POST-INSTALLED ANCHORS IN NUCLEAR POWER PLANTS: PERFORMANCE AND QUALIFICATION

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ABSTRACT

In Nuclear Power Plants (NPP), post-installed anchors are widely used for structural and non-structural connections to concrete. In many countries, anchor products employed for safety relevant applications have to be approved by the authorities. For the high safety standards in force for NPP, special requirements have to be met to allow for extreme design situations. Therefore, a Guideline for Anchorages in Nuclear Power Plants and Nuclear Technology Installations (DIBt KKW Leitfaden (1998)) [1] provides guidance for anchor qualification testing and gives assessment criteria. This paper discusses the relevant details of the testing procedures, the requirements, and the assessment criteria. Further, exemplary results of an undercut anchor tested according to the guideline are presented and the importance of the anchor displacement behaviour for the evaluation of the anchor performance is demonstrated.

INTRODUCTION

Anchor Types

Post-installed anchors are often used to fix structural elements and non-structural components and systems (NCS). NCS are among others piping, mechanical and electrical equipment, architectural and other building contents. Post-installed anchors are easy to install and provide more flexibility than cast-in anchors like headed studs. 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. [2]. Fig.1 shows some common anchor types.

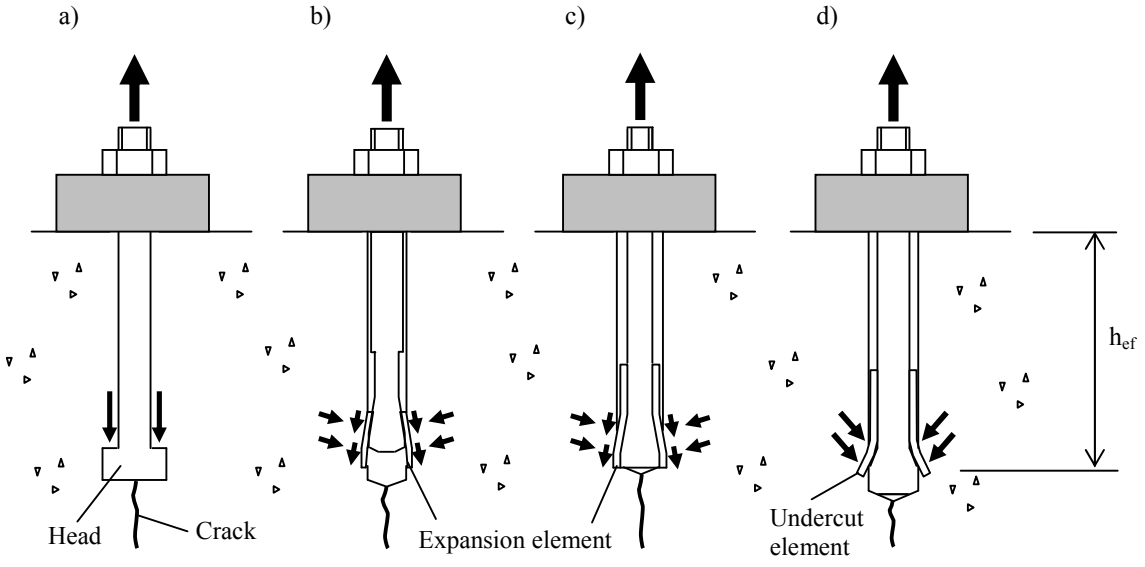

Fig. 1: Different anchor types a) Cast-in headed stud; b) Torque-controlled expansion anchor (bolt type); c) Displacement-controlled expansion anchor (stud type); d) Undercut anchor

General Performance of Qualified Anchors

The anchor load-displacement behaviour is 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. It is therefore necessary to assess the effect of cracking on anchor performance. The diagrams in Fig. 2 depict the tension load-displacement behaviour of anchors tested in cracked and uncracked concrete. The curves in Fig. 2a demonstrate the effect of cracks on the load-displacement behaviour of torque-controlled expansion anchors (sleeve type) failing by concrete breakout in uncracked and cracked concrete. These anchors are installed by applying a specified torque which draws the cone at the anchor's base into the expansion elements and presses the expansion elements against the concrete. The tension load is transferred by frictional resistance (Fig.1b). If a crack intersecting the anchor location opens, suitable torque-controlled anchors are able to develop adequate follow-up expansion to re-establish the lost frictional force. However, the anchor looses some of its stiffness and ultimate strength. For comparison, Fig. 2b shows load-displacement curves of a headed stud (Fig.1a) of same size and embedment depth. Due to its load transfer mechanism by mechanical interlock, headed studs are less sensitive to cracks and the crack width.

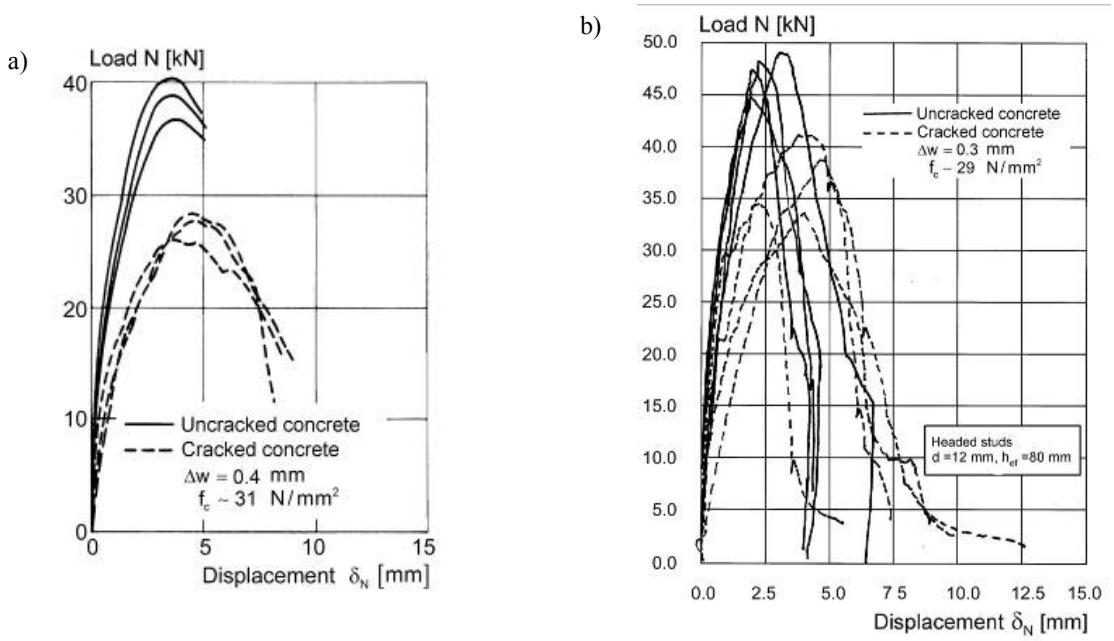

Fig. 2: Load-displacement curves of a) torque-controlled expansion anchors (sleeve type) suitable for cracked concrete (after Dieterle et al. [3]); and b) Headed studs (after Furche et al. [4])

Performance of Anchors Not Qualified for Cracked Concrete or Improperly Installed

Anchors not suitable for cracked concrete may experience a tremendous deterioration in their load capacity and displacement behaviour when tested in cracked concrete. The load-displacement curves in Fig. 3a depict the behaviour of torque-controlled expansion anchors (bolt type) (Fig.1b) which were developed for applications in uncracked concrete, but tested in uncracked and 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. Torque-controlled expansion anchors of the sleeve type designed for uncracked concrete may also show a similar behaviour when tested in cracked concrete. Fig. 3b depicts the load-displacement curves of fully and partially expanded displacement-controlled expansion anchors (drop-in type) tested in cracked concrete. Displacement-controlled expansion anchors generate the expansion force necessary for the frictional load transfer by driving an expansion element over the conical end of the bolt (stud type) (Fig.1c), or by driving a plug into the expansion element (drop-in type). Drop-in anchors do not develop follow-up expansion and their load capacity is reduced significantly in particular when they are not fully expanded. This demonstrates the paramount importance of correct anchor installation and adequate qualification. Stud type displacement-controlled expansion anchors may show

follow-up expansion in uncracked concrete but often do not expand further in cracked concrete. Then the strength of these anchors will be reduced significantly comparable to drop-in anchors.

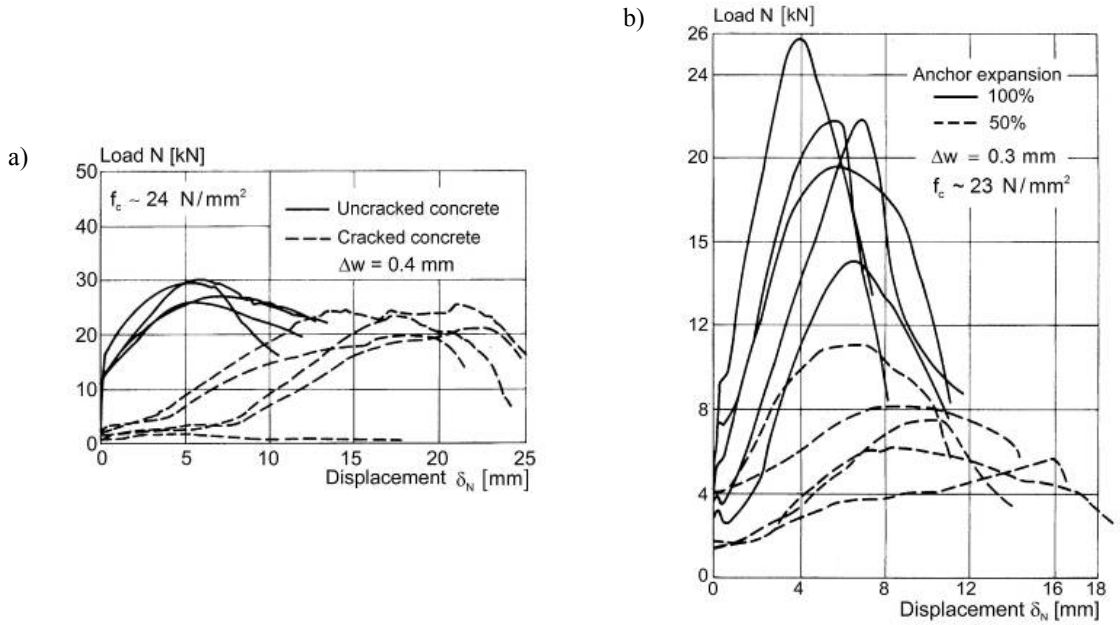

Fig. 3: Load-displacement curves of a) torque-controlled expansion anchors not suitable for cracked concrete (after Dieterle et al. [3]); and b) fully and partially expanded displacement-controlled expansion anchors (drop-in type) (after Meszaros and Eligehausen [5])

Qualification Guidelines

In Europe, anchors used for safety relevant connections need to be approved to ensure proper functioning. Anchors may be qualified for installation in uncracked concrete only or for installation in uncracked and cracked concrete. The qualification according to the Guideline for European Technical Approval of Metal Anchors for Use in Concrete (ETAG 001) [6], however, does not cover seismic design loads. Due to the high safety standards effective for NPP, additional requirements should be met to allow for seismic actions and impact loading as well as large crack widths. Therefore, the German Guideline for Anchorages in Nuclear Power Plants (DIBt KKW Leitfaden (1998)) [7] was implemented to give supplementary provisions. The guideline was revised in 2010 (DIBt KKW Leitfaden (2010) [1], from now on addressed as NPP Guideline (2010)). In the following, the 2010 revision guideline is briefly explained and the behaviour of a typical undercut anchor is shown.

NPP GUIDELINE FOR ANCHOR QUALIFICATION

Scope

The NPP Guideline (2010) is valid for anchors to be used for safety relevant connections in NPP. Safety relevant connections are those which connect safety relevant elements to concrete or fasten elements which failure might affect safety relevant elements. Safety relevant elements include, but are not limited to, radiation control, cooling system, and containment of radioactive substances. The NPP Guideline is applicable to new anchorages in normal weight concrete of strength class C20/25 to C50/60. It is also applied to judge the strength of existing anchorages. Cracked concrete is generally assumed, however, the NPP Guideline 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 NPP Guideline (2010) is valid for all anchor types with a European Technical Approval (ETA) for use in cracked and uncracked concrete. However, due to their general robustness, undercut anchor types (Fig.1d) are recommended by the authors for applications in NPP. An undercut is created by means of a special drilling apparatus or by a self-cutting action of the anchor during installation. The anchor is inserted into the borehole and

the undercut elements are allowed to unfold into position at the level of the undercut. This load transfer mechanism by mechanical interlock is similar to that of cast-in-place systems such as headed studs and makes the undercut anchor system very reliable under earthquake conditions: It can cope with wide cracks, crack cycling due to the cyclic response of the structure, and load cycling.

Design Procedure and Design Categories

The design procedure is based on the concrete capacity design (CCD) method given in CEN/TS 1992-4 [8]. It is based on the concept of partial safety factors as given in EN 1992-1-1 [9]. The following three design categories are distinguished:

1. Design Category A1: Combination of permanent and temporary design loads.
2. Design Category A2: Combination of extreme design loads which occur several times during service life.
3. Design Category A3: Combination of extreme design loads which occur only once during service life. This includes loads from differential pressure and temperature variation, as well as from extreme earthquakes, blasts, and aircraft impacts.

Particular attention is paid to the installation safety. It is required that the anchor product allows an easy and explicit control of its correct installation to avoid improperly installed anchors. A consistent quality management with a strong emphasis on training of the installer and a detailed documentation of the installation procedure is introduced. Furthermore, the guideline contains requirements in respect to protection of the anchor against corrosion, fire, and radiation.

Qualification Tests: Requirements and Assessment Criteria for Design Category A3

During extreme earthquakes, which are covered by Design Category A3, large cracks may occur. 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. Because simultaneous load and crack cycling (Fig. 4a) is rather difficult for qualification tests, the anchor is qualified according to the NPP Guideline (2010) by different load and crack cycling tests: Tension and shear load cycling of anchors located in an open crack (Fig. 4b and Fig. 4c), and cycling of the crack between an upper and a lower crack width while the anchor is loaded by a constant tension load (Fig. 4d). In addition, monotonic reference tests with anchors located in an open crack are required (Fig. 4e).

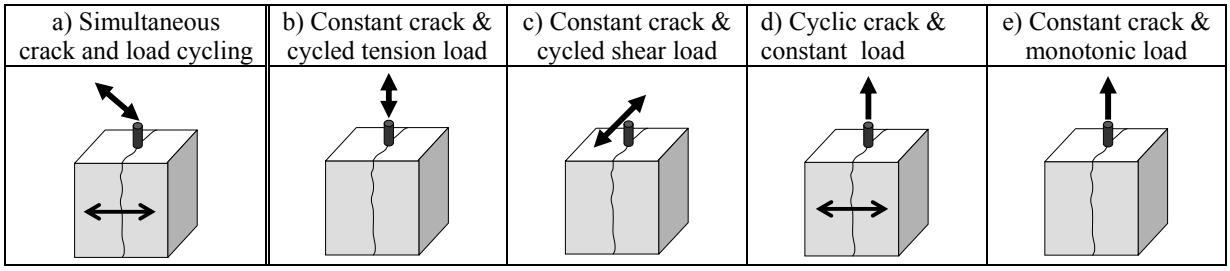

Fig. 4: Simultaneous load and crack cycling (a) simulated in different tests (b) to (d) after Hoehler [10]

The NPP Guideline (2010) distinguishes three fundamental types of tests with respect to the requirements. They are denominated A, B, and C in the following:

A: Suitability tests to check the proper functioning of the anchor under extreme conditions
B: Tests for the determination of the characteristic anchor capacity under service conditions
C: Tests for the determination of the anchor displacement under service condition

The crack width in areas of plastic hinges cannot be predicted reliably. Therefore, the NPP Guideline (2010) covers only anchors in locations where the steel strains are expected to be lower than the strain at yield and where no spalling of the concrete cover will occur. The expected crack width depends on many parameters and may vary between about 0.5mm and 1.5mm [10]. The NPP Guideline (2010) contains two cases: (i) No detailed analysis

of the crack width to be expected in a certain NPP is performed. Than the suitability tests have to be carried out in cracks with a width of $w_2 = 1.5$mm and the other qualification tests in cracks with $w_1 = 1.0$mm. (ii) If a detailed analysis is performed for a certain NPP, the crack width calculated according to EN 1992-1-1 [9] is taken as w_1. Because the crack width in a structure may be larger than the calculated value, w_2 is taken as $1.5w_1$. For several NPPs a detailed analysis has been performed. In general, the following crack widths have been verified: $w_2 \leq 1.0$mm and $w_1 \leq 0.7$mm.

Table 1 provides a comprehensive overview of all required tests, the test conditions and the assessment criteria. For load and crack cycling tests, the load capacity assessment criteria are valid for the residual load capacity tests.

Table 1: Compilation of tests, test conditions and acceptance criteria according to NPP Guideline (2010)

Test Type	Test Conditions		Nos. of	Nos. of	Assessment criteria		
	Crack Width	Anchor Load	Cycles	Tests	Coefficient of Variation		Load Capacity
A Suitability Tests					CoV (F_u)	CoV (s($0.5F_{u,m}$)	reqN_u
A.1 Monotonic Tension	w_2	-	-	$\geq 10^{1)}$	20%	50%	$0.8 \cdot N_{u,m}$(B.1)
A.2 Cyclic Tension	w_2	$N_{min} = 0.0$kN $N_{max} = N_{Rk}/\gamma_{Mc}$	15	$\geq 10^{1)}$	-	50%	$0.9 \cdot N_{u,m}$(A.1) and $0.7 \cdot N_{u,m}$(B.1)
A.3 Cyclic Crack	w_{min} $w_{max}=w_2$	$N_P = N_{Rk}/\gamma_{Mc}$	10	$\geq 10^{1)}$	-	50%	$0.9 \cdot N_{u,m}$(A.1) and $0.7 \cdot N_{u,m}$(B.1)
B Service Condition Tests					CoV (F_u)	CoV (s($0.5F_{u,m}$)	reqV_u
B.1 Monotonic Tension	w_1	-	-	≥ 5	15%	40%	-
B.2 Cyclic Shear	w_1	$V_{max} = \pm V_{Rk}/\gamma_{Ms}$	15	≥ 5	10%[4)]	-	$0.9 \cdot V_{u,m}(w_1)$[3)]
C Anchor Displacement Tests					CoV (s(F_u))		
C.1 Cyclic Tension	w_1	$N_{min} = 0.0$kN $N_{max} = N_{Rk}/\gamma_{Mc}$	10	$\geq 10^{2)}$	$\leq 40\%$		-
C.2 Cyclic Crack	w_{min} $w_{max}=w_1$	$N_P = N_{Rk}/\gamma_{Mc}$	5	$\geq 10^{2)}$	$\leq 40\%$		-
C.3 Cyclic Shear	w_1	$V_{max} = \pm V_{Rk}/\gamma_{Ms}$	10	$\geq 10^{2)}$	$\leq 40\%$		-

N_{Rk} = characteristic strength N_{Rk} derived from test series B.1 normalized with reference to the concrete strength $(f_{c,measured}/f_{c,nominal})^{0.5}$

V_{Rk} = characteristic strength V_{Rk} derived from monotonic shear tests in cracks with $w = w_1$; if these tests are not performed, see [3)]

γ_{Mc} = partial safety factor for concrete failure = 1.7

γ_{Ms} = partial safety factor for steel failure = 1.25 for typical steel

[1)] The number of tests may be reduced to n = 5 if CoV ≤ 10% and CoV(s($0.5F_{u,m}$) ≤ 30%

[2)] The number of tests may be reduced to n = 5 if the CoV of the displacements after load and crack cycling is ≤ 30%

[3)] If no reference test results in $w = w_1$ are available, V_{Rk} and $V_{u,m}$ may be either calculated or taken from the ETAG approval tests in 0.3mm cracks

[4)] For CoV > 10% but ≤ 30%, the characteristic shear load capacity shall be reduced by $\alpha_V = 1/(1+0.03(\text{CoV}[\%]-10\%))$

The principal test setups are similar to those described in the qualification guidelines ETAG 001 [6] or ACI 355.2 [11] and are therefore not discussed in this paper. For further details, see Mahrenholtz et al. [12]. During strong earthquakes the cracks in a structure open and close due to load reversals. Therefore, according to NPP Guideline (2010), in cyclic crack tests with $w_2 \leq 1.2$mm after opening the crack to w_2 the crack is closed to $w_{min} \approx 0.0$mm by applying a compression force equal to $0.15 \cdot A_c \cdot f_c$ (A_c = cross section of concrete specimen; f_c = concrete compressive strength of the test specimen). Dynamic effects during cycling are eliminated by cycling frequencies of ≤ 1Hz for cyclic load tests and ≈ 0.2Hz for cyclic crack tests.

The aim of the suitability tests is to check the anchor behaviour under extreme conditions. Because the crack width has a small influence on the anchor behaviour under shear load, only tests with tension loaded anchors are performed. The results of the service condition tests are used to evaluate the characteristic resistance (5% quantile of failure loads) under tension (N_{Rk}) and shear (V_{Rk}) loading. From the results of the anchor displacement tests, anchor displacements which may be expected during earthquake loading under the design load of the anchor are deduced.

In all tension tests, the load-displacement curves shall show a steady increase. No uncontrolled slip is allowed for a load $N < 0.7N_u$. In the suitability and service condition tests, test series A and B, respectively, the scatter of the load-displacement curves under monotonic loading and in the residual load tests after load or crack cycling is limited. The coefficient of variation (CoV) of the displacement at 50% of the mean failure load must be $\leq 40\%$ (service condition tests) and $\leq 50\%$ (suitability tests), and the CoV of the failure loads must be $\leq 15\%$ (service condition tests) and $\leq 20\%$ (suitability tests). These requirements ensure that the CCD method for anchor groups is valid. Furthermore, the anchor failure load should not be reduced too much by the crack width w_2 and by the load and crack cycling. Therefore, requirements on the mean ultimate anchor capacities measured in the suitability tests and the cyclic shear tests series B.2 are defined. If premature failure occurs during load or crack cycling or the above described requirements are not fulfilled, the tests have to be repeated with a lower load level (N_{max}, V_{max}, N_P) and the characteristic strength is reduced accordingly.

The anchor displacement behaviour under service condition is measured by test series C. In axial direction, the cyclic crack tests are crucial since they generally yield larger axial displacements than cyclic tension tests. In transversal direction, cyclic shear load tests determine the critical anchor displacements. 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.

ANCHOR PERFORMANCE IN EXPERIMENTAL TESTS

In the following, results of a typical undercut anchor (M12; $h_{ef} = 80$mm) tested according to the NPP Guideline (2010) are presented. Only results of tests associated with axial loading (monotonic and cyclic tension as well as cyclic crack tests) are shown. The concrete strength was $f_c \sim 45$N/mm².

Service Condition Tests

Fig. 5 shows the load-displacement curves measured in monotonic tension tests with anchors in a crack of width $w_1 = 0.7$mm (test series B.1). The characteristic load capacity N_{Rk} determined from the results of this test series forms the input for the test series A and C.

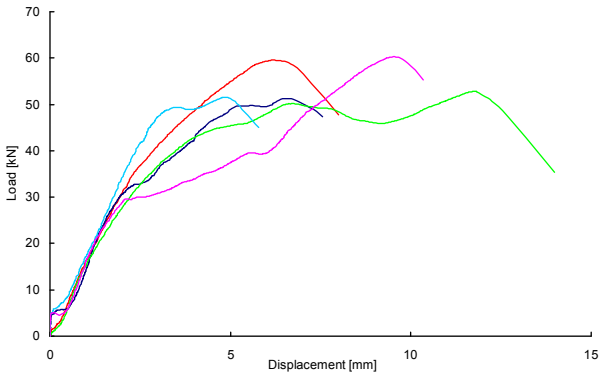

Fig. 5: Load-displacement curves of undercut anchors M12 ($h_{ef} = 80$mm) measured in test series B.1 (service condition test); $w_1 = 0.7$mm

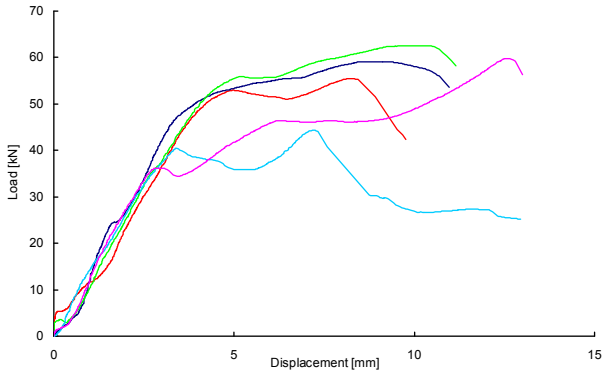

Fig. 6: Load-displacement curves of undercut anchors M12 ($h_{ef} = 80$mm) measured in test series A.1 (suitability test); $w_1 = 1.0$mm

Suitability Tests

The diagram in Fig.6 depicts the load-displacement curves for monotonic tension tests with anchors in a crack of width $w_2 = 1.0$mm (test series A.1).

In all tension tests no uncontrolled slip was observed for loads $N \leq 0.7N_u$. The influence of the crack width on the failure load was small (compare Fig.5 with Fig.6).

Fig.7 shows the load-displacement curves measured in cyclic tension tests with anchors in a crack of width w_2 = 1.0mm (test series A.2). The maximum axial load during the 15 cycles was N_{max} = 13.3kN.

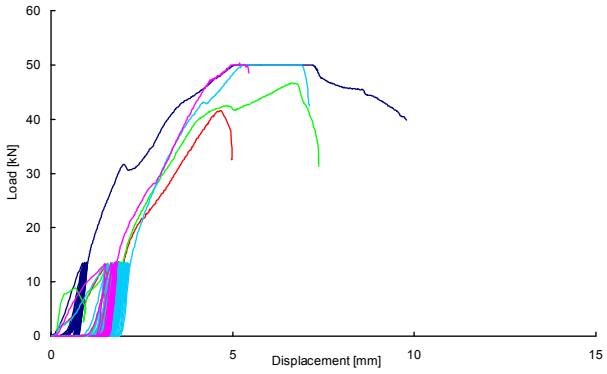

Fig. 7: Load-displacement curves of undercut anchors M12 (h_{ef} = 80mm) measured in test series A.2 (tension load cycling); w_2 = 1.0mm

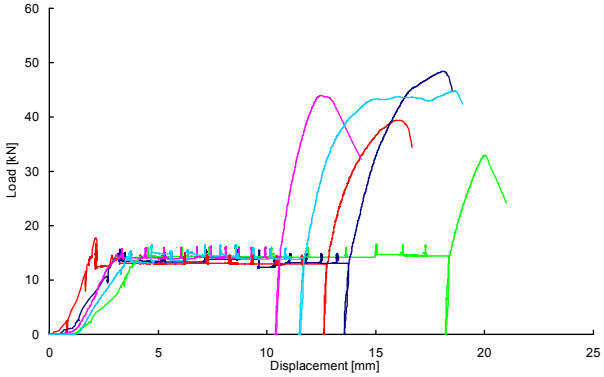

Fig. 8: Load-displacement curves of undercut anchors M12 (h_{ef} = 80mm) measured in test series A.3 (crack cycling); w_{min} = 0.0mm and w_{max} = 1.0mm

The diagram in Fig. 8 illustrates the load-displacement curves for cyclic crack tests (test series A.3). The constant anchor tension load during cycling was N_P = 14.3kN. The crack was cycled ten times between w_{min} = 0.0mm (compression load on concrete specimen) and w_{max} = 1.0mm.

In all residual load capacity tests no uncontrolled slip was observed for loads $N \leq 0.7N_u$. The failure load was not much influenced by load cycling and crack cycling (compare Fig. 7 and Fig. 8 with Fig. 6).

Displacement Tests

Fig. 9 demonstrates the load-displacement curves measured in crack cycling tests (test series C.2). The permanent tension load during cycling was N_P = 13.7kN. The crack was cycled five times between w_{min} = 0.0mm (compression load on concrete specimen) and w_{max} = 0.7mm.

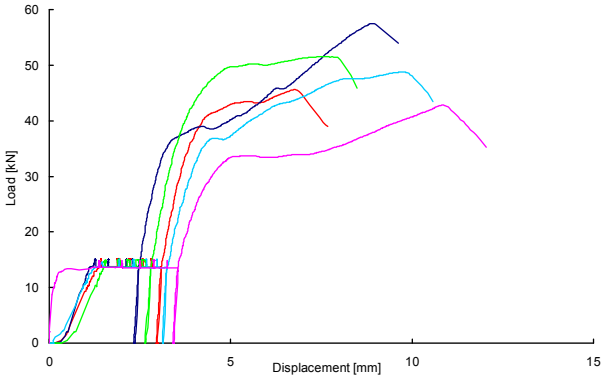

Fig. 9: Load-displacement curves of undercut anchors M12 (h_{ef} = 80mm) measured in test series C.2 (anchor displacement test); w_{min} = 0.0mm and w_{max} = 0.7mm

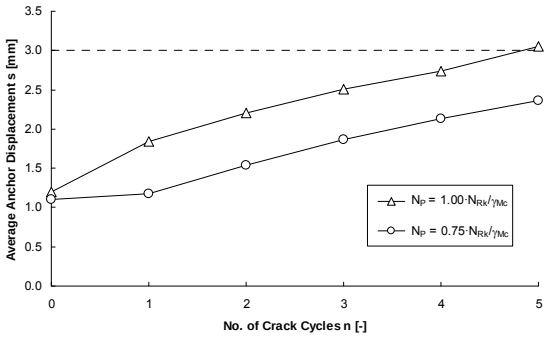

Fig. 10: Mean anchor displacement versus no. of cycles measured in test series C.2 with two different constant anchor tension loads during cycling

The displacement is to be extracted after completion of all crack cycles and with the load of N_P still applied. The diagram in Fig. 10 depicts the mean anchor displacement versus the number of crack cycles. The displacements increase with increasing number of crack cycles. The mean anchor displacement for $N_P = 1.0 \cdot N_{Rk}/\gamma_{Mc}$ is just below 3mm. This shows that the displacement behaviour of the anchor may be critical in the assessment of

the anchor capacity. Test series C.2 was repeated with $N_P = 0.75 \cdot N_{Rk}/\gamma_{Mc}$. The measured displacements were smaller (see Fig. 10).

CONCLUSIONS

Post-installed anchors are commonly used for safety relevant connections in NPPs. Anchors that do not function properly under the conditions expected in a NPP (e.g. earthquakes) are a hazard and may lead to failure of the attached structure. Therefore, in a NPP only anchors should be used that have been qualified for this application. The anchors should be installed by well trained installers to avoid installation inaccuracies. The German NPP Guideline (2010) provides tests and assessment criteria for anchors to be used in a NPP. Anchors qualified according to this guideline provide a high level of safety. The guideline provides a sound basis for designers and authorities dealing with anchors in NPP. It is valid for all types of anchors, however, for safety relevant connections, undercut anchors are recommended by the authors. As shown by tests, provided the undercut is large enough and the anchors are installed correctly, this type of anchor shows a predictable behaviour even under extreme conditions and fulfils the acceptance criteria of the NPP Guideline (2010).

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