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EXPERIMENTAL INVESTIGATIONS ON SEISMIC BEHAVIOR OF POST-INSTALLED ANCHORAGES IN NUCLEAR POWER PLANTS

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Abstract

Anchorages with post-installed anchors are commonly used in nuclear power plants to connect non-structural components such as piping systems to concrete structures. For nuclear safety related fastenings, particular requirements concerning their load and displacement behavior are demanded to avoid failure or loss of functionality of certain components.

During an earthquake, the anchorage has to transfer the seismic loads resulting from interactions between the structural and non-structural elements, while cracks open and close in the concrete structure in which the anchor is installed.

In existing qualification guidelines, the seismic performance of anchors is evaluated by means of experimental load and crack cycling tests on single anchors. In order to investigate the behavior of anchor groups supporting non-structural components under real earthquake conditions, dynamic interactions between the coupled system consisting of concrete structure, post-installed anchors with anchor plate and component have to be considered.

Within the scope of a research project, large-scale experiments were carried out on a 2-anchor group connecting a piping system to a concrete slab. The test specimens were subjected to seismic loading by an electrodynamic shaker mounted on the pipe and representative cycling crack widths in the concrete member. Two different types of undercut anchors qualified for application in German nuclear power plants were tested.

This paper presents a detailed description of the specially designed test setup and testing methodology considering realistic earthquake excitations.

The results of a total of ten conducted tests provide information on the load-displacement behavior of the anchorage at different crack widths and under various load levels. Anchors subjected to simultaneous load and crack cycling experience continuously increasing displacements. This effect becomes more pronounced in particular for large crack widths. Residual displacements of the anchors may lead to impacts in case of tension-compression loading on the anchorage. However, the anchor displacement performance observed in the presented tests agrees fairly well with results obtained on isolated single anchors.

Keywords: seismic testing; nuclear power plant; non-structural component; post-installed anchor; displacement behavior

1. Introduction

In nuclear power plants (NPP), components and structural supports are fastened to the concrete building structure by means of steel embedments (anchors) which transfer applied loads by tension, shear, or a combination of both to the base material. With regard to the time of their installation, these fastenings are subdivided in cast-in-place and post-installed anchor systems. Since post-installed anchorages (Fig.1) are installed in the hardened concrete, they provide flexibility for planning and execution and moreover, they are an efficient solution where strengthening or retrofitting of existing structures is becoming necessary.

The application of these anchors as safety relevant fastenings connecting non-structural components such as electrical equipment, boilers, machinery, steel constructions or piping systems to the primary structure causes particular requirements concerning their load and displacement behavior to avoid failure or loss of functionality of the nuclear safety related systems.

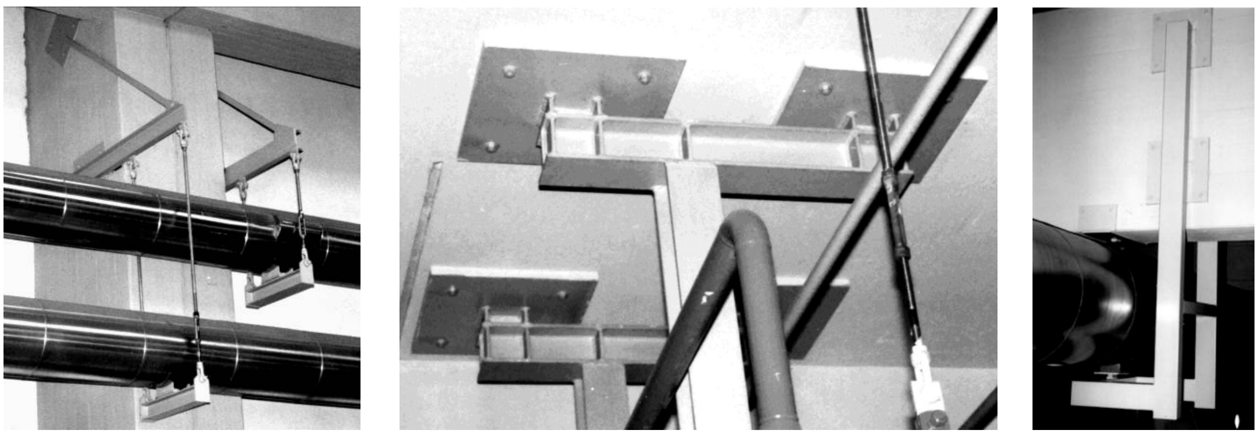

Fig. 1 – Post-installed anchorages of piping systems [1]

During a seismic event, ground accelerations generate varying forces and displacements in the building structure. According to the dynamic response of the structural elements, cracks in the concrete members open and close cyclically. Consequently, anchors installed therein may be influenced by the crack behavior during earthquake. In addition, the anchorages may be subjected to combined cyclic tension and shear forces which result from interactions between structure and non-structural component connected.

In order to ensure the high safety requirements in NPP even under extreme loading including earthquakes, the German DIBt-NPP-Guideline [2] provides supplemental criteria for qualification of anchors to be used as safety relevant anchorage in NPP. The guideline considers different load and crack cycling tests, whereby crack cycling is performed at constant load and load cycling is required on anchors located in an open crack. For these tests, large crack widths up to 1.5 mm shall be taken into account. However, in order to simplify the test setup, simultaneous load and crack cycling tests are not proposed. Moreover, the qualification tests conducted on isolated single anchors neglect possible load redistribution effects between anchors acting in a group as well as contact problems between anchors, anchor plate and component occurring in case of alternating tension and compression loading.

In the context of a recent research project, numerical and experimental studies focus on dynamic interactions of the coupled system structure-anchorage-component under earthquake loading. As part of the project, a large-scale experimental test setup was developed for investigating the seismic behavior of a 2-anchor group connecting a piping system to a concrete slab. The test program comprised ten tests with two different types of post-installed undercut anchors qualified for application in NPP according to [2]. This paper presents the experimental procedure of these tests. Selected test results obtained in particular on one anchor product which is commonly used in German NPP are shown.

2. Experimental Investigations

2.1 Test program

Within the scope of the experiments a total of ten large-scale seismic tests were performed on a 2-anchor group connecting a piping system to a concrete slab. The test program is given in Table 1. Two different undercut anchor products qualified for use in German NPP were tested. The seismic loading was realized by means of an electrodynamic shaker mounted on the piping system and acting in vertical direction. Hence, the anchor specimens were subjected to predominantly axial loading. The damage behavior of the anchorage material during earthquake was simulated by a cyclic opening and closing crack in the concrete slab. As indicated in Table 1, three different specified crack width ranges were investigated. Test series 1 was carried out in un-cracked concrete for comparison. Two tests were performed for each series to show the scatter of the test results.

Table 1 – Test program

Test series	Crack width	Crack opening	Loading	Anchor type	Number of tests
1	0 mm	Uncracked	Vertical vibration of piping system: Axial load cycling for anchorage	HILTI HDA M12	2
2	0 - 0.4 mm	Crack cycling		HILTI HDA M12	2
3	0.5 - 0.8 mm	Crack cycling		HILTI HDA M12	2
4	1.0 - 1.5 mm	Crack cycling		HILTI HDA M12	2
5	1.0 - 1.5 mm	Crack cycling		FISCHER FZA M12	2

2.2 Tested anchorage and concrete specimen

Two types of post-installed undercut anchors qualified for their use in German nuclear safety related structures [3], [4] from different manufacturers were tested. Both anchor products, namely HILTI HDA-T-22-M12x125/30 (HDA) and FISCHER FZA-18x100-M12-20 (FZA) had a nominal diameter of 12 mm and were made of galvanized zinc-plated steel. HDA is a self-cutting undercut anchor installed by through-fastening with an effective embedment depth of h_{ef} = 125 mm. FZA is installed in a predrilled undercut hole and anchored by mechanical interlock with displacement-controlled through-fastening installation. The effective embedment depth of FZA is h_{ef} = 80 mm. Photographs of the anchors are shown in Fig.2. The installation of the anchors was performed in accordance with the manufacturer instructions. Before testing, the specified torque moment was reduced to 50% T_{inst} about ten minutes after tightening the anchors to consider time dependent relaxation effects in practice. Further description of the anchor installation in the concrete slabs is provided in Section 2.3.

The anchorage was designed as a group of two anchors with 160 mm spacing between the anchors. The anchors were connected by an anchor plate with the dimensions of 250x200x30 mm³, whereby the load was applied via a hinged connection at the center of the fixture.

a) HILTI HDA-T-22-M12x125/30 (www.hilti.de) b) FISCHER FZA-18x100-M12-20 (www.fischer.de)

Fig. 2 – Photographs of tested anchor products

As anchorage material, normal weight concrete of strength class C30/37 was used. The mean compressive strength measured on 150 mm standard cubes was between 40.1 MPa and 46.0 MPa at the time of testing.

In order to enable the opening and closing of a parallel crack with the required crack width during testing, special concrete slabs as shown in Fig.3 were developed. The basic dimensions of the slabs were 1400x1200x210 mm³. The test member thickness corresponds to $1.7 \cdot h_{ef}$ (HDA) and $2.6 \cdot h_{ef}$ (FZA) respectively which was chosen considering the minimum values of the tested anchors specified by the manufacturers. On both sides of the concrete slab a recess of 300 mm x 450 mm was formed in which two hydraulic cylinders were positioned to open the crack. The longitudinal reinforcement of the slab consisting of eight reinforcing steel bars Ø20 mm (reinforcement ratio of about 2%) with a tested yield strength of $R_{p0,2}$=576 N/mm² was anchored by two weld-on anchor plates at both ends. The reinforcing bars were debonded in the desired crack area to facilitate large crack widths at steel stresses below the yield strength of the bars. To control the location of the crack, a thin 2 mm metal sheet acting as crack inducer was cast into the concrete slab. Both reinforcement and crack inducer were configured in a way that the anchor capacity was not affected. Additionally, so-called corbel reinforcement in the form of stirrups was placed in order to transfer the forces within the concrete slab induced by the acting hydraulic cylinders.

The concrete specimens used for two tests of Test series 1 in uncracked concrete were produced with the same basic dimensions and reinforcement as shown in Fig.3, but as solid slab without recesses. Since no cracking of the concrete slab was desired, the crack inducing metal sheet has been omitted.

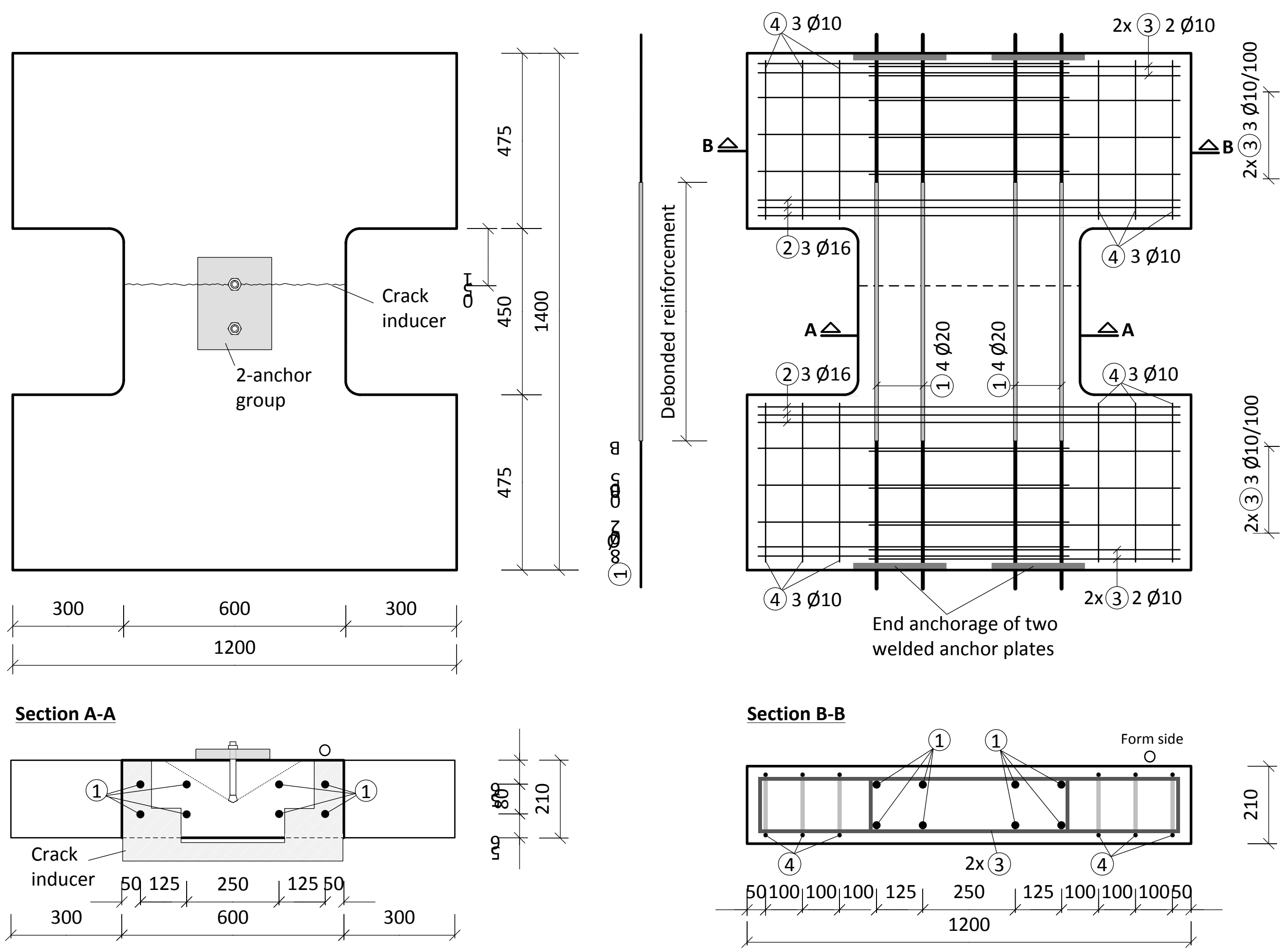

Fig. 3 – Drawing of concrete specimen (all units in mm)

2.3 Test setup and testing procedure

The large-scale experiments were carried out at the Materials Testing Institute University of Stuttgart. A photograph and the schematic side view of the realized test setup are shown in Fig.4. In general, the setup can be divided into two main parts: the mechanical non-structural component represented by the piping system and the concrete slab imitating the ceiling of a reinforced concrete structure in a NPP. Both parts are coupled by means of a double hinged rigid strut which is connected via the post-installed anchorage to the concrete slab. All mechanical attachments of the piping support were prequalified for application in German NPP.

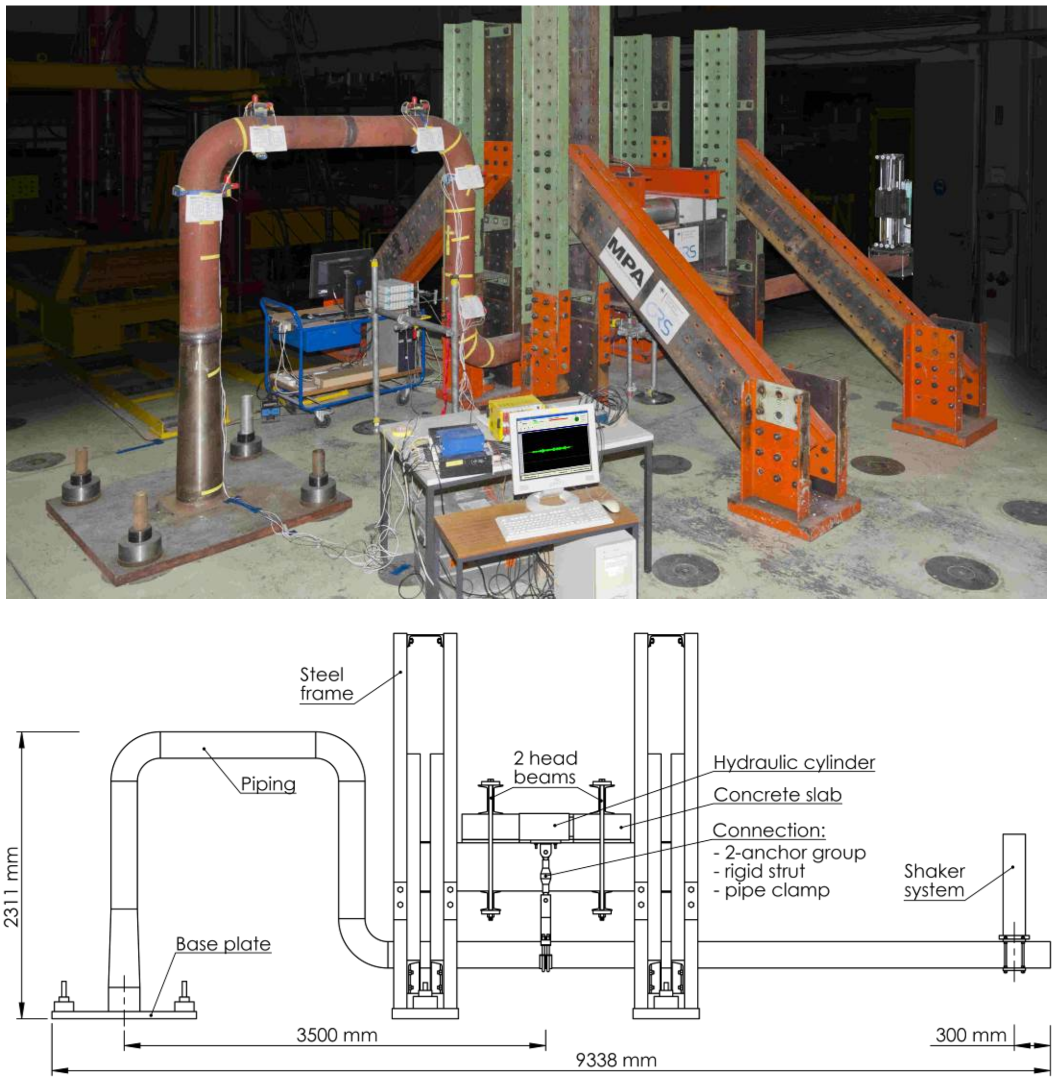

Fig. 4 – Photograph and schematic side view of test setup

For excitation of the experimental setup, an electrodynamic shaker system was positioned at the free end of the pipe. Due to vertical vibrations of the shaker, the anchorage was subjected to predominantly axial loading resulting from the dynamic response of the coupled system piping-anchorage-concrete slab. A realistic earthquake excitation was generated on the basis of numerical simulations of a representative German NPP reactor model. A detailed description of the calculations is available in [5]. The input signal of the shaker is shown in Fig.5 (left). Different incrementally increasing seismic loading levels were investigated by linearly scaling the time history amplitudes of the shaker signal. The target loading levels given in Table 2 were determined according to the technical approvals [3], [4] of the investigated anchors. The design tensile resistance of the anchorage with HDA is limited to N_{Rd} = 50.3 kN governed by concrete cone failure with the partial safety factor of γ_M = 1.5. The design value of the anchor group with FZA is N_{Rd} = 24.4 kN. Thereby, pull out of the anchor is determined as decisive failure mode (γ_M = 1.7). Finally, a sinusoidal resonant excitation with increasing shaker force amplitudes was carried out until failure respectively large displacements of the anchorage occurred.

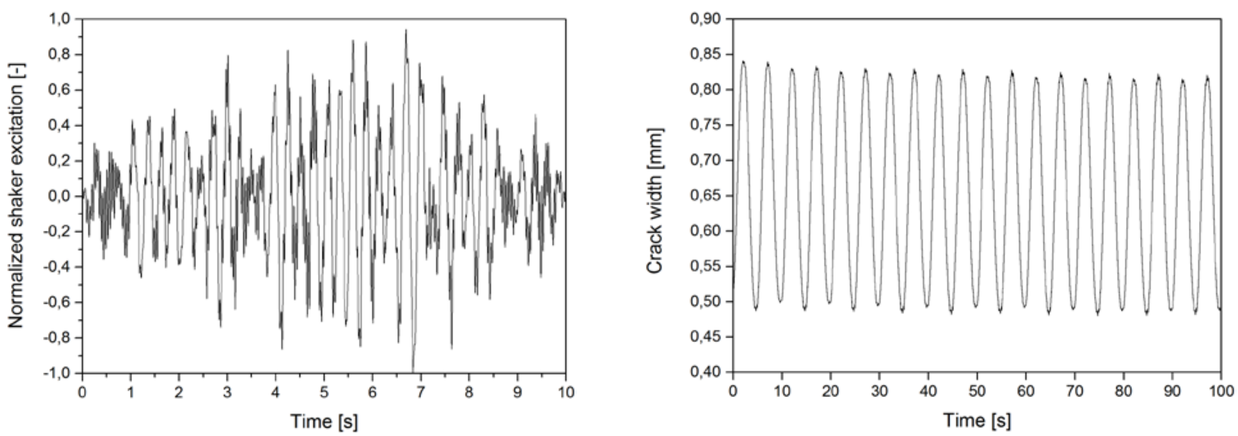

Fig. 5 – Normalized time history of shaker (left) and crack width during test 3.1, loading level γ_M N_{Rd} (right)

Table 2 – Loading protocol for each test

No.	Loading level	Dead load	Test duration	Crack opening *	Remarks
1	0.5 N_{Rd} **	Tension load N≈18 kN	20 s	Hairline crack	* valid for Test series 2-5 ** loading level omitted for Test series 5
2	1.0 N_{Rd}		100 s	Crack cycling	
3	γ_M N_{Rd}		100 s	Crack cycling	
4	Sine sweep		120 s	Crack cycling	

In the crack cycling tests, one anchor (Anchor 1) was located in a crack and the other anchor in uncracked concrete (Anchor 2). At first the borehole of the anchors was drilled and then a hairline crack was initiated in the concrete slab by means of the setup described below. All boreholes of Anchor 1 were visually inspected using a borescope to ensure that the crack passes through the depth of the hole.

After installation of the anchor, the concrete slab was attached to a steel frame and was fixed in vertical direction. The support of the slab was constructed with a fixed and sliding bearing at its ends to allow horizontal movement.

During crack cycling, the crack width alternates between the specified upper and lower values according to Table 1 following a sinusoidal shape with constant frequency of 0.2 Hz (Fig.5, right). Thus, a test configuration as shown in Fig.6 was developed for opening and closing the crack in the concrete member. The crack was controlled by means of two parallel acting 1000 kN hydraulic cylinders which were placed horizontally in both recesses of the slab. A third cylinder of similar type connected with the hydraulic system of the two cylinders was loaded displacement controlled using a vertical servo hydraulic actuator with a load capacity of 1000 kN. By applying a compression force to the third cylinder, the same load is generated on both sides of the slab to open the crack. The crack width corresponds to the elastic elongation of the longitudinal reinforcing bars. When unloading, the oil pressure in the hydraulic system is reduced and the crack is closed owing to the elastic restoring force of the reinforcement.

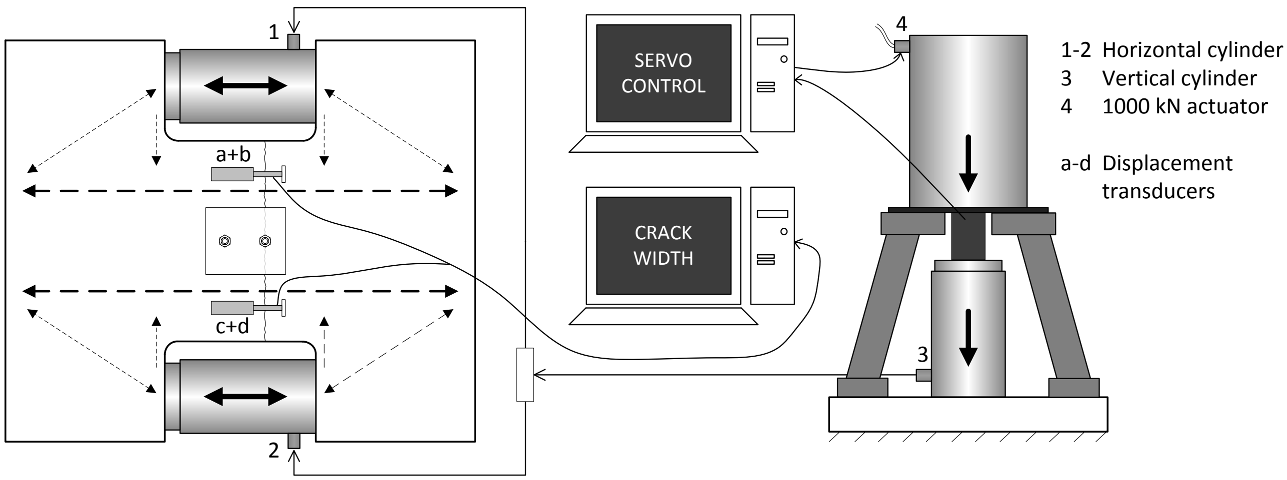

Fig. 6 – Test configuration for crack cycling

The test setup was instrumented with various types of acceleration sensors, displacement transducers and load-measuring devices comprising a total of 44 data channels. Due to high loading rates during earthquake, all data were recorded continuously with a sampling rate of 800 Hz. In addition, the test observations of piping and anchorage behavior were captured using two digital cameras.

The crack width was measured on either side of the anchor at the top and bottom of the concrete slab using four linear variable displacement transducers (LVDT). The mean value of the four measurement signals was used to monitor the crack behavior during the tests (Fig.6). The axial loads acting on the anchorage were measured by means of strain gauges applied on the rigid strut. The anchor loads were obtained by special bolt axial strain gauges applied in the central longitudinal axis of the anchor. Five LVDTs were used for measuring the vertical displacement behavior of the anchorage. In particular, three LVDTs were installed to record the local deformations of the anchor plate and two LVDTs for monitoring deformations of the concrete slab. Hence, assuming a rigid fixture, the relative vertical displacements of the anchorage could be determined for any location of the anchor plate.

3. Test Results and Discussion

3.1 Load-displacement curves and failure behavior of anchorage

Test results expressed in terms of load-displacement curves of the anchorage that were obtained in the tests with HDA anchors in uncracked concrete and at two different crack width ranges of 0.5 to 0.8 mm and 1.0 to 1.5 mm respectively are exemplary provided in Fig.7. In the diagrams, the measured total load F acting on the anchor group is plotted versus the center displacement s of the fastening in the axis of the load application.

It can clearly be seen from the envelopes that the load-displacement behavior of the anchorage is strongly affected by crack cycling. The curves show continuously increasing displacements of the anchorage under tension. As expected, increasing crack widths lead to higher displacement values. Due to the increase of occurring damage, the maximum loads achieved during the sine sweep test decrease significantly.

Dynamic load excitations higher than the dead load of about 18 kN acting on the anchorage cause alternating tension-compression loading. Under compression load, the anchor plate is in contact with the concrete slab and the loads are directly transferred to the concrete. Due to large plastic displacements of the anchor located in the cycled crack, a vertical gap between the anchor plate and the anchor nut appears. This gap displayed by a horizontal shift of the load-displacement curves leads to impacts in case of re-tensioning the anchorage. However, when the anchor plate comes into contact again, the gradient of the anchorage's tension loading path seems to remain rather constant.

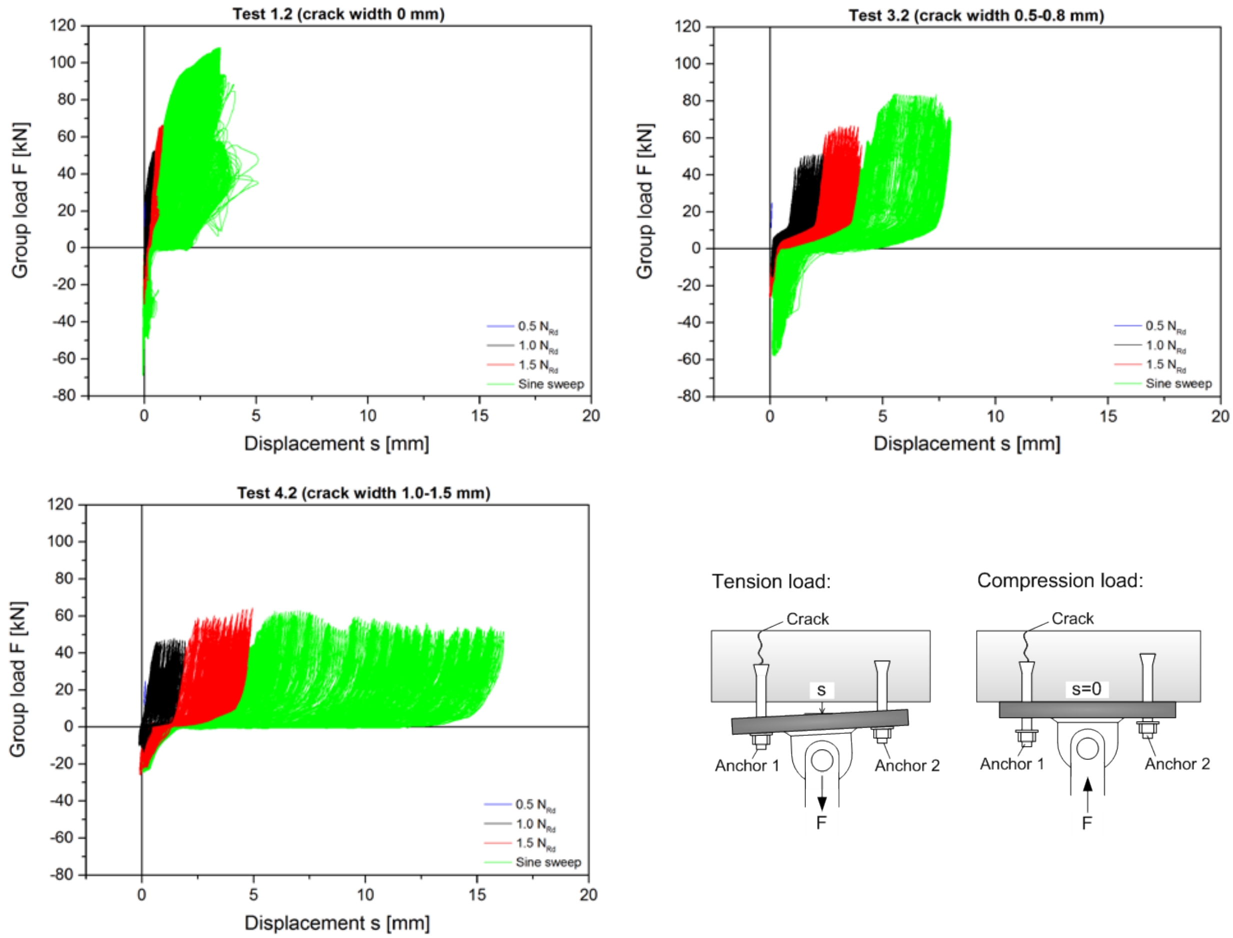

Fig. 7 – Load-displacement behavior of anchorage

Fig.8 shows photographs of the anchorage specimen after the test. During resonant excitation tests, continuously increasing displacements were observed, predominantly for the anchor installed in the cycling crack. However, no failure was achieved for all tests performed with HDA anchors. The residual displacements of Anchor 1 measured after testing range between 19 mm for crack width range of 0 mm to 0.4 mm and 30 mm for crack widths of 1.0 mm to 1.5 mm. The failure mode of Test series 5 with FZA anchor was pull-out failure of Anchor 1 during the final sine sweep test. The ultimate tension load was observed with 175% (Test 5.1) and 200% (Test 5.2) respectively of the design resistance of the anchor group (N_{Rd}).

Fig. 8 – Photographs of anchorage after testing: Test 2.2 (left), Test 4.2 (center) and Test 5.2 (right)

3.2 Anchor displacement behavior under seismic loading

The test results presented in the previous section indicate the pronounced effect of crack cycling on the load-displacement curves of the anchorage. Hence, further attention is paid to the seismic behavior of the individual anchor located in the crack, Anchor 1. In particular, the anchor's displacement performance is of high importance since plastic displacements lead to loosening of the anchor from the fixture, which may influence the dynamic system response of the coupled piping as investigated in [6].

The load transfer mechanism of undercut anchors is provided by the mechanical interlock of the undercut. A description of the behavior of these anchors during crack cycling at constant tension load is shown schematically in Fig.9 with reference to [7]. Due to crack opening, the anchor displaces for reasons of geometrical compatibility between the undercut and the borehole wall. During crack closure to the lower crack width w_{min}, the anchor remaining in its current position is pressed in the concrete. As result of the concrete damage, the anchor experiences slippage when the crack opens again. This process is repeated with the number of crack cycles.

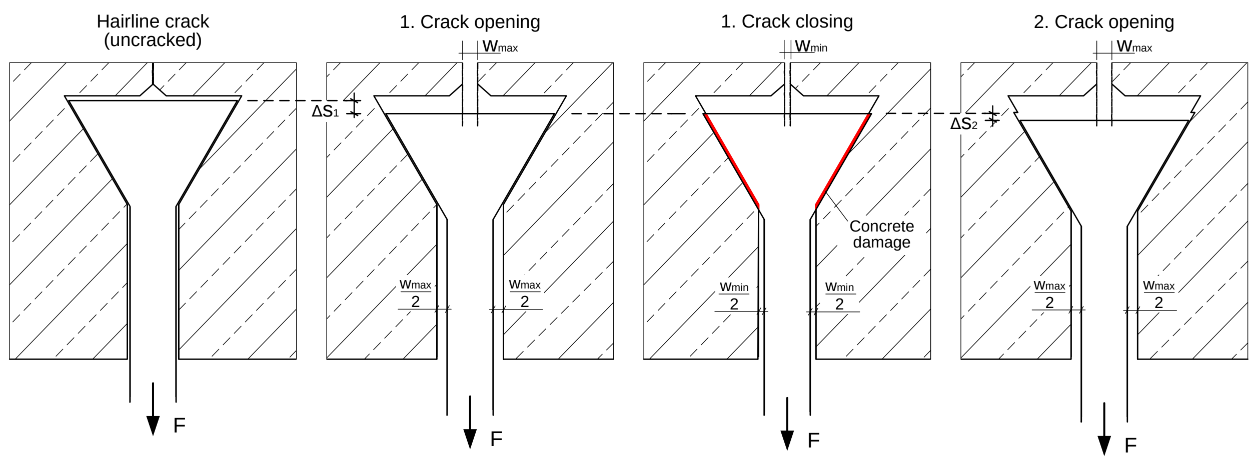

Fig. 9 – Load-displacement behavior of undercut anchors during crack cycling at constant load acc. to [7]

Fig.10 shows drilled core samples taken from concrete members with HDA anchors, which were tested in uncracked concrete (left) and with a crack cycling range of 0-0.4 mm (right) respectively. The photographs demonstrate the plastic anchor displacements occurring due to opening and closing of cracks during seismic loading. Moreover, an increase of crack width level may enhance this effect as discussed in the following.

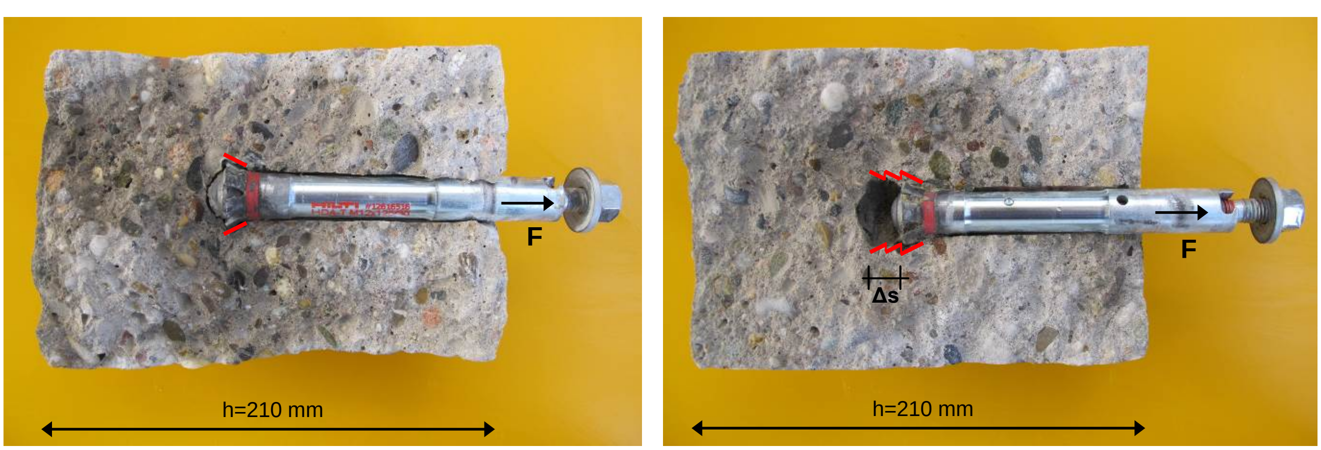

Fig. 10 – Plastic displacements of HDA anchors after testing: uncracked (left) and crack width 0-0.4 mm (right)

The displacement behavior of the anchor plate at location of Anchor 1 observed in Test 3.2 at loading level 1.0 N_{Rd} is presented in Fig.11 (left). Furthermore, for the same loading level, the maximum anchor displacements of all tests for the 10 seconds time periods of loading sequence are summarized in Fig.11 (right). The initial anchor displacements result from previous loading history including loading level 0.5 N_{Rd} (HDA) and crack opening under dead load (HDA and FZA). The test results indicate that the absolute anchor displacements increase significantly for higher crack width levels in the range of 0.5-0.8 mm as well as 1.0-1.5 mm. However, when comparing the anchor displacements of both tests within these test series, large scatter becomes apparent.

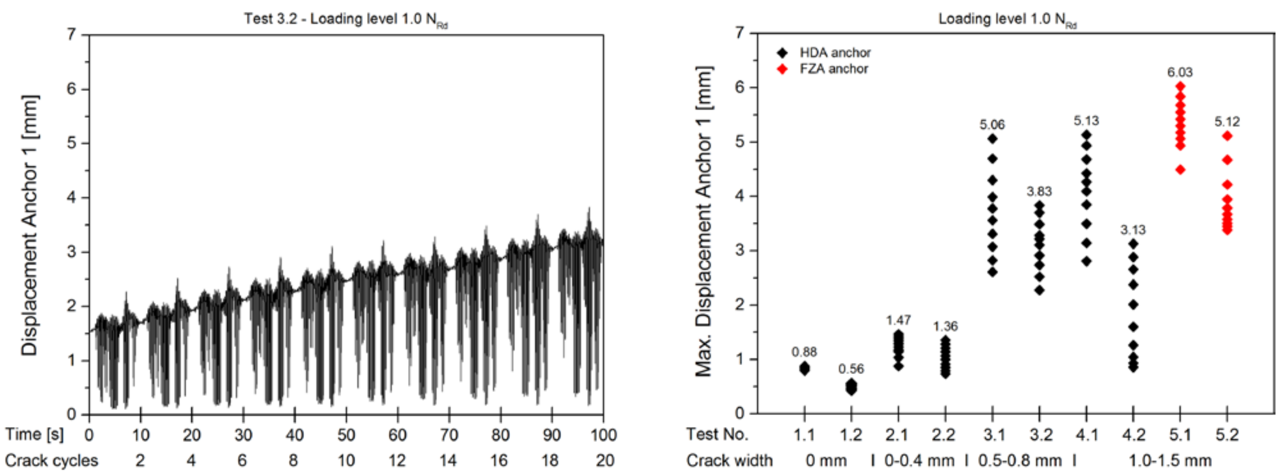

Fig. 11 – Displacements of Anchor 1 at loading level 1.0 N_{Rd}

The influence of the load level on the anchor displacements is illustrated exemplary for one test of each test series with HDA anchors. The maximum tension loads achieved in Anchor 1 at loading level 1.0 N_{Rd} and 1.5 N_{Rd} respectively are given in Table 3. The anchor displacements at maximum load of these tests are shown in Fig.12. The initial displacements at the beginning of the tests were set to zero. The displacement curves demonstrate the effect of the actual load level. In comparison with the test results at 1.0 N_{Rd}, higher anchor loads of about 30% lead to increasing anchor displacements between 30% (Test 1.2) and 80% (Test 4.2) at the end of the tests.

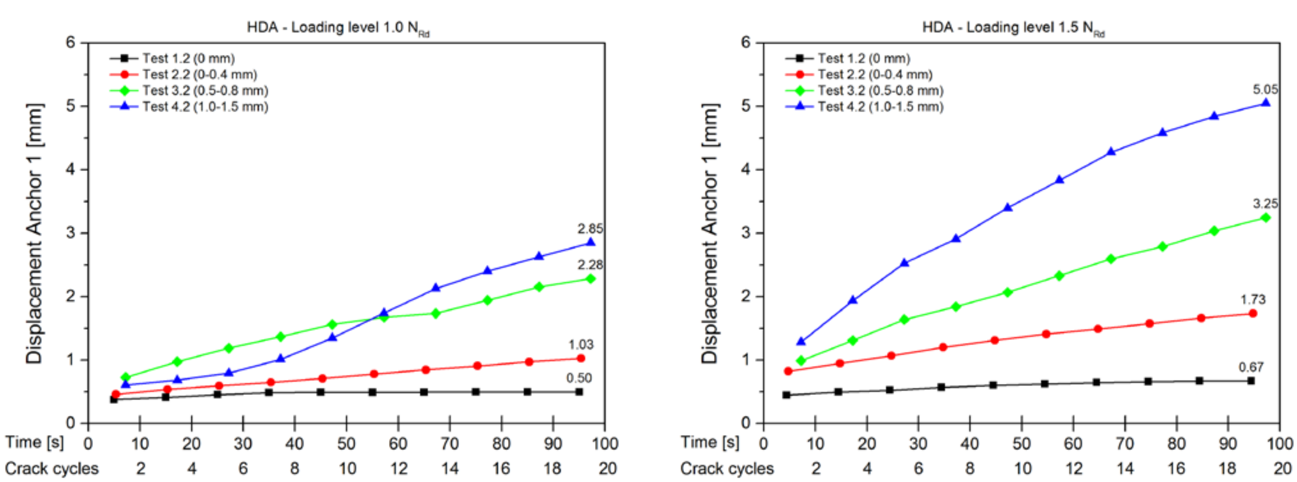

Fig. 12 – Comparison of anchor displacements at maximum anchor load: 1.0 N_{Rd} (left) versus 1.5 N_{Rd} (right)

Table 3 – Maximum anchor loads at loading level 1.0 N_{Rd} and 1.5 N_{Rd}

Loading level	**Test 1.2 (0 mm)**	**Test 2.2 (0-0.4 mm)**	**Test 3.2 (0.5-0.8 mm)**	**Test 4.2 (1.0-1.5 mm)**	**Mean value**
1.0 N_{Rd}	27.2 kN	24.5 kN	20.4 kN	24.6 kN	24.1 kN
1.5 N_{Rd}	34.4 kN	31.6 kN	27.5 kN	31.3 kN	31.2 kN
1.5 N_{Rd} / 1.0 N_{Rd}	126 %	129 %	135 %	127 %	129 %

3.3 Comparison of large-scale tests with single-specimen test results

The large-scale seismic tests presented herein were performed under earthquake excitations considering dynamic interactions of the coupled system piping-anchorage-concrete structure. In doing so, the anchor located in the crack (Anchor 1) was subjected to randomly phased simultaneous load and crack cycling.

As already mentioned in the introduction, in the current guideline for qualification of anchors for use in NPP [2], separate load and crack cycling tests are assumed to be conservative. Thus, in another part of this research project, experimental tests on single anchors of same type HDA and FZA were carried out in order to investigate the effect of simultaneous load and crack cycling compared to different phasing on the anchor performance. As shown in Fig.13 (right), crack cycling tests with various loading protocols at design tension load level of the anchor (N_{max}) were conducted, namely constant tension, in-phase tension and out-of-phase tension. Further details of these tests and the results can be found in [8].

By considering the example of HDA anchors tested with cycling crack width in the range of 1.0-1.5 mm, the mean plastic anchor displacements obtained per crack cycle during Test series 4 at loading level 1.0 N_{Rd} and 1.5 N_{Rd} and corresponding test results on single anchors acc. to [8] are presented in Fig.13 (left). Since Anchor 1 was loaded nearly to the design load of N_{max}=30 kN during loading level 1.5 N_{Rd} (Table 3), a direct comparison of the results can be made. The actual results show that the residual displacements observed in the large-scale seismic tests are between the cycling cases of constant tension and out-of-phase tension representing the upper and lower limits of expected anchor displacements. Thus, impacts resulting from tension-compression loading on the anchorage seem not to have a detrimental effect on the plastic anchor displacements.

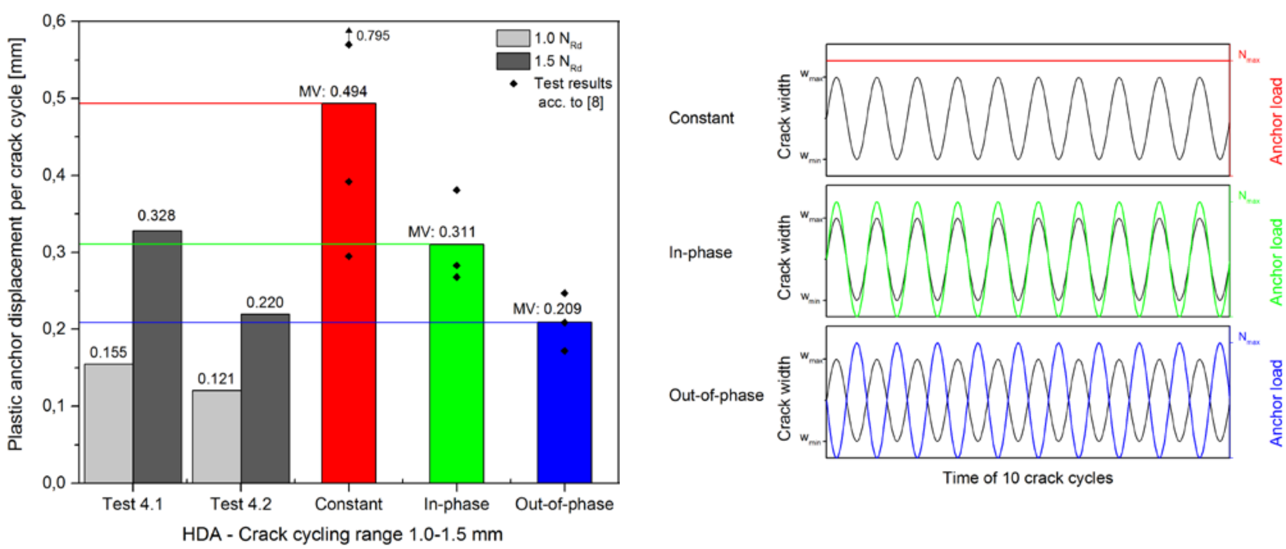

Fig. 13 – Comparison of plastic displacements for HDA anchors during tests with cycling crack width in the range of 1.0-1.5 mm (left) and loading protocol for tests on HDA anchors (right) with reference to [8]

4. Conclusions

In this paper, the findings of an experimental program to investigate the seismic behavior of post-installed anchorages which are used as safety relevant fastenings in nuclear power plants and other nuclear related facilities are presented.

In order to investigate possible dynamic interactions of the coupled system structure-anchorage-component, ten large-scale seismic tests were performed on a group of two anchors connecting a piping system to a concrete slab. Within the test program, two types of mechanical undercut anchors qualified for use in German NPP were tested. In contrast to commonly known shake table testing, an alternative approach for a test setup was created, whereby the seismic loads were generated by means of an electrodynamic shaker positioned on the pipe acting as vibratory system. At the same time, crack cycling in the concrete slab was realized by a specially developed test configuration.

The test results indicate that the load-displacement behavior of the anchorage is governed by the effect of crack cycling in the concrete. The tests conducted at different crack width ranges demonstrate a significant increase of anchor displacements for crack widths larger than 0.4 mm. Furthermore, an influence of the actual load level on the anchor displacements is obvious. The plastic anchor displacements observed in the tests show a good agreement if compared to corresponding tests on single anchors. However, it is noted that the results presented in this paper mainly focus on tests with one type of anchor. The conclusions cannot be generalized since the behavior of the anchorage is dependent on product-specific characteristics of the applied anchors.

Further experimental investigations are in progress considering crack cycling in the anchorage material at earthquake relevant frequencies. Therefore, the piping system will be mounted to a vibrating concrete slab.

5. Acknowledgements

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