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A new rate-dependent stress-based nonlocal damage model to simulate dynamic tensile failure of quasi-brittle materials

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ABSTRACT

The development of realistic numerical tools to efficiently model the response of concrete structures subjected to close-in detonations and high velocity impact has been one of the major quests in defense research. Under these loading conditions, quasi-brittle materials undergo a multitude of failure (damage) mechanisms. Dynamic tensile failure (e.g. spalling), characterized by a significant strength increase associated with loading rate, has revealed to be particularly challenging to represent.

In this contribution, a rate-dependent stress-based nonlocal damage model has been introduced for the simulation of dynamic tensile failure of quasi-brittle materials. The recently proposed stress-based nonlocal criterion has been updated in order to be consistently combined with a rate-dependent version of the well-known Mazars damage model. The model was implemented in LS-DYNA using a fully explicit computational scheme.

Two sets of numerical examples have been presented. First, one-dimensional numerical analyses were conducted to evaluate the model capabilities, applicability and limitations. Second, the model has been validated against experimental results. It has been shown that the proposed model, in addition to correcting spurious mesh sensitivity, also provides a more realistic representation of damage initiation and growth, in particular around discontinuities (notches and free boundaries) and damaged areas.

1. Introduction

The development of realistic numerical tools to efficiently model the response of concrete structures subjected to close-in detonations and high velocity impact has been one of the major quests in defense research. Even with today's state of the art finite element tools, it is still a great challenge to properly and efficiently simulate the response of a complex concrete structure under extreme dynamic loadings. For example, when a concrete structure is subjected to a contact detonation or high velocity impact, a shock wave is locally generated and expands radially through the structural element. The consequence is a complex process of interfering stress waves where the material is exposed to rapidly changing multi-axial stress states and strain rate conditions which lead to very different failure (damage) mechanisms: (*i*) compaction and crushing (hydrostatic damage), (*ii*) tensile failure (spalling) with an apparent dynamic increase of strength and (*iii*) mixed mode failure associated with anisotropic behavior [1]. In a later stage, (*iv*) structural oscillations at moderate strain rates become the leading loading condition, thus the main cause for further material mechanical degradation [2].

Dynamic tensile failure (e.g. spalling), characterized by a significant strength increase associated with loading rate, has revealed to be particularly challenging to represent. Failure in concrete develops from growth and coalescence of micro-cracks followed by formation of a fracture process zone, where the stresses are transfered by aggregate interlock and crack bridges. This process eventually culminates in a visible traction-free macro-crack. Concrete behavior is often described by nonlinear phenomenological models using a strain softening law in order to describe progressive cracking and stiffness reduction, and a regularization technique to correct spurious mesh sensitivity. Commonly, these constitutive laws are modeled in the framework of continuum damage mechanics [3–5], plasticity [6–8] or a combination of both [9–11]. There are also formulations promoted under different fracture-based approaches such as *microplane* models [12], lattice models [13] and discontinuous models [14,15] (fracture mechanics, XFEM, GFEM, etc.).

Continuum damage mechanics models with a nonlocal formulation of integral or gradient type are among the most successful to represent concrete behavior, especially when used under monotonic tensile loading situations. The key idea behind nonlocal regularization methods is that the stress response at a material point

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depends on the state of its neighborhood. An internal length is introduced into the constitutive relation in order to describe microstructural interactions. In the continuum damage mechanics context, regularization is obtained by the direct coupling of damage to a nonlocal variable, derived from a weighted average over a certain volume in the vicinity of the considered integration point of its local counterparts. Although successful in mitigating the spurious localization and pathological mesh sensitivity [16], this regularization technique is prone to some erroneous results and may lead to unrealistic damage initiation and evolution [17]. These misrepresentations are usually visible in the vicinity of free boundaries and discontinuities. This is the consequence of an inadequate treatment of interaction in these particular situations. There is now general consensus that the interaction domain should expand and contract as a function of the stress state, damage evolution and geometry of the problem. In the last decade several nonlocal damage models with evolving length scale have been proposed to mitigate some of these deficiencies [18–26].

For models based on an integral regularization schemes, Krayani et al. [19] have proposed a model to improve the representation of damage in the vicinity of free boundaries. One of the limitations of this model is the need of a specific preprocessing technique where the effect of free boundaries on nonlocality are explicitly introduced in the model. Furthermore, the model does not take into consideration the effect of damage in the nonlocal interaction domain. To overcome this, Pijaudier-Cabot and Dufour [20] and Desmorat and Gatuingt [21] proposed models where the interaction domain is indirectly made a function of local damage. Both models were developed following the *path attenuation in the nonlocal transfer of information* concept. Although very promising results have been presented for 1D examples, the extension of these models to 2D and 3D calculations is a difficult open challenge [25].

Finally, Giry et al. [23] proposed a model where the interaction domain (internal length) varies as a function of the stress state in the neighboring elements. A contraction of the weight function in the direction of the smaller principal stress-states is induced by this technique. Consequently, the interactions between elements decrease close to free boundaries, geometrical discontinuities (cracks) and damaged areas in their normal directions. The result is a desirable localization effect observed in these situations. In this contribution the stress-based nonlocal criterion [23,27] has been updated in order to be consistently combined with a rate-dependent version of Mazars damage model [3]. This makes it possible to study dynamic tensile failure of quasi-brittle materials.

As it is well known, quasi-brittle materials exhibit a significant strength increase associated with high rate straining, in particular under tension [28]. The representation of dynamic tensile failure has motivated many experimental and numerical researchers. The retardation of internal microcracking observed at high deformation rates has been pointed out by several researchers as the leading cause of the observed strength increase, in particular in tensile stress conditions [2]. In the continuum damage mechanics framework one may say that the evolution of damage has a strong connection with the rate sensitivity of the material. Notwithstanding, the rate sensitivity of concrete and other geomaterials is still not completely understood. In particular, the rate effects in the post-peak regime are still very difficult to properly analyze and characterize. Thus, a simple damage-delay criterion is proposed where only the damage threshold (peak stress) in the Mazars model is affected by rate. The corresponding modifications were made to the stress-based nonlocal formulation.

The model has been implemented within the framework of LS-DYNA [29] using a fully explicit computational scheme recently developed by de Sá et al. [30,31]. This algorithm is used to determine the nonlocal quantity. It has been developed under the premise that the variation of the ratio between the local and nonlocal variables is infinitesimal in consecutive time steps. Accordingly, the current nonlocal quantity is simply determined by multiplying its local counterpart by a correction factor computed from weight averaging the results obtained in the previous time step.

After a complete description of the model and explicit algorithm (sec. 2 and 3), two sets of numerical studies are presented in this paper. First (sec. 4), one-dimensional examples are used to explore the limitations and applicability of the stress-based nonlocal formulation and the explicit computational scheme considering a rate-independent damage model. Second (sec. 5), the rate-dependent version of the stress-based model is validated against experimental results. Two experiments conducted at Delft University of Technology using a split Hopkinson bar are simulated [32].

2. Stress-based nonlocal formulation

2.1. Isotropic damage model (local formulation)

Continuum damage mechanics has been widely and successfully used to describe quasi-brittle materials (concrete). The *damage* quantity is the macroscopic representation of the material stiffness degradation associated with micro-cracking (and other microscopic phenomena) that lead to fracture and rupture. Damage is driven by the density and orientation of micro-defects; thus, in order to take the anisotropic nature of material failure into account, it should be represented by a vector or tensorial variable. However, simple isotropic damage models are generally sufficient to describe the behavior of concrete especially under monotonic uniaxial loading. For the present study, an adapted version of the damage model developed by Mazars [33] has been updated with different nonlocal formulations. Since this model is well described in literature, only a brief explanation is presented in order to introduce the nonlocal formulation discussed hereafter.

The Mazars model is an isotropic damage model that considers a single scalar variable ω to represent the material stiffness degradation. This damage parameter evolves from zero (virgin or undamaged material) to one (complete failure). Assuming that the Poisson's ratio is not affected by damage, i.e. the relative reduction of all stiffness coefficients is the same and independent of the direction of loading. The stress tensor is expressed as:

$$\sigma = (1-\omega)C : \varepsilon \tag{1}$$

where ε is the strain tensor and C the elastic stiffness tensor. During loading, the damage evolution is assumed to be a function of the internal variable κ that denotes the maximum equivalent strain (ε_{eq}) level reached in the material:

$$\kappa(t) = \max \varepsilon_{eq}(\tau) \quad \textit{for all} \quad t \geqslant \tau \tag{2}$$

$$\varepsilon_{eq} = \sqrt{\sum_{I=1}^{3} \langle \varepsilon_I \rangle^2} \tag{3}$$

where $\langle . \rangle$ are the Macaulay brackets; consequently $\langle \varepsilon_I \rangle$, with $I = 1$, 2, 3, are the positive parts of the principal strains. Damage initiates when the equivalent strain surpasses the damage threshold (κ_0) and its growth is described by the Kuhn–Tucker conditions:

$$f \leqslant 0 \qquad \dot{\kappa} \geqslant 0 \qquad \dot{\kappa} f = 0 \tag{4}$$

where $f(\varepsilon, \kappa) = \varepsilon_{eq} - \kappa$ is the loading function.

Mazars introduced two damage parameters, ω_t and ω_c, in order to describe the uniaxial behavior of concrete under tension and compression. For general stress states, ω results from the weighted combination of tensile and compressive damage according to

$$\omega = \alpha_t \omega_t + \alpha_c \omega_c \tag{5}$$