NUMERICAL INVESTIGATION OF ANCHOR GROUPS UNDER SEISMIC TENSION ACTIONS

NUMERISCHE UNTERSUCHUNG VON GRUPPENBEFESTIGUNGEN UNTER SEISMISCHER ZUGBEANSPRUCHUNG

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SUMMARY

In this work a tension loaded 2 x 1 anchor group is investigated numerically. The numerical analysis is performed within the framework of a 3D FE analysis using microplane model with relaxed kinematic constraint as the material model for concrete. The anchor group includes two bonded anchors, a fixture connecting the anchors and a concrete slab in which the anchors are embedded in. At first the anchor group behavior is investigated when subjected to static and centric tension load. In the second step the anchor group is loaded with a displacement-controlled loading protocol for pulsating tension load which allows the assessment of the cyclic performance of the anchor group even in the post-peak range. The results of the static and cyclic tests are assessed regarding their load-displacement behavior and the damage in the concrete (crack pattern).

ZUSAMMENFASSUNG

Diese Arbeit beschäftigt sich mit der numerischen Untersuchung einer zugbeanspruchten 2 x1 Ankergruppe. Für die numerische Berechnung wird hierbei das sogenannte „Microplane model with relaxed kinematic constraint" verwendet um das Materialverhalten des Betons zu simulieren. Die betrachtete Ankergruppe besteht aus zwei Verbunddübeln und einer, die Dübel verbindenden Ankerplatte. Als Verankerungsgrund dient eine Betonplatte. Zunächst wird das Verhalten der Ankergruppe bei statischer Zugbelastung untersucht. Darauf aufbauend wird die Ankergruppe zyklisch belastet. Die Belastung wird gemäß einem verschiebungsbasierten Belastungsprotokoll für schwingende Zugbeanspruchung aufgebracht. Mit diesem Belastungsprotokoll ist es möglich das zyklische Verhalten auch im Nachbrauchbereich der Last-Verschiebungskurve zu untersuchen. Die Ergebnisse werden anhand des Last-Verschiebungsverhaltens und des Rissbildes im Beton bewertet.

KEYWORDS: Anchor groups, seismic loading, numerical investigation, concrete breakout

1. INTRODUCTION

During the lifecycle of a building, the structure often undergoes certain alterations like the addition of stories or a new usage of the building. Such alterations in general result in increased loads on the existing structure. In these cases it becomes necessary to strengthen the existing structure to ensure the safety of the residents and the structural integrity. Also structural damages that were caused by, for example, settlements may render it necessary to strengthen the existing building. In order to connect a strengthening solution to the existing reinforced concrete (RC) building using post-installed anchors has become quite common in the recent years. This is linked to the uncomplicated installation process and the low-invasiveness of the concept. In general multiple-anchor groups are used to connect the structural elements with each other and therefore it is crucial to know the anchor group load-displacement behavior. Another field of application for post-installed anchors that has become more and more popular in recent years is the use in retrofitting solutions for seismic strengthening. Earthquakes in the past years have shown that RC structures designed before the introduction of modern seismic codes are particularly vulnerable to seismic actions [1, 2, 3]. Numerical studies using nonlinear dynamic analysis and static push-over analysis [4, 5] have shown that especially non-seismically detailed RC frame structures are prone to collapse under dynamic loads. In order to overcome structural deficiencies and to improve the seismic performance of RC frame structures, strengthening solutions have been developed [6, 7] and one popular and effective way is to add steel bracings to the frame, which results in increased global stiffness and strength. The development of buckling restrained braces (BRB) has further increased their effectiveness by increasing the energy dissipation capacity [8, 9]. In order to connect the strengthening elements to the original RC structure, post-installed anchors have proven to be a feasible alternative [10, 11] to other direct connection methods [12, 13].

It becomes obvious that in such an application the demands on the anchor group are rather high and hence there are several challenges to be faced. The displacement demands on the anchor groups are very high and cyclic in nature. Depending on the layout of the RC frame structure and the layout of the bracing system, the angle of the load direction varies and combined shear and tension loads act on the anchor group. Since the steel bracings are connected to the RC frame corners, the anchors are installed in plastic hinge zones and therefore the crack widths are very large. Additionally these cracks are opening and closing along with the deformation of the structure. Furthermore the ability of the anchors to develop a concrete cone or to transfer bond forces is limited due to the dimensions of the columns and beams they are installed in.

Considering the above-mentioned challenges, standard force-based design approaches are often found insufficient and lead to rather unreliable or impractical solutions. A new approach is therefore necessary, taking into account the complete load-displacement behavior of cyclically loaded anchor groups. Herein the distribution of forces, the influence of load eccentricity, closely spaced anchors and close edges as well as the behavior of the anchor plate should be included in the design.

In this paper, a first attempt is made to better understand the static and cyclic load-displacement behavior of anchor groups. Therefore a numerical investigation is performed on a 2 x 1 anchor group under tension loading. The static case will be further used to compare with the cyclic results. For cyclic loading, a new displacement-based protocol has been used which also captures the cyclic and hysteretic anchor behavior in the post-peak range of the load-displacement curve. The results are presented hereinafter.

2. NUMERICAL SIMULATION

2.1 FINITE ELEMENT CODE MASA

The numerical simulations were performed using 3D finite element software MASA (Macroscopic Space Analysis), developed at the Institute of Construction Materials, University of Stuttgart. This program can be used for the nonlinear analysis of concrete and RC structures. Hereby a smeared crack approach is deployed to capture damage and fracture phenomena. The constitutive law for concrete is based on the microplane model with relaxed kinematic constraint proposed by [14]. The basis of the microplane model are planes of various orientation which can be interpreted as damage planes or weak planes on a microstructural level. In case of concrete for example, these planes can be construed as the contact layer between the aggregates. Every microplane holds normal (ε_N) and shear (ε_T) strain components, whereby ε_N is decomposed into a volumetric (ε_V) and a deviatoric (ε_D) part. The decomposition is required to realistically capture concrete behavior in case of dominant compressive load and to control the initial elastic value of the Poisson's ratio. To guarantee the uniqueness of the solution for softening (quasi-brittle) materials like concrete, static constraint are replaced by kinematic constraint. In MASA this is achieved by calculating the strain components on the microplanes as the projection of the macroscopic strain tensor. Since the decomposition of the normal strain components leads to a pathological behavior when it comes to dominant tensile load, microplane strain components are modified in a way that relaxes the kinematic constraint. To secure mesh independent results, the total energy consumption has to be independent of the element size [15]. Therefore so-called localization limiter have to be implemented in the model. In MASA, crack band method [16] is implemented to solve the problem. For the steel components (anchors and fixture) a linear-elastic material behavior is assumed to reduce computational time. For the given problem steel nonlinearity can be neglected since concrete failure is expected before yielding of steel in the anchors or in the fixture.

The rules for cyclic loading (loading, unloading and reloading) for the microplane strain components are given in [14]. To account for the effect that loading in one direction is causing damage in the opposite direction and herby deteriorates shear strength and stiffness, the microplane shear component is modified by multiplying the microplane shear stiffness moduli with an additional damage function.

2.2 NUMERICAL MODEL

As the base material for the anchorage, an unreinforced concrete slab is modelled with a side length of 1000 mm and a thickness of 300 mm. The anchor group is placed in the middle of the slab and consists of a fixture and two bonded anchors. The fixture is modelled with a length of 160 mm, width of 80 mm and thickness of 25 mm. The diameter and effective embedment depth of the anchors are d_s = 16 mm and h_{ef} = 80 mm, respectively. The considered anchor spacing is 80 mm. 4-node tetrahedral elements are used to model the concrete and 8-node hexahedral elements to model the anchors and the fixture. To model the bond between steel and concrete 2-node bar elements are used. These elements are able to transfer compression and shear forces. The contact layer between steel plate and concrete is modeled using tension only contact elements, without accounting for friction. The material properties for steel and concrete are given in Table 1. Note that for concrete only the basic macroscopic concrete properties have to be defined. Based on these properties the microplane model parameters are generated automatically. Since steel is only considered as linear-elastic, only Young's modulus and Poisson's ratio have to be defined.

Table 1: Material properties

Material	Young's modulus E [N/mm²]	Poisson's ratio ν [-]	Tensile strength f_t [N/mm²]	Compressive strength f_c [N/mm²]	Fracture energy G_f [N/mm]
Concrete	30400	0.18	2.32	21.45	0.07
Anchor / Fixture	210000	0.33	-	-	-

Load is applied in terms of displacement in the middle of the fixture (see Figure 1). The constraints are applied on a line of nodes on either side of the anchor group at a distance of 160 mm (= 2*h_{ef}) away from the outer most anchors. The sides of the concrete slab are constraint in the x- and y-direction to prevent sliding and the constraints are placed far enough away from the anchor group to avoid any influence on the load-displacement behavior of the anchors. The discretization of the concrete specimen, the anchors and the fixture is shown in Figure 1.

3. LOADING PROTOCOL

3.1 STATIC LOADING

In the first step, the anchor group is subjected to static pullout. The anchor group is loaded by applying displacement increments of 0.02 mm on the top of the fixture. The numerical test ended when a displacement of 6 mm was reached. The purpose of the static pullout test is (i) to investigate the static anchor group behavior in order to draw parallels between the static and the dynamic load-displacement behavior and (ii) to obtain the parameters that are required for the cyclic protocol for pulsating tension load. Two displacement values are required, namely s_u and s_{max}. The value s_u is defined as the displacement corresponding to the peak load and s_{max} is defined as the higher value of either the displacement

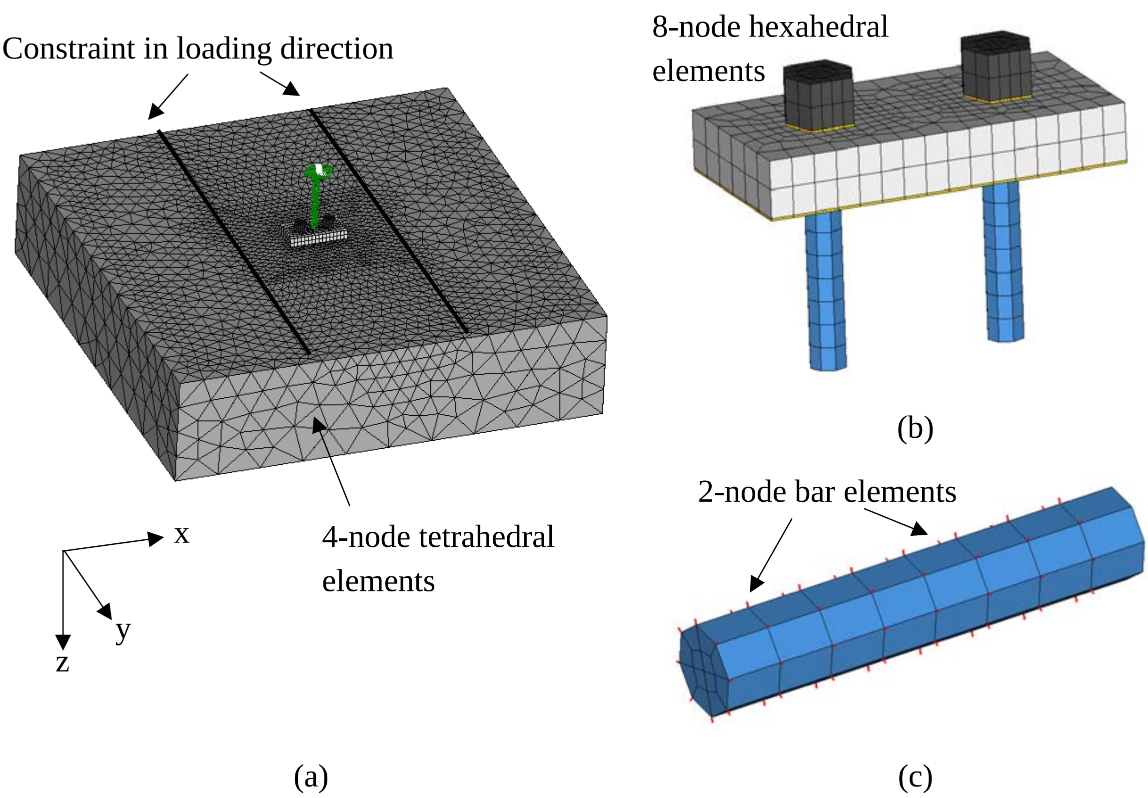

Fig 1: FE Model: (a) Complete model (b) Discretization of fixture, anchors and nuts (c) Anchor with 2-node bar elements for bond

when 80% of the peak load is reached in the post-peak range or two times the value s_u.

3.2 PULSATING TENSION LOADING

The utilized protocol for pulsating tension load is divided into nine displacement levels with three cycles per level. As with the static loading protocol, the displacements are applied on the fixture incrementally. In the first six levels, the displacement is stepwise increased until s_u is reached. The six displacement levels correspond to 10%, 20%, 30%, 50% 70% and 100% of s_u respectively. After reaching s_u another three displacement levels are applied to investigate the cyclic behavior in the post-peak range. Again the displacement is stepwise increased after each level until s_{max} is reached with the levels being equally spaced between s_u and s_{max}. Thereafter follows a static pullout to obtain the complete load-displacement curve. The schematic structure of the loading protocol is given in Figure 2. Note that after reaching the target displacement, in the cyclic test, the anchor displacement was not brought back to zero but the anchors were simply unloaded. This was done to avoid numerical problems.

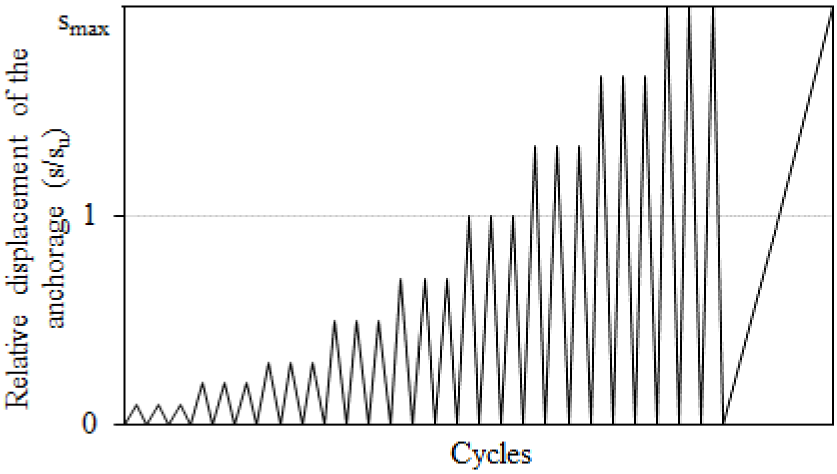

Fig. 2: Schematic loading procedure for pulsating tension load

4. NUMERICAL RESULTS

4.1 LOAD-DISPLACEMENT BEHAVIOR

In this section the results of the numerical investigation are presented. Figure 3 shows the load-displacement behavior of the anchor group exposed to static and cyclic loading. In the static test (dotted curve), the obtained peak load is 58.28 kN and the corresponding displacement is s_u = 0.26 mm. As can be seen from the load-displacement curve, the anchor group shows a rather flat post-peak behavior and hence s_{max} is determined as the displacement value corresponding to a strength decay of 20% after reaching peak load, thus s_{max} = 2.60 mm. By comparing the results of the static and cyclic test in Figure 3, it can be seen that the envelope of the curve obtained from the cyclic test follows the static load-displacement curve. In general the results obtained from both cases correspond very well. The peak load reached in the cyclic case is 59.03 kN at almost the same corresponding displacement as in the static test. It is seen, that cycling below peak load has practically no negative influence on the behavior of the anchor group. This was also observed by [17]. Also cycling at the same displacement amplitude had no considerable negative effect on the strength of the subsequent cycles at displacement levels below s_u. When it comes to the performance in the post-peak range cycling appears to have no significant influence on the overall load-displacement behavior of the anchor group either and the envelope of the cyclic curve matches very well with the static reference curve. This observation matches the general observation that the envelope of cyclic hysteretic loops in case of reinforced concrete is very similar to the monotonic load-displacement curve [18]. Furthermore, it was observed that cycling at a displacement level greater than s_u

comes with a nominal strength degradation in the subsequent second and third cycle of each level. In Figure 4 the ratio between the strength corresponding to the displacement amplitude of the first cycle to the strength of the second and third cycle of a displacement level is plotted. From the graph it can be seen that in particular the last two displacement levels suffer from a nominal strength degradation of around 10% in the second and third cycle. This is attributed to the concrete cone breakout failure mode. The degradation per cycle could be much severe in case of pullout failure mode. This needs further investigations.

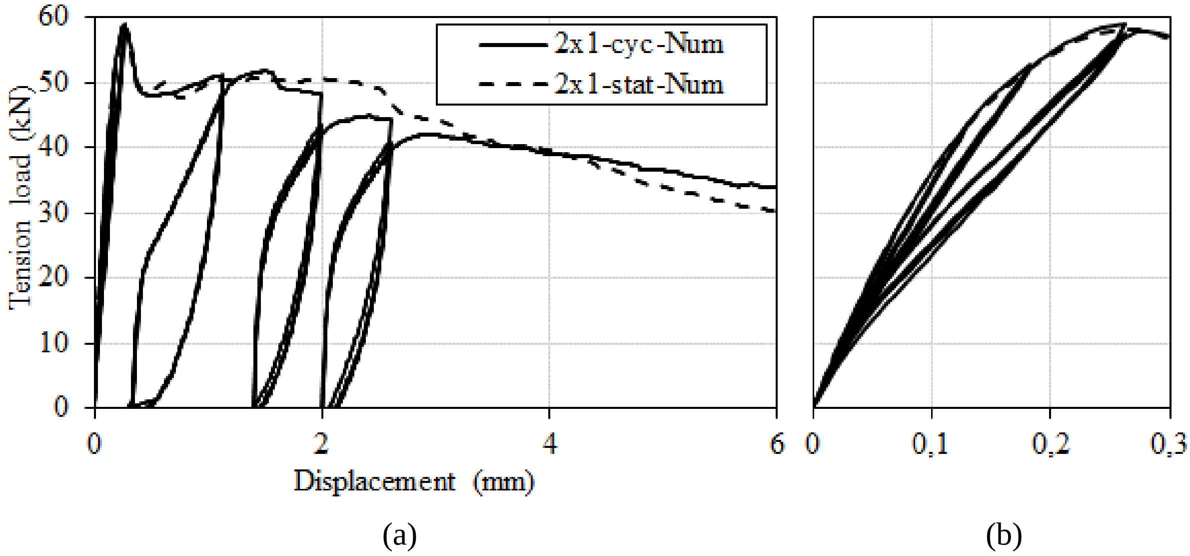

Fig. 3: Load displacement curves obtained from static and cyclic loading (a) Complete load-displacement behavior (b) First six cycles.

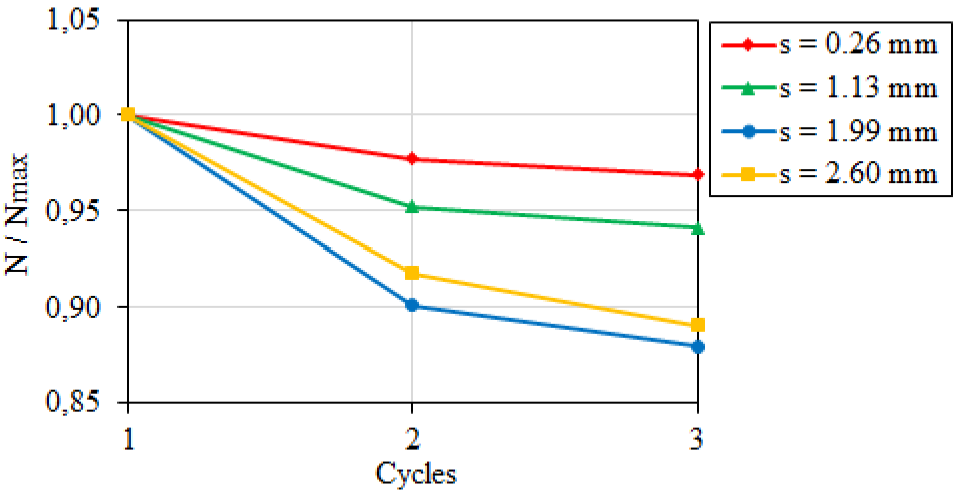

Fig. 4: Strength degradation ratio in subsequent cycles.

4.2 CRACK PATTERN

The numerical simulation allows the evaluation of the damage inside the concrete in respect of cracks and crack propagation. Hereby the cracks are displayed in terms of principal tensile strain. The crack patterns for both loading situations for certain displacement levels are illustrated in Figure 5 and 6. As can be seen the observed failure mode in both cases was concrete cone failure. The crack of the concrete cone propagates from the tip of the embedded end of the anchors towards the concrete surface. First cracking appears at a displacement of approximately 0.13 mm. From there cracking continues and at peak load the crack length is about 35% of the total side length of the cone surface area. The slope of the concrete cone is approximately 30° from the horizontal. These observations agree well with the findings reported for concrete cone failure [17]. At the bottom of the cone, cracks propagate from the tips of the embedded end of the anchors towards each other and merge to form a horizontal crack. Also from the upper part of the anchors, cracks propagate towards each other and merge to a relatively deep crack. From Figure 6 the propagation of the cracks on the concrete surface can be observed. It can be seen that at peak load a horizontal crack between the anchors has formed. Upon further loading radial cracks propagate from the anchors and the concrete breakout body forms.

5. CONCLUSION

In this work, the first attempts are made to investigate numerically the cyclic behavior of anchor groups using a displacement controlled protocol. The numerical analysis is performed on 2 x 1 anchor group under static and cyclic loading. The static test is performed to obtain certain parameters which are vital for the preparation of the cyclic loading protocol and further serves as a comparison for the cyclic test results. The cyclic protocol uses a displacement-based approach where the anchor group is exposed to cyclic loading in displacement control even in the post-peak range. Such an approach allows to assess the cyclic and hysteretic behavior of the anchor group throughout the complete range of the load-displacement curve. The analysis helps creating a better understanding of the behavior of anchor groups and the damage processes in the anchorage material. From the numerical results the following conclusions can be drawn:

1. The comparison of the obtained load-displacement curves from the static and the cyclic test has shown that cycling has no significant influence on the behavior of the anchorage regarding the initial stiffness, peak load or the displacement at peak load. Furthermore the envelope of the cyclic curve follows the static curve.

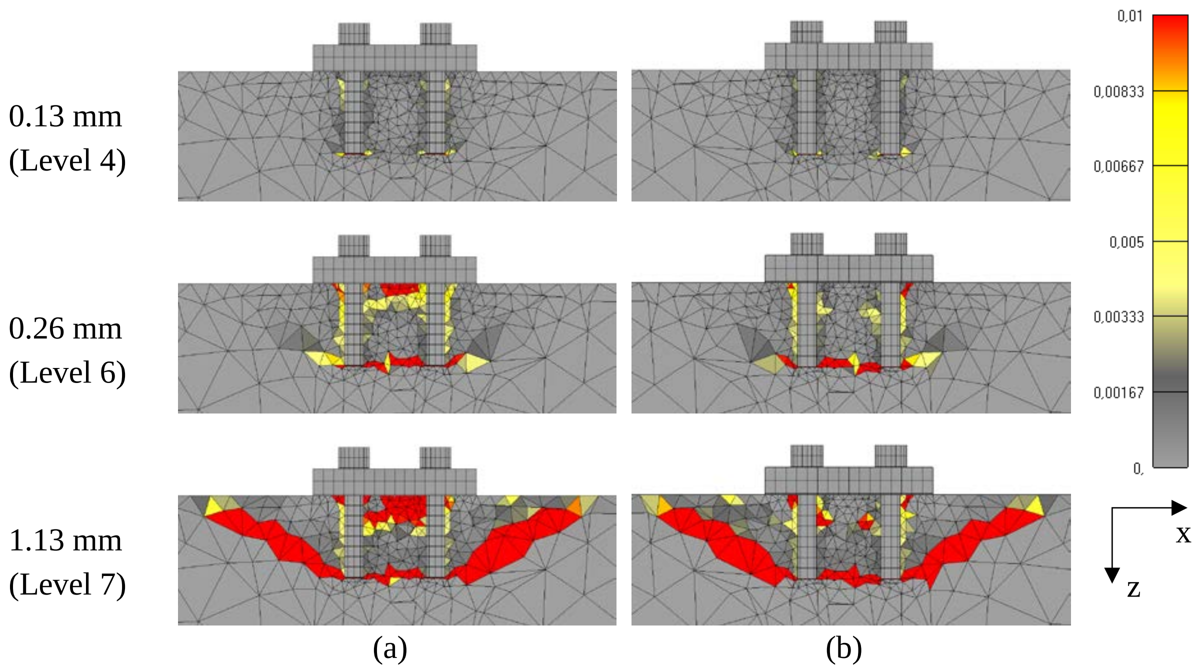

Fig. 5: Crack pattern inside the concrete for various displacement stages (a) Static load (b) Cyclic load

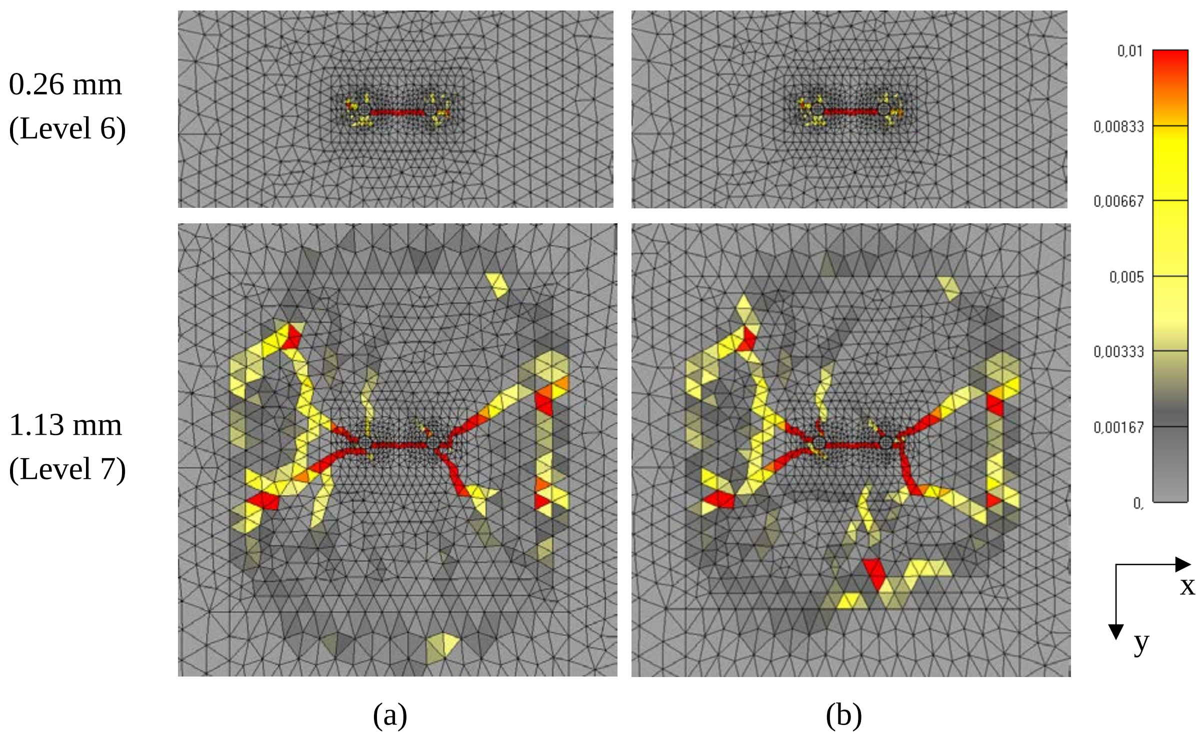

Fig. 6: Crack pattern on concrete surface for various displacement stages (a) Static load (b) Cyclic load

2. After reaching peak load in the cyclic test a nominal strength degradation was observed in the second and third cycle of a displacement level compared to the strength in the first cycle. This is attributed to the concrete cone breakout failure mode. Further investigations on other failure modes are needed since,

for example in case of pullout failure mode the strength degradation per cycle could be much severe.

3. The numerical simulation allows the assessment of damage in the concrete during the complete experiment. This helps in understanding the damage process in the concrete. For the investigated anchor group, first cracks form at a displacement of approximately 0.13 mm. Upon reaching peak load the cracks have propagated towards the concrete surface and reached around 35% of the cone's final side length. The slope of the concrete cone is approximately 30° from the horizontal.

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