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SEISMIC SAFETY OF ANCHORAGES IN CONCRETE CONSTRUCTION – THE LATEST PERSPECTIVE

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ABSTRACT

Seismic behaviour of anchorages in concrete construction has relatively recently being explored as an important research topic. The safety of various structural and non-structural components connected using the headed fasteners or post-installed anchorages depend on the seismic performance of the anchorage used for the connection. The seismic performance depends on various parameters such as type of product, load-transfer mechanism, cracking and crack width of concrete, amount and type of load applied, correctness of installation etc. A good fastening includes the right selection of anchor type for given loading scenario, proper design and correct installation. This paper tries to answer several questions with respect to the use of cast-in and post-installed (PI) anchors against seismic forces in concrete structures. The basic seismic behaviour of different anchor types, their test and assessment criteria, latest requirements of the German (DIBt) guideline for anchorages in NPP and design issues are addressed in the paper. Recommendations are made for selection of anchors and for additional provisions to be kept in mind for seismic design. Further, it is demonstrated that the design method recommended by old codes and standards for the design of anchorages may lead to significant overestimation of the strength of the anchorages thus leading to unsafe anchorage design.

INTRODUCTION

Cast-in and post-installed anchors are widely used for connecting the structural and non-structural components to the concrete structures. Seismic performance of these anchors forms a wide and open topic of debate, discussion and research throughout the world. Large amount of work has been done over past few decades on characterizing the behaviour of different kinds of anchors under normal loads (Eligehausen et al., 2006). However, the seismic usage of the anchors brings up many open questions starting from selection, testing and assessment criteria, design, installation and inspection etc.

Though, modern fastener industry is already a few decades old and over the years better products as well as more advanced design and testing methods have been developed (Eligehausen et al., 2006), the seismic behaviour of fasteners in concrete structures requires special attention. A good fastening includes the right selection of anchor type for given loading scenario, proper design and correct installation. The failure of anchorages under normal forces is rare due to better products, design rules and installation procedures, however, failures of anchors under seismic conditions is a major issue. Several instances of anchorage failure under seismic loads have been reported in the past. Fig. 1 shows a few anchorage failures that have occurred during past earthquakes due to which structural and non-structural components failure occurred.

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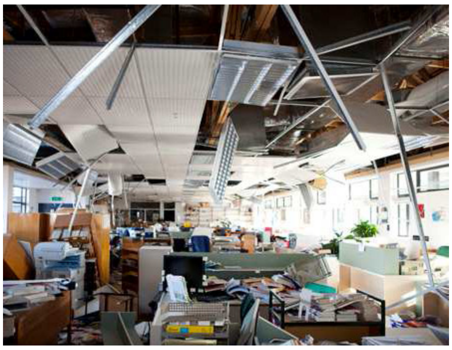


(a) Darfield 2010 (b) Chile 2010

Figure 1. Failure of structural/non-structural components due to anchorage failure during past earthquakes

In general, the design of anchors is performed by considering all the possible failure modes that an anchor may undergo under the action of applied forces and evaluating the resistance of the anchor against each failure mode (Eligehausen et al., 2006). The design load is then recommended as the minimum value of all the resistances. Anchors transfer applied tension loads to concrete by one or the combination of the following mechanisms namely, (i) mechanical interlock, (ii) friction and (iii) bond. The major possible failure modes for an anchor in tension are steel failure, concrete cone failure, pull-out and side face blow-out. Out of these, the concrete cone failure is the most critical and therefore it is also most studied failure mode.

Post-installed anchors are easy to install and provide more flexibility than cast-in anchors like headed studs or embedded plates. However, post-installed anchors are more sensitive to the boundary conditions than cast-in anchors. A comprehensive description of anchor behaviour can be found in Eligehausen et al (2006). Fig. 2 shows some common mechanical anchor types (Mahrenholtz et al., 2011). Based on the large amount of experiments performed in the past, it is recognized that headed studs and undercut anchors are the most reliable type of anchors from seismic safety view point. The discussion through most of this paper is restricted to such anchors, along with torque controlled expansion anchors for comparison.

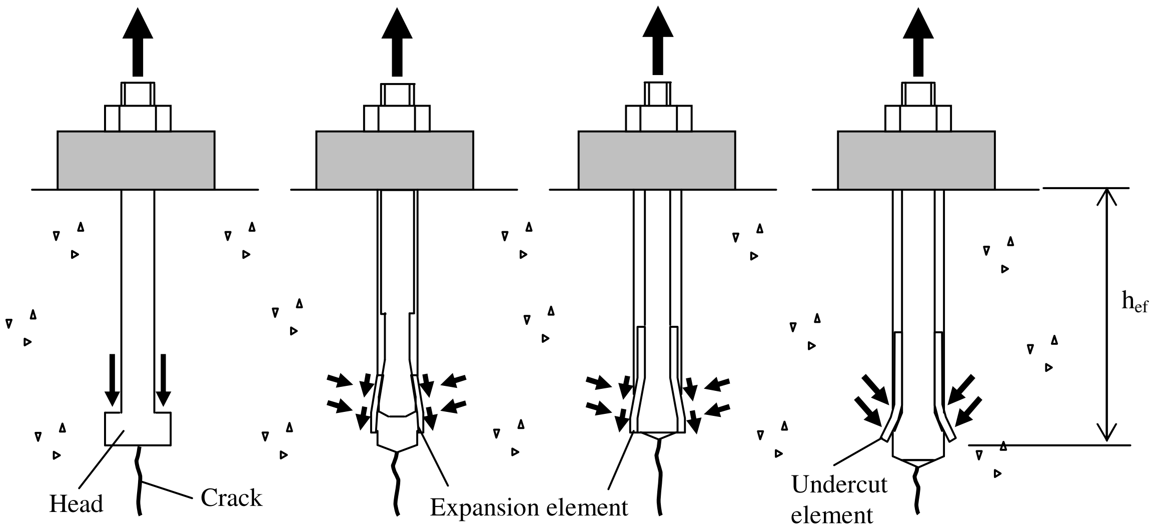
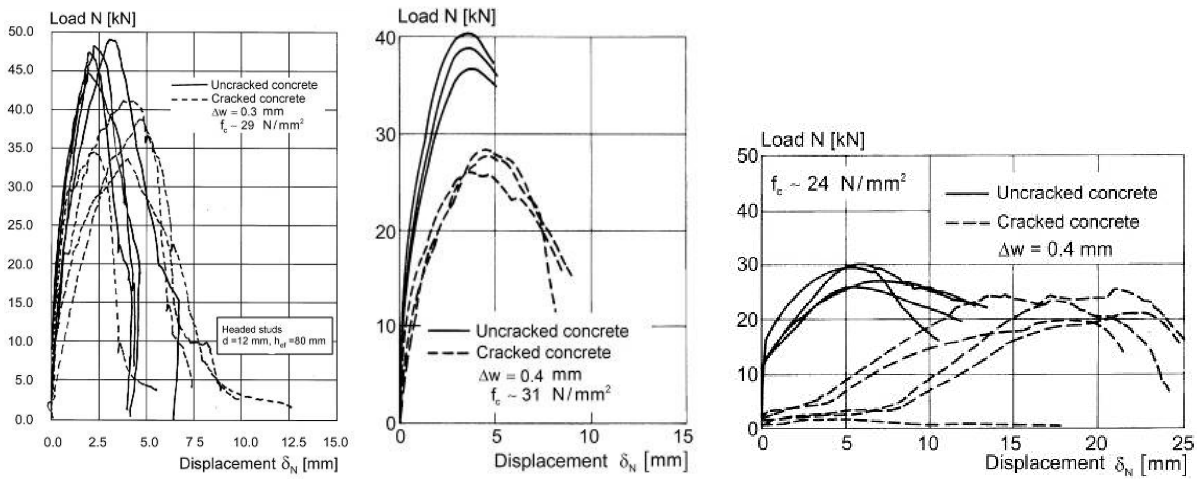


Figure 2 Common mechanical anchor types (Mahrenholtz et al., 2011) a) Cast-in headed stud; b) Torque-controlled expansion anchor (bolt type); c) Displacement-controlled expansion anchor (stud type); d) Undercut anchor

INFLUENCE OF CRACKS ON ANCHORAGES

Due to the low tensile strength, concrete members invariably experience cracking, either due to external loading or due to thermal constraints. There is a high probability that fasteners installed in non-cracked concrete will be located in a crack when cracks form (Eligehausen et al., 2006). This is mainly due to the fact that high tensile stresses are caused due to prestressing and loading of the anchor and the drill holes act as notches leading to stress concentration. The effect of cracking on anchor concrete breakout capacity is two-fold. First, the distribution of hoop stresses around the anchor gets modified to maintain equilibrium, which is applicable for all types of anchors. Second, there is a degradation of force-transfer mechanism due to opening of hole that affects especially bonded anchors and expansion anchors (Eligehausen et al., 2006). Consequently, the anchor load-displacement behaviour is significantly affected by the load acting on the anchor in any direction and the crack in which the anchor may be located. Since cracks have a significant negative influence on the anchor performance, the assumption that the anchor is situated in a crack is conservative, especially when seismic behaviour is concerned.

Anchors, not suitable for cracked concrete, may experience large deterioration in load capacity as well as displacement behaviour, when tested in cracked concrete. Fig. 3 demonstrates the influence of cracks on the load-displacement behaviour of (a) headed studs and expansion anchors (b) qualified and (c) not qualified for cracked concrete. Due to its load transfer mechanism by mechanical interlock, headed studs as well as undercut anchors are less sensitive to cracks and crack width. Fig. 3b demonstrates the effect of cracks on the load-displacement behaviour of qualified torque-controlled expansion anchors (sleeve type) failing by concrete breakout in uncracked and cracked concrete. The tension load in case of such anchors is transferred by frictional resistance. If a crack intersecting the anchor location opens, such “qualified” anchors are able to develop adequate follow-up expansion to re-establish the lost frictional force. However, the anchor loses some of its stiffness and ultimate strength. Anchors, not suitable for cracked concrete, may experience large deterioration in the load carrying capacity as well as displacement behaviour, when tested in cracked concrete. The load-displacement curves in Fig. 3c depict the behaviour of torque-controlled expansion anchors (bolt type) which were developed for applications in un-cracked concrete, but tested also in cracked concrete. It can clearly be seen that in cracked concrete the anchors do not function properly, resulting in very large displacements und unpredictable low ultimate capacities. Anchors which cannot develop a follow up expansion force are therefore not suitable for use in cracked concrete. Drop-in type anchors typically fall in such category. Since there is a high probability that the anchor will be intercepted by a crack (unless special provisions are made), only anchors suitable for use in cracked concrete should be used. Headed studs and undercut anchors being least susceptible to cracks are most recommendable of all anchor types.



(a) Headed Studs (b) Qualified expansion anchors (c) Not qualified expansion anchors

Figure 3. Load-displacement behavior of anchors in uncracked and cracked concrete (Eligehausen et al., 2006)

Fig. 4 presents the relative values of peak tension load for cracked concrete to that of uncracked concrete plotted for large number of tests performed on headed studs and undercut anchors[1]. Within the scatter band of test results, typical of anchors, a gradual reduction in the load carrying capacity of the anchors with increasing crack width has been reported. Nevertheless, a reliable behaviour of the anchorage can still be counted up on provided due consideration to cracking of concrete is given at the design stage.

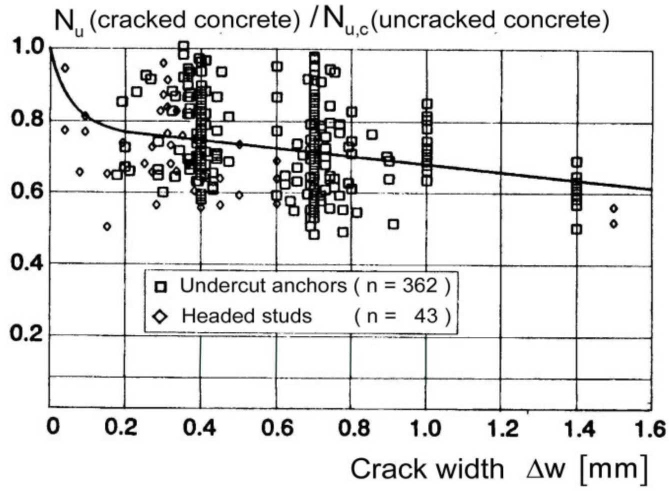


Figure 4 Reduction in load carrying capacity of headed studs and undercut anchors with increasing crack width

DESIGN OF ANCHORAGES UNDER TENSILE LOADING

In general, the design of anchors is performed by considering all the possible failure modes that an anchor may undergo under applied action and evaluating the resistance of the anchor against each failure mode. The design load is then taken as the minimum value of all the resistances after applying the suitable partial safety factors. The failure modes for an anchor in tension are steel failure, concrete cone failure, pull-out, side face blow-out and splitting failure. Out of these, concrete cone failure is the most critical and therefore it is also the most studied failure mode. Traditionally, the concrete cone has been assumed to be a 45 degrees cone initiating at the bearing edge of the anchor (anchor head) and radiating toward the free surface of the concrete member. Till the last decade of previous century, the major standards such as ACI 318 recommended a 45° failure cone and a constant tensile stress over the projected failure surface. This approach cannot be applied over the full range of embedment depths since the size effect is neglected and the assumption of a constant tensile stress over the failure surface is unrealistic (Eligehausen et al., 2006). Later numerical and test results displayed that the angle of the breakout cones is approximately 35 degrees (Eligehausen et al., 2006). Also, it was found that an equation assuming a constant tensile stress over the height of the failure cone over-predicts the strength of the anchors with larger embedment depths. The predictive equation, was modified as

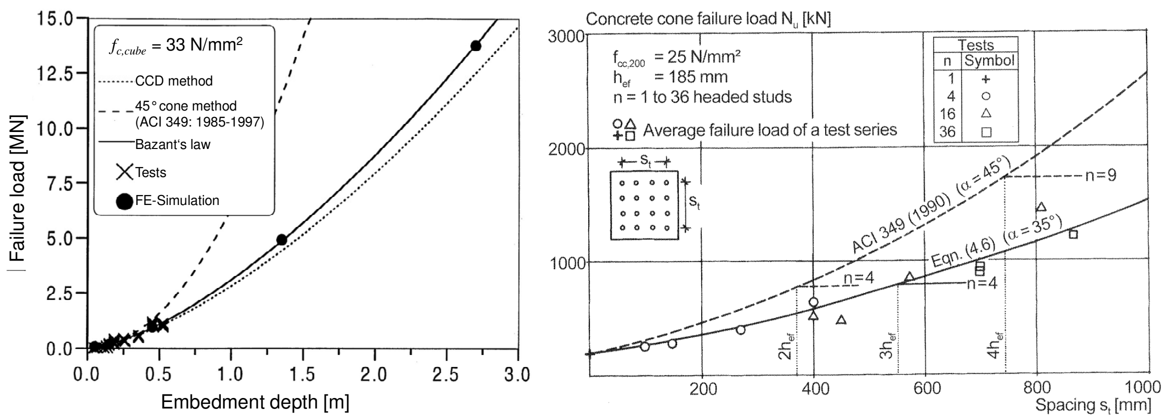
$$N_{u,c} = k_1 f_c^{0.5} \bullet k_2 h_{ef}^2 \bullet \frac{k_3}{h_{ef}^{0.5}} \tag{1}$$

or simply,

$$N_{u,c} = k h_{ef}^{1.5} f_c^{0.5} \tag{2}$$

Where, $N_{u,c}$ is the breakout failure load of concrete cone; f_c is the cylinder strength of concrete; h_{ef} is the effective embedment depth; and k, k_1, k_2 and k_3 are constants. In eq. (1), the first term ($k_1 f_c^{0.5}$) specifies the concrete tensile capacity, the second term the surface area of the failure cone and the last term considers the effect of size on failure load. This method came to be known as the Concrete Capacity Design or "CCD Method" (Fuchs et al., 1995). This method now forms the basis of design procedures for anchors in various international codes and standards (ACI 318, 2011; ACI349, 2006; DIBt 2010; CEN/TS 1992-4, 2009). It has been shown by comparison with a large number of experiments that the CCD method can provide with high confidence a good estimate of the failure load of anchors, while the 45° cone method may highly overestimate the failure load.

Fig. 5a gives a comparison of the failure load estimated by the 45° cone method, which was included in old codes and the CCD method for a single anchor having no edge influence. The analytical results are compared with the experimental results for anchors with normal embedment depths (up to 500mm) and numerical results for anchorages with very large embedment depths (up to 2.6m). It is clear that the results of the CCD method compare very well with the experimental as well as numerical results, while the 45° cone method largely over-predicts the strength of the anchorage with increasing embedment depth. Fig. 5b gives a comparison of analytical failure loads obtained for anchor groups comprising of four to 36 headed studs with h_{ef} = 185mm installed at uniform spacing following the CCD method (35° cone) and the 45° cone method along with experimental values. Again, no edge influence is included. The failure load is plotted as a function of the spacing between outermost studs. It can be seen that the failure load estimated by the CCD method follows the experimental values closely while the 45° cone method generally overestimates the strength of the anchorages. This overestimation increases with increasing embedment depth due to size effect.



(a) Single anchor (b) Group of anchors

Figure 5. Failure loads predicted by 45° cone method and CCD method

Fig. 6 displays a comparison between analytically obtained breakout loads calculated with the 45° cone method and the CCD method for a case of an anchor group consisting of four anchors with an anchor spacing as well as edge distance equal to h_{ef}. In this case, the results are given only up to h_{ef} = 500mm. It can be seen that in case of such configuration, the ratio between the failure load predicted by the 45° cone method and that predicted by the CCD method can be as high as 4 for an embedment depth of 500mm. This ratio further increases with increasing embedment depth. For certain configurations of anchor groups and large embedment depths the failure load predicted by the two methods can be different up to almost an order of magnitude.

It is very important to note that a large number of important industrial including nuclear safety related structures across the world were designed and commissioned before the CCD method was included in the design codes. Therefore, the estimated load carrying capacity for a large number of anchors may be much higher than their real capacity, especially for anchors with $h_{ef} \geq$ 200mm. It is therefore imperative that as a part of a seismic re-qualification procedure, all anchorages should also be re-evaluated for their actual load carrying capacity as per the CCD method.

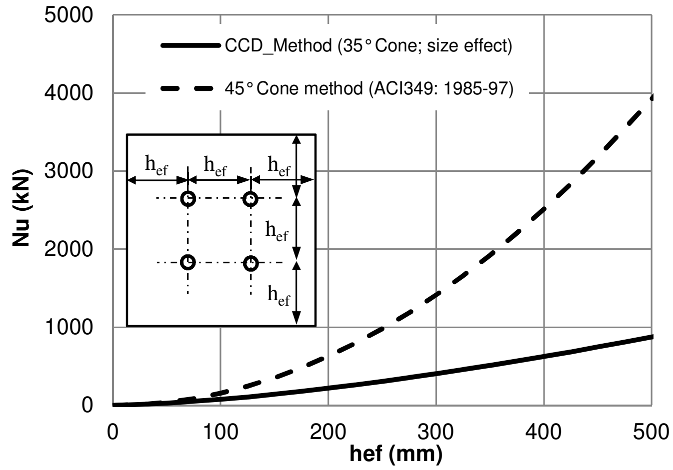


Figure 6. Failure loads predicted by the 45° cone method and the CCD method for an anchor group with four headed studs (s = c = h_{ef})

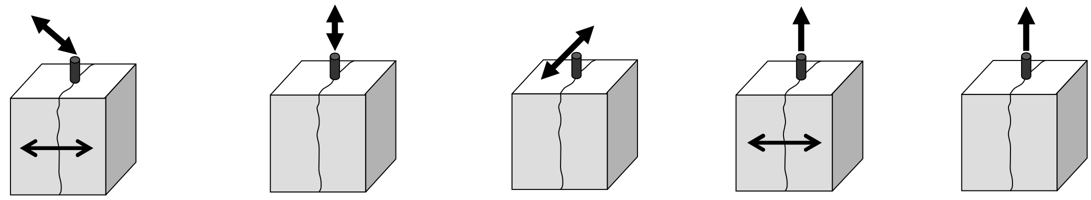
QUALIFICATION GUIDELINES FOR POST-INSTALLED ANCHORS AGAINST SEISMIC LOADS

In Europe, anchors used for safety relevant connections need to be approved to ensure proper functioning. Anchors may be qualified for installation in un-cracked concrete only or for installation in un-cracked and cracked concrete (crack width ≤ 0.5mm) (ETAG001, 2012). The test procedures and assessment criteria to qualify anchors for seismic loading have recently been added in ETAG001 (2012). The corresponding US standard for qualification of anchors against seismic loads is ACI 355.2 (2007). This guideline applies to post-installed mechanical anchors intended for use in structural applications covered by the design guideline ACI 318. Seismic qualification can be acquired and is based on simulated seismic tests as cyclic tension and cyclic shear tests (Mahrenholtz, 2013). Further requirements for the qualification of post-installed mechanical anchors are given in the Acceptance Criteria for Mechanical Anchors in Concrete Elements (AC193, 2010).

The European qualification guideline ETAG001 (2012) and the US qualification guideline ACI 355.2 (2007) were harmonised in many aspects over the past decade. These guidelines follow a similar approach to differentiate the tests according to their purpose. The suitability tests (ETAG001, 2012) and Reliability Tests (ACI 355.2, 2007) are included to establish whether an anchor exhibits a safe and effective behaviour under ‘adverse’ conditions. If the anchor does not achieve the required strength under the prescribed ‘extreme’ conditions, the characteristic strength to be used in design is reduced (Mahrenholtz, 2013). Further, Admissible Service Condition Tests (ETAG001, 2012) and Service-Condition Tests (ACI 355.2, 2007) reflect conditions which are generally understood as (interchangeably) ‘normal’, ‘realistic’, or ‘moderate’ and serve the determination of the characteristic load capacity, i.e. characteristic resistance, as well as the minimum spacing between two anchors and minimum distance to the adjacent edge necessary to achieve the full design strength.

Due to the high safety standards effective for NPP, additional requirements should be met to allow for seismic actions as well as large crack widths. The German guideline for anchorages in nuclear power plants (DIBt, 2010) addresses these issues. The NPP Guideline (DIBt, 2010) is valid for post installed anchors used to connect safety relevant elements to concrete or fasten elements whose failure might affect safety relevant elements. Cracked concrete is generally assumed. However, it does not apply to anchors which are installed in areas that are prone to concrete spalling or extreme crack widths, e.g. in plastic hinge zones. The guideline is valid for all anchor types with a European Technical Approval for use in cracked and un-cracked concrete.

During extreme earthquakes, large cracks may occur and anchors, which are located in such a crack, may be loaded by cyclic tension and shear loads. At the same time, the structure serving as base material is cycled as well, resulting in opening and closing of the cracks. Since simultaneous load and crack cycling (Figure 7a) is rather difficult for qualification tests, different load and crack cycling tests are required: Tension and shear load cycling of anchors located in an open crack (Figure 7b and 7c), and cycling of the crack between an upper and a lower crack width while the anchor is loaded by a constant tension load (Figure 7d). In addition, monotonic reference tests with anchors located in open cracks are required (Figure 7e).



a) Simultaneous crack and load cycling | b) Constant crack, cycled tension load | c) Constant crack, cycled shear load | d) Cyclic crack, constant load | e) Constant crack, monotonic load

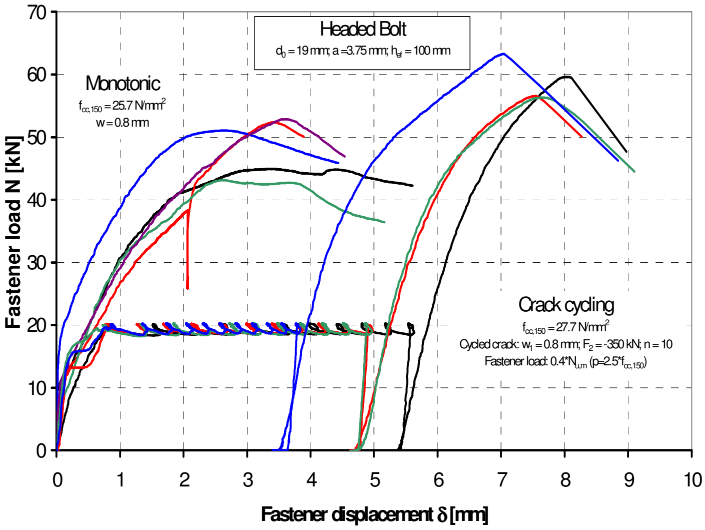
Figure 7. Load and crack cycling (a) simulated in different tests (b) to (e) (Hoehler, 2006)

ETAG001 (2012) defines a suitability test the functioning of the anchor under repeated load. The anchor is installed in uncracked concrete and is subjected to 100,000 tension load cycles between pre-defined maximum and minimum tension loads at a maximum load cycle frequency of 6 Hz. The residual strength measured in the pullout test after the load cycling should reach 100 % of the monotonic reference strength; otherwise the characteristic strength is reduced. Very similar tests under repeated loads are also prescribed by ACI355.2 (2007). Additionally, simulated seismic tests, where 140 cycles of tension load are applied on the anchor installed in cracked concrete. For the first ten cycles, the maximum anchor load, designated as earthquake load, N_{eq} is applied which corresponds to half of the mean monotonic reference strength $N_{u,m}$ tested in 0.3 mm crack width (Mahrenholtz, 2013). The maximum anchor loads are reduced to $N_i = 0.75\ N_{eq}$ for next thirty cycles and to $N_m = 0.5\ N_{eq}$ for the last 100 cycles. Qualification criteria is based on (1) completing all load cycles, and (2) achieving a residual capacity of at least 160 % N_{eq}, i.e. 80 % of the mean monotonic reference strength. If the anchor fails to fulfill the aforementioned requirements, the tests have to be repeated with a reduced maximum anchor load and the nominal seismic strength has to be reduced linearly (Mahrenholtz, 2013). The DIBt (2010) guidelines for nuclear safety related structures recommend 15 cycles at a maximum frequency of 1Hz, between maximum load, N_{max} = design anchor load and $N_{min} = 0$ on anchors installed in cracked concrete with a crack width as high as 1.5mm. The assessment criteria requires that residual capacity obtained after the load cycling tests is at least 90 % of the mean ultimate load measured in monotonic reference tests in the same crack width.

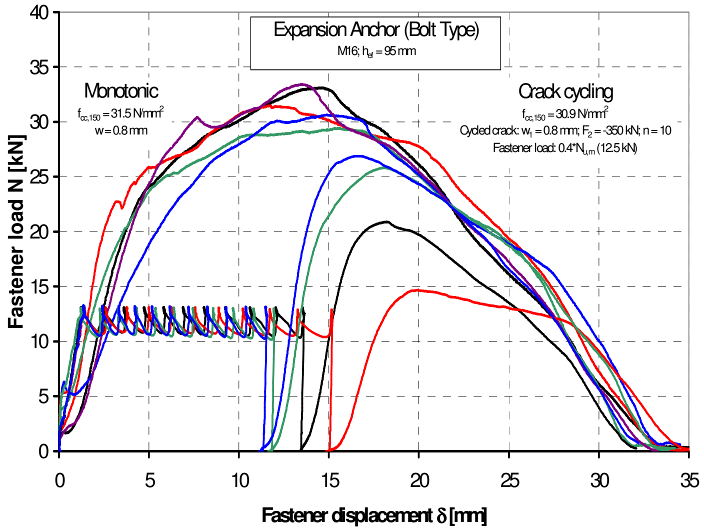
Both ETAG001 (2012) and ACI355.2 (2007) recommend crack cycling tests on anchors subjected to a constant tension load. The anchor is loaded to the specified tension load, which is given by ETAG001 (2012) as 0.5 times the characteristic load obtained from reference tests on anchor in 0.3mm crack width, $N_{Rk0.3mm}$ and by ACI355.2 (2007) as 0.3 times $N_{Rk0.3mm}$. The crack is cycled 1000 times between the minimum and maximum crack widths specified as 0.1mm and 0.3mm by both the standards. DIBt (2010) guideline recommends to perform cyclic crack tests with 10 cycles between crack widths of $w_{min} = 1.0$mm and $w_2 = 1.5$mm for suitability tests. During crack cycling, a constant permanent axial load equal to the design anchor load is applied to the anchor. The residual capacity in the suitability test is required to achieve 90 % of the mean ultimate load measured in monotonic reference tests in the same crack width. In case of failure during cycling or not meeting the requirement regarding the residual load capacity, the tests are retaken with lower permanent load and the design strength is reduced accordingly (Mahrenholtz, 2013). Additionally, the anchor displacement behaviour under service condition is measured by anchor displacement tests, in which 5 crack cycles between crack widths of 0.0mm and maximum specified crack width (e.g. 0.8mm or 1.0mm). The zero crack width is achieved by applying a compression force to the concrete test specimen equal to 15 % of the compressive strength of concrete specimen. If in the static analysis of the element fastened to the concrete, the anchor is assumed to be rigid, the mean displacement of the anchor is limited to 3mm. To ensure that the maximum displacement is limited, the CoV of the displacements after load and crack cycling after load or crack cycling is limited to 40%. If the limit on the displacements is not met, the tests shall be repeated with a lower load until the displacement criterion is met and the characteristic anchor resistance shall be reduced accordingly.

BEHAVIOUR OF ANCHORS UNDER CRACK CYCLING

The crack cycling test is probably the toughest seismic test that an anchor has to undergo. The crack cycling test involves the following steps (Mahrenholtz et al., 2010): Generating the hairline crack in concrete; installing the anchor in the pre-defined crack; applying constant tension load on the anchor; opening and closing of crack for specified number of cycles, and; performing monotonic pull out test to obtain residual capacity. Fig. 8 (a) and (b) show the load-displacement plots for headed studs and bolt type expansion anchors, suitable for use in cracked concrete, respectively subjected to a crack cycling between a closed crack (achieved by applying a compression force) and wmax = 0.8mm, followed by a pull out test (Hoehler, 2006). As seen from the curves, it can be said that the peak load of the headed studs is not affected by the crack cycling, however, there can be a significant influence of crack cycling on the behaviour of bolt type expansion anchors.



(a) Headed studs



(b) Bolt type expansion anchors

Figure 8. Anchors subjected to crack cycling (w_{max} = 0.8mm, w_{min} = 0) followed by pull out (Hoehler, 2006)

From the crack cycling tests, typically the following conclusions may be drawn: (i) Headed studs and undercut anchors are most suitable for use in seismic loading cases and can perform well even in large crack widths; (ii) Displacement controlled expansion anchors are unsuitable for cracked concrete and perform not satisfactorily under seismic loading; (iii) Depending on anchor design and anchor diameter, torque controlled expansion anchor may perform well in small crack widths (w ≤

0.5mm) but may be less suitable for large crack widths; (iv) In general, sleeve type expansion anchors show a superior behaviour compared to bolt type expansion anchors with the same diameter (v) Concrete screws should only be used if small crack widths are expected. A rather broad guideline for the suitability of anchors for use in cracked or non-cracked concrete under seismic loading is given in Table 1 below.

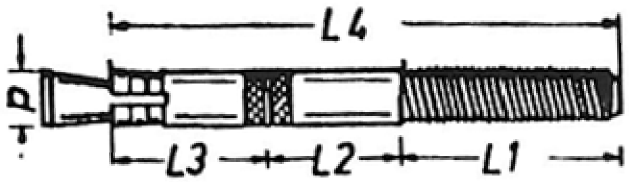
Table 1. A broad guideline for suitability of PI anchors for use in in NPPs

Type of anchor	Undercut anchors	Expansion anchors			Concrete Screws
		Displacement controlled	Torque controlled		
			Bolt Type	Sleeve Type	
Uncracked Concrete	Suitable	Suitable	Suitable	Suitable	Suitable
Crack width ≤ 0.5 mm	Suitable	Limited*	Suitable**	Suitable**	Suitable
Crack width between 0.5-1 mm	Suitable	Unsuitable	Limited*	Limited*	Limited*
Crack width > 1 mm	Suitable	Unsuitable	Limited*	Limited*	Unsuitable

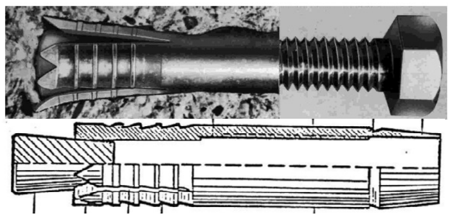
* Suitability depends on design and anchor diameter
** Anchors are suitable if designed for use in cracked concrete

BEHAVIOUR OF ANCHORS INSTALLED IN INDUSTRIAL STRUCTURES AND NUCLEAR POWER PLANTS TILL LATE NINETIES

Till late 90's, in important industrial structures as well as in certain nuclear power plants, often anchors were used that were designed for use in uncracked concrete. Torque controlled stud type expansion anchors (Fig. 9a) and self-drill anchors (Fig. 9b) were employed.



(a) Stud type expansion anchor



(b) Self drill anchor

Figure 9. Typical anchors used in nuclear industry prior to late 90's

Fig. 10 shows the effect of cracking on the load carrying capacity of self-drill anchors (Eligehausen and Balogh, 1995). It demonstrates that the failure load of these anchors decreases significantly with increasing crack width. This is valid also for stud type expansion anchors.

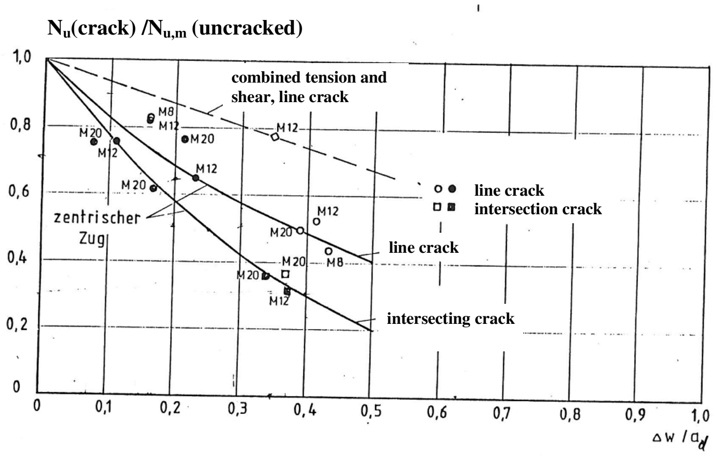


Figure 10. Relative failure load of self-drill anchors in cracked concrete (Eligehausen and Balogh, 1995)

Furthermore, galvanized anchors may corrode (example see Fig. 11), which further reduces the failure load of torque controlled expansion anchors. Often, post installed anchors may not have been installed correctly; therefore the load carrying capacity is further reduced.

Figure 10. Corroded torque controlled expansion anchor in an NPP

Table 2 shows a broad estimation of the relative capacities of typical anchors used in older nuclear power plants in different scenarios. To judge the capacity of a particular anchor more precisely, the results of corresponding tests (as per qualification guidelines) must be available.

Table 2 Relative capacities of typical anchors used in older industries and nuclear power plants

Type of anchor	Anchor size	h_{ef} (mm)	Type of loading	Crack width (mm)	N_u (cracked) / N_u (uncracked)	
					correct installation	installation inaccuracies and/ or corrosion[2)]
Torque controlled sleeve type	M12 – M20	80 - 140	service load seismic loading	≈ 0.3 ≈ 0.8	≈ 0.65 ≈ 0.25	≈ 0.35 -
Self-drill anchor	M12 – M20	53 – 83	service load seismic loading	≈ 0.3 ≈ 0.8	≈ 0.70 ≈ 0.40	≈ 0.35 ≈ 0.15
Stud anchor[1)]	M12 – M20	65 – 75	service load seismic loading	≈ 0.3 ≈ 0.8	≈ 0.65 not acceptable	≈ 0.15 not acceptable
Drop-in anchor[1)]	M12 – M20	50 – 80	service load seismic loading	≈ 0.3 ≈ 0.8	≈ 0.5 not acceptable	≈ 0.20 not acceptable

[1)] Deformation controlled expansion anchor
[2)] For torque controlled expansion anchor

CONCLUSIONS

Cast-in as well as post-installed anchors are commonly used for connections in industrial structures and in nuclear safety related structures. The seismic safety of structural and non-structural components, connected to the primary structure using fasteners, relies heavily on the performance of the anchors. The safety and reliability of anchorages depend largely on three aspects: selection of suitable anchors, proper design and correct installation. The right selection for a particular usage can be made by referring to the Technical Approvals for the anchor system, e.g. if cracking of concrete cannot be excluded with sufficient reliability, only anchors approved for use in cracked concrete must be selected. Recently developed various qualification guidelines (such as ETAG001, 2012 and ACI355.2, 2007) recommend test and assessment criteria for anchors subjected to seismic loads, in general. The German NPP Guideline (DIBt 2010) provides tests and assessment criteria for anchors to be used in a nuclear safety related structure. Anchors qualified according to these guidelines perform well under seismic loads and provide a high level of safety. The guidelines provide a sound basis for designers and authorities dealing with anchors. The guidelines are valid for all types of anchors, however, for nuclear safety relevant connections, headed studs and post installed undercut anchors are recommended by the authors. In older structures, post installed anchors designed for use in uncracked concrete have often been used. Under severe seismic loading, cracking of concrete must be expected which will reduce the failure load of these anchors significantly (see Table 2). The design of anchors as per old codes can be very unconservative especially for anchorages with large embedment depths. Therefore, existing anchorages with anchorages not qualified for cracked concrete and seismic loading or designed using older codes should be re-evaluated using the new and more realistic CCD design method, which is adopted in newer codes. Finally, if anchors have not been installed by following the manufacturer's specifications, installation inaccuracies cannot be excluded, which may reduce the capacity of the anchorages.

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