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BEHAVIOR OF POST-INSTALLED CONCRETE UNDERCUT ANCHORS SUBJECTED TO HIGH LOADING RATE AND CRACK CYCLING FREQUENCY

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ABSTRACT

Post-installed anchors are used for the connection of structural components including seismic retrofit measures (e.g. dampers or additional bracings and shear walls) and non-structural elements to the structure (e.g. façade elements). When testing the suitability of post-installed anchors for seismic application, several load aspects are investigated in separate tests. These are conducted at quasi-static loading rates well below the rates to be expected during a seismic event. This approach is neglecting the phenomenon of improved material properties due to short term loading which is known from material sciences. This paper presents the results of tests carried out to quantify the effect of high loading rates and crack cycling frequencies on the seismic anchor behavior.

Introduction

In general, the anchor load-displacement behavior is a function of the load acting on the anchor in any direction and the crack in which the anchor may be located. Since cracks have a significant negative influence on the anchor performance, the assumption that the anchor is always situated in a crack is conservative. This approach is particularly important when seismicity plays a role. As the structure responds to the ground motion, degradation of the global structure, which serves as the anchorage material, can occur. In reinforced concrete structures this degradation is in large part expressed through cracking in the structural elements. The cracks will open and close due to the cyclic response of the structure. Thus, a seismic event causes cycling of anchor load and cracks in the anchorage material simultaneously.

In order to reduce the complexity of simultaneous load and crack cycling testing, the loading conditions are approximated by separate tests. For each test either the load or the crack is cycled at most. Further, the effect of combined tension and shear loads is tested separately (Fig. 1). This approach is practical, less expensive and deemed to be conservative. At the end of each cyclic test, the residual capacity is determined by a monotonic pullout test.

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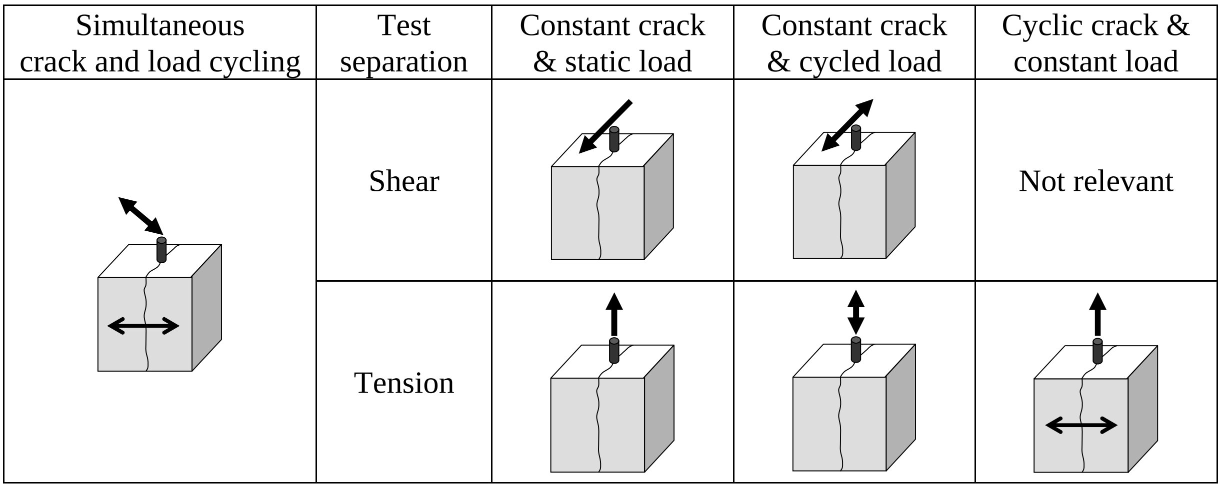

Figure 1. Simultaneous load and crack cycling tested by separate tests.

According to the relevant test standards, the assessment tests are performed under quasi-static loading conditions: The loading rate of tension and shear tests is 1 to 3 min to ultimate load, the crack cycling is performed within 1 or 2 min per cycle, and pulsating tension and alternating shear loads are applied with a maximum frequency of 0.2 Hz.

However, the actual loading rate, load frequency, and crack frequency will be higher during a seismic event. As known from material sciences, e.g. (Zielinski, A.J. 1982) quoted in (Curbach, M. 1987), short term loading may influence the concrete properties in a positive way. Hence, a concrete anchor loaded rapidly is expected to develop an increased initial stiffness. Another positive effect would be a higher ultimate load capacity and a smaller overall displacement. Fig. 2 shows a schematic diagram to illustrate the expected beneficial effects of high loading rates on the anchor load-displacement behavior.

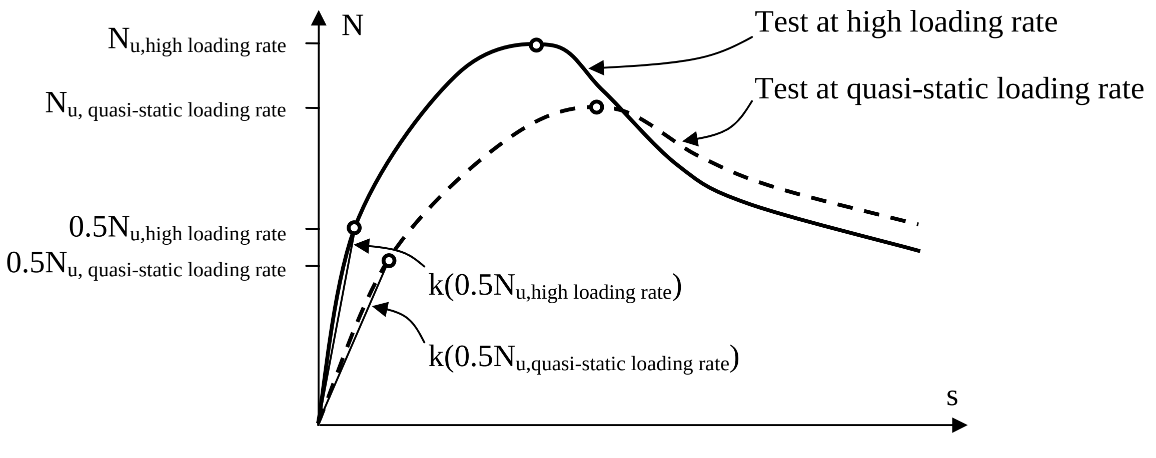

Figure 2. Schematic diagram of the anchor load-displacement behavior subjected to quasi-static and high loading rate.

In conclusion, testing under quasi-static conditions is deemed to be a conservative approach. This makes testing easier, but is neglecting the beneficial effects of higher loading conditions. As a consequence, the margin of safety is increased by an unknown factor which leads to less economic anchor design values. Even undercut anchors, considered to react stiff, exhibit total displacements larger than 3mm under seismic testing conditions according to DIBt NPP Guideline 1998. Such displacements have to be respected for the structural analysis, making the design of fixations often difficult and uneconomic.

Monotonic and cyclic tests in shear and tension as well as crack cycling tests carried out at rates and frequencies typical for seismic events are required to quantify the beneficial effects of higher loading rates. The results could give evidence whether the testing conditions may be relaxed considering a possible reserve of resistance. A relaxation of the evaluation criteria would potentially lead to reduced displacements and increased capacities stipulated in the anchor approval.

Experiments

Test Standard and Setup

For most anchor types (undercut, expansion, bonded anchors), seismically induced crack cycling in the anchorage material rather than load cycling on the anchor is decisive for the anchor performance. However, simulated seismic crack cycling is not considered in both, the US-American anchor approval guidelines ACI 355.2-07 2007 and in the European approval guideline ETAG 001 2007. Simulated seismic tension and shear load tests are included in ACI 355.2-07 2007, but currently not in ETAG 001 2007. Therefore, the tests for this study have been performed based on the German DIBt NPP Guideline 1998, which is the only published approval guideline considering simulated seismic crack tests known to the authors. The application of this standard is mandatory for anchors used in German nuclear power plants (NPP) and is valid for undercut anchors which are approved according to ETAG 001 2007.

In order to investigate the influence of the high loading rate best, undercut anchors were tested (Fig. 3). Undercut anchors are widely used in nuclear power plants because their mechanical interlock facilitates smaller load displacements, compared to other anchors, at a high safety level. In addition, the effects of high loading rates on the fracture mechanic is not interfered by other effects such as friction (clip of expansion anchor) and visco-elasticity (mortar of bonded anchor).

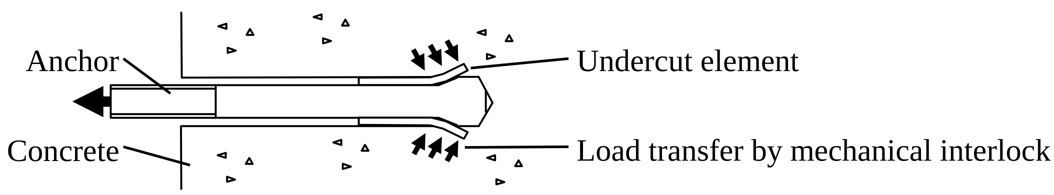

Figure 3. Undercut anchor and its load transfer mechanism (schematically).

The test schemes specified in DIBt NPP Guideline 1998 for monotonic and cyclic tension and shear tests are similar to those described in ACI 355.2-07 2007 and therefore not explained in detail in this paper. The cyclic crack test, however, is not part of the ACI 355.2-07 2007 and thus the setup used for this study is briefly described in the following.

The cyclic crack test is generally considered as the most demanding seismic test type. The displacement sensitiveness of the anchor towards the actual crack width required a test setup that enabled a high accuracy at high crack cycling frequencies.

The anchors were installed in a prefabricated concrete members (dimension 700/400/200 (L/W/H), f_c' = 24 N/mm²) with four high strength tie rods protruding at both ends (Fig. 4). Two thin metal sheets were embedded in the centre at both sides to aid the crack formation. The tie rods were debonded at both sides of these crack inducers, to enable large cracks.

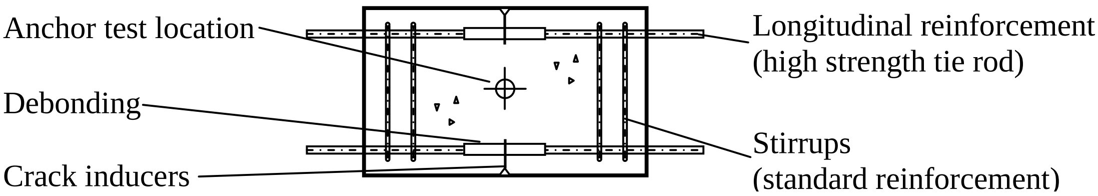

Figure 4. Horizontal section of concrete member used for cyclic crack tests.

At one side the tie rods were connected with a fixed bearing, at the other side with a servo controlled actuator for crack generation (Fig. 5). The servo control system used the input signal of an LVDT measuring the crack width to control the forces applied on the concrete member. A second servo controlled actuator mounted on a steel support was used for anchor loading.

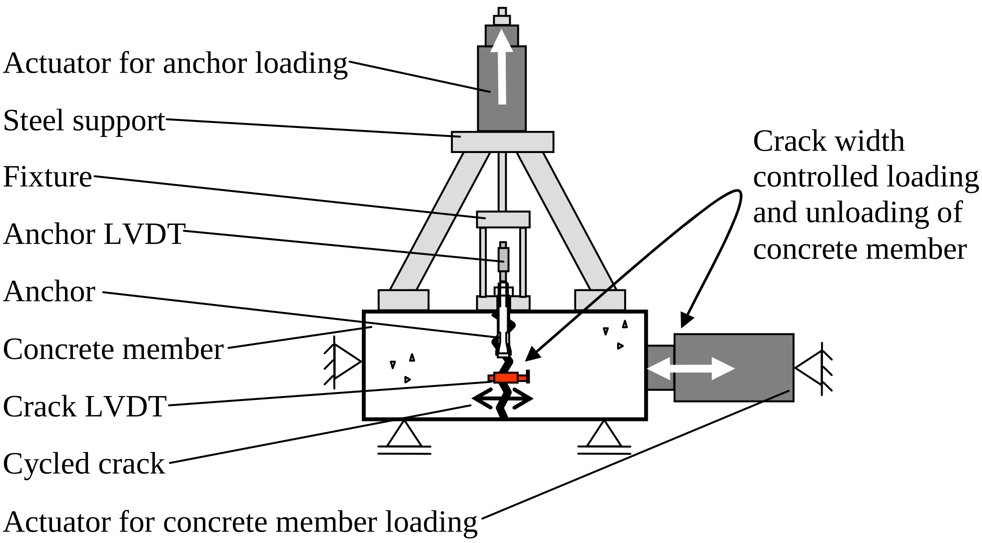

Figure 5. Side elevation of test setup used for cyclic crack tests.

Test Program and Parameter

Technically relevant earthquake induced oscillations range between a frequency of 1Hz and 10 Hz (Eibl, J., and Keintzel, E. 1989, Hoehler, M. S. 2006). This results in periods between 1s and 0.1s. Loading rates t_{Rise} between 0.25s and 0.025s are required to reach the ultimate load within a quarter of a period. Tab. 1 shows the concluded definition for the quasi-static, medium and high rates and frequencies. The quasi-static rate and frequency will not cause any dynamic effects on the material. The medium rate and frequency was defined as the lower value, the high rate and frequency as the upper value anticipated for seismic events. Due to technical reasons, 5Hz was chosen as the maximum frequency for cyclic shear and cyclic crack test.

Table 1. Definition of loading rate, load cycling frequency and crack cycling frequency.

Rate and frequency	**Loading rate (rise time t_{Rise})**	**Load cycling frequency f_{load}**	**Crack cycling frequency f_{crack}**
Quasi-static	180s	0.1Hz	0.005Hz
Medium	0.25s	1Hz	1Hz
High	0.025s	5Hz / 10Hz	5Hz / 10Hz

The DIBt NPP Guideline 1998 specifies as the maximum crack width 1.5mm which is hardly to be achieved at 5Hz crack cycling even for well equipped test labs. Therefore, the maximum crack width was reduced at cyclic crack tests to 0.8mm since any significant effect due to increased rates and frequencies should still be detectable. Tab. 2 comprises the test program. The determination of the cyclic load level bases on the characteristic resistances N_{Rk} and V_{Rk} for the service load condition in 0.3mm cracks. They were taken from the relevant approval report.

Table 2. Test program.

Test type	**Monotonic shear**	**Cyclic shear**	**Monotonic tension***	**Cyclic tension**	**Cyclic crack**
Anchor size	M10	M10	M12	M12	M12
Crack width	1.0mm	1.0mm	0.7mm	1.5mm	0.5 – 0.8mm
Number of cycles	-	15	-	15	10
Maximum a. minimum cyclic load	-	$V_{max}=V_{Rk}/\gamma_M$ $V_{min}=-V_{max}$	-	$N_{max}=N_{Rk}/\gamma_M$ $N_{min}=0kN$	-
Constant load	-	-	-	-	$N_w=N_{Rk}/\gamma_M$
Rate and frequency	**Number of tests**				
Quasi-static	3	3	6	5	5
Medium	3	3	-	5	5
High	3	3	6	5	5

*Evaluation of available test result (Eibl, J., and Keintzel, E. 1989)

Results and Evaluation of Experimental Results

In the following, the results for the displacement at half the ultimate load $s(0.5V_u)/s(0.5N_u)$, the initial stiffness $k(0.5V_u)/k(0.5N_u)$, the displacement at ultimate load $s(V_u)/s(N_u)$, and the ultimate load V_u/N_u, are given for each test type separately. All values in the diagrams are normalized with reference to the quasi-static test because the aim of the study was to determine the relative influence of the loading condition.

For the evaluation of the displacement and the stiffness during the final pullout, the displacement already present after cycling s_n is deducted. This is indicated by an asterisk at the annotation of the diagrams ($s^*(0.5V_u)/s^*(0.5N_u)/s^*(V_u)/s^*(N_u)/k^*(0.5V_u)/k^*(0.5N_u)$). In addition, the displacement accumulated during cycling minus the initial displacement s_n-s_1 is shown in the diagrams of cyclic tests. These displacements often dominate the overall load-displacement behavior of anchors and are crucial in the course of anchor assessments.

Monotonic Shear Load Tests

The influence of the loading rate on the load-displacement behavior at monotonic shear load tests is limited (Fig. 6). The displacements $s(0.5V_u)$, $s(V_u)$ and stiffness $k(0.5V_u)$ vary between ±20% but no clear tendency can be identified. In the contrary, the ultimate load V_u is increased by about 20% due to higher loading rates.

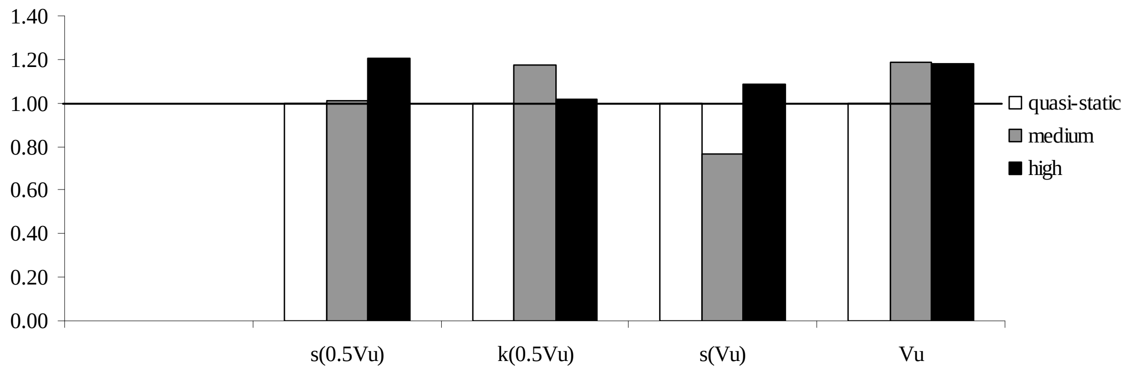

Figure 6. Mean monotonic shear load test results in constant 1.0mm cracks normalized with reference to quasi-static test results.

Cyclic Shear Load Tests

The influence of the load cycling frequency on the displacement s_n-s_1 during load cycling is inconsistent (Fig. 7). Surprisingly, the displacement at half the ultimate load $s^*(0.5V_u)$ increased and, in return, the initial stiffness $k^*(0.5V_u)$ decreased for medium and high rates. A reason for this could not be found. Further, higher loading rates lifted the ultimate load V_u by almost 20%.

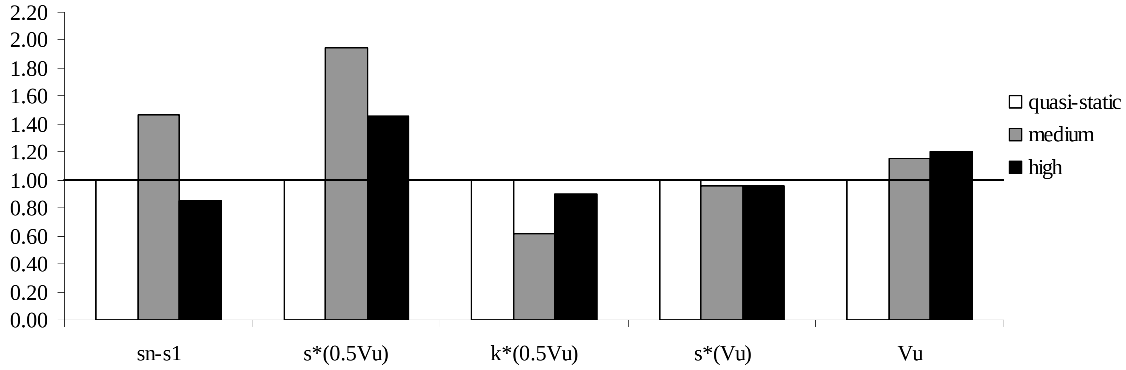

Figure 7. Mean cyclic shear load test results in constant 1.0mm cracks normalized with reference to quasi-static test results.

Monotonic Tension Load Tests

The anchors pulled out at high loading rate exhibit a 24% higher capacity N_u in comparison to the anchors pulled out at a quasi-static loading rate (Fig. 8). The displacement at half the ultimate load $s(0.5N_u)$ remains almost constant though the initial stiffness $k(0.5N_u)$ is increased by 15%.

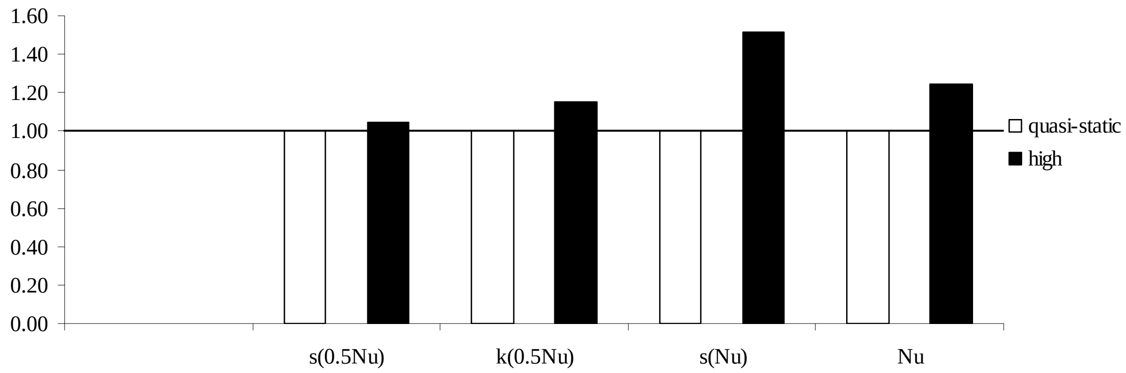

Figure 8. Mean monotonic tension load test results in constant 1.5mm cracks normalized with reference to quasi-static test results.

Cyclic Tension Load Tests

The load cycling frequency has little influence on the displacement s_n-s_1 during load cycling. No clear trend can be identified for the influence of the loading rate on the displacements $s^*(0.5N_u)$, $s^*(N_u)$ and the stiffness $k^*(0.5N_u)$ (Fig. 9). An influence on the ultimate load N_u is not detectable.

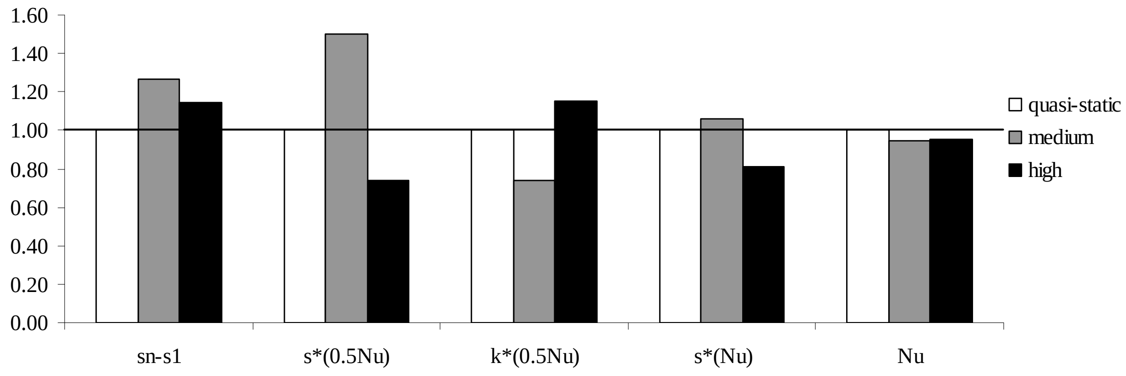

Figure 9. Mean cyclic tension load test results in constant 1.0mm cracks normalized with reference to quasi-static test results.

Cyclic Crack Tests

Fig. 10 demonstrates an unexpected and significant increase (+70%) of the anchor displacement during cycling s_n-s_1 at medium frequencies whereas the increase at high frequencies is considerably less pronounced (+20%). However, the displacements s*(0.5N_u) decreased by roughly 20% as anticipated but s*(N_u) does not show a clear trend. At this test series, higher pullout rates increased the stiffness k*(0.5N_u) by about 40% whereas no influence on the ultimate load was observed.

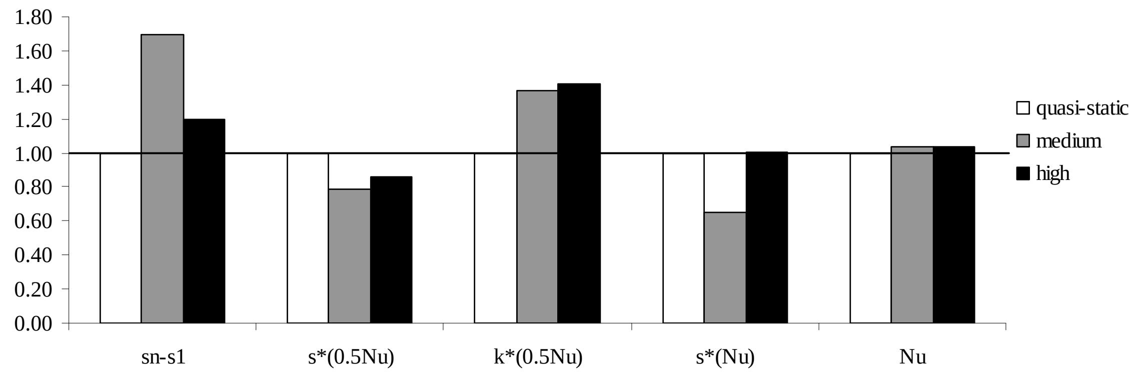

Figure 10. Mean cyclic crack test results with 0.8mm maximum cracks normalized with reference to quasi-static test results.

Conclusions

Undercut anchors were tested by earthquake relevant loading rates and frequencies, and crack cycling frequencies. Their effect on the load-displacement behavior was investigated and assessed.

Contrary to what could be expected according to the general material sciences, statistically significant reduction of the displacements at half the ultimate load could not be inferred. Further, a clear relationship between the initial stiffness and the loading rate does not exist. The high scatter (COV up to 60%) of the results is preventing any statistically sound interpretations.

The displacements during load and crack cycling show large scatter. Therefore, and due to the lack of any meaningful mechanical interpretation, the measured increase of the displacements for higher load and crack cycling frequencies is deemed to be of statistical nature has to be put into question.

The ultimate loads increase up to 20% for all tests at medium and high rates except for the cyclic tension load tests and cyclic crack tests.

Conclusively it can be stated, that high loading conditions neither reduce the displacements nor increase the ultimate load of anchors significantly. A relaxation of the evaluation criteria of approval guidelines cannot be justified. The displacements determined by quasi-static assessment tests cannot be reduced for the seismic design.

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