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SUITABILITY OF ANCHOR CHANNEL WITH CHANNEL BOLTS FOR USE IN NUCLEAR POWER PLANTS

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ABSTRACT

The design of safety relevant structures in nuclear power plants has to take into account extraordinary loads such as earthquakes, airplane impacts or explosions. In reinforced concrete structures, these loads may cause extreme stresses which lead to large crack widths beyond the regular widths. It is important that also components anchored in reinforced concrete members do not fail in this situation when their functioning is needed most, e.g. for the securing of safety and backup equipment.
The suitability of anchoring systems for reinforced concrete structures of nuclear power plants may be shown by simulated seismic tests on the basis of several qualification guidelines. The test regimes take extreme seismic conditions into account which impede the qualification of most conventional anchoring systems for nuclear power plants.
Cast-in anchor channels are a robust and reliable system for anchoring in reinforced concrete members. During the outfitting works, channel bolts are used for the convenient connection of components. Advanced anchor channels with matching channel bolts were developed to cope with the extreme loading conditions which have to be taken into account for nuclear power plants.

INTRODUCTION

Anchor channels with channel bolts (aka T-bolts) also provide versatile possibilities for power plants to connect non-structural components and systems (NSC), e.g. MEP works, platforms, ladders and elevator railings to reinforced concrete structures (Figure 1). Special attention has to be paid to adequate qualification of the anchor channel-channel bolt-system used for important or sensitive connections. The seismic performance of the system is vital, in particular in nuclear power plants (NPP), to avoid failures during earthquakes with hazardous consequences endangering life and health and causing substantial economic loss due to disruptions.

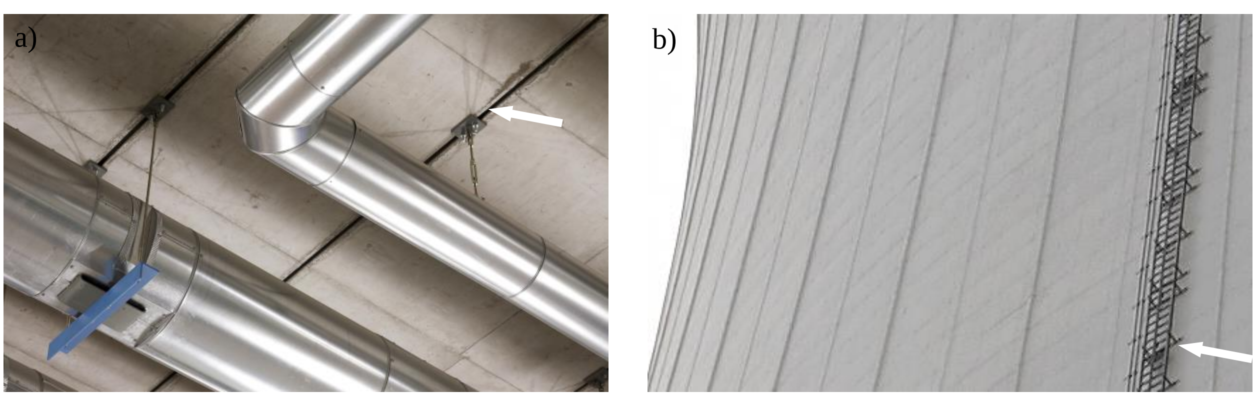

Figure 1. Anchor channel system for installations a) inside and b) outside of power plants.

The system of cast-in anchor channels with channel bolts was invented in 1913 (*German Patent 292751 (1913)*). Ever since, many products of this fastening type have been developed with various properties and qualifications. The goal of this paper is to point out important aspects with regard to the properties and relevant qualifications for anchor channel-channel bolt systems used in NPPs, which allows the specifier the identification of suitable products.

BACKGROUND OF ANCHOR CHANNELS WITH CHANNEL BOLTS

Anchor channels made of C-shaped channels and connected headed anchors are attached to the formwork before the casting of the reinforced concrete element. After hardening of the concrete and stripping of the formwork, the open side of the channel is flush with the surface. T-shaped channel bolts can then be inserted and twisted to create a detachable connection of bolted components. Conventional anchor channels with smooth channel bolts allow the transfer of tension loads and shear loads perpendicular to the channel. To enable the load transfer also in the direction of the channel, serrated anchor channels and matching serrated channel bolts were developed in the 1980s (Figure 2a). These anchor channel-channel bolt systems are very practical e.g. when installed vertically in walls to carry the load of components which require a precise tolerance compensation such as pipelines (Figure 2b). Since the direction of seismic loads is unpredictable, serrated systems are especially suitable for seismic applications as these systems sustain loading in any direction.

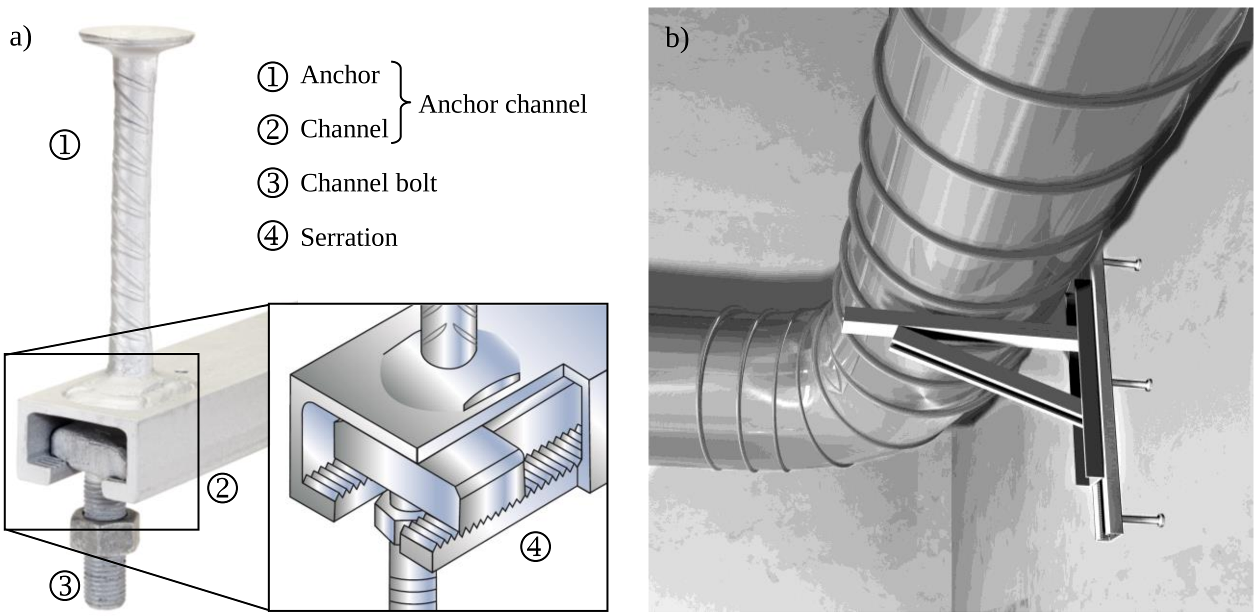

Figure 2. Serrated anchor channels with matching serrated channel bolts a) before being cast in concrete and b) after installation of components, e.g. pipelines.

Anchor channels with channel bolts became very popular for the connection of components with steel base plates to the reinforced concrete structure mainly because of the following benefits:

- Compensation of building tolerances by adjustable bolt fit during installation
- Robust load transfer due to mechanical interlock (bolt-channel, anchor-concrete)
- No on-site welding required as for anchor plates, thus no quality issues
- No on-site drilling required as for post-installed anchors, thus no cut reinforcement
- Quick, easy and fool-proof installation of anchor channels during construction
- Connecting, disconnecting and sliding of attachment using channel bolts during the complete life cycle
- Capability to transfer loads acting in any arbitrary direction if a serrated system is used

The necessity of sound design and qualification of these connections pushed the development of codified design equations and standardized qualification certificates published by construction authorities or similar bodies. Research on anchor channels with channel bolts was intensified during the last two decades and included studies to determine the behavior of anchor channel-channel bolt systems when installed in thin reinforced concrete members and with supplementary reinforcement (*Oluokun, F.; Burdette, E. (1993)*; *Wohlfahrt, R. (1996)*). After the development of scientifically proven design equations for non-seismic loads (*Kraus, J. (2002)*; *Potthoff, M. (2008)*), the influence of seismic loads was investigated in detail (*Güreş, S. (2005)*; *Butenweg, C.; Park, J. (2011)*). Simulated seismic load tests showed that the load bearing behavior of the serrated connection is very robust because adjacent teeth are activated after failure of the teeth in the contact area between the head of the channel bolt and the lips of the anchor channel (*Park, J.; Plamper-Hellwig, D. (2012)*). As will be pointed out in the following, codification of qualification and design documents for anchor channel-channel bolt systems is still "under construction" (Table 1).

Table 1: Current qualification and design documents in the USA and Europe for anchor channels with channel bolts used for non-seismic and seismic applications.

	Application	USA	Europe
Qualification	Non-seismic	AC232	EAD 330008-02-0601
	Seismic		–
Qualification Specification with Design Data		E(S)R	ETA
Design	Non-seismic	ACI 318, AC232	EN 1992-4, CEN/TR 17080
	Seismic		–

Qualification

In the *USA*, non-seismic qualification of concrete anchors according to ACI 355 (*ACI 355.2 (2007)*; *ACI 355.4 (2011)*) does not yet include anchor channel-channel bolt systems. Here, the only available qualification document are the Acceptance Criteria (AC)232 (*AC232 (2016)*) published by the Evaluation Service of the International Code Council (ICC-ES). Also seismic qualification of post-installed and cast-in anchors is included in ACI 355 for a long time and AC232 has been amended to allow the use of anchor channels with channel bolts for Seismic Design Category (SDC) C to F. Note that SDC A and B does not require a seismic qualification.

In *Europe*, post-installed and cast-in anchors are qualified for non-seismic applications according to European Technical Approval Guideline (ETAG) 001 (*ETAG 001 (2013)*), supplemented with Common Understanding of Assessment Procedure (CUAP) 06.01/01 (*CUAP 06.01/01 (2010)*) for anchor channels with channel bolts. Currently, the ETAGs and CUAPs are converted into European Assessment Documents (EAD). The EAD 330008-02-0601 for anchor channel-channel bolt systems (*EAD 330008-02-0601 (2016)*) has been recently published by the European Organisation for Technical Assessments (EOTA). In Europe, qualification of post-installed and cast-in anchors is possible also for seismic applications since ETAG 001 was amended in 2015: The Annex E includes the Seismic Category C1 for moderate seismic conditions, which mirrors the conditions stipulated in ACI 355, and Seismic Category C2 for extreme seismic conditions tested by cyclic load and crack cycling tests. At this point of time, however, no equivalent qualification document is available for anchor channel-channel bolt systems. To cover the gap, the internationally renowned association for NPPs, AFCEN, incorporates in the 2017 revision of RCC-CW rules for civil works the qualification of these systems (*RCC-CW (2017)*).

The test setups required for qualification tests are mostly identical in the *USA* and *Europe*. The test setup for monotonic tests in tension and shear available for non-seismic qualification may also be used for cyclic tests in tension and shear required for the seismic qualification if slightly modified (Figure 3). The test setup for crack cycling tests is used in the USA to determine the performance under varying life loads as part of the non-seismic qualification only, whereas in Europe additional crack cycling tests are carried out for seismic qualification (Figure 4).

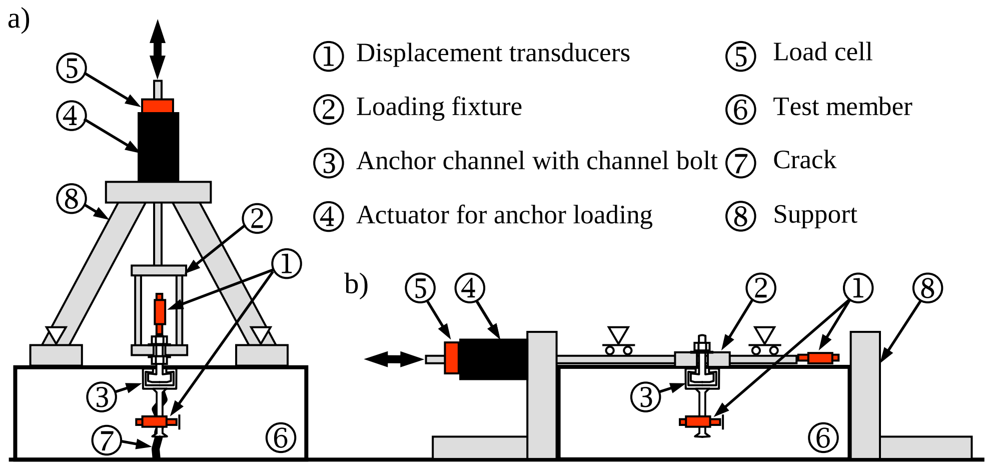

Figure 3. Test setup used for monotonic and cyclic a) tension tests and b) shear tests; detail of channel bolt positioned c) at the anchor of the channel and d) midspan.

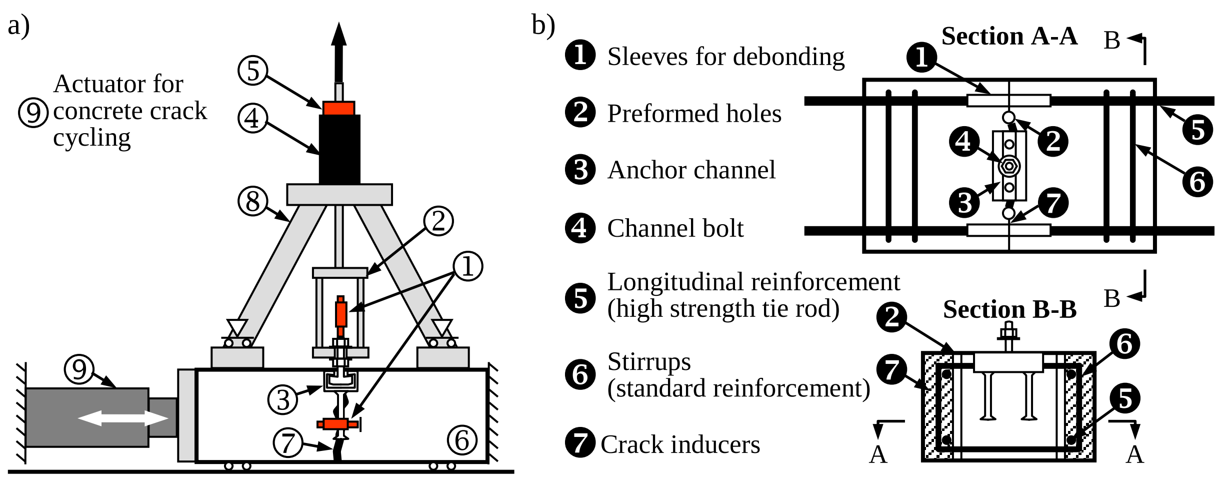

Figure 4. a) Test setup and b) test member used for crack cycling tests.

The test procedure is explained briefly in the following. Note that the term anchorage is used to address post-installed and cast-in concrete anchors as well as anchor channels with channel bolts. If stipulated, loading is applied after the crack is opened to the specified width. For monotonic tests in tension and shear, the anchorage is loaded to failure to determine the ultimate load F_u as the capacity and the displacement at half of this value $s(0.5F_u)$ needed for the assessment. The first phase of cyclic load tests starts with a pulsating tension load or alternating shear load. At the beginning of the first phase of crack cycling tests, the anchorage is loaded by the permanent load N_w which is a fraction of the capacity determined by reference tests. After the cycling of load or crack, the anchorage is unloaded to determine the displacement after cycling s_{cyc}. In the second phase of cyclic load and crack cycling tests, the anchorage is loaded to failure to measure the residual capacity $F_{u,res}$ and the displacement $s(0.5F_{u,res})$.
In the *USA*, the qualification outcome, i.e. the suitability of a tested product for certain applications, are provided in Evaluation (Service) Reports (E(S)R) issued by independent test laboratories, e.g. IAPMO (e.g. *ER 0293 (2013)*) and ICC-ES (e.g. *ESR-2854 (2016)*). In *Europe*, qualification is documented by

European Technical Assessment (ETA) certificates (e.g. *ETA-09/0338 (2013)*) which are issued by any recognized Technical Assessment Body (TAB). E(S)Rs and ETAs certify not only the qualification but also provide parameters required for the design.

Design

In the *USA*, the latest revision of the design code for concrete structures, ACI 318 (*ACI 318 (2014)*), provides design rules for post-installed and cast-in anchors in Section 17 which were dealt with in Appendix D of previous revisions. The design rules for anchor channel-channel bolt systems are not yet included. For this reason, AC232 provides amendments to the relevant clauses of ACI 318 to allow the non-seismic and seismic design of anchor channels and channel bolts.
In *Europe*, the design provisions for concrete anchors including anchor channels and channel bolts are provided in a prenorm (*FprEN 1992-4 (2016)*), currently in the formal vote process to become Part 4 of the Eurocode 2 (*EN 1992-4 (2017)*), the design code for concrete structures. An amendment (*FprCEN/TR 17080 (2016)*) was prepared to allow the non-seismic design of anchor channels, in which channel bolts are loaded in the longitudinal direction. However, the seismic design of anchor channel-channel bolt systems is not yet codified but is expected to follow soon. To cover also this gap, AFCEN incorporates in the 2017 revision of RCC-CW rules for civil works the design of these systems (*RCC-CW (2017)*).

SEISMIC SUITABILITY OF ANCHOR CHANNELS WITH CHANNEL BOLTS

In order to avoid over-engineered solutions and to foster economic approaches, the level of seismic qualification and design of construction products have to be reasonable. To determine the suitable standard in terms of performance requirements, the importance of the considered building and the seismicity of the location where the building is erected may be taken into account (Figure 5). Clearly, components for a building of low importance constructed in a region of low seismicity do not require any seismic qualification. In the contrary, the components for buildings of a high importance should always have a high level of seismic qualification even if constructed in a region of low seismicity.

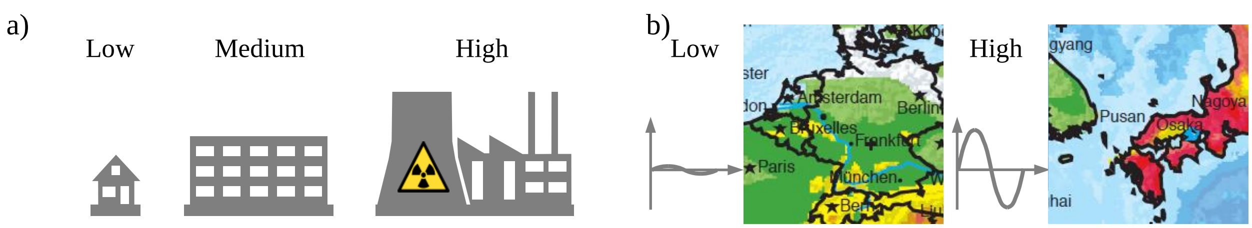

Figure 5. Seismic performance demand depending on a) the importance of the building and b) the seismicity of the region.

Due to the high risks, safety relevant construction products in NPPs should always be qualified and designed according to the highest standard. In order to achieve the highest possible safety level, RCC-CW rules for civil works (*RCC-CW (2017)*), requires anchor channel-channel bolt systems to be qualified in analogy to the Seismic Category C2 of ETAG 001 Annex E and to be designed according to EN 1992-4, CEN/TR 17080. Note that RCC-CW alternatively allows the qualification according to the German Guideline for Anchorages in NPPs (*DIBt NPP Guideline (2010)*) which was published by the German Institute for Civil Engineering (DIBt) for the first time in 1998 to ensure that anchoring to concrete in NPPs is safe even under extreme earthquakes, airplane impacts or explosions. The qualification according to the German Guideline for Anchorages in NPPs, however, is reasonable only if concrete crack widths larger than 0.8 mm (though not larger than 1.0 mm) have to be anticipated since this alternative basically includes also the Seismic Category C2 qualification according to ETAG 001 Annex E. The history of the

code development as well as further information on the performance of anchors under extreme loading can be found Mahrenholtz, C. et al. (*Mahrenholtz, C.; Eligehausen, R. (2013)*).
From the technical viewpoint, the suitability for extreme seismic applications mainly depends on the *steel type* of the profile used for the anchor channel-channel bolt system and the *concrete condition* of the reinforced concrete member in which the anchorage is situated. Special systems were developed which are in particular suitable for severe conditions such as extreme seismic applications, e.g. the serrated JORDAHL® anchor channel JXA-PC with matching channel bolt JX (Figure 6). The profiles of this advanced system are hot rolled to ensure i.a. a ductile behavior, and the anchors are made of deformed reinforcement with extra-large heads to allow large capacities and to guarantee small displacements even under severe conditions. These two aspects of seismic suitability are discussed in the following.

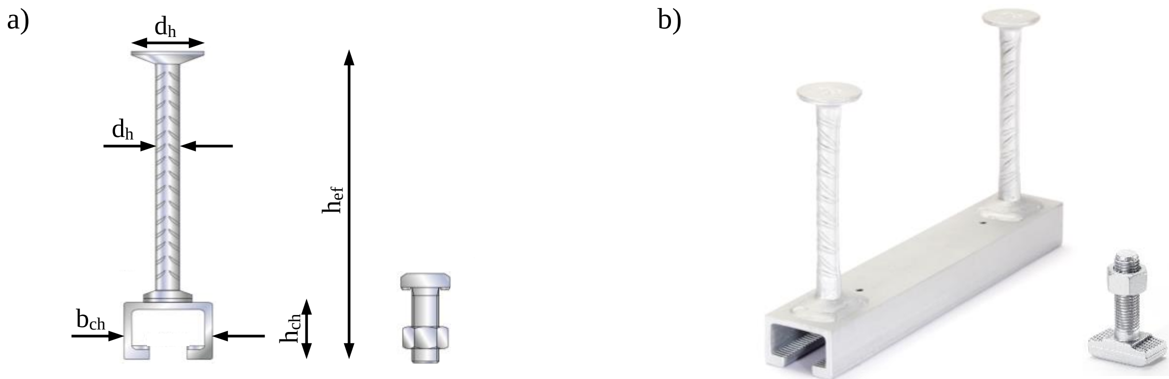

Figure 6. Example of serrated anchor channel with matching serrated channel bolt designed to ensure suitability for extreme seismic applications: a) Drawing; b) Photo.

Influence of Steel Type on Performance – Benefits of Hot Rolled Profiles

In structural engineering, ductile behavior is generally considered as desirable because ductility allows the (re-)distribution of the load to stronger elements of the structure, the development of large displacements before imminent failure and the dissipation of energy, e.g. during seismic loading. For this reason, also the codes dealing with anchoring to concrete in the USA and Europe differentiate between ductile and brittle elements in particular with regard to seismic applications. Since cold formed profiles lack ductility (e.g. *Dubina, D.; Ungureanu, V.; et al. (2012)*), anchor channels made of cold formed profiles should be avoided for seismic applications. Anchor channels made of hot rolled profiles are more suitable to resist high-energy loading as shock load tests showed (*ZfZ 24/03 (2003)*).
Furthermore, hot rolled profiles have lower and homogeneously distributed residual stresses if compared with cold formed profiles where the bending during production leads to strain hardening (e.g. *Krampen, J. (2005)*). The absence of stress peaks in particular in the crucial transition zone between straight and curved sections leads to increased fatigue strengths of hot rolled profiles. Because of their superior low cycle and high cycle fatigue resistance, anchor channels made of hot rolled profiles have been in the focus of cyclic tests (e.g. *Eligehausen, R.; Asmus, J.; et al. (2007)*).
Finally, the weldability is very limited for cold formed profiles because the heat due to welding leads to strain softening (e.g. *Krampen, J. (2005)*). The manufacturing of advanced anchor channels in which anchors are welded to the channel (Figure 5) therefore requires hot rolled profiles. In addition, anchor channels may be welded to the reinforcement or formwork for fixation during concreting. It is almost impossible to control on the construction site that anchor channels made of cold formed profiles are not welded which would result in the loss of their certified capacity.
For the above given reasons, anchor channels made of hot rolled profiles should be specified in preference to cold formed profiles when robust performance is required, e.g. for seismic applications. Some codes strictly require the profile of the anchor channel-channel bolt-system to be hot rolled, e.g. if used for safety relevant connections in NPPs (*RCC-CW (2017)*).

Influence of Concrete Condition on Performance – Benefits of Large Anchor Heads

In RCC-CW rules for civil works, the effect of cracks on the performance of anchorages in concrete is in the focus for good reason. Because of the stress concentration (amplified by the notch effect) and the reduction of the concrete net cross section (due to the anchorage body), the probability that an anchorage in concrete is located in cracks – caused by external loading or thermal constraints exceeding the low tensile strength of concrete – is high. For shear loads, the influence of cracks on the load-displacement behavior of the anchorage is relatively small. For tension loads, however, cracks may have a significant impact on the behavior. For this reason, the *non-seismic performance* of concrete anchors is tested according to ACI 355 (*ACI 355.2 (2007)*; *ACI 355.4 (2011)*) and ETAG 001 (*ETAG 001 (2013)*) in test members with 0.3 mm cracks as the mean crack width to be anticipated in reinforced concrete members subjected to fundamental loads (*ACI 224 (2001), EN 1992-1-1 (2010)*). Due to their insensitivity to cracks, however, anchor channel-channel bolt systems are tested in test members without cracks.
In contrast, tests on anchor channels with channel bolts installed in cracked test members are carried out to determine the *seismic performance* in analogy to concrete anchors. Seismic excitation causes significantly larger cracks in reinforced concrete structures and, furthermore, anchorages have to endure cyclic loads with high confidence. For this reason, *moderate seismic performance* qualification tests according to ACI 355 and ETAG 001 Annex E Seismic Category C1 are carried out on anchorages installed in cracks which are opened to a constant width of $\Delta w = 0.5$ mm representing the presumed characteristic upper crack width. After 140 load cycles the anchorage is pulled out monotonically. More severe conditions deriving from extreme earthquakes, airplane impacts or explosions should be taken into account for NPPs where the functionality of anchorages used for safety relevant connections is of vital importance. Therefore, *extreme seismic performance* qualification tests, described in the German Guideline for Anchorages in NPP for the strictest category A3 according to DIN 25449 (*DIN 25449 (2008)*) and the ETAG 001 Annex E for the Seismic Category C2, anticipate the maximum crack width which may be encountered during the once-in-the-service-life event (*Hoehler, M. (2006)*). The most challenging test of these two qualification guidelines, which are both specified in the RCC-CW rules for civil works, is the crack cycling test on anchorages. During this test, the crack width is cycled to mimic the dynamic impact on reinforced concrete structures where the reversed cyclic deformation cause opening and closing of the cracks in the concrete elements. For Seismic Category C2 qualification according to ETAG 001 Annex E, reference tests are carried out in $\Delta w = 0.8$ mm large cracks to derive $N_{u,cr0.8}$, 40% of which is applied during the first 45 cycles and 50% during the remaining 14 cycles. According to the crack protocol, the upper crack width is stepwise increased from 0.1 mm to 0.8 mm and the lower crack width is defined as full crack closure by compression of the test member. After cycle 45 the displacement $s_{cyc,45}$ is measured and after completion of crack cycling, the permanent load is released to determine the displacement $s_{cyc,59}$.
The "pumping" crack cycling cause anchorages, metaphorically speaking, to crawl out. The displacement reduces the embedment depth and thus the capacity of the anchorage (*Furche, J. (1994)*). In addition, the displacement of the anchorage may have to be taken into account for the structural analysis of the anchored components, e.g. pipelines, if larger than 3 mm (e.g. *KTA 3205.3 (2006)*). The large displacement of anchorages in concrete of which functioning is based on friction or adhesion, i.e. expansion anchors or bonded anchors, may therefore impede their use in NPPs (*Mahrenholtz, C.; Eligehausen, R.; et al. (2017)*). In general, anchorages of which functioning is based on mechanical interlock are more suitable, e.g. undercut anchors and anchor channels with channel bolts. Conventional anchor channel-channel bolt systems, however, cannot cope with the 3 mm displacement criteria as will be shown in the following.
The theoretical analysis of the suitability according to crack cycling tests allows a scatter-free study. The displacement s_{cyc} accumulated during the crucial crack cycling test according to the Seismic Category C2 of ETAG 001 Annex E can be roughly estimated under the assumption that the incremental displacement during one cycle i is approximately equal to the difference in the displacement for anchorages loaded in

non-cracked and cracked concrete which is a function of the bearing pressure acting on the head due to the permanent load $\sigma_p = N_w / A_h = N_w / (\pi \cdot (d_h^2 - d^2)/4)$:

$$\Delta s_i \approx s(\sigma_p)_{cr} - s(\sigma_p)_{ucr} \quad (1)$$

This is conclusive for load levels in the elastic range where crack cycling takes place: The difference in displacement tested in non-cracked concrete and tested in cracked concrete with a crack width Δw approximately corresponds to the displacement increment of a permanently loaded anchor due to opening of the crack from full crack closure to Δw. The estimated accumulated displacement shows the superior behavior of the advanced JORDAHL® anchor channel JXA-PC-channel bolt JX-system specialized for severe seismic applications if compared with a conventional, non-specialized system with similar properties of the channel as an example (Table 2). The calculated displacement of the advanced system during cycling $s_{cyc,45}$ of about 1 mm is well below the displacement limit criteria of 7 mm according to ETAG 001 Annex E and the displacement after cycling $s_{cyc,59}$ of less than 3 mm is below the displacement limit criteria of 3 mm which allows the negligence of displacement for the structural analysis of components, e.g. piping. In contrast, the conventional product accumulates displacements of $s_{cyc,45} > 7$ mm and $s_{cyc,59} > 3$ mm and is therefore unsuitable for seismic applications which require Seismic Category C2 qualification – in particular for the installation in NPPs.

Table 2: Estimated accumulated displacement during the Seismic Category C2 qualification crack cycling test on advanced and conventional anchor channel-channel bolt-systems.

Type[1)]	$d^{2)}$ mm	$d_h{}^{2)}$ mm	$h_{ef}{}^{2)}$ mm	$k_{ucr,N} \cdot \alpha_{ch,N}$ mm	$\sigma_{p,max}{}^{3)}$ MPa	$s(\sigma_p)_{ucr,max}{}^{4)}$ mm	$s_{cyc,45}{}^{5)}$ mm	$s_{cyc,59}{}^{5)}$ mm	$N_{u,res}/N_{u,cr0.5}{}^{6)}$ -
Advanced	14	43	177	12.7	27.0	0.05	1.1	2.8	0.81
Conventional	10.86	23	175	12.6	106.6	0.40	8.5	21.4	0.69

1) Advanced: b_{ch}/h_{ch} = 53 mm/34 mm, I_y = 93.262 mm^4 (serrated JORDAHL® anchor channel JXA-PC with matching channel bolt JX); Conventional: b_{ch}/h_{ch} = 45 mm/40 mm, I_y = 95.457 mm^4

2) Refer to Figure 6 for explanation of denomination

3) $\sigma_p(N_w) = N_w / N_{u,cr0.8} \cdot 0.75 \cdot k_{ucr,N} \cdot \alpha_{ch,N} \cdot h_{ef}^{1.5} \cdot f_c^{0.5} / (\pi \cdot (d_h^2 - d^2)/4)$

4) $s(\sigma_p)_{ucr} = \max\{(5/(0.5(d_h - d)))^{0.5}; 1\} \cdot 0.5(d^2 + 9(d_h^2 - d^2))^{0.5} - 0.5d_h / (23{,}300 \cdot 1.1875f_c)\ \sigma_p^2 = s(\sigma_p)_{cr0.3}/2$

5) $s_{cyc,n} = \Sigma\, s(\sigma_p)_{cr0.3} \cdot (0.5 + 0.5/0.3 \cdot \Delta w_i) - s(\sigma_p)_{ucr}$; linear inter- and extrapolation of value for $\Delta w = 0.3$ mm

6) $N_{u,res} = 0.75 \cdot k_{ucr,N} \cdot \alpha_{ch,N} \cdot h_{ef,res}^{1.5} \cdot f_c^{0.5} = 0.75 \cdot k_{ucr,N} \cdot \alpha_{ch,N} \cdot (h_{ef} - s_{cyc,59})^{1.5} \cdot f_c^{0.5}$

Notes: [4), 5)] According to *Furche, J. (1994), Eligehausen, R.; Mallée, R.; et al. (2006), Mahrenholtz, P. (2012), Berger, W. (2014)*; [3), 6)] factor of 0.75 to account for large crack widths and $f_c = f_{cc,200}/1.1875 = 20$ MPa assumed

SUMMARY AND CONCLUSIONS

The anchor channel-channel bolt-system is introduced. The design codes and qualifications guidelines for anchorages in concrete are explained and the missing gaps with regard to anchor channels with channel bolts are identified. It is pointed out that the design of anchorages require data from their qualification which must suit their intended use. The seismic suitability is shown by cyclic load tests and crack cycling tests. The Seismic Category C2 qualification shows the suitability for extreme seismic applications.

The most relevant properties of anchor channel-channel bolt-systems with regard to seismic suitability are the steel type of the profile and the concrete condition of the reinforced concrete element of the anchorage. The beneficial properties of hot rolled profiles are discussed and it is reasoned why the behavior during crack cycling is crucial. An advanced serrated anchor channel with matching serrated channel bolts is presented which was developed specifically to sustain the adverse conditions to be anticipated for extreme seismic applications. The large anchor heads of this advanced anchor channel-channel bolt-system allow the compliance with the stringent capacity and displacement criteria stipulated for seismic applications in particular in nuclear power plants.

The views expressed in this paper are the views of the authors only and do not necessarily reflect the views of Jordahl GmbH.

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