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Division II

ASSESSMENT OF PIPING INTEGRITY WITH POST-INSTALLED ANCHOR FASTENINGS DURING SEISMIC 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 (PI) 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 a concrete crack is passing through the borehole of an anchor 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 PI 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 such a way, that during the load case “dead load plus earthquake loading” the design value of N_{Rd} for the anchor group is achieved. Furthermore, it is postulated that one or both anchors are installed in cracked concrete. Realistic loading scenarios were derived 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 in this paper.

INTRODUCTION

PI anchorages for realizing a structural connection of various components (also called as sub-systems or secondary structural systems) with the primary reinforced concrete structure are used in nuclear safety-related structures. Standardized practices guidelines ACI-355.2 (2007), DIBt-KKW-Leitfaden (2010) and ETAG-001 (2006) 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 PI 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 coupled system structure-anchor-component. 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 a significant amount of permanent displacement is 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 coupled system structure-anchor-component.

The present work deals with a new generalized numerical model consisting of a nonlinear constitutive law taking into account PI anchor displacements. It was validated by 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. Pre-calculations of PI anchor displacements during seismic loading for real piping systems are presented and discussed regarding the integrity of piping.

MODEL FOR THE LOAD-BEARING BEHAVIOR OF SINGLE PI ANCHORS

It was found essential to model the inelastic seismic behavior of anchors, see also Watkins (2011). An experimental database was presented in Mahadik et al. (2016) that could form a basis to develop 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:

- Type A: Hilti® HDA-T-22-M12x125/30 self-undercut anchor and
- Type B: Fischer® FZA-18x80-M12/25 anchor installed in a predrilled undercut hole.

The development of product-specific numerical inelastic models for the anchors using the experimental data has been demonstrated 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 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. During the research project, see Kerkhof et al. (2017), experiments of single undercut anchors were performed in order to evaluate their load-bearing behavior and general format of the load-displacement behavior, see Mahadik et al. (2015). The experiments yield statistical evaluations for a lower bound (LB), a mean value (MEAN) and an upper bound (UB). Based on these results numerical studies regarding seismic loading came to the conclusion that it is possible to reduce the general format to one stiffness parameter k_1: PI anchors in German nuclear power plants (NPP) loaded in tension are usually designed in such a way that the design value of tensile strength N_{Rd} is not exceeded during earthquake loading. Therefore, the complete penta-linear approximation is not needed. Just the ascending branch up to 80 % of the ultimate tensile load N_u with stiffness k_1 must be used for investigation. This assumption was verified within the research project, see Kerkhof et al. (2017), and further developed in Dwenger (2019).

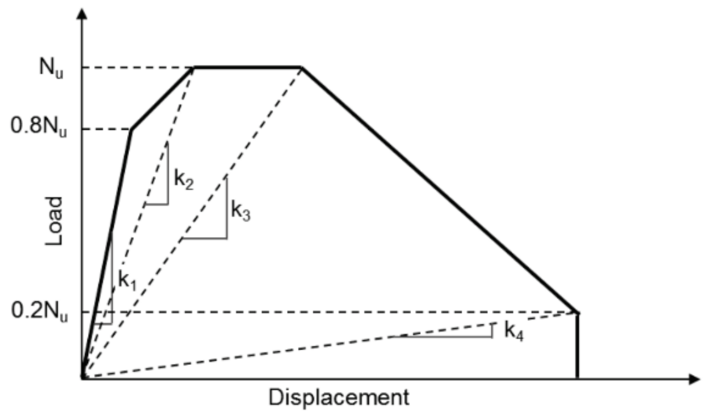


Figure 1: General format for the load-displacement characteristics assigned to the spring model

The results are also summarized in Dwenger (2015) and Dwenger (2017). Basing on mock-up tests and verification tests (see below) a new methodology was created to describe the load-bearing behavior and the structural dynamics of the PI anchorage especially for seismic loading. The developed model is based on the penta-linear model derived from the tests with single anchors. The extended model is able to describe the load-bearing behavior for any type of crack width time histories as well as different crack geometries (parallel or flexural cracks). An overall valid calculation methodology using Finite Element Code Abaqus (2018) and a user subroutine for the constitutive law of axially loaded PI anchors has been developed. The anchor displacements have been studied using three realistic piping systems. A modelling strategy is given.

The constitutive law consists of a user subroutine UMAT for Abaqus using altogether 9 independent parameters and 6 dependent parameters which is described in equation (1) to (3):

$$v_{tot} = v_{CT} + v_{CC} \tag{1}$$

v_{tot}: total anchor displacement
v_{CT}: elastic anchor displacement from cyclic tension loading
v_{CC}: total inelastic/permanent anchor displacement from crack cycling

with

$$v_{CT} = \begin{cases} \frac{N}{k_{1,w}}, & N \geq 0 \\ 0, & N < 0 \end{cases} \text{ with } k_{1,w} = \alpha_{k1}(w) \cdot k_{1,R} \tag{2}$$

N: tensile anchor load
$k_{1,w}$: elastic tensile stiffness of the anchor for current crack width w
α_{k1}: stiffness correction factor for stiffness k_1
$k_{1,R}$: reference value of tensile stiffness k_1 for non-cracked concrete

$$\Delta v_{CC,i} = \begin{cases} s_V \cdot \frac{N}{N_{Rd}} \cdot \Delta w_i, & \Delta w_i \geq 0 \\ 0, & \Delta w_i < 0 \end{cases} \tag{3}$$

s_V: correction factor for consideration of test scatter
Δw_i: change of crack width w
i: increment index

For the calculation of the crack width w(t), a three-dimensional brick element is used as a so-called “sensor element”. For example, the “sensor element” can be part of a large RC structure where the anchor is placed in an assumed crack. The first principal strain ε_1 (t) of the brick element is used to calculate the crack width w(t), because concrete cracks mainly occur perpendicular to the first principal stress because of brittle material behavior. For each time increment, the first principal strain ε_1 (t) is evaluated.

MODEL VERIFICATION BY MEANS OF FULL-SCALE TESTS

Two different full-scale test programs were carried out for development and evaluation of the overall numerical model for simulating a coupled system building – post-installed anchor – piping at earthquake loading:

1. **Mock-up tests** with postulated cracks intersecting the borehole of an anchor with crack opening and closing procedures according to codes and standards were executed. During these tests crack opening and closing was performed for a 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 PI 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. The test results are given in Hofmann et al. (2015), Kerkhof et al. (2015) and Kerkhof et al. (2017).
2. Structural dynamic **Verification tests** of a coupled system "concrete slab – post-installed anchor – piping" at earthquake loading were performed. The test set-up was subjected to vibrations of both the concrete slab and the piping system with earthquake-like frequencies.

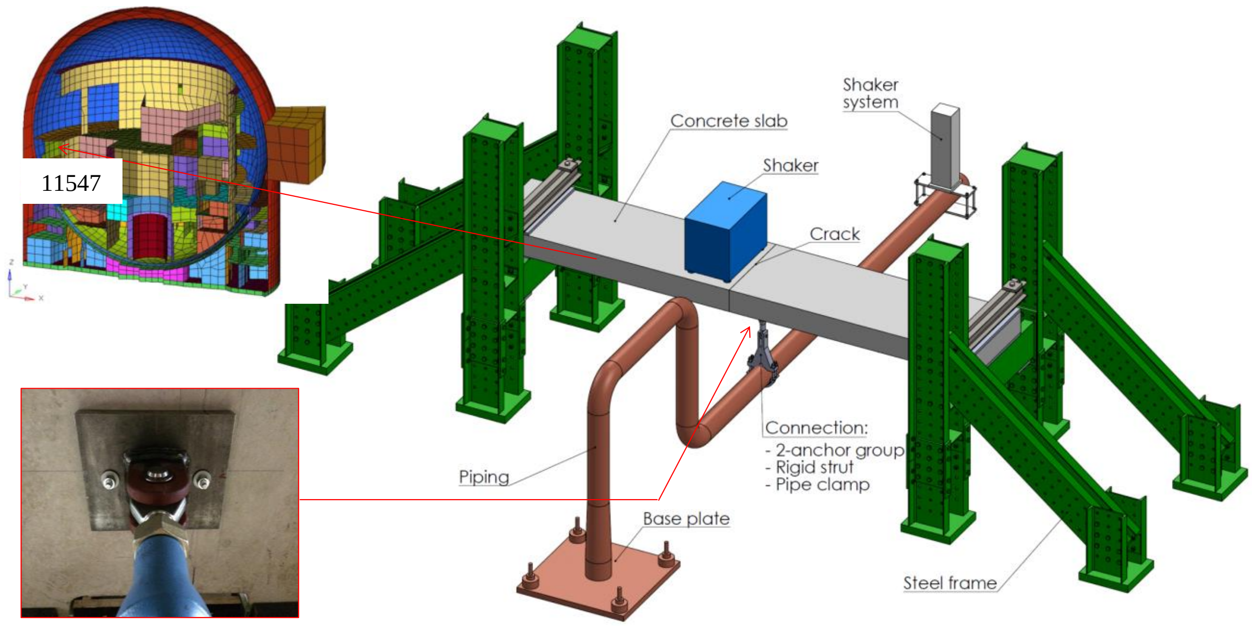


Figure 2: Test set-up of Verification tests with postulated V-shaped crack in the borehole and crack cycling at earthquake-like frequencies, position of node 11547 of the building model

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. Both full scale-tests consist of a piping system which is mounted to a RC slab by a double hinged strut and an anchor plate with two PI undercut anchors. The piping is connected by a pipe clamp and a rigid strut to the RC slab. The design of the fastening has been performed in such a way, that the load case "dead load plus vertical earthquake loading" achieves nearly the design value of N_{Rd}. Realistic loading scenarios were derived from a reactor building model situated at a typical German site with different assumptions for the soil parameters. 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 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 valley (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 load-bearing elements by means of solid, shell or beam elements respectively and with consideration of the masses by geometry and material weight and density. The results of these analyses, presented in Ries et al. (2015) furnish realistic acceleration time histories and 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 limitations. 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 for the design of the mock-up and results are given in Kerkhof et al. (2015) and for the verification tests in Kerkhof et al. (2017).

For the tests 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, see also Ries (2015). These signals were scaled to achieve a loading level at the anchorage close to the decisive design value of tensile strength during the mock-up and verifications test series. The design value of tensile strength of this fastening construction is N_{Rd} = 50.3 kN. Afterwards the loading level was increased to determine the present seismic safety level.

VERIFICATION TESTS

One challenge in the design stage of the test set-up was on the one hand to achieve the design value of tensile strength for the PI anchor group and on the other hand to achieve displacements of the concrete slab with amplitudes which are large enough for earthquake-like crack opening and closing in the anchorage zone of the PI anchors. To fulfill these demands another large imbalance shaker was installed on the concrete slab with a length of L = 5 m, see Figure 3.

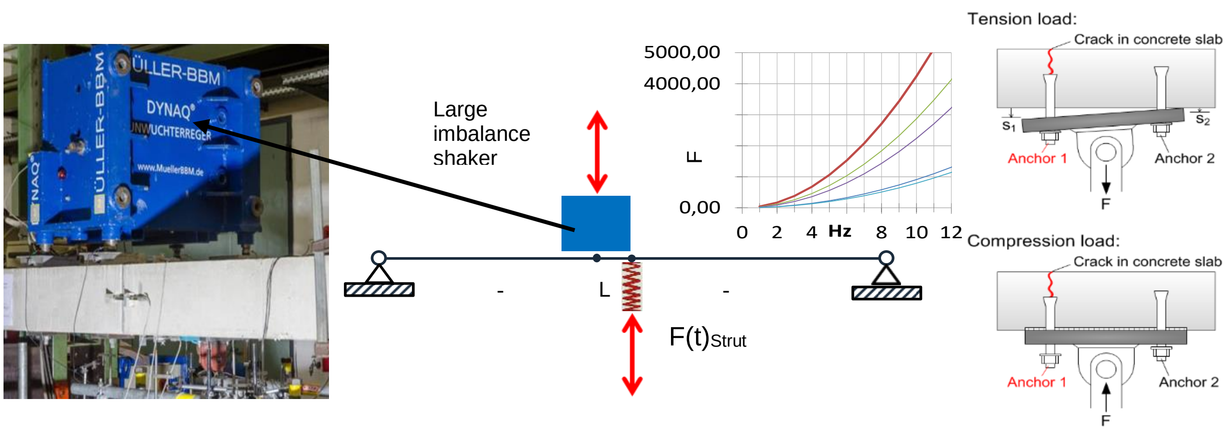


Figure 3: Imbalance shaker on the concrete slab for the verification tests (left) – calculational model (middle) (piping not shown) – crack in the anchorage zone (right)

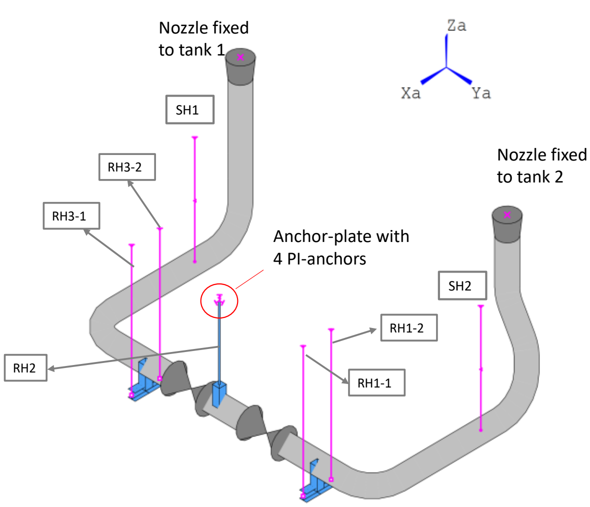
The design calculations were performed by means of the Finite-Element-Code Abaqus (2016) and time history dynamic integration (THDI) using mode superposition. The iterative process for model finding from pre-calculations with variation of the slab geometry and of the coupling point between piping and concrete was summarized in Kerkhof et al. (2019). Excitations with combination of two large imbalance shakers - one positioned on the concrete slab and one at the end of the pipe – finally yielded earthquake-like crack cycling and strut forces close to $F(t)_{Strut}$ = 50 kN which meets the command design value of N_{Rd} = 50.3 kN. A comparison of measurements and calculation is given in Kerkhof et al. (2017), (2019) and Dwenger et al. (2022) showing a good agreement.

CALCULATION OF ANCHOR-DISPLACEMENTS AT REAL PIPING SYSTEMS

In the framework of another research project, see Kerkhof et al. (2021), the above mentioned UMAT was applied to real piping systems mounted to a concrete floor by PI anchors. The investigations comprise three different systems. This paper presents results of a piping system named MECOS, which is similar to the one which was initiated during a SMiRT 25 Conference workshop as benchmark-system by Berkovsky et al. (2019), and which is part of a feed water system. Figure 4 shows the geometry and supports of this system (Figure 4 left) subjected to dead load plus seismic loading SSE (Figure 4 right).

It is assumed that the piping system is mounted at node 11547 to the reactor building model with a seismic design according to the situation in the Rhine Valley, see . Focal points of the investigation are realistic seismic loads with a crack cycling in a range of 0 mm < w < 0.8 mm and furthermore in a range of 0 mm < w <1.5 mm which is commonly used during certification tests for PI anchors in NPP. It is assumed that the fastening of RH2 consists of an anchor group of 4 PI anchors type Hilti® HDA T M12.

Since the load case Gravity (G) + SSE should reach or exceed the design value $N_{rd} = 0.75\ N_{Rk,c}$ = 71.8 kN for an anchor plate with 4 PI anchors fastened to the RC structure, the piping system was modified slightly. That means for the MECOS-System presented in this paper that the longitudinal stiffness (cross section area) regarding the double hinged struts RH1 and RH3 was reduced beside some other small modifications.



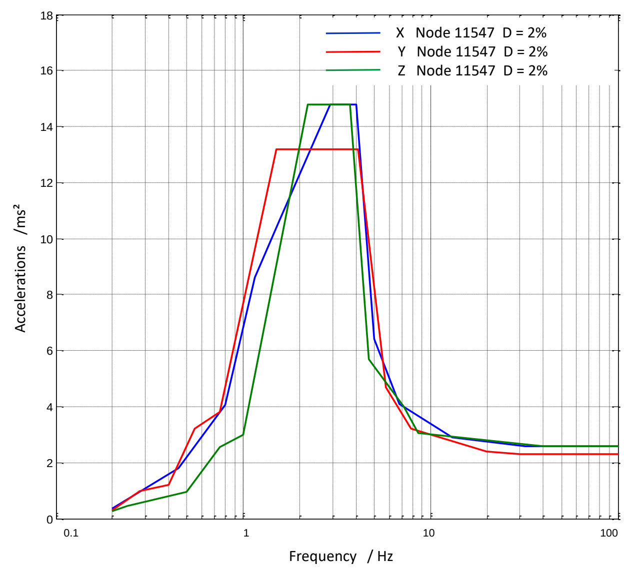
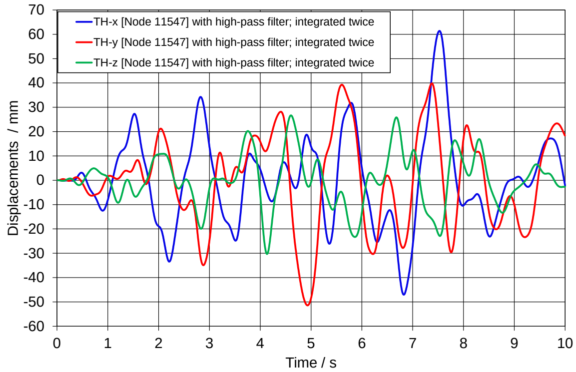


Figure 4: Piping system with two fixpoints at vessels tank 1 and tank 2, two spring hangers (SH) and three rod hangers (RH), postulated PI anchor group at RH2 (left), applied floor response spectrum (right)

Figure 5 shows base motion displacement time histories corresponding to the floor response spectrum of Figure 4 right. In this case a crack cycling was chosen corresponding to the bending moment time history during seismic loading at a floor close to node 11547 of the building model. The maximum crack width was scaled to w = 1.5 mm and w = 0.8 mm. These functions are given in Figure 5 as well. The parameters chosen for the UMAT are given in Dwenger et al. (2022).



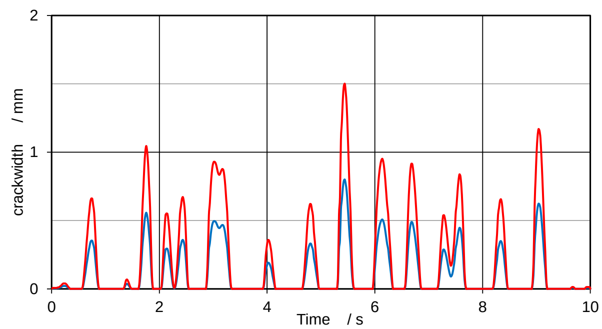


Figure 5: Base motion displacement time histories corresponding to the floor response spectrum (left) and applied crack cycling time history functions 0 < w < 0,8 mm (blue) and 0 < w < 1,5 mm (red) (right)

Linear calculations by Response Spectrum Modal Analysis (RSMA) were carried out for checking the level of N_{Rd} regarding the reaction forces at the fastenings before and after system modifications using the Finite Element Code ROHR2 (2019) and for system MECOS as well Abaqus (2018). Figure 6 shows the RSMA results of the reaction forces for RH2 of MECOS for a wide range of anchor group stiffness values (assumption: resulting stiffness of parallel springs). The LB estimation represents 4 anchors in cracked concrete and the UB estimation represents no anchors in cracked concrete and a damping value of D = 2%. Some of these values are marked in the diagram. For anchor group stiffness values below 120 kN/mm all anchors must be placed in cracked concrete with crack width cycling up to 1.5 mm.

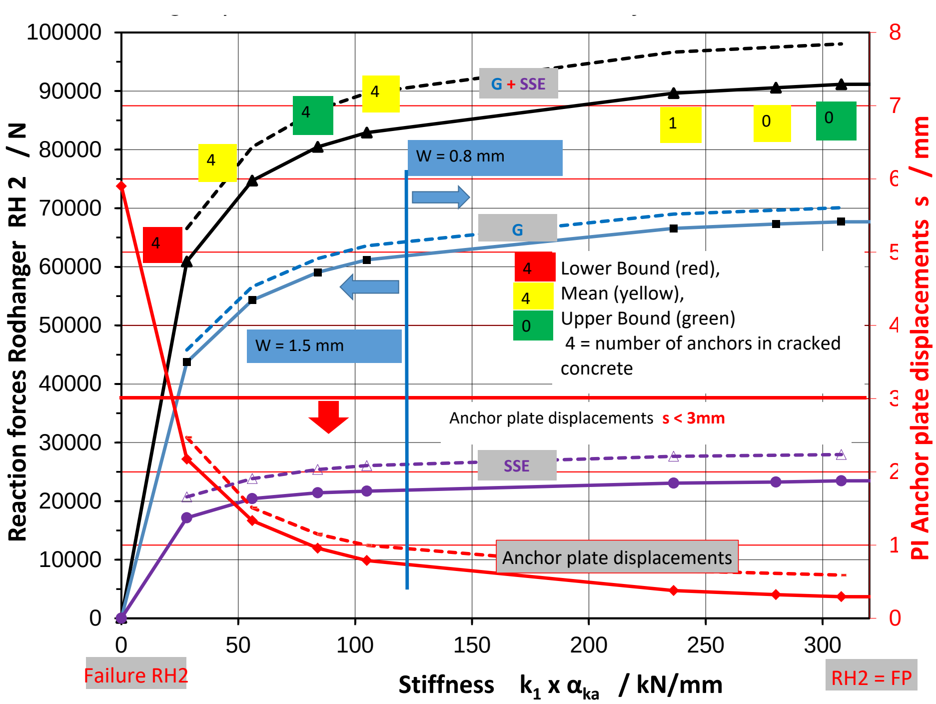


Figure 6: Linear calculations (D=2%) of reaction forces and anchor displacements by RSMA with Rohr2 (dotted line) and Abaqus (solid line) for load case gravity load (G), seismic load (SSE) and (G)+(SSE)

Figure 7 displays the results of the dynamic analyses with Implicit Time Integration for the modified MECOS piping system with different fastening models. Three fastening models for RH2 with linear elastic stiffness in the range from 28 to 280 kN/mm and two fastening models with a nonlinear load-displacement behavior according to the UMAT - for chosen parameters see Dwenger et al. (2022) - were compared.

Crack widths during crack cycling is the decisive influence parameter for remaining anchor displacements after seismic loading. Crack cycling in the range of 0 mm < w < 0.8 mm leading to rather small anchor displacements of 2 mm during seismic loading yields decreasing reaction forces at the support RH2 which is visible in Figure 8. The dead load already leads to an elastic anchor displacement of 0.24 mm and a reduction of the reaction force at the support RH2.

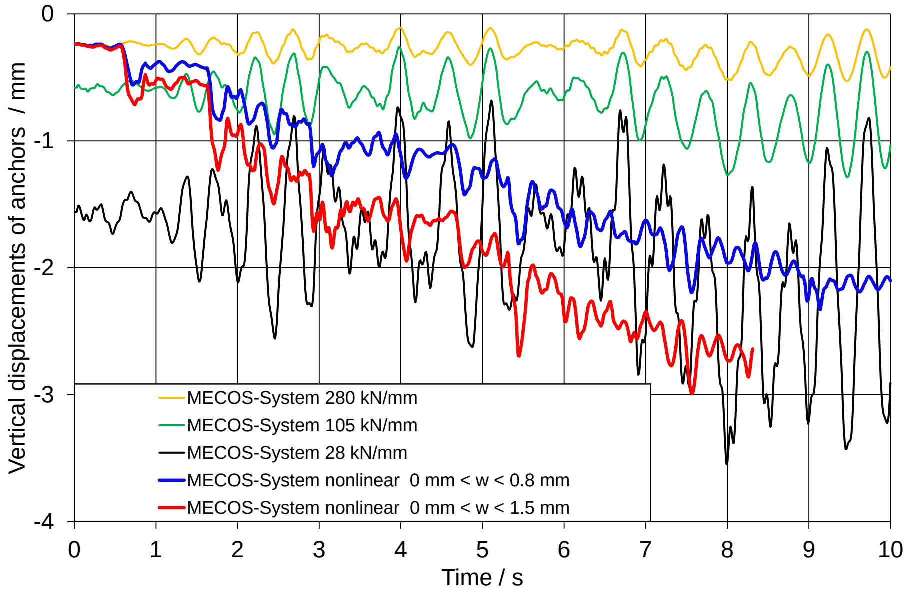


Figure 7: Linear calculations of PI anchor displacements by THDI with FE-Codes ABAQUS for the load case G + 10s SSE for three PI anchor stiffness values compared to the nonlinear calculations with UMAT

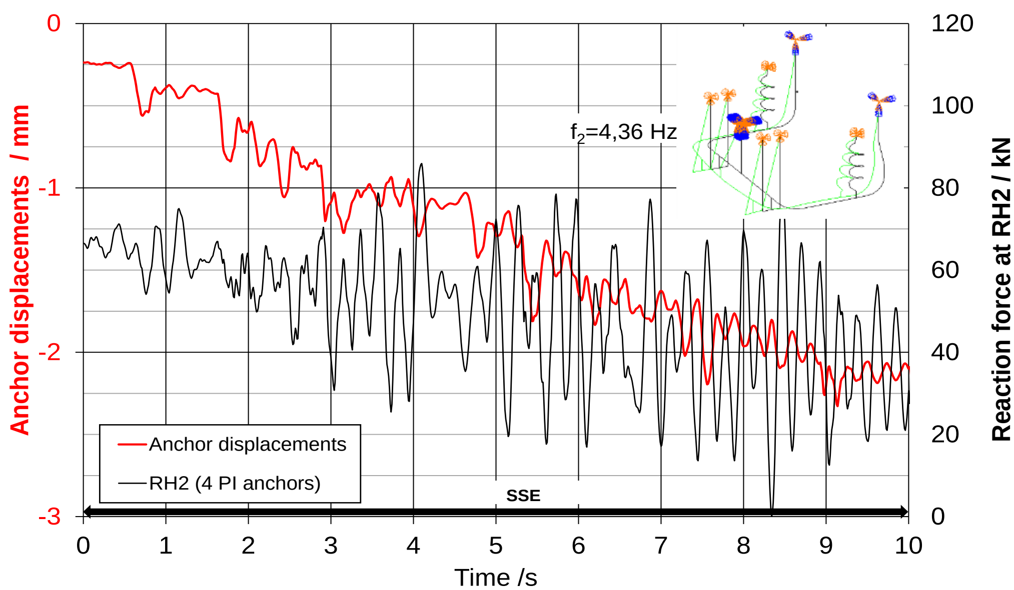


Figure 8: PI anchor displacements and reaction forces at support RH2 during 10s – SSE loading for nonlinear calculations with UMAT

Figure 9 shows results of an extended nonlinear calculation until the force amplitude fades. During seismic loading a load shifting from the reaction force at the support RH2 to neighboring supports of about 47% takes place. The reaction force is reduced from 65.5 kN to 34.7 kN.

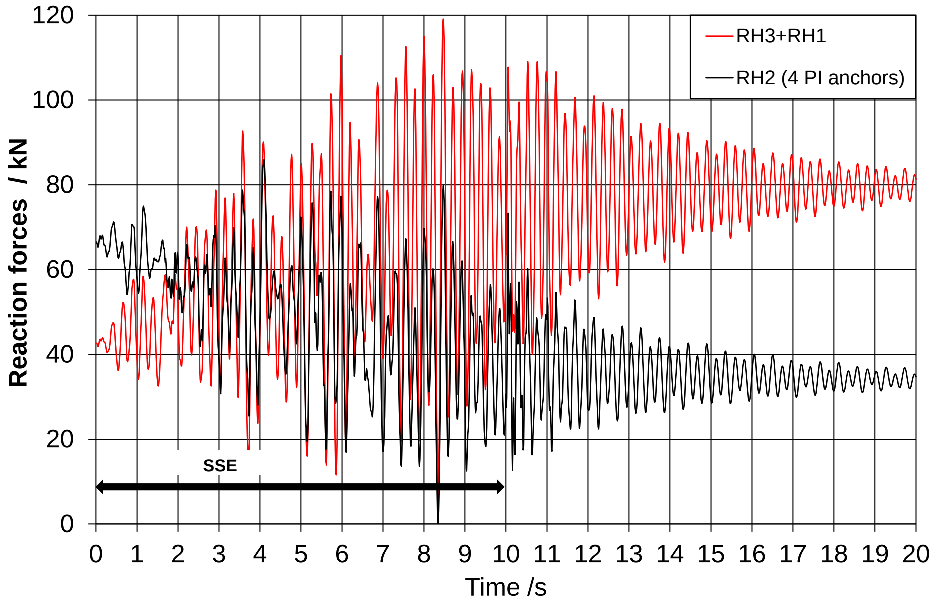


Figure 9: Load shift to neighboring supports during 10s-SSE due to anchor displacements at RH2

CONCLUSION

Two different large-scale test set-ups were designed in order to study the load-displacement behavior and safety level of PI anchors under seismic loading conditions similar to German NPP.

The test results which were obtained during the test programs for the two test set-ups served as an experimental database for the development of a nonlinear numerical model of a PI fastening.

A nonlinear numerical model consisting of a nonlinear constitutive law considering PI anchor displacements was validated by full-scale dynamic tests and was applied to a realistic piping system.

The assumption that one support consists of a fastening with 4 PI anchors and an anchor plate shows that anchor displacements due to seismic loading with seismic conditions applicable for NPP buildings in the Rhine Valley might induce quite large load shifting to neighboring supports in a range of 47%. It should be pointed out that this load shifting already occurs for small anchor displacements of about 2 mm.

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REFERENCES

Abaqus (2018). *Finite Element Program*, SIMULIA, Version Abaqus/Standard 3DEXPERIENCE R2018x.

ACI-355.2 (2007). *Qualification of post-installed mechanical anchors in concrete (ACI 355.2-07) and commentary*, American Concrete Institute (ACI), Farmington Hills, Michigan.

ASCE-4-98 (2000). *Seismic analysis of safety-related nuclear structures and commentary*, American Society of Civil Engineers.

DIBt-KKW-Leitfaden (2010). *Leitfaden für Dübelbefestigungen in Kernkraftwerken und anderen kerntechnischen Anlagen (Guideline for fastenings in nuclear power plants and other nuclear technical facilities)*, Deutsches Institut für Bautechnik (DIBt), Berlin (in German).

Berkosky, A. and Sollogoub, P. (2019). *New trends in the seismic design of pressurized piping und the beyond design basis earthquake.* JASMiRT-Workshop presentation: Towards innovative systems performance and safety of nuclear power plant under extreme events. SMiRT 25, Charlotte, NC, USA.

Dwenger, F., Garrecht, H., Kerkhof, K. (2017). *Development and verification of models for post-installed anchors under dynamic loading and crack cycling in the anchorage zone.* Proceedings of SMiRT 24, Busan, Republic of Korea.

Dwenger, F. (2019). *Einfluss des Tragverhaltens von Dübelbefestigungen auf die Bauwerk-Komponenten-Wechselwirkungen bei Erdbebenbeanspruchung.* PhD thesis, University of Stuttgart, Germany.

Dwenger, F., Kohler, C., and K. Kerkhof. (2022). *Modelling of the load-displacement behavior of undercut anchors and comparison with large-scale tests (planned).* Proceedings of SMiRT 26, July 10 – 15, 2022, Potsdam/Berlin, Germany.

ETAG-001, (2006). *Guideline for European technical approval of metal anchors for use in concrete, Parts 1 – 6*, European Organization of Technical Approvals (EOTA), Brussels.

Hofmann, J., Mahadik, V., Sharma, A. (2015). *Modelling Structure-anchor-component interaction for Nuclear Safety Related Structures under Seismic Loads–part 2: Development of Numerical Model*. Proceedings of SMiRT 23, Manchester, United Kingdom.

Kerkhof, K., Dwenger, D., Birtel, V., Fröhlich, T., Henkel, F.-O (2015). *Influence of piping support conditions on structural dynamics including post-installed anchors.* Proceedings of SMiRT 23, Manchester, United Kingdom.

Kerkhof, K., Bauer, Th., Birtel, V., Dwenger, F., Froehlich, T., Henkel, F.-O., Hofmann, J., Lotze, D., Mahadik, V., Ries, M., Sharma, A. (2017). *Interactions of the coupled system "building - post installed anchor - piping" at earthquake loading Experimental part*, Final Reports, phase I, German Reactor Safety Research – Project No. 1501450 (2015), and phase II – Project No. 1501478, (2017), Germany.

Kerkhof, K., Garrecht, H., Weihe, S. (2019). *Large scale tests on the coupled system building – post installed anchor – piping at earthquake loading*, Proceedings of SMiRT 25, Charlotte, NC, USA.

Kerkhof, K., Dwenger, F., Hofmann, J., Kohler, C., Sharma, A., Stehle, E., Henkel, F.-O., Jeong, M., Ries. (2021). *Influence form displacements of post-installed anchors on the safety assessment of piping systemes at earthquake loading*, German Reactor Safety Research – Project No. 1501598 (2021), Germany.

Mahadik, V., Sharma, A., Hofmann, J. (2015). *Modelling of structure-anchor-component interaction for nuclear safety related structures under seismic loads–Part 1: Generation of experimental database.* Proceedings of SMiRT 23, Manchester, United Kingdom.

Mahadik, V., Sharma, A., Hofmann, J. (2016). *Inelastic seismic behavior of post-installed anchors for nuclear safety related structures: Generation of experimental database.* Nuclear Engineering and Design 297, pp. 231-250.

Mahrenholtz, P. (2012). *Experimental Performance and Recommendations for Qualification of Post-installed Anchors for Seismic Applications,* PhD thesis, University of Stuttgart, Germany.

Ries, M., Bauer, Th., Hahn, T., Henkel, F.-O. (2015). *Seismic test of pipe system supporting anchors by a linear shaker,* Proceedings of SMiRT 23, Manchester, United Kingdom.

ROHR2 (2019). SIGMA Ingenieurgesellschaft mbH, Finite-Elemente-Software für Rohr- und Tragwerks-analysen. (Version 32.1)

Sharma, A., Eligehausen, R., Hofmann, J. (2014). *Numerical Modeling of Joints Retrofitted with Haunch Retrofit Solution*, ACI Structural Journal 111, 861–872, (2014).

Sharma, A., Mahadik, V., Hofmann, J. (2015). *Crack Cycling Tests on Undercut Anchors for Application in Nuclear Safety Related Structures with Different Tension Loading Protocols.* Proceedings of SMiRT 23, Manchester, United Kingdom.

Watkins, D. A. (2011). *Seismic Behavior and Modelling of Anchored Nonstructural Components Considering the Influence of Cyclic Cracks,* PhD thesis, University of California, San Diego, USA.