2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

ASSESSMENT OF POST-INSTALLED ANCHORS FOR SEISMIC STRENGTHENING OF RC STRUCTURES USING STEEL BRACING

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Abstract: *Strengthening with steel bracing is one of the popular retrofitting methods used to improve the seismic performance of reinforced concrete frame structures. Commonly the steel braces are connected to additional steel frames which in turn are fixed to the RC frames using post-installed anchors or reinforcing bars. This method of connection leads to addition of significant weight and is also rather invasive. Instead, a direct connection using post-installed anchors to connect the bracing to frame corners offers an efficient and low invasive solution. However, in this case, the demands imposed on the post-installed anchors due to seismic actions are rather high. In this case, the performance of retrofitted structure is highly dominated by the performance of the anchors, especially by their displacement behavior.*

The current guidelines for seismic qualification of anchors only provide a force-controlled assessment procedure, which is deemed suitable for non-structural connections but is not sufficient to obtain the information required for the assessment of their seismic performance in structural applications. In this work, a new displacement-controlled approach for testing and assessment of post-installed anchors under seismic conditions is presented. Through this approach, the complete load-displacement behavior as well as the hysteretic response of the anchors could be obtained even in the post-peak range. It is shown that such an approach is more suitable for the assessment of anchors used in structural strengthening applications under seismic actions compared to the force-controlled approach recommended by the existing guidelines.

Introduction

Problem statement

Severe earthquakes in the recent years have highlighted the vulnerability of reinforced concrete (RC) structures in earthquake prone regions. Especially, the RC frame structures designed before the modern seismic codes were introduced are susceptible to collapse under seismic events. To overcome the deficiencies in the structural design, retrofit solutions are developed to improve the seismic performance of the structure. These solutions can be categorized in two groups. The first approach targets the local enhancement of the structural member by methods such as concrete jacketing, steel jacketing, FRP wrapping etc. to improve the members' performance and therefore the overall ductility of the structure itself. The second approach targets the alteration to global structural behavior by addition of structural members like shear walls to the existing building. In this way, the structural system is modified by changing the load transfer mechanism from a moment resisting frame to a truss mechanism and the strengthening solution results in an improved global performance of the structure with increased strength and stiffness.

A suitable and less-invasive alternative to shear walls for seismic retrofitting are steel bracings. Commonly the steel braces are connected to additional steel frames which in turn are fixed to the RC frames using post-installed anchors or reinforcing bars. Such an indirect connection significantly increases the weight of the structure, the installation is still quite invasive, technically difficult and elaborate rendering this solution as rather costly. The invasiveness of this system can be significantly reduced by connecting the steel bracings directly to the RC frame. Direct connections have proven to be a viable solution for seismic strengthening as shown by Maheri and Hadjipour (2003) and Massumi and Tasnimi (2008). In their studies they determined different

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methods like steel-jackets, bolted-through connections or pre-cast hooked anchor bolts embedded in concrete. However, besides being architecturally unattractive such solutions require a two-sided access for the installation, which makes the method still quite invasive. A direct connection using post-installed anchors might offer an efficient and low invasive solution for such cases.

Mahrenholtz et al. (2015) conducted an experiment on a full-scale RC frame with the buckling resistant steel bracing connected using post-installed anchors. In this study, bonded expansion anchors were used for the connections and the tests could clearly highlight the feasibility of the concept since a fivefold increase in the dissipated energy compared to the bare frame was observed. Although the tests proved the effectiveness of this solution they also showed that the performance of the anchors is crucial for the success of the whole strengthening system. At higher drift levels, the accumulated unrecoverable anchor displacement caused the gusset plate to misalign which in turn led to the buckling of the connected steel bracing. Experiments on fully fastened haunch retrofit solution performed by Sharma (2013) also showed the importance of the anchor performance on the effectiveness of the retrofit solution. Sharma (2013) used different post-installed anchor types to fasten the haunch element. Only in case where the anchorage performed well, the entire retrofit solution could serve its desired purpose.

For post-installed anchors used to connect the strengthening element with the concrete structure, the demands placed are rather high. As the structure is deemed to undergo in the inelastic range, the anchors are subjected to the demands of high forces that are cyclic in nature. In addition, invariably, the anchors are intercepted by cracks, which may be of relatively large widths and are also opening and closing with the structural deformations. Additionally, due to limited dimensions of the structural members, the area to transfer bond forces and to develop concrete cone is rather limited. Therefore, a standard force-based approach followed for the design of anchorages is often not sufficient to provide a solution for seismic strengthening connections.

Current anchor qualification guidelines for the assessment of anchors under seismic action like ETAG 001, Annex E only provide a force-controlled testing and assessment procedure. However, in certain cases, an indirect displacement check is made. For anchors used to connect non-structural elements demands on the anchorage can be reasonably well estimated in terms of inertial forces. In such cases, these procedures can be considered to provide sufficient information for qualification. However, in structural applications, the demands on the connections cannot be simply given in terms of forces due to the inelastic behavior of the structure. In this case the information obtained from a force-controlled assessment procedure is not sufficient for the assessment of anchor seismic performance.

Scope

In this paper, a new displacement-controlled procedure for seismic qualification of anchors used in seismic strengthening applications is introduced. With this approach, it is possible to obtain the seismic and hysteretic behavior of an anchor in the complete range of the load-displacement curve and not only for a limited range in the ascending branch. To show the effectiveness of this new approach, experimental tests were carried out on single anchors in cracked and uncracked concrete under pulsating tension load. To compare the proposed displacement-controlled protocol, one test series was performed according to the load-controlled protocol given in ETAG 001, Annex E and one test series with the new procedure. To obtain the parameters required for the preparation of the two loading protocols, initially a series of static reference tests has been performed.

Proposed displacement-controlled loading protocol

The new protocol is divided into three phases. The entire protocol is displacement-controlled. Phase I comprises stepwise increasing cyclic loading until peak load. In Phase II, cyclic loading is continued up to a certain displacement level, s_{max} beyond peak load and in the last phase a residual static pullout test is performed. To define the displacement levels for the initial two phases, the first step is to perform static reference tests in order to obtain the values s_u and s_{max}. The first value, s_u is defined as the mean displacement corresponding to the peak load obtained from the static reference tests. The second value, s_{max} is determined as the higher of either the mean displacement of the point where the load value drops down to 80% of its peak value in the post-peak region, $s_{80\%Nu}$, or twice the value corresponding to peak load, $2s_u$. The value $s_{80\%Nu}$ applies for post-installed anchors with a rather distinct post-peak behavior and accounts for the ability of some anchors to fail in a ductile manner. The value, $2s_u$ applies for post-installed anchors which fail in a rather brittle manner and in which case the value $s_{80\%Nu}$ would only represent an insufficient fraction of the post-peak region. The identification of the displacement values is shown in Figure 1.

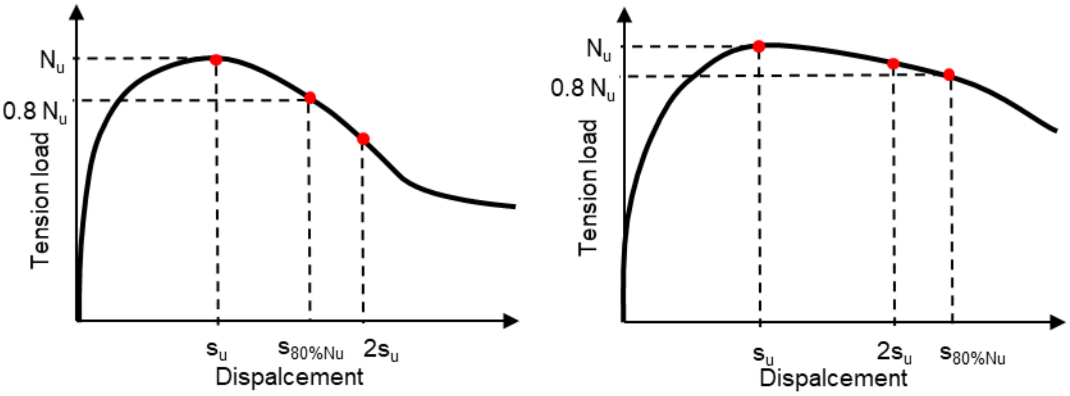


Figure 1. Identification of the displacement values

Figure 2 shows the schematic structure of the complete test protocol. As can be seen, Phase I consists of six displacement levels with three cycles applied for each level. The displacement levels correspond to 10%, 20%, 30%, 50%, 70% and 100% of the mean displacement corresponding to the peak load, s_u, obtained from the static reference tests. Immediately after Phase I follows Phase II. Here another three displacement levels, equally spaced between s_u and s_{max}, are applied with again three cycles each. Phase III consists of a residual static pullout test up until failure to determine the residual capacity. For tests on anchors in cracked concrete, for ease of testing, the crack width is kept constant throughout the procedure.

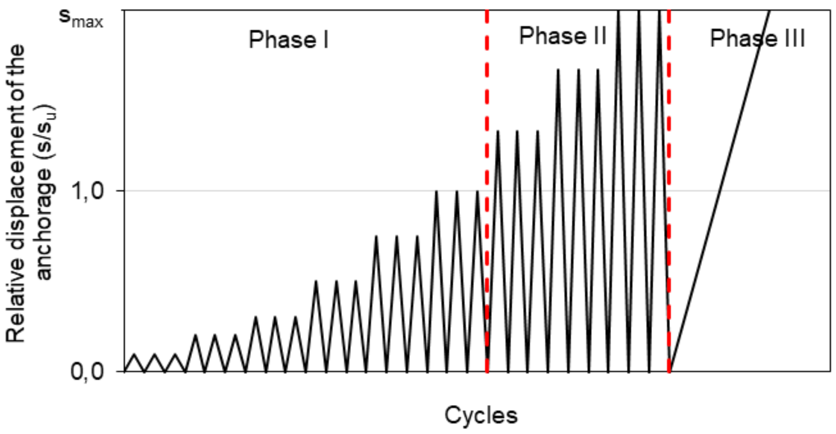


Figure 2. Schematic test procedure for displacement-controlled protocol

Experiments

Experimental program

In this study, the main focus is laid on the comparison of a force-controlled and a new displacement-controlled seismic loading-protocol for pulsating tension load. The force-controlled loading protocol follows the procedure C2.3 given in ETAG 001, Annex E, with the exception, that the test is conducted with a constant crack width of Δw = 0.8 mm at all load levels. This is done to ensure a better comparison of the two protocols. The displacement-controlled loading protocol follows the procedure as explained in the previous section. Besides the tests in cracked concrete, additional experiments are conducted in uncracked concrete to evaluate the new protocol for seismic actions in uncracked concrete as well. The test parameters are summarized in Table 1. Each test series comprises three tests, consequently a total of 18 pullout tests are performed on single bonded anchors. The bonded anchors comprise of high strength threaded rods of the size

M16 and the two-component injection system FIS EM Plus by manufacturer fischer. Technical design details are provided in the corresponding technical assessment ETA-17/0979 (2018). The anchors were installed according to the manufacturer's installation instructions. The applied load on the anchor, the anchor displacement and the crack width was measured throughout the test. As with the procedure C2.3, a lower bound had to be implemented in the procedure for the displacement-controlled protocol to avoid servo control problems. Hence, the anchor was unloaded only until a load limit slightly greater than zero has been reached. This means that the anchor displacement could not be brought back to zero in most of the cases.

Test ID	**Anchor size**	**Embedment depth, h_{ef} [mm]**	**crack width Δw [mm]**	**Mean concrete cube strength $f_{cc,150,m}$ [N/mm^2]**	**Loading type**	**Protocol**	**Number of tests**
BA-RF-UCR	M16	80	0.0	26.75	static	static reference	3
BA-RF-CR	M16	80	0.8		static	static reference	3
BA-ETAG-UCR	M16	80	0.0		cyclic	ETAG	3
BA-ETAG-CR	M16	80	0.8		cyclic	ETAG	3
BA-DISP-UCR	M16	80	0.0		cyclic	displacement controlled	3
BA-DISP-CR	M16	80	0.8		cyclic	displacement controlled	3

Table 1. Experimental program

Specimen and test setup

Concrete slabs used as the anchorage material were made of normal-strength concrete (C20/25). All slabs as well as the concrete cubes were made from the same concrete batch. Tests in uncracked concrete were performed in an unreinforced slab of 300mm thickness and a side length of 1635 mm. The clear distance between the anchors as well as the edge distance was greater than four times the embedment depth to ensure that the anchors do not influence each other. For the tests in cracked concrete special slabs were utilized which feature I-shaped, cast-in crack inducers and special holes. The crack inducer guarantee the formation of the crack along a defined plane and the holes are essential for the initiation of the cracks by hammering in the wedges. Before the cracks were opened, the holes for the anchors have been drilled. In this manner it is much more likely for the crack to cross the drill hole since notches tend to attract cracks as shown by Eligehausen et al. (2006). The cracks are then opened by putting sleeves into the aforementioned holes and hammering wedges into the sleeves. The test setup for the seismic tests is shown in Figure 3. To apply the load and displacement on the anchors a servo hydraulic cylinder was used. For the displacement controlled protocol the anchor displacement was directly measured on top of the anchor, using a Linear Variable Differential Transformer (LVDT). The LVDT was fixed to the concrete specimen via a bridge-like stand as shown in Figure 3 (b). In case of the ETAG protocol the anchor displacement was indirectly measured by means of a steel wire connecting the LVDT with the top of the anchor (Figure 3 (c)).

Figure 3.Test setup for the seismic tests a) Servo hydraulic cylinder b) setup for displacement controlled protocol in cracked concrete c) setup for ETAG protocol in uncracked concrete

Test results

Results of tests in uncracked concrete

In the following section the results of the tests in uncracked concrete are presented. The tests consist of monotonic tension tests that served as reference tests and cyclic tension tests according to the two protocols as mentioned above.

The load-displacement curves for the reference tests and the typical failure mode are given in Figure 4. In all three tests the observed failure mode was concrete cone failure. The input parameter for the ETAG protocol is the mean ultimate strength $N_{u,m}$. In this case $N_{u,m}$ = 57.72 kN. The values s_u and s_{max} are 0.97 mm and 1.94 mm respectively. Note that if only the first two reference tests are considered the mean displacement at ultimate load would only be s_u = 0.57 mm. By taking into account the third test as well the mean displacement at ultimate load increases significantly, resulting in higher displacement levels and thus a conservative loading history. For the preparation and the definition of the displacement levels of the displacement controlled protocol s_u and s_{max} were adjusted to 1.00 mm and 2.00 mm respectively.

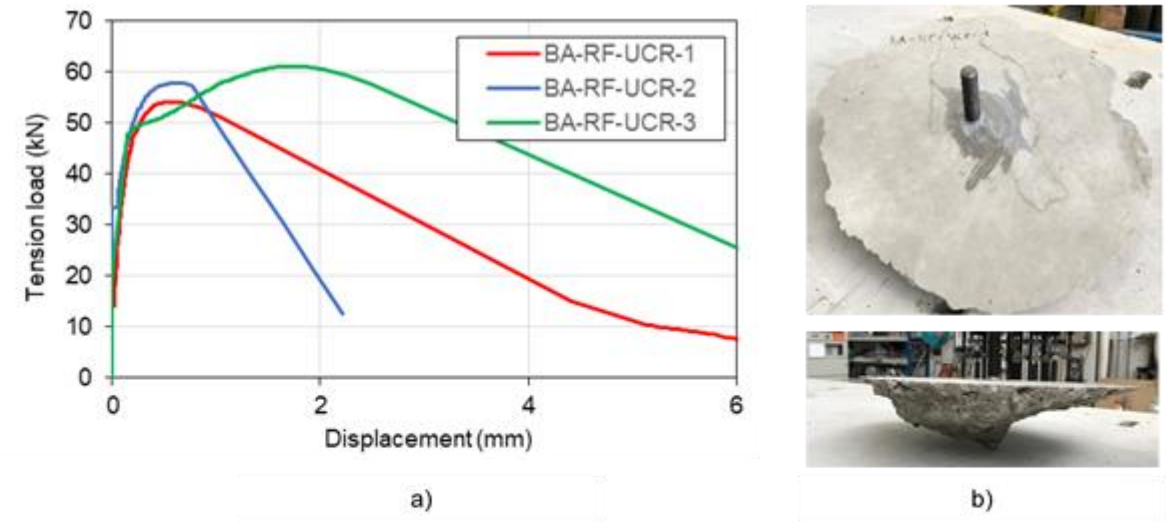


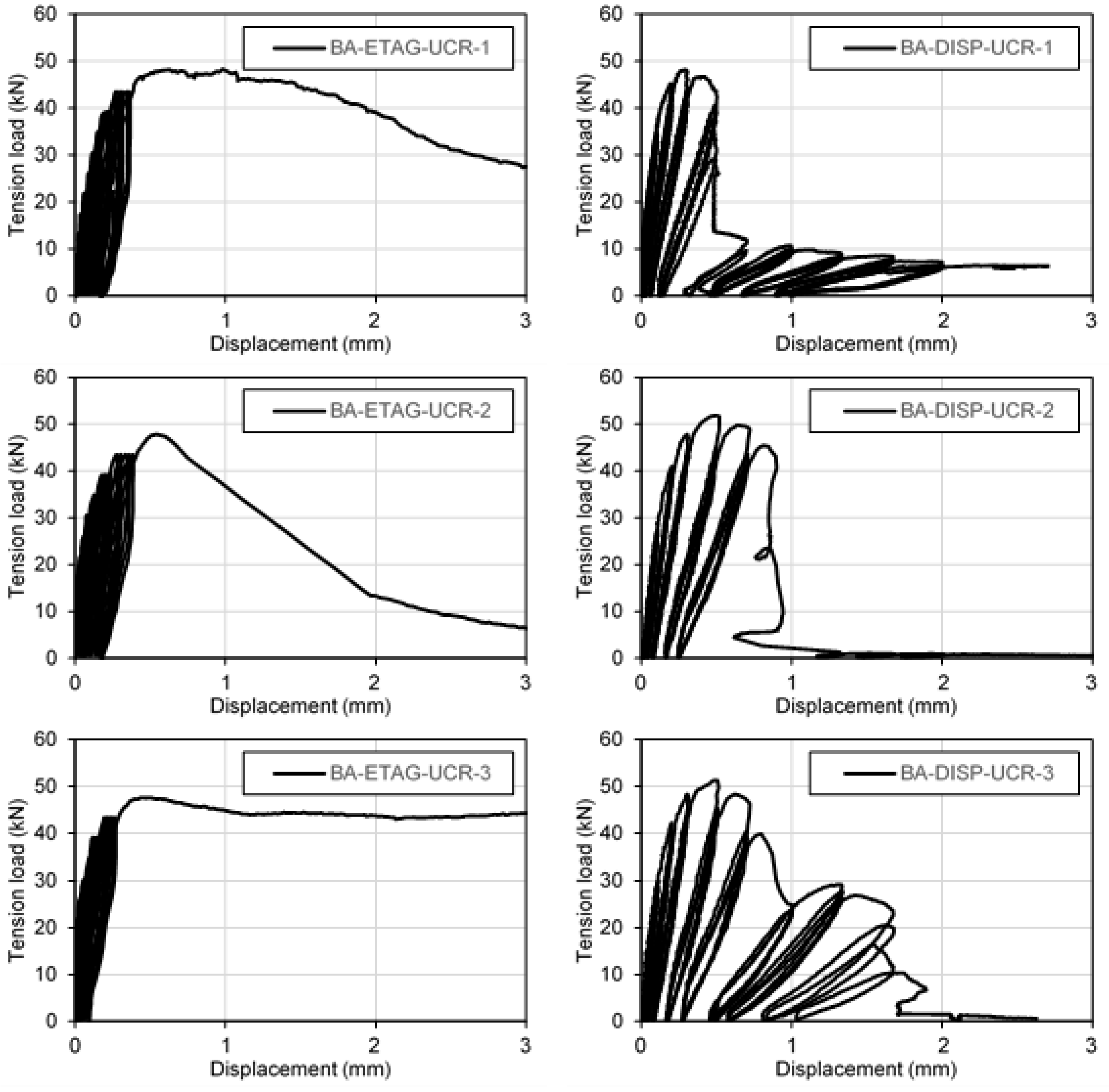
Figure 4. Load-displacement curves (a) and the typical failure mode (b) for the monotonic reference tests in uncracked concrete

Figure 5 shows the results of the tests performed with the two seismic protocols (a) according to the ETAG protocol and (b) according to the new displacement controlled protocol. The observed failure mode in all cyclic tests was concrete cone failure. The ultimate loads observed in the cyclic tests were similar for the two different protocols and in both cases the mean ultimate load decreased by around 15% compared to the reference tests. As for the displacement controlled protocol all tested anchors failed before the procedure could be completed. The anchors in test BA-DISP-UCR-1 and BA-DISP-UCR-2 even failed before the displacement was brought to s_u. This may be attributed to the fact that the third reference test deviates widely from the other two reference tests in terms of displacement and therefore has a strong influence on s_u and s_{max}. Hence the displacement levels are relatively high. Another observation in the tests with the displacement controlled protocol was a strength degradation in the second and third cycle of each displacement level.

Results tests in cracked concrete

These tests are aimed at investigating the load-displacement behavior of bonded anchors installed in cracked concrete and subjected to different types of seismic loading protocols. Again, the experimental program comprises monotonic tension tests and cyclic tension tests according to the two protocols. The experimental results are presented in the following section.

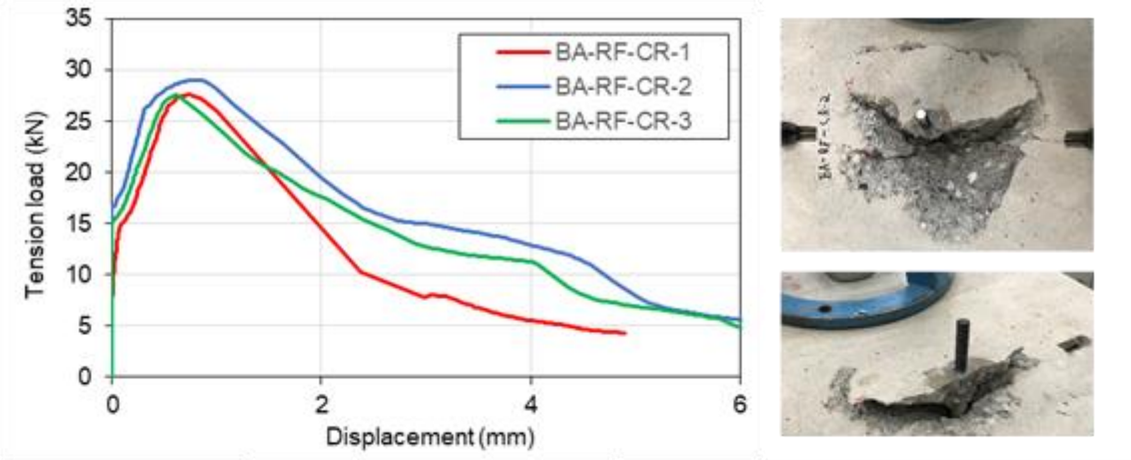
The load-displacement curves obtained from the static reference tests as well as typical failure modes for the tests in cracked concrete are given in Figure 6. Concrete cone failure was the observed failure mode in all three reference tests. The load-displacement behavior of the anchors in the three tests was very similar. The mean ultimate strength $N_{u,m}$ was 28,04 kN. Due to the presence of a relatively wide crack, the ultimate load of the bonded anchor was significantly lower than its capacity in uncracked concrete. The values s_u and s_{max} are 0.70 mm and 1.45 mm respectively.



a) b)

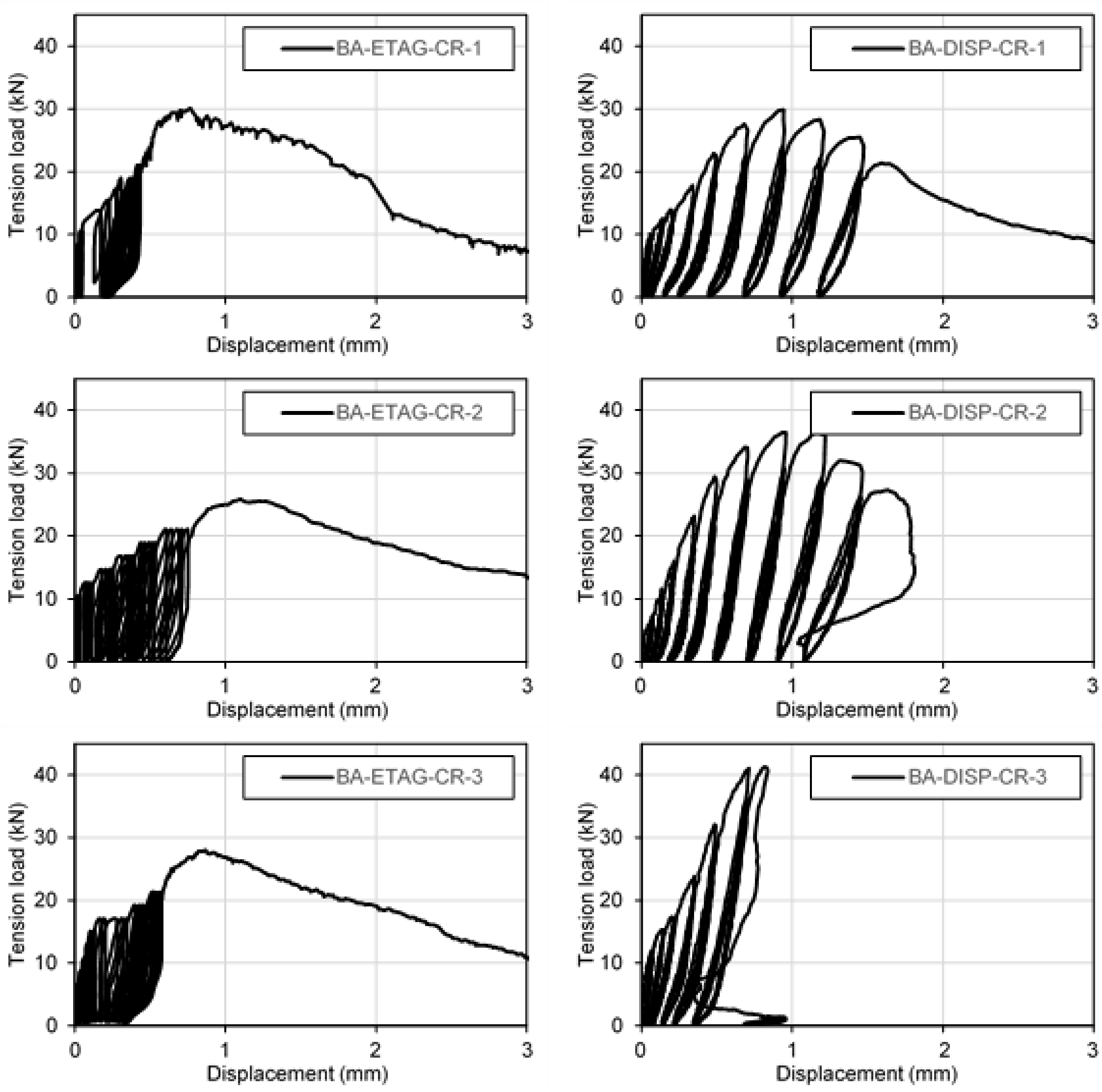
Figure 5. Results of the cyclic tension tests in uncracked concrete a) according to ETAG protocol b) according to the displacement controlled protocol

The results of the cyclic tests performed according to the ETAG protocol and the displacement controlled protocol are given in Figure 7 (a) and Figure 7 (b) respectively. In all cases, the observed failure mode was either concrete cone failure or a combined concrete cone and pullout failure. Combined failure occurred in the tests BA-ETAG-CR-2 and BA-DISP-CR-1. The obtained envelopes of the ETAG protocol show a good correlation with the static reference tests with respect to the ultimate load and displacement at ultimate load. In case of the displacement controlled protocol an increase in the ultimate strength for the tests BA-DISP-CR-2 and BA-DISP-CR-3 was observed. It is noteworthy, that the secant stiffness at ultimate load is nevertheless almost the same in case of the static tests and the tests according to the displacement controlled protocol. As with the tests in uncracked concrete again a significant strength degradation in the second and third cycle of each displacement level was observed. In test BA-DISP-CR-3 the anchor again failed during the seventh displacement level before the procedure could be completed.



a) b)

Figure 6. a) Load-displacement curves for the monotonic reference tests in cracked concrete and b) typical failure modes in cracked concrete



a) b)

Figure 7. Results of the seismic tension tests in cracked concrete a) according to ETAG protocol b) according to the displacement controlled protocol

As can be seen from the tests in both cracked and uncracked concrete, by following the displacement controlled procedure it is possible to obtain the complete hysteretic behavior of an anchor. The anchors are exposed to cyclic loading up to the ultimate load and even further in the post-peak range of the load-displacement curve. Whereas in case of the ETAG protocol the hysteretic behavior is only obtained for a limited section of the ascending branch of the load-displacement curve.

Conclusions

In the present work static and cyclic tension tests in cracked and uncracked concrete have been performed on bonded anchors. For the cyclic tension tests two different loading protocols have been utilized: (i) the load controlled protocol C2.3 given in ETAG 001, Annex E for the assessment of anchor performance under seismic action, and (ii) a new displacement controlled protocol. The aim of this study was to highlight the necessity of a new assessment procedure for post-installed anchors under seismic action used in structural applications and the comparison of the two cyclic procedures. The following conclusions can be drawn from the experiments:

1. The performed tests on single bonded anchors have shown that the new displacement controlled protocol provides much more information about the anchor performance than the standard ETAG protocol.
2. The displacement controlled protocol provides information on the hysteretic behavior of the anchor even in the post-peak range, whereas the ETAG protocol requires only a cyclic loading to 75% of the mean ultimate load obtained from static reference tests and therefore gives a rather small insight into the seismic performance of post-installed anchors. Hence, by following the displacement controlled approach it is possible to obtain additional information as for example the load-cycling stiffness in the complete load-displacement range.
3. While no anchor failed before the procedure according to the ETAG protocol has been completed, only in two tests the anchor did not fail before the end of the procedure in case of the displacement controlled protocol. This implies that the latter protocol is more demanding in terms of assessment and hence more suitable for the assessment of anchors in structural applications such as seismic strengthening.
4. With the additional information obtained from the new displacement controlled protocol a more accurate numerical modelling of the anchor behavior is possible considering the hysteretic behavior of the anchor.

Acknowledgement

The presented experimental studies were sponsored by fischerwerke GmbH & Co. KG. The support provided by fischerwerke is greatly acknowledged. The supports and efforts of Dr. Joachim Schätzle, fischerwerke is much appreciated. Opinions, conclusions, and recommendations expressed in this paper are those of the authors and do not necessarily reflect those of the sponsoring organization.

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