Beyond Bond Strength of Adhesive Anchors

Testing, Design, and Specification

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A variety of factors influence an engineer's decision to use cast-in anchors or post-installed anchors including working principles, installation, and the impact on project timeline and budget. Above all, a licensed engineer shall hold paramount their code of ethics and the safety, health, and welfare of the public. At a time in which budget and scope have tightened for professional engineering work, it is difficult to allocate resources to sift through technical data and footnotes for a comprehensive comparison of post-installed anchoring systems. This article establishes an understanding of the chemical and physical factors that affect the performance of post-installed adhesive anchor systems. It also explains how product testing is incorporated into design calculations and provides suggestions for designing and specifying adhesive anchor systems.

Must-See Section	What's most important to find here	Example(s)
1.0 Evaluation Scope	Compliance with the building code under which your project is designed	2018, 2015, 2012 International Building Code, National Building Code of Canada
2.0 Uses	Allowable and intended application(s) for product	Cracked concrete, seismic, development of rebar
3.0 Description	Hole cleaning equipment allowed or required, anchor elements allowed	Proprietary cleaning equipment, dust-removal systems, development of rebar
5.0 Conditions of Use	Permissible temperature ranges, installation orientation	Floor, wall, and overhead installations at temperatures between 23F and 104F

Figure 1. Quick references within an ICC-ES report.

Why is this important? Inappropriate selection or improper installation of adhesive anchor systems can result in a reduction in anchor capacity or anchorage failure. The consequences can lead to expensive repairs, project delays, and, possibly, endangerment to public safety.

The International Code Council Evaluation Service (ICC-ES) developed the *Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements* (AC308) in 2006. AC308 includes provisions to qualify adhesive anchor systems for compliance with the *International Building Code* (IBC). Adhesive anchor systems that demonstrate compliance with the IBC can be used with the anchoring-to-concrete provisions of the American Concrete Institute (ACI) publication *Building Code Requirements for Structural Concrete* (ACI 318).

Structural connection design includes cast-in anchors and post-installed anchors. Cast-in anchors can be used directly with ACI 318 anchoring-to-concrete provisions. Post-installed anchors are qualified per ICC-ES acceptance criteria to (a) demonstrate compliance with the IBC, and (b) obtain data to design the anchor with ACI 318 anchoring-to-concrete provisions.

In 2011, ACI developed the test standard *Qualification of Post-Installed Adhesive Anchors in Concrete* (355.4) to qualify adhesive anchor systems, thereby harmonizing AC308 with an ACI test standard. To dive deeper, read *Changes in Adhesive Anchor System Approvals* (STRUCTURE, September 2015).

Evaluation Service Reports and Design Code

ICC-ES reports serve as a third-party evaluation of engineered products. These evaluations can be used to demonstrate product compliance with the IBC, subject to approval by the Authority Having Jurisdiction (AHJ). ICC-ES reports provide technical information in a standard format but may vary significantly in depth and breadth between product reports. The Report sections include valuable information for selecting the appropriate adhesive anchor system for an application (*Figure 1*).

ICC-ES reports also include tables of published data that can be used to design the anchor with ACI 318 anchoring-to-concrete provisions. Information in these tables can include the following:

- Specifications and physical properties of anchor elements
- Design information for anchor elements
- Concrete breakout design information
- Bond strength

Load Reduction Factor Design (LRFD), per ACI 318-14, requires the assessment of capacities corresponding to possible failure modes in tension and shear to determine which failure mode governs the adhesive anchor system performance. An abbreviated method to compare adhesive anchor systems is to compare nominal bond strengths as listed in ICC-ES report tables. These tables, however, may be differentiated by the condition of concrete, special inspection levels, in-service temperature range, or drilling method. Footnotes at the end of tables can include several reduction factors for design calculations.

The ICC-ES report concludes with the manufacturer's printed installation instructions (MPII), which should describe congruent installation procedures to those that have been tested and included in the body of the report.

Adhesive anchor systems rely on adhesive bonding as a result of a chemical reaction between hardener and resin. The bond formed with the base material as a result of this chemical reaction can be affected by several factors, including temperature and/or the presence of dust or water. ACI 318 Section 17.8.2.1 notes characteristic bond stress parameters that should be included in the language of an adhesive anchor specification (*Figure 2*). This article focuses on three bond stress parameters: drilling or hole-cleaning methods, moisture condition of the concrete, and temperature at time of installation.

Code (ACI 318-14)

17.8.2.1 For adhesive anchors, the construction documents shall specify proof loading where required in accordance with ACI 355.4. The construction documents shall also specify all parameters associated with the characteristic bond stress used for the design according to 17.4.5, including minimum age of concrete; concrete temperature range; moisture condition of concrete at time of installation;

type of lightweight concrete, if applicable; and requirements for hole drilling and preparation.

Commentary (ACI 318R-14)

R17.8.2.1 Due to the sensitivity of bond strength to installation, on-site quality control is important for adhesive anchors. Where appropriate, a proof loading program should be specified in the construction documents. For adhesive anchors, the construction documents must also provide all parameters relevant to the characteristic bond stress used in the design. These parameters may include, but are not limited to:

(a) Acceptable anchor installation environment (dry or saturated concrete; concrete temperature range)
(b) Acceptable drilling methods
(c) Required hole cleaning procedures
(d) Anchor type and size range (threaded rod or reinforcing bar)

Figure 2. ACI 318-14 Section 18.8.2.1 encourages specific parameters be specified.

Reliability Testing of Manufacturer's Installation Procedure

Proper adhesive anchor installation includes drilling into cured concrete using an approved drilling method, cleaning the drilled hole to remove dust and debris, properly injecting the adhesive, and inserting the anchor element within the gel/working time of the adhesive (*Figure 3*).

Properly cleaning the drilled hole can have a significant impact on adhesive anchor performance. AC308 provisions include *reference* and *reliability tests* to establish a proper hole cleaning procedure. Reference tests establish a baseline cleaning procedure by which the adhesive is qualified and bond stress values are established. Typical steps for hole cleaning include blowing out the drilled hole, brushing of the hole with a steel wire brush, and blowing out the hole again. Although the blow-brush-blow method is a typical cleaning method for adhesive anchor systems, the number of iterations for each step, proprietary steel wire brushes, and prescribed pressure of compressed air can vary for each system. In the subsequent reliability test, the same anchor configuration is tested at half the number of cleaning steps of the reference test with the purpose of validating that at least a certain percentage of the bond stress value is achieved under reduced hole-cleaning procedure. It follows then, with the lowest possible reliability test cleaning procedure of 1 blow, 1 brush, 1 blow, the lowest allowable reference test cleaning procedure is 2 blow, 2 brush, 2 blow.

Manufacturers have the freedom to select any level of cleaning procedure for reference tests. More cleaning iterations reduce the amount of dust and debris in the drilled hole, increasing bonding between the adhesive and concrete. Some manufacturers choose to use the minimum cleaning steps possible (2x2x2) with the intention of reducing the expectation of installer diligence to follow manual cleaning procedures, relying on the adhesive anchor system's resilience to deliver performance.

If an adhesive anchor system does not achieve a specific percentage of the reference test bond stress value in reliability testing, the anchor may report a lower category than intended or the number of iterations or intricacy of cleaning steps may increase in the reference test to provide a cleaner hole in which the adhesive can reliably reach the intended level of performance (*Figure 4*). Intricate cleaning steps to help achieve and maintain bond stress include proprietary steel wire brushes specific to the adhesive anchor system, or drill-mounting of brushes that may have wider or more densely packed bristles to remove dust.

In 2011, Concrete International published *A Field Study of Adhesive Anchor Installations*, reporting that 77% of installations did not comply with the MPII. In 2013, some manufacturers offered anchoring technology to help reduce the human error inherent to the hole-cleaning of adhesive anchor systems. These technologies include (a) a torque-controlled anchor element that relies on friction-hold rather than adhesive bonding to transfer load and thus requires no hole-cleaning to achieve load capacity, and (b) a hollow drill bit system that extracts dust while drilling.

Step	Objective	Concerns
1. Drill hole	Create void of correct diameter and depth in which to install the adhesive anchor	Final anchor position may not have enough embedment depth to develop required capacity
2. Clean hole	Remove dust and debris from hole for proper bonding of adhesive to concrete	Reduced or improper cleaning may result in inability to properly transfer load to concrete via bond
3. Inject adhesive	Properly inject accurate ratio of two-part adhesive without air voids	Improper curing of resin and hardener mix may result in lower capacity; air voids may reduce surface area for bond
4. Insert steel element	Insert steel element to full embedment depth and in specified position	Too short of gel times may not allow steel element to be positioned deep enough or correctly

Figure 3. Installation steps and objectives.

Table 10.5—Anchor categories for adhesive anchors subject to installation conditions according to Table 10.7*

Anchor category	Threshold value of α_{req} for selected reliability tests				
	Reliability test numbers according to Table 3.1, Table 3.2, or Table 3.3				
	2a	2b	2c†	2d†	2e
1	0.95	0.90	0.90	0.90	0.95
2	0.80	0.75	0.75	0.75	0.80
3	0.70	0.65	0.65	0.65	0.70

*(periodic special inspection)
†Optional tests; refer to Table 10.7 for permissible combinations.

Table 10.6—Anchor categories for adhesive anchors subject to installation conditions according to Table 10.8*

Anchor category	Threshold value of α_{req} for selected reliability tests							
	Reliability test numbers according to Table 3.1, Table 3.2, or Table 3.3							
	2a	2b	2c†	2d†	2e	2f‡§	2g†§	2h†§
1	0.80	0.75	0.75	0.75	0.80	0.90	0.90	0.90
2	0.70	0.65	0.65	0.65	0.70	0.75	0.75	0.75
3	0.60	0.55	0.55	0.55	0.60	0.65	0.65	0.65

*(continuous special inspection and on-site proof loading program)
†Optional tests; refer to Table 10.8 for permissible combinations.
‡If Test 2g is performed, then Test 2f may be omitted.
§Omission of less severe tests is permitted in specific cases: for example, if the desired category is fulfilled with the results of Tests 2b, 2c, and 2d, then Tests 2f, 2g, and 2h may be omitted.

Figure 4. Percent of bond stress to be achieved for various anchor categories.

Due to rising numbers of severe health conditions and fatalities associated with silicosis, a lung disease attributed to inhalation of silica dust from concrete or masonry, the Occupational Safety and Health Administration (OSHA) heightened respirable silica dust regulations and renewed enforcement in June 2017. OSHA's *Respirable Crystalline Silica Standard for Construction*, known as *OSHA 1926.1153*, or *Table 1*, outlines the maximum levels and methods to reduce exposure to respirable silica dust allowable by application, including the cleaning method of post-installed anchor systems.

Existing hole-cleaning technology included in ICC-ES reports were tested and confirmed to meet the purpose of dust-removal to comply with *Table 1*. Anchor manufacturers that did not have existing hole-cleaning technology partnered with tool manufacturers to develop dust-removal systems to comply with *Table 1*. To date, some manufacturers have included dust-removal systems in an MPII without including them in ICC-ES report testing. Some manufacturers that do include dust-removal systems in an ICC-ES report may still require manual cleaning steps, or their anchor may only be allowable in dry concrete conditions.

Effect of Moisture Conditions

Adhesive product testing per AC308/ACI 355.4 establishes a strength reduction factor (ϕ-factor) relevant to the reliability or sensitivity of the product with respect to installation conditions. Adhesive sensitivity can be influenced by mixing the hardener and resin, hole cleaning, and moisture content of the base material, among others. ϕ-factors vary for tension loads, as shown in *Figure 5*. Note that adhesives with high reliability have a ϕ-factor of 0.65 while adhesives with low reliability have a ϕ-factor of 0.45. ϕ-factors for an adhesive product can vary with respect to anchor diameter, special inspection levels, core-drilling, or whether the drilled hole in the concrete is dry, water-saturated, water-filled, or wholly submerged.

Lower ϕ-factors typically result from a single adverse installation condition or compounding adverse conditions. Some adhesive products perform at the highest level of reliability, achieving a 0.65 ϕ-factor for both favorable and adverse conditions, like dry concrete and water-saturated concrete, respectively. It is essential to be aware of any compounding conditions in testing for reliability as the resulting ϕ-factor directly affects design capacity and performance of the anchor.

Other adhesive products have a ϕ-factor of 0.65 for a ⅜-inch-diameter anchor element and a ϕ-factor of 0.45 for a ½-inch-diameter anchor element. Some ϕ-factors are obtained with the requirement that all adhesive anchors, regardless of installation orientation, are under continuous inspection, although 2015 IBC Chapter 17 requires continuous inspection for only adhesive anchors that are horizontal-to-upwardly-inclined with sustained tension loads. ϕ-factors are strongly influenced by the presence of water that may affect the bond of an adhesive anchor system to the base material.

Although the office environment in which we design anchorage is climate-controlled and dry, the job sites where the product is installed rarely are. AC308 defines dry concrete as concrete that has not been exposed to water in 14 days. Most regions of North America are likely to experience precipitation, regardless of season, within a two-week period.

ACI requires consideration of moisture conditions in the design phase. Whether an anchorage design is generated in response to a Request for Information (RFI) for installation later that day or a general notes section is developed for anchors that are installed throughout the duration of a project, water-saturated concrete is realistic to assume for a design basis.

	Condition A	Condition B
(i) Shear loads	0.75	0.70
(ii) Tension loads Cast-in headed studs, headed bolts, or hooked bolts	0.75	0.70
Post-installed anchors with category as determined from ACI 355.2 or ACI 355.4		
Category 1 (Low sensitivity to installation and high reliability)	0.75	0.65
Category 2 (Medium sensitivity to installation and medium reliability)	0.65	0.55
Category 3 (High sensitivity to installation and lower reliability)	0.55	0.45

Condition A applies where supplementary reinforcement is present except for pullout and pryout strengths.

Condition B applies where supplementary reinforcement is not present, and for pullout or pryout strength.

Figure 5. The reliability of an adhesive anchor is reflected in a ϕ-factor.

Product ICC-ES Report	Installation Temperature	Required Cure Time
ESR-3814	41 F	24 hours*
ESR-3298	41 F	48 hours
ESR-2583	41 F	50 hours
ESR-4057	40 F	8 days*
ESR-2508	50 F**	3 days*
ESR-4094	43 F	6 days

*Cure times double in wet concrete conditions
**Lowest applicable temperature

Figure 6. Published cure times required at approximately 41°F.

Impacts of Installation Temperature

Adhesive anchors cure because of a chemical reaction between a precise ratio of hardener and resin. Temperature greatly influences the rate at which the adhesive cures. When the concrete temperature is high at the time of installation, the reaction is accelerated; when the concrete temperature is low at the time of installation, the reaction slows. Four considerations of temperature include the range in which the product can be installed, the required cure time at a given temperature, the gel/working time at a given temperature, and conditioning requirements of the product to be installed properly in a given application.

Installation temperatures are included in ACI 318 anchoring-to-concrete provisions. Adhesive anchor manufacturers typically test their products for a wide range of installation temperatures. The most common temperature ranges include 41°F to 104°F. Some, although not all, products have been tested for installation at minimum temperatures as low as 14°F. Reference the ICC-ES report for the installation temperatures specific to an adhesive anchor system to validate applicability in the realistic temperatures your projects may experience.

Ideally, adhesive anchor systems strike a realistic balance between cure time and gel/working time. As construction schedules continue to tighten, priority is given to shorter cure times that allow for more immediate loading. Waiting for the full required cure time for a given base material temperature before loading is critical to the performance of the adhesive bond. A general rule-of-thumb followed by many installers is to wait 24 hours after installing an adhesive anchor system before loading, regardless of the MPII. Some products require cure times that exceed this rule-of-thumb, as shown in *Figure 6*. Additional cure time may be required in water-saturated conditions, as shown in footnotes in either an ICC-ES report or MPII.

Gel/working time is another significant consideration in adhesive anchor selection. During gel/working time, the installer must inject the required amount of adhesive into the drilled hole with no air voids, insert the anchor element to the required embedment depth, and position it properly. At elevated temperatures, most products have a gel/working time of at least five minutes in which the installer can reasonably execute these steps; other products allow for only 90 seconds of gel/working time.

Depending on their chemical makeup, products may require special conditioning to be used in certain environmental conditions. Water-based adhesives require minimum conditioning of the adhesive product to above 32°F, and a common conditioning requirement among products is a minimum of 41°F. Other products require installers to condition adhesive products to 70°F when base material temperatures are less than 70°F.

Basis-of-Design Parameters in ACI 318

ACI 318 recognizes the reliability of adhesive anchor system performance is influenced by adverse job site conditions including moisture condition, temperature at time of installation, hole drilling methods, and cleaning procedures. While these aspects are addressed by testing per AC308, the resulting bond strengths, reduction factors, and conditions of use included in the ICC-ES report vary significantly between products.

A best practice to help ensure the adhesive anchor system meets ACI 318-14 Section 17.8.2.1 requirements is the inclusion of basis-of-design parameters in your design and specified in the general notes. Examples include:

- Cracked concrete
- Water-saturated concrete
- Base material temperature at the time of installation of 23°F to 104°F
- Allowable drilling methods to include hammer-drill, hollow drill bit, and diamond core drill

By including basis-of-design expectations of the final installed product, engineers can help ensure reliable performance in realistic job site conditions.▪

The online version of this article contains references. Please visit **www.STRUCTUREmag.org**.

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