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Three-dimensional modeling of anchoring systems in concrete

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ABSTRACT:

Numerical simulation is a valuable tool for getting inside information on the mechanism occurring in fastening technology. The additional knowledge and understanding of the anchoring behavior, like e.g. the load transfer and the damaging state in the base material, is the basis for innovative product development. Reliable simulation results require a sophisticated material modeling, especially for concrete material which is widely encountered as base material for anchoring systems. Concrete shows completely different behavior underlying different loading conditions, and it often determines the load carrying capacity of the structure and the corresponding failure mechanism.
The basic knowledge of the working principles of anchors is investigated first and than utilized for a case study of an undercut anchor. Here the behavior of the anchor in cracked concrete is investigated and compared with the application in undamaged base material.

1 INTRODUCTION

Numerical simulation, especially the finite element technology is getting more and more into practice also in the field of fastening systems. Numerical simulation serves for additional knowledge and general understanding of the occurring mechanism as well as for the speed-up of the development process for new products.

The development of new, innovative anchors can only be successful with an in-depth understanding of the physical phenomena involved in the complete process of setting and pull-out of the anchor. In order to satisfy these requirements the Hilti AG develop own simulation tools for the specific applications occurring within its product range. Many of these products are used in combination with concrete material. Hence a suitable and reliable material model must be utilized to realistically describe the concrete behaviour.

In the field of fastening technology the numerical simulation is a well introduced tool within the development process (Nienstedt & Dietrich (1995), Nienstedt, Mattner & Wiesbaum (1999)). This was only possible with the corresponding numerical robustness of the program and especially the material model.

2 ANCHORING IN CONCRETE

Fasteners in concrete can generally be divided according to the mechanism of transferring the force into the base material. These are friction, keying or bonding (s. Figure 1).

The application of loading force on the anchoring system is limited by a maximum force which is determined by a failure mechanism, like e.g. concrete cone break out or steel failure. For the approval pro-

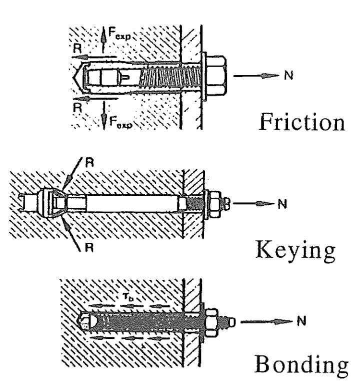

Figure 1. Working principles of anchoring systems, Hilti AG (1993)

cess, especially for safety relevant anchors special application conditions become of increasing interest. These are for example applications close to the edge of the base material or fastenings in cracked concrete. These fastenings are illustrated in Figure 2.

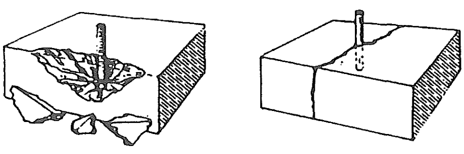

Figure 2. Fastening conditions (close to an edge, cracked concrete), Hilti AG (1993)

3 MATERIAL MODELLING

The material modelling of the concrete base material uses the well known smeared crack approach (Hillerborg, Modeer & Petersson (1976)) for concrete under tension loading. The utilization of the rotating smeared crack approach is integrated in an uniaxial stress-/strain environment. Figure 3 shows a schematic sketch of the stress-strain law for uniaxial loading conditions.

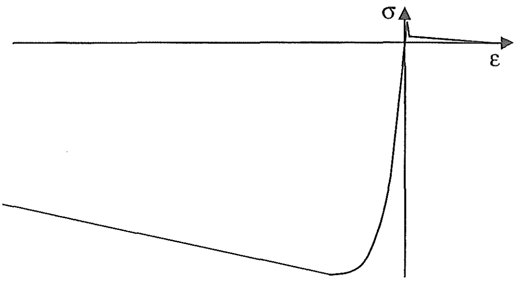

Figure 3. Constitutive law for uniaxial loading conditions

The complex loading states in the base material, especially in the area where the load transfer from the fastening element into the concrete takes place, require the additional consideration of the multiaxiality of the stress state. This is done by a direct interaction between the stress state and the stress-strain relationship in the corresponding integration point.

This constitutive model has been proven for several applications to be very robust and easy to handle for the development engineer in his daily business. Comparisons between simulated results and the corresponding experiments show very good agreement within the scatter of the experiments.

4 NUMERICAL SIMULATION

The numerical simulation presented here first concentrates on the differences of the working principles mentioned before. The working principles are investigated with typical representatives for each. These simulations are performed utilizing axisymmetric simulations.

A more detailed view is taken on the Hilti HDA undercut anchor. One feature of this anchor is the applicability in cracked concrete. The undercut mechanism ensures the load carrying capacity of the anchor also in case it is set directly in a crack. Applications with these special boundary conditions lead to the need of 3D-simulations.

4.1 *Working principles*

The characteristics of the working principles will be illustrated with a typical representative for each. These are a Hilti HSL heavy duty anchor (friction principle), a Hilti HVZ adhesive anchor (bonding principle) and a Hilti HDA undercut anchor (keying principle).

4.1.1 *Stress distributions*

The main difference of the working principles, the way of transferring the load into the base material, can be illustrated by displaying the stress distributions. Figures 4 and 5 show the distribution of the minimum principle stresses in the base material for the anchor set with the recommended setting conditions. The adhesive anchor shows a large area of uniformly distributed stresses along the borehole (see Figure 4). This fact explains the suitability of these anchors for applications close to an edge.

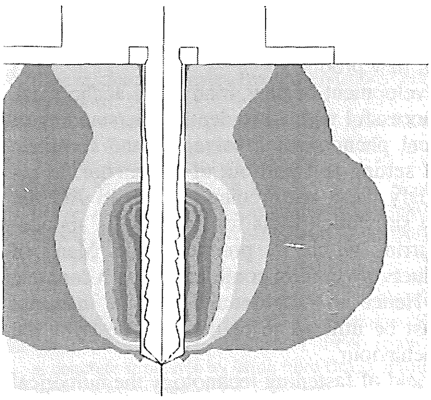

Figure 4. Distribution of the minimum principle stresses for an adhesive anchor

The friction principle and the keying principle show a locally concentrated load transfer in the depth of the borehole (see Figure 5). Hence, the magnitude of the stresses is much larger than in the case of the adhesive anchor.

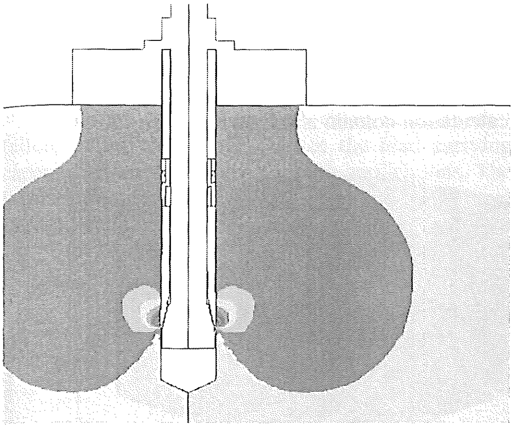

Figure 5. Distribution of the minimum principle stress for a friction anchor

Figure 6 illustrates the distribution of the maximum principal stresses for the friction anchor at a load value above the recommended load during the pull-out process.

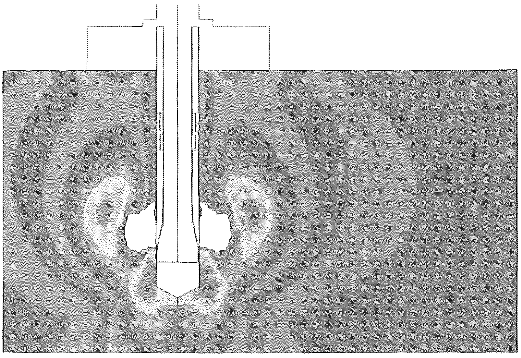

Figure 6. Distribution of the maximum principal stresses for a friction anchor

A comparison with the undercut anchor shows an advantage of the undercut principle (see Figure 7). The stress distribution in this figure is plotted for a comparable loading state.

The level of the stresses above the white zone of compressive stresses shows much higher stress values for the friction based anchor. The extension of the zone with comparable high stresses in radial direction is much larger for the friction based anchor. To achieve a large pull-out force requires a corresponding - due to the frictional principle - radial force.

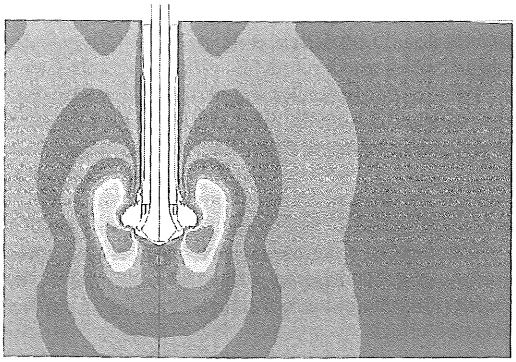

Figure 7. Distribution of the maximum principle stresses for an undercut anchor

4.1.2 *Failure mechanisms*

Different kinds of failure mechanisms are known and have to be simulated. The simulation of the frictional anchor show a typical concrete cone failure (see Figure 8)

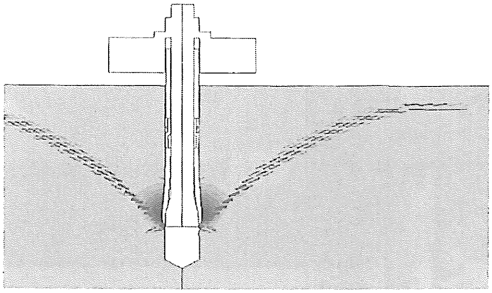

Figure 8. Concrete cone failure

A mixed failure mechanism can be observed in case of the adhesive anchor (see Figure 9).

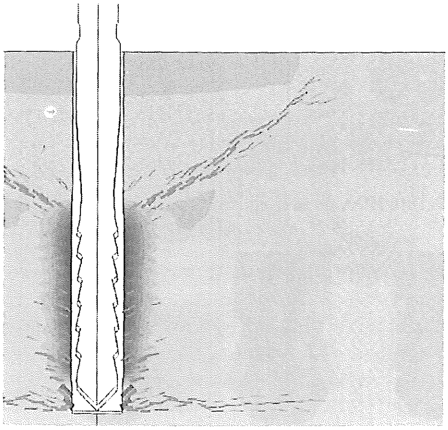

Figure 9. Combination of bonding and concrete cone failure

In the lower part of the borehole a bonding failure occurs combined with a concrete cone failure in the upper part of the borehole.

For the third principle, the undercut anchor fails due to steel failure. In this case the steel strength is reached and a rupture of the anchor rod occurs.

4.2 *Undercut anchor in cracked concrete*

The keying principle has its main advantages in transferring the load into the base material in the depth of the borehole and its applicability in cracked concrete.

4.2.1 *Structural modeling*

Figure 10 shows the undercut anchor after performing the setting procedure. This procedure includes the drilling of the borehole with a defined depth. This is followed by the introduction of the anchor in the borehole. Utilizing a special setting tool with the rotary hammer the tongues of the sleeve produce their own undercut.

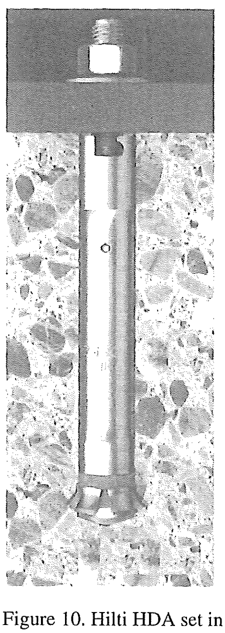

Figure 10. Hilti HDA set in concrete

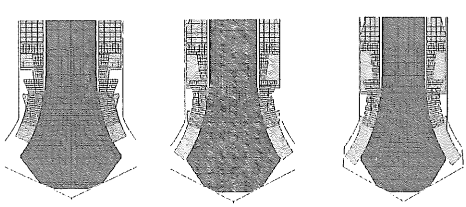

Figure 11. Expansion process of the sleeves

The creation of the undercut is done during the expansion process of the sleeves, i.e. the tongues of the sleeve, which is shown in Figure 11.

The geometry of the anchor and the boundary conditions for the axial pull-out loading also in cracked concrete allows the limitation of the calculation to one quarter of the complete structure. This calculation domain is shown in Figure 12.

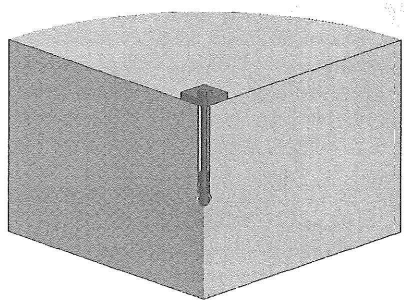

Figure 12. Calculation domain

In case of concrete base material without crack the two vertical planes cutting the anchor are symmetry planes. In case of a predefined crack one of these planes (here the right one) has a small gap to the plane of symmetry. Hence in this case it exist no boundary conditions on this plane.

The finite element discretization of the structure can be seen in Figure 13.

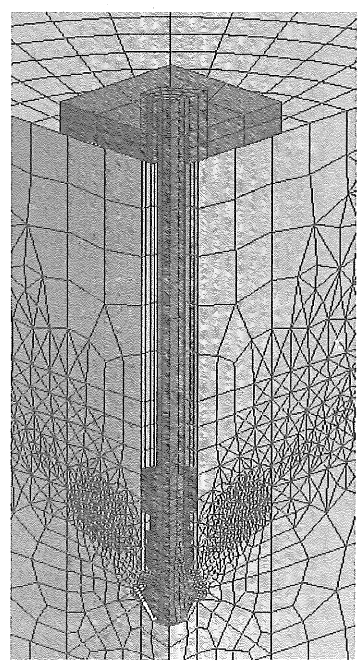

Figure 13. 3D finite element discretization of the anchor

4.2.2 *Simulation results*

The general difference of the structural behavior can be illustrated with the force-/displacement curve of the anchor for both applications – cracked and uncracked concrete (see Figure 14). The displacement and the force are measured at the top of the anchor.

The failure criterion for both calculations is steel failure of the anchor rod. Hence the load carrying capacity remains the same for both applications. The level of the maximum load is determined by the steel strength and is not influenced by the crack.

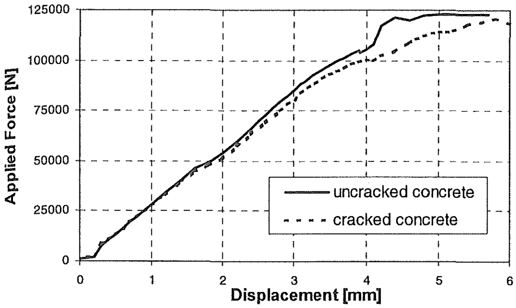

Fig. 14. Load/displacement curves of the HDA M16

The influence of the crack can be seen by the slightly decreased stiffness of the fastening system when set in cracked concrete. The circumferential load carrying capacity is weakened by introducing the predefined crack and hence the stiffness decreases. The support in circumferential direction is missing for the material at the crack surfaces.

The stress distribution in the base material can be illustrated by displaying the maximum principal stresses. Figures 15 and 16 show the loading conditions in the base material just before steel failure occurred.

The concrete without a crack shows a clear radial symmetry with the centre in the axis of the borehole (see Figure 15).

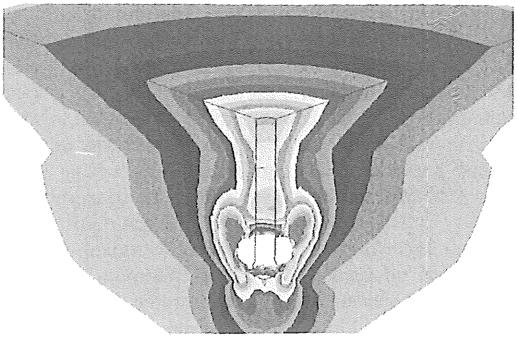

Fig. 15. Stress distribution of maximum principal stresses in the uncracked base material

The compressive domain directly above the undercut is displayed in a white colour. The region of higher stresses, going up from there, indicates an area close to the tensile strength of the concrete. The size of this area is relatively small. Hence the concrete loading shows still some potential for carrying increasing load.

The only non-symmetry is introduced by the number of tongues of the sleeve. This has a locally restricted influence directly in the contact zone between anchor sleeve and concrete.

The distribution of the maximum principal stresses for the cracked concrete application shows clearly the disturbed characteristics. The free surface of the predefined crack has to be stress-free in normal direction. Hence the isolines of the stresses tends to go towards the anchor approaching the free surface. This effect can clearly be seen in Figure 16.

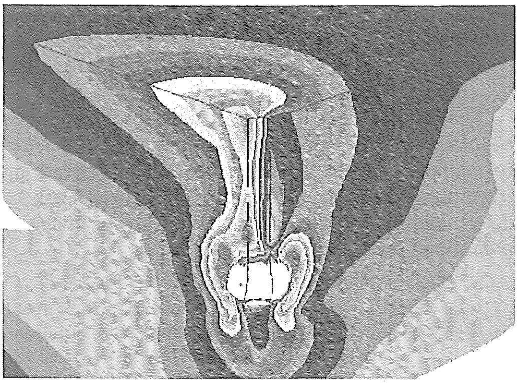

Figure 16. Stress distribution of maximum principal stresses in a predefined crack

The damage occurring directly in the contact area between the sleeve of the anchor and the concrete base material is shown in Figure 17. This figure il-

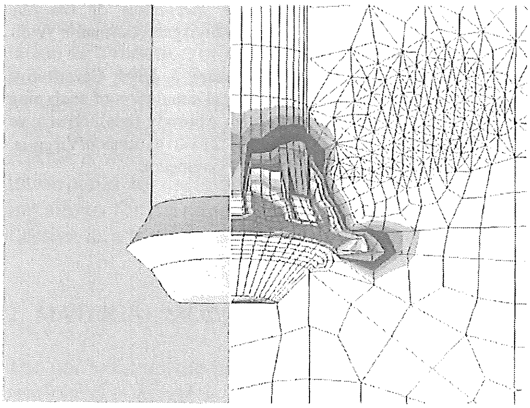

Figure 17. Damage distribution in the contact zone between sleeve and concrete

lustrates the initial geometry on the left and the crack width displayed on the deformed mesh on the right side.

The direct contact surfaces can be identified by the white zones on the upper side of the undercut. The maximum crack width occur around these contact zones.

In case of the structure with the predefined crack the maximum of the concrete damage can be observed at the free surface of the crack in the direct neighborhood of the tongue of the sleeve.

5 SUMMARY

The finite element program utilizing the smeared crack approach has been proven to be a suitable tool for simulating anchor applications in concrete. Basic mechanisms can be evaluated, interpreted and the resulting understanding utilized for further product development. The finite element program developed by the Hilti AG is a well introduced tool within the development process for anchors.

The applicability even to complex 3D-structures has been shown. Numerical simulation is a successful supplement to experiments. Trends resulting from changes of e.g. geometrical parameters can be determined and can be used to steer experiments in predefined directions.

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