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LARGE SCALE TESTS ON THE COUPLED SYSTEM BUILDING – POST INSTALLED ANCHOR – PIPING AT EARTHQUAKE LOADING

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ABSTRACT

Site-specific seismic loading is of particular importance for design of structures and components located therein. The seismic event leads to loads that can exceed those of normal operation and may be relevant to failure. During seismic events, power plants are subjected to horizontal and vertical vibrations. Components such as piping systems are often mounted to massive concrete constructions like floors and shear walls using post-installed anchors. Post-installed fastening constructions with anchor plates and anchors are required to transfer the forces resulting from the interactions between structure and component. The coupling of the individual sub-systems (structure, support, and component) leads to dynamic interactions that are significantly influenced by the load-bearing behavior of the fasteners.

There is a high probability that the anchor is intercepted by the crack before the earthquake strikes. The cracks can lead to reduced anchor load capacity. This leads to anchor displacement, gaps and impacts between anchor plate and concrete as well as to increasing permanent displacement especially when significant crack-cycling occurs during an earthquake.

To investigate the structural dynamic interactions including inertia loads of the coupled system "building – fastening with post installed anchor – piping" during earthquake loading, large scale tests were created, where a piping system is mounted to a reinforced concrete slab (RC slab) by a double hinged strut and an anchor plate with two undercut post installed anchors. In order to achieve crack cycling at a typical earthquake frequency, a very large imbalance exciter excites the RC slab. The design of the fastening is performed in this way, that during the load case "dead load plus earthquake loading" the design value of tensile strength for the anchor group is achieved. Furthermore, it is postulated that one or both anchors are installed in cracked concrete. Realistic loading scenarios were deviated from a finite element model of a reactor building situated at a typical German site with different assumptions for the soil parameters. Worst case soil parameter combinations are assumed for the large scale tests. In order to achieve the predicted strut loads and time histories a suitable shaker time history of a shaker mounted to the piping is determined from the complete calculation model consisting of soil, building and piping within the building.

The test results show, that 3 mm anchor displacement occurs during the design load level "dead load plus earthquake loading". The procedure of test design and results of the research project are presented.

INTRODUCTION

Post-installed anchorages for realizing a structural connection of various components (also called as sub-systems or secondary structural systems) with the primary reinforced concrete (RC) structure are used in nuclear safety related structures. Standardized practices guidelines ACI-355.2 (2007), DIBt-KKW-Leitfaden (2010) and ETAG-001 (006) for nuclear related structures demand certain stringent criteria, which an anchor has to satisfy in order to qualify for use in nuclear safety related structures. The guidelines are aimed to ensuring a robust load transfer mechanism of the post-installed anchors. Although the anchors retain their robustness while subjected to cycling actions simulating seismic loads, the displacements resulting from these actions can significantly affect the overall dynamic characteristics of the structure-anchor-component system. In case of nuclear safety related structures, it is mandatory according to ASCE-4-98 (2000) to perform a structure-component (secondary systems) interaction analysis subjected to operating basis earthquake (OBE) as well as safe shutdown earthquake (SSE). Studies, such of Watkins (2011), Mahrenholtz (2012), Mahadik et al. (2016), Mahadik et al. (2015), and Sharma et al. (2015) and others have shown that significant amount of permanent displacements are caused because of cycling actions of cracks in RC members and loads on the anchor which simulate earthquake loading. It was concluded that the assumption of rigid anchorages for a structure-component-interaction analysis is no longer valid since the permanent anchor displacement will alter the dynamic characteristics of the structure-anchor-component system.

The present work deals with full-scale dynamic tests performed on a concrete-anchor-piping system taking into account structural dynamics with inertia loads and realistically earthquake like frequencies regarding crack cycling.

IDEALIZATION OF THE LOAD BEARING BEHAVIOR OF SINGLE POSTINSTALLED ANCHORS

It was found essential to model the inelastic seismic behavior of anchors, Watkins (2011). An experimental database was presented in Mahadik et al. (2016) that could form a basis of development of such numerical models for anchors. It was emphasized that in view of the diverse behavior of anchor products, a product specific modelling approach is required for anchorages. A set of experiments that are required for generating the necessary background information for development of numerical models has been performed in this study, and the results are presented for two anchor products:

(Typ A) Hilti® HDA-T-22-M12x125/30 self-undercut anchor and

(Typ B) Fischer® FZA-18x80-M12/25 anchor installed in a predrilled undercut hole.

A demonstration of working out of product specific numerical inelastic models for the anchors using the experimental data has been provided in Hofmann et al. (2015).

As previously described, the interactions between structure and component are influenced by the load-bearing behavior of the anchors. Therefore, the modelling of the anchors for the finite element analysis of coupled structures and components during seismic loading is essential for the accurate prediction of pipe stresses and pipe hanger loads. A penta-linear format presented in Figure 1 is utilized to idealize the nonlinear spring characteristics. The format is valid for both the anchors, for all crack widths and for both tension and shear loads. The format is selected because it can reasonably well simulate the general load-displacement behavior of the anchor and has been already successfully used by Sharma et al. (2014) to model the anchor behavior.

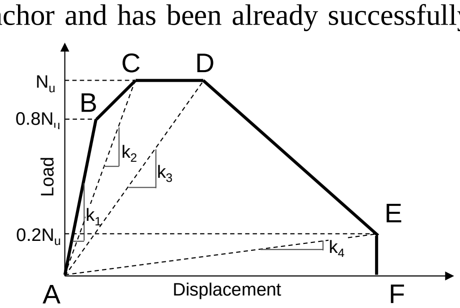

Figure 1: General format for the load-displacement characteristics assigned to the spring model

During the research project, Kerkhof et al. (2017), experiments of single undercut anchors were performed in order to evaluate their load-bearing behaviour and general format, Mahadik et al. (2015).

FULL SCALE TESTS

Two systems with two different designs (test-setups) simulating a coupled system building – post-installed anchor – piping at earthquake loading were conducted:

1. **Mock-up tests** with postulated cracks intersecting the borehole of an anchor with crack-opening and closing procedures according to codes and standards, Figure 2, were executed. During these tests crack-opening and -closing was performed at a static mounted concrete slab by means of hydraulic cylinders with frequencies at 0.2 Hz. A piping system was fixed to the slab by means of post-installed anchors subjected to earthquake loading. Due to the low frequent crack cycling one test-series with different crack sizes comprises 10 sequences of 100% SSE-earthquake loading lasting 10 s each (tests 3-1 and 3-2 excepted). Accumulated max. displacements of each test-series are given in Figure 3.

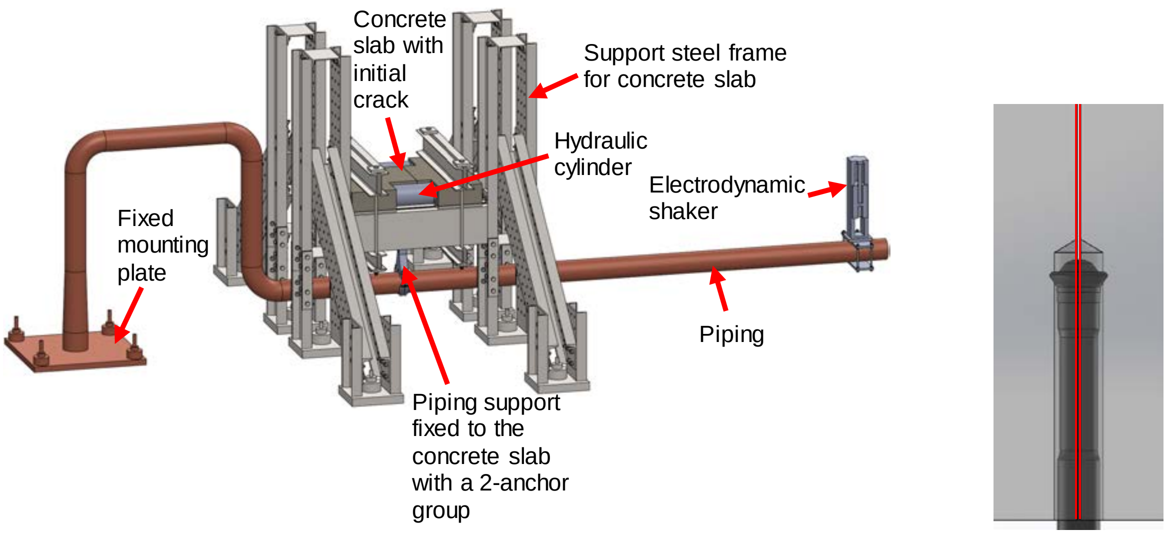

Figure 2: Mock-up tests with parallel cracks in the anchor borehole and crack width cycling at 0.2 Hz

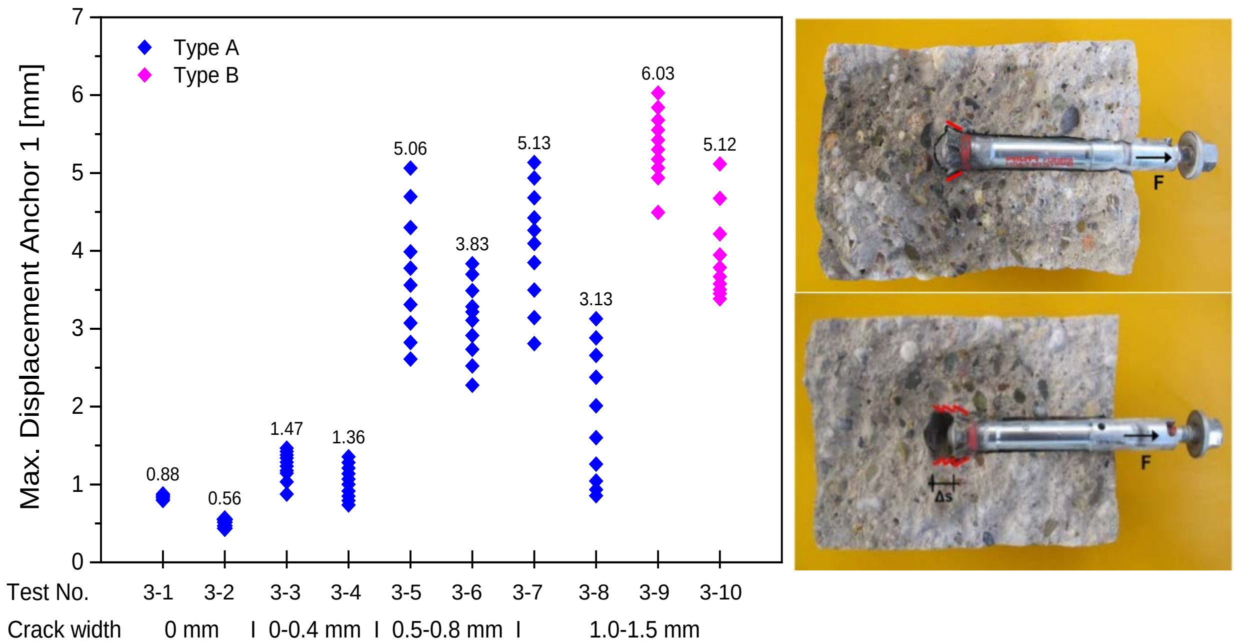

Figure 3: Accumulated max. displacements for anchor 1 in cracked concrete during earthquake loading at N_{Rd}

2. Structural dynamic **Verification tests** of a coupled system “concrete slab – post-installed anchor – piping at earthquake loading were performed subjected to vibrations of both, the concrete slab and the piping system with earthquake like frequencies regarding crack-opening and – closing, Figure 4.

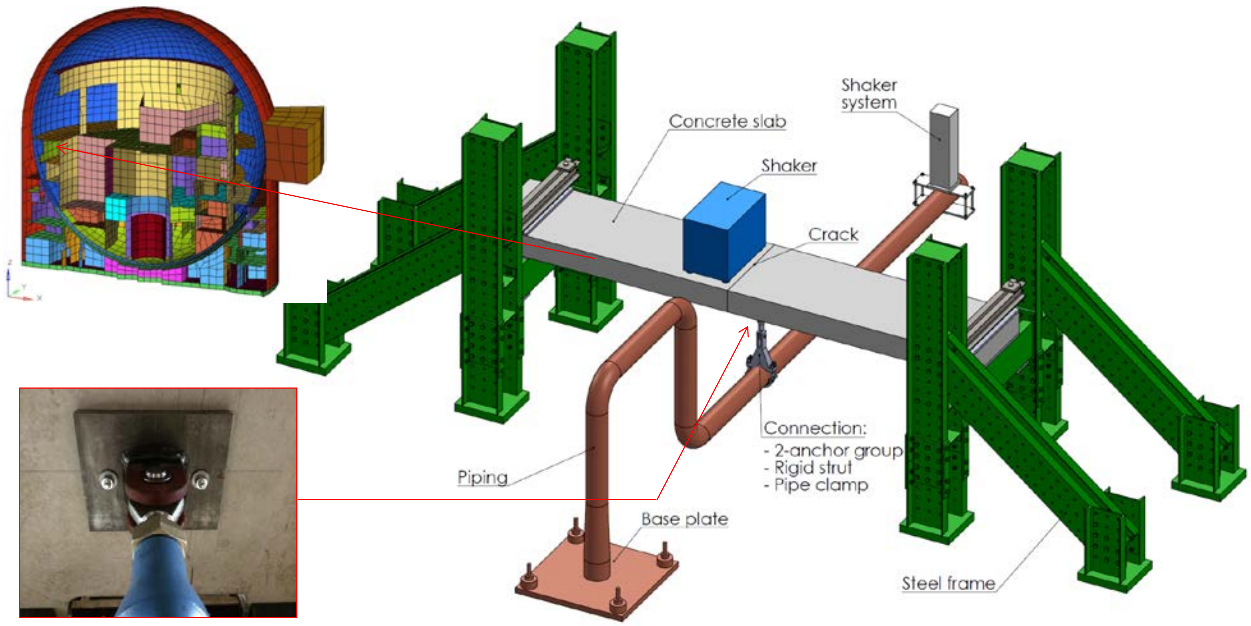

Figure 4: Verification tests – with postulated V-shaped-crack (due to a bending moment) in the borehole and crack width cycling at earthquake-like frequencies

Common design for both systems

The scope of the tests is, to investigate the structural dynamic interactions including inertia loads of the coupled system “building – fastening with post installed anchor – piping” during earthquake loading. Large scale tests were created, where a piping system is mounted to a reinforced concrete slab (RC slab) by a double hinged strut and an anchor plate with two undercut post installed anchors during. While axial loading of the anchors are specified during these first structural dynamic test series, shear force loading of the anchors in addition to axial loading is specified during another currently planned test series.

The pipe is connected via a pipe clamp and a rigid strut to the structural part of the model. The design of the fastening has been performed in that way, that the load case “dead load plus vertical earthquake loading” achieves nearly the design value. Realistic loading scenarios were deviated from a reactor building model situated at a typical German site with different assumptions for the soil parameters. Worst case parameter combinations were determined. In order to generate a seismic time history for the shaker excitation, numerical simulations were carried out as follows: The test-up was theoretically mounted to a floor of the above mentioned nuclear power plant model subjected to high seismic accelerations at a realistic typical point of the building.

A representative German earthquake load case was simulated by time history analyses. The time histories of the strut load were defined by the following procedure: The Design Basis Earthquake [DBE in German: BEB; in US: SSE (Safe Shutdown Earthquake)] is the decisive seismic impact for the representative German earthquake load case for the design of nuclear plants and serves as basis for the definition of the engineering - seismological parameters. The foundation soil corresponds to the structure characteristic for the Rhine Graben (sands and gravels covered by fillings at the surface). As second element of the transfer chain a reactor building with realistic structure, geometry and material data is used as example and implemented in a FE-model with idealization of all significant loadbearing elements by means of solid, shell or beam elements respectively and with consideration of the masses via geometry and material weight and density. The results of these analyses, presented in Ries et al. (2015) furnish realistic acceleration time-histories or building response spectra that can be derived from the possible connection points of piping systems in the reactor building and are therefore realistic input values for large-scale testing. The numerical analyses revealed that with the selected test set-up the tensile strength with total failure of the fastening construction can be achieved by an anchor plate with two anchors in order to determine design margins. Either a Hilti HDA-T M12 anchor resp. a Fischer FZA M12 anchor meet the demands and were chosen for the mock-up tests. The verification tests were carried out with the Hilti HDA T M12 anchor only.

Further details to the design of the mock-up and results are given in Kerkhof et al. (2015) and to the verification tests in Kerkhof et al. (2017). For the tests, as mentioned above, a shaker signal was generated which creates a system response of the test set-up with strut load time histories similar to those calculated in situ by means of the above mentioned nuclear power plant building model, Ries (2015). These signals were scaled to achieve a loading level at the anchorage close to the decisive design resistances during the mock-up and verifications test series. The design resistance of this fastening construction for tension loading is N_{Rd} = 50.3 kN. To determine seismic safety margins, the loading level during the mock-up test series was then scaled with the partial safety factor for material strength γ_M.

SYSTEM DEVLOPMENT STUDIES FOR THE VERIFICATION TESTS

One challenge of this construction was to create the level of the designed loading in the doubled hinged strut and another-one to perform displacements of the concrete slab with amplitudes, large enough for crack opening and closing in the undercut region of the post-installed anchors. To fulfill these demands another very large imbalance shaker was installed on the concrete slab with a length L, see Figure 5.

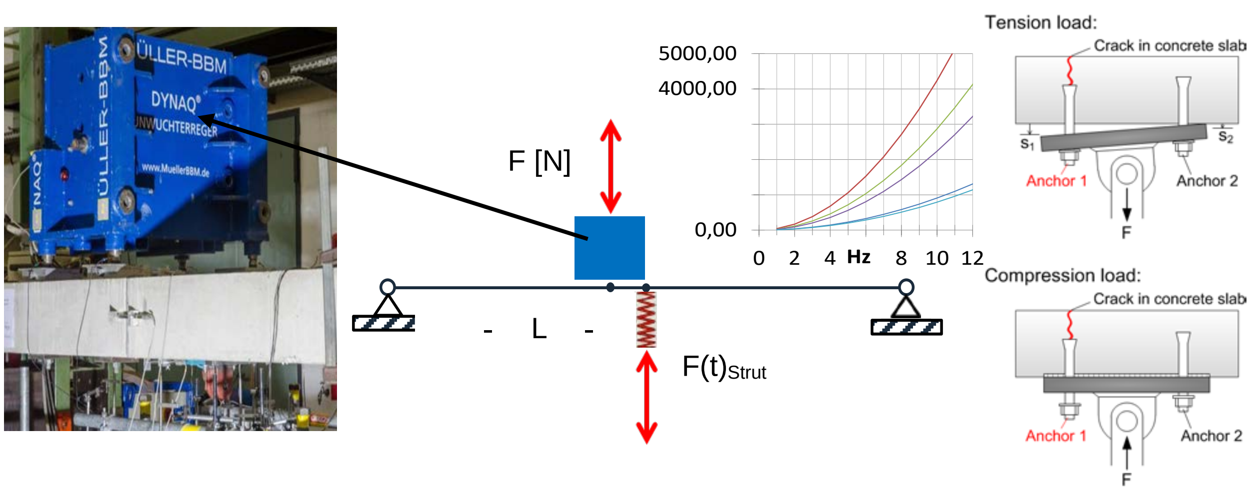

Figure 5: Modell of the verificarion tests – calculational modell (piping not visualized in this figure)

The calculations were performed by means of the Finite-Element-Code Abaqus [Abaqus 2016] and time history dynamic integration (THDI) using mode superposition. Shell elements were used for the concrete slab and "ELBOW31" beam elements for modelling the system response of the piping taking into account deformations in circumferential direction such as ovalization. The resulting spring stiffness of the two post-installed anchors is idealized with one spring symbol and on resulting spring stiffness und one resulting spring force which receives the same value in line with the strut force $F(t)_{Strut}$. The designed spring stiffness yields 14 kN/mm for an anchor in cracked concrete and 70 kN/mm in uncracked concrete, cf. Figure 1.

Milestones of the huge iteration-process in model finding from pre-calculations with variation of the slab geometry and of the coupling point between piping and concrete slab showed:

- Excitation of the system in its first vertical mode f_2 yields synchronization of the piping with the slab motions. Large strut forces do not occur and are lying below the level of the commanded variable of $F(t)_{Strut} \sim 50kN$, cf. Figure 6 (left).
- Excitation of the system close to f_5, cf. Figure 6 (right), yields synchronization of the piping motions with the slab motions as well. Large strut forces do not occur because of the rather small modal mass of the piping. $F(t)_{Strut} \sim 50kN$ would not be achieved.

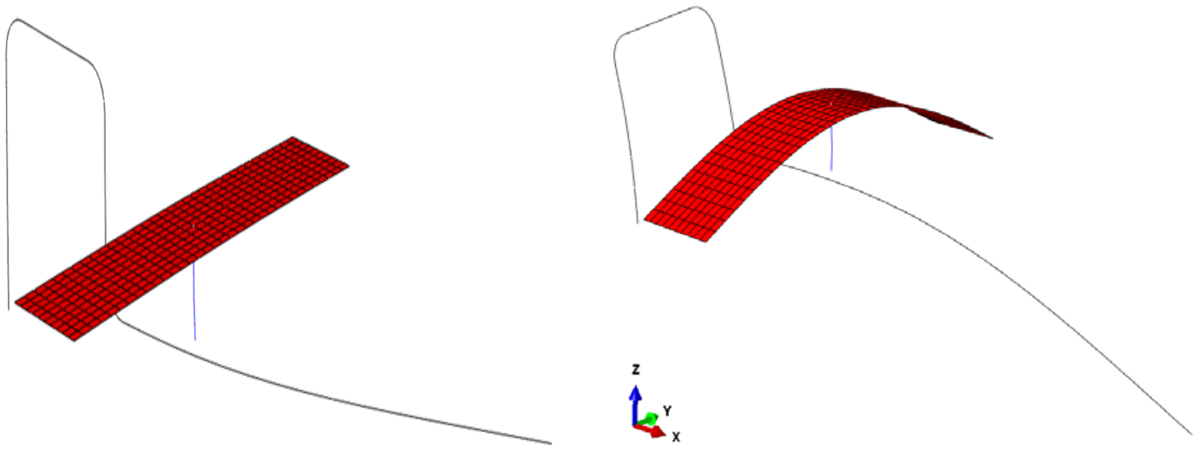

Figure 6: Left: 1. vertical mode (f_2= 3.23 Hz) of the coupled system; right: Mode with large amplitudes of the concrete slab together with the mounted piping (f_5 = 10.32 Hz)

Larger transfer – forces only occur, if both components, the concrete slab and the piping itself would suffer excitations separately. An unbalanced shaker named DYNAQ with a mass of 1metric tonne, cf. Figure 5, was available. The designed excitation was performed as follows:

1. Sinusoidal resonance excitation of the concrete slab with an amplitude A_Ω by means of the shaker DYNAQ close to the frequency of the vertical mode f_5 of piping and slab.
2. Excitation of the piping with a signal created during the mock-up test, since the first vertical piping mode shows nearly an identical frequency.

Since static loads are not combinable as initial condition before starting the THDI this load case was carried out as a THDI as well. In this case the initial condition was realized by switching on gravitation which means for the experiment: Releasing the locking device (time domain 0s < t < 1s), cf. Figure 7. In this connection virtual damping of D = 20 % was used.

Subsequent, starting with the initial condition of dead load in position of rest (time axis 1s < t < 11s) a THDI computation of the load case 100% Earthquake (SSE) earthquake loading with a duration of 10 s and a realistic damping value was started, cf. Figure 7 right. Thereafter, a fading is demonstrated, (time axis 11s < t < 13s).

This procedure was used for all steps of design calculation. Three important calculated results during system developing, nominated with calculation model # 1 to #3, are explained by means of Table 1 and Figure 8. Without experience regarding damping, a damping value was chosen generally to D = 2%.

The model spring stiffness of the anchor group according to the linear ascending branch in Figure 1 yields 84 kN/mm (cf. Figure 1) for the anchor group, if one anchor lies in a cracked borehole and one in a non-cracked borehole.

Excitation forces vs. rotation frequency of the DYNAQ-Shaker are given in Figure 5. During calculation the 10s lasting SSE-earthquake sequence starts at t = 1s. Figure 7 shows the calculated strut forces vs. time of two THDI calculations.

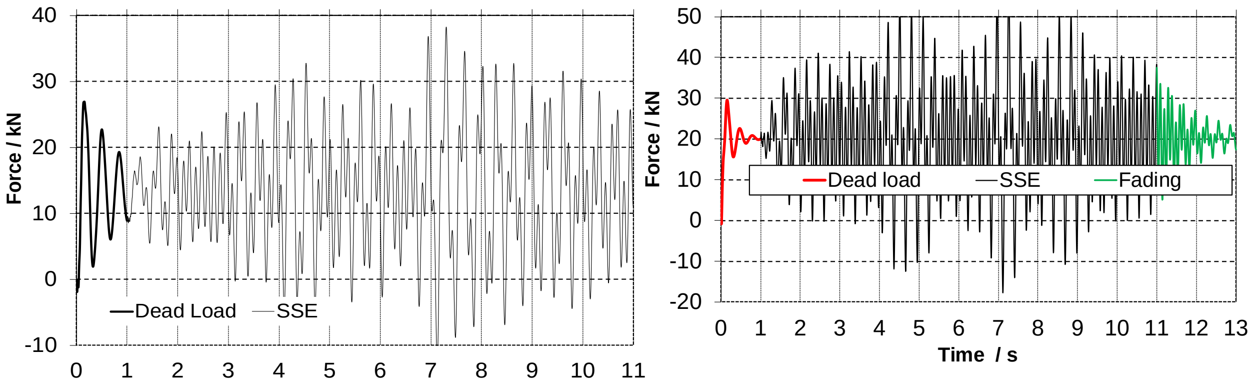

Figure 7: Results of calculation model #1 (left) and model #3 (right)

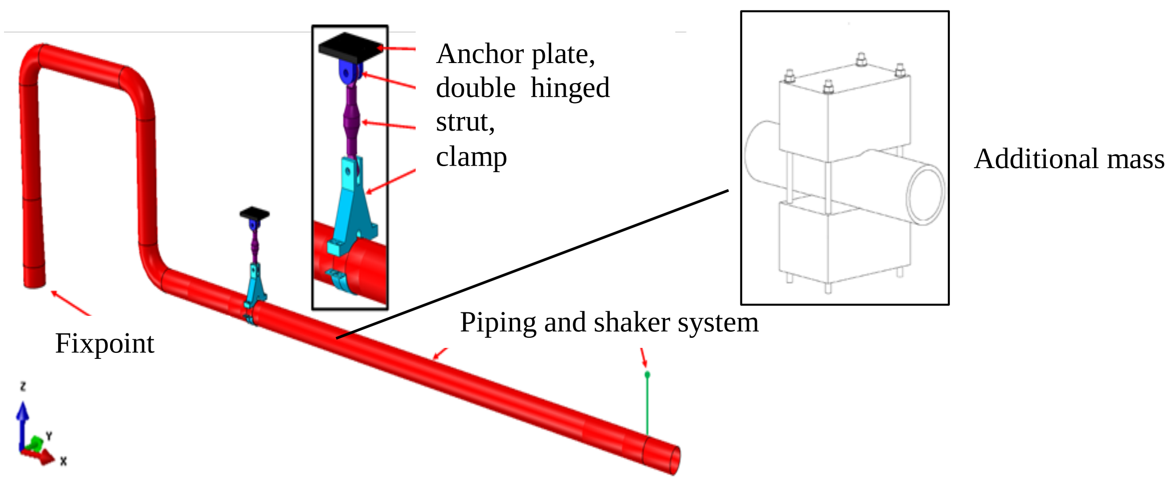

Figure 8: Features of system developing

Table 1: Important steps of design calculation (milestones)

#	*Parameter*			*Result → Conclusion*
#	Main characteristic of model	DYNAQ Excitation-frequency Ω of slab	Frequency of modes with large vertical vibrations of the slab / and modes with large piping - vibrations	Maximum achievable force at the double hinged strut $F_{Str.}$, DYNAQ amplitudes of excitation forces A_Ω / remarks
1	Length of concrete slab L, starting value: L= 7 m	Ω = 52 Hz	f_4 = 8,28 Hz / f_2 = 2,97 Hz	$F_{Str.} \leq 40$ kN, A_Ω = 4 kN (at 8 Hz not feasible) → new length of concrete slab
2	Resulting length after parameter study: L = 5 m	Ω = 69 Hz	f_5 = 11,02 Hz / f_2 = 3,27 Hz	$F_{Str.} \leq 39$ kN, A_Ω = 5 kN (at 11 Hz hardly feasible)
3	Adding of a lumped 500 kg mass to system #2	Ω = 64 Hz	f_5 = 10,22 Hz / f_2 = 3,24 Hz	$F_{Str.} \leq 59$ kN, A_Ω = 4 kN at 10 Hz now feasible

Finally the command value “strut force N_{Rd} = 50.3 kN” was achieved with model #3. The lumped mass could represent e.g. a part of a piping branch.

Also, the influence of pre-stresses in the strut was taken into account for the reason of further unexpected resp. unknown energy dissipation. During the tests, this measure was carried out for enlarging the level of strut forces with a value of 2 kN.

RESULTS OF THE VERIFICATION TESTS COMPARISON OF MEASUREMENT AND CALCULATION

The realized test program of the verification tests, carried out with the above mentioned HDA-Anchor, cf. Figure 4, is listed in Table 2. To avoid unexpected strut loads, the following procedure was carried out:

1. Start of the DYNAQ Shaker with imbalance masses moving in phase
2. When a constant rotational frequency was achieved after ca. 30 seconds, the imbalance masses were switched on to out of phase movements.
3. Immediately afterwards the shaker system at the end of the piping was started with its time signal developed according to the mock-up tests of 10 seconds duration each.

After the end of two earthquake loading sequences (1 DBE + Aftershock) experimental modal analysis and system identification investigation were carried out. Thereafter, the robustness of the system was demonstrated by resonant excitation with strut forces up 90 kN: No failure occurred.

Table 2: Test program of the verification test, for test – setup refer to Figure 4

Test	*Target load for anchor group*	*Anchor 1*	*Anchor 2*	*Remarks to the test*
V5.1	2x 1.0 SSE (10s) + sine run-up	crack		crack only close to borehole
V5.2		crack		ok
V5.3		crack	crack	ok
V5.4		crack	crack	ok

Figure 9 shows strut forces, experimental determined by means of strain gauges and measured surface crack-widths over time. It is visible that the command variable "strut force" was achieved by 90% and the desired surface crack-width with 1.5 mm by 100%. Since the geometry of the crack has a V-shape, the undercut crack amounts about ¼ of the surface crack-width. It is obvious from Figure 10 that anchor-displacements occurred temporarily greater than 3 mm during two SSE earthquake simulations. This value is quite large compared to those values of the mock-up test series with 10 sequences of earthquake loading at 100% N_{rd}, Figure 3. Earthquake loading was started with an initial condition of around 1 mm anchor-displacement subjected to dead load (mounting the piping), very small ambient vibration loads for model updating, and the pre-stress force of 2 kN. The initial strut force yields altogether 20 kN.

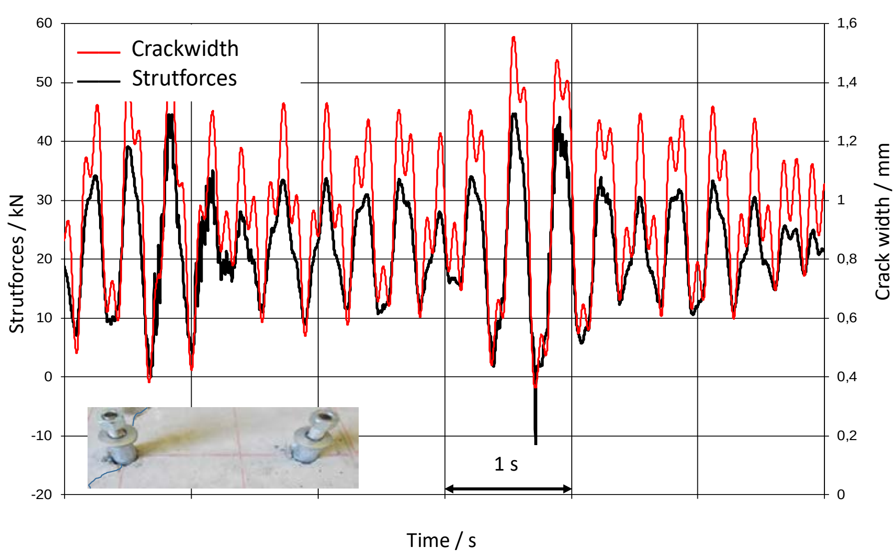

Figure 9: Result of test 5.2, second ~90% SSE (time slot), one borehole is intersected by a crack, strut forces and crack-with vs. time, strut forces are negative during impact of the anchor-plate with the slab

Finally a non-linear numerical concept for simulating interactions of plant-building and piping component regarding the structural dynamical behavior of anchor-displacements including crack opening and closing and including impacts of anchor-plate to concrete slab resp. to anchor-nuts was developed by Dwenger et al. (2016), Dwenger et al. (2017) and Dwenger (2019). Dwenger et al. (2015) report that interactions caused by anchor-plate impacts might increase local piping stresses.

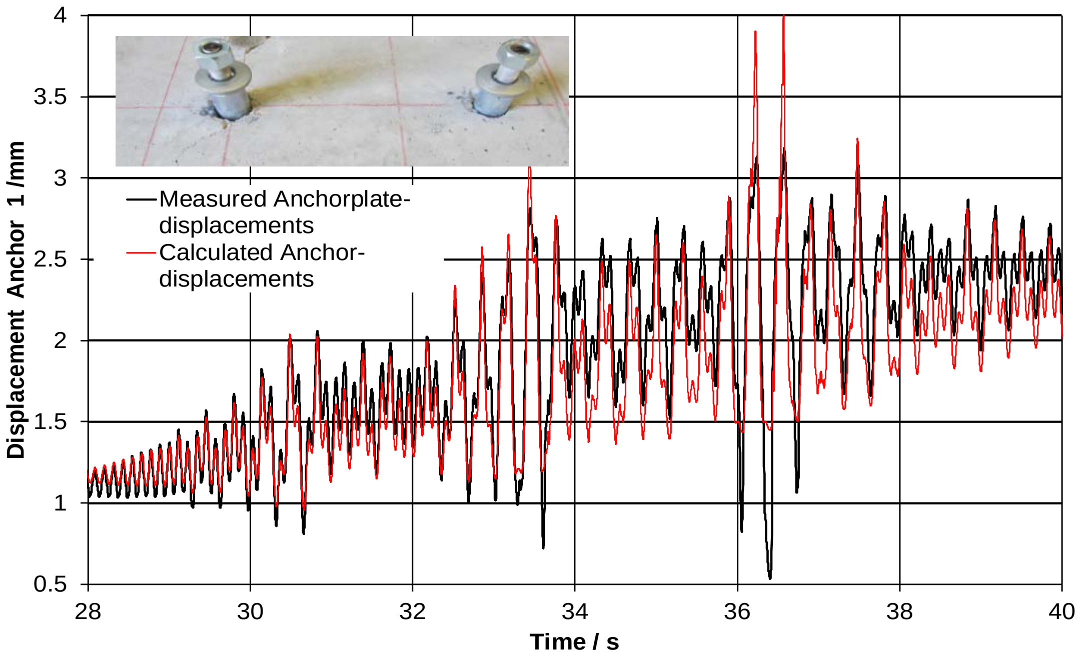

Figure 10: Measured vs. calculated anchor-displacements of test 5.2 (first 90% SSE), Kerkhof et al. (2017)

CONCLUSION AND RECOMMEDATION

Experimental investigations on the interactions concrete slab (building) – anchorage – piping component, have been carried out simulating earthquake loading with postulated cracks in the borehole of anchors and realistically crack cycling frequencies. The results show: The transfer force at the anchorage yields anchor displacements in the range of 3 mm during earthquake loading with maximum loads up to 0.9 N_{rd} starting with an initial condition of around 1 mm displacement. Calculations show that interactions like impacts of anchor-plate with the slab might increase local piping stresses. Within this phase of research, only axial loading was applied. It could be expected, that a combination of axial and shear load on the anchorage will lead to even greater anchor displacements. A generalization and a transfer of the current results on real safety relevant piping taking into account shear forces as well is planned for further research. Nevertheless, the robustness of the anchorage was demonstrated: After two 0.9 SSE sequences no failure occurred during resonant excitation of the system with forces up to 90 kN (180% N_{rd}) measured at the strut.

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