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Code Background Paper:*

Behavior of Fasteners Loaded in Tension in Cracked Reinforced Concrete

by Rolf Eligehausen and Tamas Balogh

Many reinforced concrete structures are designed under the assumption that the concrete is cracked due to external loads or restraint of imposed deformations (e.g., due to creep, shrinkage, temperature variations, or support settlement). Research shows that fasteners will attract cracks or even induce cracking. Therefore, the behavior of different types of fastener in cracked reinforced concrete has been studied extensively.

Fasteners suitable for use in cracked reinforced concrete such as cast-in situ headed studs or headed anchors, post-installed undercut anchors, and specially designed torque-controlled expansion anchors show a reduction of the concrete cone failure load of about 25 to 35 percent compared to uncracked concrete when located in or close to cracks with a width ~ 0.3 to 0.4 mm (0.012 to 0.016 in.). This crack width can be expected in typical concrete members designed with ordinary crack control provisions. The failure load of ordinary torque-controlled expansion, deformation-controlled expansion, and bonded anchors is more influenced by cracks and may be unpredictable, especially if installation inaccuracies that might occur on site are taken into account.

Fasteners used in zones with potential concrete cracking must be suitable for this application. A test program to check the effective functioning of fasteners in cracked reinforced concrete is described in technical guides by UEAtc and EOTA, a basis for the proposed ASTM specification.

Keywords: anchors (fasteners); control joints; cracking (fracturing); failure; **loads (forces)**; studs; **tension**.

Extensive research has been performed on the behavior of different fastener types loaded in tension in uncracked concrete, and several models have been developed to predict the concrete cone failure load.[1,2] Two of these models, one according to ACI 349[3] and the concrete capacity design (CCD) method (based on the κ-method[4-6]) are presented and compared by Fuchs, Eligehausen, Breen,[7] who also provide a description of the different fastener types.

The design of reinforced concrete elements for flexure and tension traditionally assumes that concrete is cracked wherever tensile stresses might occur. Cracks may not only be caused by external loads, but also by restraint of intrinsic deformations (e.g., creep and shrinkage) and extrinsic deformations (e.g., temperature variations and support settlement). It has been suggested that cracks can be caused by tensile stresses, even in regions where compression stresses occur due to external loads.[8,9] Cracking in structural members takes various forms. Cracks may occur in one direction (e.g., beams, one-way slabs, and tension members) or in two directions (e.g., two-way slabs and walls). The crack width may be constant over the member depth (tension members) or may reduce as the crack approaches the compression zone (flexural members).

Even when neglecting tensile stresses due to restraint of imposed deformations, the length of the tension zone in continuous beams or slabs subjected to bending can be rather large compared to the compression zone if all possible loading cases are considered (Fig. 1). In plate structures (slabs and walls) supported on four sides, single-point loadings induce bending moments in two orthogonal directions. Fig. 2 demonstrates how walls subjected to out-of-plane loads may develop a biaxial tension/compression state of stress at the face where the fastening is placed.

For these reasons, it is often difficult in practice to clearly distinguish between regions of cracked or uncracked concrete in concrete structures.

RESEARCH SIGNIFICANCE

Many reinforced concrete members are designed under the assumption that the concrete is cracked under service load. When fastenings are installed in zones of potential concrete cracking, their design should also be based on the assumption that the concrete is locally cracked. However, in most current fastening designs, the influence of concrete cracking on anchor behavior is neglected. This might be due to the rather limited knowledge in this field. Therefore, extensive

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research has been carried out during the last decade at the University of Stuttgart on the behavior of different fastener types in cracked reinforced concrete.

PROBABILITY FOR FASTENERS TO BE SITUATED IN CRACKS

Several experimental investigations have been performed to determine whether fasteners can actually attract or induce cracks. Eligehausen, Lotze, and Sawade[10] and Lotze[11] tested concrete slabs with a depth of 250 mm (9.8 in.) reinforced with wire mesh or deformed bars. The spacing of the transverse reinforcement was 250 mm (10 in.). Torque-controlled expansion and undercut anchors with M12 bolts (1/2-in. diameter) and an embedment depth $h_{ef} = 80$ mm (3.1 in.) were tested. Loading of the fasteners (prestressed only or loaded with 1.3 times the admissible load) and distance of fasteners to the transverse reinforcement [40 and 80 mm (1.6 and 3.2 in.)] were varied. For comparison, holes were also drilled without fasteners being placed. The fasteners were installed and loaded in uncracked concrete. Afterward, the slabs were incrementally loaded up to the admissible service load according to the German code for reinforced concrete, DIN 1045.

Cracking started at about 40 percent of the slab service load. The cracks started over the transverse reinforcement but deviated to the fasteners. Under the allowable service load of the slab, practically all fasteners and most drilled holes were situated in cracks [average crack width ~ 0.2 mm (0.008 in.)], independent of the position relative to the transverse reinforcement and type and loading of anchors (Fig. 3). The cracks ran directly through the anchorage zone of the fasteners. The measured fastener displacements demonstrated that the fasteners were situated in a crack from the initial phase of the crack formation process. Similar results were obtained by Cannon,[12] Bergmeister,[13] and Bensinhom, Lugez, and Combette.[14]

In addition, theoretical investigations on the tensile stresses in concrete due to prestressing and loading of torque-controlled expansion anchors were conducted using nonlinear finite element codes by Mayer[15] and Hsu.[16] In these studies, various assumptions were made concerning the magnitude of the expansion forces and behavior of concrete in tension. Both investigators concluded that an expansion anchor placed in the tension zone of a concrete member stressed nearly to the point of cracking may, in fact, initiate concrete cracking (Fig. 4). The probability of cracking was shown to increase with increasing anchor diameter.

For anchor types that tend to develop higher splitting forces than torque-controlled expansion anchors (e.g., drop-in anchors), the probability of crack initiation may be assumed to increase. Likewise, this tendency may be assumed to decrease for anchors that develop lower splitting forces (e.g., headed, undercut, and bonded anchors).

The previously mentioned experimental and theoretical investigations have confirmed that fasteners placed in a reinforced concrete member may affect the tensile stress distribution in the member so that it actually attracts or induces cracks precipitated by subsequent external loads or restraint of imposed deformations. This phenomenon may be explained as follows:

1. Prestressing and external loading of the fastener result in expansion (splitting) forces in the concrete, which cause high tensile stresses in the vicinity of the fastener.

2. The drill hole acts as a stress riser in the concrete continuum (notch effect).

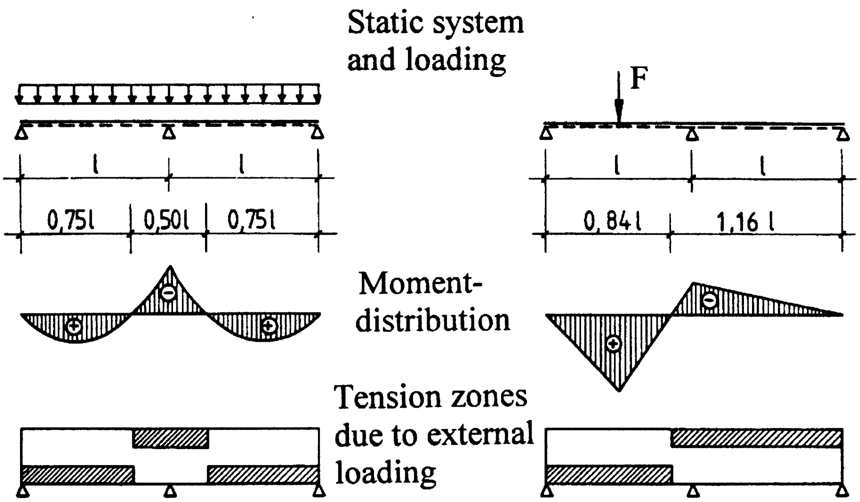

Fig. 1—Tension zones due to external loading for two-span beam[6]

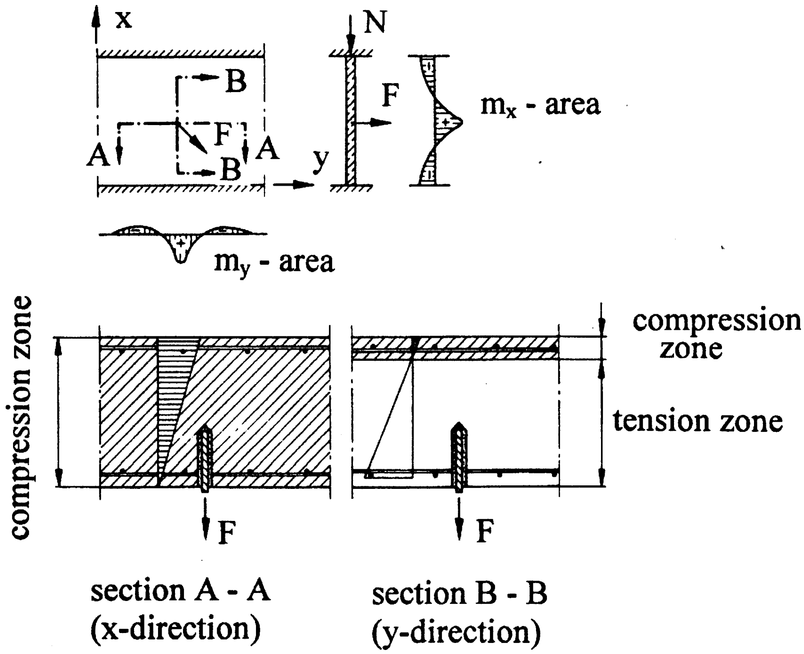

Fig. 2—Anchor in wall[31]

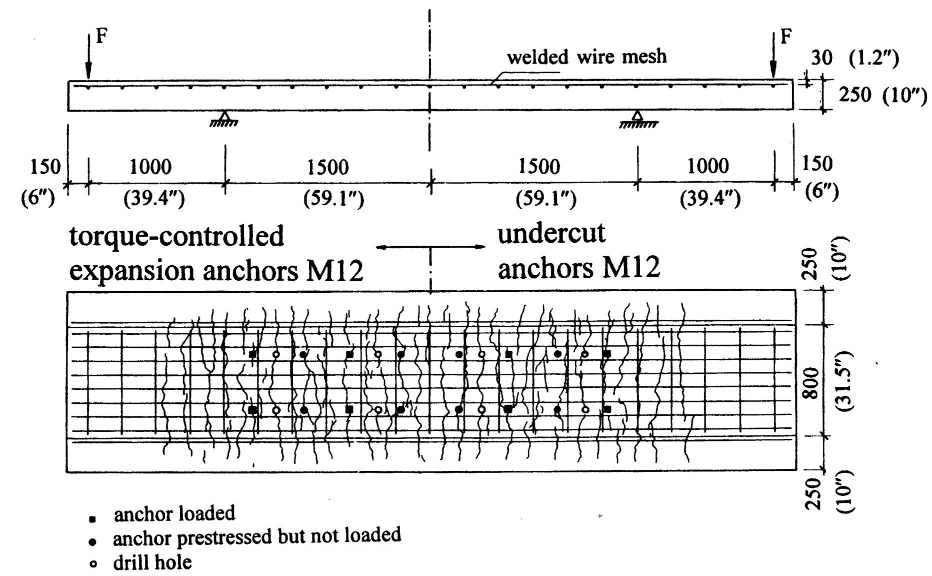

Fig. 3—Crack pattern at service load[11]

3. For two-way slabs and walls, loads transmitted by fastenings induce high local moments, and, therefore, locally high tensile stresses in the concrete near the anchor (Fig. 2).

BEHAVIOR OF FASTENERS IN CRACKS

Several test methods have been developed to investigate the effect of cracks on the behavior of fastenings. Use is made of various types of reinforced test specimen, including bending specimens, tension specimens, and specimens for producing intersecting cracks. In the tests described in the following, post-installed fasteners have been placed in or close to previously produced hairline cracks while the member was in an unloaded state. In tests with cast-in situ headed studs, crack inducers were placed in the concrete member to insure the desired positioning of the fastener with respect to the crack. If required by the manufacturer, the anchors were prestressed with the recommended torque moment. In general, after 10 min, this torque moment was reduced to 50 percent to account for reduction of the torque moment with time. The cracks were then widened to the desired width by loading the specimen, and the fastener was loaded to failure in either a load- or deformation-controlled manner with the crack kept open.

In practice, several different loading sequences of anchors may occur. The loading sequence chosen in the tests represents an unfavorable but possible application.

In the following, the results of tests will be presented with fasteners located in a crack running in onè direction, with a

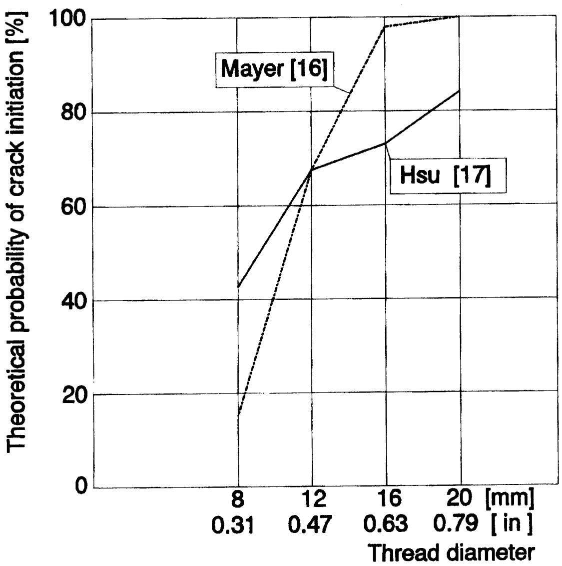

Fig. 4—Probability that cracking is initiated by torque-controlled expansion anchors, $f_{cc}' = 25\ N/mm^2$ ($f_c' = 3.1$ *ksi*)[15,16]

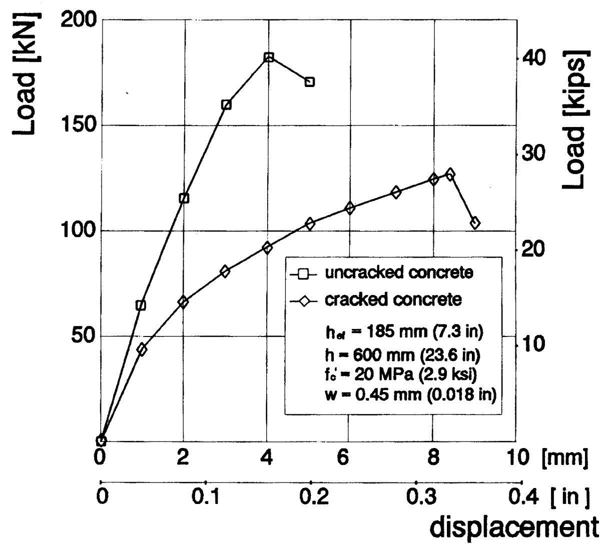

Fig. 5—Typical load-displacement curves of headed anchors in uncracked and cracked reinforced concrete (concrete cone failure)[32]

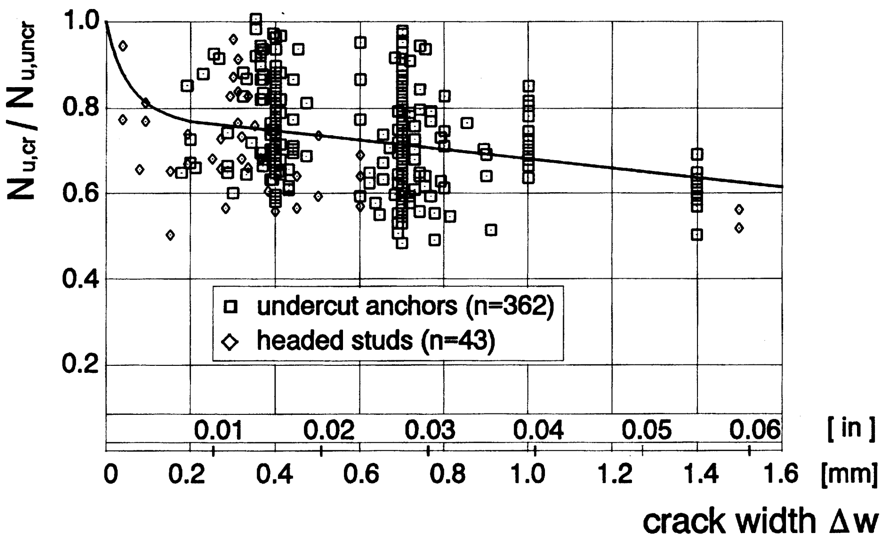

Fig. 6—Ratios of concrete cone failure loads of undercut anchors and headed studs in cracked reinforced concrete (line cracks) to values valid for uncracked concrete calculated according to Eq. (1) as function of crack width

nearly constant width over the member depth. This crack is called a line crack. Furthermore, influence of bending cracks and intersecting cracks on the concrete cone failure load will be discussed.

Failure modes exhibited by fasteners loaded in tension in uncracked concrete (compare to Reference 7) are also observed in tests in cracked concrete. However, expansion anchors that fail by breaking out a concrete cone in uncracked concrete may fail by pulling out in cracked concrete.

Headed studs and undercut anchors

Headed studs and undercut anchors will be discussed together, because their load transfer mechanism is similar: a tension load is transferred to the concrete by mechanical interlock.

Fig. 5 shows typical load-displacement curves for tension tests with headed studs in uncracked concrete and located in a crack, respectively. During the test in cracked concrete, the crack width w was held constant at 0.45 mm (0.018 in.) across the depth of the specimen. Both fasteners exhibited concrete cone failures; however, the load-displacement curve of the headed stud in the crack is flatter, the ultimate load is markedly reduced, and displacement at failure is increased.

According to ACI 318,[17] the maximum allowable crack width is $w = 0.4$ mm (0.016 in.). The behavior of an anchor in a crack with width $w = 0.4$ mm (0.016 in.) would not be much different than shown in Fig. 5 (compare to Fig. 6).

In Fig. 6, failure loads of undercut anchors ($n = 362$) and headed studs ($n = 43$) located in cracks related to values expected in uncracked concrete are plotted as a function of the crack width Δw (Δw = difference between crack width at testing and that at fastener installation). The tests were performed at the bottom side of tension specimens. In all tests, failure occurred by breaking out a concrete cone. Since comparison tests in uncracked concrete have seldom been performed because of cost reasons, failure load in uncracked concrete was calculated using the empirical formula proposed in References 4, 6, and 7. This equation is sufficiently accurate[7]

$$N_u = k_{nc} \cdot \sqrt{f_{cc}'} \cdot h_{ef}^{1.5} \text{ , N} \quad (1)$$

with

k_{nc} = 13.5 for post-installed fasteners

= 15.5 for cast-in situ headed studs and headed anchors

f_{cc}' = concrete strength measured on cubes with side length of 200 mm at time of testing, N/mm²

h_{ef} = embedment depth, mm

In customary units, Eq. (1) becomes with 1 in. = 25.4 mm, 1 psi = 0.006895 N/mm², 1 lb = 4.448 N, and $f_{cc}' = 1.18 f_c'$

$$N_u = k_{nc} \cdot \sqrt{f_c'} \cdot h_{ef}^{1.5} \text{ , lb} \quad (1a)$$

with

k_{nc} = 35, post-installed fasteners

= 40, cast-in situ headed studs and headed anchors

f_c' = concrete compression strength measured on 6 by 12-in. cylinders at time of testing

According to Fig. 6, on an average for a crack width $w \approx 0.3$ mm (0.012 in.), concrete cone failure load is about 75 percent of the value expected in uncracked concrete. It decreases gradually with increasing crack width.

Eligehausen and Ozbolt[18] performed a three-dimensional nonlinear finite element analysis, modeling a pullout test of a headed stud located in a crack. As a material model for concrete, the advanced nonlocal microplane model was employed, which is based on nonlinear fracture mechanics.[19] According to this study, the concrete cone failure load decreases to about 70 percent of the value valid for uncracked concrete for a crack width $w \sim 0.1$ mm (0.004 in.), and is almost constant for larger crack widths.

According to Reference 4, the lower concrete cone failure load in cracked concrete is attributable to disturbance of the stress state caused by a crack in the load-transfer area. In uncracked concrete, stresses are distributed axis symmetrically with respect to the fastener [Fig. 7(a)]. Equilibrium is provided by hoop stresses in the concrete. If the fastener is situated in a crack of width sufficient to prevent transfer of tensile stresses perpendicular to the crack, stress distribution in the concrete is altered and the surface area available for transfer of the tensile forces is decreased [Fig. 7(b)].

A more refined explanation for reduction of the concrete cone failure load of fasteners located in a crack based on

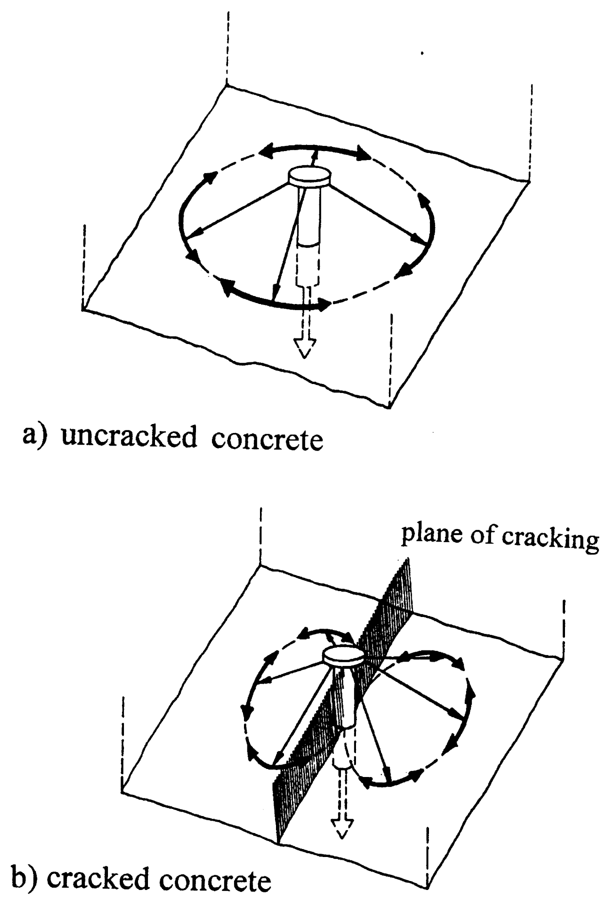

Fig. 7—Influence of crack on mechanism of load transfer into concrete[4]

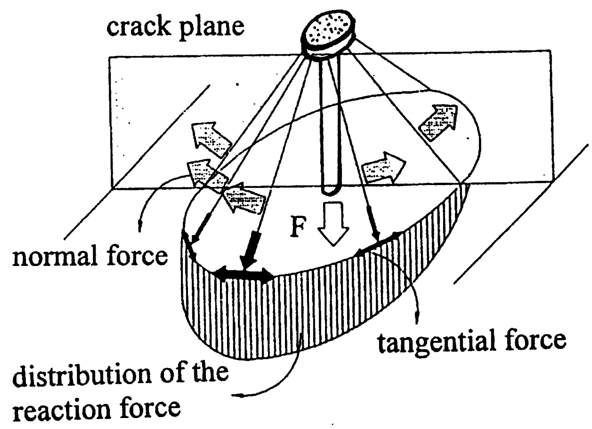

Fig. 8—Load-transfer mechanism of headed anchors in cracked concrete[18]

stress distribution found in a nonlinear finite element analysis has been given in Reference 18 (Fig. 8). According to this study, the shape of the failure cone is similar in cracked and uncracked concrete. This agrees with test observations. However, only a small part of the anchor load is transferred into the concrete in the direction of the crack, because the concrete stiffness in that direction is much less than that perpendicular to the crack. The distribution of tensile hoop stresses on the fracture area is changed by shear stresses, so that no tensile stresses are present perpendicular to the crack.

In Fig. 9, the test results presented in Fig. 6 are plotted as

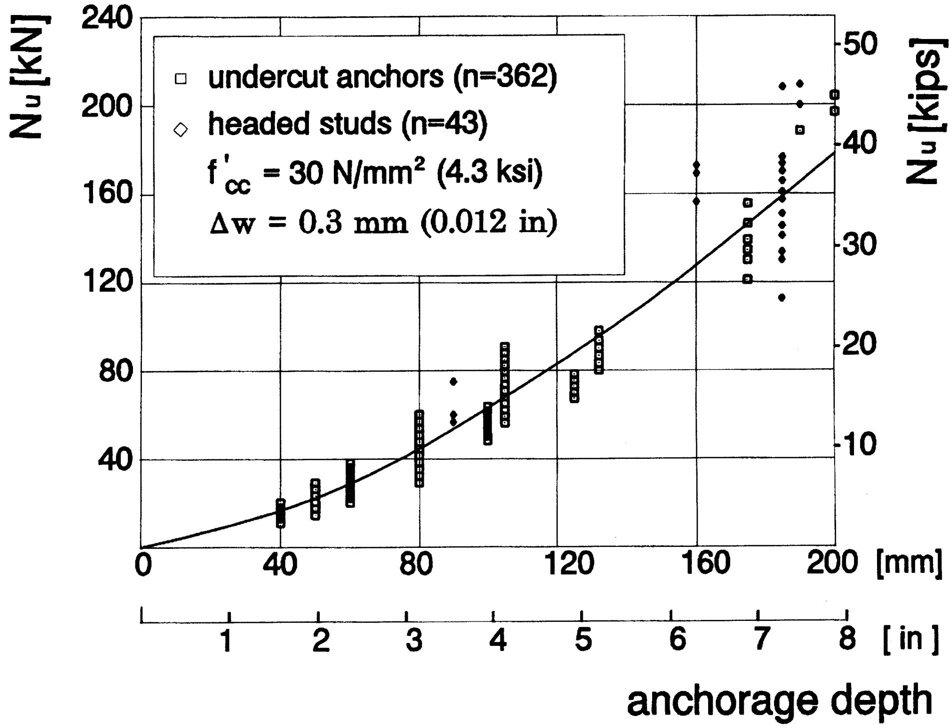

Fig. 9—Concrete cone failure loads of undercut anchors and headed studs in cracked reinforced concrete (line cracks) as function of embedment depth. Failure loads of undercut anchors multiplied by 15.5/13.5 = 1.15

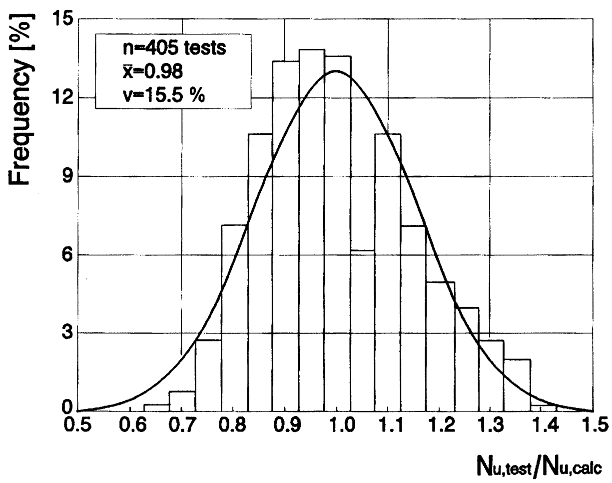

Fig. 10—Frequency distribution of ratios of measured concrete cone failure loads of undercut and headed anchors in cracked reinforced concrete to values calculated according

a function of the embedment depth. The figure is valid for headed studs. Therefore, failure loads for undercut anchors were multiplied with the factor 15.5/13.5 = 1.15. Since the tests were performed on concrete with different compressive strengths, the measured failure loads were transformed to a concrete strength $f_{cc}' = 30$ N/mm^2 ($f_c' = 3.7$ ksi), using Eq. (2)

$$N_u (f_{cc}' = 30) = N_{u,test} \cdot (30/f_{cc,test}')^{0.5} \quad (2)$$

with

$N_u (f_{cc}' = 30)$ = failure load for concrete strength $f_{cc}' = 30$ N/mm^2 ($f_c' = 3.7$ ksi)

$N_{u,test}$ = failure load measured in test

$f_{cc,test}'$ = concrete strength of test member

To account for the small influence of crack width on the failure load, measured values were transformed to a crack width $w = 0.3$ mm (0.012 in.) using a linear regression function of the data [Eq. (3)]

$$N_u (w = 0.3) = N_{u,test} \cdot \frac{\alpha(0.3)}{\alpha(w)} \quad (3)$$

with

$\alpha(0.3)$ = value of linear regression function for crack width $w = 0.3$ mm = 0.76

$\alpha(w)$ = value of linear regression function for crack width w in test

$$= 0.79 - 0.11w, \text{ mm} \quad (3a)$$

$$= 0.79 - 0.0043w, \text{ in.} \quad (3b)$$

Fig. 9 shows that the failure load of headed studs and undercut anchors in cracked reinforced concrete increases in proportion with $h_{ef}^{1.5}$. This agrees with the behavior found in uncracked concrete.[4,6,7] Therefore, the failure load increases less than the fracture area, which can be attributed to size effect.[20]

The average failure load of anchors in cracked concrete [$w \cong 0.3$ to 0.4 mm (0.012 to 0.016 in.)] can be given by

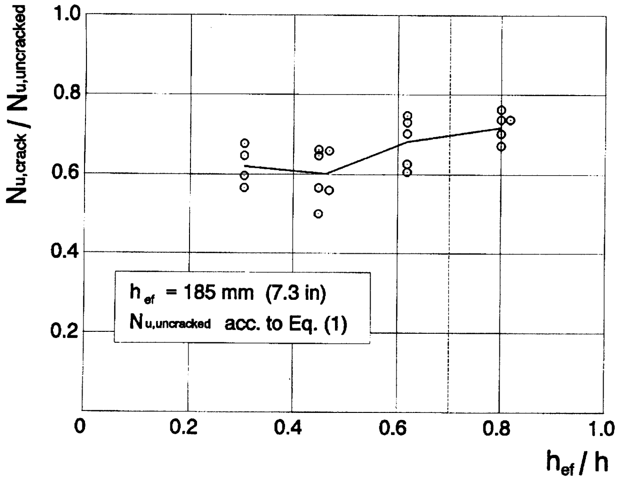

Fig. 11—Ratios of failure loads of headed studs in cracked reinforced concrete to values valid for uncracked concrete calculated according to Eq. (1) as function of ratio of embedment depth to member thickness[24]

$$N_u = k_1 \cdot (f_{cc}')^{0.5} \cdot h_{ef}^{1.5} \text{ , N} \quad (4)$$

with

k_1 = 0.75 · 13.5 ~ 10.0, undercut anchors

= 0.75 · 15.5 ~ 11.5, headed studs

In customary units, Eq. (4) becomes

$$N_u = k_1 \cdot (f_{cc}')^{0.5} \cdot h_{ef}^{1.5} \text{ , lb} \quad (4a)$$

with

k_1 = 26, undercut anchors

= 29.5, headed studs

Eq. (4) is valid only if the bearing area is large enough to prevent a significant reduction of the embedment depth by large anchor displacements. For cast-in situ headed studs and headed anchors, the bearing area must be so large that concrete stresses under the head at failure are smaller than about $9 f_c'$.[21] In applications where crack widths may change due to loading and unloading of the structural element serving as base material, the pressure under the head at service load should be smaller than about $3 f_c'$ to limit the anchor displacements under service load.[21] For undercut anchors, the necessary bearing area should be evaluated by tests.[22,23,36]

In Reference 7, the limiting value for the pressure under the head is given as $13 f_c'$. This value is valid for noncracked concrete. Since, under otherwise constant conditions, the displacements of anchors in cracks are larger than in uncracked concrete (Fig. 5), the limiting pressure under the head is smaller for anchors in cracks compared to those in uncracked concrete.

Fig. 10 shows a histogram of the ratios of measured failure loads [transformed to a crack width $w = 0.3$ mm (0.012 in.) according to Eq. (3)] to values calculated according to Eq. (4). The ratios $N_{u,test}/N_{u,calc}$ are normally distributed. On an average, they amount to $\bar{x} \approx 1.0$. The coefficient of variation is $v = 15.5$ percent, not larger than for tests in uncracked concrete. The 5 percent fractile of the test results is about 0.75 times the value according to Eq. (4).

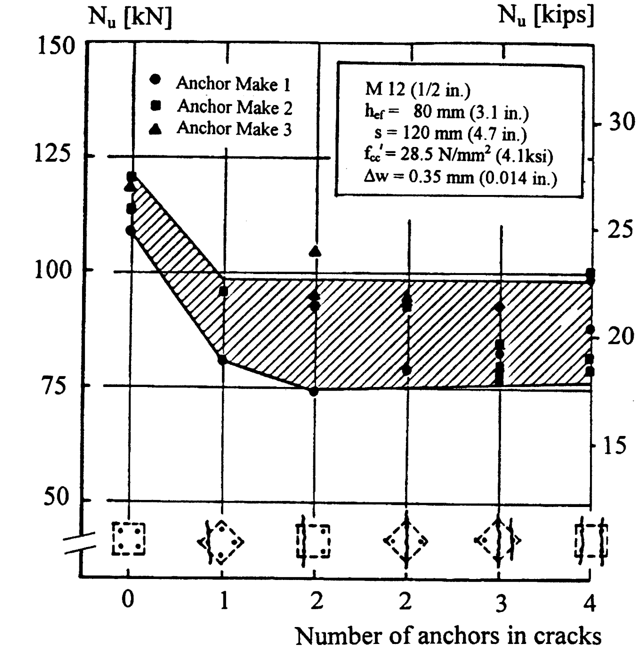

Fig. 12—Failure loads of quadruple fastenings with expansion and undercut anchors subjected to tension loading as function of number of anchors in line crack[25]

If headed studs or undercut anchors are located in the intersection of cracks running in two directions (e.g., in slabs spanning in two directions), the concrete cone failure load is about 20 percent lower than the value according to Eq. (4).[6]

In flexural members, crack width decreases with increasing distance from the tension force of the component. Eligehausen et al.[24] reported tension tests with cast-in-place headed studs located in the tension face of flexural members (f_{cc}' ~ 25 N/mm²) (f_c' ~ 3.1 ksi), loaded to produce an average crack width of 0.35 mm (0.014 in.) at the tension side of the member. In Fig. 11, the measured anchor failure loads divided by failure loads predicted for uncracked concrete according to Eq. (1) are plotted as a function of the ratio embedment depth to member depth. The failure loads for $h_{ef}/h \approx 0.4$ are only about 60 percent of the value valid for uncracked concrete. The relatively low ratio of 0.6 compared to Fig. 6 might be explained by the fact that the headed studs were situated at the top side of the test member, where the concrete tensile strength is generally lower. The failure loads were found to increase slightly with increasing ratio h_{ef}/h. This is due to the fact that with increasing ratio h_{ef}/h, the average crack width over the anchorage depth decreases; however, because the influence of crack width on the failure load is rather small (compare to Fig. 6), influence of the ratio h_{ef}/h on N_u is small as well.

Mayer and Eligehausen[25] conducted tests with quadruple fastenings exhibiting concrete cone failure in uncracked and cracked concrete. Fig. 12 shows the failure load of the group as a function of the number of fasteners positioned in cracks. Control tests conducted in uncracked concrete yielded ultimate loads about 30 to 40 percent higher than those recorded in cracked concrete, and with considerably less scatter. As predicted by theoretical studies,[25] the lowest load was observed when three fasteners were situated in cracks and one

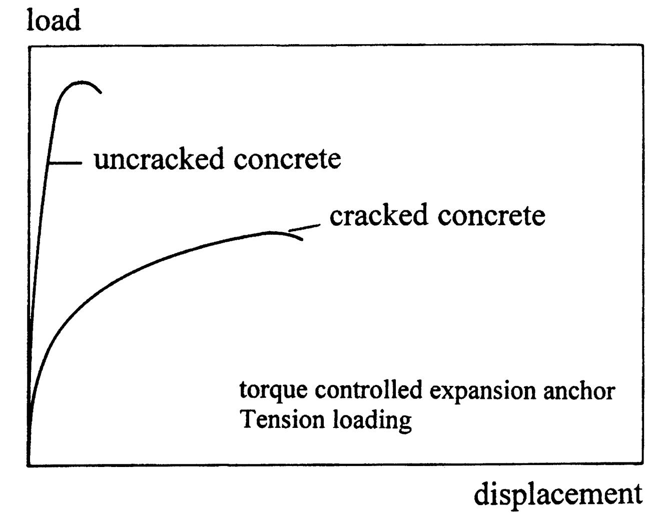

Fig. 13—Load-displacement relationships of suitable torque-controlled expansion anchors in uncracked and cracked reinforced concrete (schematic)[26]

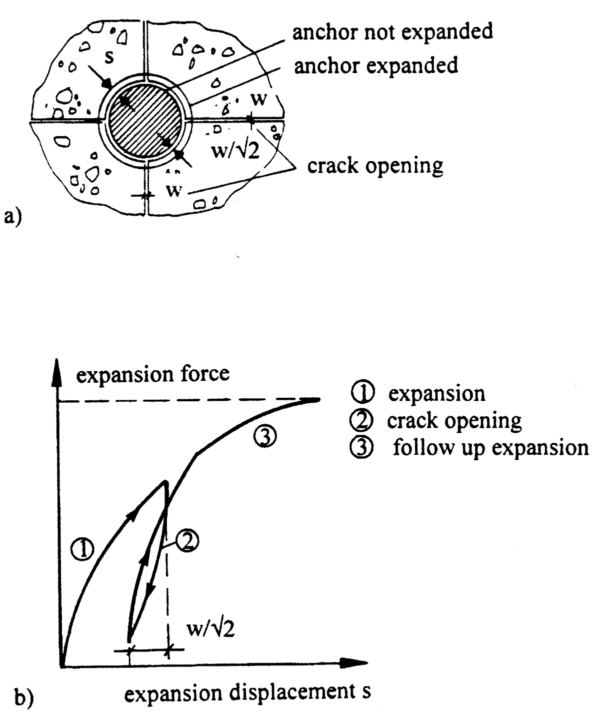

Fig. 14—Influence of opening of intersecting cracks on expansion force generated by torque-controlled expansion anchors[4]

fastener was located in uncracked concrete. The authors concluded that the group strength reduction is approximately equal to the strength reduction for a single anchor in a crack, and that the overall performance of the group is only slightly affected by positioning of anchors relative to the cracks. While these tests were conducted with undercut anchors and torque-controlled expansion anchors designed for use in cracked concrete, the results are believed to be generally applicable to headed anchors because of the similar nature of the load-transfer mechanisms.

According to tests conducted by Rehm and Lehmann,[26] the concrete cone failure load of expansion anchors located close ($\leq 0.5h_{ef}$) to a crack is reduced approximately as much as the failure load of anchors placed in a crack, because the failure cone will be truncated by the crack. This result is also valid for headed studs and undercut anchors.

The behavior of cast-in situ headed studs and headed anchors in cracked concrete is little influenced by small installation inaccuracies occurring on site. This is valid also for undercut anchors, provided they are well designed and the undercut is large enough.

Torque-controlled expansion anchors designed to function in cracked concrete

Modern torque-controlled expansion anchors may be specially designed to function both in uncracked and cracked concrete. Fig. 13 presents typical load-displacement curves for such fasteners set in uncracked and in cracked concrete, loaded statically to failure. At low load levels, the behavior of fasteners located in cracks is similar to that of fasteners in uncracked concrete. The load at which the load-displacement behavior of a fastener in a crack begins to deviate from the curve valid for uncracked concrete depends on the prestressing force, type of crack, and crack width. At higher load levels, displacements of fasteners in cracks are usually much greater than values in uncracked concrete. Furthermore, the failure load in cracked concrete is smaller than that in uncracked concrete.

The opening of a crack causes a significant reduction of the anchor expansion force. This is depicted by Fig. 14, which schematically represents a fastener situated in an intersecting crack. Torque-controlled anchors designed to function in cracked concrete will expand further under tension loading; therefore, the expansion force again increases and the anchor may produce concrete cone failure.

In Fig. 15, failure load of torque-controlled expansion anchors designed to function properly in cracked concrete [related to the value expected in uncracked concrete according to Eq. (1)] is plotted as a function of crack width Δw. In all cases, concrete cone failure was reported as a failure mode. As can be seen, the failure load at a crack width $\Delta w \approx 0.4$ mm (0.016 in.) is about 65 percent of the value expected in uncracked concrete. A similar reduction of the failure load was found in Reference 12. The influence of larger crack widths on failure load is somewhat higher than that for undercut anchors and headed studs.

In Fig. 16, the test results shown in the previous figure are plotted as a function of the embedment depth. The failure loads were transformed to $f_{cc}' = 30$ N/mm^2 ($f_c' = 3.7$ ksi) by Eq. (2) and to $w = 0.3$ mm (0.012 in.) by Eq. (3), with $\alpha(0.3) = 0.675$ and $\alpha(w) = 0.72 - 0.15 \cdot w$ (w in mm). Fig. 16 shows that concrete cone failure load increases in proportion to $h_{ef}^{1.5}$. The average failure load for a crack width $w \approx 0.3$ mm can be predicted by Eq. (5)

$$N_u = 9.0 \cdot (f_{cc}')^{0.5} \cdot h_{ef}^{1.5}, \text{ N} \qquad (5)$$

In customary units, Eq. (5) reads

$$N_u = 23 \cdot (f_c')^{0.5} \cdot h_{ef}^{1.5}, \text{ lb} \qquad (5a)$$

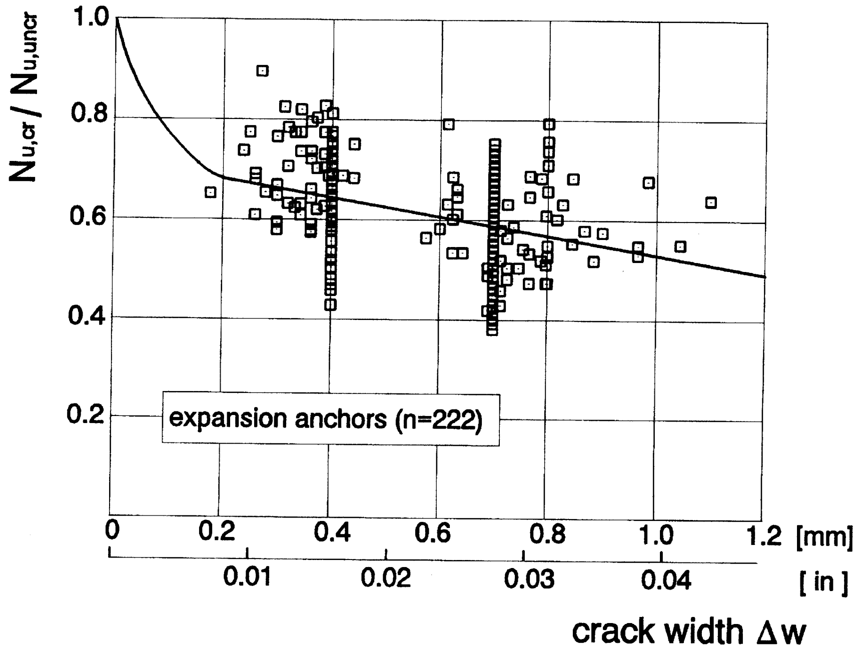

Fig. 15—Ratios of concrete cone failure loads of suitable torque-controlled expansion anchors in cracked reinforced concrete (line cracks) to values valid for uncracked concrete calculated according to Eq. (1) as function of crack width

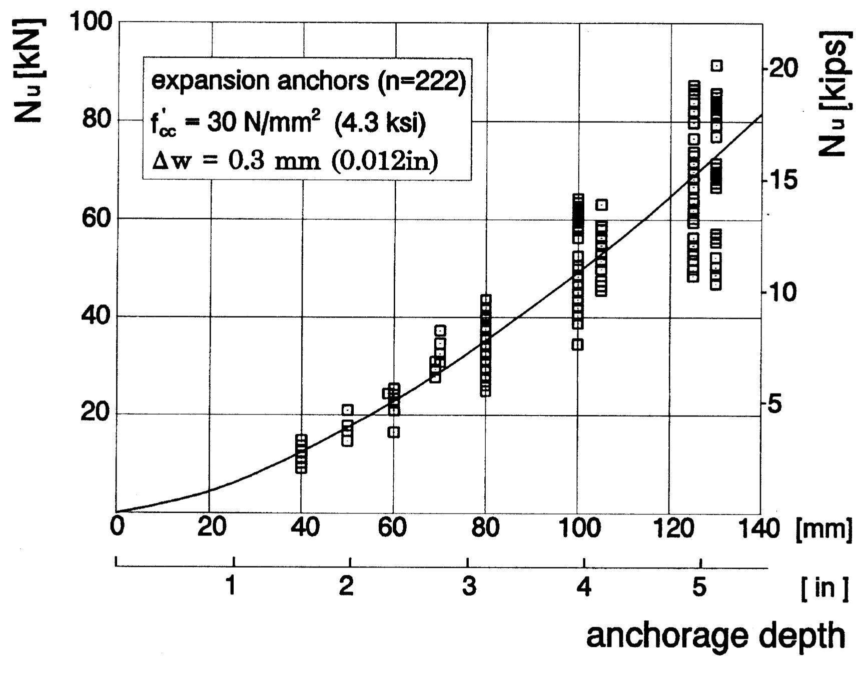

Fig. 16—Concrete cone failure loads of torque-controlled expansion anchors in cracked reinforced concrete (line cracks) as function of embedment depth

Fig. 17 shows a histogram of the ratio of measured failure loads [transformed to crack width w = 0.3 mm (0.012 in.)] to values calculated according to Eq. (5). The ratios $N_{u,test}/N_{u,calc}$ are normally distributed. On an average, they amount to $\bar{x} \approx 1.0$. The coefficient of variation is v = 15.8 percent, not larger than that for tests in uncracked concrete.

According to test results, concrete cone failure loads of torque-controlled expansion anchors are about 10 percent lower than that for comparable undercut anchors. No significant difference in concrete cone failure load for the two anchor types was found in uncracked concrete.[4,6,7] The different behavior may be due to the fact that, with expansion anchors, the expansion cone is pulled further into the expansion sleeve in cracked reinforced concrete than in uncracked concrete, thus reducing actual anchorage depth by bringing the point of maximum expansion forces closer to the concrete surface.

The failure load of fasteners designed to fail in uncracked

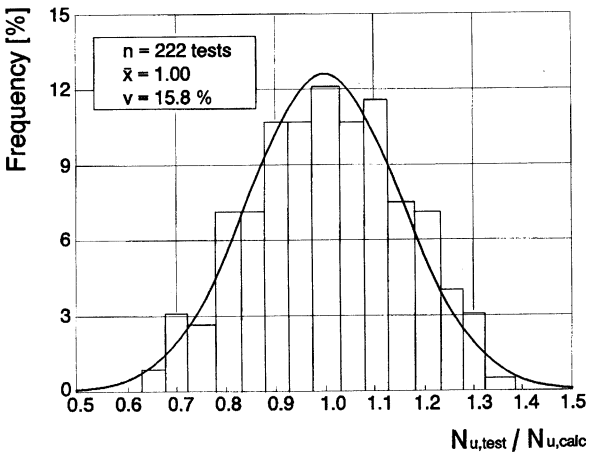

Fig. 17—Frequency distribution of ratios of measured concrete cone failure loads of suitable torque-controlled expansion anchors in cracked reinforced concrete to values calculated according to Eq. (5)

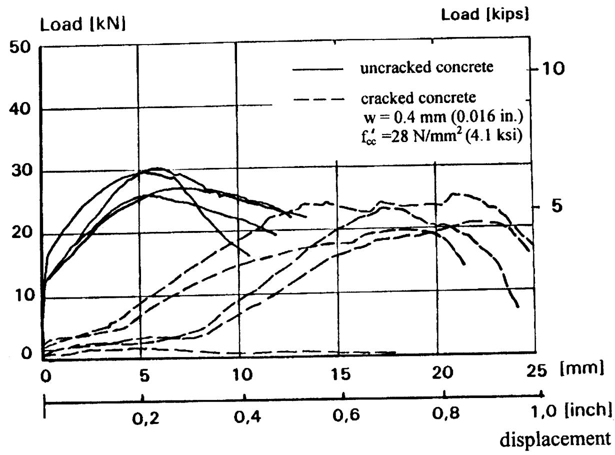

Fig. 18—Load-displacement curves of expansion anchors designed to function in uncracked concrete anchored in uncracked concrete and in line crack [Δw = 0.4 mm (0.16 in.)][33]

concrete by pulling the expansion cone through the expansion sleeve or segments may be significantly more reduced by a crack opening than shown in Fig. 15. The actual reduction depends on the design of the anchor and must be measured in tests.[22,23,36]

In general, behavior of torque-controlled expansion anchors designed to function in cracked concrete is not very sensitive to installation inaccuracies that might occur on site (e.g., applied torque moment too small).

Torque-controlled expansion anchors designed to function in uncracked concrete

Torque-controlled expansion anchors designed to function well in uncracked concrete may function poorly in cracked concrete because of the large reduction of expansion force caused by the crack opening (compare to Fig. 14). These anchors may either not expand further under tension load and be pulled out at rather low loads or may re-expand only after considerable movement of the anchor in the drill hole, until the expansion sleeve reaches a part of the hole where the hole diameter is locally smaller. This is demonstrated by Fig. 18. Therefore, the behavior of these fasteners in cracked concrete may not be predictable. This is especially true if installation inaccuracies that might occur on site (e.g., installation torque smaller than the value recommended by the manufacturer) are taken into account.[27]

Drop-in anchors

Typical load-displacement relationships of drop-in anchors [Fig. 1(c_1) in Reference 7] in uncracked and cracked concrete, respectively, are shown in Fig. 19. In uncracked concrete, the load-displacement curve is rather stiff due to high expansion forces, and a brittle concrete cone failure occurs. Drop-in anchors are not able to re-expand under load. Therefore, the expansion force is significantly reduced by the crack opening (Fig. 20). In cracked concrete, the initial load-displacement curve is similar to the curve measured in uncracked concrete up to load, where the friction force caused by the still available anchor expansion force is overcome. Then the anchor slips in the hole until the expansion sleeve is in full contact with the concrete over the anchor perimeter. After that, the load is mainly transferred by mechanical interlock. However, due to the relatively small bearing area, anchor stiffness is much smaller and scatter of the load-displacement curves is considerably larger than in uncracked concrete. Failure is often caused by pullout. Therefore, the failure load is significantly reduced by cracks (Fig. 21). Reduction in failure load caused by cracks is much larger for these anchors than for torque-controlled expansion anchors with followup expansion capability (compare Fig. 21 with Fig. 15).

To fully expand drop-in anchors, about 10 to 20 hammer blows are necessary, depending on anchor design, concrete strength, and hole diameter.[27] Because the energy required for full anchor expansion is rather high, drop-in anchors are often only partly expanded in practice. According to a study reported in Reference 28 on about 220 drop-in anchors, M8 to M12 (bolt diameter 0.31 to 0.5 in.), installed on site, actual expansion may be as low as 30 to 70 percent of the required value.

In cracked reinforced concrete, due to the load-transfer mechanism, drop-in anchors not fully expanded show a larger scatter of load-displacement curves and significant reduction of the failure load compared to fully expanded anchors. This can be seen from Fig. 22. Furthermore, influence of the hole diameter on failure load is more pronounced in cracked concrete than in uncracked concrete.[29]

Self-drill anchors and stud anchors

When installing self-drilling anchors [Fig. 1(c_2) in Reference 7], the concrete is mainly ground and only partly displaced. Therefore, a tension force is predominantly transferred by mechanical interlock and less by friction. However, because the bearing area is rather small, the failure load is significantly reduced with increasing crack width. Investigations described in References 29 and 30 indicate that the ratio of failure load in cracked concrete to failure load in uncracked concrete is independent of anchor diameter if the ratio of crack width to maximum expansion displacement is held constant (Fig. 23). Because the maximum expansion

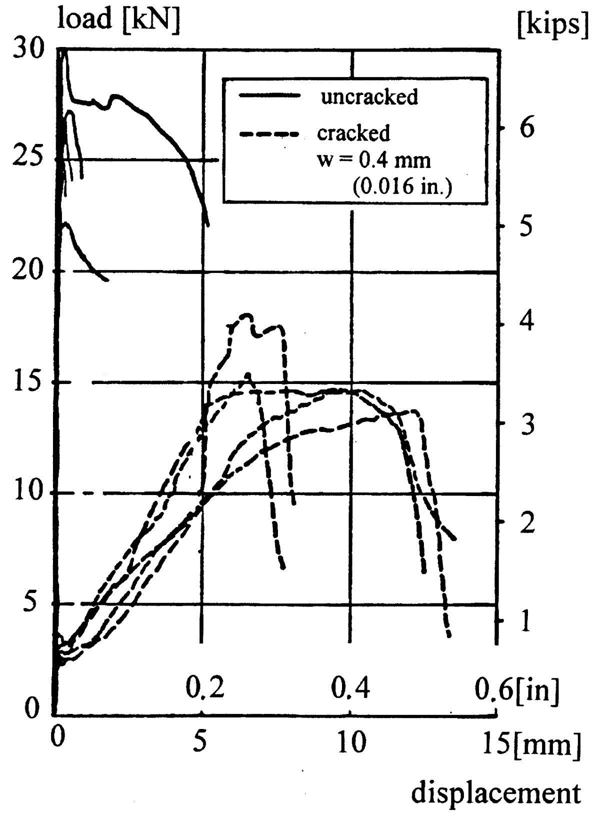

Fig. 19—Load-displacement curves of drop-in anchors M12 (1/2 in.) in uncracked and cracked reinforced concrete [h_{ef} = 60 mm (2.36 in.)], [f_{cc}' = 25 N/mm^2 (f_c' = 3.1 ksi)][27]

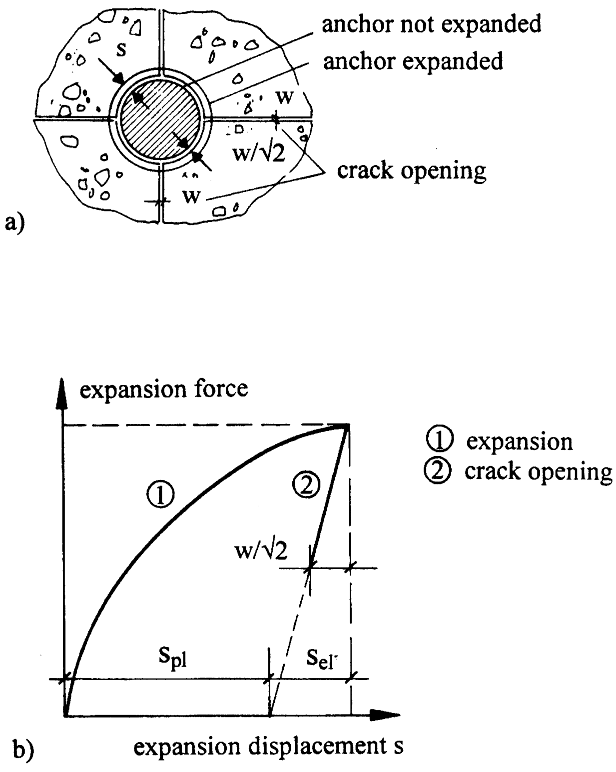

Fig. 20—Influence of opening of intersecting cracks on expansion force of drop-in anchors

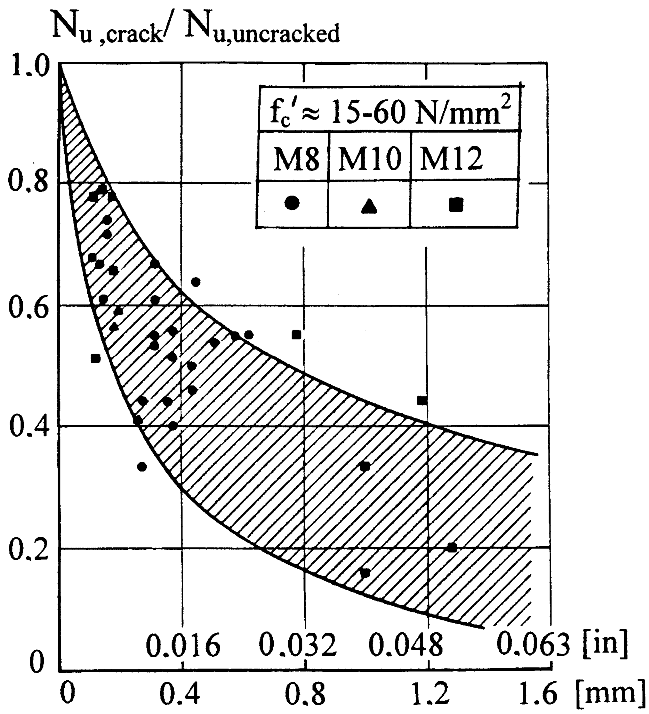

Fig. 21—Ratios of failure loads of drop-in anchors located in cracked reinforced concrete (line cracks) to values valid for uncracked concrete calculated according to Eq. (1) as function of crack width[4]

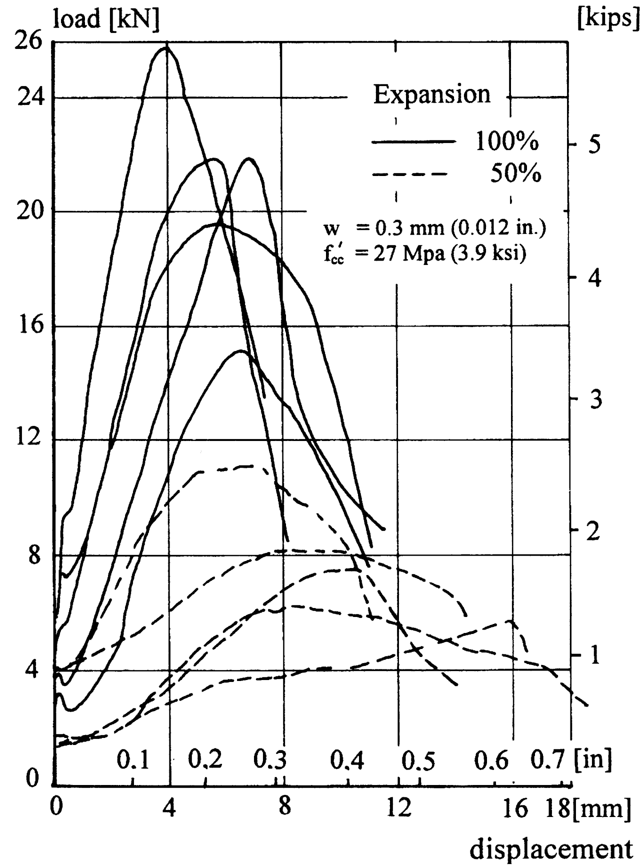

Fig. 22—Load-displacement curves of fully and partially expanded drop-in anchors M12 (1/2 in.) in cracked reinforced concrete[34]

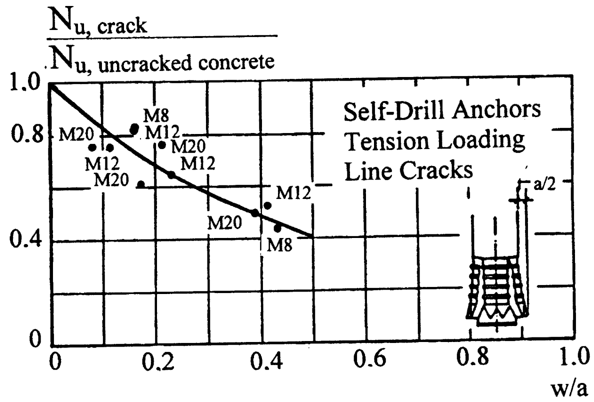

Fig. 23—Ratios of failure loads of self-drill anchors in cracked reinforced concrete (line cracks) to values measured in uncracked concrete as function of ratio crack width to expansion displacement[30]

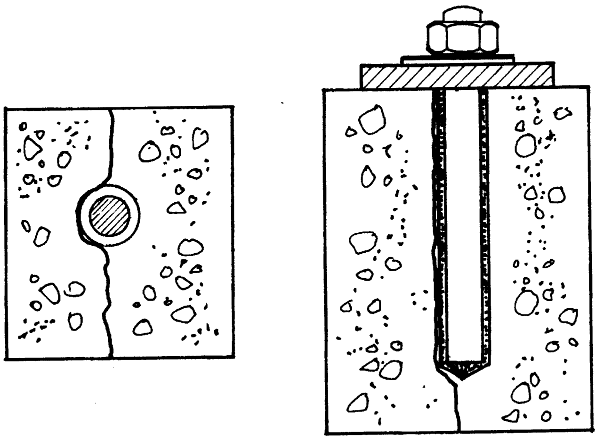

Fig. 24—Typical crack location of bonded anchor[6]

displacement increases with increasing anchor diameter, reduction of the failure load for a constant crack width is larger for smaller anchors than that for bigger ones.

According to the research in Reference 29, the load-displacement curve and failure load of self-drill anchors in cracked concrete are influenced significantly if the anchor is not fully expanded. Furthermore, behavior is rather poor if the anchor is located in a crack with variable crack widths, e.g., due to changes of load on the structural member.

The load-transfer mechanism of stud anchors [Fig. 1(c_3) in Reference 7] is similar to that of self-drill anchors. However, because of the drilling operation, the tolerances in the diameter of the drilled hole are much larger for stud anchors than those for self-drill anchors, leading to reduction of the actual bearing area. Therefore, failure loads of stud anchors in cracked concrete will be significantly lower than those of self-drill anchors with the same thread diameter.

The actual expansion of many stud anchors cannot be controlled on site. If these anchors are not fully expanded, their behavior in cracked concrete may be unpredictable.

Chemical anchors

With chemical anchors, a tension load is transferred to the

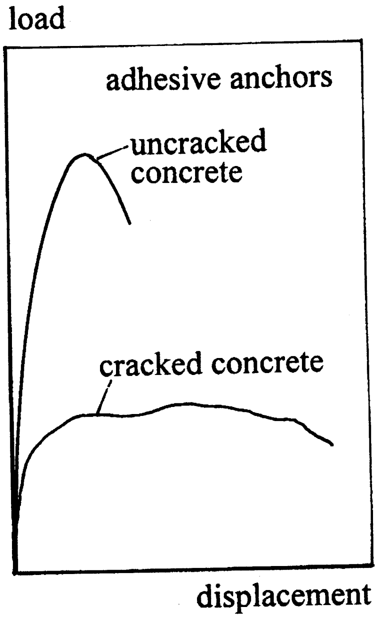

Fig. 25—Load-displacement curves of bonded anchors in uncracked and cracked concrete (schematic)[6]

concrete by bond stresses between the anchor rod and mortar (adhesive) and between the mortar and wall of the drilled hole. Because the strength of the mortar is usually much higher than that of the concrete, a crack in the base material will run around the anchor (Fig. 24) and destroy the bond between concrete and mortar. Therefore, the initial part of the load-displacement curve of bonded anchors in cracked concrete is less stiff than in uncracked concrete (Fig. 25). When the bond strength is overcome, the anchor slips in the hole. A further increase in resistance might occur due to friction (local interlock) of the rough mortar surface in the drilled hole.

Failure load is significantly reduced with increasing crack width (Fig. 26). For a crack width $\Delta w = 0.3$ mm (0.012 in.), the anchor strength may only be about one-third of the value expected in uncracked concrete. In the case of variable crack widths, e.g., resulting from changes of load on the structural member, or in the case of changes in the direction of the load on the anchor, there will be an even further reduction of the failure load or the anchor may even be pulled out.[12] The scatter of the failure loads is rather large due to the irregular crack pattern along the anchor length and around the anchor perimeter.

Data shown in Fig. 26 represent tests with capsule-type anchors with unsaturated polyester resin. Comparable results can be expected for other types of resin and for injection anchors, as well as for grouted anchors, due to the similar load-transfer mechanism.

For bonded anchors, cleaning of the drilled hole may significantly influence anchor behavior. This is especially true for anchors located in a crack. Fig. 27 gives load-displacement curves for capsule-type anchors with vinyl ester resin anchored in a line crack [$\Delta w = 0.4$ mm (0.016 in.)]. In tests,[27] the holes were either cleaned carefully by compressed air and brushing, or were not cleaned after drilling, except the drilling machine was lifted twice during drilling of the hole

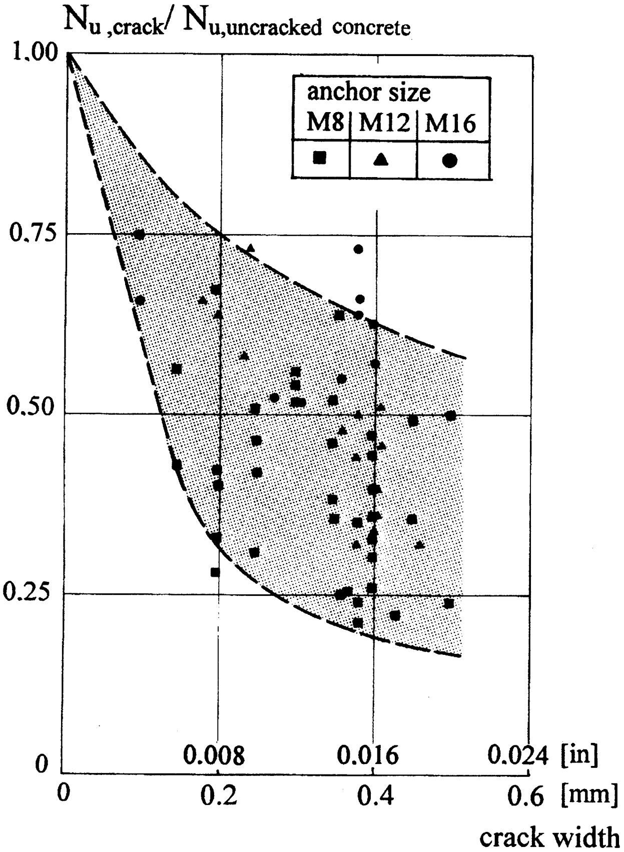

Fig. 26—Ratios of failure loads of capsule-type bonded anchors on cracked concrete (line cracks) to values measured in uncracked concrete as function of crack width ($h_{ef} \approx 8\ d_0$, *polyester resin, holes cleaned)*[35]

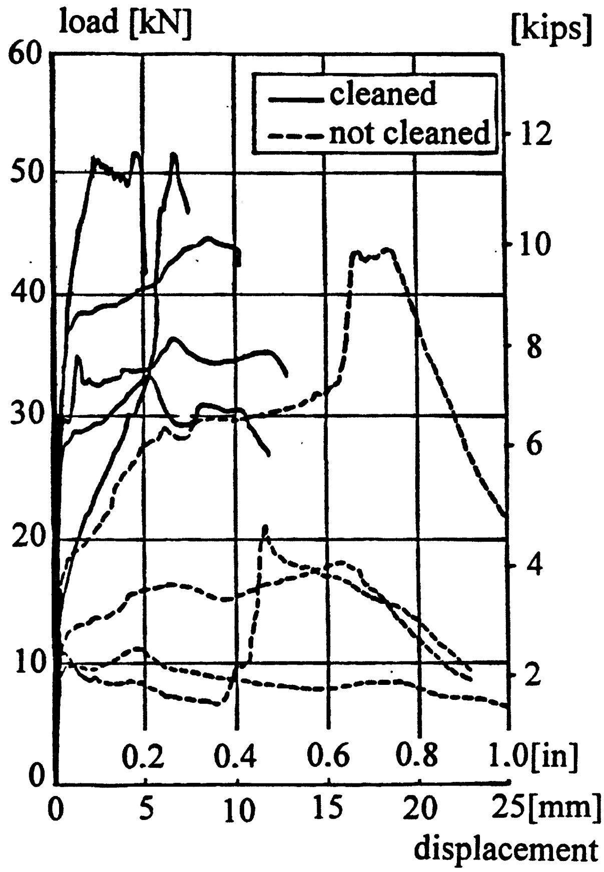

Fig. 27—Load-displacement behavior of capsule-type bonded anchors in cracked concrete [line cracks Δw *= 0.4 mm (0.016 in.)] with holes cleaned and not cleaned after drilling [M12 (½ in.),* h_{ef} *= 110 mm (4.3 in.),* $f_{cc}' \approx 30\ N/mm^2$ *(* $f_c' = 3.7$ *ksi)]*[27]

vertically downward. Scatter of the load-displacement curves of bonded anchors installed in uncleaned holes is significantly greater and failure loads are much lower than that for anchors placed in carefully cleaned holes. In comparable tests performed by the first author in uncracked concrete, the influence of hole cleaning on anchor behavior was insignificant.

CONCLUSIONS

In this paper, behavior of different types of fastener in cracked reinforced concrete was discussed. Based on the current investigations, the following conclusions can be drawn:

1. Many reinforced concrete members are designed under the assumption that concrete is cracked due to external loads or restraint of intrinsic or extrinsic deformations. Experimental and theoretical research shows that anchors will attract cracks or even may induce cracking. Therefore, in general, design of fastenings should be based on the assumption that concrete is cracked.

2. Behavior of fasteners under tension load is influenced considerably by concrete cracking, depending on the type of fastener.

3. Fasteners suitable for use in cracked concrete, such as cast-in situ headed studs or headed anchors, undercut anchors, and specially designed torque-controlled expansion anchors, show reduction of anchor stiffness and of concrete cone failure load of about 25 percent (headed and undercut anchors) or 35 percent (torque-controlled expansion anchors), respectively, compared to the value valid for uncracked concrete when located in or near cracks with widths typical for reinforced concrete members designed with ordinary crack control provisions. Failure load of suitable torque-controlled expansion anchors failing by pulling the expansion cone through the expansion sleeve or segments will be additionally reduced by cracks. The corresponding failure load must be evaluated by tests.[22,23,36]

4. Torque-controlled expansion anchors designed for use in uncracked concrete may behave poorly when located in a crack and failure load may be unpredictable. This is especially true if installation inaccuracies that might occur on site (e.g., applied torque moment is smaller than the manufacturer's recommended value) are taken into account.

5. The expansion force of drop-in anchors is significantly reduced by a crack opening. This leads to a significant change of load-displacement behavior compared to that of uncracked concrete. While concrete cone failure occurs in uncracked concrete, in cracked reinforced concrete, failure is often caused by pulling out. Therefore, reduction of the failure load by cracks is larger than that for headed and undercut anchors. Because the energy required to fully expand drop-in anchors is rather large, in practice these anchors may often

be only partly expanded. Such anchors will show a significantly larger scatter in the load-displacement behavior and more pronounced reduction of failure load when located in a crack than fully expanded anchors.

6. Self-drill anchors transfer a tension load mainly by mechanical interlock and less by friction. However, the bearing area is rather small. The failure load in cracked concrete depends on anchor size. For M12 (0.5-in.) anchors, it amounts to about 40 percent for a crack width $w \sim 0.3$ mm (0.012 in.) compared to the value in uncracked concrete. In cracked concrete, anchor behavior is rather sensitive to incorrect anchor expansion.

7. The load-transfer mechanism of stud anchors is similar to self-drill anchors. However, because of the additional tolerances in the diameter of the drilled hole, behavior of stud anchors will be more influenced by concrete cracking than that for self-drill anchors. Furthermore, actual expansion of these anchors often cannot be controlled on site, which causes additional uncertainties regarding anchor behavior.

8. With bonded anchors, cracks in the concrete partly destroy the bond between mortar and the wall of the drilled hole. This causes a rather large reduction of failure load compared to that of uncracked concrete. Furthermore, in cracked reinforced concrete, these anchors are rather sensitive to installation inaccuracies that might occur on site (e.g., improper cleaning of the hole).

9. Anchors used in cracked reinforced concrete must be suitable for this application. A test program to check effective functioning of fasteners in cracked concrete is described in the technical guides by UEAtc[22] and EOTA,[23] a basis for the proposed ASTM specification.[36]

NOTATION

d_0	=	nominal anchor diameter
N_u	=	ultimate tensile load of anchor
f_{cc}'	=	concrete compressive strength, measured on cubes with 200-mm side length at time of testing
f_c'	=	compressive strength, measured on 6 by 12-in. cylinders at time of testing
h	=	depth of test member
h_{ef}	=	effective anchorage depth
k_{nc}	=	constant, depending on anchor type, uncracked concrete
k_1	=	constant, depending on anchor type, cracked concrete
n	=	number of tests
x	=	ratio of measured failure load to calculated value
$\bar{x}$	=	mean value of ratios x
w	=	crack width
Δw	=	difference between crack width at testing and crack width at anchor installation

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