CYCLIC BEHAVIOR OF SCREWED HEAD ANCHOR SYSTEM FOR APPLICATIONS IN NUCLEAR POWER PLANTS

G. Di Nunzio(1), G. Muciaccia(2)

(1) PhD Candidate, Politecnico di Milano, giuseppe.dinunzio@polimi.it
(2) Assistant Professor, Politecnico di Milano, giovanni.muciaccia@polimi.it
…

Abstract

Construction industry is undergoing considerable changes in recent years: continuous request for more flexible systems, as well as strengthening and repair of existing structures are leading to the development of new anchoring solutions for both structural and non-structural applications. Thousands of fasteners are installed everyday all around the world, but knowledge about their structural response is still limited. Construction codes in Europe and United States recently adopted a specific approach for the design of fastening to concrete, which accounts for two main steps: derivation of forces acting on the fastener and, successively, verifications at limit states for different failure modes and load directions. Specific product characteristics are required, particularly, for seismic resistance verification. Strictly speaking, it can be assumed that the basic seismic resistance of a post-installed anchors is lower than the basic static resistance. For cast-in anchors, nonetheless, the dimensions are usually such big to believe that the bearing capacity is not affected by the presence of the cracks. However, no codes for the seismic assessment of cast-in place anchors are currently available.

Within such a framework, cyclic behavior of cast-in place anchors, named “screwed head anchors” is experimentally investigated. A screwed head anchor is basically composed of an embedded steel plate connected to a threaded rod by means of nuts and washers. Such an anchoring solution is specifically designed to fasten heavy equipment in nuclear power plants. They are installed in combination with other systems designed to transfer shear and torsion. Screwed head anchors are intended to transfer tensile load only, thus assuming no interaction with the above-mentioned systems. Unconfined pullout tests were carried out in cracked concrete conditions as expected during a seismic event. Test samples were prepared by embedding screwed head anchors in reinforced concrete members designed with “crack inducers” to force the passage of the crack plane through the anchor’s axis, once loaded in tension. The anchors were tested adopting protocols developed to simulate the effect of a seismic event. In particular, three different test series were carried out: i. Reference static pullout tests with fixed crack opening displacement; ii. Pulsating tensile tests with fixed crack opening displacement; iii. Tests with constant tensile load and with varying crack width. Results are presented and commented demonstrating how the available theoretical models for the evaluation of the load bearing capacity are rather conservative. Evolution of permanent displacements during the cyclic part of the tests are commented as well.

Keywords: Cast-in; Headed anchors; Seismic tests; Cyclic; Pull-out.

1. Introduction

In the past, the design and the verification of fastening in concrete was limited to simply detailing rules and to the designer's experience. Due to relative recent development of efficient post-installed fasteners, most of research efforts were dedicated to their structural safety and their influence in the global behavior of the structures. The most important results have been included in codes and national regulations, which encompass both the assessment and the design of fastening systems. Assuming that the structural performances of cast-in-place anchors are always satisfied, they are limited to post-installed anchoring solutions only.

Within such a framework, the behavior of cast-in-place anchoring solution in presence of cracks was experimentally investigated. Monotonic pull-out tests were carried out in “widely” cracked concrete. To improve the knowledge about the behavior of cast-in-place anchors in cracked concrete, tests with pulsating tensile load and with varying crack width were performed as well.

2. Background

Cracks in concrete structures may develop has consequence of stresses, or imposed deformations, which overcome the tensile resistance of the material. Concrete possesses relatively low tensile strength and, generally, members under tensile or flexural loads are characterized by the presence of a cracked tension zone. Depending on the considered structure, cracks may occur in various forms: (i) in one direction only for beams and tension member; (ii) in two directions for slabs and walls (cit.). It is known, from experience, that in continuous beams or in slabs the tension zone is larger than the compression zone. Furthermore, it has been shown that cracks usually intersect the anchors, which behave as crack inducers or deviate the existing crack paths [1].

In service conditions, it has been proved that crack widths seldom exceed values of 0.3÷0.4 mm, under quasi-permanent loads, and values of 0.5÷0.6 mm, under maximum service loads [1]. Wider cracks may be expected under exceptional conditions as earthquake loading. During a seismic event, an anchor experiences extreme loading being the primary structures subjected to cracking and crack cycling and the secondary structures to inertia forces [2].

Fasteners to be used in seismic regions shall be qualified for cracked concrete. In Europe and in United States there is a complete set of standards to guarantee the safe installation of fasteners in seismic areas. The approach consists of a specific design procedure for earthquake conditions [3], [4] coupled with product qualification for the required performances [5], [6]. In Europe, different seismic performance categories are defined, namely C1 and C2 [5]. In particular, the code relates the two categories to the seismicity level and the building importance class [7].

Because of difficulties in conducting and controlling combined tests, current test methods for the assessment of fasteners under seismic action foresee separately tests for both the conditions of crack movement and cyclic loading [8]. Unfortunately, no specific procedures are available for the seismic assessment of cast-in-place anchors, since current methods are intended for post-installed anchors only [5], [6]. It has to be mentioned that European Technical Approvals for headed studs and for stud plates of major manufactures guarantee the use in cracked concrete not having performed specific tests [9], [10].

Three different methods can be used to form cracks in concrete test members: (i) use of splitting wedges similar to those for rock splitting; (ii) use of hydraulic expanders set into drilled holes; (iii) application of a centric tensile loading on the reinforcing bars [11]. All the methods use reinforcing bars to control crack widths [12], [13]. Exploiting the theory of cracking process in reinforced concrete ties, the specimen's geometry (i.e. cross-section and debonding length) and the reinforcing bars can be designed and verified once fixed the target crack width. Cracking process in concrete members is usually approximated assuming an average behavior to calculate a conventional value of the crack width [14]. The typical stressstrain diagram of an R/C tie can be represented with three segments: (i) a stiff linear branch till concrete tensile strength, (ii) full cracking of the tie with activation of bond and (iii) stabilized third branch almost corresponding to stresses on the steel bar alone. As a matter of facts, the distance between the behavior of the steel bar and the concrete tie, after stabilized crack process, represents the stiffening effect given by concrete segments between cracks (phenomenon known as "tension stiffening") [14].

Seismic assessment of fastening to concrete is usually carried out in "widely" cracked conditions (i.e. cracks larger than 0.5 mm). The main theoretical background is available in Wood and Hucthinson [15] in which, the behavior of concrete prototype structures, was studied via numerical analyses. The dynamic variability of real structures was simulated considering five concrete frames and two coupled wall frames. The curvature time histories were converted to crack widths and treated with rain-flow counting to obtain a normalized crack protocol. The authors then suggested to determine the maximum crack width to scale the protocol with special care. The typical crack widths for fasteners qualification are 0.5 mm and 0.8 mm. They are treated as extreme values for serviceability (50% fractile) and the ultimate limit states (95% fractile). Concerning this point, a critical comparison on the estimation of the crack widths is given by Nuti and Santini [16]. They concluded that concrete conditions should be evaluated using the capacity design being the crack width related to the specifications of the element considered.

3. Experimental study

3.2 Cast-in-place anchors

Cast-in-place anchors for the test campaign are composed by a square bearing plate screwed to a threaded shaft, from which the name “screwed head anchors” will be adopted hereinafter. The samples were assembled using steel grade Cl.8.8 M30 threaded rods [17] and steel grade S275 [18] for the bearing plate. Details of the final assembly are reported in Fig. 1a, while a picture of an assembled anchor is presented in Fig. 1b.

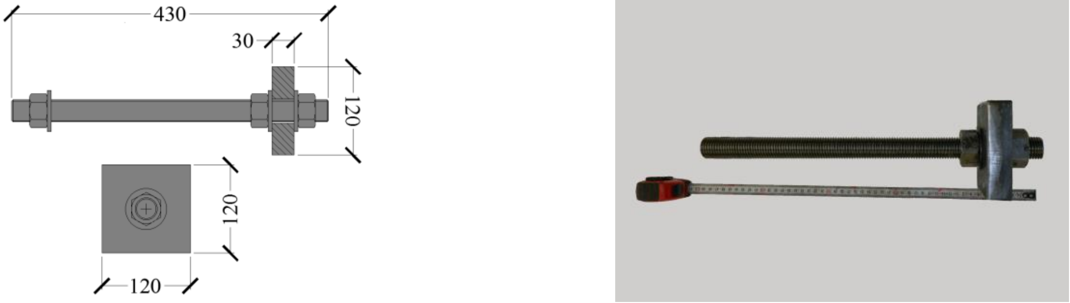
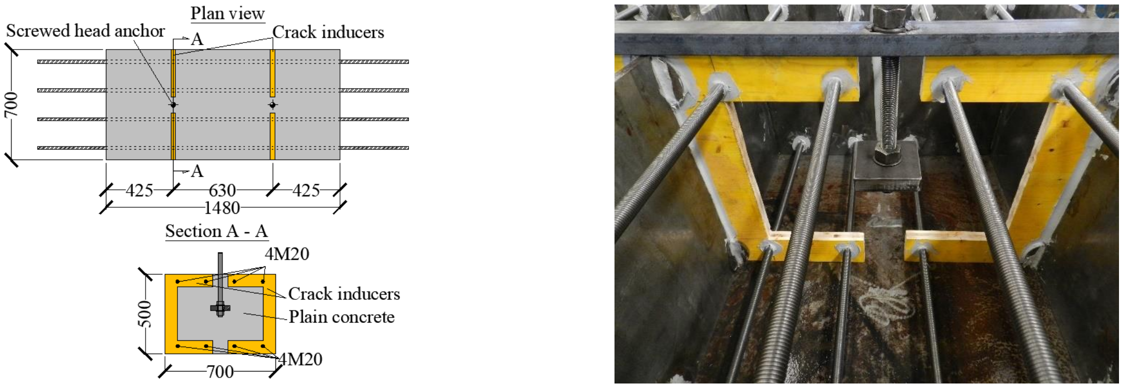


Fig. 1 – Investigated cast-in-place anchors: (a) Schematic drawing; (b) picture of a sample.

3.3 Reinforced concrete members

Test samples were embedded 200 mm in reinforced concrete member designed (called “specimen” in the following) to develop cracks at the anchor’s bearing position. The cross-section geometry and the length of the specimen were designed to guarantee the full development of concrete cone. Member depth was fixed higher of two times the embedment to avoid splitting failure. In fact, several authors suggested such a minimum value for the thickness to reduce the interaction with concrete member [1], [19], [20].

For each member, two anchors were placed prior to concrete cast using steel profiles as positioning rails (Fig. 2). Nominal C20/25 [21] concrete class was used to cast the specimens. Such a concrete does not represent the typical concrete grades used to build the structures of NPPs, but it guarantees that failures occurred on concrete side.



(a) (b)

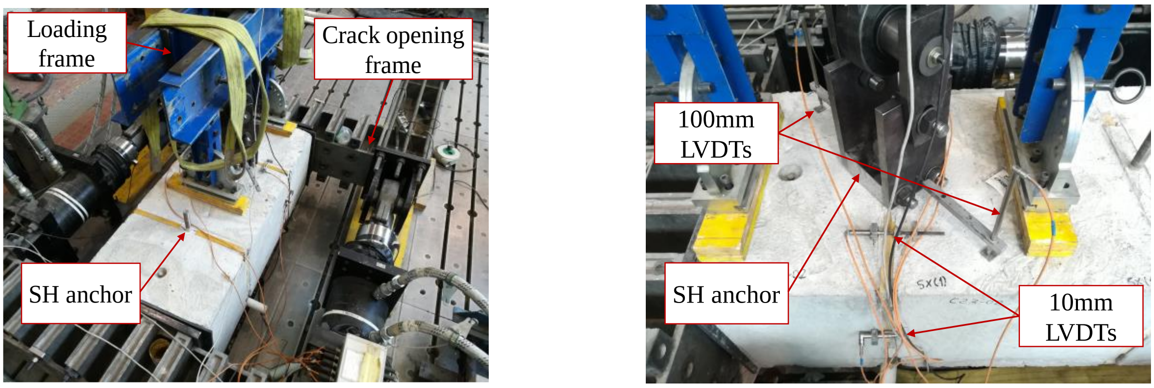
Fig. 2 – Reinforced concrete members: (a) Schematic drawing; (b) detail of a sample prior to concrete cast.

3.1 Test program and experimental procedure

In this study, the test protocols for post-installed anchors were assumed as a reference. Objections could arise in using such a reference, particularly regarding the crack widths. Nonetheless, it was conservatively adopted being the expected crack openings lower than those for lightly reinforced framed elements.

Pull-out tests were carried out (i) opening the crack up to 0.8 mm and thus (ii) loading the anchor till failure. Crack width was monitored and controlled during the pull-out. Any increasing, due to bending/splitting mechanism, was zeroed by reducing the pulling force applied to the concrete member. Pulsating tension tests and crack movement tests were carried out adopting the protocols from EOTA TR049 [5]. The complete tests program is reported in Table 1.

A special built-in steel frame, named "cracked opening frame", was used to apply a pulling force to reinforced concrete specimens and to achieve the target crack opening displacement (Fig. 3a). The frame was recently developed at Politecnico di Milano, for the so-called "seismic crack movement tests" on anchors, thus it respects the requirements of all international standards concerning crack-slip-and-opening tests for anchor's seismic assessment. Samples were loaded using a portal frame with 630 mm bending span equipped with a double action hydraulic jack (300 kN capacity) (Fig. 3a). Vertical displacements were monitored via LVDTs placed outside the theoretical projection of the concrete breakout body (Fig. 3b). The signals from LVDTs and from load cells were recorded using 5 Hz acquiring frequency.



(a) (b)

Fig. 3 – Experimental procedure: (a) test setup; (b) transducers layout.

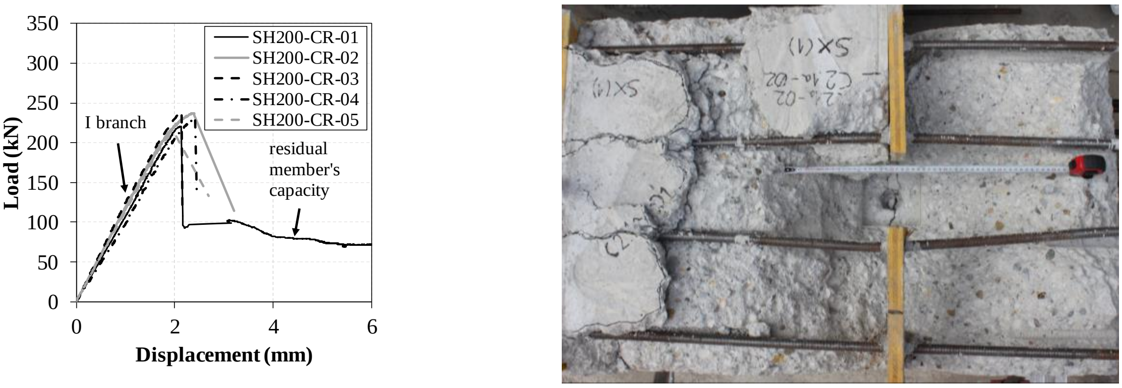
Table 1 – Test program

Test series	**hef (mm)**	**Concrete**	**Load and boundary conditions**	**N. of tests**
SH200-CR	200	C20/25	Static + constant crack	5
SH200-CR-P	200	C20/25	Pulsating + constant crack	5
SH200-CR-W	200	C20/25	Static + varying crack	5

4. Test results

The mechanical response of screwed head anchors in cracked concrete is reported considering (i) the load-displacement behavior and (ii) the crack pattern at failure.

Concrete cone failure characterized the investigated cast-in-place anchoring solution (Fig. 4b). Three different stages can be clearly recognized in the load-displacement curves for 200 mm embedment (Fig. 4a): (i) an almost linear branch up to the peak load is followed by (ii) an abrupt drop of load and (iii) a constant residual bearing capacity mainly related to the residual concrete member resistance. Such a residual contribution was probably given by the dowel effect of bars incorporated in the breakout body.



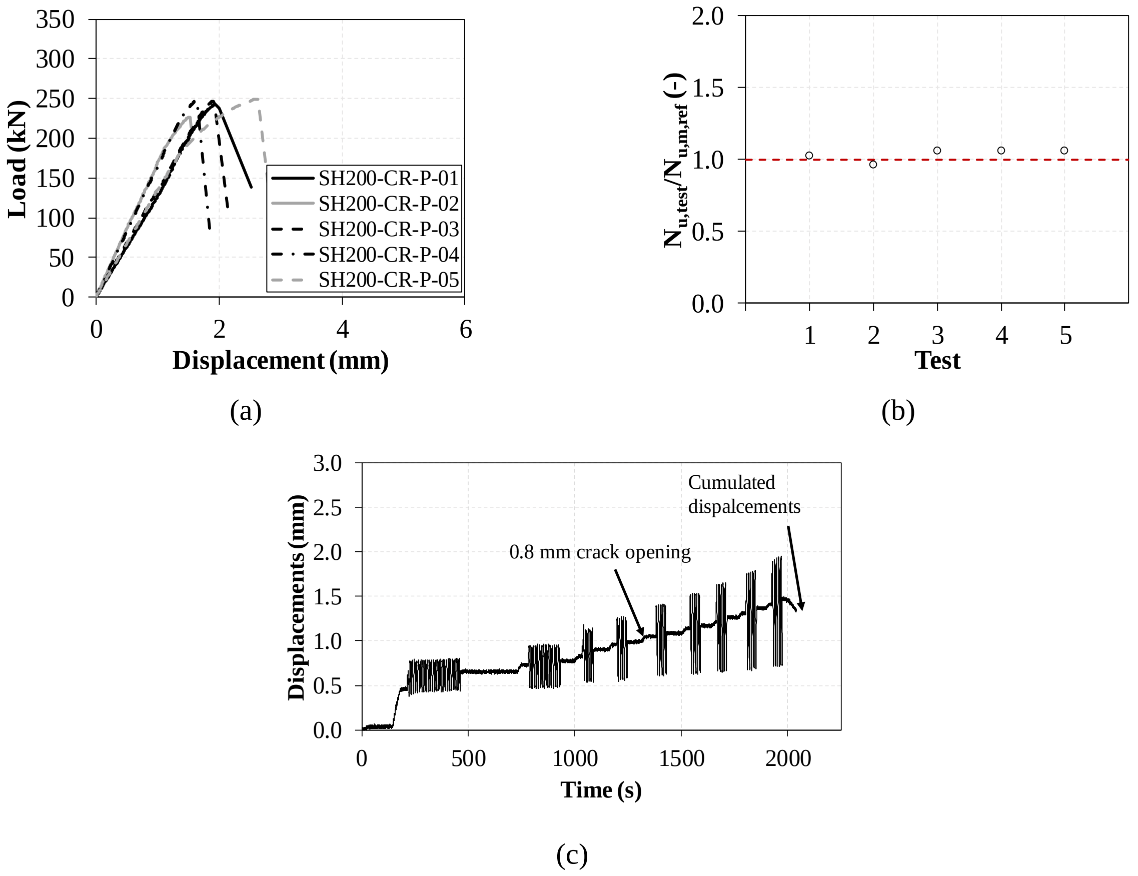
(a)

(b)

Fig. 4 – Results from reference monotonic tests: (a) load-displacement curves; (b) failure mode.

It is generally accepted that the application of a cyclic tensile loading, in presence of a constant crack width, is not decisive when assessing the anchor performances under seismic conditions [13]. This is the case of screwed head anchors, because none of the samples failed due to pulsating tension. Tests were carried out without any load reduction (Fig. 5b). Although stiffness was preserved in the load cycling (Fig. 5a), significant permanent displacements were cumulated (Fig. 5c). An average displacement of 0.92 mm was measured for the test series. This value approximately corresponds to the displacements at 50% of the peak load for the reference test series (i.e. pull-out tests with constant crack width). It is worth noticing how, for the investigated anchoring solution, the damage in the bearing zone could be a combination of concrete crushing at the bearing head and bond-slip along the anchor shaft.

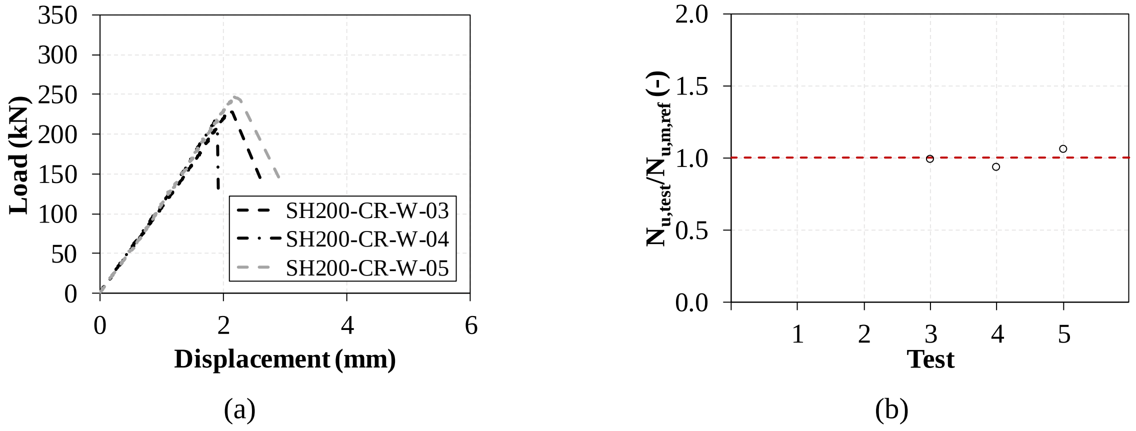
The experience in anchor testing demonstrated that crack movement is the most decisive test while determining final anchor performances [13]. In fact, differently from tests with pulsating tension only, two of the samples failed during tests with varying crack width. Therefore, the remaining tests were completed with 20% of load reduction. After crack movement, the residual load-bearing capacity was preserved (Fig. 6b). The initial stiffness was not significantly affected (Fig. 6a) but significant permanent displacement cumulated. In particular, the average value of permanent displacements is comparable to the results from pulsating tension (i.e. 1.07 mm versus 0.92 mm) suggesting a similar development for the irreversible damage. Recordings of transducers for anchor displacement and for crack opening are presented in Fig. 7 for two tests: test SH200-CR-W-02, which failed at 0.8 mm crack opening, and test SH200-CR-W-04, which passed the cyclic part. A rather different behavior is observed considering the passage from N_{w1} to N_{w2}. An exponential drift of the displacement was observed for SH200-CR-W-02, whereas only a step-jump was recorded for SH200-CR-W-04 test. On the concrete member side, a drift of the crack closure is clearly noticed in the first case only. It is worth noticing how a negative crack opening has no physical meaning except the shortening along the measurement basis.



(a) (b)

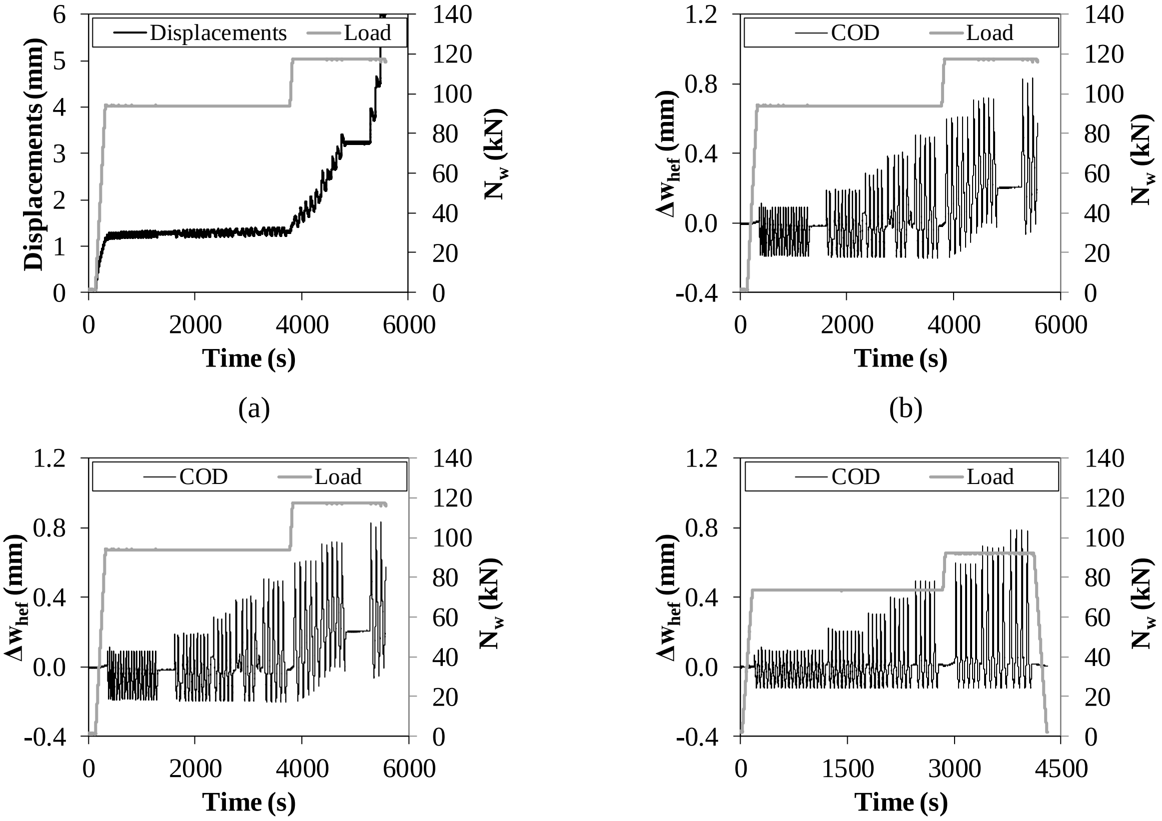
(c)

Fig. 5 – Results from pulsating tension tests: (a) load-displacement curves; (b) capacity reduction, (c) Displacements time history after load cycling for SH200-CR-P-05 test.



(a) (b)

Fig. 6 – Crack movement tests: (a) residual load-displacement curves, (b) comparison with the average load-bearing capacity after static loading.



(a) (b)

(c) (d)

Fig. 7 – Crack movement tests: (a) vertical displacements and (b) crack width for SH200-CR-W-02, (c) vertical displacements and (d) crack width at the embedment depth for SH200-CR-W-04.

5. Discussion of the results

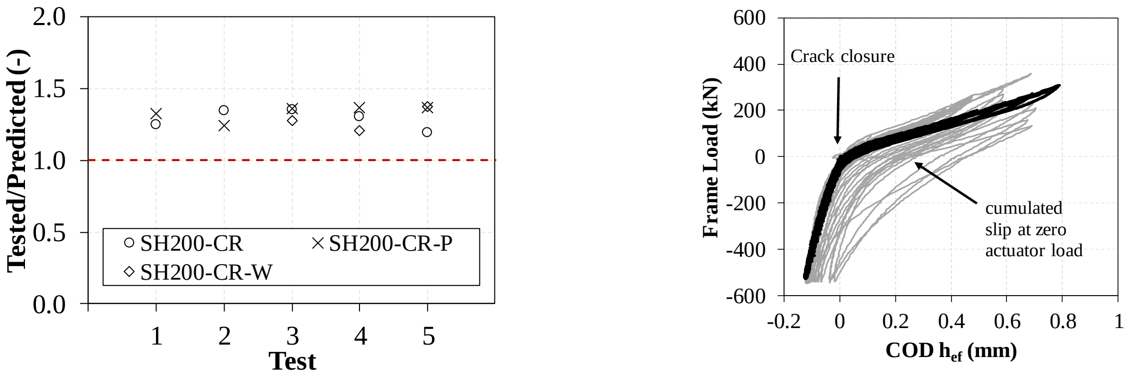
The results from pull-out tests in presence of cracks are discussed in this section starting from the failure mechanisms. For 200 mm embedment depth, the cone surface was not symmetric (Fig. 8). In particular, the measured slope was approximately 35° in direction parallel to the bending span (Fig. 8a), but it was flatter in the other direction. Furthermore, it reached the lateral sides of the specimen (Fig. 8b). Failure geometries with flat extraction cones seems to be rather common for cast-in-place anchors with large bearing heads [20], [22], [23]. It is believed that flatter cones are related to lower bearing pressure. In author's opinion, this phenomenon could be explained considering the superimposition with the structural response of the concrete member. However, this aspect is out of the scope of the paper and it will not be discussed. As consequence of high stress state in the longitudinal bars, a secondary splitting/bending failure mode developed with spreading cracks on the lateral side and on the top of the specimen.

Concrete Capacity Design approach (CC approach hereinafter) represents the current state of the art for fastening to concrete design. Therefore, comparison between tested and predicted load capacity is shown in Fig. 9a (the corresponding average values are reported in Table 2). The measured load capacities increase with respect to the predictions by CC approach. This phenomenon was noticed also in other research projects and may be related to the low bearing pressure developed by the specific anchoring solution [24].

(a) (b)

Fig. 8 – Concrete cone geometry: (a) failure surface parallel to bending span, (b) failure surface perpendicular to bending span.

Seismic resistance, as from results of crack movement tests, led to unexpected reduction of the load-bearing capacity. Such limitation can be explained considering the actuator load/crack opening behavior (Fig. 9b). Four paths can be recognized: (1) tensile path at crack opening value; (2) unloading path up to zero actuator's load; (3) slip recover with compressive force; (4) compressive force applied to concrete with crack closure [13]. Cumulation of slip at zero actuator load is evident in the case of the test carried out without load reduction, meaning that the combined effect of splitting and bending yields unrecoverable damages to the concrete member. Significant permanent displacements are cumulated after pulsating tensile loading, while crack movement affects both the load-bearing capacity and the displacement capacity. Consequently, when serviceability of the attached element is intended to be preserved, it is suggested to explicitly account for the compatibility of displacements. This verification, in general, can be performed assuming displacements at Serviceability Limit State (SLS) and at Ultimate Limit State (ULS) as from the current code approach [3]:



(a) (b)

Fig. 9 – Concrete cone geometry: (a) failure surface parallel to bending span, (b) failure surface perpendicular to bending span.

Table 2 – Results and comparison with CC approach.

Test series	**$N_{u,test,m}$ (kN)**	**$f_{cc,test}$ (MPa)**	**$N_{u,cc,m}$ (kN)**	**R_m (-)**
SH200-CR	227.5	28.7÷29.4	174.7	1.30
SH200-CR-P	242.5	30.5÷31.0	180.4	1.34
SH200-CR-W	230.2	29.7÷29.8	177.4	1.30

6. Conclusions

A campaign about the structural behavior of a cast-in-place anchoring solution, named “screwed head anchor”, was presented in this paper. Pull-out tests were carried out in “widely” cracked concrete. The experimental evidences highlight the need for a specific assessment procedure for cast-in-place anchors under seismic conditions as already prescribed for post-installed fasteners. The disturbing effect induced by cracks was investigated performing (i) static tests with constant crack width, (ii) tests with pulsating tensile loading and (iii) crack movement tests. An increment of the capacity is generally observed. Such an increase seems to be related to the large bearing head, as noted also in other research studies. The effects of cyclic loading and of crack movement should be definitely accounted for the design of cast-in-place anchors. If pulsating tensile loading seems the main responsible of permanent displacement cumulation, a cast-in-place anchor may collapse as consequence of varying crack width (a typical example is a seismic event). Data from failed tests confirmed the cumulation of unrecoverable slip at zero actuators load, which may interpret as a measure for the damage induced by the anchor. An approach based on the limitation of permanent displacements was presented as well.

Acknowledgements

The results presented in this paper were developed in the framework of a research project funded by Electricité de France, DIPNN-DT, Villeurebanne: Mr. Thierry Roure and Mr. Clément Harvé are warmly thanked for authorizing the use of experimental data. Tests were carried out at Material Testing Laboratory of Politecnico di Milano: the author would like to express appreciation to Mr. Daniele Spinelli and Mr. Michele Dezio for carrying the laboratory activities.

References

[1] R. Eligehausen, R. Mallèe, and J. Silva, *Anchorage In Concrete Construction*. Berlin: Ernst & Sohn, 2006.

[2] M. S. Hoehler and R. Eligehausen, “Behavior and testing of anchors in simulated seismic cracks,” *ACI Struct. J.*, vol. 105, no. 3, pp. 348–357, 2008.

[3] CEN/TC250, “EN 1992-4 - Eurocode 2 Design of concrete structures - Part 4 Design of fastenings for use in concrete,” CEN, 2018.

[4] ACI Committee 318, *ACI 318-19*. 2019.

[5] EOTA, “TR 049 - Post-installed fasteners in concrete under seismic action,” 2016.

[6] ACI Committee 355, *ACI 355.2-07 Qualification of Post-Installed Mechanical Anchors in Concrete & Commentary*. Farmington Hills: American Concrete Institute, 2007.

[7] CEN/TC250, “EN 1998-1 - Eurocode 8 : Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildingsICS,” 2013.

[8] P. Mahrenholtz, “Experimental Performance and Recommendations for Qualification of Post-installed Anchors for Seismic Applications,” Institut für Werkstoffe im Bauwesen der Universität Stuttgart, 2012.

[9] Deutsches Institut für Bautechnik, “European Technical Approval ETA-03/0041: Nelson Headed Studs,” Berlin, Germany, 2018.

[10] Deutsches Institut für Bautechnik, “European Technical Approval ETA-03/0039: KÖCO Headed Studs,” Berlin, Germany, 2018.

[11] R. Eligehausen, L. Mattis, R. Wollmershauser, and M. S. Hoehler, “Testing anchors in cracked concrete—guidance for testing laboratories: how to generate cracks,” *Concr. Int.*, vol. 26, no. 7, pp. 66–71, 2004.

[12] C. Mahrenholtz and A. Sharma, “Testing of Anchors and Reinforcing Bars in Concrete under Cyclic Crack Movements,” *J. Test. Eval.*, vol. 45, no. 4, p. 20160082, 2017.

[13] A. Marchisella and G. Muciaccia, “Influence of Specimen Geometry on the Response of Post-Installed Anchors

Subjected to Constant Load under Crack Opening and Crack Cycles," *J. Test. Eval.*, vol. 48, no. 5, p. 20180281, 2020.

[14] G. Toniolo and M. Di Prisco, *Reinforced concrete design to eurocode 2*. Springer Tracts in Civil Engineering, 2017.

[15] R. L. Wood and T. C. Hutchinson, "Crack protocols for anchored components and systems," *ACI Struct. J.*, vol. 110, no. 3, pp. 391–401, 2013.

[16] C. Nuti and S. Santini, "Fastening technique in seismic areas: A critical review," *Proc. Int. FIB Symp. 2008 - Tailor Made Concr. Struct. New Solut. our Soc.*, p. 192, 2008.

[17] CEN/TC185, "EN ISO 898-1:2013 - Mechanical properties of fasteners made of carbon steel and alloy steel Part 1: Bolts, screws and studs with specified property classes — Coarse thread and fine pitch thread," 2013.

[18] ECISS/TC10, "EN 10025-2: 2004 : Hot rolled products of structural steels," 2004.

[19] R. Nilforoush, M. Nilsson, and L. Elfgren, "Experimental Evaluation of Influence of Member Thickness, Anchor-Head Size, and Orthogonal Surface Reinforcement on the Tensile Capacity of Headed Anchors in Uncracked Concrete," *J. Struct. Eng.*, vol. 144, no. 4, p. 04018012, Apr. 2018.

[20] M. Nilsson, U. Ohlsson, and L. Elfgren, "Effects of Surface Reinforcement on Bearing Capacity of Concrete with Anchor Bolts," *Nord. Concr. Res.*, vol. 2011, no. 44, pp. 161–174, 2011.

[21] CEN/TC104, "EN 206:2013+A1:2016 - Concrete - Specification, performance, production and conformity," 2016.

[22] N. H. Lee, K. S. Kim, C. J. Bang, and K. R. Park, "Tensile-headed anchors with large diameter and deep embedment in concrete," *ACI Struct. J.*, vol. 104, no. 4, pp. 479–486, 2007.

[23] J. Ožbolt, R. Eligehausen, G. Periškić, and U. Mayer, "3D FE analysis of anchor bolts with large embedment depths," *Eng. Fract. Mech.*, vol. 74, no. 1–2, pp. 168–178, 2007.

[24] G. Di Nunzio, A. Marchisella, and G. Muciaccia, "The effect of very low bearing pressure on the behavior of cast-in anchors," in *Proceedings of CONSEC 2019*, 2019, pp. 1–10.