



## SEISMIC DISPLACEMENT BEHAVIOR OF ANCHORS CONNECTING NONSTRUCTURAL COMPONENTS TO CYCLING CRACKED CONCRETE

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### ABSTRACT

Post-installed anchors are often used to fix nonstructural components and systems (NCS) to concrete. For applications in earthquake prone areas, the anchors have to be qualified for the extreme demands arising from seismic actions. As the structure responds to the ground motion, the anchor loads develop according to the inertial response of the NCS to the floor acceleration. Simultaneously, cracks in the concrete member the NCS is attached to open and close cyclically. As a result, the anchors displace substantially, which may render the NCS inoperable. The anchor behavior under this complex load demand condition was investigated by shake table tests. For these tests, a suspended model component was connected to a cyclically cracked concrete slab by means of post-installed anchors. The effects of anchor type, as well as anchor load level and maximum crack width on the resulting anchor displacements were investigated. This paper presents the experimental test setup and describes the measured dynamic behavior of the anchored component. Displacement data is presented and compared to results obtained from quasi-static tests carried out on isolated anchors for seismic qualification. The findings help to evaluate new testing procedures for seismic anchor qualification.

### INTRODUCTION

Nonstructural components and systems (NCS) may be broadly categorized as mechanical-electrical-plumbing (MEP), architectural, or contents. Importantly, NCSs are designed to facilitate the service needs of a building, and for this reason are not considered explicitly in the seismic design of the primary structure, nor intended to contribute as a load carrying element (Eurocode 8 (2006), ASCE 7 (2010)). Poor seismic performance in past earthquakes has shifted NCSs into the focus of the seismic research community (e.g. Gould and Griffin 2003, Taghavi and Miranda 2003, Whittaker and Soong 2003). It was concluded that, first, the NCSs generally represent the major portion of the total building investment costs and thus represent a large potential loss. Second, damage to NCSs in buildings is usually triggered at levels of deformation much smaller than those required to initiate structural damage. Third, important economic loss can result from a temporary loss of function due to NCS failure. However, anchorage especially of an NCS is often neglected in the design process, potentially leading to earthquake damage and significant economic losses caused by anchor failure (e.g. Marxer et al. 2003, Griffin and Winn 2009, Masek and Ridge 2009, Zareian et al. 2012).

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NCSs are connected to concrete structures either by cast-in-place or by post-installed anchors. Due to their flexibility and easy handling, post-installed anchors have clear advantages over cast-in-place anchors. However, earthquakes are very demanding for post-installed anchors as seismic actions cause substantial anchor displacement and may result in severe reduction of load capacity. Moreover, as the primary structure responds to the ground motion, it oscillates and its deformation leads to degradation, which can be potentially significant in the case of reinforced concrete structures. This degradation is in large part expressed through cracking in the structural elements. Considering this scenario, the primary structure serves as a filter, which amplifies the ground acceleration  $a_g$  near the natural frequencies of the structure. The floor level acceleration  $a_{\text{floor}}$  varies throughout the height and location of the building. The inertial response of the NCS to the acceleration of the floor they are connected to then results in further amplification of the acceleration  $a_{\text{NCS}}$  (Fig. 1).

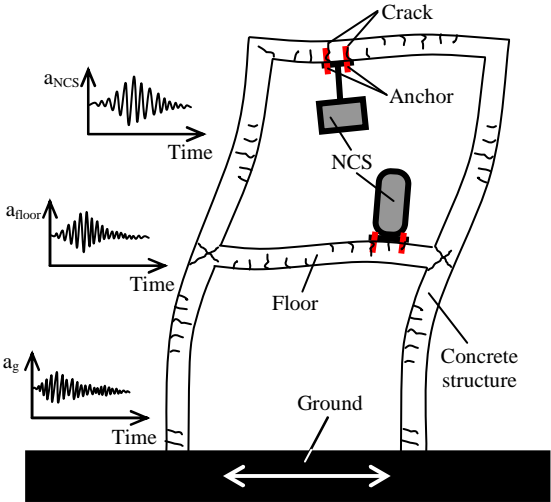


Figure 1. Structure and NCS response to earthquake motion

The connecting anchors are loaded according to the resulting forces. The anchor displacement in turn feeds back the NCS behavior by modifying its eigenfrequency. To study this complex interaction, shake table tests were conducted at the University of California, San Diego (UCSD) as part of an international research project on seismic performance of anchors. For these tests, a suspended model component was connected by anchors to a cyclically cracked concrete slab and subjected to floor accelerations. Further tests were carried out at the Institute for Construction Materials (IWB) of the University of Stuttgart, Germany. The later tests involved isolated anchors tested using load and crack cycling test protocols. In this paper, expansion and undercut anchor types test results are presented (Fig. 2).

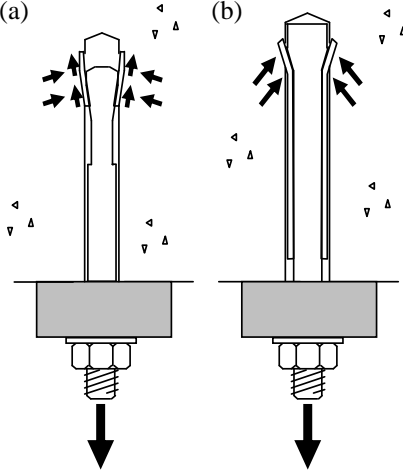


Figure 2. Post-installed anchor types tested: (a) Expansion anchor; (b) Undercut anchor

Expansion anchors less stiff and more sensitive to large cracks when compared to undercut anchors. Further details on these anchor types and their specific load-displacement characteristics can be found in Eligehausen et al. (2006).

## DYNAMIC SHAKE TABLE TESTS

### Test Approach, Setup, and Procedure

During a seismic event, the excited reinforced concrete primary structure and attached NCS are loaded cyclically. As a consequence, the seismic event causes simultaneous cycling of the anchor loads and of the crack widths in the concrete elements to which the NCSs are connected. Since cracks have a significant negative influence on the anchor performance in general, in design it is conservatively assumed that the anchor is always situated in an open crack.

For the dynamic tests reported herein, the anchor performance was investigated by using a model NCS component, which was fixed to a model concrete slab via four post-installed anchors. The test setup was designed to mimic the floor acceleration and corresponding crack behavior anticipated in a concrete structure during a scenario earthquake. The main elements of the test setup are the shake table, an elevated steel frame, the loading rig, the concrete slab and the NCS model component (Fig. 3).

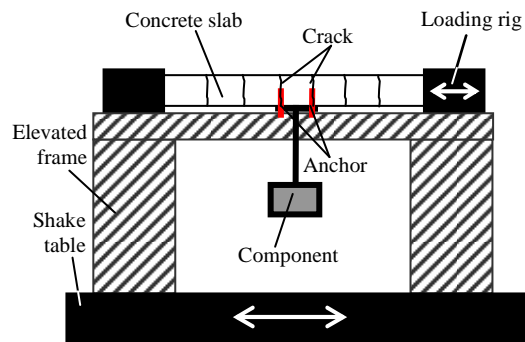


Figure 3. Schematic of shake table test setup

The total mass of the elevated test setup is approximately 8750 kg, with a center of gravity at approximately 1775 mm above the shake table floor and total height of nearly 3 m. The single axis shake table (3050 x 4875 mm plan platen dimension) is operated by a single, double acting actuator (445 kN nominal capacity) allowing a maximal acceleration of the unloaded table of 9g. The elevated steel frame was assembled by steel sections forming a stiff frame (4064 x 2133 mm side elevation). The picture in Fig. 4 captures the complete test setup.

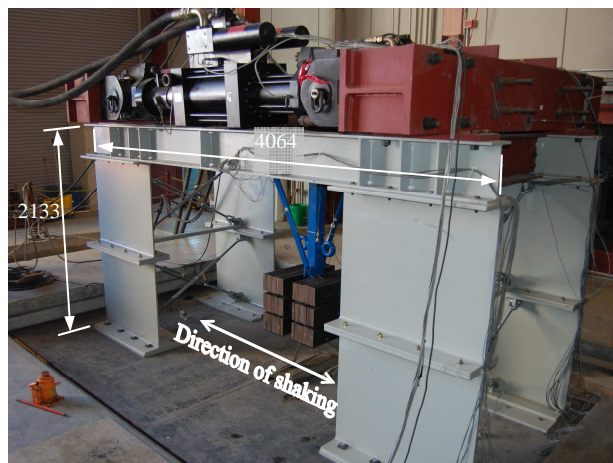


Figure 4. Picture of test setup (all units in mm)

The loading rig (3238 x 2438 mm plan view) consisted basically of two head beams coupled with a pair of servo hydraulic actuators. The head beams of the loading rig were mounted on the two longitudinal beams of the elevated frame. One head was permanently fixed while the other rested on sliding plates allowing free movement in the longitudinal direction (parallel with shaking direction). The longitudinal reinforcement in the slabs consisted of four high strength bars, with the protruding ends connected to the head beams of the loading rig. The actuators (735 kN each) allowed opening and closing of the cracks in the concrete slab dynamically. The model concrete slab (2438 x 1067 x 254 mm) represents any type of concrete component (e.g. a beam or slab) that a nonstructural component may be anchored to. It was constructed of normal weight concrete with a nominal concrete compressive strength of  $f'_c = 25$  MPa and detailed to crack at 330 mm spacing using steel sheet metal crack inducers.

The footing of the component was fixed to the soffit of the concrete slab by means of four anchors (Fig. 5). The suspended installation was chosen since this configuration permanently loads the anchor and therefore represents the more critical condition, when compared with floor-mounted installations, which would benefit from natural re-centering during seismic excitation. The total weight of the suspended model component was 11.3 kN and its fundamental period was determined to 0.25 seconds. It should be noted that the model component was designed to remain elastic during seismic shaking, such that all nonlinear action would be concentrated at the anchorage. To investigate the impact of anchor type on the anchor load and displacement demands, tests were carried out on undercut anchors and expansion anchors. In each case, all four anchors were located in the predefined crack positions. In addition, a test series was conducted on the undercut anchor type for which only one anchor pair was located in a crack while the other anchor pair was installed in uncracked concrete (Fig. 6).

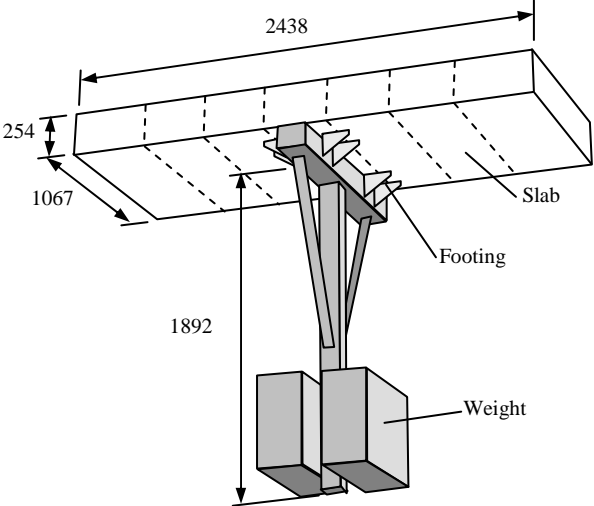


Figure 5. Isometric view of component anchored in slab (all units in mm)

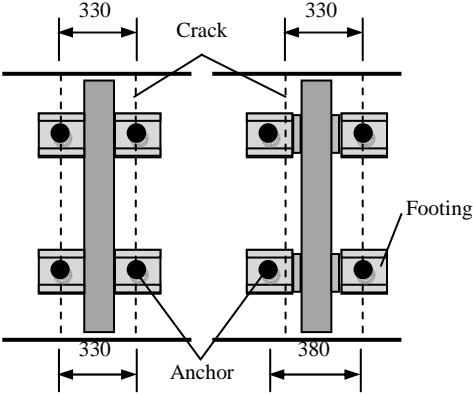


Figure 6. Configuration with a) both anchor pairs located in a crack and b) only one anchor pair located in a crack (all units in mm)

A detailed description of the loading rig, the model slab and model component is available in Watkins et al. (2012). The control command files for the shake table and the loading rig actuators were based on nonlinear simulations of representative reinforced concrete structures presented in Wood and Hutchinson (2012). Frame structures with 2, 4, 8, 12, and 20 stories were subjected to 21 ground motion time histories of real earthquake records. The numerical simulation of the seismic response yielded specific floor acceleration and corresponding curvature time histories. For the test program discussed in the following, 11 floor motions were selected (Table 1).

Table 1. Selected floor motions used in the test program including the basic building details

Floor Motion	EQ <sup>1)</sup> Record	PFA <sup>2)</sup> 100% (g)	Sa <sup>3)</sup> @ T <sub>1</sub> =0.25sec (g)	Building	
				Height (story)	Floor (story)
FM01	K	0.950	7.28	2	1
FM02	N	1.371	13.8	2	1
FM03	S	0.592	1.54	4	1
FM04	N	0.786	1.71	4	2
FM05	K	0.450	2.71	8	5
FM06	S	0.564	2.52	12	2
FM07	S	0.596	1.57	12	5
FM08	K	0.401	1.13	12	10
FM09	K	0.450	1.95	20	4
FM10	S	0.460	1.45	20	9
FM11	S	0.475	0.76	20	18

<sup>1)</sup> Earthquake: K = Kobe 1995, N = Northridge 1994, S = Superstition 1987;

<sup>2)</sup> PFA: Peak floor acceleration for 100% scale; <sup>3)</sup> Sa: Spectral acceleration at 0.25 sec calculated at 5% damping

It should be noted that a linear relationship between curvature and crack width was adopted, assuming that the NCS would be anchored in a region outside of the plastic hinge zone of any structural component. Anchoring within the plastic hinge zone is not allowed in the anchor design codes (ACI 318 (2011), CEN/TS 1992-4 (2009)). For the tests covered in this paper, a maximum anchor load equal to the seismic design strength was targeted. This load level fully utilizes the nominal anchor capacity and represents the highest load the anchor can be designed for. The seismic strength was taken as the characteristic strength  $N_{Rk,seis}$  evaluated by load and crack cycling tests on isolated anchors as briefly introduced in the section on quasi-static qualification tests of this paper. Utilizing this method, the targeted maximum anchor loads were 24 kN for the undercut anchor and 11 kN for the expansion anchor. To evaluate the influence of the crack width on the anchor performance, maximum crack widths of 0.5 or 0.8 mm were targeted. A value of 0.5 mm is the maximum crack width adopted in current anchor qualification guidelines (ACI 355.2 (2007), ETAG 001 (2006)). A value of 0.8 mm is deemed in excess of these potentially realized in design earthquake scenarios, just outside of plastic hinge zones. Further details regarding the testing conditions can be found in Mahrenholtz et al. (2012).

The response of the model slab, model component and anchors was measured by various sensors, namely displacement transducers, load cells, accelerometers and strain gages. Furthermore, information was collected from the shake table and loading rig actuators, including the displacement, velocity, and acceleration, to control floor acceleration and cracking. In total, 84 data acquisition channels recorded information at a sampling rate of 200 Hz. In the context of this paper, the anchor loads, anchor displacements, and crack widths at the anchor locations are the focused key measurements.

### Experimental Results and Discussion

During shaking, the horizontal acceleration of the model component creates inertial forces, which are transferred as tension loads to the anchors connecting the component to the concrete. As a result of earthquake and dead loads, the anchors displace and the component rotates around its footing (Fig. 7). Further information on the load transfer mechanism as well as on the analysis of spectral accelerations

can be found in Mahrenholtz et al. (2012). After shaking, the anchor displacement may be severe, and in these tests under design level earthquake scenarios were clearly visible (Fig. 8).

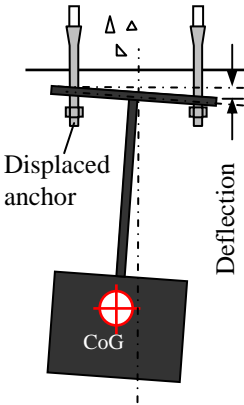


Figure 7. Schematic of rotating model component during shaking

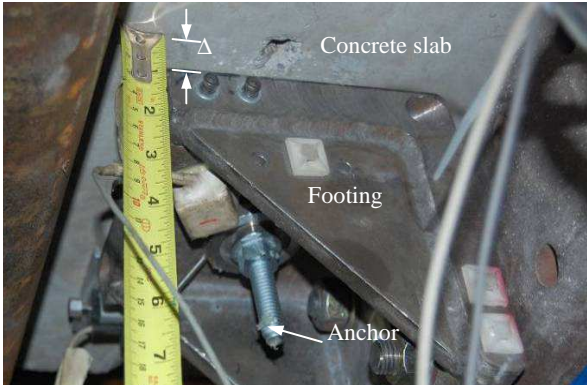


Figure 8. Example picture showing the observed displaced anchor after shaking

Fig. 9 shows the anchor displacement behavior during the complete shaking action for one test. The records of the earthquake motions used lasted approximately 20 to 30 seconds. It can be clearly seen that during the strongest amplitude motion period of shaking (approximately 10 to 13 seconds), which correspond to the largest amplitude crack widths, the increases in cumulative displacement of the anchor is most pronounced. With ongoing shaking, the anchor displacement cumulates rendering a residual displacement  $s_{res}$  at the end of the motion.

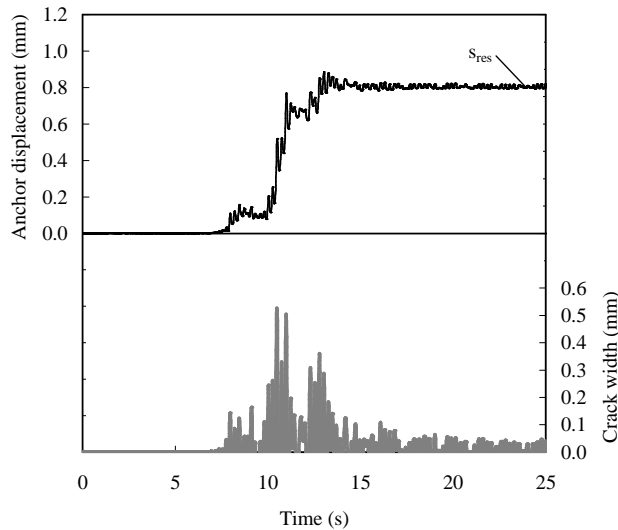


Figure 9. Time histories of anchor displacement and crack width during shake table test (example: Expansion anchor FM01, 15% scaling, 0.5 mm targeted maximum crack width, SE anchor)

The time histories in Fig. 10 illustrate the anchor displacement and component deflection history, now zoomed into the largest amplitude shaking intensity region in time. When the deflection matches the anchor displacement, the opposite footings are in contact with the concrete. It can be clearly seen that the footings are cyclically touching the concrete as long as anchor loads and displacements increase. Once the acceleration acting on the component decreases, the deflection of the component decreases and the footings do not touch the concrete anymore.

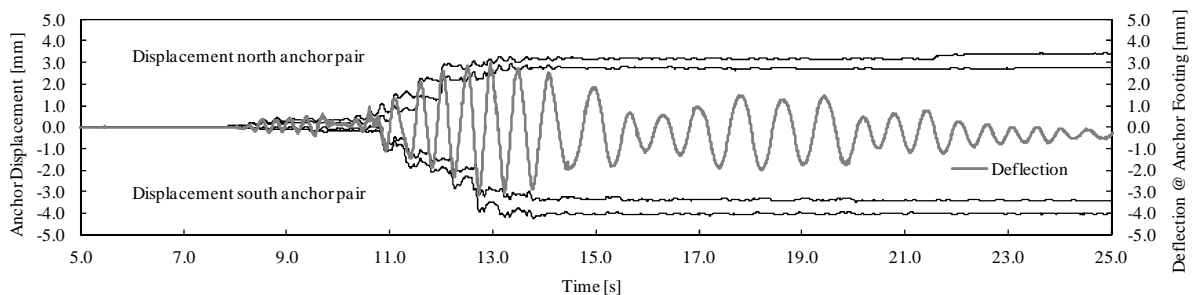


Figure 10. Time histories of anchor displacement and component deflection (example: FM01, 15% scaling, 0.8 mm targeted maximum crack width)

The anchor displacement evolves from the seismic demand imposed as anchor load and crack width oscillate, these in turn depend on the characteristics of the underlying floor acceleration and crack width time histories. Fig. 11 shows the residual anchor displacement for all tested floor motions, presented as the average of the four anchor locations. The displacements are smaller for 0.5 mm crack widths, when compared with the 0.8 mm maximum crack widths cases. Likewise,  $s_{res}$  is smaller for the stiffer undercut anchors than for the expansion anchors. For the tests on the undercut anchors with just one anchor pair located in a crack, the average anchor displacement decreased for same amplitude scaling of the floor acceleration by approximately 40% on average, though the maximum anchor loads increased by 10% on average.

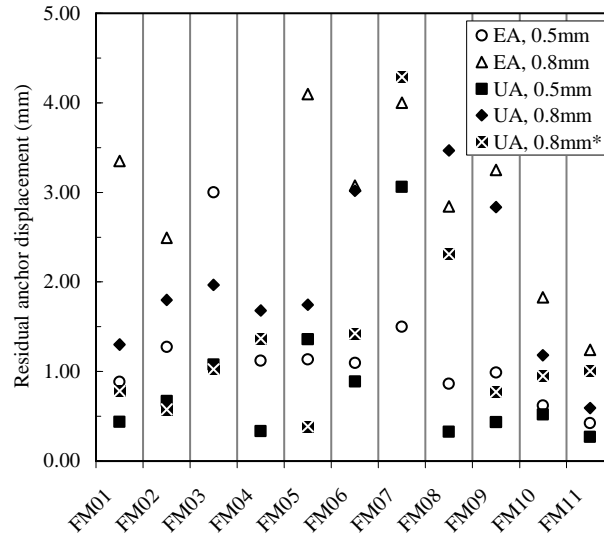


Figure 11. Residual anchor displacement for the expansion anchor (EA) and undercut anchor (UA); test suite with only one anchor pair in a crack marked by \*

As the crack width time history is not affected by any response action of the component, the targeted maximum crack width is generally achieved with a high degree of accuracy. In contrast, the anchor load is the result of the complex interaction of floor acceleration, component acceleration and anchor response. In consequence, the maximum anchor load cannot be predicted accurately. For this reason, the scale factors required to achieve the targeted anchor loads for specific floor motions were estimated on the basis of earlier test runs, and therefore the anchor loads may over- or undershoot the targets. To allow a more conclusive evaluation, the average anchor displacement was extrapolated for the exact target maximum anchor load, i.e. seismic design strength. For the extrapolation, an approximately linear relationship between anchor load and displacement was assumed (Mahrenholtz et al. 2012b). Table 2 and 3 present the extrapolated residual anchor displacement, presented as the average of the four anchor locations. The data for the expansion anchor is given in Table 2; the data for the undercut anchor in Table 3. The tests on the undercut anchors with just one anchor pair located in a crack are not further considered here.

Table 2. Key test results and extrapolation of residual anchor displacement: Expansion anchor

Floor Motion	Scaling (%)	0.5mm Crack <sup>(1)</sup>		0.8mm Crack <sup>(1)</sup>	
		Load <sup>(2)</sup> (kN)	S <sub>res</sub> <sup>(3)</sup> (mm)	Load <sup>(2)</sup> (kN)	S <sub>res</sub> <sup>(3)</sup> (mm)
FM01	15	9.4	1.03	9.3	3.98
FM02	18	11.8	1.20	11.2	2.46
FM03	36	14.0	2.37	14.2	3.91
FM04	14	7.6	1.63	12.6	4.43
FM05	41	10.7	1.16	12.7	3.56
FM06	38	12.5	0.97	16.2	2.09
FM07	27	12.9	1.28	20.1	2.19
FM08	30	8.7	1.09	12.4	2.53
FM09	24	8.6	1.27	11.1	3.22
FM10	30	12.4	0.55	12.0	1.67
FM11	40	10.2	0.46	12.5	1.09
		μ (mm)	1.18	μ (-)	2.83
		CV (%)	43.3	CV (%)	37.5

<sup>1)</sup> Targeted maximum crack width; <sup>2)</sup> Achieved maximum anchor load; <sup>3)</sup> Extrapolated average residual anchor displacement



Table 3. Key test results and extrapolation of residual anchor displacement: Undercut anchor

Floor Motion	Scaling (%)	0.5mm Crack <sup>(1)</sup>		0.8mm Crack <sup>(1)</sup>	
		Load <sup>(2)</sup> (kN)	s <sub>res</sub> <sup>(3)</sup> (mm)	Load <sup>(2)</sup> (kN)	s <sub>res</sub> <sup>(3)</sup> (mm)
FM01	38	23.5	0.45	18.0	1.73
FM02	48	26.4	0.61	20.0	2.16
FM03	90	26.6	0.98	29.3	1.61
FM04	34	12.7	0.63	22.4	1.80
FM05	103	23.5	1.39	22.2	1.89
FM06	96	31.9	0.67	30.6	2.37
FM07	67	38.7	1.90	33.1	4.36
FM08	74	23.3	0.34	30.6	2.72
FM09	59	28.3	0.37	26.7	2.55
FM10	74	27.4	0.46	30.4	0.93
FM11	101	19.4	0.33	19.6	1.00
		$\mu$ (mm)	0.74	$\mu$ (-)	2.10
		CV (%)	47.5	CV (%)	44.8

<sup>1)</sup> Targeted maximum crack width; <sup>2)</sup> Achieved maximum anchor load; <sup>3)</sup> Extrapolated average residual anchor displacement

In general, the average residual displacement for these two anchor types is relatively low when loaded to their seismic design strength. The mean anchor displacement ( $\mu$ ) is less than 3 mm even for the large maximum crack width of 0.8 mm. This is an important benchmark in anchor design in particular for safety relevant connections of components in nuclear facilities under service conditions (Mahrenholtz et al. 2011). The specific characteristics of the floor motion have a significant influence on the anchor displacement as the coefficient of variation (CV) is in the order of 40%.

## QUASI-STATIC QUALIFICATION TESTS

### Brief Description

To ensure that post-installed anchors are fit for the assigned purpose, durable and safe, they need to be qualified. In the US and Europe, anchors used for safety relevant connections need to be qualified according to ACI 355.2 (2007) and ETAG 001 (2007), respectively. Anchors tested according to ACI 355.2 (2007) can be qualified for static and seismic applications. The ETAG 001 (2007) guideline did not recognize seismic qualification for long time, however, an Annex covering seismic qualification was recently put in force (ETAG 001 Annex E (2013)). For qualification according to these guidelines, tests are carried out on isolated anchors, which are loaded quasi-statically according to stipulated test conditions.

For tension loads, the most demanding test type is the crack movement test. This test is critical because of the likelihood for unacceptable anchor displacements occurring during crack cycling. Anchor displacement also reduces the embedment depth and by this the ultimate load capacity. For this test type, the anchor is installed in a preformed crack in a special concrete specimen. The specimen is then mounted on a testing rig and connected to a servo-hydraulic actuator which allows opening and closing of the crack according to the given test protocol. At the same time, the anchor is permanently loaded in tension by a second actuator (Fig. 12, compare with Fig. 3).

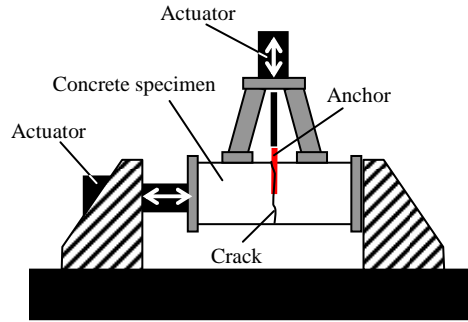


Figure 12. Schematic of test on isolated anchor

The test protocol used for the crack cycling tests presented in the following was developed at the UCSD and IWB (Wood et al. (2009)) for connections of structural members. This seismic crack cycling test protocol prescribes 59 crack cycles. The crack width is increased in 0.1 mm steps to a maximum crack width of 0.8 mm while the anchor is permanently loaded in tension. A detailed report of the test setup and procedure, as well as more technical background can be found in Mahrenholtz (2012). Further examples of tests based on the same test protocol are presented in Muciaccia (2012).

### Comparison of Displacement Data

Seismic qualification tests were conducted using the same expansion and undercut anchor types as employed for the shake table tests. The exact description of the test conditions is beyond the scope of this paper, however, it is noted that the maximum permanent anchor load was 10.9 and 17.1 kN for the tests on the expansion and undercut anchor, respectively. Fig. 13 shows the time histories of one of the three test repeats on the expansion anchor. The anchor displacement  $s_{cyc}$  develops according to the crack cycling with stepwise increasing crack width. Critical displacement values are extracted after the completion of the 0.5 mm crack cycles and of the 0.8 mm crack cycles (compare with Fig. 9).

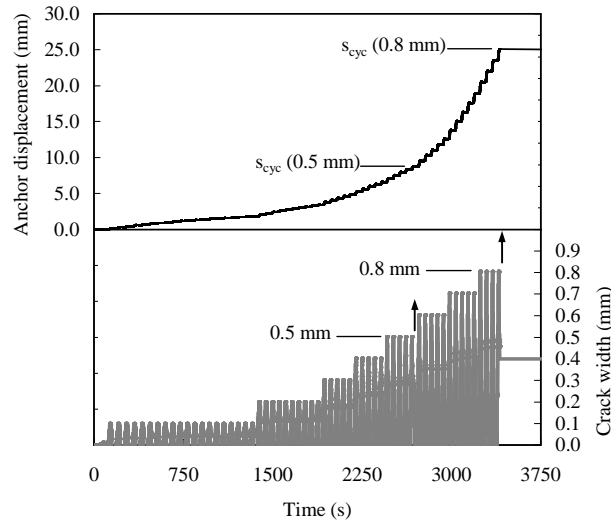


Figure 13. Time histories of anchor displacement and crack width during qualification test (example: Expansion anchor)

In Table 4, the mean anchor displacements measured for the shake table tests and for the qualification tests are compared. For the shake table tests, the mean anchor displacements were taken as  $s_{res}$  given in Table 2 and 3 for tests with target maximum crack width of 0.5 and 0.8 mm. For the qualification tests, the anchor displacements  $s_{cyc}$  were evaluated for the respective crack width in the crack cycling protocol.

Table 4. Comparison of mean anchor displacement measured for shake table and qualification tests

Mean Anchor Displacement (mm)	Shake Table Tests		Qualification Tests	
	$s_{res}$ for tests with max. crack width		$s_{cyc}$ after completion of crack width	
	0.5mm	0.8mm	0.5mm	0.8mm
Expansion Anchor	1.2	2.8	8.5	23.2
Undercut Anchor	0.7	2.1	2.0	4.5

It is evident that the anchor displacements experienced during shaking of a nonstructural member in a real seismic environment and as a part of a responding system (shake table tests) are much smaller than the corresponding anchor displacements cumulated as an isolated anchor during crack cycling according to a given test protocol (qualification tests). This is conclusive since the anchor is not permanently loaded during shake table tests and the average anchor load level is relatively low, whereas qualification tests are carried out on anchors which are permanently loaded to their full seismic design strength.

## CONCLUSIONS

The shake table tests on anchors connecting a suspended component to a cyclically cracked concrete slab were the first of its kind and allowed investigation of the anchor response to real earthquake motions. The anchor behavior was tested for representative floor accelerations and corresponding crack demands.

As the anchors respond to the cyclic actions, they continuously displace during shaking. The anchor displacement may cumulate to one or several millimeters. The tests on expansion anchors yielded displacements, which were throughout larger than the corresponding tests on undercut anchors. The impact of various floor motions on the test results is significant, however, has to be judged as small in light of the scatter prevalent in anchor testing. A dependence of the anchor displacement to the period of component oscillation could not be inferred:

Anchor displacement data derived from the dynamic shake table tests were compared with the displacement of isolated anchors during quasi-static qualification tests. Due to the relatively low average anchor load level, the shake table tests yielded anchor displacements which were much smaller than those measured for qualification tests on the same anchor type. The shake table test replicated only one specific design situation, however, the findings clearly indicate that the permanent anchor load applied during qualification tests is potentially overestimating the anchor load level for nonstructural connections and therefore may be too conservative for several applications:

## Acknowledgements

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