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
Eligehausen and Fuchs

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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
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 AC 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.
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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 Gроссer 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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ACI C601A (2011), *Adhesive Anchor Installer Certification Program.* American Concrete Institute, Farmington Hills.


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
compared to the relevant reference values to establish reduction factors on the design bond stress for both the long- and short-term temperature cases.

The design bond strength is established. Freezing and thawing tests are optional under AC308 (ICC-ES 2006), but values. Where these criteria are not met, the test is repeated with a reduced sustained load and a reduction factor on the decline with increasing cycle count, trending towards zero, and the residual strength is compared with reference values.

Temperature category A requires assessment of the anchor for 110 °F (43 °C) whereby the second, higher temperature is assumed to represent a short-term condition. Temperature category B permits establishment of anchor 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 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 30 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.
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](image1.png)

**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.
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.

\[ N_{ba} = \lambda \tau_{cr} \pi d_a h_{ef} \]  

where

- \( N_{ba} \) = characteristic basic bond strength
- \( \tau_{cr} \) = characteristic bond stress in cracked concrete (psi, MPa)
- \( d_a \) = anchor diameter (in., mm)
- \( h_{ef} \) = effective embedment depth (in., mm)
- \( \lambda \) = 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.

\[ c_{na} = 10d_a \sqrt{\frac{\tau_{uncr}}{1100}} \]  

\[ c_{na} = 10d_a \sqrt{\frac{\tau_{uncr}}{7.5}} \]  

where

- \( c_{na} \) = critical edge distance (in., mm)
- \( d_a \) = anchor diameter (in., mm)
- \( \tau_{uncr} \) = 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.

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 \( \psi_{c,Na} \geq 1 \) which accounts for the increased bond area associated with very closely spaced or bundled adhesive 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, \( \psi_{g,\infty} \) – 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 \( \psi_{g,\infty} \) 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, \( k_b \), 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 overhead 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. ¹

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 strengths.

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, \( \lambda_a \), 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, \( \lambda_a \), for lightweight concrete

<table>
<thead>
<tr>
<th>Concrete breakout failure of cast-in and undercut anchors</th>
<th>All-lightweight concrete</th>
<th>Sand-lightweight concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.75</td>
<td>0.85</td>
</tr>
<tr>
<td>Concrete breakout failure of expansion and adhesive anchors</td>
<td>0.60</td>
<td>0.68</td>
</tr>
<tr>
<td>Bond failure of adhesive anchors</td>
<td>0.45</td>
<td>0.51</td>
</tr>
</tbody>
</table>

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 parameters

<table>
<thead>
<tr>
<th>Characteristic bond strength</th>
<th>1,400 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading</td>
<td>static</td>
</tr>
<tr>
<td></td>
<td>sustained</td>
</tr>
<tr>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Strength reduction factors</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>Design assumption</td>
<td>crack</td>
</tr>
<tr>
<td>Compressive strength range</td>
<td>f ‘C = 4,000 – 6,000 psi</td>
</tr>
<tr>
<td>Composition</td>
<td>aggregate</td>
</tr>
<tr>
<td>Max. in-service temperature</td>
<td>110°F</td>
</tr>
<tr>
<td></td>
<td>sustained</td>
</tr>
<tr>
<td></td>
<td>transient</td>
</tr>
<tr>
<td>Thread sizes</td>
<td>5/8” – 1”</td>
</tr>
<tr>
<td></td>
<td>#4 - #9</td>
</tr>
<tr>
<td>Material</td>
<td>A193 B7</td>
</tr>
<tr>
<td></td>
<td>Gr. 60</td>
</tr>
<tr>
<td>Min. specified tensile strength</td>
<td>125 ksi</td>
</tr>
<tr>
<td></td>
<td>75 ksi</td>
</tr>
<tr>
<td>Treatment</td>
<td>hot dip galvanized</td>
</tr>
<tr>
<td>Installation temperature range</td>
<td>40°F</td>
</tr>
<tr>
<td></td>
<td>50°F</td>
</tr>
<tr>
<td>Lowest</td>
<td></td>
</tr>
<tr>
<td>Highest</td>
<td></td>
</tr>
<tr>
<td>Presence of water</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>Drilling method</td>
<td>rotary impact drill or rock drill</td>
</tr>
<tr>
<td></td>
<td>core drill</td>
</tr>
<tr>
<td>Inspection requirements</td>
<td>no</td>
</tr>
<tr>
<td></td>
<td>periodic</td>
</tr>
<tr>
<td></td>
<td>continuous</td>
</tr>
<tr>
<td></td>
<td>proof loading</td>
</tr>
</tbody>
</table>

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).

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

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ACI Committee 318, 2002, “Building Code Requirements for Structural Concrete (ACI 318R-02) and Commentary (ACI 318R-02),” American Concrete Institute, Farmington Hills, MI, 443 pp.

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ACI Committee 355, 2007, “Qualification of Post-installed Mechanical Anchors in Concrete (ACI 355.2-07) and Commentary (ACI 355.2R-07),” American Concrete Institute, Farmington Hills, MI, 31 pp.

ACI Committee 355, 2011, “Qualification of Post-installed Adhesive Anchors in Concrete (ACI 355.4-11) and Commentary (ACI 355.4R-11),” American Concrete Institute, Farmington Hills, MI, 150 pp.


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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Jacob Olsen currently holds the position of Managing Director of Powers Fasteners Shanghai. He has 8 years of experience working with concrete anchors including the last 5 years working with Powers Fasteners. He holds a Master’s Degree in structural engineering from San Francisco State University. He is a licensed professional civil engineer in the state of California and a member of ACI committee 355.

**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 ACI 308. 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.

![Post-installed adhesive anchor](image)

**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

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:

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

**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](image)
**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.

**Similarties 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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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 survey\(^1\) 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 308 or ACI 355. 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 Mattis; information on factors influencing the behavior of adhesive anchors can be found in Eligehausen, Mallée, Silva.

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

<table>
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<th>Illinois</th>
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<th>Pennsylvania</th>
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<td>7</td>
<td>5</td>
<td>2</td>
<td>3</td>
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<tr>
<td>applications</td>
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<td>8</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>26</td>
</tr>
<tr>
<td>surveys</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>31</td>
</tr>
</tbody>
</table>

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.
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 ≈ 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.
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.
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 MPIIs 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.
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 5 — Influence of special inspection of anchor installations on site on proper borehole cleaning

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.

![Installation training](image)

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).
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 308 and ACI 355.4 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.

### ACKNOWLEDGEMENT

The authors wish to express special thanks to the company Powers Fasteners, Inc. for its support of the field research project.
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SYNOPSIS: Inspections in building construction have vital importance and are needed to verify that work considered critical to life, public safety and property protection is being or has been performed according to the approved plans and specifications. While the building official is obligated to inspect the construction progression at certain stages, some building construction activities demand closer scrutiny. This additional level of surveillance is known as special inspection. Because proper installation of adhesive anchors requires inspection procedures beyond those in the building codes, special inspection is needed. Clear, detailed specifications are essential to assure that the anchor is installed as intended, and verification in the form of inspection is needed to further assure installation-related tasks are performed properly.

Key words: adhesive anchors, International Building Code®, special inspection.
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INTRODUCTION

A key component in the modern building construction process is an inspection program. Inspections are needed to verify that work considered critical to life, public safety and property protection is being or has been performed according to the approved plans and specifications. The duty of enforcing inspections lies with the building official, the individual enforcing the building ordinance. Several driving factors, including legal liability, insistence on competent performance and completion of work as specified and approved, and more involvement of local government have been cited in the Model Program for Special Inspection (ICC, 2007) as reasons for building official involvement. In most localities within the USA, the International Building Code® (IBC, 2009), a model building code that has been adopted in all 50 states, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, the Department of Defense, the Department of State, and the Department of Commerce, along with several other countries, forms the core of the jurisdictional ordinance. In turn, the IBC draws upon other resources, such as ACI 318 (2008), to more completely define the code enforcement process.

Post-installed adhesive anchors are not directly within the scope of the IBC. Rather, adhesive anchors are alternatives, which can be accepted when satisfactory evidence complying with IBC Section 104.11 is submitted to the building official. This paper reviews the current inspection requirements in the IBC, along with the roles and responsibilities of the different parties involved. The paper then examines adhesive installations and summarizes special inspection requirements for adhesive anchors as currently there are no provisions in the IBC.

INSPECTIONS AND BUILDING CODES

IBC Section 110 requires construction or work for which a permit is required to be subject to inspection by the building official. While the building official is obligated to inspect the construction progression at certain stages, some activities demand further scrutiny. One additional level of surveillance is known as “special inspection” and is introduced in IBC Section 1704. Section 1704 of the 2009 IBC states that where application is made for construction, either the owner or the registered design professional (engineer or architect) in responsible charge acting as the owner’s agent must employ one or more special inspectors to provide inspections during construction on the types of work listed under Section 1704. The IBC also states that the special inspections defined in Section 1704 are in addition to the inspections specified in Section 110. Special inspections apply to structural and other critical systems.

Section 1702 of the 2009 IBC also defines two types of special inspection: “continuous” and “periodic.” While continuous inspection requires full-time observation of work, periodic inspection requires part-time or intermittent observation.

Besides special inspection, IBC Section 1702 refers to “structural observation,” which is service performed by the responsible registered design professional. All of these activities – inspections by the building official and special inspector, along with structural observations by the registered design professional – constitute project quality assurance.

Special Inspection Program

As set forth in IBC Section 1705, the registered design professional, typically the Structural Engineer of Record (SER), establishes the special inspection program by preparing a Statement of Special Inspections; this is submitted with the construction documents to the building official during the process of obtaining a building permit. The Statement of Special Inspections needs to:
• Provide general project information
• Indicate individuals involved in the project
• Include the schedule of special inspections, which will indicate the project-related structural elements and their components that require special inspection, such as anchors
• Designate the appropriate firms and/or individuals to perform special inspections
• Outline responsibilities of the special inspector, including reporting requirements

As outlined in IBC Section 1705.2, the statement of special inspections must cover:
1. The materials, systems, components and work required to have special inspection or testing by the building official or by the registered design professional responsible for each portion of the work.
2. The type and extent of each special inspection.
3. The type and extent of each test.
4. Additional requirements for special inspection or testing for seismic or wind resistance as specified in Section 1705.3, 1705.4, 1707 or 1708.
5. For each type of special inspection, identification as to whether it will be continuous special inspection or periodic special inspection.

Special Inspector Function

Special inspectors are not employed by the building official, but rather are independent parties retained by the building owner or registered design professional. The special inspectors have skills and experience for certain construction disciplines, such as concrete. In addition, because special inspectors review the work of building contractors, the IBC prevents contractors from hiring the special inspectors to avoid this conflict of interest.

The IBC provides some fundamental requirements for special inspectors, but leaves other details to the discretion of the building official. For example, the building official is responsible for approving the special inspector. The IBC does not elaborate further on what specific qualifications a special inspector should possess beyond demonstrating competence, experience, and training.

There are certain assumptions about special inspectors that must be clarified. First, the special inspector does not replace the building official, who has responsibilities for general inspections, while the special inspector typically inspects a certain type of work during construction. Second, the special inspector does not have authority to stop work if discrepancies are uncovered and not resolved; this work stoppage is the responsibility of the registered design professional and the building official.

The special inspector is assigned to inspect certain construction work as outlined in the Statement of Special Inspections. In the 2009 edition of the IBC, great emphasis is placed on the need for special inspectors to prove their competence, training, and experience as a condition of being approved for such work.

Typical duties of special inspectors include the following:
1. General requirements: Special inspectors are charged with reviewing plans and specifications, approved and stamped by the building official, for special inspection requirements.
2. Signify presence at jobsite: Special inspectors must inform the contractor of their presence and responsibilities at the jobsite. The building official may require the inspector to sign in on the appropriate form posted with the building permit.
3. Observe assigned work: Special inspectors must inspect all work for which they are responsible (for conformance with the approved plans and specifications), in accordance with the applicable provisions of IBC Section 1704, and local ordinances.
4. Report nonconforming items: Once discovered, special inspectors need to bring all nonconforming items to the immediate attention of the contractor. If the item is not fixed in a timely manner or is about to be incorporated into the work, the special inspector must immediately notify the registered design professional in responsible charge and the building official. The nonconforming item must be noted in the special inspector’s written report as required in IBC Section 1704.1. The special inspector also must write a separate report to be posted at the jobsite regarding noted discrepancies, which should contain, as a minimum, the following information about each nonconforming item:
   • Description and exact location
• Reference to the applicable detail of approved plans/specifications
• Name and title of each individual notified and the method of notification
• Resolution or corrective action taken

5. Provide timely reports: The special inspector must complete written inspection reports for each inspection visit, and provide the reports on a timely basis as determined by the building official. The special inspector must furnish these reports directly to the building official, the registered design professional in responsible charge, and others as designated in accordance with IBC Section 1704.1.2. These reports should be organized daily, but may be submitted weekly at the option of the building official. In these reports, special inspectors should:
  • Describe inspections and tests made, with applicable locations
  • Indicate how nonconforming items were resolved
  • List unresolved items, parties notified, and time and method of notification
  • Itemize changes authorized by the registered design professional in responsible charge, if this information is not included in nonconforming items summary

6. Submit final report: Special inspectors must submit a final signed report to the building official, stating that all items requiring special inspection and testing were observed and reported and, to the best of their knowledge, are in conformance with the approved plans, specifications and the applicable provisions as set forth in IBC Section 1704.1.2. Items not in conformance, unresolved items or any discrepancies in inspection coverage (i.e., missed inspections, periodic inspection when continuous was required, etc.) should be specifically itemized in this report.

**Registered Design Professional Function**
In addition to designing the project, and providing plans and specifications reflecting this design, the registered design professional is a key player in the special inspection activity. As mentioned previously, the registered design professional may act as the owner’s agent in hiring the inspector and must prepare the statement of special inspections.

The registered design professional in responsible charge must respond to special inspector reports of uncorrected, noncomplying items and must approve remedial measures. The registered design professional in responsible charge must acknowledge and approve shop drawings that may detail structural information. The registered design professional must submit written approval of any verbally approved deviations from the approved plans to the building official and to the special inspector, and must submit revised plans for building official approval as required.

**Contractor Function**
The contractor’s duties include notifying the special inspector regarding inspections required by the Statement of Special Inspections. Adequate notice should be allowed so that the special inspector has time to become familiar with the project. The contractor is responsible for providing the special inspector with access to approved plans. When required by the building official, the contractor is responsible for retaining at the jobsite all special inspection records submitted by the special inspector, and providing these records for review by the building official upon request.

Also, where the contractor is constructing a building’s wind or seismic lateral force resisting system, he or she must issue a written statement of responsibility to the building official, acknowledging the need for special inspections, as indicated in the Statement of Special Inspections. While IBC Section 1709 only requires this statement of responsibility for construction of the lateral force resisting system, it is preferable to seek the contractor’s acknowledgement for all construction where special inspections are stipulated.

**Building Official Function**
Of all the team members involved in the construction process, the building official is the only one with the legal authority to enforce the special inspection provisions of the IBC. The employment of a special inspector or agency does not relieve the building official of the responsibility for inspections required by the IBC. Building official inspections of items also requiring special inspection should not be signed off without the concurrence of the special inspector.

The specific duties and responsibilities of the building official relating to special inspection include the following:
1. Review submittal documents for compliance with special inspection requirements. The building official is given legal authority to review the plans, specifications, Statement of Special Inspections, statement of contractor responsibility, and other submittal documents for compliance with code requirements.

2. Approve the special inspection program. The building official is responsible for approving the special inspection program as outlined in the Statement of Special Inspections submitted by the design professional, and may require a preconstruction conference to review the program with all applicable members of the construction team.

3. Approve special inspectors/inspection agencies. The building official is responsible for determining the competence of special inspectors for the construction work they will be inspecting.

4. Monitor special inspection activities. The building official should monitor the special inspection activities at the jobsite to assure that qualified special inspectors are performing their duties when work requiring special inspection is in progress.

5. Review inspection reports. The building official receives and reviews special inspection progress reports, and final reports, for conformance with the approved plans, specifications and workmanship provisions of the code.

6. Perform final inspection. The building official should not perform the final inspection and approval of a project until the final special inspection report has been reviewed and approved.

**ANCHORAGE TO CONCRETE**

Anchors placed in concrete have been subject to special inspection since the inception of the IBC. However, IBC Table 1704.4 previously included these requirements only for cast-in-place anchors complying with the allowable stress design provisions in IBC Section 1911. Therefore cast-in-place and post-installed anchors permitted by IBC Section 1912 for strength design technically had no inspection requirements. Nonetheless, many interpreted IBC Section 1912 as an alternative to IBC Section 1911, and extended the need for special inspections, particularly given that Section 1912 permitted a wider range of concrete strengths and types, as well as installation conditions such as embedments. The 2009 IBC corrected previous oversights by extending the need for continuous inspections to cast-in-place anchors designed according to IBC Section 1912, which in turn references ACI 318 Appendix D (2008). In addition, IBC Table 1704.4 permits post-installed anchors to be installed with periodic inspections. An excerpt from IBC Table 1704.4 is provided in Table 1.

**Adhesive Anchors**

The post-installed anchors addressed thus far are expansion or undercut types, as described in IBC Section 1912. Adhesive types are not directly within the scope of the IBC. Rather, adhesive anchors are alternatives, which can be approved if satisfactory evidence is presented to the building official. General guidelines for this evidence are given in IBC Section 104.11, which states that the alternative material must proven to be equivalent of that prescribed in the code in quality, strength, effectiveness, fire resistance, durability and safety. Adhesive or bonded anchors typically consist of an adhesive compound and either a steel threaded rod or a deformed reinforcing bar placed in a predrilled hole. These anchors can resist tension and shear loads after the adhesive has fully cured. The adhesive, depending on the type, will have inherent properties, including temperature sensitivity and resistance to sustained (creep) loads. The manufacturer has the option to provide data indicating adequate performance for certain serviceability conditions, such as placement in a cracked member, resistance to seismic loadings, and performance in wet, water-filled or submerged holes. This approach is allowed by IBC Section 104.11. Section 104.11.1 permits research reports from approved sources to be a source of information. ICC Evaluation Service, a subsidiary of the International Code Council, the publisher of the IBC, is one source of reports.

ICC-ES has published reports on adhesive anchors for many years and currently bases the adhesive anchor evaluations on its Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements (AC308, 2009). AC308 (2009) also specifies special inspection requirements for adhesive anchors. Two levels of special inspection are available: periodic inspection and continuous inspection combined with an on-site proof testing program. Periodic inspection is permitted under AC308 (2009) when the anchor exhibits superior performance in installation safety tests; these include reduced hole cleaning, reduced adhesive mixing, and the ability to place anchors in wet, water-filled, or submerged holes. Anchors not performing to the expected levels may be subjected to reduced acceptance levels and additional tests, with the condition that continuous inspection and a proof loading program be instituted. However, for overhead installations, continuous special inspection is required regardless of how well the anchor performs in the installation safety tests.

Because adhesive anchors in concrete require inspection procedures beyond those in the IBC, certain installation details need to be observed by the special inspector. Before any work is done, the special inspector...
should verify that the adhesive system components, which include the adhesive type and the steel insert type, are as specified on the approved plans. The adhesive packaging needs to be reviewed for manufacturer’s instructions (known as the MPII – manufacturers published installation instructions), published research reports, expiration dates, cleaning brushes, storage temperatures, and dispensing accessories. The steel insert parameters include material type, such as carbon or stainless steel; coatings such as hot-dipped galvanizing; configuration (commonly threaded rods or concrete reinforcing bars); and steel grade or specification, such as mild or high-strength steel. The manufacturer’s instructions and research reports will provide specifications for permitted ambient conditions, such as temperature; whether the holes can be dry, wet, water-filled, or submerged underwater; and the orientation of the anchor – vertical, horizontal, or overhead.

As installation commences, other items to check are location of anchors in the structure, location tolerances, concrete type (normal-weight or lightweight), concrete compressive strength, spacing, edge distance, hole size, insert embedment, concrete thickness, and size and type of steel insert, which are typically as specified by the registered design professional (subject to available qualification data).

In preparing the holes, the approved documents must be consulted as to the drilling method, drill bit size and type, hole size, and hole cleaning steps, which need to occur as specified on the approved documents. Hole cleaning typically consists of blowing drilling debris out of the hole using compressed air, brushing the hole with matching size wire or nylon brushes, and blowing the hole again. If the concrete is damaged by the hole drilling, the registered design professional needs to be notified to determine remedial measures. The holes need to be measured for depth and checked for any loose debris. Generally adhesives are multi-component materials that are mixed together, typically in a special nozzle before dispensing. The special inspector should observe that the components are mixed together properly before they are dispensed. After dispensing, the steel rod or bar is inserted (Before insertion, however, the steel needs to be checked to assure cleanliness and straightness). The steel should be placed to the bottom of the hole and agitated slightly to ensure adhesive contact.

After insertion, the adhesive must fill the hole to the concrete surface, and any excess material must be removed. The inspector should verify that the inserts are placed within the specified gel time and, once placed, are positioned against movement and are not disturbed until the full cure time has passed. Any damage to the concrete in the vicinity of the anchor needs to be brought to the attention of the registered design professional and the building official. The adhesive has inherent properties, including temperature sensitivity and resistance to sustained (creep) loads. The manufacturer has the option to provide data indicating adequate performance for certain serviceability conditions, such as placement in a cracked member, resistance to seismic loadings, and performance in wet, water-filled or submerged holes.

When specified on the approved plans, field or proof testing must be performed on the installed anchors. Typically, proof testing of the installed anchors is in accordance with the applicable sections of ASTM E 488 (1996). Testing should be conducted by a testing laboratory approved by the building official; the laboratory should have evidence that the measuring devices were calibrated recently.

The testing schedule should be addressed in the Statement of Special Inspections. The anchors should be organized into groups of the same type, diameter, strength, embedment length, and adhesive. The proposed testing locations should be specified. From each group, a portion of the anchors are tested, typically in tension. The tests subject the anchor to the load level specified in the Statement of Special Inspections and the load may need to be held for a certain time period. If failures occur, the special inspector should read the Statement of Special Inspections to see whether additional testing needs to be performed. This task, however, may be assumed by the registered design professional performing structural observations. Testing should only begin after the manufacturer’s recommended cure time has been reached. For anchors that fail, typically the adhesive and anchor steel must be removed and the anchors reinstalled with new materials.

**SUMMARY**

This paper provides the special inspection requirements for adhesive anchors, noted in the ICC-ES Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements (AC308, 2009). Clear, detailed specifications are essential to assure that the anchor is installed as intended, and verification in the form of special inspection is needed to further assure that installation-related tasks are properly carried out. The building official, by gathering resources and directing the inspection process, provides impartial confirmation that the anchor will
perform to expectations. The special inspector is responsible for verifying that every aspect of the undergoing inspection is in compliance with the plans and specifications. The registered design professional identifies specific components or elements within the construction that require special inspection, and responds when deviations from the plans and specifications are observed. The contractor notifies the special inspector when the work commences, and is required to correct in a timely manner any deficiencies identified.

Adhesive anchors are versatile fasteners for connections to concrete. Installations, though, require many steps such as hole preparation, adhesive preparation, component placement and curing. Successful and safe installations depend on properly following all relevant details. A well coordinated special inspection program should ensure that the adhesive anchors will perform as intended.

REFERENCES


ACI 318, “Building Code Requirements for Structural Concrete”, American Concrete Institute, Detroit, Michigan, 2008.


<table>
<thead>
<tr>
<th>Verification and Inspection</th>
<th>Continuous</th>
<th>Periodic</th>
<th>Referenced Standard</th>
<th>IBC Reference</th>
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<td></td>
<td>ACI 318: 8.1.3, 21.2.8</td>
<td>1911.5, 1912.1</td>
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<tr>
<td>Inspection of anchors installed in hardened concrete.</td>
<td></td>
<td>x</td>
<td>ACI 318: 3.8.6, 8.1.3, 21.2.8</td>
<td>1912.1</td>
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DESIGN METHOD FOR SPLITTING FAILURE MODE
OF ADHESIVE ANCHOR SYSTEMS

by Jörg Asmus

SYNOPSIS

Adhesive anchor systems loaded by tension can fail in a splitting failure mode. Splitting failure of a concrete member can be expected if the member dimensions are relatively small or if the anchors are installed near to an edge or corner in large concrete members. The splitting failure load depends on dimensions, on material properties of the concrete member, and on the anchoring system. The corresponding splitting failure load may be smaller than the pullout or concrete cone failure load.

In the last years, the load capacity of adhesive anchor systems was significantly increased and the range of the embedment depth was enlarged ($h_{ef} = 4d$ to $20d$). High performance adhesives have a high load-bearing capacity and are better able to utilize the concrete capacity. Therefore, the splitting failure mode has to be considered under certain admissible service conditions in the design of adhesive anchors.

This paper presents a design method for splitting failure for different post-installed adhesive anchor systems and compares calculated splitting failure load with the results of experimental investigations. Details of the design method are given to illustrate how installation parameters (edge distance, member thickness, embedment depth and material properties) and the anchor types influence the splitting resistance. In addition, the critical distances for splitting failure for post-installed adhesive systems with high, medium, and low pullout (bond) capacity are discussed.
BIOGRAPHICAL INFORMATION

Jörg Asmus graduated from the Technical University of Dresden, Department of Civil Engineering, Dresden, Germany, 1985. He served as a research associate and acting Laboratory Director Building Materials, Institute of Reinforced Concrete, Dresden from 1985-1990. After completing his Doctoral studies with Prof. Eligehausen at the University Stuttgart he joined the Engineering Firm Eligehausen in 1998. Dr. Asmus is a member of national and international committees in the field of fastening technology, and he is the author of several publications relating to these topics.

INTRODUCTION

Post installed adhesive anchor systems loaded under tension may fail by pullout failure (i.e. bond failure), concrete cone failure, or steel failure. For these failure modes, design methods are available. [1], [2], [3]. If the member dimensions are relatively small or if the anchors are installed near to an edge or corner, failure can occur by splitting of the member. The corresponding failure load may be smaller than the concrete cone failure load or pullout failure load. Therefore, the splitting failure mode has to be considered in the design of anchors.

The ultimate load associated with splitting failure is not easily predicted due to numerous influencing factors. Currently, splitting design is by prescribing minimum edge distances and spacing (splitting failure due to anchor installation) or critical edge distances (splitting failure due to loading) in design code documents. These parameters are determined by tests in unreinforced concrete. Numerous tests are required due to the wide range of embedment depth (h_ef = 4d to 20d) of adhesive anchors and the myriad of combinations of edge distances, spacings, and member thicknesses. In order to reduce the number of tests and to design safer and more economical anchorages, a realistic calculation method which accounts for splitting failure is needed.

In this paper, a method to address splitting failure of post-installed adhesive anchors will be presented. Details of the method are given to illustrate how installation parameters (edge distances, member thicknesses, embedment depth, and material properties) influence the splitting resistance. In addition, the critical distances for splitting failure for post-installed adhesive systems with high, medium, and low bond pullout capacity are discussed.

POST-INSTALLED ADHESIVE ANCHOR SYSTEMS

Post-installed adhesive anchor systems transfer tension loads along the embedment depth into the concrete by bond stresses between some type of steel rod or bar element and adhesive as well as by bond stresses between adhesive and surface of the drilled hole (Figure 1a). The bond stress shown in Figure 1a is the bond stress between the adhesive and the drill hole.

It is assumed that the installation of the adhesive anchors is according to the manufacturer’s installation instructions. After drilling a cylindrical hole by hammer drilling, the drilled hole thoroughly cleaned. Injection of the adhesive into the drilled hole is assumed by squeezing the material out of a dispensing cartridge (Figure 1b) and component materials are mixed in a static mixing nozzle. Immediately after the adhesive is injected into the drill hole, the element to be bonded is slowly twisted as it is gradually inserted into the hole to the required embedment depth.
Understanding Adhesive Anchors: Behavior, Materials, Installation, Design

When calculating the splitting failure load of anchors, several influencing factors must be considered: load transfer mechanism (type of anchor); dimensions of the application (embedment depth, edge distance, spacing, member thickness), concrete properties, and conditions of the drilled hole in the embedment material.

In the past, proposals to design for splitting failure of headed studs, undercut anchors and expansion anchors \cite{4} and adhesive anchors \cite{5} were published. For anchors with different load-transfer mechanisms different calculation methods are derived. In the recent past a simplified model for different anchor systems (undercut anchors, torque controlled expansion anchor, bonded anchor, bonded expansion anchor) was proposed. \cite{6} The different load transfer mechanisms, that is, mechanical interlock, friction, bond and the anchor construction were taken into account by using different product factors. The design methodology is based on the Concrete Capacity Design Method (CCD). \cite{1,3} In the following paragraphs, a design method to calculate the splitting failure load for post-installed adhesive anchors is presented.

The splitting failure load of an anchor group can be calculated by Equation (1). Equation (1) is based on the average splitting failure load $N^0_{\text{un,sp}}$ (Equation (2)) of a single anchor at the edge. The splitting failure load of a single anchor depends on the edge distance, the member thickness, and the concrete properties. Moreover, the effect of the load transfer mechanism and the load bearing area must be taken into account. Therefore, a so-called product factor, $k_p$, is proposed, which can be derived independent of the regulations in by conduction unconfined tension tests in the corner according to \cite{7}, \cite{8}, \cite{9}. The ratio $A_{\text{csp}}/A^0_{\text{csp}}$ (Equations (4) and (5)) takes the influence of spacing and, if applicable, of an additional edge effect from the splitting failure load. These effects are taken into account in a manner analogous to the CCD Method for a concrete edge failure mode under shear loading. The ratio $A_{\text{csp}}/A^0_{\text{csp}}$ predicts that the failure load will be proportional to the projected area and, hence, directly proportional to the thickness of the concrete member. However from experimental investigations, the splitting failure load is less than directly proportional to the factor $A_{\text{csp}}/A^0_{\text{csp}}$. Therefore, the factor $\psi_{h,sp}$, Equation (6), is inserted into Equation (1). The effect of the spacing $s_2$ of anchor groups perpendicular to the edge is considered by the factor $\psi_{s,sp}$, Equation (8). It is noted that the characteristic spacing $s_{\text{cr,sp}} = 2c_{\text{cr,sp}} = 3c_1$, Equation (7), is assumed consistent with that in the CCD-Method.
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\[ N_{um,sp} = N_{um,sp}^0 \cdot \frac{A_{exp}}{A_{exp}} \cdot \Psi_{h,sp} \cdot \Psi_{s,sp} \]  \[\text{[N]}\]  \[\text{(1)}\]

with

\[ N_{um,sp}^0 = \text{splitting failure load of a single anchor at the edge, see Figure 4} \] \[\text{[N]}\]

\[ k_p = \text{product factor for unconfined test support (splitting failure)} \] \[\text{[-]}\]

\[ c_1 = \text{edge distance} \] \[\text{[mm]}\]

\[ h_{cr,sp} = \text{characteristic member thickness, see Figure 3} \] \[\text{[mm]}\]

\[ h_{cr,sp} = h_{ef} + c_{cr,sp} \] \[\text{[mm]}\]

\[ c_{ef} = \text{embedding depth} \] \[\text{[mm]}\]

\[ c_{cr,sp} = \text{characteristic edge distance (splitting failure)} \] \[\text{[mm]}\]

\[ f_{cc,150} = \text{concrete compressive strength, measured on cubes 150 x 150 x 150 mm} \] \[\text{[N/mm²]}\]

\[ A_{exp}^0 = \text{s}_{cr,sp} \cdot h_{cr,sp} \text{ for single anchor near the edge, see Figure 4} \] \[\text{[mm²]}\]

\[ A_{exp} = (c_2 + c_{cr,sp}) \cdot h \text{ for single anchor near the corner} \] \[\text{[mm²]}\]

\[ \Psi_{h,sp} = \left( \frac{h_{cr,sp}}{h} \right)^{0.5} \geq 1 \] \[\text{(6)}\]

\[ h = \text{member thickness of the application, see Figure 6} \] \[\text{[mm]}\]

\[ s_{cr,sp} = \text{characteristic spacing (splitting failure)} \] \[\text{[mm]}\]

\[ s_{cr,sp} = 2c_{cr,sp} = 3c_1 \] \[\text{[mm]}\]

\[ c_2 = \text{edge distance, see Figure 2} \] \[\text{[mm]}\]

\[ \Psi_{s,sp} = \left( 1 + \frac{s_2}{s_{cr,sp2}} \right) \leq 2 \] \[\text{[mm]}\]

\[ \Psi_{s,sp} = \text{factor to account the influence of the spacing s_2} \] \[\text{[-]}\]

\[ s_1 = \text{spacing anchor groups (see Figure 2)} \] \[\text{[mm]}\]

\[ s_2 = \text{spacing anchor groups (see Figure 2)} \] \[\text{[mm]}\]

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**Figure 2**--Definitions of the edge distance c, spacing s, and member thickness h

**Figure 3**--Definition of the characteristic member thickness \( h_{cr,sp} \)
**EXPERIMENTAL INVESTIGATIONS**

**Derivation of the product factor**

The splitting failure load can be calculated using Equation (1), which contains the product factor $k_p$. This factor depends on the anchor system. The factor $k_p$ is derived like the $k$-factor for concrete breakout, that is, according to Equation (9). Splitting failure results come from unconfined tension tests on post-installed adhesive anchor systems (spacing of the supports: $3h_{cf}$ to $4h_{cf}$). To consider the effect of the anchor size, the relation between the factor $k_p$ and the nominal anchor diameter, $d_{na}$, is determined by a regression analysis of Equation (10).

The slope $u$ and exponent $v$ of Equation (10) is derived from splitting failure mode tension tests. Results are listed in Table 1 for post-installed adhesive system in the supporting database.
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\[
k_p = \frac{N_{u, test}}{A_{esp}^{0.8} \cdot \psi_{h, sp} \cdot \psi_{s, sp} \cdot c_1 \cdot h_{cr, sp} \cdot f_{cc, 150}^{0.5}}
\]  \hspace{1cm} (9)

\[
k_p = u \cdot d^v
\]  \hspace{1cm} (10)

with

\[
d = \text{Diameter (nominal steel element size for adhesive systems)}
\]

\[
u = \text{Slope of Equation (10)}
\]

\[
v = \text{Exponent of Equation (10)}
\]

<table>
<thead>
<tr>
<th>Anchor</th>
<th>Thread size [mm]</th>
<th>Adhesive type (^1)</th>
<th>Product factor (k_p = u \cdot d^v)</th>
<th>(N_{u, test}/N_{um, sp}) (Equation (1))</th>
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<tr>
<td>12-30 VG1</td>
<td>10.95 0.20</td>
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1) Description of the mortar type, used in Figure 7
2) \(n = \) number of tests; \(x = \) mean value; \(V = \) coefficient of variation

Table 1--Summary of test conditions and evaluation of the ratio \(N_{u, test}/N_{um, sp}\) (Equation (1)), comparison of measured failure loads with calculated values, unconfined single anchor tension tests at a corner

Figure 7--Product factor \(k_p\) (Equation (9)) of different adhesive anchor systems derived from tension tests in the corner as a function of the diameter
The splitting failure load \( (N_{um,sp}) \), according to Equation (1), is calculated by using the product factor \( k_p \) listed in Table 1, columns 4 and 5. The ratio of the measured test failure load \( (N_{u,test,i}) \) divided by the load predicted by the proposed model \( (N_{u,m,sp,i}) \) are calculated in Equation (12). The mean value and the coefficient of variation of the \( N_{u,test,i}/N_{u,m,sp,i} \) ratios for the corresponding anchor systems are presented in, columns 7 and 8 of Table 1. The splitting failure load and the product factor \( k_p \) depend on the test setup. Therefore, only tests with unconfined test setup were assessed. Moreover, the splitting failure load is influenced by bending stresses in the concrete embedment material, which is caused by the test setup. Therefore, only tests with a spacing of the supports of 3\( h_{ef} \) to 4\( h_{ef} \) were used in the data analysis.

The splitting failure loads for individual anchor systems, for example VG1, are calculated with the corresponding average value for \( k_p \) (see Table 1, columns 4 and 5). As a rule, the coefficients of variation if just one anchor system series is considered are less than 15\% (see Table 1, column 8).

Adhesive anchors that use normal threaded rods, transfer tension loads exclusively by bond. It is assumed, that the type of adhesive has no influence on the splitting failure load. Tests were conducted by four different laboratories using six different adhesive systems with several different anchor diameters. Making the assumption that the test data is independent of adhesive type, all data was analysed and the results listed at the bottom of Table 1. For the two-hundred twenty-two (222) tests, the average product factor can be described by Equation (11).

\[
k_p = 5.93 \cdot d^{0.37}
\]

The mean value of the \( N_{u,test}/N_{u,calc} \) ratio is slightly greater than 1.0 and the coefficient of variation is \( V \approx 18\% \). The scatter of the ratios \( N_{u,test}/N_{u,calc} \) is not significantly larger than the scatter of the concrete tensile strength. Therefore, it is reasonable to calculate the splitting failure load of conventional bonded anchors according to Equation (1) using a common product factor \( k_p \) (see Table 1, last line and Equation (11)).

**Comparison of measured and calculated splitting failure loads**

The measured failure load for tests in the corner are compared to the calculated splitting failure load according to Equation (1) and using the product factor according Equation (11) for all 222 tests at the corner (see Equation (12)).

\[
x_i = \frac{N_{u,test,i}}{N_{u,m,sp,i}}
\]

with

- \( N_{u,test,i} \) = measured splitting failure load in the tests \([kN]\)
- \( N_{u,m,sp,i} \) = calculated splitting failure load using Equation (1) using the factor according Equation (11) \([kN]\)

The ratios of the measured and calculated splitting failure loads for all tests with single anchors at a corner are plotted as a function of the following parameters

- a) embedment depth \( h_{ef} \), see Figure 8
- b) member thickness, see Figure 9
- c) edge distance, see Figure 10

In Figure 8, 9, and 10, a “best fit” trend line is also plotted. If these trend lines are horizontal and are located at \( N_{u,test}/N_{u,calc} = 1.0 \) the influence of the different parameter on the failure load is taken into account very well by the calculation model. These figures clearly show that the calculation model provides a reasonable fit of the experimental results.

The behaviour model for splitting failure captures the effect of influencing parameters and it predicts the splitting failure load obtained by the tests with good accuracy. We note that the factor \( k_p \) given in Equation (11) is valid for
unconfined tests with a spacing of the support reactions of 3h_{ef} to 4h_{ef}. If the support spacing is smaller, lower bending stresses are induced and therefore higher splitting failure loads and a larger product factor are expected. Therefore, the splitting product factor is calibrated to be conservative.

![Embedment depth vs. xi](image1)

**Figure 8**--Tension tests with single anchors in the corner with failure mode splitting; Ratio of the measured failure loads to the calculated (Equation (1)) splitting failure loads as a function of embedment depth h_{ef}

![Embedment depth vs. xi](image2)

**Figure 9**--Tension tests with single anchors in the corner with failure mode splitting; Ratio of the measured failure loads to the calculated (Equation (1)) splitting failure loads as a function of member thickness h
Figure 10--Tension tests with single anchors in the corner with failure mode splitting: Ratio of the measured failure loads to the calculated (Equation (1)) splitting failure loads as a function of edge distance $c_1 = c_2$

DERIVATION OF THE CRITICAL DISTANCES

The load capacity of adhesive anchors is determined by the bond strength. The bond strength of adhesive anchors is product specific. A review of adhesive anchor tests available on the market reveals that systems with low, medium, and high pullout capacity (bond stress) exist.

According to Equation [2], the critical edge distance for splitting failure can be estimated by evaluating the average failure load for an anchor without edge and spacing effects for the same concrete strength. This requirement is satisfied if the bond stress in splitting is according to Equation (13).

$$
\tau_{Rm,sp} = \min (\tau_{Rm,p}; \tau_{Rm,c}) \tag{13}
$$

with

- $\tau_{Rm,sp}$ = Mean bond strength for splitting failure according to Equation (14), factor $k_p$ according to Equation (11)
- $\tau_{Rm,p}$ = Mean bond strength for pullout failure according to Equation (15)
- $\tau_{Rm,c}$ = Mean bond strength for concrete cone failure according to Equation (17)

For comparison, bond strength is calculated according to Equation (14) from the mean splitting failure load. The bond strength for splitting failure is compared with the bond strength for pullout failure (Equation (15)) and concrete cone failure (Equation (17)). All equations are expressed in SI-units.

$$
\tau_{Rm,sp} = \frac{N_{um,sp}}{\pi \cdot d \cdot h_\varepsilon} \tag{14}
$$

with

- $N_{um,sp}$ = Mean splitting failure load according to Equation (1) with factor $k_p$ according to Equation (11)

$$
\tau_{Rm,p} = \tau_{Rm,0} \cdot \frac{A_{Na}}{A_{Na,0}} \cdot \Psi_{ed,Na,0} \cdot \Psi_{p,Na} \tag{15}
$$

with

- $\tau_{Rm,p}$ = Average bond strength for adhesive anchor systems with high ($\tau_{um} = 20 \text{ N/mm}^2$), medium ($\tau_{um} = 15 \text{ N/mm}^2$) and low ($\tau_{um} = 10 \text{ N/mm}^2$) pullout capacity

and for $A_{Na}, A_{Na,0}, \Psi_{ed,Na,0}, \Psi_{p,Na}$ see [2]
Asmus

\[ s_{cr,Na} = 20 \cdot d \cdot \left( \frac{\tau_{Rm,p}}{10} \right) \leq 3h_{ef} \]  

(16)

\[ \tau_{Rm,c} = \tau_{m,max,uncracked} = \frac{k}{0.75 \cdot (\pi \cdot d)} \cdot h_{ef}^{0.5} \cdot f_{c}^{0.5} \cdot \frac{A_{Nc}}{A_{Nco}} \cdot \Psi_{ed,N} \cdot \Psi_{c,N} \]  

(17)

with

- \( \tau_{Rm,c} \) = Average bond strength for adhesive anchor systems for concrete cone failure
- \( k \) = 10 (Effectiveness factor for uncracked concrete, see Reference [2], Table 11.6)
- \( f_{c} \) = Concrete compressive strength
- \( A_{Nc} \) = Projected concrete failure area of a single anchor or group of anchors, for calculation of strength in tension, as defined in [3]
- \( A_{Nco} \) = Projected concrete failure area of a single anchor, for calculation of strength in tension if not limited by edge distance or spacing, as defined in [3]
- \( \Psi_{ed,N} \) = Factor used to modify tensile strength of anchors based on proximity to edges of concrete member, as defined in [3]
- \( \Psi_{c,N} \) = Factor used to modify tensile strength of anchors based on presence or absence of cracks in concrete, as defined in [3]

The mean bond strength for splitting failure, for example, is calculated in Figure 11 for M16 diameter anchors with minimum \( (h_{ef} = 5d) \) and maximum \( (h_{ef} = 20d) \) embedment depth as well as different member thicknesses \( (h_{min} = h_{ef} + 2d; h_{min} = 2h_{ef}) \).

In Figure 11 a) \( (h_{ef} = 5d) \) and Figure 11 b) \( (h_{ef} = 20d) \), the mean bond strength for splitting failure is shown as a function of the edge distance to embedment depth ratio. In these figures, the mean strength for pullout (Equation (15) and concrete cone failure (Equation (17)) are also plotted. To show the influence of adhesive anchor systems with high \( (\tau_{Rm,p} = 20 \text{ N/mm}^2) \), medium \( (\tau_{Rm,p} = 15 \text{ N/mm}^2) \), and low \( (\tau_{Rm,p} = 10 \text{ N/mm}^2) \) bond pullout capacity are assumed. While the load capacity of adhesive anchors with a small embedment depth and the medium and high bond pullout capacity is limited by concrete cone failure (Figure 11 a) anchors with large embedment depth, \( h_{ef} = 20d_{ac} \), are able to utilize the bond capacity (Figure 11 b).

It is obvious from the plots in Figure 11 that partial bond pullout or concrete cone failure controls the decision of the critical edge distance. It can be seen from Figure 11 that the critical edge distance for splitting controls. As the member thickness increases, ratio critical edge distance to embedment depth decreases (see Figure 11 and 13).

According to Reference [9], Section 7.1, the required critical edge distances for member thickness \( h \geq 2h_{ef} \) to ensure the characteristic tension load resistance of an adhesive anchor should be about \( c_{cr,sp} = 1h_{ef} \). For the data available, this edge distance only applies to adhesive injection systems with low pullout capacity (see Figure 11a). It is believed that the regulations given in Reference [9], Section 7.1, are not safe for adhesive anchor systems with larger embedment depths \( (h_{ef} \geq 8d) \) and for products with medium and high pullout capacity.

The effect of the member thickness on the bond strength for splitting failure for single anchors in the corner is shown for the M16 anchor size with an embedment depth \( h_{ef} = 12d \) (Figure 12). The splitting failure load is calculated according to Equation (14) for different edge distances \( (c = 1.5h_{ef}; 2h_{ef}; 3h_{ef}) \). The results illustrate that increasing member thicknesses correspondingly increases the splitting failure loads. Therefore, the required critical edge distances can be reduced with increasing member thickness (Figure 12).

In Figure 13, the bond strength for pullout or concrete cone failure (without edge effects) of an adhesive anchor \( d_{a} = 16 \text{ mm} \) is compared with the value for splitting failure of an anchor in corner with different edge distances \( (c = 1.5h_{ef}; 2h_{ef}; 3h_{ef}) \). Anchors with \( d_{a} = 16 \text{ mm} \) and minimum embedment depth \( h_{ef} = 4d \) and medium and high bond stress at pullout capacity, fail by concrete cone failure and the critical edge distance reverts to that of a concrete cone failure, \( c_{ac} = 2h_{ef} \). With increasing embedment depth, larger critical edge distances are required.
Please note that the ratio of critical edge distance to embedment depth is not constant for the different diameters. This condition makes it difficult to write simple design rules for the critical edge distance.

Figure 11--Mean bond strength (Splitting failure, Pullout/Concrete cone failure) as a function of the ratio edge distance to embedment depth
Figure 12--Mean bond strength (Splitting failure ($c = 1.5h_{ef}$; $2h_{ef}$; $3h_{ef}$), Pullout/Concrete cone failure (no edge effect)) as a function of the ratio member thickness to embedment depth

Figure 13--Mean bond strength (Splitting failure ($c = 1.5h_{ef}$; $2h_{ef}$; $3h_{ef}$), Pullout/Concrete cone failure (no edge effect)) as a function of the ratio embedment depth to diameter
SUMMARY

In the last few years, the load capacity of adhesive anchor systems was significantly increased and the range of the embedment depth was enlarged ($h_{ef} = 4d$ to $20d$) to achieve better performance of the anchor bond strength. High performance adhesives are available that are able to utilize the concrete capacity. Therefore, the splitting failure mode has to be considered under certain admissible service conditions in the design of these anchors.

A design method for splitting failure of post-installed adhesive anchors is presented. Details of the design method were given to illustrate how installation parameters (edge distances, member thicknesses, embedment depth, and material properties) influence the splitting resistance. The proposed calculation method agrees well with the results of 222 tests with different adhesive anchors.

Additionally the critical edge distances for splitting failure of post-installed adhesive systems with high, medium and low pullout capacity were discussed. Please note, that critical edge distances are not independent of anchor diameter.

REFERENCES

[3] ACI 318-08; Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary
[8] AC 355.2-07: Qualification of Post-Installed Mechanical Anchors in Concrete
OUTLINE OF JAPANESE GUIDELINE FOR INFLUENCE OF THE EMBEDMENT LENGTH AND THE EDGES ON TENSILE RESISTANCE OF POST-INSTALLED BONDED ANCHOR

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Synopsis: This paper describes and comments on AIJ Design Guideline 2010 of post-installed bonded (adhesive) anchor. This paper presents tension tests to clarify the influence of the embedment depth and the edges on the tensile behavior of a single post-installed bonded anchor. The 4 parameters of the test are established; embedment length ($l_c = 7d_a$, $14d_a$ and $21d_a$; $d_a$: anchor diameter), edge configuration (anchorage at an edge, a corner and thin member), edge distance and adhesive system (glass capsule type, film foil type and injection type). In those tests, we investigated failure mode and failure load of bonded anchor close to the edge(s), and discussed about resistance of anchors to tensile load. Further, the method to estimate the tensile strength (failure load) of single-anchor or of anchors in the groups was proposed with the influence on edge(s). The method in bond failure type is modeled based on a uniform bond stress, and the uniform bond strength is evaluated with reduction coefficient which considered the number of edges and the edge distance.

Keywords: post-installed bonded anchor, tensile resistance, embedment length, edge distance, Japanese Guideline

INTRODUCTION

This paper describes and comments on AIJ Design Guideline 2010 of post-installed bonded anchor. In Japan, post-installed anchors are mainly used for fastening of equipment. However, some are used for connection of structural members, and many of are being used for connection of structural members for strengthening existing buildings. Also, some of the bonded anchors are used for anchorage close to the edge(s).

In those cases, the embedment length of post-installed bonded anchors is generally designed from 7 to 10 $d_a$ ($d_a$: anchor diameter) (JBDPA RC Guideline 2001, AIJ Design Composite Construction 1985), and differs from that of cast-in-place-system (of 30 to 40 $d_a$) (AIJ Standard RC 1999). The reason is that the failure load of post-installed bonded anchor is not evaluated with the edge influence appropriately.

It means that the tensile strength of bonded anchor in concrete cone-failure type is evaluated with the actual projected area and that in bonded (pull-out) failure type is not evaluated with edge influence. So, the target of this paper is to clarify the influence of embedment length and edge(s) on the tensile behavior of single post-installed bonded (adhesive) anchors. Further, the aim of this paper is to estimate the tensile strength of post-installed bonded anchors from tests.

OUTLINE OF TEST

Specimen

The tensile test was conducted to clarify the tensile behavior of the single post-installed bonded (adhesive) anchor close to the edge or the edges (anchorage close to corner or anchorage in thin member). Details of specimens are shown in Table 1 and Figure 1. Those 79 specimens were prepared for the test. Bonded anchors were installed in hardened concrete blocks. The concrete blocks were unconfined and were un-cracked.

Those 4 parameters were established; embedment length, edge configuration, edge distance and bonded type. The embedment length were $7d_a$ ($d_a$: anchor diameter, 133mm), $14d_a$ (266mm) and $21d_a$ (399mm). The edge configuration meant number of edge, were Center (no edge), 1-edge (anchorage at an edge) and 2-edge (corner and both sides: anchoring thin member). The edge distances were 75mm and 150mm. The type of bonded anchor was adhesive system; Glass capsule type (G-Type), Film foil type (F-Type) and Injection type (I-Type). The compounds of bonded anchor were epoxy acrylate. The installation of adhesive anchor was as follows;

1) For G-type and F-type, the capsule (glass capsule or film foil) was placed in the clean hole drilled in to concrete and then anchor rod was driven in mechanically by hand drill until the required embedment depth.
2) For I-type, bonding material (delivered separate chambers of the injection cartridge) was injected into the hole and then the anchor rod was inserted manually. The mixing process of the bonding material is carried out in the mixing spiral of the top of the cartridge extension during the insertion.

Post-installed anchor rod was deformed bar (D19: diameter was 19mm.) and high strength steel (yield strength was 685 N/mm² level). The diameters of hole drilled into concrete were 24mm (I-type, F-type) or 25mm (G-type). Concrete strength of this test (100 x 200 mm cylinders) were 29-36 N/mm².

**Load system**

Figure 2 shows a diagram of the test apparatus used to perform the tensile tests. Concrete was not confined by the load system. A tensile load was produced by a hydraulic ram in combination with a hand pump. The applied load was transferred to the anchor rod by wedge. The reaction load was transferred to the concrete through a steel frame. The steel frame was separated 200mm (about 7da), 300mm (about 14da), and 400mm (about 21da) from the anchor rod. Tensile loads were measured using a load cell and top of anchor displacements (d₁, d₂) were measured by displacement meters. For injection type (I-type), strains of anchor rod were measured using foil strain gage which adhesive on rod surface with waterproof.

**TEST RESULT**

**Failure mode**

In the tests four type of failure mode were obtained which are shown in Figure 3 and listed in Table 2 as a concrete cone failure (C), a bond failure with a concrete cone (BC), a bond split failure with a concrete cone (BSC) and a bond split failure (BS). For shallow embedment (lₑ = 7da), the failure mode appeared as a concrete cone failure (C). For deeper installation (lₑ = 14da, 21da), failure resulted in a bond (or bond split) failure with a shallow concrete cone (BC, BSC). Some of anchors in thin members (2-Edge both sides) exhibited a bond split failure. A typical failure mode of anchor surface after loading is shown Figure 4. In G-Type, the failure mode of anchor surface was steel/adhesive interface.

On the other hand, since resin had adhered to the concrete, the failure mode of anchor surface in F, I-Type was adhesive/concrete interface. The concrete cone length versus embedment length is showed Figure 5. The embedment length has small influence on the concrete cone lengths, which were dispersed 10-130 mm (Ave.63mm).

**Tensile load – displacement relationship**

Figure 6 shows a typical tensile load – displacement relationship of 1-edge lₑ=14da in comparison with adhesive system (G-type, F-type and I-type). The adhesive system has no influence on elastic stiffness and failure load of F-type and was about 5-10% larger than that of G, I-types. Therefore, the result shows small influence of adhesive system on the tensile behavior of bonded anchor.

Figure 7 shows typical tensile load–displacement relationship for embedment length lₑ. The embedment length had little effect on elastic stiffness, and the failure load increased as the embedment length increased. Additionally, since the bond length increased, the displacement in failure load was larger with increasing the embedment length.

Figure 8 shows typical tensile load–displacement relationship for edge configuration. Although stiffness was variable, influence of the edge configurations on stiffness was not observed. The failure load was larger in order of 2-edge (Both sides), 2-edge (Corner), 1-edge and Center. Furthermore, with increasing edge distance, increase of the failure loads was observed.

**Influence of embedment depth and edge on failure load**

Table 2 shows failure load and Figure 9 shows failure load versus embedment depth (in c =75mm). For all adhesive systems (G-Type, I-Type, F-Type), the value of failure load was dispersion, but the failure load of bonded anchor increased almost linearly in proportion to the embedment depth. Furthermore, the failure load was larger at the smaller number of edge surface, and at the larger edge distance.

**Bond resistance to tensile load (strain distribution)**

Figure 10 shows a typical strain distribution of anchor rod versus embedment length with increasing load. The gradient of strain became large gradually with increasing load. Since a shallow concrete cone failure occurred, the gradient of strain distribution near concrete surface decreased. After shallow concrete cone failure, bond length (section where gradient of strain existed) was deeper. So, deeper installation (lₑ =14da, 21da) improved the failure load in anchorage close to edge(s). Further, the strain distributions at failure load were almost linear in bond length, so the bond stress was almost constant throughout the bond length in failure load.
### Table 1 -- Parameter of Test

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| Table 2 -- Test result and calculated value |

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<tr>
<td>2B</td>
<td>242</td>
<td>BS</td>
<td>-</td>
<td></td>
<td>124</td>
<td>BSC</td>
<td>132</td>
<td>B</td>
<td>142</td>
<td>B</td>
</tr>
</tbody>
</table>

*1 C: Center, 1: 1-Edge, 2C: 2-Edge(Corner), 2B: 2-Edge(Both Side)  
*2 CC: Concrete Cone Failure, B: Bond Failure, BC: Bond Failure with a Concrete Cone,  
BSC: Bond Split Failure with a Concrete Cone, BS: Bond Split Failure, SF: Steel Failure  
*3 Calculated. *4 Impossible Loading. *5 Concrete Strength $f_c = 29$N/mm², *6 $f_c = 35$N/mm²
concrete cone failure (CC)

bond split failure with a concrete cone(BC, BSC)

bond split failure (BS)

Figure 3 -- Failure mode of single bonded anchor

Figure 4 -- Failure mode ($l_c = 14d_a$)

Figure 5 -- Concrete cone length versus $l_c$
Understanding Adhesive Anchors: Behavior, Materials, Installation, Design

Figure 6 -- Load-Displacement for Bond-Type (150mm, Corner)

Figure 7 -- Load-Displacement for $l_e$ (75mm, I-Type)

Figure 8 -- Load-Displacement for Edge(s) (I-Type, 14d)

Figure 9 -- Failure Load versus $l_e$ (C=75mm)

Figure 10 -- Strain Distribution
DESIGN METHOD OF BONDED ANCHOR CLOSE TO EDGE(S)

The design method is suggested in AIJ Guideline 2010 for failure load (tensile strength) of a bonded anchor. In this guideline, in view of the findings from the results of experiments involving effective embedment lengths of $7d_a$ to $21d_a$, the strength of a bonded anchor is evaluated in terms of the strength determined by the yielding of the anchor rod and the strength determined by adhesion, and strength reduction due to the group effect is evaluated by reducing the bond strength between the anchor rod and the concrete.

Eq. (2) and eq. (3) give the tensile failure load of a bonded anchor. The allowable tensile force $p_a$ for a bonded anchor secured in preplaced concrete shall be taken to be the value calculated from Eq. (2) or the value calculated from Eq. (3), whichever is smaller. Eq. (2) calculates the value of steel failure mode and eq. (3) gives the tensile failure load of bond failure, is simple model based on a uniform bond stress.

The value of concrete cone failure mode with the actual projected area is given by reference (JBDPA RC Guideline 2001, AIJ Design Composite Construction 1985) is not considered in this guideline, because the cone length had little influence on the failure load of a bonded anchor in deeper embedment. In addition, this simple bond model is assumed that the failure surface could occur either at the steel/adhesive or adhesive/concrete interface. The allowable tensile force $p_a$ is given by eq. (1).

$$p_a = \min. (p_{a1}, p_{a3}) \quad (N) \quad (1)$$

$$p_{a1} = \phi_1 \cdot \sigma_{pa} \cdot a \quad (N) \quad (2)$$

$$p_{a3} = \phi_3 \cdot \tau_s \cdot \pi \cdot d_a \cdot l_{ce} \quad (N) \quad (3)$$

where:

- $p_{a1}$ = allowable tensile force for bonding anchor determined by yielding of anchor rod (N)
- $p_{a3}$ = allowable tensile force determined on the basis of bonding (N)
- $\phi_1$ = reduction coefficient determined by steel failure
  - = 2/3 (long-term allowable force), 1.0 (short-term allowable force)
- $\phi_3$ = reduction coefficient determined by concrete failure
  - = 1/3 (long-term allowable force), 2/3 (short-term allowable force)
- $\sigma_{pa}$ = tensile strength of anchor rod where $\sigma_{pa} = \sigma_s$ provided
  - that $\sigma_{pa} = \alpha_{ys} \cdot \sigma_s$ when the upper limit tensile force (N/mm$^2$) in the case where yielding of anchor bolt is guaranteed is calculated
- $\alpha_{ys}$ = reduction coefficient (1.25 or greater) for standard-specified yield point strength allowing for variability of material strength of anchor rod
- $\sigma_s$ = yield strength of anchor rod (N/mm$^2$)
- $\sigma_{pa}$ = cross-sectional area of anchor rod, calculated as the cross-sectional area of the non-threaded portion of the shank or the effective cross-sectional area of the threaded portion, whichever is smaller (mm$^2$)
- $d_a$ = diameter of anchor rod (mm)
- $l_e$ = effective embedment length of anchor-rod (mm)
  - $\leq 10d_a$
- $l_{ce}$ = effective embedment length of anchor-rod for calculating $p_{a3}$ (mm)
  - $= l_e - 2d_a \quad (l_e \leq 10d_a)$
- $\tau_s$ = uniform bond strength to tensile force of bonded anchor taking into account edge distance and anchor spacing
  - $= \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \tau_{avg} \quad (N/mm^2)$
- $\alpha_a$ = reduction factor for bond strength due to edge distance and anchor spacing, calculated from Eq.(5)
  - (n = 1, 2, 3); two surfaces with the smallest dimensions to be taken into account
  - $= 0.5 + 0.5 \frac{c_e}{l_e}$

Figure 11 – $l_e$ and $l_{ce}$

where ($c_e/l_e$) is taken to be equal to 1.0 if ($c_e/l_e$) $\geq$ 1.0, and $l_e$ is taken to be equal to $10d_a$ if $l_e$ $\geq$ 10 $d_a$.  

\[ r_{avg} = \frac{\text{sum of bond strength}}{\text{number of anchor rods}} \]

\[ \text{failure load} = \min(\text{yielding of anchor rod}, \text{adhesion}) \]

\[ \tau = \frac{\text{failure load}}{\text{effective cross-sectional area of anchor rod}} \]

\[ \alpha_a = \frac{1}{n} \left[ 1 + \frac{c_e}{l_e} \right] \]

\[ \text{allowable load} = \min(\alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \tau_{avg}) \]

\[ \text{allowable load} = \min(\text{allowable load by yielding of anchor rod}, \text{allowable load by adhesion}) \]
The allowable tensile force for a bonded anchor is given as the value calculated from Eq. (7) or the value calculated from Eq. (9), whichever is smaller. The value calculated from Eq. (7) is the allowable tensile force determined by yielding in tension of the anchor bolt, and the value calculated from Eq. (9) is the allowable tensile force determined by adhesion. These are determined by applying the ultimate strength equations of Eq. (7) and Eq. (9), respectively.

In the case of a bonded anchor with a small embedment length, the influence of cone failure is great, and the method of using three equations including Eq. (8) may be used as for headed anchor bolts. It is thought, however, that the failure mode that determines the ultimate strength is determined by bond failure in a non-concrete-cone section, regardless of effective embedment length. In this guideline, therefore, the tensile strength of a bonded anchor rod is evaluated in terms of the strength determined by yielding of the anchor rod and the strength determined by adhesion.

The allowable bond strength of Eq. (3) is given by multiplying the embedment length for strength calculation, $l_{ce}$, by the average bond strength $\tau_a$. This is based on the assumption that tension is resisted by the average bond stress that is uniform over the embedment length for strength calculation. Figure 10 shows measured anchor bar strain

$$\tau_{avg} = \text{nominal uniform bond strength (N/mm}^2)$$

$$= 10\sqrt{F_c/21}$$

$F_c$ = concrete compressive strength (cylinders) (N/mm$^2$)

$c_n$ = edge distance or 1/2 of anchor spacing $a$ ($= a_n/2$, $a_n$= anchor spacing)

2-Edge (Both Side)  2-Edge (Corner)  1-Edge  1-Edge and affected anchor spacing

Figure 12 -- Edge-type and Anchor-spacing

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The average bond strength $\tau_\text{a}$ of Eq. (4) is determined by multiplying the basic average bond strength $\tau_\text{bavg}$ by $\alpha_n$, which is an influencing factor for edge distance and the number of anchors (group effect). The basic average bond strength $\tau_\text{bavg}$ is the bond strength of a bonded anchor free from the influence of edge distance and the group effect and is an experimentally determined strength. The maximum value is $10\sqrt{F_c/21}$, and this value is reduced to 90% if lightweight concrete is used.

Figure 14 shows an example of an experimental method for determining the basic average bond strength $\tau_\text{bavg}$. In the experiment, the concrete was confined with a steel pipe to prevent the concrete from splitting, and a self-contained reaction device was used to apply tensile force to the bonded anchor. Figure 14 (b) shows the results of an experiment involving the following factors as ones affecting bond strength:

- Type of adhesion: 3 levels (post-installed bonded anchor (injection type and film type), deformed bar)
- Concrete strength: 2 levels ($F_c = 24$ and $48$ N/mm$^2$)
- Bar diameter: 2 levels (D19 and D25; drilled hole diameters 24 mm and 32 mm, respectively).

In the experiment, the average bond strength $\tau_\text{bavg}$ was higher in the following order: capsule type (film type) > cast-in-place type > injection type. The distributions for the capsule type and preplaced type anchors have a lower limit value of $\tau_\text{bavg} = 10\sqrt{F_c/21}$. The values for the capsule type anchors greater than 1.2 times $\tau_\text{bavg}$. The basic rule of post-installed bonded anchors is to secure an edge distance ($c$) of $10d_a$ or more and a steel bar spacing ($a$) of $20d_a$ or more. If the edge distance or the anchor spacing mentioned above cannot be secured, the average bond strength $\tau_\text{a}$ is reduced by use of the reduction factor $\alpha_n$ of Eq. (5). The reduction factor $\alpha_n$ is calculated by using the edge distance $c$.

In Eq. (4), the basic average bond strength $\tau_\text{bavg}$ is multiplied by the reduction factor $\alpha_n$ once if there is only one free edge and twice if there are two free edges (two opposite edges, two adjoining edges). If two or more anchor rods are placed close together and tensile force and shear force act in a similar manner, their mutual influence on their bond properties is allowed for in the form of the group effect. The tensile strength reflecting the group effect is calculated by multiplying the strength of the lowest-strength rod in the rod group by the number of rods.

To calculate the tensile strength of a single rod, if the anchor spacing is $20d_a$ or less, $c = a/2$ is assumed and the basic average bond strength $\tau_\text{bavg}$ is reduced by using an edge distance reduction factor. If both the free edge effect and the group effect are involved, the basic average bond strength $\tau_\text{bavg}$ is multiplied by an edge distance reduction factor for the number of times such influence occurs.

In this guideline, in connection with cone failure, edge distance (free edge effect) and anchor spacing (group effect) are allowed for in design by using the effective horizontal projected area. Similarly, in connection with bond failure, the free edge effect and the group effect are allowed for in design by using the reduction factor mentioned above instead of the effective horizontal projected area.

Comparison between the failure load of test and the calculated values is shown in Figure 16. In Figure 16, the uniform bond strength ($\tau_\text{u}$) is not considered the influence of the edge(s) ($\tau_\text{a} = \tau_\text{bavg}$). In concrete cone (C) failure mode (embedment depth $7d_a$), the ratios of test values to calculated values are 0.65 to 1.49 (average 1.05). In bond failure mode (BC, BSC, BS), the calculated values of "Center" are agreed with the tests result (average 1.07), but the ratios of test values to calculated values are 0.45 to 1.07 in anchoring close to edge (1-edge, 2-edge).

Therefore, the uniform bond strength is reduced by reduction coefficient. The Eq.(5) reduction coefficient $\alpha_n$ was suggested from pullout test in reference(Nakano and Matsuzaki 2006). Calculated results are plotted in Figure 17, and the uniform bond strength ($\tau_\text{u}$) is reduced by Eq.(5): $\tau_\text{u} = \alpha_n \cdot \tau_\text{bavg}$). The ratios of test values to calculated values are 0.81 to 1.48 (average 1.19) in case of "1-edge", but the ratios of "2-edge (Corner and Both sides)" are 0.47 to 1.11. So, the uniform bond strength ($\tau_\text{u}$) is given by proposed eq.(10) to (12). The uniform bond strength of "2-edge (Corner and Both sides)" is calculated using twice the reduction coefficient $\alpha_n$. 
\[ \tau_a = \tau_{barg} \quad (\text{N/mm}^2) \text{ for } c \geq l_c \text{ (no edge)} \quad (10) \]

\[ \tau_a = \alpha_1 \cdot \tau_{barg} \quad (\text{N/mm}^2) \text{ for 1- edge} \quad (11) \]

\[ \tau_a = \alpha_2 \cdot \tau_{barg} \quad (\text{N/mm}^2) \text{ for 2- edge} \quad (12) \]

In Figure 18, all test results are compared with the values given by design formulas, and the calculated value is listed in table 2. In “2-edge (Corner and Both sides)”, the ratio of test values to calculated values are 0.71 to 1.57 (average 1.21), so all calculated value agree with test results by the suggested method. Also, the method can predict the failure (concrete cone or bond) mode of tests.

Figure 19 shows a pull-out experiment in which a group of bonded anchor rods was pulled out. As shown in Figure 19(a), in the experiment, tensile force was applied uniformly to four deformed steel bars (D19). The anchor rods were uniformly spaced (150 mm), and the strength-affecting factors considered in the experiment were (1) the type of anchorage (cast-in-placed, injection type), (2) embedment length \(l_e(= 7d_a, 14d_a, 21d_a)\), (3) free edge (1, no free edge (center)) and (4) edge distance (75 mm (3.5\(d_a\)), 150 mm (7\(d_a\))).

Figure 19(b) compares the calculated values calculated by taking into account the edge distance and anchor spacing with the measured values. Evaluation is made as in the single-bar tensile test by using 1/2 of the anchor spacing a as the edge distance \(c = b/2\).

CONCLUSION

The conclusions in this paper are follows:
1) For shallow embedment \((l_e = 7d_a)\), the failure mode appears as a concrete cone failure. For deeper installation \((l_e = 14d_a, 21d_a)\), failure results in a bond (or bond split) failure with a shallow concrete cone.
2) The failure load of bond failure type and the embdenment depth have a linear relationship. The failure load decreases as the number of edges increase, and increase as the edge distance lengthens.
3) n failure load, the bond stress is almost constant throughout the bond length.
4) The method to estimate the tensile strength (failure load) of an anchor is proposed with the influence on edge(s) and anchor spacing. The method in bond failure type is model based on a uniform bond stress, and the uniform bond strength is evaluated with reduction coefficient which considered the number of edge and the edge distance.

REFERENCES


4.5 Design of Bonding Anchor Bolts
Figure 13 -- Tensile force and $l_{cv}$

Figure 14 -- Bond test of Post-installed bonded anchor
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Figure 15 -- Actual projected area

Figure 16 -- Calculation compared with test
(case 1: \( \tau = \tau_{\text{berg}} \))

Figure 17 -- Calculation compared with test
(case 2: \( \alpha_1 \cdot \tau_a = \tau_{\text{berg}} \))

Figure 18 -- Calculation compared with test
(case 3: \( \alpha_1 \cdot \alpha_2 \cdot \tau_a = \tau_{\text{berg}} \))

Figure 19 -- Tensile result of group anchor
STRESS VERSUS TIME-TO-FAIL TEST METHOD FOR EVALUATING
THE SUSTAINED LOAD PERFORMANCE OF ADHESIVE ANCHOR SYSTEMS
IN CONCRETE

by Todd M. Davis, P.E. and Ronald A. Cook, Ph.D., P.E.

Synopsis: ASTM E488 and ASTM E1512 as well as ICC-ES AC308 and ACI 355.4 have extensive testing protocols for the short-term and long-term evaluation of adhesive anchor systems. Currently the sustained load testing procedures establish residual load and displacement criteria on projected displacements from a 1000 hour sustained load test. An anchor is considered approved for sustained load if it meets these pass/fail criteria.

In an NCHRP research project conducted at the University of Florida, an AASHTO standard (AASHTO TP 84-10) was developed to evaluate the sustained load performance of adhesive anchor systems based on a stress versus time-to-failure approach common with many testing protocols. Adhesive anchors are loaded to failure at various percentages of the mean static load as determined from static load tests. The resulting stress versus time-to-failure relationship generated from this test method is very useful to an engineer designing with adhesive anchors under sustained load.

A subsequent NCHRP research project conducted in partnership at the University of Florida and the University of Stuttgart will utilize this test method to evaluate the long-term performance of adhesive anchor systems under sustained load coupled with various installation and in-service conditions (temperature, moisture, etc).

Keywords: Adhesive anchors, creep, stress versus time-to-failure, sustained load testing.
BIOGRAPHICAL SKETCH

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INTRODUCTION

In July 2006, several concrete panels fell from the ceiling of the Boston Tunnel onto a vehicle, causing one fatality. The subsequent National Transportation Safety Board (NTSB) (2007) investigation found that the collapse was due to poor sustained load capacity of the adhesive anchors that were used to secure the concrete panels to the ceiling of the tunnel.

Adhesive anchors in concrete are typically threaded rods installed in a hole drilled in cured concrete with the hole diameter no greater than 1.5 times the anchor diameter. The anchor rod is installed with an adhesive, typically a two-part epoxy. Other anchor systems exist for concrete (cast-in-place, mechanical and grouted anchor systems). The main difference between grouted and adhesive anchors is that grouted anchors are installed in holes greater than 1.5 times the anchor diameter and typically use a cementitious grout.

Creep, or the slow deformation of a material over time due to a sustained load, is a significant issue for adhesive anchor systems. Test methods have been established to measure creep and qualify an adhesive anchor system for use under a specific sustained loading condition. However, these test methods only provide a pass/fail evaluation at a certain stress level and do not define the relationship between various stress levels and the resulting lifetime (time-to-failure) analogous to an S-N curve in fatigue analysis.

This paper will briefly discuss the current state of the art in sustained load testing for adhesive anchors. A new test method proposed by the American Association of State Highway and Transportation Officials (AASHTO) will be introduced that evaluates the stress versus time-to-failure relationship of adhesive anchor systems in order to qualify a product for sustained loading applications. Finally, current research will be presented that is being conducted to evaluate the effects of various parameters on the long-term performance of adhesive anchor systems.

BACKGROUND ON SUSTAINED LOAD TESTING

A brief overview follows on the state of the art of adhesive anchor sustained load testing. Discussion covers ASTM, International Code Council Evaluation Service (ICC-ES), and current American Concrete Institute (ACI) efforts.

ASTM E488. ASTM E488-96 provides the fundamental test procedures to determine the static, seismic, fatigue and shock, tensile and shear strengths of concrete and masonry anchors. These procedures serve as the basic building blocks for most anchor testing and are either adopted in full or slightly modified by governing agencies. Static load tests as described in ASTM E488 are conducted as a step in most sustained load test procedures in order to generate reference points.

The static load tension test as defined in ASTM E488 subjects an anchor to a tensile load at a continuous load rate that will produce failure in one to three minutes while monitoring load and displacement readings. The tension test can either have a confined or an unconfined test setup wherein the confined test setup isolates the failure to the adhesive bond surface in order to determine the bond strength and the unconfined test setup allows for a concrete cone failure. Figure 1 shows a confined tension test setup; Figure 2 shows an unconfined tension test setup.
ASTM E1512. ASTM E1512-01 builds upon the test program established in ASTM E488 and while ASTM E488 is for all concrete anchor systems, ASTM E1512 is solely for bonded anchors. ASTM E1512 covers many different tests for adhesive anchors and sustained load testing is covered in section 7.4.8 entitled “Creep Test”.

The ASTM E1512 “Creep Test” initially conducts two different static load tests per ASTM E488. One static load test (five repetitions) is conducted at 75°F (24°C) in order to determine the average ultimate tension load. The second static load test series (five repetitions) is conducted at 110°F (43°C) in order to determine the average displacement at the ultimate tension load. Following the two static load test series, a 110°F (43°C) sustained load test series (five repetitions) is conducted in which 40% of the ultimate tension load determined from the 75°F (24°C) static load tests is applied to the anchors and maintained for 1000 hours (42 days). Displacement readings are recorded during the course of the test and upon completion of the 1000 hours, the displacements are projected out to 600 days using a logarithmic projection of the form:

\[ \Delta = a \cdot \ln(t) + b \]  (1)

where:

- \( \Delta \) = projected displacement
- \( t \) = time
- \( a, b \) = constants evaluated by regression analysis

This trendline is constructed from not less than the last 20 days (minimum of 20 data points). The projected displacement at 600 days is compared to the displacement from the static tension test series at elevated temperature. See Figure 3 for a graphical presentation of this projection.
ICC-ES AC58. ICC-ES AC58 provides acceptance criteria based on allowable stress design (ASD) developed by the International Code Council Evaluation Service (ICC-ES) and first approved in January 1995. The purpose of these acceptance criteria is to provide a standard method and report for manufacturers to qualify their adhesive anchor products for use in concrete and masonry elements. Beginning in 2008, ICC-ES AC58 was no longer accepted by the International Building Code for anchorages in concrete and was replaced by ICC-ES AC308 (discussed later); the current version of ICC-ES AC58 (2007) only addresses anchorages in masonry elements. A brief discussion of ICC-ES AC58 (2005) is presented to provide a historical basis of adhesive anchor testing.

The Creep Test specified in ICC-ES AC58 refers to ASTM E488 and ASTM E1512 with a few minor differences. Under ICC-ES AC58 (2005), creep testing was optional and manufacturers that did not perform creep testing could not qualify their product for sustained load applications.

Under the ICC-ES AC58 (2005) creep test, the data is projected as discussed in the creep test procedure in ASTM E1512-01 (Figure 3). The anchor is accepted for creep if the average projected displacement at 600 days is less than (a) the average displacement at mean static load determined from static tension test series at elevated temperature and (b) 0.12 inches (3.0mm) (see Figure 4).

**ICC-ES AC308.** ICC-ES AC308 provides acceptance criteria for adhesive anchors in concrete elements based on ultimate strength design (LRFD) developed by the International Code Council Evaluation Service (ICC-ES). Beginning in 2008, ICC-ES AC308 replaced the previous acceptance criteria ICC-ES AC58. The creep test was slightly modified in that the sustained load is 55% of the ultimate tension load as opposed to 40% in ICC-ES AC58. Furthermore, the displacements are projected over the service life using a least squares fit through the data points using the Findley Power Law equation:

$$\Delta(t) = \Delta_{t=0} + a \cdot t^b$$  \hspace{1cm} (2)

where:

- $\Delta(t)$ = projected displacement
- $\Delta_{t=0}$ = initial elastic displacement
- $t$ = time
- $a, b$ = constants evaluated by regression analysis

The estimated displacement is calculated at 50 years for the standard temperature test and 10 years for the elevated temperature test. The average estimated displacement values must be less than a limiting displacement values, and no single value can be more than 120% the limiting displacement value. Additionally, a static load test is conducted on the anchors following the 1000 hour sustained load test and the residual load must be at least 90% of the ultimate tension load.

**ACI 355.4.** ICC-ES AC308 served as the basis for ACI 355.4-10. ACI 355.4-10 will be referenced in future editions of ICC-ES AC308 in place of its existing testing and evaluation program for post-installed adhesive anchors.

**PROPOSED AASHTO TEST METHOD**

Due to the findings from the NTSB (2007) investigation of the Boston Tunnel collapse, the American Association of State Highway and Transportation Officials (AASHTO) via the National Cooperative Highway Research Program (NCHRP) contracted with the University of Florida to develop a test method for AASHTO (TP 84-10) to determine the ability of adhesive anchors to resist sustained tensile load. Due to the uncertainty involved
with the pass/fail criteria in the standards mentioned earlier a test method based on a stress versus time-to-failure approach which establishes the relationship between stress level and the expected time to failure was investigated.

The stress versus time-to-failure approach is common in the testing of adhesive joints in wood, plastics, and metals. Several ASTM standards were consulted in the development of TP 84-10.

**ASTM D4680.** ASTM D4680-98 presents test methods for creep of wood joints bonded with adhesives. The time-to-failure test begins by determining the mean strength by applying a load to the specimen to produce failure within one minute. Subsequent tests are conducted at lower stress levels until failure. It recommends at least four equally spaced stress levels (90%, 80%, 70% and 60% of the mean strength). The lowest stress level should produce failure at about 3000 hours (~4 months).

The resulting data is used to calculate a linear regression equation of the stress versus time-to-failure relationship on a log or semi-log plot for each temperature. The curves can be extrapolated to obtain the time-to-failure for lower stress levels. This type of curve can provide engineers a safe stress level to use if the lifecycle of the anchor is known. Figure 5 is a Stress versus Time-To-Failure graph.

![Stress versus log of time-to-failure](image)

**Figure 5 -- Stress versus log of time-to-failure**

**ASTM D2990.** ASTM D2990-01 presents the test procedures for creep and creep rupture of plastics under specified conditions. Tests are conducted on samples at various temperatures that span the anchor’s useful temperature range. Deflection is measured at the times chosen so as to produce relatively equally spaced points on a log scale graph. Logarithmic scales are normally used in presenting creep data because the curves plot essentially as straight lines due to the long time frames encountered in creep testing. ASTM D2990 sets the time-to-failure at either rupture for materials that fail catastrophically, or at the onset of tertiary creep (yielding, flowing, or drawing) for materials that do not fail catastrophically. See Figure 6 for a sample creep curve for hypothetical data that shows the levels of creep and the location of tertiary creep.
AASHTO TP 84. Unlike the “displacement projection” test method found in ASTM E1512, ICC-ES AC58, ICC-ES AC308 and ACI 355.4, the “stress versus time-to-failure” method does not rely upon projections of measured displacements for questionable time periods with questionable limits but simply records the time to tertiary creep failure of the anchor. AASHTO TP 84 establishes the mean static load by conducting ASTM E488 similar short-term confined tension tests (five repetitions) at an elevated temperature of 110°F (43°C). Subsequent sustained load test series are conducted on five specimens at two lower stress levels at an elevated temperature of 110°F (43°C). It is recommended that these lower stress levels be within the ranges of 70% to 80% and 60% to 70% of the mean static load. Ideally, the stress levels chosen would create data points in separate log cycles. The sustained load tests are conducted until failure which is defined as the initiation of tertiary creep.

The data is plotted on a stress versus time-to-failure graph (log or semi-log plot). The mean static load represents a 100% stress level at a two minute time to failure. A least squares trendline drawn through each data point is projected forward linearly (on the log or semi-log scale). According to Klompen et al. (2005), most polymers show a linear relationship between the logarithm of increasing time-to-failure and decreasing stress however, some polymers do exhibit a lower bound stress level, analogous to an endurance limit.

While a linear projection would be sufficient and possibly conservative, a manufacturer can perform longer term tests at lower stress levels in order to better define the curve. See Figure 7 for a sample Stress versus Time-to-Failure graph. The test data can also be summarized in a table of estimated failure loads at specified structure lifetimes. As mentioned earlier, this curve (or table) can provide engineers a safe envelope in which to design given the lifetime of their system. Moreover, given a structure lifetime, this chart or table can generate a reduction factor for sustained load to be used in an LRFD analysis.
Several advantages of AASHTO TP 84 over the current ICC-ES AC308/ACI 355.4 test method are as follows:

- Test results in the form of a Stress versus Time-to-Failure graph or a table of stress values for given structure lifetimes provide useful design data for the practicing engineer as opposed to the *pass/fail* criteria in ICC-ES AC308.
- The reduction factor generated from the stress versus time-to-failure approach can easily be incorporated in an LRFD approach which is in agreement with current AASHTO and ACI design philosophy.
- Existing data from ICC-ES AC308 can be incorporated into Stress versus Time-to-Failure graphs which build upon the database of current test results.
- Allows a method for manufacturers to qualify a product above the minimum *pass/fail* standard as established by ICC-ES AC308 in order to distinguish their product amongst competitors.
- Removes the uncertainty associated with the mathematical projection of displacement and the imposed limits on that projection in the ICC-ES AC308 approach.
- Provides a platform for evaluating the long-term effect of various installation and in-service parameters on sustained load (discussed below).

More information including the proposed AASHTO test method can be found in NCHRP (2009) Report 639.

**CURRENT RESEARCH**

Currently much is known regarding the short-term effects of various installation and in-service conditions (moisture, temperature, hole cleanliness, etc.) on adhesive anchors but not much is known whether these same parameters have a more pronounced effect over long time periods. Currently researchers at the University of Florida in partnership with researchers at the University of Stuttgart under contract by the National Cooperative Highway Research Program (NCHRP) are conducting over 200 sustained load anchor pullout tests on three types of adhesive anchor systems to investigate the effect of various parameters on the long-term performance of adhesive anchors in concrete. These parameters include:

- Increased service temperature
- Horizontal installation direction
- Vertical installation direction
- Moisture during installation
- Moisture during service
- Reduced hole cleaning
Reduced installation temperature
- Reduced service temperature
- Anchor diameter
- Type of hole drilling

Concrete composition:
- With blast furnace slag
- With fly ash
- Unconfined support condition

Figure 8 shows the basic concept behind the use of the stress versus time-to-failure test method to evaluate the effect of a particular parameter on the long-term performance of an adhesive anchor under sustained load. First, a baseline stress versus time-to-failure test series (shown as the solid line in Figure 8) must be performed for each adhesive product. (Note that sample data points are not included in Figure 8 for clarity)

After the baseline stress versus time-to-failure relationship has been established for each product, similar stress versus time-to-failure tests can be performed with the only variation being the parameter under investigation (e.g. moist concrete). The ratio between the mean static load of the five test repetitions with the parameter included divided by the mean static load of the five repetitions of the baseline tests is noted as $\alpha$ and is shown in Figure 8.

For each test series, the $\alpha$ reduction factor is then applied to the entire baseline stress versus time-to-failure curve and a resulting $\alpha$-baseline curve for that parameter is plotted showing the expected stress versus time-to-failure trend if the parameter has no effect on the long-term performance of the adhesive anchor over time.

Based on comparing the slope of the parameter’s stress versus time-to-failure relationship to the slope of the parameter’s $\alpha$-baseline stress versus time-to-failure relationship it can be determined if the parameter affects an anchor’s long-term performance under sustained load any more than it does under short-term load performance. As shown in Figure 8, if the slope is greater than that of the $\alpha$-baseline then the parameter does have an adverse effect that needs to be accounted for in product approval standards and design standards. If the slope is the same or less than that of the $\alpha$-baseline then the $\alpha$ reduction factor determined from short-term product approval tests is acceptable for use for long-term performance under sustained loads.

![Figure 8 -- “Stress versus time-to-failure” comparison of baseline to parameter studies](image)

In addition to the above mentioned anchor pullout tests, several series of adhesive alone sustained load tests will be conducted on specimens of the adhesive alone to evaluate if a correlation can be made between anchor pullout tests and other common adhesive only tests like Dynamic Mechanical Thermal Analysis (DMTA) tests.

**CONCLUSION**

This paper presented the state of the art in sustained load testing and qualification for adhesive anchor systems. Current pass/fail test methods by ASTM, ICC-ES and ACI were discussed. It was shown that AASHTO TP 84, which defines the relationship between stress level and the expected time to failure for an adhesive anchor
system under specific conditions, is a valuable tool for designers. Additionally, it provides a platform upon which to rationally evaluate the effect of various parameters on the long-term performance of adhesive anchor systems. In order to add to current adhesive anchor understanding, researchers at the University of Florida and the University of Stuttgart are evaluating the long term effects of multiple parameters on the long-term performance of adhesive anchor systems.
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BEHAVIOR AND DESIGN OF ADHESIVE ANCHORS UNDER SUSTAINED LOAD

by Rolf Eligehausen, Ronald Blochwitz, and Werner Fuchs

Synopsis: Adhesive anchors are used worldwide for structural and non-structural connections. Because their structural behavior is influenced by many factors, adhesive anchors must be prequalified. In the US this is done according to ICC-ES AC308 and ACI 355.4-10. Design provisions for bonded anchors are stated in ICC-ES AC308 and the ACI 318-11, Appendix D. Only prequalified adhesive anchor systems are covered by the ACI Standard.

In this paper the testing procedure, assessment criteria and design provisions with respect to sustained tension loading are described and – based on test results – the validity of the design provisions is discussed. It is concluded, that adhesive anchors qualified according to ACI 355.4-10 and designed according to the ACI 318-11, Appendix D can safely be used to resist sustained tension loading provided that they are installed properly. The design provisions given in ICC-ES AC308 and ACI 318-11, Appendix D should be applied to all anchors that must resist sustained tension loads and not only to anchors installed overhead.

Keywords: Adhesive anchors, sustained load, creep, design
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INTRODUCTION

Adhesive anchors are widely used around the world to address a variety of structural and non-structural fastening problems in both new concrete construction and structural renovation or strengthening of concrete structures. In this paper the term adhesive anchor refers to anchorages comprised of a steel anchor element, usually a threaded rod or deformed reinforcing bar, installed in a drilled hole and bonded to the surrounding concrete with a polymer based adhesive filling an annular gap of no more than 1.5 times the steel anchor element diameter. The adhesive used in the industry are of different types of resin (e.g. epoxy, vinylester) or hybrid systems (mixture of resin and cement). Because the behavior of adhesive anchors is influenced by many parameters prequalification of the adhesive anchor system is necessary. In 2005 ICC-ES published the Acceptance Criteria for adhesive anchors (ICC-ES (2005)) which superseded AC58 (ICBO-ES (1995)). AC308 is based substantially on the European Technical Approval Guideline (ETAG) 001, Part 5 “Bonded Anchors” (EOTA (2002)) and it serves as basis for ACI 355.4-10 (ACI 2010). ACI 355.4-10 substantially agrees with AC308. The provisions in ICC AC308 and ACI 355.4-10 require tests to check the anchor behavior under normal and adverse conditions during installation as well as in service and under sustained tension loads. Only adhesive anchors which have passed these tests are permitted to be designed in accordance with ACI 318-11 App. D (ACI 318 (2011)).

AC308 and ACI 318-11 cover the design of anchorages using adhesive anchors. According to these design provisions adhesive anchors subjected to tension resulting from sustained load must satisfy an additional design check given as (Eq. (1)).

\[ N_{ua} \leq \alpha_e \cdot \phi N_n \]  

with

\[ N_{ua} = \text{tension component of the factored sustained load (usually factored dead load and that portion of the factored live load that is considered as sustained)} \]

\[ \phi N_n = \text{design resistance for bond failure calculated with the bond strength generated by the AC308 or ACI 355.4-10 qualification process respectively} \]

\[ \alpha_e = \text{reduction factor to account for the long-term bond strength being lower than the value valid for short-term loading} \]

\[ \alpha_e = 0.75, \text{according to AC308 for overhead applications only} \]

\[ \alpha_e = 0.55, \text{according to ACI 318, App. D for all applications} \]
According to AC308 the additional design check is required only for overhead application. However, according to ACI 318-11, App. D it must be performed for all applications subjected to sustained tension loads. According to AC308 the design resistance for bond failure is calculated taking into account the influence of spacing and edge distances, while for ACI 318-11, App. D these factors are neglected for the additional sustained load design check.

In July 2006, several concrete precast components fell from the ceiling of the Boston I-90 Seaport Portal tunnel onto a vehicle causing one casualty. The precast panels were suspended from the tunnel ceiling by adhesive anchors. These anchors were installed overhead and loaded by a sustained tension load. Based on the results of a thorough investigation, the National Transportation Safety Board (NTSB) identified as cause of the collapse creep failure of the adhesive anchors. Other parameters, such as the poor installation of the adhesive anchors were not considered as significant by NTSB for the failure.

This tragic failure raised an awareness that designers and builders did not have sufficient understanding of the behavior of bonded anchors, their sensitivity to wrong installation and their functioning under long-term sustained tension load. Furthermore, the validity of existing standards with respect to testing and design of bonded anchors under sustained loads was questioned.

In this paper, the testing of adhesive anchors under AC308 and ACI 355.4-10 is described and the behavior of bonded anchors under sustained tension load is discussed. Furthermore, the validity of the design provisions for bonded anchors under sustained load according to AC308 and ACI 318-11 App. D will be addressed.

**TESTING OF ADHESIVE ANCHORS UNDER SUSTAINED LOADING ACCORDING TO AC308 AND ACI 355.4**

According to AC308 and ACI 355.4-10 testing of adhesive anchors under sustained load is mandatory. Five (5) anchors each (d = 1/2" (M12) or the smallest nominal diameter if it is larger than 1/2" (M12)) are tested at standard temperatures (73°F (23°C)) and maximum long term elevated temperature. The latter is defined as that elevated temperature that may exist over a period of weeks or months. While according to AC308 the maximum long term temperature may be chosen by the manufacturer, in ACI 355.4-10 it is defined as at least 110°F (43°C). The creep test must be performed in a concrete test member made from low strength concrete and from the same concrete batch as the test member used for reference tests. The installation must be carried out in strict accordance with the manufacturer’s installation procedures. After heating the test chamber to the desired temperature the anchor is loaded by a constant tension load \( N_{sust} \) equal to 55% of the mean ultimate load established from both short term tension tests to failure at the standard and the maximum long-term temperature. In these short-term tests an unconfined tension test setup is used (Fig. 1). The embedment depth must be chosen such that bond failure (in contrast to concrete cone or steel failure) will occur. The sustained load tests, that is, creep tests may be performed with an unconfined, semi-confined or confined test setup (Fig. 2). Usually they are performed as confined tests because of its simplicity. The load is held constant (usually by disc springs) for a period of at least 42 days. During this time the anchor displacements are measured at regular intervals. After the creep test is terminated a confined tension test to failure is conducted at the test temperature.
The expected total long-term displacement, which includes the initial elastic displacement and the creep displacement at the end of the intended anchor service life is determined for each specimen by projecting a trend line forward over the intended anchor service life. The trend line is determined by calculating a least square fit through the data points using Eq. (2) with the data from not less than the last 20 days of the creep test.

\[
\delta(t) = \delta_{t=0} + a \cdot t^b
\]  

(2)

with

- \( \delta(t) \) = total displacement recorded in the test at time \( t \)
- \( \delta_{t=0} \) = initial displacement recorded under sustained load
- \( t \) = time corresponding to the total recorded displacement, hours
- \( a, b \) = constants evaluated by regression analysis
Equation (2) was originally proposed by Findley et. al. (1976) for visco-plastic materials. It describes a straight line in a double logarithmic scale. Generally, the intended anchor service life is given as 50 years (438,000 hrs, at standard temperature) and 10 years (87,600 hours, at long-term elevated temperature). It is then assumed that the maximum long-term temperature will occur for about 5 hours a day during the service life of 50 years, this means that the elevated temperature exists for almost 2.5 months per year. The mean values of the extrapolated total displacements \( \delta_{\text{service}} \) at standard and long-term elevated temperature shall not exceed the mean displacements \( \delta_{\text{adh}} \) corresponding to loss of adhesion \( N_{\text{adh}} \) as measured in reference tension tests conducted at the respective temperatures. The extrapolated displacement \( \delta_{\text{service}} \) in any test shall not exceed \( 1.2 \cdot \delta_{\text{adh}} \). The evaluation of \( N_{\text{adh}} \) and \( \delta_{\text{adh}} \) is described in detail in AC308 and ACI 355.4-10 and shown graphically in Fig. 3 for two typical cases.

![Figure 3 – Establishment for \( \delta_{\text{adh}} \) (displacement at loss of adhesion) according to ICC-ES AC308 and ACI 355.4-10 for two different load-displacement curves typically found during adhesive anchor testing](image_url)

If the requirements on displacement are not met, the sustained load tests must be repeated with a reduced sustained load until the requirements are met and the characteristic bond strength given by the manufacturer for standard approval will be reduced accordingly (see Eq. (3)).

\[
\tau_k = \tau_{k,0} \cdot \alpha_p
\]

with

\[
\tau_k = \text{characteristic bond strength given in the Approval document}
\]
\[
\tau_{k,0} = \text{characteristic bond strength established from short term tests}
\]
\[
\alpha_p = \text{reduction factor}
\]
\[
\alpha_p = \frac{N_{\text{sust,red}}}{N_{\text{sust,req}}}
\]
\[
N_{\text{sust,red}} = \text{reduced sustained load}
\]
\[
N_{\text{sust,req}} = \text{required sustained load}
\]

In Equation (3) the value \( \tau_{k,0} \) is included. It takes into account other reduction factors that might apply (compare AC308 and ACI 355.4-10).

The residual capacity measured after the creep tests must be at least 90% of the capacity of the corresponding reference tests. If this condition is not met, the characteristic bond strength given in the approval document is
reduced accordingly. However, based on the experience of the authors, anchors that meet the creep behavior requirement usually also meet the requirement on the residual capacity.

VALIDITY OF CURRENT METHOD FOR PREDICTING CREEP BEHAVIOR

The methodology for determining the response to sustained tension load in both AC308 and ACI 355.4-10 fundamentally assumes that relatively short-term testing (typically in the range of 1000 hours) can be extrapolated to long term behavior. This is an admissible assumption assuming that the adhesive behaves like a visco-elastic material and it has been applied in thin bond lines (e.g. externally applied carbon fiber reinforcing) (Triantafillou, Fardis (2006)). It further assumes that the behavior of the tested anchor diameter and embedment is representative of the entire anchor diameter and embedment range, and that all factors influencing the short term bond strength of the anchor, such as incomplete hole cleaning, affect the long-term behavior to the same degree. The validity of these assumptions has not yet been checked by systematic testing. However, there is currently no indication that these assumptions are incorrect. The additional design check according to Equation (1) should be performed with the actual sustained bond strength of the product. Assuming that the ratio of the sustained bond strength $\tau_{u,\text{sust}}$ to short-term bond strength $\tau_{u,t=0}$ is known, the value $\alpha_{\infty,\text{req}}$ to be inserted in Eq. (1) may be obtained from Eq. (4)

$$\alpha_{\infty,\text{req}} = \frac{\tau_{u,\text{sust}}}{\tau_{u,t=0}} / \alpha_p$$

with $\alpha_p$ according to Equation (3a).

To validate the factor $\alpha_{\infty}$ given in AC308 and ACI 318-11, App. D respectively the ratio $\tau_{u,\text{sust}} / \tau_{u,t=0}$ should be known. However, with the testing and assessment procedure described above, this ratio depends on the accuracy of the assumption in respect to

(a) influence of test setup on behavior

(b) limiting creep displacement $\delta_{\text{adh,m}}$

(c) extrapolation of measured displacements

If by the Findley’s creep law the above described assumptions are correct, then the approved sustained bond strength would be 55% of the mean short-term bond strength.

The code design provisions specify that the applied sustained load is no more than 55% of the mean ultimate load causing bond failure measured in an unconfined test. In this test tensile stresses are induced in the concrete near the surface of the specimen perpendicular to the anchor which reduce the bond strength, Meszaros (2002). These tensile stresses do not develop in the case of a confined test. Therefore the bond strength measured in an unconfined test is lower than the value measured in a confined test, on average about 25%. Creep tests may be performed either with the unconfined or confined test setup. In general, a confined test setup is used for creep tests as stated earlier. Then the applied sustained load is only about $0.75 \cdot 0.55 = 41\%$ of the mean failure load measured in a confined short-time test. With a decreased ratio $N_{\text{sust}} / N_{u,m}$ a decrease of the creep rate must be expected.

AC308 and ACI 355.4-10 assume that creep failure occurs if the total displacement under sustained load reaches the mean displacement under $\delta_{\text{adh,m}}$ at loss of adhesion. This assumption is rather conservative as described in the sections below.

The projection of the displacements over a relatively short time to the intended service life time using Findley’s creep law may be accurate as shown in Fig. 4 or rather conservative as shown in Fig. 5 and Fig. 6. In general, the Findley prediction is more accurate if test data over a longer period of time is used for the time-dependent prediction (Fig. 5).
Figure 4 – Comparison of measured displacements under sustained load with projection according to Findley’s creep law, injection system M12 (1/2”), $f_c' \approx 29$ N/mm² (4200 psi), $N_{sust} / N_{u,m,ref} = 0.41$, Eligehausen, Silva (2008)

Figure 5 – Comparison of measured displacements under sustained load with projection according to Finley’s creep law. Injection anchor (cartridge system) M16 (5/8”), $f_c' = 20$ N/mm² (2900 psi), $N_{sust} \approx 0.36 N_{u,m}$. Findley approximation using test data measured over 2000 hours and 5000 hours respectively, test results provided by company Hilti, partly published in Eligehausen, Silva (2008)
Figure 6 – Comparison of measured displacements under sustained load with projection according to Findley’s creep law. Bonded expansion anchors M12 (1/2”), hybrid system, $f'_c \approx 18$ N/mm$^2$ (2600 psi), $N_{sust} \approx 0.5 N_{u,m,ref}$, data provided by company fischerwerke.

Fig. 7 shows the load-displacement characteristic of an adhesive anchor measured in a short term confined test. The curve is typical for many adhesive anchors. The mean displacement at loss of adhesion is $\delta_{adh,m} \approx 1$ mm (0.04 in.). In general, the displacement at creep failure is much larger (Fig. 8). Therefore, Findley’s creep law gives conservative results for bonded anchors. Because of the conservative predictions the relationship between the long-term bond strength measured by the methodologies embodied in AC308 and ACI 355.4-10 and the values valid for short-term load tests cannot be evaluated with sufficient accuracy for design purposes. Therefore tests are in progress at the University of Stuttgart to establish this relationship that is more representative of the real behavior than the conservative approach using the Findley model.

Figure 7 – Load-displacement curves of confined reference tests, epoxy anchor M12 (1/2”), cartridge system, $h_{ef} = 80$ mm (3.15”), $f'_c \approx 30$ N/mm$^2$ (4350 psi), $T = 43$°C (110°F).
SUSTAINED LOAD TESTS

Sustained load tests and reference tests per ACI 355.4-10 and AC308 were performed with an epoxy injection type anchor M12 (1/2"), \( h_{ef} = 80 \text{ mm} \) (3.15") in normal weight concrete with a compression strength \( f'_{c} \approx 30 \text{ N/mm}^2 \) (4350 psi) at a temperature \( T = 43^\circ \text{C} \) (110°F) using a confined test setup. To avoid steel failure high strength threaded rods were employed. The product tested under sustained load obtained an ICC-ES Evaluation Report after passing the AC308 approval tests. Figure 7 shows the load-displacement curves measured in reference tests. The mean bond strength is \( \tau_{u,m} \approx 31 \text{ N/mm}^2 \) (4500 psi) and the mean displacement at loss of adhesion \( \delta_{adh,m} \approx 1.0 \text{ mm} \) (0.04 in.). Typical measured creep curves of test anchors exhibiting creep failure or that did not fail during test duration are shown in Fig. 8 and Fig. 9 respectively. The mean displacement of the anchors exhibiting creep failure evaluated as shown in Fig. 8 was \( \delta_{adh,m} \approx 2.1 \text{ mm} \) (0.083 in.), much larger than the value \( \delta_{u,m} \) shown in Fig. 7.

Figure 8 – Typical creep curve of an anchor exhibiting creep failure and evaluation of the failure displacement. Epoxy anchor M12 (1/2"), \( h_{ef} = 80 \text{ mm} \) (3.15"), \( f'_{c} \approx 30 \text{ N/mm}^2 \) (4350 psi), \( T = 43^\circ \text{C} \) (110°F)

In Fig. 10 another presentation methodology is shown plotting the ratio of applied sustained bond stress to mean reference bond strength as a function of the time to failure or, if the anchors did not fail during the duration of the test, as a function of the test time. From these results, the mean sustained bond strength for 10 years is estimated as 53% of the values valid for short-term loading. Some of the anchors did not fail during the test duration. For the anchors that did not fail the time to failure was extrapolated using Findley’s creep law and the mean failure displacement \( \delta_{u,m} = 2.1 \text{ mm} \) (0.083 in.), see Fig. 9. These results generate a mean sustained bond strength for 10 years of about \( 0.55 \tau_{u,m,ref} \) (Fig. 11).

Comparison tests were performed with a low sustained load \( (\tau_{sust} / \tau_{u,m,ref} = 0.25) \) which should fulfill the deformation requirements of ACI 355.4-10. The time to failure was assessed using Findley’s law and a limiting displacement \( \delta_{u} = \delta_{adh,m} = 1 \text{ mm} \) (0.04 in.). For all tested anchors the extrapolated time to failure is longer than 10 years (Fig. 11). Therefore the requirements on the displacement behavior will be met for a higher ratio \( \tau_{sust} / \tau_{u,m,ref} \) than applied. The time to failure of the anchors loaded by a low sustained load was also assessed using as limiting displacement the value \( \delta_{u,m} = 2.1 \text{ mm} \) (0.083 in.) obtained for the tests with creep failure. For the estimated time to failure the sustained load strength is much smaller than the value obtained from the regression curve of the tests with a higher sustained load (Fig. 11). This indicates that for the tested product, the sustained bond strength evaluated by an extrapolation of measured creep displacements using Findley’s creep law to a limiting value is very conservative. However, based on the experience of the authors with other products significantly better results can be obtained if
the sustained load test is performed for at least 2000 hours instead of 1000 hours that is the minimum sustained test duration required by AC308 and ACI 355.4-10.

In principle, the displacements under sustained load anticipated to occur over the life of the anchorage could also be extrapolated using a logarithmic function of the form \( y = c \cdot \ln(x) + b \) as it was required by AC58 (1995). However, in case of the tested product this is assumed not to be reasonable because creep of the adhesive and concrete under the applied moderate stress conditions starts out at a very rapid rate immediately after loading and progresses at a continuously decreasing rate (Fig. 9). This behavior is described by Equation (2) proposed by Findley.

![Diagram](image)

Figure 9 – Typical creep curve of an adhesive anchor that did not fail during the test duration and extrapolation of the time to failure, epoxy anchor M12 (1/2”), h_{ef} = 80 mm (3.15”), \( f'_c \approx 30 \text{ N/mm}^2 \) (4350 psi), T = 43°C (110°F)

![Diagram](image)

Figure 10 – Ratios \( \tau_{u,sust}/\tau_{u,mref} \) as a function of time to failure with regression curve, epoxy anchor M12 (1/2”), h_{ef} = 80 mm (3.15”), \( f'_c \approx 30 \text{ N/mm}^2 \) (4250 Psi), T = 43°C (110°F), confined test setup
In Figure 11 results of confined sustained load tests are plotted. The reference bond strength $\tau_{u,m,ref}$ is taken as 0.75 times the value measured in confined tests. The time to failure of anchors that did not fail during the test time was assessed as explained before using the mean failure displacement of tests with creep failure (2.1 mm (0.083 in.)). The mean sustained bond strength is evaluated as 47% of the reference bond strength valid for confined tests. This value is lower than the related sustained bond strength found in confined creep tests with...
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$h_{ef} = 80$ mm (3.15 in.). However, it is slightly higher than the corresponding sustained bond strength assessed from the results of confined creep tests with $h_{ef} = 105$ mm (4.13 in.), not shown here. Therefore it is concluded, that the related sustained bond strength is not influenced much by the test setup (confined or unconfined) if creep and reference tests are performed with the same test setup.

From the results of the confined creep tests (see Fig. 11) it is estimated that the requirements of ACI 355.4-10 would be met for a ratio $\tau_{sust} / \tau_{u,m,ref}$ (confined) $\approx 0.28$. The required code design maximum sustained bond stress is $0.55 \times 0.75 = 0.41 \tau_{u,m,ref}$ (confined). This gives $\alpha_s = 0.28 / 0.41 = 0.68$ (Eq. (3)). With $\tau_{u,sust} / \tau_{u,t=0} = 0.55$ (see Fig. 11) we obtain according to Eq. (4) $\alpha_{\infty,req} = 0.81$. This value is larger than the value $\alpha_{\infty} = 0.75$ or 0.55 given in AC308 and ACI 355.4-10 respectively. The described analyses were performed on a product which meets the requirements on the displacement behavior only with a significantly reduced sustained load. Currently sustained load tests are performed at the University of Stuttgart with a product with a higher related sustained bond strength. Preliminary results indicate that the value $\alpha_{\infty,req}$ is significantly higher than 0.55.

In the future the current methodologies to assess the long-term bond behavior of adhesive anchors should be replaced by a method which yields the long-term bond strength directly (Ellegausen, Silva (2006), Cook, Davis (2010)). While a different methodology is appealing for its simplicity, the current approval process assumes that the necessary long-term bond strength can be generated in a reliable and confident manner. To verify the validity of this assumption corresponding research is under way at the University of Florida and the University of Stuttgart.

### SUMMARY

Based on the presented results, the following conclusion can be drawn.

1. The long term bond strength of adhesive anchors is significantly lower than the short term bond strength. The ratio $\tau_{u,sust} / \tau_{u,t=0}$ is product dependent. The sustained bond strength should be taken into account in the design of adhesive anchors subjected to sustained load.

2. Adhesive anchors qualified according to ACI 355.4-10 and designed according to ACI 318-11 Appendix D may safely be used to resist sustained tension loads, provided they are installed correctly. The reduction factor $\alpha_{\infty} = 0.55$ given in ACI 318-11, App. D to account for the reduced long-term bond strength is conservative.

3. The design provisions in AC308 to account for sustained tension loads should not only be applied to adhesive anchors installed overhead, but to all adhesive anchors that have to resist sustained tension loads. According to the current test results, the factor $\alpha_{\infty} = 0.75$ given in AC308 is adequate, provided the anchors are installed correctly.

4. In the future the current test and assessment methodology to assess the behavior of adhesive anchors under sustained load should be replaced by a method that directly yields the sustained bond strength of a product.
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ACI (2011): ACI 318-11, Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute, Farmington Hills.


Synopsis:

Bonded anchors are frequently used for connections between structural or non-structural elements to concrete members. These connections are loaded by long-term and short-term loads respectively. The evaluation of the long-term behavior in the current approval guidelines in the U.S. and Europe is established by sustained load tests having a minimum duration of 1,000 hours in the U.S. and 2,000 hours in Europe. The results of these tests are extrapolated to approximately 450,000 hours (50 years) for tests at standard temperature and to roughly 90,000 hours (10 years) for tests at elevated temperature. The extrapolation technique and the evaluation criteria are developed to allow for an evaluation on the safe side.

The paper presents results of tests on anchors installed using a proprietary adhesive anchor system that were subjected to sustained loads for up to approximately 21,000 hours (2.4 years). In these tests not only the time of testing but also the load level were beyond the requirements of the current approval guidelines. Based on these results the current evaluation method is analyzed and the conservatism associated with several aspects of the testing and evaluation methods is discussed.

Keywords: bonded anchor, sustained load, Findley
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CURRENT APPROVAL TESTING AND EVALUATION

The current evaluation system in the U.S. qualifies adhesive anchorage systems for short-term and long-term applications [AC308]. The characteristic resistance of these systems is established on the basis of short-term testing, taking into account the suitability of the system under several different conditions. Reference tests are conducted in low- and high-strength concretes. The sensitivity of the system to adverse jobsite conditions, e.g., insufficient hole cleaning, installation in water saturated or submerged concrete, or installation in water-filled holes, is determined in the reliability tests. It is assumed that the relative influence of these conditions on the anchor behavior under short-term and long-term loading is equivalent.

Based on this assumption, sustained load tests for evaluating the long-term behavior of the system are conducted under proper installation and base material (i.e., uncracked concrete) conditions. Tests are conducted applying a sustained tension load equal to 55% of the mean ultimate load derived from short-term tension tests. This load level corresponds to approximately 1.6 times the design load for typical cases. Anchors are loaded for 42 days (1008 hours), over which time the displacement is continuously monitored. After 42 days, the anchors are unloaded and subsequently loaded in tension to failure. The sustained load tests are performed at standard temperature and maximum long-term elevated temperature.

The displacements measured during the sustained load tests are used for an extrapolation using the Findley Creep Law [Findley]. The displacements are approximated by the general equation \( \varepsilon = \varepsilon^0 + \varepsilon^+ \cdot t^n \) where \( \varepsilon^0, \varepsilon^+ \) and \( n \) are a function of the test results. Figure 1 provides an example data plot from a test conducted over 1008 hours.

![Figure 1 – Findley Approximation for a 1008-hour Sustained Load Test](image-url)
The displacements calculated by extrapolation to 50 years (standard temperature) and 10 years (maximum long-term elevated temperature) are compared to a specific displacement derived from the short-term reference tests which represents the theoretical loss of adhesion of the system under tension loading. Figure 2 shows such an extrapolation to 50 years for the tests results shown in Figure 1.

Figure 2 – Findley Extrapolation for 1008 h Sustained Load Test to 50 Years

Figure 3 shows four possible load-displacement conditions resulting from tension tests for which the displacement at loss of adhesion must be derived. If there is a point in the load displacement curve where the stiffness changes significantly (Figure 3a), this point can be taken to denote loss of adhesion. For tests which do not show such a significant stiffness change (Figures 3b, 3c and 3d), the initial stiffness in the test is divided by a factor of 1.5 to establish an intercept point with the load-displacement curve. If the interception is at the ascending branch of the load displacement curve, this displacement is defined as the displacement corresponding to loss of adhesion. If the interception is at the descending branch of the load displacement curve (Figure 3c) the loss of adhesion displacement is assumed to correspond to the peak load.

Figure 3 – Determination of Loss of Adhesion Displacement [AC 308]
A passing sustained load test is one for which the extrapolated displacement is less than the displacement defined as loss of adhesion for the anchor.

With this approach it is verified that the system does not fail under a sustained load of approximately 1.6 times of the design load.

This approach is based on two assumptions: first, that the Findley extrapolation to 50 years (438,000 hours) from data derives over a period of 1008 hours is conservative; and second, that the displacement at loss of adhesion as derived from short-term tests in accordance with Figure 3 represents a conservative estimate of the failure displacement. There has recently been a general discussion regarding how accurate and conservative these assumptions are and subsequently how safe the adhesive anchors that are loaded according to the corresponding approvals and evaluation reports generated from these tests actually are in practice. In order to gain more knowledge on the real safety level of the evaluated adhesive anchor systems, an extensive test program has been undertaken.

**DESCRIPTION OF TEST PROGRAM**

All tests were performed with one adhesive injection system which consists of a vinyl ester resin with additional cementitious content. The system holds an Evaluation Service Report (ESR) from the ICC Evaluation Service which is based on acceptance criteria contained in AC308 [AC308]. Since the test program was intended to evaluate the safety level associated with the assessment system, all test results are presented as a function of the characteristic bond stress value for long-term sustained loading as given in the ESR, whereby AC308 dictates that the anchor design strength for sustained tension loading be taken as 75% of the characteristic design value based in part on sustained load testing.

Sustained load tests were performed at five different load levels. The tests were continued well beyond the time limits established in current assessment requirements. All tests with the exception of those conducted at the highest sustained load level were performed in a partly unconfined loading setup. The high-load tests were conducted in a fully confined test rig. All test results were converted to unconfined loading using an assumed ratio of unconfined to confined of 0.75 in order to be able to make a correct comparison to the approval values. The tests were performed at the standard (room) temperature of 20°C (68°F). The test results are summarized in Table 1:

<table>
<thead>
<tr>
<th>Sustained load level in relation to characteristic long-term bond strength in the evaluation report</th>
<th>Sustained load level in relation to the design long-term bond strength in the evaluation report</th>
<th>Duration of sustained load testing</th>
<th>Number of replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{\text{test}} / \tau_{\text{k,uncr,lt}} )</td>
<td>( \tau_{\text{ult}} / \tau_{\text{d,uncr,lt}} )</td>
<td>(hours/days)</td>
<td>(n)</td>
</tr>
<tr>
<td>1.05</td>
<td>1.61</td>
<td>12900/538</td>
<td>3</td>
</tr>
<tr>
<td>1.12</td>
<td>1.72</td>
<td>21000/875</td>
<td>3</td>
</tr>
<tr>
<td>1.30</td>
<td>2.00</td>
<td>12900/538</td>
<td>2</td>
</tr>
<tr>
<td>1.54</td>
<td>2.36</td>
<td>7100/296</td>
<td>3</td>
</tr>
<tr>
<td>1.75</td>
<td>2.69</td>
<td>7100/296*</td>
<td>3</td>
</tr>
</tbody>
</table>

*1 failure occurred at 3200 hours/133 days

Table 1 – Sustained Load Tests

**EVALUATION OF FAILURE CRITERIA OF CURRENT APPROVAL SYSTEM**

As discussed previously, in order to determine the theoretical failure associated with sustained loading the displacement at loss of adhesion must be derived from short-term reference tests. For the tested adhesive anchor system at the tested diameter and embedment depth, the displacement at loss of adhesion was established as \( \delta_{\text{adh}} = 0.39 \text{ mm} \). The average displacement at ultimate load was \( \delta_{\text{ult}} = 0.62 \text{ mm} \).
Figure 4 shows the time-displacement plots for the sustained load tests. The plots represent the average of all tests performed at each load level with the exception of the plots for loading at 1.75 times the rated long-term bond strength which represent single tests. The displacement at loss of adhesion and at ultimate load are shown as well. The tests are ongoing. At the time of this writing, no failures have occurred in tests up to a loading level of 1.54 times the characteristic long-term approval bond stress. All curves have stabilized and the anchors show only negligible further displacement after several thousand hours of testing despite having reached the displacement level corresponding to loss of adhesion. In the tests with bond stress levels of 1.54 times rated, the displacements now exceed the displacement at peak load by approximately 30% and the anchors show no evidence of impending failure. One anchor failed when tested at the load level corresponding to 1.74 times the characteristic long-term rated bond stress. The displacement at failure was 1.1 mm, which is approximately 2.8 times higher than the displacement at loss of adhesion and 1.8 times higher than the displacement at peak load. Two other anchors tested at this load level have not failed at the time of this writing and show only negligible displacements after approximately 4000 hours of loading.

For these tests, the displacement at loss of adhesion as a failure criterion is quite conservative (by a factor of 2.8). Also the displacement at peak load as a failure criterion would be conservative (by a factor 1.8).

![Figure 4 – Displacement Behavior for Sustained Load Tests](image)

**EVALUATION OF TIME OF TESTING OF CURRENT APPROVAL SYSTEM**

The minimum required duration of testing according to AC308 [AC 308] is 1008 hours. In the test program described here, sustained load tests up to 21000 hours were performed. In order to show the effect of testing duration, the Findley approximation is shown in Figure 5 for one test. The red curve is extrapolated from displacements measured between 0 and 1008 hours, whereas the blue curve is derived from test results up to 21000 hours. The Findley approximation from 1008 hours of measured displacements is shown in detail in Figure 1. Comparing the two curves in Figure 5 it can be seen that the extrapolation based on the shorter test duration overestimates the displacements quite significantly.
Extrapolating both curves to the relevant 50 years (438000 hours) as shown in Figure 6 shows that for this test series the extrapolation based on the shorter test duration as permitted in AC308 (1008 hours) yields approximately 20% higher displacements at 50 years than if the extrapolation is taken from measured displacements up to 21000 hours.

**EVALUATION OF THE SAFETY RESERVES IN THE TESTING AND EVALUATION APPROACH**

Based on the measured displacement behavior in the sustained load tests, extrapolation using the Findley Creep Law can be performed as described above. By extrapolation to a defined displacement, the theoretical duration to failure under applied sustained tension load can be derived.

As a first step, this extrapolation was performed using all available data from the sustained load tests, which includes testing from 7000 to 21000 hours. The required minimum test duration according to AC308 is 42 days (1008 hours). The theoretical failure was evaluated for each loading level for three different displacement criteria levels: Displacement at loss of adhesion (0.38 mm), displacement at peak load (0.62 mm), and the measured
displacement corresponding to sustained load failure (1.1 mm). The results are presented in Figure 7 using a logarithmic time scale. For better evaluation of the data, the results for each failure criteria are represented with a logarithmic trend line.

![Figure 7 – Evaluation of Tests for Time to Failure](image)

To evaluate the safety level of the current U.S. assessment procedure (AC308) the reduced test duration requirement must be taken into account. To evaluate the difference between sustained load testing up to 1008 hours and longer-term testing, the extrapolation was repeated with test results from the first 1008 hours only. The results are presented in Figure 8 as dashed lines. It can be seen that for each failure displacement assumption, there is a significant difference in the predicted sustained load time to failure for a given load level. The theoretical time to failure at the characteristic long-term bond stress level decreases for the evaluation using the loss of adhesion criterion from 45 to 2.3 years, for the evaluation using displacement at failure load from 262 to 84 years, and for the evaluation using the displacement at sustained load failure from 54000 to 11500 years.

![Figure 8 – Time to Failure Evaluation of Performed Tests - Comparison of Assessment Procedures](image)
In order to evaluate the safety margin inherent in the current assessment approach, the extrapolation using data from the first 1008 hours of testing is combined with the assumption of failure at the loss of adhesion displacement (red line). This is compared with the same extrapolation taking the displacement at peak load as the failure criterion (blue line). Finally, both of these predictions are compared with the results derived from extrapolating using all available data points and taking the displacement at sustained load failure as established for higher load levels (see Figure 4) as the failure criteria (black line). The time to failure lines derived from the extrapolated test results are shown in Figures 9 and 10, whereby the red line represents the current assessment procedure in AC 308 (42 days, loss of adhesion). For the tested system, the displacement at peak load could be justified as the failure criterion since the failure in the tests occurred typically between the threaded rod and the adhesive where no loss of adhesion can occur. This evaluation is shown in the graph with the blue data points and trend line. Assuming that the anchor is continuously loaded with 100% of the characteristic load given in the ESR, an average time to failure based on the current testing and evaluation approach would be 2.3 years. Using the displacement at peak load assumption, the time to failure increases to 84 years. For the same system, the time to failure based on the extended sustained load testing and the measured sustained load failure displacement indicates an average failure time of 54000 years.

Verifying the additional safety margin within the assessment procedure, the theoretical resistance corresponding to a 50-year sustained load duration can be evaluated. The results are shown in Figure 10. If the criteria uses data from only 1008 hours testing and the loss of adhesion failure criteria, a resistance of 88% of the reference value is derived. As shown, this contrasts with 142% of the reference value when all available data are used and the specific displacement at sustained load failure is taken as failure criterion.

The sustained load tests according to AC308 are conducted with 55% of the ultimate short-term mean resistance. Taking the results of the assessment for this test series, this corresponds to 0.55 x 1.42/0.88 = 0.89 or 89% of the ultimate short-term resistance.

If the displacement at peak load (short-term loading) is used as the failure criterion, a 55% test load level corresponds to 0.55 x 1.42/1.03 = 0.76 or 76% of the ultimate short-term resistance.

This evaluation shows that there is a substantial safety margin within the testing and evaluation concept of AC308. The required reduction factor of 0.75 to be taken on short-term resistance in AC308 is conservative and no reduction of this factor is indicated based on the performed tests and evaluation. Furthermore it may be considered whether this factor could be increased for suitable products based on testing.
COMPARISON OF EVALUATION REPORT VALUES TO LONGTERM TESTING AND EVALUATION

All evaluations were performed based on an average time to failure curve. To evaluate the resistances stated in the ICC-ES evaluation report for applications with sustained loads, the characteristic time to failure curve must be used. Based on the average time to failure curve, valid for the maximum available data of the sustained load tests and the displacement at sustained load failure as failure criteria (black curve in figures above), and the scatter of the single tests, a characteristic time to failure curve is established. The characteristic time to failure curve is shown in Figure 11 as a dashed line.

Evaluating the characteristic time to failure curve at different load levels, the theoretical time to failure at the specific load level can be determined. If the specific system is loaded to a level corresponding to the characteristic bond stress for sustained loading (75% of the short-term value) specified in the ESR, the theoretical time to failure is 950 years. At the design load level the theoretical time to failure increases astronomically (to 1.4 million years) and at the allowable load level the theoretical time to failure is essentially infinity. Clearly, these derived failure times indicate a large safety margin against long-term bond failure for adhesive anchor systems evaluated under AC308 [AC 308].

The characteristic resistance at 50 years (438,000 h) is 114% of the characteristic bond strength for sustained loading (75% of the short-term value) specified in the ESR. This corresponds to a reduction factor for sustained loads of 0.86.
SUMMARY

The current testing and evaluation concept requires a minimum of 1008 hours of sustained load be applied. The measured displacements are extrapolated to 50 years (438000 hours) for the standard temperature case. The derived displacement must be less than the displacement corresponding to loss of adhesion as derived from monotonic tension tests.

To evaluate the safety margins within this assessment procedure, sustained load tests at several load levels with a duration of up to 21000 hours have been performed. The tests are ongoing.

Evaluation of the test results to date show the following results:

- Extrapolation of displacements using the Findley Creep Law and data derived from a test duration of 1008 hours is conservative compared to the displacements predicted with data from a longer test duration.
- The assumption of failure at a displacement corresponding to loss of adhesion is very conservative. The tested anchors showed failure displacements of approximately 2.8 times of the displacement at loss of adhesion in sustained load tests.
- It can be concluded, that sustained load testing at 55% of the ultimate mean short-term resistance using the current evaluation concept corresponds to sustained loading at 86 to 89 % of the mean ultimate value.
- Based on the tests, the characteristic time to failure curve was established for the tested system. Assessment for the specified resistances corresponding to sustained loads in the ICC-ES ESR for the system using the time-to-failure curve indicates astronomically long times to failure.

These results show, that for the tested system at room temperature, a significant safety margin is associated with the current testing and evaluation concept of the current U.S. acceptance criteria for sustained loading. Extension of these conclusions to elevated temperature conditions and to other types of adhesive anchor systems requires additional study.
REFERENCES


Spieth
EFFECT OF ENVIRONMENTAL EXPOSURE ON THE CREEP BEHAVIOR OF ADHESIVE ANCHORS

by Adham M. El Menoufy, Khaled A. Soudki, Ahmed K. El Sayed, and Hannah Schell

Synopsis: This paper describes an experimental investigation on the long-term creep behavior of adhesive anchors under sustained tensile loads in combination with different environmental exposures. The experimental program comprises of 36 pull-out test specimens. The specimens consist of a cylindrical shape concrete block of 300 mm (12 inch) in diameter and 200mm (8 inch) in depth, with 15M (No. 5) deformed steel bars post-installed to an embedment depth of six times the bar diameter or 125mm (5 inch). Three types of adhesives were used: Type A - Fast setting two component methyl methacrylate adhesive, Type B - Fast setting two part epoxy adhesive and Type C - Standard set two part epoxy adhesive. The study is divided into four phases. Phase I consists of static pullout tests to determine the yield strength ($f_y$) and the maximum capacity of each anchor system. Phase II consists of sustained load tests under load levels of 40%$f_y$ at normal laboratory conditions. Phases III and IV are sustained load tests under load levels of 40%$f_y$ with moisture exposure and freeze/thaw cycling, respectively. All sustained load tests lasted for a period of at least 90 days. The results of the static pullout testing showed that specimens with epoxy based adhesive exhibited stronger bond strength, forcing the anchor to fail by rupture prior to bond failure. As for the sustained load test results, specimens with standard set epoxy based adhesive showed insignificant creep displacement under room conditions, however, when exposed to moisture noticeable creep displacements were recorded. Specimens with both fast setting epoxy and methyl methacrylate based adhesives showed higher creep displacements under environmental exposure versus those kept at room temperature.

Keywords: creep; adhesive; anchors; sustained load; epoxy.
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**INTRODUCTION**

Currently epoxy- and acrylic-based adhesives are widely used in concrete anchoring applications around the world. Nevertheless, the long-term performance over the expected service life of such anchors is not fully understood and lacks experimental data in particular under adverse environmental exposure. A suspended ceiling section of the Interstate 90 (I-90) connector tunnel in Boston, MA, collapsed on July 10, 2006 crushing a car and fatally injuring one of its occupants. The suspended ceiling in the collapsed section was comprised of concrete panels connected to steel hangers suspended from the tunnel concrete ceiling by an adhesive anchor system consisting of stainless steel anchor rods embedded in epoxy. The National Transportation Safety Board’s (NSTB) investigation has determined that the ceiling collapse was probably triggered by creep failure of the epoxy anchor adhesive used to hold the ceiling in place (Highway Accident Report NSTB/HAR-07/02, 2007).

In response to a solicitation of research proposals by the Ministry of Transportation of Ontario, prompted by concern with long-term durability of anchor installations in view of the US experience, and a desire to develop effective material prequalification requirements. This research study investigates the long-term creep behavior of adhesive anchors under sustained tensile loads as well as long-term durability of such anchors. The objectives of the research study are to evaluate the performance of epoxy- and acrylic-based adhesive anchor systems. The study focuses on the creep performance of these anchor systems under sustained tensile loads and on the tensile capacity after exposure to different environmental conditions. It is expected that this study will increase our knowledge regarding the long-term performance of adhesively-bonded anchors and provide practicing engineers with the tools necessary for safely designing adhesive anchors.

**BACKGROUND**

Anchoring systems for concrete are comprised of: pre-installed/cast-in-place, and post-installed anchors. A cast-in-place anchor is typically composed of a headed steel bolt or stud. The main load transfer mechanism is keying or bearing, which is the direct transfer of load from the anchor into the concrete by bearing forces in the same direction of loading the anchor (Collins et al., 1989). Possible failure mechanisms are yield and fracture of anchor shank, or formation of a concrete breakout cone. Extensive testing has been performed on cast-in-place anchors, and design models have been developed to accurately predict their behavior (ACI 318-05, Appendix D).

Post-installed anchors offer more flexibility as they can be installed in hardened concrete virtually anywhere that is accessible to a drill, making them more commonly used. Depending on the method of load transfer into concrete, post-installed anchors are divided into two types, mechanical systems (expansion and undercut) and bonded (adhesive and grouted) systems. Expansion anchors are installed by expanding the lower portion of the anchor through either torque-controlled or displacement controlled techniques, and load is transferred through friction between expansion sleeves of the anchor and the wall of the drilled hole in the concrete. Undercut anchors are
installed in a similar manner to expansion anchors, but they possess a slightly oversized hole at the base of the anchor embedment. Load is transferred through bearing of the base of the undercut anchor on the hole. Both adhesive and grouted anchors are bonded anchors. The load transfer of bonded anchors is ensured by bond stresses between the anchor, adhesive and concrete along the embedment length. Adhesive anchors can either be a threaded rod or deformed steel rebar. Different products can be used to install adhesive anchors. These products can be polymers (epoxies, polyesters, or vinyl-esters) or hybrid systems. The curing time of adhesive products is varies based on formulation. Cook et al., (1998) explain that when the resin and curing agent are mixed, the products undergo an exothermic reaction resulting in the formation of a polymer matrix that binds the anchor and the concrete together.

Adhesive anchors should be installed in clean dry holes to attain maximum bond strength. The applied load is transferred from the adhesive anchor to the concrete by one of two mechanisms: mechanical interlock or chemical binding to the concrete. Because of their reliance on chemical and mechanical bond, adhesive anchors are uniquely susceptible to a number of potentially adverse factors. Conditions that cause these factors can occur during installation and throughout the service life of the anchor. Cook and Konz, (2001) experimentally investigated the sensitivity of 20 adhesive products to various installation and service conditions through confined tension tests, and focused on the relative bond strength. Installation factors examined included variations in the condition of the drilled hole, concrete strength, and concrete aggregate type. Service conditions considered short-term cure and loading at elevated temperature. Findings showed some general trends within groups of products with similarities in chemical composition. However, responses to various conditions and factors varied significantly making it unreliable to make prediction based on chemical formulation. Higgins and Klingner, (1998) tested the effect of UV exposure and acid rain wetting and drying on the bond strength of a single type of adhesive anchor, and found no significant impact on the tensile behavior of the anchor to such exposure.

The stiffness of adhesive polymers is time and temperature dependent. If a load is applied suddenly, the polymer responds like a hard solid. But if the load is held constant, the molecules within the polymer may begin to rearrange and slide past one another, causing the polymer to gradually deform in a process called creep. As the deformation increases, it becomes irreversible and eventually leads to damage accumulation and failure. This process can also be affected by other aspects of the operating environment, such as the presence of moisture or freeze-thaw cycles. Most of the research work available in the literature concerning adhesive anchors is related to the short-term strength and performance of such anchors (Eligehausen et al., 2007; R. A. Cook et al., 1998; R. A. Cook and Konz, 2001; McVay et al., 1996).

Limited research has been performed on the creep of adhesive anchors. Ammann, (1992) studied the effect of moisture and temperature on the creep behavior of two types of adhesives: epoxy acrylate (vinylester) and unsaturated polyester. The vinylester resin with hardener and quartz granules showed a very minor increase of displacement after submerging the test specimens in water compared to polyester resin. The vinylester resin experienced lower displacements at a temperature of 80 °C compared to polyester resin. Tu and Kruger, (1996) reported that water is a harmful factor for epoxy adhesives and noticeable bond strength deterioration of joints subjected to water immersion was found. Meline et al., (2006) evaluated the creep performance of epoxy adhesive anchor systems with epoxy-coated steel rebars at elevated temperature. Three different epoxy adhesive brands were used in this investigation. They were Simpson Strong-Tie SET22, Red Head Epcon Ceramic 6, and Covert Operations CIA-Gel 7000. A total of 15 creep specimens were used (5 specimens for each type of epoxy adhesive). A sustained creep load of 40% of the average ultimate load (based on static tests) was applied on the test specimens for 42 days at 110°F ± 3°F (43.3°C ± 1.65°C). The creep displacements at 600 days were extrapolated and it was found that both SET22 and Ceramic 6 failed to satisfy the ICBO-AC58 (2005) requirements. The CIA-Gel 7000 adhesives satisfied the ICBO-AC58 (2005) requirements.

The International Building Code (IBC), and Uniform Building Code (UBC) do not include requirements for establishing the structural capacities of adhesive anchors used to create connections between structural concrete and attachments. To address the lack of design procedures and testing requirements acceptance criteria for post-installed adhesive anchors in concrete elements (AC308) were issued by ICC Evaluation Service Inc. in June 2006, and has been revised a number of times. The current version was re-approved November of 2009 and is the basis for the testing program. These criteria prescribe testing programs, evaluation requirements and design requirements for post-installed adhesive anchors intended for use in concrete.
RESEARCH SIGNIFICANCE

Most of the research work available in the literature concerning adhesive anchors is related to the short-term strength and performance of such anchors. Although adhesive anchors are used extensively in practice, they have not yet been fully incorporated in design codes. Appendix D in ACI 318-08 building code has design provisions for anchorages using cast-in-place and post-installed mechanical anchors but does not include design provisions for adhesive anchors. Major safety issues were identified in 2006 related to the Boston tunnel ceiling collapse accident included insufficient understanding among designers and builders of the nature of adhesive anchoring systems and lack of standards for the testing and pre-qualification of adhesive anchors in sustained tensile load applications (Highway Accident Report NSTB/HAR-07/02, 2007). The long-term behavior of post-installed adhesive anchors lacks experimental data and needs to be vigorously investigated. This research study investigates the long-term creep behavior of adhesive anchors under sustained tensile load and environmental exposure. This paper aims to contribute to filling this gap in the current knowledge and to identify areas requiring further research.

EXPERIMENTAL PROGRAM

The experimental investigation was divided into four phases. These phases are intended to evaluate the tensile behavior of the adhesive anchors under sustained load with adverse environmental exposures. The environmental conditions considered in this study included ambient temperature, moisture exposure and freeze-thaw cycles in the presence of moisture to assess the long-term durability of the adhesive anchors. Three types of adhesives (commonly used by the Ministry of Transportation of Ontario in bridge and highway applications) are considered: Type A - Fast setting two component methyl methacrylate adhesive, Type B - Fast setting two part epoxy adhesive and Type C - Standard set two part epoxy adhesive. The tests were based on the requirements of (ASTM E 1512-01, ASTM E 488-96, and ICC-ES AC308). ICC-ES AC308 requires for the unconfined test setup a clear radius around the anchor of 2x the embedment depth and five replicate specimens, while ASTM E 1512 requires a clear radius of 1x embedment depth and 3 replicates. In this study, the clear radius was 1 x embedment depth and 3 replicates were used.

**Test matrix**

The study comprises a total of 36 specimens. Nine specimens are tested statically up to failure to characterize the ultimate bond strength of different anchoring systems. These tension pullout tests will serve as references for the other creep and durability tests in the study. The tensile load and the displacement of the anchor relative to the concrete were recorded during the test and the mode of failure was examined. An average ultimate load was determined for each series based on the results of three specimens. The remaining 27 specimens are divided into 3 groups of 9 specimens per adhesive type. The creep tests were carried out under a sustained load of 32kN or 40% of the yield strength of the anchor for a minimum period of 90 days. Specimens with each type of adhesive were subjected to three types of exposure: ambient temperature, moisture exposure, and freeze/thaw cycles with the presence of moisture. Three specimens were tested for each exposure. A preload not exceeding 5% of the sustained creep load was applied before zeroing of the displacement readings. The remainder of the sustained creep load was applied representing the service load level. The freeze-thaw exposure and cycling were conducted following the ICC-ES AC308 requirements (2009). The top surface of the test specimen was covered with tap water, within a 76 mm radius from the centre of the test anchor, and was maintained at 12 mm depth throughout the test. The freeze and thaw cycles were at a rate of 1 cycle per day. Each cycle consisted of 16 hours at a temperature of -20±2°C and 8 hours at a temperature of +20±2°C. Moisture exposure was conducted by ponding the top surface of the specimen at room temperature. Table 1 summarizes the test matrix.

<table>
<thead>
<tr>
<th>PHASE</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I : Static testing at room temperature</td>
<td>Sustained load = 0%</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Phase II : Creep test at room temperature</td>
<td>Sustained load = 40% yield</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Phase III : Creep test under moisture exposure</td>
<td>Sustained load = 40% yield</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Phase IV : Creep test under freeze-thaw cycles</td>
<td>Sustained load = 40% yield</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total number of specimens</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

11.4
Specimen Preparation
The test specimen consisted of a cylindrical concrete block, an adhesive, and an anchor. The concrete blocks were constructed using a designed concrete mix design of 30MPa. Concrete specimens were cylindrical in shape of approximately 12 inch (300 mm) in diameter and 8 inch (200mm) in height. The specimens were cured for 14 days. Concrete cylinders (4” X 8”) were used for compressive strength testing at the beginning and end of each testing phase.

All anchors were 15M (400 grade) deformed steel bars installed to an embedment depth of approximately 125mm (5 inch). Three adhesive materials were used for the anchor installation. Type A - Fast setting two component methyl methacrylate adhesive, Type B - Fast setting two part epoxy adhesive and Type C - Standard set two part epoxy adhesive.

A total of 12 anchors were installed using each of the adhesive materials. The 0.75 inch (190 mm) diameter holes for the anchors were drilled using a rotary drill hammer with percussion, and then cleaned as per the manufacturer’s instructions which consisted of a three step process: blasting with compressed air, brush cleaning, then a final blast of compressed air (Figure 1). The adhesive material was then dispersed at the bottom of the drilled hole followed by insertion of the anchor with a slow rotational motion to allow equal distribution of the adhesive, and avoid formation of air pockets around the anchor. To ensure the verticality of the anchors, they were held in place by steel tripods until the adhesive had fully set. The full process of the anchor installation was witnessed by a representative from each adhesive manufacturer. Anchor installation took place at least 28 days after casting of the concrete specimens.

Creep Test Setup
Two creep testing setups were utilized to carry out the test phases in a timely manner. Each test setup consisted of three sets of frames; each set had three specimens of each adhesive material being tested. The first setup had a total of 9 creep loading frames manufactured for the sustained load test. The loading system was designed to magnify the load through a series of lever arms, with a magnification factor of 1:115 (Figure 2).

All 9 frames were calibrated to the required testing 32 kN (40%f,) prior to the creep testing, using a various combination of dead loads while measuring the magnified tension load using a 50,000 pound Futek-LTH500 load cell. The second testing frame relied on compression coil springs and rod assembly to apply the load. The coil springs used had a capacity of 40kN at 1.5 inch of compression displacement, and are shown in Figure 3.
Each test setup was equipped with a Scimetric Instruments System 200, Model 237 data acquisition system with 12-bit resolution. The system continuously collected the data (displacement, load, temperature) for each test phase. For Phases II and III one load cell (3 load cells in total) was utilized to monitor the load per adhesive group as the test frames were pre-calibrated, however, for Phase IV nine load cells were used (one per frame). Linear variable differential transformers (LVDTs) were used for displacement measurements which were collected every 5 minutes for the first hour, hourly for the next 24 hours, daily for the next 10 days, and every 5 days thereafter. Room temperature was monitored on an hourly basis throughout the test duration. A backup power supply APC Smart-UPS 750 was used to account for any short term power blackouts.

The required sustained tensile load was applied either by magnification of dead loads in test setup (1), or by torque on the threading end of the anchor to compress the spring in test setup (2). For both loading mechanisms the load was applied on the anchor over a period of 3-5 minutes per frame. The load was then maintained and monitored for at least 90 days duration.
Static Test Setup

Pullout tests were carried out in a UniRoyal four-post test frame, controlled with closed-loop servo-hydraulics, equipped with MTS controller-Flextest GT, and a double ended MTS-244 actuator with a stroke of 20 inches (500 mm) and a capacity of 112 Kips (500 kN). The anchors were gripped using a MTS-647 hydraulic wedge grips. The test was done in a MultiPurpose TestWare (MPT) environment using TestStar control software. A 1 inch thick steel plate with a 1 ¾ inch diameter center hole was placed on top of the concrete specimen for confinement. To ensure the load was uniformly distributed over the full surface area of the specimen, a thin layer of hydro-stone was applied between the steel plate and the concrete surface to ensure full contact. Figure 6 shows the static test setup.

The load was applied in accordance with ASTM-488, in a continuous loading regime. A linear variable differential transformer (LVDT) was mounted using an aluminum bracket to the steel anchor to measure the displacement of the anchor relative to the top of the steel plate, while load measurements were taken by a load cell on the test machine.
TEST RESULTS

Static Test Results

Concrete compressive testing for the concrete cylinders was carried out prior to conducting the static test series. The average concrete strength was 44.1 MPa (6400 psi), which is higher than the specified compressive strength of 30 MPa (4350 psi). The static test results for Phase I are summarized in Table 2.

Initially, all specimens with the 3 adhesives behaved in a similar manner. During load testing specimens with Type B and Type C adhesive exhibited stronger bond strength, forcing the anchor to fail by rupture prior to bond failure. On the other hand, all specimens with Type A adhesive failed by bond.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Exposure Condition</th>
<th>Ultimate Load (kN) Average</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-R-0%-1</td>
<td>Room Temperature</td>
<td>132</td>
<td>Yielding of the anchor followed by bond failure</td>
</tr>
<tr>
<td>A-R-0%-2</td>
<td>Room Temperature</td>
<td>122</td>
<td>Yielding of the anchor followed by bond failure</td>
</tr>
<tr>
<td>A-R-0%-3</td>
<td>Room Temperature</td>
<td>108</td>
<td>Yielding of the anchor followed by bond failure</td>
</tr>
<tr>
<td>B-R-0%-1</td>
<td>Room Temperature</td>
<td>133</td>
<td>Yielding of the anchor followed by anchor rupture</td>
</tr>
<tr>
<td>B-R-0%-2</td>
<td>Room Temperature</td>
<td>133</td>
<td>Yielding of the anchor followed by anchor rupture</td>
</tr>
<tr>
<td>B-R-0%-3</td>
<td>Room Temperature</td>
<td>134</td>
<td>Yielding of the anchor followed by concrete splitting</td>
</tr>
<tr>
<td>C-R-0%-1</td>
<td>Room Temperature</td>
<td>129</td>
<td>Yielding of the anchor followed by anchor rupture</td>
</tr>
<tr>
<td>C-R-0%-2</td>
<td>Room Temperature</td>
<td>133</td>
<td>Yielding of the anchor followed by anchor rupture</td>
</tr>
<tr>
<td>C-R-0%-3</td>
<td>Room Temperature</td>
<td>133</td>
<td>Yielding of the anchor followed by anchor rupture</td>
</tr>
</tbody>
</table>

Creep Test Results

Creep test results for anchors with Type A adhesive under all three exposure conditions showed significant variation in the measured creep displacement. Under ambient temperature, the specimens showed fairly consistent response, with decreasing creep displacement rate over time. Nevertheless, when subjected to moisture they showed significant increase in initial elastic displacement, as well as in the overall creep displacement. Similarly, when subjected to freeze/thaw cycling anchors with Type A adhesive showed an increased creep displacement and an increasing rate of creep displacement over time. It is evident that the various exposure conditions have a significant effect on anchors with Type A adhesive (Fast setting two component methyl methacrylate adhesive). Although moisture exposure triggered higher displacement during the test period, with the rate of increase in displacement caused by the freeze/thaw exposure, it could be more detrimental over a longer period of time.

Figure 7 to 11 presents the displacement versus time curves for Type A under the three exposure conditions. Figure 10 compares the maximum creep displacement for anchors with Type A adhesive under the three exposure conditions. The exacerbated effects of moisture and freeze/thaw cycling are evident.
On the other hand, anchors with Type B (Fast setting two part epoxy adhesive) showed an inconsistent behavior when subjected to the three exposure conditions. Exposure to freeze/thaw cycles in the presence of moisture appears to have no significant effect on the overall average creep displacement. Exposing anchors with Type B adhesive to moisture produces a widely variable response within the three specimens; however, higher average overall creep displacement with an increasing rate of creep displacement with time was recorded. The displacement versus time curves for anchors with Type B adhesive under the three exposure conditions are shown in Figure 11 to 15. Figure 14 compares the maximum creep displacement for anchors with Type B adhesive under the three exposure conditions.
All three exposure conditions had similar initial elastic displacement for anchors with Type C (Standard set two part epoxy adhesive). Insignificant creep displacement was recorded under ambient temperature, and slight increase in displacement when subjected to moisture. Anchors with Type C adhesive showed extremely consistent creep behavior when subjected to either ambient temperature or moisture exposure. However, when subjected to freeze/thaw cycles significant variation in response was noticed, along with substantial increase in creep displacement. Figure 15-19 presents displacement versus time curves for Type C. Figure 18 compares the maximum creep displacement for anchors with Type C adhesive under the three exposure conditions.
SUMMARY AND CONCLUSIONS

A research study was carried out to investigate the long-term creep behavior of adhesive anchors under various environmental exposures. The study was comprised of 9 static pullout specimens and 27 sustained load creep specimens with post-installed adhesive anchors utilizing three types of adhesives. Type A - Fast setting two component methyl methacrylate adhesive, Type B - Fast setting two part epoxy adhesive, and Type C - Standard set two part epoxy adhesive. Creep testing was carried out under a sustained load of 32kN (40%fy of the anchor) representing the service load. The creep testing was combined with three different environmental exposure conditions, ambient temperature, moisture exposure, and freeze/thaw cycles in the presence of moisture.

Anchors with the three types of adhesives had fairly similar initial elastic displacement, but the creep displacement varied widely throughout the test duration. In creep tests with moisture exposure, both Types A and B showed a significant increase in creep displacement (almost double the displacement for Type C). Unlike moisture exposure, freeze/thaw cycles did not have much of an effect on type B, but significant increase in overall creep displacement for Type A was recorded. Out of the three adhesive types, Type C appears to be the most consistent in terms of creep response, and show the least overall displacement. Moisture exposure showed minimal increase in creep displacement for Type C, when compared to Types A and B. Nevertheless, when anchors with Type C were exposed to freeze/thaw cycles relatively higher displacement was noted, accompanied by variation in the response within the three specimens.

The effects of moisture exposure and freeze/thaw cycles on the creep behavior of three commonly used adhesives with different chemical formulation were presented. Type C (Standard set two part epoxy) adhesive appears to be superior in terms of creep behavior over both the fast setting Types A and B adhesives. In terms of ultimate capacity, static pullout testing showed that the epoxy based both Types B and C exhibit higher bond capacity compared to the acrylic based Type A. Further extrapolation and analysis of the test data is required to be able to assess the effect of such conditions on the anchor system within their intended service life. Additional testing on a wider range of adhesives should be done to incorporate these environmental impacts in a design model.

ACKNOWLEDGMENT

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El Menoufy, Soudki, El Sayed, and Schell

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RELIABILITY ASSESSMENT OF BONDED ANCHOR SYSTEMS
BY USE OF PROBABILISTIC METHODS

by Ronald Mihala, Andreas Unterweger, and Konrad Bergmeister

ABSTRACT

Scope of this study is to estimate the reliability of bonded anchor systems. Furthermore, the use of a factor κ in order to account the effect of sustained loading on a fastening’s failure probability \( p_f \), is discussed. As a general standard in structural engineering, it was assumed that the extreme failure probability of \( p_f = 10^{-6} \) per year applies to fastenings as well. By use of the factor κ, which can be considered as an index of safety reserves as well, the sensitivity of the investigated system to variations of particular parameters can be captured.

In order to define the range of κ the input parameters were elaborated statistically considering their mean values, variations and types of distribution. Apart from that, the influence of different input parameters was determined through a parametric study. The statistic input of the study was obtained either from the Probabilistic Model Code (Joint Committee of Structural Safety) or from experimental measurements. Final aim was to find a value for the factor κ that guarantees a failure probability of \( p_f = 10^{-6} \).

Keywords: Bonded anchors, long term behavior, post-installed rebars
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Introduction

Safety, reliability and risk reduction are important issues in the context of structural design. The type of failure mode and furthermore the reliability of bonded anchors are dominated by the material properties and the installation quality on the construction site. For a reliability assessment of bonded anchors under sustained loading two types of failure modes (concrete breakout and pull-out) are investigated with probabilistic methods. Some of the stochastic parameters are estimated on basis of literature.

PROBABILISTIC INVESTIGATION

Limit states

Bond strength - Pull-out under axial loading may occur when the bond strength is too low to keep the anchor in its required position. The pull-out resistance of bonded anchorage systems is mainly dependent on the product specific bond strength and the anchor surface. The average resistance $N_u^0$ of a single anchor without influence of spacing and edges in case of bond failure can be calculated according to Equation (1). Based on this relation, the limit state function for bond failure can be determined as in Equation (2)

$$N_u^0 = \pi \cdot d_{nom} \cdot h_{ef} \cdot \tau_{u,m}$$

with: $N_u^0$: Resistance of a single anchor under axial loads against bond failure [N]

$d_{nom}$: Diameter of anchor [mm]

$h_{ef}$: Embedment depth of the fastening component [mm]

$\tau_{u,m}$: Ultimate bond strength [N/mm²]

$$\pi \cdot d_{nom} \cdot h_{ef} \cdot \tau_{u,m} - N_E = 0$$ limit state function

with: $N_E$: Load effect
Concrete breakout - Concrete cone failure under axial loading occurs when the activated tensile stress exceeds the capacity of the concrete. In this case a conical break-out body is produced and idealized as a pyramid, assuming a quadratic base length of three times the embedment depth. The inclination of the cone surface is between 30° and 40° measured to the direction of load. This type of failure occurs mainly in case of small embedment depth and is not relevant for further probabilistic investigations. It should be only mentioned at this point for completion. The average resistance $N_{0,u,c}$ of a single bonded anchor in case of concrete cone failure under axial loads can be calculated according to Equation (3). The factor 15,5 which is normally used for headed studs can be also applied for bonded anchors. That bases on experience and recommendations from leading scientists. Based on this relation, the limit state function for concrete breakout failure can be determined as in Equation (5),

$$N_{0,u,c} = 15.5 \cdot h_{ef}^{0.5} \cdot f_{cm,200}^{0.5} = 16.8 \cdot h_{ef}^{0.5} \cdot f_{cm,cyl}^{0.5} \tag{3}$$

with: $N_{0,u,c}$: Resistance of a single anchor under axial loads in uncracked concrete [N]

$h_{ef}$: Embedment depth of the fastening component [mm]

$f_{cm,200}$: Average compressive strength of concrete (cube) [N/mm²]

$= 0.95 \cdot f_{cm,150} = 0.95 \cdot 1.25 \cdot f_{cm,cyl}$

$f_{cm,cyl}$: Average compressive strength of concrete (cylinder) [N/mm]

$$168 \cdot h_{ef}^{0.5} \cdot f_{cm,cyl}^{0.5} - N_E = 0 \quad \text{Limit state function} \tag{4}$$

with: $N_E$: Load effect

Approach for the long-term performance - In order to define the performance of bonded anchorages the factor $\kappa$ was introduced. This factor serves to account the decreasing resistance of bonded anchorages subjected to sustained loading which can be the basis of considerations on the long-term strength. By use of the factor $\kappa$, which can be considered as an index of safety reserves as well, the sensitivity of the investigated system to variations of particular parameters can be captured. Then, the resistance in case of bond failure considering sustained loading can be calculated according to Equation (5). Based on this relation the limit state function could be represented by equation (6)

$$N_{0,u,lt} = \kappa \cdot \pi \cdot d_{nom} \cdot h_{ef} \cdot \tau_{u,m} \tag{5}$$

with: $N_{0,u,lt}$: Resistance of a single anchor under axial loads against long-term loading

$\kappa$: Reduction factor considering the reserves of a system’s resistance

$d_{nom}$: Diameter of anchor [mm]

$h_{ef}$: Embedment depth of the fastening component

$\tau_{u,m}$: Ultimate bond strength [N/mm²]

$$\kappa \cdot \pi \cdot d_{nom} \cdot h_{ef} \cdot \tau_{u,m} - N_E = 0 \quad \text{Limit state function} \tag{6}$$
Essential parameters for the evaluation

For a first estimation of $\kappa$, manufacturer’s material specifications were adopted. As long as it provided proper data, the "Probabilistic Model Code" was used as source for the stochastic modeling.\(^1\,^2\)

The used variables, their coefficient of variation and the applied distribution functions are listed in detail in the following sections.

**Load effect** - The load effects where estimated presuming $R_d = S_d$ (see Equations (7) and (8)). The design value of the bond strength $\tau_{Rd}$ used in the calculations was selected in compliance to the pre-qualification report of a product available in the market. At this point it should be mentioned that the design of anchorages in Europe is based on the safety concept of partial safety factors and is not necessarily a familiar aspect outside of Europe. It shall be shown that the value of the design actions $S_d$ does not exceed the value of the design resistance $R_d$. The partial safety factors for actions depend on the type of loading and shall be taken from national regulations ($\gamma_G = 1,35$ for permanent actions and $\gamma_Q = 1,5$ for variable actions are normally used). The partial safety factors for resistances depend on the type of failure modes (e.g. concrete cone failure, pull-out failure, steel failure,...), the load directions and on the installation safety of the systems and are given in the relevant ETA.\(^3\,^5\)

Figure 1— Sketch for the formalization of the load effect

$$S_d = R_d = \gamma_S \cdot S_k = \frac{R_k}{\gamma_R} \Rightarrow S_k = \frac{R_k}{\gamma_S \cdot \gamma_R} = S_{\text{mean}} \cdot (1 + k \cdot v)$$

with: $S_k$: Characteristic value for the load effect, $S_{0.95}$

$S_d$: Design value for the load effect

$\gamma_S$: Partial safety factor for the load effect

$$\gamma_S = \frac{1,35 + 1,5 \cdot a}{1 + a} ; \quad a = \frac{Q}{G} : \text{Ratio of life over dead loads}$$

$\gamma_G$: Partial safety factor for dead loads ; $\gamma_G = 1,35$

$\gamma_Q$: Partial safety factor for life loads ; $\gamma_Q = 1,5$

$R_k$: Characteristic value for the resistance, $R_{0.05}$

$R_d$: Design value for the resistance

$\gamma_R$: Partial safety factor for the resistance ; $\gamma_R = 1,5$

$$S_{\text{mean}} = \frac{R_k}{\gamma_S \cdot \gamma_R \cdot (1 + k \cdot v)}$$

with: $S_{\text{mean}}$: Mean value of the load effect
k: Quantile factor $n \to \infty$, $k = 1.645$

v: Coefficient of Variation; weighted value depending on the ratio $a = Q/G$

### Table 1—Input parameters for the load effect

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coefficient of Variation $v$ [%]</th>
<th>Type of Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead loads $N_{E,g}$</td>
<td>5</td>
<td>ND³</td>
</tr>
<tr>
<td>Live loads $N_{E,d}$</td>
<td>15</td>
<td>LND³</td>
</tr>
</tbody>
</table>

1) Values from the JCSS probabilistic model code - part 2: "Load models"¹
2) Normal Distribution
3) Log-Normal Distribution

Resistance - The mean value of bond strength $\tau_{u,m}$ and the associated coefficient of variation $v$ of the considered bonded anchor systems were provided by the manufacturers, concrete of a C20/25 class was adopted and finally an installation safety factor $\gamma_2$ of 1.0 (acc. to pre-qualification) was selected. This safety factor is determined from installation safety tests according to ETAG 001 (Guideline for European Technical Approval)² and is given in the relevant ETA (European Technical Approval). The installation safety factor $\gamma_2$ takes into account the uncertainty of the system and reduces its resistance.

### Table 2—Input parameter for the resistance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Product</th>
<th>Unit</th>
<th>Mean value $X_m$</th>
<th>Coefficient of Variation $v$ [%]</th>
<th>Type of Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bond strength $\tau_{u,m}$</td>
<td>A, B</td>
<td>[N/mm²]</td>
<td>14.6¹, 13.7¹</td>
<td>8.8¹, 8.7¹</td>
<td>LND³</td>
</tr>
<tr>
<td>Concrete strength $f_{ck,l}$</td>
<td>C20/25</td>
<td></td>
<td>25</td>
<td>15²</td>
<td>LND³</td>
</tr>
<tr>
<td>Diameter $d_{nom}$</td>
<td>M12</td>
<td>[mm]</td>
<td>12</td>
<td>deterministic</td>
<td>ND⁴</td>
</tr>
<tr>
<td>Embedment depth $h_{ef}$</td>
<td>-</td>
<td></td>
<td>110</td>
<td>5</td>
<td>ND⁴</td>
</tr>
</tbody>
</table>

1) Values from the Evaluation Report of the Injection system A and B
2) Values from the JCSS probabilistic model code - part 3: "Resistance models"²
3) Log-Normal Distribution
4) Normal Distribution

**FUNDAMENTALS OF THE PROBABILISTIC METHOD**

**Methods of probabilistic simulations**

Probabilistic Methods nowadays serve as the basis for the assessment of failure probabilities as well as the estimation of partial safety factors of certain failure models. EN1990 “Eurocode: Basis of Structural Design” – Annex C “Basis for Partial Factor Design and Reliability Analysis” offers an overview of applicable Methods (Figure 2).
Deterministic methods - The Eurocode is mostly based on Method a (Figure 2), in which partial safety factors are designated through empirical tests and/or historical experience in order to provide for a satisfactory safety level of a structure. A reliability assessment on grounds of such methods is impossible and a comparative solution on a qualitative level for different quality states or even structures is difficult. In fastening technology, particularly for some anchorages in masonry, global safety factors of a range between 3 and 5 are still met.

Semi-probabilistic methods - For the development of the Eurocode, Method c (Figure 2) and other similar methods are implemented. Particularly for fastenings, semi-probabilistic methods can also apply to estimate partial safety factors. In the present, familiar safety factors for loads (1.35 for dead loads and 1.5 for live loads) as well as concrete’s resistance (1.5) were retained. However, an additional factor for the installation safety was selected in accordance to application tests of the pre-qualification procedure.

F.O.R.M/S.O.R.M - The First Order Reliability Method uses the first term of a Taylor series in order to customize a limit state function on a design point. In that way, it allows with reasonable effort for an analytical calculation of the failure probability \( p_f \). F.O.R.M. makes use of input data defined through their mean value and standard deviation, thus being in “Level-II” of sophistication and respectively being defined as a “Level-II” Method. The results derived from such an analysis (i.e. failure probability, reliability index) have a nominal nature and they are used more as comparative values rather than absolute evidence of the failure probability. In real terms, a quantified estimation of the failure probability or the reliability of a structure is hardly achievable, since a realistic identification of the system (the overlapping of line or surface limit states through parallel or serial system approach) is impossible. The Second Order Reliability Method (S.O.R.M.) can be implemented on limit state lines of single curvature in order to calculate even absolute values of the failure probability as well. With S.O.R.M. approaches, the Taylor series is interrupted after the second member for the approximation of the limit state function.\(^6,7\)

Latin Hypercube Sampling Methods\(^{13}\) - Stochastic packages for systems’ reliability assessment such as SARA\(^8,10\) (Safety Analysis and Reliability Assessment Maintenance) integrate probabilistic components (e.g., FReET – Feasible Reliability Engineering Tool).\(^11,12\) Such solutions for the statistic, sensitivity and reliability analysis of engineering problems by use of probabilistic software have been developed in the last years\(^11,12\) with special focus on the minimization of computing effort in case of complex problems that would demand the calculation of thousands of samples (i.e. with the Monte Carlo Method). A special type of numeric probabilistic simulation techniques as described above is the so called Latin Hypercube Sampling (LHS)\(^{13}\), which requires only a small number of Monte Carlo simulations for the exact estimation of the first and second moments of the limit state function (in the design point). For that, LHS employs a layering of the theoretical cumulative distribution functions (CDF) of the input – random variables. The probability distribution is split into \( n \) intervals of equal probability, where \( n \) is the number of samples that are to be performed on the model. As the simulation progresses each of the \( n \) intervals is sampled once (see Figure 3). LHS has the advantage of generating a set of samples that more precisely

\[\text{Figure 2—Overview of reliability methods}\]
reflect the shape of a sampled distribution than pure random (Monte Carlo) samples. The general effect is that the mean of a set of simulation results more quickly approaches the ‘true’ value, particularly for models that are simply adding or subtracting a number of variables. LHS (implemented in FReET) allows for the consideration of statistical correlations between the random variables as well, where stochastic optimization techniques like the Simulation Annealing\textsuperscript{11,12} enable the adjustment of random variables to a desired (user-defined) correlation matrix at sampling. The residual error in that case is a function of the size of sample $N$ and generally ranges in an interval of 1-2\% for $N > 100$.

This method was also used in this study for the calculation of the failure probabilities. Furthermore, the significance of all random variables was defined through sensitivity analyses, which provide an influence grade for each input variable (e.g. embedment depth, bond strength). This was realized through non-parametric rank-order correlations associated to Spearman or Kendall’s Tau correlation coefficients. These functions are nested in FReET software which was developed in co-operation between the Institute of Structural Engineering in Vienna and the Institute of Structural Mechanics in Brno.

![Figure 3—Intervals of LHS in the probability density function and the cumulative distribution function](image)

For the present investigations for fasteners, the calculation process of FReET (LHS-Method) was assumed effective due to the following considerations:

- The feasible elaboration of non-linear hyperspace limit state surfaces
- The user friendly, engineering-oriented treatment of problem cases (similar to Monte Carlo Methods)
- The implementation of only a small number of Monte Carlo simulations
- The provision for statistical correlation between the random variables
- The determination of significance of random variables among the results
- The derivation of a Cornell’s reliability index through LHS probabilistic analyses

In this report, the evaluation process to select the proper probabilistic methodology is based upon:

(a) The accuracy order of the results
(b) The computation effort (i.e. the required number of simulations),
(c) The extend of information included (i.e. correlation),
(d) The extend of databases available (i.e. PDF or CDF databases), and among all,
(e) The user friendly operation of the method.

For the check of particular results the software package VAP\textsuperscript{18} was used, which also incorporates F.O.R.M. techniques.\textsuperscript{12,14,17}
Failure probability $p_f$ - The load effects $S$ and the resistance $R$ are independent, randomly varying values with density functions $f_S(s)$ and $f_R(r)$, mean values $m_S$ and $m_R$ and standard deviations $\sigma_S$ and $\sigma_R$. Hence, safety zone $Z = R - S$ is also distributed, according to the function $f_z(z)$. Consequently, cases where $Z \leq 0$ are possible and the probability $p_f$ of this incident can be interpreted as the surface under the density function $f_z(z)$ of the safety zone $Z$ for $Z \leq 0$ (see also Eq. 9).

$$p_f = \int_{-\infty}^{0} f_z(z) \, dz \quad (9)$$

As mentioned above, the failure probability $p_f$ should not exceed the value of $10^{-6}$. Figure 4 shows the probability density function of the load effect (left), the resistance (right) and the failure zone (overlapping area).

Calculation process and sensitivity analysis – At the beginning of the calculations, the diameter $d_{nom}$ of the threaded rod was assumed to be a deterministic value, the embedment depth $h_{ef}$ to have a normal distribution, the bond strength $\tau_{u,m}$ to have a log-normal distribution (see Table 2), while the reductive factor $\kappa$ set to be 1.0. Consequently, including the dead and live loads, four basic input variables are accumulated:

$$\kappa \cdot \pi \cdot d_{nom} \cdot x_1(h_{ef}) \cdot x_2(\tau) - [x_3(g) + x_4(q)] = 0 \quad \text{Limit state function} \quad (10)$$

with $x_1$, $x_2$, $x_3$, and $x_4$ being the basic input variables with a defined distribution.

In order to investigate the influence of the embedment depth $h_{ef}$ on a fastening’s resistance against bond failure, a parametric study and a further sensitivity analysis were conducted (see Figure 5). The parametric study involved the check of several values for the coefficient of variation $\nu$ of the $h_{ef}$ distribution and concluded that the probability of failure increases proportionally to the coefficient of variation and reaches the critical value of $10^{-6}$ for approximately $\nu = 15\%$.

A strong correlation between the bond strength and the resistance against bond failure is clearly presented in 5 and depends on the large coefficient of variation of the bond strength. Based on this, the variations of the embedment depth $h_{ef}$ and of the diameter of anchor $d_{nom}$ in the resistance side (= resistance against long-term loading) of the limit state function were neglected for the following investigations – they were thereafter handled as deterministic parameters – and focus was directed to the bond strength as basic variable $x_1(\tau)$.

For further calculations the limit state function was limited to involve three basic input variables:

$$\kappa \cdot \pi \cdot d_{nom} \cdot h_{ef} \cdot x_1(\tau) - [x_2(g) + x_3(q)] = 0 \quad \text{Limit state function} \quad (11)$$

12.8
Profound investigations and results – Figure 6 presents the dependence of the failure probability on the ratio of live loads Q over dead loads G \( (a = Q/G) \). An accurate estimation of the coefficient of variation is difficult. Therefore, different variation coefficients are chosen to study the influence of live loads on the investigated system. From this graph it can be identified that for an increase of the live load’s coefficient of variation \( v_Q \) from 15\% to 30\% \( (v_G = 5\%) \) the system’s reliability is negatively affected, yet to a small extend.

Based on the above mentioned findings, profounder investigations regarding values from 0 to 1 for the factor \( \kappa \) were conducted. This factor which reduces the average resistance against bond failure can be considered as an index of safety reserves. The reduction of the average resistance produces also a change in the scattering of the distribution. The estimation of the changed scattering without a secure test results is impossible and is either with the coefficient of variation \( v_R \) or the standard deviation \( s_R \) kept constant. The using of a constant variations coefficient \( v_R \) leads to a smaller standard deviation when the mean (= reduced average resistance) shifts to the left. This behavior is unusual because the scattering do not decrease with increasing uncertainty of the system. Therefore the using of a constant standard deviation \( s_R \) is preferable. Nevertheless, the calculations were performed with both parameters. Figure 7 and Figure 8 shows the influence of the factor \( \kappa \) on the failure probability \( p_f \). The ordinate has a logarithmic scaling and corresponds to the failure probability \( p_f \), while the abscissa corresponds to the \( \kappa \)-factor.
For the estimation of the factor $\kappa$, the ratios $a = Q/G$ were selected in a way to provide the maximum value for the probability of failure $p_f$. It can be seen that, by certain values of the factor $\kappa$, the failure probability $p_f = 10^{-6}$ is exceeded and the fastening no longer meets the required standards. Furthermore, when the bond strength’s standard deviation $s_R$ is kept constant, the influence of factor $\kappa$ seems to rise more intensely (high sensitivity). As a result the failure probability $p_f = 10^{-6}$ is reached faster and consequently the system fails sooner. As seen in Figure 7, the values of $\kappa$ reached for calculations with constant coefficients of variation ($v_R = \text{const.}$) are lower than those reached for constant standard deviations ($s_R = \text{const.}$). Comparing the calculations with dead loads only (see Figure 7) to those with a high participation of live loads ($a = Q/G = 2$, Figure 8), resulting $\kappa$ has negligible deviations. In Figure 7 the coefficient of variation $v_Q = 0.15$ is not to be accounted, since only dead loads ($G$) participate.
PARAMETRIC STUDIES CONSIDERING THE INSTALLATION – RELATED UNCERTAINTIES

In the following, further profound investigations with alternative input parameters are discussed. In particular, an additional installation factor is introduced as approximate means to capture possible effects of a substandard installation. Results of calculations with various input parameters are documented below, together with the modification of factor $\kappa$ in order to achieve a failure probability of $10^{-6}$.

$$\kappa \cdot \frac{1}{\gamma_2} \cdot \pi \cdot d \cdot h_{ef} \cdot x_i(\tau) - [x_2(\gamma) + x_3(\epsilon)] = 0$$  \hspace{1cm} \text{Limit state function} \hspace{1cm} (12)

with $\gamma_2$ being the installation safety factor.

Modified inputs of the bond strength and the installation safety – Since the bonding materials used in practice differ from each other in chemical composition as well as mode of structural function, the coefficient of variation of the bond strength $\tau_{u,m}$ is assumed to vary. Thereby, the coefficient of variation $\nu_R$ was raised by 15% (maximum allowed scattering acc. to ETAG 001), the characteristic value acc. to the pre-qualification $\tau_{R,k}$ remained as nominal value (given parameter for the product acc. to ETA) and a new enlarged mean value for the bond strength $\tau_{u,m}$ was determined to maintain the statistical relationship. This method is proposed to study the influence of an increased coefficient of variation for a given product without changing of the statistical relationship. A high mean value with a large scatter or a small mean value with a small scatter, both lead to the same characteristic value which remains as nominal value for the probabilistic calculations. Therefore the applied method has its authorization. Finally, further computations were conducted involving an increased installation safety factor $\gamma_2$ in order to simulate an insufficient borehole cleaning. The installation safety factor which is determined during the pre-qualification (ETAG 001) was selected as a deterministic value between 1.0 and 1.4 (acc. to ETA) and reduces the resistance of an investigated system. An installation safety factor $\gamma_2 > 1.4$ is not allowed acc. to ETAG 001. In this case the system can be regarded as unsafe. When an installation safety factor greater than 1.0 was used, the mean value and the corresponding coefficient of variation of the bond strength should also be readjusted (see Figure 9). An overview of the investigated parameter sets is given in Table 3.

Modified inputs of live loads – In order to account a fastening’s long-term performance associated with bond failure, the coefficient of variation of live loads was increased to 30%. The motivation for this consideration is the assuming that over the long-term the scatter or uncertainty regarding live load increases. Buildings are designed for a long time. But given the fast changes nowadays, nobody can predict exactly how the live loads vary in the next 30 -50 years (e.g. increase of heavy vehicles).

The results of the parametric study demonstrate the developing of the failure probability $p_f$ in relation to the ratio of live over dead loads ($a = Q/G$). Increase of the coefficient of variation of the bond strength to 15% (maximum allowed scattering acc. to ETAG 001) induces a sharp rise to the failure probability $p_f$ and furthermore, with
assumption of an installation safety factor $\gamma_2 = 1.4$ (maximum installation safety factor acc. ETAG 001) and keeping all other parameters, the required safety level of $p_f = 10^{-6}$ could no longer be achieved.

Against expectations, increasing the coefficient of variation for the live loads from 15 to 30% ($v_R = 0.15$, $v_G = 0.05$ and $\gamma_2 = 1.0$), would not bring any significant difference to the failure probability $p_f$. This is explained by the fact that this increase of the coefficient of variation would also result in a reduction (shift to the left) of the mean value $S_m$ (see Figure 10) and consequently a flattening in both sides of the curve representing the load effect’s density function. In both cases ($v_Q = 15\%$ and $30\%$) the overlaps of the curves for the load effect and the resistance are of about the same area which likewise means similar probabilities of failure $p_f$.

Figure 10—Overlapping of both load effect density functions with the resistance density function

![Figure 10](image)

Figure 11—Failure probability $p_f$ in relation to $a = Q/G$ for $v_R = 0.087-0.15$, $v_Q = 0.15$ and $v_G = 0.05$, $\gamma_2 = 1.0–1.4$; Product A and B

Figure 12 and Figure 13 illustrate that factor $\kappa$ (at the limit state) is considerably lower for a coefficient of variation $v_R = 15\%$ and an installation safety factor $\gamma_2 = 1.4$ than in the cases with the first input parameters before. However,
even when the most unfavorable parameters are assumed for the load effect, failure probability of $p_f = 10^{-5}$ can still be reached.

Only when assuming that the installation safety factor is $\gamma_2 = 1.4$ and the bond strength’s coefficient of variation is $v_R = 15\%$ at the same time, neither of the two investigated bonded anchor systems meets the standards for the failure probability of $p_f = 10^{-6}$ anymore.

The factor $\kappa$ is defined below for $a = Q/G = 0$ (dead load only) and for a coefficient of variation of $v_R = 15\%$. The factor was calculated only for the bonded anchor system A, since findings for the failure probability in case of a coefficient of variation $v_R = 15\%$ and an installation safety factor $\gamma_2 = 1.0$ are similar for both investigated systems (see Figure 11).

![Figure 12](image-url)

Figure 12—Factor $\kappa$ in relation to the failure probability $p_f$ for $a = Q/G = 0$ (only dead load), $v_R = 0.087$ ($0.088$), $v_G = 0.05$, $\gamma_2 = 1.4$; Product A and B

The factor $\kappa$ is defined below for $a = Q/G = 0$ (dead load only) and for a coefficient of variation of $v_R = 15\%$. The factor was calculated only for the bonded anchor system A, since findings for the failure probability in case of a coefficient of variation $v_R = 15\%$ and an installation safety factor $\gamma_2 = 1.0$ are similar for both investigated systems (see Figure 11).

![Figure 13](image-url)

Figure 13—Factor $\kappa$ in relation to the failure probability $p_f$ for $a = Q/G = 0$ (only dead load), $v_R = 0.15$ and $v_G = 0.05$, $\gamma_2 = 1.0$; Product A
Summary
The table below gives an overview of the fluctuation of factor $\kappa$ in relation to mean values, coefficients of variation and distribution types of diverse input parameters.

### Table 3—Sets of parameters and associated factors $\kappa$

<table>
<thead>
<tr>
<th>Parameters for the basic calculation</th>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>$\nu$ [%]</th>
<th>Distribution</th>
<th>factor $\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load $N_{E,g}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>5</td>
<td>ND&lt;sup&gt;2&lt;/sup&gt;</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Live load $N_{E,q}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>15</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.62</td>
<td>0.71</td>
</tr>
<tr>
<td>Bond strength $\tau_{u,m}$</td>
<td>A B</td>
<td>[N/mm²]</td>
<td>14.6</td>
<td>13.7</td>
<td>8.8 8.7</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Installation safety factor $\gamma_2$</td>
<td>[-]</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Modified parameters

<table>
<thead>
<tr>
<th>Parameters for the basic calculation</th>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>$\nu$ [%]</th>
<th>Distribution</th>
<th>factor $\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load $N_{E,g}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>5</td>
<td>ND&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.62</td>
<td>0.71</td>
</tr>
<tr>
<td>Live load $N_{E,q}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>30</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.75&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>0.81&lt;sup&gt;1)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Bond strength $\tau_{u,m}$</td>
<td>A B</td>
<td>[N/mm²]</td>
<td>14.6</td>
<td>13.7</td>
<td>8.8 8.7</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Installation safety factor $\gamma_2$</td>
<td>[-]</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 4—Sets of parameters and associated factors $\kappa$

<table>
<thead>
<tr>
<th>Modified parameters</th>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>$\nu$ [%]</th>
<th>Distribution</th>
<th>factor $\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load $N_{E,g}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>5</td>
<td>ND&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.79</td>
<td>-</td>
</tr>
<tr>
<td>Live load $N_{E,q}$</td>
<td>[N]</td>
<td>$f(a = Q/G)$</td>
<td>15</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
<td>0.93&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>-</td>
</tr>
<tr>
<td>Bond strength $\tau_{u,m}$</td>
<td>A B</td>
<td>[N/mm²]</td>
<td>14.6</td>
<td>13.7</td>
<td>15</td>
<td>LND&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>Installation safety factor $\gamma_2$</td>
<td>[-]</td>
<td>1.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1<sup>1)</sup> Second factor $\kappa$ corresponds to $s_{\kappa}=\text{const.}$
2<sup>2)</sup> Normal Distribution
3<sup>3)</sup> Log-Normal Distribution
FURTHER PARAMETER STUDIES CONSIDERING THE MODEL UNCERTAINTIES

In this chapter, the investigations discussed above are extended to further parameter sets. Although in the Probabilistic Model Code, as well as in all above investigations, the coefficient of variation for dead loads (G) is set to 5%, in the following it is assumed increased to 10%. This modification is based on the conclusion that the highest failure probabilities emerge for \( a = Q/G = 0 \) (dead loads only), so this increase of the dead load’s coefficient of variation represents a worst case scenario.

Next to that, a factor of model uncertainty is introduced in the calculations (mean value \( M = 1.0 \) and var. coefficient \( v_M = 0.10 \)). To estimate the bond strength, pre-qualification procedures use exactly the same analytical formulation with Equation (1) (inversed), which means that model uncertainties are virtually integrated into the value of the bond strength. However, the factor of model uncertainty is additionally incorporated as a conservative assumption and should cover uncertainties such as no borehole cleaning, inadequate filled borehole, inclined anchor and so on, all aspects which were not considered during the pre-qualification. An overview of the investigated parameters is given in Tab. 5.

\[
\kappa \cdot \frac{1}{\gamma_2} \cdot \pi \cdot d \cdot h_6 \cdot x_1(\tau) \cdot x_2(M) - \left[ x_1(q) + x_4(q) \right] = 0 \quad \text{Limit state function} 
\]

with \( x_2(M) \) being the model uncertainty factor

Table 5—Parameters for the following calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
<th>( v ) [%]</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead load ( N_{E:g} )</td>
<td>[N]</td>
<td>( f(a = Q/G) )</td>
<td>10</td>
<td>ND(^1)</td>
</tr>
<tr>
<td>Live load ( N_{E:q} )</td>
<td>[N]</td>
<td>5 15 30</td>
<td>LND(^2)</td>
<td></td>
</tr>
<tr>
<td>Bond strength ( \tau_{um} )</td>
<td>[N/mm²]</td>
<td>14.6 13.7 8.8 8.7</td>
<td>LND(^2)</td>
<td></td>
</tr>
<tr>
<td>Installation safety factor ( \gamma_2 )</td>
<td>[-]</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Model uncertainty factor</td>
<td>[-]</td>
<td>1.0 10</td>
<td>ND(^1)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Normal Distribution  
\(^2\) Log-Normal Distribution

Associated to the ratio of live over dead loads (\( a = Q/G \)), the results of this parametric study show a sharp increase of the failure probability \( p_f \) following the integration of model uncertainties and a coefficient of variation of \( v_G = 10\% \) for dead loads. The assumption of an increased coefficient of variation for dead loads up to 10% compared with an uncertainty factor of the model is not really realistic but should show the sensitivity or the limit of the investigated systems. When these two additional parameters and a coefficient of variation of \( v_R = 0.15 \) for the bond strength are employed simultaneously, the required safety level of \( p_f = 10^{-6} \) could no longer be reached for any of the two investigated bonded anchor systems (Figure 15). As expected, changes in the coefficient of variation for the live loads had no substantial impact on the failure probabilities.
Figure 14—Failure probability \( p_f \) in relation to \( a = Q/G \) for \( v_Q = 0.15 \) and \( v_G = 0.10 \), \( \gamma = 1.0 \); Product A

Figure 15—Failure probability \( p_f \) in relation to \( a = Q/G \) for \( v_Q = 0.15 \) and \( v_G = 0.10 \), \( \gamma = 1.0 \); Product A and B
CONCLUSIVE REMARKS

From the investigations on two bonded anchor systems based on probabilistic methods the following results could be derived:

a) When no reductive factors are used, the failure probability resulting from probabilistic elaboration of the given analytical formula is by far lower than $10^{-6}$ (= lower failure probability) for both bonded anchor systems. In that case, factor $\kappa$ can take values of 0.62 - 0.82 (in mean 28% possible reduction of the resistance of a single anchor under axial loads) depending on the system (Table 3) with the requirements of Eurocode 1\textsuperscript{19} ($p_f = 10^{-6}$ per year) still being met. When an installation safety factor $\gamma_2 = 1.4$ is involved in the calculations and using a coefficient of variation for the bond strength of $v_R = 8.8\%$ as obtained by pre-qualification tests, factor $\kappa$ can take values of 0.68 - 0.97.

b) Assuming that the bond strength’s coefficient of variation is increased to $v_R = 15\%$, probability of failure $p_f$ rises by 6 orders of magnitude (from $10^{-13}$ to $10^{-7}$).

c) An increase of the live load’s coefficient of variation to $v_Q = 30\%$ has hardly an impact on the developing of the failure probability $p_f$.

d) There is a strong influence by higher bond strength’s variations ($v_R = 15\%$). Assuming failure probability of $p_f = 10^{-7}$ factor $\kappa$ yields values of 0.79 ($v_R =$ const.) and 0.93 ($s_R =$ const.).

e) Keeping the above mentioned parameters raised ($v_Q = 0.30$ and $v_R = 0.15$) and introducing an installation safety factor increased to $\gamma_2 = 1.4$, the required safety level of $p_f = 10^{-6}$ can no longer be achieved.

f) Further studies have demonstrated that increasing the dead load’s coefficient of variation from 5 to 10\% (see Figure 14) – when all other parameters are retained – has no substantial impact on the system’s safety level.

g) When an additional model uncertainty factor (mean value $M = 1.0$ and var. coefficient $v_M = 0.10$) is incorporated in the calculations, both investigated systems are shifted to the limit of the required safety level. If a coefficient of variation of $v_R = 0.15$ for the bond strength is applied at the same time, the safety level of $p_f = 10^{-6}$, as required by Eurocode 1\textsuperscript{19}, can no longer be achieved.

h) Suggestion:
The bond failure can take place either within the adhesive or in the concrete layer around.

- Since structural concrete’s long-term performance is determined by a reduction factor of 0.85 in relation to short-term performance, this value could also apply for bonded anchors in fastening technology.

- Regarding the long-term performance of bonded anchor systems, it must be noted that a bond failure within the adhesive occurs only for some certain types of adhesive. Therefore, proper experiments should be conducted to ensure long-term performance.

- Approaches on the long-term performance (reference period: 50 years) should be directed to a failure probability of $10^{-5}$ (value $10^{-6}$ refers to a time period of 1 year). Therefore, the reduction factor of 0.85 which is associated to the short-term performance is modified to $0.85 / 1.15 = 0.74$ (1.15 corresponds to the failure probability of $10^{-5}$).
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CURING AND LOAD PERFORMANCE OF ADHESIVES ANCHOR SYSTEMS INSTALLED AT LOW TEMPERATURES

by Ingo Alig, Dirk Lellinger, Frank Böhm, Ralf Neuerburg, and Friedrich Wall

Synopsis: The paper is related to basic understanding of curing and load performance of adhesive anchors with special focus on thermosetting systems cured at low base temperatures. Simulations of non-isothermal curing kinetics, vitrification and softening of the adhesives are compared to results of sustained load tests. Based on models for the reaction kinetics of thermosetting materials – considering the transition from mass to diffusion controlled curing regime – and a relation between glass transition temperature and chemical conversion the “curing-induced” vitrification was simulated for different temperature programs. The temperature programs are based on meteorological data and experimentally determined heating rates of concrete. In the simulations curing times, curing temperatures and heating rates were systematically varied. The simulated “vitrification” and “softening times” are compared to sustained load tests performed under the same conditions. The test results support the assumptions of our model which provide at least a qualitative prediction of the adhesive performance after different thermal or meteorological history. The behavior of thermosetting anchor systems cured at low base temperatures followed by fast heating is explained in terms of the competition between softening and post curing.

Keywords: Adhesives, anchor, concrete, curing, load performance, low base material temperatures,
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ACI member Friedrich Wall is a Director for International Regulations and Approvals in the Business Unit Anchor at Hilti Corporation, located in the Principality of Liechtenstein. He received his PhD in Civil Engineering from the University of Innsbruck, Austria. He is a member of the EOTA Working Group “Metal Anchors” and fib SAG 4 “Fastenings to Concrete and Masonry Structures”.

INTRODUCTION

In the last years it became more and more common to install adhesive anchors in concrete also in cold weather conditions (for example during winter time). Furthermore, it is well known that curing behavior and final properties of adhesives used for anchoring are strongly influenced by the curing temperature. Therefore, the curing rate becomes low and the glass transition temperature of the cured adhesive is reduced when the anchors are installed at low temperatures. This can result in different load and creep resistance compared to anchors installed at ambient temperatures.

This paper is related to a better basic understanding of curing and creep behavior of adhesive anchors with special focus on curing and load performance after installation and curing at low temperatures. For this purpose, simulations and sustained load tests are combined. Based on equations for the description of reaction kinetics and a relation between glass transition temperature ($T_G$) and chemical conversion ($p$) “curing-induced” vitrification and temperature-induced softening were simulated for different (non-isothermal) temperature programs. For the simulation of chemical conversion as a function of reaction time ($t_{cure}$) and reaction temperature ($T_{cure}$), it is essential to include the transition from mass to diffusion controlled reaction regime in the reaction equations. For our simulation we used models, which are generally accepted for the description of thermoset curing (see 1-4 and references therein). The input data for simulation are estimated using dynamic scanning calorimetry (DSC) (see for example refs. 4,5) and dynamic-mechanical analysis (DMTA). The temperature programs are based on experimentally determined heating rates of concrete and meteorological data.

For the comparison of creep experiments under load with non-isothermal simulation of curing the same temperature programs were used for experiments and simulation. In our standard experiment the adhesive anchors were first cured at a low base material temperature (typically -5 °C / 23 °F) for a defined (variable) time interval period. In a second step the specimens were heated to a higher temperature. For heating, a realistic temperature program was used. This thermal treatment was chosen to check whether fast heating after curing below the standard temperature can create critical load performance. It can be expected that the adhesive material becomes soft (viscoelastic or plastic) and starts to deform under load when the temperature increases before the thermal activated curing improves its mechanical performance. In the simulations, curing interval and temperature at low base temperatures, heating profile/rate, and final temperature level are varied in a systematic manner. In general, with our software any realistic user-defined temperature programs can be simulated.
The paper is organized as follows: After a short description of the experimental methods the relevant equations for conversion-time and glass transition temperature ($T_G$)-conversion ($p$)-dependence are summarized and the assumptions for thermosetting adhesives for anchor systems are discussed. Then the results for the simulation of a representative curing-heating-post curing experiment are shown and discussed. The simulations are compared to creep experiments under load for an anchor system with the same thermal history. The results of experiments and simulations for different curing conditions are compared and discussed.

**EXPERIMENTAL INVESTIGATION**

**Adhesive anchor system**

The adhesive anchor system used in this investigation is an injectable two-component epoxy adhesive. The two components are separated by means of a dual-cylinder foil pack attached to a manifold. Component A contains epoxy resin, reactive diluent and inorganic filler, and component B contains amine hardener and inorganic filler. The adhesive is mainly used for installation of threaded anchor rods, inserts and reinforcing steel into concrete. At the time of installation the foil pack temperatures must be in the range of 5 °C to 40 °C (41 °F – 104 °F) and the base material temperatures must be between -5 °C and 40 °C (23 °F – 104 °F). Working time and curing time of anchor adhesives, which depend on the temperature of the adhesive and the base material temperature, are usually given in the manufacturer’s instructions.

**Input parameters for the simulation**

The material properties and material functions were measured using differential scanning calorimetry (DSC) and dynamic mechanical thermal analysis (DMTA). The time evolution of the glass transition temperature and the heat of reaction were estimated by DSC measurements on samples cured for different curing times followed by a heating ramp. The DSC measurements were performed with a TA Instruments Q1000 Differential Scanning Calorimeter under nitrogen atmosphere (specimen mass: 10 - 15mg (0.00035 - 0.00053 oz)). The samples are prepared at defined temperatures and curing times, stored at -20 °C (-4 °F) until start of measurement. Starting from a temperature of -50 °C (-58 °F) the sample was heated with a heating rate of 10 K/min to a temperature of 250 °C (482 °F) (1st heating) and then cooled to -50 °C (-58 °F) with a cooling rate of 10 K/min. In a 2nd heating step the sample was heated to 150 °C (302 °F) with a heating rate of 10 K/min. The DSC measurements deliver $T_G$ and the heat of reaction $\Delta H$. The chemical conversion was calculated from the total heat of reaction and residual heat of the reaction for each curing time (see for example 5, 6).

The DMTA measurements were performed with an oscillating rheometer (Bohlin C-VOR 120). Cylindrical specimen of cured adhesive with a diameter of 6 mm (0.236 in.) and a free length between fixtures of 35 mm (1.38 in.) were tested. The heating rate was 10 K/min and the measurement was performed with a constant torsion load. The measured values were the deformation and the torsion angle.

**Sustained load test**

The sustained load tests are performed on the basis of the ICC-ES acceptance criteria AC308 7 “Acceptance criteria for post installed adhesive anchors in concrete elements”, Section 9.6. Differences to the guideline are described in the following. Fig. 1 shows an example for the concrete cylinder used in the experiment (concrete C20/25 (3000 psi), 115 x 160 mm (4.53 x 6.3 in.) in size). The embedment depth of the anchor rod (nominal diameter: 12 mm (0.47 in.), strength class ISO 898-1 8 Class 12.9) was 110 mm (4.33 in.). The tests are confined tension tests performed in un-cracked concrete for anchors to be installed in concrete having temperature less than 5 °C (41 °F). For the tests reported in this paper a temperature of -5 °C (23 °F) has been chosen. Prior to installation the anchor rod and the test member are conditioned to the target temperature for a minimum of 24 hours. After installation the anchors are allowed to cure at the stabilized target temperature for different cure times (here: 50, 57, 70 and 144 hours). The curing times of 50, 57 and 70 hours are shorter than the curing time according to manufacturer’s instruction. Immediately after isothermal curing the anchor system was transferred from the refrigerator to the sustained load test equipment and a constant tension stress ($\tau_{sust}$) of 7 MPa (1015 psi) was applied and the total displacement $\Delta(t)$ was measured continuously. The stress value of 7 MPa (1015 psi) was chosen to provoke distinct anchor displacement during the increase of the base material temperature. In order to study the effect of a
“temperature jump” the test member was removed from the refrigerator (-5 °C / 23 °F) and directly exposed to room temperature. This raises the test member temperature with an average heating rate of about 5 K/hour to the standard temperature of 23 °C (73 °F). A thermocouple inserted into the test member was used to measure the temperature of the test members during the test. The values for displacement in this specific test were measured at the test equipment and not at the head of the anchor.

ANALYTICAL MODEL

Conversion - time curves

For the description of epoxy curing in the mass controlled curing time regime a four parameter kinetic model of the chemical conversion was proposed by Kamal \(^1\) and is widely used in the literature:

\[
\frac{dp}{dt_{cure}} = \left( k_1 + k_2 \cdot p^m \right) \cdot (1 - p)^n
\]  (1)

In this equation \( p \) is the chemical conversion ranging from 0 to 1 and \( t_{cure} \) is the curing time. Eq. (1) - sometimes also called Horie equation \(^2\) - is a combination of an autocatalytic model and an \( n^{th}\)-order reaction kinetics. The model was originally developed for amine-cured epoxies and has successfully been extended to other systems like anhydride cure as well (see for example \(^9, 10\)). In Eq. (1) \( k_1 \) and \( k_2 \) are temperature dependent rate constants, and \( m \) and \( n \) are empirical reaction order parameters. Eq. (1) is valid for mass controlled chemical reactions only. For systems which vitrify during reaction the change from mass controlled to diffusion controlled reaction has to be taken into account. This has been proposed by Fournier et al.\(^4\) and is therein accomplished by multiplying Eq. (1) with a diffusion control factor \( f_D(p) \):

\[
\frac{dp}{dt_{cure}} = \left( k_1 + k_2 \cdot p^m \right) \cdot (1 - p)^n \cdot f_D(p)
\]  (2)
Understanding Adhesive Anchors: Behavior, Materials, Installation, Design

\[ f_D(p) = \frac{2}{1 + \exp[(p - p_{\text{final}})/b]} - 1 \]  \quad (3)

where \( p_{\text{final}} < 1 \) is the final conversion reached during isothermal cure and \( b \) is a parameter of diffusion control. As an example in Fig. 2 the curing time dependence of the chemical conversion for an adhesive cured at 40 °C (104 °F) is shown together with a fit (red dashed line) with Eq. (2) and (3).

![Figure 2 – Curing time dependence of the chemical conversion for an adhesive cured at 40 °C (104 °F). The dashed line represents a fit with Eq. (2) and (3).](image)

In order to simulate non-isothermal curing reactions the temperature dependence of the reaction constants has to be known. Therefore, measurements as shown in Fig. 2 have to be performed for different curing temperatures in the interval of interest. The rate constants for the different cure temperatures can be assumed to follow an Arrhenius behavior:

\[ k_i = A_i \exp \left( -\frac{E_A}{RT} \right) \]  \quad (4)

where \( k_i \) is the rate constant, \( A_i \) is the pre-exponential factor, \( E_A \) is the activation energy, \( R \) is the gas constant and \( T \) is the temperature (in Kelvin).

Evolution of glass transition temperature during curing

Starting from the glass transition temperature of the initial reaction mixture, the glass transition temperature, \( T_G(t_{\text{cure}}) \), of a reacting system increases continuously during polymerization and/or cross-linking. When \( T_G(t_{\text{cure}}) \) becomes close to (or exceeds) the curing temperature \( T_{\text{cure}} \) the reaction becomes diffusion controlled and the reaction rate slows down until it stops. This process can be considered as a process of “negative feedback” (see \(^{12}\) and references therein) between progress of reaction and slowing down of molecular mobility (including diffusion of reacting species). One consequence of the reaction induced vitrification is, that – even for long reaction times – the chemical conversion does not reach full conversion \((p = 1)\) during isothermal curing. For the same reasons, the glass transition temperature for long curing times \( T_G(t_{\text{cure}} \to \infty) \) is below its value for full conversion \( T_G(p = 1) \). In an isothermal curing experiment \( T_G(t_{\text{cure}} \to \infty) \) does not exceed \( T_{\text{cure}} \) by more than 20 - 30 K. An example for this behavior is shown in Fig. 3 for the same adhesive as used in Fig. 2 and cured at 40 °C (104 °F). The \( T_G(t_{\text{cure}}) \) values are estimated by DSC measurements. The dashed line in Fig. 3 is a simulation using the parameters from the fit of Eq. (2) and (3) and the conversion dependence of the glass transition temperature \( T_G(p) \) (see below).
Figure 3 — Curing time dependence of the glass transition temperature $T_G$. The line represents a fit with the DiBenedetto equation (Eq. (5)) and Eqs. (2) and (3). The fit parameters given in the box. ($^\circ F = 1.8 ^\circ C + 32$)

For the description of the conversion dependence of the glass transition temperature $T_G(p)$ of cross-linking systems various models have been developed \textsuperscript{13-17}. For epoxy resins the DiBenedetto equation \textsuperscript{3} has been proposed

$$\frac{T_G(p) - T_{G,0}}{T_{G,1} - T_{G,0}} = \frac{\lambda \cdot p}{1 - (1 - \lambda) \cdot p}$$

(5)

where $p$ is the conversion, and $T_{G,0}$ and $T_{G,1}$ are the glass transition temperature of the unreacted monomer mixture ($p = 0$) and the glass transition temperature of the fully cured system ($p = 1$), respectively. $\lambda$ is a material parameter, which is usually obtained through data fitting.

Fig. 4 shows the glass transition temperature $T_G$ as a function of chemical conversion. The data for the time dependence of $T_G$ for different isothermal curing temperatures (similar to Fig. 3) were rescaled to a joint $T_G$ – conversion curve using the corresponding conversion - time curves (see for example Fig. 2). The line represents a fit with the DiBenedetto equation. The fit parameters are indicated in the figure.

From the conversion dependence of $T_G$ it is also possible to calculate the final conversion $p_{\text{final}}$ needed for the diffusion factor in Eq. (2). Since the reaction is retarded (“frustrated”) near and above $T_G$, the final value of $T_G$ is limited in an isothermal reaction. As discussed above $T_G(t_{\text{cure}} \to \infty)$ exceeds the curing temperature only by a constant value of $\Delta T$. The final conversion can be calculated by setting $T_G(p_{\text{final}}) = T_{\text{cure}} + \Delta T$ into Eq. (2) and solving for $p_{\text{final}}$. Only for $T_{\text{cure}} + \Delta T \geq T_G(p = 1)$ a final conversion of $p_{\text{final}} = 1$ can be reached. For the epoxy system investigated in this paper $\Delta T$ is about 20 K.
RESULTS AND DISCUSSION

Curing-induced glass transition: vitrification and softening

For illustration of our simulation procedure, the time-dependence of the glass transition temperature $T_G(t)$ was calculated for a simple temperature program as shown in Fig. 5. An initially uncured thermosetting adhesive is heated within 12 hours from -5 °C to 40 °C (23 °F - 104 °F) and then cured at a constant temperature of 40 °C (104 °F).

Figure 5 — Time evolution of the glass transition temperature $T_G(t)$ (upper graph) and the chemical conversion (lower graph) for heating of an initially uncured thermosetting adhesive within 12 hours from -5 °C to 40 °C (23 °F - 104 °F) followed by isothermal curing at 40 °C (104 °F). ($^\circ$F = 1.8 °C + 32)
The increase of chemical conversion (lower graph) and $T_G$ (upper graph) during heating is an indication for the curing-induced transition of a low molar mass liquid into a highly cross-linked solid polymer network. The vitrification of the adhesive is indicated by the crossover of $T_G(t_{\text{cure}})$ and $T_{\text{cure}}(t_{\text{cure}})$ curves at about 10 hours ($T_G(t_{\text{cure}}) \approx T_{\text{cure}}(t_{\text{cure}})$). During isothermal post curing the system becomes glassy and the slope of both, conversion-time and $T_G(t)$ curve decrease due to diffusion control.

It is noteworthy to mention, that the glass transition temperature – although it is an important material characteristic – does not represent a true phase transition, since it does not show the typical discontinuous changes in the physical properties\textsuperscript{18}. Upon cooling the thermal glass transition is characterized by slowing down of molecular rearrangements, where the molecules finally rearrange so slowly that they cannot adequately sample the possible configurations in the phase space in the available time allowed by the cooling rate. The structure of the liquid therefore appears to be “frozen” on the laboratory timescale. Therefore, the glass transition range for a chemical stable material is typically extended over a range of 10 to 50 K. In Fig. 6 the storage and loss components of the shear modulus, estimated from the measured deformation and loss angle are plotted versus temperature for the cured anchor adhesive used in this investigation. The graph shows the glass transition region (softening) for a specimen cured at 20 °C (68 °F) for 12 hours. The glass transition region for the storage modulus is indicated by two arrows. The width of the glass transition region is assumed to be $\delta T = 20$ K. Similar regions can be indicated in the other quantities.

In the process of vitrification, the physical properties of a thermosetting material change gradually. Therefore, the “curing-induced” glass transition is also characterized by a gradually slowing down of the molecular rearrangements related to the glass transition region. In our simulation a constant width of the glass transition region ($\delta T = 20$ K) is assumed for the reacting material.

![Figure 6 — Storage and loss component of the shear modulus as a function of temperature plotted together with the measured deformation and loss angle for a cured adhesive anchor material. ($^\circ$F $= 1.8 \, ^\circ$C + 32; ksi = 0.145 MPa)](image)
In our creep experiments isothermal curing at low temperature (mostly \(-5 \, ^\circ C / 23 \, ^\circ F\)) for defined time intervals ranging from 50 hours to 144 hours is followed by a temperature increase to 23 \, ^\circ C (73 \, ^\circ F). For determination of a realistic heating program, the temperature increase was measured in a concrete block (10 mm (0.39 in.) below the surface) after an abrupt external temperature change from \(-5 \, ^\circ C\) to 25 \, ^\circ C (23 \, ^\circ F to 77 \, ^\circ F). The time interval indicated in Fig. 7 and 8 by “heating” represents the measured temperature increase.

In Fig. 7 and 8 the simulated glass transition temperatures \(T_G(t_{\text{cure}})\) are shown for thermosetting adhesives cured at \(-5 \, ^\circ C\) (23 \, ^\circ F) for 56 hours and 144 hours, respectively, and then heated to 23 \, ^\circ C (73 \, ^\circ F). The temperature program \(T(t_{\text{cure}})\) is adapted from the measured temperature in a concrete block after an instantaneous temperature jump to room temperature.

Similar to Fig. 6, the first crossover of glass transition temperature \(T_G(t_{\text{cure}})\) and curing temperature \(T(t_{\text{cure}})\) in Fig. 7 indicates the vitrification of the adhesive. In addition to the \(T_G(t_{\text{cure}})\) curve (solid line), the curves for \(T_G(t_{\text{cure}}) + 10 \, ^\circ K\) (dashed line) and \(T_G(t_{\text{cure}}) - 10 \, ^\circ K\) (thin line) are plotted to indicate the width of the glass transition interval. As discussed above and illustrated in Fig. 6 during curing the molecular rearrangements start to become considerably slower at about 10 \, ^\circ K below \(T_G(t_{\text{cure}})\). Therefore the first crossover of the \(T_{\text{cure}}(t_{\text{cure}})\) and the \((T_G(t_{\text{cure}}) - 10 \, ^\circ K)\) curves in Fig. 7 at about 49 hours indicates the curing-induced vitrification. The heating-induced softening is indicated by the second crossing of \(T_{\text{cure}}(t_{\text{cure}})\) and \(T_G(t_{\text{cure}}) - 10 \, ^\circ K\) at about 72 hours and the vitrification due to post curing (third crossing at 82 hours) are clearly indicated in Fig. 7 for the thermosetting adhesive cured for only 70 hours at \(-5 \, ^\circ C\) (23 \, ^\circ F) and then heated to 23 \, ^\circ C (73 \, ^\circ F). The “critical” time interval between softening and re-vitrification in which the sample behaves like a viscoelastic liquid shows a duration of about 10 hours.

An isothermal curing period of 144 hours at \(-5 \, ^\circ C\) (23 \, ^\circ F) (see Fig. 8) results in a higher conversion (not shown) and consequently in a higher value of \(T_G\) when heating starts. The onset of curing-induced vitrification is again indicated by the first crossover of \(T_{\text{cure}}(t_{\text{cure}})\) and \(T_G(t_{\text{cure}}) - 10 \, ^\circ K\) after about 43 hours. Although both curves become very close at about 150 hours no further crossover can occur for longer curing times. Therefore, no heating-induced softening or vitrification due to post curing can be identified assuming a glass transition interval of \(\delta T = 20 \, ^\circ K\) and hence, no “critical” time is predicted by our simulation.
In accordance to the creep test, the same type of simulations have been performed for curing times of 50, 70 and 144 hours and isothermal curing at -5 °C (23 °F) followed by heating to room temperature. In addition, a large number of simulations with different (low) curing temperatures, heating rates and post curing temperatures have been performed in order to identify unexpected “critical” softening by extreme temperature changes. The temperature programs tested in our simulations were deduced from long term temperature data. The highest heating rates were recorded for concrete surfaces under strong solar radiation. The heating rates observed in the concrete (in 11 to 54 mm (0.43 – 2.13 in.) depth) typically do not exceed 5 K/hour and our “temperature jump” experiments are in this range.

Creep under permanent load

A series of creep tests under permanent load has been performed for a curing temperature of -5 °C (23 °F) and curing times of 55, 57, 70 and 144 hours with a tension stress of 7 MPa (1015 psi) under the experimental conditions described above. In Fig. 9 the total displacement, \( \Delta(t) \) (values measured at the test equipment), is plotted versus time after the “temperature jump”, that is after the test member was moved from the refrigerator to room temperature, for samples cured for 70 and 144 hours, respectively. The temperature increase inside the concrete is very similar to the \( T_{\text{cure}}(t_{\text{cure}}) \) – curve in Fig. 7 and 8. Starting from an initial displacement, \( \Delta_{t=0} \), an “induction period” can be identified. In this time interval the sample is in the glassy state, i.e. \( T_c(t_{\text{cure}}) >> T_{\text{cure}}(t_{\text{cure}}) \), and the molecular motions are almost frozen. When \( T_{\text{cure}}(t_{\text{cure}}) \) approaches \( T_c(t_{\text{cure}}) \) the molecular rearrangements at the glass transition gradually soften the sample. The sample becomes a viscoelastic material and may show flow behavior. For both samples an S-shaped increase of \( \Delta(t) \) is observed. For the sample with the longer curing time (144 hours) the “creep interval” (indicated by the vertical dotted lines) is small. For the sample cured for only 70 hours the “creep interval” starts earlier and is considerably longer. These findings can be explained by the more pronounced softening when the glass transition region (\( T_G \pm \delta T/2 \)) is approached.
Comparison of creep tests and simulation

In Fig. 10 the “softening” and “re-vitrification times” estimated from the creep tests under permanent load and the simulations for a curing temperature of -5 °C (23 °F) and curing times of 55, 57, 70 and 144 hours are summarized and compared. In the case of the creep tests the time of onset of softening was determined by a simple tangent construction, whereas for the time of re-vitrification a 99% value of the displacement at the end of the experiment was taken as threshold value. For the case of simulations (see above) the crossover points of the $T_{G(t_{cure})}$ and $T_{cure(t_{cure})} - 10 \, K$ are used as the criteria for estimation of the “softening” and “re-vitrification times”.

Figure 9 — Displacement $\Delta(t)$ measured at an adhesive anchor system under load after curing for 70 hours (solid) and 144 hours (dashed) curing at -5 °C (23 °F) and then heated to 23 °C (73 °F). The vertical dotted lines indicate the beginning (softening) and ending of the creep (re-vitrification).

Figure 10 — Comparison of “softening” and “re-vitrification times” estimated from creep tests under load and simulations for a curing temperature of -5 °C (23 °F). ($°F = 1.8 \, °C + 32$)
It is obvious from Fig. 10, that the “softening” ($t_{\text{softening}}$) and “re-vitrification times” ($t_{\text{vitrification}}$) estimated from creep tests and simulation show similar trends. The values for the softening time for 50, 57 and 70 hours curing at -5 °C (23 °F) are nearly identical. Although there is no crossover of the simulated values of $t_{\text{softening}}$ and $t_{\text{vitrification}}$ for 144 hours curing (see Fig. 8) a value of 6 hours is plotted in Fig. 10, since the $T_G(t_{\text{cure}})$ and $T_{\text{cure}}(t_{\text{cure}})$ curve come very close at this time. The simulated “re-vitrification times” tend to be shorter than the experimentally determined ones. This is not surprising since the experimental creep curves include reversible viscoelastic behavior and irreversible plastic behavior under load, whereas the simulation determines the “critical” interval by a simple criteria for the relation of $T_G(t_{\text{cure}})$ and $T_{\text{cure}}(t_{\text{cure}})$, which is based on the width of the thermal glass transition. The later assumption is rather related to linear viscoelastic behavior and does not include non-linear effects (for example load dependent effect, viscous flow or viscoplastic behavior). However, an extension of the model would be helpful and may provide the total displacement as a function of curing time, temperature or load.

CONCLUSION

In this investigation one specific thermosetting adhesive for anchor systems has been selected to exemplify the curing behavior and load performance after installation and curing at low temperatures. It can be expected that similar observations can also be made for other thermosetting adhesives, however, the sensitivity and extent of the influences may be different.

Based on the results of the experimental investigations and simulations in this study, the following conclusions are drawn:

- The measured anchor displacements under sustained load were found to depend on base material temperature, heating rate and load level.
- The presented model - based on generally accepted assumptions for thermoset curing - allows the simulation of the time dependence of chemical conversion and glass transition temperature for arbitrary (user-defined) variations of curing temperature and provides the basis for a better understanding of the competition between thermal softening and “curing-induced” vitrification. This competition is of specific interest for thermal-induced softening and post curing during fast heating of adhesive anchors cured at low base material temperatures.
- The comparison of experimentally determined “softening” and “vitrification” times to simulated values show a reasonable agreement between tests and simulations. This justifies the simple assumptions of the model and provides the possibility of at least a semi-quantitative prediction of adhesive performance for different thermal or meteorological history.
- From the simulation of curing-induced vitrification and thermal-induced softening, critical cases for the load performance of adhesive anchors can be identified. Furthermore, it is possible to give an estimation of the minimum curing time needed for base material temperatures below the standard temperature.

In combining this simple model with a curing time-dependent viscoelastic model for adhesive anchor materials, an extension of the model to simulations of the displacement under sustained load is expected to be possible.

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Alig, Lellinger, Böhm et al
EFFECT OF FLY ASH AS CEMENT REPLACEMENT ON THE SHORT TERM BOND STRENGTH OF ADHESIVE ANCHORS SYSTEMS

by Peter Grzesik

Synopsis: Adhesive and mechanical concrete anchor systems today are typically tested in concrete mix designs containing no fly ash. This paper investigates the influence of a certain amount of fly ash as a cement replacement on the short term resistance of common adhesive anchor systems. The result shows no significant influence for the tested conditions.

Keywords: fly ash, adhesive, anchor, bond, concrete
Grzesik

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INTRODUCTION

For many years, fly ash, a pozzolan material has been used as an admixture in the production of concrete. Advantages of using fly ash range from lower cost, improved durability and strength to saving energy and reduced CO₂ emissions. For example, using a composite cement containing fly ash can help reduce the carbon dioxide emissions per ton of concrete by about 20% - 30%.

To date, concrete anchors are tested primarily in concrete mix designs using cement with little or no fly ash content, or where the content has not been recorded as a parameter. Due to the increased use of fly ash in mix designs it is necessary to evaluate the impact on the design of concrete anchor systems. This paper focuses on adhesive anchor systems commonly used in construction practice today.

Adhesive anchor systems are evaluated with regards to their short-term resistance under laboratory installation and service conditions. The anchors for this investigation were installed in normal weight concrete using a mix design containing 25% fly ash which is the maximum percentage permitted in Section 4.4.2 of ACI 318-08. Control tests were performed in a mix design containing no pozzolans. In order to assess the bond strength of anchors a confined test setup was chosen to avoid concrete breakout. In addition, high strength steel was used in the tests to preclude steel failure.

DESCRIPTION OF PROBLEM

Fly ash

Fly ash is a by product of the combustion of coal in coal fired power plants. It is a fine powder consisting of a variety of materials, mainly silicon oxide and calcium oxide, but it also includes aluminum oxide and iron oxide. Historically, as a waste product of coal combustion, fly ash was emitted into the atmosphere or used for landfills. In an effort to reduce waste and emissions, fly ash is being recycled in various ways, for example in geopolymers or as a cement replacement. In general, fly ash is used today to improve strength, durability and profitability in concrete construction. Its fine particle size, pozzolanic and partially cementitious properties make fly ash attractive in concrete mix designs for the following benefits:

- Less need for cement that requires energy intensive production
- Reduced segregation and bleeding
- Inhibits alkali-aggregate reaction and increases sulfate resistance
- Reduces permeability

ASTM C618 lists two main classifications of fly ash. Type F is a pozzolanic material with typically less than 10% lime (CaO). Also a pozzolanic material, but with a lime (CaO) content of more than 20%, Type C does not need a cementing agent, as it is cementitious itself. Both types are being used as a cement replacement in concrete construction.

Adhesive anchors

Adhesive anchor systems have been used for many years in various forms (injection systems, capsule systems) to anchor column bases, rails, beams, ledger angles, dowels, manufacturing equipment, and many other structural or non-structural components to concrete. The tension and shear capacity for adhesive anchor systems is based on the evaluation of comprehensive test programs. These tests are described in standards including ASTM E488, ASTM E1512 and ICC-ES Acceptance Criteria, such as ICC-ES AC58 and AC308 to meet building code compliance.

The predominant testing and evaluation guideline for adhesive anchors in concrete (ICC-ES AC308, Annex A, section 5.2.3 and 5.2.4) references ASTM C33 (aggregate) and ASTM C150 (cement) for concrete test members. Section 5.2.4 states concrete mixtures shall not include materials such as slag, fly ash, silica fume or limestone powder. Although the influence of fly ash on concrete properties has been widely researched, there is
little information about the effects on adhesive anchor behavior. It is widely accepted that the compressive strength is the primary parameter necessary for describing concrete influence on concrete failure modes of anchorages. Cement replacements and admixtures have not been addressed so far.

**DESCRIPTION OF INVESTIGATION**

To obtain an initial indication about the influence of fly ash on adhesive anchor behavior, confined static (short term) tension tests were carried out at the Hilti Testing Laboratory in Tulsa with two different adhesive anchor systems; one epoxy-based and the other a Methacrylate formulation. These represent two common types of injection adhesive anchor systems currently used in the industry.

The table below describes the two anchor systems:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesive type</td>
<td>Methacrylate</td>
<td>Epoxy</td>
</tr>
<tr>
<td>Relative cure rate</td>
<td>fast</td>
<td>slow</td>
</tr>
<tr>
<td>Dispenser type</td>
<td>Manual (trigger pull)</td>
<td>Manual (trigger pull)</td>
</tr>
<tr>
<td>Mixer type</td>
<td>Static in nozzle</td>
<td>Static in nozzle</td>
</tr>
<tr>
<td>Anchor rod</td>
<td>1/2 in. (13 mm) threaded rod (ISO 898-1, class 12.9)</td>
<td>1/2 in. (13 mm) threaded rod (ISO 898-1, class 12.9)</td>
</tr>
</tbody>
</table>

The concrete test members were prepared in accordance with ASTM E488 and ICC-ES AC308. In order to obtain representative data for common practice a fly ash content of 25% was chosen. This corresponds to the maximum fly ash content permitted under Section 4.4.2 of ACI 318-08. For this comparison, control anchors were installed in concrete test members containing no fly ash. The properties of the concrete test members are summarized in the table below:

<table>
<thead>
<tr>
<th>Control concrete test members</th>
<th>Concrete test members containing fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f'_c = 5970 \text{ psi (41 MPa)} )</td>
<td>( f'_c = 5530 \text{ psi (38 MPa)} )</td>
</tr>
<tr>
<td>No fly ash content</td>
<td>Fly ash content 25% Fly ash Class C, ASTM C618</td>
</tr>
<tr>
<td>Pour date: June 2006</td>
<td>Pour date: Feb 2002</td>
</tr>
<tr>
<td>Test Date: Nov 2008</td>
<td>Test date: Nov 2008</td>
</tr>
<tr>
<td>Limestone aggregate</td>
<td>Limestone aggregate</td>
</tr>
<tr>
<td>Tests performed in concrete form side</td>
<td>Tests performed in concrete form side</td>
</tr>
</tbody>
</table>

For the evaluation of bond failure, confined tests in accordance with ICC-ES AC308 and ASTM E488 were selected in order to preclude concrete cone failure. The reaction force is transferred into the concrete close to the anchor. The diameter of the hole in the confining plate is typically 1.5 to 2.0 times the diameter of the drilled hole. The thickness of the plate is at least equal to the diameter of the tested anchor rod. To reduce the influence of friction between the confinement plate and the concrete surface on the result, a sheet of Teflon corresponding to the area of the confining plate is placed between the confining plate and the concrete surface.

The center hole actuator is placed in a way that it is centered above the anchor to be tested. The pull rod is attached with a nut to the actuator. The anchor is attached to the opposite end of the pull rod in a way to ensure that the applied load direction is in line with the centerline of the anchor.

Above the actuator a load cell is placed to record the load. To record displacements, LVDTs are attached to the anchor.

A pre load of approximately 5% of the expected failure load is applied to bring all parts of the set up into full bearing. After zeroing the displacement, the applied load is increased constantly at a rate that should lead to a failure in about 1 – 3 minutes. A displacement-controlled test set up is used in this test.

A typical test setup is shown in Fig. 1.
Figure 1—Typical test setup for confined tension tests (taken from ICC-ES AC308)

The anchors were installed away from edges and with sufficient distance between anchors to avoid unwanted splitting of the concrete. High strength steel was used to avoid premature steel failure due to the high bond capacity of the anchors.

The anchors were installed by drilling holes to the required embedment depth, using an electro-pneumatic hammer drill. After drilling, the holes were cleaned thoroughly by blowing out the remaining dust and debris using compressed air followed by brushing with a wire brush of the appropriate size and blowing out again with compressed air.

Other test parameters are summarized in Table 3:

<table>
<thead>
<tr>
<th>Table 3—Test Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole diameter: 9/16 in. (14.3 mm) (hammer drilling)</td>
</tr>
<tr>
<td>Hole depth = anchor embedment:</td>
</tr>
<tr>
<td>• System 1: 4-1/2 in. (114 mm)</td>
</tr>
<tr>
<td>• System 2: 3-1/2 in. (89 mm)</td>
</tr>
<tr>
<td>Diameter of reaction frame plate (confinement):</td>
</tr>
<tr>
<td>• Hole diameter 1.063 in. (27 mm)</td>
</tr>
<tr>
<td>• Outer diameter of reaction plate 5.25 in. (133.3 mm)</td>
</tr>
<tr>
<td>Test procedure in accordance with ICC-ES AC308, Table 4.1 test series 1b</td>
</tr>
<tr>
<td>Base Material Temperature: 70 °F (21 °C)</td>
</tr>
<tr>
<td>Dry concrete (interior storage)</td>
</tr>
<tr>
<td>Measurement of displacement directly on head of anchor</td>
</tr>
</tbody>
</table>
TEST RESULTS

A load displacement curve was recorded during the test and plotted on an X-Y diagram. The load displacement curves are shown in Fig. 2a – 2d and the results are summarized in Fig. 3:

Figure 2a—Load displacement curve of tension tests with System 1 in concrete containing fly ash

Figure 2b—Load displacement curve of tension tests with System 1 in concrete containing no fly ash
Figure 2c—Load displacement curve of tension tests with of System 2 in concrete containing fly ash

Figure 2d—Load displacement curve of tension tests with of System 2 in concrete containing no fly ash
EVALUATION OF RESULTS

Similar to the evaluation of reliability tests verifying the influence of other parameters according to ICC-ES AC308, Annex A, section 11.4.5.1, the evaluation of the effect of fly ash on the bond strength of adhesive anchor systems was done comparing the mean ultimate failure loads and the characteristic loads (5%-fractiles) according to Eq. (1). This evaluation is done to consider a potential increase of the variation of results as an effect of fly ash. The characteristic 5%-fractile was calculated according to Eq. (2) and (3).

\[
\alpha_{\text{fly ash}} = \min \left\{ \frac{N_u,m,\text{fly ash}}{N_u,m,\text{no fly ash}} ; \frac{N_{u,5\%},\text{fly ash}}{N_{u,5\%},\text{no fly ash}} \right\} \leq 1.0 \quad \text{Eq. (1)}
\]

\[
N_{u,5\%},\text{fly ash} = N_{u,m,\text{fly ash}} - k \cdot s_i \quad \text{Eq. (2)}
\]

\[
N_{u,5\%},\text{no fly ash} = N_{u,m,\text{no fly ash}} - k \cdot s_i \quad \text{Eq. (3)}
\]

where:

- \(N_{u,5\%},\text{fly ash}\) = 5%-fractile of each test series in concrete containing fly ash
- \(N_{u,m,\text{fly ash}}\) = Average ultimate load of each test series in concrete containing fly ash
- \(N_{u,5\%},\text{no fly ash}\) = 5%-fractile of each test series in concrete containing no fly ash
- \(N_{u,m,\text{no fly ash}}\) = Average ultimate load of each test series in concrete containing no fly ash
- \(s_i\) = Standard deviation of each test series
- \(k\) = Factor for a one-sided normal distribution corresponding to a 90% confidence level (Hahn and Meeker 1991).
- \(\alpha_{\text{fly ash}}\) = reduction factor for the influence of concrete containing 25% fly ash
The results for System 1 and System 2 were calculated as follows:

**System 1:**

\[
\frac{N_{u,m,\text{flyash}}}{N_{u,m,\text{no flyash}}} = 0.96 \quad ; \quad \frac{N_{u,5\%,\text{flyash}}}{N_{u,5\%,\text{no flyash}}} = 0.96 \quad ; \quad \alpha_{\text{flyash}} = 0.96
\]

**System 2:**

\[
\frac{N_{u,m,\text{flyash}}}{N_{u,m,\text{no flyash}}} = 1.00 \quad ; \quad \frac{N_{u,5\%,\text{flyash}}}{N_{u,5\%,\text{no flyash}}} = 1.03 \quad ; \quad \alpha_{\text{flyash}} = 1.00
\]

The failure occurred consistently and predominantly between the threaded rod and the adhesive for all tests. A typical failure is shown in Fig. 4:

![Figure 4—typical failure mode](image)

**CONCLUSION**

The tests presented in this paper indicate that the use of fly ash in common concentrations does not have a significant effect on the short term bond strength of adhesive anchors under the described conditions. The mean ultimate loads, standard deviations and failure modes were consistent in concrete with and without the addition of fly ash. Due to the fact that the predominant failure occurred between the threaded rod and the adhesive, it can be concluded that the small differences between mean values are not related to the addition of fly ash and lie within normal variation according to the current experience.

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SIMULATION OF ADHESIVE ANCHORING SYSTEMS IN CONCRETE

by B. Winkler, Y. Li, and F. Wall

Synopsis:
Numerical simulation has become a powerful tool for supporting the development of innovative fastening products. The information on the failure mechanism developing during the load transfer from fasteners to concrete can be obtained and analyzed by simulation, which offers the basic requirement for designing innovative fasteners. During the last 15 years Hilti Corporation has developed a simulation tool based on the finite element method and concrete material models to support the fastener design process. In this paper various simulation examples for typical post-installed anchors, particularly for adhesive anchors, are presented. Numerical simulations are carried out for single anchors and anchor groups consisting of four adhesive anchors loaded in tension. The simulation results are discussed and compared with experimental data. The comparison shows a good agreement.

Keywords:
Anchor; adhesive; anchor group; finite element method; numerical simulation; tension
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INTRODUCTION

The development of innovative fastening products requires an in-depth understanding of the physical phenomena involved in the complete process of setting and loading of anchors in construction materials such as concrete. Evidently, numerical simulation plays an important role for fulfilling this challenging task. For this purpose a simulation tool based on the finite element method has been developed at Hilti Corporation to support the development of fastening products.

In general, three different working principles or tension load transfer mechanisms, namely friction, keying and bonding are identified for fasteners in concrete. For friction type anchors the tensile load is transferred from the anchor to the base material due to the friction created by expanded segments. Keying type anchors carry the tensile load by main keys at the end of the anchor resulting in a concrete cone failure or in yielding of the steel rod. Adhesive anchors belong to the group of chemical fasteners, in which the tensile load is transferred through the adhesive bond between the anchor rod and the surrounding concrete. Typical failure modes observed for this type of anchors include concrete cone breakout failure, combined pullout (bond) and concrete cone failure and steel failure. In fact many anchors obtain their holding power from a combination of the three working principles.

This paper first presents various simulation examples of typical post-installed anchors with different working principles. Focus is then placed on simulation examples for adhesive anchors. In order to investigate the load-carrying behavior of bonded anchors using numerical simulation the behavior of the given materials as well as their interaction has to be described in a suitable way. This includes the determination of the material properties required for constitutive modeling and the investigation of the interface behavior between the anchor rod and the adhesive as well as between the adhesive and the concrete, respectively. In a first step single adhesive anchors were investigated numerically. The simulated results show good correspondence with test data. Different parameter studies were performed to analyze the influence of anchor diameter and embedment depth on the resulting bond strength. Furthermore, numerical simulations on adhesive anchor groups consisting of four anchors were performed to investigate the group effect on the load carrying capacity and the resulting failure mode, respectively. The simulation results fit well with experimental data. The numerical simulation approach provides an efficient and effective tool to understand the interaction between the individual anchors of the group as well as to evaluate the influence on the related pullout loads and failure modes.

SIMULATION OF ANCHORING SYSTEMS

The simulation of anchoring systems includes the modeling of the anchor, the base material, mainly concrete, as well as the interface between anchor and concrete. The anchor can consist of different components such as anchor rod, sleeve segments, washer and hull, etc. The modeling of the anchor should include most of the components, especially when the setting process needs to be simulated. In the context of this investigation an elasto-plastic material model is used to describe the nonlinear material behavior of steel.

For the majority of anchoring applications the base material is concrete. Evidently, the simulation of anchoring systems requires a realistic modeling of concrete including the cracking process after reaching the tensile strength of...
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the material. The concrete material is modeled using a rotating crack model for the tensile zone and a plasticity model for the compressive regime, both of which are necessary in the regions of load transfer into the base material. The interface between concrete and different parts of the anchor is usually modeled by contact models depending on the type of the anchor. The normal and tangential penetration is constrained by using penalties taking into account friction and bond, respectively. The bond behavior of mortar can be modeled in different ways as shown for example in (McVay et al. 1996), (Li et al. 2001), (Meszaros 2002), (Li et al. 2002) and (Eligehausen et al. 2006b).

The simulation system based on these models has been proven very robust and easy to handle for the development engineers in their daily business for various applications. Comparison between simulated results and the corresponding experimental data shows good agreement. Due to symmetry most of the simulations are realized either by using rotational symmetry or only a selected part of modeled application for three-dimensional problems. Depending on the different simulation purposes the simulation results can be obtained in terms of the loading capacity, the load-displacement curve, the failure process and the final failure mode. Moreover, the stress and strain distribution during the loading process plays a key role for the analysis of the failure mechanism as well as for an optimization of the geometry of the various anchor components.

As mentioned in the introduction, there are three basic working principles, namely friction, keying and bonding, which an anchor may activate to transfer the applied load into the base material. In fact many anchors obtain their holding power from a combination of these working principles. In Fig. 1 the load transfer mechanisms for the three working principles are shown.

![Friction type anchor](image1)

![Hilti heavy duty anchor (HSL)](image2)

![Keying type anchor](image3)

![Hilti design anchor (HDA)](image4)

![Bonding type anchor](image5)

![Hilti adhesive anchor (HVZ)](image6)

Figure 1 – Three work principles of anchors and corresponding Hilti anchors used in the respective analyses

To demonstrate the capability of numerical simulation three typical anchors representing the different working principles are analyzed. These anchors are the Hilti heavy duty anchor (HSL) representing a friction type anchor, the Hilti design anchor (HDA) for a keying type anchor and the Hilti adhesive anchor (HVZ) for a bonding type anchor (Fig. 1).

For the HSL anchor, as a friction type anchor, the tensile load is transferred from the anchor to the base material by employing the friction created by expanded segments. In the first step, representing the installation process, the anchoring system is loaded by applying the respective setting moment (installation torque). Due to pre-stressing the cone and the segments as well as the segments and the concrete get in contact and activate friction behavior due to
the expansion forces. Afterwards the anchor is loaded by a pullout tension force in vertical direction resulting in a typical concrete cone failure (Fig. 2a). The numerically determined crack pattern shows good agreement with the concrete cone failure as observed in the experiments (Fig. 2b).

Figure 2 – Crack pattern for (a) the Hilti heavy duty anchor (HSL) compared to (b) typical concrete cone failure for expansion anchors

Keying type anchors such as undercut anchors carry the tensile load at main keys at the end of the anchor resulting in a concrete cone failure or in yielding of the steel rod. For the HDA anchor only limited cracks appeared at the area of load introduction (Fig. 3a). The ultimate load is in this case reached by yielding of the anchor rod. The HVZ anchors, representing a bonding type anchor, transfer the tensile load mainly by means of the adhesive bond between the anchor rod and the surrounding concrete.

Figure 3 – Crack pattern for (a) the Hilti design anchor (HDA) and (b) the Hilti adhesive anchor (HVZ)

Upon loading to failure this anchor exhibits a combined pullout and concrete cone failure mode. Fig. 3b shows the numerically determined crack pattern for the HVZ anchor consisting of pullout (bond) failure in the lower part of the anchor rod and a typical concrete cone failure in the upper region.

These three examples clearly show that the numerical simulation system used for the analysis is capable of modeling the various load transfer mechanisms and captures the relevant characteristics of the different anchor types.
15.5

SINGLE ADHESIVE ANCHOR

The simulation system of single adhesive anchors includes the modeling of the threaded rod, the adhesive and the concrete, respectively. To investigate the load-carrying behavior of adhesive anchors using numerical simulation the behavior of the various materials as well as their interaction has to be described in a suitable way. This includes the determination of the related material properties, such as Young’s Modulus, Poisson’s ratio, tensile strength and compressive strength, respectively. Moreover, a realistic modeling of tensile stresses and the cracking process after reaching the tensile strength of the material is required. Therefore, the fracture energy of the respective materials has to be determined. In addition to the modeling of the threaded rod, the adhesive layer and the concrete, the respective interfaces have to be investigated carefully. The interfaces are given by the interaction between the anchor rod and the adhesive as well as between the adhesive and the concrete, respectively. The used models have been proven suitable for several applications and can be considered very robust and easy to handle for the development engineers in their daily business. Comparison between simulated results and experimental data shows good agreement.

In the first step single adhesive anchors were investigated numerically and compared to experimental results. Depending on the embedment depth different kinds of failure mechanisms can be observed (Eligehausen et al. 2006a, b). For small embedment depths concrete cone failure is given by a cone-shaped concrete breakout starting at the base of the threaded rod. For larger embedment depths the concrete failure mode usually changes to a mixed-mode type of failure. This is characterized by bond failure in the lower part of the anchor and a concrete cone breakout in the upper region. Bond failure occurs either at the boundary between the concrete and the adhesive or at the boundary between the adhesive and the steel rod. For large embedment depths the bond resistance developed over the length of the anchor can exceed the rupture strength of the steel rod resulting in steel failure of the threaded rod.

The resulting bond strength is primarily a function of the respective type of adhesive. In order to obtain the bond strength value it is necessary to enforce pure bond failure during the related pullout test. This can be achieved by using a so-called confined tension test setup (Fig 4a). This is in contrast to an unconfined test setup (Fig 4b) used in standard pullout tests, where typically mixed-mode type of failure can be observed, except for low strength adhesives.

The bond strength $\tau_u$ can be calculated as $\tau_u = F_u / (\pi d h_{ef})$, where $d$ is the diameter of the anchor rod and $h_{ef}$ is the effective embedment depth. Assuming the bond strength to be a material parameter independent of geometrical quantities the load carrying capacity should then increase linearly with both, the rod diameter $d$ or the embedment depth $h_{ef}$. However, according to experimental investigations (Eligehausen et al. 2006a) for some adhesive anchor systems an influence of the anchor diameter on the obtained bond strength has been observed. In Fig. 5a average bond strength values are plotted for different anchor diameters showing diameter sensitivity in form of clearly lower...
bond strengths at specific diameters. For the assessment of the resulting bond strength the size of the annular gap, that is the difference between the diameter of the drilled hole \( d_0 \) and the diameter of the anchor rod \( d \), should be taken into account. Primarily for ease of installation the annular gap can vary for different anchor diameter as given in the manufacturer installation instructions. The annular gap and therefore the thickness of the adhesive layer may be larger for large anchor diameter. Such conditions may typically be encountered for anchor diameter \( d > 16 \text{ mm} \) (5/8 in.). This is also the case for the results shown in Fig. 5b.

Figure 5 – Average bond strengths in concrete for different anchor diameters based on (a) test results according to (Eligehausen et al. 2006a) and (b) in comparison to simulation results (10 mm = 0.39 in.; 1 N/mm² = 1 MPa = 145 psi)

Pullout test results for anchors with different embedment depths can be found in (Meszaros 2002). Therein bonded anchors using different kinds of adhesives have been tested differentiating between confined (Fig. 6a) and unconfined test setup (Fig. 6b). Using a confined test setup the resulting bond strengths show a decreasing trend with increasing ratio of embedment depth to anchor diameter. For the unconfined test setup a less pronounced behavior could be noticed. The later is expected to be mainly driven by the mixed-mode type of failure depending of course on the material properties of the used adhesive. Please note, that for mixed-mode type of failure the related bond strength is strictly speaking the equivalent bond stress at failure.

Figure 6 – Experimentally determined bond strengths for different adhesives in pullout tests using (a) a confined and (b) an unconfined test setup (Meszaros 2002) (1 N/mm² = 1 MPa = 145 psi)

To evaluate the used simulation model as well as to investigate the influence of anchor diameter and embedment depth a series of simulations were performed. In this context different diameters \( d \) were used to investigate the influence on the pullout load carrying capacity and the resulting bond strength. The numerically determined bond strengths are shown for different anchor diameters in Fig. 5b. The simulation results fit well with experimental data showing a similar influence of the anchor diameter.
Figure 7 – Numerically determined bond strengths in pullout tests with (a) confined and (b) unconfined test setup.

Furthermore, the ratio of embedment depth to anchor diameter $h_{ef}/d$ has been varied in the numerical simulation investigation. The related bond strengths are shown in Fig. 7. Please note that for a specific value of $h_{ef}/d$ several simulations have been carried out using different values for $d$ or $h_{ef}$. Both for the confined (Fig. 7a) and the unconfined test setup (Fig. 7b) the simulation results fit well with experimental data. The comparison between test and simulation results was done in terms of the trend lines of the respective data. For the unconfined test setup the difference between test and simulation results is due to the mixed-mode type of failure depending on the material properties of the investigated adhesive anchor.

The good agreement between experimental and numerical results is a clear indicator for the capability of numerical simulation in the field of adhesive anchor applications.

GROUP OF ADHESIVE ANCHORS

The geometry of the anchorage plays a significant role with regard to the load carrying capacity. In case of anchor groups with diverse anchor spacing or anchors close to an edge different failure modes can be observed in experimental investigations (Eligehausen et al. 2006a). Anchor groups with a small anchor spacing $s$ generate a common concrete cone breakout in response to tensile loading, whereas anchor groups with large anchor spacing generally result in a mixed-mode failure of the individual anchors (Fig. 8).

Figure 8 – Test results representing different failure modes of adhesive anchor groups for constant embedment depth $h_{ef}$ while increasing the ratio of anchor spacing to embedment depth $s/h_{ef}$.
A schematic diagram for keeping the embedment depth constant while increasing the ratio of anchor spacing to embedment depth $s/h_{cf}$ is shown in Fig. 9.

![Failure mode for $s/h_{cf} = 0.5$](image1)

![Failure mode for $s/h_{cf} = 1.5$](image2)

Figure 9 – Schematic diagram for different failure modes of adhesive anchor groups for constant embedment depth $h_{cf}$ while increasing the ratio of anchor spacing to embedment depth $s/h_{cf}$ (Lehr 2003)

To investigate the influence of anchor spacing $s$ on the pullout load and failure mode numerical simulations were performed for anchor groups consisting of four adhesive anchors. For this investigation different ratios of anchor spacing to embedment depth $s/h_{cf}$ were used. Fig. 10 shows typical results for the numerically determined failure modes in terms of the respective crack pattern. The simulation results are consistent with the experimental observations (Fig.8) showing comparable failure modes.

![Simulation results in terms of crack pattern showing different failure modes of adhesive anchor groups for constant embedment depth $h_{cf}$ while increasing the ratio of anchor spacing to embedment depth $s/h_{cf}$](image3)

Figure 10 – Simulation results in terms of crack pattern showing different failure modes of adhesive anchor groups for constant embedment depth $h_{cf}$ while increasing the ratio of anchor spacing to embedment depth $s/h_{cf}$

A similar transition between the described failure modes can be seen when the embedment depth is increased while keeping the ratio of anchor spacing to embedment depth constant. Anchor groups with a small embedment depth generate a common concrete cone breakout. Increasing the embedment depth will result in a mixed-mode failure characterized by bond failure and a common concrete cone breakout (Fig. 11). Nevertheless, for large embedment depths a mixed-mode type of failure of the individual anchors can be observed. This is shown in (Eligehausen et al. 2006a, b).
The numerical simulation approach is then used to investigate anchor groups with a constant spacing but varying embedment depth. Fig. 12 shows typical results for the numerically determined failure modes in terms of the respective crack pattern. The simulation yields a similar result as given in the schematic diagram shown in Fig. 11. Again a transition from a common concrete breakout cone to a mixed-mode failure is observed. The increase of the embedment depth leads to a mixed-mode failure characterized by bond failure in the lower part of the anchor rods and a common concrete cone breakout in the upper regime.
Finally, the pullout forces computed numerically are compared with experimental data (Fig. 13). For this purpose, results from pullout tests of adhesive anchor groups with different ratios of anchor spacing to embedment depth and ratios of embedment depth to diameter were used (Appl 2009). For each test setup data with respect to the equivalent bond stress at failure of the individual anchor are available. This provides the possibility to determine the maximum pullout force of the related anchor group as \( F_u = 4 d \pi h_{ef} \tau_u \). In case of a common concrete cone breakout and small anchor spacing the pullout force can be estimated by \( F_u = 13.5 f_{cc}^{0.5} h_{ef}^{1.5} \), where \( f_{cc} \) represents the concrete compressive strength. The corresponding pullout forces with respect to different embedment depths are depicted in Fig. 13. They indicate the possible range of the respective pullout forces.

The simulation results again fit well with the experimental data. For large anchor spacing the computed pullout forces agree with the theoretical values based on the test results for the individual anchor. The decrease of the ratio of anchor spacing to embedment depth results in a reduction of the pullout forces. The related curves clearly show the influence of the interaction between the individual anchors. A similar behavior can also be observed for different embedment depths.

Evidently, the numerical results help to understand the interaction of the individual anchors as well as to evaluate the influence on the related pullout loads and failure modes. Hence, numerical simulation has been shown to be a powerful tool assisting the development of innovative fastening products, where in-depth understanding of the physical phenomena involved in the complete loading process is required.

![Figure 13](image_url)
Figure 13 – Experimentally and numerically determined pullout forces for adhesive anchor groups for different ratios of anchor spacing to embedment depth \( s/h_{ef} \) and embedment depth to anchor diameter \( h_{ef}/d \)
CONCLUSIONS

In this paper the importance and the potential of numerical simulation to drive the development of innovative fasteners has been demonstrated. In the first step various simulation examples show the capability of modeling typical post-installed anchors with different working principles. In the main body of the text the numerical simulation of adhesive anchors were discussed. For this purpose single bonded anchors with threaded rods were investigated numerically. The pullout loads determined with numerical simulation show good agreement with test data. Different parameter studies were performed to analyze the influence of anchor diameter and embedment depth on the load carrying behavior. Moreover, numerical simulations on adhesive anchor groups consisting of four adhesive anchors were performed to investigate group effect on pullout load and failure mode, respectively. The change in failure mode for different geometrical configurations could clearly be identified. Overall the simulation results fit well with experimental data. The numerical simulation results help to understand the interaction between the individual anchors as well as to evaluate the influence on the related pullout loads and failure modes. Evidently, numerical simulation has been shown to be a powerful tool to support the development of innovative fastening products.

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DESIGN OF CARBON FIBER-ANCHORS APPLIED FOR SEISMIC RETROFITTING WITH CARBON FIBER SHEETS

by J. Iketani, H. Tsukagoshi, and M. Kawakami

Synopsis:
Adhering carbon fiber (CF) sheets onto RC piers is one of the effective seismic strengthening methods. When the pier has an irregular shape such as I-shaped cross section, CF sheets cannot be adhered continuously around the pier. In such cases, the edge of the CF sheets have to be fixed with steel angles and anchor bolts in conventional fixing method. Therefore, an alternative fixing method using CF-anchors consisted of bundles of CF strands and fan shaped was developed and practically applied. One end of the CF-anchor spreaded like a fan was adhered to the CF sheet and other end is embedded in a hole drilled in the concrete member and fixed with injected epoxy resin. Applying this CF-anchor for the reinforcement of the concrete piers, it is necessary to design the adhesive load of the adhered part and the pull-out load of the embedded CF-anchor corresponding to the amount of the CF sheets.

This paper describes the design of CF-anchors based on the experimental results for the adhesive load of the adhered part and the pull-out load of the embedded CF-anchor.

Keyword: Carbon fiber sheet, CF-anchor, Design Equation, Pier, Retrofitting

Biography:
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INTRODUCTION

Highway bridges were seriously damaged during recent earthquakes in Japan. Particularly, damage was extensive in the existing concrete structures not complying with current seismic design codes [1]. Based on the investigation of those damages, it has been clarified that concrete piers with inadequate lateral reinforcement caused the destruction of many bridges [2]. Therefore, in piers with inadequate lateral reinforcement, it is imperative to provide additional external confinement to insure ductility of the piers [3]. In order to improve the ductility of the existing concrete piers, effective methods such as CF (carbon fiber) or AF (aramid fiber) sheet jacketing, steel jacketing and concrete jacketing have been used.

In this paper, the CF jacketing was adopted and investigated. The CF jacketing improves the ductility of the pier as it provides confinement of concrete by wrapping CF sheets continuously around the pier. However, the CF sheets cannot confine irregular shapes such as I-shaped cross section pier as shown in Figure 1 where the edge of the CF sheets have to be fixed with some effective methods. The steel angles and anchor bolts had been conventionally adopted for edge fixing of the CF sheets as shown in Figure 2. But this fixing method has many shortcomings as follows; (1) The steel angle is heavy, (2) The execution of work is dangerous because a crane must be used to lift the steel angles, and (3) The construction period is long because after fixing the steel angles and anchor bolts, resin should be injected between the CF sheets and the steel angles. Then, an alternative fixing method using CF-anchors as shown in Figures 3 and 4 was newly developed. CF-anchors were arranged at equal intervals as shown in Figure 4 and the fan shaped part was sewed at four lines to obtain uniform density and to hold a constant width at end of adhered part as shown in Figure 3. It is necessary to decide the specifications of the CF-anchor depending on quantity of the CF sheets to use the CF-anchor for the reinforcement of the I-shaped cross section piers.

Two major tests were executed; one is an adhesive test to obtain the effective length and width of the fan shaped part, and the other is a pull-out test to verify the ultimate pull-out load depending on the depth and angle of the embedded CF-anchor. Based on the results of the former test, practical design equations for adhered part were derived. From the latter test results, empirical equations used for design of the embedded part of CF anchor were proposed.
Outline of the Adhesive Test of the adhered part of the CF-anchor

Adhesive strength between CF sheet and CF-anchor composed of CF strands was obtained by the adhesive tests, in which the length / width ratio of the fan shaped part and the number of CF strands of the CF-anchor were set as parameters.

Materials-- The materials used and their properties are shown in Table 1. PAN type unidirectional CF sheets and CF strands were used. The ratio of the sizing agent to the CF strands was reduced about 0.002 by mass in order to improve the permeability of the resin.

Test Specimens and Test Method

The parameter of the test specimens is shown in Table 2. The number of test specimens was from 3 to 8. Figure 5 shows the schematic diagram of the adhesive test specimen. The CF-anchor was bonded to the CF sheet which had been adhered to a steel plate. The CF-anchor was embedded in a steel pipe. The grip part, in which CF strands were bundled, inserted to the steel pipe and embedded by the expansive cement, pulled in the adhesive test. The constrained expansion due to expansive cement in the steel pipe exerted pressure uniformly to avoid the stress concentration to CF anchor rods. The sheet was bolted between two steel plates in order to concentrate the tensile force on the interface between the CF-anchor and the CF sheet. Both sides of the test specimen were pulled by a universal testing machine.

Test Results and Discussions

The test results are shown in Table 3. The failure modes were peeling of the fan shaped CF-anchor from the CF sheet for all test specimens. Figure 6 shows the relationship between the experimental ultimate load and the length of the fan shaped CF-anchors which consist of 40 CF strands with 100mm in width and 60 CF strands with 200mm in width. With increase of load, the peeling started gradually from the pivot of the fan shaped CF-anchor to non-peeling area, this peeling is repeated until overall failure. Thus, it is concluded that the fan shaped CF-anchor has an effective adhesive length. Figure 7 shows the relationship between the experimental ultimate load and strength, and the interval of CF strands expressed by the width of fan shaped CF-anchor divided by number of CF strands. By decreasing the interval of CF strands, the number of CF strands increases and the experimental ultimate load increases. However, the strength of the experimental ultimate load divided by sectional area of CF strands decreases. Moreover, the values tend to converge to a constant value, therefore, the fan shaped CF-anchor has an effective adhesive width.

Adhesive Load Equation of the adhered part of the CF-anchor

The CF-anchor actually used has a shape as shown in Figure 8 for reasons of production. Meanwhile, it is considered that the tensile force to act on the CF-anchor is transmitted from the pivot to the tip point of the fan shaped part in a circular arc transmission path. The transmission area ΔABHx2 of tensile force originated in the pivot angle of the CF-anchor decreases to cos(α/2) times of the area ΔABCx2 as shown in Figure 8. This shows that the adhesive load decreases with the increasing of the pivot angle.

To derive the analytical adhesive load P_{b1} of the fan shaped CF-anchor based on the test results and the effective transmission area A_{b1} of the tensile force, the model shown in Figure 9 is assumed.

The effective adhesive length L_e and the effective adhesive width d_e of the CF strand are defined. From these, the effective adhesive area is calculated, then the tensile lap-shear strength of the adhesive resin and the decrease originated in the pivot angle of the CF-anchor are multiplied by the effective adhesive area. The notation expressed in Figure 9 is defined as follows;

- B : width of the fan shaped CF-anchor at the distance r from the pivot (mm)
- B_0 : width of the fan shaped CF-anchor (mm)
- B_L : width of the fan shaped CF-anchor when n_o CF strands are placed in d_e (mm)
- d_e : effective adhesive width (mm)
- L_0 : length of the fan shaped CF-anchor (mm)
- L_e : effective adhesive length (mm)
- ρ_f : density of the CF (=1.8 g / cm³)
- W : fiber areal weight of the fan shaped CF-anchor at the distance r from the pivot (g / m²)
- W_L : fiber areal weight at the adhesive limit of the fan shaped CF-anchor at the distance r_L from the pivot (g / m²)
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\( a_{cs} \): sectional area of the CF strand (=0.87 mm\(^2\))
\( d_{cs} \): diameter of the CF-anchor consist of \( n_{cs} \) CF strands stiffen by the resin (=1.83 \((n_{cs} a_{cs})^{1/2}\), mm)

As the diameter of CF-anchor rod depends on the amount of resin impregnated to the rod, the diameter decided by the pull out test adopted the number of CF strands, embedded depth and hole diameter as parameters.

\( n_{cs} \): number of the CF strands included in the CF-anchor
\( r \): distance from the pivot of fan shaped CF-anchor (mm)
\( r_{L} \): distance from the pivot to \( B_{L} \) of fan shaped CF-anchor (mm)
\( \alpha \): pivot angle of the CF-anchor (degrees)

If \( r = 0 \), then \( B = d_{cs} \) and if \( r = L_{0} \), then \( B = B_{0} \). Therefore the width \( B \) of the fan shaped CF-anchor and fiber areal weight \( W \) at the distance \( r \) from the pivot are given by equations (1) and (2),

\[
B = (B_{0} - d_{cs}) r / L_{0} + d_{cs} \quad \text{------------------------------------------(1)}
\]

\[
W = 1000 n_{cs} a_{cs} \rho_{f} / B
= 1000 n_{cs} a_{cs} \rho_{f} / ((B_{0} - d_{cs}) r/L_{0} + d_{cs}) \quad \text{------------------------------------------(2)}
\]

in which the fiber areal weight with \( n_{cs} \) CF strands arranged at effective adhesive intervals is defined to be the fiber areal weight at the adhesive limit \( W_{L} \). The distance \( r_{L} \) from the pivot of fan shaped CF-anchor to the position \( W_{L} \) is obtained corresponding to the assumed width \( B_{L} \),

\[
W_{L} = 1000 n_{cs} a_{cs} \rho_{f} / B_{L} \quad \text{------------------------------------------(3)}
\]

\[
B_{L} = 1000 n_{cs} a_{cs} \rho_{f} / W_{L} \quad \text{------------------------------------------(3)}
\]

\[
W_{L} = 1000 n_{cs} a_{cs} \rho_{f} / ((B_{0} - d_{cs}) r/L_{0} + d_{cs})
\]

\[
r_{L} = ((1000 n_{cs} a_{cs} \rho_{f}) / W_{L} - d_{cs}) L_{0} / (B_{0} - d_{cs}) \quad \text{------------------------------------------(4)}
\]

Therefore, the width \( B \) of the fan shaped CF-anchor at the distance \( r \) from the pivot is given by

\[
r \leq r_{L}: B = (B_{L} + d_{cs}) r / r_{L} + d_{cs}
\]

\[
r \geq r_{L}: B = B_{L}
\]

From practical use, when the length of the fan shaped CF-anchor \( L_{0} \) is assumed to be longer than the effective adhesive length \( L_{e} \), the effective adhesive area \( A_{be} \) is given by

for \( L_{e} \leq L_{0} \) and \( r_{L} \leq L_{0} - L_{e} \)

\[
A_{be} = B_{L} L_{e} \quad \text{------------------------------------------(5)}
\]

for \( L_{e} \leq L_{0} \) and \( L_{0} - L_{e} \leq r_{L} \leq L_{0} \)

\[
A_{be} = B_{L}(L_{0} - r_{L}) + (B_{L} - d_{cs})(L_{0} - L_{e}) / r_{L} + d_{cs} + B_{L}) (r_{L} - L_{0} + L_{e})/2 \quad \text{-----(6)}
\]

for \( L_{e} \leq L_{0} \) and \( L_{0} \leq r_{L} \)

\[
A_{be} = ((B_{L} - d_{cs})(2L_{0} - L_{e}) / r_{L} + 2d_{cs}) L_{e} / 2 \quad \text{------------------------------------------(7)}
\]

Therefore, considering the decrease of the adhesive load originated in the pivot angle of the fan shaped CF-anchor, the adhesive load \( P_{b1} \) of the fan shaped CF-anchor is given by

\[
P_{b1} = \tau_{p} A_{be} \cos^{2}(\alpha / 2) \quad \text{------------------------------------------(8)}
\]

where \( \tau_{p} \) is the tensile lap-shear strength of the bonding epoxy (MPa)
The effective adhesive area $A_{bc}$ in Equation (8) changes corresponding to the adhesive properties of the epoxy resin bonding the fan shaped CF-anchor. Then, to decide the fiber areal weight at the adhesive limit $W_L$ and the effective adhesive length $L_e$ which are needed to calculate the $A_{bc}$, the combination of $W_L$ and $L_e$ that correlates the analyzed load and the experimental ultimate load was decided. As a result, the correlation shown in Figure 10 was obtained by assuming $W_L = 840\text{g/m}^2$ and $L_e = 125\text{mm}$. The analyzed ultimate adhesive loads assuming fiber areal weight at the adhesive limit $W_L$ and effective adhesive length $L_e$, were in good correlations with the experimental ones as shown in Figure 10.

**PULL-OUT LOAD OF THE EMBEDDED PART OF THE CF-ANCHOR**

**Outline of the Pull-out Test of the Embedded Part of the CF-anchor**

Pull-out tests were carried out setting as parameters the number of the CF strands, embedded depth, embedded angle and the presence of the primer in order to confirm the pull-out load of CF-anchor embedded into the concrete.

**Materials**

- The materials used and their properties are shown in Table 4. Two CF strand types were used in this test, wrapped by polyester fiber and non-wrapped as shown in Figure 11. The wrapping of the CF strand is a measure to hold the linearity of the CF filaments until the breaking load of the CF strand.

**Test Specimens and Test Method**

- The number of test specimens was from 3 to 9. Preparing the test specimens was executed by the six step process shown in Figure 12. The inner surface of the hole was brushed by a wire brush and the dust was removed from the holes by flushing compressed air before CF-anchor embedded. A vertical pull-out test method is adopted as shown in Figure 13. The parameters are (1) number of the CF strands, (2) embedded depth, (3) embedded angle, and (4) presence of the primer as shown in Table 5. Here, the embedded angle was taken as a parameter for consideration of the actual execution of the CF-anchor into concrete columns as shown in Figure 14. The diameter $D$ of the hole was decided by the following Equation (9) provided by previous work on building reinforcement using the CF-anchors [4].

$$D = 2.3 (n_{cs} a_{cs})^{1/2}$$

**Test Results and Discussions**

- Tables 6 and 7 show the pull-out test results of pull-out failure and breaking failure. The failure mode of the CF-anchor was pull-out from concrete or breaking of CF-anchor as shown in Figure 15. The failure mode of the CF-anchor depended on the tensile strength of the CF-anchor rod 3400MPa: one is breaking failure and the other is pull-out failure. The typical cone-type failure in these tests was not observed. The experimental ultimate load was not influenced by the presence of the primer when the number of CF strands was 80 and embedded depth was 300mm. This is because the pull-out failure occurred between the grouting epoxy resin and the CF-anchor. Figure 16 shows the relationship between the experimental ultimate load and embedded depth of the embedded CF-anchors consisted of 40, 80 and 130 CF strands, and basically with no angle. It is confirmed that the experimental ultimate load increased linearly as the embedded depth increased regardless of the number of the CF strands. Pull-out or breaking was observed for the CF-anchor consisting of 40 CF strands with embedded depth of 200mm and that of 80 CF strands with the embedded depth of 300mm. The highest experimental ultimate loads corresponding to 40 and 80 CF strands were about 120kN at the embedded depth 200mm and 260kN at 300mm, respectively. Therefore, the experimental ultimate load does not increase even if the CF-anchor is embedded deeper because of the breaking of CF-anchor. Figure 17 shows the relationship between the experimental ultimate load and the embedded angle of the CF-anchor consisting of 80 CF strands which experienced breaking failure. It is confirmed that the experimental ultimate load linearly decreased as the embedded angle increased.

**Pull-out Load Equation of the Embedded Part of the CF-anchor**

**In Case of Pull-out**

- The diameter of the embedded CF-anchor is taken from the empirical equation $1.83 (n_{cs} a_{cs})^{1/2}$ [5], in which $a_{cs}$ is the sectional area of the CF strand and $n_{cs}$ is the number of the CF strands. The surface area $S_{cs}$ at the interface between the embedded CF-anchor and the grouting epoxy is then calculated by the following Equation (10).

$$S_{cs} = 1.83 \pi L_{cs} (n_{cs} a_{cs})^{1/2}$$

where $L_{cs}$ is the embedded depth of the CF-anchor (mm). Furthermore, the pull-out load $P_1$ of the CF-anchor in case
of the pull-out is given by the following Equation (11).

\[ P_1 = 1.83 \pi \tau_b L_{cs} (n_{cs} a_{cs})^{1/2} \cos \theta \]

where \( \tau_b \) is tensile lap-shear strength of the grouting epoxy (MPa) and \( \theta \) is embedded angle of the CF-anchor (degrees).

Figure 18 shows the relationship between the experimental ultimate load and the analyzed pull-out load \( P_1 \). As a result, it seems that the following Equation (12) is appropriate as the pull-out load equation of the embedded CF-anchor because of the tensile lap-shear strength of the grouting epoxy \( \tau_b \) in Equation (11) was 18.5MPa.

\[ P_1 = 106 L_{cs} (n_{cs} a_{cs})^{1/2} \cos \theta \]

In Case of breaking -- In case of breaking failure, CF-anchor embedded into the concrete with a certain inclination breaks at the curved part. However, it is difficult to propose a theoretical equation to evaluate the experimental ultimate load of the breaking failure because the smoothness of the concrete surface that the CF-anchor touches and the straightness of the fiber in the CF-strands greatly influence the pull-out load of the CF-anchor. Therefore, the design equation for breaking failure is generated by regression analysis of the test data. It is necessary first to normalize the wrapping data and the non-wrapping data. Therefore, test data are divided by the mean value of the breaking data of the embedded angle 0 degree (wrapping data = 3,376 MPa, non wrapping data = 2,103 MPa) and then examined using obtained stress degree ratio. The relationship between the stress degree ratio and the embedded angle \( \theta \) is shown in Figure 19. The linear relationship is confirmed between the stress degree ratio and the embedded angle and the regression can be shown by Equation (13).

\[ \frac{\sigma}{\sigma_{m}} = -0.0122 \theta + 1.0045 \]

The sectional area of CF-anchor is multiplied by both sides of Equation (13), and the pull-out load equation in case of the breaking failure using the wrapping CF strands can be showed by the Equation (14).

\[ P_2 = 3376 n_{cs} a_{cs} (-0.0122 \theta + 1.0045) \]

In Case of combined Two Failure modes-- The pull-out and the breaking equations are over imposed in Figure 20 which gives the relationship between the experimental ultimate load and the embedded angle of the CF-anchor consisting of 80 CF strands. The measured loads are in good correlations with Equation (15) as shown in Figure (20) because the experimental pull-out load decreased to \( \cos \theta \) times as the embedded angle \( \theta \) increased as shown in Equation 12 and the experimental breaking load linearly decreased as the embedded angle increased as shown in Equation 14. Though the experimental ultimate load have variance, Equation (15) is considered appropriate as the pull-out load equation of the embedded CF-anchor.

\[ P_{b2} = \text{Min} \{106 L_{cs} (n_{cs} a_{cs})^{1/2} \cos \theta, 3376 n_{cs} a_{cs} (-0.0122 \theta + 1.0045)\} \]

where \( L_{cs} \) is embedded depth (mm), \( n_{cs} \) is number of the CF strands, \( a_{cs} \) is sectional area of the CF strand (= 0.87mm²) and \( \theta \) is embedded angle (degrees).

CONCLUSIONS

An effective fixing methods of the CF sheets applied for the irregular shaped concrete piers have been strongly demanded. In this study, CF-anchors, consisting of bundles of CF strands fanned-out in one end, as fixing method of CF sheets were proposed and their adhesive properties, failure mechanisms and practical design issues were investigated.

The following conclusions were obtained;
1. With increase of load, the peeling started gradually from the pivot of the fan shaped CF-anchor to non-peeling area, this peeling is repeated until the overall failure. Thus, the fan shaped CF-anchor has an effective adhesive length.
2. By decreasing the interval of CF strands, the number of CF strands increased and the ultimate load increased. However, the strength of the ultimate load divided by sectional area of CF strands decreased. Furthermore, the width of the strands in the fan shaped CF-anchor tends to converge to an effective adhesive width.
3. An analytical adhesive load depending on the width, length, pivot angle and number of CF strands of the fan shaped CF-anchor is proposed and confirmed.

4. It is confirmed that the ultimate load linearly increased as the embedded depth increased regardless of the number of the CF strands. Pull-out or breaking as failure modes were observed when the CF-anchor consisting of 40 CF strands was embedded 200mm and that of 80 CF strands was embedded 300mm. The highest ultimate loads corresponding to 40 and 80 CF strands were about 120kN at an embedded depth of 200mm and 260kN at that of 300mm, respectively. Therefore, the ultimate load of the breaking failure of CF-anchors does not increase even if the CF-anchor are embedded deeper than the above given depths.

5. The ultimate load for the breaking failure of the CF-anchors decreased linearly with the increase of the embedded angle.

6. The pull-out load was correctly estimated by the proposed equation assuming embedded depth, embedded angle and the number of CF strands composing the CF-anchor.

REFERENCES

**Table 1-- Properties of materials used for adhesive test**

<table>
<thead>
<tr>
<th>Material</th>
<th>Mechanical properties</th>
<th>Physical properties</th>
</tr>
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<tbody>
<tr>
<td>CF sheet</td>
<td>Tensile strength ≥ 3400MPa, Modulus of elasticity = 210 ~ 269GPa</td>
<td>Fiber areal weight ≥ 200 and 300g/m², Density = 1.8g/cm³</td>
</tr>
<tr>
<td>CF strand</td>
<td>Tensile strength ≥ 3400MPa, Modulus of elasticity = 210 ~ 269GPa</td>
<td>Number of CF filaments = 24,000, Sectional area = 0.87mm², Density = 1.8g/cm², Size content = 0.2±0.1%</td>
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<tr>
<td>Epoxy resin for CF sheet</td>
<td>Tensile strength ≥ 29MPa, Bending strength ≥ 39MPa, Tensile lap-shear strength ≥ 9.8MPa</td>
<td>Viscosity ≤ 40,000mPa·s, Density = 1.17±0.10g/m³</td>
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<tr>
<td>Epoxy resin for CF-anchor</td>
<td>Tensile strength ≥ 29MPa, Bending strength ≥ 39MPa, Tensile lap-shear strength ≥ 12.8MPa</td>
<td>Viscosity ≤ 40,000mPa·s, Density = 1.17±0.10g/m³</td>
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**Table 2-- Fan shaped test specimens**

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<th>Number of the CF strands n&lt;sub&gt;c&lt;/sub&gt;</th>
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**Table 3-- Ultimate adhesive loads obtained from the adhesive test**

<table>
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<th>No.</th>
<th>Number of CF strands n&lt;sub&gt;c&lt;/sub&gt;</th>
<th>Width B&lt;sub&gt;0&lt;/sub&gt; (mm)</th>
<th>Length L&lt;sub&gt;0&lt;/sub&gt; (mm)</th>
<th>Angle of pivot α (degree)</th>
<th>Ultimate adhesive load (kN)</th>
<th>Adhesive strength (MPa)</th>
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16.7
Table 4-- Properties of materials used for pull-out test

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<th>Material</th>
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<td>CF strand</td>
<td>Tensile strength ≥ 3400MPa, Modulus of elasticity = 210 GPa</td>
<td>Number of CF filaments = 24,000, Sectional area = 0.87mm², Density = 1.8g/cm³, Size content = 0.2±0.1%</td>
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<td>Epoxy primer</td>
<td>Adhesive strength against concrete ≥ 1.9MPa</td>
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<td>Grouting epoxy resin</td>
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<td>Viscosity ≥ 3,000mPa·s, Density = 1.9±0.15g/m³</td>
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<td>Epoxy resin for CF-anchor</td>
<td>Tensile strength ≥ 29MPa, Bending strength ≥ 39MPa, Tensile lap-shear strength ≥ 12.8MPa</td>
<td>Viscosity ≥ 40,000mPa·s, Density = 1.17±0.10g/m³</td>
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Table 5-- Test specimens used for pull-out test

<table>
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<tr>
<th>Kind of CF strand</th>
<th>Number of the CF strands ( n_{cs} )</th>
<th>Embedded depth ( L_{cs} ) (mm)</th>
<th>Embedded angle ( \theta ) (degree)</th>
<th>Diameter of the hole ( D ) (mm)</th>
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Table 6-- Ultimate pull-out loads of the pull-out failure specimens

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<th>Kind of strands</th>
<th>Number of the CF strands ( n_{cs} )</th>
<th>Embedded depth ( L_{cs} ) (mm)</th>
<th>Embedded angle ( \theta ) (degree)</th>
<th>Diameter of the hole ( D ) (mm)</th>
<th>Primer</th>
<th>Average ultimate pull-out load (kN)</th>
<th>Average pull-out strength (MPa)</th>
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16.8
Table 7-- Ultimate pull-out loads of the breaking failure specimens

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<th>Kind of Strands</th>
<th>Number of the CF strands ( n_{cs} )</th>
<th>Embedded depth ( L_{cs} ) (mm)</th>
<th>Embedded angle ( \theta ) (degree)</th>
<th>Diameter of hole ( D ) (mm)</th>
<th>Primer</th>
<th>Average ultimate pull-out load (kN)</th>
<th>Average pull-out strength (MPa)</th>
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Figure 7 -- Experimental ultimate load versus interval of CF strands

Figure 8 -- Transmission area of the tensile force

Figure 9 -- Effective adhesive area

Figure 10 -- Experimental ultimate load versus analyzed load

Figure 11 -- Process of the CF strand

Figure 12 -- Six steps for preparing of the test specimens
Iketani, Tsukagoshi, and Kawakami

Figure 13-- Test method of the embedded part of the CF-anchor

Figure 14-- Installation situation of the CF-anchor

Figure 15-- Failure mode of the embedded part of the CF-anchor

Figure 16-- Experimental ultimate load versus embedded depth

Figure 17-- Experimental ultimate load versus embedded angle

Figure 18-- Experimental ultimate load versus analyzed pull-out load
Understanding Adhesive Anchors: Behavior, Materials, Installation, Design

Figure 19: Stress degree ratio versus embedded angle

\[
\sigma / \sigma_{\text{m}} = -0.0122 \theta + 1.0045
\]

Figure 20: Experimental ultimate load versus embedded angle

\[
P_1 = 106 \frac{L_{\text{cs}}}{n_{\text{cs}} \text{acs}} \left( n_{\text{cs}} \text{acs} \right)^{1/2} \cos \theta
\]

\[
P_2 = 3376 \frac{n_{\text{cs}} \text{acs}}{n_{\text{cs}} 80} \left( -0.0122 + 1.0045 \right)
\]
STRENGTH EVALUATION OF SINGLE ADHESIVE CONCRETE ANCHORS UNDER TENSILE LOAD USING ARTIFICIAL NEURAL NETWORKS

by A.M. Said and S.E. Robinson

Synopsis: Adhesive-bonded anchors are increasingly adopted as structural fasteners for connections to hardened concrete. Due to their reliance on chemical bond, the tensile capacity of adhesive anchors is uniquely dependant on a number of factors [1]. These factors include the geometric parameters of the anchorage system, installation conditions, and adhesive bond strength which is manufacture dependent. Due to the complexity of these factors and their interaction in contributing to the tensile capacity of adhesive concrete anchors, it has proved to be difficult to evaluate their tensile strength. The design guidelines of anchorages using cast-in-place and post-installed mechanical anchors is discussed in ACI 318-08, Appendix D [2]. While, bonded anchors are used extensively in practice, they have not yet been incorporated into the design provisions of ACI 318-08 [3]. The worldwide database containing 2,878 tests of the anchors’ tensile capacity was provided to the authors by Dr. Ronald A. Cook, of ACI Committee 355 on Anchorage to Concrete. The aim of this study is to estimate the tensile strength of concrete adhesive anchors in uncracked concrete using artificial neural networks (ANNs) subject to bond failure and the effect of different parameters on it. As a result of this study, the ANN model will be able to capture the complex relationship between the adhesive bond stress and geometric parameters that compose the anchorage system.
Keywords: adhesive, anchors, concrete, neural network, post-installed, bond failure

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ACI Student Member Sean E. Robinson, is an ACI student member and a student majoring in Civil and Environmental Engineering, University of Nevada Las Vegas. His current research interests are adhesive concrete anchors and concrete structures.

INTRODUCTION

In many instances, concrete and steel structural members are required to be fastened together, and as a result, the use of concrete anchorage systems has increased. Anchors are classified into two types based on the time of installation. The first type is the cast-in-place anchors, which are installed while concrete is placed. These anchors develop their load capacity through two mechanisms, adhesion and bearing along the along the anchor surface and its deformations, a head or a hook. Over the past two decades the knowledge and design of cast-in-place anchors has become well known and established in ACI 318-08 Appendix D [2]. The second anchorage type used is post-installed anchors in which anchors are installed in hardened concrete. This system is, in turn, divided into two categories: mechanical bonded anchors and adhesive anchors. Similar to cast-in place anchors, mechanical anchors develop their strength through the transfer of load to the concrete at the anchor head, while adhesive anchors develop their strength through an adhesive layer that bonds them to concrete along the entire surface [3]. Post-installed anchors have the versatility to be placed in any desired location after the concrete has hardened, which increases their simplicity and speed of construction. As a result, post-installed anchors are growing in popularity among contractors in the concrete industry especially in retrofitting applications.

As the popularity of post-installed anchors increases, it is essential to have a well-developed design model for all their types. ACI 318-08 Appendix D [2] offers design guidelines for mechanical bonded anchors. However, except for the guidelines provided by (ICC-ES) AC-308 [X] there is no provision that establishes design guidelines for adhesive concrete anchors. Currently, most designers follow manufactures’ recommendations, which are based on laboratory testing specific to individual products and applications [3]. A reliable model for tensile strength of adhesive anchors will help better implement their use in practice and a good understanding of the effect of each parameter on strength can improve the efficiency of their use.

Adhesive anchors are post-installed anchors that derive their strength from the chemical compound adhesion to the walls of the hole drilled in concrete and the steel anchor rod. Chemical compounds used include epoxy, cementitious material, polyester resin, and other similar types [4]. Typically, the hole diameter is only about 10 to 25 percent larger than the diameter of the reinforcing bar or threaded rod [3]. Structural adhesives for this type of anchorage are available prepackaged in glass capsules, in dual-cartridge injection systems, or as two-component system requiring user proportioning [3].

The difficulty in determining a sensible design approach for adhesive concrete anchors is corroborated by their diverse range of failure modes [3]. The aim of this paper is to develop an ANN model that can estimate the tensile capacity of single adhesive anchors in uncracked concrete based on experimental data from the literature. Furthermore, the study will evaluate the effect of various design parameters on the tensile capacity of single adhesive anchors.

MODES OF FAILURE

Given the complexity of the parameters that affect adhesive concrete anchors, it is difficult to develop a universal design equation. The interaction of concrete/adhesive interface in conjunction with the
steel/adhesive interface makes it extremely difficult to establish a model that evaluates both failure planes in a small space as such [5]. Figure 1 shows different modes of failure for adhesive anchors which may become challenging to distinguish, since they can intermix. There are five typical modes of failure for adhesive anchorage systems as identified by Cook et al. [3], as shown in Figure 1. Adhesive anchors with shallow embedment tend to exhibit the concrete cone pull-out mode. As the anchor embedment depth increases, a combined failure with a bond failure below a shallow concrete cone is usually observed [3]. The bond failure part can occur at adhesive/concrete or steel/adhesive interfaces and even a mixed mode bond failure maybe observed on different parts of the anchor [3,6].

CURRENT DESIGN MODELS

For the purpose of comparative analysis, the current design models for adhesive concrete anchors are listed in the following section are.

Concrete Cone Models

Concrete cone model was initially proposed by Eligehausen et al. [7]. The model is statistically derived based on multiple testing of a single adhesive type and anchors whose ratio of embedment depth to diameter is equal to nine \((h_{ef}/d = 9)\). The ultimate predicted strength \((N_U)\) of the anchor depends on the embedment depth and the concrete strength, but does not account for adhesive failure assuming a failure in a concrete cone mode. The model is presented by the following equation:

\[
N_U = 0.92 h_{ef} \frac{2}{9} \sqrt{f_c}
\]

where,

- \(N_U\) = ultimate predicted strength of anchor (N)
- \(h_{ef}\) = embedment depth (mm.)
- \(f_c\) = 150 x 300 mm (6 x 12 in.) concrete cylinder compressive strength (MPa)

Uniform Bond Stress Model

The uniform bond stress model, presented in Eq. (2), is dependent on unique bond stress of the adhesive product, the diameter, and embedment length.

\[
N_U = \tau \pi d h_{ef}
\]

where,

- \(N_U\) = ultimate predicted strength of anchor (N)
- \(d\) = anchor diameter (mm)
- \(\tau\) = unique bond stress (MPa)
- \(h_{ef}\) = embedment depth (mm)

Cook et al. [3] indicate that while using the uniform bond stress model, the anchor diameter is most appropriate to use in Eq. (2) rather than the hole diameter. The bond stress along the embedment length of the anchor \((\tau)\) in Eq. (2) can be best represented through the uniform bond stress model, which is very simple to implement [3].

Combined Cone/Bond Models

The combined concrete cone and bond stress models were proposed for adhesive anchors by Cook et al. [3] and the Japan Concrete Institute [8]. For deeper embedment, a two term equation proposed by Cook et al. [3] is used to combine the strength of the shallow cone with the bond strength. The cone depth is calculated using Eq. (3), and if it is smaller than the embedment depth, then the combined cone failure and
bond failure are calculated in Eq. (5). If the embedment depth is smaller than the depth of the concrete cone then Eq. (5) is to be used, as it is a concrete cone model as suggested by Eligehausen et al. [7].

\[
h_i = \frac{\tau d h_e}{1.84 f_c}
\]

in SI Units

\[
N_U = 0.92 h^2 c \sqrt{f_c} + \pi \tau d (h_{ef} - h_c)
\]

in SI Units

\[
N_U = 0.92 h_{ef}^2 \sqrt{f_c}
\]

in SI Units

where,

\[N_U\] = ultimate predicted strength of anchor (N)
\[d\] = anchor diameter (mm)
\[\tau\] = unique bond stress (MPa)
\[h_{ef}\] = embedment depth (mm)
\[f_c\] = 150 × 300 mm (6 × 12 in.) concrete cylinder compressive strength (MPa)
\[h_c\] = depth of shallow concrete cone (mm)

**Two interface bond model [3]**

The basis of this design model is differentiating between failure at the adhesive/concrete interface and failure at the steel/adhesive interface. Eq. (6) is appropriate for steel/adhesive interface failure, where the ultimate load depends on the bond stress evaluated at the steel/adhesive interface, the embedment depth, and anchor diameter. Similarly, Eq. (7) is for adhesive/concrete interface failure, where the ultimate load depends on the bond stress evaluated at the concrete/adhesive interface at a low concrete strength, the diameter of the hole, the embedment length, and the ratio of the square root of the concrete strength being considered to the square root of the low strength concrete used to establish \(\tau_0\).

\[
N_U = \pi \tau d h_{ef}
\]

(6)

\[
N_U = \pi \tau_0 d h_{ef} \Psi_c
\]

(7)

where,

\[N_U\] = ultimate predicted strength of anchor (N)
\[d\] = anchor diameter (mm)
\[d_0\] = hole diameter (mm)
\[\tau\] = unique bond stress (MPa)
\[\tau_0\] = bond stress evaluated at hole diameter (MPa)
\[h_{ef}\] = embedment depth (mm)
\[f_c\] = 150 × 300 mm (6 × 12 in.) concrete cylinder compressive strength (MPa)
\[\Psi_c\] = 1.0 for products with little or no influence of concrete strength

**ARTIFICIAL NEURAL NETWORK APPROACH**

Artificial neural networks (ANN) are powerful computational tools inspired by the understanding and abstraction of the structure of biological neurons and the internal operation of the human brain [9]. ANN multi-layer perceptrons (MLP) are used extensively in engineering applications due to their ability to perform nonlinear transformations for functional approximations with given inputs in order to reach desired outputs. The value of neural networks relies in its ability to be trained through adaptive data driven approaches, and therefore the system is able to analyze, learn and capture complex or hidden relationships.
MLP networks consist of multiple layers (an input layer, an output layer and one or more hidden layers). Each layer contains a number of processing elements (units) partially or fully connected to units in the consecutive layer. Connections between processing units are initially assigned random numerical values (weights) representing their strength. The main objective in building an artificial neural network-based model is to train specific network architecture to search for an optimum set of weights, for which the trained ANN can predict accurate values of outputs for a given set of inputs from within the range of the training data [8]. While the MLP networks trains the complex array of interconnected data, the training of network is driven by sufficient and relevant data to achieve optimum results. Further investigation of artificial neural networks is outside the scope of this paper. However, more details about how to construct, train and validate MLP networks are available elsewhere [9,10].

EXPERIMENTAL WORLDWIDE DATABASE

Test reports on the behavior of adhesive anchors have been collected from experimental programs in Europe, USA, and Japan. From 36 reports, a database containing the results of 2,878 tests has been established. Currently the adhesive anchor database is maintained for ACI committee 355 by Professor Ronald A. Cook, Department of Civil Engineering, University of Florida, Gainesville. The database contains tensile and shear load testing in uncracked and cracked concrete with single anchors, groups of two anchors, and groups of four anchors. It distinguishes between confined and unconfined tests as well as between tests far from the concrete edge, tests near the concrete edge, and tests with close anchors spacing. Finally, the database differentiates adhesives by manufacturer as well as types such as epoxies, vinylesters, unsaturated polyesters, hybrid adhesives, and inorganic adhesives. Some tests indicate the temperature range at which the adhesive was cured. Currently, the International Code Council Evaluation Service (ICC-ES) AC-308, “Acceptance Criteria for Post-Installed Adhesive Anchors” [11] along with ASTM E 488, “Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements” [4] and E 1512, “Standard Test Methods for Testing Bond Performance of Bonded Anchors” [12] are the testing standards that manufacturers must follow to evaluate their adhesives for commercial use. The dimensions of the geometric properties of the anchorage system are recorded for each test in the concrete anchor database, along with qualitative identification of the failure mode that was observed as well as the quantitative tensile capacity at which the anchorage system failed. However, the tests in the 36 reports (1985-1994) that were used to establish the worldwide database were performed even before the release of the previous evaluation criteria of ICBO ES AC-58 [13] and the only available guidelines at that time were for expansion anchors ICBO ES AC-01 [14]. The purpose of the current ICC-ES AC-308, as stated in Section 1.1 is to establish requirements for different manufacturers post-installed adhesive anchors in concrete elements to be recognized in an ICC Evaluation Service, Inc. [11]. This product evaluation methodology allows adhesives from different manufactures to be consistently evaluated. Accordingly, engineers can use a unique bond stress for each product for design purposes.

SELECTION OF DATABASE

The success of establishing an ANN model is dependent on the amount and quality of information provided to train it as stated before. Therefore, the worldwide database was limited to unconfined, single adhesive anchors, far from edge loaded in tension in uncracked concrete with bond failure for the purpose of this study. The exclusion of the concrete cone mode of failure from the study ensures a homogenous set of data and helps the developed model better capture the relationship between different parameters. Furthermore, tests which resulted in the yielding of steel were omitted since these specimens demonstrated sufficient bond between the borehole and adhesive as no bond failure was observed. The database used must be sufficiently large to enable the ANN to fully capture the effect of the considered design parameters on the tensile capacity of single adhesive anchors. The initial geometric and material design parameters that were used to establish and train the ANN were: the diameters of the anchor and the bore hole, the embedment depth of the anchor, the concrete strength and the bond index which is described in the following section. The selected design parameters have all been shown in previous studies and design
models to be crucial in estimating the tensile capacity of adhesive anchors [1]. Manufacturers are required by the International Code Council Evaluation Service (ICC-ES) AC-308, Section 2.1.20 “manufacturer’s published installation” [11] to specify the installation of, and condition of the borehole, as well as the curing temperature range at which the adhesive should be applied. Accordingly, the tests selected to train the ANN were in the standard ranges that adhesives would be cured (5°C - 30°C/41°F - 86°F). Previous research by Cook and Konz [1] shows that inappropriate temperature and conditions of the borehole can have detrimental effects on the performance of the anchorage system, and hence temperatures that were outside the range listed were omitted.

The difficulty of identifying the failure mode is described in more detail by Zamora et al. [5]. They indicated that upon inspection of anchor after failure it is extremely difficult to identify if the failure was purely a cone failure, a result of effective adhesive bond, or rather a pull out failure, a result of ineffective adhesive bond [3]. Consequently, it is expected that the classification of the failure mode listed within the worldwide database is subjective nature. While the characteristics of the different failure modes are physically dissimilar yet their combination creates a difficulty in distinguishing a single prevailing mode of failure. For the purpose of this study only explicitly described bond failures were selected for the training the ANN in order to isolate the complex relationship between parameters that affect this mode of failure. Concrete cone failure has already been described by the Concrete Capacity Design (CCD) model by Fuchs et al. [14]. In order to properly and accurately train the network, duplicates within the testing data were carefully eliminated in order to improve the training capability of the network. The duplicates that were found in the database were carefully reduced to a single test data point. If inconsistent values of tensile capacity were found, then the procedure discussed by ASTM E 488 [4] was followed to eliminate these outliers. The tensile capacities that met the ASTM standard methodology were then averaged and the duplications of these tests were reduced to a single data point representing the general trend observed for that specific anchorage test. Duplicates were deemed to be points with similar geometric parameters (e.g. diameter of anchor, diameter of hole, embedment depth, and concrete strength). However, as discussed in by Cook and Konz [1] and Meszaros [16], adhesive bond strengths and consequently the tensile capacity of anchors are manufacturer dependent. Accordingly, tests with identical geometries parameters yet different adhesive manufactures were not considered as duplicates. The resulting database contained 213 tests from the original worldwide database for training of the ANN model, and the characteristics of these anchors are listed in Table 2.

ANN MODEL

The ANN model implemented in this study was a single feed-forward back-propagation multi layered perceptron network that utilized a scaled gradient conjugant (SGC) function, contained within MATLAB, Neural Network Toolbox. The network was trained with 80% of the 213 data points while the remaining 20% was used to determine whether the network was appropriately trained and able to capture the relationship between the different input parameters and output. The architecture of the network, shown in Figure 2, was developed with five inputs: diameter of anchor (d), diameter of hole (d_o), embedment depth (h_e), concrete strength (f_c), and an adhesive index, as well as a single output, tensile capacity (N). The inputs and outputs were then normalized to values between 0 and 1, in order for the SGC function to be compatible for training [10]. To ensure that the operator of the network had no bias of selecting data for training or testing, all datasets were randomized previous to training. Accordingly, inputs were fed to the network through three hidden layers that utilized a tangent sigmoid transfer function. Each layer contained 8 neurons which separated the 5 inputs and output. An epoch or single pass of the data through the network created an error output, between the network’s predicted output and desired output. Data is then passed through the network again in order to reduce the error between the network’s predicted output and desired output. Subsequently, optimum training results were attained through 2000 epochs.

To train the data more thoroughly, an additional parameter, the adhesive index, was deemed necessary to represents the adhesive bond strength. Examining the ICC AC-308 reveals two main adhesive related issues: product type and anchor diameter. This is evident from ICC-ES AC-308 Section 2.1.23 [11], since different anchor diameters must be tested for each adhesive to determine strength of the adhesive at various anchor diameters. The common trend is that larger anchors have higher tensile capacity, but yet lower bond strength. Using these two design principles, the bond index was determined from the uniform
bond strength model as suggested by Cook et al. [3,6]. The bond index was defined based on ICC-ES AC-308 and assigned as a number between 0 and 1 unique to each adhesive product and diameter size range as outlined by ICC-ES AC-308 and based on the available test data for that product over the diameter size range. It is worth noting that to determine the bond index for a specific product some experimental data need to be available. A major advantage of the ANN approach is that as new adhesives are tested, their test data can be easily added to the network database.

RESULTS AND DISCUSSION

The success of the ANN model does not rely on the network’s ability to simply train the data, but rather on its ability to predict an outcome, from a set of inputs that the network was not exposed to during the training phase. Therefore, the effectiveness of the ANN model is evaluated by its ability to predict the tensile capacity of an anchor from the testing data set.

In order to evaluate the performance of the ANN model the absolute average error (AAE) of the ratio of the predicted tensile capacity, \( N_p \), to the experimentally measured capacity, \( N_m \), is used to measure how accurately the network predicts the tensile capacity relative to the experimental data. The AAE was calculated using Eq. (8):

\[
AAE = \frac{1}{n} \sum \left| \frac{N_m - N_p}{N_m} \right| \times 100
\]

Eq. (9) is used to determine the coefficient of variation among the ratio of \( N_m/N_p \):

\[
COV = \frac{\sigma(N_m/N_p)}{\mu(N_m/N_p)}
\]

Represented in Figure 3 is the evaluation of artificial neural network (ANN) model used for evaluating the tensile capacity of single adhesive concrete anchors. The 45° line represents how closely the prediction from the ANN model is compared to the experimental values for tensile strength. The limited dispersion of points demonstrates that the ANN model was able to accurately use the database to establish the weight of the connections with a \( COV = 0.098 \) for the training data set and a \( COV = 0.233 \) for the testing data set. Table 1 shows the training data has an \( AAE = 6.28\% \) which is a lower error compared to the testing data with an \( AAE = 15.41\% \). The developed ANN model was able to estimate the tensile capacity of single adhesive anchors under tensile loading in uncracked concrete with relative accuracy. Table 1 displays the \( AAE \) and \( COV \) values which, in spite of the dispersed nature of adhesive anchors testing results, reflect an adequate model performance. This model represents an advantage over existing models since it can predict the capacity of adhesive anchors taking into account geometric as well as material properties.

PARAMETRIC STUDY

The purpose of the parametric study is to investigate the design parameters that affect the tensile capacity of the anchorage system. The design parameters listed below are isolated when possible so as to solely reveal the extent each parameter has on the tensile capacity of adhesive anchors. Otherwise, a combination of different factors and their effect on the tensile capacity was investigated.

Effect of Anchor Diameter on Tensile Capacity

Current ICC-ES AC-308 provisions provide evidence that tensile capacity increases as the anchor diameter increase [11]. This is reasonable since the bond surface area of the anchor \((\pi d h_{o})\) increases
linearly with the anchor diameter increase. Figure 4 displays a plot of the relation between anchor diameter and tensile capacity. It is shown that the increase is not linear despite the linear increase in bond area. Furthermore, as the anchor diameter increases the rate of the tensile capacity increase is reduced as shown in Figure 4. In order to better understand the influence of the anchor diameter on the tensile capacity, the bond stress \((\tau)\) versus anchor diameter was also plotted on Figure 5. The bond stress calculated based on the uniform bond stress model decreases with the increase of the anchor diameter. This observation was also confirmed by Cook et al. [3] and McVay et al. [6]. The implications of this effect of the anchor diameter would be important for designers to ensure the selection of the appropriate anchor diameter to achieve an economic design or the steel-concrete connection.

**Effect of Ratio of Anchor to Borehole Diameters on Tensile Capacity**

The effect of the borehole diameter with respect to the tensile capacity is difficult to isolate and in many respects impractical since the annular gap is relative to the anchor diameter. Accordingly, the effect of the borehole diameter must be investigated through the borehole to anchor diameter ratio. The general trend from the database reveals typical ratios for borehole to anchor diameters in the range of 1.10 - 1.25 [3]. Concurrently, the parametric study examines more closely these ratios to determine the effect of this ratio on the tensile capacity of the anchor. The effect of this ratio on tensile capacity was studied for two bolt diameters \(\frac{1}{2}\) in. (12 mm) and 1 in. (25.4 mm). As illustrated in Figure 6, the tensile capacity increases with the increase in the borehole/anchor diameters ratio. This indicates that the tensile capacity increases with the increase in annular gap. For the 1 in. (25.4mm) diameter anchor, this increase was observed up to a \(d_0/d\) ratio of 1.25, as shown in Figure 6. Figure 7 shows a similar trend for the \(\frac{1}{2}\) in. (12mm) diameter anchor, except that the decrease starts at a \(d_0/d\) ratio of 1.36. These results are consistent with accepted annular gap ratios for adhesive concrete anchors as discussed by Cook et al. [3] and Zamora et al. [5].

Figure 6 and Figure 7 demonstrate that beyond a certain ratio of borehole/anchor diameters, an increasing ratio is detrimental to the tensile capacity. Understanding this ratio of the borehole diameter to the anchor diameter has importance achieving an optimum performance from an adhesive concrete anchor.

**Effect of Embedment Depth on Tensile Capacity**

The uniform bond stress model and elastic bond model both suggest that as the embedment depth of the anchor increases the tensile capacity [17]. The increase in tensile capacity associated with the increase in embedment depth is due the increase in effective bonding area along the anchor/adhesive/concrete interfaces. As shown in Figure 8, the tensile capacity increases with the embedment depth increase, as confirmed in previous research by Cook et al. [3,17]. Upon further inspection of the graph, the increase in tensile capacity becomes limited at higher embedment depths, which verifies that a uniform or linear relationship is a close approximation for the case of shallow to moderate embedment depths [3]. It is worth noting that the failure mode shifts from a shallow concrete cone/adhesive failure towards a concrete failure with the increase in embedment depth. Figure 9 shows a decrease in bond strength associated with the increase in embedment depth which further demonstrates that a uniform bond stress model is an approximation since the largest value of bond stress is located towards the upper surface of the anchorage system [18,19]. This also is explained by the fact that most anchorage failures occur near the surface for shallow embedment depths where the uniform bond stress model has the best performance [3].

**Effect of Concrete Compressive Strength on Tensile Capacity**

Figure 10 shows the effect of concrete strength on anchor tensile capacity for various embedment depths. The parametric study of this design parameter reveals that although the increase in concrete strength does not provide a substantial increase in tensile capacity, it does slightly improve the tensile capacity of adhesive anchors with bond failure [1,12]. The type of aggregates used in the concrete appears to have a more substantial and consistent influence on bond strength than the compressive strength of the concrete [1]. According to Derucher et al. [20], the porosity of the aggregates may suggest the increase in anchor tensile capacity. While the concrete is curing, permeable aggregates will absorb water molecules, allowing bond between the cement paste and aggregate directly. Likewise, impermeable aggregates will not absorb free water molecules and a thin layer of water forms around the aggregate, subsequently as the concrete cures this water layer dries out leaving a thin void space around the aggregate [20]. At the time of
installation of adhesive concrete anchors, the thin void space around the impermeable aggregate allows more paths for the adhesive to adhere to resulting in higher bond strengths [1,20]. However for universal design purposes, accounting for each constituent of concrete is impractical, especially considering that adhesive anchors are installed in existing structures. Accordingly, accounting for concrete strength in the ANN model was an important consideration since the adhesive interface is located along both the concrete and the anchor. While the anchorage system is undergoing deformation the amount of stiffness that is provided by the concrete can offer strength to the anchorage system as modeled by a 3D nonlinear finite element analyses and modeled by the microplane model described by Ožbolt et al. [21]. The strength offered by concrete is verified by physical tests as most failures of adhesive concrete anchors are a mixed failure of which adhesive and concrete failures are witnessed.[5]

**SUMMARY AND CONCLUSION**

This study investigated the feasibility of using artificial neural networks as an approach to estimate the tensile capacity of adhesive concrete anchors. The advantage of the ANN approach is in its ability to capture hidden and complex relationships between different parameters using a large database and subsequently use it to predict the tensile capacity of adhesive anchors. The ANN approach also incorporated current ASTM standards [4,12] and ICC-ES AC-308 [11] evaluation criteria when appropriate in its methodology. The developed model was able to predict the tensile capacity of adhesive anchors (with bond failure) with a relatively small error considering the variability of the experimental data. The parametric study showed similar trends to those in the literature on adhesive anchors [2,3,6,17] in a qualitative manner. The ANN model can help identify the optimum range of use for several parameters such as anchor diameter, annular gap and embedment depth, which can help the designers in the choice of anchors geometric properties. While the ANN model studied within this paper only considers adhesive bond failure, concrete strength proved to be a contributing factor to the determination of the tensile capacity of adhesive concrete anchors. This may be attributed to the fact that most failures are a mixed failure in adhesive and concrete. The ANN model once established is readily available to input unique bond stresses that are evaluated based on the guidelines of ICC-ES AC-308, ASTM E 488, and ASTM E 1512 for new adhesive products [4,11,12].

The applicability of an ANN model is best within the range of the experimental parameters that were used to train such model. The trends shown in the parametric study are applicable to their specific cases and may change at different parameters range as parameters interact.

**ACKNOWLEDGEMENTS**

The authors wish to express their sincere appreciation to the manufactures and individuals that contributed to the adhesive concrete anchor worldwide database and research. Special recognition is extended to Dr. Ronald Cook of the University of Florida, ACI Committee 355 member that currently maintains and provided the worldwide database used in this study. Financial support was provided by the Western Alliance to Expand Student Opportunities (WASEO). The support of the Howard R. Hughes College of Engineering at the University of Nevada, Las Vegas is greatly appreciated.

**REFERENCES**


Table 1 — Performance of Tensile Capacity of Single Adhesive Concrete Anchors

<table>
<thead>
<tr>
<th>Data Set</th>
<th>AAE (%)</th>
<th>STDV [σ]</th>
<th>Average [μ]</th>
<th>COV</th>
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<td>Training Set</td>
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<td>0.098</td>
<td>0.998</td>
<td>0.098</td>
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<tr>
<td>Testing Set</td>
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<td>0.972</td>
<td>0.233</td>
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<td>7.69</td>
<td>0.127</td>
<td>0.995</td>
<td>0.127</td>
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Table 2 — Range of tensile capacity design parameter used in ANN

<table>
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<th>Parameters</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
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<tr>
<td>d (in/mm)</td>
<td>(0.031/8)</td>
<td>(1.00/25.4)</td>
<td>(0.62/15.68)</td>
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<tr>
<td>d_e (in/mm)</td>
<td>(0.36/9.2)</td>
<td>(1.30/32.92)</td>
<td>(0.77/19.54)</td>
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<tr>
<td>h_eff (in/mm)</td>
<td>(3.15/80)</td>
<td>(14.57/370)</td>
<td>(6.04/153.35)</td>
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<td>f_c (psi/MPa)</td>
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<td>(11748.05/81)</td>
<td>(4458.46/30.74)</td>
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<td>N_U (kip/kN)</td>
<td>(3.51/15.6)</td>
<td>(65.04/289.32)</td>
<td>(20.99/93.36)</td>
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<td>Adhesive Index (General)</td>
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<td>0.0317</td>
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<td>Vinylester</td>
<td>0.0234</td>
<td>0.0364</td>
<td>0.0332</td>
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</table>
Said and Robinson

Figure 1 — Typical failure modes of adhesive concrete anchors after Cook et al. [3]

Figure 2 — Architecture of the developed artificial neural network model
Figure 3 — Experimental versus Artificial Neural Network model of tensile adhesive anchor capacity
Figure 4 — Effect of anchor diameter on tensile adhesive anchor capacity
Figure 5 — Effect of anchor diameter on bond stress of adhesive anchors
Figure 6 — Effect of ratio of anchor diameter and borehole diameter on tensile adhesive anchor capacity (1 in/25.4 mm)
Figure 7 — Effect of ratio of anchor diameter and borehole diameter on tensile adhesive anchor capacity
(1/2 in/12 mm)
Figure 8 — Effect of embedment depth on tensile adhesive anchor capacity
Figure 9 — Effect of embedment depth on bond stress of adhesive anchors
Figure 10 — Effect of concrete strength on tensile adhesive anchor capacity
Synopsis: The best fire protection strategies for structural components are useless if connections lack the necessary fire resistance. Many current European Technical Approvals for anchors in concrete provide details on duration of fire resistance based on EOTA Technical Report 020 – Evaluation of Anchors in Concrete Concerning Resistance to Fire – published in 2004. This report delineates testing, evaluation and design requirements for anchors subject to fire exposure. It addresses post-installed mechanical anchors, adhesive anchors and plastic anchors and includes a simplified design approach that considers all relevant concrete failure modes as well as pull-out failure and the steel resistance.

The failure modes relevant for normal service conditions also apply under fire exposure. Nevertheless, as temperatures increase the yield point of steel drops significantly. Stainless steels exhibit superior resistance to elevated temperature over carbon steels; however, in general, the reduction in the steel strength is greater than that associated with concrete breakout or pull-out failure. Thus, in most cases, steel failure is the governing parameter in the design, although concrete failure may control in case of shallow embedment, anchor groups or close to the edge.

The simplified design method to determine the steel capacity under fire exposure provided by the EOTA Technical Report 020 and by the pre-standard CEN/TS 1992-4 ‘Design of fastenings for use in concrete’ yields often very conservative results. Therefore the leading brands in fastening technology perform fire tests according to the regime given in TR 020, which result in design values which are sometimes as much as three times as high as the values according to the simplified prediction.

Keywords: EOTA TR 020, post-installed anchors, resistance to fire, design
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INTRODUCTION

With the increasing use of post-installed anchors in structural engineering the subject of fire resistance has grown in relevance. Post-installed anchors installed in concrete are not only used to connect load bearing structural components but also attachments for non-structural components such as HVAC, suspended ceilings, electrical equipment, and piping systems. Some of these components, such as fire sprinkler piping, may be critical to the fire protection of the structure. The premature failure of other suspended components may pose a falling hazard to occupants and first responders and could block escape routes.

In the past, fire testing of anchors in Europe was performed on the basis of a knowledge base developed by testing laboratories, manufacturers of fastening systems, and structural engineers. In some cases the tests were application-specific. This yielded data which did not have a uniform basis for comparison and which did not include all relevant failure modes. This led to an effort to develop commonly accepted rules for the testing, evaluation and design of post-installed anchors for fire exposure.

EOTA Technical Report 020 – Evaluation of Anchors in Concrete Concerning Resistance to Fire, issued by the European Organization for Technical Approvals in 2004, delineates testing, evaluation and design requirements for anchors subjected to fire conditions. TR 020, which serves as the basis for issuing European Technical Approvals for anchors that include fire resistance information, addresses post-installed mechanical anchors, adhesive anchors and plastic anchors and includes a simplified design approach that considers all relevant concrete failure modes as well as the steel resistance.

This paper focuses on the testing, evaluation and design of adhesive anchors as addressed by TR 020 and discusses current experience associated with the implementation and use of this standard. The discussion also includes the pre-standard CEN/TS 1992-4 Design of fastenings for use in concrete published in 2009 as part of the Eurocode 2 series. It is anticipated that the approach contained in this document for the design of anchors exposed to fire will replace the design provisions of TR 020 in the near future.

GENERAL

The load-bearing capacity of post-installed mechanical (expansion, undercut) anchors in concrete at service temperature is well documented. In Europe, over 400 European Technical Approvals based on European Technical Approval Guidelines (ETAGs) for anchors have been issued to date. In the U.S., numerous evaluation reports have been issued for mechanical and adhesive anchors based on qualification procedures developed around ACI 355.2 – Qualification of Post-installed Mechanical Anchors in Concrete. In Europe, design of anchors in concrete is regulated by ETAG 001, Annex C or the pre-standard CEN/TS 1992-4. In the U.S. the design of anchors in concrete is addressed by ACI 318 Appendix D. The European and U.S. approaches to the qualification and design of anchors in concrete are harmonized to a large degree.
On the other hand, the knowledge base for the assessment of anchors for fire exposure exists primarily in Europe and is summarized in TR 020.

Prior to the release of TR 020, numerous fire tests on anchors, typically commissioned by the larger anchor manufacturers, were conducted by laboratories in Europe. However, the tests were conducted under conditions that did not allow for a common and reproducible assessment of the test results.

Reick (2001) collected and evaluated the results of fire tests with post-installed anchors. The tests had been conducted by various manufacturers in various laboratories using different test set-ups. For his investigations he used test results based on the standard fire time-temperature curve of ISO 834 (Fig. 1). This curve, which is intended to simulate burning timber, is nearly identical to that contained in ASTM E119, and is also the basis for tests in TR 020. In other applications such as the petrochemical industry, the time-temperature curve is steeper since the fuel of the fire (hydrocarbon instead of wood) burns faster. Where these special conditions apply other curves, such as the UL 1709 hydrocarbon curve, are used. Special time-temperature curves have also been developed for tunnel fires based on the experience from the Mont Blanc and Gotthard tunnel fires.

![Figure 1 – Standard time-temperature curves](image)

Reick’s investigations demonstrated that the fastening assembly used in the test, that is the thickness and geometry of the fixture used to secure the dead weight to the anchor in the burn chamber, significantly influences the temperature field in the vicinity of the anchor. As a consequence, the geometry of the fixture for fire testing is carefully defined in TR 020.

The tests also indicated that the same failure mode types as occur in testing at service temperature are observed in testing under fire exposure. These failure modes are assessed in TR 020 in a manner similar to the assessment made under ETAG 001 for applications under service temperatures. These same failure modes must also be verified in the new pre-standard CEN/TS 1992-4.
FAILURE MODES OF ANCHORS OBSERVED IN FIRE EXPOSURE TESTS

In fire exposure tests with anchors the following failure modes occur:

Steel failure: The strength of steel decreases significantly with rising temperature. Failure is characterized by rupture of the anchor rod or stripping of the threads. The capacity depends on the duration of the fire, the type of steel and the diameter of the anchor. Stainless steels have a longer resistance to fire than zinc-plated carbon steels (Fig. 2). For the same steel stress, anchors with smaller diameters fail sooner than anchors with large diameters (Fig. 3).

Concrete failure: The different coefficients of expansion of the concrete components (aggregate, cement paste, etc.) and the higher temperature gradients between the fire-exposed surface and the lower lying layers cause thermal tension. In addition, free water bound physically in the concrete vaporizes and generates additional concrete stress often resulting in surface spalling. (This effect can be minimized if the concrete component is designed according to EN 1992-1-2 (2005). The concrete should be produced with quartzite additives and the concrete member must be protected from direct moisture exposure.) The design assumptions for evaluating concrete breakout failure otherwise apply.

Pull-out failure: The pull-out failure of expansion-type anchors is determined by the combination of materials used for the anchor in the anchorage zone, the coatings on the cone and the expansion sleeve and its geometry. Therefore the pull-out capacity of post-installed anchors under fire exposure cannot be assessed by calculation and should be determined by testing.

Figure 2 – Stress of carbon and stainless steel (M6 (1/4") to M16 (5/8")) at failure as a function of time until failure (Reick (2001))
Understanding Adhesive Anchors: Behavior, Materials, Installation, Design

**Figure 3 - Stress of galvanised carbon steel at failure as a function of time until failure for anchors M6 (1/4") to M16 (5/8") (Reick (2001))**

EOTA TECHNICAL REPORT 020 (TR 020)

TR 020 contains all steps necessary for the evaluation and assessment of post-installed anchors installed in commercial/residential structures and in normal weight concretes C20/25 to C50/60 ($f'_c = 2,900$ psi to 7,250 psi) used in applications subjected to fire exposure. The determination of the fire resistance rating is performed according to the conditions stated in EN 1363-1: 1999-10, which establishes permissible design loads for various durations of fire exposure. For example, if a post-installed anchor has an R90 designation, the anchor has documented evidence of its ability to withstand the given load for a duration of 90 minutes under consideration of the condition of the base material, the anchor, the attachment and the fire exposure type (i.e., the relevant time-temperature curve used for the testing). Any positive influence of the attachment on the fire resistance is conservatively neglected. It is presumed that the reinforced concrete serving as base material for the anchor has at least the same duration of fire resistance as the anchor.

TR 020 is valid for post-installed anchors under the following conditions:

- Post-installed anchors must have met the requirements of ETAG 001 for use in cracked and non-cracked concrete. Anchors with an approval (ETA) for use in uncracked concrete alone are not covered.
- Adhesive anchors must be tested under fire conditions to determine their resistance associated with pull-out failure.
- The test program assumes that fire exposure occurs from one side only. If the exposure is from multiple sides, as may occur at a corner condition, the design method applies only if the edge distance of the anchor is at least equal to the greater of 300mm (12 in.) or twice the anchor embedment depth.

The evaluation is valid for anchors that are otherwise unprotected against fire exposure.
Design concepts

EOTA TR 020 assumes that the fire resistance of the fixture is adequate. At the ultimate limit state of the anchor under fire exposure it shall be shown that

\[ E_{d,fi} \leq R_{d,fi} \]

where

- \( E_{d,fi} \) design value of action to be resisted under fire exposure
- \( R_{d,fi} \) design value of resistance corresponding to fire exposure

The actions are given by

\[ E_{d,fi} = E_{k,fi} \cdot \gamma_{F,fi} \]

where

- \( E_{k,fi} \) characteristic value of actions to be resisted under fire exposure
- \( \gamma_{F,fi} \) partial (safety) factor for actions during fire exposure

The resistance is given by

\[ R_{d,fi} = R_{k,fi} / \gamma_{M,fi} \]

where

- \( R_{k,fi} \) characteristic value of resistance corresponding to fire exposure
- \( \gamma_{M,fi} \) partial (safety) factor for resistance corresponding to fire exposure

The values for the partial factors depend on the European country and are determined by national regulation. In general, the values of \( \gamma_{F,fi} = 1.0 \) and \( \gamma_{M,fi} = 1.0 \) are set to unity.

TR 020 permits the use of two different design concepts with regard to \( R_{k,fi} \); a simplified approach and a more detailed procedure based on experimental assessment of the relevant product. In both design concepts the capacity is verified for all loading directions (tension, shear, combined tension and shear) as well as all failure modes.

In the case of the simplified design approach, the verification of the capacity is performed using default characteristic resistance values conservatively established on the basis of test series with different types of post-installed mechanical anchors under fire exposure. Separate fire tests with the mechanical anchor in question are not required if this simplified approach is used in the design.

The characteristic steel resistance of an anchor under fire exposure (characteristic tension strength \( \sigma_{Rk,s,fi} \)) is given in Table 1 for carbon steel and Table 2 for stainless steel. These values are valid under tension and shear loading since limited number of tests have indicated, that the ratio of shear strength to tensile strength increases to approximately 1.0 under fire conditions, in contrast to the behavior at service temperature levels where the ratio is on the order of 0.6. For fire exposures up to 90 minutes the strength of post-installed anchors associated with the failure modes concrete breakout and in the case of post-installed mechanical anchors also pull-out (for all loading directions) is calculated as one quarter of the strength determined according to the relevant ETA for use in cracked concrete C20/25 at normal temperature under service conditions; for fire exposure up to 120 minutes the reduction is one fifth. Concrete breakout resistance is similarly calculated as a percentage of the resistance of normal temperature but as a function of the embedment depth. The simplified design concept may also be used for adhesive anchors provided that the pull-out capacity has been experimentally determined using the test and evaluation criteria established in TR 020. This simplified design concept can also be found in the new pre-standard CEN/TS 1992-4.

Where less conservatism is desired, it is permitted to determine the capacity of post-installed mechanical and adhesive anchors by test. Whereas the concrete breakout capacity is calculated in the same manner as the simplified approach described earlier, the duration of the fire resistance for steel and pull-out failure modes at a particular load level is established in accordance with the rules given in TR 020, which prescribes the number of tests to be
performed with the smallest and average anchor size, materials, dimensions and geometry of the attachments to be used for the investigation of the relevant failure mode. Furthermore the rules for the reinforcement of the concrete slabs and the location of the post-installed anchors within the concrete slab are controlled. Verification of the test results is also required to ensure the reproducibility of the test results in other laboratories.

<table>
<thead>
<tr>
<th>anchor bolt/thread diameter</th>
<th>embedment depth $h_{ef}$</th>
<th>characteristic tension strength $\sigma_{Rk,s,fi}$ of an unprotected fastener made of carbon steel in case of fire exposure in the time up to:</th>
<th>30 min (R 15 to R30)</th>
<th>60 min (R45 and R60)</th>
<th>90 min (R90)</th>
<th>120 min ($\leq$ R120)</th>
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<td>$\geq 1\frac{1}{8}$ (30)</td>
<td>1450 (10)</td>
<td>1300 (9)</td>
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<td>1150 (8)</td>
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<td>$\geq 2$ (50)</td>
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<td>2175 (15)</td>
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Table 2 — Characteristic tension strength of a stainless steel fastener under fire exposure

<table>
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<th>anchor bolt/thread diameter</th>
<th>embedment depth $h_{ef}$</th>
<th>characteristic tension strength $\sigma_{Rk,s,fi}$ of an unprotected fastener made of stainless steel in case of fire exposure in the time up to:</th>
<th>30 min (R 15 to R30)</th>
<th>60 min (R45 and R60)</th>
<th>90 min (R90)</th>
<th>120 min ($\leq$ R120)</th>
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<tr>
<td>1/4 (6)</td>
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<td>1000 (7)</td>
<td>725 (5)</td>
<td></td>
</tr>
<tr>
<td>5/16 (8)</td>
<td>$\geq 1\frac{1}{8}$ (30)</td>
<td>2900 (20)</td>
<td>2300 (16)</td>
<td>1750 (12)</td>
<td>1450 (10)</td>
<td></td>
</tr>
<tr>
<td>3/8 (10)</td>
<td>$\geq 1\frac{1}{2}$ (40)</td>
<td>3625 (25)</td>
<td>2900 (20)</td>
<td>2300 (16)</td>
<td>2030 (14)</td>
<td></td>
</tr>
<tr>
<td>1/2 (12) and greater</td>
<td>$\geq 2$ (50)</td>
<td>4350 (30)</td>
<td>3625 (25)</td>
<td>2900 (20)</td>
<td>2300 (16)</td>
<td></td>
</tr>
</tbody>
</table>

Experience with the design concepts

The simplified design approach is practical only for cases where relatively minor load bearing capacities under fire exposure are sought. In practice these capacities are often inadequate, and many manufacturers perform fire tests to utilize the full capacity potential of their products. In most cases the governing failure mode in case of mechanical anchors is steel failure, and the tests for the determination of the fire resistance associated with steel failure under tensile loading are alone sufficient to justify considerably higher values compared to the simplified concept since the calculated capacities associated with the other applicable failure modes (pull-out and concrete breakout) determined via the simplified concept are sufficiently high. Depending on the product, the steel capacity under fire exposure resulting from tests can be 2 to 3 times as high as the capacities dictated by the simplified concept. Therefore anchor manufacturers who perform fire tests according to TR 020 have product results which are sometimes at least twice as high as the value compared to the simplified prediction.
Summary and conclusions

With the publication of the EOTA TR 020, a guideline is available which allows for the consistent assessment of post-installed metal anchors for exposure to fire and the implementation of data for anchors in European Technical Approvals with regard to their fire resistance. While it is permitted to conservatively predict the capacity of post-installed anchors under fire exposure with the simplified design method, for cases where higher capacities are required product-specific design based on assessment by test is permitted as well.

REFERENCES

ACI 318 (2008), *Building Code Requirements for Structural Concrete and Commentary*. American Concrete Institute, Farmington Hills.

ACI 355.2 (2007), *Qualification of Post-Installed Mechanical Anchors in Concrete and Commentary*. American Concrete Institute, Farmington Hills.


