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BEHAVIOR OF POST-INSTALLED ANCHORS TESTED BY STEPWISE INCREASING CYCLIC CRACK PROTOCOLS

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ABSTRACT

Opening and closing of cracks due to cyclic demands imposed on reinforced concrete structures is one of the most demanding actions to which anchorages in concrete are subjected. These actions can result in degraded load capacities or even failure of the anchorage. To achieve reliable anchor performance in earthquakes, consideration of crack movement behavior is essential during product qualification testing. Qualification tests on post-installed concrete anchors according to the American Concrete Institute (ACI) standard ACI 355 consider crack movement caused by repeated live loads only; requiring a large number of small amplitude crack cycles. In contrast, recent research has shown that stepwise-increasing cyclic crack protocols with a moderate number of cycles better represents the conditions anticipated during earthquakes. This paper investigates the load-displacement behavior of common post-installed anchors in stepwise-increasing crack movement tests that were recently adopted in European approval guidelines for seismic qualification of post-installed anchors.

Keywords: Anchor; crack cycling; crack; earthquake; axial load; testing

INTRODUCTION

During earthquakes, structures undergo reversed cyclic deformation, which may cause opening and complete closing of cracks in reinforced concrete structures. If post-installed concrete anchors are located in these cracks, which is likely since anchors tend to attract cracks[1], the anchors can experience substantial displacement when they are loaded axially

and simultaneously subjected to crack cycling (Fig. 1). The characteristics of seismic crack cycles (amplitude, frequency and number) differ from the crack movement tests in the American Concrete Institute (ACI) standards ACI 355.2[2] and ACI 355.4[3] to qualify mechanical and adhesive anchor products for use in cracked concrete in non-seismic applications according to ACI 318[4]. The non-seismic crack movement tests, which have a relatively small maximum crack width of 0.3 mm (0.012 in.) and a relatively large number of crack opening and closing cycles (1000), are intended to mimic the effects of live load or thermal load variation over the service life (50 years) of the anchors (Fig. 2). This test is one of the most demanding anchor qualification tests, despite the small crack width prescribed. Qualification of post-installed anchors for seismic applications in the United States currently requires only simulated seismic tension and shear load cycling tests in a non-moving (static) crack width of 0.5 mm (0.020 in.). Historically, the European Technical Approval Guideline (ETAG) for post-installed anchor qualification ETAG 001[5] did not cover seismic use. This limitation was a motivation for the research presented in this paper.

Early studies of anchor behavior in cycled cracks conducted by Rehm and Lehmann[6] investigate expansion anchors installed in simply supported reinforced concrete members that were cyclically loaded to open and close the cracks by bending. They found that progressively increasing anchor displacement during crack cycling indicates imminent failure. Later studies by Lotze and Faoro[7] establish that 1000 crack cycles with a maximum crack width of 0.3 mm (0.012 in.) is representative for a 50 year anchor service life. Their tests on undercut anchors show that anchor displacement behavior also depends on the crack closing width during crack cycling and that the anchor influences the crack width as it generates splitting forces in the concrete member. Eligehausen and Asmus[8] evaluate acceptable displacements for anchors during crack cycling and propose a limit on displacements of 2 mm (0.08 in.) after 20 crack cycles and 3 mm (0.12 in.) after 1000 cycles with a maximum

crack width of 0.3 mm (0.012 in.). A sustained tension load on the anchor of 1.3 times the allowable service load was prescribed during crack cycling. While the aforementioned studies provide useful indications of anchor displacement capacity during crack cycling, all were for non-seismic applications.

During seismic events, the number of crack cycles is far fewer than that experienced during the service life of the anchor however the crack widths are larger. Such extreme, transient events may cause reinforcing steel to experience large strains and crack widths may increase significantly. Therefore, qualification of anchors according to the German Guideline for Anchorages in Nuclear Power Plants[9], which is intended to cover extreme events such as earthquakes, includes cyclic crack tests in large cracks of up to 1.5 mm (0.06 in.) width. In these procedures however, only 10 crack cycles of constant amplitude are imposed. The minimum crack width during crack cycling is taken as 0.5 mm (0.02 in.) smaller than the maximum crack width. These crack widths assume that the reinforcing steel in the concrete has yielded. Hoehler and Eligehausen[10] conducted simulated seismic crack tests with post-installed and cast-in anchors with a targeted maximum crack width of 0.8 mm (0.03 in.) and ten equal-amplitude cycles. The maximum crack width was based on analytical studies of crack widths just outside of plastic hinges, assuming non-yielding reinforcement, in flexural members designed according to Eurocode 2[11] and Eurocode 8[12] and cyclic damage accumulation during earthquakes. During these tests, cracks were opened under load control and forced closed by compressing the concrete test member with up to 15 % of the concrete compressive strength to capture the effects of moment reversals in structural members during earthquakes. The authors demonstrate experimentally that a compressive stress of 10 % to 15 % of the concrete compressive strength is sufficient to achieve crack closure and that their protocol provides a conservative indication of seismic anchor performance outside of plastic hinge zones of reinforced concrete members[10]. It is noted that neither the design provisions

nor qualification guidelines in the United States or Europe cover anchors installed in plastic hinge zones. Hoehler and Eligehausen conclude that full closure of the crack cannot be substituted by increasing the crack opening width to maintain a representative difference between maximum and minimum values, e.g. crack cycling between 1.0 mm (0.04 in.) and 0.2 mm (0.008 in.) instead of 0.8 mm (0.03 in.) and 0.0 mm (0.0 in.), which would simplify testing.

More recently, extensive numerical investigations of the deformation behavior of reinforced concrete structures in high-seismic regions performed by Wood and Hutchinson resulted in a proposal for an anchor crack cycling test protocol[13,14]. In the present study, the Wood and Hutchinson crack cycling protocol is adopted, together with an improved test setup, to investigate seismic behavior of common post-installed anchors under representative and precisely-controlled conditions. The present effort was part of an extensive research program carried out at the *Institut für Werkstoffe im Bauwesen*, *Universität Stuttgart* (IWB)[15] to help develop the new European Technical Approval Guideline for seismic testing of concrete anchor.

RESEARCH SIGNIFICANCE

This paper provides comprehensive data from simulated seismic crack cycling tests conducted on concrete anchors for the first time using direct crack width control and stepwise-increasing crack width protocols. The tested anchors were from various manufacturers and cover the most common post-installed anchor types and critical failure modes. Test results demonstrate the effect of the crack protocol on the displacement and load capacity of the investigated anchors. Furthermore, these tests increase understanding of anchor behavior in earthquake-relevant crack conditions – thus supporting the design of safer

anchors in seismic applications – and form the basis for the development of seismic crack anchor qualification test procedures.

EXPERIMENTAL INVESTIGATION

Fourteen cyclic and monotonic test series were conducted, typically with three test repeats per series, resulting in a total of 74 individual anchor tests. The primary goals of the tests were to investigate the performance of common anchor types under axial load and representative simulated seismic cycled cracks. These tests aimed to generate load-displacement curves for governing anchor failure modes and to study the effectiveness of using a stepwise-increasing crack cycling protocol to simulate the seismic behavior of anchors.

Anchors and concrete

Eight medium-size (10 mm to 16 mm (3/8 in. to 5/8 in.) nominal diameter) anchor products from various manufacturers were investigated, of which five were mechanical and three were adhesive anchors (Table 1). One self-cutting undercut anchor (UA1), one screw anchor (SA1), one sleeve-type and two bolt-type torque-controlled expansion anchors (EAs1 and EAb1, EAb2), two bonded anchors with epoxy-formulations (BA1, BA2) as well as one bonded anchor with a methacrylate-formulation (BA3) (all bonded anchors with threaded rod M12) were tested. The screw anchor was qualified according to ETAG 001[4] for use in uncracked and cracked concrete (non-seismic) and all other investigated anchor products were qualified according to ACI 355 including seismic applications. Fig. 3 illustrates the tested anchor types as well as the corresponding load transfer mechanisms after crack opening.

The concrete test members were constructed of normal weight concrete with a nominal concrete compressive strength of f'_c = 20 MPa (2900 psi). Reference tests were carried out in 1635 mm × 1550 mm × 260 mm (64 in. × 61 in. × 10 in.) wedge-split concrete slabs as reported by Mahrenholtz[16]. Strain-split concrete slabs 700 mm × 420 mm × 270 mm (27.5 in. × 16.5 in. × 10.5 in.) were used as the anchorage material for the cyclic crack tests (Fig. 4). The strain-split specimens were designed to test single anchors where the crack width is controlled with high precision. Four high-strength (yield strength ≥ 950 MPa (138 ksi)) tie rods with bar diameter d_b equal to = 15 mm (0.59 in.) were cast lengthwise in the concrete slab and protruded at both ends of the specimen. Two 2 mm (0.8 in.) thick metal sheets were embedded in the concrete through the depth of the specimen on both sides of the calculated crack location to aid crack formation (Fig. 4). Additionally, the tie rods were debonded from the concrete on both sides of these crack inducers over a total length of 500 mm (20 in.) to facilitate large crack widths while allowing the reinforcement to remain elastic. Pilot holes 10 mm (0.39 in.) in diameter were drilled at the center of the slab to help ensure that the crack transects the anchor location after the slab is cracked. A hairline crack was generated by hammering wedges into hardened metal sleeves placed in two prefabricated holes along the crack plane. After a hairline crack appeared, the wedges were removed and the pilot hole was re-drilled to the required diameter for the investigated anchor. The anchors were then installed according to the manufacturers' published installation instructions. The installation torque was reduced to 50 % of the installation value immediately prior to testing to account for relaxation as specified in ACI 355.

Crack protocol, target crack width and sustained anchor tension load

The crack protocols utilized for these tests were developed using the results of nonlinear finite element simulations of reinforced concrete buildings representative of typical

building stock in high-seismic regions of the world with mature building seismic design codes[15]. The stepwise-increasing protocols were derived using Rainflow counting (an algorithm to reduce an arbitrarily varying time series to a set of simple reversals) of building member curvatures extracted from the nonlinear time-history analyses of seven buildings ranging from 2- to 20-stories, which were subjected to 21 amplitude-scaled earthquake ground motions. The cycle counting, after normalization, re-arranging with respect to their amplitudes, and averaging, resulted in several crack cycling protocols that differed depending on the level of statistical significance and processing method. For the present study, the protocol involved 32 crack cycles with the crack width amplitude increased in ten equal steps to reach the maximum considered crack width w_{max} (Fig. 5). This would be typical for mean cycle counts of buildings subjected to the design earthquake in regions of moderate to high seismicity. For further discussion see Wood[13].

The maximum considered crack width was defined as w_{max} = 0.8 mm (0.03 in.), which has been shown to be typical of characteristic crack widths occurring in concrete flexural members at the onset of reinforcement yielding outside of plastic hinges[17]. For reference purposes and to investigate the effect of maximum crack width on anchor performance, select anchor products were also tested with w_{max} = 0.5 mm (0.02 in.), which is the specified crack width for simulated seismic tests with cyclic loads according to ACI 355.2[2] and 355.4[3]. The monotonic reference tests were carried out on anchors installed in wedge-split concrete slabs with $w = w_{max}$. The averaged results allowed the determination of the mean monotonic capacity $N_{u,mon,m}$ and its corresponding displacement $s(N_{u,mon,m})$.

The sustained tension load N_w applied during crack cycling is intended to represent the load for which the tested anchor will be designed in applications. Because the seismic capacity is unknown at the time of seismic qualification testing, N_w is taken as a fraction of its mean monotonic capacity $N_{u,mon,m}$. In accordance with the safety concept underlying the

strength design of modern building codes such as the Eurocode 2[18], the analyzed structural element is shown to be safe if the design load N_{Ed}, i.e. the characteristic load N_{Ek} magnified by the load safety factor γ_F, is less than the design strength N_{Rd}, i.e. the characteristic strength N_{Rk} divided by the material safety factor γ_M ($N_{Ed} = N_{Ek} \cdot \gamma_F \leq N_{Rk} / \gamma_M = N_{Rd}$). A similar equation can be written according ACI 318[4], where factored loads are compared with nominal strengths multiplied by the strength reduction factor ϕ. With the load safety factor $\gamma_F = 1.0$ for load combinations governed by earthquake loads and the material safety factor for concrete-related failure modes of $\gamma_M = 1.5$, this equation can be expressed as $N_{Ed} \leq N_{Rk} / 1.5$. Assuming that the characteristic strength equals approximately 75 % of the mean monotonic capacity ($N_{Rk} = 0.75 \cdot N_{u,mon,m}$)[1], the design strength can be taken as $N_{Ed} \leq 0.75 \cdot N_{u,mon,m} / 1.5 = 0.5 \cdot N_{u,mon,m}$. Under earthquake conditions, however, the design anchor load will not act permanently, but rather the load will vary as the structure and the element that the anchor attaches respond dynamically. To account for this behavior, a factor of 0.8 is applied the sustained tension load resulting in $N_w = 0.8 \cdot N_{Ed} = 0.8 \cdot 0.5 \cdot N_{u,mon,m} = 0.4 \cdot N_{u,mon,m}$. The 0.8 factor is supported by probabilistic investigations[19] and has been confirmed by experimental studies[20]. It noted that it is acceptable to reduce the target load N_w to less than the above prescribed value during testing to improve an anchor's seismic performance, however, the anchor will be assessed a correspondingly reduced design capacity.

Test setup and procedures

After installation of the anchor, the strain-split slab was mounted in the testing rig by connecting the high-strength tie rods to a fixed reaction frame on one side and to a 630 kN (140 kip) horizontally-aligned servo-hydraulic actuator on the other side. Another 50 kN (11 kip) vertically-aligned servo-hydraulic actuator was placed on supporting beams and

connected to the anchor. Mechanical anchors were tested under unconfined conditions with a clear distance between the supporting beams of four times the effective embedment depth (h_{ef}). Adhesive anchors were tested under confined conditions to ensure bond failure. For the confined configuration, a smooth sheet of polytetrafluoroethylene (PTFE) and a steel plate with a clearance hole equal to ≈ 2.0 times the drill hole diameter (d_0) were placed around the anchor (Fig. 6a).

Load measurements were captured using load cells placed co-linear with the actuators. A displacement transducer was connected to the top of the anchor using a pulley and magnet and transducers were placed on either side of the anchor to measure crack width (Fig. 6b). The measured crack width provided the input signal for control of the actuator force applied to the concrete test member. A cyclic crack history was imposed by controlled ramps at quasi-static rates of about 20 seconds per cycle (≈ 0.05 Hz). Although high loading rates increase concrete and steel strength, anchor behavior at increased loading rates is complicated. Importantly, the loading rates which would significantly affect anchor behavior are faster than those anticipated under seismic loading, thus tests with low cycling frequencies are more practical and yield conservative results compared to high cycling frequencies[21,22]. Based on previous research[10], full crack closure was assumed to correspond to the concrete gross cross-section area stressed to 12 % of the nominal concrete compressive strength, i.e. $0.12 \cdot f'_c$. The target axial tension load of N_w was applied during crack cycling using a separate control system from that used to load the concrete specimen. After completion of the crack cycles, the anchor was unloaded and the concrete test member relaxed and the remaining displacement after cycling (s_{cyc}) was determined (Fig. 2). To determine the residual axial load capacity of the anchor, a tension test was then performed, while the 630 kN actuator opened the crack load controlled to the specified maximum crack width of 0.5 mm or 0.8 mm (0.02 in. or 0.03 in.) depending on the test series. This approach was observed to generate

crack conditions that are comparable to those created by the restoring forces of reinforcement in the wedge-split concrete slabs used for the reference tests. As in the monotonic reference tests, the anchor was loaded to failure in 1 minute to 3 minutes, resulting in the residual capacity of the cyclic crack test $N_{u,cyc,m}$ and its corresponding displacement $s(N_{u,cyc,m})$. Anchor load, anchor displacement, and crack width were measured and recorded at a sampling rate of 5 Hz.

EXPERIMENTAL RESULTS AND DISCUSSION

It is noted that the test conditions with respect to maximum crack width as well as the maximum anchor load were more demanding than those for which the anchors had been previously qualified. Thus, any adverse load-displacement behavior should not be considered to disqualify the investigated anchors from the qualification guidelines in effect at the time.

Anchor performance and displacement behavior

The test program and a summary of key test results are provided in Table 2. The subscripts *u*, *mon*, *cyc* and *m* stand for ultimate, monotonic, cyclic and mean. Figs. 7 and 8 show typical cyclic load-displacement curves and the corresponding monotonic mean curve calculated as the average of the monotonic reference tests. All anchors that completed crack cycling were tested to failure to determine their residual capacity. The observed anchor failure modes included concrete breakout, pull-through, pullout and bond failure. Sufficient steel strength and embedment depths precluded anchor steel failure.

All **load-displacement curves** demonstrate a characteristic load plateau representing the crack cycling phase of the test, where constant anchor tension load was imposed and the anchor displacement incrementally increases. It is noted that the initial loading branch of the cyclic crack tests is generally steeper than that of the monotonic reference tests. The reason

for this is that the permanent load was applied at a crack width of w_{max} / 10 whereas the monotonic reference tests were carried out with a crack width equal to w_{max}. The stiffness of the load-displacement curves of concrete anchors increases with decreasing crack width[1]. The load-displacement curves from the cyclic crack tests with the undercut anchor UA1 showed little cumulative anchor displacement during crack cycling (Fig. 7f). All undercut anchor samples failed by concrete cone breakout when loaded to failure during monotonic tension tests following the crack cycling. This suggests that undercut anchors are relatively insensitive to crack cycling, even with large crack widths, if sufficient mechanical interlock is provided to bridge the open crack. The behavior of expansion anchors, which transfer load by friction, is different for the two tested expansion anchor types. While the sleeve-type expansion anchor (EAs1) failed by concrete cone breakout (Figs. 7a and b), the bolt-type expansion anchors (EAb1 and EAb2) experienced pull-though, with the anchor bolts pulling through the relatively thin expansion elements (Figs. 7c to e). This failure mode shows dome-shaped ascending and descending load-displacement curves with a displacement span approximately equal to the height of the expansion element. The load-displacement behavior and residual capacity is bounded by the monotonic curve. Screw anchors transfer load via their threads cutting into the concrete forming multiple small, mechanical interlocks. During loading, the concrete between the threads deteriorates and the anchor is ultimately pulled out of its borehole. Despite the similarity of the load transfer mechanism of screw anchors and cast-in deformed reinforcing bars, the displacement at peak load of the tested screw anchor (SA1) was around 3 mm (0.12 in.) (Figs. 8a and b) and thus in general larger than that for cast-in reinforcing bars of similar diameter, which is known to be generally between 1 mm and 2 mm (0.04 in. and 0.08 in.). This may be attributed to the larger thread spacing of the screw anchors if compared to the ribs of reinforcing bars. This trend corroborates similar observations by Hoehler and Eligehausen[10] in which screw anchors with large thread spacing

of 15 mm (0.59 in.) survived over 8 mm (0.31 in.) of displacement without shearing of the concrete between the threads. The relationship between the interlock depth and the crack width also plays an important role for screw anchors. If the crack opens more than the interlock depth, the anchor will pull out of the concrete. Bonded anchors transfer tension loads to concrete by adhesion and micro-interlock with the concrete along the entire embedment depth. Confined test setups force bonded anchors to fail by bond failure. The high-strength threaded rods of the tested bonded anchors (BA1, BA2 and BA3) were pulled out partly with, partly without, the mortar. While the residual capacity after the cyclic crack tests was significantly smaller than in monotonic tests (Figs. 8c to e), some bonded anchors did not complete all crack cycles and could not be tested for residual capacity (Fig. 8f). An additional advantage of stepwise-increasing crack amplitudes over constant or decrease amplitudes is that they provide an indication of the maximum sustainable crack width for an anchor even if all of the cycles are not successfully completed. This allows for faster test iteration to obtain allowable anchor design capacities.

The dissimilar displacement behavior of the investigated anchor types can be observed in the **displacement accumulated during crack cycling** s_{cyc} (Fig. 9a). This displacement depends not only on the anchor response to the investigated crack cycling protocol, but also on the level of the sustained load N_w, since larger loads lead to larger displacements. The mechanical interlock of undercut anchors limits the displacements during cycling to less than 3 mm (0.12 in.), which is the displacement limit specified for non-seismic crack movement tests according to ACI 355.2[2] and ACI 355.4[3], as well as ETAG 001[4] and below which a connection is assumed to be rigid according to some building codes[21]. The tested expansion anchors developed large displacements of up to 12 mm (0.48 in.) during crack cycling with a follow-up expansion behavior as demonstrated by the residual load test. In contrast, the displacement capacity of bonded anchors is smaller and sudden failure occurs once the

adhesion is destroyed ($s_{cyc} \rightarrow \infty$). While the tested screw anchor SA1 completed the crack cycling with less than 3 mm (0.012 in.) of displacement, as discussed above, this is related to the specific thread spacing and depth of the anchor.

For anchors completing crack cycling, the mean **residual ultimate load capacities** $N_{u,cyc,m}$ were in general smaller than the corresponding capacities $N_{u,mon,m}$ of the reference tests (Fig. 9b). The reduction in capacity is caused by the damaging of the concrete in the vicinity of the anchor due to the repetitive compression and the anchor displacement toward the concrete surface during crack cycling and resulting reduction of embedment depth. Only for the investigated undercut and sleeve-type expansion anchors (UC1 and EAs1) were the ratios of $N_{u,cyc,m} / N_{u,mon,m}$ larger than or close to 1.0. Despite the limited number of test repeats, the scatter of the failure loads for these two anchor types was low with coefficients of variation v less than 15 %, which is consistent with anchors failing in concrete-related failure modes under non-seismic conditions[1]. For the investigated screw anchor (SA1) as well as the bonded anchors (BA1, BA2, BA3), the coefficients of variation of the residual load capacities (where available) were considerably higher (above 20 %). No residual capacity is reported for test series of bonded anchors where at least one tested anchor failed during crack cycling ($N_{u,m} \rightarrow 0$). The coefficients of variation for the bolt-type expansion anchors in the residual capacity tests varied between 4.9 % (EAb1) to 15.8 % (EAb2). The coefficient of variation of the residual load capacity provides an indication of the robustness of the anchor under a specific set of conditions; a smaller coefficient of variation is preferable.

The mean **anchor displacements** $s(N_{u,cyc})_m$ of the cyclic crack tests were always larger than the corresponding displacements $s(N_{u,mon})_m$ of the reference tests (Fig. 9b), resulting in ratios of $s(N_{u,cyc})_m / s(N_{u,mon})_m$ which are larger than 1.0. The displacements of the cyclic crack tests ranged from less than 3 mm (0.12 in.) for the bonded anchor BA1 to more than 20 mm (0.80 in.) for the bolt-type expansion anchor EAb1 and equaled approximately the

displacements of the monotonic reference tests $s(N_{u,cyc})_m$ plus the displacements accumulated during cycling s_{cyc}.

As mentioned above, the peak residual load for anchors failing by concrete cone breakout, i.e. undercut and sleeve-type expansion anchors (UA1 and EAs1), is greater than the mean value in monotonic reference tests. This behavior was reported in previous studies[17,23] and is attributed to the compaction of the concrete during crack cycling at the point of tension load transfer. Although excessive damage due to concrete compaction decreases load capacity, limited compaction is presumed to have a beneficial effect on residual strength. The curves of the residual load tests for the investigated bolt-type expansion anchors (EAb1 and Eab2), failing by pull-through, and the screw anchor (SA1), failing by pullout, are approximately bounded by the mean curve of the monotonic reference tests. This agrees with previous findings[10]. New in this study are the results for adhesive anchors. The residual load-displacement curves for the investigated bonded anchors (BA1, BA2, BA3), failing by bond failure, do not reach the mean curve of their monotonic reference tests. The tension load transfer mechanism for adhesive anchors in cracks, which relies on micro-interlock once adhesion is lost, often results in a spontaneous failure during crack cycling. This makes the **displacement capacity** of adhesive anchors during or after crack cycling more difficult to predict than for mechanical anchors.

Because load is constant during crack cycling, it is also useful to visualize time-histories to understand anchor behavior. Fig. 10 shows the anchor load and displacement as well as the crack width as a function of time for a tested undercut anchor UA1. It is noted that other investigated anchors showed a similar behavior. During crack cycling under sustained anchor tension load, the anchor slips when the crack is opened, and is held in place when the crack is closed. The amplitude of anchor displacement increment per cycle increases with increasing crack width amplitude. The **energy dissipation** by the anchor during crack cycling

is negligible ($N_w \cdot s_{cyc}$) because the load-displacement curves do not exhibit hysteresis (refer to Fig 7. and Fig. 8)

The anchor products tested in 0.5 mm and 0.8 mm (0.02 in. and 0.03 in.) cracks (EAs1, EAb1, SA1 and BA1) demonstrated that the **crack width** in a monotonic test as well as the maximum crack width during cycling have a significant influence on the test results. Larger crack widths result in reduced anchor capacities[24]. Furthermore, for a given anchor load, the incremental displacement during crack cycling increases with increasing crack width, resulting in a greater reduction of the residual capacity. For the tests presented in this paper, however, the permanent anchor loads applied during cyclic crack tests were defined as 0.4 times the mean failure load in monotonic reference tests which is lower for tests with w_{max} = 0.8 mm (0.03 in.) compared to tests with w_{max} = 0.5 mm (0.02 in.) cracks. For this reason, the reduction of residual capacity due to larger crack widths is counteracted by the increase due to lower sustained tension anchor loads (N_w). This may lead to larger ratios of $N_{u,cyc,m}$ / $N_{u,mon,m}$ for the cyclic crack tests with w_{max} = 0.8 mm (0.03 in.) when compared with tests conducted with w_{max} = 0.5 mm (0.02 in.).

Tests with increased number of crack cycles

Some seismic events may impose larger crack widths and an increased number of deformation cycles. For this reason, some of the anchor products were also tested with a target maximum crack width of w_{max} = 0.8 mm (0.03 in.) and with additional crack cycles. To this end, the number of crack cycles in each step of the crack protocol developed by Wood[15] were recalculated using a more stringent Rainflow cycle binning strategy, resulting in an additional 9 cycles across the crack width steps, thus an increase in number of crack cycle by about 30 %. Fig. 5 compares this crack protocol consisting of 41 cycles to the original protocol with 32 cycles. It is noted that while these protocol are similar to those found in

Wood's report[14], they are not identical. The development of the protocol was an iterative process with input from both the numerical and experimental studies.

Exploratory tests with the more severe cycle count were carried out on EAb1 and UC1 anchors installed in 0.8 mm (0.03 in.) cracks. Key results from these tests are presented in Table 3. Fig. 11 shows load-displacement curve for EAb1 along with the corresponding test conducted with original number of cycles for reference. The increased number of cycles resulted in substantially increased anchor displacements, however, the reduction in embedment depth was too small to significantly affect the residual capacities. This agrees with previous findings for undercut anchors under simulated seismic crack cycling[14]. It is noted that 7 out of the 9 additional cycles were added to the low amplitude cycles ($w \leq 0.5 \cdot w_{max}$). The effect of increased number of crack cycles would be more pronounced if more high amplitude cycles ($w > 0.5 \cdot w_{max}$) were added.

SUMMARY AND CONCLUSIONS

During earthquakes, structures undergo reversed cyclic deformation, which may cause opening and complete closing of cracks in reinforced concrete structures. If post-installed concrete anchors are located in these cracks, which is likely since anchors tend to attract cracks, the anchor behavior may be significantly affected by the crack cycling. This paper extends previous studies on the behavior of post-installed anchors during strong earthquakes by providing comprehensive experimental results utilizing a newly-developed stepwise-increasing crack cycling protocol. Five mechanical and three adhesive anchors that represent most common post-installed concrete anchor types and failure modes were tested. Monotonic tension tests with the anchors installed in 0.5 mm (0.02 in.) and 0.8 mm (0.03 in.) wide cracks were first performed. Subsequently, 40 % of mean monotonic failure load was applied as a sustained tension load on the anchors while the crack in which the anchor was installed

was cycled according to the new protocol. Zero crack width was assumed to correspond to a compressive stress applied to the test specimen equal to 12 % of the concrete compressive strength. Additional tests were performed in which the total number of crack cycles was increased by 30 %.

All anchors exhibited increased displacements during crack cycling. The increase was greater for larger maximum crack widths and a larger number of crack cycles. The tests demonstrated that the investigated undercut anchor could survive crack cycling expected during strong earthquakes. Moreover, the residual capacity of the undercut anchor was not reduced relative to its monotonic capacity. Similar results were observed for the investigated sleeve-type expansion anchor. The investigated bolt-type expansion anchors survived the simulated seismic crack cycling, but exhibited a 15 % reduction in the residual capacity. The investigated screw anchor and adhesive anchors showed significantly reduced performance during crack cycling, which is believed to be due to the small thread spacing (screw anchor) and micro-interlock (adhesive anchor) being damaged during the crack cycling. They may show an acceptable behavior if the seismic design strength of the anchor in tension is significantly reduced compared to the non-seismic design strength.

The tests described in this paper contributed to the development of the European guideline ETAG 001 Annex E[25], which is valid for seismic loading and introduces new test conditions and acceptance criteria, which are more demanding than the simulated seismic tests currently in ACI 355.2[2] and ACI 355.4[3].

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LIST OF NOTATIONS

d_0 = Borehole diameter

f'_c = Concrete compression strength

h_{ef} = Effective embedment

$s(N)$ = Axial displacement

s_{cyc} = Residual displacement after load cycling

v = Coefficient of variation

w = Crack width

w_{max} = Target maximum crack width

N_w = Permanent axial load

$N_{u,m}$ = Mean ultimate tension load

N_{Rk} = Characteristic resistance

N_{Ek} = Characteristic load

γ_F = Load safety factor

γ_M = Material safety factor

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Table 1 – Investigated anchors.

Anchor designation	Anchor type	Nominal size	Steel element diameter, mm (in.)	Embedment depth h_{ef}, mm (in.)
UA1	Undercut	M10	10 (0.39)	90 (3.54)
SA1	Screw	∅16	16 (0.63)	105 (4.13)
EAs1	Expansion, sleeve-type	M10	10 (0.39)	80 (3.15)
EAb1	Expansion, bolt-type	1/2”	12.3 (0.5)	83 (3.25)
EAb2		1/2”	12.3 (0.5)	86 (3.375)
BA1	Bonded epoxy-type	M12[b]	12 (0.47)	96 (3.78)
BA2		M12[b]	12 (0.47)	96 (3.78)
BA3	Bonded methacrylate -type	M12[b]	12 (0.47)	96 (3.78)

[a] UA: Undercut Anchor; SA: Screw anchor; EAs: Expansion anchor – sleeve-type; EAb: Expansion anchor – bolt-type; BA: Bonded anchor
[b] Threaded rod with f_y = 900 MPa (130 ksi) and f_u = 1000 MPa (145 ksi)

Table 2 – Tests conditions and key test results of monotonic reference tests and crack cycling tests (values reported as average of all test repeats).

Anchor designation[a]	Target crack width w_{max}, mm	Load. type[b]	Number of tests	Failure mode[c]	Sustained load N_w, kN	$N_{u,m}$, kN	$v^d(N_{u,m})$, %	$N_{u,cyc,m}$ / $N_{u,mon,m}$	s_{cyc}, mm	$s(N_u)_m$, mm	$v^d(s(N_u)_m)$, %	$s(N_{u,cyc})_m$ / $s(N_{u,mon})_m$
UA1	0.8	mon	3	C	13.7	34.2	5.7	1.25	1.39	1.64	11.8	3.87
		cyc	3	C		42.6	8.5			6.35	17.6	
EAs1	0.5	mon	3	C	15.6	38.9	15.3	0.97	2.71	6.54	62.6	1.49
		cyc	3	C		37.9	7.8			9.76	23.5	
	0.8	mon	3	C	11.0	27.5	7.6	1.09	8.07	6.12	61.7	2.66
		cyc	3	C		29.9	8.2			16.28	11.4	
EAb1	0.5	mon	3	Pt	10.1	25.2	6.6	0.94	7.30	7.94	13.0	1.96
		cyc	3	Pt		23.8	13.9			15.57	17.1	
	0.8	mon	3	Pt	8.7	21.8	7.3	0.85	12.15	10.98	10.1	1.85
		cyc	3	Pt		18.5	4.9			20.31	25.4	
EAb2	0.8	mon	3	Pt	6.7	16.3	3.2	0.84	9.24	10.61	16.3	1.61
		cyc	3	Pt		13.6	15.8			17.03	25.7	
SA1	0.5	mon	3	Po	14.4	34.3	4.7	0.57	1.97	2.69	35.4	1.49
		cyc	3	Po		19.5	4.1			4.01	9.7	
	0.8	mon	3	Po	7.7	19.2	33.0	0.88	1.49	3.07	9.2	1.18
		cyc	3	Po		17.0	24.8			3.63	11.4	
BA1	0.5	mon	3	B	31.3	78.2	8.1	$\rightarrow 0^e$	$\rightarrow \infty^e$	1.21	29.5	$\rightarrow\infty^e$
		cyc	2	B[e]		$\rightarrow 0^e$	$-^e$			$\rightarrow \infty^e$	$-^e$	
	0.8	mon	3	B	25.0	62.6	10.3	$\rightarrow 0^e$	$\rightarrow \infty^e$	1.67	32.5	$\rightarrow\infty^e$
		cyc	2	B[e]		$\rightarrow 0^e$	$-^e$			$\rightarrow \infty^e$	$-^e$	
BA2	0.8	mon	3	B	17.5	41.4	14.2	0.68	0.92	0.97	24.3	3.06
		cyc	2	B		27.8	32.6			2.98	5.5	
BA3	0.8	mon	3	B	12.4	29.4	8.0	$\rightarrow 0^e$	$\rightarrow \infty^e$	1.14	13.9	$\rightarrow\infty^e$
		cyc	2	B[e]		$\rightarrow 0^e$	$-^e$			$\rightarrow \infty^e$	$-^e$	

[a] UA: Undercut anchor; EAs: Expansion anchor – sleeve-type; EAb: Expansion anchor – bolt-type; BA: Bonded anchor
[b] mon = monotonic; cyc = cyclic
[c] Failure mode: C = Concrete breakout, Pt = pull-through, Po = Pullout, B = Bond failure
[d] Coefficient of variation for one standard deviation
[e] Pullout failure of all or some test repeats before completion of crack cycles
Note: Refer to Fig. 2 for explanation of variables; 1 mm = 0.0394 in.; 1 kN = 224.81 lbf.

Table 3 – Tests conditions and key test results of cyclic crack tests with increased number of cycles (values reported as average of all test repeats).

Anchor designation[a]	Target crack width w_{max}, mm	Load. type[b]	Number of tests	Failure mode[c]	Sustained load N_w, kN	$N_{u,m}$, kN	$v^d(N_{u,m})$, %	$N_{u,cyc,m}$ / $N_{u,mon,m}$	s_{cyc}, mm	$s(N_u)_m$, mm	$v^d(s(N_u)_m)$, %	$s(N_{u,cyc})_m$ / $s(N_{u,mon})_m$
UA1	0.8	cyc	3	C	18.2	45.2	7.0	1.32	4.94	12.61	28.9	7.69
EAb1	0.8	cyc	3	Pt	8.7	19.5	24.2	0.89	14.23	19.97	21.6	1.82

[a-d] Refer to Table 2

Note: Refer to Fig. 2 for explanation of variables; 1 mm = 0.0394 in.; 1 kN = 224.81 lbf.

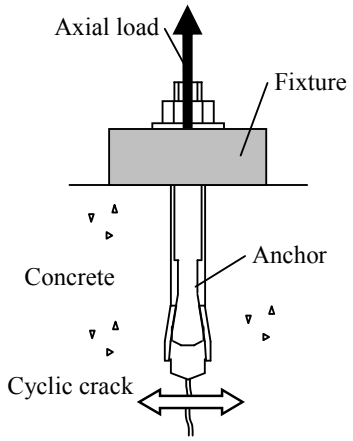


Fig. 1 – Concrete anchor loaded in tension and subjected to crack cycling.

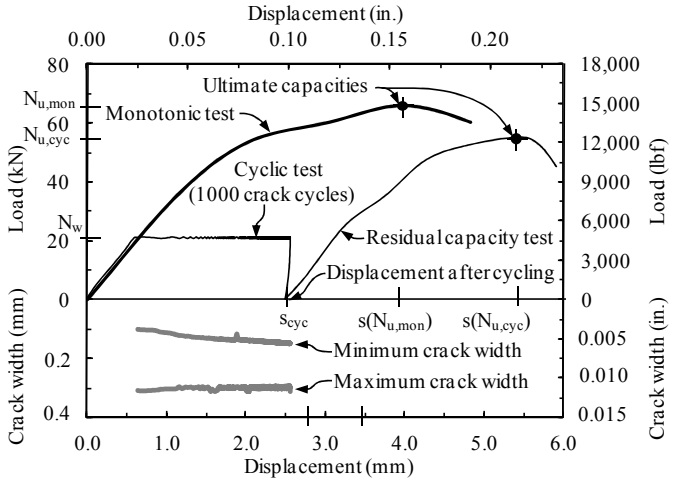


Fig. 2 – Sample load-displacement diagram for crack movement test (cyclic and residual capacity test) and corresponding mean curve of monotonic reference curve according to ACI 355.

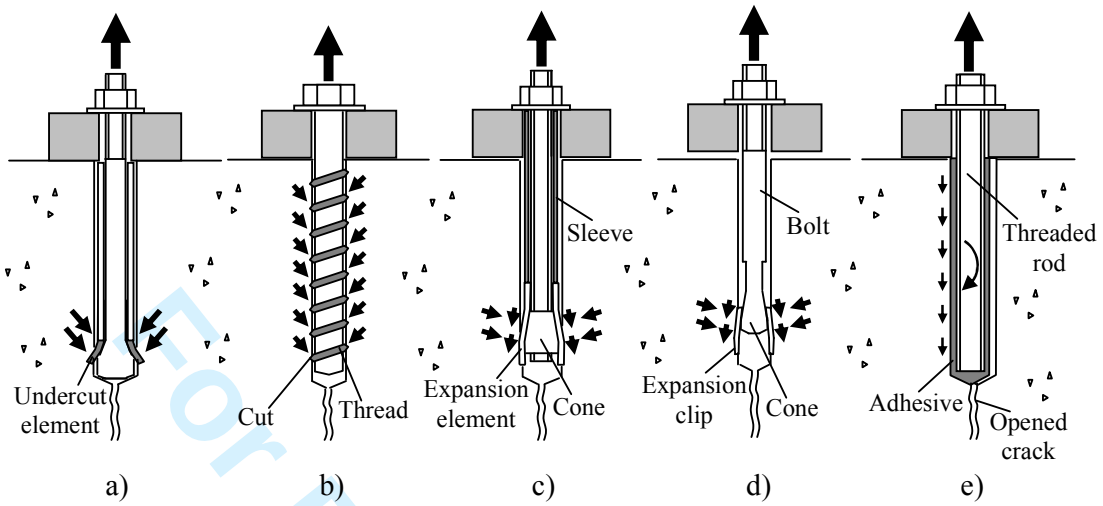


Fig. 3 – Tested anchor types with indicated transfer mechanism for tension load (located in opened crack): a) Undercut anchor (UC); b) Screw anchor (SA); c) Expansion anchor – sleeve-type (EAs); d) Expansion anchor – bolt-type (EAb); e) Bonded anchor (BA).

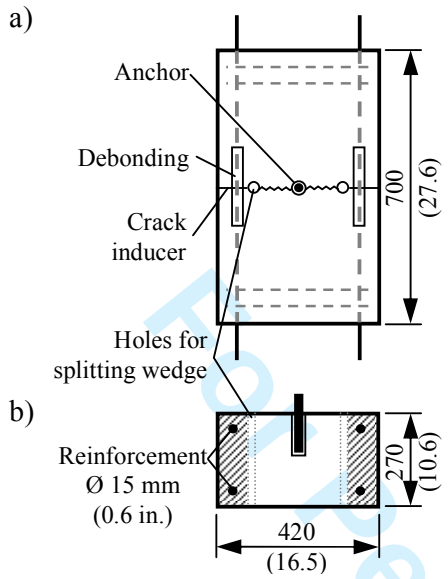
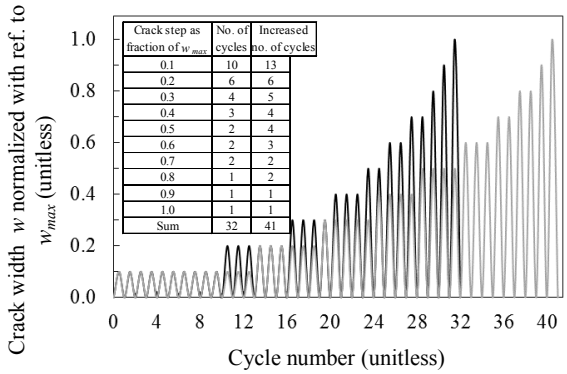
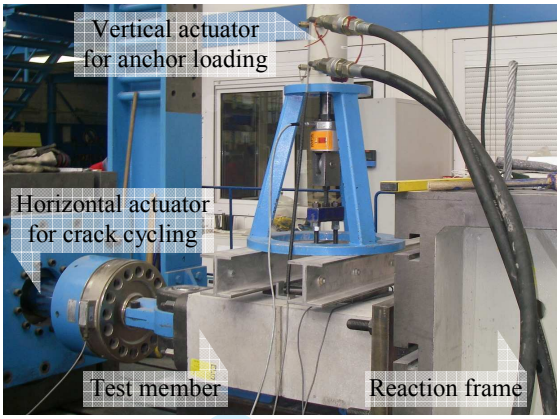


Fig. 4 – Strain-split concrete slab: a) Top view; b) Side view (units in mm (in.)).

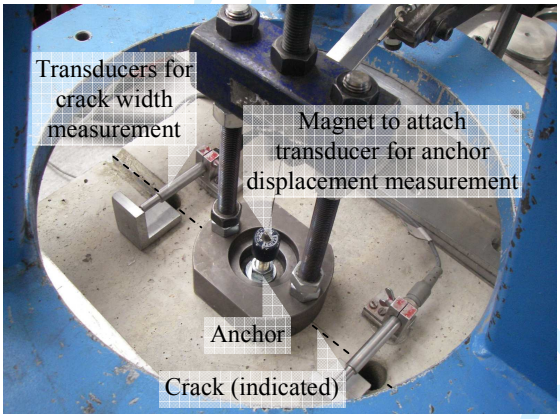


Crack step as fraction of w_{max}	No. of cycles	Increased no. of cycles
0.1	10	13
0.2	6	6
0.3	4	5
0.4	3	4
0.5	2	4
0.6	2	3
0.7	2	2
0.8	1	2
0.9	1	1
1.0	1	1
Sum	32	41

Fig. 5 – Cyclic crack protocol (increased number of crack cycles in grey).

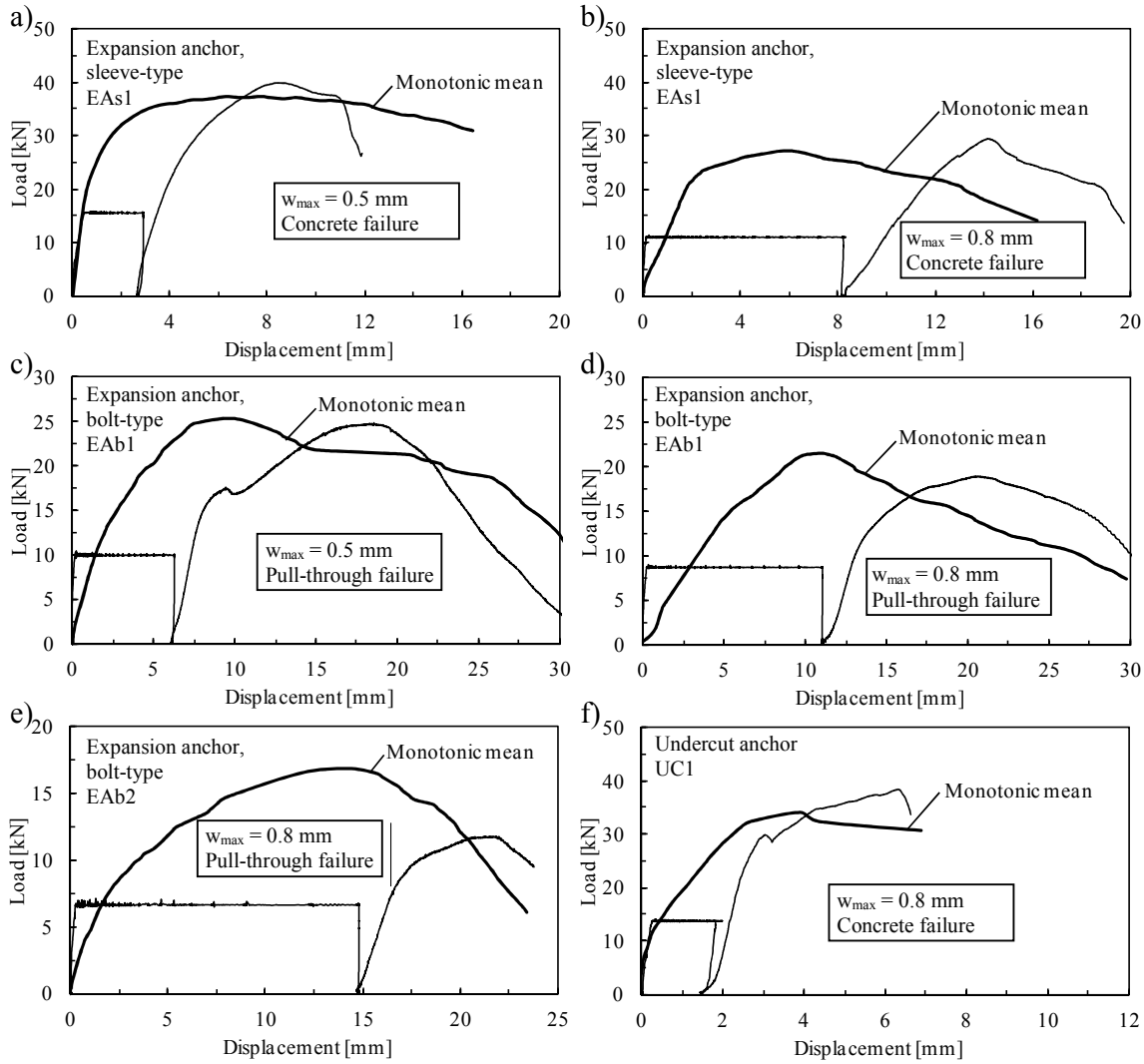


a)



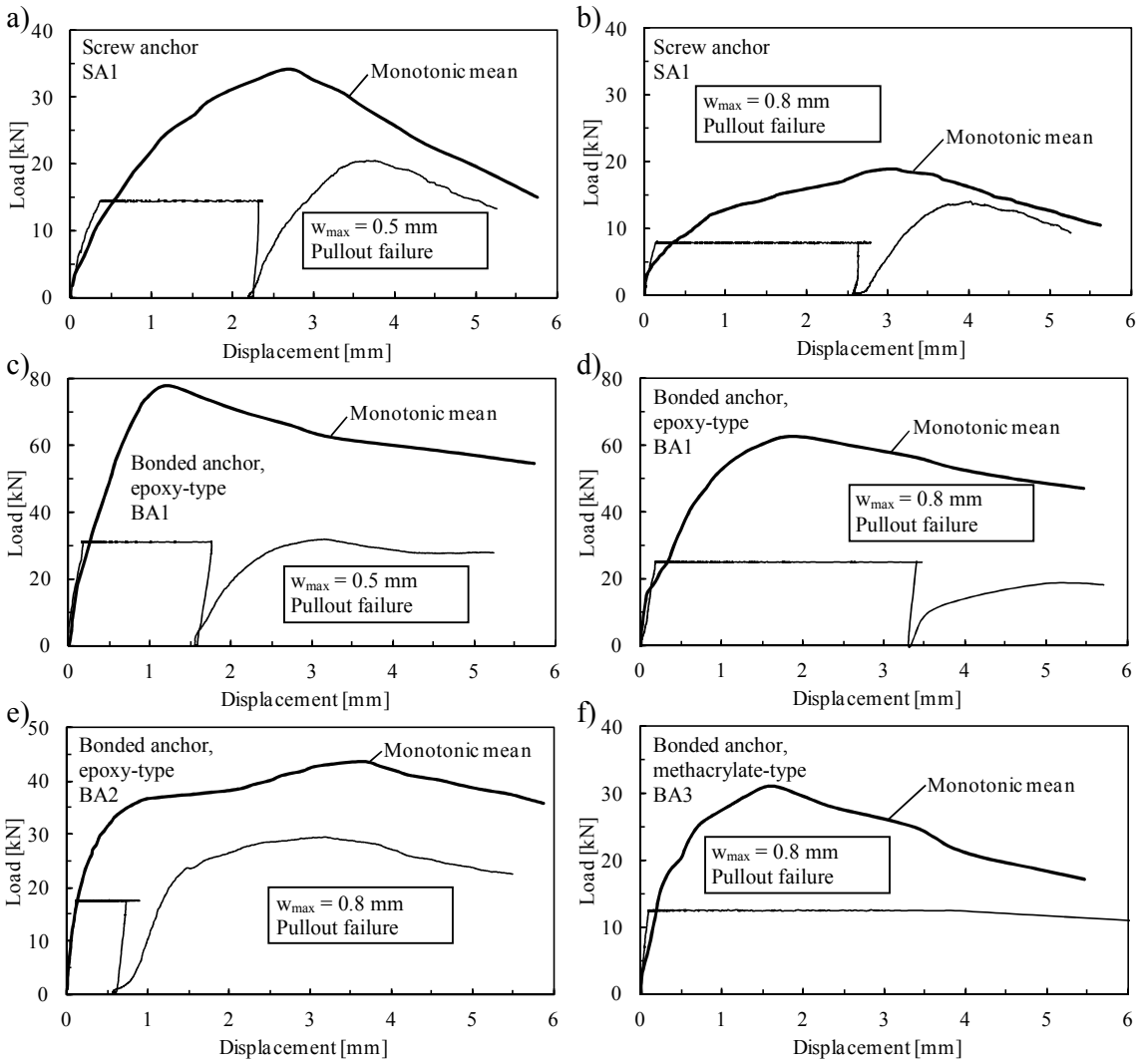
b)

Fig. 6 – Test setup: a) Strain-split concrete slab with horizontal and vertical actuators; b) Close-up of anchor and instrumentation.



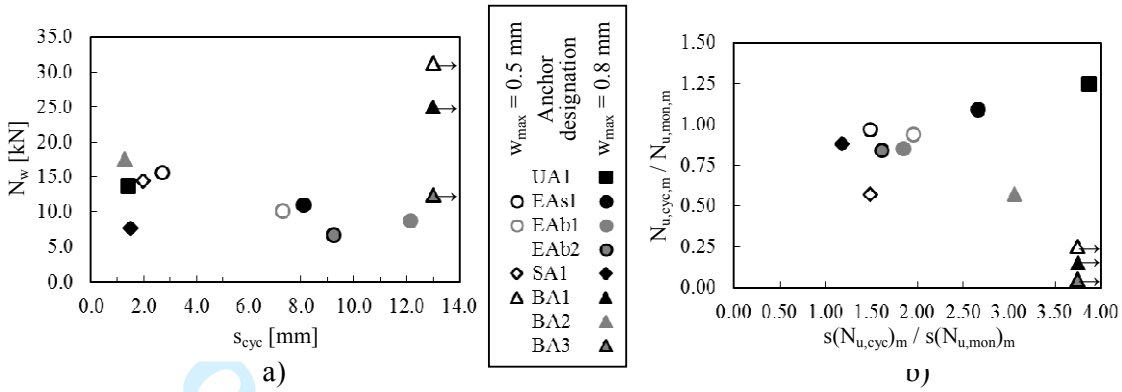
Note: 1 mm = 0.0394 in.; 1 kN = 224.81 lbf.

Fig. 7 – a) to f) Typical load-displacement curves of cyclic crack tests on undercut anchors and expansion anchors and corresponding mean curve of monotonic reference tests.



Note: 1 mm = 0.0394 in.; 1 kN = 224.81 lbf.

Fig. 8 – a) to f) Typical load-displacement curves of cyclic crack tests on screw anchors and bonded anchors and corresponding mean curve of monotonic reference tests.



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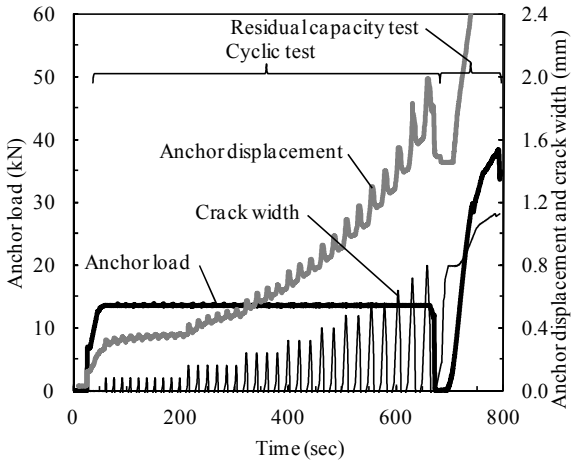
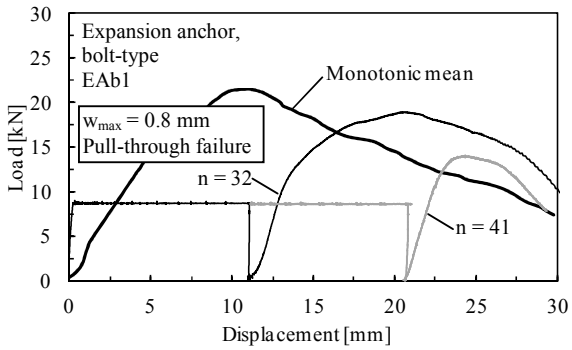


Fig. 10 – Anchor load and displacement as well as crack width as a function of time (example: undercut anchor with w_{max} = 0.8 mm (0.03 in.)).



Note: 1 mm = 0.0394 in.; 1 kN = 224.81 lbf.

Fig. 11 – Typical load-displacement curves of cyclic crack tests on expansion anchors – bolt-type with different numbers of crack cycles as well as corresponding mean curve of monotonic reference tests.