

INFLUENCE OF CRACK WIDTH ON THE CONCRETE CONE FAILURE LOAD

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ABSTRACT

In the present paper the influence of the crack width on the concrete cone failure load of headed anchors embedded in concrete is analyzed. The analysis is carried out on a reinforced concrete thick plate specimen using three-dimensional finite elements and the nonlocal microplane model. In order to introduce pre-cracking into the specimen before loading the headed anchor, the specimen is loaded in longitudinal direction by applying tension forces through reinforcement. At different crack levels pull-out of the fastening element is performed. Results of the analysis show that the concrete cone failure load is decreasing with increasing crack width up to $w \sim 0.15$ mm to approximately 70 % of the failure load obtained for non-cracked concrete. Further increase of the crack width does not cause further decrease of the failure load. Comparison between numerical and experimental results indicates good agreement.

INTRODUCTION

Presently a number of tests have been performed on fastening elements consisting of one anchor that is embedded in uncracked or cracked concrete [1]. Tests in cracked concrete are usually arranged in a way that the crack plane is passing through the anchor axis. Crack initiation as well as the crack width is controlled by reinforcement that is perpendicular to the crack plane. Comparison between concrete cone failure loads obtained for uncracked and cracked specimens indicate a decrease of the failure load in the case of cracked concrete. Measurements show that by increasing the crack width to $w > 0.3$ mm the concrete cone failure load of headed or undercut anchor decreases to about 50 - 80 % of the failure load obtained for uncracked concrete [1]. However, in spite of the number of experiments the failure mechanism is not yet quite well explained and understood.

In order to better understand the failure mechanism in such a complicated stress-strain situation, where the anchor is pulled out from the concrete that has been previously damaged, a numerical analysis is performed [2]. Due to the complexity no numerical study of the present problem has been reported in literature.

SPECIMEN GEOMETRY AND FINITE ELEMENT ANALYSIS

The influence of the crack width on the concrete cone failure load is studied on a reinforced concrete thick plate of dimensions 1000 x 1040 x 300 mm (Fig. 1). In the center of the specimen a single headed anchor is embedded with an embedment depth $h_{ef} = 120$ mm. The diameters of the steel stud and anchor head are 22 and 35 mm respectively. In order to initiate crack propagation in the anchor plane, a notch of length 100 mm is introduced on both vertical sides of the specimen (see Fig.1). The crack width in the specimen is controlled through 12 reinforcing bars of diameter 16 mm. The plate is vertically supported around the bottom edges as well as around the anchor at a distance $2h_{ef}$.

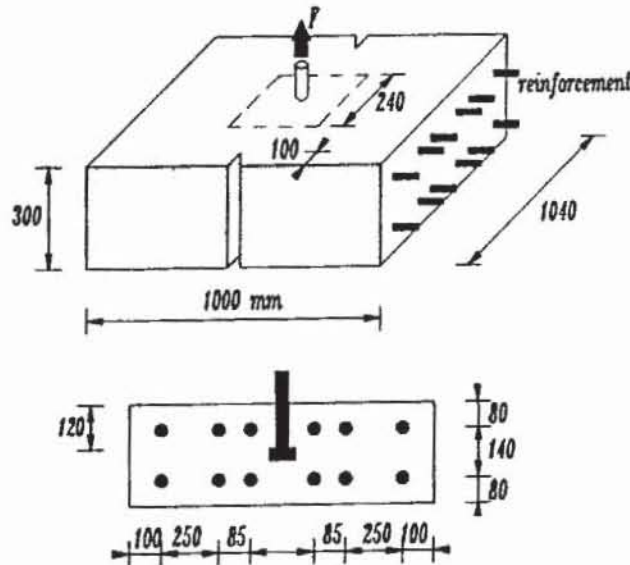


Figure 1. Geometry of the specimen

The loading procedure used in the analysis is the same as it is common in the experiments. Tensile stresses are introduced first through the reinforcement bars (displacement control) producing a crack of a certain width. In the next step the reinforcement extension is fixed and pulling out of the anchor is performed (load control). This is repeated for different tension stresses in the reinforcing bars i.e. for different crack widths.

In the finite element analysis three-dimensional eight-nodes finite elements with eight integration points are used. A finite element mesh is shown in Fig. 2. Only 1/4 of the specimen is modeled i.e. symmetry is employed. Since in the analysis a smeared crack approach is used the crack width that is introduced through the reinforcement can not be obtained explicitly from the analysis. Due to this, the empirical formula [3] is used in order to calculate the average crack width w from the known reinforcement strains:

$$w = s_m \epsilon_{sm} \quad (1)$$

$$s_m = 40 + 12.5d_s/\mu \quad (2)$$

where ϵ_{sm} = average steel strain in longitudinal reinforcement, s_m = average crack spacing (in mm), d_s = bar diameter (in mm) and μ is reinforcement ratio (in %).

The basic material properties used in the nonlocal microplane model [4], Young modulus and Poisson's ratio, are chosen as follows: $E = 30000$ MPa and $\nu = 0.20$. Microplane model parameters are chosen such that the calculated uniaxial concrete compression strength (material level) yields $f_c \cong 34$ MPa and the uniaxial concrete tensile strength $f_t \cong 1.8$ MPa.

In order to be able to represent the concrete fracture correctly, it is necessary to set the characteristic length, l , of the nonlocal continuum properly. Since no explicit relation between fracture energy, G_F , and l exists, the characteristic length is chosen such that together with the used material parameters the finite element calculation yields a correct pull-out failure load for the uncracked specimen. The reference failure load F_u (in N) for uncracked concrete specimen is calculated using the empirical expression [1]:

$$F_u = k \sqrt{f_{cc} h_{ef}^{1.5}} \quad (3)$$

where $k = 15.5$ is introduced in order to calibrate Eq. (3) and to assure dimensional correctness, f_{cc} represents concrete cube compression strength (in MPa) and h_{ef} is embedment depth (in mm). According to this the characteristic length is chosen as $l = 25$ mm.

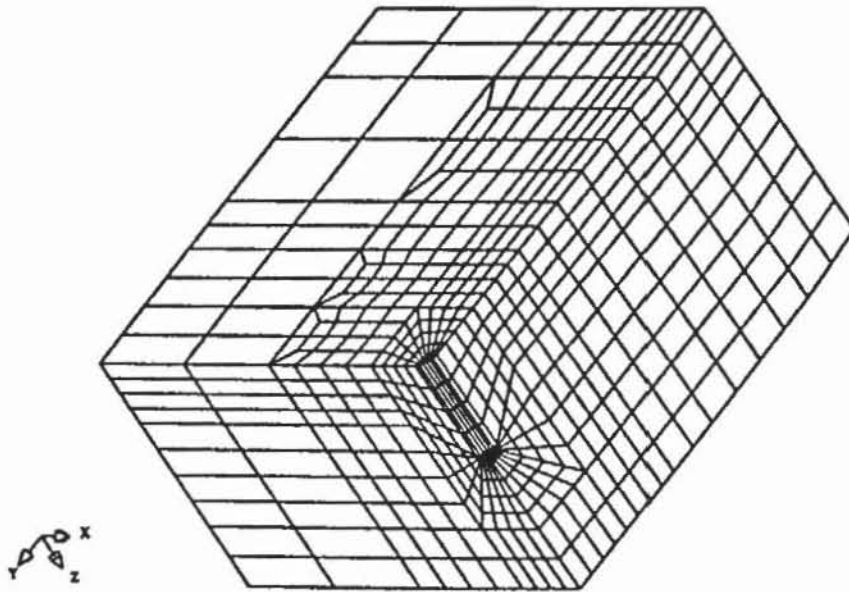


Figure 2. Three-dimensional finite element mesh - one quarter of the specimen

RESULTS OF THE ANALYSIS

In Fig. 3 the concrete cone failure load in cracked concrete related to the value valid for uncracked concrete is plotted as a function of the crack width. For comparison results of tests with headed anchors evaluated in [5] are plotted as well. It can be seen that the calculated failure load decreases with the increase of the crack width rather fast up to a crack width $w \sim 0.15$ mm. For further increase of the crack width the failure load is constant and amounts to approximately 70 % of the failure load obtained for uncracked

concrete ($w=0$). The calculated influence of the crack width on the concrete cone failure load agrees well with test results.

In order to understand the failure mechanism at different crack widths the fields of the stresses in the direction tangential to the concrete cone and in vertical (anchor) direction for the uncracked and the cracked specimens at peak load are analyzed. In cracked concrete the maximum tangential stress as well as the vertical tensile stress in the fracture process zone close to the anchor head are slightly smaller than in the case of uncracked concrete. This is a consequence of the fact that the tensile strength in the fracture process zone is reduced due to the damage introduced by stressing the reinforcement. In the plane perpendicular to the crack plane, the magnitude of the tangential tensile stresses are similar to the value for uncracked concrete. However, the zone of relatively high tangential tensile stresses is much larger than in the case of uncracked concrete. In the crack plane no tangential stresses exist because the concrete is cracked. For cracked concrete approx. 75 % of the pull-out load is transferred through the supports that lies on a line that is parallel to the crack plane. In contrast to this, in uncracked concrete in both support directions (direction parallel and perpendicular to the crack) about 50 % of the applied pull-out load is taken up.

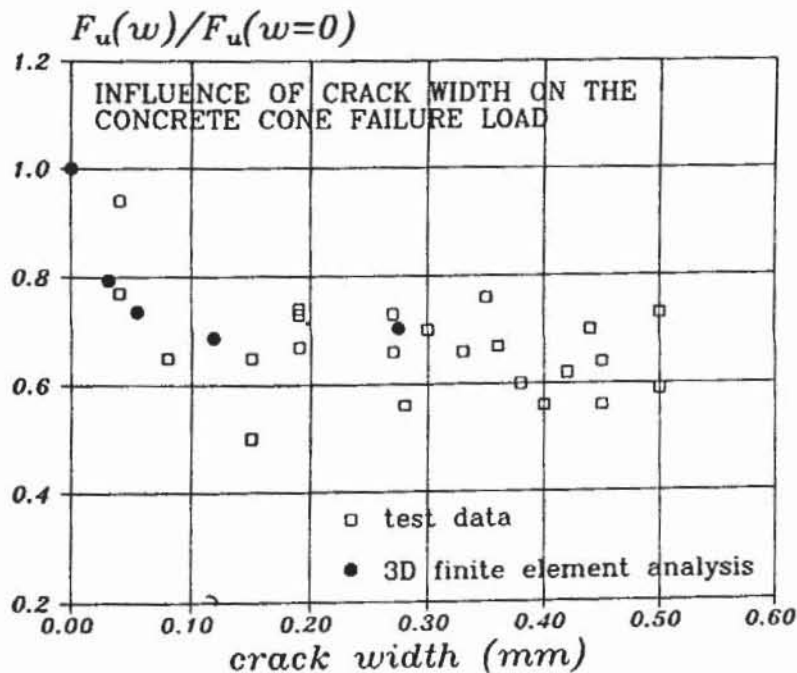


Figure 3. The calculated and measured relation between crack width and failure load

Based on the results of the analysis a simplified mechanism of the load transfer in uncracked and cracked concrete is shown in Fig. 4. In uncracked concrete the anchor load is distributed equally into the concrete (Fig. 4a). Tensile tangential (hoops) stresses are needed for equilibrium. No or only small shear stresses exist on the failure cone surface. However, in the crack plane tangential tensile stresses can not be taken up (Fig. 4b). Therefore, in this plane concrete resistance in direction perpendicular to the concrete cone surface consists only of tensile stresses acting in the direction of the crack plane i.e. there is no spatial effect. However, in the plane perpendicular to the crack plane beside these stresses significant tangential stresses in the imagined concrete cone exist

and contribute to the total resistance, stiffening the concrete cone in this direction, i.e. a spatial effect exists that is similar as in the case of uncracked concrete. A continuous drop of the tangential tensile stresses from the maximum value in the plane perpendicular to the crack plane, to zero value in the crack plane, is due to shear stresses acting in the concrete cone. Therefore, theoretically the projection of the concrete cone on the concrete surface can not have the form of a circle, as in uncracked concrete, since in such a case no change of the tangential stresses is possible. The form of the concrete cone projection should be approximately an ellipse, such that change of tangential stresses is possible.

According to this simplified model, the load transfer in the crack plane is mainly due to local bending i.e. no significant spatial effect exists and the situation is similar to a case of plane stress state. However, in the plane perpendicular to the crack plane significant tangential stresses exist. As a consequence, this plane behaves much stiffer and most of the pull-out force is transferred into the direction of this plane.

This load transfer mechanism is basically the same as in the case of an anchor in the vicinity of an edge if the edge distance of the anchor is small or zero [6]. However, there are three differences: (1) While in cracked concrete a full cone is formed, anchor at the edge will generate a half cone only for a zero edge distance. (2) Anchoring at the edge might produce a lateral local failure in the region of the head (so called blow-out failure). This failure mode is not possible for an anchor in a crack because a large lateral expansion of the concrete under the head will cause crack closing and thus confinement. (3) Anchor in uncracked concrete at the edge can utilize the full concrete tensile capacity. In contrast to that, for anchors in crack the concrete tensile capacity is reduced as explained above.

The above mechanism is activated soon after crack opening starts since the capability of the tangential load transfer in the crack plane decreases relatively fast with increasing crack width. This is demonstrated in Fig. 3 where it is shown that the concrete cone failure load decreases rather fast at small crack widths and is about constant for a crack width larger than a critical value ($w \sim 0.15$ mm).

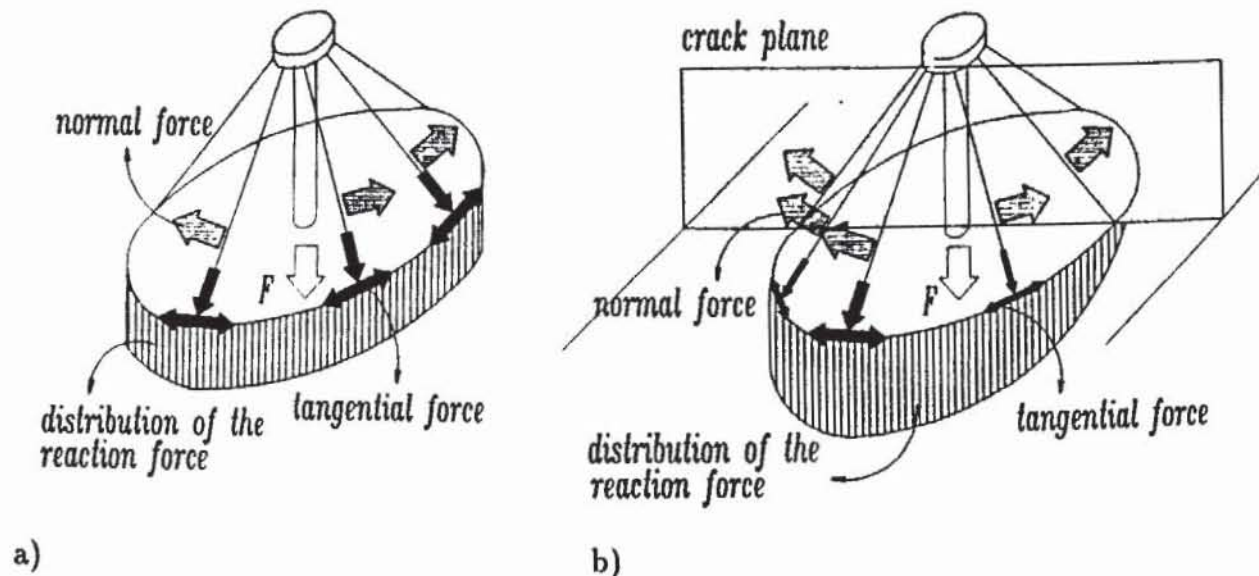


Figure 4. Simplified load-transfer mechanism, (a) uncracked and (b) cracked concrete

CONCLUSIONS

1. Similar as in the experiments the analysis confirms that the concrete cone failure load in cracked concrete decreases relatively fast with increasing crack width and reaches for $w \sim 0.15$ mm approximately 70% of the failure load valid for uncracked concrete. A further increase of the crack width has no influence on the failure load since the final load transfer mechanism has been formed.
2. In the case of uncracked concrete the load transfer in any vertical plane is the same and an axisymmetrical type of analysis can be used. Because of the axisymmetry, the forces in the concrete cone are equally distributed around the anchor. Tangential tensile (hoops) stresses exist for equilibrium reasons.
3. In cracked concrete the flow of forces is not axisymmetrical to the anchor. In the crack plane tangential stresses do not exist and the load transfer in this plane is similar as in the case of plane stress state. However, in the plane perpendicular to the crack plane the flow of forces is similar as in uncracked concrete i.e. a spatial effect exists. The change of the tangential stresses around the circumference of the cone is caused by shear stresses. As a consequence the concrete cone in the plane perpendicular to the crack plane is much stiffer than in the crack plane and approx. 75 % of the pull-out force is transferred through the support lines that are parallel to the crack. This change in load transfer mechanism causes the above mentioned failure load in cracked concrete to 70 % of the value valid for a uncracked concrete.

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