13 ANCHORAGE TO CONCRETE

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13.1 Analysis of anchorage behaviour (Literature Review) (Contribution by R. Eligehausen and G. Sawade)

13.1.1 General

Anchoring elements such as headed studs, expansion-, grouted (chemical-) or undercut anchors are used to transfer locally loads into reinforced concrete members. The load transfer takes predominantly place by mechanical interlock (headed studs and undercut anchors), friction (expansion anchors), or bond (grouted and chemical anchors). Normally the length of the load transfer area is rather small in comparison to the embedment depth (Fig. 1).

In many applications the failure load of an anchorage is limited by the resistance of the base material against pulling out of a fracture cone. Therefore the geometric and material parameters which influence the carrying capacity of an anchorage under axial tension in the case of a concrete cone failure are of major interest.

13.1.2 Empirical formulae

Based on numerous results of pull-out tests with headed-, expansion- or undercut-anchors, empirical formulae for the calculation of the of maximum load F_u of fastenings were derived in /1-4/. In general notation these equations may be writen as follows:

$$F_u = a_1 \quad f_c^{a_2} \cdot h_v^{a_3} \quad [N] \quad (1)$$

where

f_c = concrete compression strength [N/mm²]
h_v = embedment depth [mm]
a_1 to a_3 = constants

The influence of the embedment depth is given in /1-3/ by a_3 = 1.5 to 1.54. This means that the failure load does not increase in proportion to the surface of the failure cone. In /4/, however, by choosing a_3 = 2, a direct proportionality between failure load and size of the failure cone surface is anticipated. The expression $f_c^{a_2}$ represents the tensile strength of concrete derived from the compression strength. In /1,3,4/ a value a_2 = 0.5 is given, while in /2/ a_2 = 0.66 is assumed. The factor a_1 is used to calibrate the measured failure loads with the predicted values and to assure the dimensional correctness of eqn. (1).

13.1.3 Analytical description of anchorage behavior

During the last years attempts were made to analytically predict the behavior of fastenings loaded in tension. This work will be reviewed briefly in the following, the text is partly based on /5/.

13.1.3.1 Theory of elasticity

The most simple analytical method for a description of the bearing behavior of fastenings is based on linear-elastic theory. However, under service load the maximum principal tension and compression stresses in the base material are already much higher than the material strength values measured in uniaxial compression and tension tests (Fig. 2) /6,7/. This is due to the fact that, because of

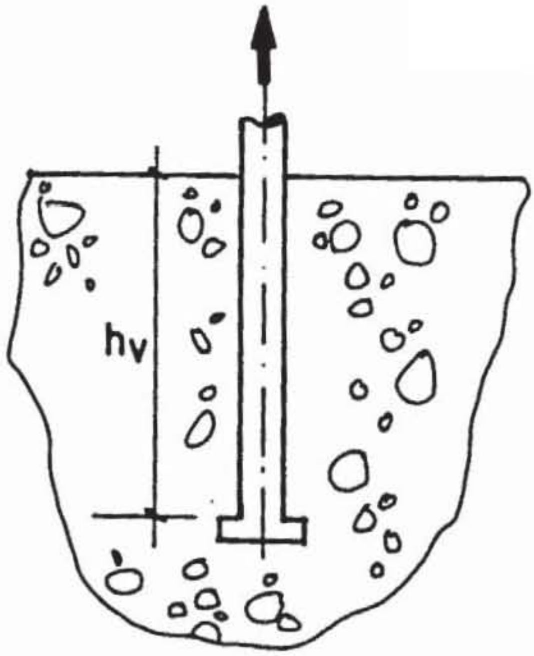


Fig. 1: Headed anchor embedded in concrete

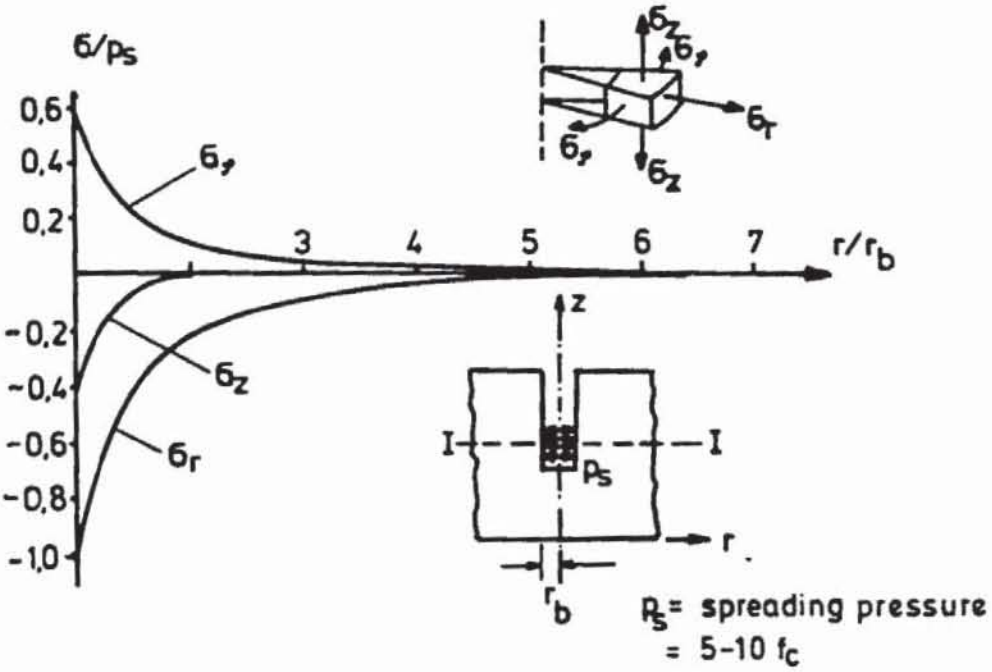


Fig. 2: Distribution of stresses in the concrete for the load case "spreading of anchor" based on theory of elasticity (after /7/)

the relatively small load transfer area, locally high deformation gradients and thereby high stresses are induced. Apparently, these stress and deformation states can only be analysed with sufficient accuracy, if the non-linear material behavior is taken into account.

13.1.3.2 Theory of plasticity

First analytical investigations with respect to non-linear behavior of concrete were performed by means of the theory of plasticity.

Wagner-Grey /8/ investigated the pull-out failure (slip failure) of an expansion anchor embedded in concrete. The expansion forces locally plastify the concrete and the dimensions of this plastified cylinder increase with increasing expansion forces. Failure (splitting) of the concrete is assumed, when the plastified area reaches the outer surface of the specimen (line B in Fig. 3). The material behavior is modelled by assuming a modified two-dimensional Mohr-Coulomb failure criterion (Fig. 4). The pull-out load is calculated by multiplying the expansion force causing concrete failure with an appropriate friction coefficient between concrete and anchorage device.

The analytically predicted pull-out loads of expansion anchors give a rough estimate only of the failure loads observed in tests /9/. They need to be confirmed by tests.

The so-called LOK-test (Fig. 5) is used for the in-situ testing of the concrete compression strength /10/. The concrete compression strength is calculated from the measured pull-out load using an empirical calibration curve. The LOK-test was analysed by Jensen & Braestrup /11/. They assumed that the failure surface is the frustum of a cone

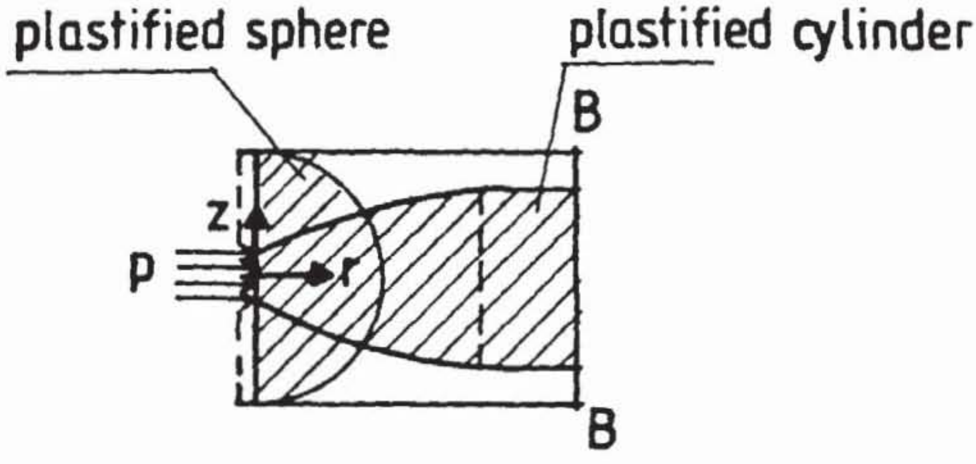
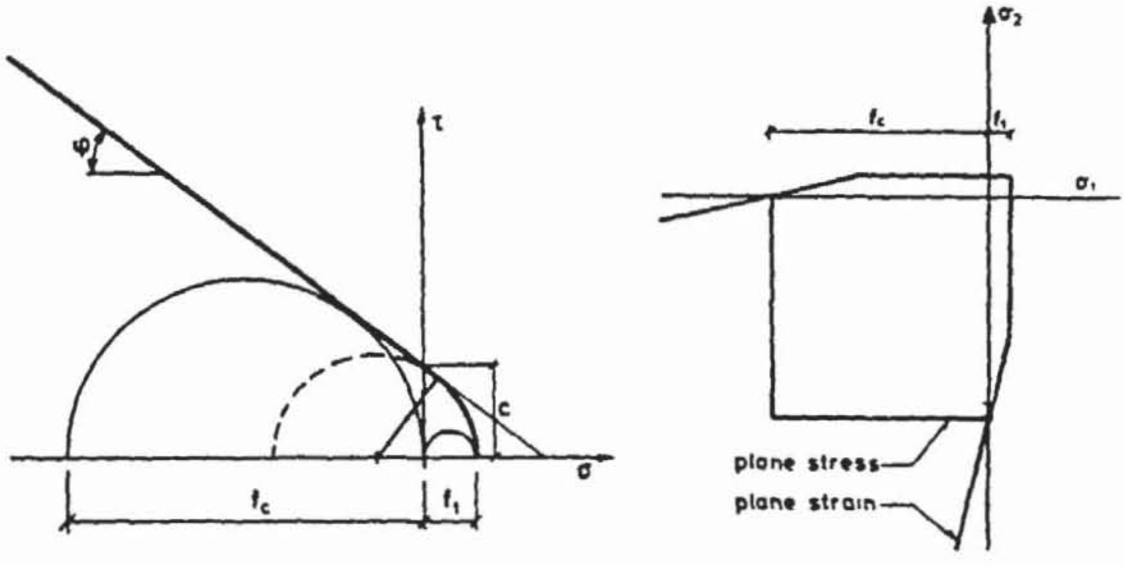


Fig. 3: Assumed failure model (concrete splitting due to spreading forces) (after /8/)



(a) Failure envelope in σ,τ plane b) Yield locus in plane stress and strain

Fig. 4: Modified Mohr-Coulomb failure criterion for concrete (according to /8/ and /11/)

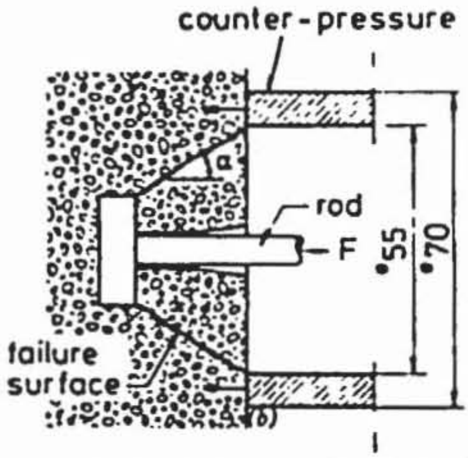


Fig. 5: Lok-Test (taken from /12/)

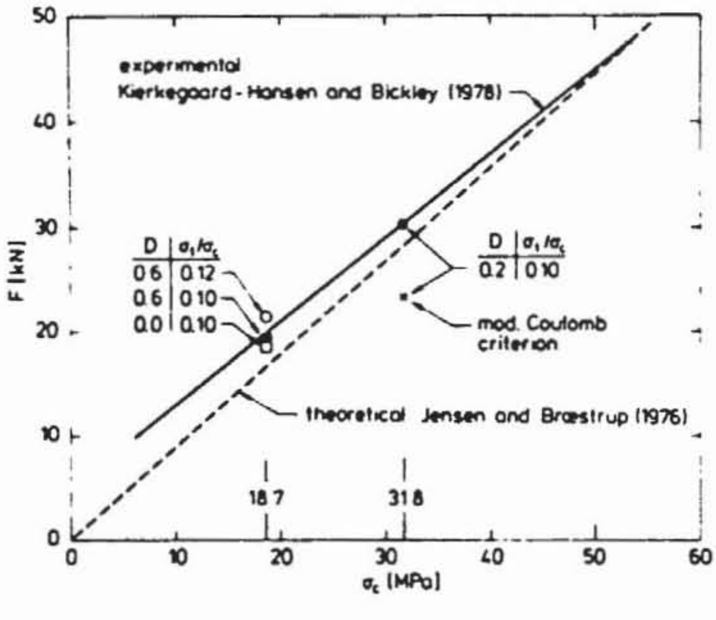


Fig. 6: Experimental data compared with theoretical failure values (taken from /12/)

and that the failure occurs by sliding along this surface. By using the modified Mohr-Coulomb failure criterion (fig. 4) and assuming the angle between the direction of deformation and the failure surface as equal to the angle of friction of the concrete as well as a very low concrete tensile strength ($f_t = 0.01\ f_c$), they could predict the pull-out loads and the shape of the failure cone, as observed in tests. For these assumptions the pull-out load was directly proportional to the concrete compression strength (Fig. 6).

13.1.3.3 Strength criteria in combination with a smeared crack approach

Ottosen /12/ analysed the LOK-test by means of axissymmetric nonlinear finite elements. His analysis followed the progression of circumferential and radial cracking by means of an iterative smeared cracking procedure. The circumferential cracks begin at the disk edge at approximately 15 % of the failure load and reach the reaction ring at about 65 % of the failure load (Fig. 7). In addition, large compressive stresses run from the disk edge in a rather narrow band towards the support. In the analysis failure is caused by crushing of the concrete and not by cracking of concrete. The calculated failure load was proportional to the concrete compression strength (Fig. 6).

Peier /13/ investigated the pull-out behavior of headed-, expansion- and adhesive anchors using the method of finite elements. The distance between the reaction force on the concrete surface and the anchor was rather wide. As material law he used a triaxial model similar to that of Ottosen /12/ with compression failure and tension cut off.

In the analysis local compression failure was observed for

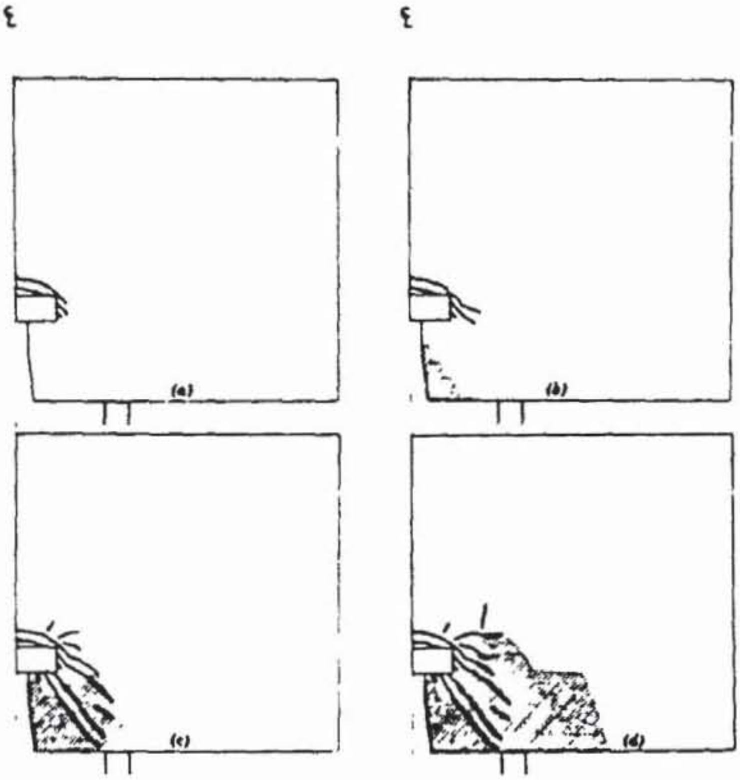


Fig. 7: Crack development with increasing load (loading is expressed in relation to predicted failure load): (a) loading = 15%; (b) loading = 25%; (c) loading = 64%; (d) loading = 98% /12/

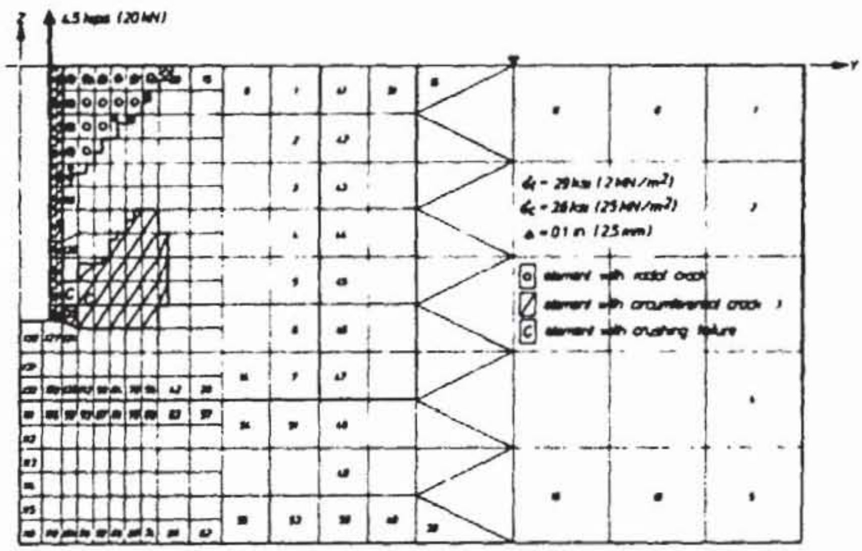


Fig. 8: Crack zone of a headed anchor under tensile loading /13/

headed anchors with a small load transfer zone. Expansion anchors and headed anchors with large heads failed due to tension stresses on the failure cone surface and subsequent circumferential cracking with stable crack growth up to failure. Figure 8 shows the calculated crack zone of a headed anchor under tension load. Note the compression failure zone in front of the anchor head. The calculated failure load of headed anchors with a small head was significantly lower than the failure load of headed anchors with a large head and of expansion anchors. The peak load of the latter two anchor types was almost identical. While the calculated failure loads of expansion anchors agree sufficiently well with test results, the peak loads predicted for headed anchors with a small head are rather low compared to experimental observations.

Eligehausen & Clausnitzer /14/ studied also the behavior of expansion anchors using the method of finite elements. They varied the constitutive model for concrete in tension. While model 1 assumes a complete plastification of concrete, model 2 assumes linear elastic behavior with tension cut off (Fig. 9). Furthermore they investigated the influence of element size and number of load steps on the peak load.

Figure 9 shows the calculated load-displacement curves of an expansion anchor for the two material models. For comparison the experimental curve is plotted as well. In the calculation slip between anchor and concrete was neglected. Therefore the predicted stiffness was higher than observed in tests. The calculated maximum load for plastic concrete behavior is about 4 times higher than the load found for brittle material behavior. The measured failure load is in between both extremes. This shows that the ultimate load of an anchorage is significantly influenced by

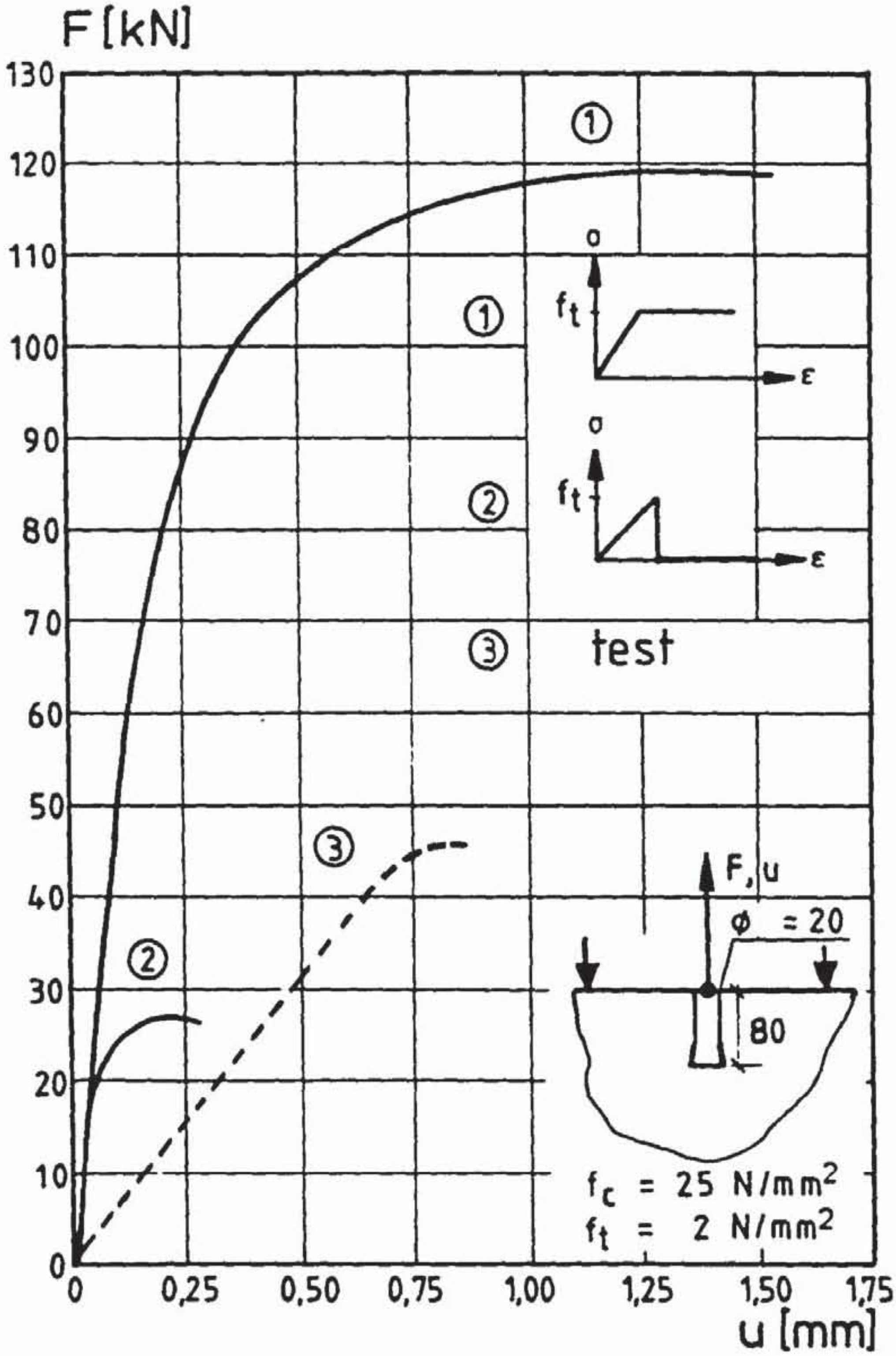


Fig. 9: Comparison of calculated load-displacement curves of expansion anchors with test results (after /14/)

the behavior of concrete after reaching the uniaxial tensile strength. Furthermore a considerable influence of the element size and number of load increments on the results was found /14/.

A similar investigation was performed by Weyerhäuser /15/. However, the predicted concrete cone failure load overestimates the influence of the embedment depth ($F_u \approx h_v^{2.3}$)

13.1.3.4 Fracture mechanics

Miller & Keer /16/ and Ballarini et al. /5/ investigated the behavior of headed studs under tension loading using linear fracture mechanics. They assumed that the crack initiation direction depends on the direction of maximum K_I.

According to Ballarini et al. who studied a two-dimensional model in an elastic half space, for relatively short reaction distances and deep embedment crack growth propagation is stable (Fig. 10) and crack initiation and tensile capacity are governed by the fracture toughness of concrete (Fig. 11). When the supports are not present, crack propagation becomes unstable (Fig. 10).

Further studies based on fracture mechanics approaches are described in Sections 13.2 to 13.4.

13.1.4 Behavior as observed in experiments

To judge the validity of the different assumptions described above, the analytical predicted behavior should be compared with experimental results.

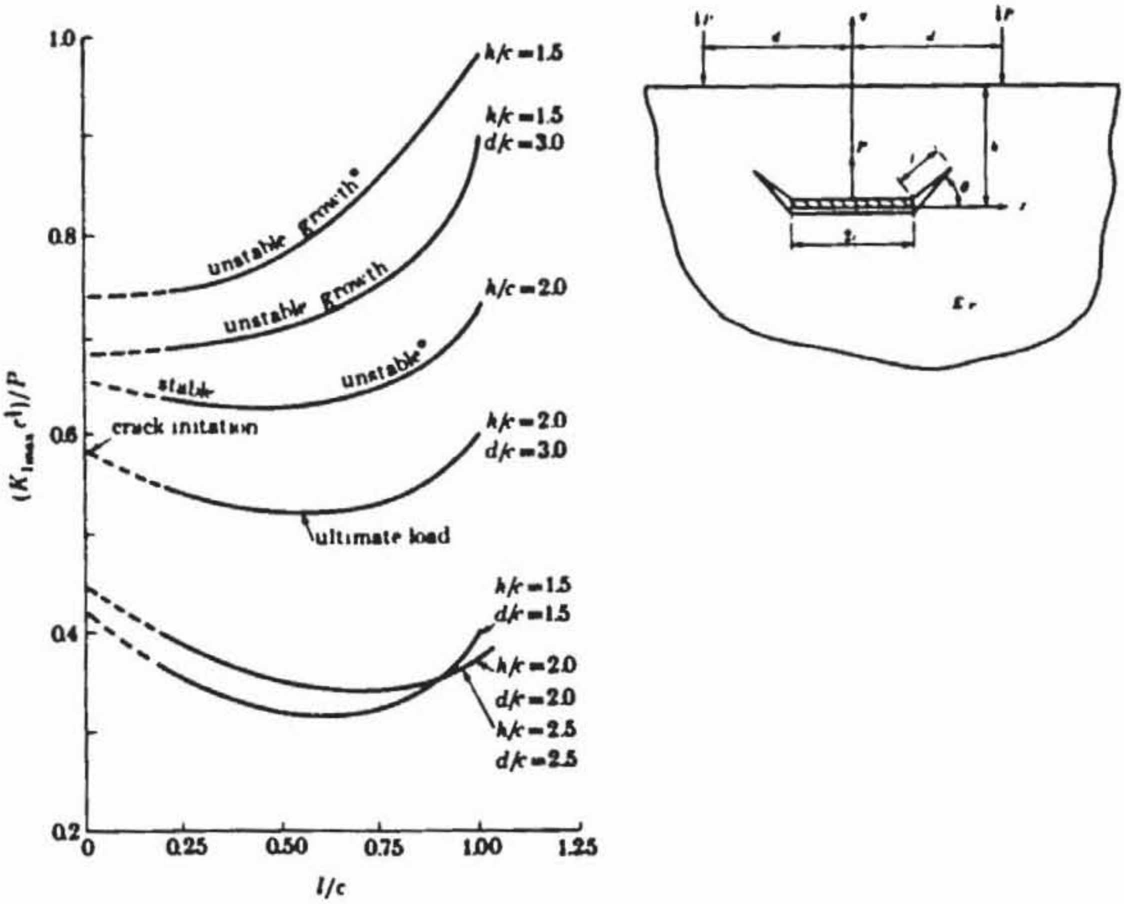


Fig. 10: Maximum mode I stress intensity factors as functions of crack length (asterisk indicates no supports) /5/

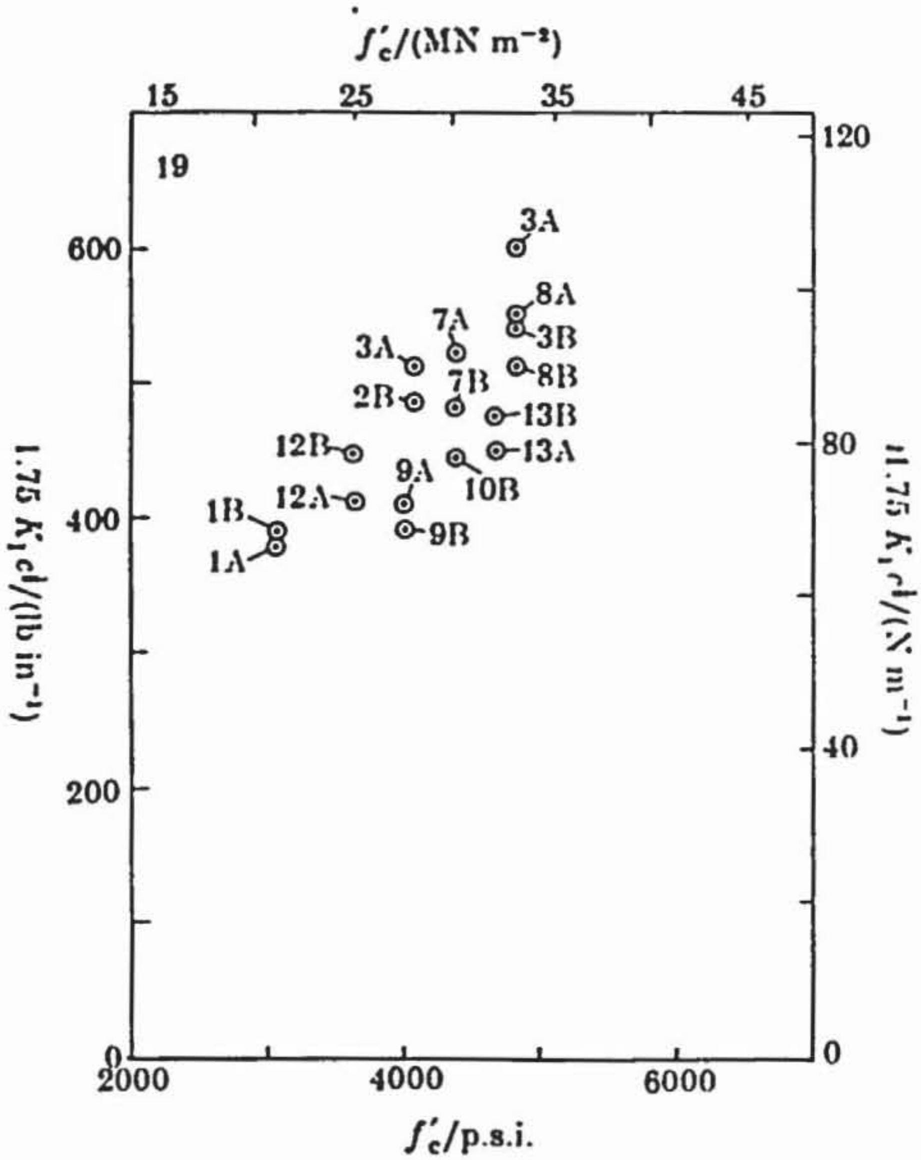


Fig. 11: Fracture toughness at ultimate as a function of compressive strength /5/

Stone & Carino /17/ conducted pull-out tests on enlarged (scale 12:1) extensively instrumented specimens simulating the LOK-test. Strains in the interior of the concrete were measured by specially designed embedded strain gauges. Furthermore the slip between the bottom of the disk and the surrounding concrete was recorded. The results can be summarized as follows:

Circumferential cracking near the edge of the disk initiates at about 30 - 40 % of the ultimate load and ends the elastic response. The circumferential crack continues to grow towards the reaction ring with increasing load. Afterwards the load is transferred mainly by aggregate interlock. The observed compressive strains adjacent to the failure surface were too small to initiate compressive failure. Formation of the failure cone and the failure load were therefore governed by concrete cracking and not by concrete compression failure, as predicted in /11,12/.

This conclusion is confirmed by the results of inscale LOK-tests performed by Krenchel & Shah /18/. To register micro cracking in concrete, accoustic emission activity was measured during the test. Furthermore to examine the development of micro-cracking, partly loaded specimens were cut into sections and observed under a microscope. The authors concluded that crack initiation starts at about 30 % of the maximum load and these primary cracks do not grow significantly up to 65 % of the peak load. For loads near the peak load secondary cracks form, running from the outer edge of the disk to the inside edge of the support.

A somewhat different behavior was found by Eligehausen & Sawade /19/ in tests on headed studs without support at the concrete surface (Fig. 12). By use of a special speci-

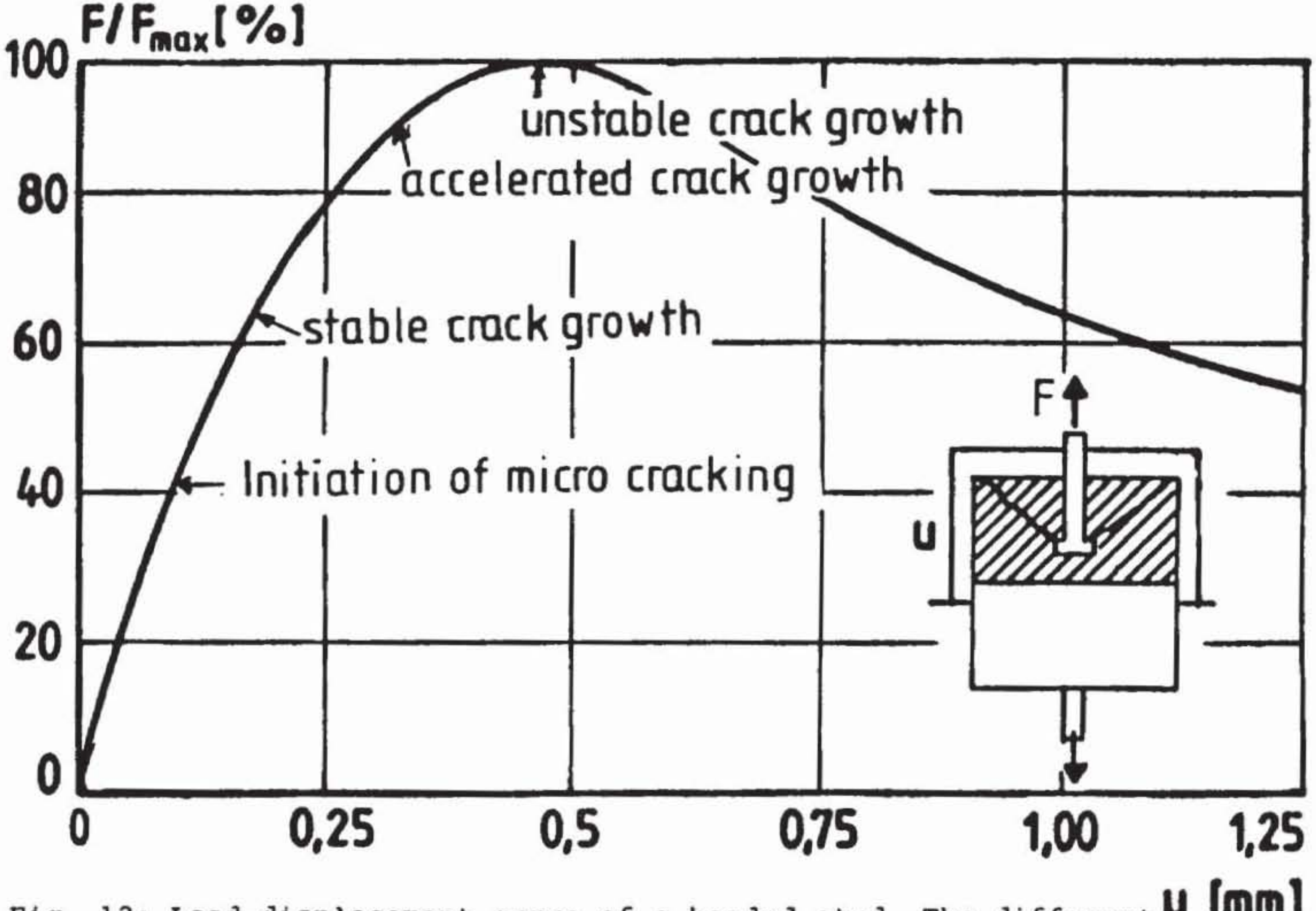


Fig. 12: Load-displacement curve of a headed stud. The different stages of cracking are indicated (after /18).

men cracking of concrete could be observed directly. Furthermore concrete strains were measured by electrical strain gauges and accoustic emission activity was recorded. In Fig. 12 a typical load-displacement curve (measured in a deformation controlled test) is plotted. The different stages of cracking are indicated. Circumferential cracking (one discrete crack) started at about 40 % of peak load from the load transfer area and grew slowly in a stable manner towards the concrete surface. At about peak load the discrete circumferential crack had penetrated about 60 - 70 % of the latter failure cone. With increasing imposed deformations on the headed stud, unstable crack growth was observed and the failure cone fully developed along the line of the micro cracks.

Summarizing it can be said that material models based on plasticity and stress-strain relationships together with stress criteria indicating failure do not catch all aspects of anchor behavior as observed in experiments. Furthermore - as explained in /20/ - the predicted failure load depends on the element size and number of load steps. A better explanation of anchorage behavior can be expected by means of fracture mechanics.

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