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Nonlocal Microplane Model for Damage due to Cracking

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Abstract

As it is now generally accepted, finite element analysis of distributed softening damage in quasi-brittle structures such as concrete structures cannot be based on a classical, that is, local, constitutive model of the material. Such a model introduces incorrect excessive localizations, spurious size effect and spurious mesh sensitivity in finite element computations. To overcome these problems, the constitutive model must be supplemented with some sort of the so-called localization limiter. One effective type of the localization limiter is the nonlocal continuum. The present paper reviews two recent developments, one dealing with the formulation and application of a special new type of nonlocal model for materials such as concrete, which is derived physically from microcrack interactions (Bažant, 1994; Bažant and Jirásek, 1994), and numerical application of this model in finite element analysis (Bažant and Ožbolt, 1994). The paper also briefly summaries a new nonlinear triaxial damage model based on the microplane concept utilizing the new idea of stress-strain boundaries (Bažant, et al., 1994).

Microcrack Interactions and Nonlocal Finite Element Analysis

The nonlocality of the macroscopic continuum is not merely an expedient mathematical device preventing spurious localization. It has its physical source in the interaction of growing microcracks. The mathematical modeling of these interactions leads to a new type of nonlocal formulation, in which two kinds of spatial integrals are distinguished: (1) the local averaging, and (2) the long-range interactions. The former defines the volume in which the energy consumption by fracture takes place. The latter controls crack opening and propagation as a function of the stress and strain fields in the neighborhood of a microcrack and, which is practically most important, achieves correct (i.e., mesh independent) energy release with a reduction of stress to zero when the microcracks coalesce into a single macrocrack.

Numerical studies have shown that the new approach to damage ensures cracking to localize into a material volume whose size and shape are independent of the

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shape and size of the finite elements (provided that the characteristic length is not larger than about one-third of the typical element size). According to arguments of concrete heterogeneity as well as randomness of microcrack distribution, the size of the domain of nonlocal integrals is a function of the typical dominant microcrack length (which is approximately equal to the maximum aggregate size), and also of the current stress-strain state.

It is demonstrated that the nonlocal material model parameters can be approximately correlated to the given macroscopic concrete properties such as the tensile strength, fracture energy and maximum aggregate size. It is pointed out how these input parameters can be used in fracture analysis of various problems with no need for their calibration according to the problem type. The same values can be used for a broad range of problems studied (including notched fracture specimens as well as shear failure of beams or anchor pullout). Together with a realistic nonlinear triaxial material model for concrete, the new approach is thus able to predict complicated failure modes automatically and realistically.

In the finite element implementation, the nonlocal inelastic stress increments are calculated from the known tensile local stress-strain curve using the superposition principle and the Gauss-Seidel iterative procedure. This solution concept is independent of the nonlinear triaxial constitutive model, which is local. In principle, any model for strain softening damage may be used, although so far broad experience exists only with the microplane constitutive model.

The results of analysis with the present nonlocal model are shown to be mesh insensitive. The new nonlocal model is shown to correctly capture the size effect of fracture and damage mechanics, in approximate agreement with the size effect law (Fig. 1). Although microscopically the damage is considered to be tensile, caused strictly by Mode I microcracks, the macroscopic nonlocal model can also describe complex shear dominated mixed mode types of failure, such as the diagonal shear failure of beams or the pullout failure of headed studs (Fig. 2). The model achieves this for the same values of material parameters. In modeling the shear fracture, the direction of propagation of the damage band is, of course, inclined with respect to the orientation of the microcracks.

a) b)

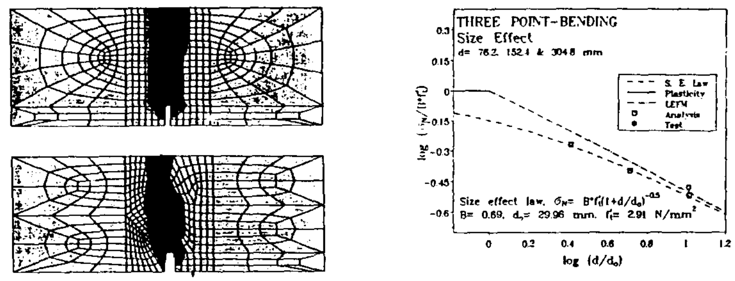

Fig.1 Normal and distorted meshes for 3PB fracture specimens and size effect obtained, compared with test data of Bažant et al (1987) and size effect law.

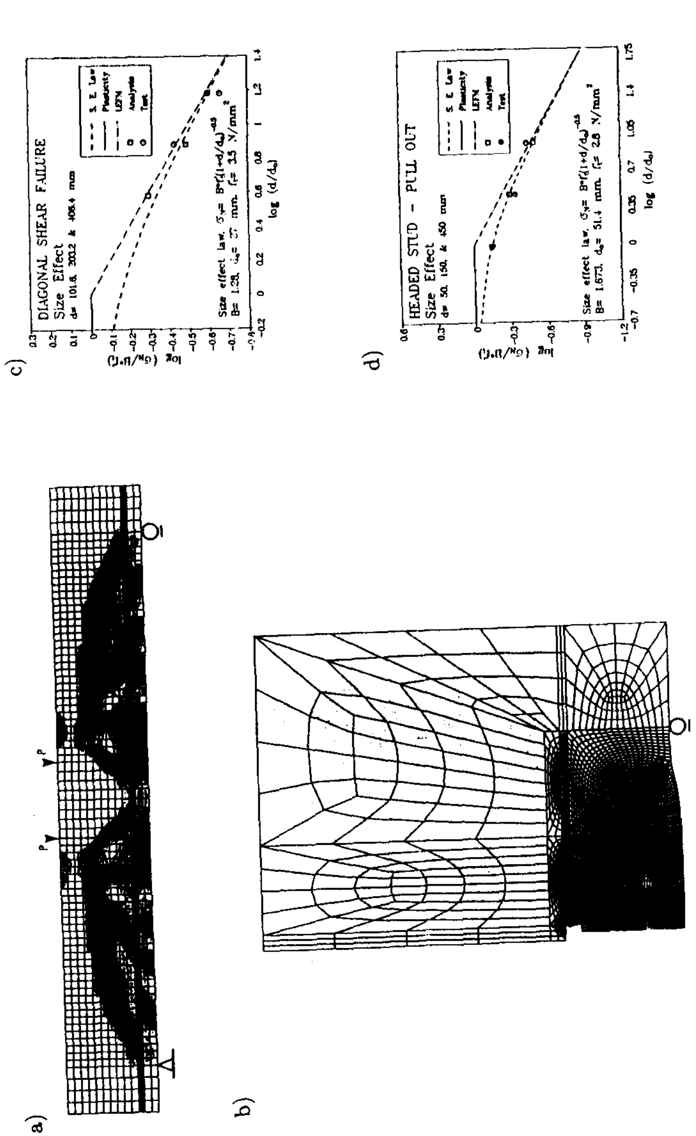

Fig. 2 Meshes for analysis of diagonal shear failure of longitudinally reinforced beam, pullout of headed stud and size effect obtained, compared with test results and size effect law.

Amalgamation of Nonlocality with New Microplane Model

Finally, the conference presentation summarizes a recent improvement of the microplane model for concrete — a constitutive model in which the nonlinear triaxial behavior is characterized by relations between the stress and strain components on microplanes of various orientation within the material, under the constraint that the strains on the microplane are the projections of the macroscopic stress tensor. The improvement is achieved by a new concept: the stress-strain boundaries which can never be exceeded. The advantage of this new concept is that various boundaries and the elastic behavior can be defined as functions of different variables (different strain components). While for compression the stress-strain boundaries must be defined separately for volumetric and deviatoric components, for tension the boundary must be defined in terms of the total normal strains on the microplanes. This is necessary in order to achieve a realistic triaxial response at large tensile strains. A smooth transition from the elastic behavior to the boundary curve is also formulated. The model is simpler than the previous microplane model, and the major advantage is that the model is fully explicit, that is, the stress can be explicitly evaluated from the given strains. The new microplane model has been extensively calibrated and verified by comparisons with test data from the literature. A new approximate method for the delocalization of test data, that is, their decontamination with respect to localization of strain softening damage during the test and to size effect, has been formulated.

Overall, the new nonlocal model based on crack interactions, coupled with the microplane model utilizing the new concept of stress-strain boundaries, represents a rather effective approach to the analysis of brittle failures of concrete structures. It captures correctly localizations of damage as well as the size effect.

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