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A new *effective rate* dependent damage model for dynamic tensile failure of concrete

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ABSTRACT

From a macroscopic point of view, the dynamic tensile response of concrete is mainly due to the viscous behavior of the bulk material and inertia effects at multi-scale levels. It has been suggested that almost all of these mechanisms have to be considered as intrinsic material properties and explicitly included in the constitutive relations of the continuum model. It is discussed and demonstrated that the use of semi-empirical dynamic strength increase factor (DIF) functions to numerically describe rate effects do not characterize true constitutive relations of the material.

A strain-rate dependent formulation is used to describe the strength and fracture energy increase of concrete under dynamic tensile loading conditions. However, instead of the commonly used $\dot{\varepsilon}$ (*instantaneous* strain-rate) to update the constitutive law, an *effective rate* (R) is considered. With this new concept a *time* scale is introduced in the constitutive law which restrains the 'evolution of rate', to represent the inherent dynamic properties of concrete. This has a weak regularization effect and acts as a localization limiter. Mesh objectivity is recovered with the addition of a *material length* scale to the constitutive relations, here accomplished by an explicit stress-based nonlocal regularization scheme.

Two sets of modified split Hopkinson bar tests are simulated for validation, using respectively notched and un-notched specimens. The results are objective and in good agreement with the experiments.

1. Introduction

Under dynamic transient conditions, concrete is known to exhibit a significant dynamic strength increase [1] in tension [2] and, to a smaller extent, in compression [3]. This increase is associated with a rise of both stiffness and fracture energy. The consideration of these strain-rate effects in the design of critical (infra-) structures, such as power plants, dams, bridges and hospitals, is crucial to protect ourselves and our societies from the devastating effects of extraordinary actions such as earthquakes, explosions, impacts and other highly dynamic loading situations. Therefore, the development of realistic numerical tools to efficiently simulate the dynamic failure of concrete is of paramount significance.

Although rate dependency of concrete has been known for a century now [4], the understanding of the underlying physical mechanisms is far from complete, despite the numerous experimental and numerical studies on dynamic fracture of

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Nomenclature

δ_t	rate parameter (B_t^{dyn})
$\dot{\varepsilon}$	'instantaneous' strain rate
$\dot{Y}_0$	strain rate above which the loading is considered dynamic
η_t	rate parameter (Y_{t0}^{dyn})
λ	characteristic time scale
ν	Poisson's ratio
ω	damage
$\overline{\varepsilon_t}$	nonlocal equivalent strain
$\rho(x,\xi)$	reduction factor of nonlocal length
σ	stress tensor
$\tilde{\sigma}$	effective stress tensor
ε	strain tensor
ε_t	equivalent strain
ζ_t	rate parameter (Y_{t0}^{dyn})
A_t	parameter damage law
B_t	parameter damage law
B_t^{dyn}	dynamic B_t
C	elastic stiffness tensor
f_t^{dyn}	dynamic tensile strength
f_t	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	*effective rate*
Y_t	historical maximum equivalent strain
Y_{t0}	yield effective strain
Y_{t0}^{dyn}	dynamic yield effective strain
SBNL	stress based nonlocal

quasi-brittle materials. It is more or less common knowledge that the dynamic response of concrete is directly related to the viscous behavior of the bulk material, as well as to the inertia effects at multiple scale levels that directly and indirectly control the cracking (damage) process. As it is well known, the evolution of cracks cannot expand arbitrarily fast [5–7]. Since damage in concrete is essentially the result of the initiation, growth and coalescence of micro-cracks, its evolution is a strongly time dependent phenomenon [8]. At high deformation rates ($\geqslant 1\ s^{-1}$), crack propagation is retarded due to inertia effects at the crack tip [9–11]. At low to moderate deformation rates, the enhanced resistance of the material is mainly caused by moisture in the pores [12,13]. Due to viscous forces caused by the *Stefan effect*, the crack initiation process is delayed. In either case, the evolution of damage is delayed due to an apparent resistance to straining [14], which results in a retarded crack opening process. This retardation of cracking (damage) is usually nominated as the main cause of the observed dynamic strength increase. Additionally, with increasing loading rates, more micro-cracks are activated at the same time, leading to an increase of effective fracture surface (damage) and of the dynamic fracture energy [15–17].

The viscous properties of the bulk material also have a considerable influence on the dynamic response of quasi-brittle materials. Eibl and Schmidt-Hurtienne [18] demonstrated that in case of rapid variations of the loading rate, its effects are not 'felt' instantaneously. The material has some kind of *memory*. Thus, in case of a sudden drop of the deformation rate an inertial-related stress relaxation process is triggered and a certain time is needed for the stress-strain state to evolve to the new rate-dependent condition.

Finally, mass inertia effects at the structural level have also been identified as another potential contributor to the dynamic strength increase. Several numerical studies with the split Hopkinson pressure bar (e.g. [19–22]) showed that the strength increase under uniaxial compression is partially caused by triaxial compressive stress states associated with inertial lateral confinement. On the other hand, Lu and Li [23] demonstrated that in the dynamic splitting test the material strength is hardly affected by stress triaxiality. Under uniaxial tensile loading condition (direct tension or spalling tests), triaxial tension stress states are induced. Thus, although structural inertial effects partially explain the strength increase under compression, it cannot explain the dynamic tensile response [24].

It has been demonstrated that the retardation of micro-cracking at high deformation rates associated with micro and meso-scale inertia effects can be analyzed by a rate-independent model as long as the material is discretized in all its phases (aggregates, cement paste and voids) [25]. However, this is not possible with phenomenological models, which provide homogenized macroscopic representations of the material. Rate enhanced formulations must be considered in order to