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Behavior of anchor groups installed in cracked concrete under simulated seismic actions

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ABSTRACT: For anchor group design, some or all of the anchors have to be assumed to be located in cracks. If installed in seismically active regions, the cracks open and close due to the cyclic response of the reinforced concrete structure to the earthquake. Due to the different stiffness of the individual anchors and the rotation-restraint of the base plate, a re-distribution of the anchor forces in the group can take place. Further, the total displacement is reduced if compared to a single anchor located in a crack. This paper presents the results of experimental and numerical investigations carried out to check those group effects for various anchor types. A model was developed to simulate the group behavior during crack cycling.

1 INTRODUCTION

Anchorages with post-installed anchors are often used as an anchor group to connect structural elements with each other or to strengthen reinforced concrete buildings. In principle, any number of anchors is feasible, but 2- and 4-anchor groups are the most common patterns. While many experimental and theoretical investigations were carried out on single anchors and therefore their basic load-displacement behavior is well understood, there are relatively few tests on anchor groups. This is especially true if the connection is exposed to cyclic loads or cyclic cracks as under seismic excitation.

All anchors of an anchor group share a base plate which allows for a load distribution among the anchors. This load distribution depends highly on the actual crack pattern present in the concrete component. One or several anchors may be located in a crack that either forms during the earthquake or has traversed the anchor location at some prior time. Anchors located in cracks lose part of their inherent stiffness and, in comparison to anchors in non-cracked concrete, slip more when being pulled-out. Any additional crack opening or crack cycling causes further slip and thus decrease of the embedment depth. This in turn leads to re-distribution of the load and has an effect on the overall load capacity of the anchor group. The load capacity can either increase or decrease in relation to the sum of the single anchor's capacities.

For a 4-anchor group, four different crack cases are possible (Fig. 1). Earlier investigations identified the crack case with 3 anchors located in a crack as being the most critical one. However, this crack case is deemed to be irrelevant in practice since the presence of two major cracks in close vicinity is unlikely. Therefore, the experimental tests focused on the second but most critical crack case, which is the crack case of two anchors parallel in a crack. Due to its symmetry and provided that the load-displacement behavior of all anchors installed in uncracked and cracked concrete, respectively, is the same, this anchor group configuration can be reduced to a 2-anchor group.

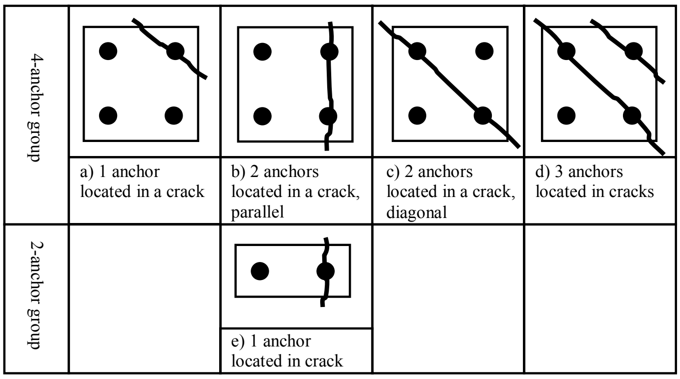

Figure 1. Crack cases of 4-anchor group and 2-anchor group.

The distribution of the load among the anchors also depends on the design of the base plate connection. This can either be rotation-unrestrained or rotation-restrained (Fig. 2). A base plate connected by a hinge between the tension load device and the base plate allows a free rotation of the base plate. Thus the load acting on any rotation-unrestrained group is distributed among the individual anchors according to their stiffness. In case of a statically determinate 2-anchor group, the resulting tension forces are the same, but not the anchor displacements. Whereas a stiff connection of a rotation-restrained anchor group requires all anchors to follow the same displacement but the tension forces differ. The resulting eccentricity creates a bending moment.

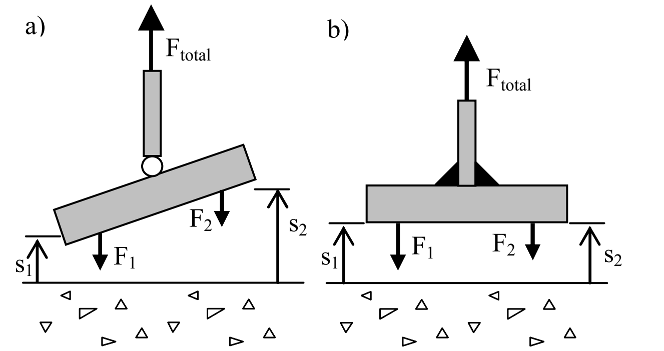

Figure 2. Base plate connection: a) Rotation-unrestrained; b) Rotation-restrained.

The experimental test program included both rotation-unrestrained and rotation-restrained configuration. This paper, however, focuses in the following on the more relevant rotation-restrained tests.

2 EXPERIMENTAL PROCEDURE

2.1 *Anchors*

In order to investigate the influence of various load-displacement behaviors on the anchor group behavior best, two types of mechanical anchors were tested. One of which was a torque-controlled expansion anchor, bolt-type, the other one a self-cutting undercut anchor (Fig. 3). The expansion anchor consists basically of a bolt with a conical end, and a clip, which is expanded and pressed against the borehole wall during the installation. The anchor load is then transferred to the concrete by friction. The load transfer mechanism of the undercut anchor is provided by a mechanical interlock between the anchor and the concrete. This interlock is created by a special installation procedure that makes the anchor cutting itself into the borehole walls.

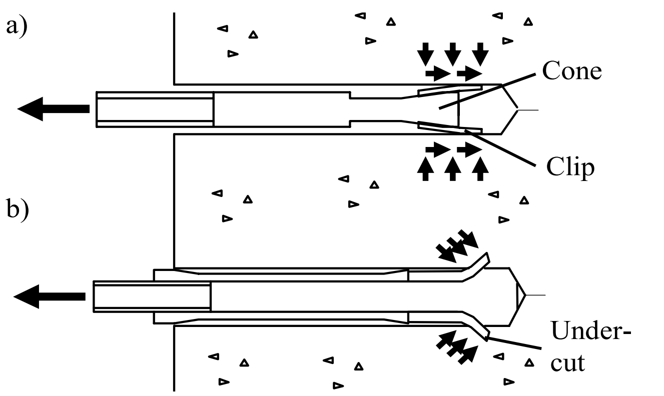

Figure 3. Anchors: a) Expansion anchor; b) Undercut anchor.

2.2 *Concrete test members*

The anchors were installed in concrete test members large enough to accommodate the anchor group and the test setup. The members were 1200 mm long and made of normal strength concrete (f_{cc} = 25 N/ mm²). Four high tension tie rods ran lengthwise through the member and were connected to an actuator (Fig. 4). The application of an adequate load formed one crack which was initialized in the centre of the member by means of a sheet metal crack inducer.

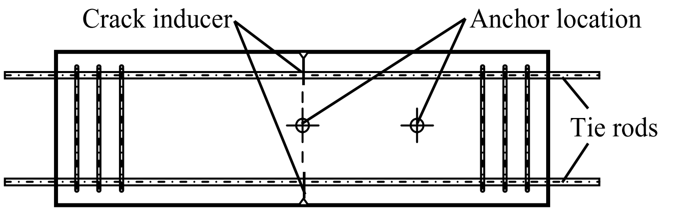

Figure 4. Horizontal section of concrete test member.

2.3 *Test setup*

Originally it was planned to run the test by means of a single actuator for anchor loading. However, exploratory tests showed that this is not feasible for rotation-restrained configurations: A base plate directly connected to the actuator simply does not provide sufficient stiffness and, moreover, caused potential damages of the actuator due to load eccentricities. Therefore, a multiple actuator loading and servo control setup was developed. It enabled the separate loading of two anchors according to defined boundary condition. For the simulation of a rotation-restrained base plate, the individual anchor displacements were servo controlled such that their magnitude was identical at all times while the total load varied.

For testing, the concrete member was mounted horizontally in between two abutments. On one side a 630 kN actuator generated the force necessary to open and close the cracks. The two 50 kN actuators for the anchor load were fixed on a steel support and assembled on top of the concrete member (Fig. 5).

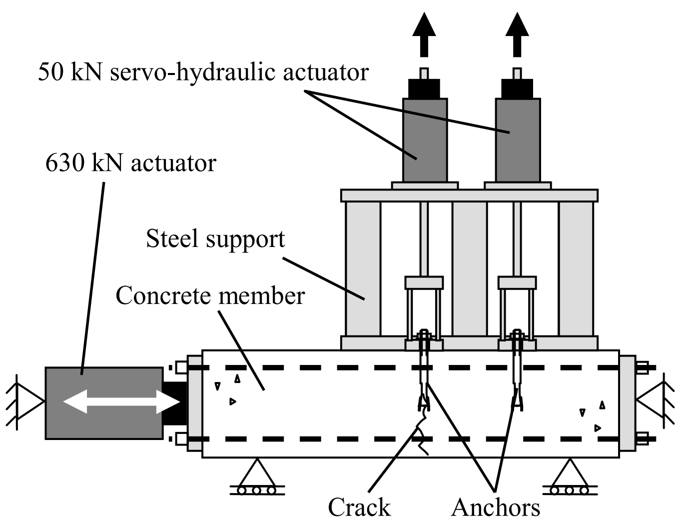

Figure 5. Side view of test setup.

2.4 *Theoretical background of test procedure*

The ultimate load of an anchor group loaded statically in tension can be easily calculated in accordance to the concrete capacity method (Eligehausen 2006). In case of a seismic event, the cracks open and close cyclically several times. The suitability of an anchor to sustain such load is tested by crack movement tests in the course of the anchor qualification. This test is known to be the most critical qualification tests, often more demanding than the current seismic test consisting of a cyclic load regime. That is because of the slip the loaded anchor experiences every time when the crack opens. More slip reduces the embedment depth and thus the concrete capacity. Further, the anchor displacement can reach magnitudes inacceptable for the designer. In case of an anchor group, however, the anchors located in uncracked concrete can support the weaker anchors located in a crack. This group effect is beneficial to the group displacement.

The crack movement test as currently defined in ETAG 001 (2007) and ACI 355.2-0 (2007) specifies 1000 crack cycles between 0.0 mm and 0.3 mm and seems to be inappropriate for seismic testing, too high the number of cycles and too small the crack width range. For the purpose of group testing under seismic conditions, the test is modified to 10 cycles between $\Delta w_1 \approx 0.0$ mm and $\Delta w_2 = 0.8$ mm, with Δw_1 defined as the crack width at a compression force equivalent to 10% of f_{cc}. The load level N_w during crack cycling was chosen as two times 40% of the mean reference load capacity determined monotonically in a static crack ($N_{u,cracked}$). This percentage equals approximately the load the anchor is designed for. In addition, the undercut anchor was also tested at a load level of two times 50% to check the capability to withstand overloading. The exact deduction of these percentages is beyond the scope of this paper and reference is made to Hoehler (2006). The experimental approach is given as a test program in Table 1.

Table 1. Test program.

Number of tests	EA	UC
Reference test, uncracked concrete	3	3
Reference test, cracked concrete	3	3
Reference test, cycled crack	3	3
Group test, 40% load level	3	3
Group test, 50% load level	0	3

(EA=Expansion Anchor; UC=Undercut Anchor)

2.5 *Loading pattern*

The loading pattern reflects the two phases of the test. Phase I begins with the expanding of the concrete member until the crack is opened by $\Delta w_1 = 0.8$ mm. Then the anchor group is loaded up to the defined load level N_w. This level is kept constant for the course of 10 crack cycles between $\Delta w_1 \approx 0.0$ mm and $\Delta w_2 = 0.8$ mm. In the following Phase II, the anchor group is loaded to failure to determine the residual load capacity (Fig. 6).

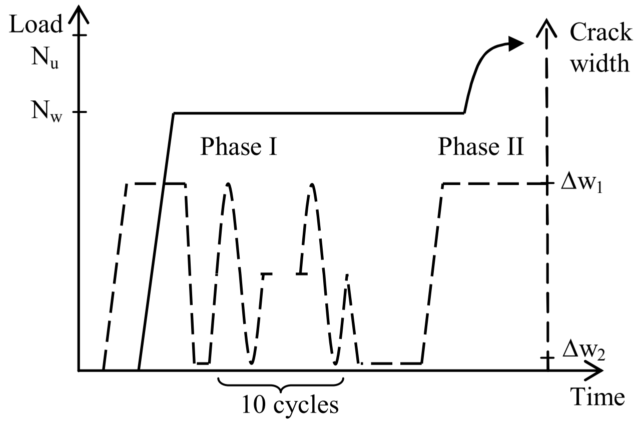

Figure 6. Loading pattern.

3 EXPRIMENTAL RESULTS AND DISCUSSION

3.1 *General*

The load-displacement curves show the two distinctive test phases (Figs. 6-8).

At the beginning of Phase I, the initial load is split up according to the individual stiffness of the anchors. Accordingly the anchor located in the uncracked concrete (denoted Anchor 1 in the following) takes up a bigger portion of the load than the anchor located in the crack (denoted Anchor 2 in the following). When the crack starts to cycle, both anchor loads alternate, each by the same but opposite magnitude. At the end of this Phase I, the load is redistributed to a certain extent.

For the determination of the residual load capacity in Phase II, the anchors are loaded displacement-controlled to failure.

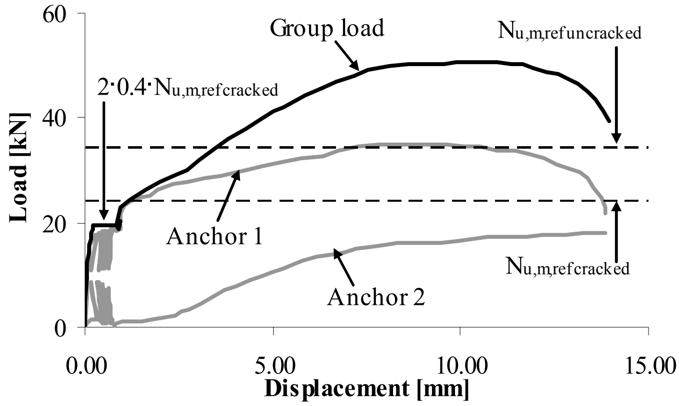

Figure 6. Example of a load-displacement curve for the expansion anchor (crack cycling at $N_w = 2 \cdot 0.4 \cdot N_{u,cracked}$).

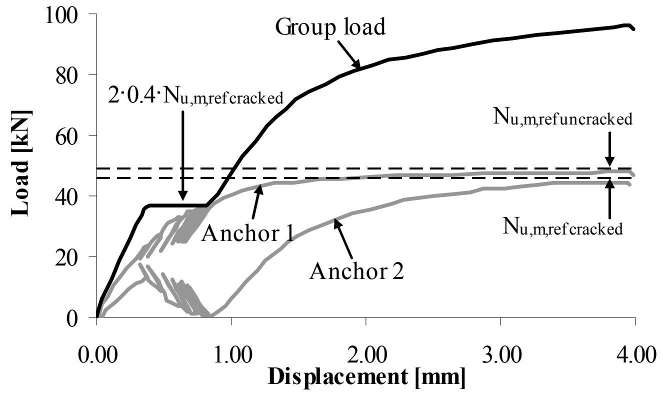

Figure 7. Example of a load-displacement curve for the undercut anchor (crack cycling at N_w= 2·0.4·$N_{u,cracked}$).

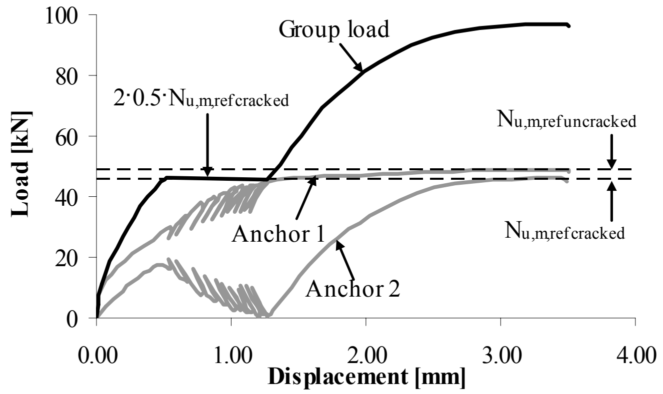

Figure 8. Example of a load-displacement curve for the undercut anchor (crack cycling at N_w= 2·0.5·$N_{u,cracked}$).

The expansion anchor experiences large displacements before it finally fails mostly in a pull-through failure mode, which is characterized by the anchor bolt being pulled through the clip. The undercut anchor is much stiffer and reaches soon its yield plateau. After huge plastic deformation it fails in a steel failure mode.

3.2 *Load re-distribution effects*

Every time the crack is compressed, Anchor 2 regains its stiffness and picks up load. Anchor 1 is unloaded by the same degree. When the crack opens again, Anchor 2 looses its stiffness and dismisses part of the load that has to be taken up by Anchor 1. This behavior recurs 10 times. The load-displacement curves of the two anchors are axially symmetric about the load level that equals half of the group load.

The load-displacement curve of Anchor 1 approaches the total group load, while the load of Anchor 2 decreases towards zero. The rate of re-distribution is different for various anchor types. The extreme difference in stiffness of Anchor 1 and Anchor 2 for expansion anchors results in an uneven load distribution already during the initial loading. This brings Anchor 1 close to the total group load before crack cycling even has started. Within the very first crack cycles, 100% of the group load is taken up by Anchor 1 each time the crack is opened up. The group load limits the maximum load Anchor 1 can pick up. From that point on, the anchor load-displacement behavior is kept unchanged till the end of crack cycling (see enlargement given in Fig. 13).

In case of the undercut anchor, the load portion of the two anchors are much closer together in the beginning and it takes more cycles before the group load is completely re-distributed. Therefore it is obvious that the load-displacement curve of Anchor 1 follows the envelope the monotonic load-displacement curve would describe (see enlargement given in Fig. 15), thus gradually approaching the group load level. Due to the overall higher load level, the increasing of the group load from 40 to 50% of $N_{u,cracked}$ results in larger displacements during crack cycling and a retarded total unloading of Anchor 2. However, after 10 cycles the anchor is also totally unloaded.

The test results make clear that in the beginning of crack cycling, the re-distribution behavior is governed by Anchor 2. This anchor tends to slip each time the crack is opened up, whereas Anchor 1 is more or less fixed. With increasing load of Anchor 1 and decreasing load of Anchor 2, the load re-distribution is slowing down. By progressive unloading of Anchor 2, the load-displacement behavior of the group is increasingly governed by that of Anchor 1. The group behaves more like a single anchor in uncracked concrete under cyclic load. This load cycling, however, is induced by crack cycling.

In conclusion it can be stated that the group load is sooner or later totally re distributed towards the stiffer anchor (Fig. 9).

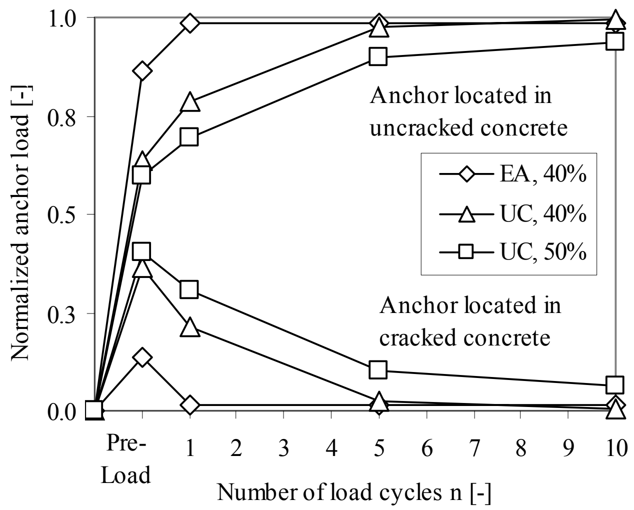

Figure 9. Load re-distribution: Anchor loads normalized with reference to the group load.

The anchor types tested cover the range of stiffness ratio typical for mechanical anchors: For the ascending load branch, the ratio of the stiffness of an anchor located in uncracked concrete and the stiffness of an anchor located in a crack (k_{uncr}/k_{cr}) is < 2 for undercut anchors and > 10 for expansion anchors.

3.3 *Displacements*

During crack cycling (Phase I), Anchor 1 takes over some or the entire load originally taken up by Anchor 2. By doing so, the displacement is substantially reduced if compared to that of a single anchor installed in a crack (Fig. 10).

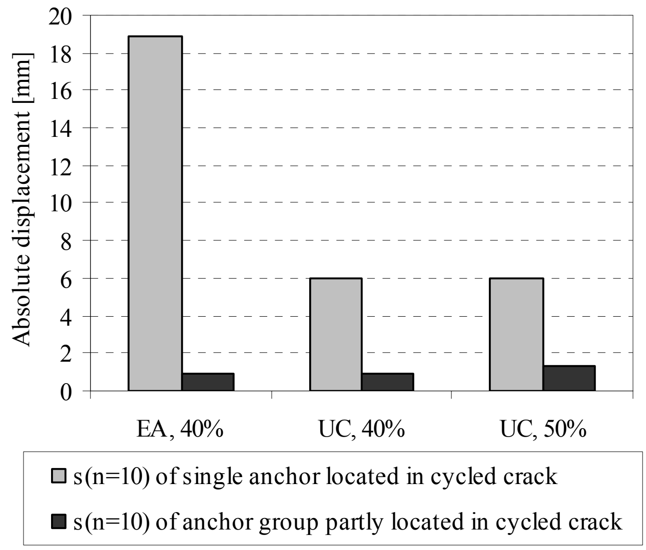

Figure 10. Absolute displacement after 10 cycles.

This beneficial effect is very pronounced for the expansion anchor. Anchor 1 is still pre-tensioned by the installation process and well within the linear-elastic loading range during crack cycling. The displacements are small in relation to the total displacement at failure.

The displacements of the undercut anchor are generally much smaller. Anchor 2 is able to carry a certain portion of the load throughout the crack cycling. The mechanical interlock of this anchor-type is not as crack sensitive as the follow-up expansion mechanism of an expansion anchor. This makes the undercut anchor predestinated for applications in cycled cracks and therefore it was chosen for the overloading tests at 50% $N_{u,cracked}$. The group displacement at this load level increases significantly in comparison to the 40% $N_{u,cracked}$ load level. However, the displacement after crack cycling is just above 1 mm and well below the displacement of 3 mm, which is considered as being critical for many applications in the plant engineering.

3.4 *Ultimate residual load capacity*

In the pull-out test (Phase II) all anchors reached the corresponding mean reference load and thus the crack cycling (Phase I) did not cause any reduction in the ultimate residual load capacity (Fig. 11).

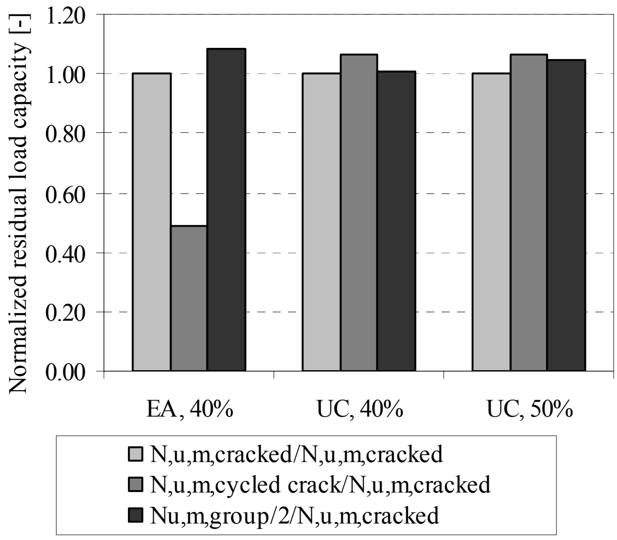

Figure 11. Ultimate residual load capacity, normalized with the reference to $N_{u,m,cracked}$.

However, sufficient ductility of Anchor 1 is required to enable Anchor 2 to catch up in load. This was the case for the anchors tested: The undercut anchor failed in a ductile steel failure mode. The expansion anchor failed in a pull-through failure mode that provides enough displacement and thus pseudo-ductility. The ultimate anchor group capacity can then be taken as $N_{u,group} = N_{u,uncracked} + N_{u,cracked} > 2 \cdot N_{u,cracked.}$

4 MODEL FOR ANALYTICAL INVESTIGATION

Group tests are complex, engage a lot of resources, require a special servo control program and consume costly concrete test members. Moreover, due to practical limitations only 2-anchor groups can be tested in the rotation-restrained configuration. Therefore, experimental group testing should be limited and simulations should be aimed for instead. The incorporation of the re-distribution effects in an analytical model is a challenging task since the stiffness of both anchors interacts and alters in the course of crack cycling. Thus no static load- displacement curve can be assigned to the anchors.

The approach presented here bases on a model as developed in Lotze (1993) that describes the load re-distribution due to continuously repeated load. The model was adapted and expanded to the conditions as they are present for anchor groups located in cyclically cracked concrete areas. The load re-distribution and group displacement is calculated for each crack cycling incrementally. The load increment is given as:

$$\Delta N_{gr,n} = \frac{\Delta s_{cr,diff,n}}{1/k_{uncr} + 1/k_{cr}} \tag{1}$$

where $\Delta s_{cr,diff,n}$: Displacement per crack cycle of a single anchor installed in a crack (product, crack width, and load level dependent); k_{uncr}: stiffness of a single anchor installed in uncracked concrete when it is loaded (load level dependent); k_{cr}: Constant stiffness of a single anchor installed in cracked concrete when it is unloaded.

For this approach it is assumed that the free displacement $\Delta s_{cr,diff,n}$ of a single anchor is fully incompatible in a statically indeterminate system and leads to the load re-distribution. In addition, the anchor group experiences an additional displacement because of the load cycling effect. Since the displacement due to load cycling is relatively low and, further, the group load is mostly borne by the anchor installed in uncracked concrete, it is assumed that this value is constant during the complete crack cycling. In conclusion, the displacement increment can be described as follows:

$$\Delta s_{gr,n} = \Delta N_{gr,n} \cdot k_{uncr} + \Delta s_{uncr,diff,n} \tag{2}$$

where $\Delta s_{uncr,diff,n}$: Displacement per load cycle of a single anchor installed in uncracked concrete (product and load level dependent).

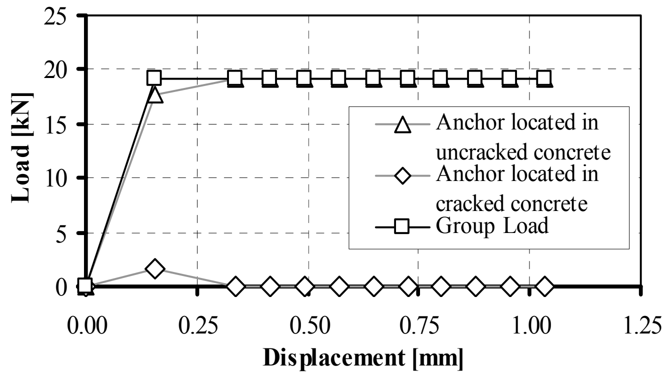

Figure 12. Load re-distribution during crack cycling for expansion anchor: Simulation.

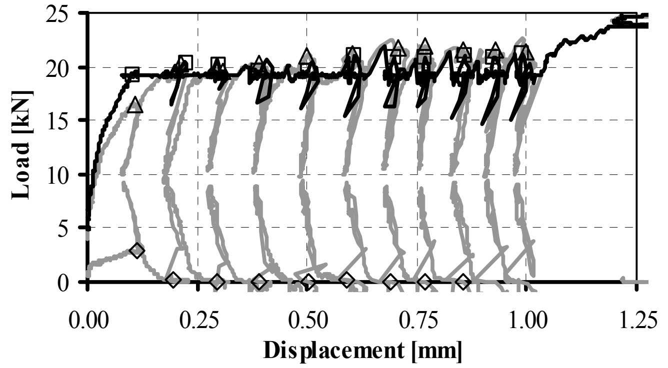

Figure 13. Load re-distribution during crack cycling for expansion anchor: Experimental test data.

Based on the displacement values gained by single anchor tests, the crack cycling induced load re-distribution and displacement of an anchor group can be calculated. The capability of this model to simulate various load-displacement behaviors of anchor groups was verified for both anchor types tested experimentally before. For the expansion anchor, the diagram in Figure 12 depicts the load-displacement curve as derived from numerical analysis. Opposed to the recorded test data (Fig. 13), it shows a good correlation in both, re-distribution of the load and displacement. The same applies to the undercut anchor, which load-displacement curve is plotted by the diagram in Figure 14. It matches well with the recorded test data (Fig. 15).

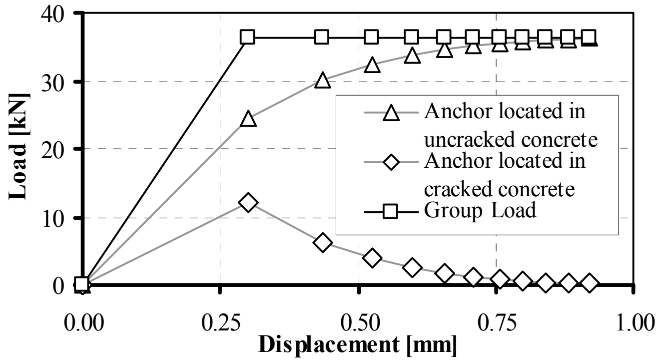

Figure 14. Load re-distribution during crack cycling for undercut anchor: Simulation.

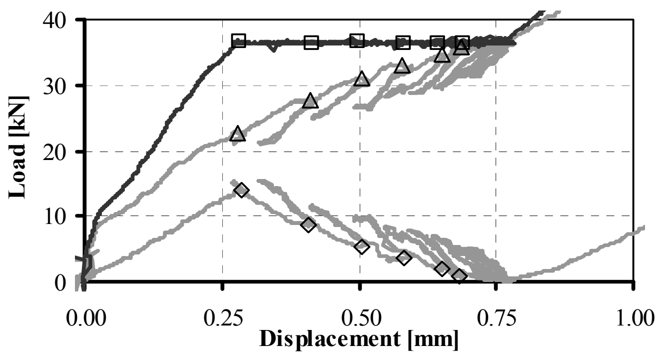

Figure 15. Load re-distribution during crack cycling for undercut anchor: Experimental test data.

5 FURTHER RESEARCH

The reference tests on single anchors are ongoing and back-up the fundamental data. Future investigations will also focus on the development of analytical model for 4-anchor groups. This is of major interest since experimental tests on rotational-restrained 4-anchor groups are virtually infeasible. Further, it is desired to extend the experimental investigations as described in this paper to other anchor types such as bonded anchors and screw anchors.

6 SUMMARY AND CONCLUSION

Anchor groups installed in cracked and seismically excited concrete structures are subject to load re-distribution effects. During crack cycling the group load is quickly shifted towards the stiffer anchors. This has a beneficial effect on the anchor displacement behavior. Anchor groups can help to limit the displacement substantially, provided that the connection of its base plate and the structural member is sufficiently rotation-restrained.

For ductile anchors, the residual group capacity is not negatively affected by crack cycling. In case of very brittle load behavior, however, the anchor located in uncracked concrete might fail before the anchor in cracked concrete picked up any substantial load. This risk of anchor overloading is the disadvantage of rotation-restrained anchor groups under seismic as well as under static application.

Based on the results of both experimental and numerical investigations on various anchor types, a model to predict the group effects on load redistribution and displacement behavior was developed.

ACKNOWLEDGEMENTS

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