Anchoring in Cracked Concrete
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Content

1   Load-bearing principles of reinforced concrete

The tensile strength of concrete is relatively low and can vary widely. For normal weight sand-gravel concrete (2,000 psi < f'c < 4,000 psi) it can be estimated as one tenth of the uniaxial compressive strength (i.e., f_t ~ 400 psi). The relationship given in the literature is $f_r = K\sqrt{f'_c}$ where K can vary from 7 to 13 (Park 1974).

The development of modern reinforced concrete construction is predicated on the assumption that induced tensile stresses in flexural members (beams, slabs, etc.) are resisted via steel reinforcing and that the contribution from the concrete below the neutral axis is small and may be neglected. In order for the reinforcing to provide the necessary contribution to the internal moment couple, the external load must be delivered to the reinforcing steel via bond stresses that develop in the concrete around the bar and along its length. Initially, the entire concrete cross section of a beam (see Figure 1) will resist the external load via tensile and compressive stresses in the concrete. (Although the elastic modulus of steel is approximately 10x that of the concrete, the small cross sectional area of the reinforcing bars relative to the concrete section dictates that the concrete will initially resist the load.)

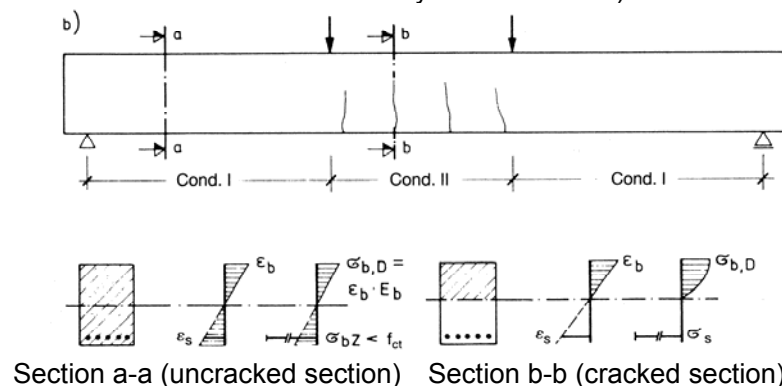Section a-a (uncracked section)   Section b-b (cracked section)

Figure 1 – Idealized behavior of a reinforced concrete section under load, *CEB Model Code*

Concrete subjected to tensile loading exhibits comparatively brittle behavior and cracking is initiated at small elongation / strain (approx. 0.01 to 0.02%). When the concrete ultimate tensile stress is reached, the tensile stress in the steel is still quite low; i.e. in the range of 3,000 psi or approximately one twentieth of its ultimate

strength (see Figure 2). Subsequently, as the load increases, cracks continually form in the concrete from the tension face to the neutral axis until equilibrium is reached in the cross section. The concrete between the flexural cracks serves to transfer the load to the reinforcing steel via bond stresses. The width and spacing of these cracks are correlated; that is, as the spacing between the cracks increases, their width necessarily increases to accommodate the steel strain. It is the goal of reinforced concrete design to keep the spacing between the cracks small in order to limit the crack width.
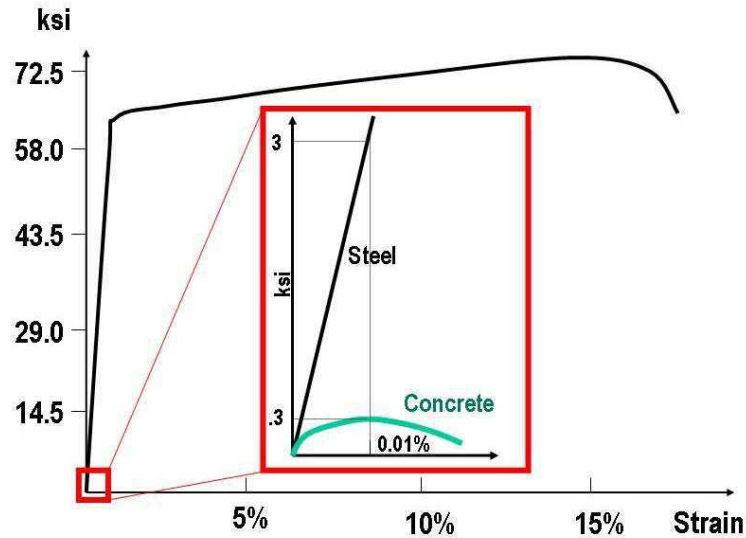

Figure 2 – Relative stress strain behavior of steel and concrete under tension

Clearly, for a concrete member to be both efficient and economical, flexural cracks are necessary in order to activate the reinforcement, utilizing the tensile strength of the steel to achieve equilibrium in the composite section (balanced condition).

Therefore, as a rule, cracking should always be anticipated in the tension zone of reinforced-concrete members such as beams, columns (where part of a moment-resisting frame) and slabs. Concrete members loaded in direct tension generally crack through the entire cross section, while members subjected to flexural shear and torsion will exhibit inclined or spiral crack patterns. Bond stresses may produce cracks along reinforcement and concentrated loads can induce splitting cracks in the concrete members.

Note that the tensile strength of concrete is not always neglected in reinforced concrete design. Cases where the tensile strength of the concrete is directly utilized include the calculation of shear resistance in walls and deep beams, punching shear in slab-column connections, bond (i.e., splitting stresses associated with bond development), and anchor bolt design for concrete cone breakout. The potential for overlap of the stresses associated with each of these conditions is considered small and is typically neglected; however, the sensitivity of the anchor performance to localized cracking should always be taken into account.

1.1 Causes for cracks in concrete

In addition to flexural cracking as discussed above, cracking in reinforced concrete may also be initiated as a result of the normal curing processes of concrete (shrinkage), by creep and settlement (long term deformations under load) and by restraint of thermal expansion and contraction. In general, the probable location and extent of the latter type of cracks may be difficult to accurately predict (ACI 1980) In such cases, the crack width is limited by provision of minimum reinforcing in

conformance with the code which is intended to result in uniformly distributed cracks. Where such reinforcement is not available, e.g., in unreinforced tunnel walls, dams, etc., wider cracks should be anticipated.

1.2 Significance of concrete cracking for structure design

Per ACI 318-05 (ACI 2004) Section R10.6.4:

…crack widths in structures are highly variable. In codes before the 1999 edition, provisions were given for distribution of reinforcement that were based on empirical equations using a calculated maximum crack width of 0.016 in. The current provisions for spacing are intended to limit surface cracks to a width that is generally acceptable in practice but may vary widely in a given structure.

Specific calculation of crack widths is rarely carried out in design since adherence to standard practice will typically result in crack widths that are consistent with aesthetics / appearance at the serviceability limit state as well as protection of the reinforcement against corrosion.

1.3 Cracking resulting from earthquakes

It may be safely assumed that earthquake loading as anticipated in code provisions (DBE, MCE) will always result in some level of cracking in concrete structures. The nature, extent and width of such cracks may only be roughly predicted; however, since code-based earthquake loading is typically assumed to correspond to inelastic structure response (i.e., steel yielding), and given the potential for extreme damage to the concrete in localized zones at this limit state, care should be exercised in the selection of appropriate anchorage systems, their location, and assumptions for design.

1.4 Summary

- The tensile capacity of concrete is typically neglected in the design of R/C flexural members and the concrete is expected to crack at service load levels.
- Cracking may also originate in concrete structures as a result of induced shear, bond or anchorage stresses, shrinkage, creep, settlement and thermal movements. It is typically assumed that the width of such cracks is controlled by the proper provision of distributed reinforcing and adherence to good design practice.
- Code provisions for reinforced concrete design are intended to limit crack widths so as not to impair the serviceability state (suitability for the intended purpose) and to protect the reinforcement.
- Cracking and concrete damage due to earthquake loading may be widespread and of much greater magnitude (width, depth) than that assumed for the serviceability limit state.

2 Safety relevance of serviceability conditions

Although the exact size and location of cracks in concrete may be of secondary significance with respect to reinforced concrete design, concrete cracking can play a more direct role in connection with anchor design and performance.

Cracks that pass near to or through the anchor location affect the distribution of stresses in the concrete around the anchor (see Figure 3 and Figure 4), and may also lead to a degradation of the load-transfer mechanism associated with various post-installed anchors types. In some cases, this can lead to excessive anchor displacement or premature anchor failure. It is important, therefore, that post-installed

anchors to be used in conditions where cracking is anticipated be specifically designed and qualified for use under cracked concrete conditions.

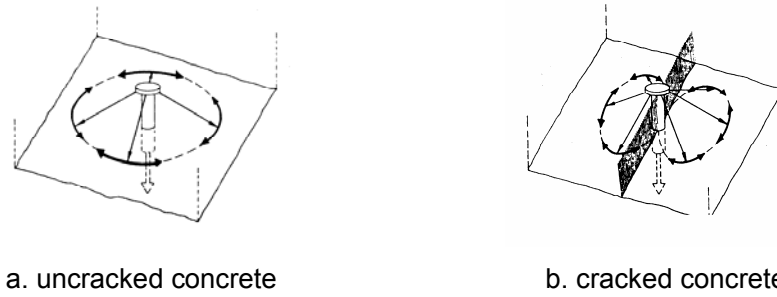a. uncracked concrete   b. cracked concrete

Figure 3 – Idealized stress state around a loaded anchor (Eligehausen 2006)

Crack widths typically encountered in reinforced concrete structures under static loading (less than 0.01 inches) should have a limited and predictable impact on the behavior of cast in place headed anchors and post-installed anchor types that have been specifically designed for cracked concrete. In post-installed anchor design, good performance in cracked concrete is achieved by design features that enhance the ability of the load transfer mechanism to accommodate changes in the anchor hole diameter. This is verified through appropriate testing of the anchor in crack widths ranging from 0.01 inches to 0.02 inches.

Certain types of traditional post-installed anchor designs are unsuitable for use in cracked concrete. Such anchors exhibit a significant reduction in holding power and/or unacceptable load versus displacement behavior in tests. Their use in conditions where cracking of the concrete can occur may result in a significant reduction in the factor of safety against failure.

Generally, the suitability of an anchor for use in cracked concrete environments depends on the type of load-transfer mechanism (e.g. friction, bond, or bearing) and its robustness, i.e., insensitivity to local variations in the concrete condition.

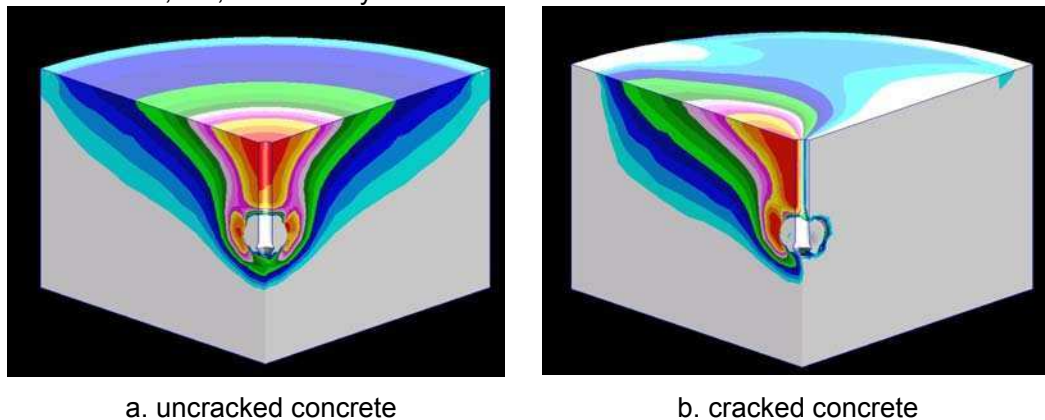a. uncracked concrete   b. cracked concrete

Figure 4 – Quarter space FE simulation of anchor stresses around a loaded anchor using FIXANA (Hilti 1994)

For anchor design the following points should be considered:

- Cracks in concrete can significantly influence the ultimate load capacity and displacement behavior of an anchor, depending on the type of anchor and its actual design features.

- The presence of a crack in the concrete at the anchor location changes the stress distribution in the concrete surrounding the anchor.

- A clear distinction should be made in the design of anchors in concrete between cracked and uncracked concrete conditions.

3   Design provisions in accordance with ACI 318 Appendix D

3.1 Background of IBC® 2003, the ACI 318 Appendix D design procedures as well as ACI 355.2 test requirements and ICC-ES Acceptance Criteria

Code provisions for the design of anchorages in concrete using cast-in (CIP) and post-installed mechanical anchors are found in Appendix D of the ACI 318 code (ACI 2004). These design provisions cover anchorage in both uncracked and cracked concrete. ACI Standard ACI 355.2 (ACI 2005) and the ICC Evaluation Service (ICC-ES) Acceptance Criteria AC193 (ICC-ES 2005/1) and AC308 (ICC-ES 2005/2) provides guidelines for how a post-installed anchor is qualified for use in both cracked and uncracked concrete or uncracked concrete only. The data derived from these test programs are necessary for the anchor design in accordance with the provisions of ACI 318 Appendix D. For post-installed anchors this information is published in Evaluation Service Reports (ESRs) issued by ICC-ES.

The relationship between these documents is illustrated in the code overview shown in Figure 5.
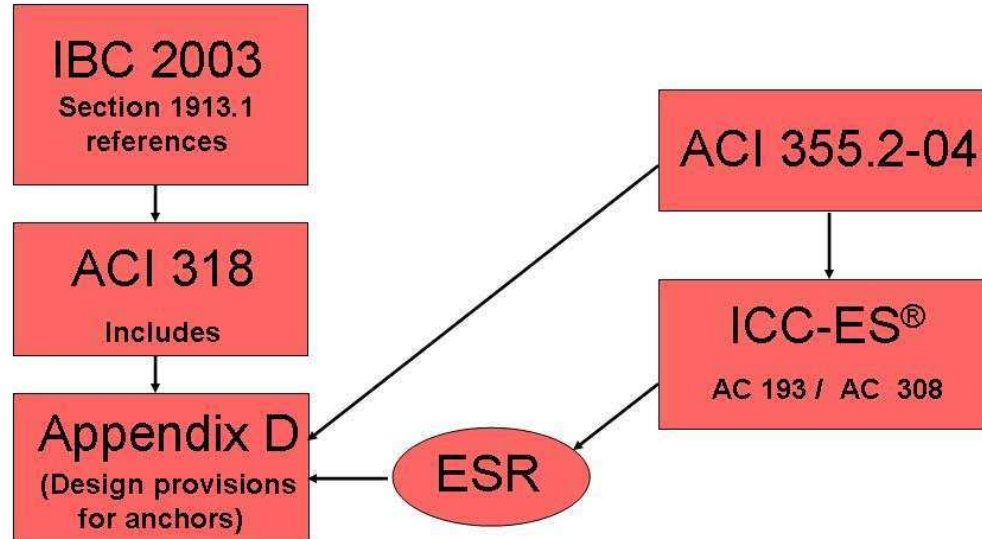
IBC – International Building Code®
ACI – American Concrete Institute®
AC 193 – ICC-ES Acceptance Criteria; acceptance criteria for mechanical anchor in concrete elements
AC 308 - ICC-ES Acceptance Criteria; acceptance criteria for post-installed adhesive anchors in concrete elements
ESR – Evaluation Service Report => final approval document containing design data

Figure 5 – Code overview

3.2   Anchor behavior in cracked concrete

Experimental investigations (Eligehausen 2006) indicate that an anchor will exhibit the greatest reduction in peak tension resistance when the anchor location is bisected by a crack that runs full depth of the member in which the anchor is installed. If the crack is adjacent to but does not transect the anchor location, the reduction will likely be smaller; however, the reduction associated with the disturbance of the stress state around the anchor remains in any case. At some distance (1-2 diameters), the crack will have little or no effect on anchor capacity.

Further experimental investigations (Lotze 1987) have shown that presence of anchors can influence the location of cracks in the tension zone of concrete members. The anchors act as stress risers in the concrete continuum, particularly if they are prestressed (torqued) or loaded. In general, cracks tend to propagate through anchor locations.

This observation leads to the following question regarding the applicability of laboratory studies to real practice: Is the influence on anchor behavior observed when an anchor is set in a pre-formed crack (laboratory condition) greater or less than that associated with an anchor set in initially uncracked concrete that later forms cracks passing through the anchor location? From an observational standpoint, the answer depends on the tension failure mode: If the anchor fails by pullout or pull-through, the ultimate load and slip associated with testing in pre-formed cracks is generally superior to that associated with cracking that occurs after the anchor is installed. If the anchor exhibits concrete cone failure, there is no appreciable difference between the two cases.

Crack widths in a typical structure will vary over the service life. This can be attributed to changes in live loading, settlement, creep and/or temperature fluctuations. The testing of anchors detailed in the relevant standards (ACI 2005, ICC-ES 2005/1, ICC-ES 2005/2) is designed to replicate these conditions.

3.3   Details of testing

Tension testing in static crack widths

The testing of anchors in static cracks is performed in cracks that have constant width over the depth of the member as opposed to flexural cracks which taper towards the neutral axis. This is done primarily to make the tests repeatable. The test specimen is typically configured like a wall or column with longitudinal reinforcing extended beyond the member boundaries and connected to the test frame. The test frame applies tension loads directly to the reinforcing which in turn induces transverse cracks in the member. The location of the cracks is controlled by sheet metal strips embedded in the concrete near the edges of the member which serve to induce cracking at uniform spacing. The load is then removed and the anchors are installed in the hairline cracks with proper checks made to assure that the crack path lies roughly in a vertical plane and that the anchor is transected by the crack over its length. The test specimen is loaded again until the specified crack width is obtained. The anchors are then tested in tension to failure.

The tests to determine the characteristic resistance for anchor design are carried out with a crack width Δw = 0.012 in. (hairline crack width plus 0.012 in.).   This corresponds to a crack width that is reached or exceeded by 5% of the cracks occurring in structures under service conditions. The anchors are thus verified using a 95% fractile value of the anticipated crack width.

The reliability of anchors in wider cracks (Δw = 0.02 in.) is also investigated to ensure a consistent probability of failure. In order to justify the use of a strength reduction factor for concrete failure of 0.65, the anchor must achieve 80% of the tension resistance corresponding to service condition crack widths. Other levels of qualification are permitted with reduced strength reduction factors in accordance with Appendix D. This verification helps ensure that the anchor system does not suffer catastrophic strength loss even if the 95% fractile crack width is exceeded.

Tension testing in cycled crack widths

In addition to testing in static cracks, anchor performance in cracks whose width is cycled between Δw = 0.004-0.012 in. One thousand load cycles are applied to the test member, representing the potential crack width cycling over the service life of the structure. Throughout the test, the anchor is subjected to a sustained tension load equal to 30% of the characteristic anchor tensile capacity. The anchor displacement is recorded throughout the test and compared with specific limits, i.e., δ_{max} = 2 mm at 20 cycles and 3 mm at 1000 cycles. The anchor is considered to have failed if these displacements criteria are exceeded at any point in the test. The test may, however, be repeated using a lower sustained tensile load until the criteria is fulfilled, with an appropriate adjustment in the design pullout capacity assigned to the anchor. The anchor is then tested in tension to failure and the residual tension capacity compared to the capacity associated with testing in static cracks. This ratio contributes to the determination of the strength reduction factor (via the anchor category) associated with concrete failure.

4   PROFIS Anchor design software

The introduction of the Concrete Capacity Design (CCD) method for cast in place and post-installed anchors was formalized with the issuance of ACI 318-02 Appendix D. The CCD method provides predictive equations for a variety of failure modes in both cracked and uncracked concrete in a framework appropriate to LRFD strength design. While the CCD method offers more flexibility and transparency in the anchor design process, it can require an increased level of calculational proficiency.

In order to expedite and standardize the design of anchors, various anchor design software packages have been developed. PROFIS Anchor from Hilti is the most comprehensive anchor design software available and includes options for design in accordance with Appendix D and ICC-ES criteria (see Figure 5). PROFIS also provides design options for allowable stress design (ASD) and contains a complete library of exportable CAD details, approval documents and specifications.
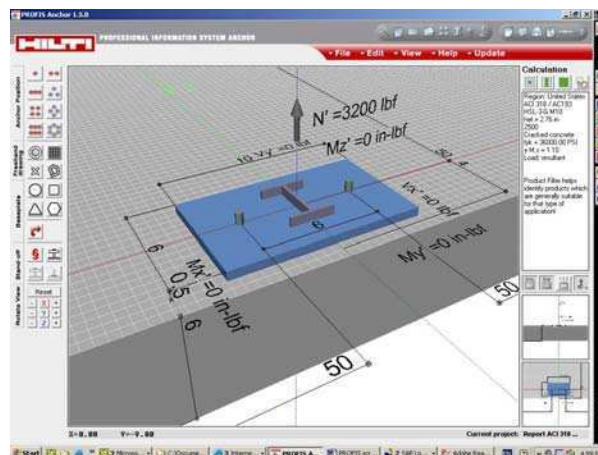

Figure 5 – PROFIS Anchor design software

5   Products suitable for use in cracked concrete

As the world leader in the field of fastening technology, Hilti has developed anchor systems specifically designed to meet the requirements mandated by the new codes.

Hilti offers several anchors suitable for use in cracked concrete:

5.1   Undercut anchor (Example: HDA)

Figure 6 – Hilti HDA Undercut Anchor

The self-undercutting Hilti HDA anchor (Figure 6) offers unsurpassed performance for use in cracked concrete due to its working principle. During the setting operation of the anchor a bearing surface is produced, allowing the anchor to develop its holding power due to bearing in lieu of friction (friction is the predominate load transfer mechanism used in common expansion type anchors). This is reflected in a stress distribution around the undercut segment comparable to a cast-in headed stud under similar loading conditions. The HDA has been tested in crack widths exceeding 1.5 mm (0.06 in.) in accordance with German nuclear qualification requirements (see Figure 7). Design information for the HDA anchor may be found in ICC-ES ESR 1546.

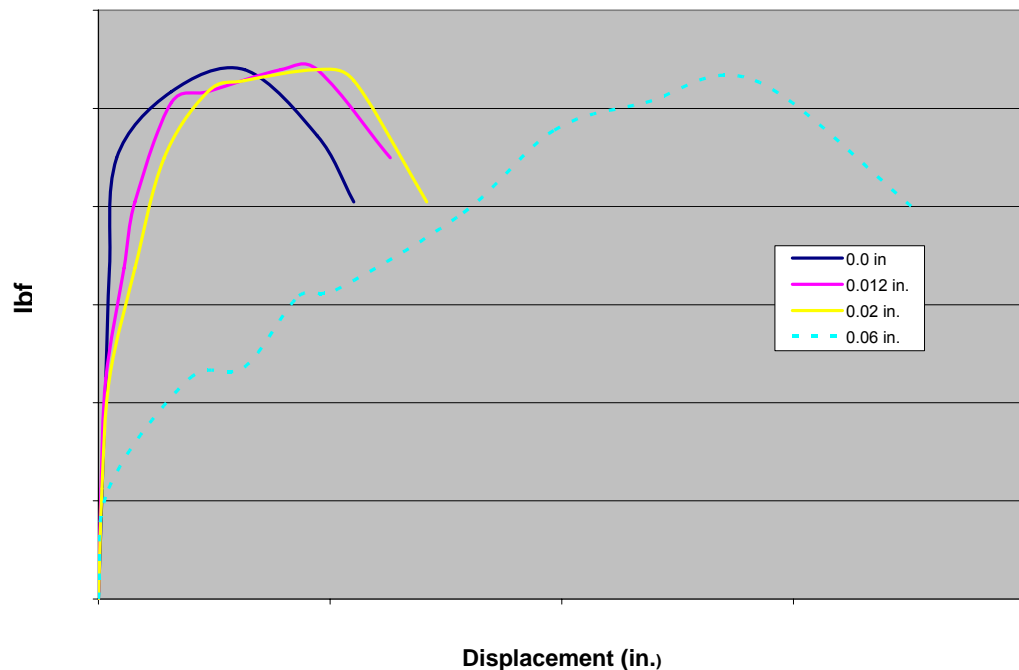**HDA: Load-Displacement vs. Crack Width**

Figure 7 – Load-displacement response of HDA subjected to tension loading

5.2 Expansion anchor (example: HSL-3)

Figure 8 – Hilti HSL-3 Heavy Duty Expansion Anchor

Expansion anchors make use of friction and micro-keying to develop tension resistance in concrete. They can be optimized for use in cracked concrete by adjusting their follow-up expansion behavior. The HSL-3 (Figure 8) provides robust and reliable follow-up expansion leading to consistent performance in cracked concrete (see Figure 9). Design information for the HSL-3 anchor can be found in ICC-ES ESR 1545.

HSL-3 Load Displacement vs. Crack Width

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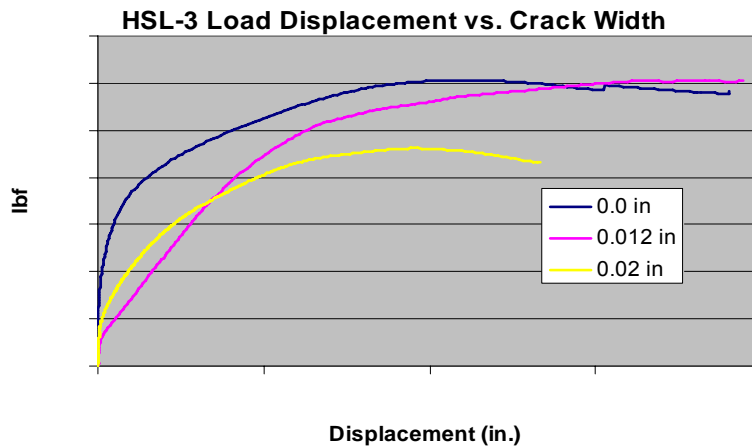— 0.0 in
— 0.012 in
— 0.02 in

Displacement (in.)

Figure 9 – Load-displacement response of the HSL-3 subjected to tension loading

5.3 Expansion anchor (example: KB-TZ)

Figure 10 – Hilti KB-TZ Expansion Anchor

The KB-TZ (Figure 10) is offered in inch sizes (3/8, ½, 5/8 and ¾-inch diameter) in both carbon steel and stainless steel versions. The functional principle of the KB-TZ is similar to that of the HSL-3. The suitability of the KB-TZ for use in cracked concrete has been verified through extensive testing in accordance with AC193 (see Figure 11). Design information for the KB-TZ anchor can be found in ICC-ES ESR 1917.
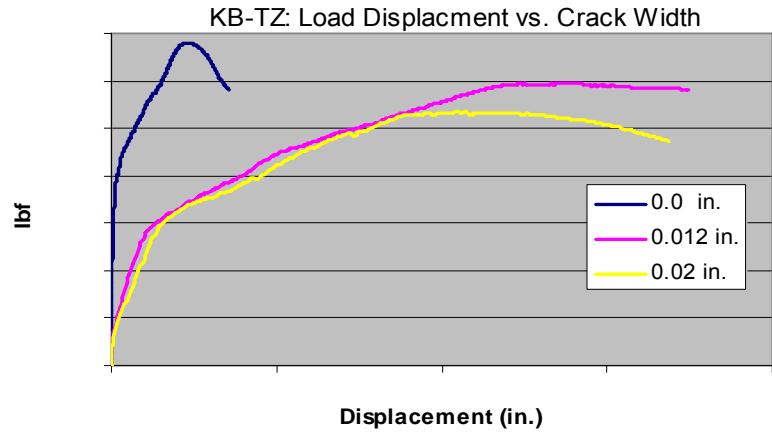
Figure 11 – Load-displacement response of the KB-TZ subjected to tension loading

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9. Park, R. and Paulay, T. (1974), Reinforced Concrete Structures, John Wiley & Sons, 1974, p. 16.