International Balkans Conference on Challenges of Civil Engineering, BCCCE,
19-21 May 2011, EPOKA University, Tirana, ALBANIA.

Post-Installed Metal Anchors Behavior In Cyclically Cracked Concrete

Pietro Crespi[1], Mentor Balilaj[2], Alberto Franchi[3]

[1] *Assistant Professor, Department of Structural Engineering, Polytechnic University of Milano, Milan, Italy*
[2] *Assistant Professor, Department of Structural Engineering, Polytechnic University of Tirana, Tirana, Albania*
[3] *Full Professor, Department of Structural Engineering, Polytechnic University of Milano, Milan, Italy*

ABSTRACT

The mechanical behavior of post–installed metal anchors is well known under quasi–static loads but is mostly unknown in seismic loading conditions. Particularly, the load bearing capacity of such construction products is greatly influenced by the presence of cracks in concrete, especially when the anchor is fixed along a crack.

In seismic conditions, fasteners are expected to transfer cyclic actions as reliably as possible, from the fixture to the concrete. At the same time, the cracks system of the concrete structure will be subjected to a variation of their width.

Actually, post–installed metal anchors are covered by two codes in Europe: ETAG–001 Guideline[6] and Eurocode 2.[2] These codes require anchors testing in cracked concrete with static crack opening of 0,3 mm. A Working Group EOTA, involving a number of writers, is currently working on a revised version of ETAG–001 Guideline[6] covering the seismic behavior too.

Today, the only one code that cover the seismic behavior of these products is ACI 355[1] which provides an experimental test with cyclic loading applied to the anchor installed in an opened crack having constant width.

In this paper the results of a recent experimental test on a torque–controlled expansion anchors (bolt–type) installed in cracked concrete specimens are presented. The originality of these tests is that the anchors are installed along a concrete crack, which undergoes to opening and closing cycles, while the design axial load is applied to the anchor and remains constant during the test. This approach could be interpreted as complementary to the one followed by ACI 355[1] code.

The testing apparatus allows the monitoring of the anchor slip during the opening/closing crack cycles. Furthermore, the effects of increasing damage in the concrete and in the anchor on the residual pull–out capacity of the anchors could be estimated.

INTRODUCTION

Post–installed mechanical anchors are frequently used to secure nonstructural elements and to connect new structural elements to existing structures in earthquake retrofit designs.

Earthquakes affect anchors in two different ways. First, they induce cracking and crack cycling in the primary structure, and, second, the movement of the structure generates dynamic tensile and shearing forces on anchors.[14]

The European product guideline ETAG 001 (2007) [6] and design standard EN 1992–1–1 (2004)[3] deal with the assessment (through CE marking) and design rules for mechanical, chemical and plastic anchors, respectively. No specific provisions, however, have been approved so far in the European Community, with reference to seismic loadings.

This is not the case in USA, where ACI 355.2–04,[1] defines specific tests based on 140 sinusoidal tension and shear, loading cycles to be performed on the installed anchor.

RESEARCH SIGNIFICANCE

The experimental research presented in this paper aims to evaluate the behavior of a bolt–type expansion anchor (approved according to ETAG001[6] option 1 for the use in cracked concrete) installed in pre–cracked concrete, under cyclic loading.

The results of this approval tests improved the understanding of anchor behavior in seismic conditions and provided the background for the development of enhanced prequalification methods for anchors.[8,10] The results provide new understanding of anchor behavior under earthquake conditions and background for the development of improved prequalification methods for anchors used in seismic regions.

BACKGROUND FOR TESTING PARAMETERS

Earthquakes affect anchors in two significant ways. First, they cause cracking and crack cycling in the primary structure that serves as the anchorage material. Second, the motion of the primary structure generates actions on secondary structures, which, in turn, generate dynamic tension and shear forces on anchors (Fig. 1). In this paper, the focus is on the crack cycling behavior. As the primary structure responds to earthquake ground motion, it experiences displacements and consequently deformation of its members. These deformations lead to the formation and opening of cracks.

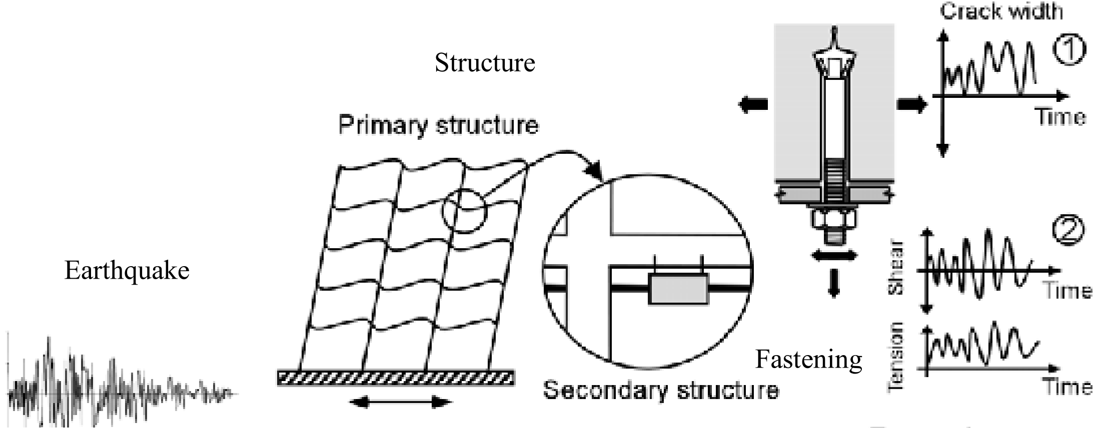


Figure 1 – Actions acting on nonstructural anchorage under earthquake loading.[9]

When the direction of displacement of the primary structure changes, moment reversal will occur in some members and cracks that had been opened during a previous displacement cycle will be pressed closed. Therefore, to assess the performance of anchors in concrete during an earthquake, it is necessary to understand their behavior in cycled cracks. The expected crack opening/closing widths, as well as the number of crack cycles, are critical parameters.

Crack width and cycling

Extensive numerical studies of crack width in reinforced concrete bending members designed according to Eurocode 2[2] indicate that the maximum crack width that can be expected to occur at steel yield in unfavorably designed flexural members is approximately 0,8 mm.[9]

For the purpose of anchor testing, it must be assumed that the type of member in which the anchor will be installed, for example, in a beam, column, slab, or wall, is not restricted.

Therefore, anchor performance under the conditions present in a member with an axial compression load and symmetric moment reversals, for example, a column or wall, should be verified. In such members, it is likely that full crack closure will occur. Current testing procedures[1] do not require full crack closure during crack cycling, but rather, they are designed to permit the crack width at zero member tension loads to be governed by the steel reinforcement ratio, bond degradation, and anchor response throughout the course of the test.

Number of crack cycles

The number of times a crack in a reinforced concrete member will open and close during an earthquake depends on the number of deformation cycles to which the member is subjected. Because earthquake shaking is irregular, some ground motion pulses will result in larger inelastic deformations of the member than others. Crack closing widths depend on the level of the resultant compressive force at the crack location. If it is assumed that only the largest amplitude deformation cycles during an earthquake lead to complete crack closure, then it would be useful to define an equivalent number of uniform–amplitude inelastic cycles at the maximum amplitude that will cause the same amount of damage to the structure as the total number of non–uniform deformations. This has been done by several investigators for various structure types and earthquake ground motions.[15–18]

Based on the results of the studies, ten symmetric, uniform–amplitude, inelastic cycles at maximum amplitude are taken to be representative of the number of crack opening–closing cycles during an earthquake for anchor testing purposes.[9]

EXPERIMENTAL TEST PROGRAM AND TEST APPARATURS

The test program consists of seven tests, after pre–cracking each specimen (as will be explained later), at least 2 anchors were installed along hairline cracked concrete and two LVDT transducer monitored the crack opening/closing to each installed anchor. At the end of the load cycles, each single anchor was subjected to a residual pull–out test.

The objectives of this research project are:

- To evaluate the anchor slip during the opening/closing crack cycles.
- To evaluate the residual pull–out capacity of the anchors, after 10 opening/closing crack cycles which ranges from 0 mm (closed crack) to 0,8 mm.
- To evaluate at the end of the tests, an average slip for the assessment of the service conditions of the fixture.

Investigated anchors

The geometric and mechanical properties of the investigated anchor types, torque-controlled (bolt–type), are given in Table 1 and Fig. 2. The investigated anchors are made of galvanized carbon steel (Steel Class 8.8), with a nominal diameter of 12 mm (M12 is extensively used in most applications).

Table 1 – Summary of the technical specifications of M12 anchor type.

d_0 mm	h_1 mm	h_{nom} mm	h_{ef} mm	d_f mm	h_{min} mm	T_{inst} Nm
12	100	81	72	14	150	60
Steel Class		f_{yk} (MPa)		f_{uk} (MPa)		E (GPa)
8.8		640		800		210

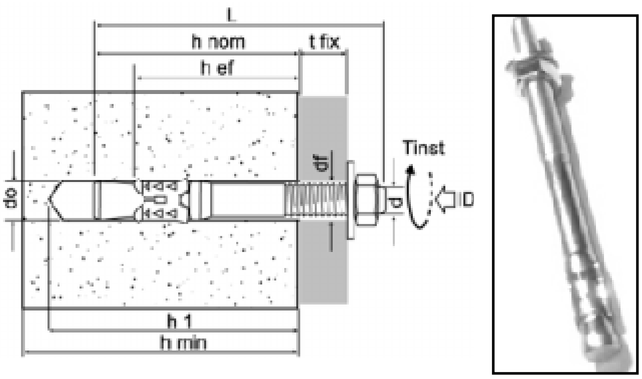


Figure 2 – Bolt–type torque–controlled expansion metal anchor.

Anchorage components

The first operation was to design the specimens on which to install the anchors. The geometry of the specimen was designed in the shape of parallelepiped with a square 250x250 mm, 360 mm in height, Fig. 1.

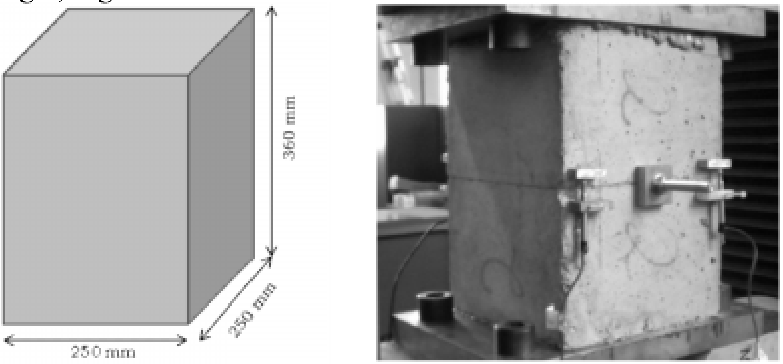


Figure 3 – Geometry and view of anchorage component for seismic crack cycling tests

The concrete specimens were fabricated in accordance with EN206, 2000,[5] and were used concrete grade $C_{40/50}$.

Seismic crack cycling and pullout tests

The specimen described in the previous section was tested at the Material Testing Laboratory of the Department of Structural Engineering of the Polytechnic University of Milano (Milan, Italy). For the seismic crack cycling tests, the artificial crack was generated in the middle of special anchorage component, by cutting through with a diamond disk.

The special anchorage component already divided in two parts by artificial cutting was glued onto two steel plates 35 mm thick, which are attached to the head of the electromechanical machine "SCHENCK" from 1000kN (Fig. 4). The crack was opening/closing (0,8mm to 0mm) by applying tensile/compressive force distributed over the head of the special anchorage component and was measured automatically by the machine, using a displacement transducer.

To monitor the progress of opening/closing of cracks during cycles were used two pairs of calibrated LVDT electronic transducers HBM with stroke 10 mm and placed alongside of the anchor, oriented perpendicular to the crack. The controller of the machine automatically, has acquired the recordings of these four instruments.

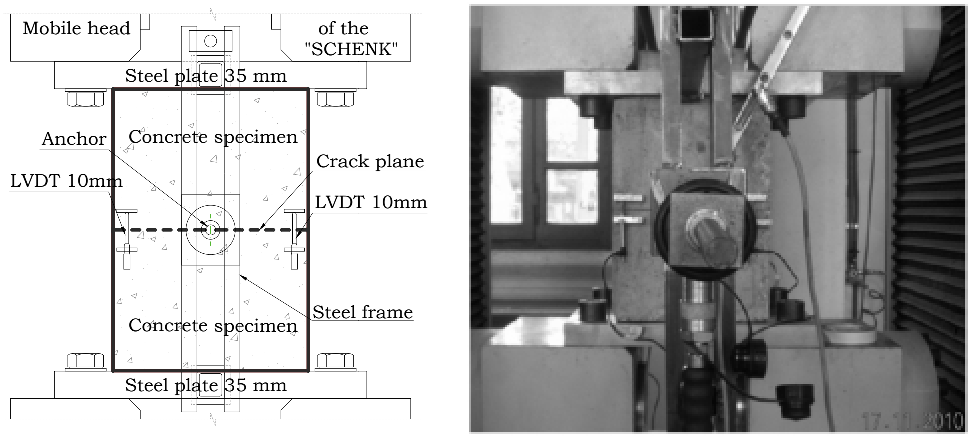


Figure 4 – Loading set–up, including the specimen.

The expansion anchors were installed in the crack in the member and loaded simultaneously with a constant tension load Nc=13kN during crack cycling. To apply the operating constant tension load we used a system that provides for an extension, consisting of two threaded bar, two threaded sleeves and two stands designed specifically for these tests.

The application of the constant tension load is carried out by a pair of cylinders on the contrasting stands opposed to auto balance all the forces exerted during the test mining. The two cylinders are connected in parallel to a hydraulic pump which regulating the oil pressure pumped into the cylinders, capable to generating a constant force in both the anchorages. For measuring the load applied by hydraulic cylinders in series with them, are mounted two calibrated load cells.

After seismic crack cycling tests, pullout tests were performed sequentially along the member using the same setup, to determine the residual strengths of the tested anchors. To monitor the slippage of anchors during the seismic crack cycling tests or pullout tests are used two calibrated LVDT electronic transducers HBM (stroke 100 mm), one for every expansion anchor (Fig.5).

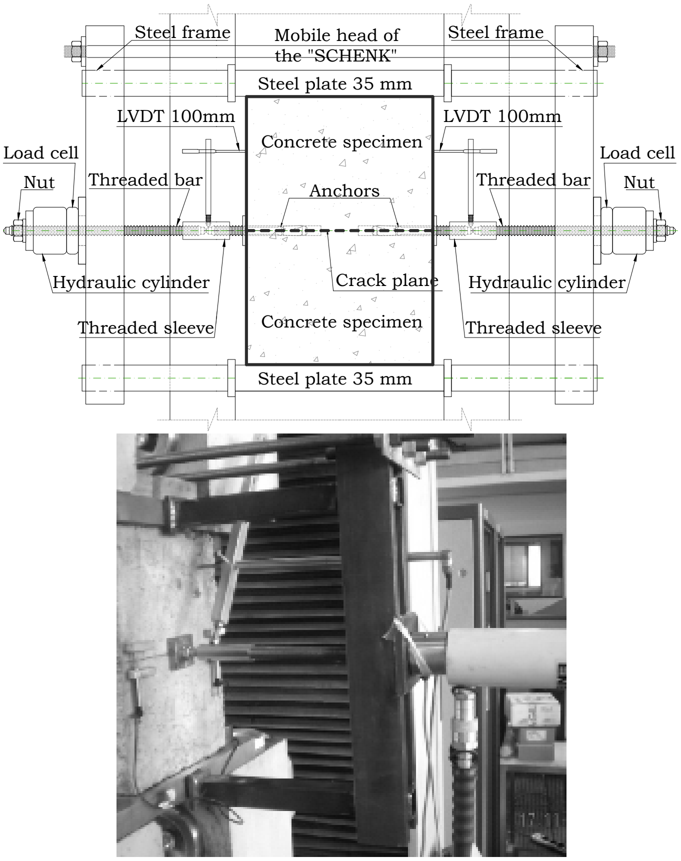


Figure 5 – Anchor loading setup for seismic crack cycling and pullout tests.

Loading time–histories for the anchors and the anchorage component are shown schematically in Fig. 6. Table 2 lists critical events in the time–histories.

Table 2 – Critical events during loading time–histories.

Time	Critical event
t_1	End of installation anchors
t_2	Anchor loading to N_c=13kN
	Start of crack cycling
t_3	First crack opening to w_1=0,8 mm
t_4	First crack closing to w_2=0 mm
t_5	End of crack cycling
	Anchor unloading to N_c=0kN
t_r	Measurement of residuals
t_u	Ultimate strength during pullout

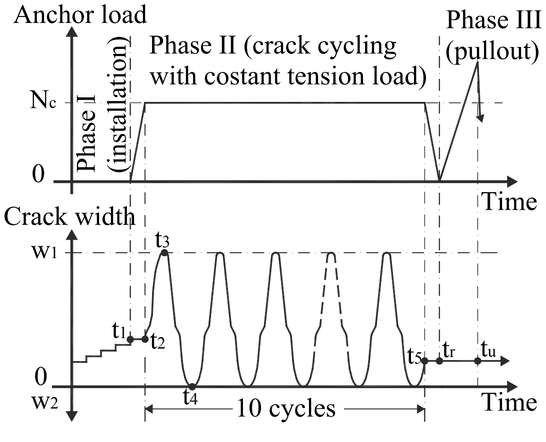


Figure 6 – Schematic loading time–histories for anchor and anchorage component.

Reference tension tests

Reference tests in static line cracks were performed on single anchor. The anchor was installed in a closed hairline crack, which was then opened by Δw=0,8 mm before loading of the anchor. Tension load was applied to the anchor using a hydraulic cylinder with a load capacity of 100 kN by slowly increasing the oil volume in the cylinder. Ultimate load was reached in approximately 30 to 40 seconds. Crack widths were controlled and monitored, during loading.

In each test, it was decided to instrumentation the special anchorage component, to allocate the acquisition channels, to denominate the faces of the installation of the anchors and the anchors themselves, as shown in Fig. 7.

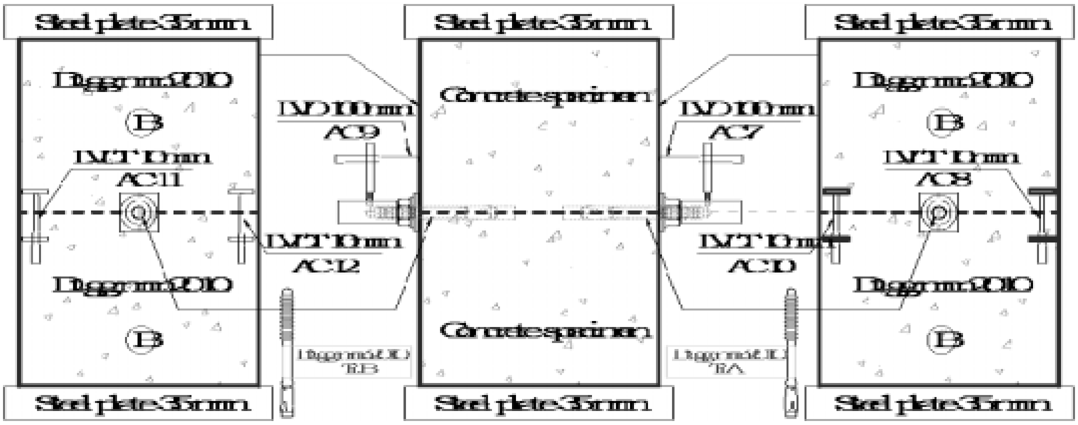


Figure 7 – Instrumentation and denomination of specimens.

With Dt.gg.mm.2010 indicates the date as day, month, and year 2010, which is conducting the tests. With A and B show the faces of the concrete block in which the anchors are installed. Ti is called the i-th anchor which has been used for testing (where i=1...n).

With LVDT 10 mm AC8, 10 (11, 12) calls the transducer LVDT HBM (stroke 10 mm), attached through channel AC8, 10 (11, 12) with the control unit, who measures (in micron) the opening/closing of the crack on the face A (B) of the concrete block.

With LVDT 100 mm AC7 (9) calls the transducer LVDT HBM (stroke 100 mm), attached through channel AC7 (9) with the control unit, who measures (in millimeters) extraction of anchor Ti.A (Ti.B) installed on the face A (B) of the concrete block.

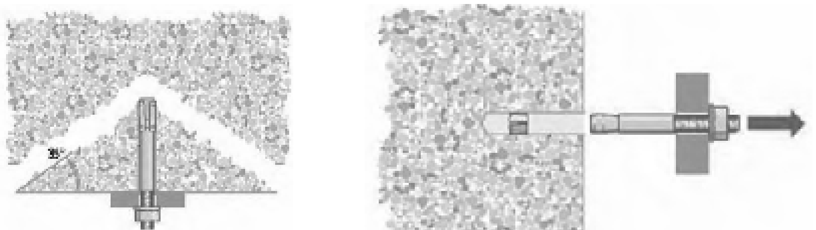
The cyclic displacement applied at the top of the specimen, was controlled by a built–in transducer that records the movements imposed at the top of the concrete block.

The moving head of test machine, in series with the specimen is positioned the load cell of 1000 kN, which records the force applied to the block of concrete during the loading cycles.

EXPERIMENTAL RESULTS AND DISCUSSION

Failure modes

The bolt–type expansion anchors investigated in this research project failed by, concrete cone breakout (Fig. 7.a)) and pull–through (the expansion elements remain in the drilled hole) (Fig. 7.b)).



a) b)

Figure 7 – Failure modes: a) concrete cone breakout; b) pull-through.

Concrete cone breakout

The behavior of a bolt–type expansion anchor failing by concrete cone breakout in tests subsequent to repeated large crack opening and closing cycles is shown in Fig. 8, Table 3.

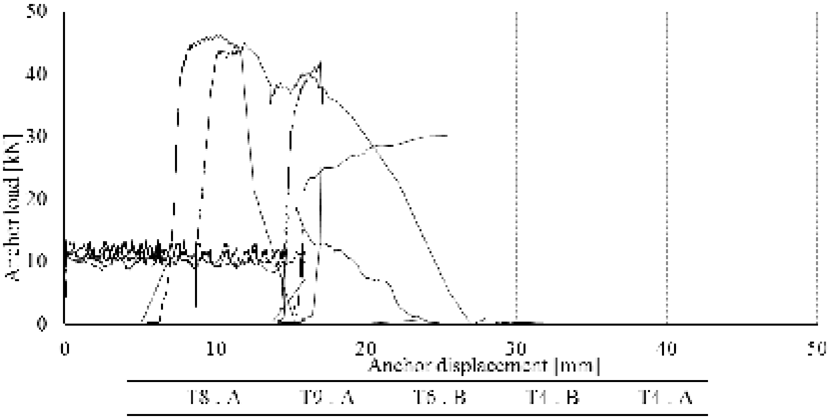


Figure 8 – Load–displacement curves for crack cycling (w_1=0,8 mm); w_2=0,0 mm; n=10; N_c=13kN tests for concrete cone breakout.

Pull–through failure

The behavior of a bolt–type expansion anchor failing by pull–through in reference tests and in tests subsequent to repeated large crack opening and closing cycles is shown in Fig. 9, Table 3.

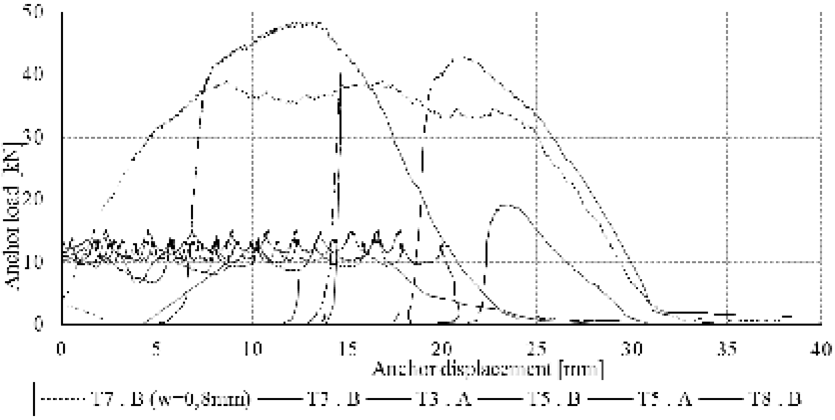


Figure 8 – Load–displacement curves for monotonic (w=0,8 mm) and crack cycling (w_1=0,8 mm); w_2=0,0 mm; n = 10; N_c=13kN tests for pull–through.

It is noted that the slight increase of the fastener load during crack cycling in Fig.8 and Fig.9 is a physical phenomenon resulting from closure of the crack. Because the oil volume in the hydraulic cylinders was used to regulate the fastener load, the load increased as the anchor was 'pressed back' into its hole during crack closure.

Table 3 – Loading histories for all specimens.

Test Date /2010	Anchor sign	Cyclic test				Compression load [kN]	Ultimate load [kN]	Anchor displacement [mm]	Failure mode
		Number of Cycles	Crack opening		Slipping after the cycles				
			Start cycles	End of cycles					

			[µm]	[µm]	[mm]				
12/10	T3.A	10	111,5	-110,0	17,84	-603,73	40,2	2,33	Pull-through
12/10	T3.B	10	213,3	-48,8	12,53	-613,95	57,5	4,67	Pull-through
17/11	T4.A	10	180,8	171,7	14,69	-72,33	39,8	2,64	Cone breakout
17/11	T4.B	10	213,3	97,4	8,74	-75,83	45,1	2,90	Cone break.
25/11	T5.A	8	13,2	487,0	19,86	-15,40	19,2	2,00	Pull-through
25/11	T5.B	8	1,7	592,3	81,00	Failure after 8 cycles			Cone break.
26/11	T6.A	9	229,5	-	81,00	Failure after 9 cycles			Cone break.
26/11	T6.B	9	243,8	68,6	14,56	-22,92	35,5	-	Cone break.
29/11	T7.B	Monotonic w=0,8 mm				0,12	39,0	7,70	Pull-through
30/11	T8.A	10	249,8	45,8	6,81	-101,96	46,2	5,20	Cone break.
30/11	T8.B	10	242,5	80,5	8,79	-91,80	48,6	8,28	Pull-through
01/12	T9.A	13	233,6	240,9	15,96	-18,87	18,7	0,31	Cone break.

CONCLUSIONS

The following conclusions can be drawn from the research results:

- The behavior of anchors is significantly influenced by crack cycling.
- Anchors may be subjected to crack cycling during an earthquake. Ten cycles of crack opening to w_1=0,8 mm and crack closing to w_2=0,0 mm are considered to represent a worst–case for anchors.
- The behavior of anchors under simulated seismic crack cycling varies depending on the anchor failure mode and can be categorized based on the amount of displacement during crack cycling relative to the displacement at ultimate load in a corresponding static pullout test in an open crack.
- Compressive load on the anchorage component significantly increases anchor displacement during crack cycling. The influence of the compressive load disappears after the crack in the component has closed sufficiently around the anchor.

REFERENCES

[1] ACI Committee 355, "*Qualification of Post-Installed Mechanical Anchors in Concrete (ACI 355.2-04) and Commentary (355.2R-04)*" American Concrete Institute.

[2] European Committee for Standardization (CEN), EN 1992–1–1, "*Design of Concrete Structures: Part 1 General Rules and Rules for Buildings*" Eurocode 2, 2004.

[3] EN1992-1-1 (2004). *Eurocode 2: Design of Concrete Structures. Part 1-1: General Rules and Rules for Buildings*. CEN/TC 250.

[4] EN1998-1 (2004). Eurocode 8: *Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Actions and Rules for Buildings*. CEN/TC 250.

[5] EN206-1 (2000). *Concrete – Part 1: Specification, Performance, Production and Conformity*. CEN/TC 104.

[6] ETAG001 (2007). *Guideline for European Technical Approval of Metal Anchors for Use in Concrete. Part 1-6.* EOTA, Bruxelles.

[7] Franchi A., Riva P., Ronca P., Roberti R. and La Vecchia M. (1996). "Failure Modalities of Reinforcement Bars in Reinforced Concrete Elements under Cyclic Loading". *Studies and Researches – Politecnico di Milano.* Ed. and pub. by Italcementi (Bergamo, Italy), Vol. 17-1996, pp. 157-187.

[8] Guillet T. and David E. (2007). "A New Seismic Test for Metal Anchors". *Proc. 2nd Int. Symposium on Connections between Steel and Concrete*, Stuttgart, Germany, 4-7 September 2007, Vol. 1, pp. 677-686.

[9] Hoehler, M. S., "*Behavior and Testing of Fastenings to Concrete for Use in Seismic Applications*", PhD dissertation, Universität Stuttgart, Stuttgart, Germany, 2006.

[10] Hoeler M. S. and Eligehausen R. (2008). "Behavior and Testing of Anchors in Simulated Seismic Cracks". *ACI Structural Journal*, Vol. 105, No.3, pp. 348–357.

[11] Macchi G., Pinto P. and Sanpaolesi L. (1996). "*Ductility Requirements for Reinforcement under Eurocode 2*". Structural Engineering International, Vol.4, pp. 249-254.

[12] Macchi G., Pinto P., Sanpaolesi L., Cantù E., Magenes G., Del Corso R., Froli M. and Nuti C. (1993). "*Experimental Research on the Minimum Requirements for the Reinforcing Bars Suitable for Seismic R/C Structures*" (in Italian). Associazione Tempcore Italia – *TEMPCORIT.*

[13] NTC (2008). *Technical Norms for Buildings (in Italian)*. Official Gazette No.29, Feb. 4 -2008.

[14] Sippel M. and Rieder A. (2007). "*Behavior of Fastenings under Realistic Earthquake Excitations*". Proc. 2nd Int. Symposium on Connections between Steel and Concrete, Stuttgart, Germany, 4-7 September 2007, Vol. 1, pp. 693-701.

[15] Krawinkler, H.; Zohrei, M.; Lashkari-Irvani, B.; Cofie, N. G.; and Hadidi-Tamjed, H., "*Recommendation for Experimental Studies on the Seismic Behavior of Steel Components and Materials*" Report No. NSF/CEE-83220, Stanford University, 1983, 251 pp.

[16] Malhotra, P. K., "*Cyclic–Demand Spectrum*" Earthquake Engineering and Structural Dynamics, V. 31, No. 7, 2002, pp. 1441-1457.

[17] Dutta, A., and Mander, J. B., "*Energy Based Methodology for Ductile Design of Concrete Columns*" Journal of Structural Engineering, V. 127, No. 12, 2002, pp. 1374-1381.

[18] Kunnath, S. K., and Chai, Y. H., "Cumulative Damage-Based Inelastic Cyclic Demand Spectrum" Earthquake Engineering and Structural Dynamics, V. 33, No. 4, 2004, pp. 499-520.

[19] ACI Committee 318, "*Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)*" Farmington Hills, MI, 2005, 430 pp.