that the weight function approach could be used as an alternative tool for determining the K_R-curve based on the cohesive stress distribution.

The influence of temperature on the fracture properties was considered by several researchers, mainly on the fracture energy and material brittleness [3,2,14,26–29], with relatively few discussions on the fracture toughness [1,17,25] and almost none on the crack extension resistance of the complete fracture process. It was found that the fracture energy sustained an increase-decease tendency, whereas the fracture toughness was greatly influenced by heating temperature and decreased steadily with the increasing temperature. However, the influence of softening curves on the fracture toughness of post-fire concrete has not been deal with so far. Considering there are many structures subjected to fire or high temperatures, the influence of elevated temperatures on the fracture properties needs to be further studied.

According to the wedge-splitting experiments previously carried out by the authors [25], the main objective of this research is to determine the residual crack extension resistance curve (K_R-curve) of the post-fire concrete based on the cohesive force distributed in the fictitious crack zone using an analytical and the weight function approach. The influence of the heating temperature and the softening curve on the K_R-curve needs to be determined. The stability analysis on crack propagation is implemented and the influence of heating temperature on the crack tip opening displacement versus crack extension curves ($CTOD$–Δa curves) of the complete fracture process is also discussed. The paper is structured as follows: (i) determination of the residual K_R-curve based on the cohesive stress distribution, (ii) briefly description of the experimental work, (iii) discussion of the crack extension resistance for various heating temperatures, and (iv) stability analysis of the crack propagation and discussion on the influence of heating temperatures on the $CTOD$–Δa curves.

2. Determination of residual K_R-curve based on cohesive stress distribution

2.1. Background for determination of residual K_R-curve

According to the K_R-curve criterion [21], the crack extension resistance of a cracked solid consists of the inherent toughness, K_{Ic}^{ini}, and the cohesive toughness, $K_c(\Delta a)$ which increases with the increase in the crack extension. The cohesive fracture toughness depends upon the cohesive stress distribution, $f(\sigma)$, which is a function of the crack opening displacement, w, the tensile strength of concrete, f_t, and the propagating crack length, a. At the onset of unstable crack propagation the stress intensity factor at the tip of the propagating crack, K, is expressed as:

$$K = K_R(\Delta\alpha) \tag{1}$$

where, $K_R(\Delta a)$ is the crack extension resistance for the crack extension length $\Delta a = a - a_o$. Also $K_R(\Delta a)$ can be expressed as follows:

$$K_R(\Delta\alpha) = K_{Ic}^{ini} + K_c(\Delta\alpha) \tag{2}$$

where, $K_c(\Delta\alpha)$ is the cohesive fracture toughness and is given as:

$$K_c(\Delta\alpha) = F_1(f_t, f(\sigma), \Delta\alpha) \tag{3}$$

In order to develop the K_R-curve for the complete fracture process considering the cohesive stress in the fictitious fracture zone, the values of the cohesive toughness K_c at different stages of loading is important to determine. During the crack propagation, four different stages are considered with the help of three characteristic crack lengths (a_o, a_c and a_{wc}) as represented in Fig. 1 in which r_u is the undamaged portion of the ligament, a_o is the initial crack length, a_c is the crack length at the critical condition of unstable crack propagation and a_{wc} is the length of the fully developed fictitious fracture zone after which the stress-free crack propagation will begin.

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

The softening traction-separation law is a prerequisite to determine the K_R-curve. At room temperature, many expressions have