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Division V

MODELLING OF THE LOAD-DISPLACEMENT BEHAVIOR OF UNDERCUT ANCHORS AND COMPARISON WITH LARGE-SCALE TESTS

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ABSTRACT

Post-installed (PI) anchorages are widely used in civil engineering to connect structural and non-structural components (NSC) such as piping systems. For heavy-duty or high-safety applications like connections between piping supports and reinforced concrete (RC) structures in nuclear power plants (NPP), undercut steel anchors are often used to transfer static and dynamic loads. Static loads mainly result from piping dead load whereas dynamic loads can result from different sources, for example from water hammer or earthquakes. The combination of static and dynamic loads as well as concrete cracking in the anchorage zone leads to a complex load-displacement behavior of the fastening.

In order to incorporate the complex load-displacement behavior of undercut anchors under tension loading for detailed numerical calculations, a numerical model for a single anchor was developed based on previous investigations by using Fortran User Subroutines in Abaqus FEA. The model incorporates the anchor displacement resulting from reversible elastic and irreversible permanent displacement during crack cycling in the anchorage zone causing anchor displacements. The developed numerical model is validated by comparing finite element (FE) simulation results with large-scale tests. Additionally, a model concept for a fastening with two anchors is developed using the numerical model of the single anchor. This model for a whole fastening can be used for anchor groups.

INTRODUCTION

During an earthquake, anchors have to transfer dynamic loads between NSC and RC structure which result from seismic excitation of the building and the dynamic interaction of the partial systems, see Figure 1 left.

Figure 1 right shows a possible behavior of a coupled system during a seismic event. The system consists of a piping, an anchor plate with anchors, a rigid piping support and a concrete floor. Large vibration amplitudes of concrete floors and piping (Figure 1 right, situation 1) lead to dynamic anchor loads and non-uniform loading of anchor groups so that leverage of the anchor plate occurs (Figure 1 right, situation 2). Tensile forces applied on the anchors in combination with cyclic opening and closing of cracks can lead to significant permanent displacement of anchors. When the relative movement between concrete floor and piping reverses, the anchor plate may lose contact to anchors and concrete floor (Figure 1 right, situation 3) due to gaps. When the anchor plate has contact to the anchors or the concrete floor again, the anchors are immediately loaded by impact loads which can be enhanced by leverage of the anchor plate and the piping support (Figure 1 right, situation 4). These impact loads are transferred to the support and piping. Situations 1-4 regarding tensile forces applied on the anchors combined with cyclic opening and closing of cracks in a concrete slab is the focus of the investigations described in this paper.

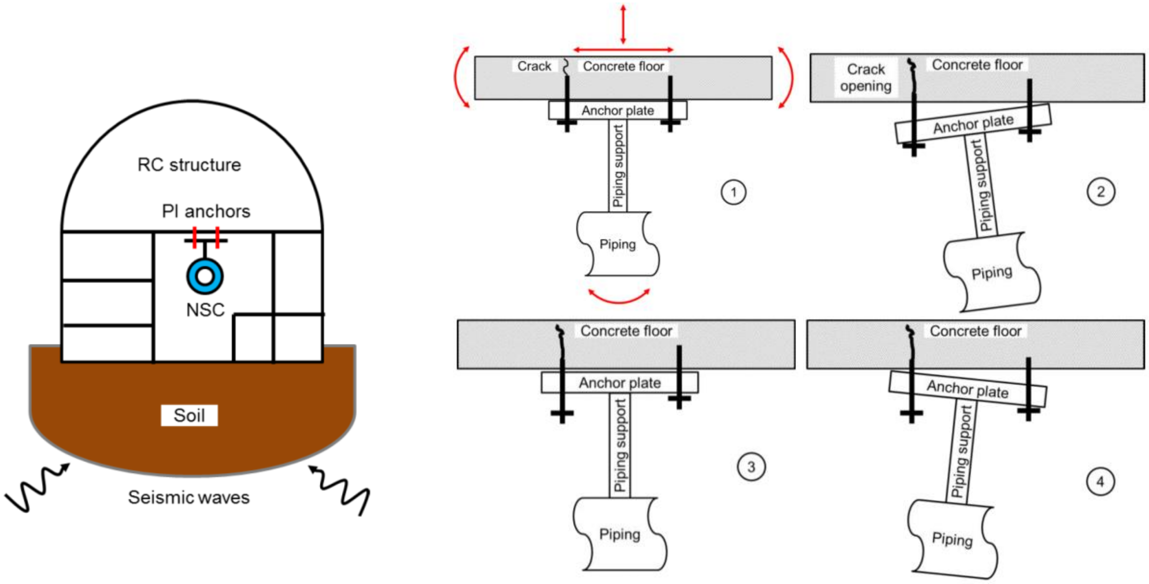

Figure 1. Loading path inside a NPP during an earthquake (left) and behavior of a coupled system during a seismic event (right) (after [Dwenger et al. (2015)], [Dwenger et al. (2017)])

The dynamic interactions are governed by the magnitude and frequency characteristics of the ground motion as well as by the modal characteristics of the partial systems like natural frequencies, mode shapes and damping. In current design guidelines like [ASCE (2000)] and [KTA (2013)], dynamic decoupling of the partial systems is allowed only under certain conditions in order to guarantee accurate analysis results. During this decoupling process, the complex load-bearing behavior of a fastening with PI anchors is usually linearized or neglected completely. For coupled systems where decoupling is not applicable, there is a need to adequately model the load-bearing behavior of a fastening for seismic analysis.

Usually, a fastening with PI anchors consists of an anchor plate and two or more anchors in order to achieve an accurate positioning of the NSC and to assure sufficient load-bearing capability. Therefore, the load-bearing behavior of the whole fastening is governed by the load-bearing behavior of the single anchors and the anchor plate.

Furthermore, the load-bearing behavior is dependent on the anchor type. In German NPPs, undercut anchors are the most widely used anchor types because of their high load-bearing capability, robustness against large crack widths and dynamic loads and installation quality. Therefore, the investigations presented in this paper focus on an undercut anchor which currently has a national technical approval for use in German NPPs [DIBt (2020)].

ANALYTICAL CONCEPT FOR THE NUMERICAL MODEL OF AN ANCHOR

In order to develop and validate a numerical model for a single anchor, standardized single anchor tests were carried out to obtain an experimental database. The results of the single anchor tests are already published in [Kerkhof et al. (2015)], [Mahadik, Sharma and Hofmann (2015)], [Sharma, Mahadik and Hofmann (2015)] and [Kerkhof et al. (2017)] and therefore are not outlined in this paper. The main results of the tests which are relevant for this paper can be summarized as follows:

- the total anchor displacement can be split in an elastic and an inelastic/permanent part
- the elastic part of the anchor displacement mainly results from cyclic loading
- the inelastic/permanent part of the anchor displacement mainly results from crack cycling when a tension load is applied on the anchor

From the abovementioned main results, a basic analytical equation for the calculation of the total anchor displacement can be formulated:

$$v_{tot}=v_{CT}+v_{CC} \qquad (1)$$

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

Analytical equation for elastic anchor displacement v_{CT}

Based on the results of the standardized single anchor tests, a penta-linear approach was developed in [Kerkhof et al. (2015)] to approximate the load-displacement curves during monotonic loading, see Figure 2 left. At first, the parameters for the penta-linear approximation were derived from the single anchor tests in non-cracked concrete, see Figure 2 right.

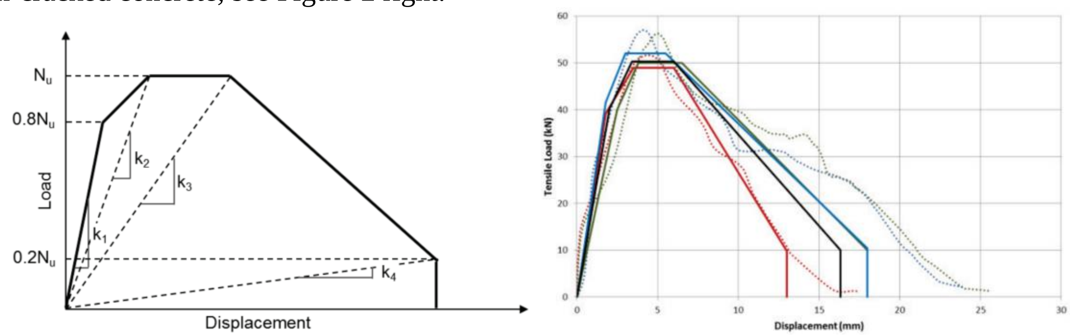

Figure 2. Penta-linear approximation of the load-displacement curve
(after [Hofmann, Mahadik and Sharma (2015)])

These parameters were then adapted with correction factors in case of cracked concrete in the anchorage zone (load and stiffness correction factors dependent on crack width), see Figure 3. A more detailed description of the methodology can be found in [Kerkhof et al. (2015)], [Hofmann, Mahadik and Sharma (2015)] and [Kerkhof et al. (2017)].

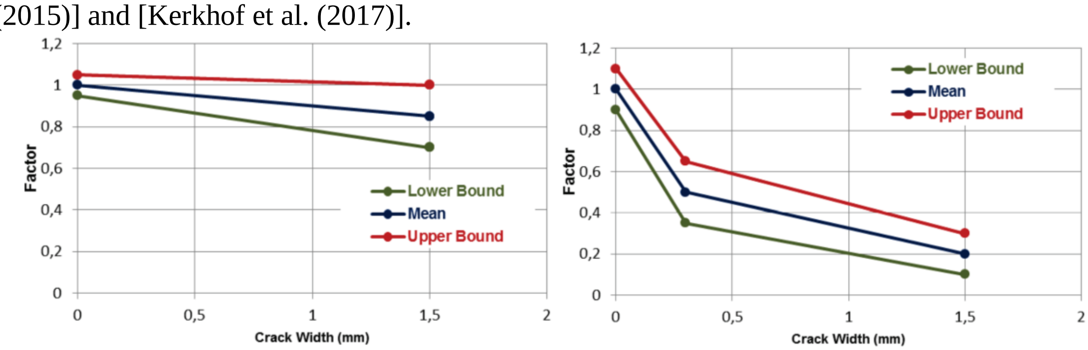

Figure 3. Correction factors for ultimate tensile load N_u (left) and stiffness k_1 (right) with test scatter bands (after [Hofmann, Mahadik and Sharma (2015)])

PI anchors in German 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. In this case, the whole penta-linear approximation is not needed and just the ascending branch up to 80 % of the ultimate tensile load N_u with stiffness k_1 can be used for investigation, see Figure 2 left. Furthermore, the cumulative number of loading cycles during earthquake loading in German NPP is usually below 100. Therefore, the amount of permanent displacement resulting from cyclic loading is neglectable.

With these simplifications, the elastic anchor displacement can be expressed by the following analytical equation:

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

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

Analytical equation for total inelastic/permanent anchor displacement v_{CC}

It was shown in [Lotze (1993)] that the inelastic/permanent displacement of an anchor loaded in tension and installed in cracked concrete is mainly dependent on the change of crack width Δw. Furthermore, inelastic/permanent displacement of the anchor can only increase when the crack is opening, and a tension load is applied on the anchor at the same time. Using these findings, the analytical equation for the change of inelastic/permanent anchor displacement $\Delta v_{CC,i}$ is defined as follows:

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

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

In order to calculate the inelastic/permanent anchor displacement v_{CC}, the incremental changes of inelastic/permanent anchor displacements $\Delta v_{CC,i}$ are added together:

$$v_{CC} = \sum_i \Delta v_{CC,i} \qquad (4)$$

DEVELOPMENT OF A USER-DEFINED MATERIAL MODEL

The analytical model concept of a single anchor is implemented in the commercial FE program Abaqus FEA by using so-called Fortran User Subroutines. The Fortran interface offers the possibility to solve FE models in conjunction with user-defined Fortran code. In this case, a user-defined material “UMAT” with an elastoplastic material behavior for a three-dimensional beam element is used for the calculation of the load-displacement behavior of a single anchor.

For the definition of the “UMAT”, the analytical equation for the elastic anchor displacement mentioned in the previous chapter has to be rewritten in such a way that it fulfills the basic FE formulation of the static equilibrium equation:

$$\underline{K}\, v = f \qquad (5)$$

$$N = \begin{cases} k_{1,w} \cdot v_{CT}, & N \geq 0 \\ k_p \cdot v_{CT}, & N < 0 \end{cases} \qquad (6)$$

$\underline{K}$: stiffness matrix
v: displacement vector
f: external force vector
k_p: fictitious anchor compression stiffness

The fictitious anchor compression stiffness is chosen in such a way that numerical problems are avoided (in this case 10^{15} N/mm).

The analytical equation for the inelastic/permanent anchor displacement is already written in such a way that it fulfills the basic formulation of an associated flow rule:

$$d\varepsilon_p = d\lambda \frac{\partial \Phi}{\partial \sigma} \tag{7}$$

$d\varepsilon_p$: plastic strain increment
$d\lambda$: hardening parameter
Φ: force potential
σ: stress
where $\Delta v_{CC,i}$ corresponds to $d\varepsilon_p$, Δw_i corresponds to $d\lambda$ and N/N_{Rd} corresponds to $\partial\Phi/\partial\sigma$.

For nonlinear seismic time history analyses, the equations (3) and (6) have to be calculated for each stable time increment. In order to initialize the "UMAT" at the first time increment, the following parameters have to be pre-defined:

- A: cross-sectional area of the anchor beam element (M12 anchor bolt: 113.097 mm^2)
- k_p: fictitious anchor compression stiffness (10^{15} N/mm²)
- $k_{1,R}$: reference value of tensile stiffness k_1 for non-cracked concrete (investigated anchor: 70,000 N/mm^2)
- s_V: correction factor for consideration of test scatter (in this case: 0.65)
- N_{Rd}: design value of tensile strength (investigated anchor: 30,000 N)
- l_0: initial length of the anchor beam element (in this case: 15 mm)
- $\alpha_{k1}(w)$: $\begin{cases} +1 \\ 0 \\ -1 \end{cases}$: parameter for curve type of correction factor for stiffness k_1 (+1: upper bound curve / 0: mean curve / -1: lower bound curve, see Figure 3 right)
- G: Fictitious shear modulus of the anchor beam element (steel anchor bolt: 80,800 N/mm^2)

IMPLEMENTATION OF THE UMAT INTO A FE MODEL OF A SINGLE ANCHOR

The numerical model of a single anchor is shown in Figure 4. The anchor is idealized as a beam element, which is loaded by a tensile anchor load N(t) at one end. At the other end, it is fixed by a boundary condition. The "UMAT" described above is assigned to the beam element. 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.

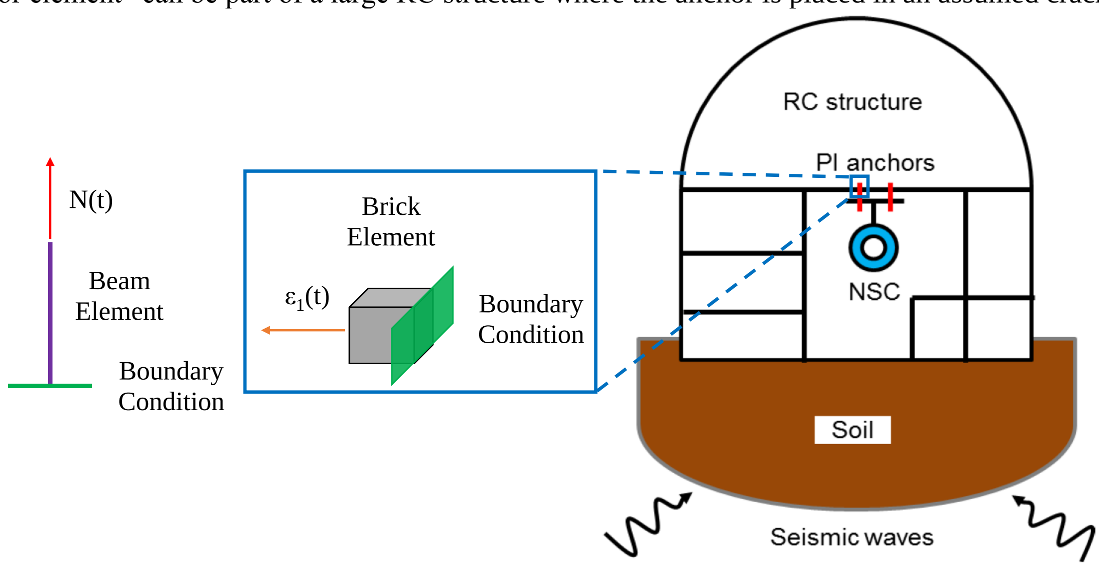

Figure 4. Numerical model of a single anchor

The first principal strain $\varepsilon_1(t)$ of the brick element is used to calculate the crack width w(t) since concrete cracks mainly occur perpendicular to the first principal stress because of brittle material behavior. For each time increment, the first principal strain $\varepsilon_1(t)$ is evaluated. Afterwards, the crack width w(t) is calculated by another user subroutine "URDFIL" (user-defined field variable) as follows:

$$w(t) = \begin{cases} \varepsilon_1(t) \cdot l_E, & \varepsilon_1(t) \geq 0 \\ 0 & , \varepsilon_1(t) < 0 \end{cases} \quad (8)$$

l_E: element size of the brick element (in this case: 1 mm)

The value for w(t) is transferred to the "UMAT" to calculate the change of crack width $\Delta w(t)$ (see equation (3)).

VALIDATION OF THE FE MODEL FOR A SINGLE ANCHOR

The FE model of a single anchor is validated by comparing simulation results with large-scale tests. Details on the large-scale tests can be found in [Kerkhof et al. (2015)], [Kerkhof et al. (2017)] and [Froehlich et al. (2017)].

For the validation, the anchor load and crack width time histories of the large-scale tests are used as input for the simulations. The anchor displacement time histories of the large-tests and simulations are compared afterwards.

During the large-scale tests, the anchor displacement is not measured directly on the anchor because of possible measurement inaccuracies. The anchor displacement is therefore measured indirectly by measuring the anchor plate displacement in the vicinity of the anchor, see Figure 5. During tension loading, the anchor plate displacement correlates well with the anchor displacement. During compression loading, the anchor loses contact to the anchor plate and stays at a fixed position while the anchor plate is pressed on the RC structure. The measured anchor plate displacement is 0 mm.

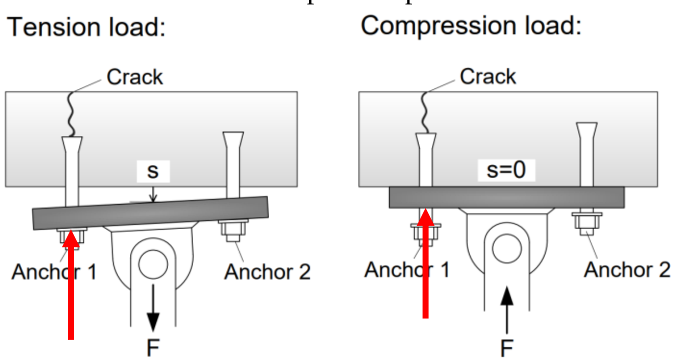

Figure 5. Measurement of anchor plate displacement (red arrow)

The FE model of a single anchor is also validated for different crack configurations. The following crack configurations are investigated:

- parallel crack configuration in case of predominant tensile stresses in the RC structure, see Figure 6 left
- flexural crack configuration in case of predominant bending stresses in the RC structure, see Figure 6 right

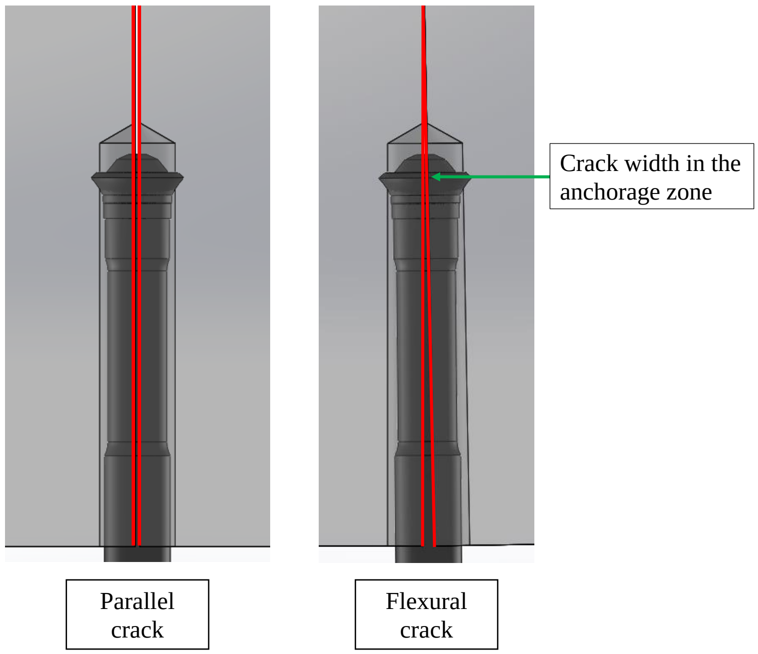

Figure 6. Investigated crack configurations (after [Kerkhof et al. (2017)])

For parallel cracks, the crack width is constant over the thickness of the RC structure whereas for flexural cracks, the crack width is dependent on the thickness coordinate. The crack is completely closed at the neutral axis. Therefore, the crack width in the anchorage zone (see Figure 6 right) has to be determined in order to calculate the inelastic/permanent displacement $\Delta v_{CC,i}$ correctly.

Model validation for parallel crack configuration

The anchor load and crack width time history used for validation is shown in Figure 7.

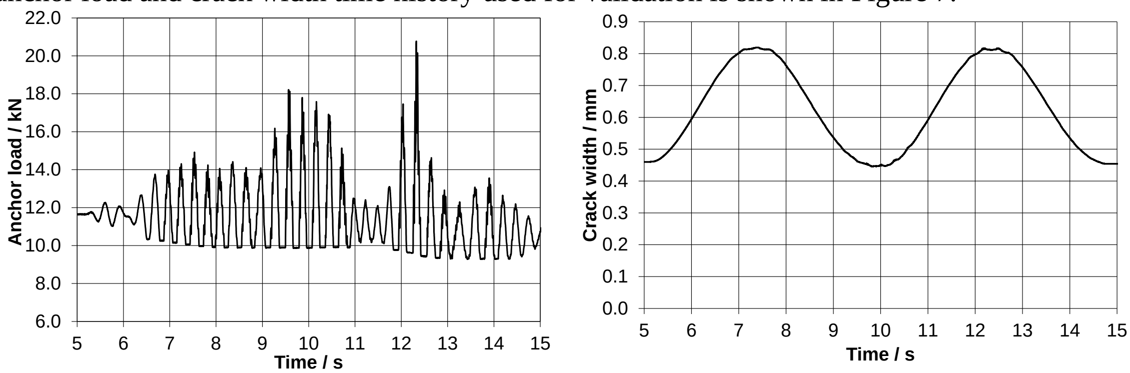

Figure 7. Anchor load (left) and crack width time history (right) during large-scale test with parallel crack configuration

Figure 8 shows the comparison of the measured and simulated anchor displacement time histories. As mentioned above, the measured anchor plate displacement only correlates well with the anchor displacement during tension loading. Taking this into account, the simulated and measured values correspond very well.

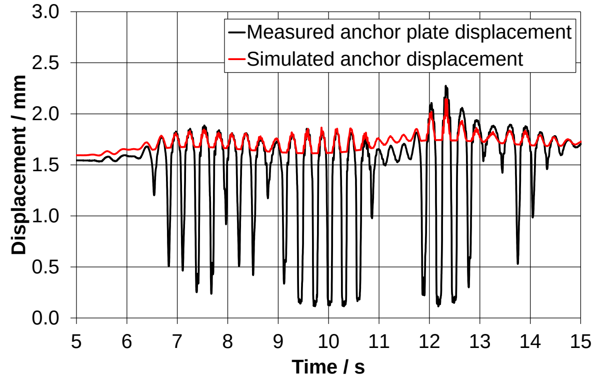

Figure 8. Comparison of anchor displacement for parallel crack configuration

Model validation for flexural crack configuration

The anchor load and crack width time history used for validation is shown in Figure 9. As mentioned above (see also Figure 6 right), the crack width in the anchorage zone is used in order to calculate the inelastic/permanent displacement $\Delta v_{CC,i}$ correctly.

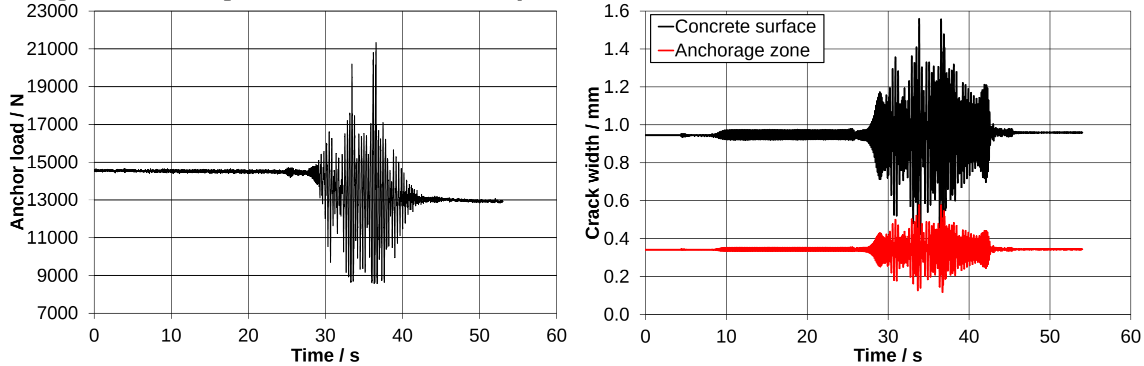

Figure 9. Anchor load (left) and crack width time history (right) during large-scale test with flexural crack configuration

Figure 10 shows the comparison of the measured and calculated anchor displacement time histories. The calculated and measured values correspond very well.

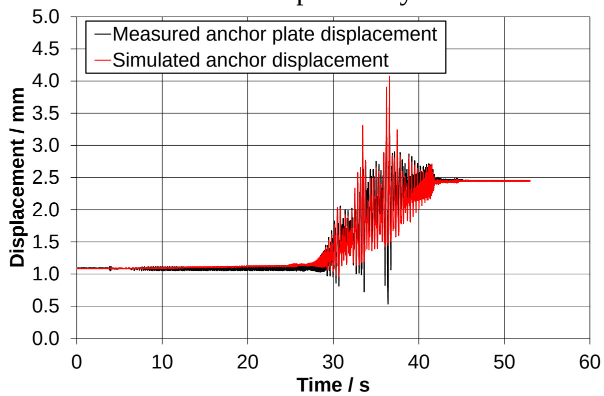

Figure 10. Comparison of anchor displacement for flexural crack configuration

FE MODEL CONCEPT FOR A FASTENING

The numerical model for a fastening with two PI anchors is shown in Figure 11. The "UMAT" is assigned to a beam element which represents the single anchor. The anchor plate is also represented by a beam element because of the symmetrical and in-line positioning of the anchors. In order to model the contact conditions between anchor and anchor plate and between anchor plate and RC structure, nonlinear spring elements are used (tension-only spring for contact between anchor and anchor plate, compression-only spring for contact between anchor plate and RC structure). Further details on the development of the numerical model of a fastening can be found in [Dwenger (2019)].

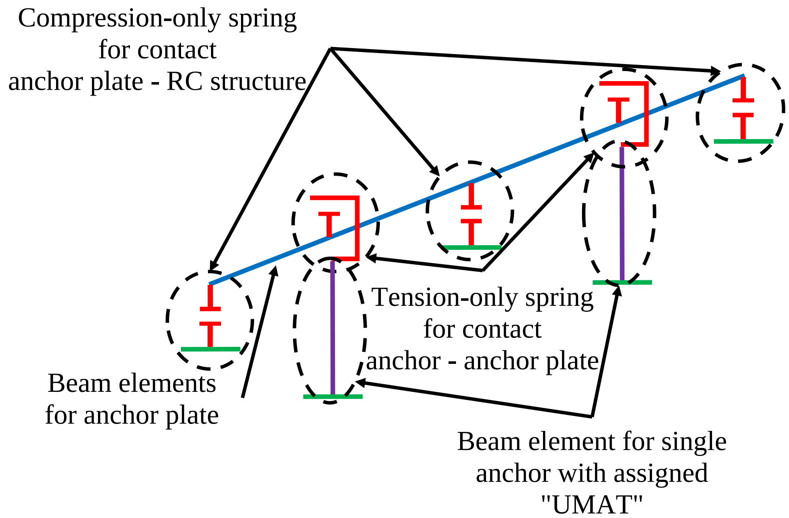

Figure 11. Numerical model of a fastening with two PI anchors (after [Dwenger (2019)])

CONCLUSION

The investigations in this paper show that the developed numerical model of a single anchor accurately describes the load-displacement behavior of a PI anchor during simultaneous tension load and crack cycling. The numerical model for a single anchor can be integrated into the FE model of a fastening which is described in this paper. This model of a whole fastening can be used for detailed seismic time history analyses of safety-relevant components with PI fastenings. By using this model, seismic safety margins of components with PI fastenings can be studied without neglecting the load-displacement behavior of the PI fastenings as it is usually the case during seismic design of components according to current rules and standards. This model was applied to realistic piping systems subjected to seismic loading and demonstrates possible influences of anchor displacements on support load redistribution in multi-supported piping systems, see also [Hofmann et al. (2022)].

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