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Basis for Design of Screw Anchors in Concrete

by Jacob Olsen, Thilo Pregartner, and Anthony J. Lamanna

Concrete screw anchors are gaining greater acceptance in building practice because they are reliable fastening elements with high capacities that can be easily installed. The current practice for designing concrete screw anchors is the concrete capacity design (CCD) method with a modified effective embedment depth determined by the geometry of the screw. This empirical model was originally based on testing conducted in Europe on several types of metric screw anchors.

The load-bearing behavior of concrete screws in concrete is explained in this study. The existing database of tension tests on metric screw anchors has been increased to include a large number of tests on inch-sized screw anchors in cracked and uncracked concrete and is evaluated with the current design model. It is shown that the current empirical design model, although somewhat conservative, continues to be the best choice as an efficient method for designing screw anchors.

Keywords: concrete capacity design method; concrete screw anchor; post-installed anchors.

INTRODUCTION

Concrete screw anchors are gaining greater acceptance in building practice because they are reliable fastening elements with high capacities that can be easy installed. While some post-installed anchors require several installation operations such as secondary drilling, mechanical cleaning, and torque application operations, screw anchors can be typically installed in a drilled hole with only a single operation with an impact screwdriver. This both reduces the chance for installer error on the job site and decreases the time required to make a fastening. Another advantage of concrete screws over most expansion-type anchors is that they can be easily removed and leave no steel elements in the drilled hole.

During installation, a screw anchor cuts a thread into the concrete, providing a mechanical interlock. Some typical concrete screws are shown in Fig. 1(a). Figure 1(b) demonstrates the undercutting of the concrete screw in the concrete. This undercutting gives concrete screw anchors an advantage in cracked concrete sections where small cracks intersecting the anchor location have less of a detrimental effect compared to anchors that depend primarily on friction for resistance (expansion anchors).

The ultimate tensile load of a screw anchor in concrete is mainly influenced by the degree of undercut of the thread in the concrete and the embedment depth. The undercut of a concrete screw can be defined as the difference between the outer diameter of the thread and drill-hole diameter. A screw with a larger undercut will have a higher ultimate load. Note that the high level of undercut will also increase installation difficulty, so a balance between these two factors is needed for practical use. The embedment, or deepest point of load transfer, of a concrete screw anchor will determine the ultimate concrete cone load according to the concrete capacity design (CCD) method equations. Deeply embedded screw anchors with small undercuts will be governed by pullout failure, whereas screws at a shallower embedment with a high degree of undercut will be controlled by concrete cone failure over the entire length of the screw (Fig. 2(a)). Between these extremes are a range of mixed failure modes incorporating a pullout failure toward the bottom of the screw with a concrete cone failure toward the concrete surface (Fig. 2(b)).

The tension load-transfer mechanism of the fastening system has a negligible influence on the behavior of anchors under shear loading. Possible shear failure modes are steel failure, concrete edge failure, and concrete pryout failure. These failure modes are addressed in the current design codes for mechanical anchors and are also applicable to screw anchors.

RESEARCH SIGNIFICANCE

While post-installed concrete screw anchors are a popular anchoring solution, they are not included in ACI 318-08, “Building Code Requirements for Structural Concrete and Commentary,” which only recognizes post-installed expansion anchors, undercut anchors, and bonded anchors.[1] This is largely due to a lack of published information, particularly in the United States, for concrete screw anchors. The intent of this study is to provide a comprehensive review of screw anchors under tension loading and verify the current design model against a newly expanded worldwide test database.

DESIGN OF ANCHORS IN CONCRETE

The CCD method has developed into an internationally recognized method for designed anchors in concrete.[2] The CCD method was first included in the 2002 edition of the ACI 318 for the design of cast-in-place anchors and post-installed expansion and undercut anchors. The CCD method was later modified for use with adhesive anchors[3] and these types of anchors are included in ACI 318-11.

In Europe, the CCD method was adopted by the European Organization for Technical Approvals (EOTA) in 1997[4] and the same method is the basis for the design prestandard CEN/TS 1992-4 for fastenings that will be published within the reinforced concrete design standard (EC 2). This design standard was developed by a working group of the European Standardization Institute (CEN).

The CCD method is a simplified design approach for anchors in cracked and uncracked concrete distinguishing between tension and shear loading and possible failure modes of a post-installed fastening. These failure modes for tension loading are:

- Concrete cone failure;
- Pullout failure (mechanical anchors);

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(a) Typical types of concrete screws (b) Undercut of concrete screws in concrete after installation[6]

Fig. 1—Photos of concrete screws and concrete after installation.

(a) Concrete cone originating near bottom of anchor

(b) Mixed failure mode of pullout and concrete cone

Fig. 2—Photos of failed concrete screws after tension tests.

- Bond failure (adhesive anchors);
- Splitting failure; and
- Steel failure.

The failure modes for shear loading are:

- Concrete edge failure;
- Concrete pryout failure; and
- Steel failure.

For each design application, all failure modes shall be checked. The failure mode with the smallest resistance is decisive for each tension and shear, and the interaction of the two controlling failure resistances will govern the final anchor strength.

European anchor design guidelines address screws in ETAG 001, "Guideline for European Technical Approval of Metal Anchors for Use in Concrete." In the U.S., concrete screw anchors fall outside the scope of ACI 318-08, Appendix D, "Anchoring to Concrete," and therefore are designed by either following the manufacturer's literature or according to ICC-ES Acceptance Criteria AC193, which serves as an alternative to the building code and includes screw anchor design provisions.[1,5] Both the AC193 design criteria and the ETAG 001 are based on research conducted by Kuenzlen[6] from 2000 to 2004 at the University of Stuttgart.

QUALIFICATION OF CONCRETE SCREW ANCHORS

Because post-installed screw anchors are proprietary systems with unique mechanical and dimensional characteristics, it is necessary to evaluate their structural properties in accordance with a recognized standard. This is not unlike the qualification process currently used for post-installed expansion anchors, undercut anchors, and bonded anchors. Qualification criteria for anchors involve a test program with the following conditions:

- Reference tests, to determine baseline anchor performance in ideal conditions;
- Reliability tests, to determine performance of anchors in adverse conditions and over long-term use;
- Service condition tests, to determine anchor performance in typical service loading conditions such as shear loading or anchors installed in corners; and
- Identification tests, to determine properties of the anchor for compliance with manufacturer's specifications.

For an anchor to be qualified, requirements for each test condition such as repeatability, displacement characteristics, scatter of ultimate load, and ultimate load must be met.

The qualification tests required for screw anchors were originally established in Europe and are found in ETAG 001 and later for the U.S. in ICC-ES AC193, "Acceptance Criteria for Mechanical Anchors in Concrete Elements."[5] AC193 references ACI 355.2-04, "Qualification of Post-Installed Mechanical Anchors in Concrete," to describe the required test program but adds additional tests for concrete screw anchors to address some of the unique considerations for concrete screws such as hydrogen embrittlement testing and verification methods for the installation of screw anchors.[7] It is the intention of ACI Committee 355 to add screw anchors and their test requirements directly into ACI 355.2 in a future revision so that screw anchors can be referenced directly in ACI 318.

EVALUATION OF AMENDED SCREW ANCHOR WORLDWIDE TEST DATABASE FOR ANCHORS UNDER TENSILE LOADING

The design approach for screw anchors under tensile loading derived by Kuenzlen[6] was based on 500 tests with concrete screw types available at that time in Europe and a limited variety of embedment depths. The database used by Kuenzlen has since been amended with additional test results of concrete screw anchors in cracked and uncracked concrete (353 tests) conducted by independent laboratories

Table 1—Summary of screw anchor database

Data source	Unique thread profiles	Diameter range, mm	Embedment range, mm	Number of tests		
				Single anchor, uncracked	Single anchor, cracked	Group of two or four anchors
Original data (Kuenzlen[6])	9	8.00 to 18.00	30 to 110	268	126	106
New data (from independent testing)	8	6.35 to 19.05	25.4 to 127	194	122	37
Total	17	6.35 to 19.05	25.4 to 127	462	248	143

Note: 1 mm = 0.0394 in.

in accordance with ICC-ES AC193. The tests represent additional, primarily inch-sized, concrete screw types at a greater range of embedments. The range of anchor types and embedment depths evaluated by Kuenzlen and the expanded database evaluated in the current paper are summarized in Table 1. Figure 3 presents a histogram of the embedment ranges from the two sets of data. The new data extend the original data[5] by adding:

- Test results at smaller and larger embedment depths;
- A larger variety of tested embedments between the small and large values; and
- Almost twice the number of tested thread profiles.

While the number of tests is not equally distributed across the range of anchor diameters, the diameters 6.35 to 19.05 mm (0.25 to 0.75 in.) are represented in each of the three sets of data: uncracked concrete, cracked concrete, and group tests.

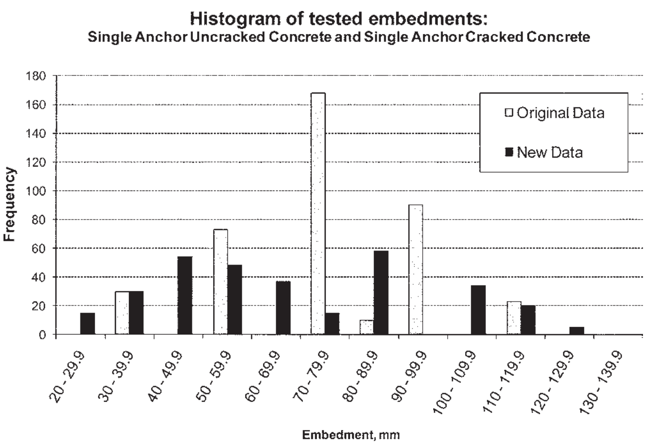


Fig. 3—Histogram of tested embedment depths from original database and additional data. (Note: 1 mm = 0.0394 in.)

DESIGN METHODS FOR TENSION LOADS

Design loads for steel failure N_{sa}, pullout failure N_p, and concrete cone breakout failure N_{cbg} must be calculated for a concrete screw anchor in tension.

Design loads for steel failure are calculated according to ACI 318-08, Appendix D, Eq. (D-3)

$$N_{sa} = nA_{se,N}f_{uta} \tag{1}$$

where n is the number of anchors in a group; $A_{se,N}$ is the effective cross-sectional area of a single anchor in tension; and f_{uta} is the specified tensile strength of anchor steel.

As required in ACI 318-08, Appendix D, pullout failure N_p must be evaluated based on the 5% fractal of actual test results in accordance with screw anchor qualification standards.[1]

A simplified design approach for screw anchors was derived by Kuenzlen[6] on the original metric screw anchor database to address the concrete cone failure mode. The existing empirical design model developed from the expansion and undercut database[2] was adapted to fit the available data of different concrete screw types by reducing the effective embedment depth of screw anchors (Eq. (2)). With this reduced embedment depth, the usual equations for mechanical anchors in concrete can be used (Eq. (3) and (4)).

$$h_{ef} = 0.85 \cdot \left(h_{nom} - 0.5 \cdot h_t - h_s\right) \tag{2}$$

$$N_{cb} = k_c \cdot \sqrt{f_c'} \cdot h_{ef}^{1.5} \tag{3}$$

$$N_{cbg} = \frac{A_{Nc}}{A_{Nc0}} \cdot \psi_{ec,N} \cdot \psi_{ed,N} \cdot \psi_{c,N} \cdot \psi_{cp,N} \cdot N_{cb} \tag{4}$$

where h_{ef} is the calculated effective embedment depth of the concrete screw; h_{nom} is the embedment depth/setting depth of the screw anchor in concrete; h_t is the distance of the thread; h_s is the length of the tip of the concrete screw; N_{cb} is the concrete cone breakout capacity, single anchor; $k_c = 13.5$ for uncracked concrete to calculate average ultimate loads (SI units); $k_c = 35$ for uncracked concrete to calculate average ultimate loads (U.S. Customary units); $k_c = 9.45$ for cracked concrete to calculate average ultimate loads (SI units); $k_c = 24.5$ for cracked concrete to calculate average ultimate loads (U.S. Customary units); f_c' is the concrete compressive strength measured on cubes (SI units) or cylinders (U.S. Customary units); N_{cbg} is the concrete cone failure load of a fastening situation; A_{Nc} is the projected area of a fastening situation; A_{Nc0} is the projected area of a single anchor; $\psi_{ec,N}$ is the reduction factor eccentricity; $\psi_{ed,N}$ is the reduction factor edge influence; $\psi_{c,N}$ is the increasing factor for uncracked concrete (always taken 1.0 for post-installed anchors); and $\psi_{cp,N}$ is the factor to consider concrete splitting failure.

Figure 4 provides a visual representation of the factors considered in Eq. (2). Further details on Eq. (3) and (4) and detailed equations to calculate the increasing or reduction factors for concrete cone failure are given in ACI 318-08, Appendix D.[1] Note that in the aforementioned equations, the value for the factor k_c is given to calculate average failure loads, whereas in the design codes, k_c is given to calculate characteristic values or 5% fractal values as described in ACI 318-08, Appendix D.

UNCRACKED CONCRETE—TENSION

Equations (2) to (4) were used to evaluate the current expanded database of concrete screw anchor data for both uncracked and cracked concrete. Figure 5 shows the ratio of

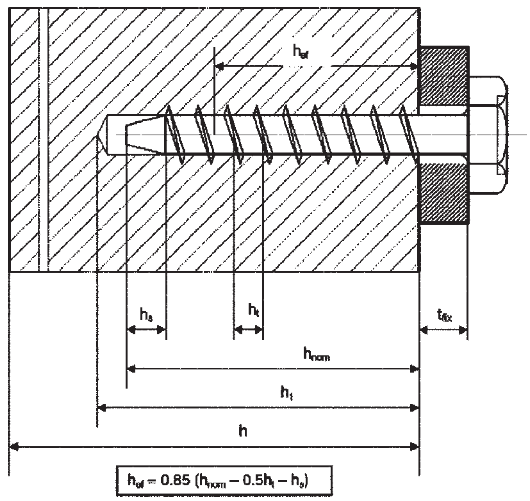


Fig. 4—Typical factors associated with embedment of concrete screw anchor.

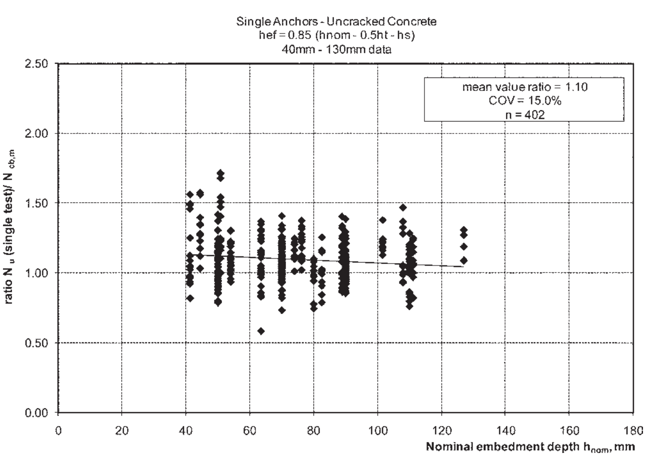


Fig. 5—Ratio of measured to predicted strength versus nominal embedment. (Note: 1 mm = 0.0394 in.)

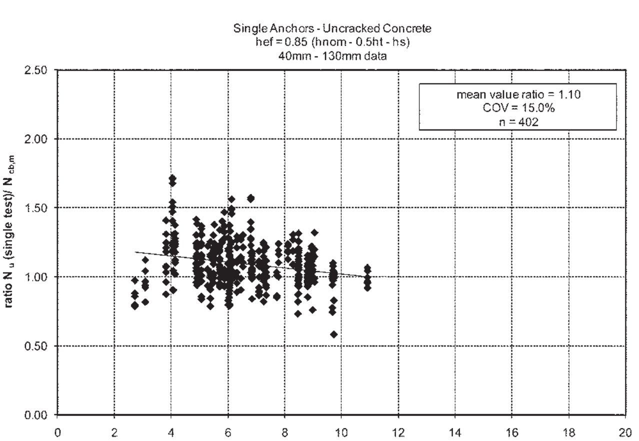


Fig. 6—Ratio of measured to predicted strength versus embedment by diameter. (Note: 1 mm = 0.0394 in.)

test values to calculated values as a function of the nominal embedment depth in uncracked concrete. This graph demonstrates, in general, the accuracy of a new design model. Whereas the mean value is slightly conservative (mean = 1.10), the design model shows a good fit with tested results. The displayed trend line shows an almost trend-free fit of the

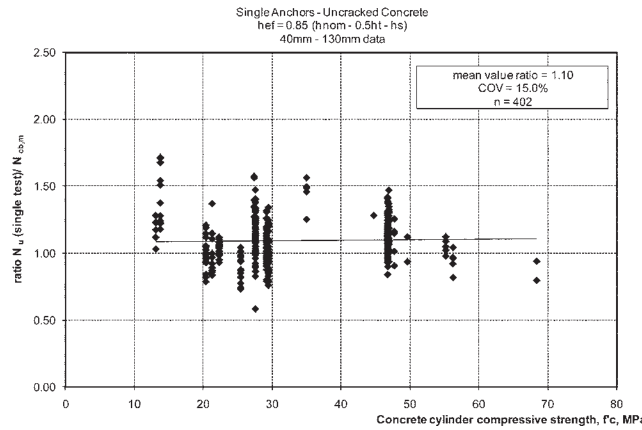


Fig. 7—Ratio of measured to predicted strength versus concrete compressive strength. (Note: 1 mm = 0.0394 in.; 1 MPa = 145 psi.)

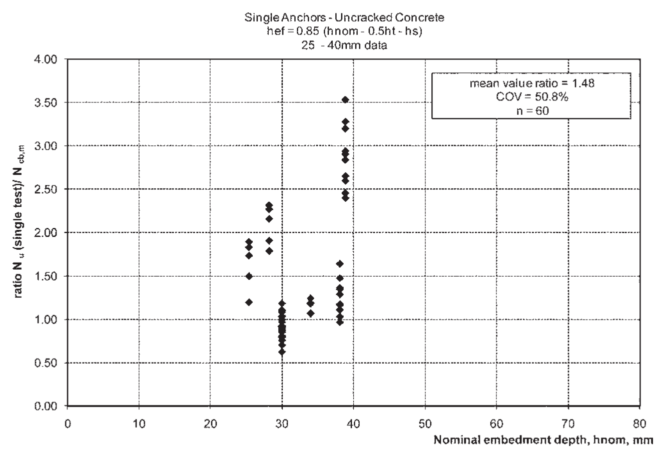


Fig. 8—Ratio of measured to predicted strength versus nominal embedment depths: shallow embedments. (Note: 1 mm = 0.0394 in.)

design approach to the existing data. Graphing the same data in terms of anchor diameters of embedment and concrete compressive strength, Fig. 6 and 7 respectively also show predictable behavior across the range of these variables. The coefficient of variation (COV = 15%) complies with current experience for concrete cone failure design models.

SHALLOW EMBEDMENTS—TENSION

The current database includes additional test data at very shallow embedments—between 25 and 40 mm (0.98 and 1.57 in.). In general, nominal embedment depths shallower than 40 mm (1.57 in.) are excluded from the scope of the testing and qualification guidelines for metal anchors in concrete (ETAG 001 and AC193).[4,5] Although the embedment depth definition makes these data generally conservative with respect to the design method (refer to Fig. 8), it is, as expected, also highly variable due to the surface effects of the concrete (COV = 50.8%). For these reasons, it is recommended that the design model be limited to screws with $h_{nom} \geq 40$ mm (1.57 in.).

CRACKED CONCRETE—TENSION

As with other anchor types, post-installed screw anchors exhibit a reduction in capacity when installed in cracked concrete. From Fig. 5, it can be seen that tensile load behavior of anchors in uncracked concrete is according to design

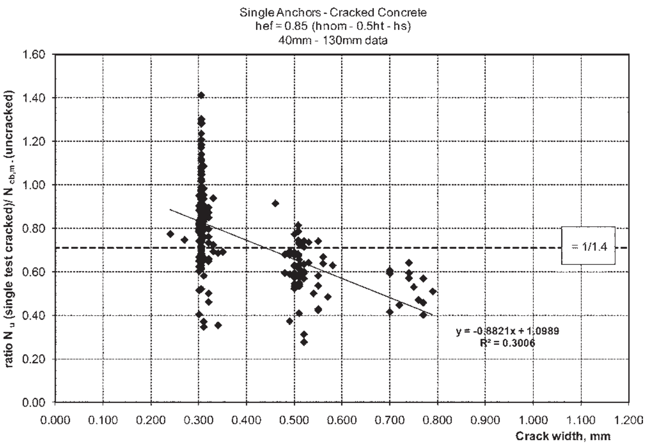


Fig. 9—Ratio of measured to predicted (uncracked) strength versus crack width. (Note: 1 mm = 0.0394 in.)

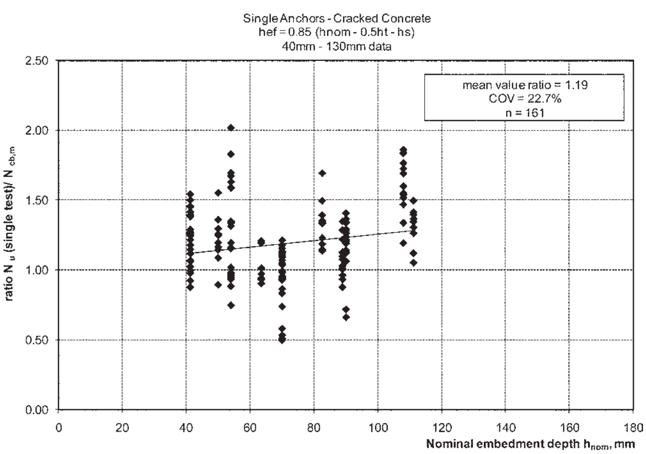


Fig. 10—Ratio of measured to predicted strength versus nominal embedment depth, 0.3 mm (0.012 in.) crack width. (Note: 1 mm = 0.0394 in.)

equations (Eq. (2) to (4)) with k_c = 13.5. Figure 9 illustrates the effect of crack width on screw anchors by comparing test results of anchors installed directly in the crack with the predicted uncracked concrete equation. It is shown that the ultimate loads decrease with increasing crack width. For the design of anchors in cracked concrete, the crack width 0.3 mm (0.012 in.) is assumed because the maximum crack width developing under service conditions shall not exceed this value. In general, screw anchors show ratios of the measured ultimate loads to predicted loads in cracked concrete between 0.4 and 1.4. The trend line demonstrates a reduction of the load at 0.3 mm (0.012 in.) crack width of approximately 20%. This is also consistent with the current experience with metal anchors, where a decrease of the ultimate loads of 1/1.4 = 0.71 is assumed.

The CCD method assumes a reduction of 9.45/13.5 = 0.7 for post-installed anchors in cracked concrete with an expected crack width of approximately 0.3 mm (0.012 in.). Figure 10 compares the tested capacity of screw anchors installed in concrete with crack widths of approximately 0.3 mm (0.012 in.) to the calculated capacity according to Eq. (2) to (4) assuming cracked concrete (k_c = 9.45). The mean value of the data set, 1.19, is conservative but also is in accord with current experience with a COV of 22.7%.

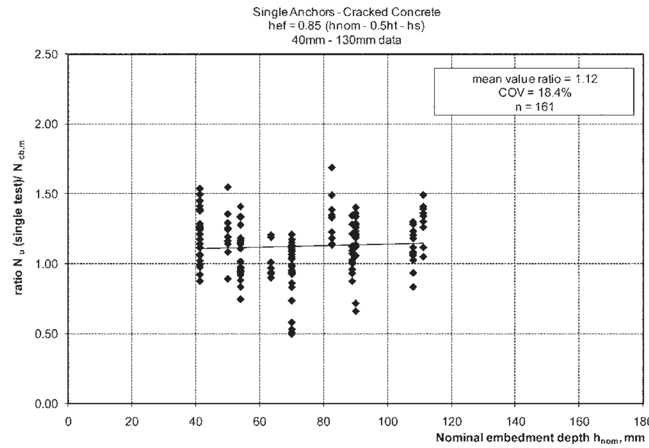


Fig. 11—Amended ratio of measured to predicted strength versus nominal embedment depth, 0.3 mm (0.012 in.) crack width. (Note: 1 mm = 0.0394 in.)

The high mean value is partly due to the fact that some screw anchor types behave very well in cracked concrete with respect to the concrete capacity equations. The ICC-ES qualification process recognizes this possibility for all anchor types and allows the k_c value to be evaluated according to actual test results rather than an assumed value for achieving a higher k_c. (This possibility also exists in the ETAG qualification process but is typically more restricted to undercut type systems.[4,5]) The cracked concrete database contains four data series (tests conducted in identical conditions) from two anchor types that, on average, exceed the calculated uncracked concrete capacity (using k_c assuming uncracked concrete) when installed in cracked concrete. Figure 11 presents the amended cracked concrete database by following the ICC-ES qualification process for these four data series compared to Eq. (2) to (4) with k = 13.5 and the remaining data compared to Eq. (2) to (4) assuming k = 9.45. The amended data set further validates the design equations with a mean value of 1.12 and COV of 18.4%.

ANCHOR GROUPS—TENSION

Figure 12 shows tests on anchors groups of two or four anchors with respect to the calculated design equations (Eq. (2) to (4)). For anchor groups, predictable strength is also found on the screw anchors. According to the CCD method, a breakout cone extending to the surface at an inclination of 35 degrees can be expected. Following this theory, anchors spaced at a distance of three times h_{ef} or greater should reach their individual full capacity when loaded as a group. Note that for concrete screws, the concrete cone is supposed to start at the end of the reduced embedment depth h_{ef} according to Eq. (2). Figure 13 verifies that in anchor groups, the basic principle of the CCD method can be applied also to concrete screws with this definition of h_{ef}.

A summary of each database compared to the design equations (Eq. (2) to (4)) is presented in Table 2. The data are also analyzed as a complete set and reveal a mean (1.08) and COV (16.5%) that are in accordance with current experience for post-installed anchors.

COMMENTS ON PULLOUT FAILURE MODE

The failure mode in the screw anchor group database was assumed to be according to the equation for concrete cone failure. While the database of screws at the typical installation

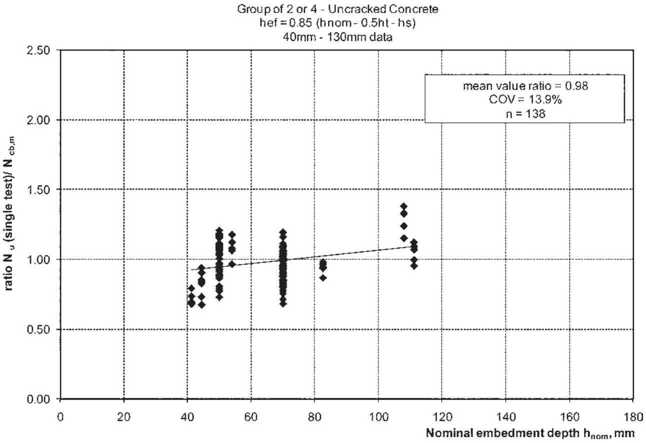


Fig. 12—Ratio of measured to predicted strength versus embedment depth. (Note: 1 mm = 0.0394 in.)

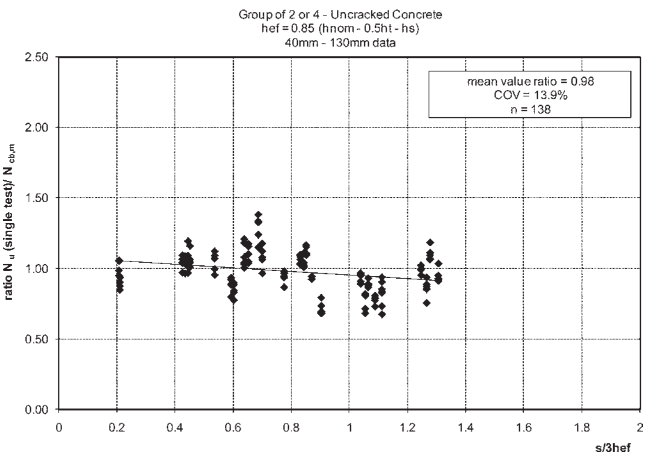


Fig. 13—Ratio of measured to predicted strength versus spacing distance. (Note: 1 mm = 0.0394 in.)

embedments agree with the assumption, a screw that cannot develop a load corresponding to the concrete cone equation will be assigned a pullout failure load (N_p) value in the same way that expansion and undercut anchors are treated.

A pullout failure load for screw anchors may be the result of:

- Unusually high embedment-to-diameter ratio;
- Poor screw design (insufficient undercut or weak threads); and
- Reductions in load due to reliability tests (moving crack, repeated load, hydrogen embrittlement).

According to the CCD method, for reasons of simplicity, the pullout failure capacity is not influenced by anchor spacing, implying anchor groups of n equally loaded anchors controlled by pullout will be designed as n times N_p in capacity.

From research conducted on bonded anchors with low spacing-to-embedment ratios, it was determined that a reduction in bond strength should be considered for closely spaced anchors when calculating the bond failure mode capacity due to internal concrete tension stresses developed between the anchors.[8] Because the load-transfer mechanism of screw anchors is similar to that of bonded anchors and can create visually similar failures, the question arises of whether the CCD method for pullout failure mode can be used for screw anchors in groups.

Table 2—Summary of new screw anchor database, 40 mm (1.57 in.) and greater embedment

Database	Number	Mean	Coefficient of variation, %
Single anchor, uncracked	402	1.10	15.0
Single anchor, cracked, 0.3 mm (0.012 in.)*	161	1.12	18.4
Group of two or four	138	0.98	13.9
All combined	701	1.08	16.5

*Data as presented in Fig. 11.

While the load transfer is roughly similar between screw anchors and adhesive anchors from an overall standpoint, the actual transfer at the anchor-to-concrete interface is quite different. Screw anchors transfer load through the undercut threads in the concrete, which typically extend 0.5 to 1.0 mm (0.02 to 0.04 in.) into the concrete. Bonded anchors depend on a combination of adhesion and “microkeying” between the adhesive and concrete surface with an insignificant amount of undercutting.[9] The tension stresses are therefore expected to have a much lesser impact on the pullout strength of groups of screw anchors. The qualification process for screws further verifies this condition by requiring tests on groups of two anchors at minimum spacing and edge distance for each embedment qualified to meet the CCD method equations.

As an added step of safety regarding the possible influence of spacing on the pullout strength of screws, the authors suggest limiting the design model for both spacing and embedment to the anchors’ conditions present in the current screw anchor database

$$\text{minimum spacing} = \max(0.6h_{ef} \text{ or } 3.5d)$$

Currently, there are seven unique structural screw anchor systems in the market qualified according to either ETAG 001 or ICC-ES AC193. These systems already comply with both the proposed minimum spacing limitation and the aforementioned proposed embedment limitation of

$$40 \text{ mm (1.57 in.)} < h_{nom} < 11d$$

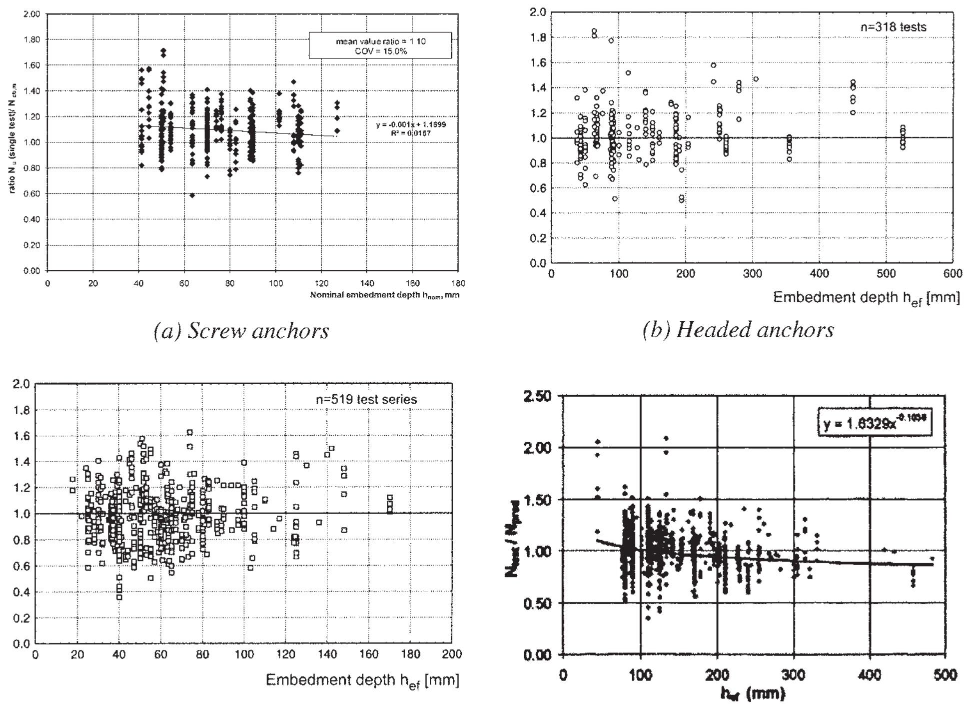
Table 3 summarizes these parameters for the currently qualified screw anchors.

DESIGN METHODS FOR SHEAR LOADS

There are three failure modes for anchors subjected to shear loads. These failure modes are steel failure, concrete edge failure, and concrete pryout failure.

The resistance of screw anchors for shear steel failure is derived in the approval procedure in shear tests. The established value is given in the approval and can be used directly for design.

Concrete screws loaded in shear close to a concrete edge may show concrete edge failure as a possible failure mode. The characteristic resistance for this failure depends mainly on concrete strength and edge distance as well as spacing in anchor groups. The resistance is also influenced by the stiffness of the anchor (the ratio of diameter to embedment



(a) Screw anchors

(b) Headed anchors

(c) Expansion and undercut anchors

(d) Adhesive anchors (bond failure)

Fig. 14—Comparison of databases for various anchor types under tension loading in uncracked concrete: (a) current screw anchor database; (b) headed studs[11,12]; (c) expansion and undercut anchors[13]; and (d) adhesive anchors—bond failure.[3] (Note: 1 mm = 0.0394 in.)

depth). For this failure mode, it is already established in the current design codes that the differences in resistance between the different fastening systems (adhesive anchors, metal expansion anchors, and cast-in place anchors) are negligible. For all these fastening system types, comparable or identical design equations are used. This is valid for ACI 318-08, Appendix D, design, AC308 design, and for the European design guidelines and codes.[1,4,10] The load-transfer mechanism of the fastening system has a negligible influence, and the stiffness to embedment depth ratios of concrete screws fall within current experience; therefore, the authors recommend using the same design equations as for expansion anchors, undercut anchors, and adhesive anchors. It is noted that with using the reduced embedment depth according to Eq. (2), a conservative design result is expected, as the equations used to predict the shear breakout and pryout strength of anchors will yield a reduced value.

The characteristic resistance for concrete pryout failure is calculated by multiplying the characteristic resistance of the concrete breakout failure in tension (Eq. (4)) by a factor k. According to ACI 318-08, Appendix D, k can have values between 1 and 2, depending on the embedment depth. It is known from the literature[9] that the design approach for concrete pryout failure gives conservative estimations of this failure mode. In addition, it is generally only decisive for anchors with large diameter to embedment depth ratios (stiff anchors with large diameters at relatively small embedment depths). Due to the similar shear-load-transfer mechanism, the existing design equations for pryout in ACI 318-08, Appendix D, can also be applied to screw anchors.

Both the shear and tension failure modes and accompanying design equations for each failure mode are similar to other types of post-installed anchors. It is therefore recommended that the interaction of tension and shear forces be designed according to the simplified trilinear method in ACI 318-08, Appendix D.

Table 3—Summary of currently qualified screw anchors

Structural screw anchors currently qualified to ETAG or ICC-ES requirements	
Unique screw systems	7
Unique diameter/thread combinations	25
Minimum embedment	44.5 mm (1.75 in.)
Minimum embedment/diameter ratio	5d
Maximum embedment/diameter ratio	10d
Minimum spacing ratio (s/h_{ef})	0.6h_{ef}
Minimum spacing ratio (h_{ef}/d)	3.6d

COMPARISON TO OTHER CONCRETE ANCHORS IN TENSION

While the database for screw anchors contains some degree of variability (particularly in the cracked concrete tests), it is noted that the natural variability of concrete tensile strength itself is a large contributor in this. As shown in Fig. 14 for different types of anchors in uncracked concrete, screw anchors exhibit a similar variability to other types of metal anchors. Table 4 summarizes the existing databases for each anchor type.

ALTERNATIVE DESIGN OF SCREW ANCHORS IN TENSION TO ADHESIVE BOND MODEL

A cursory review of the screw anchor load-transfer mechanism reveals some similarities between the current adhesive anchor design for bond failure and the screw anchor

Fig. 15—Thread wear before and after installation of two types of concrete screws currently offered in the market.

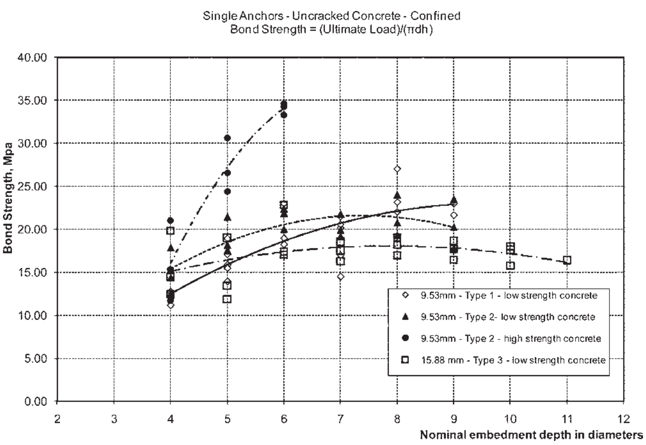


Fig. 16—Bond strength versus nominal embedment with best-fit second-order polynomial trend lines. (Note: 1 mm = 0.0394 in.; 1 MPa = 145 psi.)

pullout failure. For adhesive bond-stress design, a single bond strength τ_k is derived by testing a few embedments per diameter and then applied in design over a broad range of embedments (often four to 20 diameters).[10] The bond failure load N_{a0} is calculated by the surface area of the screw multiplied by the bond stress (Eq. (5)). This model assumes a constant bond stress developing along the complete embedment depth of an anchor.[3]

$$N_{a0} = \tau_k \cdot \pi \cdot d \cdot h_{ef} \quad (5)$$

where N_{a0} is the characteristic tension capacity of an adhesive anchor limited by bond; τ_k is the characteristic bond strength determined from testing; d is the nominal diameter of the anchor element; and h_{ef} is the effective embedment, measured to the deepest point at which bond to concrete is established.

The major barrier to applying this model to screw anchors is that the assumption of a uniform bond stress over the surface area of the embedded concrete screw is not applicable. Concrete screw anchor threads will wear during installation depending on the particular screw geometry, manufacturing methods, hardness of the concrete, and embedment depth. This effect creates a nonuniform bond strength as the degree of thread undercut is reduced toward the tip of the screw. This effect is relatively consistent and reproducible for a given embedment; therefore, a pullout load can be calculated for the condition. A meaningful uniform bond-stress derived for a particular anchor, however, cannot be used for other embedments in the bond model. Figure 15 depicts the thread wear caused by installation of a typical concrete screw. The

Table 4—Comparison of various anchor types in uncracked concrete

Database anchor type	Number	Mean	Coefficient of variation, %
Screw anchors	402	1.1	15.0
Headed studs	318	1.0	18.0
Expansion/undercut anchors	519	1.0	23.0
Adhesive anchors (bond failure)	888	1.0	20.3

threads toward the tip of the screw anchor are more worn than the threads toward the head.

Figure 16 shows results of three anchor types loaded in confined tension at increasing embedments in both low- and high-strength concrete as defined in AC193. The tests were performed as confined tension tests, as described in AC308, to avoid the possibility of a concrete cone failure. This test method is also used for adhesive anchors to establish the bond strengths at different embedment depths.[10] In general, the anchors failed by pullout failure where the concrete between the cut-in threads was sheared off. Depending on the anchor type and concrete condition, the bond stress calculated from the test results can be highly variable for a given screw type. The bond strength increases with increasing embedment depth and starts decreasing again for some anchor types at higher embedments; therefore, the uniform bond model is not appropriate for screw anchors.

The primary benefit to the bond model for adhesive anchors is that test data from a limited number of embedments can justify the design across a wide range of embedments ($4d$ to $20d$). This model is not beneficial for screw anchors because the same bond stress cannot be assumed for multiple embedments. Therefore, a particular screw anchor should be tested and qualified at each embedment intended for design in the same manner expansion anchors are treated. This is reasonable due to a relatively narrow range of practical installation embedments for concrete screw anchors.

RECOMMENDED DESIGN MODEL

The modified CCD method proposed by Kuenzlen[6] and described partly in Eq. (2) to (4) is shown to accurately describe the behavior of concrete screws in the new, extended worldwide concrete screw database and continues to be the best choice for a practical and simple design model for screw anchors. To address additional concerns not discussed in the original model, the authors suggest the following limitations for use with the model:

1. Nominal anchor embedment of 40 mm (1.57 in.) to 11 diameters; and
2. Minimum spacing = max($0.6h_{ef}$ or $3.5d$).

Given these limitations, concrete screw anchors should be considered for direct reference in the ACI Building Code as safe, reliable post-installed anchoring options.

CONCLUSIONS

Their ease and speed of installation, as well as reliable performance in both cracked and uncracked concrete, are making concrete screw anchors an increasing popular solution as a post-installed anchor. Screw anchors may be safely designed using the model for undercut and expansion anchors with modifications to the effective embedment proposed by Kuenzlen.[6]

The database used to derive the current design method has been significantly extended to incorporate additional cracked and uncracked concrete tests. The extended database further justifies that the current design approach is acceptable. Limitations according to current experience are recommended to be placed in the scope of the qualification process to ensure future screw anchors can be safely designed with the proposed methods.

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