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A new assessment approach for post-installed anchors used in seismic applications

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Abstract. Steel bracing has proven to be a very powerful method to improve the seismic behaviour of reinforced concrete frame structures. In general the steel braces are indirectly connected to the RC frame via additional steel frames that are in turn fixed to the RC frame using post-installed anchors or reinforcing bars. However, this method comes with several shortcomings including increased weight and a disruption of the buildings function during installation. Therefore new connection approaches were developed where the braces are directly connected to the RC frame. One of the most promising solutions is the connection by means of post-installed anchors to connect the bracing to the frame corners. Using this type of connection allows an effective and low invasive strengthening of the structure. In this case the performance of the retrofitted structure is highly dominated by the performance of the post-installed anchors, since the imposed seismic demands are rather high. Therefore it is deemed necessary to assess the anchor performance under seismic actions, especially their displacement behaviour in the post-peak range. The current guidelines for seismic qualification of anchors only provide a force-controlled assessment procedure which is valid for non-structural connections but is not sufficient to obtain the information required for the assessment of their seismic performance in structural applications. A new displacement-controlled approach for the assessment of post-installed anchors under seismic conditions is presented. This approach allows the evaluation of the complete load-displacement behaviour as well as the hysteretic response of the anchors even in the post-peak range. A comparison with existing force-controlled assessment procedures shows that this approach is more suitable for the assessment of anchors used in structural strengthening applications under seismic actions.

1. Introduction

During earthquakes very high displacement demands are imposed on buildings which are cyclic in nature. Often these seismic demands result in the collapse of the building. This is particularly true for non-seismically detailed structures that were constructed before the modern seismic codes were introduced. A collapse of the structure or parts of the structure is one of the major threats to life during such events and additionally causes immense economic damage. Therefore, in order to improve the performance of such insufficient structures during an earthquake and hence prevent these structures from premature failure, it is indispensable to develop retrofitting solutions. Recent earthquakes have especially shown the vulnerability of RC frame structures and hence different retrofit techniques are developed to improve their performance. Some of these methods intend to improve the ductility of the whole structure by improving the performance of individual elements, such as columns or beams, by means of concrete jacketing, steel jacketing or FRP wrapping. For some structures this approach is sufficient to achieve the desired performance but often such solutions that only target on element strengthening are not enough to reach the required performance level and it becomes necessary to strengthen the structure itself. The basic idea of system strengthening is to add new structural members in order to improve the global strength and stiffness characteristics. Hereby the load transfer mechanism usually changes from a moment resisting frame to a truss mechanism.

A popular and effective approach for global strengthening is to add steel bracings to the concrete frame. The most common method to connect the two structural members is to fix the steel braces to an additional steel frame which is in turn connected to the RC frame using post-installed anchors or reinforcing bars. However, due to the absence of design guidelines the steel frame has to be connected to the RC frame along the complete circumference, leading to an invasive and technically difficult installation, making this a rather expansive and elaborate solution. Furthermore an indirect connection results in a significant increase in the weight of the structure. Instead, connecting the steel braces directly to the RC frame corners offers a less invasive and less costly alternative. Different methods have been developed such as steel-jackets, bolted-through connections or pre-cast hooked anchor bolts embedded in concrete, that have proven the feasibility of direct connections as shown in [1] and [2]. Nevertheless, these types of connections have some practical disadvantages when it comes to retrofitting already existing structures like the requirement of a two-sided access for the installation, rendering these solutions as still rather invasive. Using post-installed anchors instead offers an effective and low-invasive solution to connect the bracings to the RC frame.

An experiment on a full-scale RC frame retrofitted with buckling restrained steel bracing using this kind of direct connection conducted by [3] clearly highlighted the feasibility and efficacy of post-installed anchors in structural applications. At the same time it became apparent that the performance of the post-installed anchors is essential for the success of the strengthening solution. At higher drift levels the accumulated unrecoverable anchor displacement of the bonded expansion anchors, used in this study, caused the gusset plate to misalign which in turn triggered the buckling of the connected steel bracing. Also [4] showed the importance of anchor performance. By using different types of post-installed anchors to connect the fully fastened retrofit haunch solution (FFRHS) to the RC members it was shown than only when the anchorage performed well, the retrofit solution had the intended effect on the behavior of the beam-column joint and the FFRHS could achieve its full potential.

It becomes evident that the demands on post-installed anchors used in structural applications are rather high. Due to the nature of earthquake motions, elements of the load-bearing system have to undergo large cyclic deformations in the inelastic range which in turn results in high displacement demands on the anchor. Furthermore cracks will inevitably form in the concrete members and hence intercept the anchors as shown in [5]. These cracks may be of relatively large widths and will open and close along with the structural deformations. In addition the dimensions of the RC members are limited and hence further problems for the post-installed anchors arise since only limited area to transfer bond forces and to develop concrete cone is available. Therefore, commonly used force-based design methods for anchorages are not sufficient. Current anchor qualification guidelines for the assessment of anchors under seismic loads are targeted on providing the required information for such design methods and hence, guidelines like ETAG 001, Annex E [6] only offer force-controlled testing and assessment procedures where displacement is only considered in terms of indirect displacement checks. In non-structural applications these force-based approaches can be considered as adequate since the main demands on the anchorage are inertial forces. But due to the inelastic behavior of the structure it is unreasonable to regard anchorage demands only in terms of forces, rendering force-controlled assessment procedures insufficient for the assessment of anchor seismic performance.

Consequently it is necessary to develop new testing protocols that are more suitable for post-installed anchors used in structural applications. In this work a new displacement-controlled protocol for post-installed anchors under pulsating tension load is introduced. It is shown that in comparison with currently used loading protocols, given in the guidelines, the complete hysteretic and seismic behavior in the complete range of the load-displacement curve can be obtained. Therefore experimental tests in cracked concrete were performed on single bonded expansion anchors with one test series according to the new displacement-controlled protocol and one test series according to ETAG 001, Annex E [6]. In order to define the load and displacement levels for both loading-protocols it is necessary to obtain certain parameters from static reference tests and hence a series of static reference tests was performed initially.

2. Conception of the loading protocols used in this study

In order to evaluate the newly proposed displacement-controlled protocol it is necessary to compare it to a force-controlled protocol. In Europe the performance of post-installed anchors under seismic actions is assessed according to [6]. This guideline offers two seismic categories, namely C1 and C2, which are related to the level of seismicity and the importance of the building with C2 being the more stringent and hence the more relevant category for structural applications. C2 category comprises five tests including a pulsating tension test (C2.3), an alternating shear test (C2.4) and a crack cycling test (C2.5). For this study the test according to C2.3 has been chosen to contrast the new protocol.

C2.3 is a force-controlled testing protocol for pulsating tension load, which is characterized by a single load value, N_{max}. N_{max} is defined as 0.75 $N_{u,m}$ where $N_{u,m}$ is the mean ultimate load derived from the static reference tests in cracked concrete with a crack width of 0.8 mm. In nine load levels the load is stepwise-increased until N_{max} is reached, following a residual pullout test. At the first load level 25 cycles and at the second load level 15 cycles are applied. Subsequent load levels comprise five cycles. The tests are conducted in cracked concrete. Starting with a crack width of 0.5 mm at the beginning of the test, the crack is widened to 0.8 mm when the load cycles at 0.5 N/N_{max} are completed. A complete description of the procedure is given in [6].

In order to define the loading history for the new displacement-controlled protocol two displacement values have to be derived from the static reference tests. The first value is the mean displacement s_u, corresponding to the peak load and the second value is s_{max} which is the higher value of either the mean displacement corresponding to 80% of the ultimate load in the post-peak range, $s_{80\%Nu}$ or twice the displacement value corresponding to ultimate load, 2 s_u. The identification of these values is shown in figure 1. As can be seen, the value 2 s_u represents post-installed anchors with a rather brittle behavior, whereas $s_{80\%Nu}$ applies for anchors with a rather ductile behavior.

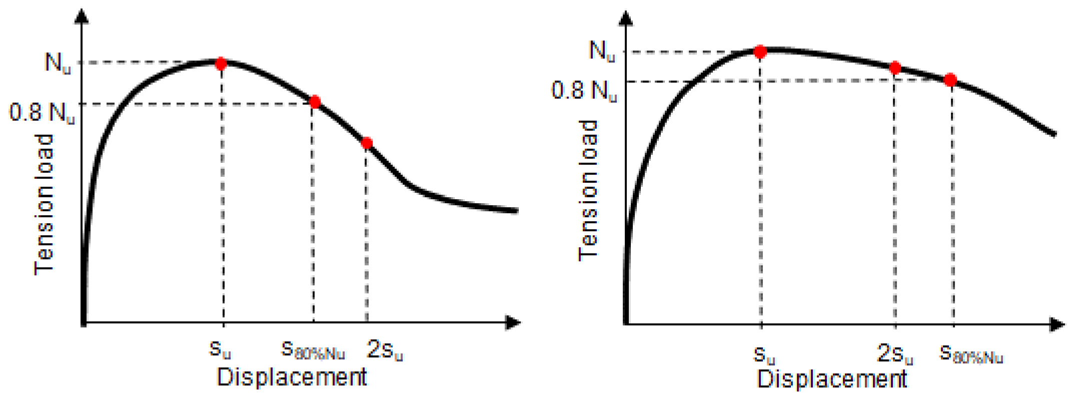

Figure 1. Identification of the displacement values.

The proposed displacement-controlled protocol is divided into three phases. Phase I comprises stepwise-increasing cyclic loading until peak-load with six displacement levels, corresponding to 10%, 20%, 30%, 50%, 70% and 100% of s_u. Subsequently follows Phase II with another three displacement levels equally spaced between s_u and s_{max} to determine anchor seismic behavior in the post-peak range. In the last phase a residual pullout test is performed until failure. The schematic structure of the test protocol is given in figure 2. As can be seen, three cycles are applied for each displacement level in contrast to the force-controlled protocol. For ease of testing the crack width is kept constant throughout the procedure.

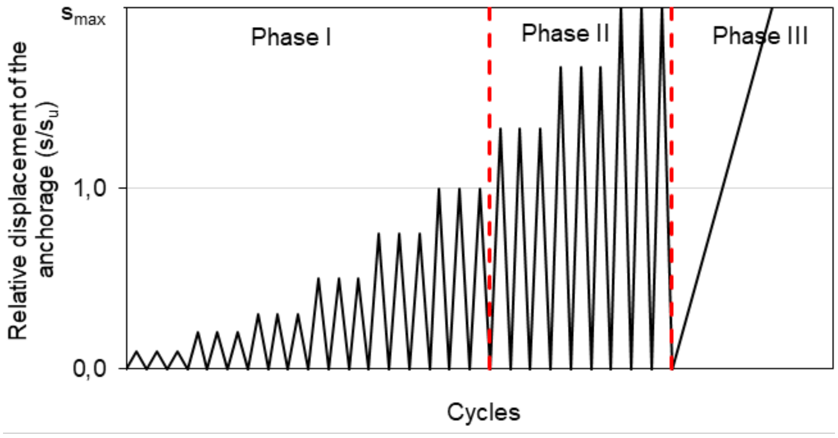

Figure 2. Schematic test procedure for displacement-controlled protocol.

3. Experiments

3.1. Testing program

The main focus of the experimental program is a comparison of a force-based and a new displacement-based seismic testing procedure for pulsating tension load. Therefore tests have been conducted in cracked concrete with one test series following the force-controlled loading procedure C2.3 specified in [6] and one test series following the displacement-controlled test procedure as explained in the previous section. To ensure a better comparability of the two loading protocols the crack width is kept constant at 0.8 mm throughout the complete loading history. This exception is also mentioned in ETAG 001 Annex E [6] and represents a more conservative approach for pulsating tension load. An additional test series of static reference tests in cracked concrete was initially conducted to obtain the load and displacement values, required for the preparation of the seismic loading protocols. Each test series comprises three tests on single anchors. Hence, a total of nine pullout tests have been performed in this study. The test parameters are summarized in Table 1. For the test procedure according to C2.3 it is stipulated that the bottom of the tension load pulses is kept slightly above zero. This is done to avoid servo control problems. To avoid these problems a lower bound had to be implemented in the procedure for the displacement-controlled protocol as well. Accordingly the anchor was unloaded in displacement control until a certain load limit slightly greater than zero has been reached, with the effect that the anchor displacement was not brought back to zero. Throughout the experiment the applied load, the anchor displacement and the crack width has been measured.

3.2. Test specimen and tested anchors

The concrete slabs used as the base material for the post-installed anchors were made of normal-strength concrete (C20/25). Concrete cubes with a side length of 150 mm were used to determine the concrete compressive strength at the time of testing. The mean concrete cube strength is given in table 1. The concrete slabs as well as the concrete cubes were made from the same concrete batch. To perform the tests in cracked concrete special slabs were used with a length of 1600 mm and a width of 800 mm. The thickness of these slabs was 300 mm. The slabs feature I-shaped, cast-in crack inducers and special holes through the specimen. The crack inducers are installed to guarantee the formation of the crack along a defined plane and the precast holes are necessary for the initiation of the cracks by hammering in steel wedges. The Highbond-System FHB II Inject by manufacturer fischer was used in this study. This bonded expansion anchor comprises the conical Highbond anchor rod FHB II-A S Inject and the injection mortar FIS HB. Details on the technical design are provided in the corresponding technical assessment ETA-16/0637 [7]. It is noteworthy that this anchor system has no seismic approval. All anchors were installed according to the manufacturer's installation instructions.

Table 1. Testing program.

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
BEA-RF-CR	M16	95	0.8		static	static reference	3
BEA-ETAG-CR	M16	95	0.8	29.21	cyclic	ETAG	3
BEA-DISP-CR	M16	95	0.8		cyclic	displacement- controlled	3

3.3. Test setup and testing

The test setup comprises a test rig, a servo hydraulic cylinder to apply the load on the anchor, and Linear Variable Differential Transformer (LVDT) to measure the anchor displacement and the crack width. The test setup for the seismic tests is shown in figure 3. In case of the displacement-controlled protocol the anchor displacement was directly measured on top of the anchor, using a LVDT. As can be seen in figure 3 (b) the LVDT was fixed to the concrete specimen through a bridge-like stand. The anchor displacement in the ETAG-protocol was indirectly measured via a steel wire connecting the LVDT with the top of the anchor as shown in figure 3 (c). The load from the servo hydraulic cylinder was transferred to the anchor via a fixture and a special hinge was used to connect the servo hydraulic cylinder with the fixture.

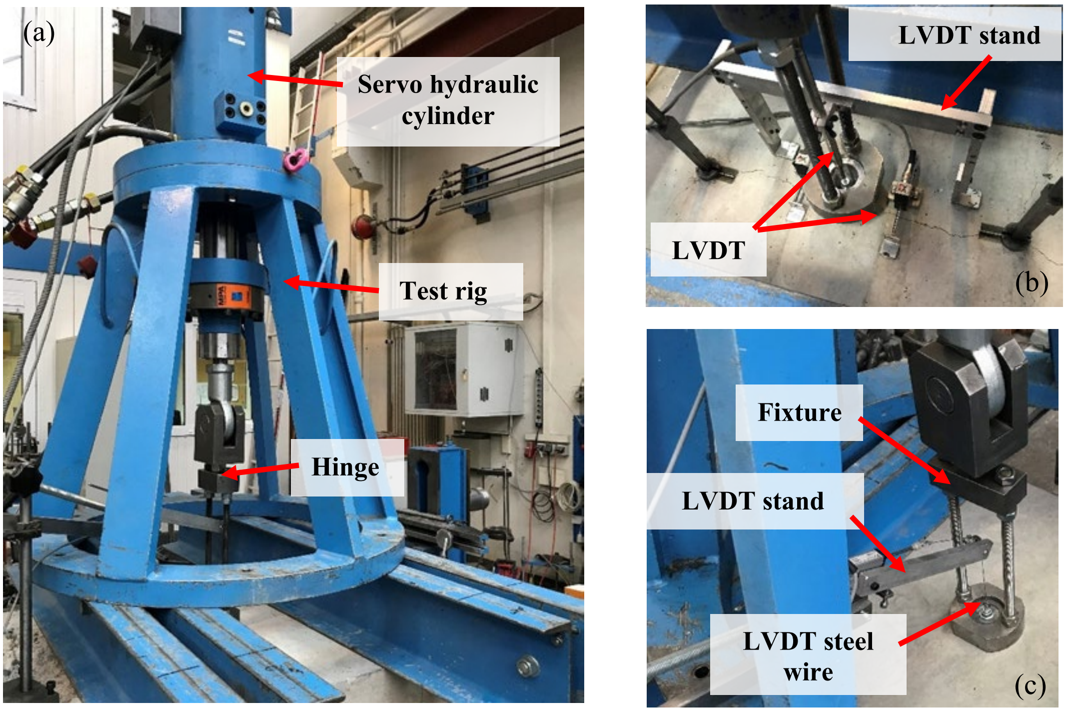

Figure 3. Test setup a) Servo hydraulic cylinder b) setup for displacement-controlled protocol c) setup for ETAG protocol.

The installation process comprises drilling of the anchor holes, then opening the cracks by putting sleeves into the aforementioned holes and hammering wedges into the sleeves. Next the wedges are pulled out again and the anchors are installed in the hairline crack. After curing of the injection mortar, the cracks are again opened to a width of 0.8 mm. During the opening procedure and also while testing, the crack width is constantly measured on both sides of the anchor via LVDTs as shown in figure 3 (b).

4. Test results

In this section the experimental results of the monotonic reference tests and the cyclic tests according to the two discussed protocols for pulsating tension load are presented.

The load-displacement curves of the static reference tests are given in figure 4. The observed failure mode in all tests was concrete cone failure. The mean ultimate load for the three tests is $N_{u,m}$ = 58.95 kN with a coefficient of variation (CV) of 3.7%. The load value, N_{max} defining the loading history in case of the ETAG protocol is hence calculated as 44.20 kN. The mean displacement at peak load, s_u is 6.62 mm. Considering the performance in the post-peak range, the bonded expansion anchors show a rather less pronounced behaviour and thus the displacement value, s_{max} is calculated as 2 s_u = 13.24 mm. For the preparation and the definition of the displacement levels for the displacement-controlled protocol, s_u and s_{max} were adjusted to 6.60 mm and 13.20 mm respectively.

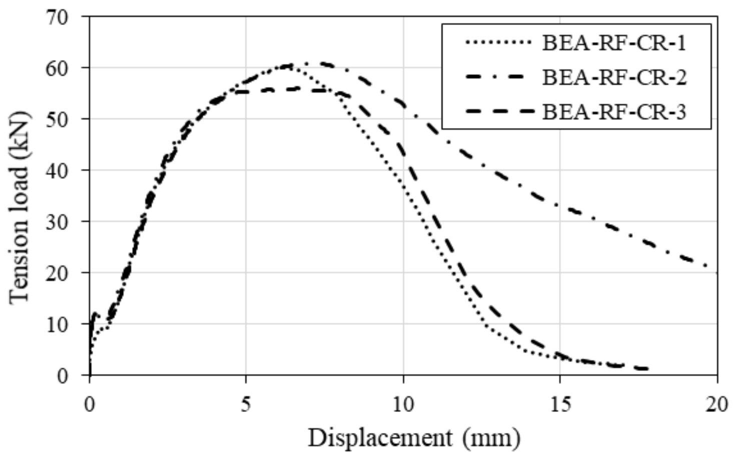

Figure 4. Load-displacement curves obtained from the monotonic reference tests.

The results of the cyclic tests performed according to the ETAG protocol and the new displacement-controlled protocol are shown in figure 5. As for the reference tests the observed failure mode in all tests was concrete cone failure. Typical failure modes are shown in figure 6. The mean ultimate load of the performed tests according to the ETAG protocol and the new displacement-controlled protocol was 55.31 kN and 59.84 kN respectively. In both cases the CV of the ultimate load was equal or less than 5%. The tested anchors were able to complete the entire loading history for both protocols without premature failure. As can be seen, the obtained envelopes of the seismic tests show a good correlation with the static reference tests with respect to the ultimate load and the displacement at ultimate load. Also regarding the initial stiffness the results correspond very well. This is true for both protocols. In test BEA-DISP-CR-2 and BEA-DISP-CR-3, it was observed that the load-displacement curves obtained from the displacement-controlled protocol show a softer post-peak behaviour than the static tests and the tests according to the ETAG-protocol. In contrast to the force-controlled ETAG protocol, the displacement-controlled protocol enables to observe significant strength degradation in the second and third cycle of each displacement level.

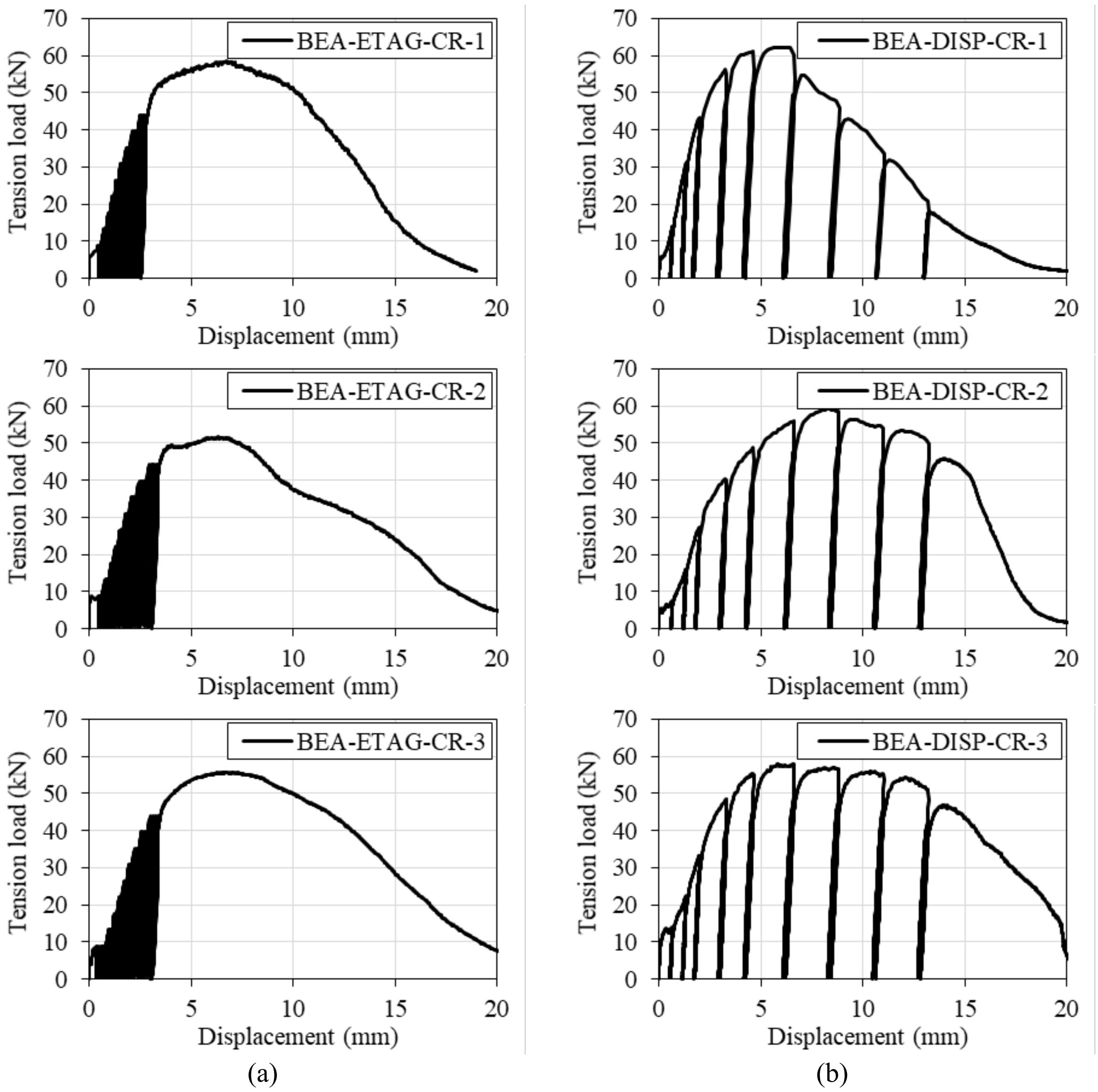

Figure 5. Results of the cyclic tension tests a) according to ETAG protocol b) according to the displacement-controlled protocol.

Figure 6. Typical failure modes.

5. Conclusion

The focus of the present work was to emphasize the need for a fresh perspective on seismic anchor testing when it comes to structural applications. Therefore static and cyclic tension tests on single bonded expansion anchors have been performed. The static tension tests function as a reference for the cyclic tests and are required to identify the load and displacement values that are needed for the definition of the seismic loading protocols. In case of the tests for pulsating tension load two different protocols have been compared: (i) the force-controlled protocol C2.3 given in ETAG 001, Annex E [6] for the assessment of anchor performance under seismic actions, and (ii) a new displacement-controlled protocol. The following conclusions can be drawn from the experiments:

1. The new displacement-controlled protocol provides much more information on anchor seismic performance than the standard ETAG protocol and at the same time, all the information needed for the assessment of anchors under seismic actions according to [6] is obtained from the new procedure.
2. In the ETAG protocol the load is only cycled up to 75% of the mean ultimate load obtained from the static reference tests. Thus, this procedure provides only limited insight into the seismic performance of post-installed anchors since only a small part of the load-displacement curve is covered. In the new displacement-controlled protocol on the other hand, the hysteretic behavior of the anchor is derived even in the post-peak range. Therefore additional information as for example the load-cycling stiffness in the complete range of the load-displacement curve can be obtained.
3. On basis of the additional information on the hysteretic behavior of the anchor a more accurate numerical modelling of the anchorage is possible. This enables a detailed modelling of connections in structural applications and hence a safer design.

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