A GRADIENT-REGULARIZED COUPLED DAMAGE-PLASTICITY MICROPLANE MODEL FOR CONCRETE-LIKE MATERIALS

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SUMMARY

Concrete, granular materials, and powder compaction are often modeled using strain softening materials, which are known to be plagued by numerical instability and pathological mesh sensitivity in a finite element analysis. To overcome this a coupled damage-plasticity microplane model, which uses an implicit gradient regularization scheme, is introduced. Implicit gradient regularization, a class of nonlocal methods, enhances the local equivalent strains by considering its nonlocal counterpart as an extra degree of freedom governed by a Helmholtz-type equation. This results in a smooth deformation field avoiding displacement discontinuities, which can lead to an ill-posed boundary value problem. A tension-compression split, to account for the transition of the stress state in cyclic loading, adds two extra degrees of freedom per node. Microplane plasticity is introduced, using microplane quantities, through laws resembling classical invariant-based plasticity models, enabling material models with a direct link to the conventional macroscopic plasticity models. Plasticity in this model is defined via a three-surface microplane Drucker-Prager model, covering a full range of possible stress states experienced in cyclic loading. The smoothness of the yield surface allows for a stable return mapping algorithm. The damage evolution behavior is motivated by the material behavior of concrete and similar materials. To realistically model the damage of concrete subject to cyclic loading, the initiation of damage and its subsequent evolution can be different between compression and tension. Furthermore, in the transition from tension to compression states, the stiffness lost during tensile cracking is recovered due to crack closure. The extra degrees of freedom essentially imply a coupled field problem and the system of equations are solved simultaneously. Examples of plain and reinforced concrete and comparisons against

experiments conducted by other authors are shown to evaluate the model.

1: Coupled damage-plasticity microplane model

The model (Zreid and Kaliske, 2018) is formulated within the microplane concept and features a coupled damage-plasticity model and an implicit gradient regularization. The coupled model is based on formulating plasticity using the effective stress (in the undamaged space) and then uses the plastic strains to drive damage. The framework of the model is summed up in the following stress-strain formula

$$\boldsymbol{\sigma} = \frac{3}{4\pi}\int_{\Omega}\left(1-d^{mic}\right)\left[K^{mic}\mathbf{V}\left(\varepsilon_V-\varepsilon_V^{pl}\right)+2G^{mic}\mathbf{Dev}^T\cdot\left(\boldsymbol{\varepsilon}_D-\boldsymbol{\varepsilon}_D^{pl}\right)\right]d\Omega \qquad (1)$$

The difference between damage, plasticity and coupled models in a one-dimensional setup are depicted in Figure 1.

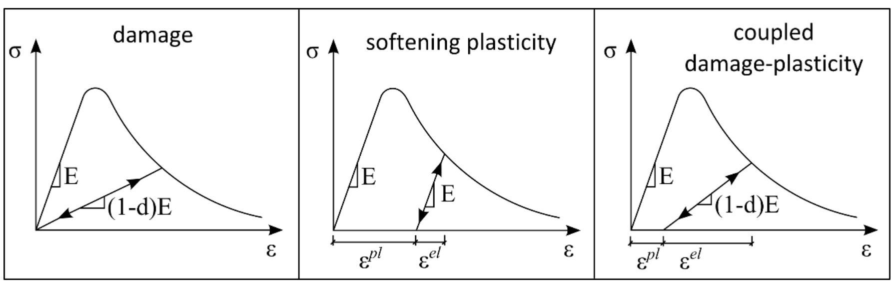

Figure 1: Inelastic material models for concrete

2: Plasticity

The response of concrete under different stress triaxialities can be modeled using a Drucker-Prager yield function supplemented with caps for the compression and tension regions (Figure 2). Some versions of the caps in the literature create non-smooth edges in the yield surface, which cause numerical difficulties. In this model, caps with smooth transitions are used.

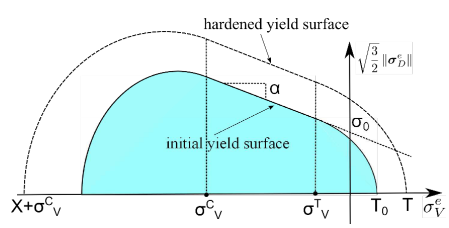

Figure 2: Smooth three-surface microplane cap yield function

3: Damage

The deterioration of concrete stiffness under cyclic loads is characterized by two main aspects. Firstly, the initiation and evolution of damage is different in compression and tension. Concrete is more brittle in tension and the softening starts directly after the elastic limit, while in compression some hardening is observed before subsequent softening. Secondly, in case of transition from tension to compression, the stiffness lost during tensile cracking is recovered, due to crack closure. However, the damage sustained under compression persists upon transition to tension. This behavior could be described using the damage split into compression d_c^{mic} and tension d_t^{mic} parts. The resulting stress strain response under reversed cyclic loading can be seen in **Error! Reference source not found.**.

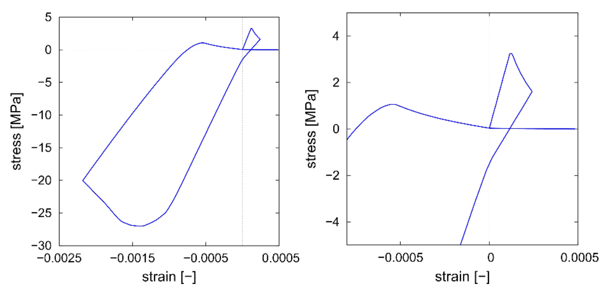

Figure 3: The effect of the damage split on the tension-compression cyclic loading response.

4: Implicit gradient regularization

The implicit gradient enhancement is a class of nonlocal methods, which calculates a nonlocal average of a local variable by considering the nonlocal value as an extra degree of freedom governed by a partial differential equation. This averaging ensures that the deformation field stays smooth avoiding strain discontinuities, which cause an ill-posed boundary value problem. Hence, in this regularization method, the balance of linear momentum, is solved along the implicit gradient equation used to define the nonlocal field with the homogeneous Neumann boundary condition,

$$\nabla \cdot \boldsymbol{\sigma} + \mathbf{f} = 0 \quad (1) \qquad \bar{\eta}_m - c\nabla^2 \bar{\eta}_m = \eta_m \quad (2) \qquad \nabla \bar{\eta}_m \cdot \mathbf{n}_b = 0 \quad (3)$$

The variables to be enhanced herein are the tension and compression equivalent strains driving the damage variables, which add two extra degrees of freedom to the system. The solution of this coupled system follows the standard fully coupled monolithic scheme, which requires unsymmetric solver but ensures a robust convergence.

5: Advantages of the new approach

1. The well-known mesh sensitivity and loss of convergence of the classical smeared cracking concrete model in Ansys (solid65 with TB,CONCR) can be avoided by using the new gradient approach. Progressive softening behavior can now be simulated until virtually total failure independent of the mesh refinement and with quadratic convergence.

2. Size effects observed in experimental data of concrete, that is the influence of the specimen size on the strength and fracture properties, is accounted for automatically in this approach by means of the nonlocal interaction, which introduces a characteristic length in the model.

3. The plasticity yield function of the new model provides a general description of concrete in all triaxial stress states, also under very high confinement pressure.

4. The damage split enables the simulation of concrete under random cyclic loading histories, where transition from tension to compression is expected.

6: Numerical examples

Torsion test of a notched concrete beam

Figure 4 shows a good agreement of the simulation results with experiments (Brockenshire, 1995) as well as the ability of the gradient regularization to eliminate the pathological mesh sensitivity.

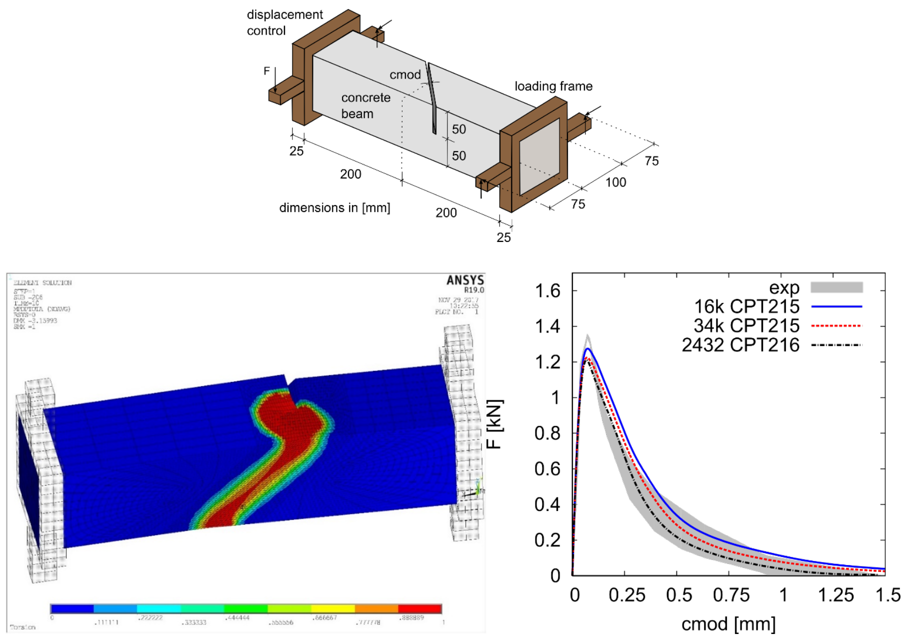

Figure 4: (a) Torsion test details, (b) Damage contours for the torsion test with 34k CPT215 elements, (c) Torsion test results

Reinforced concrete (RC) joint example

Figure 5 shows a good agreement of the simulation results with experiments (Chalioris et al., 2008).

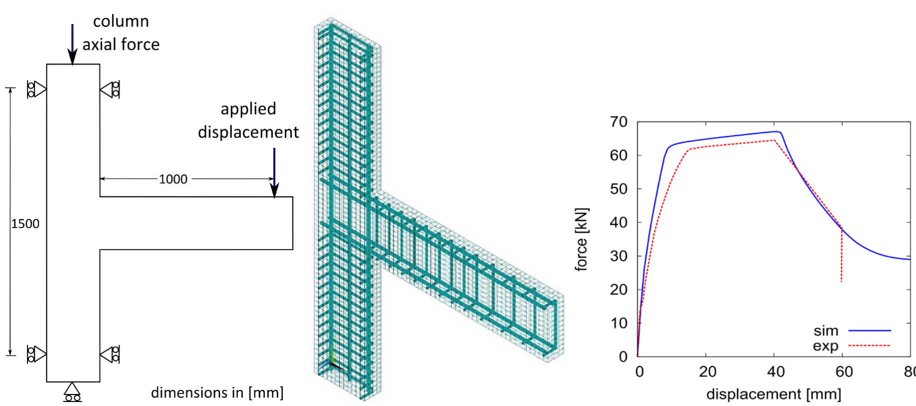

Figure 5: (a) RC Joint loading and boundary conditions, (b) Finite element mesh, (c) RC Joint results

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