

ADHESIVE ANCHORS— REQUIREMENTS FOR THEIR RELIABLE USE IN CONCRETE CONSTRUCTION

by Rolf Eligehausen and Werner Fuchs

Synopsis: In the last 10 years there have been tremendous developments made in the strength of the adhesives and the fields of applications of adhesive anchor systems. Hence these systems are used for structural attachments in a wide variety of applications in concrete construction.

Suitable products, careful selection and design, and proper installation are vital for the overall performance of a structural connection. While suitable products prequalified under provisions such as AC308 and ACI 355.4-10, and produced under strict quality control are or will be on the market – demonstrated by an Evaluation Service Report - and rational design models have been developed to ensure a reliable use of adhesive anchor systems in daily construction practice, the knowledge of the designers and installers in fastening technology is often not adequate. The knowledge of the designers should be updated regularly. Adhesive anchors should be installed by properly trained installers. However, the training of the installers needs to be improved significantly. The proper training should be demonstrated by a certificate that is issued by an independent agency after passing a corresponding test. The new ACI Anchor Installer Certification program that is currently under progress will fulfill this requirement.

Keywords: Adhesive Anchors, reliability, prequalification, selection, design, installation, use

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INTRODUCTION

A wide variety of advanced and innovative adhesive anchor systems have been invented, developed, produced and used in the construction industry over the years to achieve more flexibility in the planning, design and strengthening of concrete structures. The understanding of the behavior of these anchoring systems, the range of the fields of applications, the design methods and installation procedures have made significant advances in the past years. However, although a large number of adhesive anchors are installed every day, understanding in the engineering community about their working principles and design in some cases appears to be limited. Furthermore the installers are confronted with a bewildering multitude of anchoring systems with different installation procedures, they have to consider for proper installation.

The I-90 connector tunnel accident in 2006 in Boston and the subsequent investigations raised the awareness to the lack of knowledge of the users with regard to adhesive anchors, their sensitivity to wrong installation and their long term functioning in service. To ensure the structural reliability of adhesive anchors the prequalification procedure AC308 (ICC-ES (2011)), which superseded AC 58 (ICBO-ES (2001)) was accepted in 2005. It addresses the above mentioned concerns. Recently the new ACI 355.4-10 (ACI (2010)) was published. Both procedures require reliability tests to check the behavior under sustained and variable loads, and under normal and adverse conditions both during installation and service.

This paper gives a brief overview on the parameters which influence the reliability of adhesive anchors and how they are covered by the actual codes and in practice to ensure reliable fastenings with adhesive anchors.

GENERAL

The fastening technique industry as one of the most innovative sectors in the construction industry developed a great number of adhesive anchors in the last years with the objective to make the design of fastenings and the strengthening of structures more flexible. Research results yielded a better understanding of the load carrying-behavior of adhesive anchors and their possible use in different kind of applications. Building codes and guidelines, design concepts and installation procedures have made decisive progress during the last ten years. This means that the persons using adhesive anchors have to learn that the world of adhesive fastening consists of a rapidly changing environment of products, applications and regulations.

To facilitate this process for the user error-tolerant products based on user-centered design should be available and applied to increase the reliability of fastenings and to overcome the occurrence of unsafe installations. First steps in this direction are done with the product prequalification procedures ICC AC308, ACI 355.4-10, the design method of ACI 318-11 (ACI (2011)), which will be supported by adhesive anchor manufacturers' software, and the adhesive

anchor installer certification program which is developed on a fast track under the regime of ACI C601A. Furthermore the installation should be inspected by experienced personnel.

ADHESIVE ANCHORS

There is a multitude of adhesive anchoring systems on the market to address a large variety in structural and non-structural applications. In general adhesive anchoring systems provide the designer with a wide range of anchor element types and possible embedment depths to fit specific applications. In addition they differ in the type of resins such as epoxies, vinylesters and hybrid systems consisting of organic and inorganic bonding agents. All resins are cross-linked with a special curing agent. The resins and curing agents are modified in certain ways to achieve special characteristics for an intended use of the adhesive anchor.

Capsule anchors (Fig. 1a) consist of a cylindrical glass or a foil capsule containing a polymer resin, a hardener (catalyst) and mineral aggregate. The capsule or foil is inserted in a drilled hole; deeper embedments are typically achieved by stacking multiple capsules in the hole. Setting of the anchor is accomplished by direct boring through the capsule with a threaded anchor rod (usually equipped with a chiseled end) chucked directly into a rotary drill and hereby mixing the contents of the capsule with the fractured fragments of the capsule to form a relatively fast-setting polymer/glass matrix.

In injection anchor systems (Fig. 1b), plastic or foil cartridges containing pre-measured amounts of resin and hardener allow controlled mixing of polymer components. The components are typically mixed through a special mixing nozzle as they are dispensed, or are completely mixed within the cartridge immediately before injection. Typically, after proper borehole cleaning the catalyzed resin is injected into the hole first and the anchor rod (threaded rod or deformed bar) is pushed into the hole and rotated slightly to promote complete contact between rod and adhesive.

Bulk adhesives are two-component adhesives supplied in industrial quantities in either barrels or one-to five-gallon cans. The correct metering and mixing of the adhesive components is critical for the performance of bonded anchors. Therefore only systems that are delivered with a bulk dispensing machinery whereby metering and mixing of the components are automatically controlled during dispensing through a metering manifold and disposable mixing nozzle are covered by ACI 355.4 and AC308. However, ongoing monitoring is required to check the equipment is operating within tolerances in accordance with the Manufacturer's Printed Installation Instructions (MPII), particularly with respect to mix ratios, leak tightness, and dwell time. Bulk systems which are mixed manually with paddle mixers in buckets while appropriate for some applications, are not considered to provide controlled metering of adhesive components and are therefore not covered by ACI 355.4-10 and AC308.

Epoxy systems of different manufacturers are not equal. The same is valid for vinylester and hybrid systems. They differ in the storage requirements, the installation temperatures, the installation procedure, the sensitivity to water, temperature and chemicals in installation and service, the sensitivity to the borehole cleaning and characteristics and finally in the holding capacity.

Adhesive anchor manufacturers typically publish detailed, product-specific installation instructions critical to the proper performance of the installed anchor. However, in practice these instructions are very often not followed since the installers are not aware of the consequences of wrong installation, see Grosser et al. (2011).

While with mechanical anchors the correct installation can very often be checked by simple means, this is not possible for adhesive anchors. On site it can be only checked if there is enough mortar in the borehole after installation. Other simple checks are not possible. A problem on site is always borehole cleaning since a lot of dust sprays around if the borehole is brushed and blown out. The installers therefore very often may avoid this procedure which on the other hand is vital to ensure the capacity of the anchor. Not cleaning the borehole is defined as a gross error in prequalification procedures. It can only be detected on site by proof loading which is highly recommended by the authors. Other effects which can occur during normal on site practice are covered in the actual prequalification procedures of ICC AC308 and ACI 355.4-10.

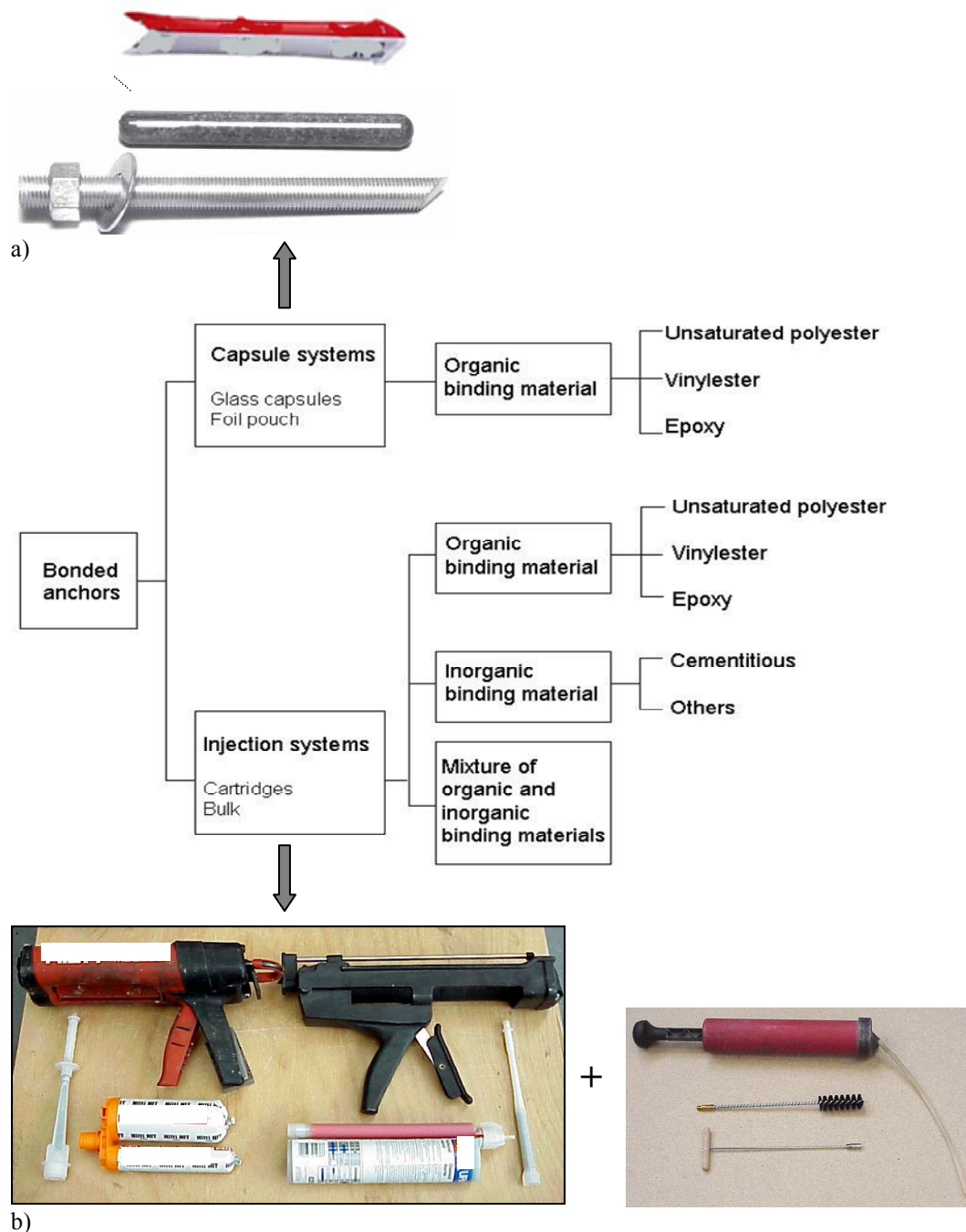


Figure 1 – Adhesive anchor systems – a) capsule systems, b) injection systems

REGULATIONS, PROVISIONS

The focus of regulations and provisions is to enhance safety and performance. Therefore actual adhesive anchor prequalification procedures require for all safety related applications quality control in production. Anchors shall be manufactured under an approved quality-assurance program with follow-up inspections by an accredited inspection agency. This ensures that only adhesives, anchor elements and installation tools with a high level of quality are sold and used in safety related applications.

To provide the necessary product characteristic data for the design the prequalification procedures establish test procedures as well as methods of assessing and judging the results of tests. The testing and evaluation agencies must be independent and preferably accredited by a recognized accreditation service conforming to the requirements of ISO 17025. Furthermore documented experience in the testing and evaluation of anchors is necessary, if tests shall be performed for evaluations during an approval process. This ensures that the tests are performed by competent staff and the results are reproducible at other laboratories.

In order to assure that the regulations are as technically sound as possible the European and US working groups in charge for drafting provisions practice co-operations with testing laboratories, technical experts and manufacturers. This cooperation caused that in the USA in principle the same test and design methods are used as in Europe.

The prequalification procedures shall ensure that the adhesive anchor is capable of safe, effective behavior under normal and adverse conditions and shall determine the basic data to predict its performance under service-conditions. Reliability tests are intended to assess the sensitivity of the tested adhesive anchor system to variations in installation and service condition parameters which are likely to be experienced in practice. These include tests to evaluate the sensitivity to deviations in the hole cleaning as required by the manufacturer's written product installation instruction (MPII) in dry concrete, in water saturated concrete (AC308: optional, ACI 355.4-10: mandatory), in a water-filled hole (optional), in submerged concrete (optional), sensitivity to mixing effort, sensitivity to freeze/thaw conditions (AC308: optional, ACI 355.4-10: mandatory), sensitivity to sustained load, sensitivity to installation direction (AC308: optional, ACI 355.4-10: mandatory) and sensitivity to torque. Furthermore for adhesive anchors intended for use in cracked concrete the behavior of the anchors in wide cracks is investigated as well as in cracks with varying width as they might occur due to varying loads on the structure. The test program to evaluate the allowable condition of use includes the determination of the adhesive anchor capacity in low and high strength cracked and uncracked concrete (optional), of the capacity at elevated temperatures, of the capacity influenced by decreased installation temperature (optional), of the influence of curing time, the check of the resistance to alkalinity and sulfur (optional), minimum spacing, edge distance and member thickness to preclude splitting of the concrete component and to develop full capacity.

However, it shall be pointed out that these tests are not intended to address installation errors which are characterized by significant deviations from the MPII or design specifications such as deviations from the specified embedment depth, use of a nominal diameter drill bit other than that specified, incorrect assembly or operation of the adhesive mixing and dispensing equipment, use of the product in base materials other than structural concrete, use of the product in concrete exhibiting compressive strength outside of the specified range, use of the product in base materials having a temperature outside of the specified range for the product, violation of specified gel and cure times and violation of storage and shelf life restrictions for the adhesive.

The prequalification criteria given in ICC AC308 and ACI 355.4-10 provide criteria for establishing the characteristic bond strength of adhesive anchors, reductions for adverse conditions as well as the anchor category and associated jobsite quality requirements such as periodic or continuous inspection of the installation process. With this information the design methods given in ICC AC308 and ACI 318-11 can be used to design safe anchorages with adhesive anchors.

Figure 2 shows the possible options of evaluation reports for chemical anchors according to AC308. Compared to AC308 and better taking into account the given situation on site the options given in ACI 355.4-10 are reduced since tests in water-saturated concrete, under freeze/thaw conditions and different installation directions are mandatory in ACI 355.4-10. However, there still exist a variety of testing options to provide technical data for the best product performance in a clearly defined field of application. The resulting Evaluation Service Reports (ESRs) may rather be very confusing for designers and installers since it makes it very difficult to find the right product for an application without exact knowledge of the environment and the condition of the base material during installation and over the lifetime. It is necessary to exactly compare the requirements resulting from design for service life and installation with the field of application documented in the ESRs of products from different manufacturers.

ICC-ES is actually in the process of reviewing AC308 with respect to ACI 355.4-10 for qualification requirements and criteria and with respect to ACI 318-11 Appendix D for design of adhesive anchors to eliminate any duplication of requirements for testing as well as evaluation and assessment of test results or conflicts in design provisions, and enabling designers to obtain ESRs for adhesive anchors that comply with the 2012 IBC.

SELECTION, DESIGN AND INSTALLATION

To ensure a professional use of adhesive anchors on the construction site by designers and installers more and more special knowledge on the nature of adhesive anchors, their design and installation is required. However, not all users do have this knowledge. Therefore for some users the variety of adhesive anchor products and the corresponding evaluation reports are hardly manageable. This leads in part to confusion and a feeling of uncertainty of the customers, and creates the possibility of an erroneous selection, design and installation of adhesive anchor systems.

For the realization of the optimum use of innovative adhesive anchor systems the following question should be answered by the case: Which kind of adhesive anchor system is most appropriate for my application and how do I use it to achieve its maximum effect?

This work is the domain of the licensed design professional since he will select and design the correct product according to the relevant environmental and structural conditions. Geometric parameters such as edge distances, spacing, member depth and loading direction as well as reinforcement and environmental conditions such as humidity, freeze/thaw conditions and durability play a role in the choice of the adhesive anchor system. To facilitate this task anchor design software packages from several anchor manufacturers are available to the designer, which address actual regulations for their product lines. Note that the results of these calculations cannot be transferred to products from other manufacturers. Furthermore it allows the specifying designers to use new design procedures, which may yield higher capacities without having in depth knowledge of the new procedures. Therefore as a matter of good practice the designer should have a clear understanding of the design basis used for the software before use.

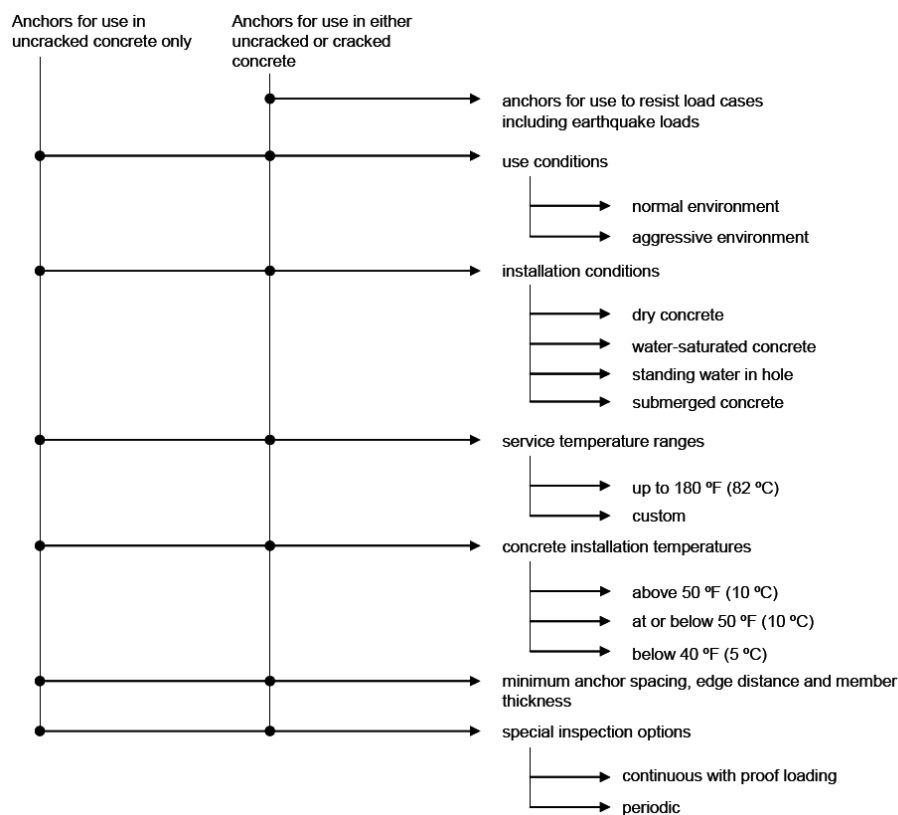


Figure 2 - Options according to ICC AC308 for chemical anchors

To ensure the reliable function of adhesive anchor systems only products with an Evaluation Service Report shall be used. The best anchor selection, the best design method and the most careful design by engineer, however, are of no use if the adhesive anchor system specified by the designer is not installed properly. Therefore the design procedures require periodic or special inspection on site. Based on the findings on site by Grosser et al. (2011) however, it is highly recommended that the designer checks if periodic or continuous inspection are properly performed by experienced personnel and that the adhesive anchors are installed by trained installers. Otherwise gross errors which are not covered by the prequalification procedure might occur and the load bearing capacity might be significantly less than calculated.

It is without saying that adhesive anchors which are supposed to transfer high loads and used in safety-related applications must be planned, designed and installed by experienced and trained personnel. Reliable connections, based on reliable products and computational calculations can only be achieved through the cooperation of designer and installer.

In order to improve the general knowledge and ensure actual information on regulations of designers and installers in adhesive fastening technology, seminars with different focus were developed.

Seminars for designers

The education of engineers and designers should start at the university. However, at the most universities the discipline of fastening technology is underestimated and very often neglected. The course of studies should envision classes in fastening technology.

For engineers and designers in midst the professional life fastening technology seminars are offered by ACI, manufactures of anchoring systems and other organizations. There the actual design regulations and fastening products, their fields of application, their selection and in some cases the design with a product specific software are presented and explained in detail. Sometimes the focus of seminars is only on fields where an urgent update is required.

The fastening technology is a very innovative discipline. This is especially valid in the case of adhesive anchors. Design procedures and evaluation service reports are under continuous improvement not just for new but also for existing products. Therefore it is required that designers continuously update their knowledge in fastening technology. Current information can be found e.g. on the home pages of the manufacturers of the adhesive anchor systems.

Seminars for installers

The correct installation of an adhesive anchor is the basic requirement for a safe fastening. An example is the anchorage of the I-90 connector tunnel ceilings in Boston where insufficient anchor installation might have contributed to the failure of the adhesive anchors. Special inspections procedures might also not be effective, since due to lack of actual knowledge they might be ill-defined in many applications or they are even nonexistent. However, up to now there is no legal obligation to demonstrate the competence of anchor installers. It is, however, undisputed that qualified installers are needed to guarantee the safe and economical installation of anchors.

All larger manufacturers of adhesive anchors offer installation training programs. However, these programs are product specific and not based on a common and agreed curriculum. This means, if a certain application requires a product from a different manufacturer the installer has to perform an additional product specific training program. This procedure is cost and time consuming and therefore normally not performed in practice. The participation in such a training program is very often verified by a certificate. However, usually this certificate is provided to the installer after the training without that a practical test or written examination verifying the competence in anchor installation has been performed and passed. Due to the fast change and the high innovation potential in the fastening technology trainings with an examination should be required and revitalization training with an examination should be completed after a certain period, e.g. three to four years.

To close the gap of general adhesive anchor installer training programs a generic certification program under the auspices of ACI is under creation by ACI C601A on a fast track, which will be nationally accredited. This installation certification program is urgently needed and viewed as a mechanism to strengthen the confidence in the reliable use of adhesive anchors. The first trainings are expected in the second half of 2011.

Summary and conclusions

Suitable products, careful design and proper installation are vital for the overall performance of a structural connection. Adhesive anchor systems are increasingly used in a large variety of applications in the construction industry. New and innovative anchoring systems have been developed, new fields of application were made accessible, corresponding testing and evaluation methods were created and reliable design methods have been incorporated in design guides.

While suitable prequalified products produced under strict quality control are on the market – demonstrated by an Evaluation Service Report - and rational design models have been developed, the knowledge of the designers and installers in fastening technology is often not adequate. The knowledge of the designers should be updated regularly. Adhesive anchors should be installed by trained installers. However, the training of the installers needs to be improved significantly. The proper training should be demonstrated by a certificate that is issued by an independent agency after passing a corresponding test. The new ACI Anchor Installer Certification program that is currently under progress will fulfill this requirement.

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DESIGN AND QUALIFICATION PROVISIONS FOR ADHESIVE ANCHORS IN CONCRETE

by John F. Silva

Synopsis: The design provisions for anchoring to concrete in ACI 318-08 Appendix D (ACI Committee 318 2008) specifically exclude adhesive anchors while noting that "Adhesive anchors are widely used and can perform adequately. At this time, however, such anchors are outside the scope of this appendix." Development of suitable design provisions for adhesive anchors requires that

1. The provisions be structured to fit the design paradigm currently being used in ACI 318-08 Appendix D (ACI Committee 318 2008); and
2. A suitable companion standard to ACI 355.2 (ACI Committee 355 2007) be developed for the testing and assessment of adhesive anchor systems to be used in conjunction with the new provisions.

The design model is substantially based on the work of Eligehausen, Cook, and Appl (Eligehausen et al. 2006). It incorporates a new failure mode (bond) that must be included along with the other tension failure modes in establishing the controlling strength. The bond failure model, which incorporates a unique approach to group and edge effects reflective of numerous experimental and numerical investigations, is nevertheless predicated on a simple uniform bond stress approach. Of equal importance is the implementation of a host of new suitability tests for adhesive anchor systems as well as a particular emphasis on long-term strength and job-site quality control. In this context, the provisions for inclusion of adhesive anchors in ACI 318-11 (ACI Committee 318 2011) are reviewed together with the approach taken to testing and qualification under the new ACI standard ACI 355.4-11 (ACI Committee 355 2011).

Keywords: adhesive, anchor, design, qualification

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BACKGROUND

ACI introduced design provisions for the design of anchors in concrete in ACI 318-02 Appendix D (ACI Committee 318 2002). Those provisions, a mandatory part of the code, are limited to cast-in anchors, expansion anchors and undercut anchors. A significant effort is underway in the current code cycle to address the qualification and design of bonded, or adhesive, anchors. This effort, which was initiated in the previous cycle, took on added urgency with the partial collapse of a concrete panel ceiling hung with adhesive anchors in a portion of Boston's Big Dig tunnel system in 2006 (Boston Globe 2006). That failure, which resulted in a fatality and required closure of the affected tunnels for an extended period, was ultimately associated in the subsequent National Transportation Safety Board investigation (NTSB 2007) with a lack of understanding by the professional design community of the issues associated with adhesive anchor performance, particularly with respect to the behavior under sustained load, as well as an absence of guidance in the code on the proper qualification, design, and use of adhesive anchors. A specific recommendation is contained in the NTSB's findings as follows (NTSB 2007):

To the American Concrete Institute:

Use your building codes, forums, educational materials, and publications to inform design and construction agencies of the potential for gradual deformation (creep) in anchor adhesives and to make them aware of the possible risks associated with using adhesive anchors in concrete under sustained tensile-load applications.

The proposed provisions include specific requirements to address the qualification and design of adhesive anchors to resist sustained loads as well as enhanced quality control measures for overhead and horizontal installation orientations.

QUALIFICATION PROVISIONS

ICC-ES Acceptance Criteria AC308

In the absence of a code-based approach to the qualification and strength design of adhesive anchors, an acceptance criteria was developed in 2004-2005 by the Concrete Anchor Manufacturers' Association (CAMA) for the ICC Evaluation Service (ICC-ES), a subsidiary of the International Code Council responsible for issuing evaluation reports to establish code compliance under Section 104.11 of the International Building Code (IBC 2006). This acceptance criteria, designated by ICC-ES as AC308 (ICC-ES 2006), represented a substantial departure from previous approaches to adhesive anchor qualification and design in that it implemented for the first time specific procedures for the establishment of characteristic bond stresses (as opposed to allowable loads) for tension loading that could be used in conjunction with a recently developed uniform bond model (Eligehausen et al. 2006). Testing under AC308 (ICC-ES 2006) consists of establishing reference bond stress values and comparing these to bond stresses derived from tests to check the sensitivity of the adhesive anchor system to a variety of plausible adverse conditions, such as saturated concrete, poorly cleaned holes, etc. The structure of AC308 (ICC-ES 2006) mimics the system established under the ACI standard for the qualification of post-installed mechanical anchors, ACI 355.2 (ACI Committee 355 2007); that is, the tests are divided into three categories (reference tests, reliability tests, and service-condition tests) associated with their purpose in establishing design parameters. This approach was adopted for the development of the ACI standard ACI 355.4-11 (ACI Committee 355 2011) to address adhesive anchor testing and qualification which is in substantial agreement with AC308 (ICC-ES 2006).

ACI qualification standard ACI 355.4-11

Scope – The standard addresses the adhesive anchor systems commonly found in use. These include cartridge systems, capsule systems, and systems used with bulk mixing and dispensing equipment. The range of embedment depths covered by the standard (4 to 20 anchor diameters) is limited by assumptions regarding the applicability of the design model as well as practical considerations related to testing. The standard also makes an important distinction between the qualification of adhesive anchor systems for designs where anchor theory is used, typically

involving threaded rod as the anchoring element, and those where reinforcing bars are installed with the adhesive and are designed in accordance with rules for development and splicing of reinforcement. This distinction is based on the following considerations:

1. The rules for development and splicing of reinforcing bars are predicated on splitting failure modes. The splitting failure mode is not explicitly addressed in the design provisions of ACI 318-08 Appendix D (ACI Committee 318 2008); instead, limitations on edge distance and member thickness are provided to preclude failures.
2. The embedment lengths are typically in excess of those associated with anchoring applications (i.e., greater than 20 diameters) and are therefore beyond the scope of the installation reliability tests in the standard.
3. The use of adhesive anchor systems for applications where splitting will control their behavior (development and splicing) is predicated on the ability of the adhesive bond to mimic the behavior of cast in place reinforcing bars with respect to bond stress distribution over the length of the bar. The standard does not address this behavior.
4. Bond stresses established from the assessment of adhesive anchors for use in uncracked and cracked concrete are not relevant to the development and splicing of reinforcing bars.

The application of adhesive anchor systems for installing reinforcing bars that are designed in accordance with provisions for development and splicing are not within the scope of the standard. The installation of reinforcing bars (dowels) that are designed using the design provisions for anchors, i.e., associated with concrete breakout and bond failure modes, are included.

A further distinction is made between adhesive anchors and grouted anchors. Grouted anchors are bolts, usually headed, installed in holes drilled vertically downward and filled with cementitious grout. The hole diameter is not less than 1.5 times the anchor diameter and the resulting thickness of the grout layer surrounding the bolt means that the bond between the grout and the concrete and between the grout and the anchor element are both relevant for determining the failure mode and tension strength (Zamora et al. 2003). Adhesive anchors, with their thin bond lines (typically 1/16 to 1/8-inch, 1.5 to 3 mm), do not exhibit this behavior. Grouted anchors are not currently included in the scope of the standard nor are they included in draft design provisions.

Organization of tests – With few exceptions, the required tests in the standard are oriented to the determination of the characteristic bond stress to be used in the design of adhesive anchors to resist tension loads. With the exception of seismic loading and the steel strength of the anchor element, shear capacity of adhesive anchors is assumed to be adequately predicted by the expressions in ACI 318-08 D.6 (ACI Committee 318 2008).

In parallel with ACI 355.2 (ACI Committee 355 2007), the standard organizes tests into four categories:

1. Identification tests to ensure product conformity with the assessed samples;
2. Reference tests which serve as the basis for the assessment of reliability test results;
3. Reliability tests, which form the basis for the anchor category as well as the reduction factors associated with less than ideal conditions associated with installation; and
4. Service condition tests which provide the basic bond stress and shear strength values as well as seismic design parameters.

In addition, a series of round-robin tension tests are included to reduce the potential for results influenced by local concrete properties, either negatively or positively. These and other critical tests included in the standard are described further below.

As with ACI 355.2 (ACI Committee 355 2007), test programs in the standard for adhesive anchor systems are fundamentally organized around assessment of systems to be used in uncracked concrete only and for those that are to be used in both cracked and uncracked concrete applications (including seismic). A further option, not included in AC308 (ICC-ES 2006) but added to the standard to reduce the test burden for manufacturers, involves a reduced test program that is associated with default bond stress values in cracked concrete.

Identification tests – Chemical and mechanical tests for identification of the adhesive are established specifically for the system being assessed. Examples include infrared absorption spectroscopy, specific gravity, and viscosity. Since not all adhesive systems are suitable for the same battery of identification tests, the determination of the appropriate tests (minimum of three test types) is delegated to the testing and assessment authority.

Reference tests – Reference tests are typically conducted as confined tension tests, that is, they are conducted in such a manner as to constrain all failure modes except bond failure. This requires establishment of an embedment depth and anchor element (threaded rod) strength suitable for the bond strength associated with the system being tested. In order to minimize scatter and avoid unintended influences on the assessment, reference test series are conducted in concrete originating from the same concrete delivery (batch) used for the reliability or service-condition tests to which they are compared.

Reliability tests – The reliability tests in the standard are of two types: those relevant for the determination of the anchor category (installation safety tests) and those used to determine reductions on the permissible bond stress for design. ACI 355.2 (ACI Committee 255 2007) introduced the concept of installation safety testing of anchors. Such tests are intended to determine the sensitivity of the anchor system to plausible variations from the specified installation requirements. They are not intended to address intentional or gross variations from defined installation parameters, which in the case of adhesive anchors include deviation from the prescribed embedment depth, incorrect assembly or use of the adhesive mixing and delivery equipment, and violation of the prescribed gel and cure times. In the standard, tests pertaining to installation focus on the sensitivity of the system to hole cleaning by requiring that tests be performed with anchors installed in holes that are purposely and in a controlled way cleaned to a lesser degree than is anticipated by the installation procedures specified by the manufacturer. These tests are conducted in dry concrete and repeated in concrete that has been exposed to water over a sufficient period as to attain a “saturated” condition. In a significant departure from AC308 (ICC-ES 2006) in the standard, tests in saturated concrete are mandatory for all products to be assessed. Saturated concrete poses a special challenge to adhesive anchor systems. Drilling with a carbide bit in saturated concrete typically produces a paste which adheres to the wall of the hole. This paste does not respond to cleaning techniques appropriate for dry conditions. Furthermore, the presence of water in the pore structure of the concrete hinders infiltration of the adhesive into the interstitial spaces of the concrete, reducing bond strength. In AC308 (ICC-ES 2006), installation sensitivity tests in saturated concrete are optional on the assumption that some products may be limited to service in dry conditions. The standard does not permit this assumption.

The results of the installation safety tests are compared with reference values to establish the anchor category, which in turn defines the partial safety factor to be used in design. This procedure parallels that established for post-installed mechanical anchors under ACI 355.2 (ACI Committee 355 2007).

Reliability tests used to establish reductions (as applicable) on the permissible bond stress include sensitivity to absolute crack width and to crack movement over time (for those systems to be assessed for use in cracked concrete), freezing and thawing, sustained loading, and installation orientation (horizontal, overhead). Sustained loading and installation orientation tests are discussed in greater detail below.

Service-conditions tests – Service condition tests constitute the main body of the test program. They include unconfined testing to establish base bond strength values, tension tests at elevated concrete temperature, tension tests at decreased installation temperature, tests to confirm curing time, resistance to chemical exposure, as well as tests to confirm adherence with the assumptions of the design model (corner and member thickness tests) and simulated seismic tests in tension and shear. Aside from the basic unconfined tests to establish the basic bond strength, tension tests at the maximum permissible short duration elevated concrete temperature, coupled with sustained load tests at the maximum long-term elevated concrete temperature, are often the most decisive for the bond stress to be used in design. Those tests relevant for long-term performance are discussed in greater detail below.

Critical tests for long-term performance and sustained tension loading

As stated at the outset of this discussion, a significant impetus for the advancement of qualification and design provisions in ACI relates to the finding by the NTSB in the wake of the ceiling collapse in the Big Dig tunnel system that insufficient knowledge and guidance exists within the design community on the subject of adhesive anchor performance under long-term loading and specifically creep behavior (NTSB 2007). The standard includes several tests that are specifically relevant for the assessment of long-term performance. These are:

1. Sustained load tests;
2. Tests for in-service behavior at elevated concrete temperatures;
3. Tests for freezing/thawing conditions; and
4. Tests for resistance to alkalinity and sulfur.

In addition, tests for installation at decreased concrete temperatures also include assessment for potential effects on long-term performance.

Sustained load tests – The term ‘sustained load test’ is used here to refer to confined tension tests whereby the tension load is held constant for a period of time. Such tests are often referred to as ‘creep tests’ in the literature (ASTM E1512 2007), a reference to the assumed mode by which anchor axial displacements increase over time in response to varying levels of axial tension load. Creep is classically understood as “the slow continuous deformation of a material under constant stress.” (Findley et al. 1976). In that adhesive anchors generally employ a variety of load-transfer mechanisms (adhesion, micro-interlock, friction) that are more or less effective at various levels of bond stress, and recognizing that the behavior of highly cross-linked polymers in the anchor application (i.e., thin bond line subjected to shear stress, laterally confined) may not conform to the definition of creep as stated above, it is far from clear whether creep mechanisms alone are responsible for measured displacements. This subject has been

explored at some length since the Boston collapse (Cook et al. 2009) and new methods of assessing the response of adhesive anchors to sustained loading in the form of a stress vs. time-to-failure relationship are under development (ASTM/AASHTO 2010). Pending the conclusion of these studies, the standard relies on a less direct but conservative approach to the assessment for sustained tension loading. This can be described as follows:

1. Subject the anchor to a sustained tension load in a confined state, established as a percentage of the mean ultimate bond stress as measured in static unconfined tension tests. The percentage of load is intended to reflect the maximum in-service bond stress that the anchor would experience in a conforming design.
2. Maintain the tension load constant and measure the anchor displacement for a period of not less than 40 days (approximately 1000 hours). Subsequently increase the tension load to cause failure of the anchor and measure the peak load.
3. Using the last 20 data points recorded from the test and the Findley model (Findley et al. 1976), extrapolate the measured displacements to a time corresponding to the service life of the anchor.
4. Compare the extrapolated displacement to a conservative estimate of the displacement corresponding to anchor failure as derived from static tension tests.
5. Compare the residual strength of the anchor to the reference value (confined to confined).

Both the extrapolated displacement and the residual tension strength of the anchor are relevant for the assessment. If either condition (displacement less than failure displacement, residual strength equal to reference value) is not met, the test is repeated with a reduced sustained load such that the acceptance criteria are fulfilled. This reduced tension load, taken as a percentage of the nominal sustained load established for the test (see item 1. above) is used to down rate the permissible design bond stress for the anchor.

This procedure, coupled with a supplementary check for sustained tension loads in the design process, appears to produce results that are conservative relative to the more straightforward stress vs. time-to-failure method currently being developed (ASTM/AASHTO 2010). In the standard, sustained load tests are conducted at room temperature (70 °F [21 °C]) and at 110 °F (43 °C). The displacements measured at room temperature are extrapolated to 50 years, while those measured in tests conducted at 110 °F are extrapolated to 10 years on the assumption that elevated concrete temperatures as resulting from sun exposure will occur over not more than 1/5 of the anchor service life.

Tests for in-service behavior at elevated concrete temperatures – The standard establishes two temperature categories for assessment of elevated temperature performance, at the option of the manufacturer. Temperature category A requires assessment of the anchor for 110 °F (43 °C) and 176 °F (80 °C) whereby the second, higher temperature is assumed to represent a short-term condition. Temperature category B permits establishment of anchor behavior at 110 °F (43 °C) and a series of short-term elevated concrete temperatures to be selected as greater than or equal to 130 °F (54 °C). All tests are conducted as static tension tests to failure. The measured failure loads are compared to the relevant reference values to establish reduction factors on the design bond stress for both the long- and short-term temperature cases.

Tests for freezing-thawing conditions – Tests for freezing-thawing resistance are conducted in an environmental chamber with 50 freezing and thawing cycles, i.e., the chamber temperature is cycled between 68 °F and -4 °F (20 °C and -20 °C) with continuous measurement of displacement using the static load determined in a manner similar to that used for the sustained load tests. Throughout the test the anchor is subjected to a minimum 1/2-inch (12 mm) layer of water covering the concrete surface. Successful completion of the freezing and thawing cycles is followed by a tension test to establish the residual tension strength. The rate of displacement measured in the test should decline with increasing cycle count, trending towards zero, and the residual strength is compared with reference values. Where these criteria are not met, the test is repeated with a reduced sustained load and a reduction factor on the design bond strength is established. Freezing and thawing tests are optional under AC308 (ICC-ES 2006), but mandatory under the standard.

Tests for resistance to alkalinity and sulfur exposure – These tests are conducted on specimens prepared by sawing cross-wise a concrete cylinder containing an installed anchor to produce cylindrical slices each approximately 1-3/16 inches (30 mm) thick. Resistance to alkalinity and water exposure is measured by subjecting the slice to a water bath with a pH level of 13.2 produced by the addition of potassium hydroxide. Resistance to sulfur is assessed with the slices via Kesternich Test (ISO 1994) but with a sulfur dioxide concentration at the outset of the test of 0.67% and a minimum of 80 cycles. The slices are subsequently tested with a punch to measure the residual bond strength as compared to reference values on unexposed slices to establish reduction factors on the bond strength for each condition.

Tests to measure behavior following installation in cold concrete – The injection of adhesive into concrete at a temperature well below room temperature (73 °F [23 °C]) may result in retardation of the curing process. In addition, this delay or truncation of the curing process may negatively impact the sustained load behavior of the

anchor, particularly as the temperature of the concrete increases e.g., due to sun exposure. Tension tests at the minimum specified installation temperature of the concrete are conducted on anchors intended to be installed in concrete having a temperature below 50 °F (10 °C). Additional tests, involving the slow increase of the concrete temperature with the anchor under sustained tension loading, are conducted on all anchor systems intended for installation in concrete having a temperature below 40 °F (5 °C). These tests also involve the measurement of displacement and testing to failure at the end of the test period. Criteria include an assessment for stabilizing displacement and comparison to reference tension values.

Tests for sensitivity to installation orientation

A critical aspect of the testing program embodied by the standard and by AC308 (ICC-ES [2006]) relates to requirements for fealty between the instructions used to install adhesive anchors in the laboratory and those used on the jobsite. Proper installation of adhesive anchors requires attention to several parameters including hole drilling methodology, hole cleaning procedures, environmental conditions at the time of installation, correct adhesive mixing and injection, and attention to gel and cure times. While in practice several sources of information, such as training videos and hands-on instructions, may be used to supplement the installation instructions that accompany the product, for the purposes of the assessment the instructions provided in the product packaging for the adhesive anchor system in question are assumed to be the only source of information for the anchor installation. Furthermore, these instructions are assumed to represent the authoritative information regarding installation procedures and limitations. This restriction has particular relevance for the installation orientation tests. These tests are mandatory for all systems that are to be deemed suitable for horizontal and overhead installation. Where such tests are not performed, the product labeling must carry a warning regarding product suitability for down-hole applications only (see Figure 2).

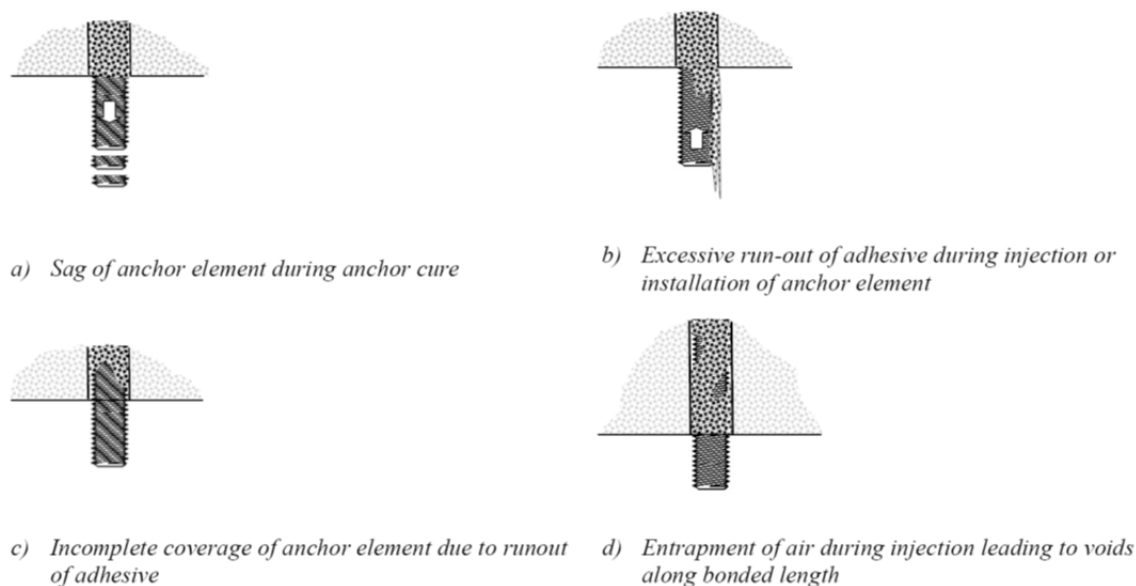
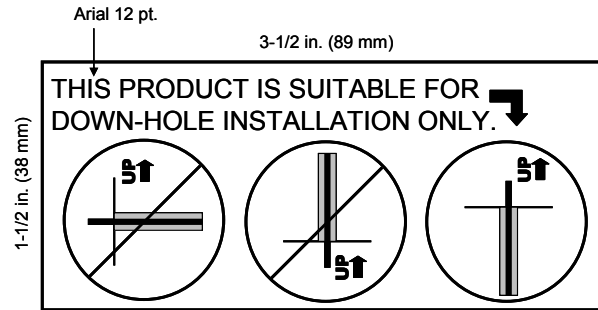


Figure 1 – ACI 355.4-11 (ACI Committee 355 2011) assessment criteria for overhead installation tests

Tests are performed separately for horizontal and overhead orientations with testing to failure for comparison with reference values. To further assess the effectiveness of the overhead installation procedures, however, a separate test is conducted whereby the injection procedure is conducted with an acrylic tube shielded from the view of the operator. These tests are judged subjectively using a list of criteria such as lack of air voids and prevention of adhesive run-out. Refer to Figure 1. Products that are either unsuitable for overhead and horizontal installation or that have not been tested for these installation directions in accordance with ACI 355.4-11 (ACI Committee 355 2011) will carry the label as shown in Figure 2.



Note: Label to appear on product as well as on packaging.

Figure 2 – Required labeling for products not tested for sensitivity to installation orientation

Assessment, reporting and quality control

Assessment for characteristic bond stress – A principal objective of the qualification program is the assignment of characteristic bond stresses for use with the design equations in ACI 318-11 Appendix D (ACI Committee 318 2011). They are developed from the results of the service condition tests in uncracked and (as applicable) cracked concrete as modified by those reliability tests not included in the assessment for the anchor category (installation safety tests) as well as the service condition tests where comparison is made to reference values. Characteristic bond stresses are generally established as a function of diameter and are typically inversely proportional to anchor diameter.

Reporting – The results of testing and assessment in accordance with the standard are reported in tables which identify all of the relevant parameters for design in accordance with Appendix D. Sample tables are provided in ACI 355.4-11 (ACI Committee 355 2011); however, the formatting and content of the tables will vary with the specifics of the qualified system.

Quality control measures – Specific measures are included in the standard to address concerns with regard to quality control. These include detailed instructions for special inspection and general information regarding the implementation of proof loading in the project specifications. Items to be verified as part of the inspection include:

1. Hole drilling method in accordance with the manufacturer's instructions;
2. Anchor edge distance and spacing;
3. Hole diameter and depth;
4. Hole cleaning in accordance with the manufacturer's instructions;
5. Anchor element type, material, diameter, and length;
6. Adhesive identification and expiration date; and
7. Adhesive installation in accordance with the manufacturer's instructions.

The intensity and frequency of inspection is dependent on the nature and criticality of the installation.

Proof loading – Proof loading as a quality control measure has two functions: 1) to detect significant deficiencies in the bond strength of the installed anchor; and 2) to motivate the installer/contractor to employ quality control measures as needed to avoid proof load failures. Proof loading programs are required to contain at a minimum the following elements:

1. Frequency of proof loading based on anchor type, diameter, and embedment;
2. Proof loads by anchor type, diameter, embedment, and location;
3. Acceptable displacements at proof load; and
4. Remedial action in the event of failure to achieve proof load or excessive displacement.

Proof loads should not exceed 50% of the expected peak load based on bond strength nor 80% of the anchor rod yield strength in order to avoid damage to otherwise correctly installed anchors. Displacement measurements are typically not required (i.e., acceptance can be verified visually) and the usual procedure in the event of proof load failure is to require increased frequency of testing until a sufficient confidence level in the installation is restored. The specifics of the proof load program must necessarily be determined by the engineer in responsible charge since requirements will vary significantly from job to job.

DESIGN PROVISIONS IN ACI 318-11

Design provisions for adhesive anchors have been introduced in ACI 318-11 Appendix D (ACI Committee 318 2011). These provisions are largely in conformance with the design approach included in AC308 (ICC-ES 2006), Section 3.0, but with differences as discussed in the following.

Uniform bond model

A prerequisite for the adhesive anchor design model is compatibility with the existing design paradigm in ACI 318-08 Appendix D (ACI Committee 318 2008); that is, an expression for the strength associated with the bond failure mode that accounts for group interaction, edge effects, and eccentricity in a manner similar to the expressions in Section D.5.2.1.

The uniform bond model proposed by Eligehausen, Cook and Appl (Eligehausen et al. 2006) provides the necessary additional expressions for assessment of the bond failure mode while maintaining consistency with the existing expressions for concrete failure modes. This model is implemented, with some modifications, in ACI 318-11 (ACI Committee 318 2011).

The uniform bond model calculates the bond strength in cracked concrete as shown in Eq. 1.

$$N_{ba} = \lambda_a \tau_{cr} \pi d_a h_{ef} \quad (\text{lb., N}) \quad \text{Eq. 1}$$

where

- N_{ba} = characteristic basic bond strength
- τ_{cr} = characteristic bond stress in cracked concrete (psi, MPa)
- d_a = anchor diameter (in., mm)
- h_{ef} = effective embedment depth (in., mm)
- λ_a = factor for lightweight concrete (see Table 1)

This expression, which has proven to best fit the existing test database, has the additional advantage of simplicity. Aside from the assumption of uniform bond stress, however, the key element in this model is an expression for the critical anchor spacing associated with full bond strength. In the concrete breakout model a constant of three times the anchor embedment is used to define the projected area terms A_{No} and A_N . The use of $3h_{ef}$ is predicated on the assumption that anchors spaced this far apart (or $1.5h_{ef}$ from any edge) will achieve their full concrete breakout strength in tension. The linear relationship between the critical spacing and anchor embedment is consistent with observations of concrete breakout failure surfaces and with the results of group tension tests and tension tests with edge influence. The bond failure model is likewise associated with a critical value that defines spacing and edge distance (characteristic value) for full bond strength (refer to Eq. 2). In contrast with the concrete breakout model, however, extensive experimental and numerical investigations have confirmed that the critical value for bond failure of adhesive anchors is not significantly dependent on the embedment depth. Instead, the critical spacing/edge distance for full bond strength is directly related to the bond area and the bond strength of the adhesive. In one sense, Eq. 2 implies that it is not the depth at which the load is introduced into the concrete, but rather the total potential tension load that the anchor is capable of delivering locally into the concrete that is decisive for the critical spacing and edge distance related to bond.

$$c_{Na} = 10d_a \sqrt{\frac{\tau_{uncr}}{1100}} \quad (\text{in.}) \quad \text{Eq. 2a}$$

$$c_{Na} = 10d_a \sqrt{\frac{\tau_{uncr}}{7.5}} \quad (\text{mm}) \quad \text{Eq. 2b}$$

where

- c_{Na} = critical edge distance (in., mm)
- d_a = anchor diameter (in., mm)
- τ_{uncr} = characteristic bond stress in uncracked concrete (psi, MPa)

This is borne out by numerical models that indicate the lateral extent of the stress field around tension-loaded adhesive anchors to be essentially responsive to bond strength and bond area (refer to Figure 3), as contrasted with headed anchor models that consistently show a dependence on embedment depth. The test record also clearly indicates that the limit on anchor strength as governed by concrete failure modes is the concrete breakout strength as predicted by Eq. (D-7) of ACI 318-08 Appendix D (ACI Committee 318 2008), confirming that the bond strength

model represents intermediate degrees of concrete strength mobilization up to and including the formation of a full-depth concrete breakout surface.

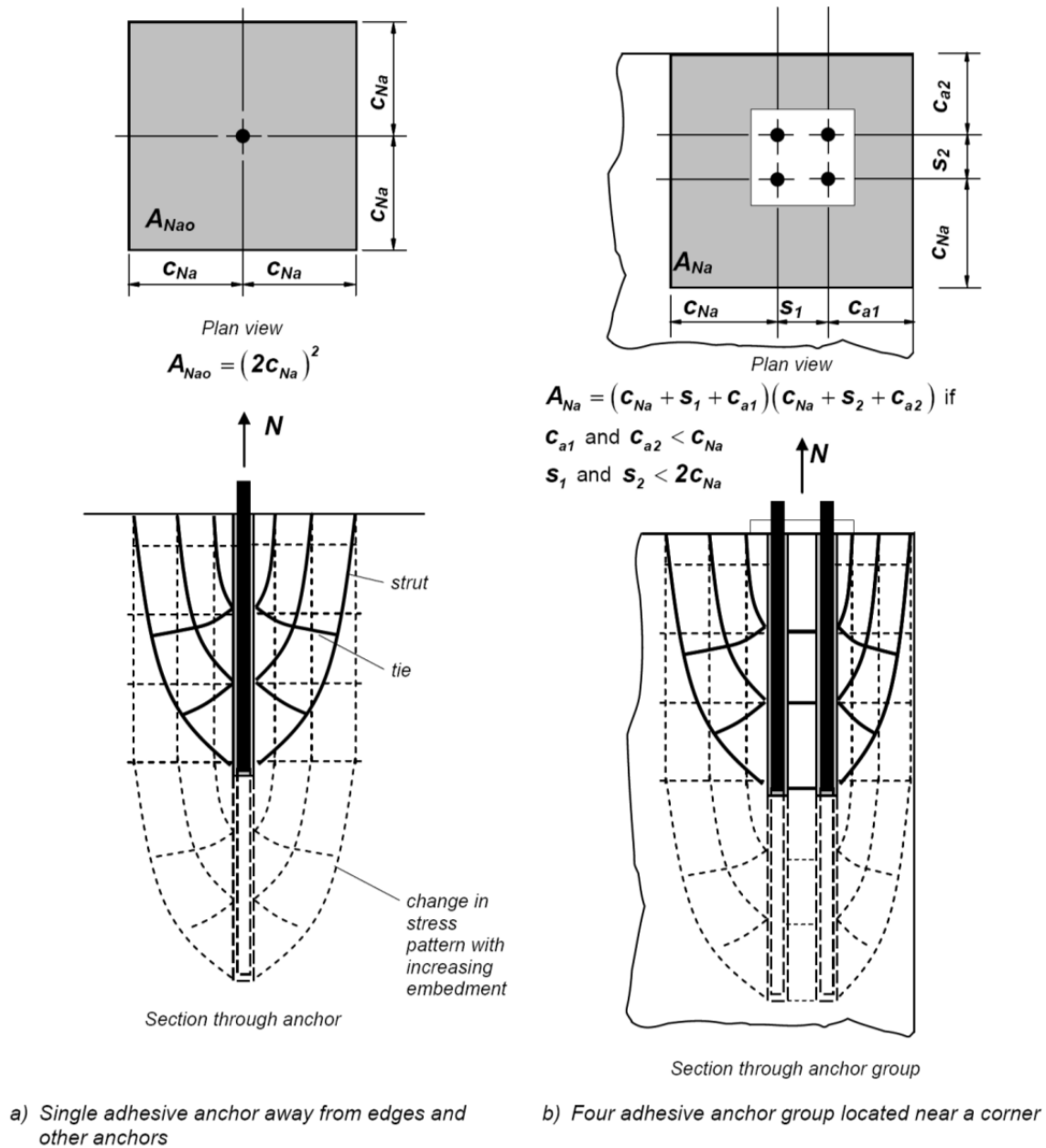


Figure 3 – Uniform bond model – calculation of influence areas

Changes from AC308

The bond model is implemented in ACI 318-11 (ACI Committee 318 2011) in much the same manner described in AC308 (ICC-ES 2006) with some important differences:

1. The group factor ($\psi_{g, No} \geq 1$) which accounts for the increased bond area associated with very closely spaced or bundled anchors is omitted for simplicity. This is conservative.
2. The factor on sustained bond strength given in AC308 (0.75) is reduced to 0.55 to increase the conservatism of the sustained load strength check.

3. Default bond stresses are included, which may be used absent specific knowledge of the (qualified) adhesive anchor system to be used. These in turn become minimum bond stresses for the qualification under ACI 355.4-11 (ACI Committee 355 2011).
4. Specific conditions for the use of adhesive anchors to resist sustained tension loads in horizontal or overhead (defined as any orientation above horizontal) applications are introduced based on the additional challenges that these installation directions present.

Omission of the group factor, $\psi_{g, No}$ – Theoretically, the tension strength of an anchor group trends towards the strength of a single anchor as the anchor spacing approaches zero. In contrast, experimental and numerical investigations [Eligehausen et al. (2006)] show that bundled adhesive anchors exhibit tension strength proportional to the square root of the number of anchors in the group. This leads to a series of expressions for the evaluation of $\psi_{g, No}$, which is always greater than one. Although included in AC308 (ICC-ES 2006), this term was conservatively omitted in ACI 318-11 (ACI Committee 318 2011) for simplicity.

Factor on sustained load bond strength – AC308 (ICC-ES 2006) introduced a specific reduction factor on bond strength for cases where anchors resist sustained tension loads. The reduced bond strength is used for a supplemental check against that portion of the load that is sustained. This approach is adopted in ACI 318-11 (ACI Committee 318 2011), but a more conservative factor is applied to the bond strength pending the conclusion of ongoing investigations into factors affecting the sustained load bond strength, and the evaluation of a range of adhesive anchor systems using the stress vs. time-to-failure test method (ASTM/AASHTO 2010).

Default bond stresses – ACI 318-08 Appendix D (ACI Committee 318 2008) provides default values for the coefficient for basic concrete breakout, k_c , to be used with post-installed expansion and undercut anchors in Eq. (D-7) to facilitate anchorage designs in the absence of specific anchor test results. Similarly, ACI 318-11 (ACI Committee 318 2011) includes default characteristic bond stresses, each corresponding to a unique constellation of installation and use parameters that are associated with indoor and outdoor conditions in uncracked and cracked concrete. Specific parameters accounted for in the development of these default bond stress values include condition of the concrete at the time of installation (dry or saturated), the temperature of the concrete both at the time of installation and over the anchor service life, the type of loading (static, seismic, sustained), and the method used to drill the hole (rotary percussive/rock drill or core drill). While use of the labels “outdoor” and “indoor” in the table is intended to assist in the selection of the appropriate bond stress, specific applications may violate the assumptions associated with each category and thus these values should be used with care. Nevertheless, the default bond stresses in ACI 318-11 (ACI Committee 318 2011) are established conservatively, based on existing experience with testing of adhesive anchor systems in accordance with AC308 (ICC-ES 2006) and, importantly, must necessarily also serve as lower-bound limits on the bond stresses evaluated for all qualifying systems under ACI 355.4-11 (ACI Committee 355 2011).

Specific provisions for horizontal and overhead installations – Owing to the increased difficulty associated with the installation of adhesive anchors in horizontal and overhead¹ orientations, as well as the specific hazard posed by adhesive anchors used to suspend dead loads in direct tension, ACI 318-11 (ACI Committee 318 2011) places specific restrictions on these cases in D.2.2 as follows:

1. Anchors installed horizontally or overhead shall have been specifically evaluated for these installation directions in accordance with ACI 355.4-11 (ACI Committee 355 2011).
2. Anchors installed horizontally or overhead to resist sustained tension loads require the specific approval of the building official or authority having jurisdiction (AHJ).
3. Installation of anchors installed horizontally or overhead to resist sustained tension loads must be performed by personnel certified in accordance with the ACI Adhesive Anchor Installer Certification Program, or an equivalent program.²

The inclusion of a requirement for specific approval by the AHJ for anchors resisting sustained tension loads in the horizontal or overhead positions is intended to ensure that particular attention is paid to the details of the design and installation of anchors in these circumstances. The initiative for an ACI Adhesive Anchor Installer Certification Program was initially developed in the context of post-installed reinforcing bar installations. The scope of this effort has been expanded to include all adhesive anchors and is anticipated to result in a certification exam consisting of a written part (proctored, multiple choice) and a practical part. The practical portion of the exam will likely include installation of an adhesive anchor in the down-hole position as well as a replication of the blind-installation test used in ACI 355.4-11 (ACI Committee 355 2011) for qualification of the adhesive anchor system for overhead installations. The exam will test for general knowledge regarding the installation factors that affect adhesive anchor

¹ “Overhead” is conservatively taken in ACI 318-11 (ACI 318 Committee 318 2011) as all orientations horizontal and above.

² Under development in Committee 601-A0.

performance, the specific skills associated with correct adhesive anchor installation in accordance with the manufacturer's instructions, and the particular safety requirements associated with the use and handling of the adhesive anchor system components.

Other changes included in ACI 318-11

The implementation of the bond model in ACI 318-11 Appendix D (ACI Committee 318 2011) is accompanied by extensive commentary on quality control measures for anchor installation and a change to the provisions for lightweight concrete.

Quality control provisions – The installation of anchors is addressed in D.9.1. This section is expanded to require adherence with manufacturer's printed installation instructions for all post-installed anchors and the use of qualified personnel for adhesive anchor installations. The commentary on this section is significantly expanded to include a discussion of issues associated with post-installed anchor installation and specific measures for adhesive anchors, e.g., proof loading, that may flow from qualification of adhesive anchor systems in accordance with ACI 355.4-11 (ACI Committee 355 2011). Excerpting from the commentary to D.9.1.1:

RD.9.1.1 – Due to the sensitivity of bond strength to installation, jobsite quality control is important for adhesive anchors. Where appropriate, a proof loading program should be specified in the contract documents. For adhesive anchors, contract documents must also provide all parameters relevant to the characteristic bond stress used in the design...

While there are no commonly used standards available for proof loading of anchors, ACI 355.4-11 (ACI Committee 355 2011) provides guidelines for the establishment of a proof loading program as described earlier.

Figure 4 provides an example for the inclusion of adhesive anchors in contract documents whereby the relevant and necessary parameters for design and installation are listed in a concise and compact format and are keyed to the details, reducing the likelihood for errors in product specification/substitution and installation.

Adjustment for lightweight concrete – Review of the existing test record for post-installed anchors in lightweight concrete resulted in unique modification factors, λ_a , for use with the expressions in Appendix D pertaining to concrete breakout failure and bond failure as shown in Table 1.

Table 1 – Modification factors, λ_a , for lightweight concrete

	All-lightweight concrete	Sand-lightweight concrete
Concrete breakout failure of cast-in and undercut anchors	0.75	0.85
Concrete breakout failure of expansion and adhesive anchors	0.60	0.68
Bond failure of adhesive anchors	0.45	0.51

SUMMARY

A new qualification standard, ACI 355.4-11 (ACI Committee 355 2011), has been developed for the testing and assessment of adhesive anchors in concrete. The standard is substantially based on acceptance criteria already in use, but with significant changes to enhance the safety margin for cases involving sustained loads and to improve anchor robustness for jobsite conditions.

Provisions for the design of adhesive anchors are included in ACI 318-11 (ACI Committee 318 2011). The provisions implement the uniform bond model in a manner compatible with the existing design paradigm in Appendix D and place particular emphasis on sustained load behavior and installation quality control.

Table # – Adhesive anchor design and installation parameters¹⁾

design parameters	adhesive	characteristic bond strength	1,400 psi		
		loading	yes	yes	no
			static	sustained	seismic
		strength reduction factors ²⁾	0.65	0.55	NA
	static		sustained	seismic	
	concrete	design assumption ³⁾	ok		
			cracked concrete		
		compressive strength range	f'c = 4,000 – 6,000 psi		
		composition	normal wt.		
			aggregate		
	anchor element	max. in-service temperature ⁴⁾	110°F	160°F	
			sustained	transient	
		type/sizes	1/2" – 1"	#4 - #9	
			threaded rod	reinforcing bar	
		material	A193 B7	Gr. 60	
		min. specified tensile strength	125 ksi	75 ksi	
treatment		hot dip galvanized	none		
installation conditions	installation temperature range ⁵⁾	40°F	80°F		
		lowest	highest		
	presence of water ⁶⁾	ok	ok	no	no
		A	B	C	D
	drilling method	yes	no		
		rotary impact drill or rock drill	core drill		
	inspection requirements	no	yes	yes	
		periodic	continuous	proof loading	

¹⁾ See manufacturer's installation instructions and drawings for additional installation parameters.

²⁾ Strength reduction factor for bond/concrete failure modes that are appropriate for use with ACI 318-08 Section 9.2 load combinations.

³⁾ Condition of concrete over the anchor service life.

⁴⁾ Maximum temperature of concrete over anchor service life. Transient temperature increases are temporary increases, that is, associated with day/night cycles.

⁵⁾ Temperature of concrete at time of installation.

⁶⁾ At time of anchor installation:

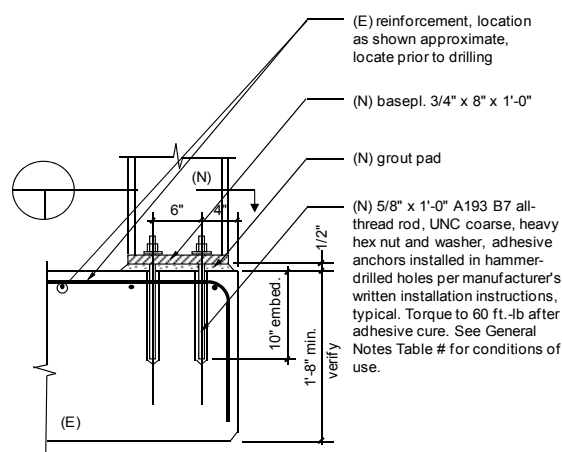
A – Concrete not exposed to water (for example, indoor application).

B – Concrete exposed to water (for example, due to rain).

C – Drilled holes filled with water (downhole).

D – Anchors installed underwater (submerged installation).

a) General notes table for design and installation



b) Typical detail

Figure 4 – Example for specification of adhesive anchors in contract documents

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**ADHESIVE ANCHORS ACROSS BORDERS:
*A CURRENT LOOK AT THE SIMILARITIES AND DIFFERENCES BETWEEN
TESTING, QUALIFICATION, AND DESIGN OF ADHESIVE ANCHORS
IN THE U.S. AND EUROPE***

by Andra Hörmann-Gast and Jacob Olsen

Synopsis:

International efforts to harmonize the testing, qualification and design of post-installed anchors have resulted in closely aligned standards / guidelines in Europe and the U.S. The implementation of ETAG 001, Part 5 (EOTA 1997) in the E.U. and AC308 (ICC-ES 2006) in the U.S. represents a major new step in the harmonization efforts and has resulted in nearly parallel approaches in the two regions with regards to the qualification and design of adhesive anchors.

Nevertheless, while the standards alignment permits portability of test data from one system to the other, significant differences remain between the two systems. In addition, efforts to adopt AC308 into the building code for structural concrete in the U.S. (ACI Committee 355 2008) have resulted in further dissimilarities.

This paper focuses on the similarities and differences between the European and American qualification systems for adhesive anchor products. An insight into the issuance of Evaluation Reports and Technical Approvals is provided. Information regarding manufacturing and quality control requirements imposed as a part of the product qualification is included.

A brief review of the design procedures adopted in ETAG 001 and in AC308 is provided. The current status of the ACI 355.X standard which is currently under development is also discussed, and regional differences in job-side quality control and installation inspection are discussed.

Keywords: ACI, Adhesive Anchors, EOTA, ICC

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ORGANIZATIONS DEVELOPING STANDARDS, CODES AND GUIDELINES

Building codes and product testing standards are typically the result of collaborative efforts between practitioners, academicians and manufacturers/material interests, under the guidance of a structured standards development organization. Memberships, voting permissions and document publication are governed by the rules of the organization.

E.U.: European Organisation for Technical Approvals (EOTA)



For the use of adhesive anchors in safety-relevant applications - in cases where failure of the anchor may cause risk to human life and/or lead to considerable economic consequences - the two Essential Requirements: *ER 1: Mechanical resistance and stability* and *ER 4: Safety in use* must be fulfilled. A clear separation of anchors used for safety-related and non-safety related applications is intended; adhesive anchors designed to attach a structural support to a column are subject to these requirements whereas adhesive anchors employed for attaching lavatory fixtures are not. The only path to show that the essential requirements are fulfilled for life-safety applications is via the EOTA process which results in the granting of a European Technical Approval (ETA) for the product.

EOTA primarily monitors and supports the progress of drafting of new guidelines such as the European Technical Approval Guidelines (ETAGs) and coordinates all activities related to the issuing of ETAs in accordance with the ETAG. EOTA comprises the Approval Bodies nominated to issue ETAs by EU Member States and EFTA States who have contracted to the European Economic Area Agreement (EEA). 27 European countries are members of the EOTA. Approval Bodies are organizations designated by their respective Member States as being competent to assess products and to issue European Technical Approvals. Each Member State notifies the Commission and the other Member States of their Approval Body or Bodies.

U.S.: International Code Council / ICC Evaluation Service / American Concrete Institute



ACI -- The American Concrete Institute ACI is a non-profit technical and educational society specialized in concrete. It is a forum for the discussion of all matters related to concrete e.g. technical publications and technical committee work.

The ACI is currently in the process of developing a standard for the qualification of adhesive anchors (ACI 355.X) based substantially on AC308. In addition, augmentation of the current provisions for cast-in-place and post-installed mechanical anchors in Appendix D of ACI 318 (ACI 318 2008) to include design requirements for post-installed adhesive anchors is under discussion. The following ACI Technical Committees (Design and Construction) are involved in this process:

1. Committee 318 (Structural Concrete Building Code): develops and maintains building code requirements for structural concrete.
2. Subcommittee 318-0B (Reinforcement and Development): subcommittee of Committee 318 responsible for building code provisions related to the development of reinforcement and anchorage to concrete.
3. Committee 355 (Anchorage to Concrete): develops standards and guides related to the subject of anchorage to concrete, e.g., ACI 355.2-07 (ACI 318 2008), Qualification of Post-installed Mechanical Anchors in Concrete.

4. Committee 601-A0 – Adhesive Anchor Installer: develops certification programs for installers of adhesive anchors.

ICC -- The ICC (International Code Council) is a non-profit membership association dedicated to the development of codes and standards for commercial and residential construction.

ICC publishes a family of 13 international codes ranging from zoning to energy conservation, the most recognizable being the International Building Code (IBC) (ICC 2009). The IBC is currently the most widely adopted building code in the U.S. IBC Section 104.11, “*Duties and Powers of Building Official - Alternative materials, design and methods of construction and equipment*” defines the conditions under which building products that are not specifically referenced in the code can be accepted as code compliant by the authority having jurisdiction (building official). Under IBC Section 104.11.1, “...*valid research reports from approved sources...*” may be relied upon by the building official to make the determination of code compliance.

Section 1912 of the IBC: “*Anchorage to concrete - strength design*” mandates the use of the design provisions of ACI 318, Appendix D for the design of cast-in-place bolts that resist seismic loads as well as for all anchors installed in hardened concrete, i.e., post-installed anchors regardless of loading type. ACI 318 Section D.2.3 in turn requires that post-installed anchors fulfil the assessment requirements of ACI Standard 355.2.

ACI 318 Appendix D does not currently provide provisions for adhesive anchors, but provides commentary in RD.2.2 as follows: “*Adhesive anchors are widely used and can perform adequately. At this time, however, such anchors are outside the scope of this appendix.*”.

As such, adhesive anchors remain outside of the code and must be addressed via research reports in accordance with Section 104.11.1.

ICC-ES -- ICC-Evaluation Service, Inc. is a non-profit subsidiary of the ICC established for the purpose of evaluating building products and systems for compliance with code.

The issuance of evaluation reports (ESR) by ICC-ES is based on published acceptance criteria developed in an open hearing process by a committee comprised of building and regulatory officials. These acceptance criteria provide test methods, evaluation requirements, and design procedures to assist the building official in establishing compliance with the intent of the code. Draft acceptance criteria are developed by ICC-ES staff in conjunction with industry/trade associations such as the Concrete Anchor Manufacturer’s Association (CAMA). Adoption or amendment of acceptance criteria occurs three times annually at hearings. In 2006, ICC-ES adopted AC308. This document, developed by CAMA over a period of 18 months, provides qualification and design provisions for adhesive anchors that are compatible with the design provisions in ACI 318, Appendix D and conform to the principles and approach to testing established in ACI 355.2.

Similarities and Differences

Reporting and hearing processes -- EOTA is comprised of the approval bodies nominated by the member states to issue European Technical Approvals. It reports to the SCC (Standing Committee for Construction) of the European Commission (governing body of the European Union). The EOTA process is not open to the general public. The development of European Technical Approval Guidelines is performed by EOTA working groups, the members of which are drawn from members of approval bodies, representatives of trade associations such as the Associations of the European Anchor Manufacturers, and national experts. While input from the manufacturing community is sought throughout the process of developing both the qualification guidelines as well as the design guidelines, final determination of the content of ETAGs and administration of the process for issuance of European Technical Approvals (ETAs) under these guidelines is confined to the SCC.

Both ACI and ICC are non-profit organizations unconnected to any governmental body. Their processes are open to the public. New codes, standards and acceptance criteria as well as revisions to them are discussed in open hearings. The products of these organizations do not have legal standing unless and until they are adopted by a legal jurisdiction, such as a state building commission or municipal building department, either directly or by reference. Voting is by committee. ACI allows manufacturers to be members and to vote in the committees, but limits their participation to keep the membership of the committee balanced. ACI is an ANSI-accredited standards development organization. The ICC-ES committee consists entirely of building officials or authorities having jurisdiction.

Status of reports/approvals -- European Technical Approvals issued by EOTA have the status of law within the EU Member States and EFTA States who have contracted to the European Economic Area Agreement. This is in

contrast to Evaluation Service Reports issued by ICC-ES or evaluation reports issued by other evaluation agencies in the U.S., which are advisory documents to assist building officials in establishing compliance with the adopted building code. This is discussed further below.

APPROVALS AND EVALUATION REPORTS FOR ADHESIVE ANCHORS

An Approval or Evaluation Report for an adhesive anchor system is generally a document that summarizes information and data needed to design and install the anchor. These documents are based on large amounts of laboratory testing but differ from a test report in that actual test data is not presented, only the summarized design values and conditions of use are included.

E.U.: European Technical Approval under ETAG 001

An ETA for an adhesive anchor represents the technical assessment of its fitness for the intended use (suitability). The basis for the European harmonization of Construction Products is the Construction Products Directive (CPD) (The Council of the European Communities 1988). The CPD provides the legal basis for the development of criteria to assess construction products for use in all member states. The introduction of a construction product into the European market requires either compliance with a harmonized European Code or an ETA. There are no harmonized European codes available for the assessment, evaluation and the design of adhesive anchors. Hence the only path to permit adhesive anchors for safety-relevant applications is via the EOTA process.

Manufacturers wishing to obtain an ETA for an adhesive anchor must apply at one of the EOTA approval bodies. This involves completion of a form, submission of test results and detailed information about the adhesive. The test reports must include all information described in the relevant ETAG as discussed below. Based on the information submitted, the approval body then develops an Evaluation Report as well as an ETA draft. These two documents are then distributed to the relevant EOTA approval bodies for review. The review period after receipt of the draft ETA and Evaluation Report is two months. If no comments are received, the ETA is issued as drafted. If comments are received, these must be resolved prior to issuance of the ETA. ETAs are issued by the European Approval Bodies e.g., in Germany by the DIBt - in the official language(s) of the Approval Body as well as in English.

A European Technical Approval is valid in all EEA states, for a period of five years, renewable thereafter.

The information given in an ETA for adhesive anchors includes (but is not limited to) the following:

- Temperature range, use categories;
- Installation parameters and instructions;
- Adhesive parameters, anchor /rod dimensions and properties;
- Characteristic values for tension and shear loads; and
- Characteristic displacement values.

Since the adoption of ETAG requirements for adhesive anchors in 2002, EOTA has issued about 275 ETAs for adhesive anchors including ETAs for post-installed rebar connections.

U.S.: Evaluation Reports created under ACI 355.X / AC308

ACI -- The ACI 355.X standard for qualification of adhesive anchors, planned for publication in 2010, will prescribe the required testing program, evaluation of results and reporting for adhesive anchors to be used in conjunction with the design provisions in the ACI 318 Standard.

The ACI 355.X standard requires testing, evaluation and reporting to be conducted by an accredited independent laboratory and certified by a licensed engineer.

When the 355.X standard is published and the ACI 318 Appendix D requirements for adhesive anchors are finalized and adopted into a model code such as the IBC, it is possible for an evaluation report issued in accordance with ACI 355.X evaluation to be used directly with the code. Until this process is complete, adhesive anchors remain as alternates to code-compliant products, i.e., under the jurisdiction of Section 104.11 of the IBC. As a matter of practicality, it is likely that the ACI 355.X standard will be incorporated into acceptance criteria such as AC308 by reference in order to facilitate the continuing issuance of documents conforming to a consistent format and administrative process that can be used by registered design professionals and building officials alike.

A precedent for this was established with the publication of AC193 “Acceptance Criteria for Mechanical Anchors in Concrete Elements” by ICC-ES. It incorporates the ACI standard ACI 355.2 “Qualification of Post-Installed Mechanical Anchors in Concrete” by reference and adds quality control and administrative requirements, as well as additions deemed necessary to incorporate updates and improvements to the standard in a timely manner. These two standards have both been in place for more than eight years, and building officials continue to seek and even demand ICC-ES ESRs rather than ACI 355.2 evaluation reports.

ICC-ES -- As previously discussed, the IBC provides the option to accept the use of materials and products not specifically prescribed in the code as an alternative material in Section 104.11. *“The alternative material, design, or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code.”*

Currently AC308 is the primary reference document for the issuance of evaluation reports used to show code compliance for adhesive anchors. Obtaining an ESR in accordance with AC308 involves completion of a form, submission of test results, and information about manufacturer’s quality control. The test / evaluation reports must include all requirements described in AC308. The tests and the evaluation must be done by an accredited ITEA (Independent Testing and Evaluation Agency). Based on the information submitted, the ICC-ES staff reviews the submitted data and evaluation of results and publishes an ESR. The ESR will include specific design requirements that are taken from AC308 to supplement the design requirements according to ACI 318, Appendix D by adding necessary requirements for adhesive anchor design. An ESR is valid for a period of one or two years, renewable thereafter. An ESR for adhesive anchors includes the following:

- Permissible loading types (e.g., static, wind, seismic);
- Permissible use conditions (uncracked, cracked concrete);
- Temperature range, use categories;
- Installation parameters and instructions;
- Adhesive parameters, anchor /rod dimensions and properties;
- Characteristic values for tension and shear loads;
- Requirements for special inspection and jobsite quality control; and
- Requirements for manufacturing audit and quality control.

Since the adoption of AC308 in 2006, ICC-ES has issued eight ESRs for post-installed adhesive anchors. The credibility and acceptance of ESRs (or other evaluation reports) by code officials is in part associated with the recognition that the entire process of testing procedures, evaluation and reporting is handled by the evaluation agency (e.g. ICC-ES). Thus the building code official is not required to possess additional specific knowledge of adhesives and anchoring to determine if a code alternative product meets the intent of the code.

Similarities and Differences

The final ETA is the result of the review process performed by all European Approval bodies via circulation of the evaluation report as well as a draft ETA. There is a standard ETA format that must be used by all of the Approval bodies. An ETA has the same level of authority as a code or standard. An evaluation report issued under ACI 355.X is similar in the sense that it also directly proves a product is in compliance with the code; however, it is different in that it may be issued by a single professional engineer without a review or circulation process.

Evaluation reports such as ESRs issued by ICC-ES under AC308 are intended to show that a product may be designed as a suitable alternative to methods and materials cited in the code – as such they are different from ETAs and evaluation reports issued under ACI 355.X. However, until adhesive anchors are directly referenced in the building code and the ACI standard ACI 355.X is published, evaluation reports issued by agencies like ICC-ES will continue to be the standard vehicle for determination of code compliance by building officials.

SPECIFIC QUALIFICATION PROCEDURES FOR ADHESIVE ANCHORS

All of the documents and processes described herein are “living” and are subject to change. The authors have attempted to represent the current status as of February, 2010.

Adhesive anchors are qualified by conducting a described collection of tests and evaluating the results. Many tests for specific conditions such as elevated or decreased temperature installations, sustained loading or near-edge installations are thoroughly defined and mandatory. The tests include a minimum passing level in order to be qualified. The standards are established to exclude some poor performing products from attaining qualification. The basic testing regimen in both continents is based on the same research primarily conducted at the University of Florida and University of Stuttgart and is therefore nearly identical. A summary of the research can be found in Anchorage in Concrete Construction (Wiley, 2006).

Guidelines / Standards in both Europe and U.S. contain the following types of tests:

- **Identification tests** to verify the adhesive product itself is what the manufacturer claims it to be and to provide a means to later confirm that the product has not been modified from the tested product. This is provided by “fingerprint”-tests, e.g. IR scans, viscosity tests and/or gel time tests.
- **Reference tests** to obtain baseline values for comparison with tests in less favorable conditions. For example confined, single anchor bond strength tests will be conducted.
- **Reliability tests** to assess anchor sensitivity to adverse installation conditions and long-term use. For example tests with reduced hole cleaning, installation in submerged or wet holes, tests under freeze/thaw conditions, and sustained loading will be conducted.
- **Service-condition tests** to establish anchor performance under expected service-conditions. For example testing will be conducted on adhesives exposed to alkalinity and sulfur, anchors installed at different installation directions, long-term and short-term temperatures, installed near the corner of a slab and pairs of anchors spaced closely.

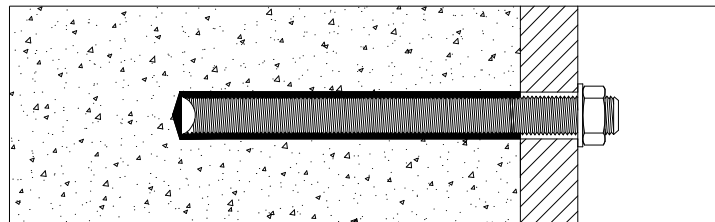


Fig. 1 -- Post-installed adhesive anchor

The goal in the evaluation of the test results is to reduce the data to a single, product-specific bond stress for use in the design model. As is usually the case, the diameter, service temperature range, concrete cracking, and drilling method have an effect on the final bond stress and therefore the final reported bond stress is discrete only for a specific combination of diameter, service temperature, hole drilling method and concrete condition.

While the basic testing is the same, the organization of the test requirements and the assessment varies between the ETAG, ACI 355.X, and AC308.

E.U.: ETAG 001 and related documents

The “Guideline for European Technical Approval of Metal Anchors for Use in Concrete” (ETAG 001) sets out the requirements for anchors, the acceptance criteria they shall meet, and the procedures and tests methods used in the assessments.

ETAG 001, Part 1: *Anchors in general* comprises the test conditions and acceptance criteria applicable to all types of metal anchors. ETAG 001, Part 1 covers the assessment of post-installed metal anchors in normal weight concrete and is valid for static or semi-static (quasi-static) loading only.

ETAG 001, Part 5 (EOTA 2002): *Bonded anchors* contains additional and/or exceptional test conditions for adhesive anchors, required number of tests and acceptance criteria valid for adhesive anchors only. Part 5 of ETAG 001 covers common adhesive and capsule systems as well as torque-controlled adhesive anchors.

ETAG 001, Annex A: *Details of tests*, Annex B: *Tests for admissible service conditions* and Annex C: *Design methods for anchorages* are part of the guideline.

ETAG 001 was adopted by the European Commission in 1997. Yet, this ETAG did not include Part 5: Bonded Anchors. This part was added in 2002, amended in 2006 and 2008.

Technical Reports -- The following EOTA Technical Reports (TR) belong to ETAG 001 and provide detail for particular subjects; they express the common understanding of existing knowledge and experience of the Approval Bodies at a particular point in time. EOTA Technical Reports are developed as a supporting reference document to different documents e.g. ETAGs and ETAs as far as reference is made therein. Technical reports are different than content directly in the ETAG because the topics covered in a TR are all-encompassing and not just related to one ETAG, a TR can be referenced in various documents. Yet, the TR content has the same importance as ETAG content. Technical Reports related to Adhesive Anchors are:

- TR 018 (EOTA 2003) – Assessment of Torque-Controlled Bonded (Adhesive) Anchors
- TR 020 (EOTA 2004) – Evaluation of Anchorages in Concrete concerning Resistance to Fire
- TR 020 (EOTA 2006) – Assessment of post-installed rebar connections
- TR 029 (EOTA 2007) – Design of Bonded Anchors.

U.S.: ACI 355.X / AC308

ACI 355.X -- *Qualification of Post-Installed Adhesive Anchors in Concrete* (ACI 355.X-YY) and *Commentary* is the new ACI standard for the assessment of adhesive anchors now under development. The ACI 355 committee approved the final draft of this document in December 2009 for submission to the Technical Advisory Committee.

ICC-ES AC308 -- AC308 was drafted by the CAMA, an organization that counts 12 U.S. and international anchor manufacturers as well as leading anchor test laboratories in its membership. ICC-ES approved this document in June of 2006 and has since reissued it ten times with revisions.

ASTM (American Society for Testing and Materials) -- The majority of the testing details are contained in the ACI 355.X and AC308 documents, however both contain references to some ASTM standards such as:

- ASTM E 488-96 (ASTM E 488 2003) *Test Methods for Strength of Concrete Anchors in Concrete and Masonry Elements*.
- ASTM E 1512-01 (ASTM E 1512 2007) *Test Methods for Testing Bond Performance of Bonded Anchors*.

Similarities and Differences

Although these three qualification standards, ETAG 001, ACI 355.X and AC308, are rooted in the same research with many of the same experts and anchor manufacturing companies involved in their development, some notable differences have emerged. These differences can be partially attributed to the development cycle - length to make changes to the document - as well as the voting constituency on each committee developing the qualification standard.

The EOTA process is flexible and able to quickly include new research e.g. via Comprehension Documents or Progress Files. Comprehension Documents are internal living EOTA documents that explain how to apply or interpret particular elements in an issued ETAG. Progress Files are worked out by the relevant EOTA Working Group. The latest endorsed version of this file is always distributed with the original ETAG and is binding (mandatory) for all EOTA bodies.

The ICC-ES process is also relatively flexible in including new knowledge via the ICC-ES hearings process. Proposed changes to Acceptance Criteria are posted on the website and are voted on at the hearings normally held three times per year. Anyone wishing to express an opinion on a topic is given the opportunity to do so in open session; the proceedings are recorded and all speakers are required to identify themselves by name and affiliation. Other evaluation agencies conduct similar processes.

ACI Committee 355 generates standards that may or may not be re-issued coincidentally with the code cycle (currently 3 years). Necessary changes or updates are generally collected and discussed during semi-annual committee meetings. Changes to the standard must be balloted and all negatives resolved before the document can be sent to ACI's Technical Advisory Committee (TAC) for review. Comments by TAC must similarly be resolved through committee balloting before the standard can be issued for public comment, generally via the ACI publication "*Concrete International*". Only after the public comment period has elapsed and public comments have been addressed can the standard be re-issued. This can be a relatively lengthy process.

Scope -- The general concept of evaluating an adhesive system for a design bond stress is comparable in both Europe and the U.S. In addition the test regimen, test procedures, testing apparatus are nearly identical. Although not explicitly discussed in these test standards, adhesive systems intended for both the European and the U.S. market have been routinely tested according to one standard such as AC308, and the majority of the data can be re-used to obtain an ETAG 001 qualification or vice versa.

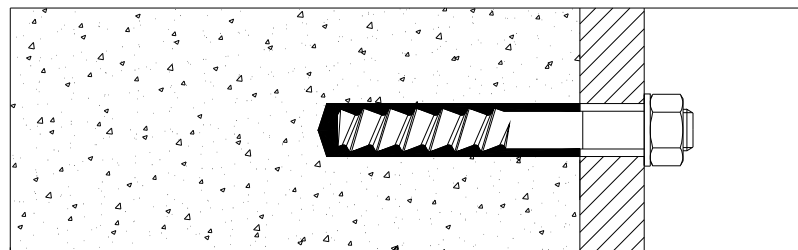


Fig. 2 -- Torque-controlled adhesive anchor

A significant difference that has emerged in the ACI standard is the exclusion of torque-controlled adhesive anchors (see Fig. 2). Both ETAG 001 and AC308 allow qualification for these types of adhesive anchors. These were excluded in ACI due to the complexity of testing and evaluating the anchors. Therefore, these types of anchors will not, for the time being, be included in the ACI 318 code and will remain alternatives to the code.

The testing program in all standards has some flexibility and depends on the manufacturer's desired recognition. Options in all three standards include optional recognition for cracked concrete, option recognition for installation in submerged holes and optional recognition for overhead installation. ACI 355.X adds further attention to the

overhead installation condition by requiring a special label on the product to show it is limited to vertically downward installation only if testing and assessment to address sensitivity to installation direction (horizontal and overhead) is not conducted.

Unique to the ACI 355.X and AC308 is optional recognition for seismic resistance which is not available in ETAG 001. Adhesive anchors that have undergone simulated seismic tests may be installed in earthquake prone regions and used to resist seismic loads according to the provisions of ACI 318 and the building code. Approval for cracked concrete is a precondition for seismic recognition.

The ETAG 001 currently provides a method to evaluate the fire resistance of adhesive anchors. As adhesive systems are known to be sensitive to elevated temperature, this is an important consideration and currently not available in the U.S. standards.

Testing -- The number of required tests in ETAG 001 Part 5, AC308, and the current draft of ACI 355.X is quite large. The number of tests may be reduced significantly under ETAG 001 when choosing different categories, options and design concepts; e. g. only one characteristic strength value may be given for all load directions independent of failure mode, influence of the concrete strength on the characteristic strength is neglected, dry internal conditions or other environmental conditions and the partial safety factor is adjusted. Similar options with regard to options e.g. cracked and uncracked concrete, installation in water-filled holes, exist in AC308; however, there is only one design concept in the building code (as defined by ACI 318 Appendix D and the load combinations in the building code), so the minimum number of tests to obtain an comparable evaluation report is typically greater for the U.S. standards.

The ETAG allows for a general reduction of the number of all types of tests in special cases, e.g. when steel failure occurs. In addition for service condition tests a reduction in the number of tests is possible if the anchor's behavior conforms to the current experience. The test program is arranged between the approval body and the manufacturer. If tests from the manufacturer are available and are consistent with the test labs results and experience the approval body is allowed to reduce the number of tests. Nevertheless, a minimum test program must be conducted to confirm that the anchor's parameters fall within the range of current anchor experience.

A precondition for evaluation reports issued under AC308 is that test reports in support of evaluation report applications must come from laboratories accredited (for the specific test method under consideration) by an accreditation body that is a signatory to the Mutual Recognition Arrangement (MRA) of the International Laboratory Accreditation Cooperation (ILAC) or by the International Accreditation Service, Inc. (IAS).

It is also required in ACI 355.X and AC308 that the tests must be conducted on randomly sampled products from the manufacturing or distribution facility by an independent personal. EOTA does not have such a requirement and samples are delivered directly by the manufacturer to the testing lab.

Adhesive anchor performance can be influenced if the anchor is installed in water-saturated concrete – especially the cleaning might be inappropriate. To account for this influence tests in water-saturated concrete are mandatory under ACI 355.X and ETAG 001. These tests are optional in AC308 because it is the intention to allow adhesive anchor qualification for dry internal use only (e.g. applications in existing buildings).

Freezing conditions during service life of the anchor can have a negative effect on the anchor performance. As a result a test is conducted to verify the anchor's performance under 50 cycles of normal temperature 68° F (20° C) and low temperature -4° F (-20° C) while applying a sustained tension load. ACI 355.X and ETAG 001 make this test mandatory, AC308 leaves this optional to the manufacturer which means it is possible to have anchors qualified for applications without freezing and thawing (e.g. indoor applications) to AC308.

Adhesive systems are known to be susceptible to creep or long term sustained loads. Temperature can have a significant effect on the resistance to long term sustained loads and experience has shown that the elevated temperature long-term load test can significantly limit the final design bond strength. ACI 355.X currently has the most conservative requirements for this test as anchors must pass at a minimum long-term temperature of 110° F (43° C). The AC308 and ETAG both allow testing and approval at a minimum long-term temperature of approximately 73° F (21° C) which will generally result in higher design bond strengths provided the designing engineer can verify the long term service temperature does not exceed the tested value.

Past experience indicates that concrete mixture and aggregate type can have a significant effect on the bond strength of the adhesive system. Typically a testing laboratory will conduct tests in concrete sourced locally which may or may not represent the most conservative condition in practice. To address this problem "Round-Robin" tests have been introduced in both the ACI 355.X and AC308 standards. This testing requires additional tests in concrete from four different geographic regions in North America.

In Europe the requirement is only that the tests have to be conducted at different concrete batches from different concrete suppliers.

Evaluation -- The evaluation in the three systems is very similar. The 5%-fractile of the ultimate loads is gained from statistical procedures assuming a normal distribution with unknown standard deviation and a confidence level of 90%. The ultimate loads are normalized to the specified concrete or steel strength depending on the failure mode. The criteria for the reliability and service condition tests (e.g. requirements of uncontrolled slip, coefficient of variation), reductions of the characteristic strength (e.g. resulting from temperature), the assessment of durability and identification are very comparable. A notable difference unique to the ACI 355.X standard is that the final evaluated bond stress must meet a minimum level in order for the product to be qualified. The intent of this requirement is to guarantee a minimum level of performance for products that are qualified for use with the building code.

There are many additional minor differences between the three standards that are not addressed in detail here. Table 1 summarizes the key points of the above-mentioned similarities and differences between the three systems:

Table 1 -- Comparison of testing and acceptance criteria			
Scope	ETAG 001	ACI 355.X	AC308
Testing scope given in criteria mandatory?	NO Approval body may reduce scope according to experience	YES (Except for tests indicated to be optional)	YES (Except for tests indicated to be optional)
Optional qualification for seismic resistance?	NO	YES	YES
Includes torque-controlled anchors?	YES	NO	YES
Procedure for evaluating fire resistance?	YES Contained in TR 020	NO	NO
Testing			
Testing on product randomly sampled by and independent party?	NO	YES	YES
Testing in wet concrete and under freeze/thaw conditions mandatory?	YES	YES	NO (optional)
Minimum long term temperature for sustained load test	68° F (20° C)	110° F (43° C)	73° F (23° C)
Tests required to determine the effects of regional concrete variations?	NO	YES via round-robin tests	YES via round-robin tests
Evaluation			
Adhesive anchor must meet a minimum bond strength to be approved?	NO	YES e.g. 650 psi (4.5 MPa) for uncracked concrete outdoor use	NO
Different design methods are included in the standard / guideline?	YES	NO	NO

COMPARISON OF MANUFACTURING REQUIREMENTS AND QUALITY CONTROL FOR ADHESIVE ANCHOR PRODUCTS

The purpose of the manufacturing and quality control system requirements is to provide assurance, verifiable through inspection that the product described in the original qualifying data and recognized in the approval or evaluation report is consistently manufactured after the report has been issued.

E.U.

Under the CPD, adhesive anchor systems must be produced under a controlled manufactured process and a constant quality must be guaranteed. The quality assurance must be provided by the manufacturer and must be supervised by an independent auditing body.

Attestations of Conformity (AoC) -- The ETAG mandate also contains a system of Attestations of Conformity (AoC) - which is intended to ensure that the product specification set out in an ETA is maintained by the manufacturer. It defines the art and manner of quality control for the product. The AoC system is established by the EC on the basis of such considerations as the consequences of failure and the sensitivity of the product.

The required AoC level for anchors qualified under ETAG 001, Part 5 (Adhesive Anchors) is “1”; it is the highest level of quality control. The requirements on the quality control associated with this AoC level are the most comprehensive ones. Hence this AoC level results in a high degree of responsibility on the independent approved bodies rather than on the manufacturer. It requires the most certifications, control and testing conducted by the independent approved bodies.

Approval bodies are approved by their respective Member States to carry out these designated tasks. Member States must notify the Commission and other Member States of their Approval Bodies.

According to AoC level “1” the **manufacturer** has the following tasks:

- factory production control
- further testing of samples taken at the factory by the manufacturer in accordance with a prescribed test plan

The manufacturer is required to have a permanent internal control of the production established in order to insure that the product is in conformity with the ETA. All the elements, requirements, provisions, and records of the results shall be documented. The factory production control shall be in accordance with a control plan which is related to the ETA and is part of the technical documentation. The control plan is deposited with the relevant approval body.

Any change to the product and / or the production process needs to be reported to the approval body.

Additionally the manufacturer shall contract an approved body to undertake the following actions necessary for the certification of conformity of the product.

According to AoC level “1” the **approved body** has the following tasks:

- initial type-testing of the product
- initial inspection of factory and of factory production control
- continuous surveillance, assessment and approval of factory production control.

The control plan is handed over from the manufacturer to the approved body and it serves as a basis for the approval body to test and check the items mentioned above.

Furthermore the manufacturer shall make a declaration of conformity with the provisions of the ETA.

As a result the approved body will issue an EC certification of conformity with the requirements of the relevant ETA.

In cases where the requirements of the ETA or the control plan are not fulfilled the approved body does not issue / withdraws the certification of conformity and informs the relevant approval body.

CE marking -- If an adhesive anchor has a valid ETA and fulfills all tasks of the associated Attestation of Conformity procedure - which is intended to ensure that the product specification set out in an ETA is maintained by the manufacturer - the CE marking is permitted to appear on the product/product packaging. The CE marking can be seen as a "passport" enabling a product to be legally placed on the market in any EU Member State. The CE marking includes important information about the product e.g., manufacturer, ETA-number, use-category, sizes, etc. The CE marking indicates that the product addresses the regulatory requirements.



Fig. 3 -- CE Marking

U.S.

ACI -- ACI 355.X requires anchors to be manufactured under an approved quality-assurance program with unannounced quarterly follow-up inspections by an accredited inspection agency. In addition each production facility must have a quality control manual complying with a nationally accredited criteria.

ICC-ES -- Evaluation reports require periodic inspections of the manufacturing facility by a third-party agency. The inspection agency must be accredited by IAS or by an accreditation body that is a partner of IAS in an MRA. Quality control procedures for the anchor manufacturing process are contained in AC10: Acceptance Criteria for quality documentation. This criteria identifies specific information that shall be submitted to ICC-ES belonging to the specific requirements of the adhesive and identifies information that shall be included in the report holder's documented quality system. The criteria requires an on-site qualifying inspection of the manufacturing facility.

The qualifying inspection shall be conducted by a representative of ICC-ES or by an agency accredited under the ICC-ES Acceptance Criteria for Inspection Agencies (AC304), to verify that the quality system is in place, is being implemented and product specific items are in compliance with the evaluation report requirements. A form must be completed and signed, attesting that the quality system incorporates the quality system documentation requirements of this criteria. Some of the key points of the mandatory quality system include:

Incoming Materials: The quality documentation includes procedures regarding inspections or tests that are conducted on incoming materials, to determine that the materials meet specifications (for example, certificates of analysis for the components for the adhesive).

In-process Quality Control: The quality documentation describes in-process quality control procedures, including how manufacturing processes are monitored to ensure that the product is consistently manufactured within the allowable tolerances.

Final Inspection: The quality documentation shall detail any final inspections and/or tests that are conducted before the product is labeled and shipped, to ensure that the finished product complies with specifications.



Fig. 4 -- ICC-ES Marking

Similarities and Differences

The quality control requirements in Europe and in the U.S. are very well defined and very similar. Also the requirement for who may conduct the audits is specified in both systems.

1. The European inspection audits are recommended to be conducted twice per year. Yet the audits may be carried out at less frequent intervals if the manufacturer provides a certified quality assurance system, whereas in the U.S. system quarterly audits are mandatory.
2. The requirements concerning the identification of steel element / the adhesive and product labeling are very similar:
 - a. Under both systems, the adhesive must be marked with the identifying mark of manufacturer, the trade name, the batch number and the date of expiration.
 - b. Commercial standard rods may be used in Europe if the mechanical properties are according to a European code, the rods have an inspection certificate acc to EN 10204 and a marking of the embedment depth exists. In Europe the geometry and the mechanical properties of steel (deformed) reinforcing bars must comply with a national or a European code. In the U.S. the markings for anchor rods are not required, but the geometry and the mechanical properties have to be according to national or international standards. Reinforcing bars must comply with a national or international standard as well.

REQUIREMENTS FOR DESIGN

The following summarizes the formal requirements for design in conjunction with the testing and assessment procedures in use.

E.U.

An ETA for an adhesive anchor states that the design shall be in accordance with the requirements according to ETAG 001, Annex C or TR 029 respectively. If another design concept is to be used the assessment according to ETAG 001 might not be appropriate.

The design must be under the responsibility of an engineer experienced in anchorages and concrete and it must be demonstrated in the design of the anchorage that the two requirements (the ultimate limit state and the serviceability limit state) are fulfilled. The design is based on the partial safety factor concept. Partial factors are incorporated in both the design action as well as the design resistance values. The safety factors for action are taken from EC2 (CEN 1992) or national regulations and depend on the type of loading. The safety factors for resistance are given in the ETA and take into account the scatter of the material as well as installation safety issues.

Additionally it must be shown that the occurring characteristic displacements are not larger than the admissible displacements.

U.S.

ACI -- The design concept used in ACI 318 (Appendix D) is currently only applicable to the design of cast-in and post-installed mechanical anchors. The main committee of 318 is in the process of adopting design provisions for adhesive anchors. Particular attention is being paid to the subject of overhead installations and sustained loads, and a request has been made by the main committee to the certification programs committee of ACI to develop a certification program for adhesive anchor installers.

ICC-ES -- In addition to the design values and installation information presented in an ICC-ES AC308 ESR report, there is also a procedure to design adhesive anchors. The design is based on ACI 318 (Appendix D) where applicable with modifications and amendments for adhesive anchors that are included in the ESR. As these requirements specific to adhesive anchors are not directly in the code, the design of adhesive anchors according to an ESR falls under the alternative materials and methods of construction provisions of Section 104.11 of the building code, whereby the ESR provides the supporting data required in 104.11.1 for determination of compliance by the authority having jurisdiction (building official).

Similarities and Differences

Safety concept -- The design provisions for adhesive anchors in ETAG 001 / TR 029, those being balloted in ACI 318 and the provisions in AC308 ESR reports are nearly identical. The design resistance values are based on strength design with factored resistance values calculated with an allowable probability of non-exceedence. In addition, a factor specific to the failure modes (steel, concrete, or bond) is applied to further reduce the anchorage resistance. Under the partial safety factor approach used in the ETAG, safety factors on both load and resistance are denoted as gamma (γ) in the ETAG 001 / TR 029 documents. Strength reduction factors on resistance are denoted as phi (ϕ) in the ACI and ICC-ES documents. Factors on load are provided in the load combinations specified in the IBC.

Sustained loads and installation orientation -- A significant difference between the three design procedures is the design of anchors installed over-head to support sustained loads. Attention was drawn to this particular circumstance by the 2006 failure of adhesive anchors installed overhead in a freeway tunnel in Boston leading to the partial collapse of the supported ceiling system. The resulting investigation and discussions, particularly in the U.S., have led to a more conservative design approach for overhead applications.

The design methods address this as follows:

- ETAG 001 / TR 029 – no reduction in design strength for sustained or overhead applications required.
- ACI 318 – these provisions are still being discussed, but an additional reduction factor of at least 0.55 will likely be applied to the bond strength for all sustained loading. In addition, for installations at any inclination between horizontal and overhead, ACI 318 has requested the development of a “certified installer program” to train and certify installers of adhesives anchors as discussed below. ACI would mandate these particular installations be performed by a certified installer.
- ICC-ES AC308 – an additional 0.75 reduction factor on the bond resistance for sustained load only (dead load and the portion of the live load that may be considered as sustained) is applied in the design, and continuous special inspection is mandated for these installations.

Limitations on anchor groups -- An often-overlooked difference between the design concept contained in ETAG 001 Annex C and that used in ACI 318 Appendix D concerns limitation on the size and configuration of groups of anchors. Annex C places explicit limits on anchor groups; the largest number of anchors in a group is 6 for groups away from edges, and 4 for near-edge anchorages. Groups are defined as orthogonally arranged anchors; other geometries are permitted in accordance with engineering judgment. ACI 318 Appendix D does not limit the size of groups and while the design method is most easily applied to orthogonal anchor groups, other geometries are implicitly permitted.

INSTALLATION AND JOBSITE QUALITY CONTROL

E.U.

In accordance with the current ETA language, anchor installation may only be carried out by an appropriately qualified person under the supervision of the person responsible for technical matters on site.

The installation must be in accordance with the ETA as well as with the manufacturer’s specifications and drawings. The manufacturer’s installation instruction set as provided with the product is not part of the ETA. Detailed installation instructions (pictures as well as written instructions) are included, however; these must be adhered to. The concrete strength class and the quality of the concrete (no significant voids) must be ensured before placing the anchor.

The definition of “appropriately qualified person” according to the rules of the ETA and the need for certification of personnel engaged in the installation of anchors in Germany is discussed by the DIBt, and certification as required for installers of post-installed reinforcing bars – a mandatory installer certification program exists in Germany – is under consideration. Discussions on this topic will likely result in a guideline that indicates keystones of certifications conducted by the anchor manufactures under their own recognizance.

The current status of the discussion in Germany is as follows: there will be no required certification or independent certification to verify the qualification of the jobsite personnel in Germany. A DIBt document will define the list of qualifications regarding the different types of anchoring systems which have to be met by the jobsite personnel. The

process or way how to reach and approve this qualification will not be defined. It will be in the responsibility of the installation company to ensure that a qualified personnel will conduct the installation on site. But different ways to train these personnel are given in the document.

U.S.

ICC: The IBC 2009 (Table 1704.4, Item 4 and Section 1704.15: *Special cases*) addresses requirements for special inspection for alternative materials and systems prescribed in the IBC. The IBC 2009 Section 1705: *Statement of special inspection* and Section 1709: *Contractors Responsibility*) outlines the requirements of the design professional and on the contractor. The special inspector has to present on site as often as required in accordance with the IBC requirements.

ACI: The committee of ACI 318 prerequisites an adhesive anchor installer certification program to supplement inclusion of adhesive anchors in a future ACI 318 Code version. The committee 318 will otherwise ban overhead – defined as everything between horizontal and vertical up – applications in combination with sustained loads for adhesive anchors. The requirement of a installer certification will be included as a “hard” requirement in the code. The ACI/CRSI joint venture task group is working on an Installer Certification Program. The certification itself would be done by the ACI.

ICC-ES: The manufacturer’s installation instructions are part of the ESR. Also the following requirements from AC308 for special inspection when installing anchors have to be considered:

- Special inspection in accordance with the applicable building codes is required. Continuous special inspection is required where overhead installations are designed to resist sustained loads is present. For all other cases Periodic special inspection / Proof loading program is sufficient.
- The need of proof loading depends on the installation conditions as well as on the results of the installation safety tests in correlation with the anchor category.
- Continuous special inspection: The special inspector is required to observe that the adhesive installation is in accordance with the manufacturer’s installation instructions: hole location, diameter and depth; the hole drilling and cleaning method; anchor element type, material, diameter, length; adhesive identification and expiration date.
- Periodic special inspection: The required verifications are the same as for the continuous special inspection but only the initial installations of each type and size of adhesive anchor need to be observed. For ongoing installation the special inspector shall make regular inspection; also changes on the product being installed and / or the personal performing the installation require a repetition of the inspection.
- Proof loading program: Where required a program for on-site proof loading shall be established by the engineer of record. The tests shall be conducted as confined tests with 50% of the expected ultimate load or 80% of the anchor yield strength. Anchor failure or excessive displacement is not acceptable.

Similarities and Differences

The installation and job site quality control is probably the most significant difference between Europe and the U.S. In Europe much more responsibility is put on the installer rather than on external inspectors, whereas in the U.S. the existence of a jobsite inspection culture, code requirements for special inspection, as well as requirements for inspector qualifications permit more emphasis to be placed on jobsite inspection.

Those familiar with adhesive anchor systems are aware of the fact that quality assurance for the installation of these systems is essential to their short- and long-term performance. Nevertheless, in the end it is not important whose responsibility the quality insurance in the field is, it is more important that the designer, the installer and the inspectors are aware of the consequences of poor installation; e. g. insufficient hole cleaning, disregarding the cure time requirements or not using the equipment specified by the manufacturer.

In order to assure that the information on installation is given to the installer on site, the manufacturer is required in all qualification standards to provide the following minimum installation data on the package and / or on an enclosed instruction sheet:

- installation data (e.g. diameter of anchor / drill bit, hole depth, effective embedment depth)

- installation instructions (including cleaning procedure with cleaning equipment)
- anchor component and concrete temperature at time of installation
- open and curing time of the adhesive
- identification of the manufacturing batch.

SUMMARY

Harmonization efforts have led to conformity in the testing, assessment and design requirements for adhesive anchors between Europe and the U.S.

Nevertheless, significant differences remain, particularly in the areas of seismic qualification, overhead installation, sustained loading, jobsite quality control, and the scope of the design methods. Although, efforts to resolve these differences, where possible, are ongoing, at the same time the state-of-the art continues to advance. In addition, local experiences with adhesive anchor applications have resulted in regional opinions of what constitutes “best-practice” for adhesive anchors. As a result, those involved with adhesive anchor testing, qualification and design standards are continuously engaged and challenged – across borders.

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INSTALLATION OF ADHESIVE ANCHORS— THEORY AND PRACTICE

by Philipp Grosser, Werner Fuchs, and Rolf Eligehausen

Synopsis: Post-installed anchoring technology with mechanical anchor and adhesive anchor systems has found widespread use in concrete construction due to their numerous fields of applications, flexibility for fastening solutions, and advantages in productivity. Continuous improvement and advancement in post-installed fastening technology has yielded different products with certain areas of application and differing installation procedures. Therefore, in many cases, a post-installed anchor seems to be the perfect choice. However, as it is for cast-in anchors, the use of post-installed anchors requires in-depth knowledge in fastening technology for all people involved. These include the designers, who select the anchors for the correct load transfer from the attachment to the load-bearing structure, as well as the installers, who have to ensure that the anchors are installed correctly on the construction site.

Lack of knowledge in the field of post-installed fastening technology is inevitably increasing the probability of misuse and misinstallations. In the recent past, discussions on the reliable use of post-installed anchors arose due to misinstalled mechanical anchors in the nuclear power plant in Biblis, Germany, or the fatal collapse of the Boston I-90 Tunnel ceiling panel that was suspended with the use of such anchors.

To counteract and avoid these situations, a survey¹ was performed in 2007 in Germany, Italy and Croatia on the installation of adhesive anchors on-site was performed as a first step in studying the issue. Based on the results of this investigation a field research project was started in 2009 in the United States to identify the situation on construction sites with regard to adhesive anchor installation in practice. The project was intended to benefit the construction industry by forming a basis for the development of easy to install adhesive-bonded anchors, and to improve the installation instructions for actual and future anchors, as well as to get information on the necessity and content of adhesive anchor installation training programs. This paper gives an overview on the findings on 23 sites in five locations in the United States and conclusions.

Keywords: Adhesive anchors, installation, post-installed fastener

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INTRODUCTION

For every fastening or anchorage to concrete application the starting point is the choice of the correct product. This requires the understanding of the loads to be resisted, the design method, the exact location of the fixing point, the environmental conditions in service and during installation, and the installation procedure of the adhesive anchor itself.

Reliable fastenings with adhesive anchors require the selection of the product which is adequate for the conditions in service and installation, and meets an actual acceptance criteria such as AC 308² or ACI 355.4⁵. This is the task of the designer. In addition, he has to take into account several different conditions which influence the correct application of adhesive anchor systems, such as drilling method, temperature and state (cracked, uncracked) of the base material, condition of the drilled hole, installation direction, etc.

Once the correct system has been selected and designed, the installation process has to be considered. To ensure a correct installation, the installer has to follow exactly the instructions found in the manufacturer’s printed installation instructions (MPII). All important steps of the installation are outlined in the MPII. Furthermore, the requirements of the Evaluation Reports have to be followed. Detailed information on the installation and inspection of adhesive anchors is given by Wollmershauser and Mattis³; information on factors influencing the behavior of adhesive anchors can be found in Eligehausen, Mallée, Silva⁴.

In theory the knowledge is available to ensure reliable fastenings with adhesive anchors, and to give designers and installers confidence and flexibility in a myriad of applications. However with the failure of adhesive anchors in Boston, the installation and use of these types of anchors has been called into question in some cases. To determine what can be improved with regard to the use of adhesive anchors, the installation of this anchor type was monitored on 23 construction sites in five locations in the United States. Within the field research project, all critical aspects were considered to analyze the situation in practice, to determine the deviations between theory and practice, and to come up with proposals for improvement of the installation in practice.

FIELD RESEARCH PROJECT

The field research project included the investigation of the installation of adhesive anchor systems in five locations in Illinois, Florida, California, Pennsylvania, and New York (Figure 1). In total 23 construction sites in broad areas of building construction, road construction, bridge construction, and hydraulic engineering were visited; 26 applications were monitored and 31 installers were interviewed (Table 1). On the construction sites, 13 different adhesives, both epoxy-based mortars and hybrid mortars were installed. Nine out of these products had an ESR number. The steel anchors were continuously threaded steel rods or deformed steel reinforcing bars. The adhesive anchors were used to connect non-structural elements to supporting concrete structures or other structural elements, as well as for the connection of load transferring structural elements. Fields of application were bridge

strengthening, earthquake retrofitting, connection of shear walls with the main structure, anchoring steel elements to existing concrete members, roadway doweling, hurricane protection, and anchoring of building façades. In 13 of the 26 applications, the anchors were installed downward. In 11 applications the anchors were installed horizontally, and in two applications they were placed overhead.



Figure 1 — Locations for the field research project

Table 1 — Details of the survey

location	Illinois	Florida	California	Pennsylvania	New York	Total
job sites	6	7	5	2	3	23
applications	7	8	5	3	3	26
surveys	8	6	8	5	4	31

All information relevant to the installation was monitored on-site by the first author and the findings were recorded in a detailed protocol. Furthermore, installers were interviewed to assess their professional and educational background, their experience in post-installed anchor installation and training, their general anchor installation practice, and their general opinion concerning the pros and cons with regard to the installation of adhesive-bonded anchors. In the following paragraphs, the findings of the research study are discussed and evaluated.

General observations

Figure 2 summarizes the general observations made on site. All manufacturers' printed installation instructions (MPII) were analyzed to evaluate whether or not the required information to ensure a correct installation was given. Nine out of the 13 products (five with an ESR and four without an ESR) do not provide all of the information that is necessary to install the adhesive anchor correctly.

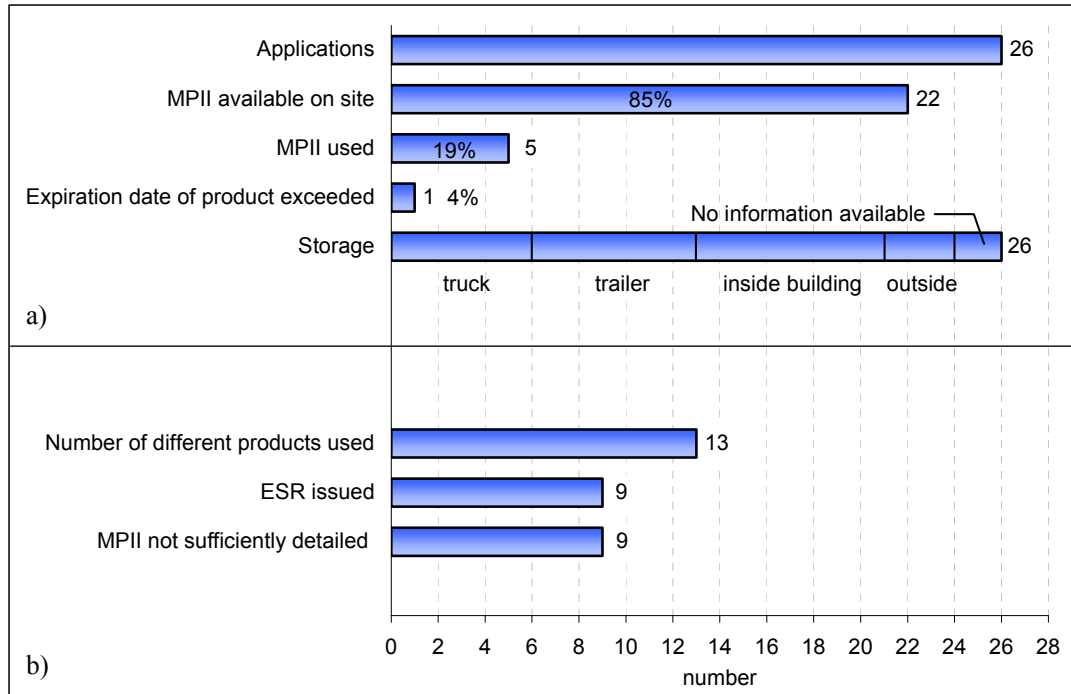


Figure 2 — General observations on job sites a) monitored applications b) different products used

In 85 percent of the 26 applications the manufacturer's printed installation instructions (MPII) for the subject adhesive system were available on site, but only 19 percent of the installers used the instructions. In one application, the expiration date of the used product was exceeded. Furthermore, the installers were asked about the storage of the adhesive: 23 percent answered that they store the adhesive inside the truck, 27 percent in the trailer, 31 percent inside the building, 12 percent outside in a job box, and 8 percent gave no information. Most systems require the adhesive to be stored in a cool, dry and well ventilated area at temperatures in a specified range, and away from excessive heat and light. Some MPIIs gave no information about the storage. This might represent foreseeable misuse.

Drilled Hole

Figure 3 shows the findings for the hole drilling, cleaning, and the resultant condition of the drillhole. In 38 percent of all applications, the correct drill bit size was used, in 23 percent the drill bit was too large (maximum deviation 33 percent), in 15 percent the drill bit was too small (extreme case drill bit $\approx$ nominal anchor rod size), and in 23 percent there was no information about the correct drill bit given in the MPII. Depending on the product, the anchor capacity might be reduced by the use of an improper drill bit size. Therefore a drill bit with defined tolerances as stated in the MPII shall be used. A depth stop or gauge was used in only 23 percent of the installations. In the MPIIs there is no specific requirement to use a depth stop, but all installation instructions state that the hole has to be drilled to the correct size and depth; this is only possible when using adequate accessories and aids.

Figure 3c illustrates the types of cleaning methods monitored on site. All products require blowing either with hand pump or compressed air, and additional brushing of the borehole. This cleaning procedure was performed in only six out of 26 installations. In a mere five out of 26 applications, the drilled holes were cleaned according to the MPII (Figure 3d). In general, the required cleaning tools were not available on site. Figure 3e shows the condition of the borehole before installing the anchor. In 85 percent of the installations the borehole was dry, but in 8 percent the anchor was installed in a water filled hole. Most systems require the drilled holes to be free of standing water, dust, debris, ice, grease, oil or other foreign materials.

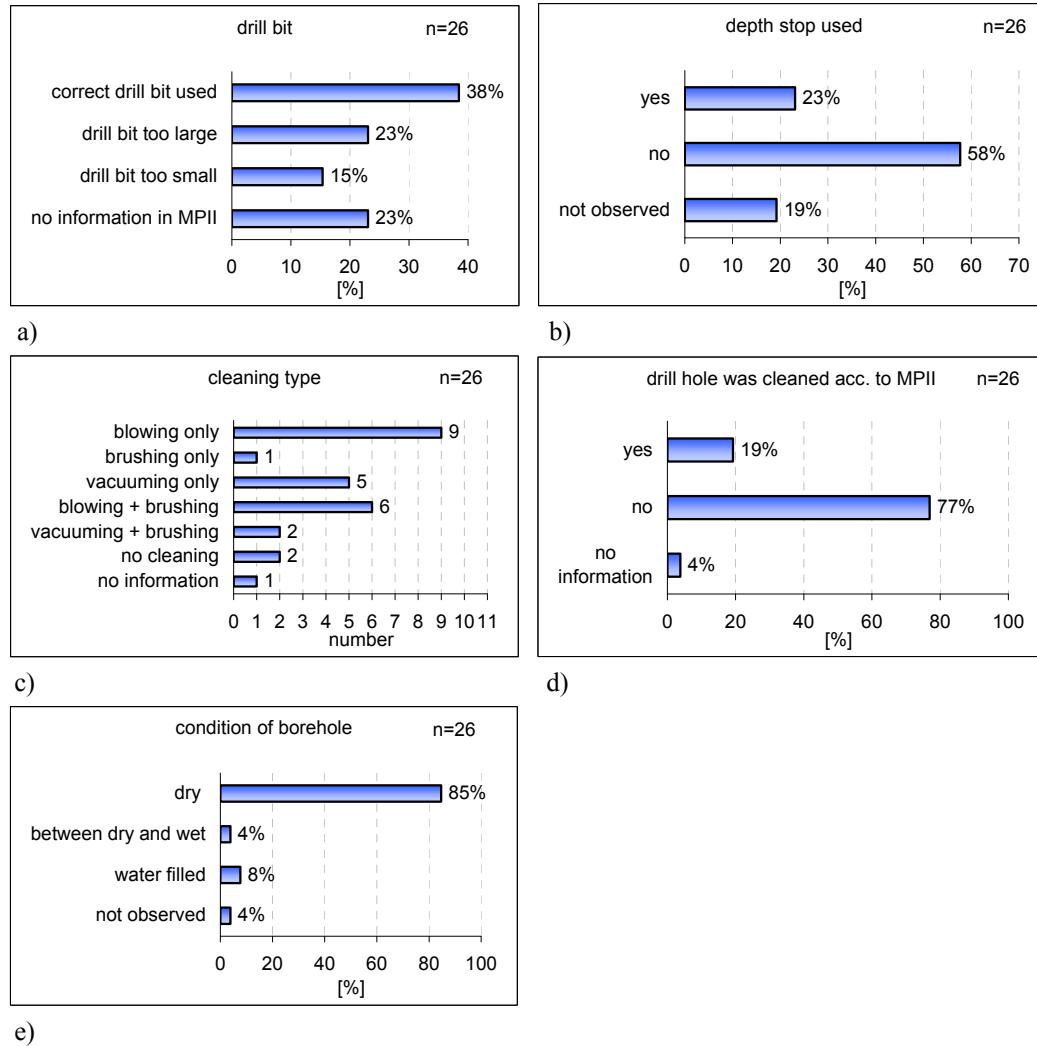


Figure 3 — Analysis of applied borehole drilling and cleaning

Adhesive, installation and curing

Figure 4 presents statistics of the observed injection and curing process. The MPIIs require that the first mortar shall be squeezed out prior to dispensing into the hole when using a new cartridge to ensure a uniform mix of the adhesive components. In only 31 percent of the applications were these requirements followed (Figure 4a). Many installers took a recently used mixing nozzle and only squeezed out the remainder of the old adhesive within the nozzle, instead of dispensing the first part of the new adhesive in a cartridge. This misinjection can yield a significant decrease in the capacity of the installed bonded anchor, because it can be assumed that the actual ratio between hardener and resin is different from the mixing ratio required for full conversion.

In 19 percent of the applications, the adhesive was not injected from the bottom of the hole (Figure 4b). In these instances the hole wall and steel insert may not be fully covered by the adhesive and air voids may be present in the hardened mortar. Both effects yield a significant reduction in capacity and durability. Furthermore, depending on the product, oxygen inhibition might interrupt the curing process of the adhesive and therefore negatively influence the anchor capacity. After insertion of the anchor rod or reinforcing bar there must be spare adhesive visible all around the mouth of the hole to ensure that the hole is fully filled with mortar. In only 58 percent of the applications, spare adhesive was visible for all the installed anchors (Figure 4c). Because of missing mortar near the top of the hole, the anchor rod is not bonded to the hole wall over its full length and therefore its capacity will be reduced.

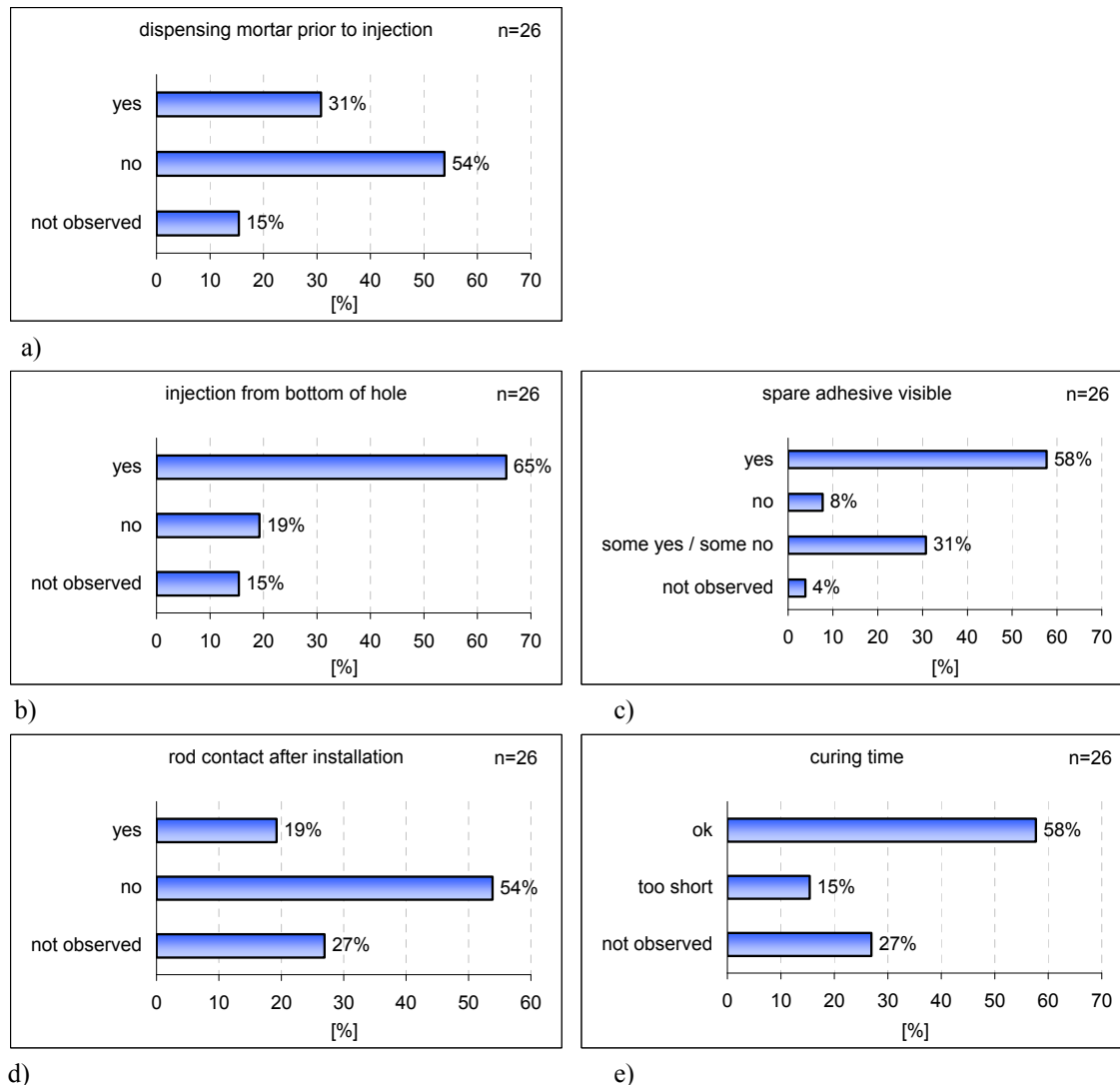


Figure 4 — Analysis of adhesive injection and curing process

After inserting the anchor into the adhesive, each system requires a curing time, that depends on the temperature of the base material. During this time it is necessary to ensure that there is no displacement or disturbing of the anchor rod. In 19 percent of all installations, rod contact was observed during the curing time (Figure 4d), which could partially destroy the bond between concrete and mortar. In 15 percent of the applications, the curing time was not followed before loading the anchors (Figure 4e).

Special inspection

Figure 5 illustrates the influence of special inspection on the drilled hole cleaning according to the MPIs for the different locations. Continuous or periodic inspection for anchor installation was only found in California and in one application in Florida. While in California all drilled holes were cleaned properly and all anchors were installed correctly, in the other locations the holes were not cleaned properly. This clearly indicates the need for effective special inspection by well-trained inspectors to ensure proper anchor installation, because the special inspection in Florida was not successful. To ensure the load capacity of the adhesive anchors predicted by the design methods is put into practice on-site, the authors highly recommend that the designers check, to see if the periodic or continuous inspection is effectively performed by experienced personnel, and the adhesive anchors are installed by suitably qualified installers.

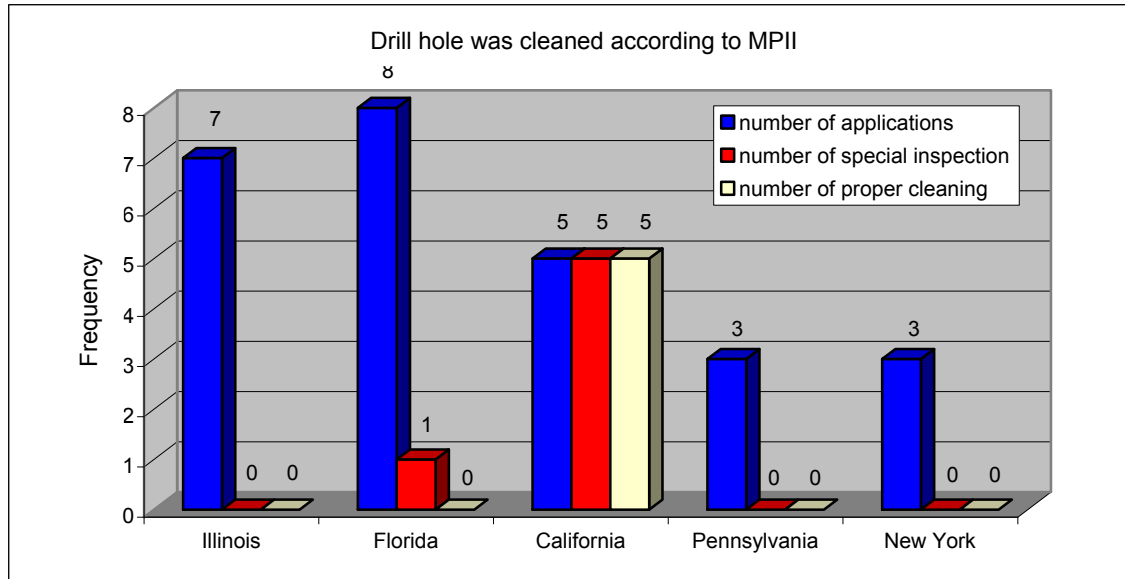


Figure 5 — Influence of special inspection of anchor installations on site on proper borehole cleaning

Installers

After monitoring the installation of adhesive anchors on the 23 construction sites, the 31 installers were asked to complete a questionnaire, which was provided in different languages to avoid translation problems. The completed questionnaire gave information on adhesive anchor installations on other sites and the educational background of the installers.

Almost all of the installers had a technical background. The majority of them had trade professions like carpenter, millwright, ironworker, or general construction workers (laborer). Figure 6 summarizes the years of experience in their professions and in post-installed anchoring technology. Most of the installers noted that they had installed anchors for several years.

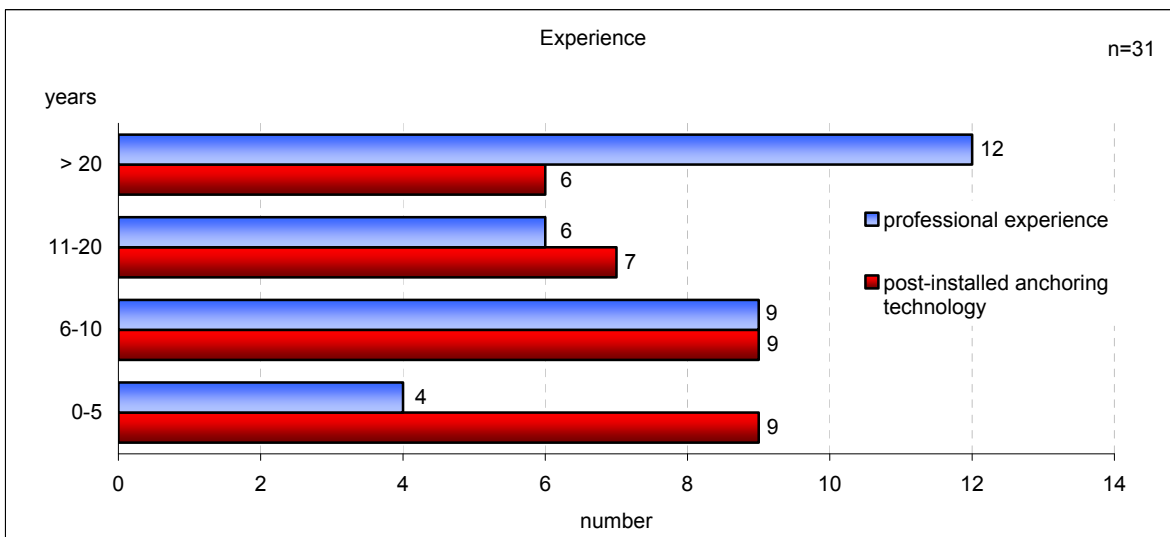


Figure 6 — Years of experience of the installers

The majority of all installers wanted to install the anchors in a proper fashion and tried to perform the installation process carefully based on their experience and knowledge. They were eager to improve their knowledge in fastening technology and installation procedures. However, in general they were not informed about changes and improvements in installation procedures. The evaluation of the questions with regard to installation training is given in Figure 7. Sixty-five percent of all installers stated that they gained their knowledge in post-installed anchoring technology either from “learning by doing” or by watching a colleague. Only 25 percent answered that they were trained by a manufacturer on-site or through an in-house seminar. Ten percent answered that they garnered their knowledge from other sources, such as schools.

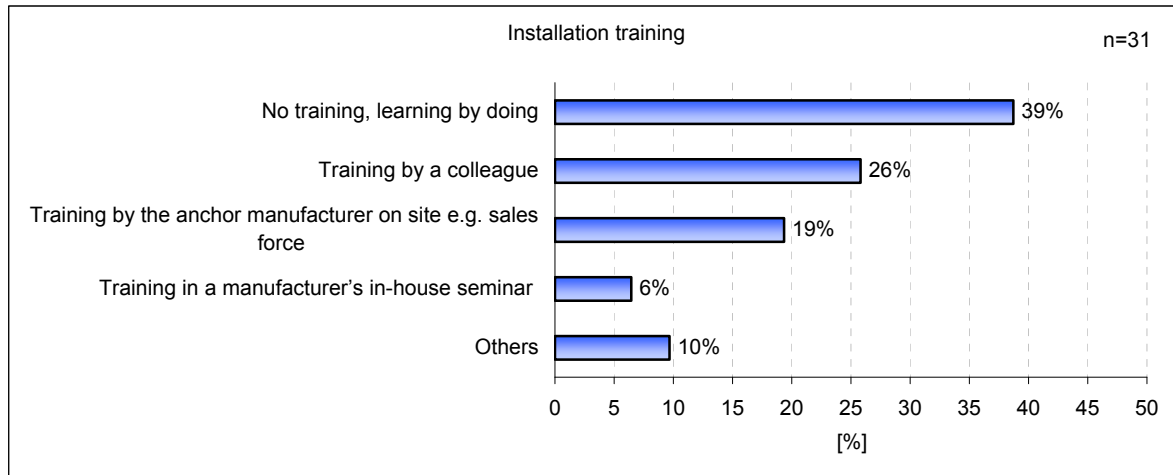


Figure 7 — Training of installers

Installers were also asked their opinion with respect to the various steps of the anchor installation process. These steps included the influence of the drilling method, the hole cleaning method and the storage of the adhesive as it related to the capacity of bonded anchors. These results are shown in Figure 8.

According to the analysis, about sixty percent of the interviewed installers knew that the drilling method had an influence on the anchor capacity (Figure 8a). Only about fifty percent of these people knew that hammer drilling gives a higher tensile capacity for adhesive-bonded anchors compared to diamond core drilling (Figure 8b) because of the rougher drilled hole wall.

About 25 percent of the installers had no knowledge regarding the influence of hole cleaning (Figure 8c). Thirty-three percent of the installers posted that they clean the holes by compressed air, only. Only 27 percent perform the required cleaning operations, that is “blowing and brushing” (Figure 8d). This agrees with the findings on site (compare Figure 3c).

Correct borehole cleaning was mainly found in California, which is likely attributed to the effective special inspection. Seventy-seven percent of the installers answered that the storage temperature has an influence on the anchor capacity; however, 56 percent stated that they store the adhesive on-site or “somewhere else”, where storage temperature cannot be controlled (Figure 8e and 8f).

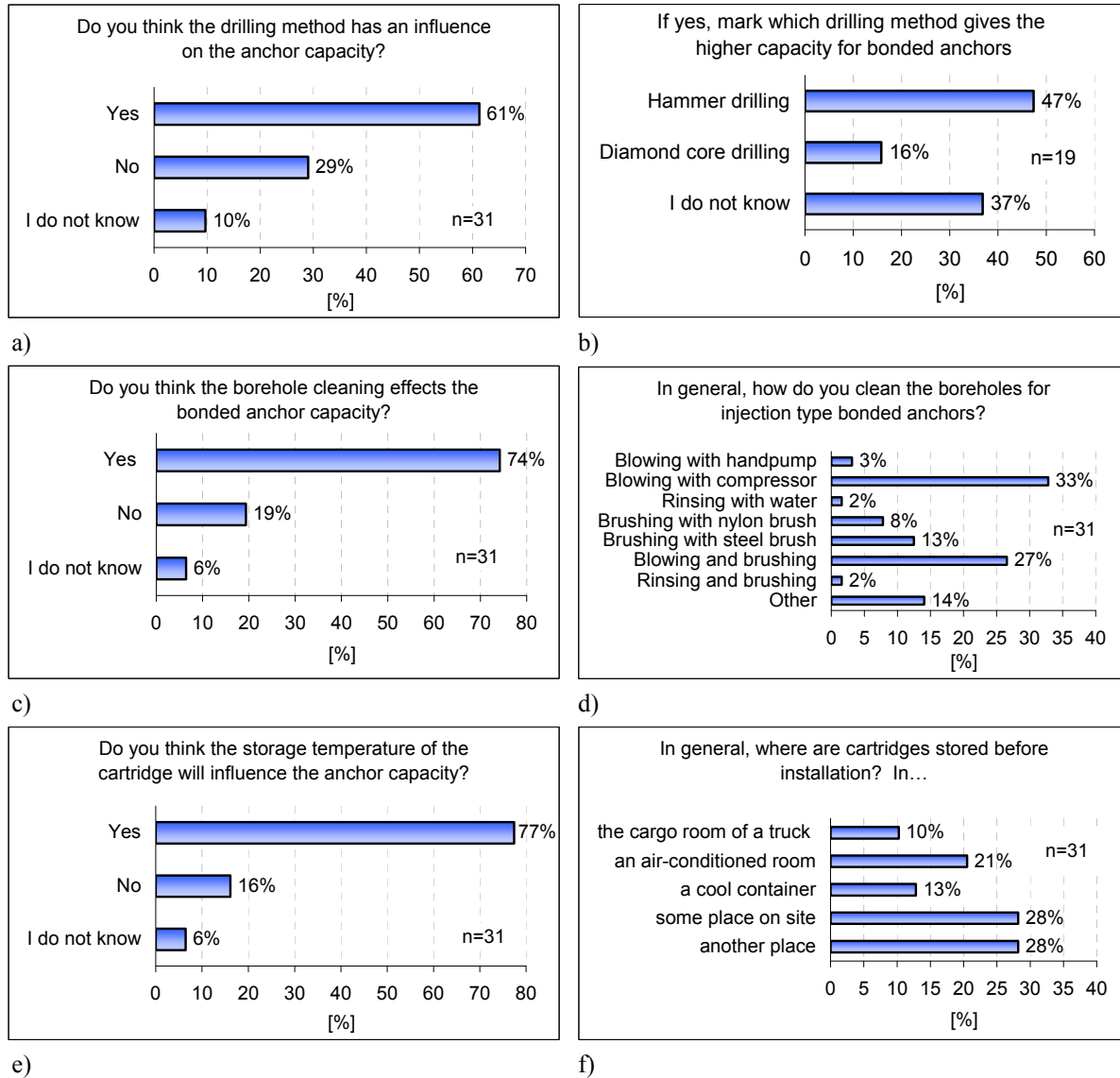


Figure 8 — General opinion of the installers

CONCLUSION

It is well known that many environmental and installation parameters significantly influence the tensile load capacity of adhesive-bonded anchors. This is taken into account by prequalification procedures for adhesive anchors e.g. AC 308² and ACI 355.4⁵ as well as by the installation instructions of the adhesive anchor manufacturers. However, when using post-installed adhesive anchors the “human factor” in the form of the designer and the installer can become an added factor. In the study reported herein, the primary focus was on the installer. To identify the difference between theory and practice (i.e. the transfer of instructions provided by evaluation services and manufacturers to the installers on-site), a field research project was performed.

The findings clearly demonstrate there is a significant difference between the requirements according to the Evaluation Reports and the manner in which the installer installs adhesive-bonded anchors on-site. In the following the findings of the project are summarized and evaluated:

- Sixty-five percent of all installers responded that they never had “proper training” in anchoring technology through a manufacturer or in school. This agrees well in the manner by which they installed the anchors. Installers were very anxious to install the anchors correctly; but in most cases, many deviations could be identified just due to a lack of proper information and knowledge.
- Twenty-six applications were monitored, in which 13 different products were used. For all products, the manufacturer’s printed installation instruction (MPII) were evaluated with respect to the information needed on site. For nine out of 13 products it was not possible to locate all of the required information to install the anchors correctly, because the MPII lacked sufficient detail. This was found for products with and without an ESR. Furthermore, in four out of 26 applications the MPII was not available on-site.
- It was discovered that in only about forty percent of the installations, the correct drill bit size was used. Installers were observed using wrong drill bits either because they had no other drill bit on site or because it was not possible to find the correct information in the MPII.
- Similar results were found for drill hole cleaning. Installers were using the tools available on site and not the required cleaning tools according to the MPII’s. In only five out of the 26 applications the cleaning of the hole cleaning technique was performed according to the MPII’s.
- On jobsites where effective special inspections were conducted, the cleaning and installation process was performed according to the MPII’s.
- It was observed in some applications that the mixing of the components and the amount of adhesive used was not sufficient. Only about thirty percent of the installers expressed the first volume of epoxy when using a new cartridge and in only sixty percent of the installations was spare adhesive visible for all anchors. This indicates a lack of training and knowledge.
- In about twenty percent of the applications, the anchor was contacted and disturbed after the installation (e.g. bending of the installed reinforcing bar).

SUMMARY

In summary, there is sufficient and proper knowledge in the industry and through technical literature regarding the installation and behavior of adhesive-bonded anchors. All critical aspects influencing the load carrying behavior are well known. Furthermore, detailed Acceptance Criteria are available to test the suitability of adhesively bonded anchors and to evaluate their allowable conditions of use. Only products with an Evaluation Service Report (ESR) confirming to the current Building Code for use in concrete (e.g. 2006 IBC) are recommended for use; these products have been thoroughly tested in concrete, and their properties are ensured by quality control during production.

This study indicates that the available information is only partially used by the installers, either by a lack of knowledge or through insufficient installation instructions. It can be concluded that there is an important need to improve the installation process for adhesive anchors on the jobsite; installers need more detailed training in installing these types of anchors. To address this issue ACI Committee C 601-A “Adhesive Anchor Installer” is working on a new certification program on a fast-track basis.

In parallel with installer certification, for critical applications, an effective special inspection program seems to be necessary to ensure anchors are installed correctly. Proof-loading will also be effective, because installations with a significant reduction in capacity are thus identified; the contractor has a vested interest in a correct anchor installation to avoid problems if the proof-loading criteria are not met.

Finally, criteria for the manufacturer’s printed installation instructions should be comprehensive enough to ensure all necessary information is available in these documents. It is recommended that they are written and illustrated in a uniform, clear and unmistakable way to facilitate the reading and understanding of the instructions by the installer.

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