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A numerical study on crack branching in quasi-brittle materials with a new *effective rate-dependent* nonlocal damage model

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ABSTRACT

This contribution presents a numerical study towards the propagation and branching of cracks in quasi-brittle materials, using a new *effective rate-dependent* damage model, enhanced by a stress-based nonlocal (SBNL) regularization scheme. This phenomenological model is mesh objective and reproduces the major phenomena associated with crack propagation and branching in quasi-brittle materials.

It is discussed and demonstrated that the branching phenomenon is not controlled by a specific, material dependent, crack speed. Instead, it is governed by the evolution of the principal stresses at the crack tip, which are controlled by the evolution of damage. It is demonstrated that, with increasing crack speeds, the principal stresses at the crack tip tend to evolve from a mode-I to a mixed-mode state. Beyond a certain (critical) crack speed, the stress distribution around the crack tip reaches a critical state at which a single crack is no longer stable. When this condition is met, crack branching occurs whenever the stress field at the crack tip is destabilized by either a physical discontinuity or an interfering stress wave reflected at the specimen boundaries.

1. Introduction

Complex damage mechanisms develop when concrete structures are subjected to dynamic loads. Cracks are the main driver of material failure [1,2], thus understanding its dynamics is of utmost importance for the design of concrete structures [3], in particular the ones that have to withstand earthquakes, high velocity impacts and explosions.

Although considerable research effort has been devoted to characterize concrete's dynamic behavior, only a few experimental and numerical studies focus on the dynamics of cracks in this material [4–6,3,7–9]. Most of the available knowledge on why a single crack often curves and/or splits into two or more branches at increasing load intensity [10] and deformation rates [7] come from studying brittle materials. For obvious technical reasons, researchers have favored homogeneous transparent materials such as glass, brittle polymers (PMMA) and more recently soft polyacrylamide gels, to conduct these studies. Nonetheless, since the fundamental laws of crack propagation are expected to be universal, the acquired knowledge is prone to be generalizable to heterogeneous materials such as rocks and concrete.

In (quasi)-brittle materials under a mode-I loading condition, a single crack splits into two or more branches when reaching a material dependent critical velocity. However, it has been experimentally reported that, for the same material,

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Nomenclature

δ_i	rate parameter (B_i^{dyn})
$\dot{\varepsilon}_i$	variation in time of equivalent strain ('instantaneous' strain rate)
$\dot{Y}_i 0$	strain rate above which the loading is considered dynamic
η_i	rate parameter (Y_{i0}^{dyn})
λ	characteristic time scale
ν	Poisson's ratio
ω	damage
ω_i	damage for tension ω_t and compression ω_c
$\overline{Z}$	nonlocal variable
$\rho(x,\xi)$	reduction factor of nonlocal length
σ	stress tensor
$\tilde{\sigma}$	effective stress tensor
ε	strain tensor
ε_i	equivalent strain for tension ε_t and compression ε_c
ζ_i	rate parameter (Y_{i0}^{dyn})
A_i	parameter damage law for tension A_t and compression A_c
B_i	parameter damage law for tension B_t and compression B_c
B_i^{dyn}	dynamic B_i
C	elastic stiffness tensor
f_t^{dyn}	dynamic tensile strength
I_ε	first invariant of the strain tensor
J_ε	second invariant of the deviatoric strain tensor
l_r	characteristic nonlocal length
l_{min}	minimum nonlocal length
$l_{x\xi}$	interaction length between the Gauss points x and ξ
R_i	*Effective rate* for tension R_t and compression R_c
R_{down}	*effective rate* in case of decrease of $\dot{\varepsilon}_i$
R_{up}	*effective rate* in case of increase of $\dot{\varepsilon}_i$
Y_i	historical maximum equivalent strain for tention Y_t and compression Y_c
Y_{i0}	yield effective strain for tension Y_{t0} and compression Y_{c0}
Y_{t0}^{dyn}	dynamic yield effective strain
DIF	Dynamic Increased Factor
FPZ	Fracture Processed Zone
SBNL	Stress Based Nonlocal

branching may occur for a relatively wide range of cracks speeds, depending on the material characteristics, load history, geometry and boundary conditions of the problem [11]. For example, the maximum crack branching velocity observed for concrete falls in a wide interval, between $0.2C_R$ and $0.57C_R$ [12,3,7], with C_R being the Rayleigh wave speed. Although we are still far from understanding this complex multiscale phenomenon, it is now accepted that the propagation of cracks is governed by the dynamic evolution of the dissipative processes occurring in the finite fracture process zone (FPZ) [13–15] and the dynamic interaction with the elastic material around the crack tip [16,17].

It has been consistently observed for different materials that, under mode-I loading conditions, the damaging process ahead of the crack tip changes considerably with increasing crack speeds, as depicted in Fig. 1. Up to a critical speed of $v_c = 0.3 \sim 0.4C_R$, cracks accelerate very fast leaving behind a nearly smooth crack surfaces (Fig. 1(a)). Above this limit (v_c), crack acceleration is retarded and the crack surface roughens while the fracture zone progressively evolves from a single discontinuity to an assemblage of small cracks (see for example [18] for images of experimental results). First, micro-cracks and voids tend to grow and coalesce parallel to the forward cracking direction (Fig. 1(b)). Then, with further increase of the crack speed (and/or load intensity), micro-branches sprout from the crack tip leaving in its wake a rough crack surface (Fig. 1(c)).

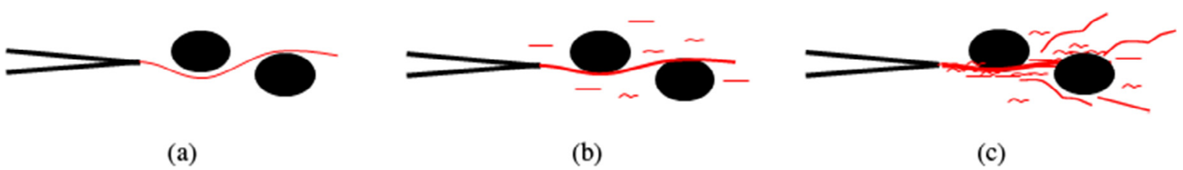

Fig. 1. Evolution of Fracture Process Zone (FPZ) with increasing crack velocity (adapted from [19]): (a) $v < v_c$, (b) $v \approx v_c$ and (c) $v > v_c$.