Anchorage to Concrete by Metallic Expansion Anchors

by R. Eligehausen

Synopsis: The behavior of metallic expansion anchors under monotonic loading is described on the basis of a large number of available test results. Expansion anchors loaded in tension will often fail in a rather brittle manner by pulling out a concrete cone. The corresponding failure load F_u is approximately proportional to $f_{ct} \cdot l_d^{1.5}$ (f_{ct} = concrete tensile strength, l_d = anchorage depth). Anchors placed too close to each other or too close to an edge produce a common cone failure or an edge failure respectively at correspondingly reduced ultimate loads. Assuming a 30 deg. failure cone, the actual behavior can be described with sufficient accuracy for practical purposes. If anchors are placed in cracks, the failure load will be significantly lower than for anchors installed in uncracked concrete, depending on the type and make of anchor and the crack width.

Keywords: anchors (fasteners); concretes; cracking (fracturing); expansion; failure mechanisms; loads (forces); structural design; tension

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INTRODUCTION

The demand in recent years for more flexibility in the planning and construction of concrete structures has resulted in an increased use of metal and plastic fasteners to attach elements to walls, floors, etc., subsequent to the pouring phase. Currently employed for this purpose are expansion anchors, grouted anchors, powder actuated fasteners and inserts. This paper deals only with metallic expansion anchors. It contains information about the load-bearing performance of anchors subjected to various types of stress and proposes provisions for their selection and use. More detailed information and consideration of other fastening systems are given in (1).

TYPES OF METALLIC EXPANSION ANCHORS

Fig. 1 shows the different mechanisms used to expand anchors either by controlling the torque or the expansion displacement. The externally applied load is transferred to the concrete by friction and/or mechanical interlock. The surrounding concrete is stressed in tension.

In Fig. 2 typical metallic expansion anchors utilizing different methods to expand the anchor sleeve are shown. Torque-controlled expansion anchors (type A, Fig. 2a) are anchored by applying a defined torque with a torque-wrench to the bolt or nut. The expansion cone is drawn into the anchor sleeve, thereby forcing the leaves of the sleeve to expand against the walls of the predrilled hole. This action creates the necessary pre-loading friction. The amount of expansion displacement is dependent on the deformability of the concrete. In addition, as the anchor is torqued, a preload is introduced into the anchor bolt. The ability to develop this preload is used as an indicator of correct anchor installation. The preload diminishes with time to appox. 0.4 to 0.6 times its original value (2,3) due to relaxation of the concrete. However, by applying the same torque again, the loss in preload can be significantly reduced (3,4). If the externally applied load exceeds the preload, the cone of a properly designed expansion anchor will be pulled further into the sleeve, thus increasing the expansion forces.

Type B anchors (Fig. 2b) are expanded by hammering a cone into the anchor sleeve. The full anchor expansion is achieved during the installation process. Subsequent loading has no influence on the expansion of the anchor. The expansion force depends on the expansion displacement, the gap between anchor and hole and the deformability of concrete. Under service load this force is normally larger than for anchors of type A. Because the anchor cannot expand further under load, the anchor strength depends on the diameter of the anchor hole. Therefore the hole must be drilled carefully and the use of a proper drill bit size for a given anchor diameter is critical.

Anchors of type C (Fig. 2c) are expanded by hammering the sleeve a given distance over the cone. The expansion displacement is largest at the tip of the sleeve and decreases rapidly. The concrete is mainly ground and pulverized. Therefore the expansion forces are smaller than for anchors of type B and external loads are mainly transferred to the concrete by "mechanical interlock". A typical anchor of this type is the self-drilling expansion anchor. The sleeve is designed to serve also as a drill bit; in theory enabling precise matching of hole and anchor diameter.

BEHAVIOR OF METALLIC EXPANSION ANCHORS

The load-displacement performance and the strength of an anchor are mainly influenced by the direction of loading (Fig. 3), the type of expansion mechanism and the concrete strength. Also of significance are the quality of installation, anchor spacing and edge distance, the width of subsequent cracks in the concrete, the nature of loading (static, sustained or repeated, dynamic), and the design of the anchor plate (stiff or flexible).

In order to properly select an anchor for a given fastening application, considerable knowledge about the anchor behavior is required. In the following, an attempt is made to summarize the current knowledge available on this subject with respect to short-time loading.

Anchors in Uncracked Concrete and Loaded in Tension

Load-displacement behavior-- Typical load-displacement relationships, measured in a force-controlled test, for anchors of types A, B and C having approximately equal strengths and exhibiting concrete cone-type failures are plotted in Fig. 4. The displacements shown represent the slip of the anchor in the hole, the deformation of the concrete and the deformation of the expansion anchor. The anchors were properly installed in uncracked concrete; however, before the test the preload of type A anchors applied during installation was reduced to zero. Because of the high expansion forces, type B anchors exhibit relatively low slip values. Therefore the load-displacement relationship is almost linear up to failure.

After installation the expansion force of type A anchors is smaller than that of type B anchors and therefore the displacements are larger for equal loads. If the external load exceeds the preload generated in the bolt during installation, the expansion cone is pulled further into the sleeve, which leads to increased displacements. At failure, the displacements are much larger than for comparable type B anchors.

Self-drilling expansion anchors (type C) show larger displacements in the total load range than type A and B anchors. This is due to the load transfer by mechanical interlock which causes large concrete deformations.

In Fig. 5 an ideal load-displacement curve is plotted. Under service load the anchor should behave elastically with very little additional displacements after installation. However, under ultimate load, a plastic behavior is desired and in the case of cyclic loading only limited strength degradation should occur. In the common case of multiple anchor fastenings this ductile behavior allows a redistribution of forces and prevents a brittle failure of the anchorage. A comparison of Fig. 5 with Fig. 4 shows that the actual load-displacement behavior of the currently available expansion anchors differs somewhat from this ideal behavior.

It should be noted that anchor failures due to steel rupture do not necessarily provide a ductile behavior with the desired large displacements. This is due to the fact that often high strength steel with relatively low elongations at maximum load is used for anchor production and in addition the embedment depth is often relatively small. Furthermore, it should also be recognized that in certain applications (e.g. fastenings under static loadings) brittle behavior may be acceptable. However, more research is urgently needed to distinguish those applications where a ductile anchor behavior is essential for the surviveability of a fastening from cases where a brittle behavior may be acceptable.

Failure modes--The possible failure modes of anchors loaded in tension are shown in Fig. 6.

a) The anchor is pulled out of the anchor hole without significant concrete damage. The expansion force is too small to utilize the full concrete strength (Fig. 6a).

b) The anchor developes a concrete failure cone (Fig. $6b_1$). The concrete strength is fully utilized. If the anchors of an anchor group are spaced too close to each other, or an anchor is placed too close to the edge, a common cone failure or an edge failure, respectively, may occur (Figs. $6b_2$, $6b_3$) at correspondingly reduced ultimate loads.

c) The concrete is split by the anchor (Fig. 6c). This failure mode will occur only, if the dimensions of the member are too small, the anchors are placed too close to the edge or too close to each other, or the expansion forces are too high. The failure load is usually smaller than in case b).

d) The bolt or the sleeve fails. For given material properties and anchor dimensions this case defines the upper limit for the anchor strength.

Pull-out failure--By expanding the sleeve the anchor locally enlarges the hole and produces the radial expansion pressure, the integration of which over the contact area gives the expansion force, S. The failure load, F_u, of the anchor is proportional to S.

$$F_u = \mu \cdot S \quad (1)$$

with μ = coefficient of friction.

According to (4) the factor μ for type A anchors falls in the range of 0.2 - 0.3, and for type B anchors it is about 0.35. The expansion force S depends on the local maximum deformation of the concrete as well as its deformability. Equations for the calculation of S are given in (4,6). They were deduced theoretically by assuming for the concrete a linear elastic-ideal plastic behavior and the validity of the Mohr-Coulomb failure criteria. The equations are rather complicated and must be solved by iteration or by use of a monogram.

However, comparison of the failure loads predicted by the above equations with the results of extensive testing (91 test series with approx. 10 tests per series) demonstrated that these equations do not reliably predict the failure load in the case of a pull-out failure (7). Therefore they can only be used to get a first estimate of the expected maximum load which must be checked - as proposed in (6) - by tests.

Concrete cone type failure--Fig. 7 shows a typical failure cone of expansion anchors with an anchorage depth l_d = 125 mm (5 in.). The angle between the failure surface and a line parallel to the concrete surface averages about 30 deg., and the depth of the cone is about 0.8 to 1.0 times the anchorage depth, l_d (10).

In Fig. 8 the failure loads measured in 173 test series with about 2000 tests are plotted as a function of the anchorage depth, l_d. Each point represents the average failure load of one test series. The test results are adjusted to a concrete compression strength f'_c = 20 N/mm² (2900 psi) by multiplying the measured failure loads with the factor $(20/f'_c)^{2/3}$. The tests were performed with 16 different makes of expansion anchors (12 type A anchors, 2 type B anchors and 2 type C anchors) with bolt diameters ranging between 5 mm (0.20 in.) and 24 mm (0.94 in.). The concrete compression strength varied between $f'_c \sim 10$ N/mm² (1450 psi) and $f'_c \sim 50$ N/mm² (7250 psi) with the bulk of the tests close to f'_c = 20 N/mm² (2900 psi). Edge distances and spacings of the anchors were large to avoid edge influences or overlapping of the failure cones. Using these data, it was shown in (7) that the concrete cone pull-out load only depends on the anchorage depth, l_d, and the concrete tensile strength which can be assumed to be proportional to $f_c'^{2/3}$. Other parameters, such as type or design of anchor, bolt diameter etc., are of minor importance. Evaluation of the data by regression analysis yielded the following equation for the average failure load, F_u. The correlation coefficient is 0.97.

$$F_u = 7.4 \cdot l_d^{1.54} \cdot f_c'^{\,2/3} \quad (\text{N,mm,N/mm}^2) \tag{2}$$
$$= 8.7 \cdot l_d^{1.54} \cdot f_c'^{\,2/3} \quad (\text{lbs,in,psi})$$

with l_d = anchorage depth (see Fig. 8)
f_c' = concrete compression strength, measured on cylinders

In Fig. 8 the failure load according to equation (2) is plotted as well. As can be seen, the predicted anchor capacities agree rather well with the large body of test results. The quotients F_u (prediction/F_u (test) are normally distributed and the average value amounts to about 1.0. The coefficient of variation is 17 %, not much larger than the usual scatter of the concrete tensile strength.

In Fig. 9 the failure loads predicted by eqn. (2) are compared with the values predicted by ACI 349, Appendix B, and other authors. The failure loads were calculated according to the following equations (si-units):

ACI, Appendix B (8) : $F_u = 1.043 \cdot \emptyset \cdot l_d^2 \cdot (1+\frac{d_h}{l_d}) \cdot \sqrt{f_c'}$ (3)
headed anchors

$F_u = 1.043 \cdot \emptyset \cdot l_d^2 \cdot \sqrt{f_c'}$ expansion anchors (4)

Braestrup et.al. (9) : $F_u = 0.31 \cdot l_d^2 \cdot (1+d_h/l_d) \cdot f_c'$ (5)

Pusill-Wachtsmuth (10): $F_u = (0.73+1.06 \cdot d/l_d) \cdot l_d^2 \cdot f_c'^{\,2/3}$ (6)

Bode and Roik (11): $F_u = 12.1 \cdot l_d^{1.5} \cdot (1+d_h/l_d) \cdot \sqrt{f_c'}$ (7)

with (see Fig. 9)

l_d = anchorage depth
d = diameter of the sleeve
d_h = diameter of anchor head

ACI 349 (8) assumes a 45 deg. failure surface and a constant tensile stress, $f_t = 0.33\,\emptyset\sqrt{f_c'}$ (units: N/mm²), over the projected failure area at the surface of the concrete. A strength reduction factor $\emptyset = 1.0$ was used in equations (3) and (4) to predict the average failure load as it is done by the other formulae. Pusill-Wachtsmuth (10) assumes a 30 deg. failure surface and a constant tensile stress, $f_t = 0.27 \cdot f_c'^{\,2/3}$, over a critical area, which in normal applications is smaller than the total failure surface. Equation (5) was deduced by applying the theory of plasticity to headed anchors. Equation (7) was found empirically by fitting the data of a sufficiently large number of results of tests with cast in place anchor studs.

As can be seen from Fig. 9, the failure loads predicted by the empirical equations (2) and (7) compare favourably. From this it may be assumed that the concrete cone pullout load is almost in-dependent of the mechanism of load transfer to the concrete either by friction (expansion anchors) or compression stresses (headed anchors). This behavior is not well reflected by the provisions of ACI 349, because the predicted strength of headed anchors is about 30 % higher than for expansion anchors with the same anchorage depth. This is due to a different definition of the diameter of the projected failure area for headed and expansion anchors, respectively.

For anchorage depths, $l_d \lessapprox 150$ mm (6 in.), the failure load is proportional to $l_d^{\sim 1.5}$ (Fig. 8). This is taken into account by the empirical equations (2) and (7). Tests with deeper anchors are very limited. According to the results with headed anchors, the influence of the anchorage depth for $l_d > 200$ mm (8 in.) may even be smaller than predicted by eqns. (2) and (7). In contrast to the real behavior, the proposals (8-10) assume the failure load to be proportional to l_d^2. This means, the strength of shallow anchors ($l_d \sim 50$ mm (2 in.)) or deep anchors ($l_d \gtrapprox 200$ mm (8 in.)) calculated according to these proposals may significantly be under- or overestimated, respectively (Fig. 9).

While in general the failure load is predicted as a function of the concrete tensile strength, Braestrup et.al. (9) compute the failure load as a function of the concrete compression strength. When compared to test results, the assumption (9) significantly overestimates the influence of the concrete compression strength.

Equation (2) is valid for expansion anchors whose diameter and expansion force are adjusted to the anchorage length. If an anchor of a certain size is installed with a deeper than normal anchorage depth, the concrete cone pullout load increases less than predicted by equation (2)(1,10), because the anchor slips before failing the concrete. However, a deeper installation is favorable, because in this way the desired plastic behavior under maximum load may be achieved.

If the anchors of an anchor group are placed too close to each other, the failure cones of the individual anchors will overlap or a common failure cone will be pulled out (Fig. $6b_2$). The failure load will be reduced compared to widely spaced anchors. If the height of the failure cone is taken as 1.0 times the anchorage depth, l_d, and its slope as 30 deg., an overlapping of the failure cones can be expected when the actual spacing is smaller than the critical value, s_c, for full anchor capacity, with

$$s_c = 2\, l_d / \mathrm{tg}\ 30° \cong 3.5\, l_d \qquad (8)$$

If the spacing is $s = 0$, the strength of an individual anchor in a fastening with 2 or 4 anchors will be 50 % or 25 %, respectively, of the maximum value. A linear relationship is assumed between these limiting values.

In Fig. 10 the capacities of anchor groups consisting of 2 and 4 anchors, respectively, measured in tests are compared with the values predicted by the above described theoretical model. Plotted are measured failure loads, related to the maximum value for large spacings, as a function of the ratio spacing to anchorage depth. In the tests a rigid attachment was used to distribute almost equal loads to all anchors of the group. The anchorage depths varied between 50 mm (2 in.) (M 8) and 125 mm (5 in.) (M 20). The thickness of the unreinforced concrete specimens was $> 2\ l_d$ to prevent a splitting failure. As can be seen from Fig. 10, the simplified theoretical model is sufficiently accurate for practical purposes.

Following the above reasoning, it can be assumed that the failure load of anchors placed close to the edge is reduced in proportion to e/e_c, where e is the actual edge distance and e_c is the critical value for full anchor capacity, with

$$e_c = l_d/tg\ 30° \cong 1,75\ l_d \tag{9}$$

In Fig. 11 results of tests with anchors ($l_d \sim 50$ mm (2 in.) to 150 mm (6 in.)) placed close to the edge of unreinforced concrete specimens are plotted as a function of the edge distance. The strength predicted by the simplified theoretical model is conservative compared to the tests.

Splitting of the concrete--The strength of expansion anchors which fail by splitting of the concrete is not as well known as the strength in the case of a cone type failure. In (10) the splitting behavior of anchors has been investigated theoretically. It was assumed that splitting occurs when the tensile stresses averaged over a critical area reach the concrete tensile strength. The size of this area was found by evaluating tests with concentrated loads and tests of thick concrete rings subjected to a constant inner pressure. According to this theory, the necessary splitting length to transfer the maximum load predicted by equation (2) without splitting the concrete member (Fig. $6c_1$) must be larger than the values l_0 given by equation (10), which are valid for a member thickness $\geq 2\ l_d$.

$$\begin{aligned} l_0 &\sim 3.5\ l_d \quad \text{type A and C anchors} \\ l_0 &\sim 6.0\ l_d \quad \text{type B anchors} \end{aligned} \tag{10}$$

For anchor groups the average splitting length per anchor in both directions should be in accordance with eqn. (10). This means, if the actual spacing within the group is $s < l_c$, the distance to the neighbouring anchors should be increased to meet the requirement of eqn. (10).

According to (10), the necessary edge-distance e_0 to reach the full anchor capacity (eqn. (2)) is

$$e_0 \sim 0.5\ l_0 \tag{11}$$

with l_0 given by eqn. (10).

If the actual edge distance, e, or splitting length ,l, respectively, are smaller than the values given by eqns. (10) and (11), it may be assumed that the anchor capacity is approximately reduced in proportion to e/e_0 or l/l_0, respectively (10). However, to prevent splitting cracks due to anchor installation, the folowing minimum values for edge distance and spacing should be observed (12):

$$\min e = \min s = \begin{cases} 1\ l_d & \text{type A and C anchors} \\ 3\ l_d & \text{type B anchors} \end{cases} \qquad (12)$$

The proposed provisions - summarized in Fig. 12 - should be taken as tentative. They are confirmed by the available very limited test results. However, more research is urgently needed to clarify the splitting behavior of expansion anchors.

Anchors in Cracked Concrete and Loaded in Tension

If anchors are placed in the tension zone of reinforced concrete elements, cracks can occur in the anchorage region. These cracks can run either in one direction only, or in two directions (e.g. in a slab spanning two ways).

Under service load the displacement of an anchor sitting in a crack with a normal width is only slightly larger than for a comparable anchor in uncracked concrete. However, with increasing load the difference in deformation between the anchor in cracked and uncracked concrete becomes progressively greater (Fig. 12). Failure is caused either by simply pulling out the anchor (Fig. 6a) or by producing a concrete cone (Fig. 6b) after relatively large displacements. The different behavior of anchors in cracks compared to anchors in uncracked concrete is due to the reduction of the expansion force by opening of the crack.

The strength of anchors sitting in cracks is lower than the value reached in uncracked concrete (Fig. 14). The plotted test results were found using different test specimens (slabs, tension specimens) and different types and make of anchors with a bold diameter of 8 mm (0.31 in.). The anchors were installed in small cracks, the cracks were then opened by loading the specimens and the anchors were statically failed with the cracks open. The scatter of the test results is relatively large. The plotted line can be accepted as a lower bound of the results for type A anchors placed in cracks running in one direction. If the anchors are placed at the intersection of cracks running in two directions, an even larger reduction might be expected. The same is true for type B anchors, because they cannot expand further to increase the expansion force under load after the crack opens.

Under service load the width of cracks should not exceed $w \sim 0.3$ mm to 0.5 mm (0.012 in. to 0.02 in.). Under these conditions a reduction of the anchor strength of 20 % to 60 % of the value in uncracked concrete can be expected, depending on the type or make of anchor. According to more recent tests, on an average the reduction is about 40 % for well designed type A anchors and for undercut anchors with a bolt diameter of 12 mm (0.5 in.).

The mechanism of load transfer in the case of expansion anchors placed in cracks is not as yet well known. Some explanations are given in (1). However, studies are presently in progress at the University of Stuttgart to resolve these questions (14).

In the tests summarized in Fig. 13, the anchors were placed in the region of constant steel stress, and therefore tensile stresses in the concrete were mainly induced by the anchors. However, in the shear region of beams and slabs and in the region of anchorages and lap splices of deformed bars, locally high tensile stresses are already induced in the concrete due to the loading of the structure. If anchors are placed in this region, the tensile stresses that they induce in the concrete interface with the tensile stresses due to loading of the structure. In this application a more severe reduction of the anchor strength might be expected than shown in Fig. 13.

The strength of the reinforced concrete member in which the anchors are installed could also be adversely affected by the above described interfacing of stresses caused by loading of the structure and by anchors. Critical applications are discussed in (13). The problem is of course highly dependent on the loading and spacing of the anchors. If only small loads at large distances are transferred into the tension zone by anchors, the effect on the member strength will be negligibly small. Currently, studies are underway at the University of Stuttgart to resolve these questions.

Anchors Loaded in Shear

Expansion anchors with large edge distances loaded in shear normally fail by rupture of the steel after large displacements. Just prior to failure, some local crushing of the concrete can occur in front of the anchor in the direction of the loading. Anchors placed close to an edge and loaded towards the edge may fail by cracking of the concrete in a conical failure surface (compare Fig. 6b$_3$), at loads considerably below the maximum anchor shear resistance.

If the anchor is placed sufficiently away from the edge to avoid a concrete edge failure, the strength of Type A anchors is normally higher for shear loading than for tension loading. For anchors of types B and C this statement is only true for low strength concrete ($f_c' \lesssim 25$ N/mm² (3625 psi)).

For constant edge distances, anchors loaded in shear towards the edge may fail the concrete at smaller loads than anchors loaded in tension. However, more tests are needed to quantify this statement.

For anchors with a sufficiently large edge distance to prevent edge failure, the influence of significant parameters, such as concrete strength, spacing of anchors and crack width on the failure load is much smaller for shear loading than for tension loading. This can be explained by consideration of the usual type of failure (rupture of steel).

DESIGN RECOMMENDATIONS

Suitability of an Anchorage System

Expansion anchors must be designed in such a way, that safe fastenings can be expected in all applications. Therefore the installation process must be as simple as possible to prevent gross installation errors. The proper installation should be easily verifiable. Furthermore, the anchor behavior must not be sensitive to small handling errors. Therefore it is desirable that all of the components of a fastening system (anchor, drill-bit, drilling machine and setting tools) are properly matched to each other. A high degree of system safety built in by the producer will reduce the influence of the "weak link" which is still the worker on the site.

To decide the question of whether the system safety of a specific expansion anchor is sufficient and the anchor is suitable for practical use, systematic experimental and theoretical investigations are necessary. These investigations should be planned, carried out and evaluated by experienced engineers. In tests, it must be shown that the anchor behavior is not significantly affected by inaccuracies of installations that might occur in practice. Some examples of such inaccuracies are given below.

- Tolerances in the size of the drilled hole
- Installation in poorly compacted concrete
- Insufficient cleaning of drilled holes
- Improper anchor installation, e.g. applied torque too low (type A anchors), cone not completely driven over the sleeve (type B anchors), or sleeve not driven sufficiently over the cone (type C anchors)
- Installation too close to reinforcing bars

Safety Requirements

Expansion anchors, as well as most of the fastening systems currently available, utilize locally the tensile strength of concrete. In reinforced concrete it is normally assumed that tensile forces are taken up by reinforcement. However, in some applications (e.g. slabs without shear reinforcement, lap splices not enclosed by stirrups) the concrete tensile strength is utilized as well. In these cases a factor of safety - relation between failure load and admissible service load - $\gamma = 2.1$ is required in Germany. The lower bound of the test results (5%-fractile) is taken as relevant ultimate load to take into account unavoidable scatter of the concrete tensile strength. For fastenings, a higher factor of safety is necessary aginst an eventual concrete failure to cover also uncertainties in the installation process. A factor of safety $\gamma = 3.0$ against the 5%-fractile of the results of short time tests seems to be adequate. This factor of safety is required in Germany. Because the safety factor does not cover gross installation errors, the proper installation should be checked on site.

Design Load

A reliable and comprehensive theory to describe the behavior of all types and makes of expansion anchors under various loadings is not yet available. Therefore the provisions for the use of an approved expansion anchor must be formulated from the results of corresponding tests, with due consideration of safety requirements. Obviously, current knowledge and prior experience with similar systems should be used when planning these tests and evaluating the results.

For anchors loaded in tension and failing the concrete (see Fig. 6b) the admissible service load can be estimated from equation (13).

$$F_{adm} = 2.0 \cdot l_d^{3/2} \cdot f_c'^{2/3} \quad \text{(units: N,mm,N/mm}^2\text{)} \qquad (13)$$

$$= 2.1 \cdot l_d^{3/2} \cdot f_c'^{2/3} \quad \text{(units: lbs,in,psi)}$$

with

F_{adm} = admissible service load of a single anchor or of the maximum loaded anchor of an anchor group

l_d = anchorage depth (see Fig. 8)

f_c' = specified concrete strength

For deducing equation (13), an upper limit of the coefficient of variation V = 20 % was assumed and a factor of safety $\gamma = 3.0$ was applied. The admissible load according to eqn. (13) is only valid, if edge distance, e, and spacing, s, of the anchors are larger than the values e_c and s_c given by eqns. (8) and (9). In practice, edge distances or spacings smaller than the critical values will occur frequently. In these applications the admissible load must be reduced using the information given in Figs. 10 and 11. Edge distances and spacings should not be smaller than the values given in eqn. (12) to prevent splitting cracks during installation. Furthermore, to resist the splitting forces under ultimate load, the spacing of anchors should also comply with Fig. 12, or the splitting forces must be taken up by appropriately placed and dimensioned reinforcement.

If expansion anchors are placed in the tension zone of reinforced concrete members, the maximum admissible load according to eqn. (13) must be reduced, using the information given in Fig. 14. For well designed type A anchors and normal crack width, the reduction factor is about 0.6. However, the maximum load per anchorage should be limited to minimize possible negative effects on the strength of the reinforced concrete member in which the anchors are installed.

SUMMARY

As a result of extensive research and testing carried out during the last decade, the understanding of the behavior of metallic expansion anchors has improved considerably. The current state of knowledge can be characterized as follows:

1. The principal behavior of different types of expansion anchors under various loadings is reasonably well known.

2. The ultimate load for a concrete cone type failure can be predicted with a degree of accuracy sufficient for practical purposes. The effects of edge distances and anchor spacings can also be taken into account.

3. In the cases of pullout and splitting type failures under tension loading, the ultimate load can only be very roughly predicted. This is also true in the cases of shear and combined shear and tension loadings and small edge distances.

4. Some knowledge about the influence of cracks on anchor behavior has been compiled.

However, the expanded use of anchors of all types in new and increasingly critical structural applications together with the corresponding increase in new fastening systems requiring evaluation for safety and allowable use have created the need for more research and development. Corresponding studies are currently in progress at the University of Stuttgart.

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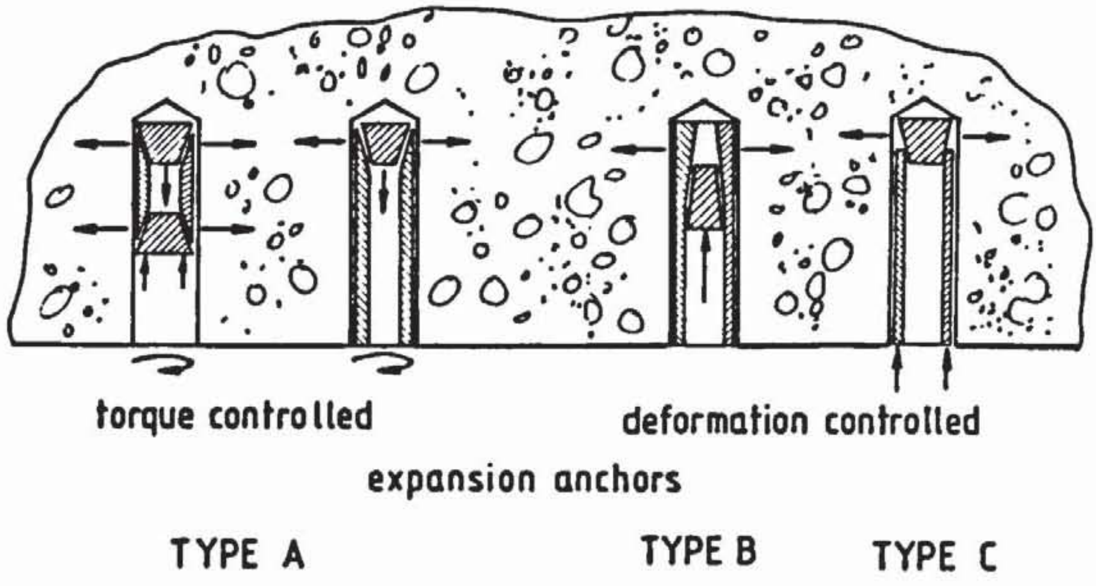


Fig. 1--Principle methods of expanding anchors, after (5)

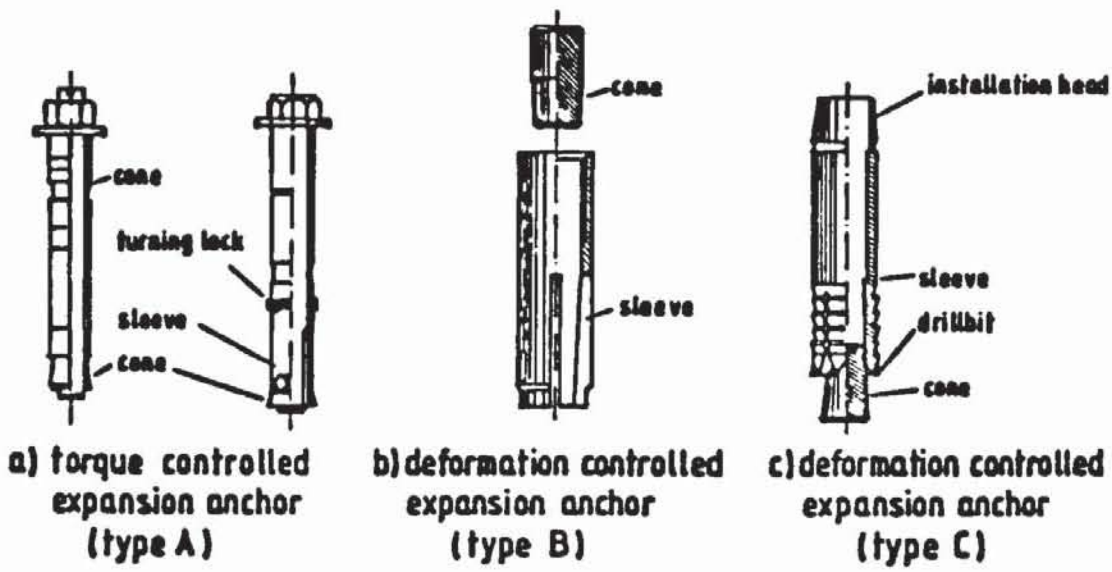


Fig. 2--Different types of metallic expansion anchors

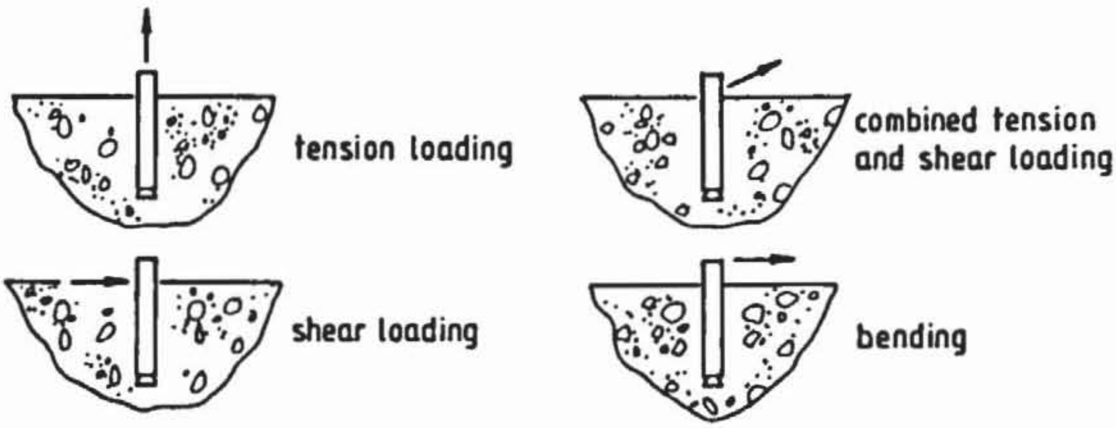
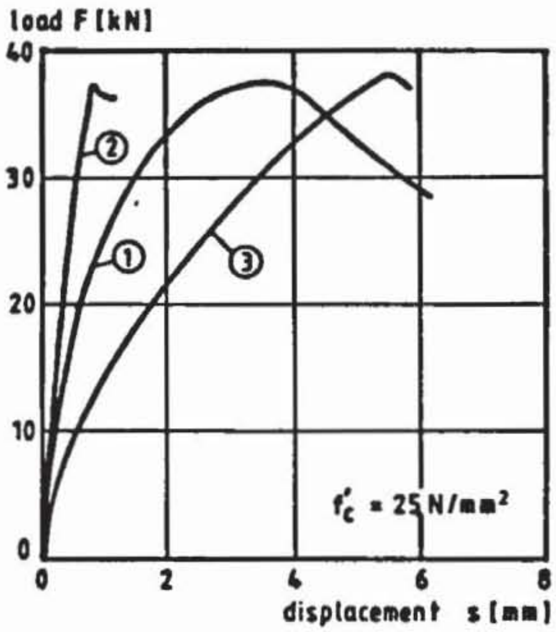


Fig. 3--Possible loadings of anchors



line	anchor type	bolt diameter mm	anchorage depth mm
①	A	10	65
②	B	16	65
③	C	16	63

Fig. 4--Typical load-displacement relationships under tension loading, after (1)

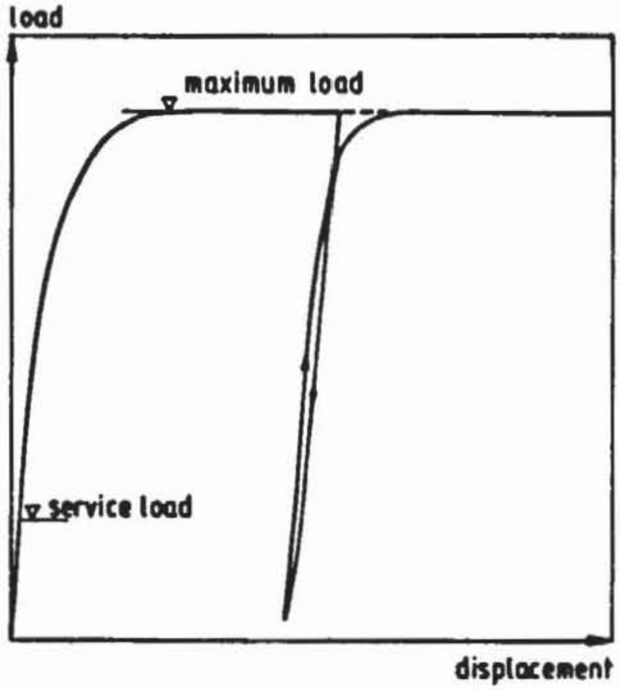


Fig. 5--Ideal load-displacement relationship of anchors

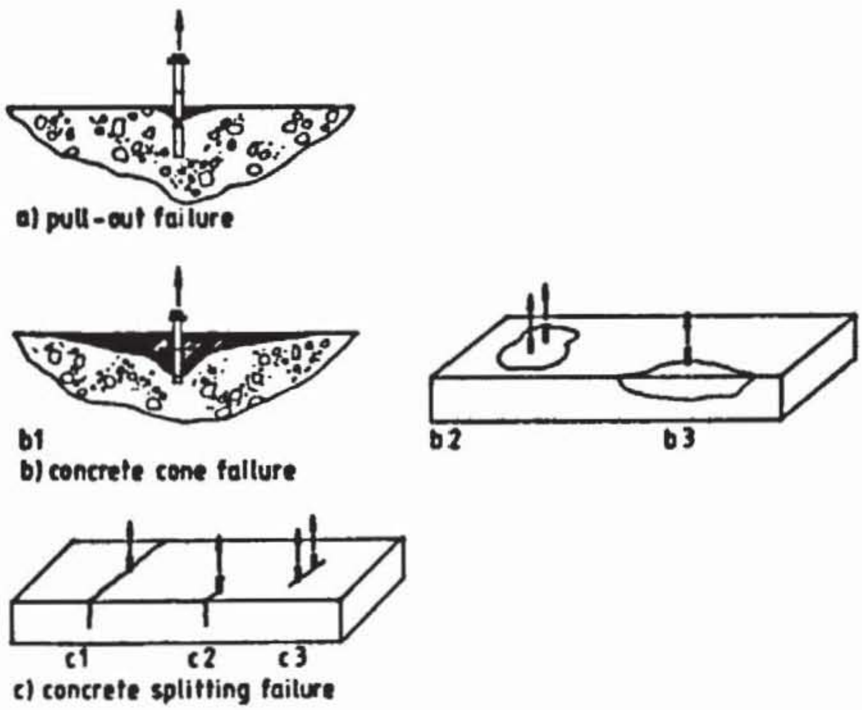


Fig. 6--Failure modes of expansion anchors under tension loading

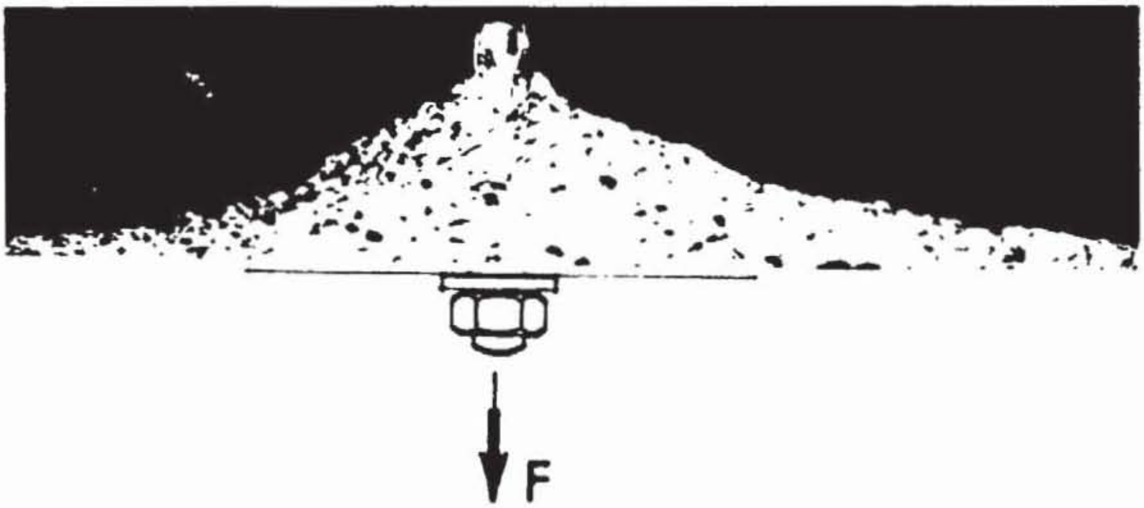


Fig. 7--Typical failure cone, type A anchor with anchorage depth l_d = 125 mm (5 in)

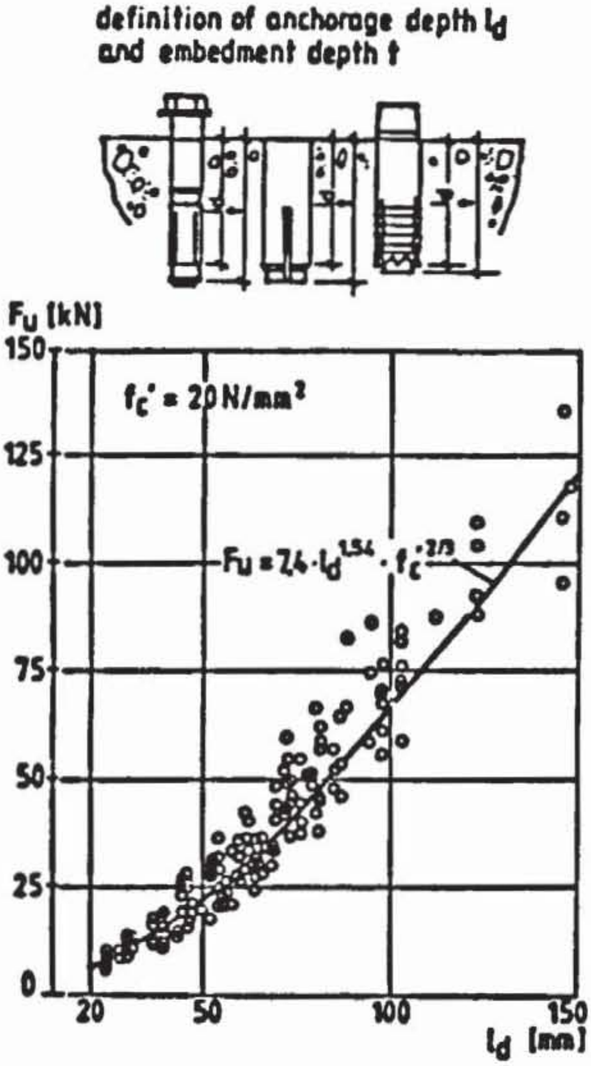


Fig. 8--Concrete cone pullout load: test results, after (1)

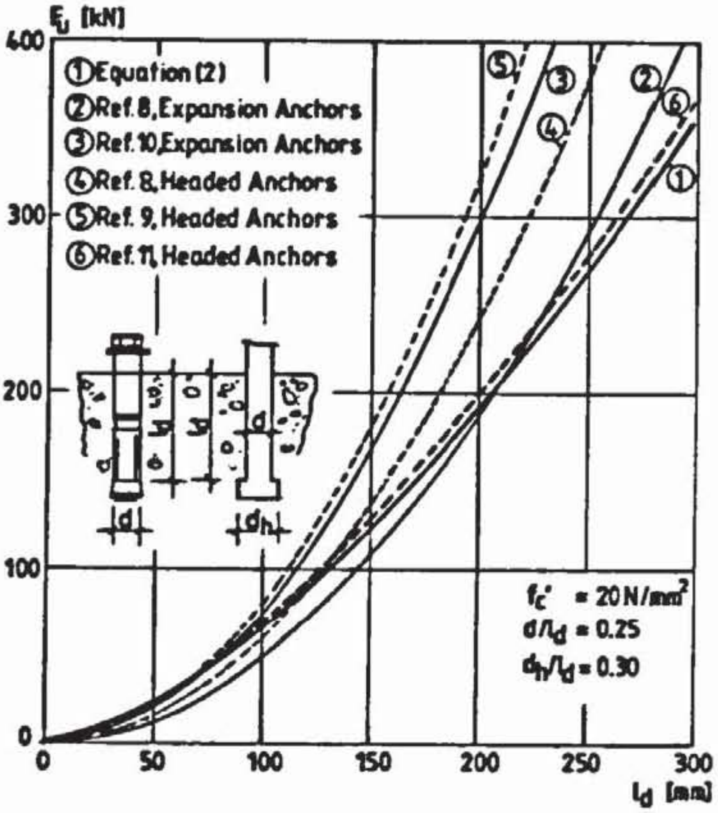


Fig. 9--Concrete cone pullout load: predictions

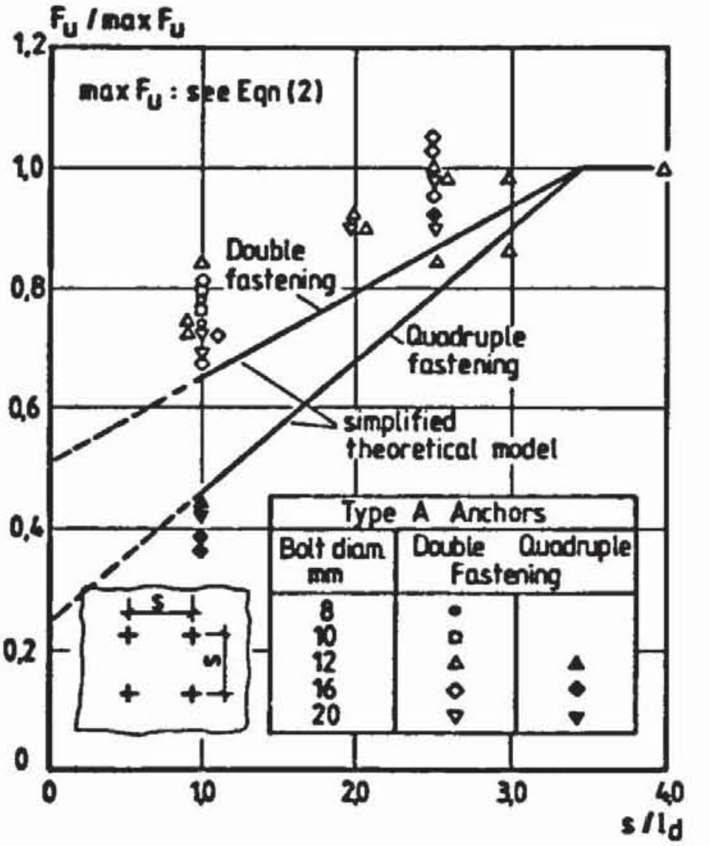


Fig. 10--Influence of spacing on ultimate load of anchor groups loaded in tension, after (1)

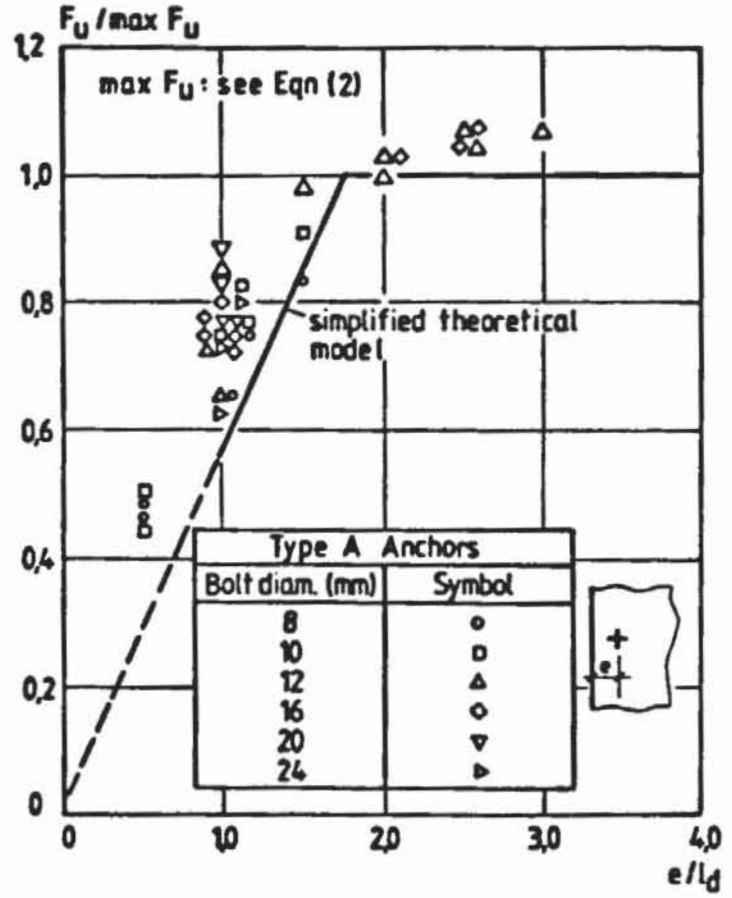


Fig. 11--Influence of edge distance on ultimate load of single anchors loaded in tension, after (1)

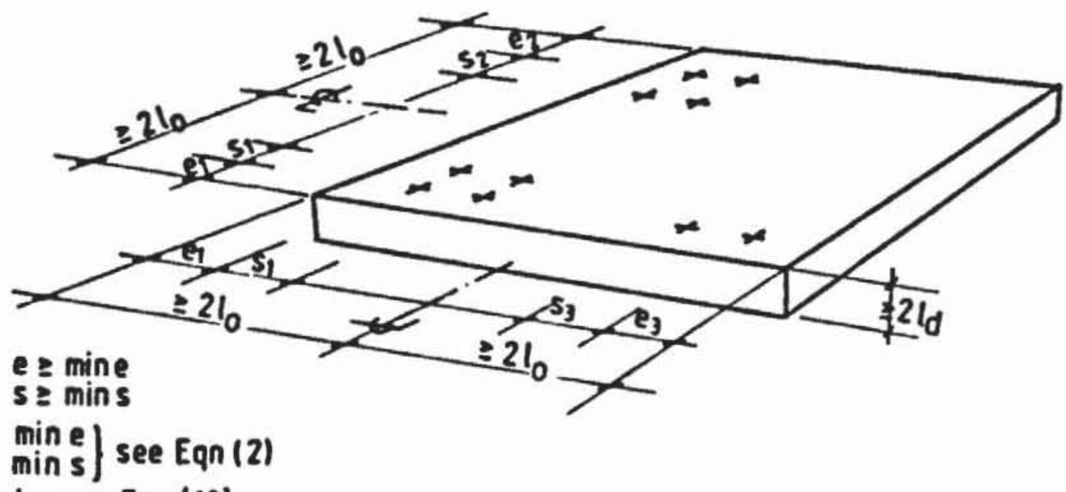


Fig. 12--Recommended spacings of expansion anchors to prevent splitting, after (10)

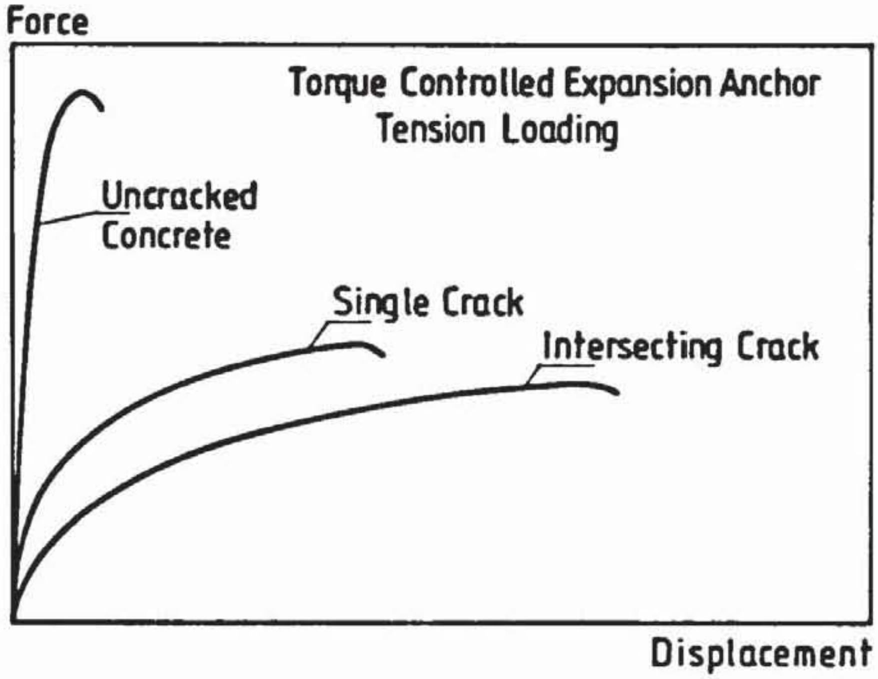


Fig. 13--Influence of cracks on the load-displacement relationships of expansion anchors (schematic), after (14)

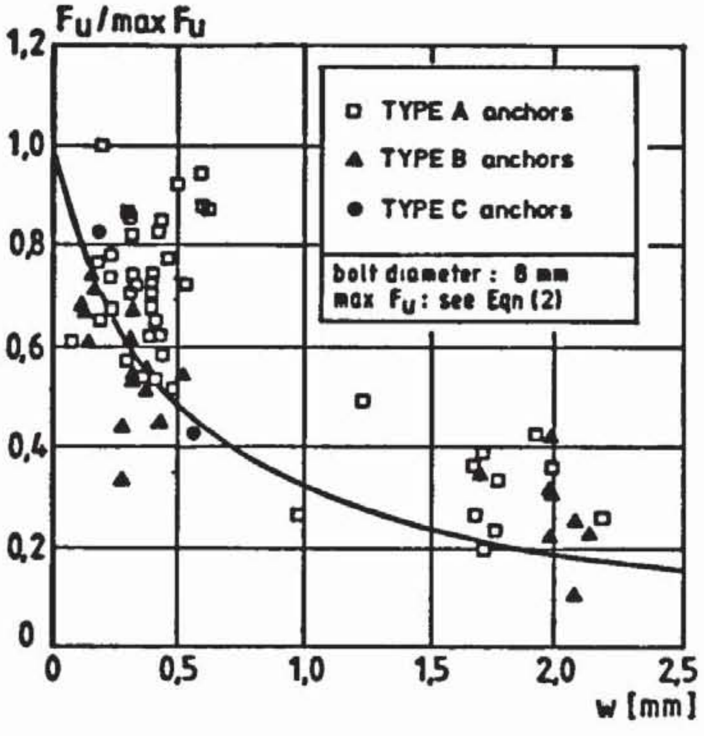


Fig. 14--Influence of crack width on ultimate load, after (1)