Connections between Steel and Concrete

Volume One

Connections between Steel and Concrete

Volume One

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Preface

Anchorage by fasteners and composite structures of steel and concrete have seen dramatic progress in research, technology and application over the past decades. The understanding of the fundamental principles underlying both disciplines has significantly improved. Concurrently, there has been rapid growth in the development of sophisticated new products and the establishment of international directives and codes to ensure their safe and economical use in a wide range of engineered structures.

Although they deal with very similar problems, the two disciplines have developed independently from each other. To optimize the use of composite structures and fastenings to concrete, however, it is necessary to have knowledge of both: the local behavior of the fastening system and the global behavior of the structure. It became apparent that a forum offering the opportunity to expand and to exchange experience in the field of connecting steel and concrete would benefit all involved. Furthermore this forum would aid in the rapid dissemination of new ideas, technologies and solutions as well as explore new areas of research.

To meet these objectives after the big success of the first symposium on 'Connections between Steel and Concrete' in Stuttgart, Germany the 2nd Symposium was conducted from September 4th to 7th, 2007 organized under the auspices of fib, the International Federation for Structural Concrete and the Universität Stuttgart. The event was cosponsored by the American Concrete Institute (ACI) and the Structural Engineering Institute (SEI). Experts from all facets of the research, design, construction and anchor manufacturing community from around the world were invited to present papers covering the topics of testing, behavior and design, durability, exceptional applications, strengthening and structures as well as related topics.

Regrettably, due to the limitation on the number of papers, dictated by the time frame of the Symposium, not all worthy papers proposed for presentation could be considered. In total 129 papers were accepted by the Scientific Committee. They are gathered in these proceedings. We hope this volume will significantly contribute to knowledge in the field of connecting steel and concrete, related design methods, code specifications and new applications.

We wish to thank the authors for their excellent contributions and the members of the Scientific Committee for the useful technical advice. Furthermore we would like to express our thanks to Mrs. Silvia Choynacki for her essential assistance in the local organization of the symposium.

Rolf Eligehausen, Werner Fuchs, Giovacchino Genesio, Philipp Grosser
Stuttgart, September 2007

Part One

Keynote Lectures

RECENT DEVELOPMENTS IN COMPOSITE STRUCTURES

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Abstract

Composite structures combine the advantages of both materials concrete and steel. Developments in the recent years show a tendency to optimise design and construction of composite constructions by an increasingly flexible use of structural forms and techniques. An overview over some innovative trends is given. As a consequence of that tendency, the borderline between building and bridges as well as the difference between girders, slabs and other structural elements start to diminish which demands of the engineers a broad knowledge and a holistic conceptual view.

1. Introduction

Composite constructions combine the high-strength performance of structural steel with the stiffness and compressive strength of concrete. As each material can be used to its best advantage, composite structures show economy in overall cost and are fast to construct. For these reasons they have become increasingly popular.

As composite structures also show an increasing variety, it is nearly impossible to give a complete overview. In the following some specific topics showing especially innovative developments will be addressed such as

- composite girders and slim-floor girders,
- composite slabs,
- composite columns,
- composite joints and frames,
- composite bridges,

On the basis of these examples the attempt will be made to highlight also some general tendencies and chances of composite structures in the future.

2. Composite Girders and Slim-floor Girders

2.1 General

The composite constructions have achieved a high market share, especially in the UK and the Scandinavian countries. The reasons therefore can be found in the developments of composite girder constructions and the effort to raise the efficiency of these constructions.

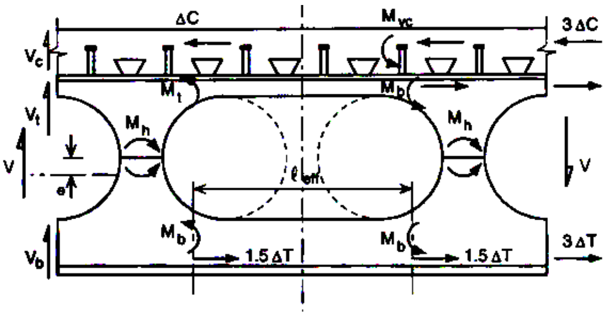
The following examples will give an overview of some current and new research fields on composite girders.

2.2 Cellular beams

Cellular beams offer aesthetical appearance advantages as visible steel structures but also the possibility to pass service integrations through the openings, which helps to minimize the storey height.

The design of composite cellular beams is influenced by asymmetry of the cross section, which causes additional bending moments (see Figure 1) between the closely placed openings. In addition, due to the Vierendeel mechanism, web-posts buckling problems [1], [2] exist.

So far, there are no design recommendations for composite beams with web openings. Therefore, several research projects with composite cellular girders tests were executed [1], [2], [3] with objectives like composite action close to support, behaviour of elongated openings, asymmetric design and stiffening of web opening.



(a) Forces at an elongated opening

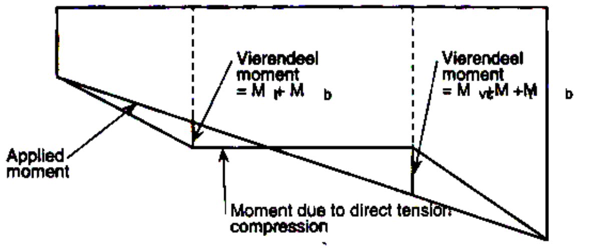


Fig. 1: Vierendeel bending at elongated openings [2]

In these research projects design methods for the web-post buckling are presented which are based on a series of girder tests and Finite Element Analyses.

2.3 Composite slim-floor beams with precast concrete slabs

Slim-floor girders form a modification of a composite girder with reduced height. It is a flat slab system with an in the slab integrated steel girder [4].

Precast concrete floors (see Figure 2) - as one type of a composite slim-floor beam - are widely used in building constructions. Traditionally, the steel beams have been designed to support the precast slab, the structural interaction with the steel frame is still often neglected [5].

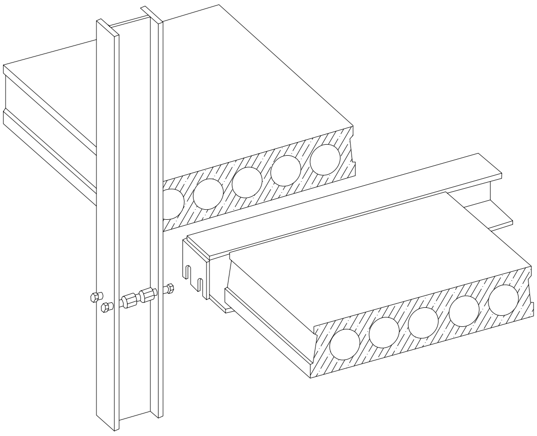


Fig. 2: Steel girder with precast slab

However, a composite action can be developed by welded shear connectors and transverse reinforcement. This significance is at the moment outside the provisions of the current codes of practice. To consider the composite action, some tests were executed in the UK [5] and Finland [6]. The experimental results showed composite action between the steel beams and the hollow core units. The experiments further showed that it is necessary to set some transverse reinforcement into the hollow cores to enlarge the composite action between the precast slab and the steel girder.

2.4 Slim-floor beams used as composite girders

A slim-floor girder with a planned composite action was developed by the Institute of Structural Design together with Salzgitter AG. The composite girder consists of a steel hat profile (see Figure 3) and a concrete slab. Due to the shallow steel section studs can be easily placed for the composite action. Further the transverse reinforcement allows taking the advantage of a continuing action of the concrete slab in transverse direction to the composite girder.

Fig. 3: Test with a slim-floor girder

Girder tests showed that the assumed effective width according to current codes is underestimated so that the deformation (determining the composite section) is overestimated and may lead to inefficient composite sections [7], [8]. Therefore, a research project was executed and a deformation-based effective width was developed.

In general, these composite slim-floor beams offer a high bearing capacity due to their shallow steel girder section. For the construction and the design of the beam an approval [9] has been introduced and for the design of the joints a construction book [10] has been developed, that offers different solutions for the construction of the joints.

A similar section was investigated in [11] using concrete dowels instead of studs for the composite action.

2.5 Comfort and vibration of slim-floor slabs

For high-rise buildings the deck floor height plays an important role for the total number of storeys and thus for the efficiency [12]. For these slim-floor slabs the characteristics of the design for the ultimate limit state and the serviceability have to be considered, especially for the deformation of the slab and the comfort and vibration conditions.

Therefore, several slim-floor slabs have been tested [12] to investigate the serviceability properties, especially the vibration behaviour due to human activities. As these slabs are light-weight structures with long spans, they have low natural frequencies and react very sensitively to dynamic loads. The experimental test frequency of a composite deck system spanning up to 9.5 m is shown in Figure 4. The composite deck shows satisfying results for most types of walking. The real support conditions and the additional damping (e.g. due to friction, partition walls and screed) were neglected in the tests, so that the results are assumed to be conservative regarding the real behaviour concerning comfort and vibrations. Beside the technical investigations the cost-efficiency was also compared for these deck slab systems [12].

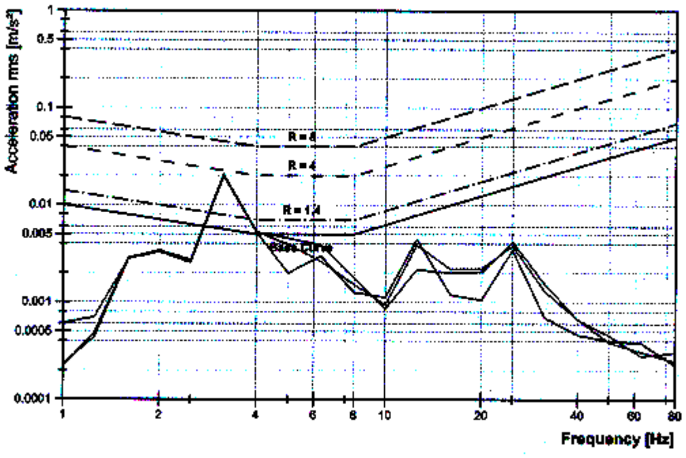


Fig. 4: Frequency - walking of one person [12]

3. Composite Slabs

3.1 General

New developments and research projects show that the potential of composite construction especially of composite slabs are not yet fully applied. Due to this fact this section will give a short overview about some new interesting research results.

3.2 Ultra long spans using composite slabs

Composite slabs have different advantages in comparison to solid slabs.

A good example for the advantages of composite slabs is the Hoesch Additive Floor System shown in Figure 5. The chosen trapezoidal sheet allows to span up to 5.80 m during the concrete placing phase. Further advantages are for example the low weight, the rapid mounting and that no further cost-intensive equipment such us a crane is required during the construction.

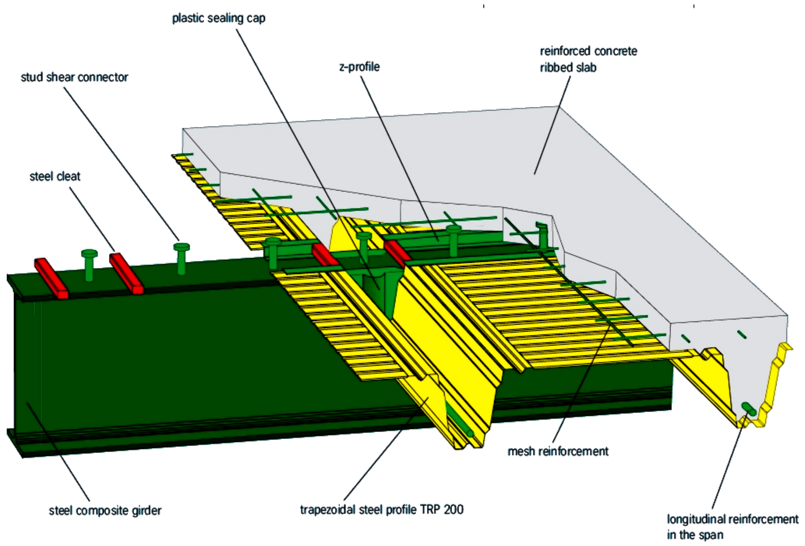


Fig. 5: Hoesch Additiv Floor System in [17]

A further interesting idea is to compose a hybrid decking from a number of modular elements so that it takes on optimal shapes, thickness, steel grades and coatings. In [14] an example of a long spanning, hybrid decking for composite slab construction has been presented.

3.3 Resistance of headed studs in composite beams incorporating profiled steel sheeting

In EN 1994-1-1 [13] the carrying capacity of headed studs in composite beams with profiled steel sheeting is determined by multiplying the shear resistance of headed studs in composite beams with solid slabs with a reduction factor k, although for headed studs used in profiled steel sheets different failure modes may occur [15].

So, the application of headed studs in trapezoidal profiled sheeting laid transverse to the longitudinal axis of the steel beam may exhibit unwanted brittle failure modes with low stud strength and poor ductility [16].

In that case, additional waveform reinforcement can be used to prevent this special kind of shear failure in the concrete flange over the top of the sheeting ribs ([16], cf. Fig. 6-7).

Fig. 6: Rib-shearing failure [16]

Fig. 7: Pull-Out failure [16]

The comparison and re-assessment of about 120 experimental results in [18] shows that the calculated mean resistance (see EN 1994-1-1 [13]) overestimates the test results and confirmed the results in [16]. Based on results in [18], a new research project including experimental tests and numerical simulations supported by the “Deutsches Institut für Bautechnik” is currently in progress.

4. Composite Columns

4.1 General

With EN1994-1-1 [13] the simplified design of composite columns was changed using second order analysis and equivalent initial bow imperfections taking into account the effects of residual stresses and geometrical imperfections. Therefore, the simplified method can be extended to sway frames, where the design of the column can be carried out together with the analysis of the whole system. Beside this change some more interesting new developments may be noticed.

4.2 Composite columns with additional steel core

Especially for high rise and multi-storey buildings in spite of high load transfer slender constructions with small profiles get more and more popular. Therefore, special concrete filled circular or rectangular hollow sections with additional steel core sections are used, see Fig. 8, [19], [20]. The possibility of filigree constructions, the smooth sections ready for painting, the fire resistance without any further protection of the section and the ability of fast construction period are some advantages of this construction. Special constructions for load introduction into the column like steel collars extend the economic efficiency of those columns.

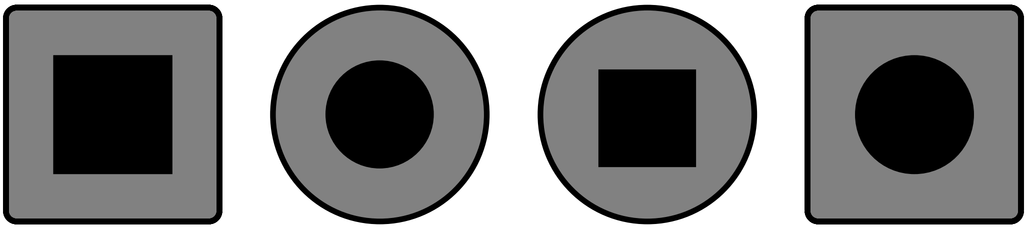


Fig. 8: Composite column sections with steel core

When using massive steel core sections other problems arise. The high residual stresses due to the cooling process after rolling and also nonlinear distribution of strengths over the core section have to be considered. In addition, the influence of the strain gradient α_M and the strain limitations are very important aspects. The design of these sections with residual stresses is not covered by the simplified design methods for composite columns in EN1994-1-1 [13]. So the capacity of these columns have to be determined using a more general method e.g. by FEM. As a result the residual stresses may lead to a buckling curve even lower than European buckling curve *d* [19]. Until now a general concept for the determination of the bearing capacity by a simplified method does not exist.

4.3 Load introduction in composite columns

The application of slender composite columns requires practical solutions for load introduction.

Due to the small dimensions of slender composite columns, the verification of punching may be difficult. A possible solution is the application of special mounting parts that increase the punching resistance of the concrete slab. In Fig. 9 a possible solution is shown using a lying steel cross and headed studs for load introduction, see [22].

The advantages of concrete filled hollow sections lead to an increased application of these composite columns. Therefore, the load introduction has been optimized over the years. Typical joints for load introduction are shown in Fig. 10 considering partially loaded areas and reinforcement without direct connection to the end plate. New research results [21] show the effect of both confinement and partial loading.

Fig. 9: Steel composite construction for resisting punching shear developed by s+v [22]

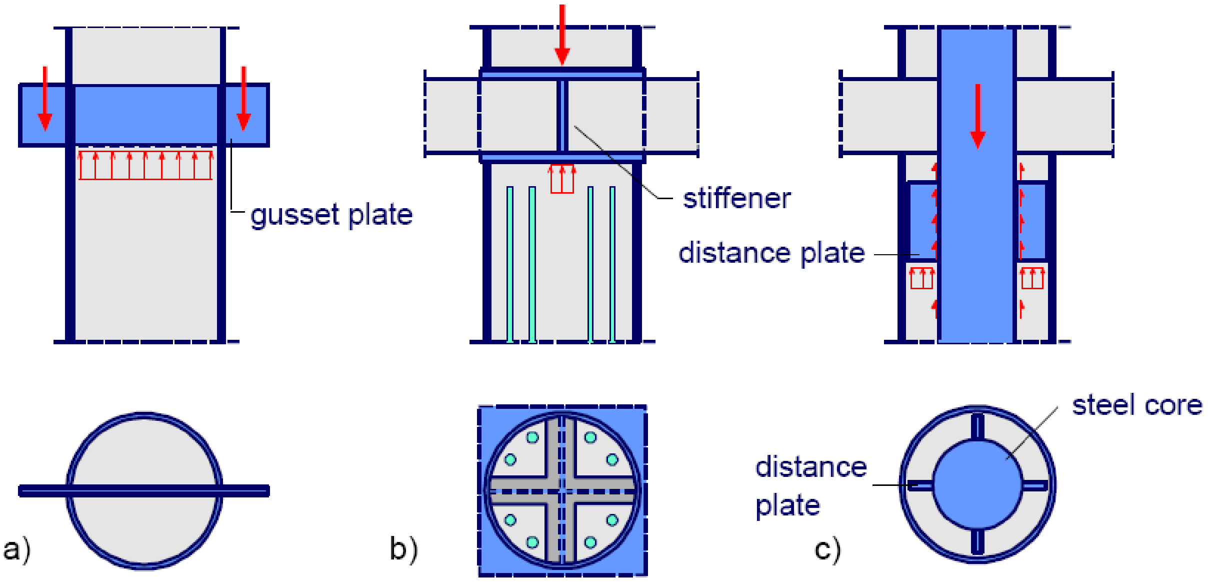


Fig. 10: Load introduction in concrete filled tubes with partially loaded areas and reinforcement without direct connection to the end plate [21]

5. Composite Joints and Composite Frames

5.1 General

Until now composite joints are for the most part designed as pinned or as continuous joints. A continuous joint requires stiffeners in the column and high degrees of reinforcement, whereas a pinned joint requires some minimum reinforcement for crack width control that, however, is not considered to provide any moment capacity. Optimised solutions are partial-strength and ductile joints that consider the moment resistance and that allow easy and cheap producible joints with small degrees of reinforcement and without stiffeners in the column. Using partial strength joints which are at the same time highly ductile, a redistribution of forces and moments within the structural system may be realised. Highly ductile composite joints allow the plastic design of composite frames, they also are very suitable to build redundant structures which are concurrently economical, and they are as well applicable for seismic design because of their capability to dissipate energy [25].

5.2 Specific features of partial strength and high ductile composite joints

The composite joints must have the ability to undergo large rotations and to change the internal load combination from pure bending state to a combined bending and tension exposure. Only that way membrane forces can be activated allowing a redistribution of internal forces. Thus, an adaptive structure is created which keeps sufficient strength even under exceptional loading and large deformations. However, to achieve this high ductility all single relevant components have to be chosen such that a high local deformation may be followed. For the rotational capacity of a joint the deformability of the yielding components is of crucial importance. One possibility is to design the joint in order to provoke the failure of a ductile component, e. g. by increasing the reinforcement so that the column web in compression yields instead of the reinforcement. On the other side, a higher rotational capacity of the joint can be achieved by increasing the ductility of the yielding component (e. g. using ductile reinforcement and providing a specific bolt arrangement), see the following examples:

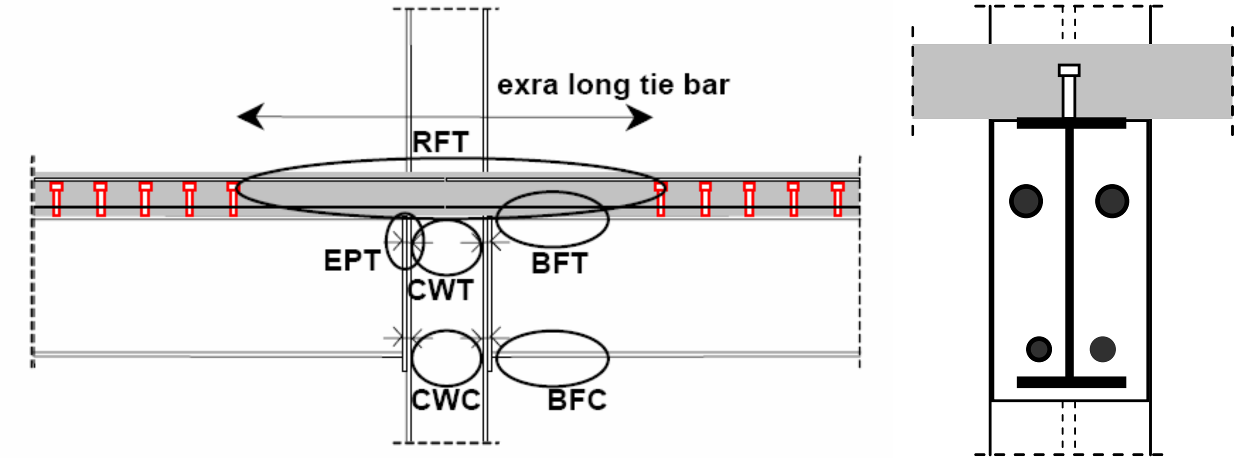


Fig. 11: Highly ductile composite joint solution with special bolt arrangement [23]

The crucial point by designing highly ductile joints with sufficient bearing capacity is to arrange the tension components in such a way that the weakest components are always ductile enough to follow a high local deformation. It is also important to have more than one ductile component to compensate over-strength effects which could lead to a totally different joint behaviour as initially planned.

5.3 Experimental investigations

The tests results of composite joint tests [23], [24] have shown that it is possible to create highly ductile semi-rigid composite joints with rotational capacities larger than 60 mrad, see Fig. 12. In a current RFCS-Research project -Robustness- [26] the tests on highly ductile composite joint solutions mainly investigate the behaviour of the joints under combined loading. Special focus is given to the load path. First test results of the composite joint tests as well as the substructure test showed the ability of the composite joints to undergo large rotations and to change the internal load combination from pure bending state to a combined bending and tension exposure. Failure was mainly induced by the concrete slab: for the hogging moment joints by increased cracks and final rupture of the reinforcement, for the sagging moment joints by crushing of the concrete and decreasing of the concrete compression zone. However, also the steel joint components decisively contribute to the rotation capacity by bending of the endplate and column flange, tension of the column web or buckling of the column web under compression. In addition, a remarkable resistance and ductility were left when the concrete slab had already failed. The tests even showed that the pure steel joints allowed a further increase of the joint rotation and resulting of this the membrane forces within the structure could be further increased [27].

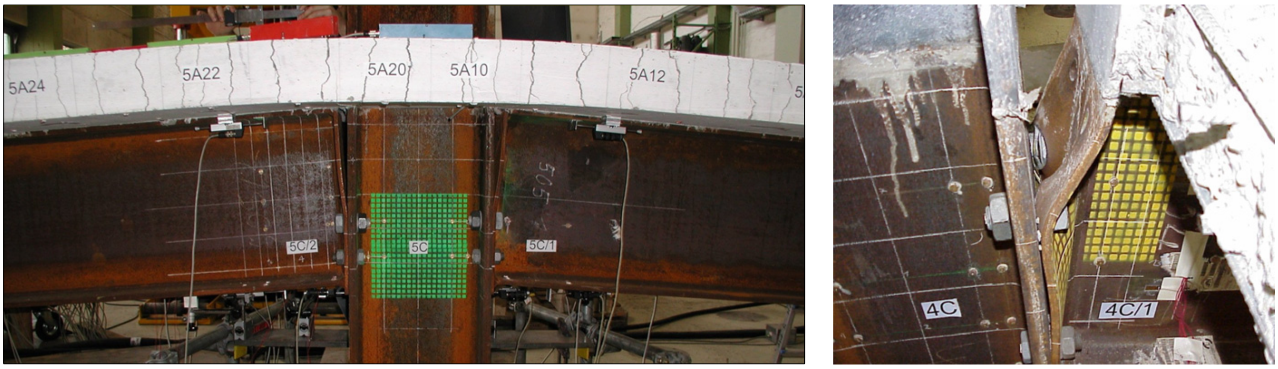


Fig. 12: Composite joint tests [23]

5.4 Composite sway-frames

The required rotation capacity is especially high for sway-frames due to their relatively high deformations. Therefore, the above mentioned highly ductile composite joint solutions are well suitable to ensure the ductility required in semi-rigid joints of composite sway-frames.

The moment resistance of partial strength joints in sway-frames is sufficient to create a moment resisting frame which is able to accept the horizontal loads. Thus, a flexible utilisation of the building is possible and interfering bracings may be avoided.

This has been proved by detailed calculations of Schäfer [24] and also confirmed by tests performed at the Ruhr-Universität Bochum within the European research project, ECSC 7210-pr-250 ”Applicability of composite structures to sway frames” [28], [29], see Fig. 13.

In a second European research project, ECOLEADER HPR-CT-1999-00059 “Cyclic and PsD testing of a 3D steel-concrete composite structure” [30] a steel building was designed and subjected to pseudo-dynamic and cyclic tests in the European Laboratory for Safety Assessment of the Joint Research Centre (Ispra).

Fig. 13: Composite sway-frame test at *Ruhr-Universität Bochum* [29]

6. Composite Bridges

6.1 Concrete slabs in tension

In concrete slabs of composite structures often tension stresses are induced by normal forces, which are far larger than in mere reinforced concrete structures where high tension is generally prevented by prestressing. For example the non-prestressed deck slab in a bowstring arch bridge or the concrete slab above the internal support of a continuous beam are nearly completely cracked sometimes even under service loading. High ratios of longitudinal reinforcement effectively limit the crack widths in these zones. However, the local shear forces from plate action e.g. of concentrated traffic loads have to be transmitted across these cracks.

Slabs in (composite) bridges are generally not provided with stirrups or any other vertical reinforcement; this would be ineffective especially because of the large amount of longitudinal reinforcement. In Eurocode 2 [31] and in the German design code DIN 1045-1 [32] a design equation is used that has been derived in order to take into account the positive effect of the compression in prestressed members - using a minus sign for tension. Both codes imply a linear influence by the normal force. As an example the equation according to DIN 1045-1 [32] is given by

$$V_{Rd,ct} = [0.10 \cdot \kappa \cdot \eta_1 \ (100 \cdot \rho_l \cdot f_{ck})^{1/3} - 0.12\ \sigma_{cd}] + b_w \cdot d \qquad (1)$$

In contrast to compression forces for tension forces by the positive normal stresses σ_{cd} this results in lower shear resistances $V_{Rd,ct}$.

Investigations by Ehmann [33] show that this leads to conservative results. To get more realistic and economical design, he proposes two equations for the shear resistance under a simultaneous tension force. The first one considers the lower effect of a tension force by changing the factor 0.12 to 0.045, see equation (2).

$$V_{Rd,ct} = [0.10 \cdot \kappa \cdot \eta_1 \ (100 \cdot \rho_l \cdot f_{ck})^{1/3} - 0.045\ \sigma_{cd}] + b_w \cdot d \qquad (2)$$

The other possibility is to keep the factor 0.12 and to limit the maximum tension stress, see equation (3)

$$V_{Rd,ct} = [0.10 \cdot \kappa \cdot \eta_1 \; (100 \cdot \rho_l \cdot f_{ck})^{1/3} - 0.12\, \sigma_{cd}] + \; b_w \cdot d \qquad (3)$$

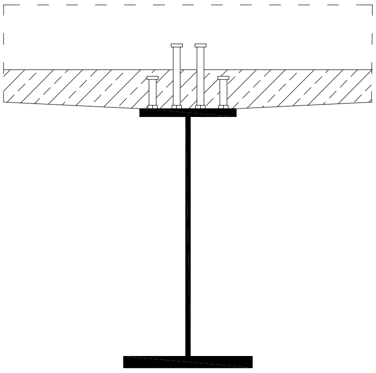
with $\sigma_{cd} = N_{Ed} / A_c \leq 1.85$ N/mm^2

Tests show that both equations lead to a safe shear design. The equations allow avoiding shear reinforcement which is expensive and difficult to put in place in a number of cases.

6.2 Prefabricated slabs

A possibility to reduce construction time is given by a high degree of prefabrication. Since a few years the VFT®-construction method is adopted successfully [34], [35]. The VFT®-girders consist of a steel beam with a partial precast concrete flange. As shear connectors headed studs are used typically, see Fig. 14. The concrete flange stabilizes the girder during transportation and while concreting the remaining part of the slab. It is used as formwork simultaneously. As this method of construction allows doing the whole work on the steel construction in the workshop under good conditions, the quality can be increased and no expensive steel work has to be done on the site.

A further advantage brings the renouncement of the top flange of the steel girder. As the semi-prefabricated concrete slab is stabilizing the system the top flange is not needed furthermore. In this case the steel web is embedded in the precast concrete. The shear connection can be done by concrete dowels for instance, see Fig. 15.



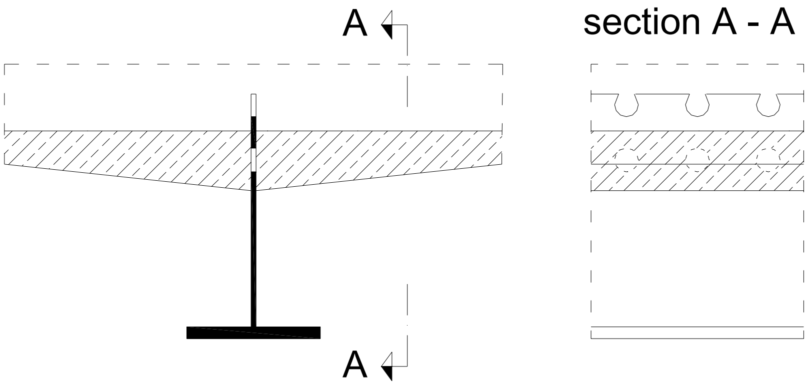


Fig. 14: VFT®-Girder

Fig. 15: VFT®-Girder with concrete dowels

Another promising alternative is to use horizontally lying headed studs as shear connector between the steel web and the concrete chord, see Fig. 16. The design rules in EN 1994-2 [36] and DIN 18800-5 [37] allow a reliable design for these studs close to the concrete surface. Fig. 17 shows the upper side of the precast girders of a bridge in Münsingen with horizontally lying headed studs.

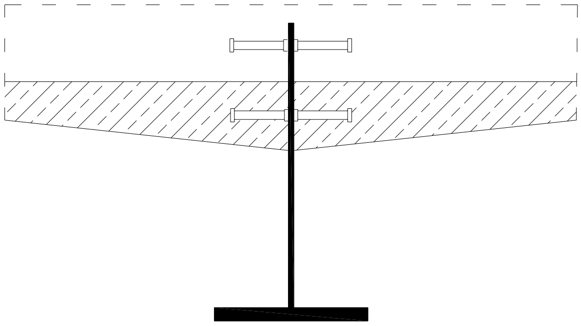


Fig. 16: Cross section with horizontally lying headed studs

Fig. 17: View on the upper side of prefabricated girders

6.3 Tubular composite bridges

There is an increasing amount of tubular composite bridges. An example is shown in Fig. 18. The nodes of the framework are key issues for the design and fabrication, see Fig. 19. A conventional construction method consists of brace-to-chord connections using gusset plates. A more contemporary method are directly welded joint of the tubular hollow sections, where the braces are cut to fit and welded to the continuous chord. Cast steel nodes offer a smooth transition between the brace and the chord members [38]. Fatigue strength of these nodes plays an important role.

Fig. 18: Korntal-Münchingen Bridge

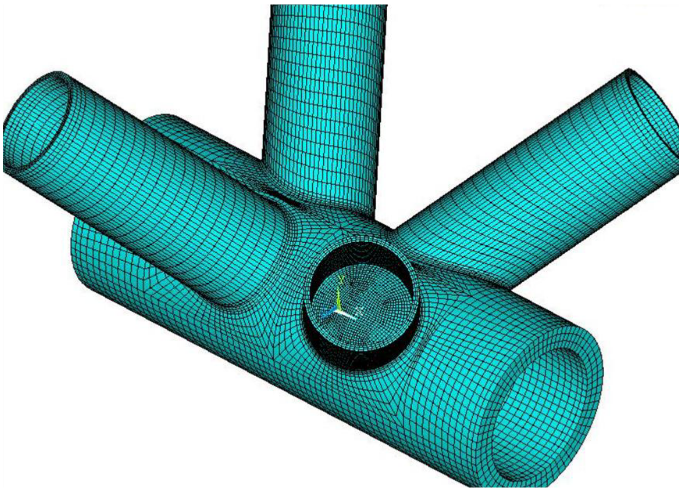


Fig. 19: Finite Element simulation of a joint

6.4 Design in view of sustainability and life-cycle assessment

Competitiveness of steel construction and, in particular, steel and composite bridges, requires a broader view that encompasses the concepts of sustainability and life-cycle assessment in parallel with the classical structural and geotechnical issues. Also, from the economical viewpoint, the progressive transfer of operational duties from the National Road Authorities to private companies in the context of design, build and operate contracts, reinforces the need for an integrated approach [40].

Environmental aspects like energy consumption, raw materials and environmental aspects as well as maintenance and degradation act as a part of sustainability. A view over the whole life-cycle comes to different findings than only to the construction period even if the analysis is only cost based.

A reduction of construction time leads to a diminishing of the traffic disability. This aspect is neglected in conventional cost analysis [41].

Rather than a comparison between the pure construction costs a life-cycle assessment disarranges the comparison often in favour of the composite solution.

7. Summary and Outlook

For the fields of composite buildings and bridges some innovative developments have been explained. On this basis the attempt was made to highlight also some general tendencies and chances of composite structures in the future. There is obviously a tendency to no longer only aim at safety and functionality but to fulfil also criteria of robustness in order to take care of unforeseen situations and in view of future. The aspects of sustainability start to play a new role.

Composite structures are especially qualified to satisfy modern basic requirements like
- Economy, functional ability
- robustness
- environmental and aesthetical needs and
- durability and sustainability.

This requires new concepts of mixed structures and a new thinking of engineers.

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RECENT DEVELOPMENTS AND OPEN PROBLEMS IN FASTENING TECHNIQUE

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Abstract

Anchorage by fasteners has seen dramatic progress in research, technology and application over the past years. The understanding of the fundamental principles of the load bearing-behavior of fasteners in different fields of applications has yielded a rapid growth in the development of sophisticated new products and the establishment of international directives and codes to ensure their safe and economical use in a wide range of engineered structures. In this paper the current status of research and future trends of modern fastening technology are described.

1. Introduction

The demand for more flexibility in the planning, design and retrofit of structures is as old as the construction industry itself. Fastening technology has always played an important role in meeting this demand. Consequently with the evolution of the hammer drilling-technique in addition to the traditional cast-in fastening technology with headed anchors and anchor channels more and more post-installed mechanical and chemical fastening devices are being used for the introduction of concentrated loads into buildings made of concrete and masonry. Fasteners such as single anchors grouted in masonry joints or cast-in wooden elements to allow for flexibility in the location of the fastening via wood screws as shown in Figure 1 have become obsolete.
Modern fastening systems solve a wide range of fastening tasks safely and economically and more and more special knowledge is developed in order to create optimal fastening solutions.

Over the past two decades increasing pressure to reduce the construction time of structures has yielded rapid developments in the field of fastening technology. This paper is intended to provide a small extract of the actual tendencies in fastening technology and to give information on open questions in research and practice.

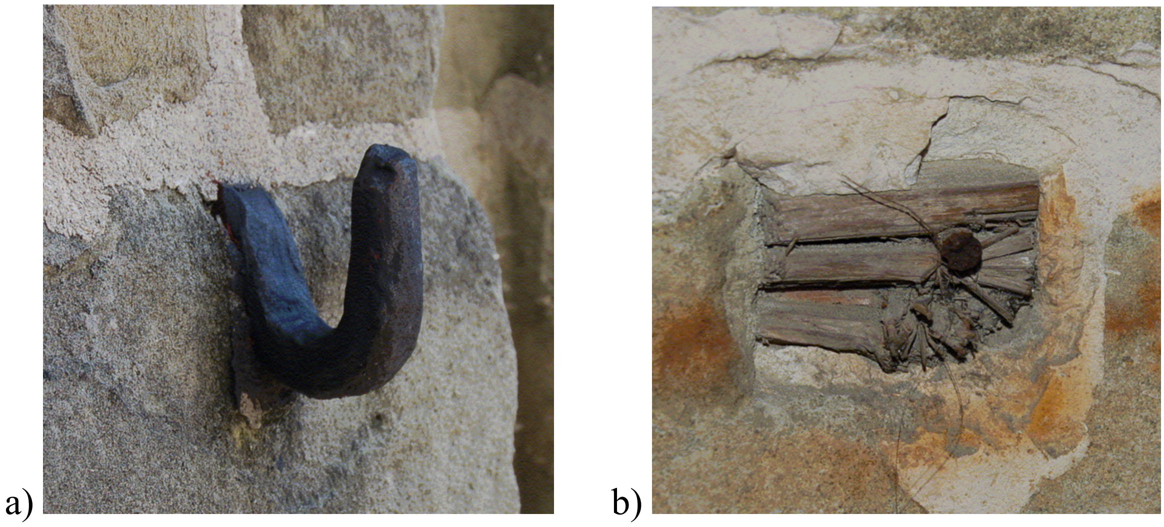


Fig. 1: Ancient anchorages: a) mortar anchor b) wooden screw board

2. Structural and nonstructural applications

Modern fastening systems are used in nearly all types of civil engineering constructions. When discussing fastenings and their fields of application it is useful to distinguish between structural and nonstructural applications (Fig. 2).

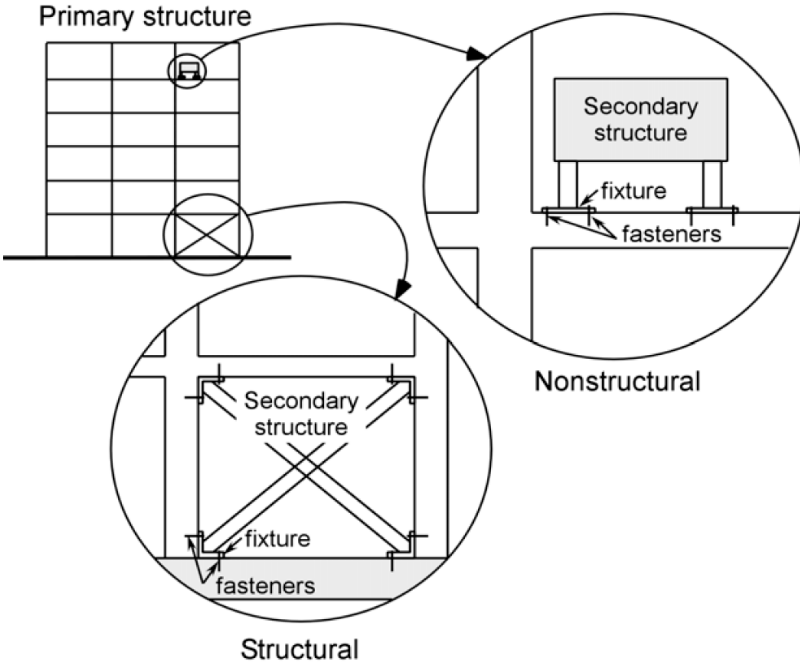


Fig. 2: Structural and nonstructural applications for fastenings, [15]

Nonstructural elements are architectural, mechanical or electrical elements, systems and components such as facades, suspended ceilings, pipes and machines etc. which are not considered to carry structural loads. Structural elements are members considered as part of the structural system that resists actions, modeled in the analysis for the relevant design situation according to the design codes.

This distinction is important since different loadings exist for the two types of applications and different factors of safety may need to be considered in the design of the fastening. Because the failure of a fastening may lead to an endangerment of human life or to major economic consequences, reliable fastenings are necessary.

To fulfill this requirement the fastening technology has significantly advanced by the implementation of research findings in international guidelines in the last years with high speed. This is demonstrated by the development of national and international systems of rules for the qualification, design and installation of fasteners.

3. Qualification and design of fasteners

To ensure reliable fastenings a good co-operation between producer, engineer and user is needed (Fig. 3). The producer has to supply efficient and well functioning fastening systems, the engineer must choose the optimal fastening system for the application in question and proof the adequate safety of the fastening by accurate design methods and the user has to ensure a correct installation of the fasteners.

The risk of failure of a fastener can be minimized if suitably qualified products are applied and designed using appropriate design provisions (Fig. 4). Design guidelines establish the boundary conditions that must be represented in qualification tests. Furthermore, most modern design methods for fasteners explicitly require characteristic resistance obtained from product qualification approvals.

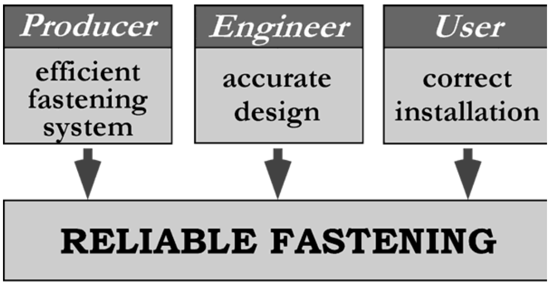


Fig. 3: Requirements to ensure reliable fastenings

To ensure proper function in the application in question pre-qualification testing of fasteners is necessary. During the last years, starting in 1997 test programs to check the suitability of anchors and to evaluate allowable conditions of use have been worked out in Europe by EOTA for headed fasteners, anchor channels, post-installed mechanical and chemical fasteners [1], redundant fastening systems [9], post-installed rebars [17] and anchorages in concrete concerning resistance to fire [14]. The fasteners that have passed the approval tests which are mainly performed by an independent testing institute receive a European Technical Approval (ETA) which is required for the use of fasteners in safety related applications. Furthermore the test results provide the basic values required for the design.

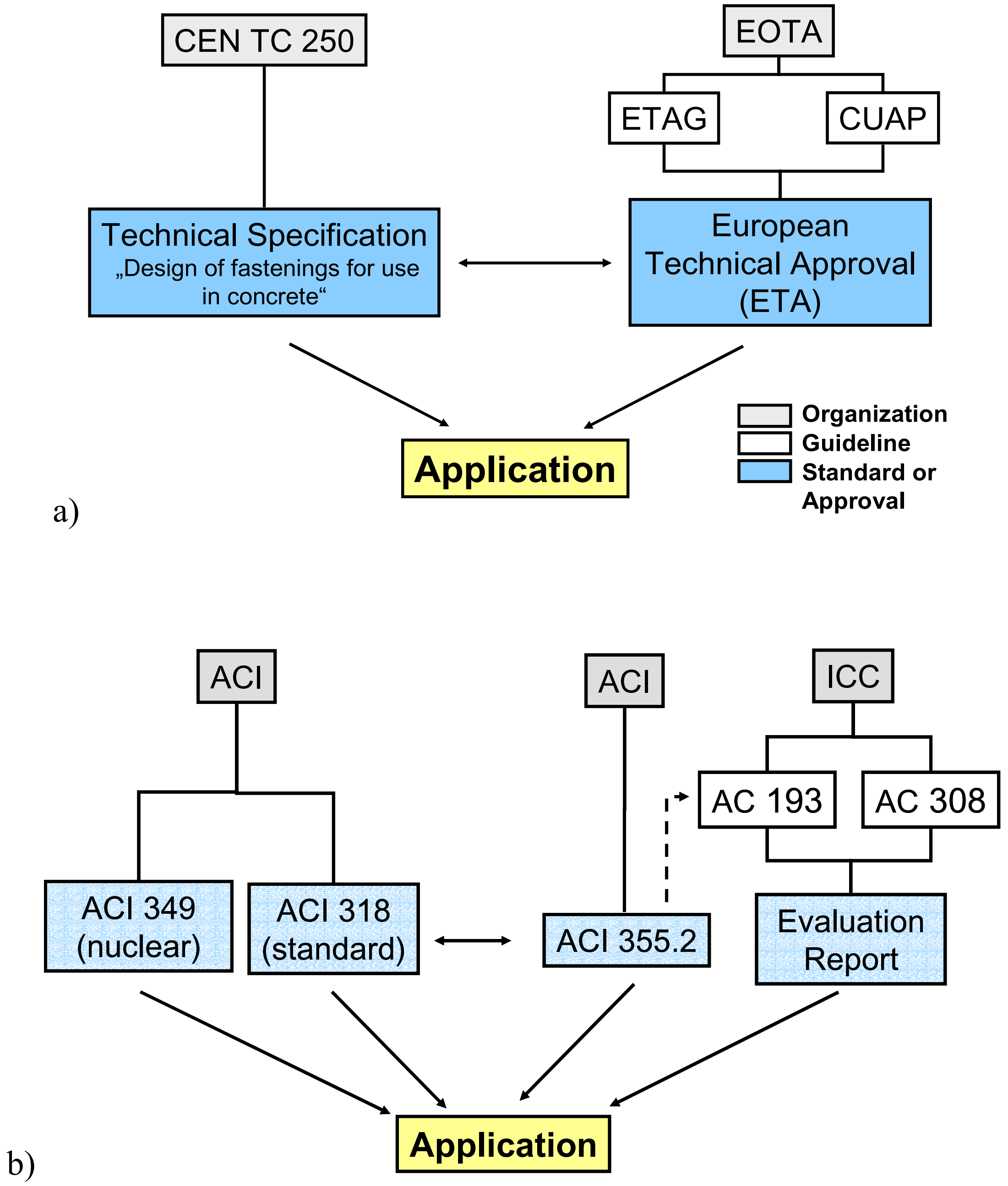


Fig. 4: Connection between design guideline and qualification testing in a) Europe and b) USA

Design guidelines that represent the current state of knowledge in Europe are given in ETAG, Annex C [1] and the CEN Technical Specification [2]. These design methods apply only to fasteners covered by an ETA which provides data relevant for the design.

In 2001 in the USA a modern test program evaluating the performance of post-installed mechanical anchors was reported by ACI 355 [4]. This ACI Standard was adopted and further improved by ICC and released as AC 193 [5]. Finally, in 2005 AC 308 for post-installed chemical anchors was released [6]. The test regimes and evaluation procedures in the USA follow the European testing and evaluation philosophy i.e. the test program and evaluation process are nearly identical. This is due to the fact that the design provisions in Europe and in the USA are based on the same principles. The current state of knowledge in the design of mechanical fasteners is given in ACI 318 [7] and for chemical fasteners in ICC AC 308 [6].

The fib Design Guideline [3] provides sophisticated design models which are the basis for the simplified models in [2, 6, 7]. The European guidelines, which regulate the qualification of fasteners, do not currently include testing guidelines or assessment criteria for seismic applications. Therefore, an extension to this guideline to cover this application will be developed in the next few years. This new qualification guideline should include test methods and performance assessment criteria that reflect the actual demands placed on fastenings during earthquakes. In the USA there exist already qualification tests for fasteners under seismic loading. However, it is under discussion, if they represent all necessary seismic conditions. Design guidelines that represent the current state of knowledge for seismic applications using fasteners are given in the fib Design Guideline [3], ACI 318 [7] and in the CEN Technical Specification [2].

4. Installation of fasteners

The best prequalification procedure and the most careful design, however, are of little use if the fastener, pre-qualified by an independent approval agency and specified by the designer, is not installed properly.

It goes without saying that connections for safety relevant applications should be carried out by properly trained and experienced installers. However, experience shows that fasteners are not always properly installed. A survey of German installers indicates that only 70% of the boreholes for post-installed chemical fasteners are cleaned [8]. Out of this 70% only about 50% of the boreholes are cleaned according to the manufacturer’s installation instructions by blowing and brushing (Fig. 5). This means that in Germany only about 35% of the bore holes of post-installed fasteners are produced properly. Depending on the bonded anchor system the bond resistance may be significantly reduced if the borehole is not cleaned properly.

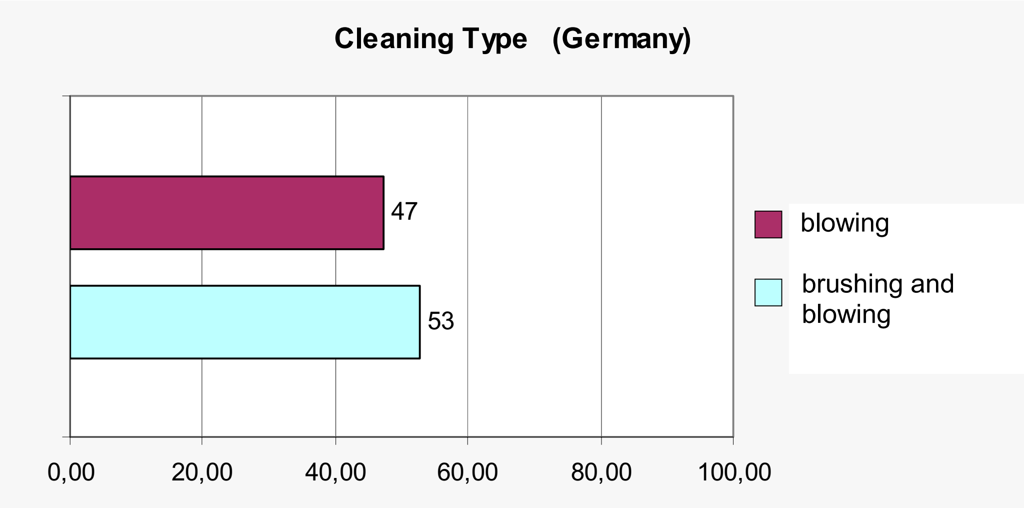


Fig. 5: Borehole cleaning for chemical anchor installation, [8]

Even in a nuclear power plant, where during installation strict surveillance should be applied, a significant part of post-installed undercut anchors were not installed correctly.

Suitable products, careful design and proper installation are vital for the overall performance of a structural connection. While suitable products are on the market and rational design models have been developed, 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. Very good experiences have been made in Germany with this approach e.g. for the post-installation of rebars. Another possibility is to impose proof loading on site after unclear installation.

5. Statically determinate and indeterminate applications

In the design of a fastening one should consider the statical system: statically determinate or indeterminate (redundant), the condition of the concrete: cracked or uncracked, and the function of the component to be fastened: structural or non-structural.

A system is statically determinate if its internal load distributions can be determined using equilibrium equations without the need for deflection and stiffness criteria. In this case the failure of a fastening point can cause the failure of the complete construction and reliable fasteners with an approval according to [1] or [4, 5, 6] have to be used.

In the case of redundant systems such as statically indeterminate structures like suspended ceilings, pipes, railings and pipes, where a part of the fasteners might be located in cracked concrete while the rest is situated in non-cracked concrete, fasteners for so-called multiple use can be used.

By multiple anchor use it is assumed that in the case of excessive slip or failure of one anchor the load can be transmitted to neighboring anchors without significantly violating the requirements on the fixture in the serviceability and ultimate limit state.

For this application it is allowed not only to use fasteners that fulfill the stringent requirements of [1] or [4, 5, 6] but also fasteners of lower quality. The requirements for fasteners in redundant structures are covered in ETAG 001, P.6 'Metal anchors for multiple use in concrete for non-structural applications' [9]. Anchors for multiple use are tested in concrete members with reduced crack widths of $w = 0{,}2$mm and 0,35mm. Therefore it is possible that a fastener might fail in practice when located in a very wide crack, e.g. $w \geq 0{,}5$mm. Then to maintain structural integrity the structural component must transfer the load taken by this fastener to neighboring anchors (Fig. 6b).

Failure of a statically determinate system occurs when only one anchor fails (see Fig. 6a). The failure of a redundant system does not necessarily occur after the failure of only one anchor, but occurs when the allowable bending stress (design resistance) or deformation (serviceability) of the structure is exceeded (Fig. 6b) or when 2 neighboring anchors fail.

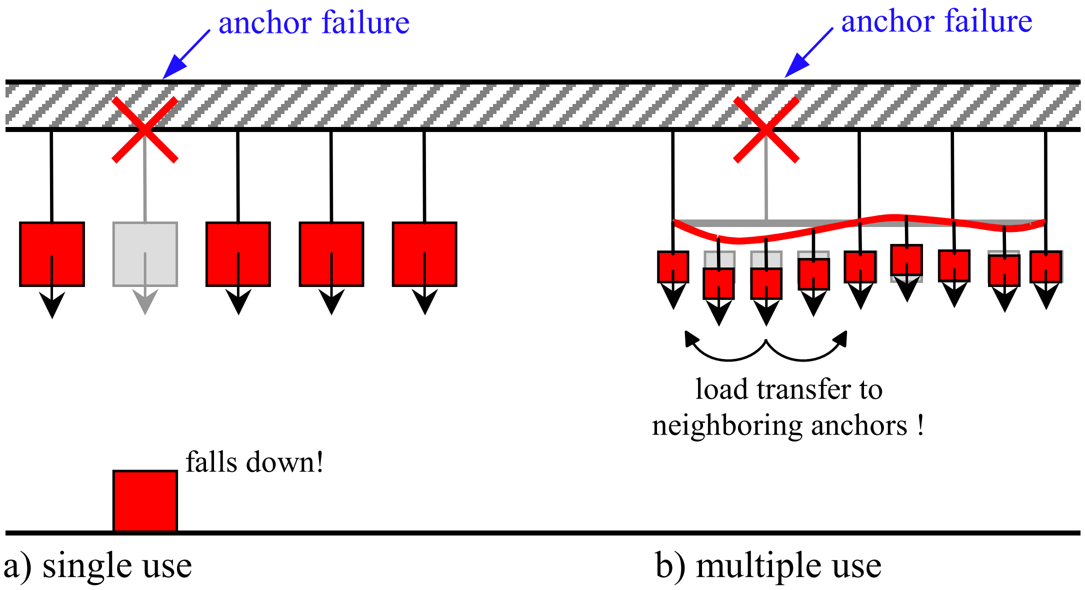


Fig. 6: Relation between anchor failure and system failure, [10]

The crack widths for testing of anchors for multiple use given in [9] have been established in [10] for the following assumptions:

a) The distribution of the widths of cracks in a structure is independent from the type of anchors used (for single or multiple use).
b) The probability of failure of redundant systems fixed with fasteners for multiple use should equal statically determinate structures fastened with anchors for single use.
c) After failure of one anchor the statically indeterminate system is able to redistribute the load taken up by the failed anchor to neighboring anchors.
d) The statically indeterminate system fails after the failure of two neighboring anchors.

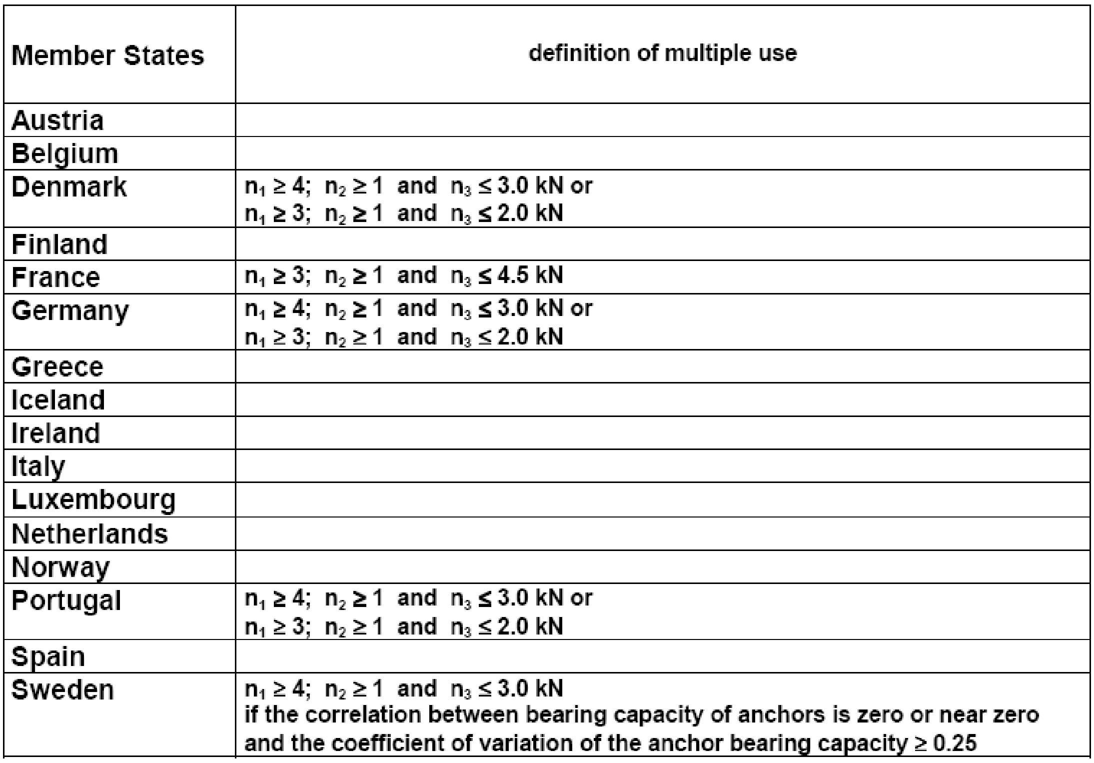
To ensure that the statically indeterminate structural system does not fail or show too large deflection after excessive slip or failure of one anchor, two design options exist:

1) The structural system is designed under the assumption that the most unfavorable anchor has failed.
2) The structural system is designed under the assumption that all anchors are intact and the capability to redistribute loads after the failure of one anchor is ensured in an indirect way.

In practice the design of pipes, light weight suspended ceilings etc. should be rather simple. Therefore option (2) has been chosen in [9]. After the eventual failure of one anchor the moments and deflections of the fastened structural system increase significantly. Therefore, to ensure that the fastened structural system shows an acceptable behavior even if one anchor fails, it must be overdesigned for the case that all anchors are assumed to resist load. The required overdesign can be achieved by limiting the design load on the fixing points to $N_{Ed} \leq 3kN$ for $n_1 = 4$ fixing points and $N_{Ed} \leq 2kN$ for $n_1 = 3$ fixing points [10]. A fixing point may consist of 1 to 4 anchors. The rationale for this is given in [10].

In Table 1 the multiple use of anchors as defined by the European Member States is summarized. An example for the definition of n_1 and n_2 is given in Fig. 7. Some Member States are quiet on the definition of multiple anchor use. In this case, in [9] the values used in Denmark, Germany and Portugal are recommended as default values. If the conditions in Table 1 are fulfilled excessive slip or failure of one anchor needs not to be taken into account in the design of the fastened structural system.

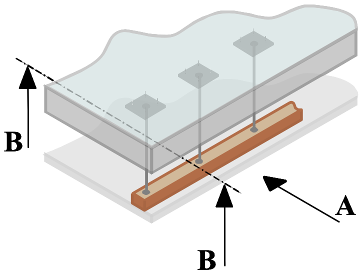
Table 1: Definition of multiple use according to the Member States, extract, [9]



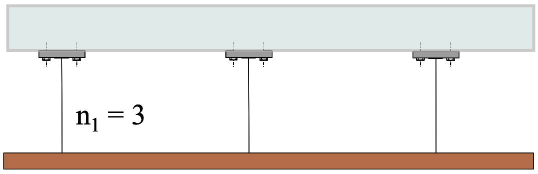
Member States	definition of multiple use
Austria	
Belgium	
Denmark	$n_1 \geq 4$; $n_2 \geq 1$ and $n_3 \leq 3.0$ kN or $n_1 \geq 3$; $n_2 \geq 1$ and $n_3 \leq 2.0$ kN
Finland	
France	$n_1 \geq 3$; $n_2 \geq 1$ and $n_3 \leq 4.5$ kN
Germany	$n_1 \geq 4$; $n_2 \geq 1$ and $n_3 \leq 3.0$ kN or $n_1 \geq 3$; $n_2 \geq 1$ and $n_3 \leq 2.0$ kN
Greece	
Iceland	
Ireland	
Italy	
Luxembourg	
Netherlands	
Norway	
Portugal	$n_1 \geq 4$; $n_2 \geq 1$ and $n_3 \leq 3.0$ kN or $n_1 \geq 3$; $n_2 \geq 1$ and $n_3 \leq 2.0$ kN
Spain	
Sweden	$n_1 \geq 4$; $n_2 \geq 1$ and $n_3 \leq 3.0$ kN if the correlation between bearing capacity of anchors is zero or near zero and the coefficient of variation of the anchor bearing capacity ≥ 0.25

n_1 …	number of fixing points to fasten the fixture
n_2 …	number of anchors per fixing point
n_3 …	limitation of the design value of action N_{Ed} [kN] per fixing point so, that excessive slip or anchor failure need not be taken into account in the design of the fixture

Some Member States recommend less stringent requirements than recommended as default values in [9]. This is especially valid for Great Britain. In case of fastenings with 4 anchors a design action of $N_{Ed} = 40kN$ is allowed. According to [10] this design action is much too high to ensure a satisfactory behavior of the fastened structural system.



lateral view A



bottom view B-B

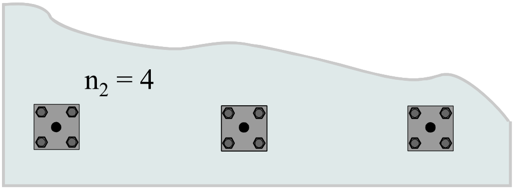


Fig. 7: Multiple use system, definition of n_1 and n_2 - example

6. Current and future research projects

The research in fastening technology at the Universität Stuttgart, Institute of Construction Materials is focused on the target to come up with test requirements and design models which are based on sound physical models and respect the conditions found in practice. It is intended to implement these proposals in worldwide harmonized test and design rules. The first step in this direction has been done for fasteners in concrete under static and sustained loading, where the test procedures and design methods in Europe and the USA are almost identical. Similar standards have been adopted in China recently.

Currently several research projects are carried out which deal with the following topics

- optimization of the design methods for fastenings
- behavior and design of fastenings with anchor reinforcement
- fire resistance of fasteners
- fastenings under seismic excitations
- strengthening and retrofitting of structures
- new fastening technologies

- influence of the concrete composition on the behavior of chemical anchors
- durability of chemical anchors
- connections with post-installed rebars
- fastening in solid and hollow masonry

In the following some of these research projects are briefly explained.

6.1 Fire resistance of fasteners

The trend of increased use of post-installed fasteners drew the attention also to the performance of components anchored to the concrete structure of buildings when subjected to fire.

In [11] a review of test reports and results of theoretical and empirical investigations provided a first general insight as to key issues that need to be addressed to better understand the behavior of fasteners in concrete elements exposed to elevated temperatures.

A major factor that influences the fire performance of fasteners is the steel quality. The evaluation of results of tests at different laboratories with post-installed anchors of various diameters from different manufacturers in Figure 8 indicates that stainless steel has a higher fire resistance than carbon steel. Furthermore a larger diameter is less sensitive to elevated temperatures than a smaller diameter.

The evaluation of the above data yielded the tables in [2], where the characteristic fire resistance of fasteners in case of steel failure is given dependant on steel quality, diameter of the fastener and time of exposure. Based on a very limited number of tests described in [11] the characteristic pull-out resistance in case of 90 min or 120 min fire exposure is assumed 25% or 20% respectively for the value for cold state. In case of concrete failure the fire resistance is influenced primarily by the embedment depth of the anchor [11]. In Figure 10 the measured concrete cone failure loads related to the calculated mean value in the cold state are plotted as a function of the embedment depth. The results of further investigations on the concrete break-out capacity of headed studs with different embedment depth by means of numerical studies with the 3D non-linear FE program MASA (Fig. 9) are presented in [12]. The fire exposure followed ISO 834 [13]. In Figure 10 the results of the numerical analysis are plotted as well. The agreement between numerical and experimental results is satisfactory. Based on these results the design approach as given in [2] was derived. For a 90 min fire exposure Equ. (1) is valid:

$$N^{0}_{Rk,c,fi(90)} = \frac{h_{ef}}{200} \cdot N^{0}_{Rk,c} \le N^{0}_{Rk,c} \qquad (1)$$

The fire resistance has to be reduced by 20% for a 120min fire exposure. According to Figure 10 the conservatism in the prediction of the fire resistance (Equ. (1)) increases with increasing embedment depth.

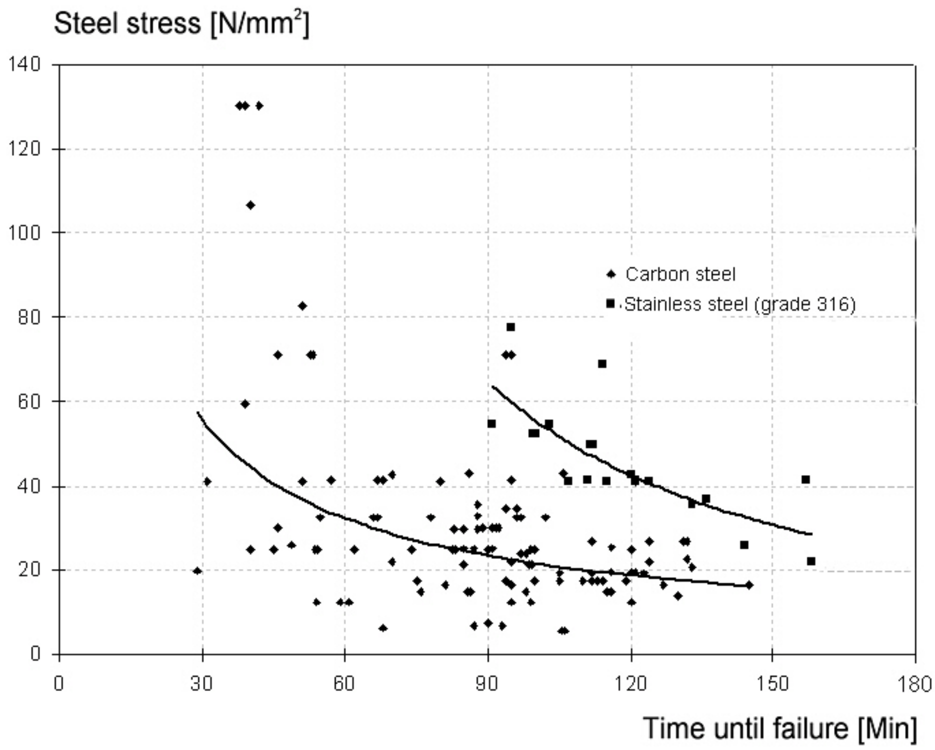


Fig. 8: Steel stress as function of time until failure for carbon and stainless steel, [11]

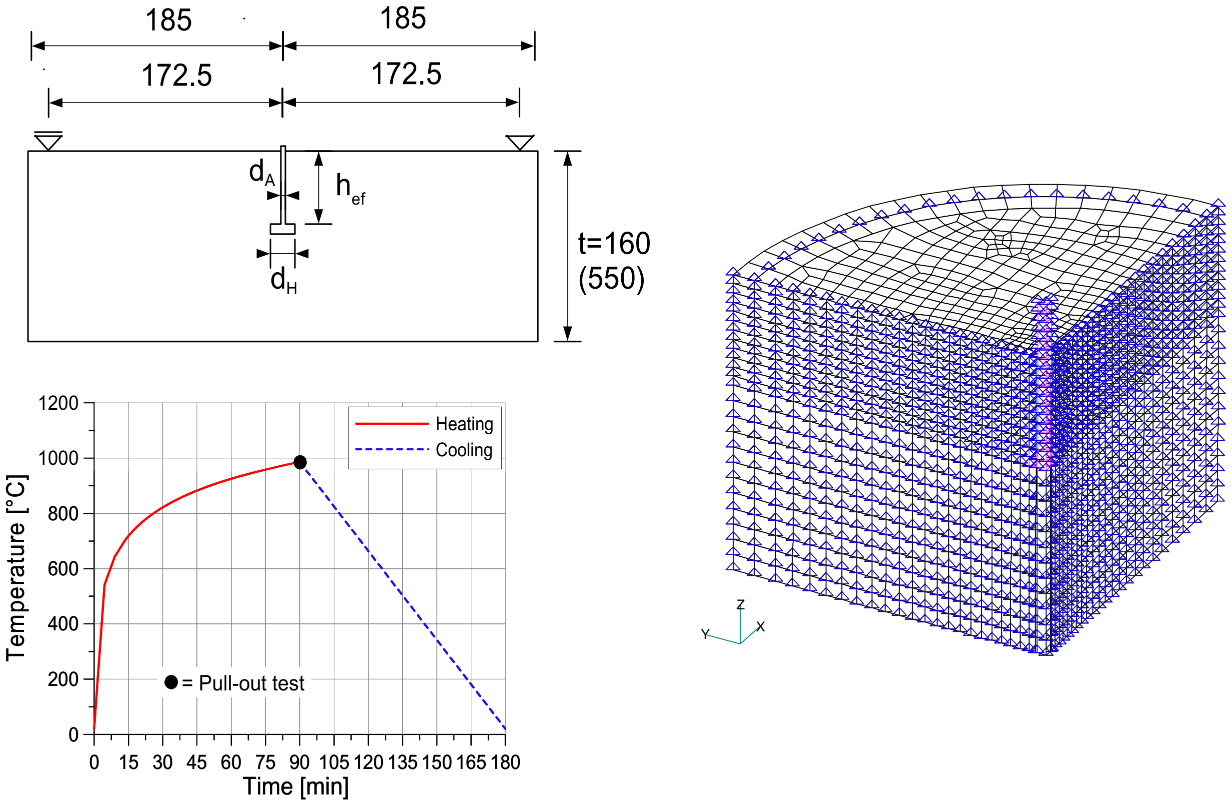


Fig. 9: Idealization of a fire test by means of FE analysis, [12]

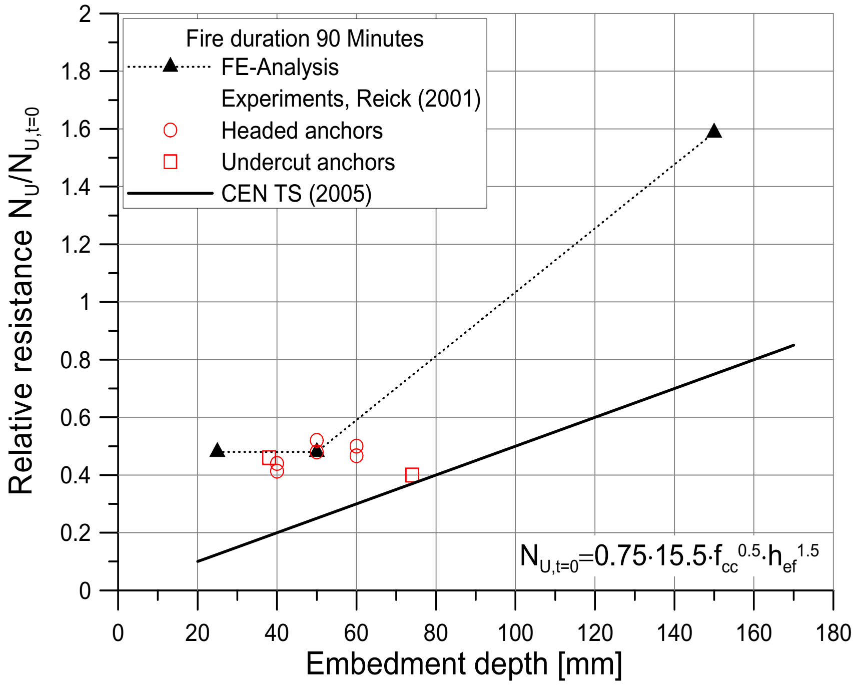


Fig. 10: FE analysis results compared to test results and the CEN TS design approach

The design method presented in [2] predicates on the condition that the fasteners have passed the test and evaluation criteria for anchors to be used in cracked and non-cracked concrete according to [1], because in case of a fire attack cracking will occur in the concrete. Furthermore the reinforced concrete member, in which the fastener is anchored, should have at least the same duration of fire resistance as the anchorage itself. The provisions are limited to a fire attack from one side only and to normal weight concrete with a strength of C 20/25 to C 50/60. Less conservative design provisions or other applications may be possible, if this can be demonstrated by tests according to the TR 020 'Evaluation of Anchorages in Concrete concerning Resistance to Fire' [14].

Currently the behavior of fastenings with one and more anchors is studied for a fire attack from 2 and 3 sides and for tension and shear loads.

6.2 Fasteners under seismic loading

Earthquakes occur worldwide, and the damages caused by earthquakes increase continuously. High risk potential exists not only classic earthquake countries as for example Japan, USA or Turkey but in spite of expected small earthquake magnitudes also industrial countries as Germany, when buildings and infrastructure can not be immediately used after an earthquake. Essential damages may be caused e.g. by falling wall panels, suspended ceilings, overturning non-bearing walls or cupboards and/or insufficient safeguarded devices as for example EDV devices, piping systems, devices in operating rooms and machinery. Up to now no generally accepted rules exist in Europe for the testing, evaluation and design of fastenings which are supposed to resist seismic loads when subjected to seismic excitations. The behavior of anchors under seismic excitations has been studied in [15]. As the primary structure responds to the earthquake ground motion, the anchors experience reversed cycling shear loads and cyclic tension loads (Fig. 11). Furthermore, due to the cyclic loading of the primary structure the anchor may be located in a crack which is opened to a certain crack width and closed again for several times. The width of cracks in regions of plastic hinges may be very large (Fig. 12). Outside of plastic hinges the cracks may be opened up to a width of about 0,4mm to 1,0mm. Therefore, to assess the performance of anchors in concrete during an earthquake it is necessary to understand their behavior under cyclic tension and shear loading but also in cycled cracks. The expected crack opening and closing widths, as well as the number of crack cycles, are critical parameters.

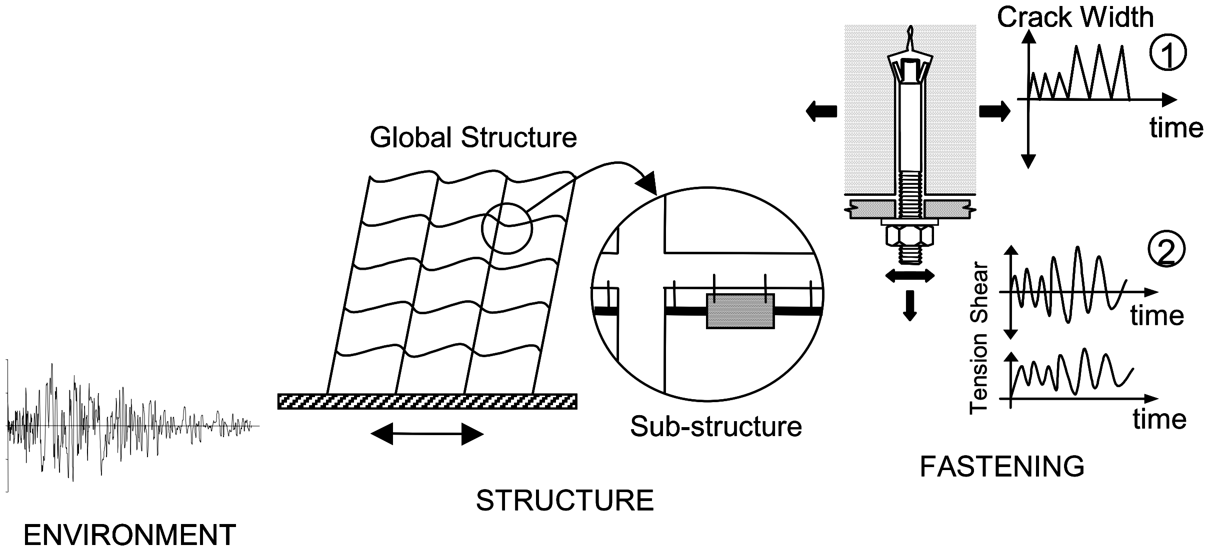


Fig. 11: Development of actions on fasteners under seismic loading, [15]

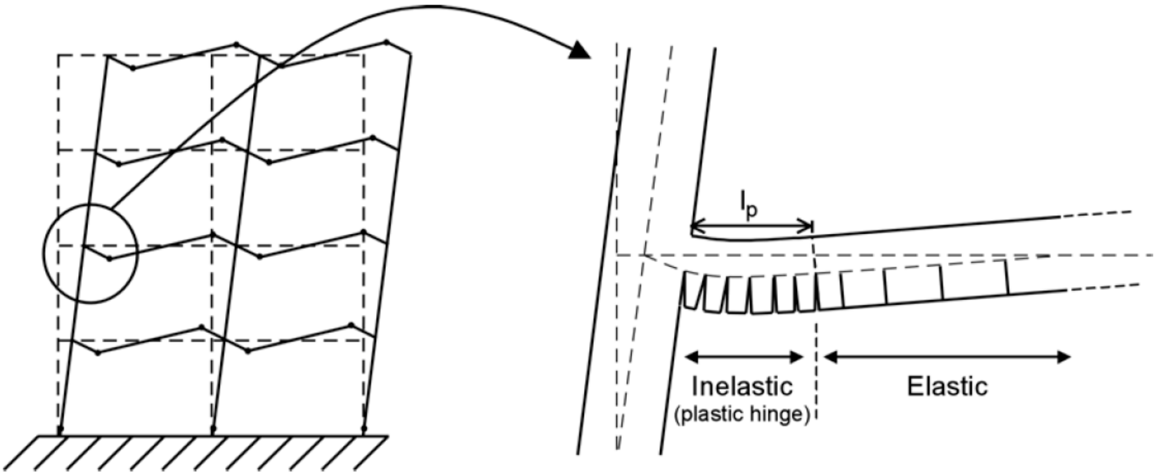


Fig. 12: Crack in a beam caused by transverse motion of the structure, [15]

Up to now, the most used test regime to check the suitability of fasteners in seismic applications is given in ACI 355.2 [4] which is valid for post-installed mechanical fasteners. ACI 355.2 requires tests under pulsating tensile and alternating shear loading with a maximum load cycling level N_{eq} or V_{eq} of 50% of the mean capacity measured in monotonic tests in cracked concrete, w = 0,5mm (Fig. 13). During the test no failure of the anchor shall occur and the residual load capacity shall be at least 80 % of the capacity valid for the static short term test. No requirements are given with regard to the load-bearing behavior. In general, fasteners which have been qualified for use in cracked concrete pass the cyclic tension tests. To pass the requirements in the cyclic shear tests, often the maximum load on the anchor has to be reduced, which leads to a reduced seismic shear resistance compared to the static shear capacity. However, it is questionable whether a crack width of 0,5mm is sufficient to simulate the load bearing behavior under severe earthquake conditions since even outside of the zones of plastic hinges considerably wider cracks must be expected. Furthermore ACI 355.2 does not consider that during an earthquake the cracks in the reinforced concrete member are opened and compressed to a zero width several times.

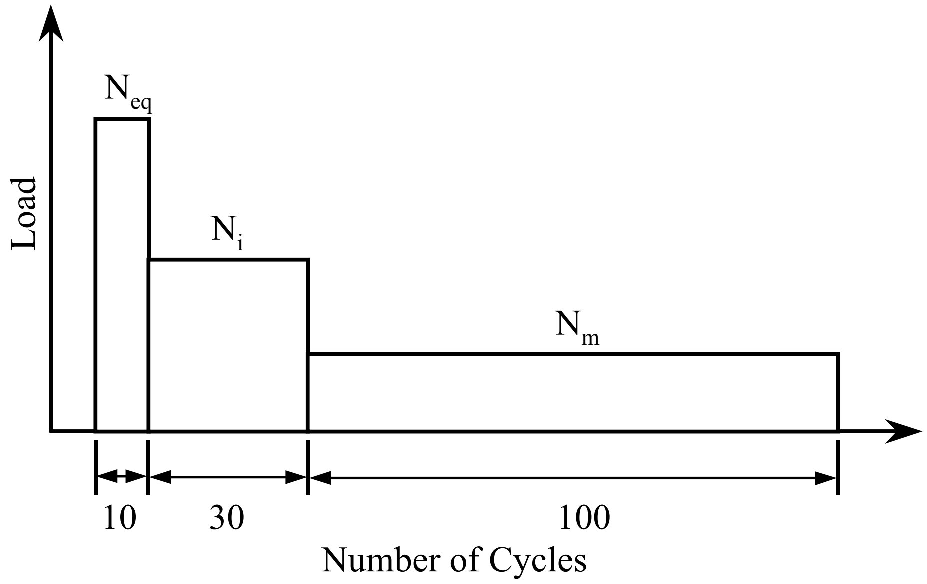


Fig. 13: ACI 355.2, loading pattern for simulated seismic-tension test

Figure 14 shows the behavior of a bolt type expansion anchor located in a w = 0,8mm crack under monotonic and stepwise increasing loading cycles. It demonstrates that the cyclic load does not significantly influence the anchor behavior. In contrast the behavior of the anchor is significantly influenced when it is loaded by a constant tension load and the crack width is cycled. Fig. 15 shows the behavior of the bolt type expansion anchor of Fig. 14, when loaded by a constant tension load of 40% of the mean static ultimate load in a crack of w = 0,8mm and subjected to 10 crack cycles between w =0,8mm and w =0mm. The residual anchor capacity is less than the static capacity. A new test guideline to check fasteners for use in seismic regions should cover these effects.

The behavior of fasteners in plastic hinge regions is not predictable. Therefore fasteners should not be used in these areas.

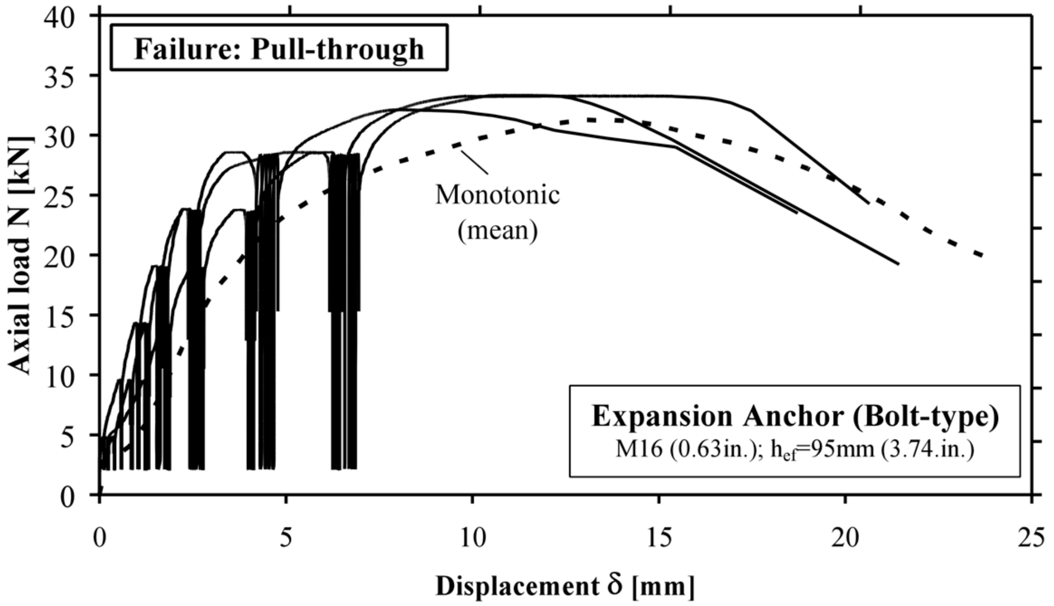


Fig. 14: Load-displacement curves of a bolt type expansion anchor M16, monotonic and stepwise cyclic loading, w=0,8mm [15]

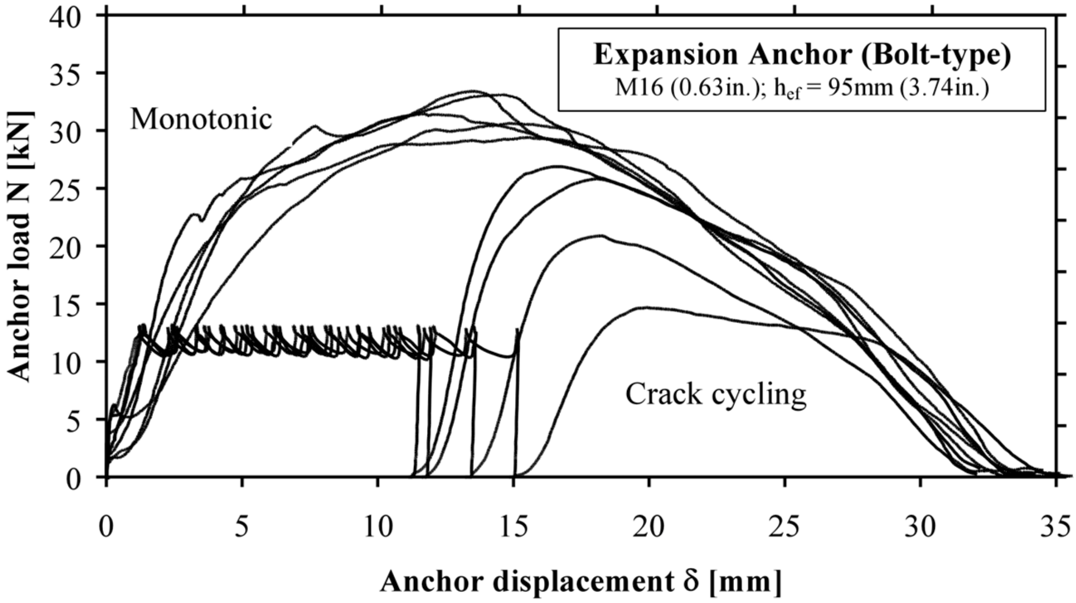


Fig. 15: Load-displacement curves of a bolt type expansion anchor M16 under monotonic loading, w=0,8mm and crack cycling, w_1=0,8mm, w_2=0mm, n=10, N_w=0,4$N_{u,m}$ [15]

6.3 Post-installed rebars

Post-installed rebars transfer loads into the base material by means of mortar in a cylindrical hole in hardened concrete (Fig.16). The bonding material may be manufactured from synthetic mortar, cementitious mortar or a mixture of the two including fillers and/or additives. The influence of the chemical mortar on the bond stress-slip behavior of post-installed rebars is shown in Figure 17.

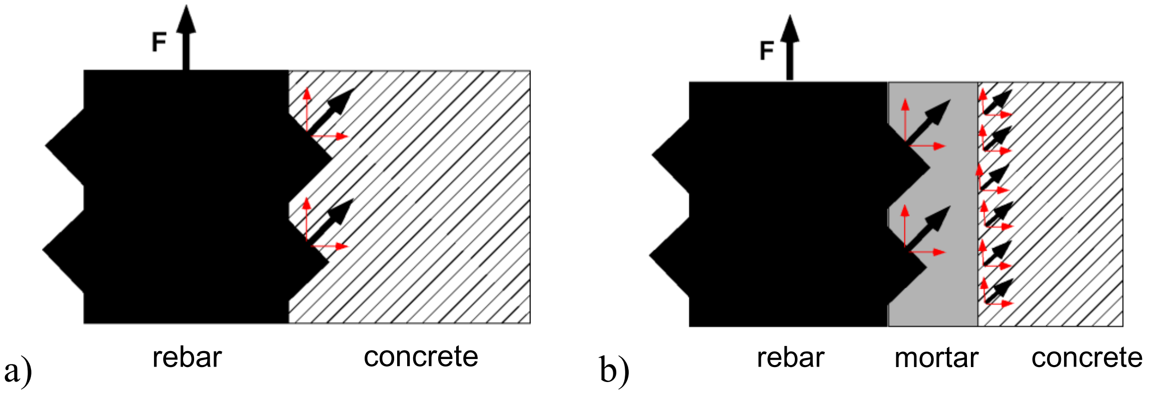


Fig. 16: Load transfer via a) cast-in rebars and b) post-installed rebars, [16]

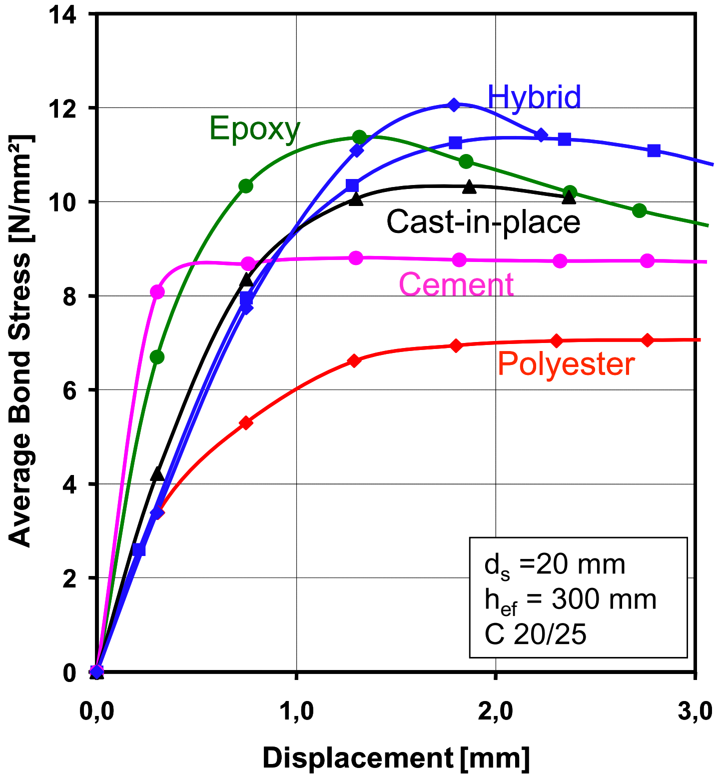


Fig. 17: Bond stress of cast-in rebars compared to post-installed rebar systems, [16]

In the past the design of connections with post-installed rebars was based on manufacturers' recommendations. The recommended development lengths were derived from the results of tests in uncracked concrete with the failure modes pull-out and steel rupture. Furthermore, in general the manufacturers' design concepts did not distinguish between anchorages and splices and they did not consider the failure mode splitting of the concrete in case of normal concrete cover. This yielded considerably smaller development lengths compared to code provisions (Fig. 18). Tests showed that provided a suitable mortar is used, the strength of overlap splices with post-installed rebars is not significantly different from those with cast-in rebars (Fig.19). Therefore under otherwise constant conditions the bond length of connections with post-installed rebars using a suitable mortar should be the same as for connections with cast-in-place rebars.

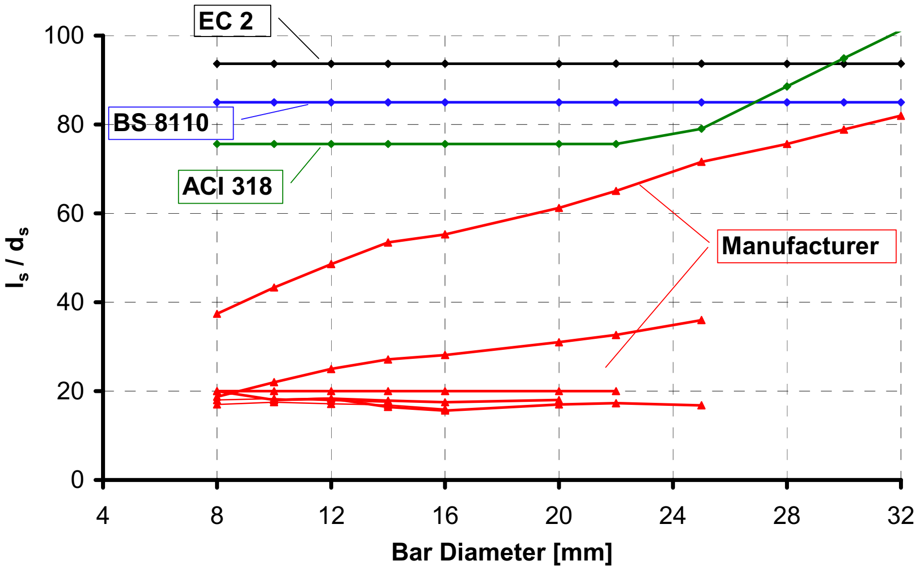


Fig. 18: Comparison of development length for post-installed rebars according to manufacturers' recommendations and codes for cast-in rebars, [16]

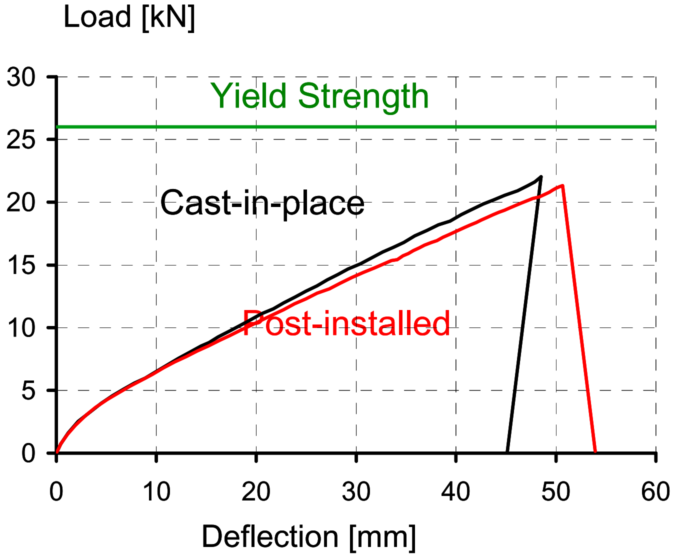


Fig. 19: Cast-in rebars compared to post-installed rebars in splices, [16]

To put post-installed rebar connections on the same level of safety and reliability as cast-in rebars, in 2006, the Technical Report TR 023: 'Assessment of post-installed rebar connections' was released by EOTA [17]. This Technical Report covers post-installed rebar connections designed in accordance with EN 1992-1-1 (EC2). It deals with the preconditions, assumptions and the required tests and assessments for post-installed rebars:

- The test results shall confirm that connections with post-installed rebars using a qualified mortar have a comparable behavior as cast-in-place rebar connections in respect to strength and displacement behavior.
- Connections which according to Eurocode 2 are allowed for straight deformed cast-in rebars may be performed with post-installed rebars using the design provisions in EC2 for deformed bars.

- Only pull-out or splitting failures are considered, concrete cone failure is avoided by compressive struts resulting from the strut and tie action.
- Only skilled installers are allowed to perform post-installed rebar connections.

Fatigue, dynamic or seismic loading of post-installed rebar connections are not covered by TR 23. However, post-installed reinforcing bars are frequently used in seismic zones. Extensive experimental and numerical investigations were performed in [18] to study the behavior of post-installed rebars under simulated seismic conditions in uncracked and cracked concrete. For comparison cast-in place rebars were tested under the same conditions. In Figure 20 the results of tests with post-installed rebars are compared to the behavior of cast-in rebars. From the results presented in [18] the following can be concluded for the bond behavior of post-installed rebars under cyclic loading:

- The behavior of post-installed rebars under cyclic loading depends on the failure mode under monotonic loading.
- The bond behavior of post-installed rebars during monotonic and cyclic loading is similar or even superior compared to the bond behavior of cast-in-place rebars if under monotonic loading the failure occurs at the interface between rebar and mortar.
- Post-installed bars failing at the interface between mortar and borehole wall under monotonic loading show a bond behavior under cyclic loading which is inferior compared to cast-in rebars.
- Mortar systems which perform well under monotonic loading in cracked concrete and which are properly installed can most probably be used also in seismic zones

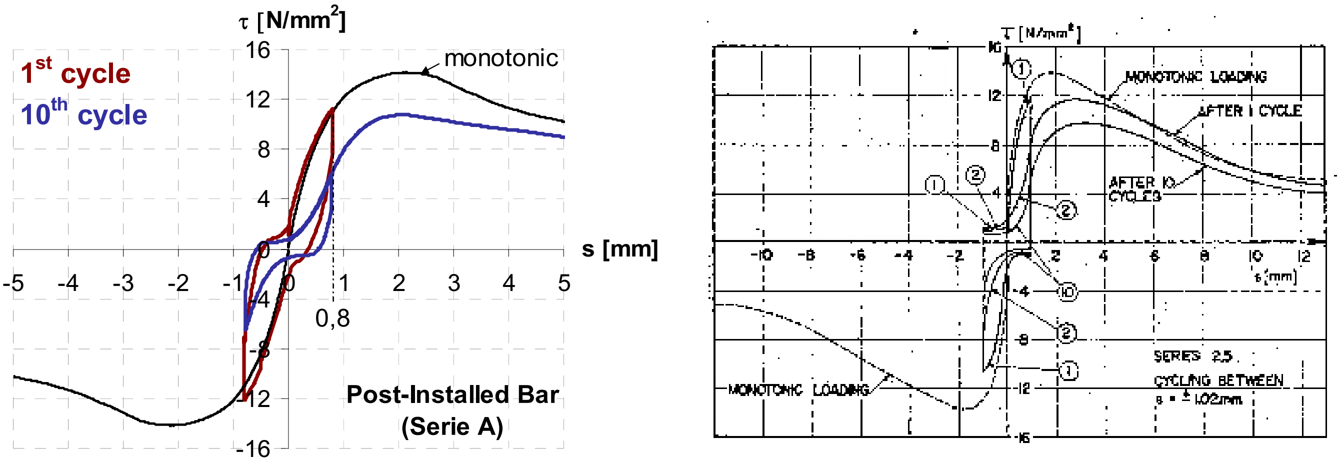


Fig. 19: Post-installed and cast-in rebars under cyclic loading, after [18]
a) post-installed rebar, cyclic loading, displacement s = ± 0,8mm
b) cast-in rebar, cyclic loading, displacement s = ± 1,0mm

7. Conclusions

Modern fastening technique is increasingly used in the construction industry. New and innovative fastening 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.

However, there are still some white and grey spots on the map of modern fastening technology. This is valid e.g. for the application of fasteners in seismic zones. These problems will hopefully be solved in the near future. However, last but not least the education and training of designers and installers with regard to fastening technology should not be forgotten and must be improved considerably.

Detailed information on the state of the art in fastening technology is given in [19].

8. Acknowledgement

The authors wish to express special thanks to the companies Fischer, Hilti and Würth for the financial support of the investigations.

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Part Two

Code and Practice

THE HUMAN FACTOR IN FASTENING TECHNOLOGY- A FORCE TO BE RECKONED WITH

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Abstract

A wide variety of advanced and innovative fastening systems have been invented, developed, produced and used in construction industry over the years to help achieve more flexibility in the planning, design and strengthening of concrete and masonry structures. The understanding of the behavior of these fastening systems, the range of the fields of applications, the design methods and installation procedures have made significant advances in the past three decades. Although a large number of fasteners are installed every day, understanding in the engineering community about their working principles and design is very limited. Furthermore the installers are confronted with a bewildering multitude of fastening systems with different installation procedures, they have to consider for proper installation. This paper gives a brief overview on where the human factor in fastening technology comes into play. Emphasis is placed on the questions, if fasteners meet the intended function, if designs are prevented that are susceptible to misuse, if usability issues and installation errors are minimized to enhance safety.

1. Introduction

The diversity of fastening products increased with the number of possible applications of cast-in or post-installed fastening devices. For the user in the practice, it became difficult to find the correct fastening solution and to design safe connections. It became apparent that guidelines to aid in the design of structures using fastening systems were necessary. With the increase in the fields of applications the installation conditions changed. The fastener should be capable of safe and effective behavior under normal and adverse conditions. Therefore testing guidelines were developed to prequalify fasteners to provide data required by the design guidelines and to confirm the reliability of the fastener during installation and service. However, in practice fasteners face the same problem often with different solutions i.e. different working principles, proprietary designs and performance characteristics. For optimal utilization of fasteners the designers and installers should be aware of all these differences. This paper provides an overview on the human factor in the development, prequalification, design and installation of fasteners.

2. Reliability

Human reliability is a crucial part to the reliability of structures. In fastening technology it refers to humans and their behavior in research, development, approval agencies, manufacturing, marketing, consulting, design and installation. Reliability depends on the amount and effect of human errors on the structural behavior. In this context it should be mentioned that human error is part of the ordinary spectrum of human behavior. Human errors on different levels may add and yield systematic errors. Therefore erroneous contributions of humans to the construction process should be minimized i.e. 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, insufficient supervision and unfavorable organizational influences.

Furthermore the persons involved have to learn the world of fastening consists of a rapidly changing environment of products, applications and regulations. Therefore to make fastening technology better suited to applications and reliable the communication flow between all persons involved in the process from development to application of fasteners has to be confirmed.

3. Fastener development

Many prototypes of fastening elements which look good on paper, in theory and testing laboratory fail in real world application. Therefore a key element of the development process is the practical consideration for the actual application and installation environment and here are users the best source for new ideas. An installer expects an easy to install product with easy to understand technical data. It should relate to his experience, to his way of working, to his equipment and to his tools.

If these preconditions are not met, poor installation is probable, even if the manufacturer's published instructions for installation, application, curing and design, including allowable loads, are submitted.

An example for a mechanical fastener is a torque controlled expansion anchor which is not torqued properly with a torque wrench (Fig. 1). In case of a high torque the concrete in the edge of a concrete slab will be split by the fastener, in case of a small torque the fastener will be pulled out well below the expected capacity.

To overcome the problem of wrong torquing a manufacturer developed a heavy duty fastener with torque cap, where no torque wrench is needed to apply the correct torque (Fig. 2). For correct installation the head of the fastener is turned with a normal wrench until the red cap shears off and a green tamper proof seal is visible. However, most users are not aware of the cost-benefit ratio of this heavy duty fastener, so that it is applied mostly in applications with high safety relevance such as power plants.

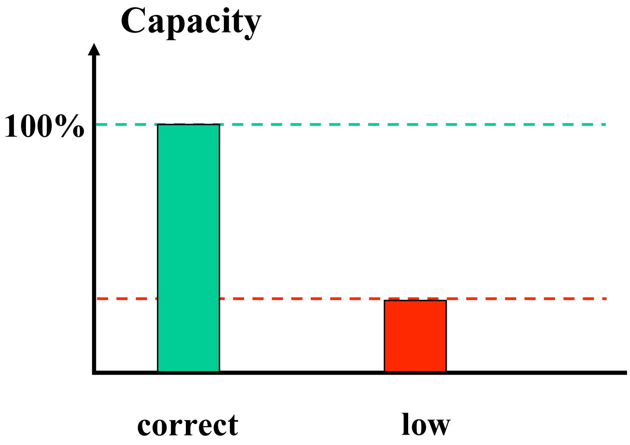

Fig. 1: Influence of the installation torque on the capacity of torque controlled fasteners

Fig. 2: Torque controlled expansion anchor with red shear-off cap

Other types of fasteners such as drop-in or undercut anchors indicate correct installation by means of different kinds of marks on the sleeve or anchor rod. This makes it easy to check the quality of the installation. However, it would be much more favorable to have fasteners that would be so easy to install that misuse and misinstallation could be avoided in advance – three 90° turns after contact of the screw with the attachment and the connection is finished could be criteria.

For adhesive anchors it can be only checked if there is enough mortar in the borehole after installation. Other checks are not possible on site. A problem on site is always borehole cleaning since a lot of dust sprays around if the borehole is blown out. The installers therefore very often avoid this procedure which on the other hand is vital to ensure the capacity of the fastener. To overcome insufficient borehole cleaning during installation the first products were developed where borehole cleaning is not part of the standard installation procedure.

In general to gain acceptance of the user and to avoid human errors in application the aim of the developer should be to ensure that the fastener is developed to

- fit to the construction process
- account for the experience, limitations and capabilities of the user
- to meet the intended function
- prevent designs that are susceptible to misuse
- identify usability issues
- provide non-ambiguous installation instructions
- provide guidance to designers and installers
- minimize error and enhance safety.

Simply spoken the development of fastening systems involves working to make the fastener environment function that seems natural and standard to the users.

4. Regulations

Regulations must focus on problems that exist. The regulations must play a governing role to enhance safety and performance. With the introduction of quality management procedures in the production of fasteners it is ensured that the fasteners themselves are on a high level of quality.

Worldwide research effort has brought reproducible test methods [1, 4, 5, 6] which created more detailed information on the behavior of the different types of fasteners and yielded technical data and design methods [2, 3, 7]. These utilize the performance of the fasteners in a wide variety of applications at optimum. On the other hand the design methods became more application oriented and complicated even if simple problems shall be solved. Therefore designers with only a basic knowledge in fastening technology are often over-burdened by understanding and using the design methods, so that they have to rely on the results of the programs. This could cause misinterpretations. Furthermore the educational level of installers on site decreases constant. Installers are very often not able to read installation instructions. Very often they install products based on their experience and standard practice even if an innovative product requires another installation procedure. Regulations have to consider this aspect to avoid failures.

4.1 Quality control in production

Regulations require in all safety relevant applications quality control in production. Fasteners shall be manufactured under an approved quality-assurance program with follow-up inspections by an accredited inspection agency. This ensures that only flawless fasteners are sold.

4.2 Testing

The basic aim of testing regulations is to establish test procedures, methods of assessing and judging the results of tests to provide the necessary product characteristic data for the design.

Basic requirement to meet this goal is that the testing and evaluation agencies are 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 fasteners 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 regulation working groups practice co-operations with testing laboratories, technical experts and manufacturers. In Europe ETAG 001 [1] was created to cover the testing of mechanical and chemical fasteners. In the USA ACI 355.2 [4] for mechanical anchors was released by ACI, and AC 193 [5] for mechanical anchors and AC 308 [6] by ICC.

In Table 1 the possible options for testing according to ETAG 001 are summarized.

Table 1: Options according to ETAG 001 [1] for mechanical and chemical fasteners

Option N°	Cracked and non-cracked	Non-cracked only	C20/25 only	C20/25 to C50/60	F_{Rk} one value	F_{Rk} function of direction	c_{cr}	s_{cr}	c_{min}	s_{min}	Design method according to Annex C
1	x			x		x	x	x	x	x	A
2	x		x			x	x	x	x	x	
3	x			x	x		x	x	x	x	B
4	x		x		x		x	x	x	x	
5	x			x	x		x	x			C
6	x		x		x		x	x			
7		x		x		x	x	x	x	x	A
8		x	x			x	x	x	x	x	
9		x		x	x		x	x	x	x	B
10		x	x		x		x	x	x	x	
11		x		x	x		x	x			C
12		x	x		x		x	x			

There exist 10 different testing options to provide technical data (spacing, edge distance) for 3 different design methods to account for the best product performance. This is very confusing for the designers and installers since it makes it very difficult to find the right product for an application without consulting and to compare products from different manufacturers. However, practice shows that only a few options are used in practice. In the USA in principle the same test and design methods are used as in Europe. However, for the user it is much easier to compare products since in ICC AC 193 and ACI 355.2 only procedures similar to Options 1 and 7 with design method A are regulated.

In case of chemical anchors in the USA it is much more complicated for the user to find the correct product. Fig. 3 shows the possible options of approvals or evaluation reports for chemical anchors according to AC 308.

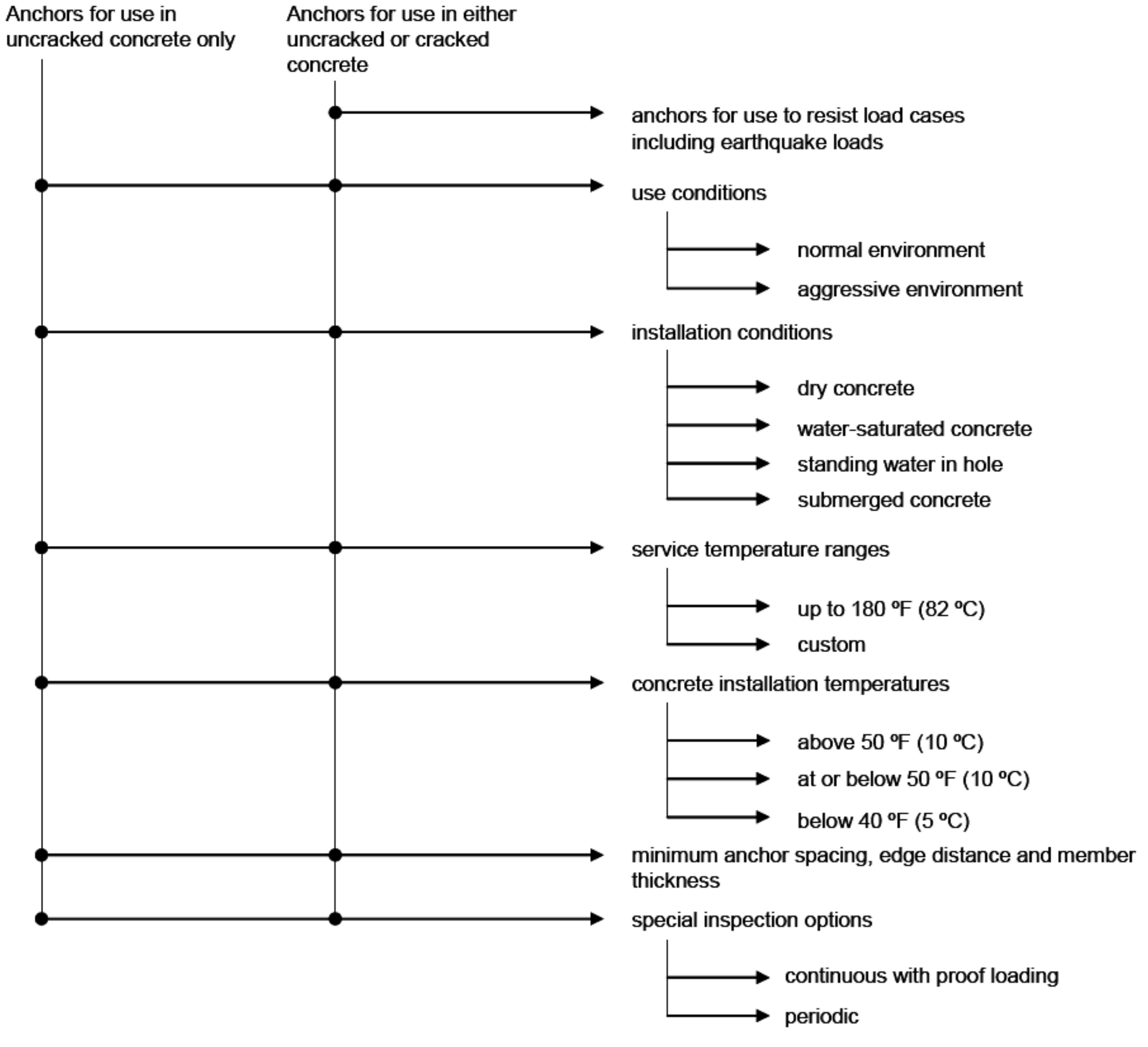

Fig. 3: Options according to ICC AC 308 [6] for chemical fasteners

Due to the high degree of innovation in fastening technology the period of validity of a product approval is in general 5 years. During this time increasing knowledge might have yielded new test requirements and evaluation methods which could create a change in technical data. This has to be considered before extension of the approval. In general, it takes one to two years before new approvals and design methods are implemented on practice. The challenge for the involved parties is to shorten this time significantly to avoid unforeseen events.

All interested parties who can contribute in a positive way have the opportunity to participate in regulation committee work. However, in the past no representatives from the user side participated actively in the committee work. Therefore to make the design regulations less academic, the testing procedures in step with actual practice and the products less sophistic to avoid human errors it is necessary that the users in practice contribute more to the regulations. Then it is expected that users will become more confident in fastening technology that follows new regulations based on more practical approximations and requirements.

5. User

5.1 Designer

Planning of safe connections between steel and concrete should start at the design stage. Design engineers should take into account actual design provisions, installation requirements and ensure safe working conditions. However, fastening technology is very often not part of their daily business. Therefore it might be difficult for them to keep pace with new products and regulations. On the other hand they need and use fasteners for the connection between steel and concrete or masonry as structural problem solvers.

One of the most difficult aspects of assessing a specific fastening problem is defining the correct product for the relevant environmental and structural conditions. Geometric parameters such as edge distances, spacing, member depth and loading direction as well as reinforcement play a role in the choice of the fastener. To facilitate this task free fastener design software packages from several fastener manufacturers which address actual regulations for their product lines are available to the designer. However, 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. To a certain extent this is already provided by specific seminars offered by regulation bodies and manufacturers. Furthermore technical support can be provided by field engineers of the manufacturers and on phone base by technical staff of the customer service departments.

In addition the designer should know about the handling and installation of the products. Without taking into account the actual installation conditions on site the optimum product in design could be the wrong choice with regard to application. Consideration should be given on the ease of making connections on site. Designers should also provide information to the installers with detailed information on the application including exact definition of the fastener, location of the fastening and installation instructions.

5.2 Installer

Basic requirement for a correct installation is that the machines and tools are properly maintained and that during installation of the fasteners the parts given in the designer's drawings are used according to the manufacturer's instructions. This is not self-evident since very often due to impact on costs, schedule and other benefits and without review by the designer installers intend to alternate to products from other manufacturers which look alike but differ in material, characteristics and installation requirements.

In case of questions for an installer in general it is not as easy as for a designer to get support. The only contact to the manufacturer of a fastener is in most cases the sales force with limited in depth technical knowledge. Therefore therein general there is a technical back-up for the sales force. However, if the sales force does not respond quick and competent to the questions, the installer might reach a wrong decision.

Therefore all persons installing fasteners should be appropriately trained according to an appropriate scheme and competent to carry out the work. The installer should be aware of his competence and when to ask experts for support. If fasteners are used under new regulations or if a new fastening system will be used more attention to installation procedures might be required and training under the direct supervision of a competent person on site will likely be recommended.

5.2.1 Trained installer

Trainings for installer address the normal installer on the construction site. They are supposed to provide sufficient knowledge on regulations, installation procedures and behavior of different fastening systems in concrete and masonry in a short, quick and easy way to minimize the unproductive times for the employer.

All leading manufacturers have established training programs in internal training centers, academies as well as external seminars or even on jobsite. However, the curricula are different, of different duration and focused on the respective fastener line. At the end of the training the installer receives a certificate of attendance issued by the manufacturer.

5.2.2 Certified installer

An installation training scheme exceeding the normal manufacturer's training programs represents the qualification to the „Certified Technician' in Germany. Here the Institute of Construction Materials at the Universität Stuttgart (IWB) and a manufacturer of fasteners realized the idea of a uniform education which is succeeded after examination by a neutral third party.

First of all fastener experts of the manufacturer were trained by means of a defined curriculum in theory and practice and examined as trainers by the IWB. Special attention of this coach training lies on the transfer of knowledge in the fields of selection and application of fastening systems according to the environmental conditions, the load-bearing behavior and the installation according to the corresponding regulations and instructions. After 3 years the examination has to be repeated.

These examined trainers are entitled to passing on their professional knowledge to installers in 2½day seminars. The curriculum for the education was elaborated by the IWB and contains about equal parts of theory and practice. Next to fundamental knowledge of the fasteners and regulations the application in concrete and masonry according to approvals is explained. To practice correct installation techniques the participants have to install fasteners in cracked and uncracked concrete as well as masonry. With these fasteners tests are performed to demonstrate the difference between wrong and correctly set fasteners.

At the end of the seminar the IWB as a neutral body examines the participants. After successful completion of the exam the participants receive a certificate issued by the Universität Stuttgart.

This certificate indicates that the graduates of the training are qualified to professionally select fasteners for the corresponding application and to install them correctly. Due to the fast change and the high innovation potential in fastening technology the validity of this certificate is limited to three years. Then revitalization training with examination has to be performed.

5.2.3 Certified installer for post-installed rebar connections

The application of post-installed rebars was not regulated for many years. However, the consequences which arise from defective applications can be very fatal. Therefore in this case for the first time as verification for safe use the German approval body DIBt has required not only the indication of basic suitability of the adhesive mortar but also of the persons involved in the installation process.

The approvals for post-installed rebars connections postulate that only companies with valid suitability proof with installers certified for this application are allowed to carry out this application. The verification suitability of the company is checked by an independent agency acknowledged by the DIBt and valid for 3 years. The company must demonstrate a qualified management, sufficient knowledge in reinforced concrete construction qualified construction specialists with confirmation of the successful participation in a one day training course on the installation of post-installed rebars with theoretical and practical examination performed by an independent agency, acknowledged by the DIBt. Furthermore the proper installation equipment must be available.

This evaluation procedure for product and installation competence makes it easy for the designers to choose a reliable partner for the installation of post-installed rebars.

6. Conclusion

Basis for the reduction of the influence of human factors on the performance of fasteners i.e. the minimization of human errors is that all persons involved in the fastening process have the right information.

Once the information requirements have been identified, the functional requirements for the fastener can be derived. The analysis needs to be based on the existing code, approval and application environment in which the fastener must function. These requirements include impacts on fastener development, system effectiveness, safety implications and cost-benefit analysis. For those systems which have favourable benefit profiles, preliminary regulations or fasteners are developed for field studies. Based on acceptance of the users the transition of the new products and regulations into practice and applications may occur.

For approval bodies and code organizations, producers and users it is important to understand the relationships among the involved persons.

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REQUIREMENTS OF TECHNICAL APPROVALS VERSUS PRACTICE (BONDED ANCHORS AND POST-INSTALLED REBARS)

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Abstract

Bonded anchors as well as post-installed reinforced rebars are more and more used in building constructions, thanks to their good versatility (e.g. they allow small edge distances) and to the improved performances offered by the mortar systems. The disadvantage of this type of post-installed anchor is that it is more sensitive to hole cleaning than any other system. To ensure that the anchors reach their design capacity, Technical Approvals specify requirements for the installation of different products taking into account experimental results obtained in laboratories. It may not be excluded that in the practice bonded anchors are not always installed taking into account all the requirements of Technical Approvals.

In this paper a study about the installation of bonded anchors in practice is presented and analysed. Installers and engineers had to answer questions concerning the installation of bonded anchors. The survey was conducted in different European countries in order to get an overview of European fastening practice.

1. Introduction

A wide range of bonded anchor systems is currently available on the market. They can usually be distinguished according to the way they are installed:

a) capsule anchors, where the bonding material is contained in glass capsules or foil pouches, which have to be inserted into the drill hole prior to the anchor;
b) injection systems, where the bonding material has to be injected through special nozzles.

The bonding materials may consist of polymer resins, cementitious materials, or a combination of the two. An overview of the classification of bonded anchors is given in Fig. 1.

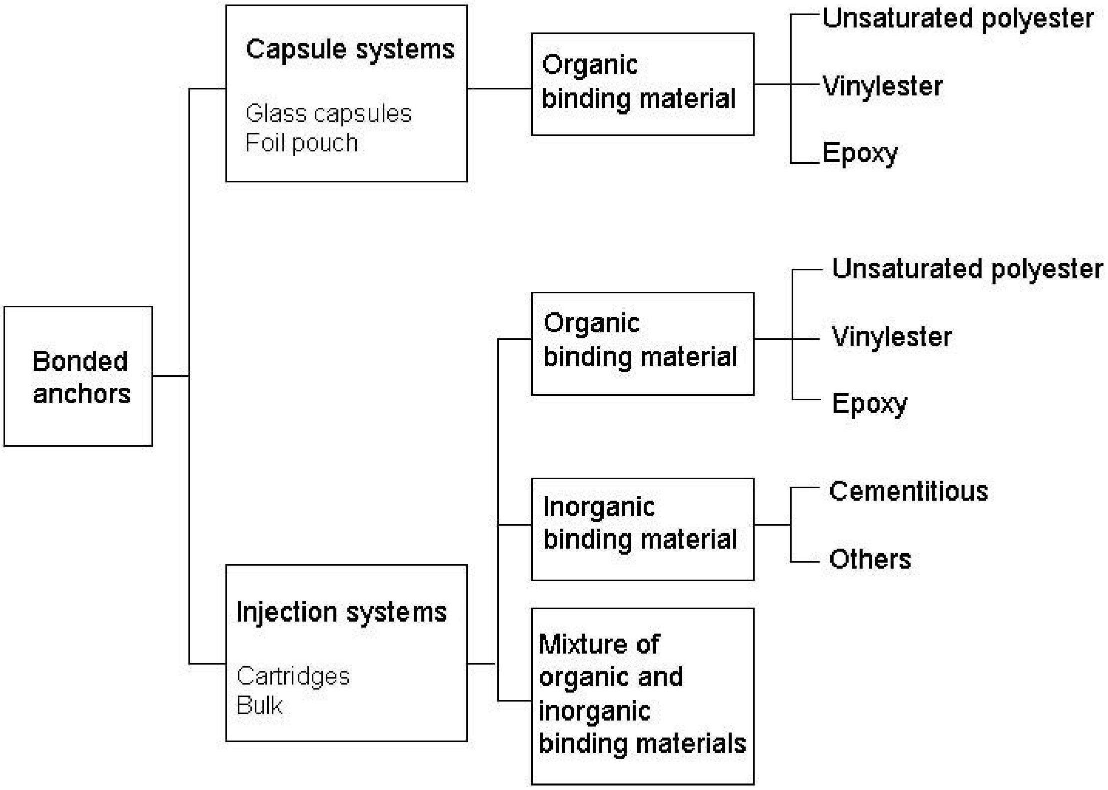


Fig. 1: Classification of bonded anchors (after Comité Euro-International du Béton (CEB) (1994))

Thanks to the continuous development in the last years these anchors are more and more used in practice. The high performance reached by bonding materials, the possibility of application with small edge and spacing distances (since smaller expansion forces are generated during the installation and under load than in the case of mechanical expansion anchors) and the low price of these systems compared to mechanical ones with similar performance are some of the reasons of the success of bonded anchors.

The efficiency of these anchorage systems depends strongly on correct installation of the anchor. The installation procedure of bonded anchors is regulated by Technical Approvals and if these prescriptions are followed, the desired performance of the anchorage is reached.

In the approval tests the sensitivity of bonded anchors to hole cleaning is checked under specific conditions. However, in practice it may not be excluded that bonded anchors are installed in a way that is not reflected in the approval tests.

The goal of this study is to investigate the impact of Technical Approvals on the installation of bonded anchors. A survey was conducted on installers and engineers, who have installed or supervised the installation of bonded anchors at least once. In order to evaluate the installation quality, some general questions were asked:

1) Have the requirements of the Technical Approval been applied?
2) Do installers and supervisors have basic knowledge about the main factors that are relevant for the correct installation of bonded anchors and their influence on the loading behaviour of these anchors?
3) How were the bonded anchors installed in reality?

In section 2 an overview of the main installation parameters and their influence on the performance of bonded anchor is given. In sections 3 and 4 the survey is presented and analyzed. The results of the study are summarized in section 5.

2. Installation parameters and their influence on the performance of bonded anchors

In addition to the provisions that have to be followed for every type of anchor, e.g. diameter, depth and orthogonality of the hole in base material, for bonded anchors some additional provisions are particularly relevant in order to achieve a correct performance. These are:

a) Cleaning of the drill hole, usually by means of air jetting and brushing according to the Technical Approval and / or manufacturer's instructions;
b) inspection of the base material (concrete) to determine whether it is cracked or uncracked. Bonded anchors, with the exception of a few products (e.g. bonded undercut anchors and bonded expansion anchors), are usually less suitable for usage in cracked concrete since they exhibit a large drop down in their carrying capacity;
c) further provisions concerning bonding materials due to installation:
    - storage conditions (temperature and production date);
    - temperature of the base material;
    - dry, wet or water filled hole;
    - curing time, it shall be chosen according to the manufacturer's instructions depending on the temperature and other environmental influences.

The reason why the condition of the drill hole and of the bonding material prior to installation are so important for bonded anchors is that the carrying capacity of bonded anchors under tension loading is determined by adhesion and mechanical interlock between mortar and rod and between mortar and drill hole.

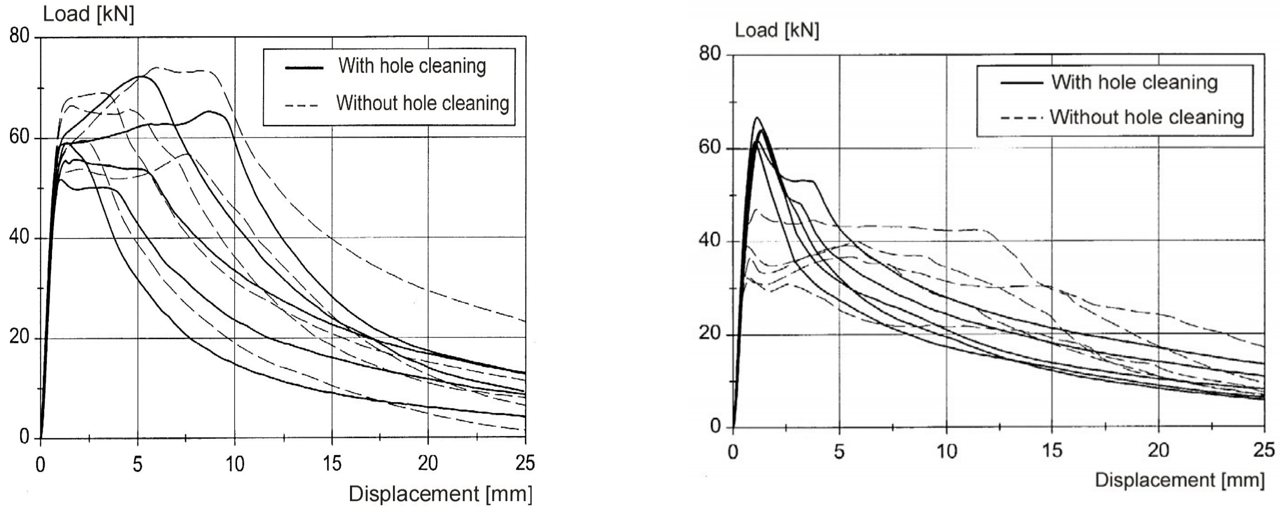
The influence of the main installation parameters on the bond behaviour of different products is taken into account by installation safety tests according to [3]. Installation safety tests are intended to assess the sensitivity of the tested mortar system to the variations of installation parameters, as they are likely to be experienced in practice. They are not intended to address major installation errors. Major installation errors are characterized by significant deviations from the manufacturer's installation instructions or design specifications.

For this study the main provisions that were considered are those of a). Some extensive studies about the relevance of these provisions can be found in the literature [1],[2]. An explanation of the influence of hole cleaning on the behaviour of bonded anchors is given in section 2.1.

2.1 Influence of cleaning intensity on bond strength

Fig. 2a and Fig. 2b show the influence of hole cleaning on the load-displacement behaviour of anchors installed in dry concrete. In both figures the load-displacement curves for thorough cleaning of the hole using a stiff brush and by blowing with a hand pump are compared to those measured on anchors installed without cleaning of the hole. Depending on the mortar system, the lack of hole cleaning can have either a minor effect on the load displacement behaviour and the ultimate load (bond strength) or a more pronounced one. Capsule systems that are installed by forcing the rod through the capsule with both hammering and drilling are generally among the least sensitive types of bonded anchors systems. This may be attributed to the rotary action which, in combination with the quartz aggregate contained in the resin capsule, rubs the dust from the hole wall. The reduction in tension capacity of such systems installed in uncleaned holes is usually less than 20%. In case of injection systems the reduction in tension capacity associated with inadequate hole cleaning depends on the bonding material and can range from less than 20% to as much as 50%. It is therefore important that in case of injection systems the hole is mechanically cleaned with a suitable stiff brush and subsequently blown out. Compressed air alone is generally not adequate to remove the dust from the side of the hole. In wet concrete effective cleaning of the hole is particularly difficult, because the drilling dust tends to stick to the wall of the hole. In addition, depending on the type of mortar, the water film on sides of the hole can have an unfavourable effect on the bond strength.

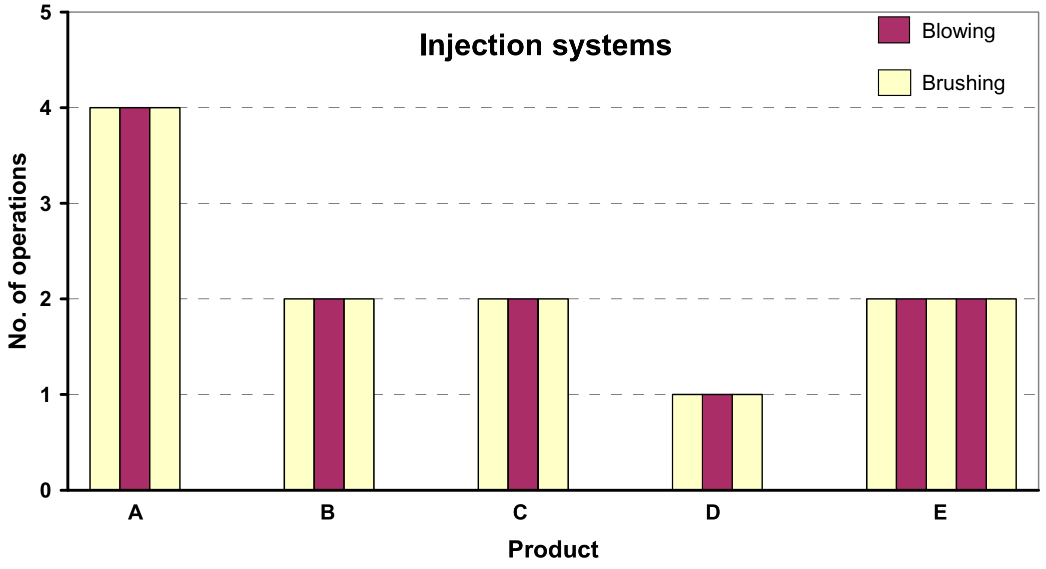
The bond strength associated with bonded anchors installed in dry / wet concrete is highly product dependant and should therefore be determined for each system through testing. This is done in Approval tests.



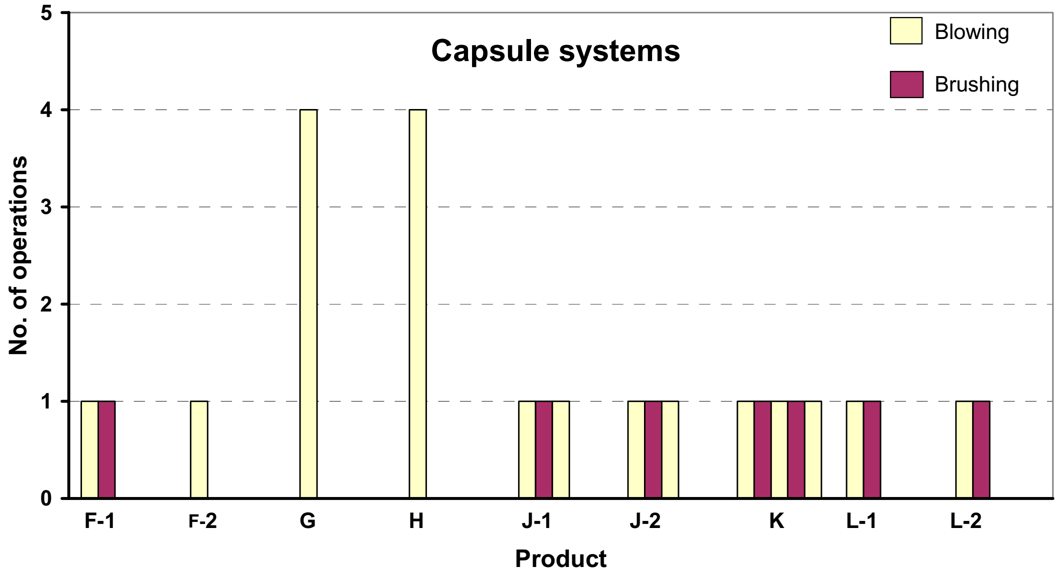
a) b)

Fig. 2: a) Load-displacement curves of bonded anchors, anchored with and without cleaning the drill holes (anchor type not sensitive to hole cleaning) [2]; b) load-displacement curves of bonded anchors, anchored with and without cleaning the drill holes (anchor type sensitive to hole cleaning) [2]

The hole cleaning requirements are usually strongly product dependant. The number and sequence of cleaning operations are shown in Fig. 3 for injection and capsule systems according to manufacturer's instructions. For example, for a correct installation of product "A" in Fig. 3a the drill hole has to be blown out 4 times, brushed 4 times and blown out again 4 times.



a)

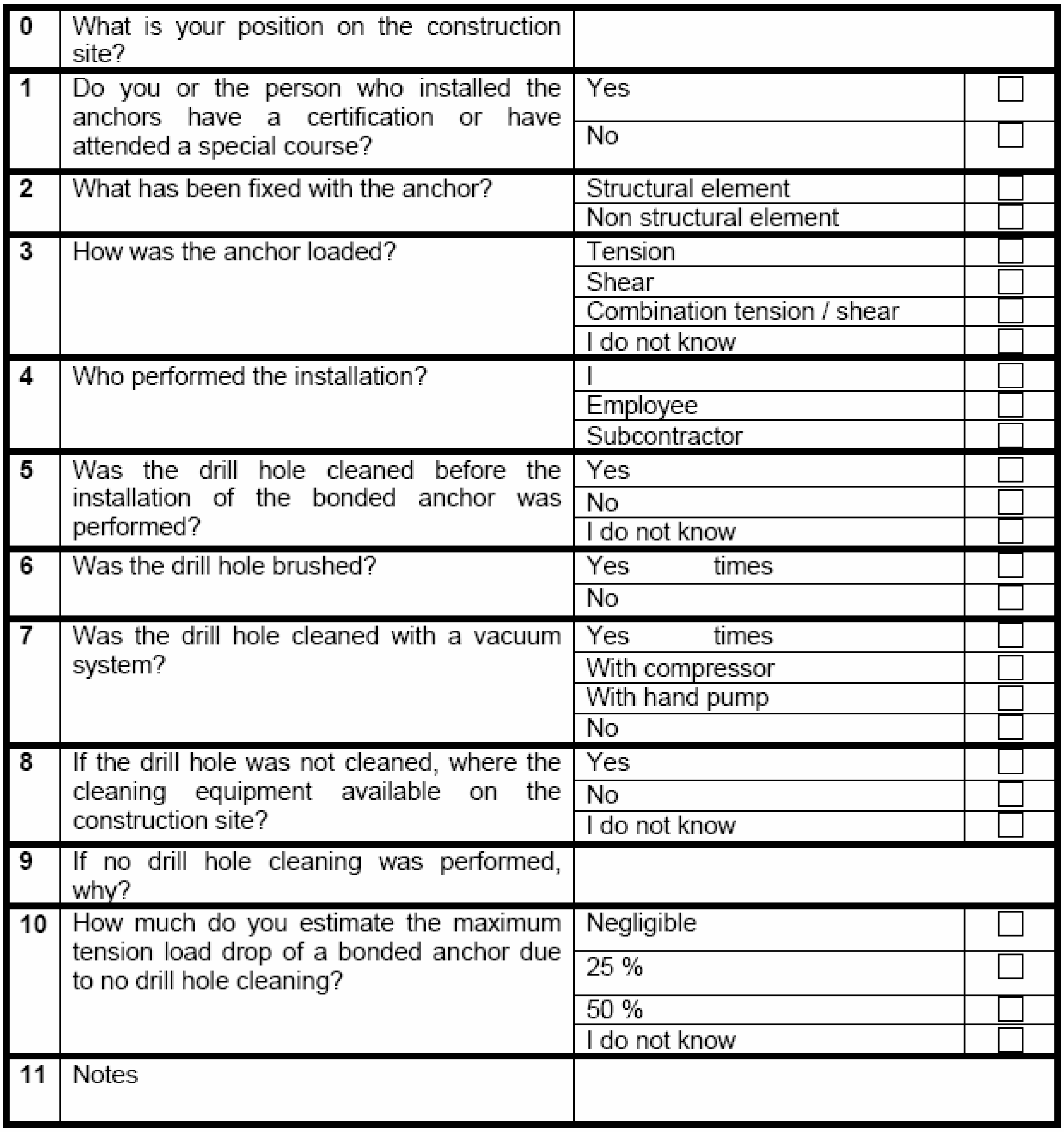


b)

Fig. 3: Comparison of hole cleaning requirements for different adhesive anchors:
a) injection systems; b) capsule systems

3. Survey

In the context of this study, anchor installers and engineers, who had at least once installed a bonded anchor or supervised its installation, had to answer some basic questions about how the installation was performed. The questions of the survey were chosen to be generic (i.e. no product specific questions were asked) and as simple as possible in order to be understandable for everyone. The survey was performed in three European countries: Germany, Italy and Croatia. The text of the survey, presented in Fig. 4, was translated into the corresponding language.

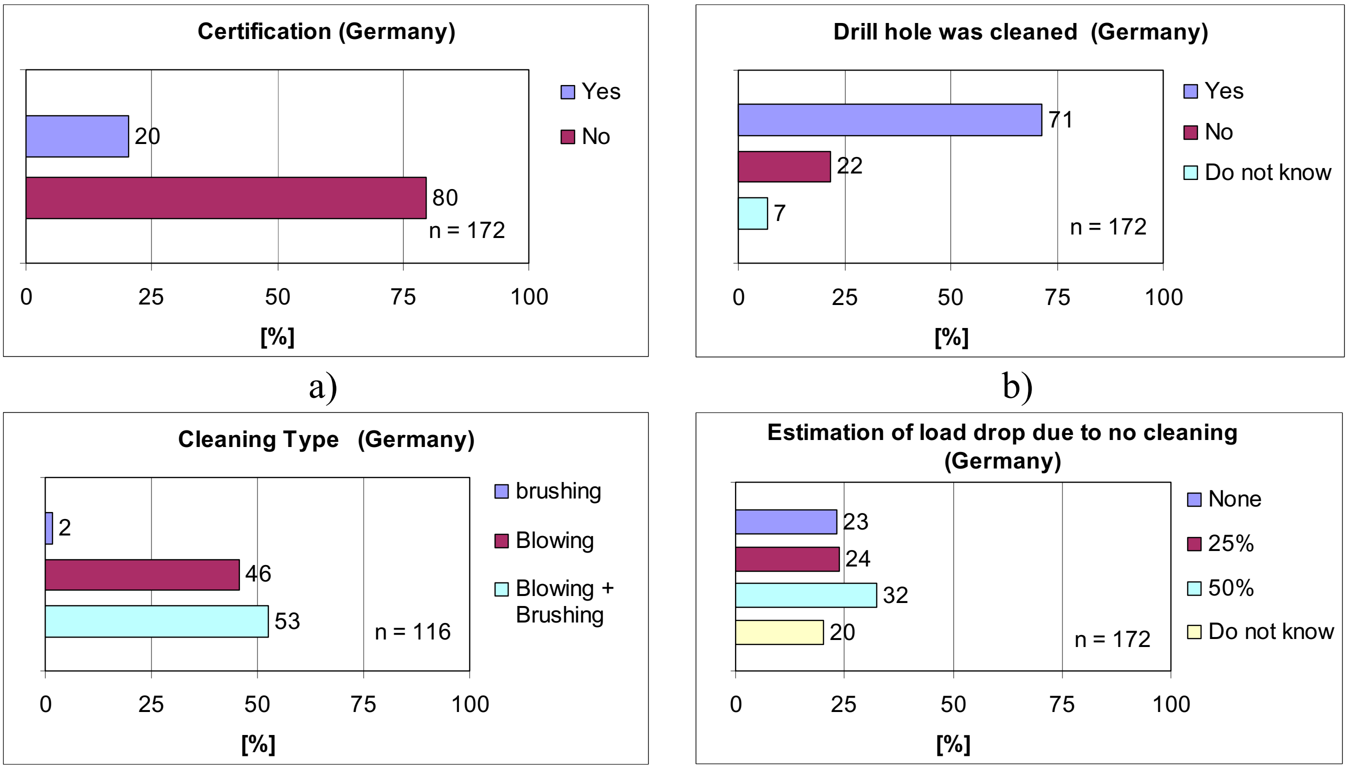


0	What is your position on the construction site?		
1	Do you or the person who installed the anchors have a certification or have attended a special course?	Yes	☐
		No	☐
2	What has been fixed with the anchor?	Structural element	☐
		Non structural element	☐
3	How was the anchor loaded?	Tension	☐
		Shear	☐
		Combination tension / shear	☐
		I do not know	☐
4	Who performed the installation?	I	☐
		Employee	☐
		Subcontractor	☐
5	Was the drill hole cleaned before the installation of the bonded anchor was performed?	Yes	☐
		No	☐
		I do not know	☐
6	Was the drill hole brushed?	Yes times	☐
		No	☐
7	Was the drill hole cleaned with a vacuum system?	Yes times	☐
		With compressor	☐
		With hand pump	☐
		No	☐
8	If the drill hole was not cleaned, where the cleaning equipment available on the construction site?	Yes	☐
		No	☐
		I do not know	☐
9	If no drill hole cleaning was performed, why?		
10	How much do you estimate the maximum tension load drop of a bonded anchor due to no drill hole cleaning?	Negligible	☐
		25 %	☐
		50 %	☐
		I do not know	☐
11	Notes		

Fig. 4: Text of the survey

4. Analysis of the survey

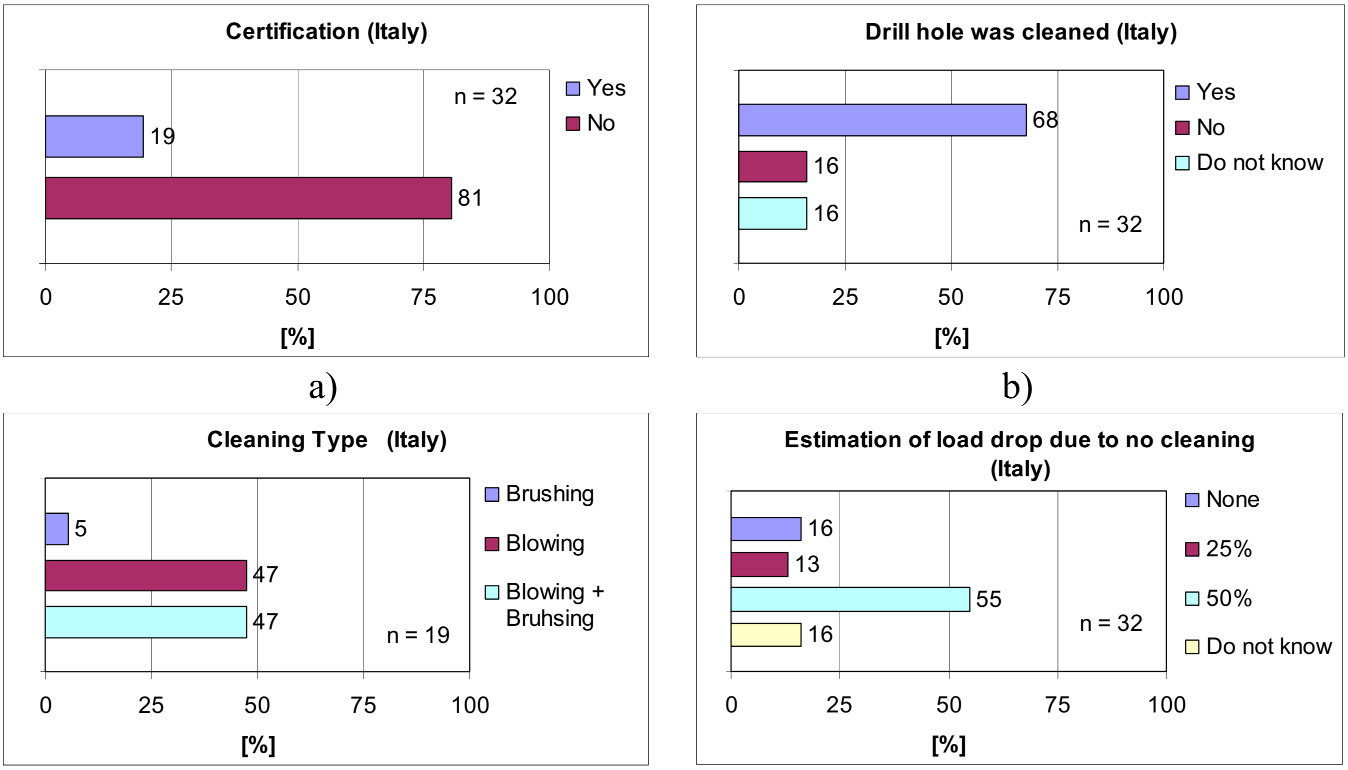
The survey was conducted in Germany, Italy and Croatia over a period of approx. 6 months. In Germany it was possible to have a quite extensive sample of the whole country (n = 172 persons). In Italy the sample can be representative only for the central and north-east area (n = 32 persons). In Croatia the sample was very limited (n = 8 persons), but it has to be considered that the country is much smaller than the other two and that the usage of bonded anchors is probably not widespread yet. In Fig. 5 and Fig. 6 the main results of the survey in Germany, Italy and Croatia are presented respectively.



a) b)

c) d)

Fig. 5: Main results of the survey in Germany



a) b)

c) d)

Fig. 6: Main results of the survey in Italy

A comparison of the survey results from Germany and Italy shows evident analogies even if the difference of dimension of the sample is quite large ($n_{\text{Germany}} = 172$ vs. $n_{\text{Italy}} = 32$). In both countries the percentage of installers who have a certification or have attended a special course for anchor installation was about 20% (see Fig. 5a and Fig 6a).

In about 30% of the cases either no hole cleaning was performed at all or no information was given about it (an occurrence that was recorded as „no cleaning“) (see Fig.5b and Fig. 6b). Considering the 70% of the installations where a drill hole cleaning was performed, in only approx. 50% of them the drill hole was both brushed and blown out, although most of the products available on the market require both operations (see Fig. 3). Only a minority of the installers were able to describe with precision the cleaning procedure (e.g. number and sequence of the operations).

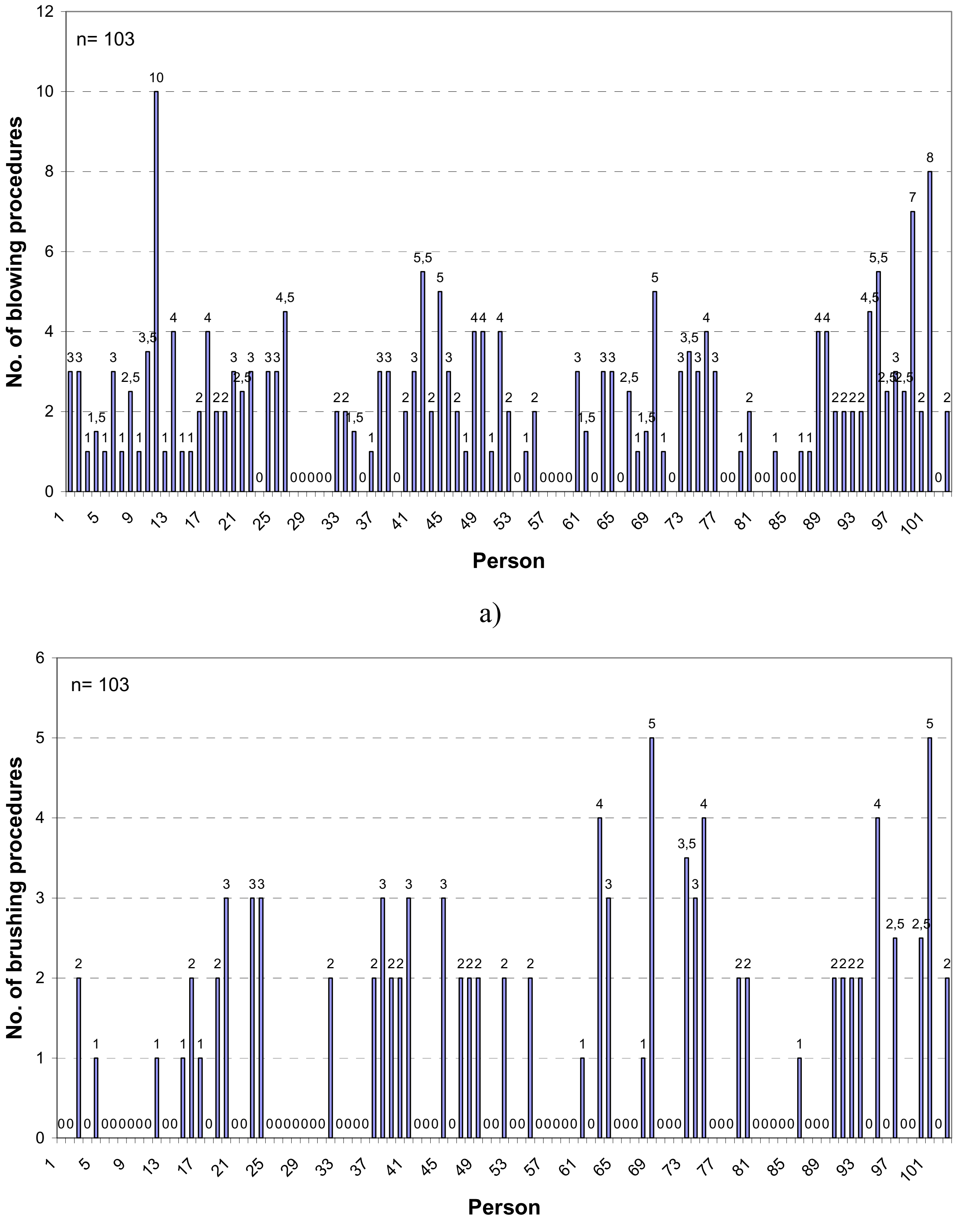
According to the analysis of the estimation of tension load drop due to no hole cleaning, in both countries approx. 35% of the people interviewed do not seem to be familiar with the problem (see Fig. 5b and Fig. 6b).

A detailed analysis of the survey conducted in Croatia was not possible, because the sample was too small. Still, even for this small sample the main trends observed for Germany and Italy seem to be confirmed.

In Fig. 7 the sequences of cleaning procedures are presented. The sample (n) of 103 persons (49% of the whole sample) takes into account:

a) the installers who did not performed any hole cleaning and
b) the installers who performed the hole cleaning and gave precise information about how the hole cleaning was conducted.

Unfortunately it was not possible to get detailed information on how the cleaning procedure was performed by about 50% of the interviewed persons. Due to this lack of information it was not possible to realistically estimate the average number of cleaning operations performed in practice. However, Fig. 7 shows that the average amount of blowing procedures is 2,1 and the amount of brushing procedures is 0,97. Taking into account only those installers, who performed blowing and / or brushing, the average number of blowing operations is 2,74 (n = 79) and of brushing operations is 2,37 (n = 42) Furthermore Fig. 7 confirms that blowing out is a more common cleaning procedure than brushing. Note that blowing alone is generally not adequate to remove the dust from the hole.



a)

b)

Fig. 7: Sequences of cleaning operations: a) number of blowing procedures; b) number of brushing procedures

5. Conclusions

The high sensibility of bonded anchors to some installation parameters like hole cleaning is theoretically well known and has been experimentally verified. Installation safety tests are intended to assess the sensitivity of the tested mortar system to variations in installation parameters that are likely to be experienced in practice. The survey was conducted in order to evaluate the general knowledge about the installation of bonded anchor in the practice. According to the answers given by 212 respondents in three different European countries (Germany, Italy and Croatia) the following observations can be done:

The general difficulty of the installers in giving exact information about the cleaning operations that they performed is comprehensible, if the hole cleaning prescriptions of different manufactures are compared (see

- Fig. 3). The differences are even larger if cleaning components of different manufactures are considered: nylon and steel brushes, manual and mechanical brushing, hand pumps and special air nozzles. Each manufacturer in selling their own cleaning tools and prescribing different cleaning procedures is against the interest of the practice, where standardised procedures are easier to apply by installers. The issue then becomes whether this strong differentiation is really necessary;
- hole cleaning was considered in most of the cases (approx. 70%), but often it does not seem to be performed in the right way;
- the results of the survey should be completed and validated by interviews on construction sites.

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THE "CERTIFIED FASTENING TECHNICIAN" AS AN EXAMPLE OF ADVANCED TRAINING FOR USERS

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Abstract

Over the past 30 years, fastening technology evolved into one of the most innovative branches within the construction industry. Last year, the number of product manufacturers in this field came to more than 20 throughout Europe. In January 2006, e.g. approximately 230 German and around 240 European technical approvals for fastening products have been issued. Despite this development the fastening technology is still a relatively young discipline. There is no defined state of the art documented in mandatory regulations or standards [1]. The design normally follows the German or European technical approvals.

1. Introduction

The user can choose from a vast number of different fastening devices which have been developed for certain fields of application. Today, there are suitable anchoring systems made of steel or plastic for nearly every application which ensure reliable and lasting transfer of loads into the base material. Through different anchorage mechanisms, materials and dimensions they are suited to various applications in surfaces such as reinforced concrete and masonry. The European Technical Approval says on the setting of anchors: “anchor installation carried out by appropriately qualified personnel under supervision of the person responsible for technical matters on site“ [2]. Apart from that, there is no regulation which defines how the technician should be trained.

Therefore, we have developed a concept for imparting the necessary basic knowledge for correct assembly and the handling of the partly very extensive approvals to the craftsperson in cooperation with the Institute of Construction Materials of the University of Stuttgart. The training as "Certified Fastening Technician" was brought into being in 2003. So far, more than 1,200 craftspersons – ranging from apprentices to company owners – have completed the training successfully. The seminar stretches over two and a half days and conveys to the user not only the most important theoretical basics for securely fastening anchors but comprises also an extensive practical part. This part focuses on incorrect fastening and potential risks arising from it.

2. Contents

The following chapters will summarise the contents of the training. It is our goal to show that the knowledge needed for secure assembly is very extensive and that profound education is contributing greatly to safely handling fastening materials and processes (Fig. 1). The curriculum was developed in cooperation with the Institute of Construction Materials of the University of Stuttgart.

Fig. 1: Every anchor system is dealt with thoroughly and "dry" theory is illustrated with examples as well as anchors that can be grabbed [3].

3. Actions

The actions on fastening material can be divided into load-related actions and actions unaffected by the loads. Load-related actions are e.g. the dead weight of a component to be fastened or loads which are changing only slowly such as weight of people. Besides these static loads there are dynamic loads such as impulsive ones, e.g. caused by an impact, or frequently repeating loads like loads on lifts. The static and dynamic actions can act as tension load, compression load, shear load and combined tension and shear load under a certain inclination to the axis of the fastener.

Actions unaffected by the loads such as air and rain containing pollutants may remove the protective coating like e.g. zinc of the anchors. This may lead to corrosion and thus weakens the cross-section. On the outside or in damp locations only stainless steel must be used. In addition, direct sunlight in summer may heat up the surfaces to more than 80° C. Further actions unaffected by the loads are frost and fire.

4. Anchorage material

The basis for secure fastening is knowledge on the anchorage material. Anchorage materials suitable for the use of anchors are, among others, concrete, lightweight concrete blocks, solid brick, perforated brick, sand-lime bricks, aerated concrete etc. There are anchors which have been especially developed for each of these surfaces, differing much in their field of application and the transferable loads. For a lot of surfaces there are anchor systems which European Technical Approvals and German approvals are available for. Approval certificates for the use of bonded and plastic anchors in concrete mostly apply for the strength classes from C12/15 to C50/60, approval certificates for metal expansion and undercut anchors for the classes between C20/25 and C50/60. For brick according to DIN there are anchors which are approved by the construction supervising authority. Besides, there are also many stones which are approved by the construction supervising authority. Anchor approvals for these stones do not contain any load ratings. Therefore, tensile tests have to be carried out directly at the building. DIN stones are available as brick and sand-lime bricks as well as blocks of lightweight concrete, normal concrete and aerated concrete. Bricks can be further divided into perforated and solid bricks. They differ in the percentage of perforations.

5. Assembly and function

Anchor systems can be classified according to three different anchorage mechanisms. These are: mechanical interlock (e.g. undercut anchor), friction (e.g. bolt-type anchor) and bonding (e.g. bonded anchors). Different guidelines have to be complied with in order to ensure secure fastening of any of these systems. These guidelines are specified in the respective approvals. Among other things the right drilling technique, cleaning the drill hole (Fig. 2) and applying the specified torque moment belong to the most important assembly parameters. Since almost all systems differ in their way of assembly it is of utmost importance to adhere to the specifications given in the approvals.

Fig. 2: Correctly cleaning the drill hole is extremely important [3].

Fig. 3: The consequences of wrong assembly (here: edge distance too small) are proven in an impressive way [3].

6. Regulations / Contents of the approvals

As fastening technology is a field which shows huge innovative potential and which is not yet fully explored, fastening has not yet been included in standards. The proof of suitability as a construction product is provided with a German approval by the German Institute for Construction Engineering DIBt in Berlin or a European Technical Approval (ETA) which can either be obtained through the DIBt or another European approval body for new construction products.

7. Practical tests

Ignoring the assembly instructions given in the approvals such as edge or spacing, cleaning of drill holes, drilling technique, assembly torque, temperature etc. may lead to serious damage. Therefore, it is extremely important to know about the correct use of the individual anchors. It is furthermore essential to have a good command of dealing with the partly very extensive approvals (Fig. 4).

Fig. 4: Correct handling of the extensive approvals has to be practiced [3].

That is why the practical part of the training as "Certified Fastening Technician" focuses on correctly dealing with approvals and avoiding typical assembly mistakes. (Fig. 5). Therefore, setting of anchors is carried out according to the approvals respectively with typical assembly mistakes. E.g. bonded anchors with and without cleaning the drill hole or bolt-type anchors with specified and too low or too high torque are assembled. In addition, the difference of the maximum transferable load between non-cracked and cracked concrete (tension zone) is shown with different anchors.

Fig. 5: A reinforcement detector helps avoiding to hit the reinforced bars [3].

For simulation purposes two concrete blocks of non-cracked and cracked concrete are available during the training (Fig. 6). Through hydraulic draw gear and complex electronic measurement technology the anchors fastened by the seminar participants can be loaded directly to failure (Fig. 7). Thus, it is possible to directly illustrate the effects of incorrect assembly with the help of load-displacement curves (Fig. 8).

Fig 6: The tension zone (cracked concrete) is simulated [3].

Fig. 7: Is it not easier to understand the individual forms of failure when you see them yourself? The anchors are loaded to failure using extensive measuring technology [3].

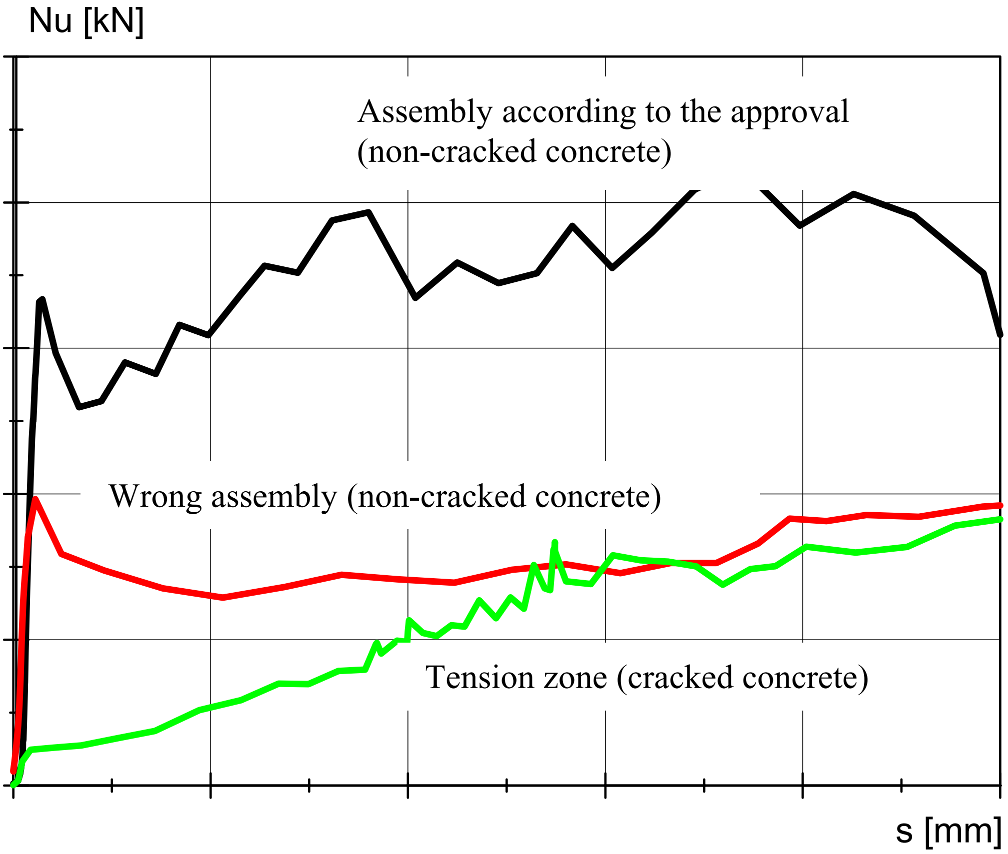

Fig. 8: It is not only theory that the wedge anchor does not work in the tension zone (cracked concrete). This can be demonstrated impressively during the tests [3].

8. Certificate

On the third training day the participants take their exam and receive their university certificate from the University of Stuttgart after passing the exam (Fig. 9). This certificate confirms that the participant has acquired the necessary professional knowledge on anchors with technical approval and qualifies him/her to employ this knowledge in theory and practice – this is a clear advantage towards other competitors, especially since the question of safety today is placed in the focus more than ever before.

Fig. 9: Happy participants who successfully passed the exam in Mönchengladbach in January 2006 [3].

9. Acknowledgement

Special thanks are accorded to Beate Küenzlen who spent many hours in improving the English.

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EUROPEAN TECHNICAL APPROVAL (ETA) FOR ANCHORAGES

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Abstract

Since 1998 European Technical Approvals (ETAs) have been issued for several metal anchors for use in concrete. Anchors with an ETA, satisfying the Attestation of Conformity provisions, may carry the CE-marking and may be placed on the market in any of the Member States of the European Union and used under the same conditions.

The European Organisation for Technical Approvals (EOTA), the existing Guidelines for European Technical Approval (ETAGs) and the issued European Technical Approvals (ETAs) for different anchor types will be presented. It will be explained how new research for anchorage systems and service conditions can become integrated fast into Guidelines via a Progress File or Technical Reports. Finally, the possibility of getting an ETA for anchor products without an existing guideline will be introduced.

1. Introduction

The uniform assessment for metal anchors and the general design method for anchorages according to a European Guideline have been a big step towards harmonisation and acceptance of the new technology for fastening systems in Europe. However only a few ETAs for anchors have been issued after the first ETAG 001 was available in 1997. Now, after ten years, anchor products with ETAs are established and very successful. Approximately 360 ETAs are available for different anchor types used in different base materials. The ETAs have been issued for more then 80 applicants in 18 Member States of the European Union and show the great acceptance of the system in Europe.

Since the technology of fastening systems is subjects to new developments, which should be considered quickly in the corresponding ETAs, the Guidelines have to be "a living document". Also new knowledge and experience developing during the approval work require a permanent adaptation of the Guidelines. The instruments for a fast implementation of new developments and experiences are included in the general rules of the ETA procedure. This big advantage is intensively used for the assessment of anchor systems and will be introduced in the following.

2. EOTA

The European Organisation for Technical Approvals (EOTA) [1] comprises the Approval Bodies nominated to issue European Technical Approvals (ETAs) by EU Member States who have contracted to the European Economic Area agreement. The EOTA operates in close co-operation with the European Commission, EFTA, CEN, European trade associations and industrial organisations. The EOTA has been created in the framework of the implementation of the Construction Products Directive [2] for the harmonisation of construction products in the European Union.

The role of the EOTA is primarily to monitor and to progress the drafting of ETA Guidelines (ETAGs) and to coordinate all activities related to the issue of ETAs. ETAGs are elaborated for a certain product area within working groups and project teams. The elaboration is based on a mandate issued by the European Commission and on an approved work programme.

There are four mandates given by the European Commission for the elaboration of Guidelines for the different anchor systems. EOTA has assigned the Deutsches Institut für Bautechnik [3] the convenor ship and the secretariat for all the four working groups. The European manufacturers of anchors represented by their associations CEO (Comité Européen de l'Outillage - European Tool Committee) and ECAP (European Concortium of Anchor Producer) are also involved in the elaboration of the Guidelines.

3. ETAG

3.1 ETAG 001

The Guideline for European Technical Approval of Metal Anchors for Use in Concrete [4] was adopted in 1997 as the very first ETAG. ETAG 001 is the most important Guideline because almost all anchor products can be evaluated according to this Guideline.

It consists of a general part (Part 1) for all types of metal anchors and of five further parts applying to the following:

Part 2: Torque-controlled expansion anchors

Part 3: Undercut anchors

Part 4: Deformation-controlled expansion anchors

Part 5: Bonded anchors

Part 6: Anchors for multiple use for non-structural applications.

Part 1 includes the requirements and assessment methods for all metal anchors, whereas the subsequent parts contain additional and/or deviating requirements, the required tests and assessment methods. These parts shall only be used in connection with Part 1.

The Guideline covers the assessment of metal anchors if their use shall fulfil the Essential Requirements 1 and 4 of the CPD and if failure of the anchors made with these products would compromise the stability of the works, cause risk to human life and/or lead to considerable economic consequences.

Fixtures with anchors according to Part 2 to 5 can be supported either statically determinate (one or two supports) or statically indeterminate (more than two supports). In contrast, fixtures with so called part six anchors (anchors evaluated according to Part 6) can only be used for multiple use for non-structural applications. The design of this fixture is in a way that in the case of excessive slip or failure of one anchor the load can be transmitted to neighbouring anchors without significantly violating the requirements on the fixture in the serviceability and ultimate limit state. This requirement for the design has to be considered unconditionally, because the assessment of anchors assuming multiple use according to Part 6 is carried out at a lower level as the anchors of Part 2 to 5. The definition of multiple use is up to the Member States and is given by them. Annex 1 of Part 6 contains the definition of multiple use of the several Member States and gives the default values.

The Guideline also includes the following three Annexes:

Annex A: Details of tests

Annex B: Tests for admissible service conditions – Detailed information

Annex C: Design methods for anchorages.

Annex A includes details of tests, such as test samples, test members, anchor installation, test and measurement equipment, test procedure and test report.

Annex B contains detailed information on the type and number of tests for admissible service conditions.

Annex C describes the design methods for anchors for use in concrete. The design of the individual anchorages (e.g. static background, anchor groups, influence of concrete member edges or corners) is based on the characteristic values of the single anchor determined for the different failure modes and the different load directions according to the above mentioned parts of the Guideline and given in the relevant ETA for the anchor concerned. Only the individual product characteristic for the product specification should be included in the ETAGs. However the design method was also integrated in the Guideline because the whole concept of ETAG 001 (tests, assessment and design) belongs together. In the near future the general design method will be transferred into a Technical Specification “Design of Fastenings for Use in Concrete” in the context of a CEN standard of Eurocode 2.

3.2 ETAG 014, 020 and 029

The following Guidelines in the field of anchors have been prepared:

ETAG 014: “Plastic Anchors for fixing of external thermal insulation composite systems with rendering” issued January 2002.

ETAG 020: “Plastic Anchors for multiple use in concrete and masonry for non-structural applications” issued March 2006.

ETAG 029: “Metal injection anchors for use in masonry” not issued yet.

4. Progress Files

The EOTA has created so-called “Comprehension Documents” and “Progress Files” for the corresponding Guideline. These are used for a fast realisation of knowledge and experience developing through approval work and consideration of new developments and research of systems and service conditions.

These above mentioned instruments have been used often since the establishment of ETAG 001 in 1997; to ensure that the approval process may follow fast the development of the fastening techniques.

The Comprehension Documents contain only interpretation of specific items of the Guideline which are mostly detected during the approval work by the different Approval Bodies. These items will be discussed at first in the Working Group "Anchors" to find a technical solution. After the endorsement of the Comprehension Document in the Working Group and the agreement in the EOTA the document may be used for approval process. All Approval bodies are informed by EOTA, but the documents are not published.

Progress Files contain real amendments of the Guideline. The procedure is the same as described above for the Comprehension Documents. Since the Progress File includes amendments or changes of the Guideline these new conditions have to used for updating the Guideline. Therefore the content of a Progress File has to be endorsed by the European Commission and will be integrated in the Guideline. The Progress File itself is not published, but the Approval Bodies inform about current documents.

A Progress File for ETAG 001 (dated April 2004) exists. The main items of this Progress File are to delete some test series and reduce the number of tests. This may be possible due to many experiences in the evaluation during several approval procedures with different anchors. A significant reduction of the number of tests is also feasible if the design method of Annex C of ETAG 001 is used. As described above the content of the Progress File is now integrated in ETAG 001 and the amended version of ETAG 001 [4] is available on the EOTA website.

5. Technical Report

5.1 General

EOTA Technical Reports are developed as supporting reference documents to European Technical Approval Guidelines and can be applicable as far as reference is made therein. Technical Reports go into detail in some aspects and express the common understanding of existing knowledge and experience of the Approval Bodies at a particular point in time. The Working Group "Anchors" has prepared three Technical Reports in the field of anchors according to ETAG 001. These Technical Reports are endorsed and published by EOTA [1] and will present in the following.

5.2 TR 020, Resistance to fire of anchorages

The judgment of the fire resistance of anchorages is an important item in the design of structures including the fixture. It is known that a lot of manufacturers have carried out fire tests with their different metal anchors in concrete. Because these fire tests have been executed at different tests labs under unequal conditions the results are not comparable and may not be used for the common assessments for ETAs. After further basic research with metal anchors in concrete under fire exposure the Working Group anchors prepared a general paper (Technical Report TR 020) for “Evaluation of Anchorages in Concrete concerning Resistance to Fire” to get common rules for this judgment. The Technical Report TR 020 [5] has been issued in May 2004.

The Technical Report TR 020 contains the evaluation for anchorages in normal weight concrete with a strength of at least C 20/25 and at most C 50/60 used for normal structures under fire exposure. The determination of the duration of the fire resistance is according to the "Standard Temperature/Time Curve" (STC). In general, the duration of the fire resistance of anchorages depends mainly on the configuration of the structure itself (base materials, anchorage including the fixture). It is not possible to classify an anchor for its fire resistance. The evaluation concept in TR 020 includes the behaviour of the anchorage in concrete and the parts outside the concrete. The influence of the fixation is considered unfavourable.

The evaluation according to TR 020 is only valid for metal anchors with a European Technical Approval (ETA), which can be used in cracked and non-cracked concrete. This is understandable because under fire exposure cracks may occur in the concrete and therefore a general suitability of the anchors in cracked concrete is a precondition.

The Technical Report TR 020 contains two different design concepts. By using the simplified design concept for all load directions and failure modes the limit values must be observed (characteristic resistance in ultimate limit state under fire exposure), which were developed by general test series and are on the save side. Tests with fire exposure are not necessary when using the simplified design concept. The Technical Report contains all design rules for the different load directions and failure modes for the simplified design concept, the terminology of the design follows the design method under normal temperature according to Annex C of ETAG 001. The characteristic resistance of anchorages in case of steel failure under fire exposure (characteristic tension strength $\sigma_{Rk,s,fi}$) is given in the Technical Report. These values are also valid for the unprotected steel parts of the anchor outside the concrete and these values have been determined from many hundred tests which were collected in the basic research. The values are on the save side because the worst results with a safety distance had to be considered. The following Table 1 shows the characteristic tension strength of an anchor made of normal carbon steel under fire exposure.

Table 1: Characteristic tension strength of an anchor made of C-steel under fire exposure

anchor bolt/thread diameter [mm]	anchorage depth h_{ef} [mm]	characteristic tension strength of an unprotected anchor made of C-steel in case of fire exposure in the time up to: $\sigma_{Rk,s,fi}$ [N/mm²]			
		30 min (R 15 to R30)	60 min (R45 and R60)	90 min (R90)	120 min (R120)
Ø 6 / M6	≥ 30	10	9	7	5
Ø 8 / M8	≥ 30	10	9	7	5
Ø 10 / M10	≥ 40	15	13	10	8
Ø 12 / M12 and greater	≥ 50	20	15	13	10

In some cases the above values are not sufficient for the design of the anchorages under fire exposure. Therefore the Technical Report TR 020 contains also a second design concept (experimental determination) where the duration of fire resistance of the anchor can be determined from the test results. For all load directions and failure modes the required tests or investigations are given. The Technical Report contains all details of the test set-up and the description of the test procedure and the verification in detail to get a unique assessment and comparable results for the different anchors. The following Figure 1 shows the test set up for determination of the most important behaviour of the steel failure under fire exposure.

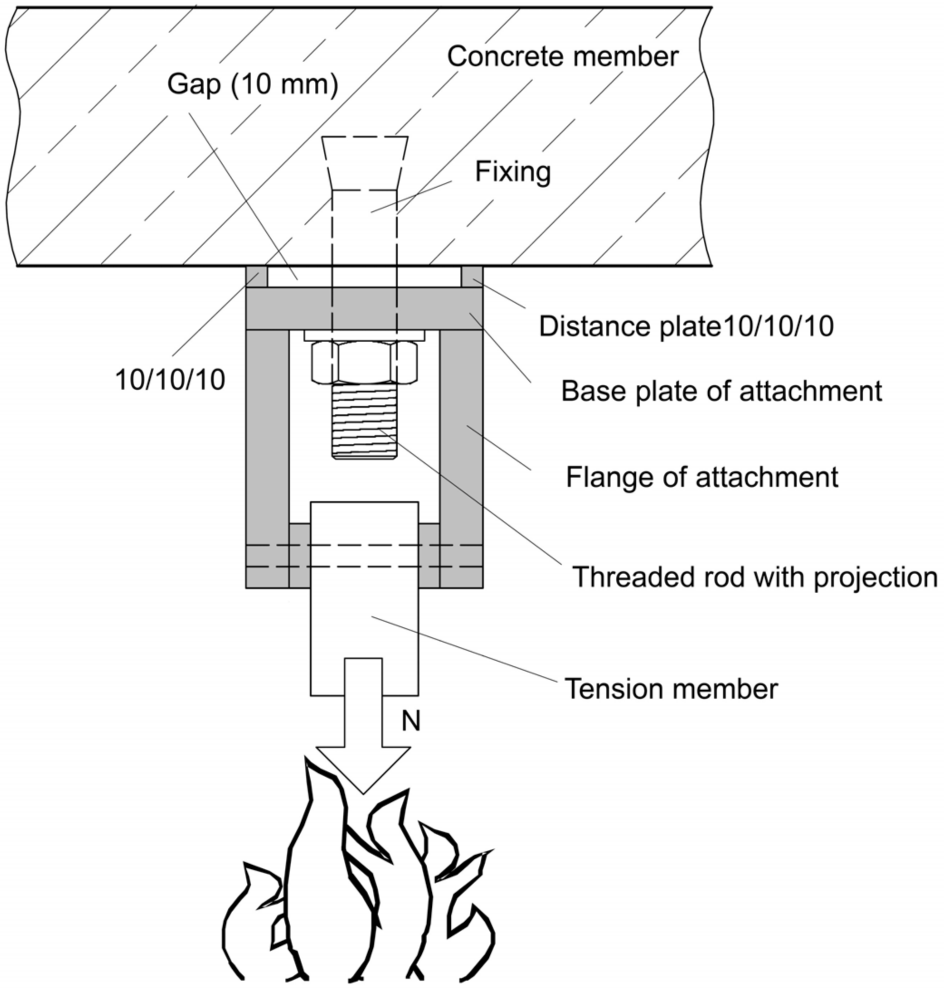

Fig. 1: TR 020 – Test set-up for the determination of steel failure under fire exposure

In general, the Technical Report TR 020 allows unique assessments of anchorages in concrete concerning resistance to fire. Several ETAs for metal anchors have been issued with characteristic resistance values under fire exposure according to the Technical Report TR 020 with the simplified design concept but also with the experimental determination via fire tests.

5.3 TR 018 and TR 023, Bonded anchors

Bonded anchors with a standard anchor rod (see Figure 2) and bonding material (mortar) can be evaluated according to the ETAG 001, Part 5. When Part 5 of the ETAG 001 was originally discussed, there was not enough knowledge about bonded anchors. The only operating principle known at this time was the anchorage by bonding the anchor rod to the sides of the drilled hole. Therefore Part 5 of ETAG 001 contains an advice only that the evaluation of the other operating principles of bonded anchors will be specified in a Technical Reports later on. The two following Technical Reports are available.
TR 018 [6] Assessment of torque-controlled bonded anchors and
TR 023 [7] Assessment of post-installed rebar connections

The Technical Reports TR 018 and TR 023 can only be used in correlation with Part 5 of ETAG 001.

Torque-controlled bonded anchors according to TR 018 (see Figure3) are installed in cylindrical holes, the load transfer is realised by mechanical interlock of a cone or several cones in the bonding mortar and then via a combination of bonding- and friction forces in the anchorage ground (concrete). Torque-controlled bonded anchors act like torque-controlled expansion anchors corresponding to Part 2 of ETAG 001 in case of use in cracked concrete. Therefore these anchors are suitable particularly for use in cracked concrete. The required test programme and the assessment are given in the Technical Reports TR 018. ETAs for these kind of special bonded anchors have already been issued.

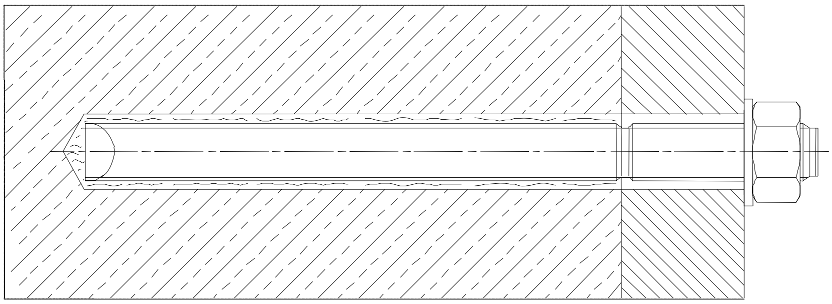

Fig. 2: ETAG 001, Part 5 – Bonded anchors

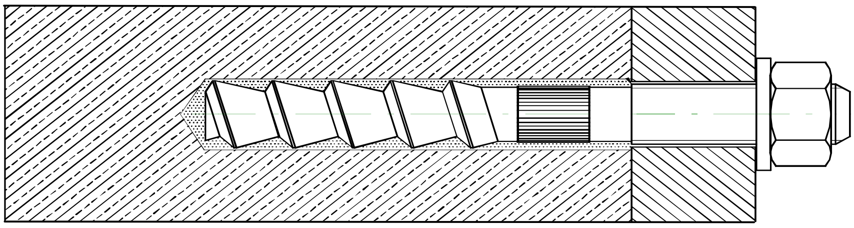

Fig. 3: TR018 – Torque controlled bonded anchors

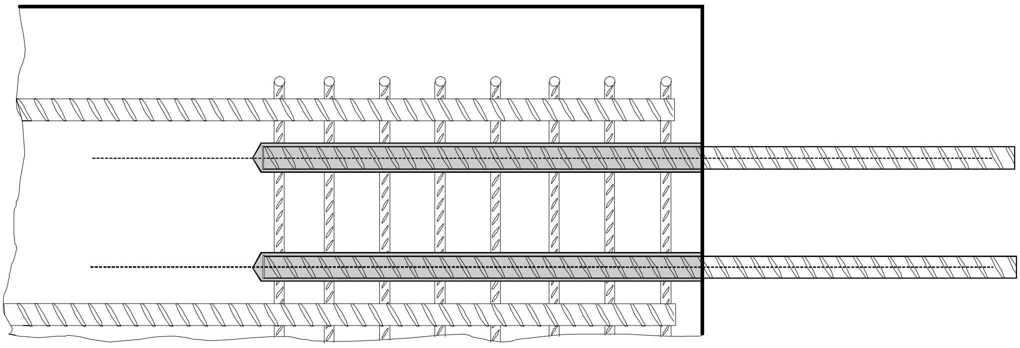

Fig. 4: TR023 – Post-installed rebar connections

The Technical Reports TR 023 covers applications with post-installed rebar connections (see Figure 4) in concrete C 12/15 to C 50/60 (EN 206) only, which are also allowed with straight deformed cast-in bars according to Eurocode 2. The general basis of this application is ETAG 001, Part 1 and 5. The Technical Report deals with the preconditions, assumptions and the required tests and assessments for post-installed rebars. The fire resistance of post-installed rebar connections as well fatigue, dynamic or seismic loading of post-installed rebar connections are not covered by this Technical Report. The installation of post-installed rebars is not basic and requires specific care, therefore the installation shall be done only by suitable trained installers and under supervision on site. The conditions under which an installer may be considered as suitable trained and the conditions for supervision on site are up to the Member States in which the installation is carried out.

6. ETAs

Based on the Guideline ETAG 001 and also according to the corresponding Technical Reports a lot of ETAs have been issued by the different Approval Bodies in the meantime. An Evaluation Report is needed for every product to show that the test requirements of the ETAG are fulfilled. During a transitional period determined individually for each ETAG by the EOTA, in order to ensure the comparability of the ETAs issued by the Approval Bodies, the draft ETA with the accompanying Evaluation Report are submitted to the relevant Approval Bodies for prior consultation; asking for their comments within two months. This rule has been proved well for ETAs according to ETAG 001 and is accepted by all Approval Bodies. The ETAs for anchors have a uniform assessment and the results are comparable. Therefore ETAs have a great acceptance by the users within Europe.

The ETA will be issued in the national language of the Approval Body. It is pointed out that every ETA is also available in English, because the English version is needed for the above described transitional period. The product with an ETA may carry the CE-marking and can be placed on the market in any of the Member States of the European Union and used under the same conditions.

Usually the manufacturer distributes the ETAs for their products. The EOTA [1] also services a list with valid ETAs. Further information may be given by the Approval Bodies.

7. ETA without Guideline

Typically metal anchors for use in concrete can be evaluated according to the ETAG 001. The EOTA has also installed a procedure to get an ETA for products, which cannot be categorised into a Guideline. Examples of these anchors are headed bolts, concrete screws or channel bars as well as metal anchors in aerated concrete. All these products are outside the scope of ETAG 001 but can get an ETA via a so called CUAP procedure. CUAP is the abbreviation of **C**ommon **U**nderstanding of **A**ssessment **P**rocedure. This paper has to contain all the details for the assessment for the specific product and will be prepared by an Approval Body. After a consensus of all EOTA approval bodies is reached, the product can be assessed according to the CUAP and an

ETA for the specific product may be issued. Since the CUAP documents are not published, the Approval Bodies should be contacted for further information.

8. Summary

The ETAs for metal anchors for use in concrete have opened the market in Europe for these products. The CE-marking allows the anchors to be placed on the market in any of the Member States of the European Union and they are used under the same conditions. Uniform assessment and standard design methods create a high level of confidence in the anchor products. The EOTA procedure with Guidelines but also Progress Files and Technical Reports ensure a fast transformation of new knowledge and experience in the fastening technique into the ETAs.

9. References

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4. Guideline for European Technical Approval of Metal Anchors for Use in Concrete - ETAG 001, EOTA (amended version November 2006)

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6. EOTA: Technical Report TR 018; Assessment of torque-controlled bonded anchors, edition March 2003

7. EOTA: Technical Report TR 023; Assessment of post-installed rebar connections, edition November 2006

PRACTICAL FASTENING DESIGN – A DECADE OF THE ETAG ANNEX C

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Abstract

It is over 10 years since the first document (Design of Fastenings in Concrete CEB Bulletin 226, S. 1-144, 1995) were published detailing a new design method for post-installed fastenings and became later the ETAG Annex C [1]. This [1] has successfully replaced all other methods in Europe and created a technically higher level of understanding, how fastenings behave in concrete. The ETAG design comes with a comprehensive approval (ETA), which not only guaranties a fair platform to compare different manufactures but offers clear and statistically validated, design guidelines for engineer specifiers. During this time period the ETAG design model gained international recognition and after the European engineering community the North American and the Chinese engineers also accepted it. The article is at one hand recognizes the worldwide success of [1] on the other hand it points out some topics requires research to develop this design further. The paper shows the possibility how to solve fastening applications by exactly following the ETAG Annex C methodology. In addition an example is given using the freedom, the so called “engineering judgment” allowed by [1].

1. Introduction

It is approximately 10 years since the first document was published detailing a new design method for post-installed fastenings, the ETAG Annex C [1]. This [1] has successfully replaced all other methods in Europe and created a technically higher level of understanding, how fastenings behave by identifying all of the possible failure modes. The [1] design comes with comprehensive approvals (ETA) based on a test regime, which not only guarantees a fair platform to compare different manufactures but offers statistically validated design data for specifiers. During this time period the [1] design gained international recognition and after the European engineering community the

North American and the Chinese engineers also accepted an [1] like document for their daily practice of designing fastenings in concrete.

The presented paper at one hand recognizes the worldwide success of the [1] model on the other hand it points out some topics requiring additional research or just simply suggests to re-think current ways to develop this design further and bring its governing ideas closer to practicing engineers. It is described how seemingly routine design tasks also need the active contribution of the designer as the original model in [1] can not describe all possible fastenings that are designed nowadays. This individual contribution to the design is called "engineering judgment" in [1] where certain design parameters are deviating from the ETA lines (e.g. anchor arrangement, base plate shape, base material thickness, base material strength class, etc.) and it is necessary and possible to apply it to solve daily fastening problems. It is shown that applying engineering judgment with additional test & FEM confirmation, which is based on the modeling from [1] and data from relevant ETA gives extremely accurate prediction for the governing capacity and failure mode of any fastening.

2. Experiences with the [1] model

2.1 The Safety Concept

In [1] Section 3.2.1 as an ultimate limit state design took over the partial safety factors for actions from [2]. This is a practical decision as it easy for engineers to relate to it and its validity is proven. There are cases however, where this decision may result in a conservative design. Firstly, the European construction practices assume a 120 to 150 years of service life for RC structures including at least 2 changes of the function of the structure. This gives an estimated 50 years of life span of fastenings. In the light of this the current load factors are probably conservative as the probability of highest action during a much shorter period of time is likely to be lower. Secondly, [1] is used mainly to design "steel to concrete" connections. For these cases the dead weight of the steel components can be more accurately assessed and the γ_G=1.35 from a RC code is again perhaps conservative.

2.2 Serviceability Limit State – Ultimate Limit State

The [1] 4.2.2.3 deals with the phenomena "Shear loads with lever arm". The method correctly identifies the problem and the influencing parameters and gives a formula to asses the characteristic resistance of a circular steel cross-section (Eq. 5.5b). The secret why it is perhaps wrong - embedded in the following details. The original problem was that the "W_{el}" of the circular anchor shaft – is derived from rigid body mechanics, which is only valid if there is zero shaft rotation. Therefore, the factor 1.2 is applied, in [1] Eq. 5.5.b, which means that a shaft rotation is limited (0.5-1^o). All this has been experimentally verified as the whole [1] model. This deformation limit is essential to fulfill the most important criteria of any fastening, namely any fixture has to be fixed – to stay there where it is foreseen. So if this criteria is based on a given deformation limit, thus this is in reality a “Serviceability Limit State” condition and it may be better in Section 6.

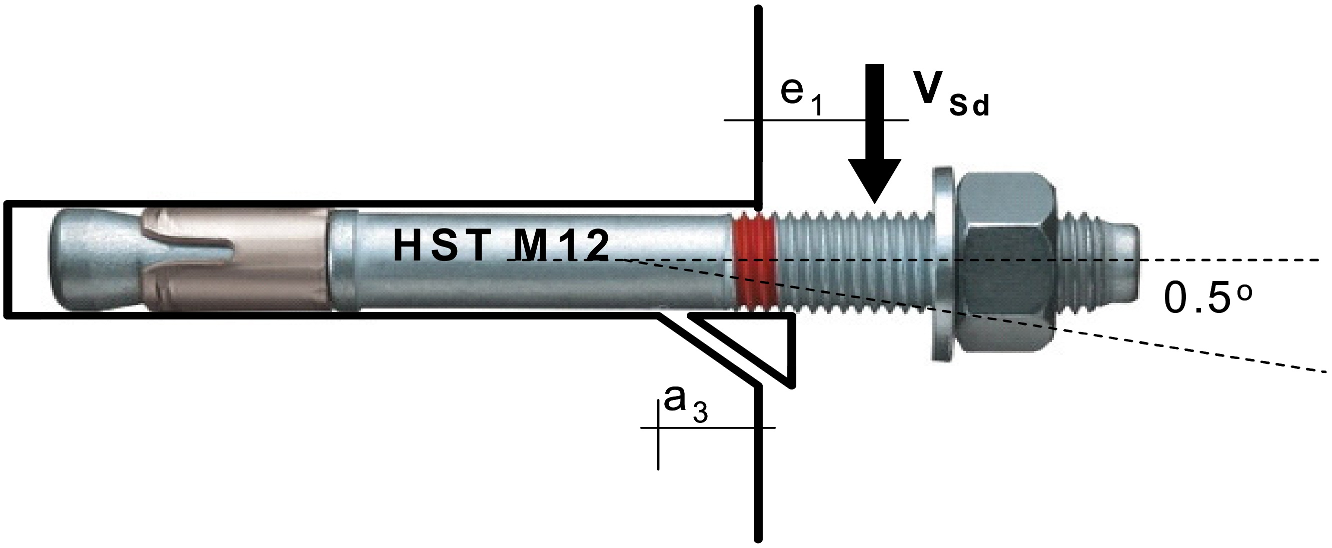

Fig. 2.2: Shear load with lever arm - shaft bending

Secondly, there is sometimes a given difference between [1] and the relevant approval of the product. In Eq. 4.2 the “a_3” is defined as 0.5d, where d is the nominal diameter of anchor bolt or thread. In the ETA-s to asses the $M_{Rk,s}$, the characteristic bending capacity of the shaft, often a different diameter is applied correctly - the effective steel diameter in the threaded section. After [1] and ETA most anchor shafts have two stiffness – (if a HST M12 is designed after [1] a_3=6mm, if designed after [3] where $M_{Rk,s}$=98Nm gives an equivalent a_3=5.07mm.) The a_3 value should be determined how much bending can be transferred into the concrete by the anchor shaft stiffness.

2.3 Design in Cracked or in Non-cracked Concretes

In [1] 4.1 it is described a $F_{Sk}<60$ kN limit of characteristic resultant load and if the actual characteristic load is greater, cracked concrete should be assumed for design. This limit is perfectly relevant and valid from an engineering point of view. To apply this limit can be criticized on the following grounds: the anchor reaction itself is the result of a calculation, a design which is influenced by the anchor and by the concrete stiffness. Practically, each anchor diameter results in different anchor reactions assuming that the acting load on the fixture is bending. Then the design process is logically limping as the stage of the concrete, cracked or non-cracked, is an initial designer input, which has to be revised depending on the calculated, stiffness dependent reactions. In extreme cases it is possible that for example the M10 version of anchor can be designed in non-cracked but the M12 must be designed in cracked concrete. Example if M_{Sd}=21,8 kNm (γ_F=1.0) and concretes C 20/25 – C50/60 the reactions N_{Sk}(M10) = 59.98 – 59.77 kN thus non-cracked concrete, N_{Sk}(M12) = 60,36- 60.13 kN thus cracked concrete should be used. So the actual criteria is load type (bending!), anchor diameter and concrete strength dependent.

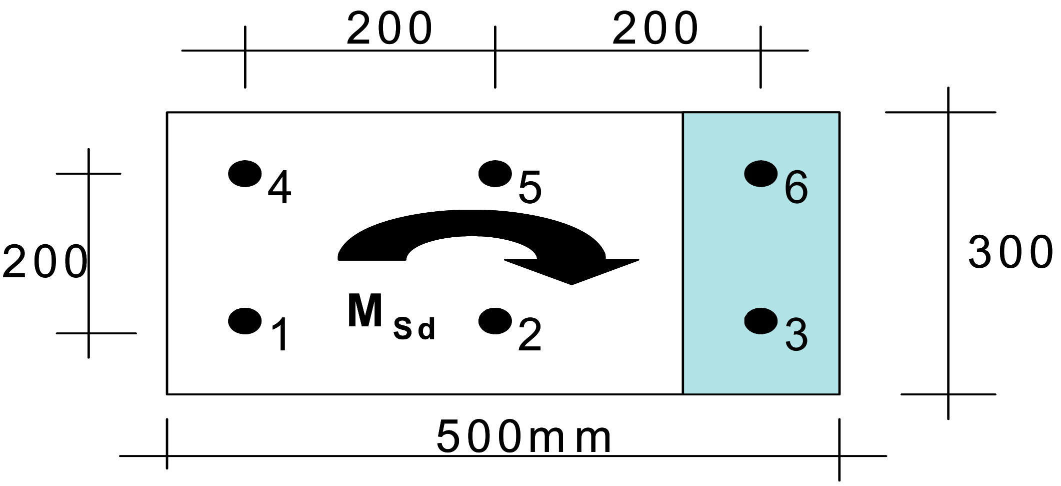

Fig. 2.2: Influence of load type, anchor diameter and concrete strength on design input

2.4 Definition of an Anchor Group

The example of 2.3 also shows that the definition of anchor group is actually load dependent. In spite the fact the [1] in ETAG-Eq. 5.2b defines the $A_{c,N}$ as the "actual area of the concrete cone of the anchorage at the concrete surface", if the load is bending this area is partially compressed and not all anchors in the group are tensioned. This has additional influence when the effect of internal eccentricity on the tensile capacity is calculated. Anchor design software [7] considers both cases: a) only those anchors which are effectively are tensioned, b) all anchors in the group as in [1] text – but report only indicates the solution yields to a lower usage of the given capacity.

2.5 The Rigid Fixture

Any design after [1] assumes that the anchor plate does not deform (rigid) in 4.2.1 a) and anchor reactions are calculated accordingly. The same [1] in 4.2.1 a) in text states that anchor plate should be sufficiently stiff and it also requires an elastic behavior of the fixture steel. A more realistic, practical definition of the anchor plate to limit either the elastic deformation or the stresses in the anchor plate under load is somewhat missing. Nevertheless, this gave the idea that all anchor plates are sufficiently stiff as long as remaining elastic under the effects of the design actions.

2.6 Internal Shear Load Distribution

The gap between anchor and clearance hole plays an important role and special assumptions in 4.2.2.1 [1] originally took care that under no circumstances the concrete edge is overloaded from un-even internal load distribution. It was then realized, that the assumptions are conservative and do not treat cases well when shear force acts parallel with the governing edge. A temporary document by CEN/TC [4] in 2003 improved the situation.

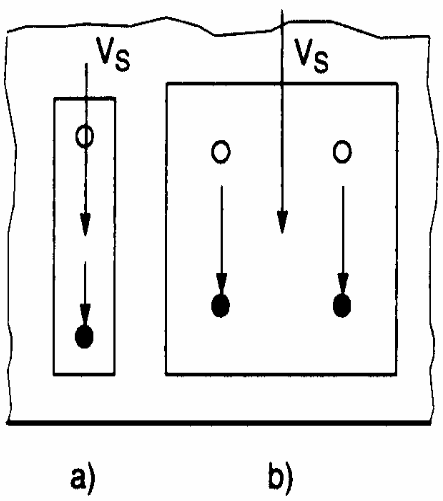

Fig. 2.3: Internal shear load distribution close to edges or wrong hole tolerance

In a group situation the direction of any edge with the relevant direction of the shear loads determines together the shear load distribution. As load and resistance are the function of direction, the concrete resistance in all 4 directions must be calculated taking into account the acting shear load related to the edge in question. The direction with the highest usage $\mathrm{Max}(V_{Sd,i}/V_{Rd,c,i})$ will eventually govern the design. The introduction of special cases in [1] in ETAG-Fig. 5.9 is extremely useful to simplify and to ease the conservatism of the design. Must be stated, that a smooth transition between the different and possible edge resistances is not given with current modeling (see ETAG 4.2.2.1 - b) if $c < 10h_{ef}$ only then anchor carries shear load.)

2.7 Pry-out Resistance

In [1] 5.2.3.3 Eq. (5.6) $V_{Rk,cp}= k^* N_{Rk,c}$, where the $N_{Rk,c}$ is the characteristic tensile concrete cone capacity of the loaded group. If the load is a torsion, the resulting shear load ($\Sigma V_{Sd,i}$) is zero, which gives the impression that there will be no stresses in the concrete due to torsion. This assumption is obviously wrong so fastening designers must modify Eq.(5.6) and solve this proof differently. The [7] calculates conservatively as the proportional capacity of a single anchor from the loaded group ($N_{Rk,c,i}=N_{Rk,c}/n$). Which is then compared with the highest individual shear reaction acting within the group ($V_{Sd,i}^h \leq N_{Rd,c,i}$).

2.8 Combined Load Check

The 5.2.4 is a relatively short chapter in [1] though it would deserve some detailing as design currently yields conservative solutions. The aim of this check is to make sure that highest stresses are identified and limited from tension and from shear to avoid an overload. Current version ignores the place of the actual highest stress within the group, thus calculation is simplified for quick and safe solution. In Fig. 2.4 the example shows, that in spite that highest steel stress and highest concrete stress from tension and shear respectively are 200mm apart and in different materials. The ETAG model treats them as a group stress as long as $s<s_{cr,N}$. (Example: s=200mm, c=100mm, anchor M12,

h_{ef}=110mm, M=2kNm, V=3 kN, C20/25, Plate 150x300mm, T=8.5 kN, $N_{Rd,s}$= 25.3 kN - 34%, V=3 kN, $V_{Rd,c}$=13,8 kN - 22%).

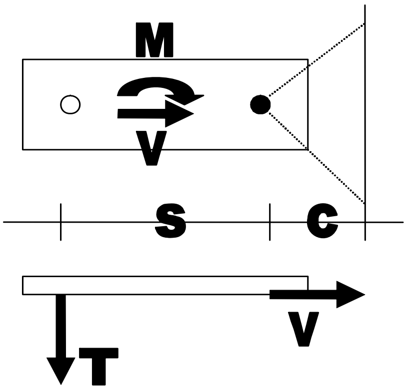

Fig. 2.4: Combined load check for group of two anchors

2.9 ETA Approvals vs. ETAG Annex C

It has been stated in 2.3 that there are differences between [1] and some ETA approvals, see additional examples:

-5.2.2.4 Eq. (5.2a) [1] the calculation of $N_{Rk,c}^0$ is given as ***7.2****$\sqrt{f_{ck,cube}}$ * $h_{ef}^{1.5}$, the same calculation in the [5] in Section 4.2.1 is already ***8.3*** *$\sqrt{f_{ck,cube}}$ * $h_{ef}^{1.5}$.

-5.2.3.3 Eq. (5.6) [1] the pry-out resistance $V_{Rk,cp}$= k* $N_{Rk,c}$, where the factor k is set in (5.6a) and (5.6b) as 1.0 if $h_{ef} < 60$mm and 2.0 if $h_{ef} \geq 60$ mm, respectively. In [6] the condition for Eq (5.6a) is not met as the k=2 with h_{ef} = 30mm.

Additionally, there are new ETA-s, where a number new design input parameters have appeared such as base material temperature (short term and long term) with up to three different temperature ranges, four drilled hole conditions and three cleaning conditions. These already give a number of 108 possible combinations, which designers should theoretically check with other conditions (s_{min}, c_{min}, h_{min}, etc.) prior to the actual design to decide, is the use of the actual product feasible?!

3. Engineering Judgement in Action

3.1 Deviations of Design from ETAG

The list presented in section 2 indicates that even a routine design can not be made without a certain depth of engineering understanding and special considerations by the designer – this is called “Engineering Judgment”. In [1]-1.1 the user is given the possibility and in the light of 2.1-2.9 from this paper arises the necessity of engineering judgment to solve routine and special cases as long as the modeling of [1] is followed. Such an extension of [1] with engineering judgment elements is the SOFA (Solution for Fastening) method, which is available in [7].

In the following example it is summarized, that even if simultaneous deviations a) in anchor arrangement (free anchor arrangement not only 2x3), b) in fastening geometry (more than 2 anchors close to an edge), c) in anchor approved depth – (deeper setting factor=1.2) and in d) hole tolerance conditions – (filled hole) are introduced to a design – the ETAG Annex C model coupled with good knowledge of the actual fastener result in an extremely accurate prediction of the failure mode and the corresponding resistance. The example shows a summary of the tensile resistances of 2x3 and 3x3 anchors in fastenings built in C35/45 concrete from HY150 + HAS M20-200, with spacing in both directions 150 and 200mm, the 200mm depth is 1.2 times the ETA approved depth the observed failure mode is concrete cone. There were 4 influencing edges after the ETAG modeling. The tested individual values are $N_{Ru,ci}$, the average ultimate mean values are shown as $N_{Ru,m}$ and the values calculated with the SOFA method [7] as governing characteristic tensile capacity, concrete cone are given under $N_{R,SOFA}$.

Table 3.1: Tensile resistance and failure mode of non-ETA fastenings

nxn	s=150mm					s=200mm				
	N_Ru,c1	N_Ru,c2	N_Ru,c3	**N_Ru,m**	***N_R,SOFA***	N_Ru,c1	N_Ru,c2	N_Ru,c3	**N_Ru,m**	***N_R,SOFA***
2x3	538 kN	475 kN	496 kN	**503 kN**	***499 kN***	637 kN	620 kN	629 kN	**629 kN**	***610 kN***
3x3	690 kN	708 kN	626 kN	**674 kN**	***667 kN***	792 kN	808 kN	971* kN	**857 kN**	***846 kN***

*failure mode concrete-cone/splitting the rest of specimen concrete cone

Another important SOFA deviation, is the valid concrete classes, in [1] validity of Eq. (5.2a) [1] is assumed as in SOFA concretes lower than C20/25 strength class are allowed. The general relationship between any concrete strength and concrete resistance has been published in [8] in Figure 4.10b, further to this, the owner of [7] has numerous, 33 series of tests and FEM modeling with various types of anchors in B15 concrete to support this.

3.2 Site Testing

For applications often site testing is required not only to prove the correct setting but also to justify load bearing and displacement properties of anchors. Normally site testers are not accurate enough to be used in quasi approval testing on the construction site. The HAT 175 site tester has been developed for internal use by the Hilti AG. This tester has a 550mm free span, a 175 kN tensile and a 100 kN shear capacity and a full electronic data logging with automated reporting including statistical analysis of the measured data. It is not only versatile but has a less then 2% electronic accuracy between 10 and 150 kN, thus as hardware even fulfills all requirements to be used in approval tests so such a device can efficiently aid the design.


Fig. 3.1: HAT 175 Anchor Site Tester

4. Conclusions

It was shown that even a regular use of the [1] model for designing fastenings requires the individual and specific considerations from the designer. The possibility to use engineering judgment when we design fastenings is practically unlimited and it is given in the [1] text. There are simple cases such as a group of fasteners close to an edge and loaded by torsion or fancy cases when a fixture sunk into the concrete, where the [1] model gives only indirect references but these with test evidence are sufficient to calculate an accurate fastening resistance. It was pointed out that the [1] modeling may seem simple at the first glimpse but fastening designers with limited practical experience need to be careful not to be lost between the [1] text and the actual approval of the anchor. The steadily increasing design input parameters (short and long term temperature, drilled hole conditions, hole cleaning types, drilling type) through the years may over complicate an originally simple design.

The section 3 of this paper gave evidence of the validity of the [1] model including the possibility of deviating from the presented cases in text. By taking the [1] modeling as a guide the governing failure mode and the corresponding resistance can be calculated. Example showed that the [1] modeling is extremely accurate even if the anchor arrangement, depth, edge - spacing and hole tolerance were altered from approved conditions. It is also stated that any deviation from ETA lines is only possible if an ETA or ETAG testing of the product is available and additional reference tests and /or control FEM analysis and/or comprehensive site testing proof are at hand.

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HISTORY OF ANCHORING STEEL TO CONCRETE IN NORTH AMERICA, 1900-1977

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Abstract

This paper is an historical literature review of anchoring of steel to concrete in North America. Consideration is given to available information published between 1900 and 197 that documents research, testing, building code requirements and applications. The relevanc of these publications is assessed and the more important papers are summarized, and thei impact on the progress of the state of the art in anchorage is discussed.

The range of documents reviewed will span from Duff Abrams' University of Illinois Bulletin No. 71, published in 1913, through Hasselwander, Jirsa, Breen and Lo's University of Texas at Austin Research Report 29-2F issued in 1977. Abrams' *Test of Bond Between Concrete and Steel* provides one of the earliest discussion of "Methods of making Pull-out Tests." The Hasselwander et al report titled *Strength and Behavior of Anchor Bolts Embedded Near Edges of Concrete Piers* is one of the first to describe failure modes such as side cover spalling and splitting.

An annotated bibliography of all considered publications is presented.

1. Introduction

In December of 1913 Associate Professor Duff A. Abrams of the University of Illinois Engineering Experiment Station published Bulletin No. 71 which in-part describes the "Effec of Anchoring Ends of Bars." Professor Abrams' publication marks the beginning o publications describing the design, performance and testing of anchors in North America This paper provides an annotated bibliography consisting of the more prominent and available.

North American publications on anchorage from 1900 to 1977. Some of the more significant developments in cast-in-place and post-installed anchors and the supporting documentation during this time frame are discussed. More than sixty publications are listed, they are divided into the two general categories of cast-in-place and post-installed.

The time period chosen begins with start of the twentieth century and the advent of significant use concrete as a building material. Thirty years ago, 1977, the design and construction of nuclear power plants was at it peak. These plants, which are almost exclusively constructed of heavy concrete elements, make extensive use of all types of anchoring devices. If Abrams' publication in 1913 marks the beginning of an era, then the Tennessee Valley Authority report "Anchorage to Concrete" is the culminating document in the time period being considered.

Shortly after this time the performance of anchors was challenged by the United States Nuclear Regulatory Commission when Inspection and Enforcement Bulletin 79-02 was issued. This bulletin, which required inspection and verification of all safety related post-installed anchors, resulted in a significant increase in the study of these structural components and a corresponding growth in the literature that documents them.

2. Developing the Bibliography

The first step in compiling this bibliography was to develop a search strategy that could be applied to explore the existing anchorage literature. Recognizing that synonyms, such as "anchorage", "anchor bolt", "anchor-bolt", "anchorbolt", and "rock bolt", return different results when entered in various databases an exhaustive list of search terms or keywords was developed to describe the process of anchorage to concrete. To ensure that all results fell within the scope of the study a series of limits were determined based on place of publication, date, and language.

After keywords and limits were determined the next process was to identify suitable resources in which to perform our searches. One open-access and three subscription indexing and abstracting databases were used during the search process with various results.

The American Concrete Institute's website hosts a database called *Searchable Abstracts of ACI Publications*. This database is freely accessible to anyone with an internet connection. *Searchable Abstracts* is an excellent source for finding articles appearing within ACI publications between 1929 and the present. *Searchable Abstracts* also provides a date range feature which ensured that all of the returned results fell within the desired date range. During the research process the monograph *Mechanical Fasteners for Concrete* (alternately titled ACI *Publication SP-22*) was identified as being of particular importance to the study of the development of anchorage to concrete. Although not fully indexed, *Searchable Abstracts*, was the only database consulted over the course of this research that listed any of the articles appearing in this monograph. It is also worth noting that *ACI Publication SP-22* contains an excellent bibliography that was also consulted for the development of this literature review and highly recommend as further reading by anyone interested in anchorage to concrete Searching for and identifying relevant articles with *Searchable Abstracts* was less user friendly than the other subscription databases. The results can not be manipulated to allow for easy or orderly browsing. Also, the lack of controlled vocabulary makes serendipitous discover difficult if not impossible.

As it was necessary to broaden the focus of this literature review beyond the scope of ACI publications, a series of searches were preformed in *COMPENDEX*. In addition to providing robust searching capabilities, *COMPENDEX* also provides bibliographic information for millions of articles, proceedings, monograph chapters and dissertations including a full backfile of the Engineering Index from 1884 to present. Search terms can easily be combined using Boolean operators which allow for the construction of more detailed search statements then *Searchable Abstracts*. Once the results are returned in *COMPENDEX* the user is able to sort results by a variety of criteria including relevance and publication date which allows for easy browsing. A series of facets are also employed by *COMPENDEX* which allow for refining results based on author affiliation, country of publication, and controlled vocabulary The controlled vocabulary in *COMPENDEX* is designated by a team of indexers in order to standardize the way articles are described, and to ensure consistency and accuracy in search retrieval. The controlled vocabulary in *COMPENDEX* and other subscription databases also function as hyperlinks within the description of an article. Clicking these hyperlinks allows for deeper exploration and the collocation of like items.

The final sources consulted for this literature review were the FirstSearch Databases *WorldCat* and *Dissertations Abstract*. Both databases have the same functionality with the ability to combine search terms with Boolean operators, limit by date of publication language, etc. They also have the ability to collocate items based on the hyperlinking of controlled vocabulary. The main advantages of these two databases are the volume of data available, *Dissertations Abstracts* provides access to dissertations published in the U.S. and abroad from 1861 to present, and the strength of the controlled vocabulary, which tends to be more descriptive since it is based on the Library of Congress Subject Headings. *WorldCat* is a collection of more than 62 million items cataloged at libraries around the world. Begun in 1971 this database, in addition to books, includes articles, chapters, papers, computer files archival materials and government documents. An extensive and diverse dataset allowed for the location of unique items; like university research reports and *Post-installed anchors: a literature review* by Cheok and Phan. Published in 1998 by the US Department of Commerce, Cheok and Phan's literature review is an excellent source for those interested in the development of anchorage after 1977.

During the creation of the accompanying bibliography on the development of anchorage to concrete in North American it was noted that there was a lack of materials published in Mexico. In order to remedy this gap it was undertaken to identify a major structural engineering journal published in Mexico and determine if that source had an available index Using *Ulrich's Guide to Periodicals* it was determined that while a number of journals may provide the desired information, none had indexes that were available for the desired date range of 1900 to 1977.

3. Cast-in-place Anchors

The literature available for cast-in-place anchors can be generally divided into those publications that deal with column anchor bolts and those that discuss headed studs used as shear connectors.

Surprisingly the topic with the least amount of published information is the discussion of tensile performance of cast-in-place bolts. Only Abrams and Breen et al., address this subject in any detail. [1, 5, 13]

From the late 1950's until the early 1970's more than a half-dozen publications addressed headed stud shear connectors [6, 9, 10, 11, 16, 18, 19]. This was the time period when design procedures for composite steel and concrete structures, especially bridges, where being developed. Both the behavior of these anchors and test methods for determining strength and stiffness are described in the literature.

In addition to the study of anchor bolt and shear stud performance a number of papers related to specific construction applications were also published. These include connections for precast concrete structures and issues related to column anchor bolt installation [2, 3, 4, 8, 12, 14]

4. Post-installed Anchors

The literature for post-installed anchors begins with a large body of work devoted to rock bolting. A considerable amount of this information comes from the Canadian mining industry. In the late 1940s the use of rock bolts to support the roofs of mines started to become popular. Roof bolting eliminated costly timber props providing a greater open space for mining operations. Because of these benefits numerous studies of rock bolting were published.

A wide variety of rock bolting devices are mentioned in the literature [25, 26, 27, 28, 30, 31, 32, 33, 34, 39, 42, 43, 44, 45, 46, 54, 55, 58, 59, 61, 62, 63]. The earliest form of rock bolt is a simple split rod inserted over a wedge. This device evolved with the development of more sophisticated expander mechanisms such as the single bail, multiple bail, and prong types. In addition to mechanical devices during this time period bonded rock bolts using "resins" were also developed. The most unique of the anchoring mechanisms described is the explosive rock bolt. This device used an explosive change inside a hollow sleeve which expanded into the base material when detonated. Two publications mention the use of wooden rock bolts, one manufactured from red oak and the other from Douglas fir.

During the 1950s lead caulking anchors came into prominence, along with the rock bolts, i the literature discussing post-installed anchors [20, 21, 22, 35]. Testing techniques and anchorin parameters such as preload and angle of concrete cones failures are described. By the earl 1970s the design of nuclear power plants was at its peak. These massive concrete structure employed numerous post-installed anchors and a wide variety of anchor types were studied [23 38]. The effects of edge distance, anchor groups and seismic loading were considered.

5. Conclusion

More than 60 publications dealing with a wide variety of anchoring devices and application have been identified. All of the publications listed are available in the public domain an should be readily accessible.

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HISTORICAL PERSPECTIVE OF ANCHORAGE TO CONCRETE STANDARDS AND CODES IN THE USA

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Abstract

Anchorage requirements in the USA have their beginnings in the middle of the twentieth century. While the development of anchor technology has been progressing steadily over the past 50 years, anchorage standards and related codes were slow in their development and implementation, with most of the significant progress having taken place in the last 15 years.

Early standards addressed global safety factors, with a U.S. Government standard used for procurement. Early codes addressed cast-in-place anchorages, but not post-installed anchors. ACI Committee 318 attempted to rectify this situation by initiating related activities in 1970. While those efforts took almost two decades to elicit significant progress, important but uneven progress has taken place in the last 15 years.

Standards for different types of anchors, as well as code requirements, have since been developed. This paper gives a general overview of these activities, outlining the key developments over the past 40 years, as well as assessing the current status.

1. Introduction

The development of anchoring standards and codes in the USA had an auspicious start with the publication of a U.S. Government purchasing specification, and continuing with the development of very simple guidelines to test methods and criteria, eventually culminating in the development of lengthy qualification criteria and design code procedures. The progression starts with allowable stress design and moves about the turn of the century to strength design. Let us follow this progression from about 1957, continuing into the 21st century, during which a complex spectra of criteria and standards have been promulgated and others are still under development.

2. Earliest anchor documents and activities

The development of anchor standards and codes began about the 1950's in the USA, with a U.S. Government purchasing standard, *FF-S-325* [1]. This document was a compendium of early mechanical anchoring devices that contained expansion shields of various types (lead, bolt and stud anchors, self-drilling tubular expansion shields, wood screws and lag bolts, and expanded drive-bolt and drive studs). Anchor capacities were given that represented a sampling of published data from manufacturers and suppliers.

ICBO-ES created its first acceptance criteria in 1975, *Standard for Testing Expansion Anchors in Concrete* [2] to allow a method of approving mechanical anchors for use under the *Uniform Building Code* for allowable stress design. This criterion was later designated *Acceptance Criteria for Expansion Anchors in Concrete and Masonry Elements* and received the number AC01 in 1993. It went through a series of revisions and refinements until it was supplanted as the primary mechanical anchor criteria in April of 2002 with AC193.

In the 1970's, *EAMI* (*Expansion Anchor Manufacturer's Institute, Inc.*) an organization of 7 mechanical anchor manufacturers was organized. This organization in 1975 published *Standard for Testing Anchors in Concrete* [3], giving guidelines and detailed procedures for testing anchors in concrete that were very similar to the ICBO-ES criteria. By 1980, *EAMI* was no longer an active organization.

In 1976, ASTM Subcommittee E06.13, currently designated *Performance of Connections in Buildings*, created a set of test methods, *ASTM E 488-76 Standard Test Methods for Strength of Anchors in Concrete and Masonry Elements* [4]. This was the earliest known set of consensus-developed comprehensive test methods in the USA for testing anchors. It has subsequently undergone several revisions, and is currently being rewritten to include all test methods from several other criteria.

In 1978, in response to anchor issues at nuclear power stations, the US Nuclear Regulatory Commission published IE Bulletin 79-02 [5], which required verification by inspection of anchoring applications. It required evaluation and testing of in-place anchorages and extensive reporting and specified design considerations for anchoring applications. It had the significant effect of raising the awareness of the importance of design and installation of anchors.

And thus, with the ASTM and ICBO ES documents, the anchoring industry had the beginning rudiments of the development of very significant standards and codes.

3. Some other early key activities

ACI Committee 349 (*Nuclear Building Code*) adopted *Appendix B, Embedments* [6] in 1976, which included the first real code for anchoring to concrete for cast-in-place anchors. It included the 45° cone method, and extended it to intersecting cones. Later, in a July 1981 article in *Concrete International* [7], this method was extended to allow the design method to be used for post-installed anchors. Thus a popular design method for anchorage to concrete was now available to design engineers.

In 1988 the Uniform Building Code [8] adopted Section 2624 Anchorage to Concrete that included the 45° cone method for strength design and design of anchors. These provisions applied to cast-in-place bolts and headed bolts only, but formed a basis for later post-installed anchor acceptance criteria.

Adhesive anchors were introduced into the marketplace in the USA, with both injection and capsule anchors. Most "chemical" anchors in previous years had been epoxy, a common product used on road construction. The predominant material standard was ASTM C 881 [9], which was the typical specification referenced for adhesive anchoring products. Since many of the adhesives anchoring products were not epoxies, this reference was not compatible with the newer products. In the late 1980's, ASTM Subcommittee E 06.13 developed ASTM E 1512-93 *Standard Test Methods for Testing Bond Performance of Adhesive-Bonded Anchors* [10]. This was expected to be the referenced document for adhesive anchor requirements. The document introduced creep testing, freeze-thaw tests, as well as other temperature- and environmental-sensitive test methods. It has subsequently been referenced in ICBO-ES and ICC-ES acceptance criteria.

In October 1989 the Loma Prieta earthquake awakened certain organizations to the need to look closed at anchoring requirements. The January 1993 Northridge earthquake caused governmental authorities to take action, requiring seismically qualified anchors for use in earthquake zones under the *Uniform Building Code*.

At the same time, ICBO-ES proposed a draft set of acceptance criteria for adhesive anchors in 1994, which, by this time were well established in the marketplace, but without approvals for use under the codes. Several manufacturers formed a working group in 1994 and began preparing a more comprehensive adhesive anchor acceptance criteria. After over a year of continuous effort, an AC was approved by ICBO-ES in January 1995 as *Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements AC58* [11]. It included the first criteria for seismic qualification of anchors.

During the development of this criteria, the manufacturer's group formally established the *Concrete Anchor Manufacturers' Association* (CAMA) [12], which has continued to work closely with ICBO-ES and recently with ICC-ES in the development and modification of acceptance criteria.

CAMA then tackled the issue of seismic testing for mechanical anchors and proposed criteria to be added to AC01 in 1997 similar to the procedure in AC58. The Structural Engineers Association of Southern California also proposed a testing methodology for mechanical anchors, based on strength design principles. In September 1997 ICBO-ES adopted both criteria as alternative options for seismic qualification of post-installed mechanical anchors.

After the introduction of newer mechanical undercut anchors, ICBO-ES in 1998 approved *Acceptance Criteria for Undercut Anchors in Concrete Elements AC140* [13]. Thus, by the end of the twentieth century most basic types of post-installed anchor were covered by acceptance criteria, mechanical anchors, adhesive anchors, and undercut anchors, although only for allowable stress design.

4. The American Concrete Institute enters the field

In 1970, ACI Committee 318, (*Concrete Building Code*), requested that the American Concrete Institute create a committee to develop anchoring to concrete provisions including post-installed anchors that could be used in conjunction with the concrete building code. Thus, ACI Committee 355, *Anchorage to Concrete* was created in 1970. It initiated an investigation into anchoring devices. The Committee held 3 symposia during 1982 through 1984 and again in 1989 and 1990 and published many of these papers in two ACI documents *SP-103* [14] *and AP 130* [15]. During the Mid-1980's, the Committee also began the development of a state-of-the-art document on anchorage to concrete. After several years of work, and much controversy over the issue of anchor performance in cracked concrete, *State-of-the-Art Report on Anchorage to Concrete, ACI 355.1R-91* [16] was published, which gave a basis for further work by this Committee.

ACI 318, recognizing that ACI 355 was not going to develop anchor strength design provisions any time soon began in 1993 to develop a set of design provisions that culminated in a draft *Appendix D, Anchorage to Concrete* [17] that included a strength design concept for both headed bolts and post-installed mechanical anchors and included performance in compression zones (uncracked concrete) and both compression and tension zones (uncracked and cracked concrete). The basis for this design methodology was the European ETAG design found in Annex C Design Methods. Anchorage provisions for cracked concrete were a key aspect of the design method. Anchors could be designed for either uncracked concrete or both cracked and uncracked concrete. Appendix D was ready for the ACI 318-99 version of the code, but required a corresponding post-installed anchor qualifying criteria.

In response to a request from ACI Committee 318, ASTM Subcommittee E06.13 began work in 1993 on a standard for the evaluation and approval of mechanical anchors in concrete based initially on the European UEAtc M.O.A.T. 49 [18], which introduced the concept of proper functioning tests (later called reliability tests). The UEAtc document was taken over by the ETAG, which clearly defined the concepts of testing the performance of anchors in cracked concrete versus non-cracked concrete. The ETAG Parts 1 through 4 [19] and Annexes A, B, and C were used a source materials and guidance. Initially, two standards were drafted, one for uncracked concrete and one for cracked concrete. After 4 years of drafting and balloting and redrafting, it became apparent that the ASTM path was not going to yield the needed anchor prequalification standard in the time frame needed for ACI timelines. ACI Committee 355 was requested to take over the ASTM work and create such a document. The ACI drafts considered separately, qualification for uncracked concrete, and qualification for both uncracked and cracked concrete. Because of the similarity, both drafts were merged into one document. After 27 months of balloting, one major lawsuit that was withdrawn, and the resolution of many negatives, ACI Committee completed work on a provisional standard *Evaluating the Performance of Post-Installed Mechanical Anchors in Concrete ACI 355.2-00* [20]. This allowed ACI 318 to proceed with the publication of *Appendix D* in ACI 318-02. ACI 355.2 proceeded on to become a full standard, with the "provisional" designation removed and was published as ACI 355.2-01. It has undergone 2 subsequent updates, in the years 2004 and 2007; and will undoubtedly continue to be updated in the next years.

Meanwhile, ACI 318 *Appendix D* has been updated for the 2005 code and the 2008 code (currently in process). ACI 318 is the model concrete code referenced in the *International Building Code* (*IBC*). But that is the next story.

5. New Codes require strength design approaches

The three model building code organizations formed a single code agency in the late-1990's to establish a single model building code for the USA. Thus the International Code Council created the *International Building Code* [21] in 2000. Since there was a desire to have anchoring to concrete provisions in the code even though ACI had not finalized *Appendix D*, the ICC included 2 Sections that applied to cast-in-place headed bolts, Section 1912 *Anchorage to Concrete – Allowable Stress Design*, and *Section 1913 Anchorage to Concrete – Strength Design*. The former was basically a table that allowable loads for headed bolts and specifically did not apply where earthquake loads were to be considered. Section 1913 introduced the strength design provisions for headed bolts and was taken directly from the draft ACI 318 Appendix D, but without any provisions for post-installed anchors. It also was the basis for seismic design. This was a key turning point in the development of strength design criteria for anchoring to concrete. Any anchor seismic qualification had to be for strength design and not for allowable stress design, as had been allowed under the previous Uniform Building Code and AC01 and AC58.

ACI Committee 349 considered the new design procedures in ACI 318 Appendix D and concluded that the two codes should be aligned as closely as possible. Thus ACI 349 Appendix B was replaced with an Appendix D in the ACI 349-01 [22] code that was patterned after ACI 318 Appendix D, but did not require ACI 355.2 as the qualifying standard. It also included other types of embedments not found in ACI 318's Appendix D. It has been subsequently updated as part of ACI 349-06.

With the passage of ACI 355.2-01, ACI 318-02 including Appendix D became part of the 2003 IBC, containing strength design provisions for post-installed mechanical anchors in concrete. And, more importantly it referenced a post-installed anchor qualification method, ACI 355.2-01.

After the adoption of the 2000 IBC, ICC-ES (the successor to ICBO-ES) required that acceptance criteria be established for post-installed mechanical anchors for use under this new code. Since ACI 355.2 was now in existence, and would appear by indirect reference in the next IBC, ICC-ES approved AC-193 [23] in April 2002, using ACI 355.2 as the base document for use with the 2000 IBC. Thus, strength design anchor prequalification procedures for post-installed mechanical anchors were finally in place.

6. Adhesive anchors activities gel

With the inclusion of post-installed mechanical anchor strength design provisions in the 2003 IBC and 2006 IBC, the next serious need was to include adhesive anchors in the design and prequalification procedures. In late 2003, CAMA began work on acceptance criteria for adhesive anchors that would be a companion to AC193. The methodology was based on the European ETAG Part 5 provisions. After almost 1-1/2 years of monthly meetings, the criteria was presented to ICC-ES and was subsequently adopted in June 2005 as *Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements AC308* [24]. Since ACI 318-02 or -05 did not contain specific design procedures for adhesive anchors, AC308 contained a set of design procedures that were generally the same as were under consideration by ACI 318.

After ACI Committee 318 adopted Appendix D for mechanical anchors, it requested that ACI Committee 355 prepare a prequalification standard for adhesive anchors. Committee 318 considered modifications and additions to Appendix D for including adhesive anchors. While accepting most of the design methodology, it put the effort on hold until Committee 355 completed a prequalification standard. Thus, in early 2006 ACI 355 balloted a document based primarily on AC308, but without the design provisions. That effort is continuing at this time. It is expected that ACI 355 will complete work in 2009 on such a standard and that ACI 318-11 Appendix D will include design procedures for post-installed adhesive anchors.

ASTM Subcommittee E 06.13 in 2006 embarked on an ambitious effort to rewrite ASTM E 488 to include all the basic test methods found in ACI 355.2, the new ACI standard under preparation for adhesive anchors, as well those in the ICC-ES criteria AC193 and AC308. After ASTM E 488 is approved containing these test methods, the test methods will only be referenced in the two ACI and two ICC-ES documents. This will require continuing coordination among these three organizations in order for anchor prequalification to proceed on a smooth basis.

7. Conclusion

In this work, there are no conclusions. The efforts continue, adding additional anchors that make it to the marketplace, modifying current standards and code as needed to correlate to testing and results that, in turn, cause changes. Continuing efforts in ASTM, ACI, ICC-ES, CAMA as well as other organizations will contribute to a continually moving arena of these many codes and standards.

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QUALIFICATION AND DESIGN PROVISIONS FOR BONDED ANCHORS IN THE U.S.

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Abstract

AC308 – Acceptance Criteria for Post-Installed Adhesive Anchors in Concrete Elements was adopted by the ICC Evaluation Service in the U.S. in June of 2005 and as of January 1, 2007 it will, for all intents and purposes, be the basis for the approval of bonded anchor products in North America going forward. AC308 represents a significant departure from past practice in the qualification and design of bonded anchors.

This paper reviews the format and concepts underlying AC308 as well as previous criteria used in North America for the qualification and design of bonded anchors and discusses ongoing issues associated with their use in practice.

1. Introduction

The introduction in 2002 of strength design provisions for mechanical anchors in concrete to U.S. building codes in the form of ACI 318-02 Appendix D [1] and ACI 355.2 – *Qualification of post-installed mechanical anchors in concrete* [2] led to an almost immediate request for parallel provisions to address bonded (adhesive) anchors. In response, and anticipating the rather longer lead time required for development of provisions through the ACI consensus process, the Concrete Anchor Manufacturers Association (CAMA), in conjunction with the ICC Evaluation Service (ICC-ES), developed the acceptance criteria *AC308 – Acceptance Criteria for Post-installed Adhesive Anchors in Concrete* [3]. While not a consensus standard, AC308 is intended to complement the design provisions of ACI 318 Appendix D and the qualification provisions of ACI 355.2. AC308 was adopted for implementation by the ICC-ES Evaluation Committee in June of 2005. It provides a vehicle for the issuance of Evaluation Service Reports addressing the use of proprietary adhesive anchor products over a wide range of use conditions in accordance with the International Building Code (IBC) [4].[1]

2. Previous criteria for qualification and design of bonded anchors in the U.S.

Use of adhesive and cementitious grouts to set threaded rods and reinforcing bars in hardened concrete has been practiced in the U.S. for several decades. Nevertheless, proprietary bonded anchor products remained largely unregulated until the issuance of *AC58 – Acceptance Criteria for Adhesive Anchors in Concrete and Masonry Elements* [5] by the ICBO Evaluation Service (precursor to ICC-ES) in January of 1995. AC58 was developed in the early 1990s by the newly formed Concrete Anchor Manufacturers Association in response to calls from the design and building regulation communities for standard testing and assessment procedures. Largely based on *AC01 – Acceptance Criteria for Expansion Anchors in Concrete and Masonry Elements* [6], AC58 is a "you-get-what-you-test" standard; i.e., recognition is granted under the criteria only to the specific anchor embedments and diameters tested for specific concrete strengths. AC58 references *ASTM E1512 – Standard Test Methods for Testing Bond Performance of Bonded Anchors* [7] for tests to determine e.g. the sensitivity of the adhesive to temperature variations and sustained loads. Because the criteria generally calls for the application of a global factor of safety (typically 4.0) to the mean peak loads attained in the testing, AC58 provides so-called "allowable loads" for anchor products which are suitable for use under an "allowable stress design" paradigm. Significantly, AC58 assumes that the product is installed on the job site with continuous special inspection by a qualified inspector retained by the project owner.

3. Structure and intent of AC308

AC308 consists of a short "boiler-plate" section addressing, e.g., reference standards, quality assurance requirements and reporting requirements. This is followed by Annex A, which contains the primary document as developed by CAMA and approved by the ICC-ES Committee.

The table of contents of Annex A is provided as Fig. 1

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[1] Evaluation Service Reports are advisory documents intended to assist building officials in determining code compliance for materials or methods not explicitly addressed in the code. While they are often referred to as "approvals", they may only be considered as such in the context of a decision by the authority having jurisdiction to accept their findings, e.g., per IBC Section 104.11.

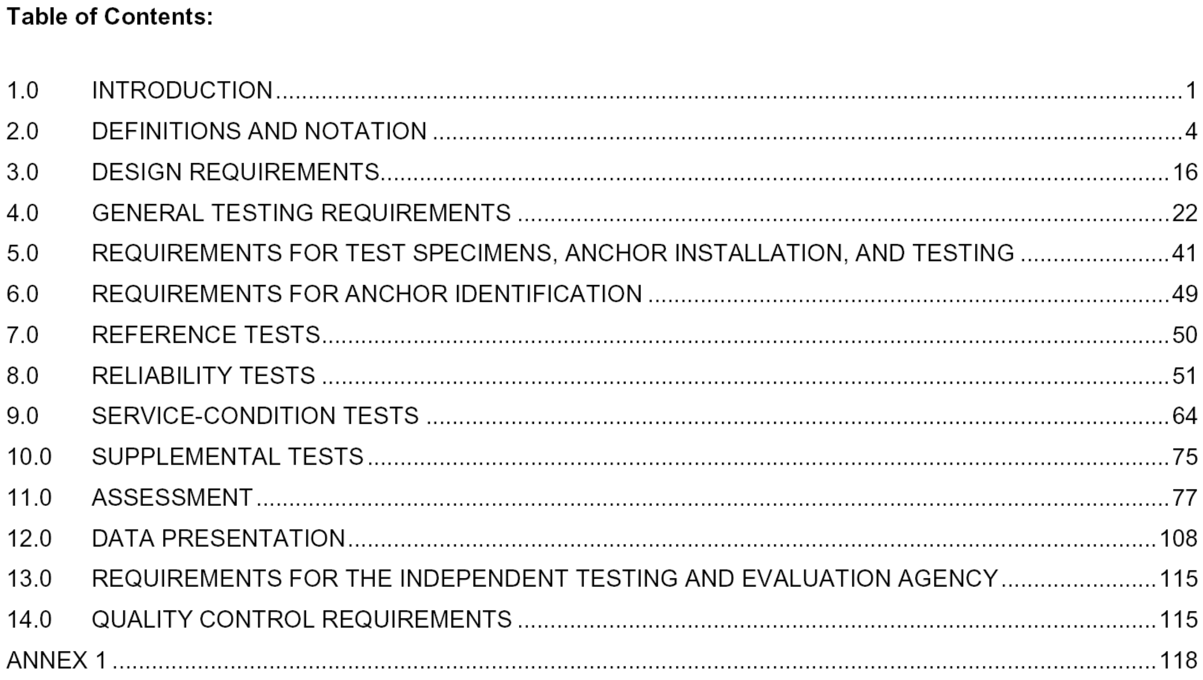

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Fig. 1: Table of contents, AC308 Annex A

Brief descriptions of some of the most relevant portions of the document are provided here.

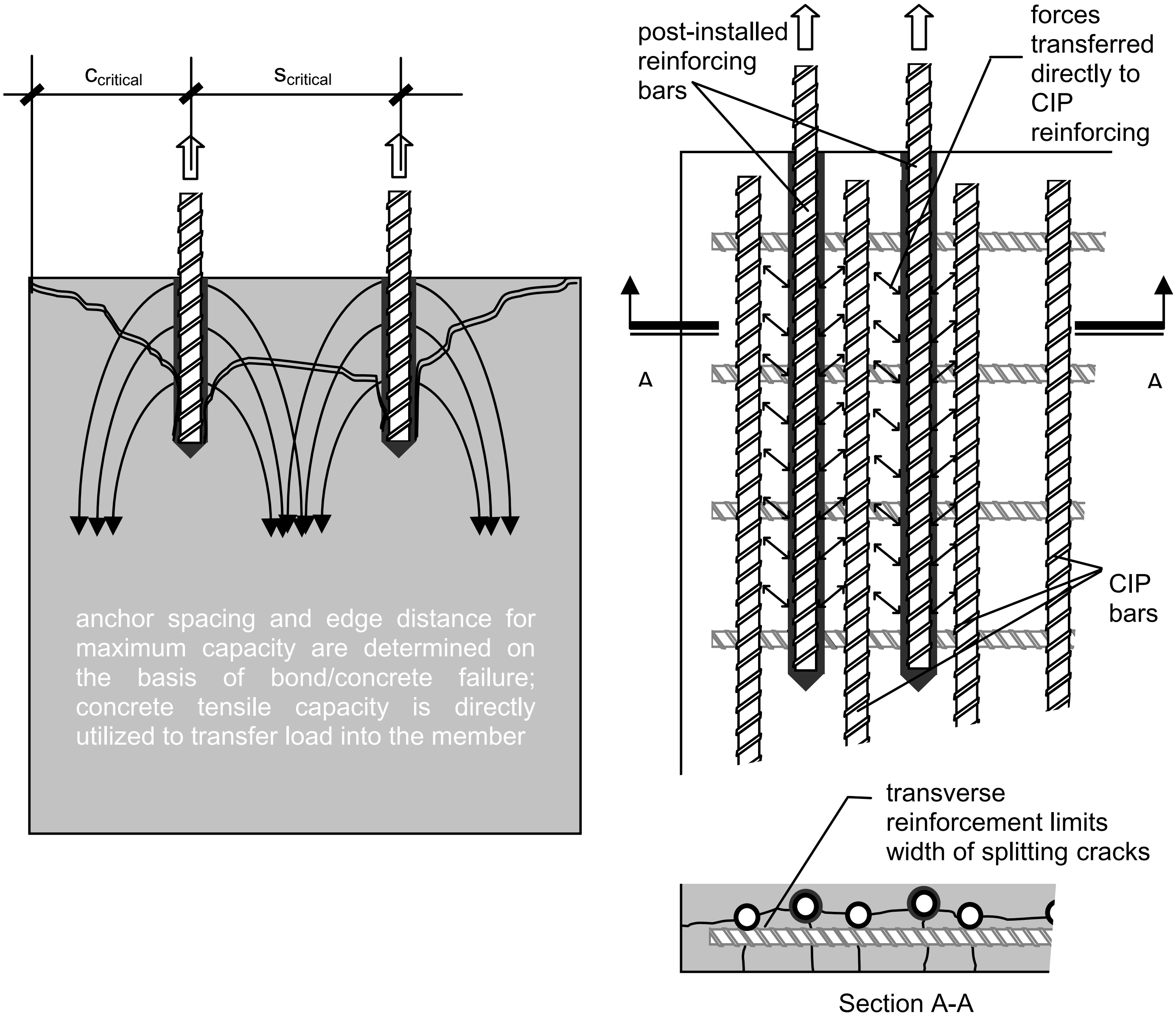
4. Scope of AC308

Section 1.0 establishes the scope of the AC308 as shown in Table 1. Both adhesive anchors based on the use of threaded rod or reinforcing bars as well as torque-controlled adhesive anchors are included. Qualification and design for uncracked and cracked concrete are addressed. The use of bonded reinforcing bars in lap splices as shown in Fig. **2** is not addressed since this would require validation of the adhesive with respect to the splitting failure mode and as a practical matter such tests (similar to those used to determine permissible bond stresses for cast-in-place reinforcing) have not been included.

Table 1: Overview of anchor systems addressed by AC308 [3]

Anchor Type	Embedded part	Assessment Criteria		Design
Adhesive anchor	Steel bar with deformations or threads; reinforcing bar	Use in uncracked concrete only	Table 4.1	ACI 318-02 as modified by Section 3.0
		Use in cracked and uncracked concrete	Table 4.2	
Torque-controlled adhesive anchor	Round steel element with deformations designed to generate expansion forces	Bond/slip force verified	Table 4.3	ACI 318-02
		Bond/slip force not verified	Table 4.4	

Also of significance is the range of anchor embedments (4d – 20d) addressed by the acceptance criteria. Traditionally, adhesive anchors have been tested in the range of 5d – 12d, the most common embedment being 9d. This was in part dictated by the practicalities associated with testing multiple embedment depths under “you get what you test” acceptance criteria. It was also a reflection of the strength limits of the steel anchor elements used for testing: tests resulting in steel failure provide little or no useful design data. With AC308, the objective of testing is to establish a design bond strength which can be applied to any embedment within the 4 to 20 diameter range. This provides much greater flexibility for the designer and permits the design of group and near-edge anchorages that are not limited by concrete or bond capacity.



anchor group (addressed by AC308) rebar lap splice (not addressed by AC308)

Fig. 2: Anchor vs. rebar theory [3]

5. Design provisions

Section 3.0 contains supplementary design provisions necessary to address the bond failure mode. These provisions are fully described in [8]. A brief recapitulation is provided here:

Determination of adhesive anchor strength in tension recognizes the following possible failure modes:

1. steel failure
2. concrete breakout
3. bond failure
4. splitting

The bond failure mode is analogous to the pullout failure mode considered in the case of mechanical post-installed anchors; however, it is the behaviour of adhesive anchor groups exhibiting bond failure that requires special attention. While the concrete breakout failure mode points to a clear relationship between embedment depth and critical spacing, the bond strength formulation requires calculation of a unique value for the critical anchor spacing that is dependent on anchor diameter and the bond capacity of the adhesive. The basic bond strength is determined using a uniform bond stress formulation.

The tension strength of an adhesive anchor group is limited as follows:

$$N_{ag} = \frac{A_{Na}}{A_{Na0}} \cdot \psi_{g,N_a} \cdot \psi_{ec,N_a} \cdot \psi_{p,N_a} \cdot N_{a0} \quad \leq \quad N_{cbg} \tag{1}$$

where:

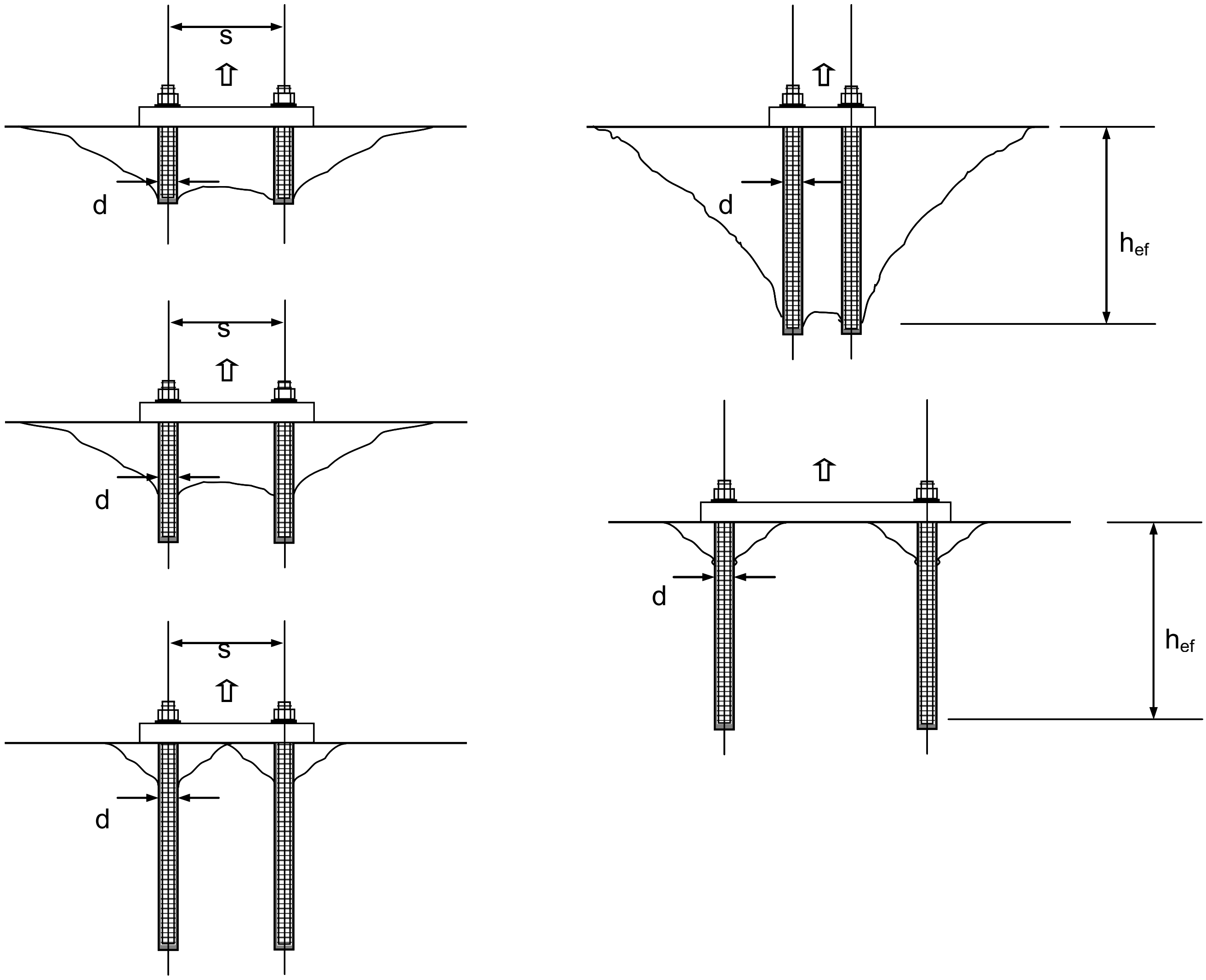
N_{ag} = the nominal bond strength of an adhesive anchor group;

N_{cbg} = the nominal concrete breakout strength of an adhesive anchor group;

$\frac{A_{Na}}{A_{Na0}}$ = a term to account for the group effect of multiple proximate adhesive anchors;

N_{a0} = the nominal bond strength of a single adhesive anchor; and

$\psi_{g,N_a};\psi_{ec,N_a};\psi_{p,N_a}$ are terms to account for bundled anchors, eccentric loading, and splitting behavior.



increased embedment, spacing constant

increased spacing, embedment constant

Fig. 3: Bond failure mode transition of adhesive anchor groups (after [9])

The nominal bond strength of a single adhesive anchor is calculated using a uniform bond stress concept. The critical anchor spacing is determined as follows:

$$s_{cr,Na} = 25 \cdot d \cdot \left(\frac{\tau_k}{1,450} \right)^{2/3} \leq 3 \cdot h_{ef} \quad (\text{lb/in}^2\text{, in.}) \qquad (2)$$

where:

$s_{cr,Na}$ = the critical anchor spacing for determination of the bond strength of an adhesive anchor group;

τ_k = the nominal bond stress established for the adhesive;

d = the nominal anchor diameter; and

h_{ef} = the effective anchor embedment depth.

That the critical spacing (and edge distance) is a function of the anchor diameter and bond strength may be understood as a reflection of the manner in which adhesive anchors deliver load into the concrete: it is the localized load intensity, as governed by bond area and bond strength, that is decisive for the behavior of anchor groups. This formulation for the critical spacing is supported by a substantial database comprised of both physical testing and finite element simulation. Additional details are provided in [8].

6. Reliability tests

The reliability testing concept of AC308 is substantially based on Part 5 of ETAG 001 [10]. Reliability tests are intended to determine whether the product has a special sensitivity to so-called "foreseeable" installation conditions that deviate from the ideal. In particular, the level of hole cleaning effort and the presence of water are singled out as critical variables to be investigated. Under this paradigm, the manufacturer is required to define the hole cleaning procedures with a degree of specificity that will permit tests to be conducted with "50%" of the specified hole cleaning. This naturally anticipates certain types of hole cleaning methods, such as repeated use of a brush (mechanical hole cleaning) and repeated use of vacuum or compressed air. With regards to the latter, since the amount of air pressure and the duration of the air application could have a significant effect on the hole surface characteristics and thus the anchor performance, these variables should also be specified by the manufacturer.

In the ETAG formulation, a maximum number of hole cleaning steps is implied. Per Section 5.1.2.1a:

> *Clean the hole with the hand pump and brush supplied by the manufacturer using two blowing and one brushing operation in the order prescribed in the manufacturer's installation instructions. This test procedure is valid only if the manufacturer's installation instructions specify hole cleaning with at least four blowing and two brushing operations.*

In AC308, no specific limit is provided, however, in accordance with Section 8.5.3

> *…the manufacturer's published installation instructions for the product shall be reasonable with respect to the extent and complexity of the cleaning process…*

The "reasonableness" of the manufacturers specified installation procedure is intended to be in part self-regulating owing to a requirement in AC308 that a facsimile of the installation instructions as used for the tests and as included with the product packaging be included in the approval. Per Section 12.4.1:

> *The evaluation report shall include sufficient information for complete product identification, manufacturer's printed installation instructions, and design data.*

Installation procedures (and the products with which they are associated) that may be optimal for achieving commercially competitive bond stresses but that are overly complex or unrealistic from the standpoint of typical jobsite conditions will presumably not find favour in the design and construction community.

In any case, the reliability tests are not intended to address gross installation errors, such as violation of specified gel and cure times, deviations from the specified embedment, etc.
Also included in the reliability category are tests to check for sensitivity to freeze-thaw conditions, sustained load, crack width cycling (where recognition for use in cracked concrete conditions is desired) and installation direction.

7. Service condition tests

Service condition tests are designed to establish a reference bond stress for the adhesive. They are conducted in high and low strength concrete. Where recognition for use in cracked concrete is desired, they are repeated in cracks having a width of 0.3 mm (0.012 in.) and 0.5 mm (0.020 in.).

8. Round-robin tests for regional variations in concrete

A unique feature of AC308 is the use of so-called round-robin tests to establish calibration factors for the data set based on potential regional differences in concrete. Anecdotal evidence has long indicated that such regional variations can have a measurable impact on bond strengths as measured in tension testing. The round-robin tests consist of 5 tension replicates at an embedment that will produce bond failure in four batches of concrete having similar compressive strengths but produced with aggregates originating in four widely separated geographic regions of the U.S. The results of these tests are used to generate a calibration factor to be applied to the characteristic bond stress determined in the qualification tests.

9. Torque-controlled adhesive anchors

Provisions for the testing and assessment of torque-controlled adhesive anchors substantially mirror those contained in EOTA Technical Report 18 – *Assessment of torque-controlled bonded anchors* [11]. The design of torque-controlled adhesive anchors is largely regulated by the provisions of ACI 318 Appendix D for cast-in and post-installed mechanical anchors.

10. Special inspection requirements

Special inspection refers to jobsite quality control of welds, reinforcing placement, concrete quality, etc. by a special inspector in accordance with Sec. 1704 of the IBC. It is typically required that inspection of the placement of cast-in anchors in the formwork be performed prior to casting; as such, special inspection is also required for post-installed

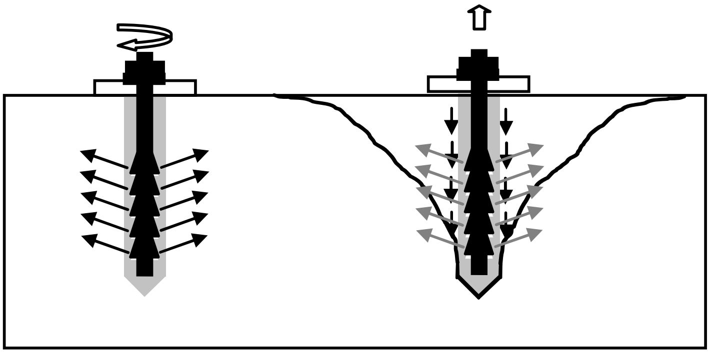


Fig. 4: Schematic representation of a torque-controlled adhesive anchor (after [3])

anchors, whereby the inspection requirements are detailed in the approval. AC308 provides for two levels of jobsite quality control in the form of special inspection (either continuous or periodic as per Section 14.4.2 and 14.4.3, respectively) and proof-loading in accordance with Section 14.4.4. At a minimum, special inspection includes review of the drilling method being used, the hole depth and diameter, the cleaning methods employed, the product identification and expiration date, and the product installation in accordance with the manufacturer’s instructions. The quality control requirements are directly linked to the threshold requirements applied to the results of the reliability tests. Products that satisfy more stringent standards with respect to reliability are rewarded with relaxed jobsite quality control (periodic vs. continuous special inspection and no proof loading requirement).

11. Future code implementation

The existence of an ICC-ES acceptance criterion to regulate a specific building component or procedure implies that the subject component or procedure has yet to be formally addressed in the building code. The well-publicised failure of an adhesive anchor system in the U.S. [12] has prompted widespread interest in the structural engineering and building official communities regarding regulation of the use of adhesive anchor products in building and civil construction (tunnels, public works, etc.). In view of this interest, ACI is actively pursuing the implementation of qualification and design procedures in committees 355 and 318, respectively. It is anticipated that these provisions will in large part mirror those contained in AC308. At such time as they are formalized in future editions of ACI 318 and ACI 355, AC308 will either be revised to substantially refer to the relevant ACI documents or will be withdrawn.

12. Summary

AC308 provides comprehensive requirements for the qualification and design of adhesive anchors in conformance with strength design provisions of ACI 318 and the IBC. It establishes procedures for the determination of the characteristic bond stress taking into account the sensitivity of the anchor system to foreseeable variations in jobsite conditions and links the sensitivity to jobsite quality control measures. It further provides design provisions for the bond failure mode that complement those in ACI 318 for concrete breakout, steel failure, etc.

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INTERNATIONAL BUILDING CODE COMPLIANT ANCHOR APPROVALS

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Abstract

Greater understanding of post-installed anchors installed in hardened concrete has emerged from extensive product testing and research during the last 25-years. Consequently, new design provisions have been developed enabling the Structural Engineer to increase the efficiency of an anchor without compromising the safety of the connection. The new design concept recently introduced in the US results in added failure mode transparency by allowing the Structural Engineer to determine the connection capacity based on the failure mode offering the least resistance. As the number of municipalities adopting the 2003 IBC (International Building Code) in the United States grows, an increasing number of Structural Engineers will be designing anchorage to concrete according to the new provisions. This article provides an overview of the new testing and evaluation concept for the performance and classification of post–installed fastening systems. The general content and layout of new approvals issued by ICC-ES are explained and benefits are highlighted by contrasting old and new approvals.

1. Introduction

The evolution from allowable stress design (ASD) to strength design (SD) is not new to the American Structural Engineering community. Analogous to the adoption of a new concrete design procedure in the late sixties and to some extent steel design today, anchorage to concrete is undergoing a similar design transformation. Greater understanding of anchor behavior in concrete has emerged from extensive product testing and research during the last 25-years. Consequently, new design provisions have been developed which enables the Structural Engineer to increase anchor efficiency without compromising the safety of the connection. The new design concept provides added failure mode transparency by allowing the Structural Engineer to determine the governing connection capacity based on the failure mode which offers the least resistance. A typical example of a fastening situation the engineer might encounter in his daily work is shown in

Fig. 1: design of a group of four anchors, located close to a free edge. The new design concept allows for a realistic and economical approach when taking into account the various effects such as spacing and edge distance on the load carrying capacity.

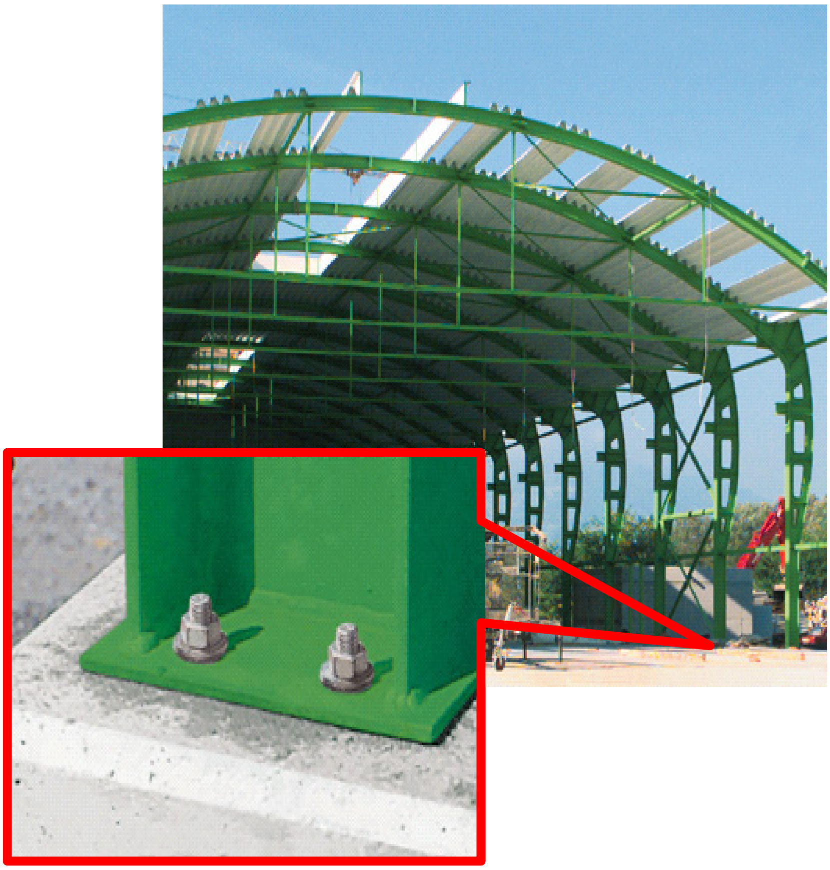

Fig. 1: Typical fastening situation

2. Background

2.1 Numerical investigations

With the publishing of the 2000 IBC, United States' three model code groups addressed the need for uniformity by merging Building Officials and Code Administrators International, Inc. (BOCAI), International Conference of Building Officials (ICBO), and Southern Building Code Congress International, Inc. (SBCCI) into the International Code Council (ICC). ICC is a nonprofit organization dedicated to develop a single set of comprehensive and coordinated national model construction codes. The progression of design provisions for anchoring to concrete in recent building codes [1, 2, 3] is summarized in the table below.

Table 1: US building codes development

Code	Anchor type	ASD	SD
1997 Uniform Building Code™	Cast-in	UCS[1]	UCS[1]
2000 International Building Code®	Cast-in	UCNS[2]	UCS[1], UCNS[2], CC[3]
2003 International Building Code®,[4]	Cast-in	UCNS[2]	UCS[1], UCNS[2], CC[3]
	Post-installed		UCS[1], UCNS[2], CC[3]

1) UCS = Uncracked concrete including seismic applications
2) UCSN = Uncracked concrete; non-seismic applications
3) CC = Cracked concrete including seismic applications
4) IBC 2003 references ACI 318-D for design provisions

Preceding the publication of IBC 2003, ASD Evaluation Reports (ER) were published for post-installed anchors placed in hardened uncracked concrete. These approvals, an ER = approval, addressed alternative materials, design and methods of construction and equipment, not specifically included in a given model code. The majority of these reports incorporated seismic design provisions for products passing the required qualification tests in uncracked concrete. Independent approval agencies issued these reports, i.e. International Conference of Building Officials (ICBO, presently ICC-Evaluation Service). IBC 2003 includes an equivalent statement regarding alternative materials, design and methods of construction and equipment. However, IBC 2003 references ACI 318 Appendix D directly, where strength design (SD) equations are provided for both cast-in and post-installed mechanical anchors in uncracked and cracked concrete. The new design standard referenced in IBC 2003 requires post-installed anchor Manufacturers to provide strength design load values (characteristic design values) and additional parameters supplementing the provisions of ACI 318-D. This additional design information is generally provided in an Evaluation Service Report (ESR = approval) published based on product qualification in accordance with new acceptance criteria. At the time of publication of this article, 47 states plus Washington D.C. use the IBC. As the number of municipalities adopting the IBC 2003 increases, a growing number of Structural Engineers will be designing anchorage to concrete according to the new provision.

3. Product qualification

3.1 General

Typically, post-installed anchor capacities originate from product testing. The test regimes used by a Manufacturer to derive anchor capacities are commonly mandated by independent approval agencies (i.e. ICC-ES in the US). The extent of these test programs is outlined in Acceptance Criteria (AC) published by the approval agency [4]. New AC reflecting the strength design requirements of IBC 2003 have been developed [5, 6]. The evolution of ACs used to derive load values in solid concrete as a base material is illustrated below.