SIMULATION OF CYCLING BOND-SLIP BEHAVIOR

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ABSTRACT

In the present paper results of a numerical analysis for a deformed steel bar embedded in a concrete cylinder and pulled out by monotonic and cyclic loading are shown and discussed. The analysis is performed by the use of axisymmetric finite elements and an improved 3D general microplane model for concrete. Instead of the classical interface element approach, a more general approach with spatial discretization modeling the ribs of a deformed steel bar is employed. The pull-out failure mechanism is analyzed. Comparison between numerical results and test results indicate good agreement. The present approach is able to correctly predict the monotonic as well as cyclic behavior including friction and degradation of pull-out resistance due to the previous damage.

INTRODUCTION

In several experimental investigations the behavior of deformed bars under cycling excitations has been studied [1]. It has been found, that reversed cycling causes a degradation of the bond resistance and significant pinching. Some explanation for this behavior has been offered. However, the reason of the bond degradation and the development of cracks in the concrete during reversed cycling loading have not been fully understood. In recently published numerical studies of the bond-slip behavior, the analysis is usually carried out by the use of macroscopic bond-slip relations that is implemented in the finite element code employing interface elements (e.g. [2]). However, in order to better understand the mechanism of the bond-slip behavior in monotonic and cyclic loading it is necessary to perform spatial finite element discretization with an exact modeling of the ribs of the deformed steel bar. In the analysis a realistic material model must be used that is able to describe the behavior of concrete in complicated stress-strain states where large compressive, tensile and shear stresses are present in a small volume of the material. Therefore, in the present study a nonlinear finite element analysis of a deformed steel bar embedded in a concrete cylinder and loaded by monotonic and cyclic loading has been performed which fulfils the above requirements.

MATERIAL MODEL AND FINITE ELEMENT ANALYSIS

Material Model

In the present study the general three-dimensional microplane model for concrete is used. In the microplane model the material properties are characterized separately on planes of various orientations within the material, called microplanes, 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. The model and its implementation into a 3D finite element code is described in [3] and [4]. In that version of the microplane model microplane shear stress-strain relations are the same and mutually independent for positive and negative shear deformations. This is sufficient in the case of monotonic loading. However, from the bond cycling experimental evidence [1], it is well known that a loading in one direction causing damage introduces a stiffness and strength degradation in the opposite loading direction. Due to this the microplane shear stress-strain law is here modified in a way that the microplane shear stiffness is multiplied by the damage function:

$$\omega = exp[-1.2(E/E_0)^{1.1}] \tag{1}$$

where E represents accumulated microplane shear energy dissipation and E_0 is a constant representing the area under the monotonic (undamaged) microplane shear stress-strain curve. Eq. 1 has been proposed in [1] and is based on a large number of cyclic bond test data. Except this improvement the basic microplane cyclic rules, in normal and shear directions, are the same as shown in [4].

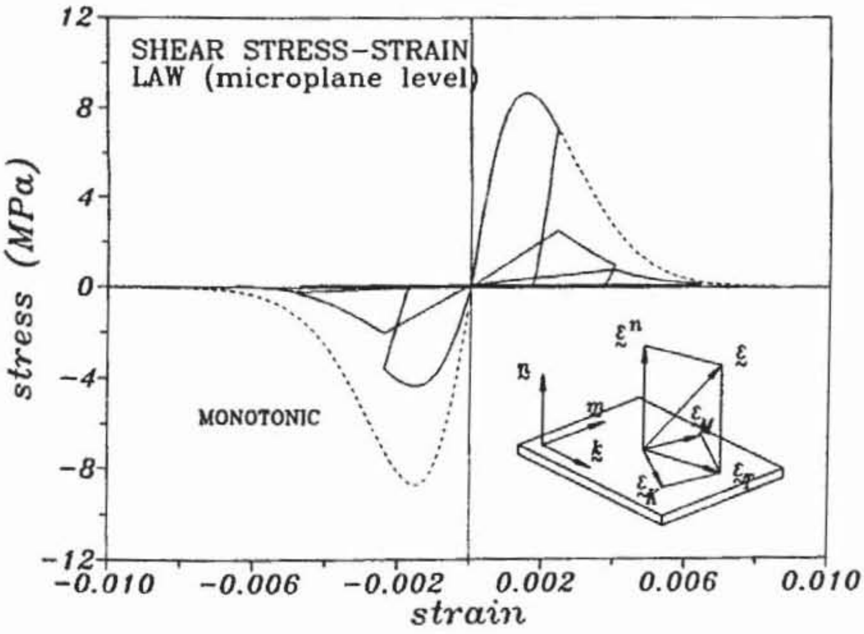

Figure 1. Shear stress-strain law on the microplane level

Using the shear stress-strain law introduced in [4] and the shear damage function (Eq. 1) a typical shear stress-strain relation on the microplane level is plotted in Fig. 1. The macroscopical shear response of the microplane model is shown in Fig. 2 where only one axisymmetric finite element is loaded by displacement control between two (positive and negative) displacement limits. As can be seen from Fig. 2, the shear resistance is decreasing with increasing number of cycles.

Note that according to Fig. 1 the shear strength at large deformations should tend to zero. This corresponds to a shear response on the microplane under the assumption that the normal stress on the microplane is zero. However, generally normal stresses are present and in the microplane model [4] the interaction between shear and normal (compressive) stresses is taken into account, i.e. with increasing normal compressive stresses the shear resistance is increasing.

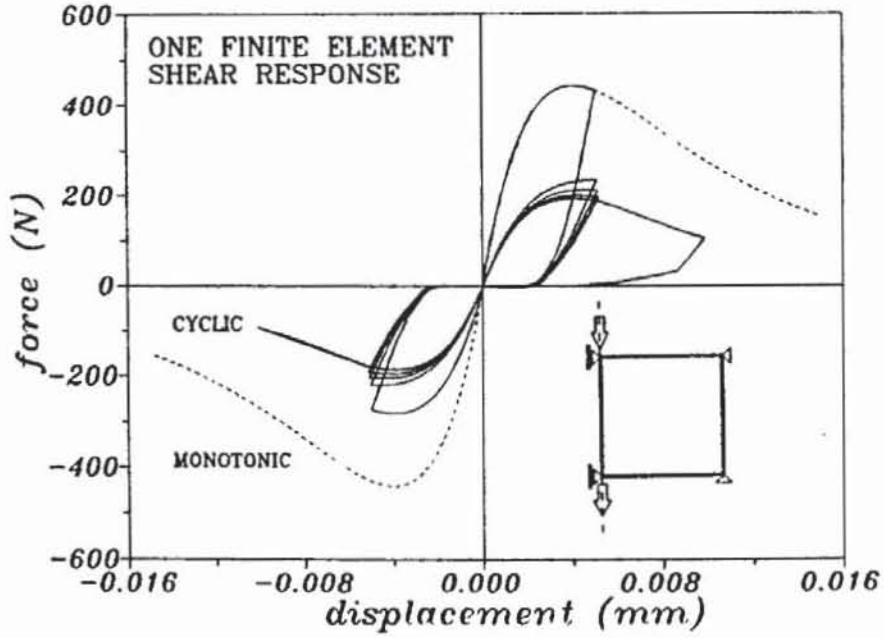

Figure 2. Shear stress-strain law on the level of one finite element

Finite Element Analysis

The geometry of the specimen employed in the present example is based on the geometry of the test specimen that has been used in [4]. The diameter of the concrete cylinder is 200 mm and the length 189 mm. The diameter of the deformed steel bar is d =25.2 mm, the height of the ribs a= 1.7 mm, the rib distance c= 13.4 mm and the embedment length l =5d. In order to avoid vertical splitting, reinforcement has been introduced as lateral confinement. The specimen is designed such that the failure is due to pull-out rather than yielding of the steel bar or splitting of the concrete. For comparison a specimen without confining reinforcement was also analyzed. The geometry (one half) and the axisymmetric finite element mesh are shown in Fig. 3. As can be seen from Fig. 3 the shape of the deformed steel bar is exactly modeled and displacement compatibility between ribs and concrete is assumed. In the analysis axisymmetric four node finite elements with four integration points are used.

The basic material parameters, Young's modulus and Poisson's ratio, are taken as E= 25000 MPa and ν= 0.18. The microplane model material parameters [4] are chosen such that the tensile and compressive concrete strength are f_t= 1.9 MPa and f_c= 28.0 MPa.

The behavior of the steel bar is assumed to be linear elastic. The analysis is based on the local continuum approach.

The specimen is loaded (monotonic and cyclic) by controlling the displacement at the top of the steel bar. The bottom or the upper side of the concrete cylinder are supported as in the test depending on the pull-out direction such that the support reactions are compressive forces. As a consequence the boundary conditions are not fixed during the cyclic analysis. In the analysis the loading type (monotonic and cyclic), the amount of confining reinforcement (none or strong) and the peak values of slip between reversed cycling were varied.

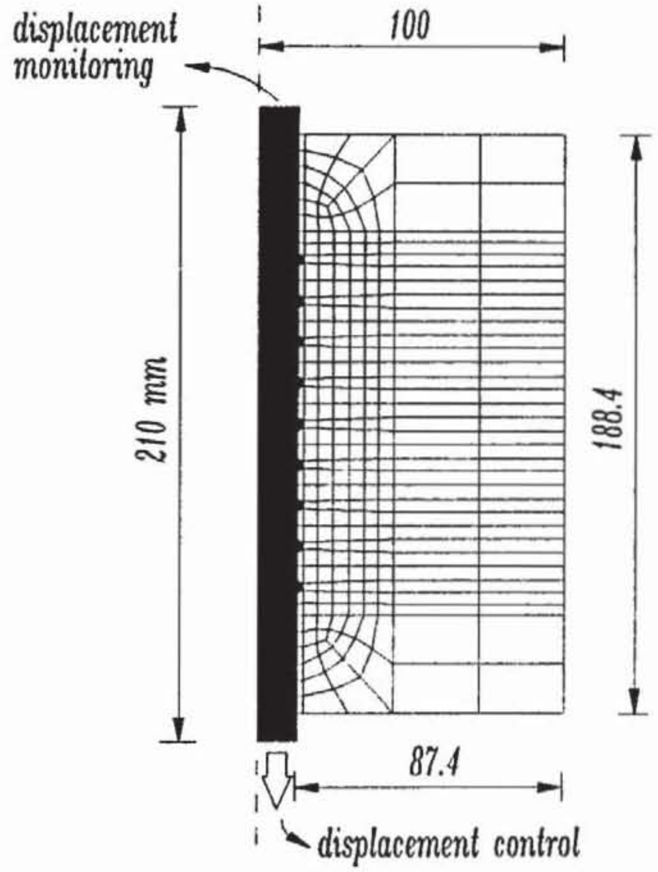

Figure 3. Geometry of the specimen and finite element mesh

RESULTS OF THE ANALYSIS

In Fig. 4 load-displacement curves for monotonic and cycling loading are plotted. The displacement is monitored at the unloaded end of the steel bar. Cyclic loading is performed by controlling the displacement (slip) at one side of the bar between two fixed and equal positive and negative values. The chosen value is slightly larger than the displacement at peak load under monotonic loading.

The shape of the load-displacement curve for monotonic loading as well as the value of the peak load (bond strength $\tau \sim 15$ N/mm^2) is in good agreement with experimental observations [1]. However, the total displacement at peak load is much smaller than measured in tests. There are several reasons for this such as: (a) The problem of an exact modeling of the concrete behavior for a stress-strain state with large volume dilatancy and high axial and lateral compression and shear stresses in a small concrete volume under the ribs, (b) while in the analysis geometrical linearity (small deformations and small displacements) was assumed - in reality large deformations occur and (c) axisymmetric approximation of the problem.

Fig. 4 clearly indicates a decrease of the pull-out capacity as well as significant decrease of the shear stiffness with an increase of the number of cycles. As shown in [1] this is a consequence of accumulated damage. When increasing the slip to large values, the bond resistance is about constant. That is due to the fact that in the material model the interaction between normal and shear stresses, as mentioned above, is introduced on the microplane level. As a consequence, the macroscopical response at large shear deformations yields a residual force that represents friction. In the present example the friction is activated since strong lateral confinement prevents volume dilatancy in radial direction and causes compression stresses in the damage zone. Fig. 4 shows that the frictional resistance is decreased by cycling loading. Except for the magnitude of the slip, the calculated cyclic bond behavior agrees rather well with the behavior found in experiments [1].

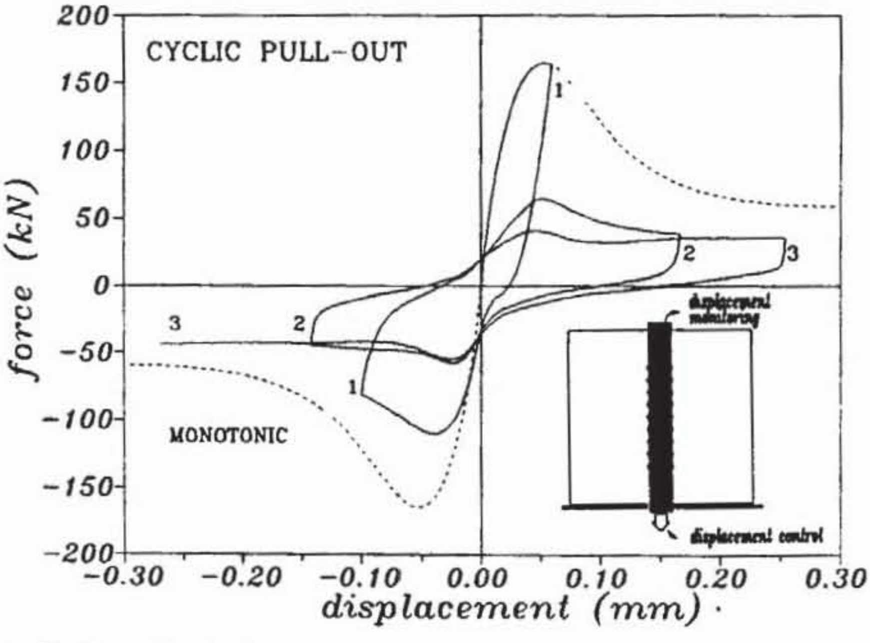

Figure 4. Pull-out load-slip relationship obtained in the finite element analysis

In order to understand the failure mechanism the stress-strain states under the bar ribs are analyzed at different load stages. Here, only a brief description of the mechanism is given.

At monotonic loading the nonlinearity starts at approx. 30% of the peak load caused by bond cracks that initiate at the ribs and propagate at an angle of approx. 65^0 measured from the bar axis. The next nonlinearity appears at approx. 60% of the peak load caused by splitting cracks which activate the reinforcement. As a consequence of the lateral confinement a further load increase is possible and significant compression stresses are developed under the ribs in axial and radial direction causing large displacements and a significant non-linear behavior. Failure is caused by shear cracks in the concrete under the ribs. Peak load, displacement at peak load as well as descending part of the load-displacement curve, for the same specimen geometry, strongly depend on the lateral confinement.

In the case of reversed cycling loading basically the same mechanism is active except that the pull-out capacity in the reverced direction is reduced due to accumulated damage that was introduced in the concrete volume under the ribs during loading in the first direction. If cyclic loading is done between slips smaller than the peak value under monotonic loading, no significant damage is introduced in the concrete and the bond resistance is not much reduced by a few cycles. However, unloading from about peak load or after the peak has been passed causes a larger drop of the bond resistance in the reversed direction since a relatively large volume of the concrete under the ribs has been damaged. In this case only a few cycles cause complete damage reducing the pull-out resistance to friction only.

CONCLUSIONS

1. Comparison between experimental results and the results of the numerical analysis indicate that the present approach, based on the microplane model for concrete and the exact modeling of the shape of deformed reinforcing bars can in principle predict the behavior and the failure mechanism under monotonic and reversed cyclic loading in spite of the complicated stress-strain situations in the concrete close to the ribs (high compression and large volume dilatancy, large tensile and shear deformations). However, the computed slip values at peak load are much smaller than obtained in tests.

2. Bond failure in confined concrete specimen is due to the shear failure of the concrete under the ribs. In monotonic loading most of the nonlinearity up to peak load is due to concrete compression and shear deformations under the bar ribs. Reversed cyclic loading significantly decreases the shear capacity if first unloading is done from a bond stress that is larger than about 60 to 80 % of the monotonic bond strength or from the softening range. The numerical analysis indicates that the pull-out response strongly depends on the lateral confinement.

3. Further 3D finite element analyses are needed in order to investigate the influence of lateral confinement as well as the influence of the loading history and different geometrical shapes on the bond failure mechanism.

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