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Effects of loading rates on concrete double-*K* fracture parameters

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ABSTRACT

The effects of loading rates on concrete double-*K* fracture parameters were investigated using central-notched split tension cubes, both experimentally and analytically. Four loading rates varying from 10^{-5}/s to 10^{-2}/s was adopted. Results showed that, with the increase of loading rates, the initiation fracture toughness linearly increased while the unstable fracture toughness varied by a first increase and a followed constant trend. It was also confirmed that double-*K* fracture model may be further extended to wider dynamic loading rates, such as seismic dynamic excitation. Finally, the models describing the loading rate influences on double-*K* fracture toughness parameters were developed.

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1. Introduction

There is great likelihood for most concrete structures to work under dynamic or moderate loads in their life cycles, in addition to static loads. Therefore, investigation on rate-dependence of concrete fracture properties is in need to reasonably predict crack propagation and failure response of concrete structures. In the past decades, many studies have been conducted by researchers to reveal the influence of loading rates on fracture behavior of concrete-like quasi-brittle materials. Du et al. [1] numerically modeled the dynamic crack propagation of the notched and unnotched mortar beams subjected to impact action. John et al. [2] analytically predicted the strain rate sensitivity on concrete fracture behavior based on the two-parameter fracture model [3]. Bažant et al. [4,5] applied the size effect law to study fracture parameters of limestone at various loading rates in the static regime (crack mouth opening displacement CMOD rate 10^{-7}–10^{-2} mm/s). A slight increase in both fracture toughness and nominal strength was observed with an increase of loading rate. Fracture process zone length and the brittleness index, however, were found to be rate-independent. Zhang et al. [6] measured fracture toughness of rock over a wide range of loading rates using short-rod fracture specimen. It was stated that the fracture toughness presented a constant and then rising trend with the loading rate. Lambert et al. [7] conducted split Hopkinson pressure bar test on notched-cavity splitting tension cylinders to investigate the variation of concrete fracture parameter with loading rates. As concluded, a significant increase in the effective fracture toughness was observed as loading rate increased. Tadon and Faber [8] studied the effects of loading rates on the fracture of cement paste, mortar, and concrete using notched split-tension cylinders. In the tested range of loading rates (0.25, 1, 10 and 100 μm/min), the peak fracture toughness was

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Nomenclature

a	half effective crack length (mm)
a_0	half initial crack length (mm)
a_c	half critical effective crack length (mm)
a_s	half characteristic effective crack length (mm)
A_i	coefficients relating to relative load-distributed width (i = 0–3)
B	specimen thickness (mm)
B_i	coefficients relating to relative load-distributed width (i = 0–3)
C	secant compliance for load-CMOD curve (mm/N)
C_i	initial compliance for load-CMOD curve (mm/N)
CMOD	crack mouth opening displacement (mm)
$CMOD_c$	critical rack mouth opening displacement (mm)
COD	crack opening displacement (mm)
CTOD	crack tip opening displacement (mm)
$CTOD_c$	critical crack tip opening displacement (mm)
d_{max}	maximum aggregate size used in tested concrete (mm)
D	half specimen width or depth (mm)
E	Young's modulus of concrete (MPa)
f_{ck}	characteristic compressive strength of concrete (MPa)
f_{cm}	mean compressive strength of concrete (MPa)
f_{tm}	mean tensile strength of concrete (MPa)
G_f	fracture energy (N/mm)
h	total depth of specimen (mm)
$k(\alpha, \beta)$	non-dimensional function for K_I or geometry factor
K_I	stress intensity factor (MPa m$^{1/2}$)
K_I^c	stress intensity factor caused by cohesive stress (MPa m$^{1/2}$)
K_{Ic}^c	cohesive fracture toughness (MPa m$^{1/2}$)
K_{Ic}^{ini}	initial fracture toughness (MPa m$^{1/2}$)
$K_{Ic}^{ini,0}$	initial fracture toughness at reference strain rate of 10^{-5}/s (MPa m$^{1/2}$)
$K_{Ic}^{ini\text{-}exp}$	experimentally initial fracture toughness (MPa m$^{1/2}$)
$K_{Ic}^{ini\text{-}th}$	calculated initial fracture toughness (MPa m$^{1/2}$)
K_{Ic}^{un}	unstable fracture toughness (MPa m$^{1/2}$)
$K_{Ic}^{un,0}$	unstable fracture toughness at reference strain rate of 10^{-5}/s (MPa m$^{1/2}$)
$K_{Ic}^{un\text{-}exp}$	experimentally unstable fracture toughness (MPa m$^{1/2}$)
M_i	universal weight function parameters (i = 1–3)
m_{ij}	polynomial coefficients (i = 1–3, j = 0–7)
$m(x, a)$	weight function
$m(x, a_c)$	weight function at P_{max}
P	load (kN)
P_{max}	maximum load (kN)
P_{ini}	initial cracking load (kN)
t	half load-distributed width (mm)
t_{ini}	time to initial cracking load at tested strain rate (s)
t_{ini}^0	time to initial cracking load at reference strain rate of 10^{-5}/s (s)
t_p	time to maximum load (s)
v_c	critical crack propagation velocity at tested strain rate (mm/s)
v_c^0	crack propagation rate at reference strain rate of 10^{-5}/s (mm/s)
$V(\alpha, \beta)$	non-dimensional function for CMOD
w	crack opening width (mm)
w_0	critical crack opening of bilinear softening curve (mm)
w_s	crack opening at turning point of bilinear softening curve (mm)
$w(x)$	crack opening along crack line (mm)
Δa_c	half critical crack extension (mm)
α	crack-depth ratio or relative crack length
α_0	initial crack length-depth ratio or initial relative crack length
α_c	critical relative effective crack length
α_F	parameter relating to maximum aggregate size
β	ratio of load-distributed width to the specimen depth
λ	parameter describing deformation performance of concrete
σ_N	nominal tensile stress produced by applied load (MPa)

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