Anchors in Concrete: The Tools to Find Acceptable Concrete Anchors—Part 2 of a four-part series

by Dr. Donald F. Meinheit

This article is part 2 in a four-part series addressing concrete anchorage in the reorganized Section 5 of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] published in 2017. Part 1 (see the Summer 2020 issue of *ASPIRE*®) outlined a PCI educational program sponsored by the Transportation Research Board to educate bridge engineers on the implementation of the new provisions adopted from the American Concrete Institute's *Building Code Requirements for Structural Concrete* (ACI 318-14) *and Commentary* (ACI 318R-14).[2] This article focuses on the qualification of post-installed concrete anchors.

Traditionally, state highway authorities (SHAs) have published their own materials and testing standards. AASHTO has published a collection of individual standards as the *Standard Specifications for Transportation Materials and Methods of Sampling and Testing* since 1931.[3] However, SHAs have abandoned some of the individual AASHTO materials specifications for lack of use or have substituted standards from other organizations, usually ASTM International (formerly the American Society for Testing and Materials).

The AASHTO materials specifications are separated into three types:

- Materials (M series)
- Practice (R series)
- Testing (T series)

Standards in each series are numbered consecutively: M 1–334, R 1–84, and T 1–378. Currently, there are 134 M standards, 72 R standards, and 232 T standards.

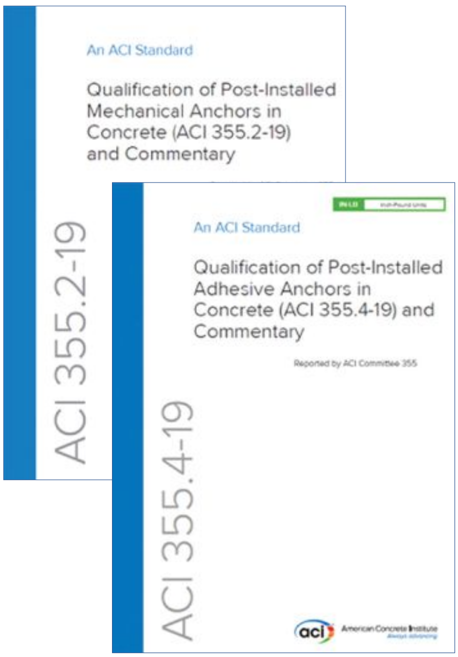
One standard in the AASHTO collection addresses concrete anchors: M 314-90 (2018), *Standard Specification for Steel Anchor Bolts*.[4] This standard does not address post-installed anchors for concrete, which should perhaps trigger a need in the AASHTO materials standards to create a specification for post-installed concrete anchors. However, it is the consensus of the concrete anchorage community of experts (designers, researchers, installers, and suppliers) that it is not necessary to have any additional AASHTO or SHA standard for the qualification of post-installed steel anchors because a qualification protocol already exists as an ACI standard.

In the United States, there are no ASTM standards for qualifying concrete anchors. The standards writing body for concrete anchor qualification is ACI. Specifically, ACI Committee 355, Anchorage to Concrete, writes and updates anchor qualification testing protocols. ACI assumed responsibility for writing the qualification standard in 2002, when the first ACI code requirement appeared in ACI 318-02.[5] The ACI standards for qualifying concrete anchors are modeled on and consistent with the qualification documents in Europe.

Qualification Standards for Anchors

Voting membership on the ACI 355 Committee includes anchor manufacturers, users, and individuals with a general interest (academics). One might think that having anchor manufacturer representatives on the committee is like having a fox watching the henhouse. However, the anchor qualification standards need to be rigorous, and the testing required by the ACI standards, as approved by ACI 355, indicates that the anchor manufacturers agree to comply with the requirements.

The International Code Council Evaluation Service (ICC-ES) is a nonprofit company that performs technical evaluations of building products and materials and publishes an evaluation service report (ESR) for products. (For a directory of these reports, visit https://icc-es.org/evaluation-report-program/reports-directory.) ICC-ES has a for-profit subsidiary that tests products per ICC-ES acceptance criteria (AC).



There are two ACI standards for qualifying anchors, which prescribe testing programs and evaluation requirements in accordance with ACI 318. One standard is for mechanical anchors: ACI 355.2, *Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary*,[6] which includes torque-controlled wedge anchors, torque-controlled sleeve anchors, concrete screws, and undercut anchors and was updated in 2019. The other is for polymeric adhesive anchors: ACI 355.4, *Qualification of Post-Installed Adhesive Anchors in Concrete and Commentary*,[7] which addresses anchors embedded in a polymeric adhesive and was also updated in 2019. Earlier versions of these two standards were in place when the eighth edition of the AASHTO LRFD specifications added Article 5.13 on anchors. The 2019 versions of the ACI standards for concrete anchors are discussed in this article because the standards did not substantially change but now include additional anchor types like concrete screws. Anchors embedded in cementitious grout do not yet have a qualification standard.

Anchor manufacturers submit test results for their products performed per the requirements of the AC to ICC-ES for evaluation and reporting, which are performed for a fee. The test protocols established by ICC-ES are AC193 for mechanical anchors (torque-controlled wedge anchors, torque-controlled sleeve anchors, concrete screws, and undercut anchors) and AC308 for adhesive (polymeric) anchors. These ACs address anchor qualification requirements given in the ACI qualification standards: AC193 for ACI 355.2 and AC308 for ACI 355.4.

Qualification Standard Tests

Within each of the ACI or AC qualification test protocols, testing is separated into four parts:

- *Identification tests* evaluate the anchor's compliance with critical manufacturing characteristics, which can include, but are not limited to, dimensions and tolerances, constituent materials (mill test reports for steels used in the product), surface finishes, coatings, fabrication techniques, the marking of the anchors and components (nuts and washers), a fingerprint of the adhesive, and the classification of the steel anchor elements as ductile or brittle, as this makes a difference in the strength reduction factor ϕ assigned for the design of the anchor.
- *Reference tests* establish the baseline strength performance against which subsequent mechanical tests to investigate the reliability and service conditions are compared. Both cracked and uncracked concrete conditions are tested. These tests are essential in establishing the anchor performance category (1, 2, or 3) for designing the anchor.
- *Reliability tests* are performed in both cracked and uncracked concrete to establish whether the anchor is safe and will perform acceptably under normal and adverse conditions. Tests are conducted during installation and in service and are intended to assess the sensitivity of the anchor to various adverse installation conditions, different strengths of concrete, performance under repeated load (but not fatigue loading), installation in a concrete crack and subsequent cycling of the crack width, and verification if brittle behavior exists under a tensile load.
- *Serviceability tests* are service-condition tests to evaluate the performance of the anchor under expected service conditions, such as the minimum member thickness in which the anchor can function; how close to a corner the anchor can be installed and still carry the same load as when away from the corner; and the minimum spacing that can be tolerated between anchors such that the concrete does not crack due to installation. Finally, if post-installed anchors are used in moderate- or high-seismic design categories, they must pass a simulated seismic test to be qualified.

Grading Anchor Performance

The primary purpose of the qualification standard is to confirm an anchor's reliability and place it in the appropriate category based on its performance. The anchor category is an index of the anchor's sensitivity to conditions of installation and use. Criteria for determining the anchor category for mechanical anchors and adhesive anchors are contained in ACI 355.2 and ACI 355.4, respectively. The assigned anchor category carries with it a ϕ-factor set by the ACI 318 design code. For mechanical anchors, the category is numerically evaluated using the smallest ratio of the various reliability tests to the corresponding reference test from the ACI document. **Table 1** conceptually shows how the anchor category is assigned for mechanical anchors.

Table 1. Anchor categories for mechanical anchors from ACI 355.2.[6]

Smallest ratio of characteristic capacities	Anchor category
$0.80 \le \frac{N_{b,r}}{N_{b,o}}$	1
$0.70 \le \frac{N_{b,r}}{N_{b,o}} \le 0.80$	2
$0.60 \le \frac{N_{b,r}}{N_{b,o}} \le 0.70$	3
If $\frac{N_{b,r}}{N_{b,o}} < 0.60$	Anchor is unqualified

Note: $N_{b,r}$ = the characteristic tension capacity (5% fractile) in the reliability tests; $N_{b,o}$ = the characteristic tension capacity (5% fractile) in the reference tests.

Assigning the anchor category for an adhesive anchor follows the same concept of comparing the reliability tests to the reference tests, but is somewhat more complicated. Adhesive anchor performance is more sensitive to hole cleaning, moisture in the drill hole, mixing effort of the adhesive, and whether the adhesive will work if the concrete is saturated or under water. Therefore, ACI 355.4 (AC308) includes a series of reliability tests that are compared to reference test results. The ratios of results of these reliability tests to reference tests, called α-values, are compared to a table of required α-values, α_{req}. If the test α-value is below the required α-value in the table, the category number increases and, consequently, the ϕ-factor decreases to reflect poorer performance.

The characteristic tension bond stress is also determined by how well or poorly the adhesive performs in other reliability and service-condition tests, which include assessments for long-term temperature exposure (α_{lt}), short-term temperature exposure (α_{st}), durability (freezing/thawing) (α_{dur}), durability of the anchor system to environmentally aggressive chemicals and crack-width cycling (α_{o}), the coefficient of variation of test results (α_{COV}), regional concrete variations (α_{conc}), and a reduction if the anchor system is in category 3, the lowest capacity category (α_{cat3}). The last reduction on bond stress is a factor accounting for the reliability tests that were used to determine the anchor category (β). All of these reduction factors are applied to the nominal characteristic tension bond stress ($t_{k,nom\ (cr,uncr)}$)

$$\tau_{k\,(cr,uncr)} = t_{k,nom\,(cr,uncr)}\ \beta\ \alpha_{lt}\ \alpha_{st}\ \alpha_{dur}\ \alpha_{\varrho}\ \alpha_{conc}\ \alpha_{COV}\ \alpha_{cat3}$$

Equation 10-12 from ACI 355.4-19[7] for determining characteristic tension bond stress for cracked or uncracked conditions accounting for numerous reduction factors defined in text.

to determine the value of the characteristic design tension bond stress (τ_k) for cracked (*cr*) or uncracked (*uncr*) conditions using the equation shown above.

From this detailed evaluation process, it is clear that the design stress for the adhesive anchor system failing in bond is taken seriously. The design tension bond strength must also incorporate the appropriate ϕ-factor and any other modification factors as found in Section 17.4.5.2 and other provisions of Chapter 17 of ACI 318-14.

All the geometric requirements (such as edge distance, minimum anchor spacing, and concrete thickness) and installation recommendations for a specific concrete anchor or adhesive, plus the performance of the anchor in concrete breakout and pullout/pull through, and the steel strength, are summarized for the designer in a downloadable ESR from ICC-ES.

Part 3 of this four-part series on concrete anchors will focus on specifications and procurement of concrete anchors.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC: AASHTO.
2. American Concrete Institute (ACI) Committee 318. 2014. *Building Code Requirements for Structural Concrete* (ACI 318-14) *and Commentary* (ACI 318R-14). Farmington Hills, MI: ACI.
3. AASHTO. 2020. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 40th ed. Washington, DC: AASHTO.
4. AASHTO. 2018. *Standard Specification for Steel Anchor Bolts* (M 314-90). Washington, DC: AASHTO.
5. ACI Committee 318. 2002. *Building Code Requirements for Structural Concrete* (ACI 318-02) *and Commentary* (ACI 318R-02). Farmington Hills, MI: ACI.
6. ACI Committee 355. 2019. *Qualification of Post-Installed Mechanical Anchors in Concrete* (ACI 355.2-19) *and Commentary*. Farmington Hills, MI: ACI.
7. ACI Committee 355. 2019. *Qualification of Post-Installed Adhesive Anchors in Concrete* (ACI 355.4-19) *and Commentary*. Farmington Hills, MI: ACI.

PERSPECTIVE

A Call to Action for All Bridge Engineers

by Tim Keller, Ohio Department of Transportation

The article "Why Didn't They Just Close the Road?" in the Spring 2020 issue of *ASPIRE*® is a call to action for the bridge industry. One of the points of the article is that it takes strong leadership to make difficult decisions. Strong leadership, both politically and technically, must be evident for those affected to accept and understand the decision. The political leadership must have trust in the technical staff. "Trust is not given, but earned" is a statement that all bridge engineers should embrace. Trust is not given because of a person's title. Trust is earned over time as relationships are developed. Trust must exist before a crisis so that the "pushback" described in the article is not a roadblock or delay to a difficult decision. Trust must exist to push fear out of the decision process.

The concurring statement by National Transportation Safety Board (NTSB) vice chairman Bruce Landsberg on page 106 of the NTSB highway accident report on the 2018 pedestrian bridge collapse at Florida International University[1] should be read by everyone in the bridge industry. It stung the first time I read it. Powerful and basic, it is a call for our industry to learn from this failure. Elsewhere in the report, the NTSB issued recommendations specifically to the Federal Highway Administration (FHWA), Florida Department of Transportation (FDOT), American Association of State Highway and Transportation Officials, and the Engineer of Record. I believe these recommendations are meant for all of us in the industry.

My fellow state bridge engineers, as bridge owners, please join me in evaluating your state practices and processes with Landsberg's message in mind. You may find, as I did, that the complacency that he described has crept into some of your practices. With FHWA and our industry partners, we must continue to improve our specifications and the understanding on how to implement them. We all should take care that the training recommended in the accident report is not limited to how to make a shear calculation. The training we all are entrusted with is key to the future of bridge design. We have the responsibility to invest in people, so that future lessons learned are not a result of loss of life.

Reference

1. NTSB. 2019. *Pedestrian Bridge Collapse Over SW 8th Street, Miami, Florida, March 15, 2018*. Highway Accident Report NTSB/HAR-19/02 PB2019-101363. Washington, DC: NTSB. https://www.ntsb.gov/investigations/AccidentReports/Reports/HAR1902.pdf.