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Safety reduction in anchor groups due to uneven crack distribution

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Abstract. In the present paper, the safety reduction in anchor groups composed of cast-in place headed anchors was experimentally investigated. In particular, groups of two anchors were installed in concrete members designed such that one of the anchors was located in a crack and the other one in plain concrete. The samples were loaded in tension, thus simulating a connection with clamped rotation under both monotonic and cyclic conditions. The results are commented and discussed demonstrating how the presence of uneven crack distribution could lead to a safety reduction, which should be properly taken into account in the design of anchor groups.

1. Introduction

1.1. Problem statement

Simply speaking, the fasteners layout in real structures is strictly related to the magnitude of applied loads. As a general rule, it can be assumed that the higher are the forces to be transferred to concrete, the higher will be the number of anchors for the fixture. Consequently, the use of closely spaced anchors is more likely for structural applications, where design loads are typically greater than in non-structural applications. If extensive knowledge is available about the behaviour of single anchors in concrete, less information about anchor groups is available in technical literature.

In Europe, the design of anchorage in concrete is currently covered by EN 1992-4 [1], which assumes the analytical models from Concrete Capacity Design approach (CCD hereinafter) [2]. Assuming that concrete cone breakout is the decisive failure mechanism, the group capacity under tension load provided by CCD is as the following:

$$N_{u,m,group} = N^{0}_{u,m} \cdot \frac{A_{c,N}}{A^{0}_{c,N}} \cdot \psi_{s,N} \cdot \psi_{ec,N} \tag{1}$$

where: $N_{u,m,group}$ is the load capacity of the group, $N^{0}_{u,m}$ is the load capacity of the undisturbed single anchor, $A_{c,N}$ is the actual projected area of the considered group, $A^{0}_{c,N}$ is the reference projected area of the single anchor, $\psi_{s,N}$ is a factor that takes into account for the disturbance in the stress field due to the proximity of an edge, $\psi_{ec,N}$ is the factor that takes into account for the effect of eccentricity in the load condition.

Such an analytical model may lead to both conservative or unconservative designs depending on several factors, among which: i. the geometrical configuration of the group, ii. the stiffness of the base plate, iii. the influence of the eccentricity [3].

Regarding the stiffness of the base plate, the load re-distribution in the anchors of a group is strictly related to the design of the fixture. In a group composed of two anchors with a stiff base plate, the same displacements are imposed to all the anchors, thus leading to different values of the tensile force according to their stiffness [4]. It is well known how the presence of a crack decreases the stiffness of an anchor. Cracks in a real structure could be randomly located as function of the properties of the concrete member and of the imposed actions. Moreover, the cracks could cross the anchors' locations, which sometimes work as a "crack inducer" [5]. All such conditions may lead to uneven boundary conditions for fasteners in the same group.

While such possibility is disregarded with respect to quasi-static loading, in presence of seismic action EN 1992-4 takes it into account providing the following equation for the resistance for a group of fasteners:

$$R_{k,eq} = \alpha_{gap} \cdot \alpha_{eq} \cdot R^{0}_{k,eq} \tag{2}$$

where: $R^{0}_{k,eq}$ is the characteristic seismic resistance, α_{gap} is a reduction factor which takes into account inertia effects due to annular gap between fastener and fixture, in case of shear loading, α_{eq} is the factor which takes into account for the influence of seismic actions and associated cracking on concrete cone resistance, or other mechanisms, due to uneven load transfer to the individual fastener of the group.

As it can be noticed, the above-mentioned equation directly links the seismic resistance of an anchoring system to the behaviour of an anchor group. In this sense, the α_{eq} may be interpreted as a measure of the safety reduction in a group installed in cracked concrete accounting for the presence of uneven crack distribution in the concrete member. However, no product or design provisions are currently available to assess α_{eq} factor.

1.2. Scope of the work

The present paper reports parts of the results obtained from an extensive research program recently carried out at Politecnico di Milano. The aim of the research program is to investigate the behaviour of cast-in place anchors under simulated seismic conditions and to generate an experimental database on the concrete cone breakout. Experimental tests were performed both in cracked and uncracked concrete, thus simulating the effects of seismic action on the anchoring solutions. Within this context, groups of two fasteners were tested by imposing uneven crack distribution in the anchor group. Such a condition was obtained by installing the anchors in reinforced concrete slabs designed to develop one crack only in correspondence of one anchor in the group. According to the obtained results, a procedure to establish the safety reduction of groups of anchors was proposed. The structure of the paper is as it follows: the section "Materials and methods" reports the details of the samples and the experimental setup; in the section titled "Test results" the outcomes of the experimental campaign are described; the section "Discussion of results" links the results with the analytical models from technical literature; finally, some conclusions are provided placing the current work in a larger context.

2. Materials and methods

2.1. Cast-in anchors

Cast-in place anchors for industrial applications were used for the experimental campaign. In particular, the anchoring solution is used to fasten heavy equipment to reinforced concrete elements in Nuclear Power Plants (NPPs). The solution is composed of an embedded S275 steel plate 120×120×30 mm connected to a Cl.8.8 M30 threaded rod by means of nuts and washers.

2.2. Reinforced concrete specimens

Anchoring solutions were casted in reinforced concrete slabs optimized for the use of materials and to prevent splitting failure induced by anchor loading. The slabs were designed to develop a maximum crack opening displacement up to 1.0 mm with the longitudinal reinforcement still in the elastic range. The debonding length (bond breakers length) was calibrated to ensure a constant tensile strain in the reinforcement across the crack plan. Threaded rods were used instead of deformed bars to clamp the specimens to the crack movement test system. Nominal C20/25 was used as reference concrete class for the experimental tests.

For reference tests, a beam specimen having a cross section 700×500 mm^2 and a length of 1480 mm was used. Two samples per each slab were installed prior to casting of concrete.

Minimum spacing for groups was fixed equal to the effective embedment depth. Due to the geometry of hydraulic jacks used for the experimental tests, however, the spacing was slightly increased to 210 mm. The same beam specimens adopted for the reference tests were modified for group tests. Specifically, they were designed such that one of the anchors was located in the crack plane and the other one in plain concrete. Due to cone surface development, only one group per slab was casted.

In order to measure the compressive strength of concrete, four cubes per concrete formwork were casted: the first one was tested after 21 days of curing for quality control, while the other ones were tested the day of the test.

2.3. Experimental program and test setup

The complete experimental program is reported in table 1.

Table 1. Test program.

Embedment depth (mm)	Concrete class	Crack opening (mm)	N. of tests
200	C20/25	0.8	5
200	C20/25	0.8	3
200	C20/25	0.5 ÷ 0.8	3

Reference tests were performed using a new crack movement machine designed by Politecnico di Milano. Crack width was measured at effective embedment location and at slab surface, while vertical displacements were continuously recorded using two linear transducers placed outside the theoretical cone development area. The loading frame for applying tensile load to the samples was equipped with 300 kN hydraulic jack. For group tests, the samples were loaded in tension using independent loading plates, thus simulating a connection with clamped rotation as depicted in figure 1. Specifically, two independent hydraulic jacks of 300 kN capacity were used to apply the tensile load to the anchors.

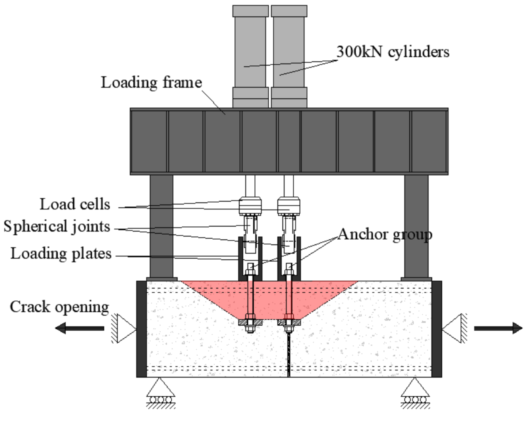


Figure 1. Schematic drawing of test setup for group tests.

2.4. Test protocols

Currently, no product or design codes are available for the assessment of cast-in place anchors under seismic actions in Europe. Therefore, the protocols presented hereinafter were obtained as interpretation of protocols from post-installed metal fasteners in concrete [6].

2.4.1. Reference tests. Reference tests were carried out in cracked conditions only. Basically, reference tension tests can be identified as monotonic tensile tests up to the failure on cracked concrete. The reinforced concrete specimen was loaded in tension till a crack width of 0.8 mm was measured on the side of the specimen at the effective embedment depth.

After that first part, the anchor was loaded till the failure. The loading system was displacement controlled using a dedicated control unit. The crack width was monitored and controlled during the test. If an increasing of crack opening displacement at the effective embedment depth was observed, the tensile load applied to the slab was reduced to keep 0.8 mm crack width constant during the test.

2.4.2. Monotonic group tests. The main objective of fastener group tests series is the measurement of the load capacity reduction due to uneven crack distribution.

Therefore, the following test protocol was applied: i. opening of the crack to 0.8 mm (the value is measured at effective embedment depth); ii. Simultaneous application of the tensile load to the anchors of the group using the same displacement ratio till failure.

As for the reference tests, to ensure a constant crack width, the tension load applied to concrete member was gradually adjusted during the following part of the test;

2.4.3. Cyclic group tests. The proposed protocol for cyclic tests aimed to investigate the effect of alternate cyclic tension loads on a clamped rotation connection with two anchors.

This test protocol is a direct interpretation of the test for the assessment of post-installed fasteners under pulsating tension load [6]. The anchors are alternatively loaded assuming 180° phase angle (i.e. when one of the anchors is subjected to the maximum amplitude for the considered step, the other is almost unloaded). After load cycling the specimen was unloaded, the crack width was opened to 0.8 mm and the residual part was performed.

The cyclic part of the test protocol is reported in figure 2. The maximum amplitude of the pulsating tension load was calculated as function of the anchor group load capacity from reference monotonic tests. Since the decisive failure mechanism is concrete cone breakout, it was calculated as it follows:

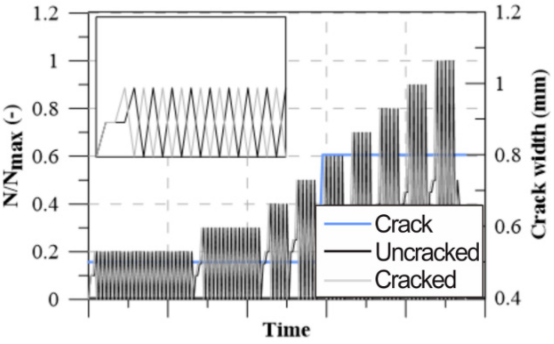
$$N_{max} = 0.75 \cdot N_{u,m,ref} \cdot \left(\frac{f_{c,ref}}{f_{c,test}}\right)^{0.5} \tag{3}$$

where: $N_{u,m,ref}$ is the mean capacity from the reference tests, $f_{c,test}$ is the mean compressive strength at the time of testing and is $f_{c,ref}$ the mean compressive strength at the time of testing of reference test series.

The reference tensile load for the single anchor was calculated assuming the simplified hypothesis of even load distribution among the fasteners:

$$N_{u,m,ref} = 0.5 \cdot N_{u,m,group} \tag{4}$$

where: $N_{u,m,group}$ is the mean capacity from the monotonic anchor group tests.



(N/N_{max})	N. of cycles	Δw (mm)
0.2	25	0.5
0.3	15	0.5
0.4	5	0.5
0.5	5	0.5
0.6	5	0.8
0.7	5	0.8
0.8	5	0.8
0.9	5	0.8
1.0	5	0.8
SUM	75	

Figure 2. Cyclic part of the group test.

3. Test results

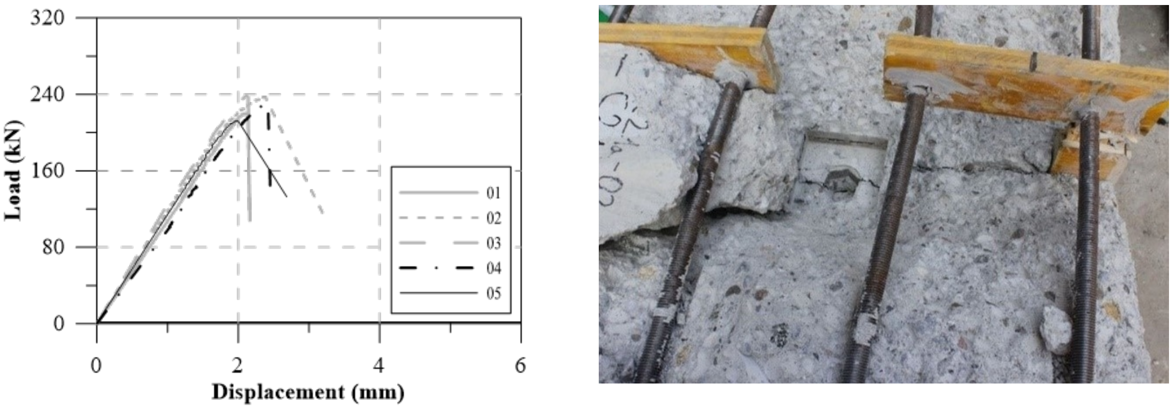
Although specimens were designed to allow the free development of concrete cone, fracture surface reached the lateral sides of the specimens. The cone projection as intended according to the CCD approach does not take into account for the current anchor's geometry. The effective shape of the cone may, in fact, be influenced by the shape of the hammer head in contact with concrete. If a large lower steel plate with elevated bending stiffness is installed, a wider cone surface is observed. In fact, it was noticed that the low pressure under the head preserved concrete from local crushing. Indeed, crack starts almost horizontally in the neighbourhood of the lower plate and the cone surface significantly deviates from the theoretical 35° degrees (figure 3b).

For anchor groups, the observed failure mechanism is characterized by the development of a concrete cone with the centroid perfectly located between the anchors (figure 4b) under both monotonic and cyclic loading. The extraction cone is composed by steep surfaces around the group and a flat crack between the anchors. Additionally, a splitting crack was detected for some of the test specimens.

The application of a cyclic loading has minor impact only on the capacity of groups. The measured load capacity after the residual part of the tests is, hence, comparable to the average value from monotonic reference tests (figure 4b).

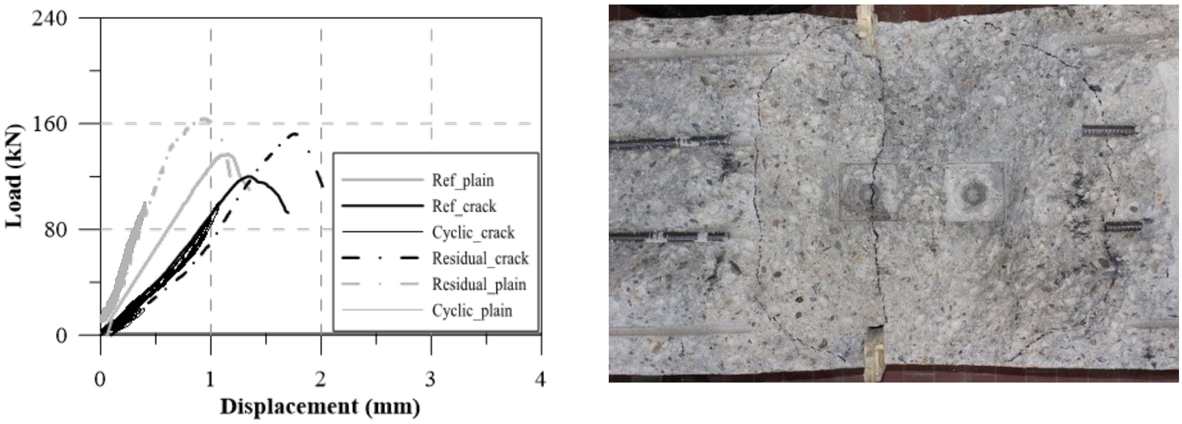
It can be clearly observed how the stiffness of the anchor installed in the crack plane is affected by the presence of the crack. However, very low permanent displacements are cumulated after the cyclic part of the tests for both the anchors (figure 4a). Furthermore, no stiffness degradation is observed as result of the application of the pulsating tension.

Table 2 summarizes the results from experimental tests.



a) b)

Figure 3. Reference tests: a) load-displacement curves, b) failure mechanism.



a) b)

Figure 4. Group tests: a) load-displacement curves, b) failure mechanism.

Table 2. Test results.

Test	$N^t_{u,m,cr}$ (kN)	$N^t_{u,m,ucr}$ (kN)	$N^t_{u,m,group}$ (kN)	$f_{c,test}$ (N/mm^2)	CV($N^t_{u,m,cr}$)	CV ($N^t_{u,m,ucr}$)	CV ($N^t_{u,m,group}$)
Reference tests	227.5	-	-	28.7÷29.4	4.9%	-	-
Monotonic group tests	125.3	133.2	258.5	31.8÷34.0	7.4%	4.3%	1.4%
Cyclic group tests	146.7	158.2	304.9	35.1÷35.2	6.2%	3.0%	4.3%

Where: $N^t_{u,m,cr}$ is the measured load capacity for the anchor installed in the crack plane, $N^t_{u,m,ucr}$ is the measured load capacity for the anchor installed in plain concrete, $N^t_{u,m,group}$ is the measured load capacity for the anchor group, $f_{c,test}$ is the measured compressive strength at time of testing.

4. Discussion of the results

Since concrete was casted in different batches, the tested load capacities are normalized with respect to concrete strength according to the following equation:

$$N_{u,m} = \left(\frac{f_{ck}}{f_{c,test}}\right)^{0.5} \cdot N^t_{u,m} \tag{5}$$

Where: $N^t_{u,m}$ is the ultimate load recorded during the experimental test, $N_{u,m}$ it the ultimate load normalized with respect to concrete strength, f_{ck} is the reference concrete strength and $f_{c,test}$ is the concrete strength measured at the time of testing.

Normalized load capacities are then compared with the predicted load capacities for concrete cone breakout calculated according to CCD approach. The related “k” coefficient is assumed equal to 11.5 for mean values of the resistance [5]:

$$N^p_{u,m} = k \cdot f_c^{0.5} \cdot h_{ef}^{1.5} \tag{6}$$

where: f_c is the concrete compressive strength and it is fixed equal to 25 N/mm^2, h_{ef} is the effective embedment depth.

It is observed how the adopted theoretical model for the evaluation of the resistance of anchoring solutions in cracked concrete is conservative (figure 5). As demonstrated in other research projects [7], a rather increasing in the load bearing capacity can be found as the head-size increases. Such a phenomenon was firstly identified as the “head-size effect”. In the framework of a very recent research project the authors, however, showed how low bearing pressure, as consequence of very large head-sizes, could lead to a more complex interaction with the structural response of the reinforced concrete member [8]. Such an aspect shall be further investigated.

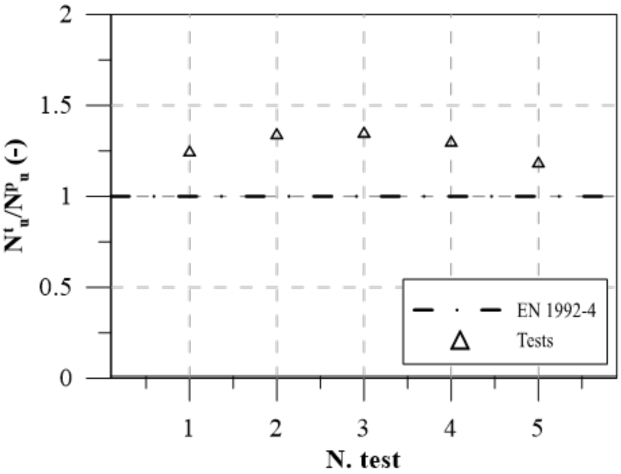


Figure 5. Comparison between tested and predicted load capacities from reference tests in cracked concrete. The load capacities are normalized with respect to concrete compressive strength. The predicted capacities are calculated according to equations from EN 1992-4, with respect to mean values for the calibration coefficients.

When displacement limitation of the attached element is sought, anchor groups can effectively help to limit the displacements. From load-displacement plot of Figure 6a, it can be observed how the displacement at the peak is halved if a group of anchors in used instead of a single anchor installed in a crack. The vertical displacements for the group are calculated under the hypothesis that the fixture is rigid. Hence, the total displacement is equal to the average of the displacements measured for the two anchors of the group.

Load-bearing capacity of anchor groups installed in members with uneven crack distribution can be assessed using the following procedure, where the safety reduction is measured as the ratio between the cone projection for the group and the reference cone projection of the single anchor:

$$\alpha_{eq}=N^t_{u,group}\cdot\left(N^p_{u,group}\right)^{-1} \tag{7}$$

where: $N^t_{u,group}$ is the tested group capacity normalized with respect to concrete strength, $N^p_{u,group}$ is the predicted group capacity calculated with respect to the normalized reference tests, as it follows:

$$N^p_{u,group}=A_{c,N}\cdot\left(A^0_{c,N}\right)^{-1}\cdot N_{u,m,ref} \tag{8}$$

Where:

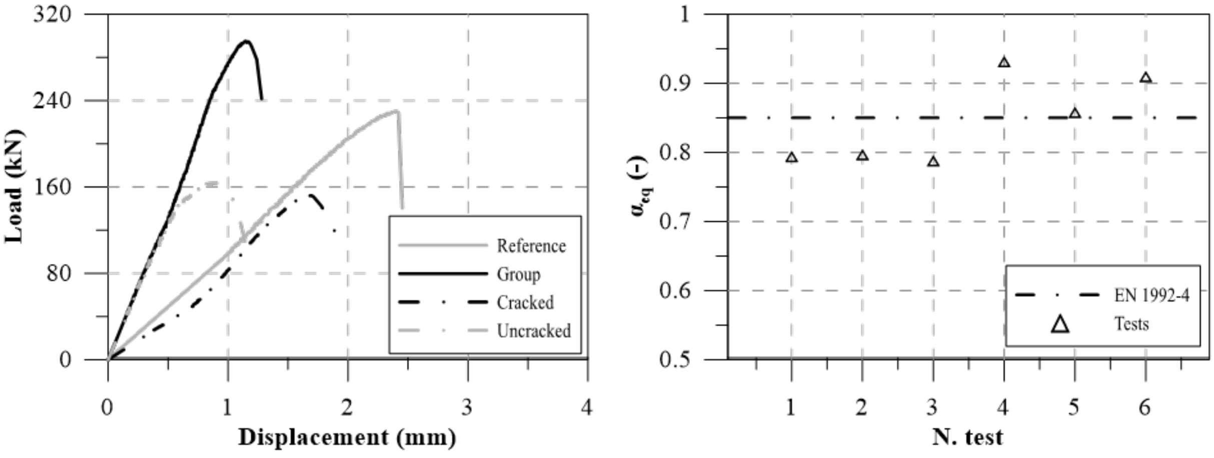
$$A_{c,N} = (3 \cdot h_{ef}) \cdot (3 \cdot h_{ef} + s) \tag{9}$$

$$A^0_{c,N} = 9 \cdot h^2_{ef} \tag{10}$$

In case of concrete cone breakout, anchor spacing, as well as the presence of free edges, has a significant influence on the capacity of the group. It can be assumed that the group behaves more like a single anchor in cracked concrete rather than a group with one of the anchors located far from the crack plane (i.e. located in plain concrete). Furthermore, the crack may introduce an additional disturbance in the stress-strain field leading the cone surface to develop not symmetrically. Consequently, the available load-bearing capacity is further decreasing with respect to the theoretical prediction.

Figure 6b compares the calculated α_{eq} factors with the value prescribed by EN 1992-4 for concrete cone breakout and headed fasteners, which is equal to 0.85. The values calculated according to the proposed model agree with the one from the code. Nevertheless, the code slightly overestimates the

α_{eq} factor calculated from the results of monotonic tests, while it slightly underestimates the factor from the residual part of cyclic tests.



a) b)

Figure 6. a) Comparison between tested and predicted load capacities for reference tests, b) Capacity reduction for group tests.

5. Conclusions

The capacity reduction in anchor groups composed by cast-in anchors was experimentally investigated focusing on the influence of uneven crack distribution on the anchor response. To this purpose, reference tests and group tests in cracked concrete were carried out. Specifically, group tests were designed such that only one anchor of a group of two was located in a crack. Clamped rotation boundary conditions were reproduced by using separated loading plates during the tests.

From the results of experimental tests, the following major conclusions can be drawn:

- Reference tests on single anchors confirmed that CCD approach could be conservative for predicting the load capacity of cast-in anchoring solutions with larger head-sizes. The shape of the extraction cones seems to suggest that the fracture propagation happens in a rather different way with respect to the 35° degrees model. This phenomenon should be further investigated;
- The application of alternate pulsating tension load has no impact on the ultimate capacity of the groups. Indeed, no reduction in the load capacity and very limited permanent displacements were observed after loading cyclic for both the anchors in cracked and uncracked concrete;
- Anchor groups can be effectively used when limitation of displacement in the fastened equipment is sought. Assuming that the fixture is rigid, the peak displacements in a group are almost halved with respect to the one for the single anchor;
- A model for the assessment of α_{eq} factor was proposed demonstrating how the presence of a crack in the concrete cone breakout body yields to disturbed conditions, which should be properly taken into account in the design of cast-in anchor groups.

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