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Division V

DEVELOPMENT AND VERIFICATION OF MODELS FOR POST-INSTALLED ANCHORS UNDER DYNAMIC LOADING AND CRACK CYCLING IN THE ANCHORAGE ZONE

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ABSTRACT

Post-installed (PI) anchors are widely used to connect structural and non-structural components (NSC) with reinforced concrete (RC) structures. For the application of PI anchors in nuclear power plants (NPP), anchors have to meet high safety requirements to assure integrity of attached components during all load cases. In the design of NPPs, the earthquake load case is of special interest because of its high dynamic loading. RC structures are highly loaded by seismic waves from the soil foundation and by inertia loads resulting from the dynamic interaction between RC structure and attached NSC. Cracks in the concrete occur which can intersect boreholes of PI anchors. Crack cycling in combination with inertia loads can lead to significant permanent displacements of PI anchors. This paper presents at first a simplified modelling approach for the complex load-displacement behavior of PI anchors under dynamic loading for the seismic analysis of coupled systems consisting of RC structures and NSCs. The simplified model comprises dynamic tension and shear loading in presence of (quasi-) static cracks in the RC structure. This model is then implemented in commercial software Abaqus FEA. For verification of the models, tests on single anchors and large-scale dynamic tests are used. Additionally, a second numerical study is carried out with a detailed model of a single anchor installed in cracked concrete. In this study it is shown that opening of cracks in the anchorage zone can lead to a significant loss of prestressing force in the anchor bolt.

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. 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. The load-bearing behavior encompasses both the load-displacement behavior and the failure mode [Hoehler (2006)].

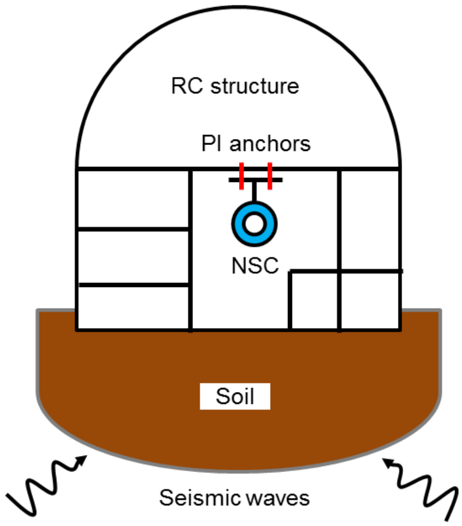

Figure 1. Loading path Soil-RC structure-PI anchors-NSC during an earthquake

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

The load-bearing behavior of an anchor is dependent on the loading conditions, see Figure 2. During an earthquake, an anchor is usually subjected to dynamic tension and shear loads (b and c) or combined tension and shear loads (a). When cracks intersect the borehole of an anchor and the RC structure shows large deflections, a significant amount of crack cycles occur (a and d).

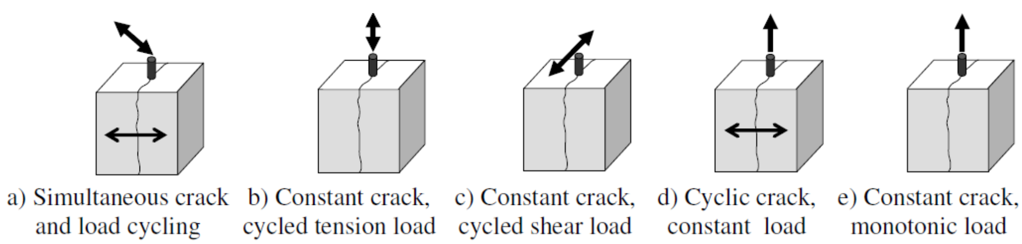

Figure 2. Loading conditions for a single anchor (after [Mahrenholtz, Asmus, Eligehausen (2011)])

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, see Figure 3, which currently has a national technical approval for use in German NPPs [DIBt (2015)].

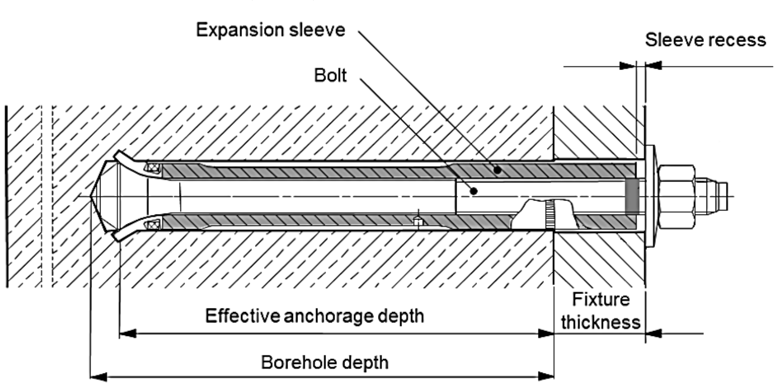

Figure 3. Investigated M12 undercut anchor (after [DIBt (2015)])

LOAD-BEARING BEHAVIOR OF INVESTIGATED UNDERCUT ANCHOR

Experimental program

First the load-bearing behavior of a single undercut anchor was investigated in specimen tests [Kerkhof et al. (2015)], [Mahadik, Sharma, Hofmann (2015)], [Sharma, Mahadik, Hofmann (2015)]. The loading conditions in the single specimen tests comprised monotonic tension and shear loading, tension cycling, crack cycling and simultaneous tension and crack cycling, see Figure 4.

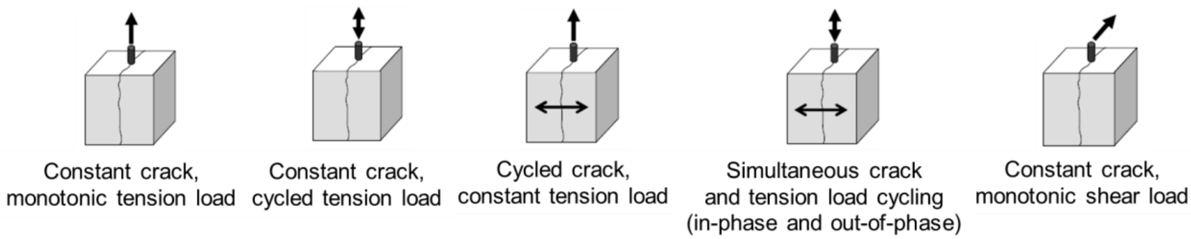

Figure 4. Loading conditions in single specimen tests (after [Mahrenholtz, Asmus, Eligehausen (2011)])

Load-bearing behavior during monotonic tension and monotonic shear loading

The load-bearing behavior of the investigated undercut anchor during monotonic tension loading is shown in Figure 5. In all tests, the anchor showed an almost linear load-displacement behavior until about 40 kN. Depending on the crack width, a flattening of the load-displacement curve occurred followed by a rapid drop until failure. In uncracked concrete, the failure mode of the anchor was always steel failure of the anchor bolt whereas in cracked concrete, the failure mode shifted from steel failure to pullout and at large crack widths to concrete cone failure.

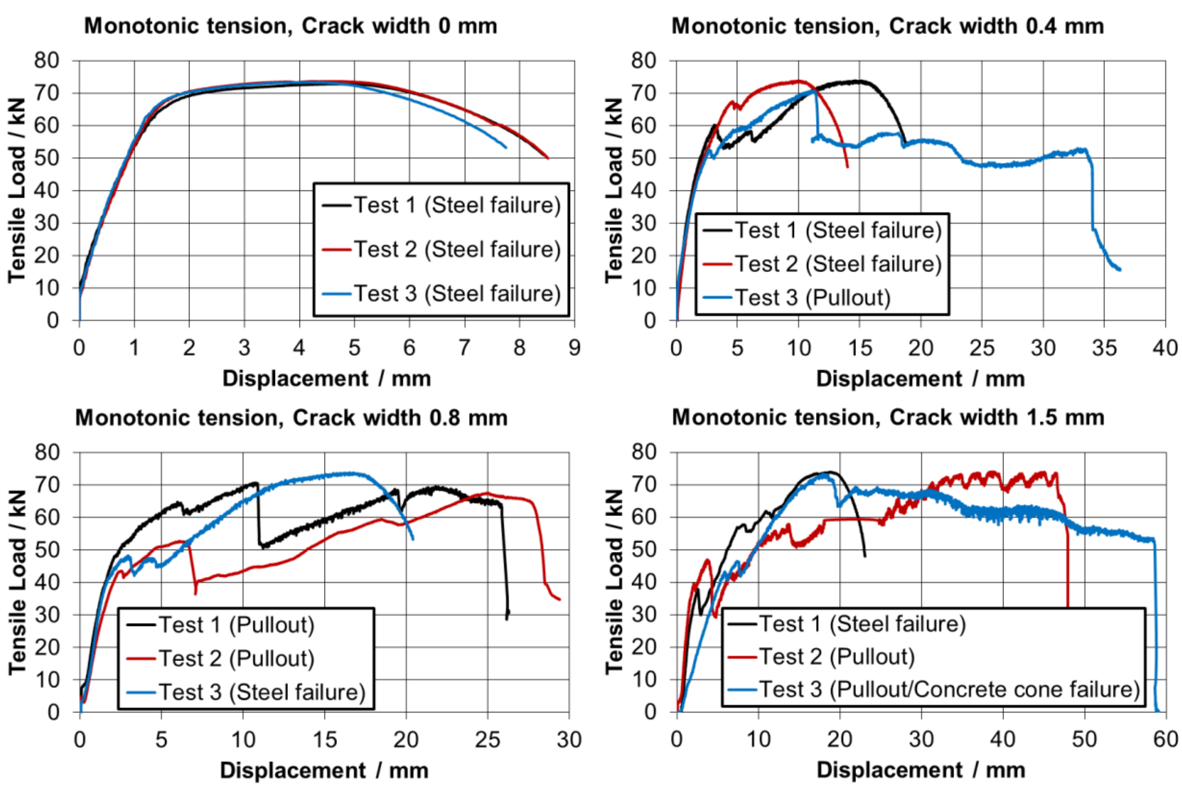

Figure 5. Load-bearing behavior during monotonic tension loading (after [Kerkhof et al. (2015)])

The load-bearing behavior of the investigated undercut anchor during monotonic shear loading is shown in Figure 6. Depending on the crack width, a flattening of the load-displacement curve occurred after an almost linear load-displacement behavior followed by a rapid drop until failure. In all tests, the failure mode of the anchor was steel failure.

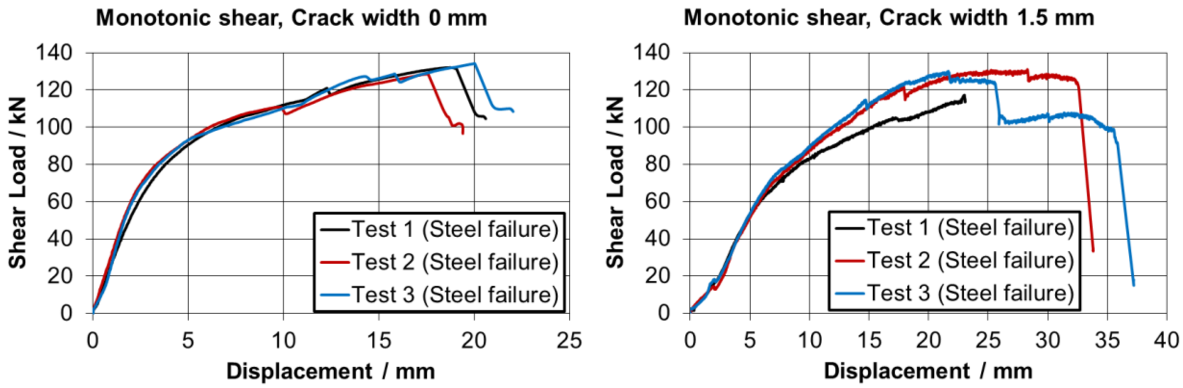

Figure 6. Load-bearing behavior during monotonic shear loading (after [Kerkhof et al. (2015)])

Load-bearing behavior during tension load cycling and shear cycling

The load-bearing behavior of the investigated undercut anchor during tension load cycling is shown in Figure 7. The anchor was subjected to a pulsating tension load between ~0 kN and the design value of tensile strength N_{Rd} = 24 kN. The tension load cycling had no significant influence on the load-displacement curve and the failure mode. Until 15 load cycles, the displacement increase due to low cycle fatigue is insignificant.

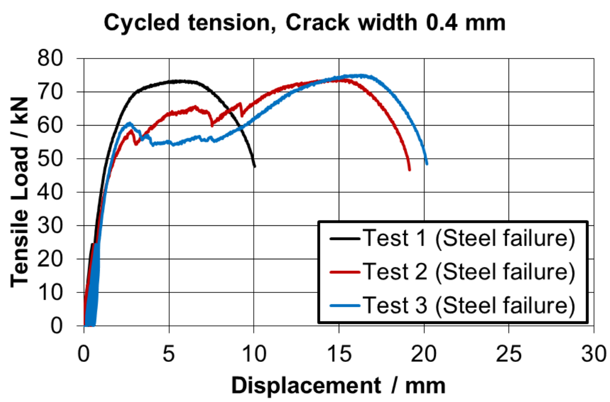

Figure 7. Load-bearing behavior during tension load cycling (after [Kerkhof et al. (2015)])

The single specimen tests carried out in [Kerkhof et al. (2015)] did not comprise tests during alternating shear cycling. However, it can be assumed that the displacement increase due to low cycle fatigue is as insignificant as for tension load cycling because the failure mode in shear is also steel failure. It should be noted that this assumption is only valid for loading up to design value of shear strength V_{Rd} and 15 load cycles.

Load-bearing behavior during stepwise increasing tension load cycling and shear cycling

Generally, the load-displacement behavior of undercut anchors under stepwise increasing tension load cycling follows the monotonic load-displacement curve during the loading part of one cycle, see Figure 8.

The unloading part of one cycle is nearly linear until 0 kN so that an increasing permanent displacement can be observed.

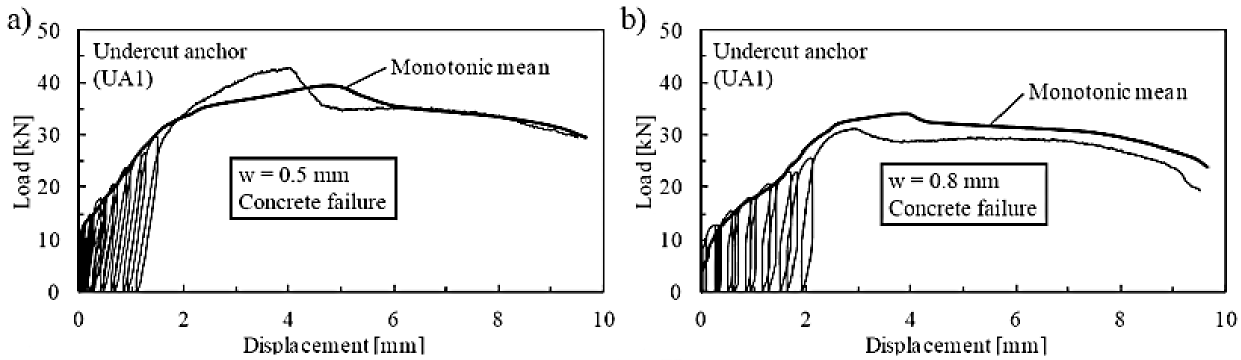

Figure 8. Load-displacement curves for undercut anchors under monotonic and stepwise increasing tension load cycling [Mahrenholtz et al. (2016)]

The load-displacement behavior during stepwise increasing alternating shear loading is slightly different from tension behavior, see Figure 9. If low cycle fatigue (LCF) does not occur during alternating shear loading, the load-displacement behavior of undercut anchors follows the monotonic load-displacement curve during alternating shear loading. The unloading part of one cycle is nearly linear comparable to tension load cycling. Also LCF might occur during alternating shear loading which means that the load-displacement curve is significantly below the monotonic curve. For anchors which have a technical approval for use in German NPPs, it can be assumed during loading up to V_{Rd} that LCF has to be excluded.

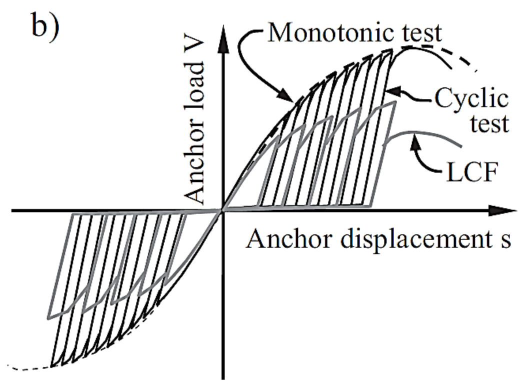

Figure 9. Possible load-displacement behavior for undercut anchors under monotonic and stepwise increasing alternating shear loading [Mahrenholtz, Eligehausen (2015)]

Load-bearing behavior of an anchor group during seismic loading and crack cycling

The structural dynamic load-bearing behavior of an anchor group with two anchors was investigated in the research project [Kerkhof et al. (2015)]. For that purpose, a large-scale test set-up was designed in order to carry out seismic tests, see Figure 10. A piping was excited to vertical seismic motion by an electrodynamic shaker. The piping is fixed to a concrete slab by an anchor group with two anchors. The borehole of one anchor is intersected by a hairline crack in order to simulate crack cycling by two hydraulic cylinders. The seismic excitation was derived from the simulated seismic response of a reactor building finite element model. The seismic time history was then scaled so that the design value of tensile strength for the anchor group was achieved. This load case was defined as “100% SSE” (safe shutdown earthquake).

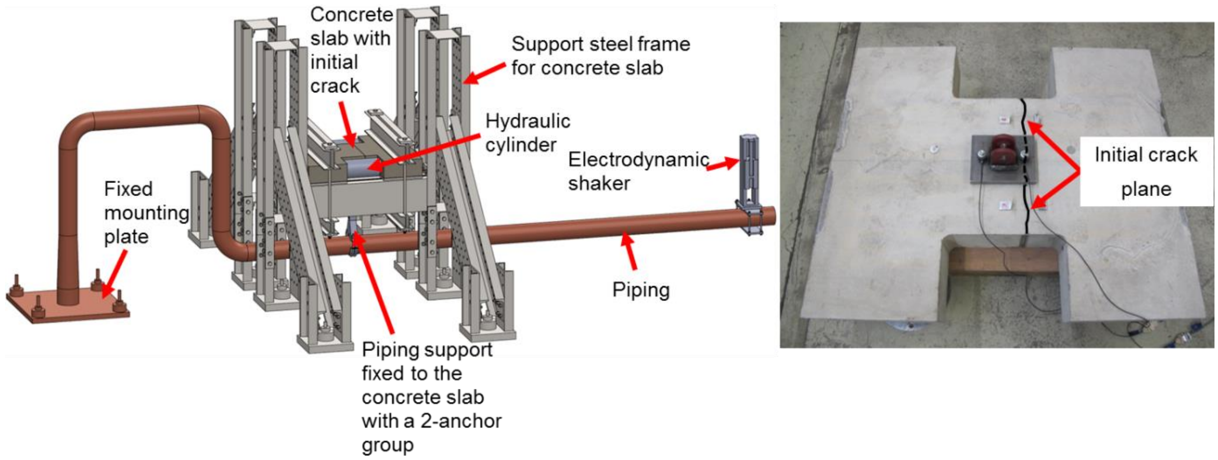

Figure 10. Large-scale test set-up for seismic tests (left) and detail of concrete slab with the anchor plate (right) (after [Dwenger et al. (2015)])

During the tests, the dynamic behavior of the anchor group depicted in Figure 11 was observed. The applied force on the anchor group changed from tension to compression and vice versa. Due to permanent displacement of the anchor in cracked concrete, an inclination of the anchor plate and impacts occurred. The impacts took place in compression between anchor plate and concrete slab and in tension between anchor plate and anchor nut.

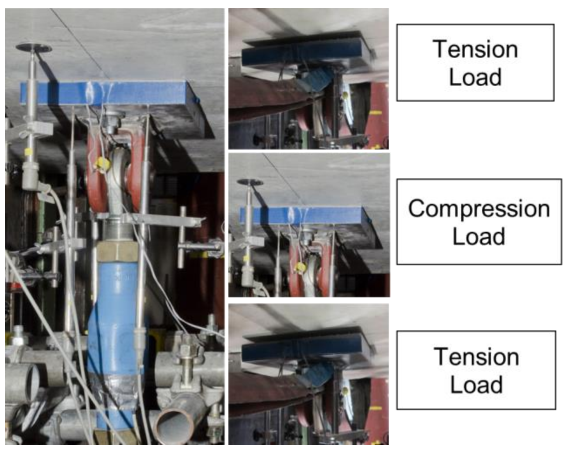

Figure 11. Dynamic behavior of the anchor group during the seismic tests (after [Kerkhof et al. (2015)])

MODELLING AND VERIFICATION OF LOAD-BEARING BEHAVIOR UNDER CYCLED TENSION AND SHEAR LOADS

Simplified model concept

The previous chapters show that a model for a precise finite element analysis (FEA) during seismic loading should be able to simulate both the load-bearing behavior of the single anchors and the load-bearing behavior of the fastening as a whole. The FEA in this paper were carried out in Abaqus FEA. The model concept which can encompass both aspects is shown in Figure 12. The anchor plate is idealized by beam elements because the investigations are carried out with an anchor group where the anchors are arranged in a single vertical plane. The contact between anchor plate and concrete is modelled by compression-only springs whereas the contact between anchor plate and anchor nut is modelled by tension-only springs. The anchor bolt is idealized by a beam element in order to apply a prestress. The actual load-bearing behavior of the anchor is represented by elastic-plastic

"Connector"-elements in both shear directions and in tension direction. Compression-only springs between anchor bolt and "Connector"-elements in shear direction allow change of contact during alternating shear loading in horizontal direction.

For the elastic-plastic "Connector"-elements in tension and shear direction, load-displacement envelope curves for the elastic-plastic behavior have to be defined. The load-displacement curves for the "Connector"-elements are obtained based on the methodology described in [Hofmann, Mahadik, Sharma (2015)]. Because of the permanent displacement occurring after unloading prior to ultimate tension load N_u and shear load V_u, the pentalinear format of the load-displacement curves is enhanced to a hexalinear format, see Figure 13, in order to allow permanent displacement below 80 % of N_u and V_u.

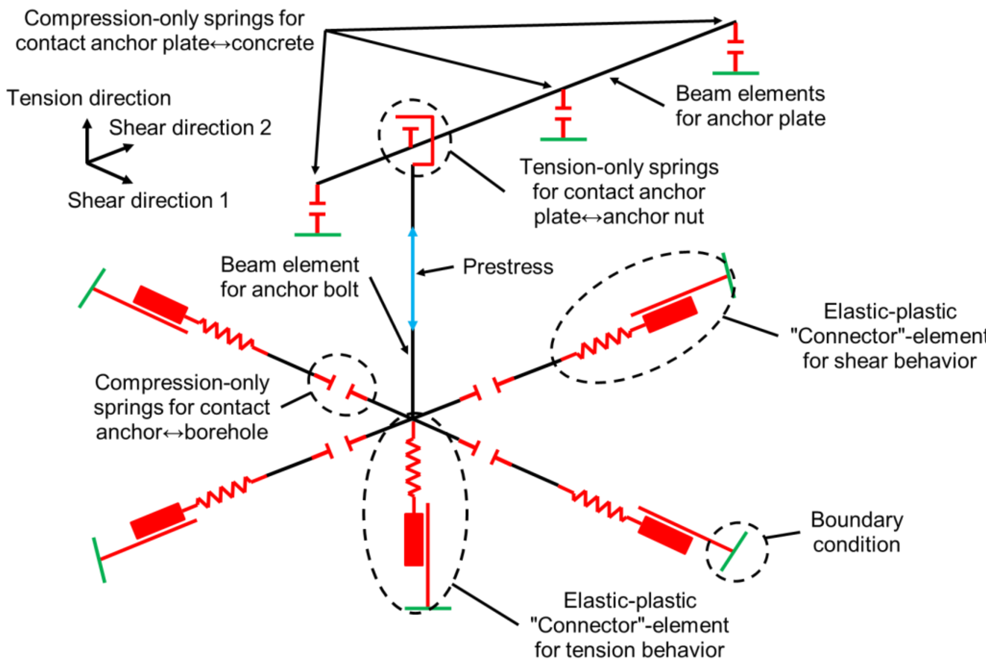

Figure 12. Simplified model concept for load-bearing behavior of a fastening

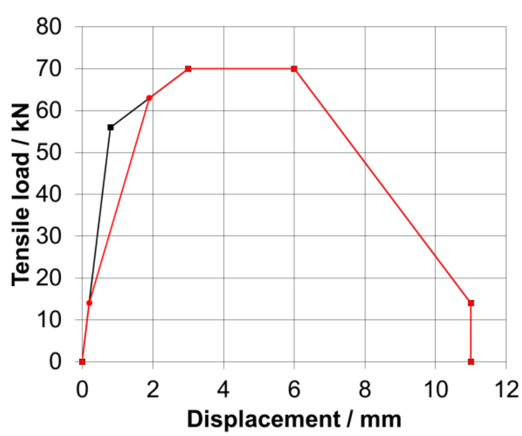

Figure 13. Comparison of pentalinear (black) and hexalinear (red) envelope curve (tension direction)

Verification of the proposed model

The previously proposed model is verified by a time history analysis (THA) in Abaqus FEA. The model for the verification is shown in Figure 14. Sinusoidal load time histories are applied on the anchor plate in tension (N(t)) and shear (V_1(t), V_2(t)) direction. The applied load amplitudes at a frequency of 3.5 Hz are ramped until failure in one direction occurs. In this case, failure in tension occurred which can be seen as nearly horizontal load-displacement behavior at approx. 11 mm. In shear direction, the alternating shear load reaches approx. 85 % of V_u. For both directions, the load-displacement behavior follows the monotonic envelopes as in the single specimen tests described in the previous chapters.

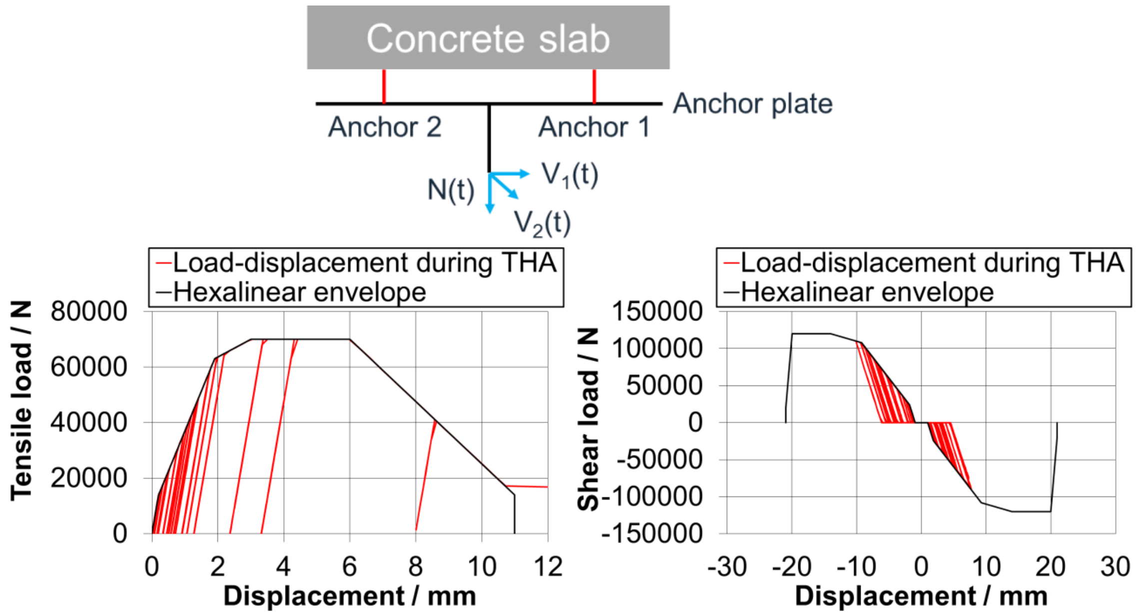

Figure 14. Model for verification of the proposed model (above) and load-displacement behavior of anchor 1 in tension (bottom left) and shear (bottom right) direction

NUMERICAL STUDY REGARDING THE INFLUENCE OF CRACK OPENING ON LOSS OF PRESTRESS

The above-mentioned model for the load-bearing behavior only has a simplified approach for assigning a prestressing force by applying a so-called “bolt load” on the beam element in Abaqus FEA, cf. Figure 12. In order to assign a correct prestressing force in this simplified model, a detailed numerical study was carried out in Abaqus FEA for the influence of crack opening on the loss of prestressing force for a single anchor. The model is shown in Figure 15. The entire model is discretized by linear brick elements in Abaqus FEA, and different material properties are assigned to each part according to the chosen constitutive models as shown in Table 1. Since the X- and Z-axes are symmetry axes, only a quarter of each part is modelled. The model is initially constrained by encastre boundary condition (BC) at the outer surface of the slab and the symmetry about the Z and X axes is utilized. The surfaces to which the symmetry BCs are assigned are colored in yellow, red and green and the free crack surface is assigned to the surface colored in blue, cf. Figure 15. A frictional finite sliding contact is applied to each contact pair belonging to slab, conical bolt or sleeve. Other contact pairs were assumed to be frictionless with small sliding contact.

Table 1. Constitutive material models used for the numerical study

Part	Material	Constitutive model
Slab	Concrete(C30/37)	Concrete Damage Plasticity (CDP)
Conical bolt	DIN 1.4044 (X22CrNi17)	Elasto-plastic
Sleeve	DIN 1.4044 (X22CrNi17)	Elasto-plastic
Anchor plate	Steel	Linear elastic
Washer	Steel	Linear elastic
Nut	Steel	Linear elastic

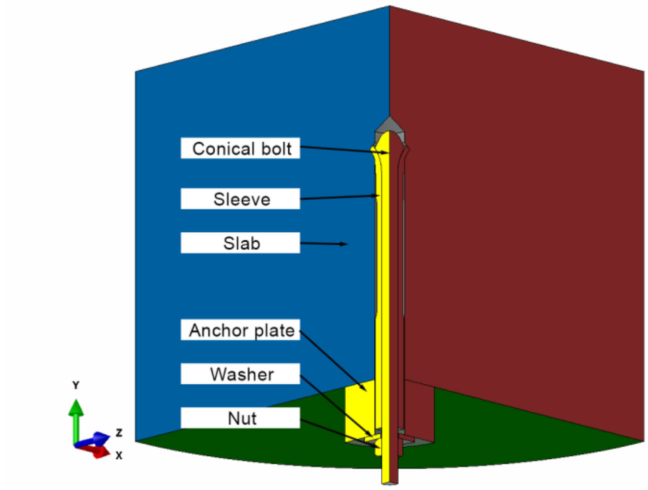

Figure 15. Model of the single anchor installed in cracked concrete

The conical bolt is loaded by 80 Nm installation torque acc. to [DIBt (2015)] which yields about 36 kN prestressing force in the bolt. To consider in-service relaxation of anchor prestressing force, the prestressing force in the bolt is then reduced to 50 % in the next step acc. to experiments in [Kerkhof et al. (2015)]. In the last step, 0.75 mm displacement in X-direction is assigned to the outer surface of the Slab to simulate 1.5 mm crack opening. The relaxation of the prestressing force is shown in Figure 16. In [Lotze (1993)], it is stated that crack opening could result in a complete loss of prestressing force in the anchor bolt. Likewise, the FEA model predicts 96.65 % relaxation of the prestressing force due to crack opening which corresponds very well with this statement.

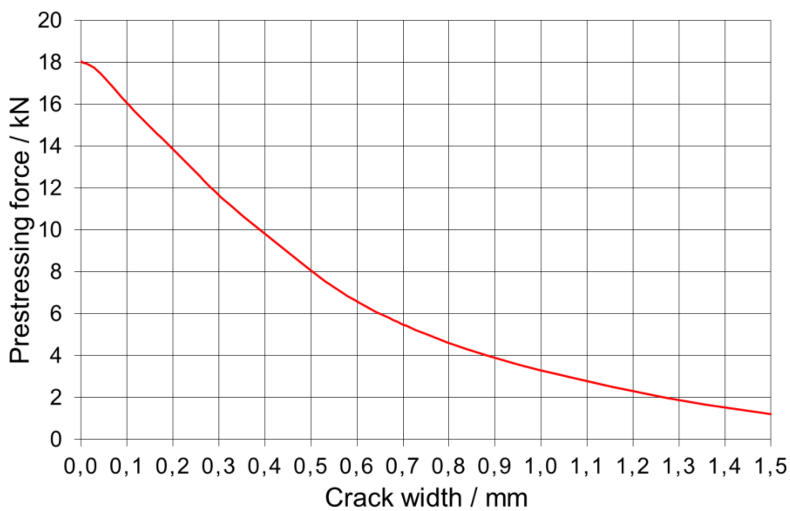

Figure 16. Prestressing force as a function of crack width

CONCLUSION

By using the simplified model concept of the fastening, seismic analyses of coupled systems consisting of RC structures and NSCs can be efficiently carried out when decoupling of the partial systems is not allowed acc. to current seismic design guidelines. The simplified model concept sufficiently represents the load-displacement behavior of a fastening consisting of a group of undercut anchors during dynamic tension and shear loading. The model also takes into account the complex contact interactions between the anchor plate and the anchor as well as between the anchor plate and the concrete surface.

The second numerical study clearly shows a significant relation between the reduction of prestressing force in the anchor bolt and the crack width in the anchorage zone. When the investigated undercut anchor is subjected to crack widths larger than 1.5 mm, an almost complete reduction of the prestressing force can be observed.

ACKNOWLEDGMENTS

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