NUMERICAL SIMULATION OF CYCLING BOND-SLIP BEHAVIOR

Joško Ožbolt and Rolf Eligehausen

Institut für Werkstoffe im Bauwesen,
Stuttgart University, Germany.

ABSTRACT

In the present paper the pull-out of deformed steel bar embedded in a concrete cylinder and pulled out by monotonic and cyclic loading is analyzed and discussed. The analysis is carried out by the use of axisymmetric finite elements and general microplane model for concrete. Current version of the model was not able to predict damage in shear due to cycling loading correctly. Therefore, the model is further improved and extended in a more general form. In the present numerical case study, instead of the classical interface element approach, a more general approach is used in which the geometry of the ribs of the deformed steel bar are exactly modeled. In the present numerical case study, the pull-out failure mechanism is analyzed and compared with experimental observations. The comparison indicate qualitatively good agreement. Predicted failure load is in good agreement with experimental results, however, calculated displacement are much smaller than measured in tests. The present approach is able to correctly predict the monotonic as well as cyclic behavior including friction and degradation of pull-out resistance caused by previous damage.

Key-words: *Cycling, Bond-slip, Microplane model, Finite elements.*

1. INTRODUCTION

In a number of experimental investigations behavior of deformed bars under cycling excitations has been studied /1,2/. It has been observed, that reversed cycling causes a degradation of bond resistance and significant pinching. Some explanation for this behavior has been offered. However, the reason for the bond degradation and development of cracks in concrete during reversed cycling loading have not been fully understood. In recently published numerical studies of the bond-slip behavior, numerical analysis is usually carried out using the interface bond-slip element that is implemented in the finite element code (e.g. /3/). However, in order to better understand the mechanism of the bond-slip behavior, in monotonic as well as cyclic loading, it is necessary to perform spatial finite element discretization with an exact modeling of the ribs of the deformed steel bar. In such analysis an 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.

Recently, it has been shown that the general microplane model for concrete is able to prescribe concrete behavior in a number of complicated stress-strain situations correctly. 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 using microplane model.

2. MATERIAL MODEL FOR CONCRETE

As already mentioned above, in order to be able to correctly predict the behavior of concrete in complicated situations such as monotonic and cyclic pull-out of deformed bar, sophisticated material model must be employed. Therefore, in the present study the general microplane model for concrete is employed.

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 in more details described in /4/ and /5/. In that version of the microplane model, microplane shear stress-strain relations were the same and mutually independent for positive and negative shear deformations. Generally, this is probably sufficient for any type of monotonic loading as well as for cycling loading, if tension dominates. However, from bond cycling experimental evidence /1,2/ where shear plays an important role, it is known that loading in one direction causing damage introduces a stiffness and strength degradation in the opposite loading direction. Due to this, the shear microplane stress-strain component form /5/ is modified such that the microplane shear stiffness is multiplied by an additional damage function which takes into account the damage accumulated in concrete that is due to cyclic load history:

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

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. All other microplane stress-strain relations i.e. volumetric and deviatoric components are taken the same as given in /5/.

Based on the shear stress-strain law introduced in /5/ and the shear damage function (Eq. 1) a typical shear stress-strain relation on the microplane level is plotted in Fig. 1.

This microplane behavior seems to be in good agreement with the macroscopical cyclic pull-out behavior. In order to check the model on the macroscopical level, one axisymmetric finite element is loaded in shear by displacement control between two (positive and negative) displacement limits. In Fig. 2 the macroscopical shear response is plotted and as can be seen the shear stiffens and strength is decreasing with increasing number of load cycles, what is qualitatively in good agreement with experimental observations.

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 /5/ the interaction between shear and normal (compressive) stresses are taken into account, i.e. with increasing normal compressive stresses the shear resistance is also increasing.

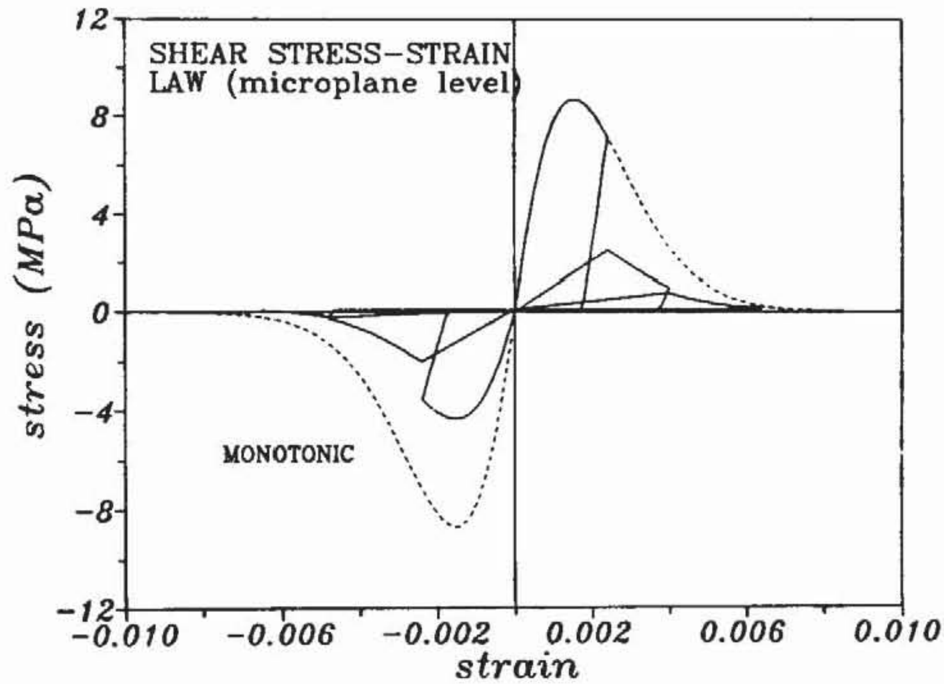

Figure 1. Shear stress-strain law on the microplane level

3. NUMERICAL CASE STUDY

3.1 Geometry, material properties and finite element mesh

In the present numerical case study the deformed steel bar was pulled out from the concrete cylinder by monotonic and cyclic loading. The geometry of the specimen used in the analysis was approximately the same as in experimental study /1/. 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 in tangential direction has been introduced as a 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. The geometry of the specimen and 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. The displacement compatibility between ribs and concrete is assumed. In the analysis axisymmetric four node finite elements with four integration points and linear displacement field are used.

The basic material parameters, Young's modulus and Poisson's ratio, are taken as $E=25000$ MPa and $\nu=0.18$. The microplane model material parameters /5/ 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 monotonic and cyclic pull-out load are in the specimen introduced by controlling displacement at one side of the deformed steel bar. The displacements are monitored on the another side of the bar. The bottom or the upper face of the concrete cylinder is supported the same as in the test, depending on the pull-out load direction, such that the support reactions are always compressive forces. Therefore, the boundary conditions are not fixed during the cyclic analysis i.e. by loading in one direction the boundary conditions in the load direction are fixed. At unloading and reverse loading these boundary conditions are released and displacement in the another side of the cylinder specimen are fixed. In the present numerical case study only results of monotonic and cyclic loading are present and no other parameter studies are present.

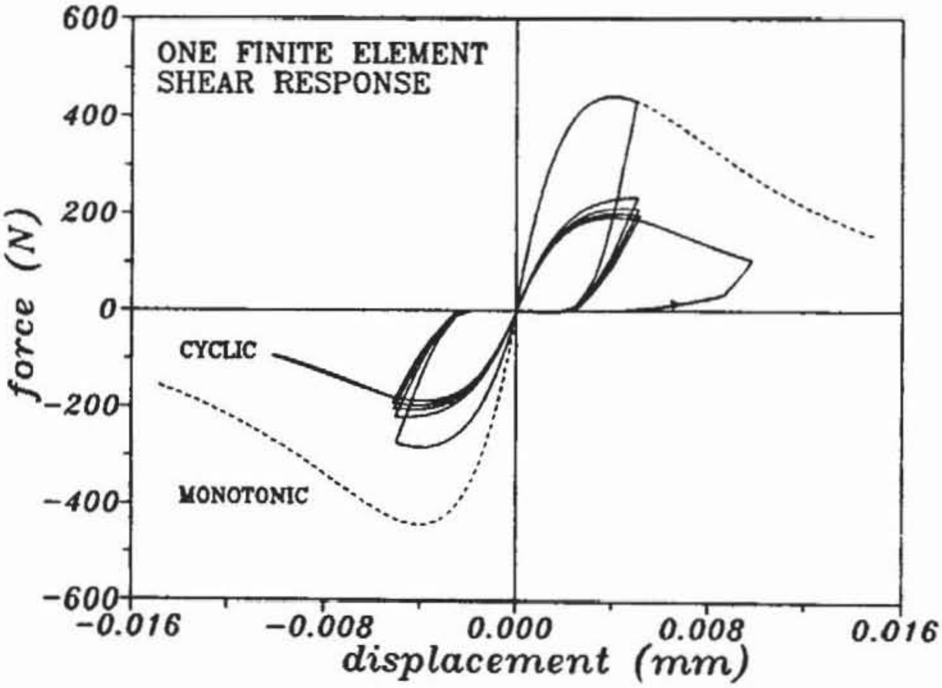

Figure 2. Shear stress-strain law on the level of one finite element

3.2 Results of the analysis

Calculated load-displacement curves for both, monotonic and cycling load are plotted in Fig. 4. The load is obtained by controlling displacement, at one side of the steel bar, between two fixed and equal positive and negative values. The chosen displacement value is slightly larger than that at peak load under monotonic loading conditions. The displacement plotted in Fig. 4 is monitored at the unloaded end of the steel bar.

The comparison between load-displacement curves measured in experiments (/1/) and calculated load-displacement curves, for monotonic as well as cycling loading, demonstrate qualitatively rather good agreement. The calculated peak stress (bond strength $\tau \sim 15$ N/mm^2) is in good agreement with experimentally obtained values /1/. However, the total displacement at peak load is much smaller than measured in tests. There are probably 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) In the analysis geometrical linearity (small deformations and small displacements) was assumed – in reality large deformations occur and (c) An axisymmetric approximation of the problem.

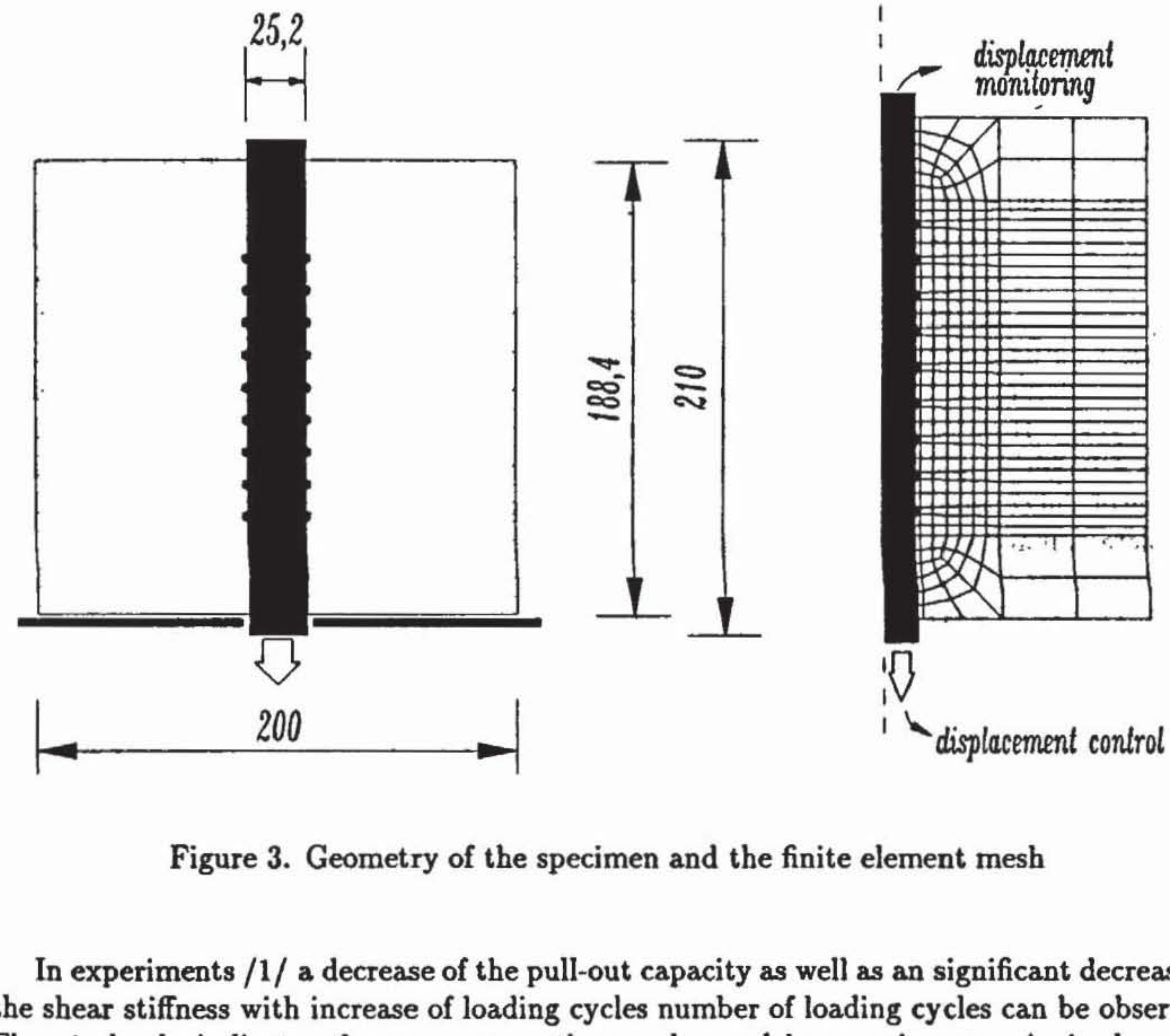

Figure 3. Geometry of the specimen and the finite element mesh

In experiments /1/ a decrease of the pull-out capacity as well as an significant decrease of the shear stiffness with increase of loading cycles number of loading cycles can be observed. Fig. 4 clearly indicates the same properties as observed in experiments. As is shown in /1/ this is a consequence of a damage that is accumulated during the cycling load history. If the displacement (slip) tends to large value, the bond resistance yields to the constant value. This is due to the fact that in the microplane material model the interaction between normal and shear stresses, as mentioned above, is taken into account. As a consequence, the macroscopical response at large shear deformations yields to 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 high compression stresses in the damage zone. Comparison between load-displacement curves for monotonic and cyclic loading (see Fig. 4) shows that the frictional resistance is decreased at cycling loading. The calculated cyclic bond behavior agrees rather well with the behavior found in experiments /1/, except for the magnitude of the slip.

In order to better 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.

Analysis indicates that at monotonic loading the nonlinearity starts at approx. 30% of 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. At approx. 60% of the peak load much higher nonlinearity appears and is caused by splitting cracks which activate the reinforcement. As a consequence of the lateral confinement a further load increase is possible, however, 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 concrete under the ribs. Some parameters studies indicate that 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.

During the reversed cycling loading basically the same mechanism is active except that the pull-out capacity in the reversed direction is reduced due to accumulated damage that was introduced in the concrete volume under the ribs during previous load history. If cyclic loading is performed between slips smaller than the peak value under monotonic loading, no significant damage is introduced in 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 and reduces the pull-out resistance to friction only.

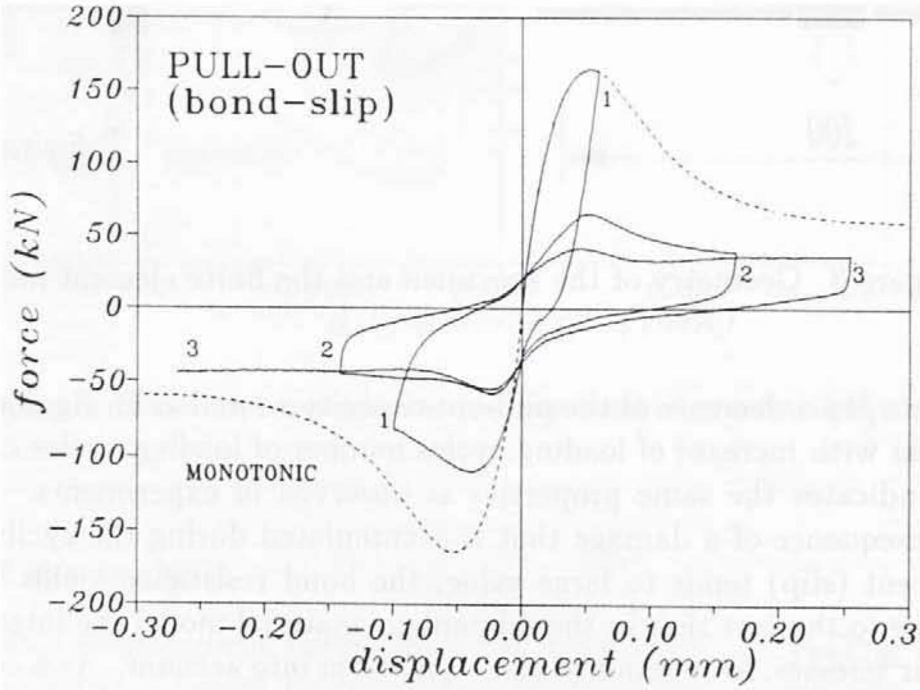

Figure 4. Pull-out load-slip relationship obtained in the finite element analysis

4. CONCLUSIONS

1. 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), comparison between experimental results and the results of the numerical analysis indicate that the present approach, based on the microplane model for concrete and exact modeling of the shape of deformed reinforcing bars, can in principle predict behavior and the failure mechanism under monotonic and reversed cyclic loading. However, the computed slip values at peak load are much smaller than measured in experiments.

2. Analysis indicates that the 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 performed from a bond stress that is larger than about 60 to 80 % of the monotonic bond strength or from the softening range. Some parameter studies, not present in the paper, indicate 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.

5. REFERENCES

1. Eligehausen, R., Popov, E.P. and Bertero, V.V.: Local bond stress-slip relationships of deformed bars under generalized excitations. Report No. UCB/EERC-83/23, Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, California, October, 1983.

2. Balázs, G.L.: Fatigue of bond, ACI Materials Journal, V. 88, No. 6, 1991, pp. 620-629.

3. Rots, J.G.: Computational modeling of concrete fracture. Dissertation, Civil Engineering Department of Delft University of Technology, September, 1988.

4. Bažant, Z.P., and Ožbolt, J.: Nonlocal microplane model for fracture, damage, and size effect in structures, Journal of Engineering Mechanics, ASCE, 116(11), 1990, pp. 2485-2504.

5. Ožbolt, J. and Bažant, Z.P.: General microplane model for concrete, Journal of Engineering Mechanics, ASCE, 1992, in press.