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 ($w_{95\%} \approx 0.3$ 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.

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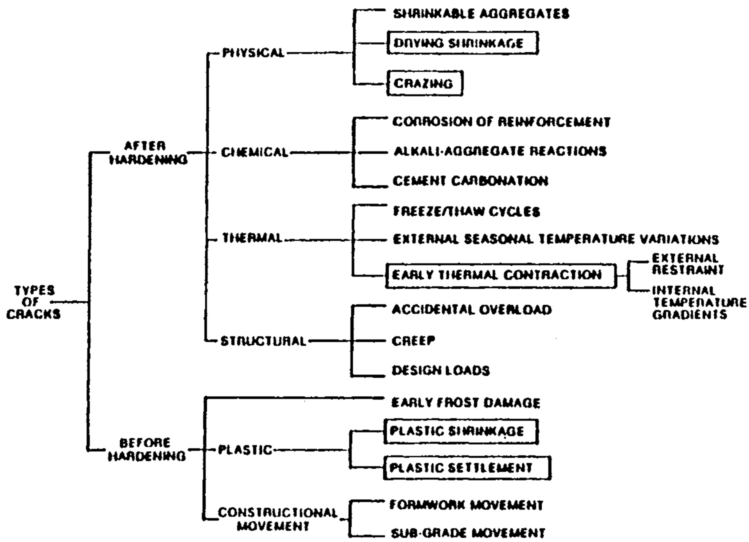

Fig. 1--Causes of cracking (after Beeby /2/)

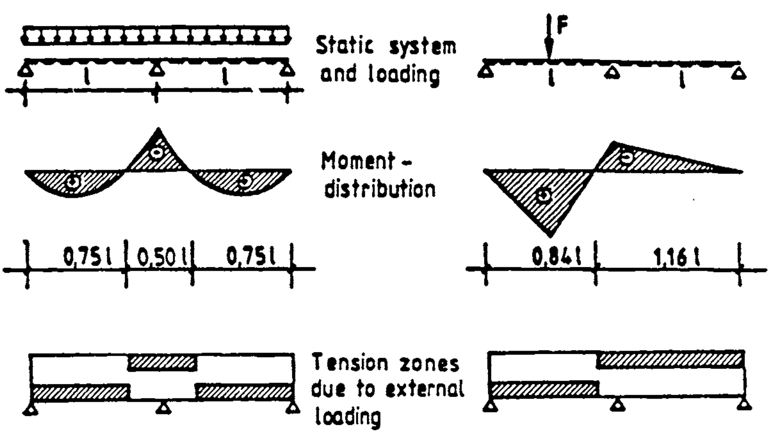

Fig. 2--Tension zones due to external loading for a two-span beam (after /4/)

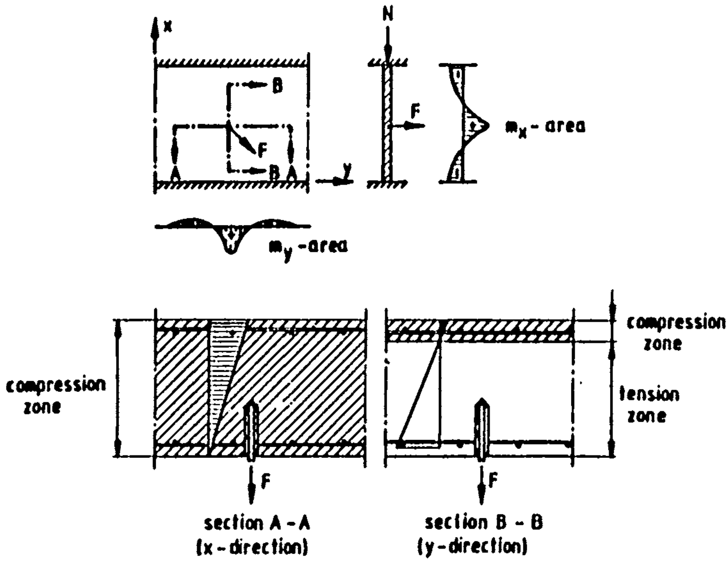

Fig. 3--Anchors in a wall (after /11/)

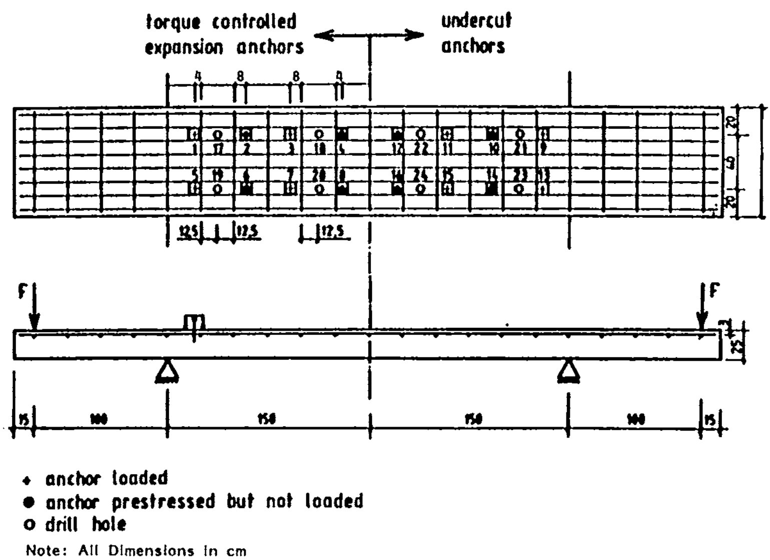

Fig. 4--Test set-up and anchor pattern (after /5/)