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MODELLING OF REINFORCED CONCRETE BY THE NONLOCAL MICROPLANE MODEL

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ABSTRACT.- The paper reviews some recent results of nonlocal finite element analysis for concrete structures using the general microplane model. The new nonlocal approach based on microcrack interactions is described. It is demonstrated that in the continuum finite element fracture analysis the microplane model together with the new nonlocal concept does not exhibit mesh sensitivity with respect of shape (orientation) and size. An example of three-dimensional analysis for fastening elements embedded in a reinforced concrete structure is shown. The numerical results are compared with experimental evidence and reasonable good agreement is demonstrated.

1 INTRODUCTION

Currently, in computational fracture mechanics two different groups of material models for strain softening damage exists: (1) Continuum macroscopical models combined with basic fracture mechanics principles (2) Microscopical material models, such as random particle models or micro-finite element models, in which the material structure is modeled.

Principally, the second group of models should predict the material behavior automatically, however they are still extremely computer time demanding and can not be used in structural analysis. Therefore, the macroscopical material models must be used.

The main difficulty in macroscopical modeling of quasibrittle materials such as concrete is due to the fact that the macroscopical models must correctly interpret the microscopical behavior of the materials. Presently, in smeared or discrete type of analysis, often are in use: (1) Classical plasticity models with degradating yield surfaces, (2) Damage models, (3) Single-crack models in form of a fixed or rotating crack approach, (4) Multi-cracking models and (5) Microplane models. The basic requirement for a smeared crack finite element analysis of concrete structures is that the analysis must not exhibit mesh sensitivities. However, when using most of the current finite element codes one should distinguish two types of mesh sensitivities: (1) Mesh sensitivities with respect of the shape (orientation) of the finite elements and (2) Mesh sensitivities with respect of the size of the elements.

Assuming that the finite element mesh is fine enough in the fracture process zone there is no reason for shape mesh sensitivity if in the continuum finite element analysis a continuum material model is used. Beside continuum material models, such as plasticity models with degradating yield surfaces, presently are very popular single or multicrack models (Rots, 1988). Using the latter types of material models one can observe large shape mesh sensitivity due to discontinuities in the material model, as demonstrated by Petrangeli and Ožbolt (1992). As a consequence, in order to fulfill the continuum requirements in the finite element analysis, stress locking occurs. In fact, these types of material models are generally not applicable to a smeared crack analysis without continuous remeshing, except if the crack pattern is known in advance.

To avoid the problems of mesh size sensitivity in the continuum fracture finite element analysis, localization of damage into a zero volume must be avoid. To do this, there are basically two approaches: (1) crack band approach and (2) nonlocal approaches. The crack band approach, introduced by Bažant and Oh (1983), is simple but not general. The more general approach is the nonlocal concept. According to the nonlocal concept, the stress at a point depends not only on the strain at the same point but also on the strain field in a certain neighborhood of that point (Kröner, 1968; Eringen and Edelen, 1972, de Borst, 1991). Recently it has been demonstrated that the nonlocality in the fracture process zone has a physical meaning of microcrack interactions (Bažant, 1991). As a result, a new nonlocal approach is developed that is based on the interaction of growing microcracks.

In the present paper it is shown that the microplane model together with the new nonlocal crack interactions approach is able to predict failure of concrete fracture correctly. It is demonstrated that the results do not exhibit mesh sensitivity i.e. no remeshing is required. Some results of complex three-dimensional fracture studies state are presented and compared with test results.

2 GENERAL MICROPLANE MODEL FOR CONCRETE

The microplane models were initiated by G.I.Taylor (1938), who suggested the principle for the modeling of plasticity. Recently (Bažant and Prat, 1988) this approach was extended to include strain softening of concrete in recognition of the fact that the approach is not limited to plastic slip but can equally well describe cracking and strain softening damage.

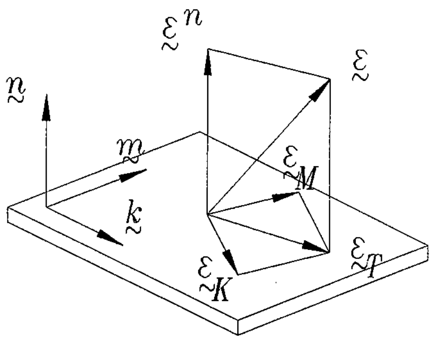


Fig. 1 Microplane strain components

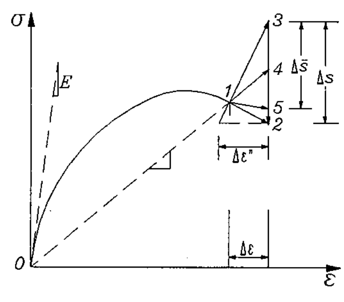


Fig. 2 Nonlocal stress increment

In the microplane model, the material properties are characterized separately on planes of various orientations within the material, called microplane (see Fig. 1), on which there are only a few stress and strain components and no tensorial invariance requirements need to be observed. The tensorial invariance restrictions are satisfied automatically since the microplanes to some extent directly simulate the response on various weak planes in the material (interparticle contact planes, interfaces, planes of microcracks, etc.). The constitutive properties are entirely characterized by a relation between the stress and strain components on each microplane, both normal and shear directions (see Fig. 1). The strain components on the microplane are assumed to be the projections of the macroscopic continuum strain tensor what is known as a kinematic constraint approach. However, it must be pointed out that, as a consequence of the kinematic constraint, at large tensile deformations in one direction the volume dilatancy is too large. In that respect the model will be in future improved i.e. discontinuities in the material will be taken into account more realistically.

The macroscopic stress tensor is obtained by integrating the stresses from all the microplanes according to the virtual work principle. Note that the simplicity of the model is due to the fact that only uniaxial stress-strain laws for each microplane component is required and the macroscopical answer is coming automatically out. Initially (Bažant and Prat, 1988) these stress-strain microplane laws were introduced such that it was possible to represent only loading and first unloading. To model unloading, reloading and cyclic loading in general, and do so for arbitrary triaxial stress states, more complex rules on the microplane levels, including rate sensitivity, have been recently introduced (Ožbolt and Bažant, 1992).

3 NONLOCALITY DUE TO THE MICROCRACK INTERACTIONS

As already mentioned above, in order to prevent localization of damage into a zero volume and to prevent spurious mesh sensitivity in the continuum fracture finite element analysis some, so-called, strain localization limiter must be introduced. Here, the new nonlocal approach that is based on the microcrack interactions is used.

In quasibrittle materials such as concrete during the softening process a number of microcracks are developing that interacts up to the final failure, when one or more dominant macrocracks are formed. The source of the nonlocality in such a microcracked continuum is due to the fact that the opening of the microcrack at a certain place (μ) can stabilize or destabilize the microcrack development in neighborhood points (ν). Using the principle of superposition (Kachanov, 1985) each loading step can be decomposed in two substeps: (1) In the first substep for strain increase $\Delta\epsilon$ (see Fig. 2) one can imagine that all the cracks are temporarily closed and the stress increase $\Delta\boldsymbol{\sigma}$ is due to the elastic stress increment i.e. the cracks are able to transfer the stresses. (2) In the second substep the stresses over the microcrack surfaces are relaxed (unfrozen). This is equivalent to applying a pressure on the crack surface. If during the load step no crack grows, unfreezing (substep 2) would result in a stress drop $\Delta \boldsymbol{S}_{34}$ (see Fig. 2). However if the cracks grow, a larger stress drop $\Delta \boldsymbol{S}_{32}$ takes place. This stress drop is defined by the local stress-strain law.

The above concept is implemented into a finite element code (Ožbolt, 1992). Qualitatively the main advantage of the new approach is that the nonlocality has a physical meaning of microcrack interactions and it is not only a mathematical device that prevents localization of damage into a zero volume.

4 NUMERICAL STUDIES

In order to demonstrate the power of the nonlocal microplane model, results of a few numerical case studies are demonstrated here. First it is shown that the present model does not exhibit mesh sensitivity and in a subsequent study the capability of the model to realistic predict the concrete behaviour in a complicated three-dimensional stress-strain situation is demonstrated.

4.1 Mesh sensitivity study

As already mentioned above, an important requirement for the continuum smeared crack analysis is that the results of the analysis must be independent with respect to the mesh shape (orientation) and mesh size. To check this for the nonlocal microplane model a simple specimen loaded in tension is analyzed under the assumption of plane stress state. In Fig. 3 four different meshes are plotted. The specimen (see Fig. 4) was loaded by prescribing horizontal displacements. To prevent vertical displacements of the edges these were fixed in vertical direction.

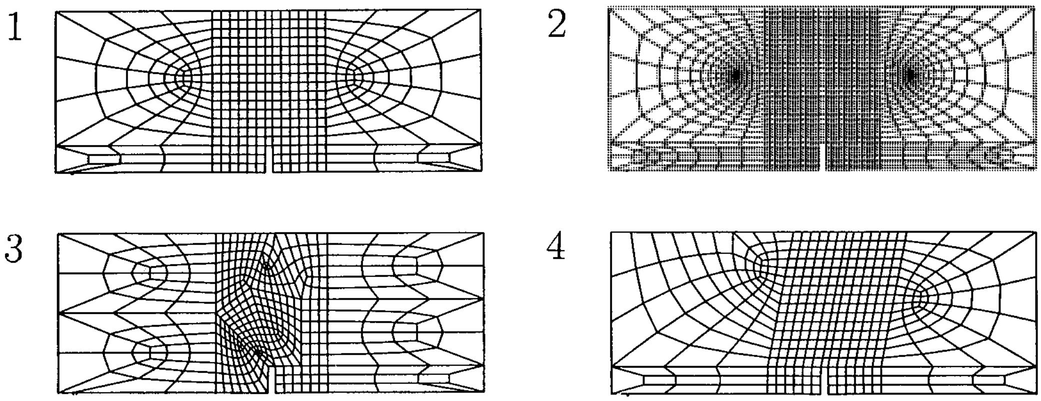
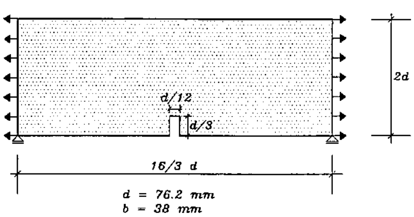


Fig. 3 Four different meshes used in the analysis

In Fig. 5 calculated load-displacement curves for all meshes are plotted. The figure shows that independent of the used mesh size and shape there is almost no difference in the load-displacement curves. This proves that the analysis is mesh (size and shape) insensitive.



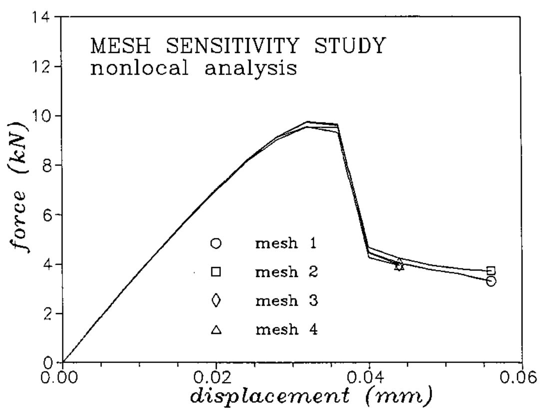


Fig. 4 Specimen geometry

Fig. 5 Load-displacement curves for four meshes

4.2 Pull-out from cracked concrete

In order to check the capability of the model in a 3D fracture analysis, the influence of the crack width on the concrete cone pull-out load have been studied. The analysis is carried out for a reinforced concrete plate with dimensions 1000 x 1040 x 300 mm (Fig. 6a) (Ožbolt, 1991). In the center of the specimen a single anchor is embedded with an embedment depth

h_v= 120 mm. The crack width in the specimen is controlled through 12 reinforcing bars. The specimen is vertically supported around the bottom edges as well as around the anchor at a distance $2h_v$.

The loading procedure used in the analysis is the same as in experiments. First tensile stresses are introduced through the reinforcement bars (controlling displacement) to produce a crack of a certain width and in the next step the reinforcement extension is kept fixed and pulling out of the anchor is performed (controlling force). This is repeated for different tension stresses in reinforcing bars i.e. for different crack widths.

Spatial discretization is performed using only 1/4 of the specimen i.e. symmetry is used (Fig. 6b). The microplane material parameters have been calibrated such that the basic macroscopical concrete material properties were the same as in the experiment i.e. Young modulus E = 30000 MPa, Poisson ratio ν= 0.18, tensile strength f_t= 1.8 MPa and compressive strength f_c= 34 MPa. This analysis was carried out using a nonlocal strain approach with the characteristic length chosen such that the concrete fracture energy was approximately G_F=0.1 N/mm.

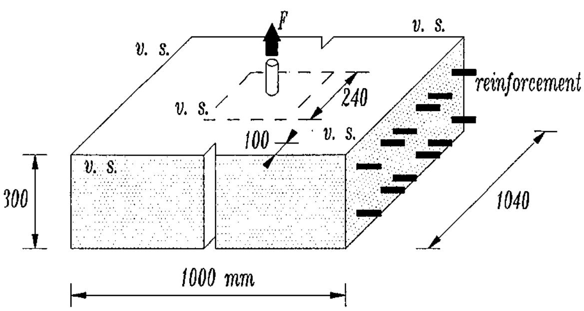


Fig. 6a Geometry of the pull-out specimen

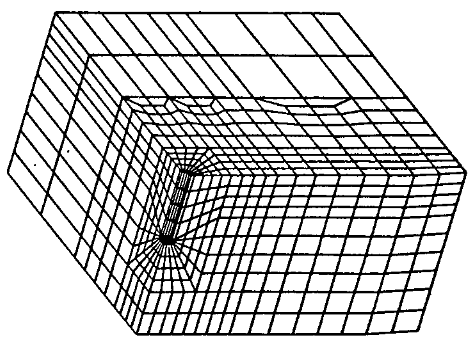


Fig. 6b Finite element mesh

Failure occurs by pulling out a concrete cone. Calculated relation between the crack width and the failure load, related to the concrete cone failure load in uncracked concrete, and results of a number of experiments are shown in Fig. 7. It can be seen that numerical results indicate a good qualitative and quantitative agreement with experimental observations.

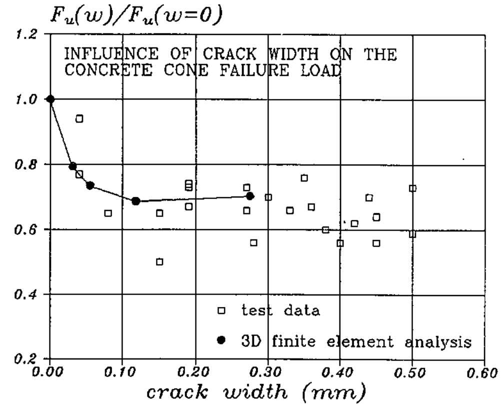


Fig. 7 Relation between crack width and pull-out load

5 CONCLUSIONS

1. Two different types of the mesh sensitivities in continuum smeared crack finite element analysis have to be distinguished: (1) Sensitivity with respect of the shape (orientation) of the finite element mesh and (2) Sensitivity with respect of the mesh size.
2. It is demonstrated that using the microplane material model, no shape mesh sensitivity is observed since there are no discontinuities in the material model in the softening regime. It is also shown that the new nonlocal microcrack interaction approach prevents localization of damage into a zero volume i.e. the analysis is mesh size insensitive.
3. The presented example indicates that the model is able to predict the concrete behavior in complicated 3D strain states. However, further work is needed to better understand the physical meaning of microcrack interactions and its relation to the macroscopical concrete properties.

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