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.

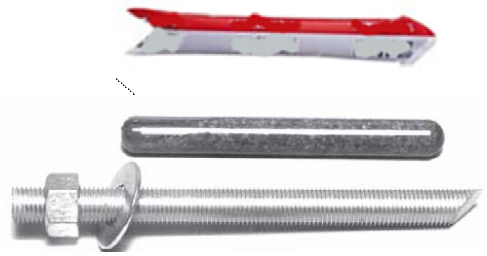
In injection anchor systems (Fig. 1b), plastic or foil cartridges containing pre-measured amounts of resin and hardener allow controlled mixing of polymer components. The components are typically mixed through a special mixing nozzle as they are dispensed, or are completely mixed within the cartridge 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.

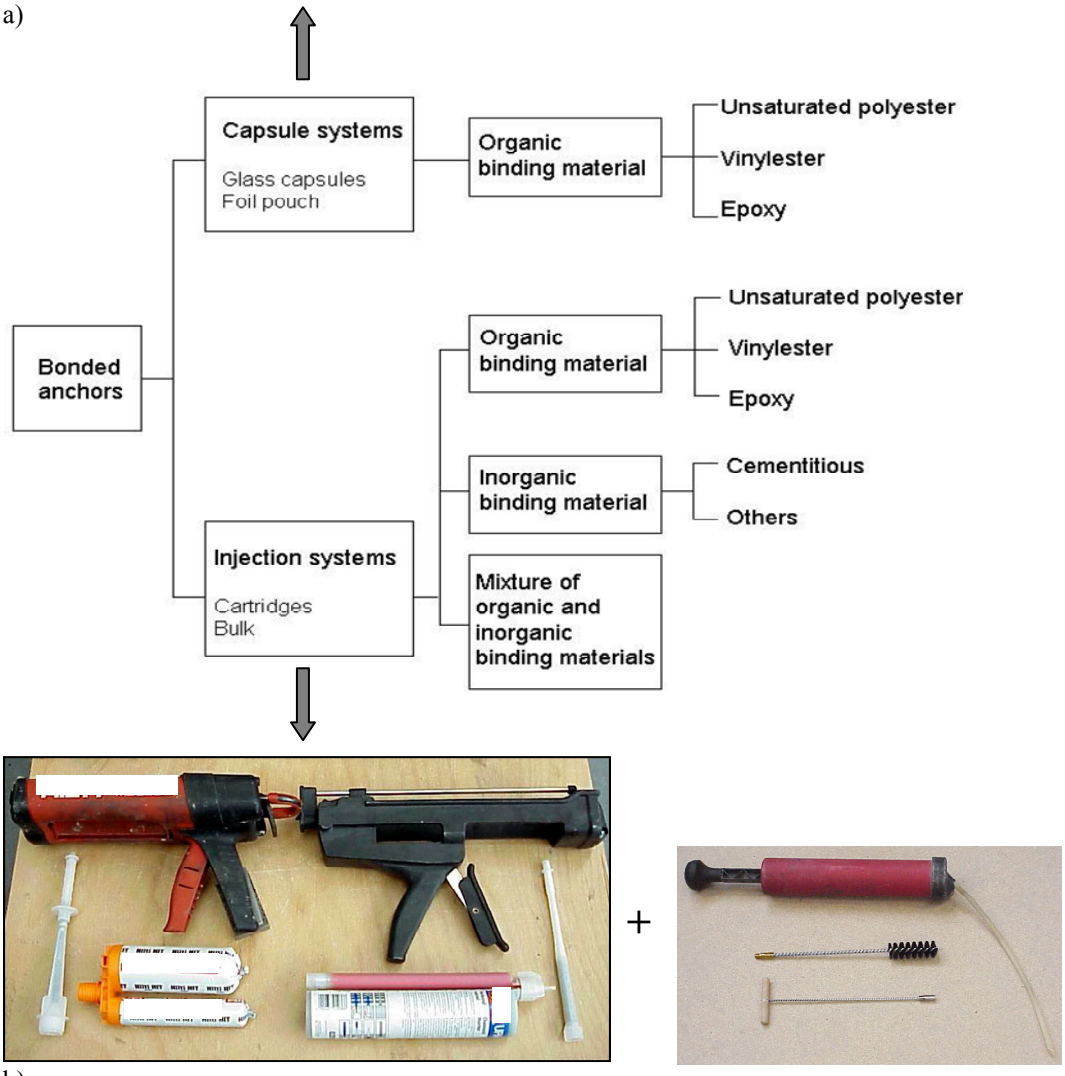
Epoxy systems of different manufacturers are not equal. The same is valid for vinylester and hybrid systems. They differ in the storage requirements, the installation temperatures, the installation procedure, the sensitivity to water, temperature and chemicals in installation and service, the sensitivity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



a)



b)

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.

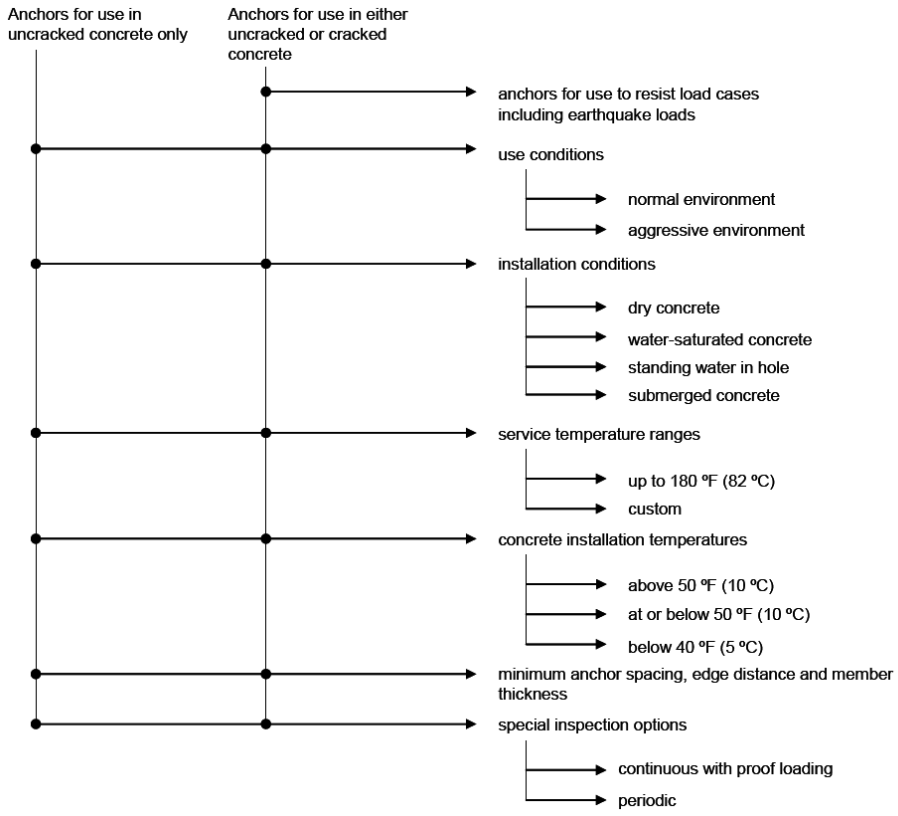


Figure 2 - Options according to ICC AC308 for chemical anchors

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