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Behavior, Design and Testing of Anchors in Cracked Concrete

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Synopsis: Reinforced concrete structures will generally be cracked under service load due to tensile stresses caused by loads or by the restraint of imposed deformations. Therefore, in general, the design of anchors should be based on the assumption that the concrete is cracked.

Under tension loading anchor behavior is significantly influenced by cracks depending on the type and design of the anchor. If the failure is caused by concrete cone break-out, the failure load is reduced by approximately 30 to 40% compared to the value expected in uncracked concrete. If the failure is caused by pullout (expansion or adhesive anchors), the reduction of the failure load may be much higher. Furthermore, installation inaccuracies may have a very significant negative effect on anchor behavior in cracked concrete.

Under shear loading the behavior of all types of anchors away from edges is not significantly influenced by cracks. The failure load of fastenings close to the edge is reduced by cracks by about 30%, however, the reduction is almost independent of the type of anchor.

A method for the design of fastenings based on rational engineering models and non-linear fracture mechanics is proposed. It distinguishes between the different loading directions and failure modes and takes into account all relevant influencing factors.

Anchors must be suitable for the intended purpose and their behavior must not be significantly influenced by installation inaccuracies that might occur in practice. Test requirements for checking the proper functioning under unfavourable conditions (suitability) and for evaluating permissible conditions of use of anchors in cracked concrete are proposed. They are based on an extensive survey of cracking that might occur in practice and take into account the results of intensive research during the last 10 years.

In the future fastenings to concrete by different types of anchors should be designed and installed with the same confidence and reliability as e.g. joints in steel and concrete structures. For this a rational design approach in accordance with modern safety concepts and anchors with a high built-in installation certainty are needed.

Keywords: Anchors (fasteners); cracking (fracturing); failure; failure mechanisms; loads (forces); shear properties; structural design; tension

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1. INTRODUCTION

According to the UEAtc Directive for the Assessment of Anchor Bolts /1/, fastenings are designed under the assumption that the concrete is uncracked. In contrast, the reinforced concrete element serving as anchor base material is normally designed assuming the concrete is cracked, if tensile stresses might occur in the concrete due to external loads or restraint of deformations.

The rationale for the design approach of reinforced concrete structures is given in Figure 1, which summarizes the various causes of cracking. Cracks may form before or after hardening of the concrete. For fastenings the latter cracks are of major interest. These cracks may be caused by structural effects due to design loads, accidental overload or creep, restraint of deformations due to shrinkage, early thermal contraction, seasonal temperature variations, freeze/thaw cycles and/or support settlements and by chemical or physical actions. Today it is generally accepted that cracks are more often formed by tensile stresses caused by (unintentional) restraint of deformations than by external loads /2,3/.

Even when neglecting tension stresses due to restraint of deformations, the length of the tension zone of continuous beams or slabs submitted to bending may be rather large in comparison with the compression zone, if all possible loading cases are considered (Fig. 2). In two-dimensional structures, bending moments in both directions are caused by single-point loadings. Therefore, walls which in the main loading direction are stressed in compression only, have a tensile zone perpendicular to the main direction (Fig. 3).

As it is difficult if not impossible in practice to clearly distinguish regions where the concrete might be uncracked or cracked, it seems appropriate to assume that fastenings are normally situated in cracked concrete. The assumption of an uncracked anchor base material may be justified in exceptional applications.

Cracks may appear predominantly in one direction (line cracks) (e.g., in beams, single span slabs, tension members) or in two mostly perpendicular directions (e.g., slabs and walls spanning in two directions, flat slabs, beams with bending and longitudinal cracks). Their widths may be constant over the member depth (tension members) or may decrease almost linearly from the concrete surface to the crack tip (bending members). Anchors may be situated beside or in cracks or - in the worst case - in the center of intersecting cracks (from perpendicular directions).

When using fastenings in cracked concrete, the following questions are of main importance:

- What is the probability that anchors are situated in a crack?
- How is the bearing behavior of fastenings influenced by cracks in the concrete?
- How should anchors be tested and dimensioned?

The paper addresses these issues in light of current knowledge.

2. PROBABILITY OF ANCHORS TO BE SITUATED IN A CRACK

Experimental investigations have been performed to determine if anchors act as crack-attracting /5,6/ or crack-inducing /7,8/.

Concrete slabs reinforced with usual welded mesh made of ribbed double bars of 6.5 mm diameter were tested /5/. The distance between the axes of transverse wires was 250 mm (Fig. 4).

Torque controlled expansion anchors and undercut anchors of the M12 size, installed to a depth 80 mm were tested. Varied were: the loading of the anchors [only prestressed or loaded with 1.3 F_{adm} (admissible service load)] and the distance of the anchors to the transverse wires (e = 4 and 8 cm). For comparison, holes were also drilled without installing any anchors. The anchors were installed and loaded in uncracked concrete. Afterwards the slabs were incrementally loaded up to F_{adm} according to DIN 1045.

Cracking initiated at about 40% of the slab service load. The cracks occurred over the transverse bars but deviated to the anchors. Under the slab service load, practically all anchors and most drilled holes were situated in cracks independent of the position relative to the transverse reinforcement and the type and loading of the anchors (Fig. 5). The cracks were running directly through the anchorage zone of the fastening elements (Figs. 6, 7). The measured anchor displacements demonstrated that the anchors were situated in a crack at the initial phase of the crack formation process. Similar results were also obtained from tests of slabs reinforced with ribbed bars/6/.

Furthermore, theoretical investigations using finite element analysis were performed /7,8/. In the two studies, the assumptions about the magnitude of the spreading forces and the behavior of concrete in tension were different. According to this work, if a torque controlled expansion anchor is located in a tension zone with almost constant tensile stresses at the concrete surface due to external loading and/or imposed deformations which do not cause concrete cracking, there is a very high probability that the anchor will initiate cracks (Fig. 8). The probability increases with increasing anchor diameter. Because of the different spreading forces, the probability of crack initiation is higher for drop-in anchors and lower for undercut and adhesive anchors than in the investigated case.

According to the above described experimental and theoretical findings, there is a very high probability that - if cracking occurs - the anchors could be situated in a crack. This result is confirmed by investigations in /9, 9a/. It can be explained as follows:

a) Prestressing and loading of an anchor result in splitting forces in the concrete, which cause high tensile stresses in the vicinity of the anchor.

b) Drilled holes act as notches, which increase tensile stresses at the edge of the hole.

c) For two-dimensional structures, single-point loads, as induced by anchors, cause high local moments and, therefore, high local tensile stresses in the concrete near the anchor (see Fig. 3).

Summarizing, it seems justified to assume that anchors installed in the tension zone of reinforced concrete structures are generally situated in a crack.

3. BEARING BEHAVIOR OF SINGLE AND MULTIPLE ANCHOR FASTENINGS IN CRACKED CONCRETE

3.1 Tension Loading

3.1.1 Single Anchors

Figure 9 shows schematically the load-displacement behavior of a torque controlled expansion anchor in uncracked and cracked concrete, respectively. The anchor has been designed for applications in cracked concrete and shows a good follow-up expansion capability in case of cracking. The stiffness of anchors in cracks is smaller and failure occurs at smaller ultimate loads and greater displacements than in uncracked concrete.

Failure loads are given in Figure 10 for fastenings in cracks running in one direction (line cracks). These include headed studs, undercut anchors, and torque controlled expansion anchors specifically designed for use in cracked concrete. This Figure shows the relationship of the ultimate load, obtainable in uncracked concrete as a function of the crack widths.

Where anchors were installed in a tension zone, breakout of a concrete cone was the general mode of failure. Failure loads of fastenings in cracks with widths 0.3 to 0.4 mm, which is considered to be the maximum admissible value for reinforced concrete structures under quasi permanent load, are only some 50 - 70% of the ultimate failure loads obtained in uncracked concrete. This reduction of the failure load is caused by the disturbance of the load transfer into the concrete by cracks (Figure 11). Furthermore, the failure cone may be cut off by neighbouring cracks.

In the case of expansion anchors, the opening of the crack causes a significant reduction of the spreading force. This is demonstrated by Figure 12 which, for reasons of simplicity, applies for an anchor situated in an intersecting crack. If the anchor is well designed and expands further when loaded, the influence of cracks on the failure load is almost the same as for undercut anchors (compare Fig. 10a with 10b).

Torque controlled expansion anchors, which are designed for use in uncracked concrete and have passed the tests according to /1/, may not work properly in cracked concrete (Fig. 13). This is especially true, if the anchors are torqued with a smaller torque than the value required by the manufacturer.

Drop-in anchors are not able to expand further when loaded. Therefore, their expansion force is significantly reduced by the opening of a crack (see Fig. 12), often resulting in a pullout failure and a larger reduction of the failure load than in the case of undercut and well designed torque controlled expansion anchors (compare Fig. 14 with Fig. 10). Furthermore, the load-displacement relationship of drop-in anchors situated in cracks illustrates lower failure loads,shows appreciable slippage of the anchor in the hole and exhibits considerable scatter when compared to the behavior in uncracked concrete (Fig. 15). This negatively influences the behavior of anchor groups and may lead to a significant reduction of the failure load (see Section 3.1.2).

To fully expand M12 size, drop-in anchors approximately 8 to 20 blows with a 1 kg hammer are necessary (Fig. 16), depending on concrete strength, hole diameter and location of the anchorage (at the upper or lower side of a specimen). If the anchors are not expanded properly, the scatter of the load-displacement curves and the anchor slippage are larger, and the failure loads are lower compared to fully expanded anchors (Fig. 17). For the tests shown in Fig. 17, the anchors were expanded according to /1/ in "small" holes (cutting diameter B = 15.15 mm) with the number of hammer blows (11 blows with a 1 kg hammer) needed to fully expand anchors installed in large holes (B = 15.4 mm). The actual spreading of the anchor was approximately 95% of the nominal value.

Tests show that fully expanded drop-in anchors can transfer a tension load in cracked concrete, which is somewhat lower than the failure load of undercut and well designed torque controlled expansion anchors. However, drop-in anchors are more sensitive to crack openings and to installation inaccuracies. Because of this, there is much need for studies on how these anchors are expanded on site.

Adhesive anchors transfer the load to the anchor base material by bond stresses. The bond between the drilled hole surface and the resin may partially be destroyed by cracks. This leads to a strong decrease of failure load in comparison to anchoring in uncracked concrete (Fig. 18). The large scatter of test results can be explained by the random flow of a crack around the hole and along the anchor depth. The load displacement relationships of anchors in cracks exhibit significant scatter compared to anchors in uncracked concrete (Fig. 19). This negatively influences the behavior of adhesive anchor groups (see Section 3.1.2). For the tests shown in Figure 19b, the drilled hole was cleaned very carefully. If the drilled hole is cleaned less meticulously or not cleaned at all, the failure loads drop significantly (Fig. 20). Therefore, the installation procedure of adhesive anchors located in cracks should be investigated.

According to /16/, the failure load of anchors located close to a crack is not much higher than the value of anchors situated in a crack. This can be explained by the fact that the failure cone may be cut off by the crack.

3.1.2 Anchor Groups

In anchor groups some anchors will be situated in cracks. Figure 21 shows the failure load of a quadruple fastening as influenced by the position of the different anchors in relationship to cracks. The tests have been performed with undercut and well designed torque controlled expansion anchors in uncracked concrete and anchors installed in a tension zone with crack widths $w \approx 0.35$ mm /17/. The fastening was subjected to axial tension and the anchor plate was supported by hinges allowing it to rotate.

As expected, the maximum failure loads were obtained for uncracked concrete. The bearing capacity of the quadruple fastening in cracked concrete was almost independent of the position of the group within the crack pattern. Minimum failure loads were obtained for three anchors in a crack and the fourth one in uncracked concrete. This agrees with theoretical investigations /17/.

Theoretical considerations show that these results are also valid for fastenings with fixed supports (no rotation possible) /17/.

The anchors used in the tests mentioned showed continuously increasing load-displacement relationships in cracked and uncracked concrete (see lines a_1 and a_2 in Fig. 22). Anchors in cracks may slip, and then accept additional load again or they may pull out without accepting any further increase in load (line c) (compare Figs. 13, 15, 17 and 20).

The influence of this behavior on the failure load of a group of anchors with large spacing has been investigated theoretically /17/. Assuming a normal load-displacement relationship for all anchors of a group results in a maximum calculated failure load of almost four times the bearing capacity of a single anchor in a crack. Failure load decreases by 1/3, if anchor 2 and/or anchor 4 (Fig. 22) are following line b. The decrease in failure load is even greater, if one of the anchors in the crack follows line c, i.e. pullout without any increase in load. The figure applies for an anchor plate supported by hinges. Similar results were obtained for a fixed anchor plate /17/.

These investigations also demonstrate that fastenings, which shall be used in the tension zone, must be suitable for this application.

3.1.3 Fastenings in a Concrete Cover

When fastening elements are anchored in the concrete cover or in the vicinity of the reinforcement, the tensile stresses they induce in the concrete overlap with the tensile stresses caused by the bond action (splitting forces) of the reinforcement. Furthermore, the (tensile) strength of the concrete in this area may be lower than the strength of the concrete in the core. In addition, the reinforcement reduces the concrete area for transferring tensile forces. These effects may lower the failure load, especially in the case of reinforced concrete members with a dense reinforcement /4/.

Fastenings anchored in the outer zone of heavily reinforced beams (Fig. 23) failed by pulling off the complete concrete cover (Fig. 24). On an average the failure load was about 30% lower than for a specimen with a large bar spacing /4/.

3.2 Shear and Combined Tension and Shear Loading

The behavior of all types of anchors with a large edge distance loaded in shear is not influenced to a large extent by cracks in the concrete /18,19/, because failure is caused by steel rupture. Anchors with a small edge distance and loaded in shear towards the edge fail the concrete. The failure load is reduced by cracks, however, the reduction is not significantly influenced by the anchor type /18,19/.

The behavior of anchors in cracks under combined tension and shear loading has not been studied to a great extent. Using the available results, the behavior is plotted in the interaction diagram (Fig. 25). The graph pertains to M12 fasteners (nominal bolt strength 800 N/mm^2, anchorage depth h_v = 80 mm, nominal concrete strength 25 N/mm^2) with large spacings and edge distances located in cracks. Anchor failure load was varied under axial tension.

Line 1 in Figure 25 represents anchors with sufficient holding power to cause a concrete cone failure (e.g. undercut and well designed torque controlled expansion anchors). The rupture loads can be described by a tri-linear relationship /20/ or an elliptic curve. Anchors for line 2, when loaded in tension, fail by pulling out; the rupture load is much lower than the concrete cone failure load. The strength of anchors for line 3 loaded in tension is relatively small. The failure load of anchors in lines 2 and 3 under predominant shear loading is not much lower than that of an anchor for line 1. However, under predominant tension loading the difference is very large.

Properly installed drop-in and adhesive anchors are situated between line 1 and line 2 but generally closer to line 2, (Fig. 26). If drop-in anchors are not fully expanded or adhesive anchors are installed in improperly cleaned drilled holes, their behavior will be close to line 3.

Figs. 25 and 26 are valid for static loading and a constant direction of the acting force. The anchor behavior might be negatively influenced by a varying load direction (e.g. constant tension load and alternating shear load).

4. DESIGN OF FASTENINGS

4.1 General

According to current German approvals, the permissible load on a single anchor and on an anchor in a double or quadruple fastening is determined by the "κ-method" (Fig. 27). It is calculated from the permissible load zul F_0^E of an individual anchor located at a considerable distance from other anchors and from an edge of the structural member by multiplying with the coefficients κ_a and κ_{ar}. These coefficients take into account the effect of the actual anchor-to-anchor distance and edge distance upon the load-carrying capacity of the fastening. The values for zul F_0^E, the critical anchor spacings, a_k, the critical edge distances, a_{rk} (for which adjacent anchors do not affect each other and there is no edge effect) and the minimum permissible spacings and distances, are stated in the certification documents.

The anchors are classified according to their anchorage depth into load classes (Fig. 28). The permissible load applies for any direction of loading. Anchorages in the tensile zone (cracked concrete) are regarded as the normal case. Anchorages in the compression zone (uncracked concrete) are considered as the exception.

A similar design concept is given in /1/. Its advantage is simplicity. However, there are certain disadvantages as well /22/.

Fig. 29 shows the permissible load for M 12 anchors (anchorage depth h_v = 80 mm), with wide spacings and large edge distances, as a function of the direction of loading. The possible values determined from test results and those determined from the rules contained in the certification documents are plotted in the diagrams. The permissible load according to these rules is valid for any direction of loading, so that the corresponding curve in the interaction diagram is part of a circle. The axial tensile loading condition governs the permissible load, while the higher load-carrying capacity under shear loading is ignored. Whereas the under-estimation of the shear carrying capacity in the compressive zone of high-strength concrete is relatively slight (Fig. 29a), for anchorages in the tensile zone it is very considerable (Fig. 29b).

Furthermore, the criterion for determining the required edge distance for full capacity is shear loading towards the edge, because the shear capacity of anchorages at the edge is smaller than the tension capacity /22/.

The design approach hitherto adopted in German approvals and by the UEAtc Directive /1/ often underestimates the load carrying capacity of a fastening. However, for reasons of economy, the capacity of fastenings should be utilized more or less equally in all applications. This can be done only, if a more differentiated approach is adopted.

According to /1/, the allowable load for anchors is determined by dividing the 5% fractile of test results by a global safety factor. In German this safety factor is generally taken as γ = 3.0, in other countries different values are used. However, in modern Eurocodes (e.g., /23-25/) the concept of partial safety factors has been adopted, because it accounts for various uncertainties in a rational manner.

The design philosophy for fastenings should be based on the current philosophy for the design of reinforced concrete and steel structures and should fully utilize the anchor capacity. Uncertainties related to fastenings must be taken into account by additional safety or design considerations.

The design approach briefly described in the following fulfills these requirements. It is based on the concept of partial safety factors and distinguishes between the different load directions (Fig. 30) and failure modes and applies to suitable expansion and undercut anchors as well as headed studs. It can easily be modified to cover adhesive anchors as well. In general, the anchor base material is assumed as being cracked. Fastenings in uncracked concrete are considered as an exception. A full description of the design method is given in /22,26,27/.

4.2 Safety Requirements

When using partial safety factors, the following basic equations must be complied with

$$S_d \leq R_d \tag{1}$$

S_d = design actions
R_d = design resistance

Equation (1) can be applied in the limit state of serviceability (e.g., allowable displacements) or in the ultimate limit state (check for sufficient safety against failure). In the latter case, the following equations apply in the simplest case:

$$S_d = \gamma_g\, S_g + \gamma_q \cdot S_q \quad (2a)$$

$$R_d = R_{u.5\%} / \gamma_M \quad (2b)$$

with

$S_g \cdot S_q$ = design actions due to dead and variable loads, respectively
$\gamma_g \cdot \gamma_q$ = safety factor for dead and variable loads, respectively
$R_{u.5\%}$ = 5% fractile of resistance (e.g., concrete cone failure load)
γ_M = material safety factor

The partial safety factors for loads and material depend on the required reliability. Three reliability or safety classes are distinguished, depending on the consequences of a possible failure (Table 1).

TABLE 1

SAFETY CLASSES ACCORDING TO /23/

SAFETY CLASS	IN CASE OF FAILURE	
	danger for loss of human life	economic consequences
1	none	minor
2	normal	high
3	high	very high

For fastenings in safety class 1, no anchor requirements are issued by state agencies. Anchorages used to fasten structural elements usually belong to safety class 2. In certain cases (e.g. fastenings in very frequented public buildings) safety class 3 may be adopted. However, a detailed list of applications in the different safety classes has not been evaluated.

In general, for reinforced concrete structures safety class 2 is assumed, which will also be used in the following:

$\gamma_g = 1.35$
$\gamma_q = 1.50$

The factor of safety for load $[\gamma_f = (\gamma_g + Q/G \cdot \gamma_q)/(1+Q/G)]$ depends on the variable load Q to dead load G ratio. For a ratio of Q/G = 0.5 or 2.0 one gets $\gamma_f = 1.40$ or $\gamma_f = 1.45$, respectively.

The partial safety factor for material depends on the type of material used and the anticipated failure mode. Therefore, it is different for concrete and for steel failure.

The partial safety factor for concrete in compression is generally taken as $\gamma_c = 1.5$. However, the strength of fastening elements depends on the concrete tensile strength. It is well known that the tensile strength of concrete made on site varies much more than the compression strength. Furthermore, the behavior of anchors may be influenced by unavoidable installation inaccuracies. Lastly, in the region of fastenings in the "compression zone", concrete cracking may occur due to tensile stresses caused by imposed deformations not taken into account in the analysis. These additional effects can be taken into account by further partial safety factors γ_1 to γ_3, giving

$$\gamma_{Mc} = \gamma_c \cdot \gamma_1 \cdot \gamma_2 \cdot \gamma_3 \qquad (3)$$

with

γ_{Mc} = material partial safety factor for concrete failure

γ_c = partial safety factor for concrete in compression
= 1.5

γ_1 = partial safety factor to take account of the larger scatter of the tensile strength of concrete made on site compared to the compression strength
= 1.1 - 1.4 depending on the care during production and curing of concrete
≈ 1.2 for normal care

γ_2 = partial safety factor to take account of unavoidable installation inaccuracies
= 1.0 anchor systems with high installation safety
≈ 1.2 anchor systems with normal installation safety
≈ 1.4 anchor systems with low (but still acceptable) installation safety

γ_3 = partial safety factor to take account of model uncertainties
= 1.0 fastenings in cracked concrete (general case)
= 1.0 fastenings in uncracked concrete. Definition of uncracked concrete see below.
= 1.1-1.5 fastenings in the "compression zone" depending on the sensitivity to cracks of the anchorage system in question. Definition of compression zone see below.

Concrete may be assumed to be uncracked if the resulting stresses due to external loads (including the loads introduced by the fastening) and the effects of unavoidable imposed deformations (which may be a source of tensile stresses up to 2 to 3 N/mm^2) at the point of fastening in primary and secondary bearing directions of the structural element are compressive ($\sigma < 0$). In this case the risk of cracking is negligible. This definition of uncracked concrete is consistent with the design philosophy of Eurocode No. 2 /24/. In general, uncracked concrete may be assumed only in linear structural elements (columns and beams) with relatively high compression stresses from external loads.

A compression zone may be assumed when the resulting stress from external loads in the primary bearing direction of the structural element is $\sigma < 0$. Because the significant influence of tensile stresses due to unintentional restraint of deformations are neglected, the risk of cracking is relatively high (see Section 1 and Ref. 2, 3 and 28).

With $\gamma_f = 1.4$, $\gamma_c = 1.5$, $\gamma_1 = 1.2$, $\gamma_2 = 1.2$ and $\gamma_3 = 1.0$ the total safety factor $\gamma = \gamma_f \cdot \gamma_M$ amounts to $\gamma = 3.0$. For systems with high installation safety ($\gamma_2 = 1.0$) one gets $\gamma = 2.5$.

The proposed numerical values for the partial safety factors γ_1 to γ_3 have only been roughly estimated. Studies are under way to quantify them. The results reached so far indicate that the total safety factor γ may be somewhat reduced compared to the values used up to now.

In /25/ the following partial safety factors for bolts with $f_u \leq 800$ N/mm^2 (f_u = nominal steel strength) are given:

$\gamma_{Ms} = 1.5$ bolts in tension
$\gamma_{Ms} = 1.25$ bolts in shear

It must be checked, whether these factors can be applied to expansion, undercut and adhesive anchors as well.

4.3 Resistance of Fastenings

The proposed design approach distinguishes between the different load directions and failure modes. According to equation (2b), the 5%-fractile of the resistance must be calculated.

4.3.1 Tension Loading

Under tension loading, fastenings may fail by steel rupture, breakout of a concrete cone, pullout or splitting (Fig. 31).

The steel failure load can be calculated by equation (4):

$$F_{k,s} = A_s \cdot f_u \quad (4)$$

with

A_s = stress area
f_u = nominal steel strength

The concrete cone break-out load is calculated according to the generalized κ-method /4,27/. The failure load of an arbitrary fastening (single anchor or anchor group) (example see Fig. 32) is calculated by multiplying the failure load expected for a single anchor in a large concrete block by appropriate κ-factors taking into account the influence of actual spacings, edge distances and load eccentricities (Fig. 33).

Sufficiently accurate analytical expressions for the calculation of the pullout failure load of expansion and undercut anchors are not yet available. Therefore, the pullout failure load must be evaluated by tests and must be given in the certification document.

In general, the failure mode "splitting" is avoided by prescribing minimum values for spacing, edge distance and member thickness. The values are given in /27/. Furthermore, for systems with high expansion forces (e.g. torque controlled expansion anchors), the critical edge distance for full capacity may be larger than in the case of concrete cone failure.

4.3.2 Shear Loading

Under shear loading, fastenings will fail by steel rupture (large edge distance) or by breaking the concrete (small edge distance) (Fig. 34).

The steel failure load is given by equation (5).

$$F_{k,s} = 0.6 \cdot A_s \cdot f_u \quad (5)$$

The concrete break-out failure load is calculated according to the generalized κ-method /18,27,29/. It is based on the same concept as for tension loading (Fig. 35). The main difference is that in the case of tension loading, the critical spacing and the critical edge distance depend on the anchorage depth, while for shear loading they are a function of the actual edge distance in the load direction. With this method, the strength of any fastening (examples see Fig. 36) can be calculated (see equation in Fig. 35).

4.3.3 Combined Tension and Shear Loading

For combined tension and shear loading, interaction equations (6) /20/ must be fulfilled.

$$F_T/F_{T,k} \leq 1 \quad (6a)$$

$$F_S/F_{S,k} \leq 1 \quad (6b)$$

$$\frac{F_T}{F_{T,k}} + \frac{F_S}{F_{S,k}} \leq 1.2 \quad (6c)$$

with

F_T ,F_S = tension and shear part of the load, respectively, calculated with γ_f according to Section 4.2.

$F_{T,k}$;$F_{S,k}$ = characteristic tension and shear failure load, calculated according to Sections 4.3.1 and 4.3.2, respectively.

An interaction equation in the form

$$(F_T/F_{T,k})^{\alpha} + (F_S/F_{S,k}) = 1$$

with

$\alpha \approx 5/3$

might be suitable as well.

The validity of the interaction equations (6) has been proved for anchors failing the concrete or the steel when loaded in tension.

The interaction equations (6) are plotted in Fig. 37 for an anchor M 12 (h_v = 80 mm, f_u = 800 N/mm², cracked concrete with β_w = 25 N/mm²). Line 1 applies for anchors which fail under axial tension by concrete cone breakout. The rupture load of anchors which fail by pullout is much smaller than the concrete cone failure load. Anchors, which can transfer a very small axial tension load only, can safely transfer a combined tension and shear force only, when the tension force acts in connection with a shear force induced by permanent (dead) loads.

In Fig. 37 it has been assumed that the interaction equations (6) are valid for anchors which fail by pullout (line 2). The validity of this assumption must be checked by further investigations. Furthermore, the interaction relationship for anchors which can transfer a very small tension load only (line 3) must be studied by further research.

Anchors which follow line 1 or line 2 can be used in cracked concrete without any restrictions. However, for predominant tension loading, the capacity of anchors failing by pullout (line 2) may be much smaller than for anchors type 1 failing the concrete (line 1). The use of anchors with a negligible amount of tension capacity (line 3) is restricted to predominantly shear loading, where the shear force must be introduced by dead load. However, for practical considerations the author is of the opinion that a minimum tensile capacity is needed.

4.3.4 <u>Load Classes</u>

When dimensioning fastening elements with partial safety factors, the allowable load for a constant characteristic strength depends on the ratio of dead to the live load. Therefore, the characteristic strength of anchors should be classified. Such a classification is used very often in civil engineering (e.g., for cement, concrete, reinforcing and structural steel). A proposal is given in Figure 38. Figure 38 gives the characteristic concrete cone failure loads of tensioned fastening elements with the minimum embedment depth of the corresponding load class anchored in cracked concrete (strength class C 20). The characteristic load increases from one load class to another by a factor of approximately 1.5. In addition, the shear strength (steel failure) should be classified.

The advantage of such a classification is that the capacity of an anchor is characterized by two numbers. Furthermore, anchor reclassification would reduce the scatter of test results for anchors installed in various concrete strengths for tests that are performed at different conditions.

5. TESTING OF ANCHORS

5.1 General

The load carrying capability of anchors must be known and they must be suitable for the appropriate application. To determine the anchor behavior, several test procedures have been proposed, which are summarized in Fig. 39.

The design approach presented in Section 4 is appropriate for statically determinate structures as well as structural elements, which, in the case of a failure of one fastening, will result in the failure of the structure fastened because no alternative load path is available. The anchor base material (concrete) may be cracked or uncracked and the primary loading direction may be tension or shear. The UEAtc Directive of 1986 /1/ applies to expansion anchors under tension and shear loading in uncracked concrete. As previously explained, fastenings in uncracked concrete must be considered as exceptional applications, especially if - as required by Eurocode No. 2 /24/ - tensile stresses due to (unintentional) restraint of deformations are taken into account.

In general, concrete should be considered to be cracked. The UEAtc draft proposal of 1987 /30/ with some modifications in 1989 /31/ covers this situation. However, it applies only to torque controlled expansion anchors loaded in tension and failing the concrete. It does not allow pullout failures and does not take into account the beneficial effect of shear loading. This approach is on the safe side, but may be critical for some fastening systems used successfully for many years.

A test program is proposed that is appropriate for expansion, undercut and adhesive anchors for both uncracked and cracked concrete. Under tension loading, the failure mode may be concrete breakout or pullout. Furthermore, the beneficial effect of shear loading should be considered.

In many applications, the structure or structural element to be fastened is statically indeterminate. Consequently, failure of a fastening may not lead to failure of the fastened structural element because with sufficient bending strength of the fastened structural element, the load can be transferred to neighbouring fastenings (redundant system). With certain fasteners (e.g., powder actuated fasteners) only statically indeterminate structural elements can be safely fastened. The beneficial effect of redundancy should be taken into account in a test assessment program. A proposal applicable for anchors used to fasten light ceilings is given in /32/. However, a more general approach can be developed after ongoing research is completed.

The proposed test program contains two parts:

(1) tests for checking the proper functioning of a fastening system, and
(2) suitability tests for the evaluation of allowable conditions of use.

In the tests for checking the proper functioning of anchors, extreme conditions should be used (which may occur in a small number of applications, including incorrect anchor installation). However, in suitability tests, normal conditions should be used.

When testing in cracked concrete, the actual crack width may have a significant effect on the anchor behavior. Therefore, the crack widths that might occur in practice will be briefly discussed in the following section.

5.2 Crack Widths in Actual Practice

An extensive survey of crack widths in structures is presented in /28/ in order to predict expected crack widths. The results can be summarized as follows:

a) In structures built under "older" codes, crack widths $w_{95\%}$ = 0.3 to 0.4 mm have been measured under permanent loadings (Fig. 40). With respect to durability of reinforced concrete structures, the crack width under quasi-permanent loads is of major interest. The safety factor of a fastening is governed by the width of cracks which stay open over a relatively short time. This is the crack width under service loads.

Because the actual loads on the structures at the time of crack measurements were generally smaller than the allowable value, the widening of cracks under service loads to $w_{95\%} \approx 0.5$ to 0.6 mm can be expected (Fig. 41). The average crack width was about 1/3 that of $w_{95\%}$.

b) In certain structures (e.g., flat slabs and slabs spanning in two directions) intersecting cracks do occur. The number of these cracks per unit area is about 25%, and their $w_{95\%}$ width under service loads is about 50% of the corresponding values for line cracks.

c) Because the crack width has a rather small influence on the durability of concrete structures /3/, the critical crack width, $w_{95\%}$, allowed by modern codes is somewhat larger compared to older codes (Fig. 42). Under service loads, the critical crack width might reach $w_k \approx 0.4$ to 0.6 mm. Because crack formulas are rather inaccurate due to the random nature of cracking, in approximately 30% of applications, crack widths up to 20 to 30% wider than those calculated are likely to occur (Fig. 43). Therefore, the allowable critical crack widths under service loads are of the same magnitude as the actual values found in structures.

d) Due to changes in recently published codes (e.g., /24/) with respect to provisions for crack control and static analysis, and due to the increasing use of high strength steel with larger diameters, more cracks with about the same critical width value, $w_{95\%}$, but with larger values for the average crack width can be expected in the future.

e) Due to spreading forces generated during installation and subsequent loading, anchors located in cracks will increase the crack width in normal cases by up to $\Delta w \approx 0.1$ mm. In some applications the crack opening may be even more pronounced.

5.3 Test Program

Figure 44 gives an overview of the proposed tests for confirming proper functioning of anchors. The figure is based on the proposals contained in /30 and 31/ and includes modifications suggested in /28/. A rationale for the test program proposed in /30/ is given in /33/.

In the anchor proper functioning tests, extreme conditions of use should be used to ensure that the anchors will function properly under all conditions encountered in practice. According to Section 5.2, line cracks with a width $w \geq 0.6$ mm are possible. Furthermore, intersecting cracks do occur in certain types of structures. However, their widths will be smaller than the width of line cracks ($w_{95\%} = 0.3$ mm). Therefore, unfavorable conditions are present if the anchor is situated in a wide line crack or in the intersection of two cracks. Taking into account that the proposed test procedure neglects some factors which negatively influence anchor behavior (e.g., opening of a crack by expansion and loading of the anchor, or environmental actions) /28/, the crack widths in the tests should be equal to the critical value, $w_{95\%}$, expected under the service load ($w = 0.6$ mm for line cracks and $w = 0.3$ mm for intersecting cracks). The proper functioning of anchors must be checked in high and low strength concrete (test series 2 to 5).

For economical reasons it would be preferable to avoid testing anchors in intersecting cracks. However, according to past experience, it is not known for a given product, which type of crack, line or intersecting, is of major influence on anchor behavior. Furthermore, it is not known whether, or under which conditions, tests in intersecting cracks may be replaced by tests in line cracks. Further research is being conducted at the University of Stuttgart. As long as these results are not available, tests in line and intersecting cracks are considered necessary. It should be noted that the number of required tests per series ($n = 5$) is rather small. If tests in intersecting cracks would not be performed, it seems necessary to increase the number of tests in line cracks to get a sufficiently reliable picture of the anchor behavior.

In test series 1, the installation safety is checked. While the anchor installation should model extreme inaccuracies which might occur in practice, the anchor base material should represent "normal" conditions (line cracks with $\Delta w = 0.3$ mm). However, before defining the test conditions, it should be known in detail how the different types of anchors are installed in practice.

In Ref. 30 and 31, a different approach is proposed: extreme cracks (intersecting cracks with $w = 0.3$ mm) in combination with modest installation inaccuracies ($M_T = 0.5 \times M_T$ (req.) for torque controlled expansion anchors). The proposal in Fig. 44 (normal cracks in combination with extreme installation inaccuracies) might be more meaningful.

For test series 1 to 5, the load must continuously increase with increasing deformations (Fig. 45). Horizontal portions of the load-displacement relationship curve, which may be caused by slip of the anchor in the hole, are not allowed. The reasons for this are given in Section 3.1.2. Furthermore, the failure load must reach a certain fraction of the value expected under normal conditions (line cracks with $\Delta w = 0.3$ mm).

The loading history of structures designed for static loading may vary during the lifetime of the building. This leads to opening and closing of cracks. If anchors are situated in cracks and stressed by a tension load, they will expand further or may slip during each cycle of crack opening and closing.

Unsuitable anchors may even pull out. The latter cannot be allowed in practice.

These conditions are limited in the so-called "reliability" tests. The anchors are loaded with a constant tension load ($F = 1.3 \times F_{adm}$) and then the cracks are opened between given upper and lower widths. These widths should reflect "normal" conditions found in practical applications.

The proposed upper crack width (w = 0.3 mm) coincides with allowable design values under quasi-permanent loads and is almost equal to the average crack width under allowable service loads. The lower crack width (w = 0.1 mm) reflects the conditions in industrial buildings /33/.

Taking into account that the widths of intersecting cracks are smaller than line cracks, the conditions for the reliability tests with anchors in intersecting cracks should be reconsidered.

The anchor displacements as a function of the number of crack openings - plotted on a semi-logarithmic scale - must be linear or decreasing, respectively (Fig. 46). A progressive increase of the displacement is not allowed, because it may indicate slip of the sleeve and pullout during subsequent cycles. Furthermore, the load-displacement curve measured in a subsequent pullout test must fulfil the requirements given in Fig. 45, and the failure load must reach a certain value.

In the tests for assessing the permissible load, normal conditions should be used. Tests in line cracks with a width, w = 0.3 mm, are appropriate (see above and Fig. 47). The load-displacement curves must fulfill the conditions given in Fig. 45. These tests can be omitted if the failure load of tests in wide line cracks reaches the value of the corresponding load class. This will often be the case (compare Fig. 10).

The proposed test conditions may be taken as an acceptable compromise between safety requirements and the anchor development possibilities of manufacturers. Experience has shown that many products do comply with these requirements. However, the design of torque controlled expansion anchors used up to now had to be modified. This is understandable, because the current anchors were optimized for use in uncracked concrete and were not designed for use in cracked concrete.

The test program proposed in /30/ is appropriate for torque controlled expansion anchors which have been tested in uncracked concrete in accordance with /1/. Because many of the tests required in /1/ are not necessary when testing in cracked concrete, the necessary tests in uncracked concrete should be stated in the test program. Furthermore, the program must be enlarged to cover deformation controlled expansion, undercut, and adhesive anchors as well.

As explained above, the proposed test program pertains to anchors which are loaded predominantly in tension and are used to fasten statically determinate structures. Because no alternative load path is available in case the fastening fails, the anchor must function properly under extreme conditions. The behavior of anchors loaded predominantly in shear is not greatly affected by cracks in the concrete and by the crack width. This beneficial effect should be taken into account in the test program.

For anchors which fail under tension loading by a rupture of the steel or by concrete cone breakout, no further tests are required. The allowable conditions of use can be calculated according to the design concept described in Section 4. For other types of anchors, more research is needed to clarify all aspects of anchor behavior under combined tension and shear loading before drafting a test program.

6. SUMMARY

a) The design of fastenings should be based on the assumption that concrete cracks. This assumption agrees with the design concept of reinforced concrete structures serving as anchor base material.

The assumption of uncracked concrete is justified in exceptional cases only. When checking whether concrete is likely to crack or not, tensile stresses due to external loads and due to (unintentional) restraint of deformations must be taken into account. This agrees with Eurocode No. 2 /24/.

b) Under tension loading, the anchor behavior is significantly influenced by cracks, depending on the type and design of the anchor. If the failure is caused by concrete cone breakout, the failure load is reduced by approximately 30 - 40% compared to the value expected in uncracked concrete. If the failure is caused by pullout (expansion or adhesive anchors), the reduction of the failure load may be much higher. Furthermore, installation inaccuracies which do not significantly influence the anchor behavior in uncracked concrete may have pronounced negative effect on anchors installed in cracked concrete.

Under shear loading, the behavior of all types of anchors, away from edges, is minimally influenced by cracks. The failure load of fastenings close to the edge is reduced by cracks. However, the reduction is almost independent of the anchor type.

The failure load of anchors under combined tension and shear loading can be expressed by simple interaction equations, if the holding power is large enough to cause a concrete or steel failure under tension loading. The behavior of other types of anchors under combined tension and shear loading is currently being researched at the University of Stuttgart.

c) A method for the design of fastenings based on rational engineering models is proposed. It uses the concept of partial safety factors, which is also employed in modern codes, and distinguishes among the different loading directions and failure modes.

Anchors which can transfer a very small axial tension load in cracked concrete may be used under combined tension and shear forces where the shear is induced by dead loads.

d) The suitability of anchors to be used in cracked concrete must be investigated by appropriate tests. It is proposed to work out a directive for the assessment of all types of anchors (expansion, undercut, and adhesive) used in cracked and uncracked concrete under tension, shear and combined tension and shear loading. Test requirements for checking the proper functioning and for evaluating permissible conditions of use of anchors in cracked concrete loaded in tension are proposed. They are based on an extensive survey that occurs in practice /28/, and takes into account the results of extensive research during the last ten years.

For anchors which fail under tension loading by steel rupture or by breakout of a concrete cone, no further tests are necessary. For other types of anchors, ongoing research programs should be completed prior to drafting a test program which considers the beneficial effect of shear loading.

In the future, fastenings to concrete by different types of anchors should be designed and installed with the same confidence and reliability as other connections in steel and concrete structures. In order to do this, a rational design approach in accordance with modern safety concepts and using anchors with a high built-in installation certainty are needed. The proposed concept seems to be a step in the right direction. It allows anchors which have been developed for use in uncracked concrete to be used in the future in cracked concrete in their main field of application, which, according to an extensive survey /35/ is combined tension and shear loading. Furthermore, it encourages producers to develop anchors with high tensile capacity in cracked concrete and high installation safety, because these anchors are rewarded by a low material safety factor and have an unrestricted field of application.

REFERENCES

/1/ UEAtc Directive for Assessment of Anchor Bolts No. 42:1986, Paris, Dec. 1986.

/2/ Beeby, A.W.: "Causes of Cracking". Proceedings, CEB/RILEM Workshop on "Durability of Concrete Structures", Copenhagen, 1983, also in CEB Bulletin No. 158 "Cracking and Deformation", Paris, 1983.

/3/ Schiessl, P.: "Einfluss von Rissen auf die Dauerhaftigkeit von Stahbeton- und Spannbetonbauteilen" (Influence of Cracks on the Durability of Reinforced and Prestressed Concrete Structures). Deutscher Ausschuss für Stahbeton, Heft 370, Verlag W. Ernst & Sohn, Berlin, 1986, in German.

/4/ Eligehausen, R; Fuchs, W.; Mayer, B.: "Tragverhalten von Dübelbefestigungen unter Zugbeanspruchung" (Bearing Behaviour of Anchor Fastenings under Tension). Betonwerk + Fertigteil-Technik, Dec. 1987 and Jan. 1988, in German and English.

/5/ Lotze, D.: "Untersuchungen zur Frage der Wahrscheinlichkeit, mit der Dübel in Rissen liegen - Einfluss der Querbewehrung" (Investigations on the Probability for Anchors to be Situated in Cracks - Influence of Transverse Reinforcement). Unpublished report No. 1/24-87/6, Institute for Building Materials, University of Stuttgart, Sept. 1987, in German.

/6/ Eligehausen, R.; Lotze, D.; Sawade, G.: "Untersuchungen zur Frage der Wahrscheinlichkeit, mit der Dübel in Rissen liegen" (Investigations on the Probability for Anchors to be Situated in Cracks). Unpublished report No. 1/20-86/17, Institute for Building Materials, University of Stuttgart, October 1986. in German.

/7/ Mayer, R.: "Wahrscheinlichkeit, mit der Dübel in Rissen liegen" (Probability for Anchors to be Situated in Cracks). Unpublished report No. 1/35-88/22, Institute for Building Materials, University of Stuttgart, Nov. 1988, in German.

/8/ Hsu, T.: "Wahrscheinlichkeit, mit der Dübel in Rissen liegen" (Probability for Anchors to be Situated in Cracks). Diploma Thesis, Institute for Building Materials, University of Stuttgart, April 1989, in German.

/9/ Bergmeister, K.: "Stochastik in der Befestigungstechnik mit realistischen Einflussgrössen" (Stochastic Methods in Fastenings with Realistic Influencing Factors). Dissertation, University of Innsbruck, 1988, in German.

/9a/ Bensimhon, J.: "Étude du Comportement de Chevilles Implantées en Zone Tendue et Fissurée du Béton" (Study on the Behavior of Anchors Installed in the Tensile Zone of Cracked Concrete). Report of the Centre Scientifique et Technique du Batiment, April 1989, in French.

/10/ Eligehausen, R.; Lehmann, R.: "Verankerungen mit Metallspreizdübeln in der Zugzone von Stahlbetonbauteilen" (Fastenings with Metal Expansion Anchors in the Tensile Zone of Reinforced Concrete Members). Unpublished report No. 1/4-84/1, Institute for Building Materials, University of Stuttgart, Jan. 1984, in German.

/11/ Eligehausen, R.: "Wechselbeziehungen zwischen Befestigungstechnik und Stahlbetonbauweise" (Interdependencies between Fastening Technology and Reinforced Concrete Construction). In "Fortschritte im konstruktiven Ingenieurbau", Verlag W. Ernst & Sohn, Berlin, 1984, in German.

/12/ Dieterle, H.; Opitz, V.: "Tragverhalten von nicht generell zugzonentauglichen Dübeln"; Teil 1: Verhalten in Parallelrissen (Bearing Behavior of Anchors Designed for Use in Uncracked Concrete; Part 1: Behavior in Line Cracks). Unpublished report No. 1/34-88/21, Institute for Building Materials, University of Stuttgart, November 1988, in German.

/13/ Dieterle, H.; Opitz, V.: "Tragverhalten von nicht generell zugzonentauglichen Dübeln"; Teil 2: Verhalten im ungerissenen Beton und im bewegten Parallelriss (Bearing Behavior of Anchors Designed for Use in Uncracked Concrete; Part 2: Behavior in Uncracked Concrete and in Opened and Closed Line Cracks). Unpublished report No. 1/36-89/1, Institute for Building Materials, University of Stuttgart, January 1989, in German.

/14/ Hahn, C.; Opitz, V.: "Tragverhalten von nicht generell zugzonentauglichen Dübeln"; Teil 3: Verhalten im unbewegten und bewegten Kreuzriss (Behavior of Anchors Designed for Use in Uncracked Concrete; Part 3: Behavior in Intersecting

Cracks with Constant and Changing Crack Widths). Unpublished report No. 1/37-89/4, Institute for Building Materials, University of Stuttgart, April 1989, in German.

/15/ Eligehausen, R.; Mallée; R.; Rehm, G.: "Befestigungen mit Verbundankern" (Fastenings with Adhesive Anchors). Betonwerk + Fertigteil-Technik, 1984, Hefte 10-12, in German and English.

/16/ Rehm, G.; Lehmann, R.: "Untersuchungen mit Metall-spreizdübeln in der gerissenen Zugzone von Stahlbetonbalken" (Investigation with Metal Expansion Anchors in the Cracked Tension Zone of Reinforced Concrete Beams). Forschungsbericht, Forschungs- und Materialprufüngsanstalt Baden-Wurttemberg, Research Report, Stuttgart, March 1980, in German.

/17/ Mayer, B.; Eligehausen, R.: "Ankergruppen mit Dübeln in der Betonzugzone" (Anchor Groups in the Concrete Tensile Zone), In: Werkstoffe und Konstruktion, Institute for Building Materials, University of Stuggart, und Forschungs- und Materialprufungsanstalt Baden-Württemberg (Eigenverlag), Oct. 1984, in German.

/18/ Fuchs, W.; Eligehausen, R.: "Tragverhalten von Befestigungsmitteln im gerissenen Beton bei Querzugbeanspruchung" (Behaviour of Fastenings in Cracked Concrete under Stress Loading). Bericht Nr. 1/41-89/15, Institute for Building Materials, University of Stuttgart, July 1989, in German.

/19/ Eligehausen, R.; Vintzéleou, E.: "Behavior of Metallic Anchors under Generalized Excitations". Proceedings, Ninth World Earthquake Engineering Conference, Tokyo, August 1988.

/20/ Bode, H.; Hanenkamp, W.: "Zur Tragfähigkeith von Kopfbolzen bei Zugbeanspruchung" (Strength of Headed Studs under Tension Loading). Bauingenieur, 1985, in German.

/21/ Dieterle, H.; Bozenhardt, A.; Hirth, and Opitz, V.: "Tragverhalten von nicht generell zugzonentauglichen Dübeln; Teil 4: Verhalten im Parallelriss (ΔW = 0.4 mm) unter Schrägzugbeanspruchung (Behavior of Anchors Not Generally Suitable for Use in Cracked Concrete, Part 4: Behavior under Combined Tension and Shear Loading in Line Cracks, ΔW = 0.4 mm) Unpublished Report No. 1/45-89/15, Institute for Building Materials, University of Stuttgart, Feb. 1990, in German.

/22/ Eligehausen, R.: "Bemessung von Befestigungen - zukünftiges Konzept" (Design of Fastenings - Future Concept). Beton + Fertigteil-Technik, Heft 5, 1988, in German and English.

/23/ Eurocode No. 1: Common Unified Rules for Different Materials and Types of Construction, 1988.

/24/ Eurocode No. 2: Design of Concrete Structures. Part 1: General Rules and Rules for Buildings, Final draft, Dec. 1988.

/25/ Eurocode No. 3: Design of Steel Structures. Part 1: General Rules and Rules for Buildings, Preliminary version, July 1988.

/26/ Eligehausen, R.: "Bemessung von Befestigungen mit Teilsicherheitsbeiwerten" (Design of Fastenings with Partial Safety Factors). Unpublished report No. 6/6-89/17, Institute for Building Materials, University of Stuttgart, Sept. 1989, in German.

/27/ Rehm, G.; Eligehausen, R.; Mallée, R.: "Befestigungstechnik" (Fastening Technique). Beton-kalender 1988, Teil 2, Verlag W. Ernst & Sohn, Berlin, 1988, in German.

/28/ Eligehausen, R.; Bozenhardt, A.: "Crack Widths as Measured in Actual Structures and Conclusions for Testing of Fastening Elements" Report No. 1/42-89/9, Institute for Building Materials, University of Stuttgart, August 1989, in German.

/29/ Eligehausen, R.; Fuchs, W.: "Tragverhalten von Dübelbefestigungen unter Querzug-, Schrägzug- und Biegebeanspruchung" (Bearing Behavior of Anchor Fastenings under Shear, Combined Tension and Shear Loading and Bending Moments). Betonwerk + Fertigteil Technik, Heft 2, 1988, in German and English.

/30/ UEAtc Directive for the Assessment of Anchor Bolts to be Used in the Concrete Tensile Zone. 1st Draft, Sept. 1987.

/31/ Eligehausen, R.: UEAtc-Test Program for Anchor Bolts to be Used in the Concrete Tensile Zone. Draft Proposal, April 1989.

/32/ Institut für Bautechnik, Berlin: "Zulassungsprüfungen für Dübel zur Befestigung von leichten Underdecken an Stahlbetondecken" (Approval Tests for Anchors for Fastening of Light Ceilings to Reinforced Concrete Slabs) Fassung October 1976, in German, not published.

/33/ Eligehausen, R.; Tewes, R.: "Rationale for the UEAtc Draft Directives on Anchor Bolts Used in the Tensile Zone of Reinforced Concrete Members". Report No. 1/29-88/4, Institute for Building Materials, University of Stuttgart, Dec. 1987, in German.

/34/ Schiessl, P.: "Grundlagen der Neuregelung zur Beschränkung der Rissbreite" (Rationale of the New Regulations for Crack Width Control). Deutscher Ausschuss für Stahlbeton, Heft 400, Berlin, 1989.

/35/ Paterson, W.S.: "Survey of Fixing Application and Cracking in Concrete". Laing Technology Group Limited, Report No. RD89/38/LS, April 1989.

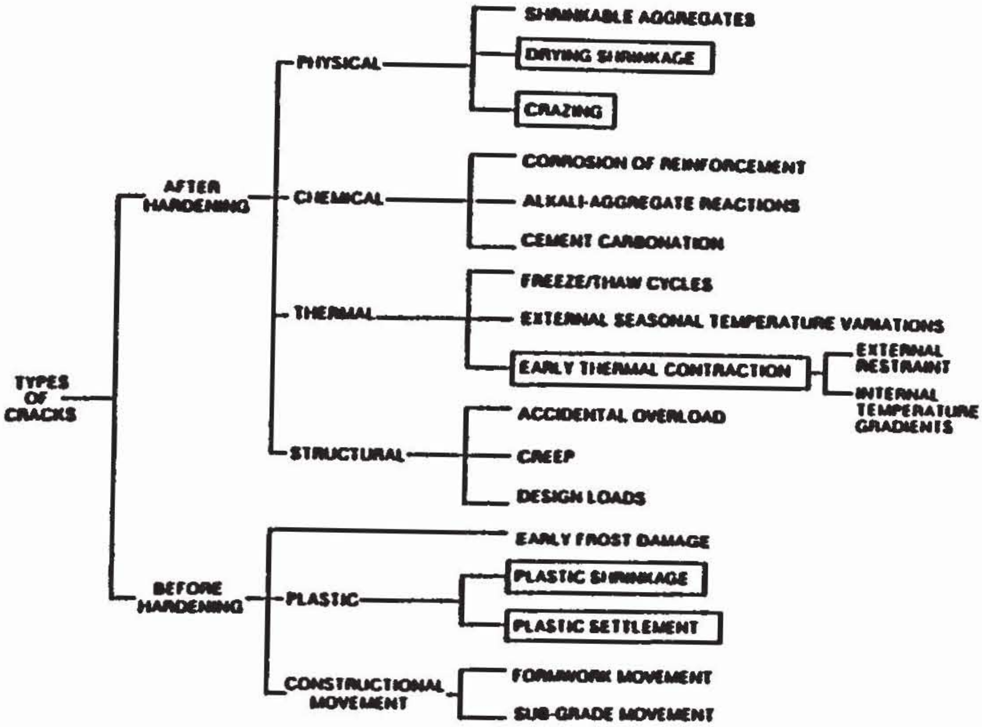


Fig. 1--Causes of cracking (after Beeby /2/)

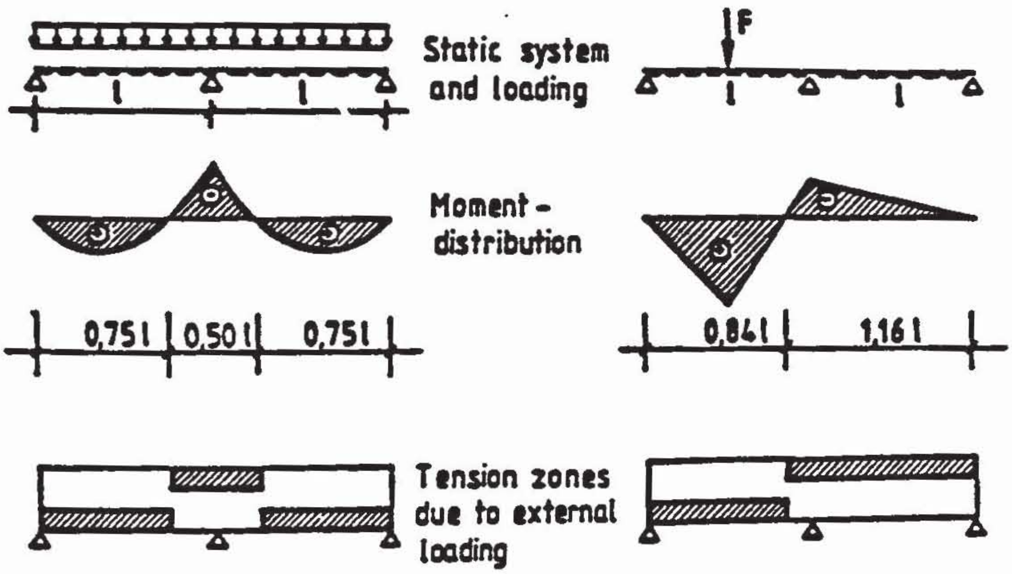


Fig. 2--Tension zones due to external loading for a two-span beam (after /4/)

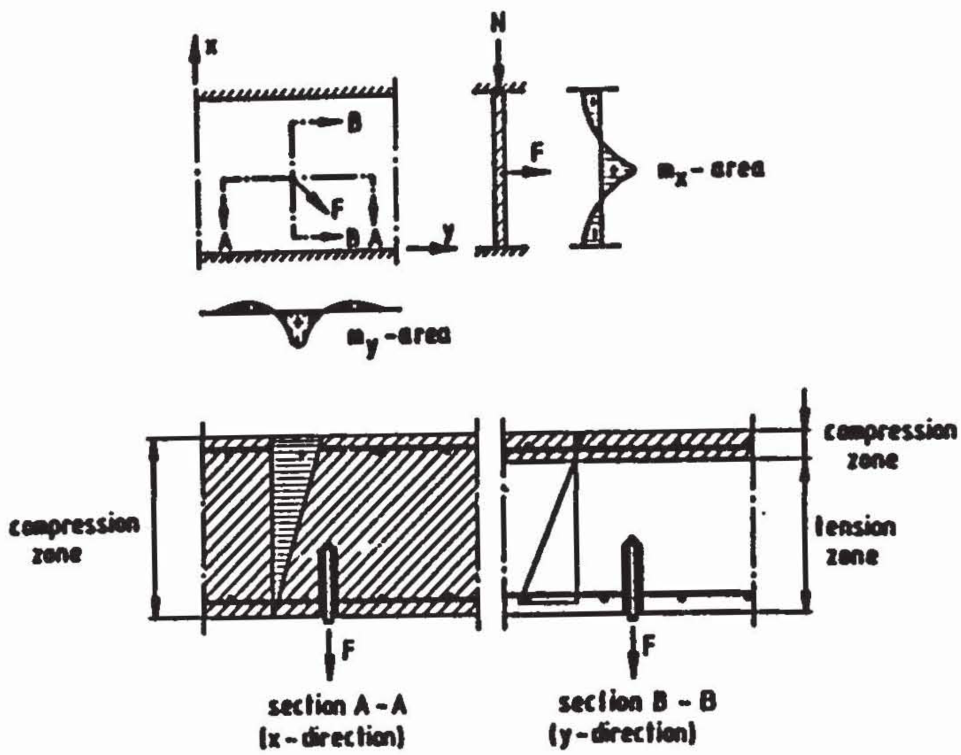


Fig. 3--Anchors in a wall (after /11/)

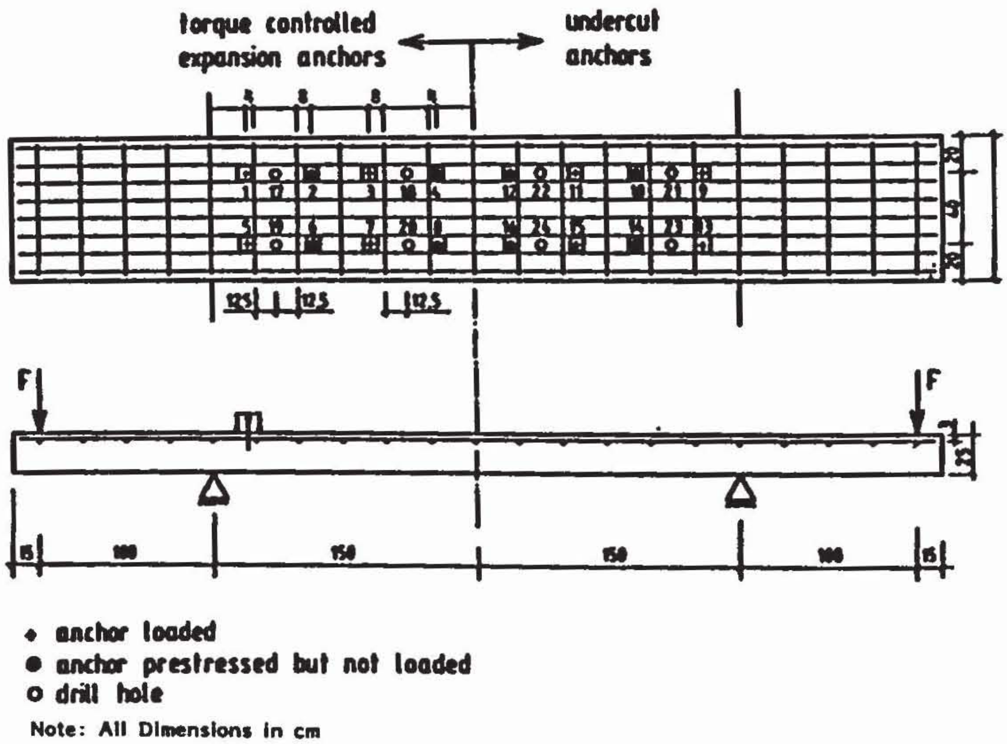


Fig. 4--Test set-up and anchor pattern (after /5/)

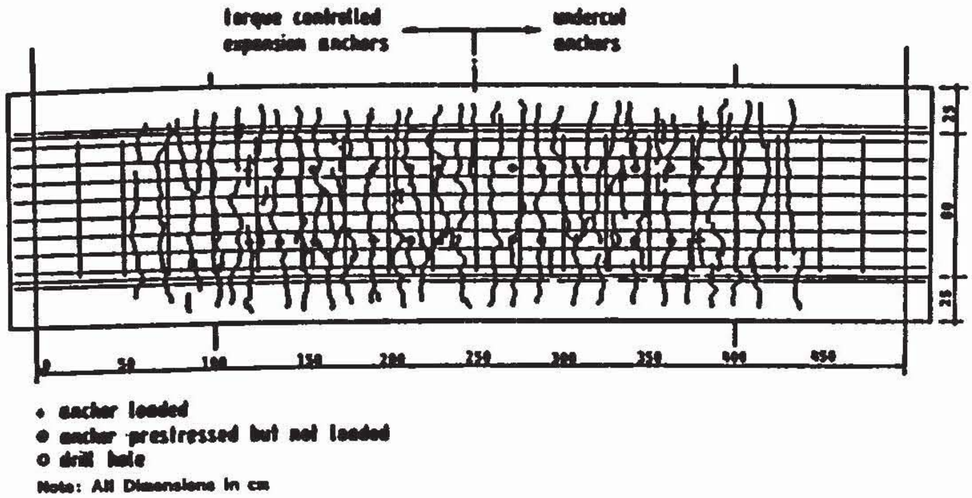


Fig. 5--Crack pattern at service load (after /5/)

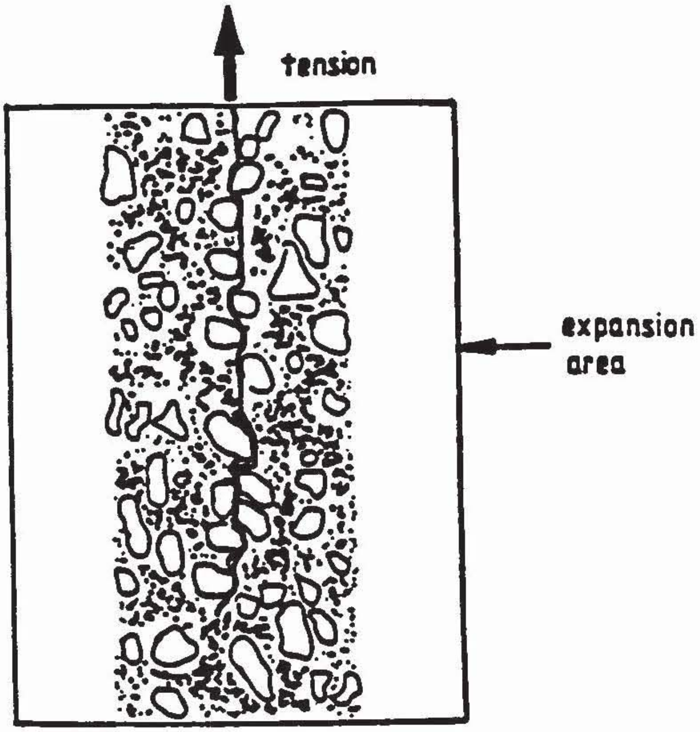


Fig. 6--Cracking as to be seen from the lateral surface of the drill core (after /6/)

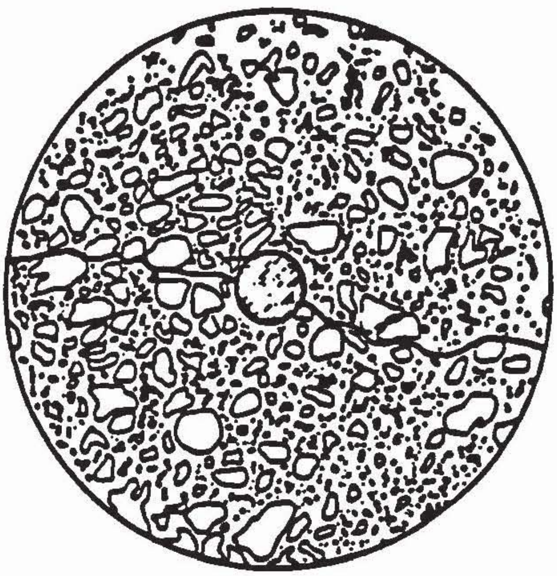


Fig. 7--Cracking in the expansion area (after /6/)

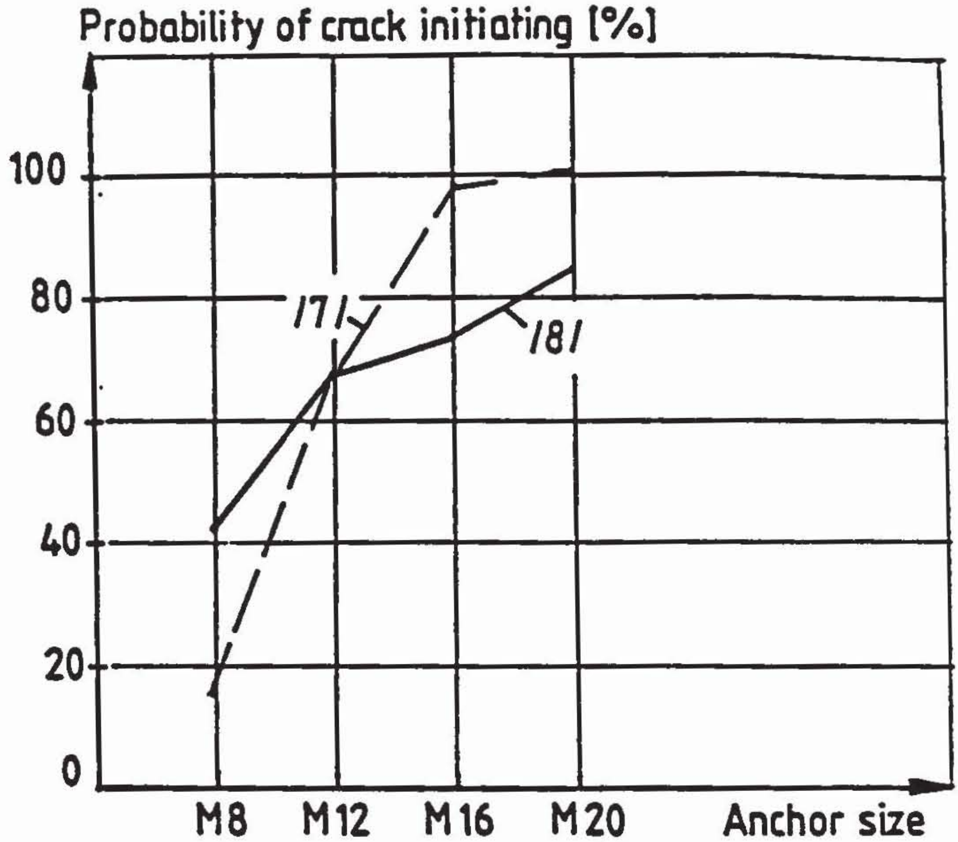


Fig. 8--Probability that cracking is initiated by torque controlled expansion anchors, concrete strength C 20 (after /7, 8/)

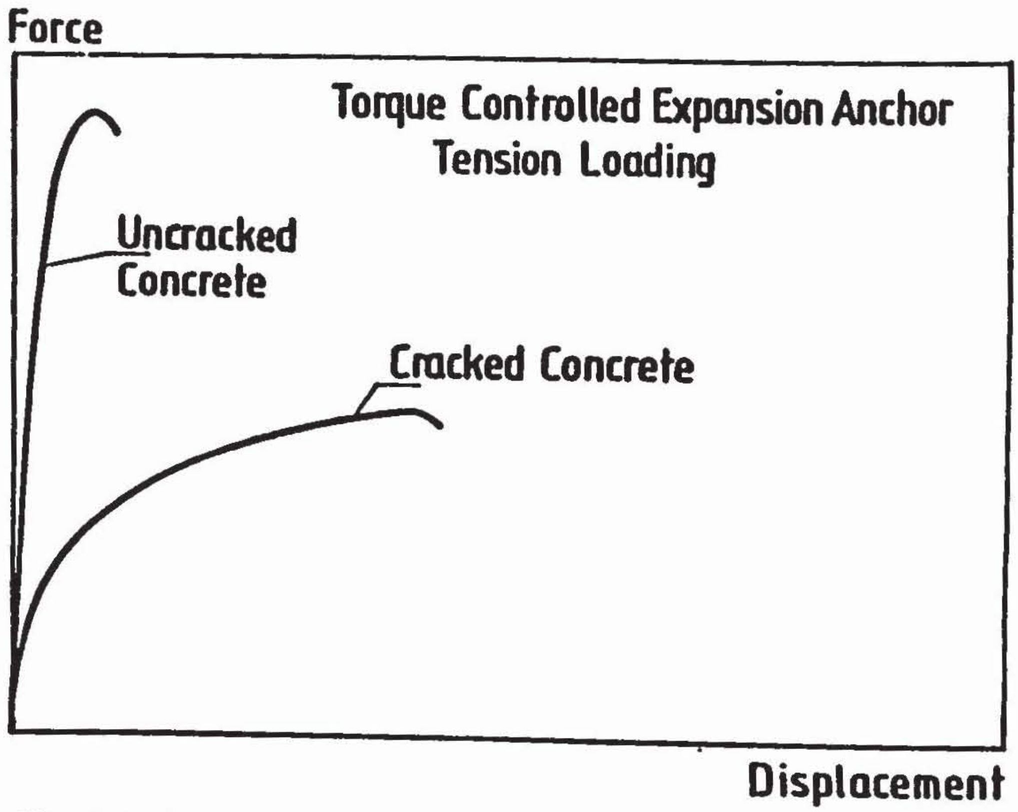
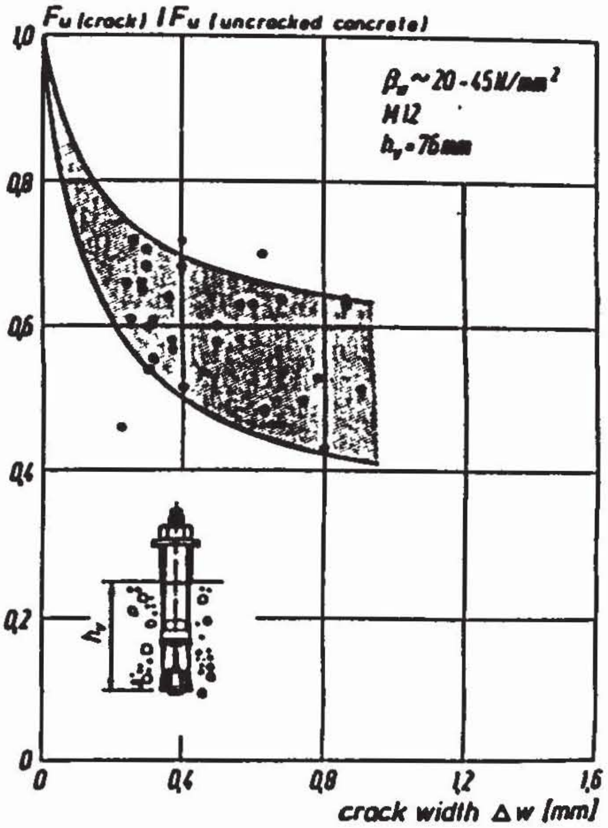


Fig. 9--Influence of cracks on the load-displacement relationships of expansion anchors (schematic) (after /10/)



a) Undercut anchors and headed studs

b) Torque controlled anchors

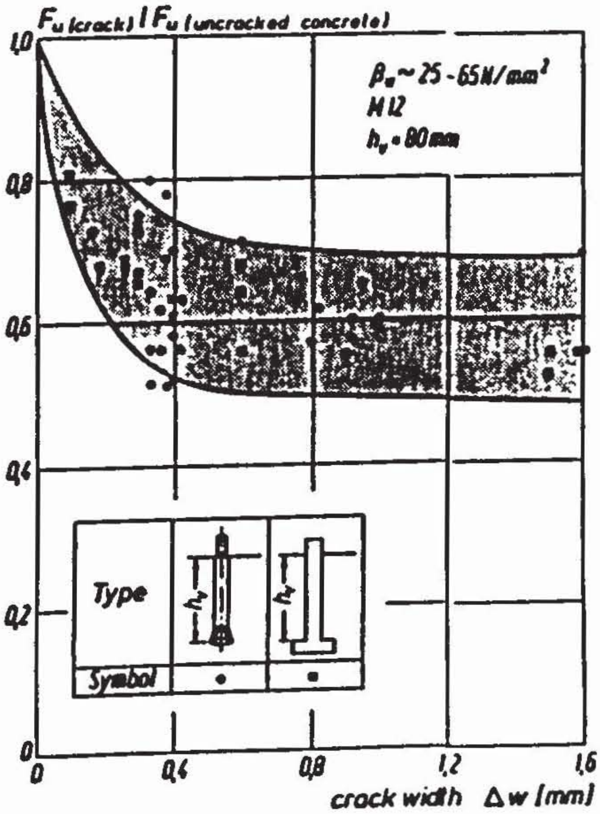
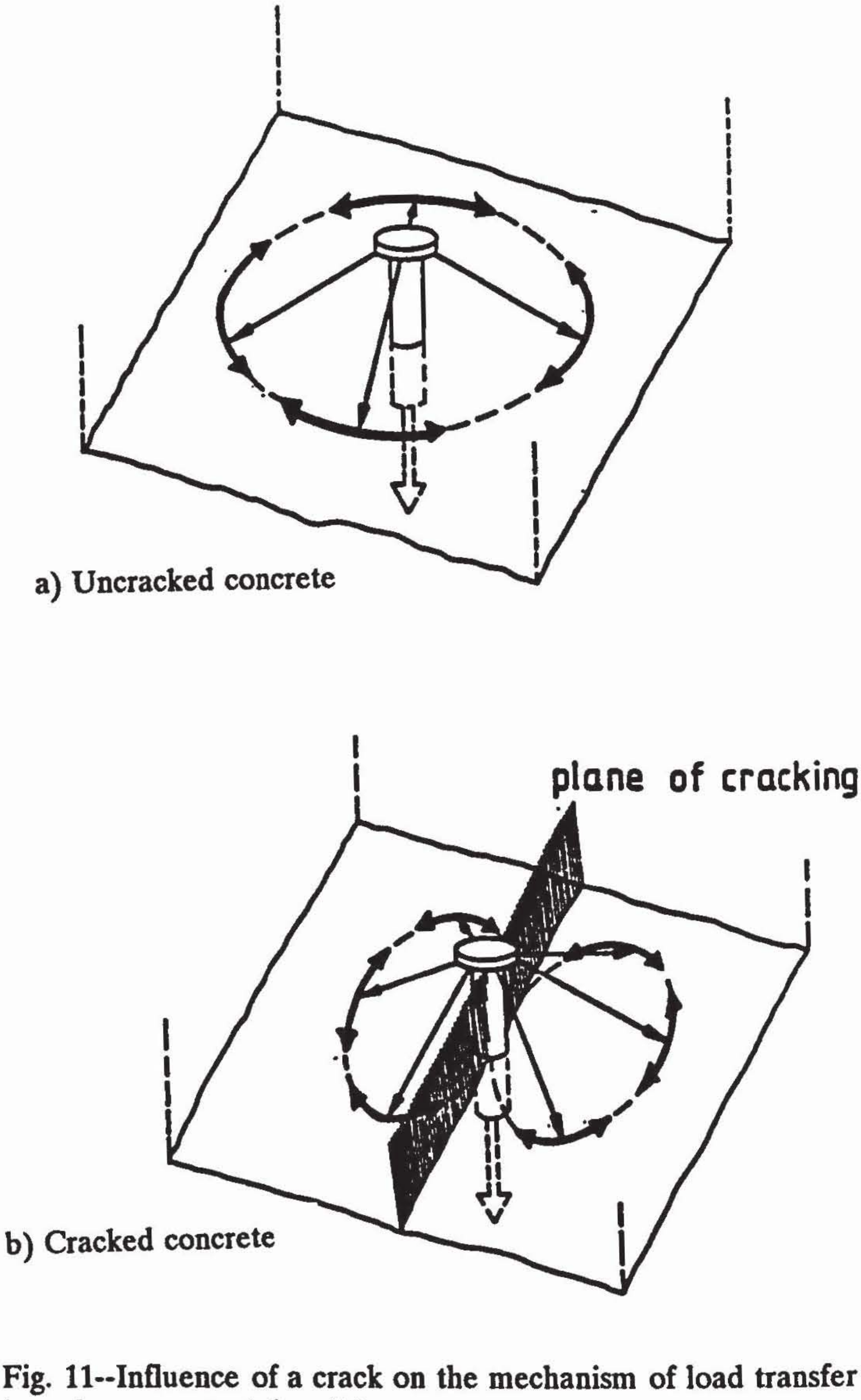


Fig. 10--Bearing capacity of fastenings in cracks under tension loading (after /11/)



a) Uncracked concrete

b) Cracked concrete

Fig. 11--Influence of a crack on the mechanism of load transfer into the concrete (after /4/)

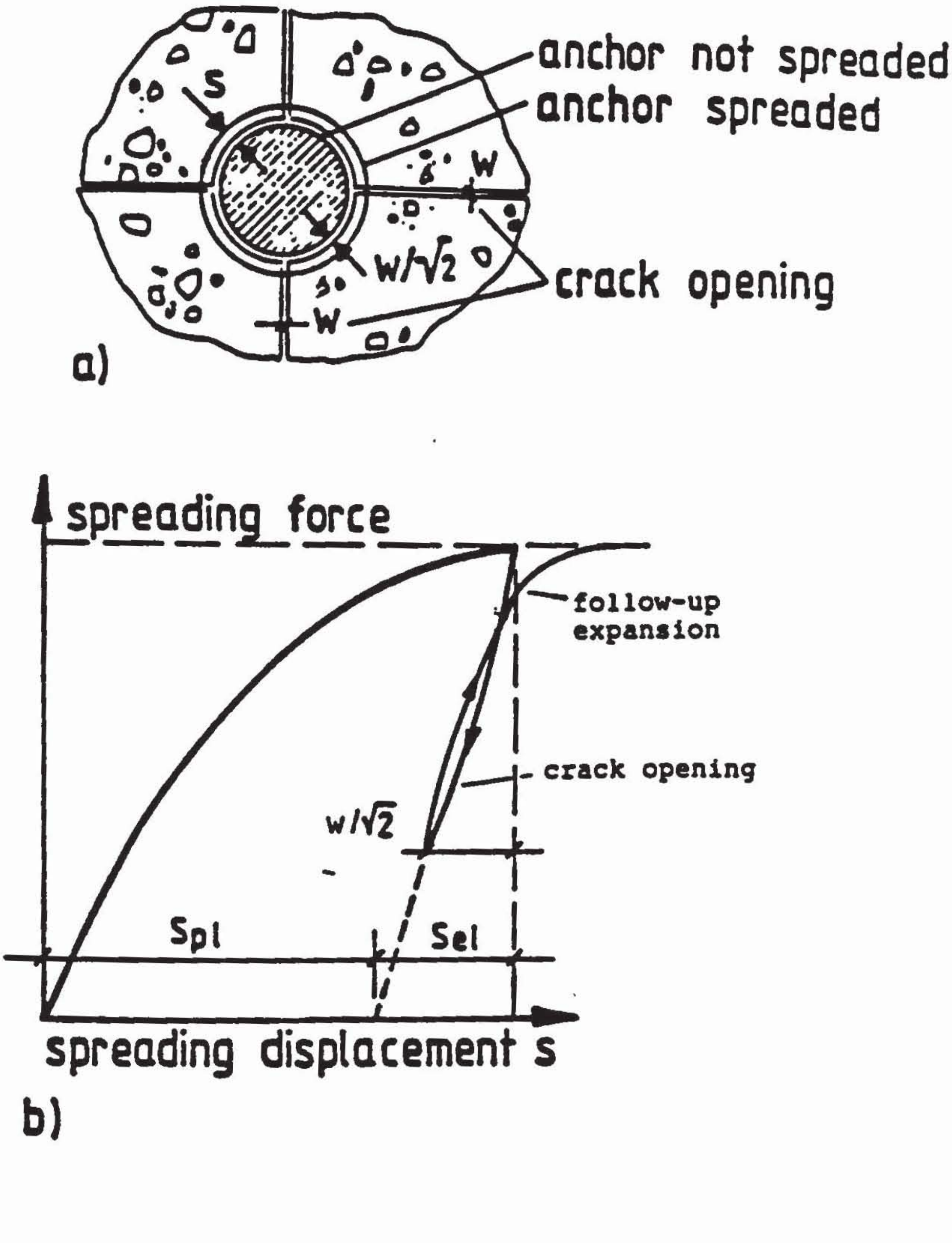


Fig. 12--Influence of crack opening on the spreading force of expansion anchors (after /4/)

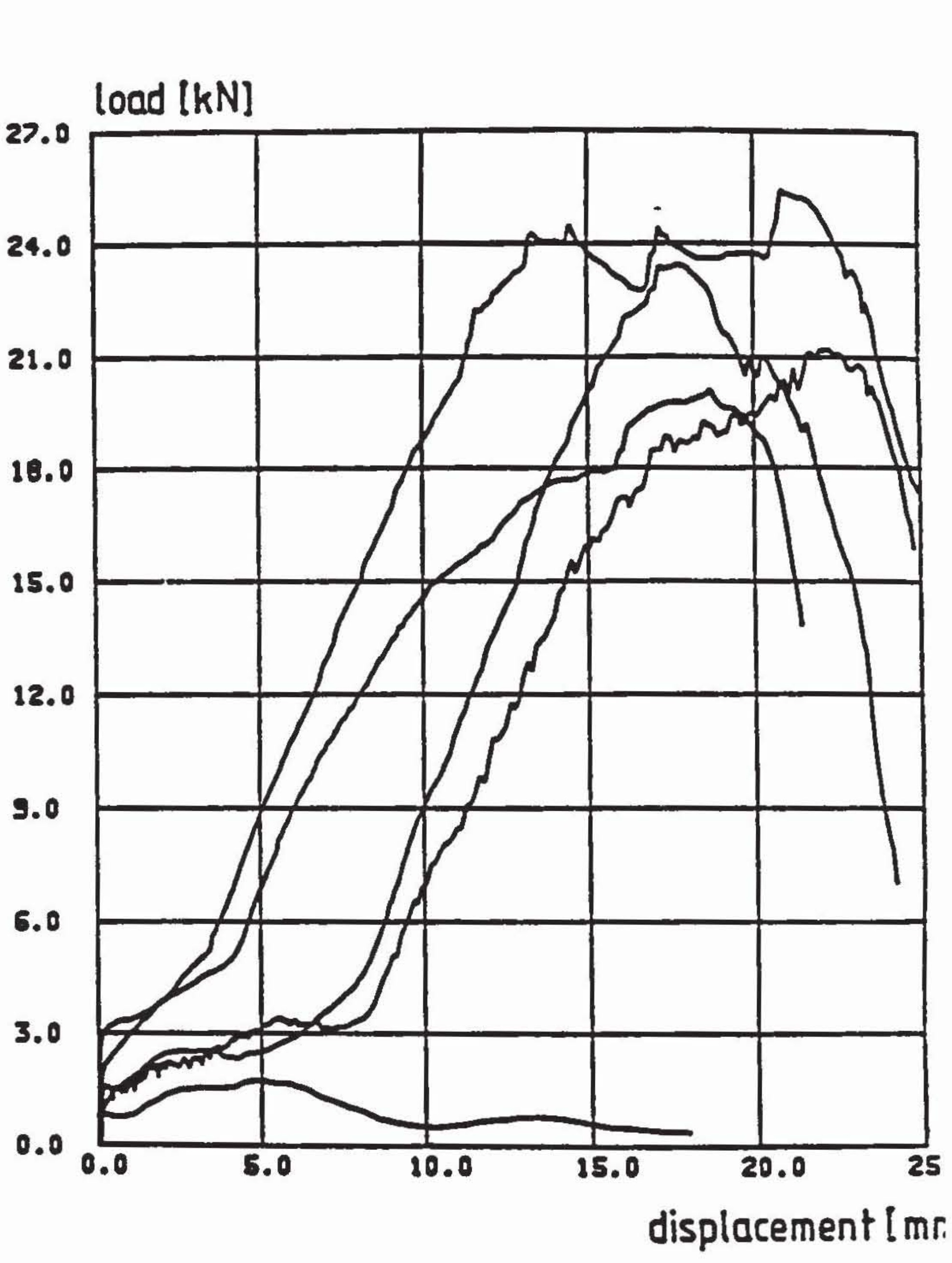


Fig. 13--Load-deformation relationships of torque controlled expansion anchors M 12, h_v = 60 mm in line cracks Δ_w = 0.4 mm, M_T = req. M_T (after /12/)

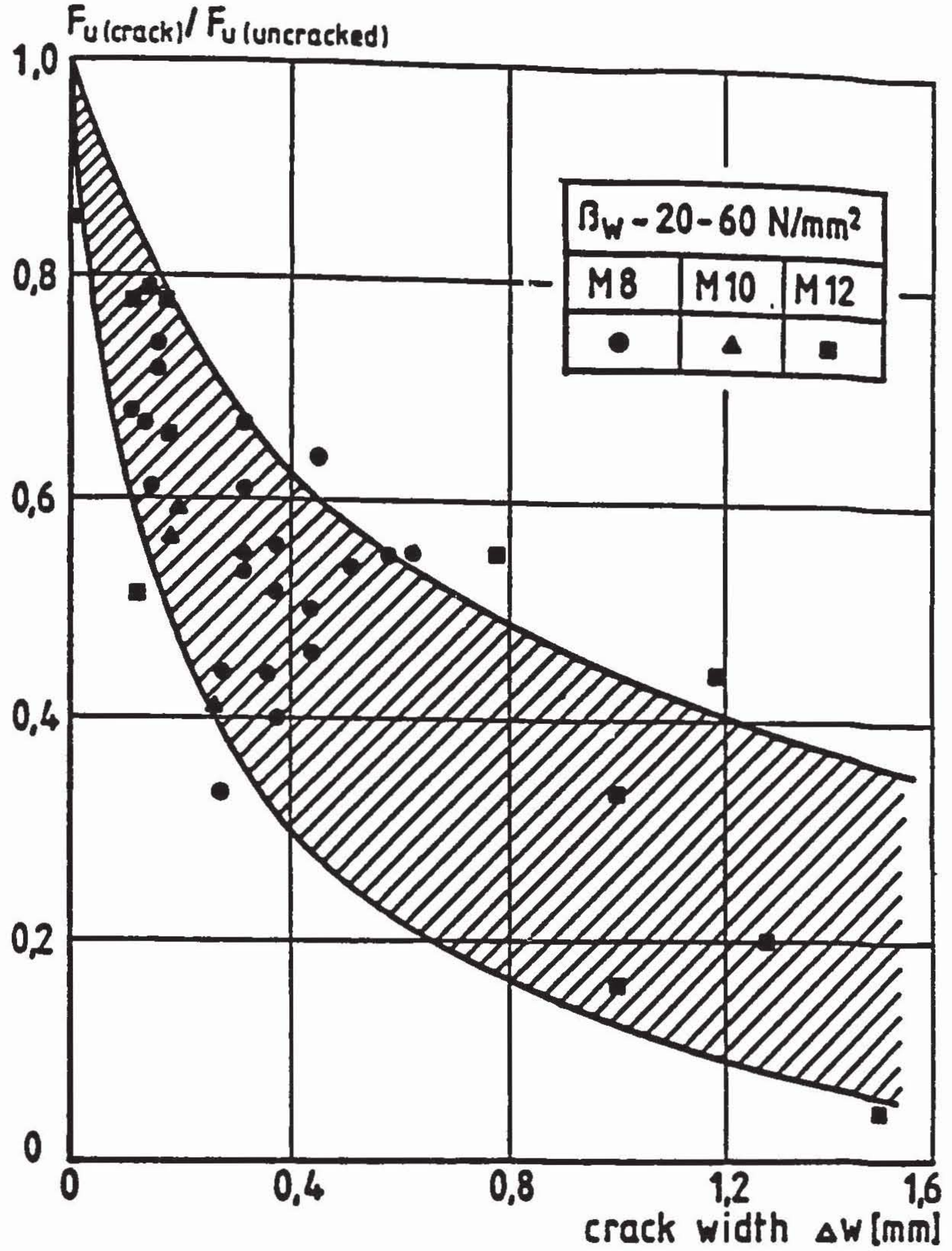
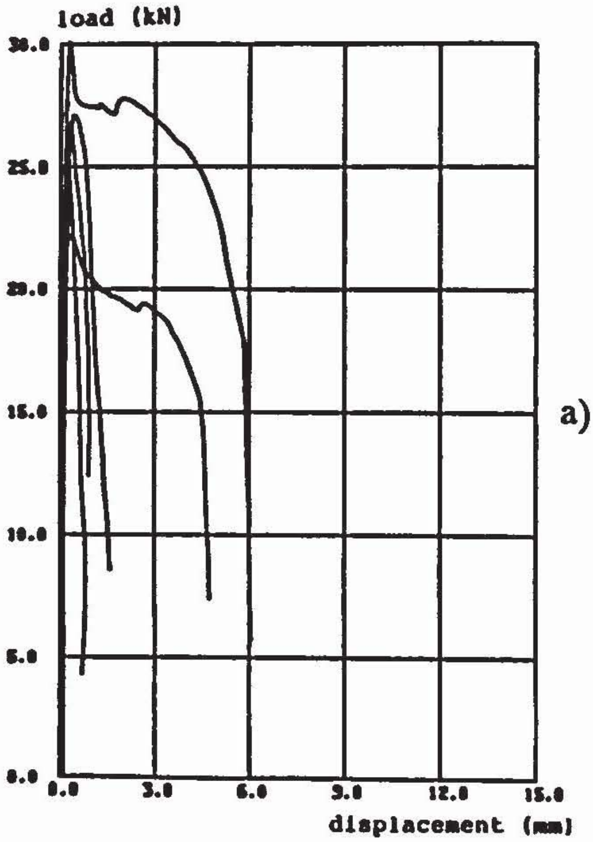


Fig. 14--Strength of drop-in anchors in line cracks under tension loading (after /11/)



a) Uncracked concrete

b) Line cracks Δ_w = 0.4 mm

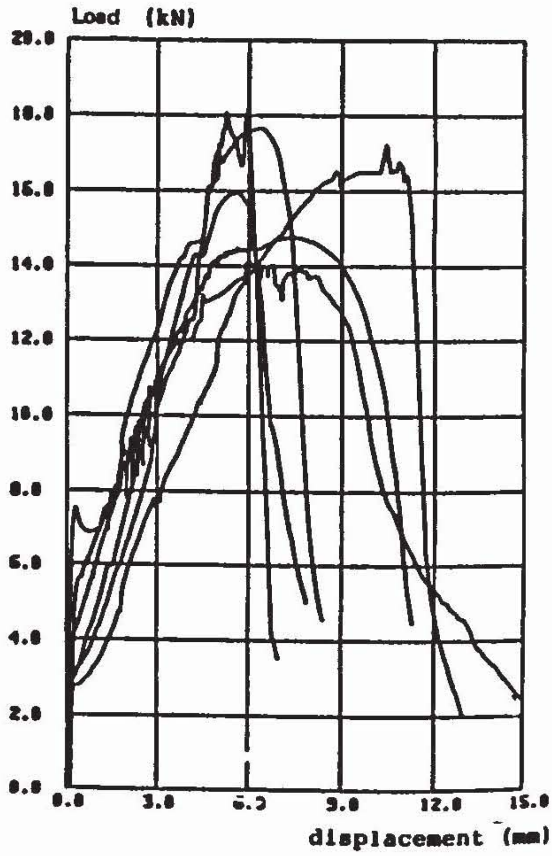


Fig. 15--Load-displacement curves of drop-in anchors M 12, h_v = 50 mm, β_w ~ 30 N/mm^2, (after /12/ and /13/)

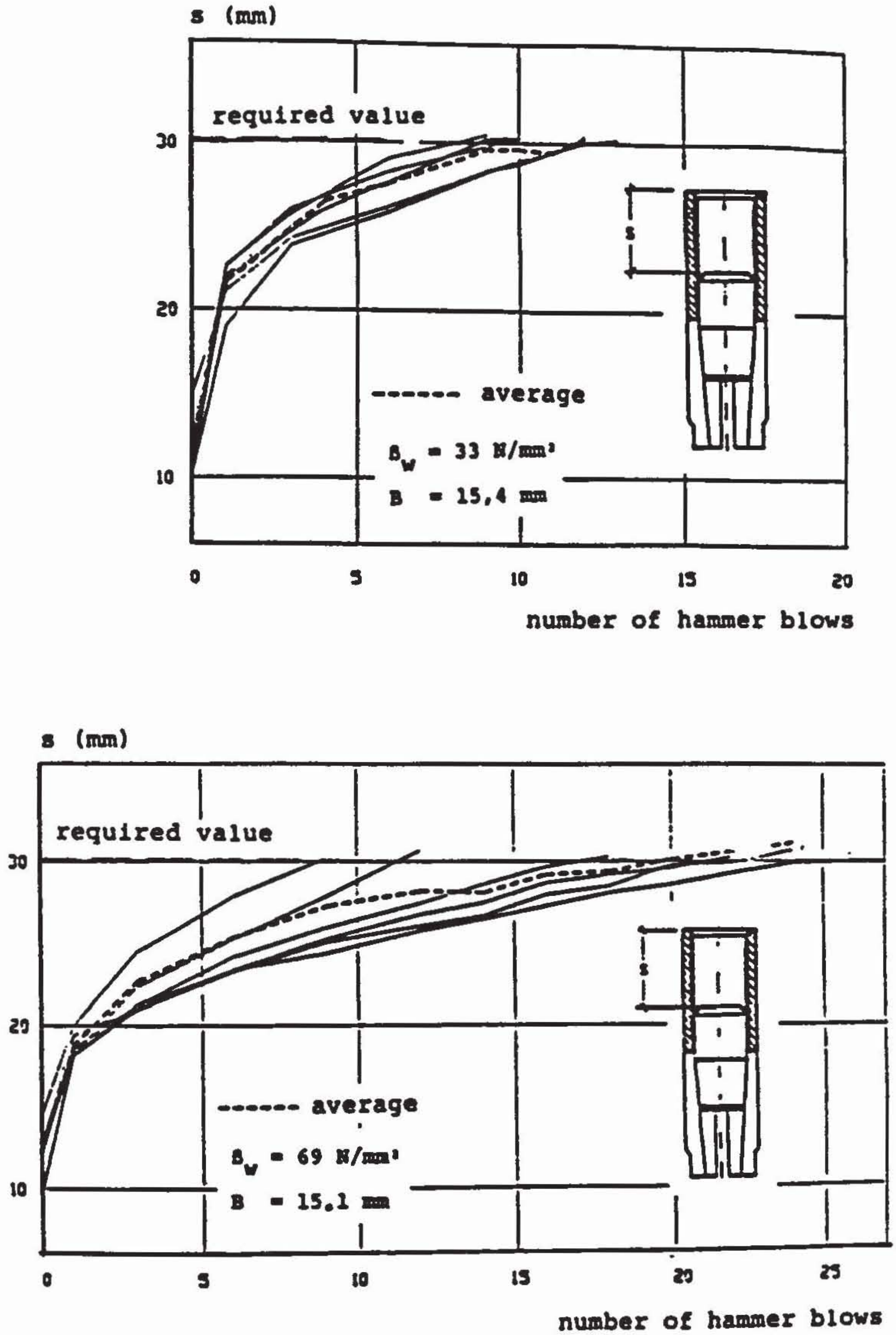


Fig. 16--Distance s between upper face of cone and shell as a function of the number of blows with a 1 kg-hammer. Drop-in anchors M 12 installed at the upper side of a slab (after /14/)

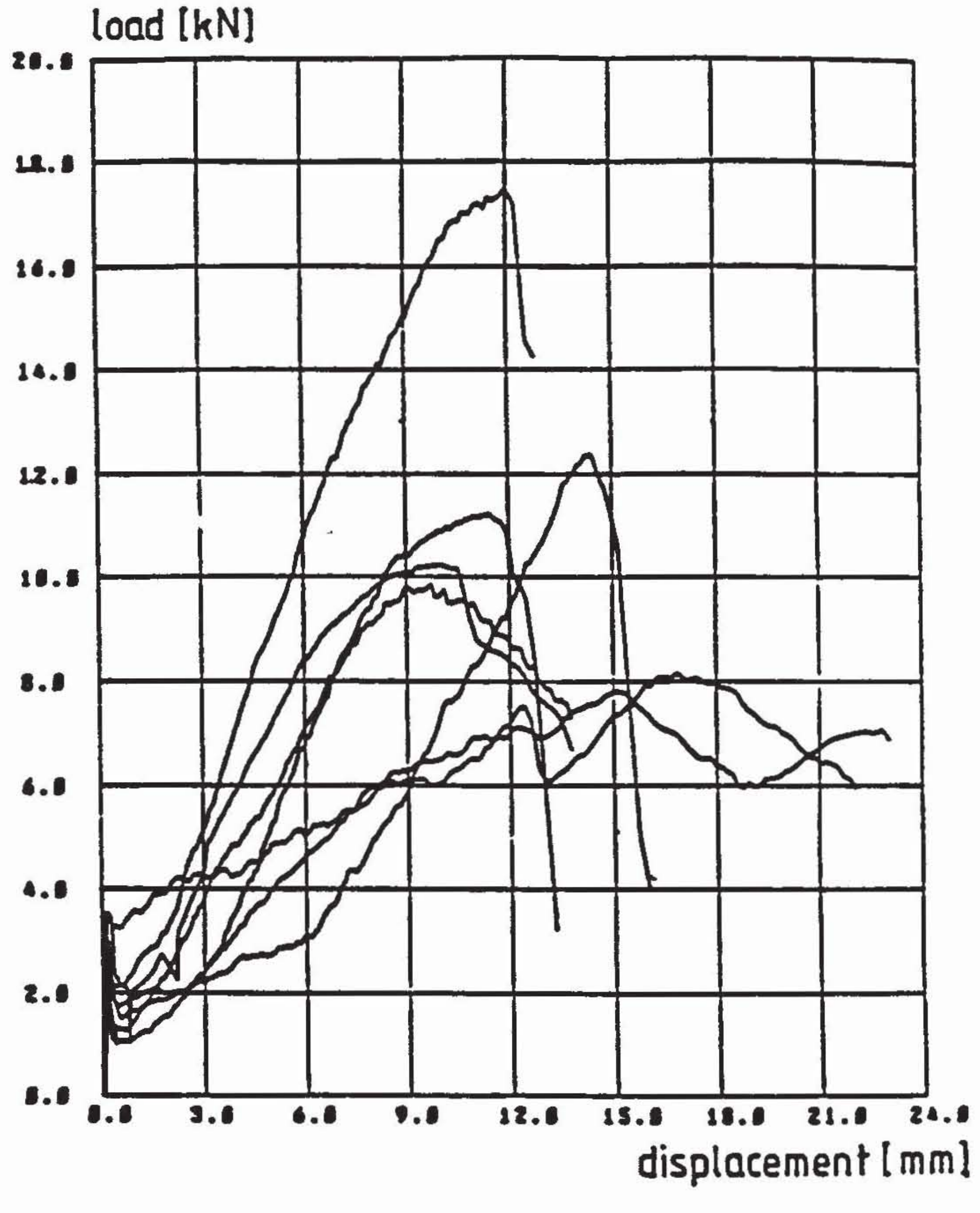


Fig. 17--Load-displacement curves of not fully expanded drop-in anchors M 12 in line cracks, Δ_w = 0.6 mm, β_v = 58 N/mm^2 (after /14/)

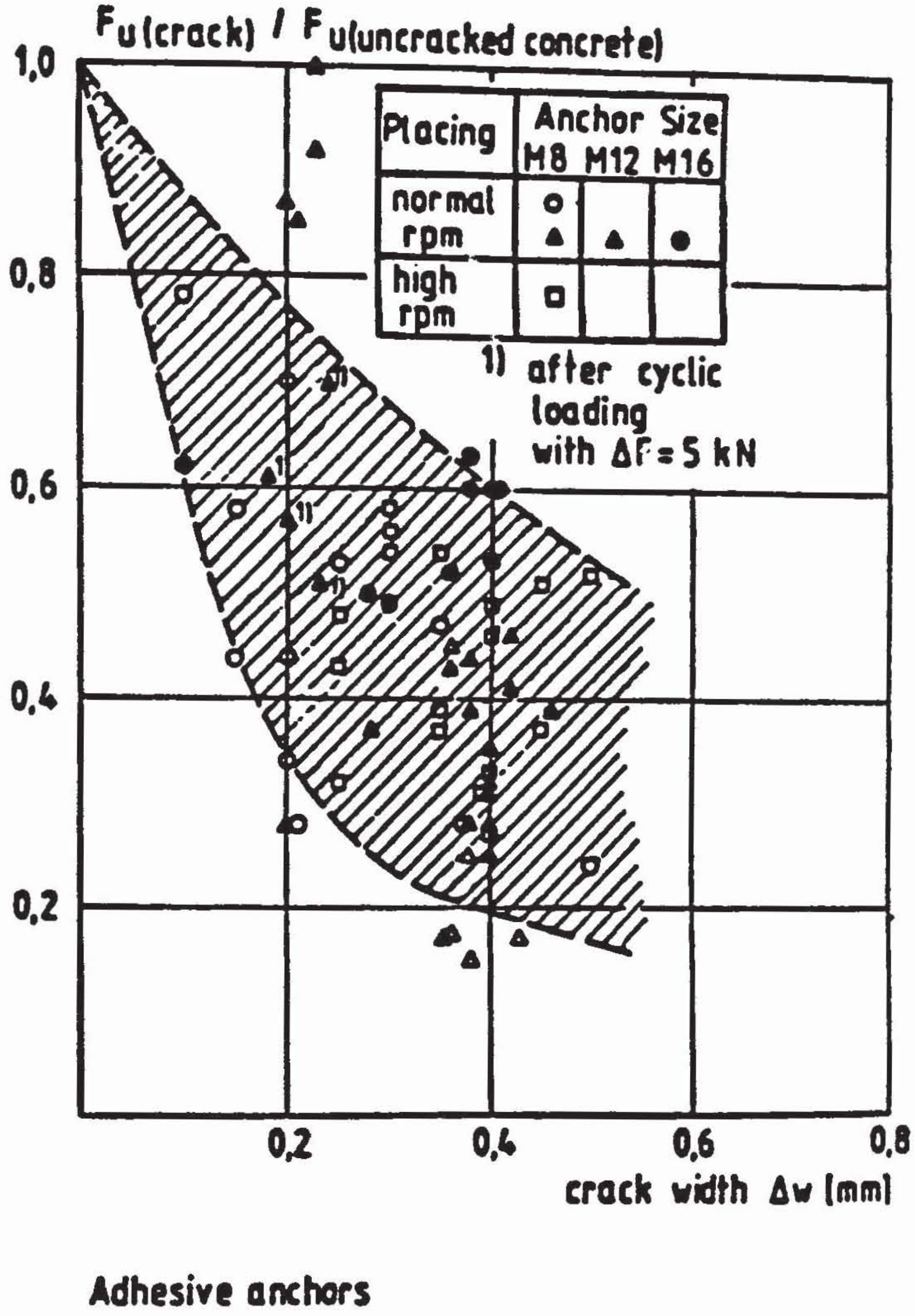
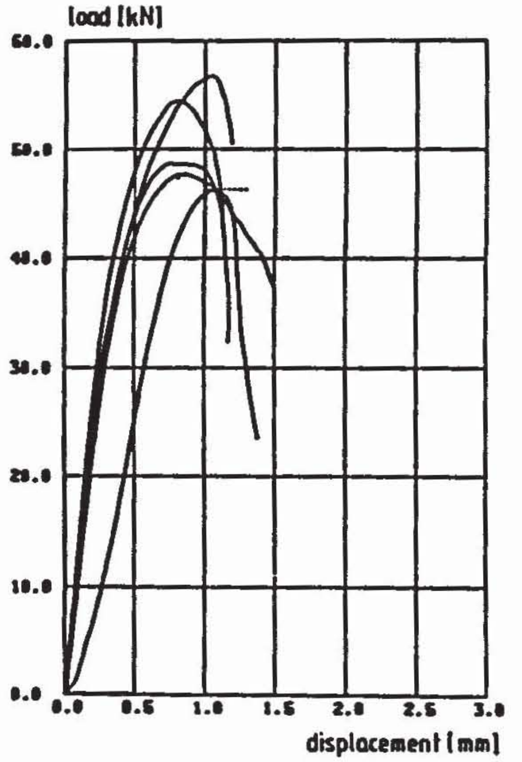


Fig. 18--Strength of adhesive anchors in line cracks under tension load (after /15/)



a) Uncracked concrete

b) Line cracks Δ_w = 0.4 mm

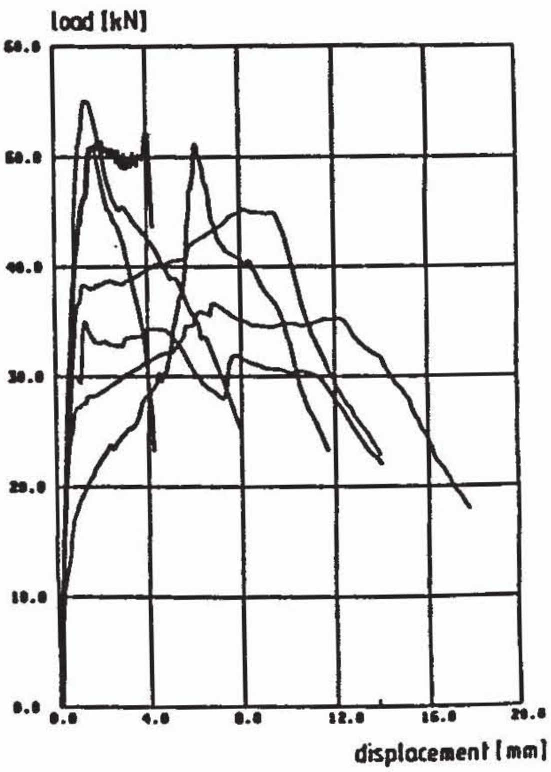


Fig. 19--Load-displacement relationships of adhesive anchors M 12, $\beta_w \approx 30$ N/mm^2, (after /12, 13/)

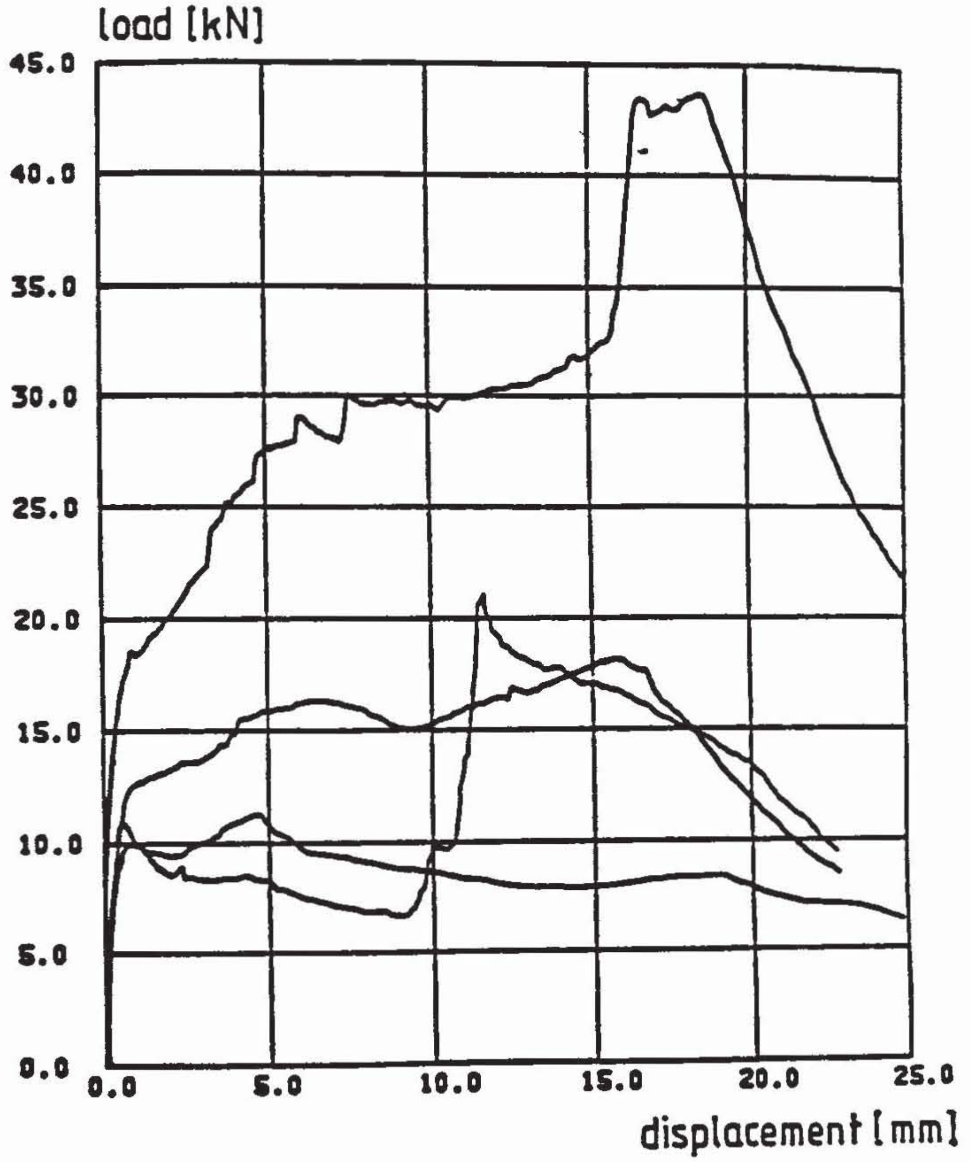


Fig. 20--Load-displacement relationships of adhesive anchors M 12 in line cracks, β_w = 28 N/mm², t = 110 mm, Δ_w = 0.4 mm, drilled hole not cleaned (after /12/)

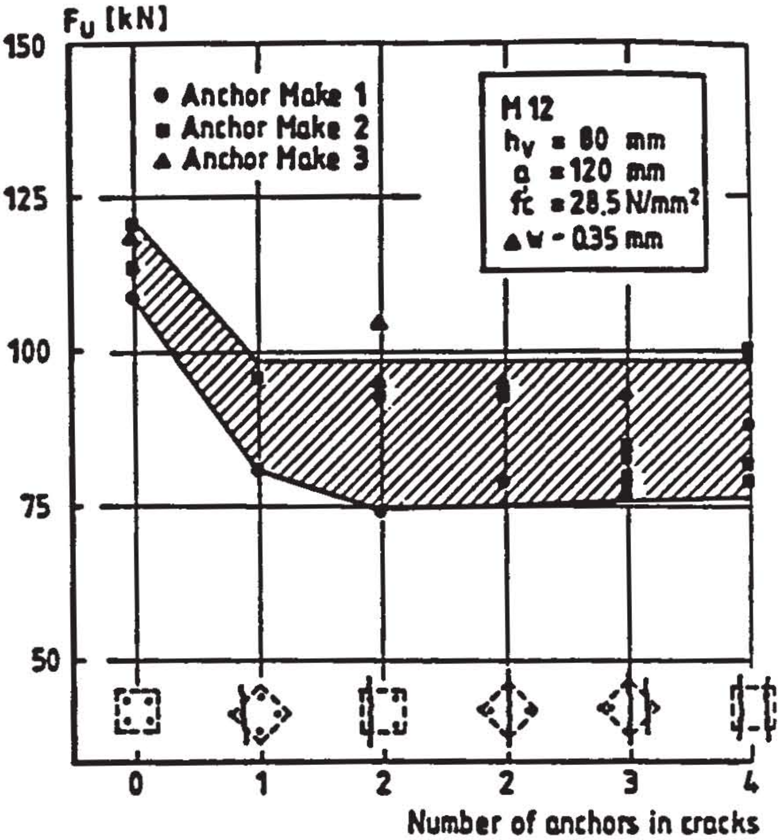


Fig. 21--Failure load of anchor groups (after /17/)

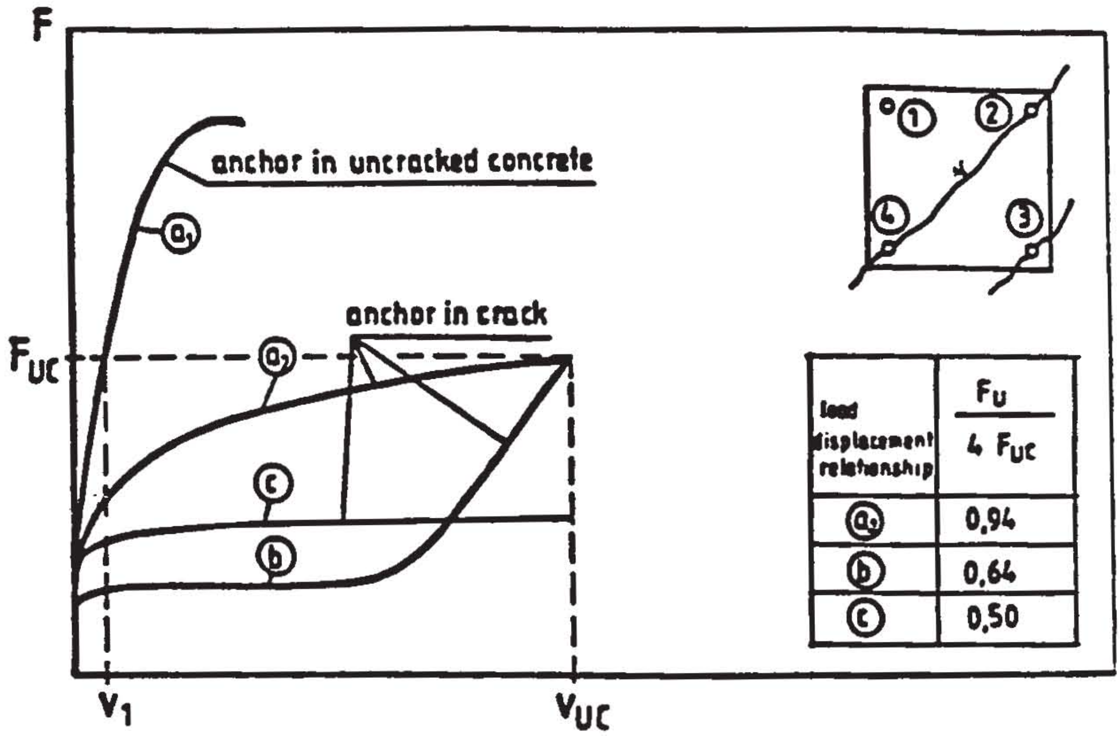


Fig. 22--Influence of load-displacement relationships of expansion anchors on the failure load of a quadruple fastening (after /17/)

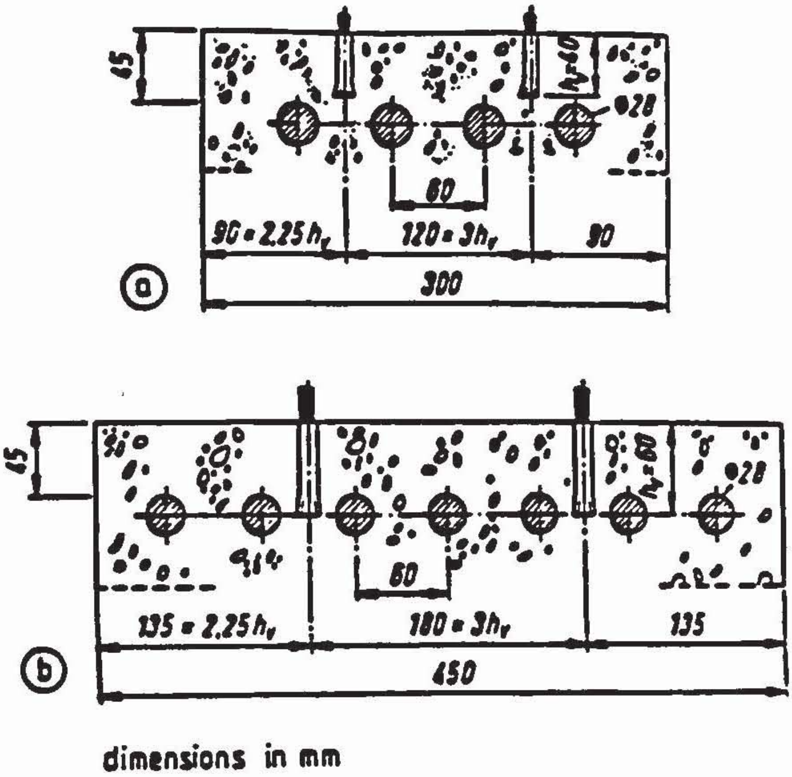


Fig. 23--Cross section of test beams with fastenings (after /4/)

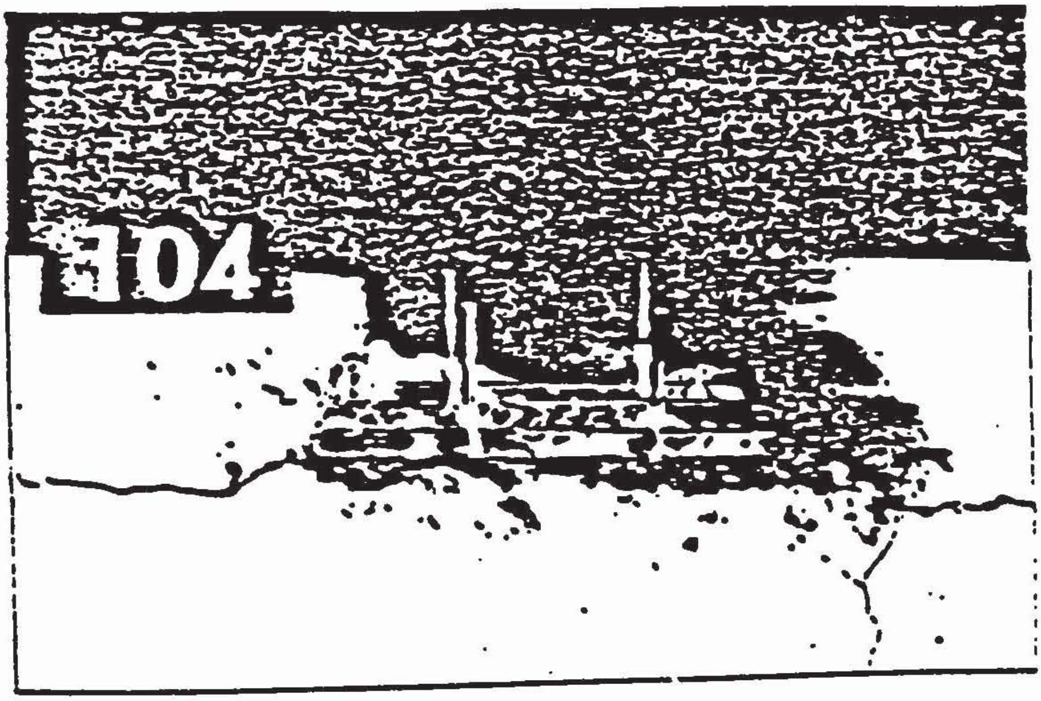


Fig. 24--Failure of an anchor group by pulling off the concrete cover (after /4/)

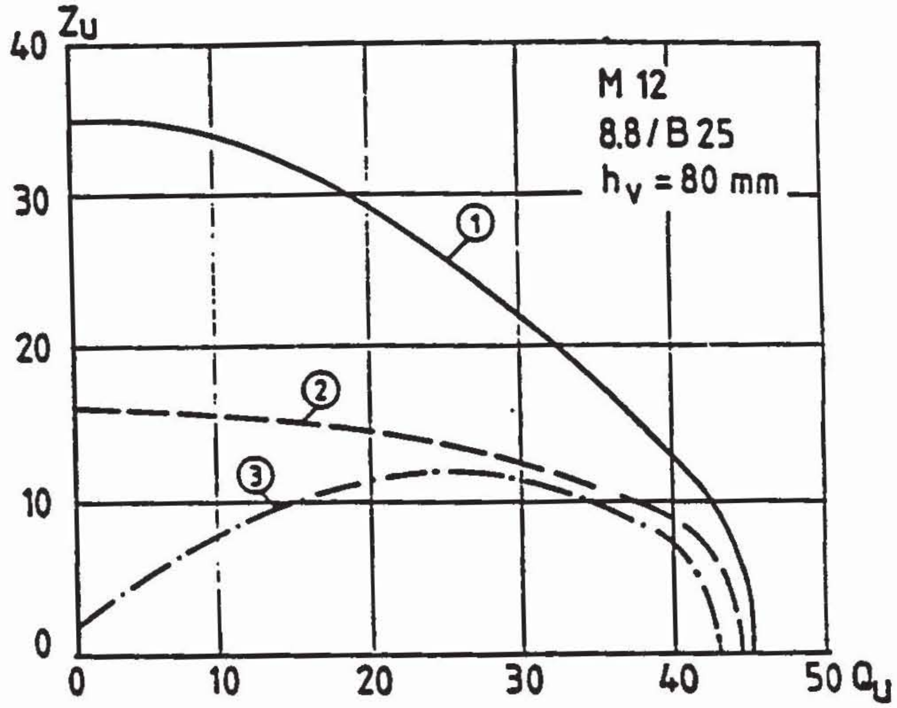


Fig. 25--Interaction diagram for anchors in cracks with different failure loads under axial tension

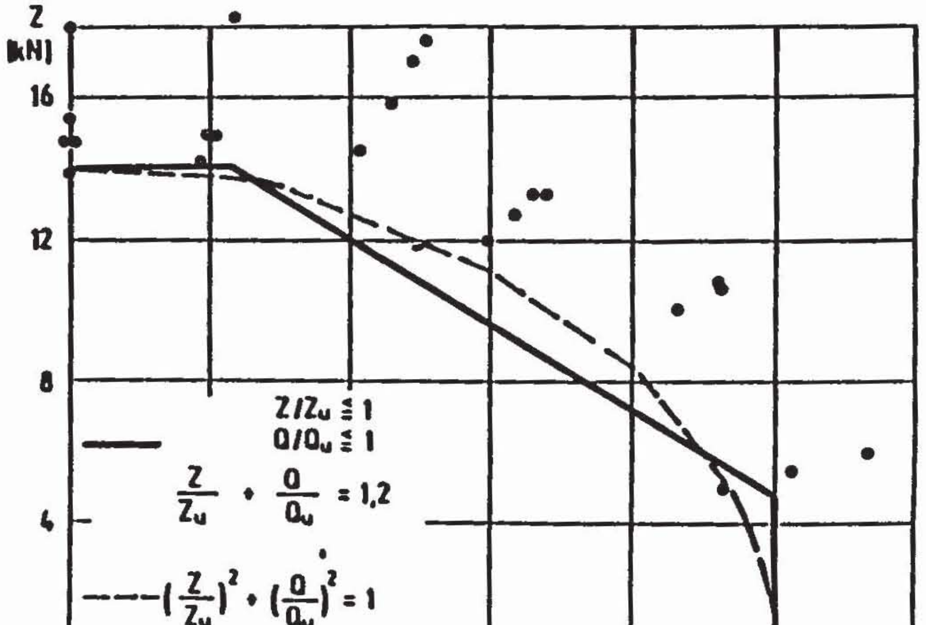
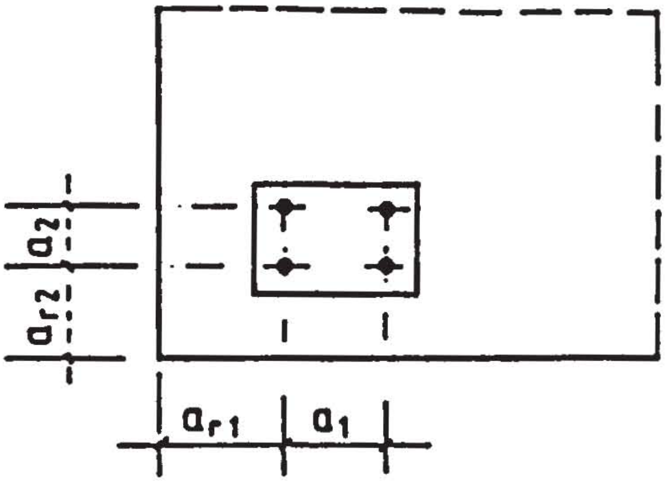


Fig. 26--Interaction diagram of fully expanded drop-in anchors M 12 in cracks, h_v = 50 mm, $\beta_w \approx$ 30 N/mm², bolt strength 55 N/mm² (after /21/)



$\text{zul } F^E$	$= \varkappa_{ar1} \cdot \varkappa_{ar2} \cdot \varkappa_{a1} \cdot \varkappa_{a2} \cdot \text{zul } F_0^E$
$\text{zul } F^E$	= reduced permissible load of an anchor
$\varkappa_{ar}$	$= \dfrac{a_r}{a_{rk}} \leqq 1$
$\varkappa_a$	$= 0{,}5\left(1 + \dfrac{a}{a_k}\right) \leqq 1$
a_{rk}	= critical edge distance
	for $\text{zul } F_0^E$
a_k	= critical anchor spacing
$\text{zul } F_0^E$	= permissible load of a single anchor

Fig. 27-- Method for anchor fastenings according to German certification documents

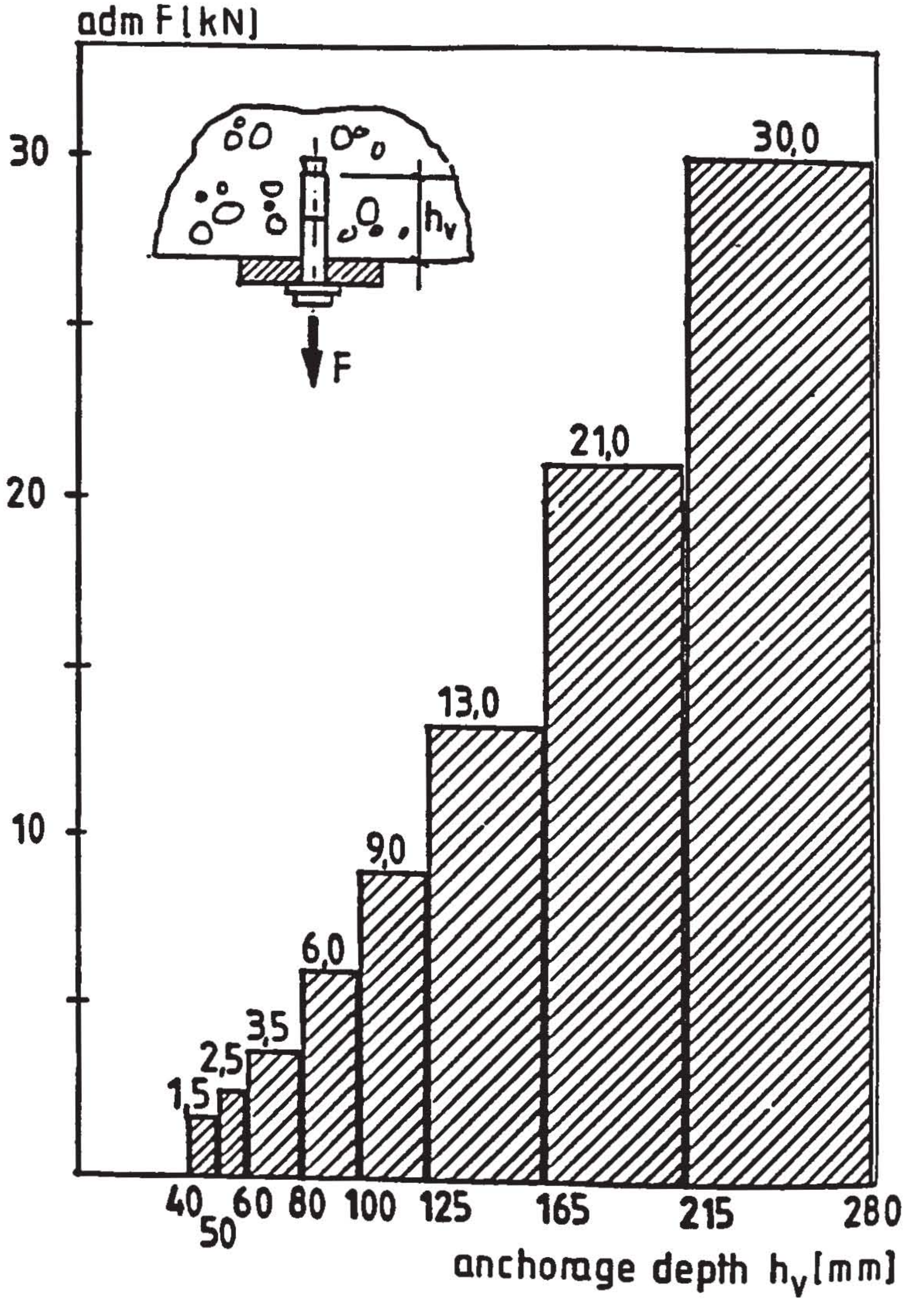
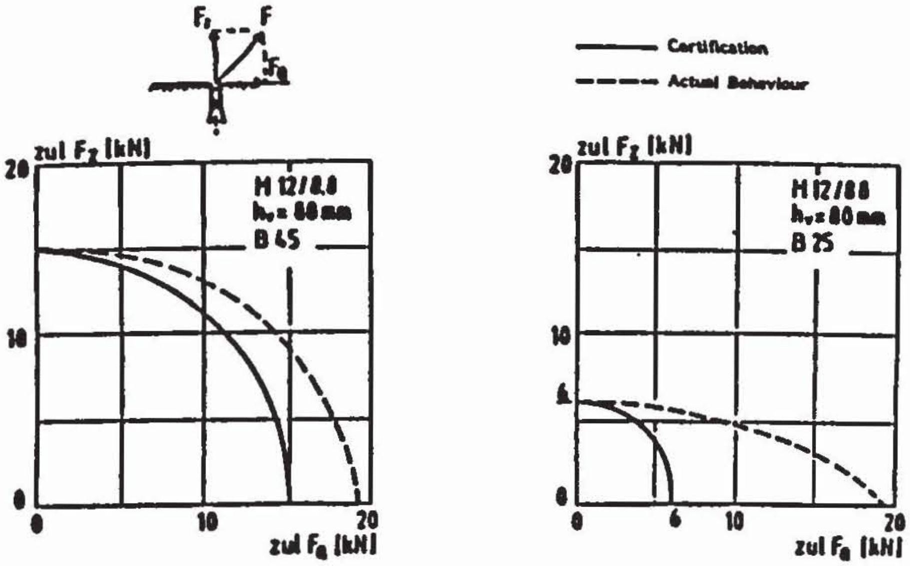


Fig. 28--Load classes for anchors in the concrete tensile zone



a) Compressive zone b) Tensile zone

Fig. 29--Interaction diagram according to certification documents and actual behaviour

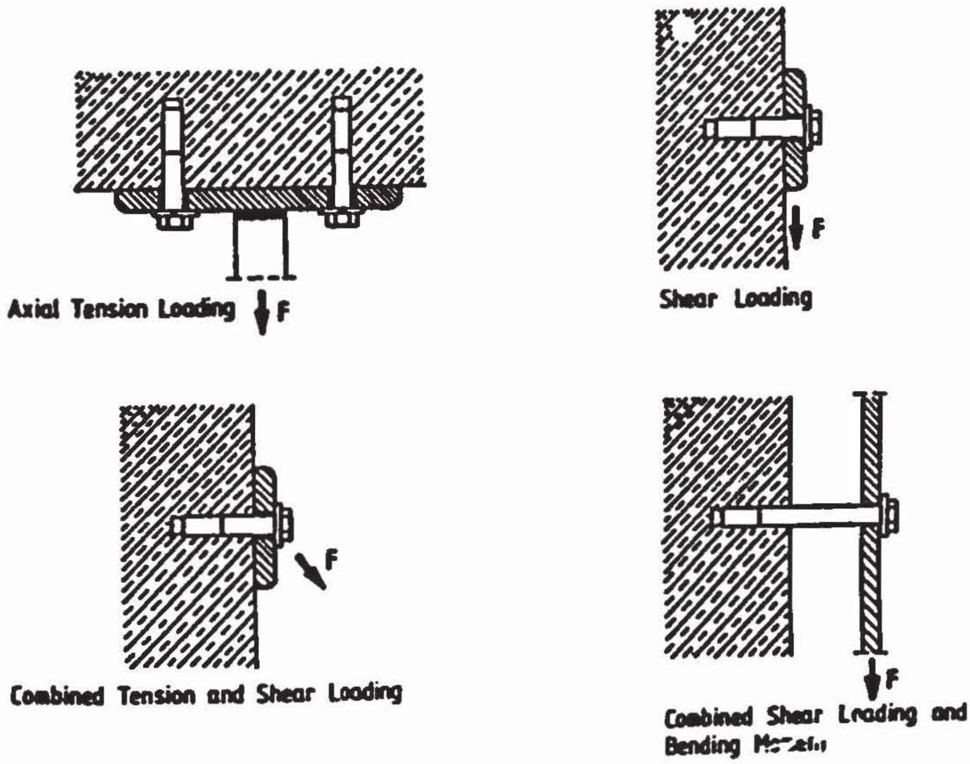


Fig. 30--Loading directions of fastenings

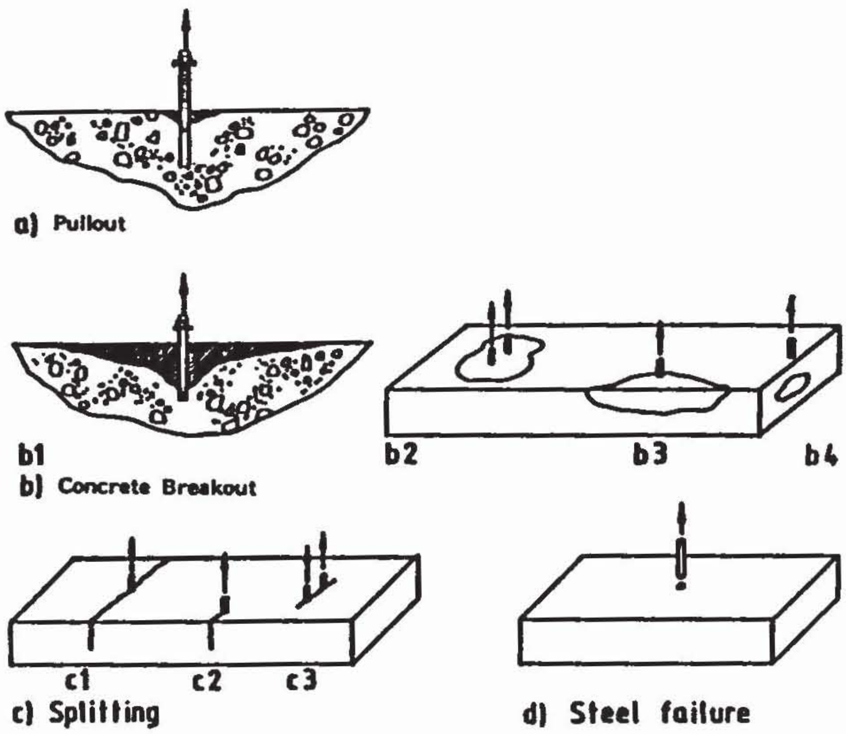


Fig. 31--Failure modes for fastening under tension load

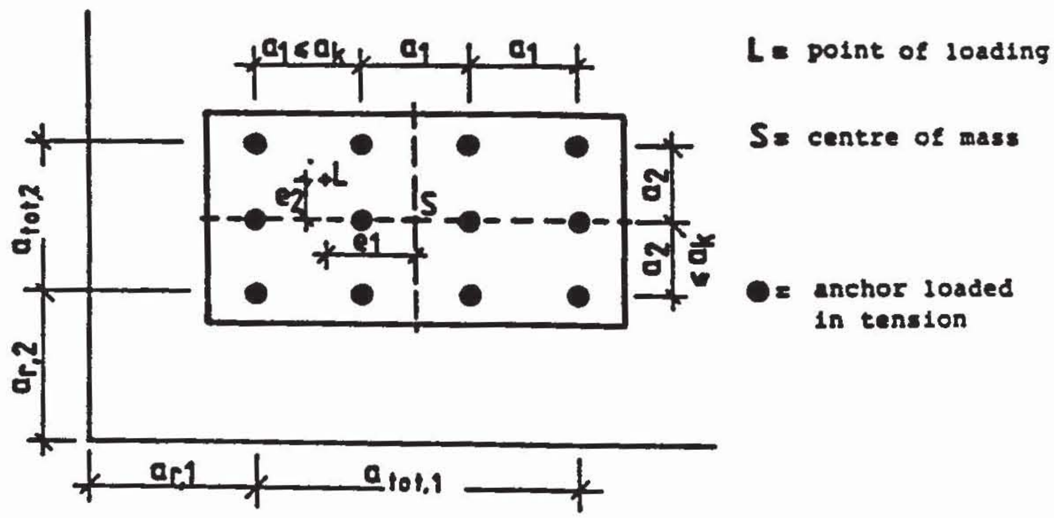


Fig. 32--Anchor group loaded in tension (example)

$$F_{k,c} = \prod_{i=1}^{m} \varkappa_{ar,i} \cdot \prod_{j=1}^{n} \varkappa_{a,j} \cdot \prod_{k=1}^{o} \varkappa_{ex,\ell} \cdot F_{k,c}^{0}$$

$$\varkappa_{ar,i} = 0{,}3 + 0{,}7 \cdot a_{r,i} / a_{rk} \leq 1 \ , \quad m \leq 4$$

$$\varkappa_{a,j} = 1 + a_{tot,j} / a_k \leq n_j \ , \quad n \leq 2$$

$$\varkappa_{ex,\ell} = \frac{1}{1 + 2 e_\ell / a_k} \leq 1 \ , \quad o \leq 2$$

$$a_k = 3\, h_v$$

$$a_{rk} = 1{,}5\, h_v$$

$$F_{k,c}^{0} = \alpha \cdot \beta \cdot 6{,}3 \cdot \sqrt{\beta_{wN}} \cdot h_v^{1.5} \quad [N]$$

α = 0,7 - 1,0 depending on anchorage depth

β = 1,0 fastenings in cracked concrete (normal case)

= 1,7 fastening in uncracked concrete (exceptional case)

h_v = anchorage depth

$\beta_{W,N}$ = design concrete strength $\leq 35\ N/mm^2$

Fig. 33--Proposed design concept
Tension loading -- Concrete failure

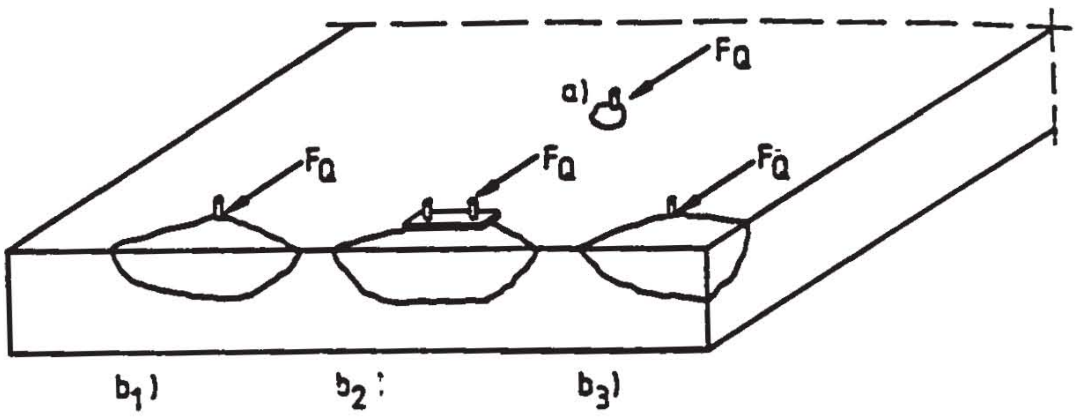


Fig. 34--Failure modes for shear loading

$$F_{k,c} = \varkappa_{ar} \cdot \varkappa_{a} \cdot \varkappa_{d} \cdot \varkappa_{ex} \cdot F^{0}_{k,c}$$

$$\varkappa_{ar} = 0{,}3 + 0{,}7\, a_{r2}/a_{rk} \leq 1$$

$$\varkappa_{a} = 1 + a_{tot}/a_{k} \leq n_p$$

$$\varkappa_{d} = (d/1.4 \cdot a_{r1})^{2/3} \leq 1$$

$$\varkappa_{ex} = \frac{1}{1 + 2\,l/a_k} \leq 1$$

$$a_k = 2\, a_{rk} \sim 3{,}0\, a_{r1}$$

$$F^{0}_{k,c} = \beta \cdot 0{,}5 \cdot \sqrt{d_B} \cdot \sqrt{\beta_{WN}} \cdot a_{r1}^{1.5}$$

d_B = anchor diameter

β = 1,0 fastenings in cracked concrete
= 1,2 fastenings in cracked concrete with edge reinforcement
= 1,4 fastenings in uncracked concr

Fig. 35--Proposed design concept
Shear loading -- Concrete failure

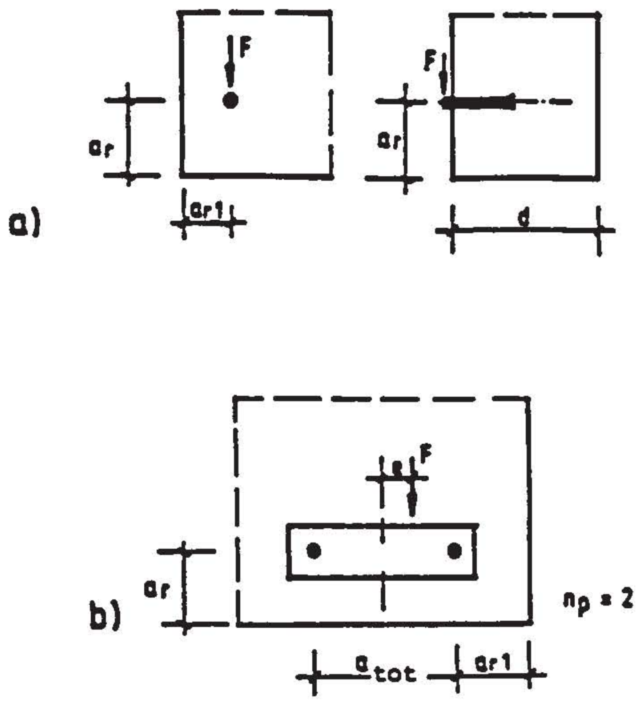


Fig. 36--Fastenings under shear loading (examples)

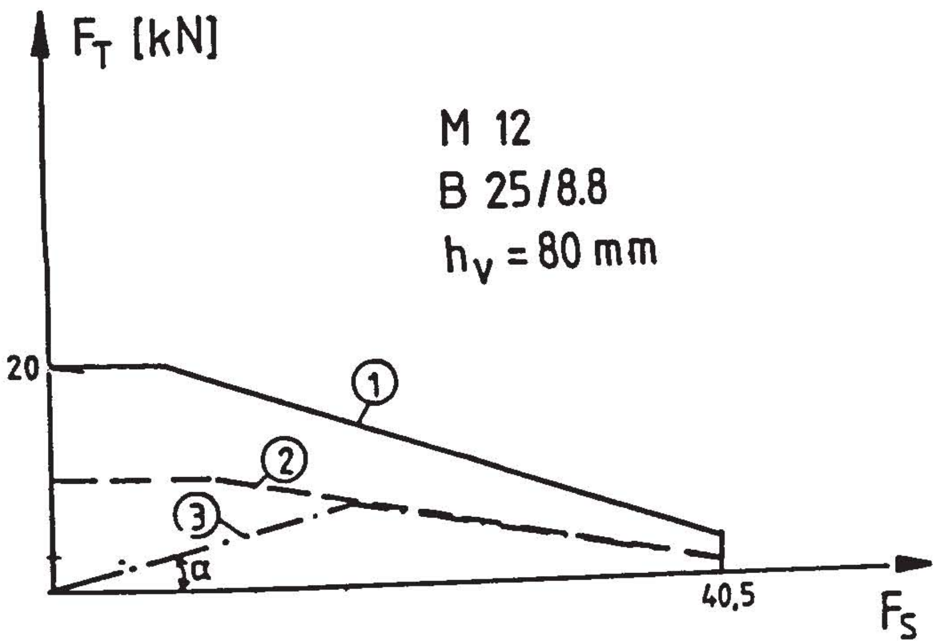


Fig. 37--Interaction diagram

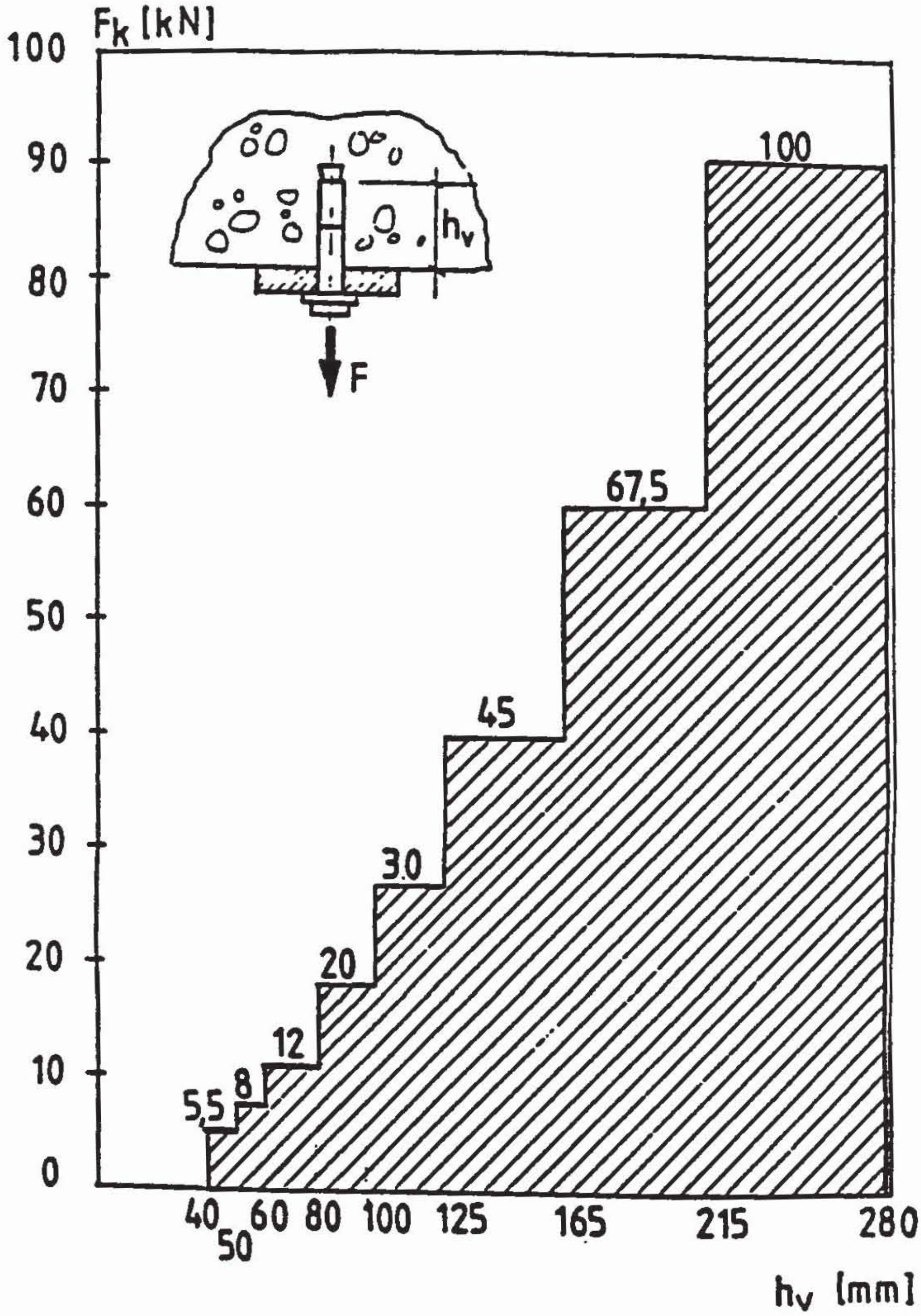


Fig. 38--Proposed design approach -- Load classes for tension loading

Static System	Concrete or Base Material	Dominant Loading Direction	Risk for Human Life: yes	Risk for Human Life: no
Determinate (non redundant)	Uncracked	Tension Shear	UEAtc 1986 /1/	No governmental requirements needed
	Cracked	Tension	UEAtc draft proposal 1987 /30/	
		Shear	—	
Indeterminate (redundant)	Uncracked	Tension	—	
		Shear	—	
	Cracked	Tension Shear	IfBt 1976 /32/	

proposed field of application of new UEAtc directive

to be covered in a second step

Fig. 39--Proposed test directives

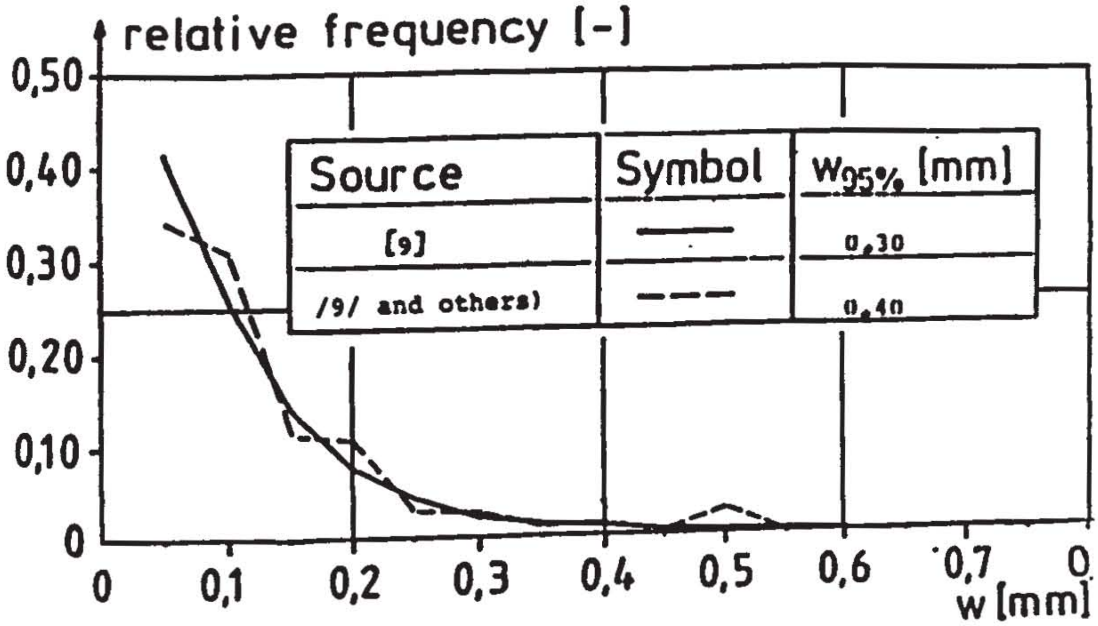


Fig. 40--Relative frequency of crack widths under permanent load (after /28/

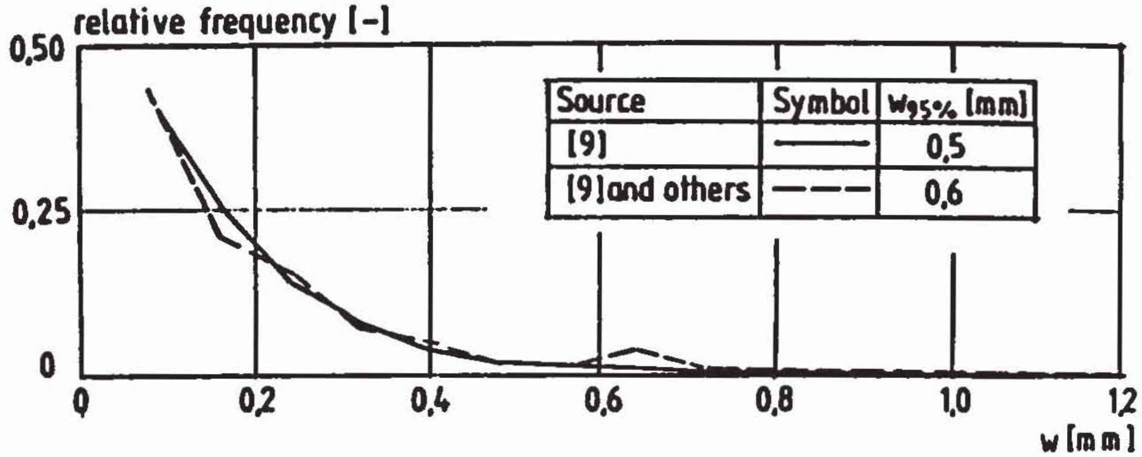


Fig. 41--Calculated relative frequency of the crack width under service load (after /28/)

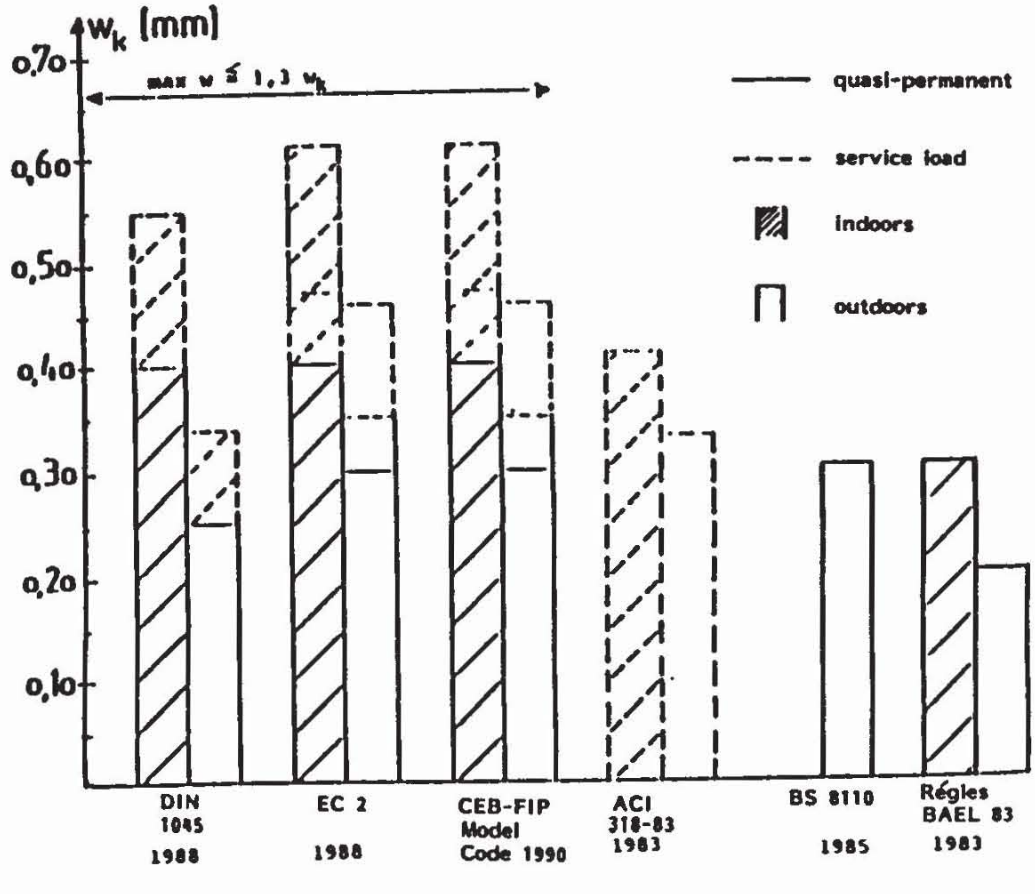


Fig. 42--Allowable critical crack widths for reinforced concrete according to different codes (after /28/)

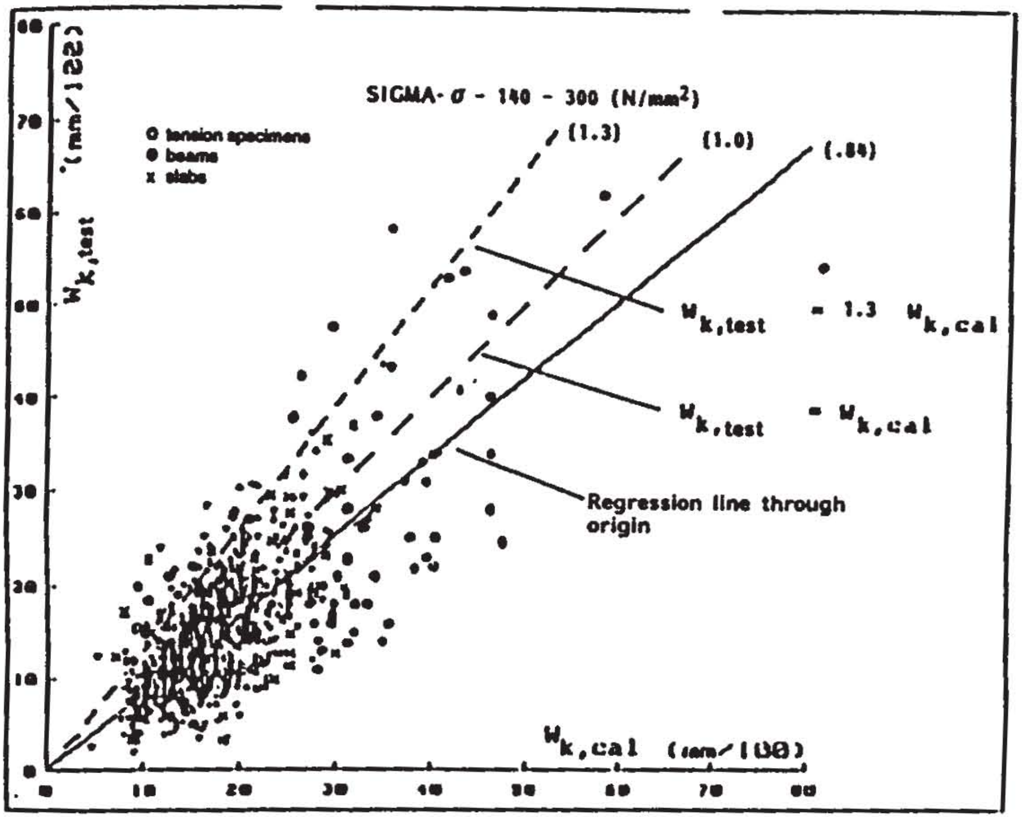


Fig. 43--Comparison of test results $w_{k,\,test}$ with values $w_{k,\,cal}$ calculated according to the equation used to deduce the provisions for crack control in /24/ n = 1150 specimens with ribbed reinforcement, taken from /34/

Test Series No.	Purpose of Test	Type of Crack	Crack Width Δ_w (mm)	Concrete	Remark
1	Installation Safety		0.3	1)	"extreme" installation inaccuracies
2	Functioning in		0.3	C 50	
3	high strength concrete		0.6	C 50	
4	Functioning in		0.3	C 20	
5	low strength concrete		0.6	C 20	
6	Reliability		~0.1 - 0.3 2)	C 20	
7			~0.1 - 0.3	C 20	

1) depends on anchor system

2) to be reconsidered

Fig. 44--Tests for confirming proper functioning of anchors in cracked concrete

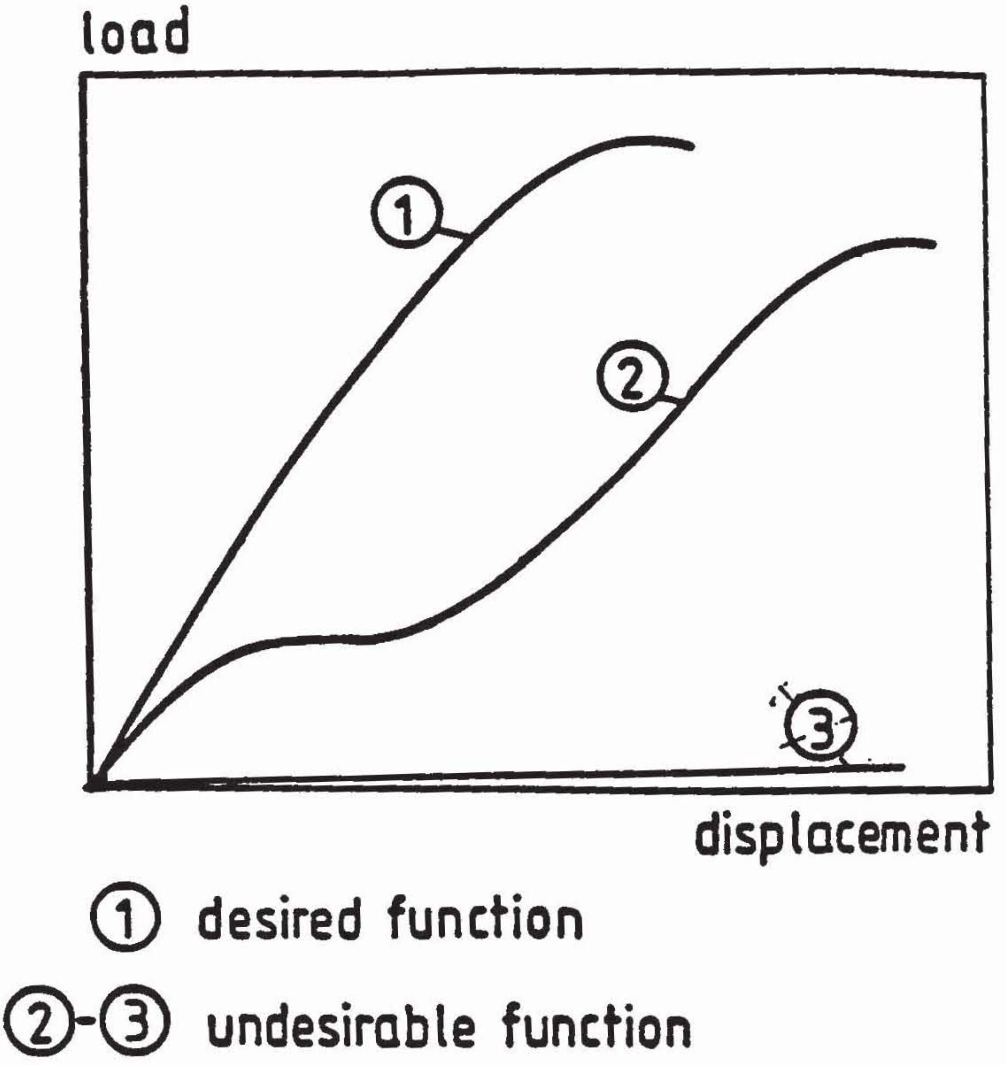


Fig. 45--Requirements on the load-displacement relationship for tension loading

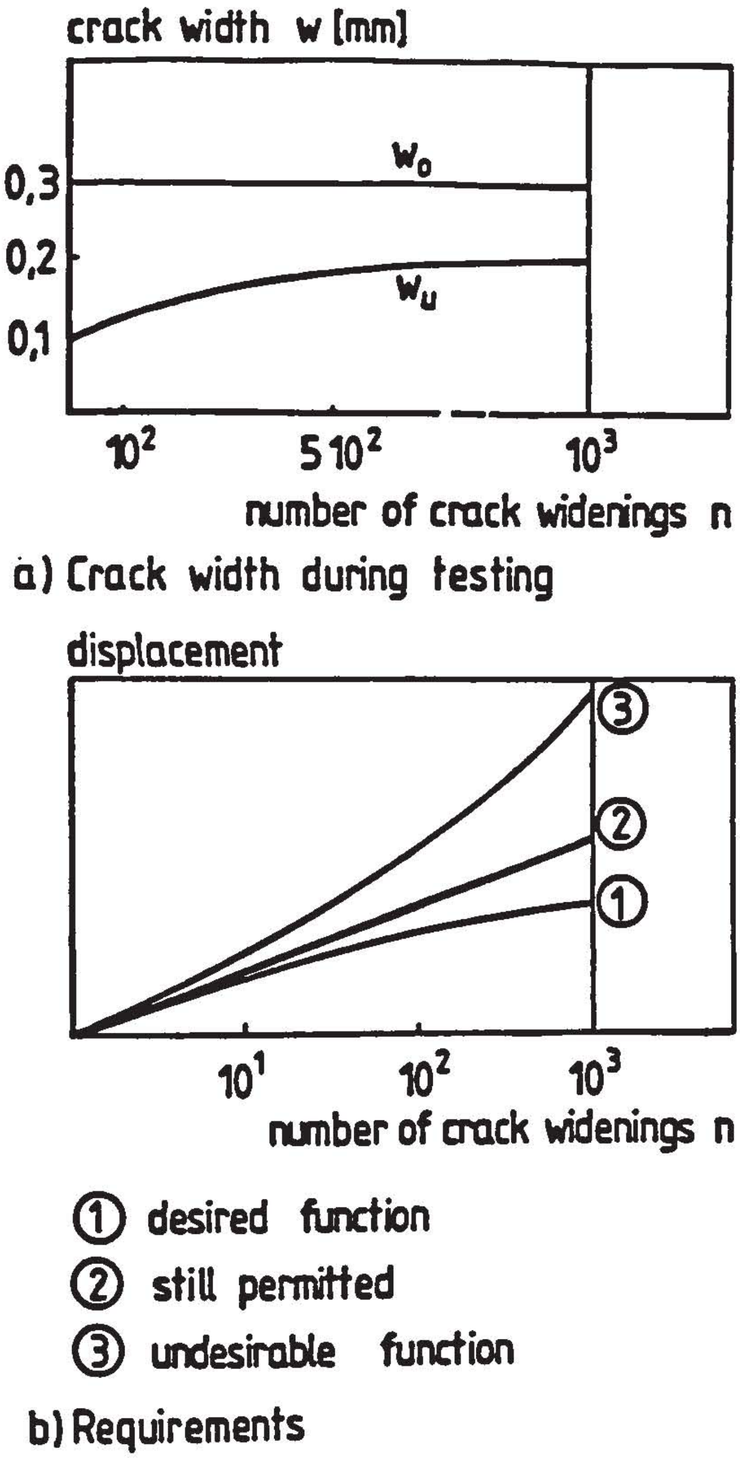


Fig. 46--Reliability test

Test Series No.	Purpose of Tests	Loading Direction	Type of Crack	Crack Width (mm)	Concrete	Number of Tests	Remark
1 2	Characteristic Load	Tension	[crack symbol]	0.3	C 20 C 20	5 - 10 5 - 10	Drill Bit Bm

Fig. 47--Tests for determining the permissible conditions for use in cracked concrete (tension loading)