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# New methodology for calculating damage variables evolution in Plastic Damage Model for RC structures

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ABSTRACT

The behavior of reinforced concrete (RC) structures under severe demands, as strong ground motions, is highly complex; this is mainly due to joint operation of concrete and steel, with several coupled failure modes. Furthermore, given the increasing awareness and concern for the important seismic worldwide risk, new developments have arisen in earthquake engineering. Nonetheless, simplified numerical models are widely used (given their moderate computational cost), and many developments rely mainly on them. The authors have started a long-term research whose final objective is to provide, by using advanced numerical models, solid basis for these developments. Those models are based on continuum mechanics, and consider Plastic Damage Model to simulate concrete behavior. Within this context, this paper presents a new methodology to calculate damage variables evolution; the proposed approach is based in the Lubliner/Lee/Fenves formulation and provides closed-form expressions of the compressive and tensile damage variables in terms of the corresponding strains. This methodology does not require calibration with experimental results and incorporates a strategy to avoid mesh-sensitivity. A particular algorithm, suitable for implementation in Abaqus, is described. Mesh-insensitivity is validated in a simple tension example. Accuracy and reliability are verified by simulating a cyclic experiment on a plain concrete specimen. Two laboratory experiments consisting in pushing until failure two 2-D RC frames are simulated with the proposed approach to investigate its ability to reproduce actual monotonic behavior of RC structures; the obtained results are also compared with the aforementioned simplified models that are commonly employed in earthquake engineering.



## 1. Introduction

Under severe seismic excitation, structural behavior of buildings and other constructions is highly complex. It involves, among other issues, soil-structure interaction, large strains and displacements, damage, plasticity, and near-collapse behavior. Moreover, in reinforced concrete structures, there are several coupled degradation and failure modes: cracking, crushing and spalling of concrete, yielding and pull-out of tensioned reinforcement, and yielding and buckling of compressed reinforcement. Therefore, in earthquake engineering, advanced numerical simulations based on continuum mechanics are strongly necessary; conversely, oversimplified models are commonly used, as a result of their moderate computational cost. Furthermore, another circumstance makes the situation more alarming: given the increasing awareness and concern on the huge worldwide seismic risk, earthquake engineering has experienced in last years substantial advances. New design and analysis strategies have been proposed, leading to relevant developments. These developments rely on extensive testing and numerical simulation; nonetheless, as discussed before, an important number of numerical analyses are mainly conducted by using simplified models. Therefore, there is a strong need of verifying the reliability of the new developments by comparison with analyses performed using more advanced simulation tools. Being aware of this circumstance, the authors have started a long-term research activity aiming to clarify this issue and to provide accurate and reliable models that are based on continuum mechanics. This paper presents early results of this research.

Quasi-brittle materials, as concrete, exhibit nonlinear stress-strain response mainly because of micro-cracking. Cracks are oriented as the stress field and generate the failure modes. In tension, failure is localized in a narrow band; stress-strain behavior is characterized by sudden softening accompanied with reduction in the

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**Nomenclature**

*Roman letters. Lower case*

$a_c/a_t/b_c/b_t$ dimensionless coefficients in Eqs. (15) and (16)
$b$ $\varepsilon_c^{pl}/\varepsilon_c^{ch}$ ratio (Eq. (28))
$c/c_1/c_2$ cohesion/coefficients in Eq. (29)
$d/d_c/d_t$ damage variable/compression damage variable/tension damage variable
$f/f_{b0}/f_{c0}/f_{cm}/f_{tm}/f_{c0}/f_{t0}/f_{ck}$ stress strength/biaxial compressive yield strength/uniaxial compressive yield strength/concrete compressive stress strength/concrete tensile stress strength/limit stress of linear compressive branch/limit stress of linear tensile branch/characteristic value of concrete compressive strength
$f_y/f_u$ steel yield point/ultimate stress
$g_c/g_t$ compressive/tensile energies per unit volume dissipated by damage along entire deterioration process
$h_c/h_t$ weighting factors accounting for stiffness recovery
$l_{eq}$ mesh size (finite element characteristic length)
$p$ hydrostatic pressure stress
$q$ Von Mises-equivalent effective stress
$r^*$ stress state; for uniaxial stress $r^*(\sigma_{11}) = 1$ for tension and $r*(\sigma_{11}) = 0$ for compression
$s_c/s_t$ coefficients accounting for stress state and stiffness recovery effects
$w/w_c$ crack opening/crack opening at fracture

*Roman letters. Upper case*

$D_b$ reinforcement bar diameter
$E/E_0/E_{ci}$ modulus of deformation/undamaged modulus of deformation/tangent modulus of deformation of concrete for zero stress
$E_s/E_{sh}$ steel modulus of elasticity/slope of hardening branch
$F$ loading function
$G/G_{ch}/G_F$ flow potential/crushing energy per unit area/fracture energy per unit area
$H$ Mohr-Coulomb yield surface function
$I_1$ first invariant of stress tensor
$J_2/J_3$ second/third invariants of deviatoric stress tensor
$K_c$ ratio of second stress invariants on tensile and compressive meridians

*Greek letters*

$\varepsilon/\varepsilon_c/\varepsilon_t/\varepsilon^{el}/\varepsilon^{pl}/\varepsilon_{cm}/\varepsilon_{tm}$ strain/compression strain/tensile strain/elastic strain/plastic strain/strain at compressive strength/strain at tensile strength
$\varepsilon_c^{pl}/\varepsilon_t^{pl}/\varepsilon_c^{el}/\varepsilon_t^{el}/\varepsilon_c^{ch}/\varepsilon_t^{ck}/\varepsilon_{0c}^{el}/\varepsilon_{0t}^{el}$ strains at Fig. 5; subindexes "c", "t", "0c" and "0t" and refer to compression, tension, undamaged compression and undamaged tension, respectively; superindexes "pl", "el", "ch" and "ck" and refer to plastic, elastic, crushing and cracking, respectively
$\varepsilon_{sh}/\varepsilon_u$ steel strain that corresponds to onset of hardening/ultimate strain
$\epsilon$ eccentricity of the plastic potential surface
$\phi$ friction angle
$\theta$ Lode similarity angle
$\rho$ octahedral radius
$\sigma/\sigma_{11}/\sigma_{t0}/\sigma_{c(1)}/\sigma_{c(2)}/\sigma_{c(3)}$ stress/first principal uniaxial stress/uniaxial tensile stress at failure/concrete compressive stress at first/second/third segment
$\overline{\sigma_c}/\overline{\sigma_t}$ effective compressive/tensile cohesion stress
$\xi$ distance from origin of stress space to stress plan
$\psi$ dilatancy angle

unloading stiffness. In compression, failure begins usually in the outside and is more complex, involving volumetric expansion, strain localization, crushing, inclined slipping and spalling; stress-strain behavior involves ductile hardening followed by softening and reduction in the unloading stiffness. In mixed stress states, failure depends usually on the ratio between the principal stresses; in tension-compression, failure is generated by the compression of the material that is between the cracks. Noticeably, in tension the behavior is closer to damage than to plasticity; conversely, in compression the participation of plasticity is higher.

Nonlinear concrete response can be represented using plasticity or damage theory. However, none of these formulations alone is able to describe adequately this phenomenon. Plastic models [21,50] might represent realistically the observed deformation in high confined concrete but do not capture the stiffness degradation observed in experiments [32]. Damage-based models [57,58,20] are based on gradual reduction of the elastic stiffness; they can describe the stiffness degradation in tension and low confined compression, but are not suitable to capture the irreversible deformations observed in experiments and the inelastic volumetric expansion in compression. In addition, fracture propagation can be represented by embedded crack models, where standard FEM interpolations are enriched with strain or displacement discontinuities [12,72,43]. These models can be used for high strain localization problems (fracture).

It is been widely accepted that coupling between damage and plasticity models is essential to capture the nonlinear behavior of concrete [63]. Plasticity for concrete can be described with isotropic hardening; however, damage in many cases is not isotropic but has preferential directions [30]. Some plastic isotropic damage models have been proposed, e.g. [54,47,16,70,45,42,32,63]; these models have shown good performance in capturing concrete behavior in tests on full-scale structures [30,63]. Anisotropy can be added to the damage to capture the anisotropy feature of concrete both for compression and tension. Although anisotropic damage models are complex and coupling with plasticity in the application to practical engineering is not straightforward, researchers have investigated this issue and proposed plastic anisotropic damage models, among others [67,73,44,35,59,37,17,38,22,82,2]. Even if isotropic damage is a simplified assumption, it is considered in this work because of its simplicity and sufficient accuracy.

Coupled damage and plasticity models for concrete differ mainly in the coupling method and the damage evolution law. In the implicit methods [54,62,70], coupling is embedded in yield and damage criteria; damage evolution law is also implicit. Other researchers describe coupling using a single function. In this context, [47,48] use a yield function; damage measure can be based on some criteria or by postulating damage variables law. This function can be also interpreted as a damage loading [29]; the damage evolution law shall be imposed.

Damage evolution law plays an important role in any damage model, particularly when this law is imposed. A number of researchers have proposed different damage evolutions laws. Most of them are based on splitting damage into compressive and tensile parts and each one is determined separately by its evolution law; total damage is calculated with some combination rules e.g. [29,13,2,52]. Few evolution laws are based on general formulae