Nuclear Engineering and Design 265 (2013) 1091–1100

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Dynamic performance of concrete undercut anchors for Nuclear Power Plants

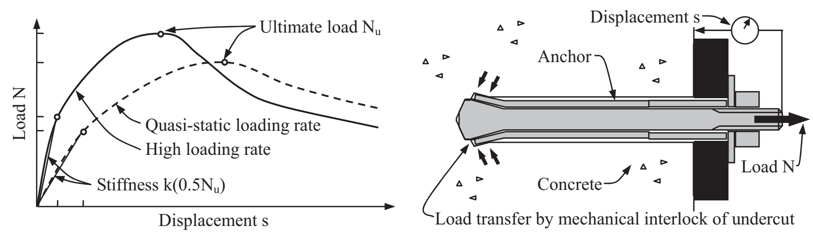
Christoph Mahrenholtz*, Rolf Eligehausen

University of Stuttgart, Pfaffenwaldring 4, 70569 Stuttgart, Germany

HIGHLIGHTS

- Behavior of undercut anchors under dynamic actions simulating earthquakes.
- First high frequency load and crack cycling tests on installed concrete anchors ever.
- Comprehensive review of anchor qualification for Nuclear Power Plants.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 4 May 2013
Received in revised form
12 September 2013
Accepted 26 September 2013

ABSTRACT

Post-installed anchors are widely used for structural and nonstructural connections to concrete. In many countries, concrete anchors used for Nuclear Power Plants have to be qualified to ensure reliable behavior even under extreme conditions. The tests required for qualification of concrete anchors are carried out at quasi-static loading rates well below the rates to be expected for dynamic actions deriving from earthquakes, airplane impacts or explosions. To investigate potentially beneficial effects of high loading rates and cycling frequencies, performance tests on installed undercut anchors were conducted. After introductory notes on anchor technology and a comprehensive literature review, this paper discusses the qualification of anchors for Nuclear Power Plants and the testing carried out to quantify experimentally the effects of dynamic actions on the load–displacement behavior of undercut anchors.

1. Introduction

Because of the robust load transfer mechanism by mechanical interlock, two anchor types are in particular suitable to cope with extreme dynamic actions: cast-in-place headed studs (Fig. 1a) are used in reinforced concrete structures since decades. Though the headed stud is an established anchor type of simple make, the required installation of the base plates fitted with the headed studs prior to concrete casting is a significant disadvantage. The position of cast-in base plates is fixed and do not allow design revisions in terms of loads and layout. Further, welding on site is often problematic in view of quality as well as accessibility and welded connections are hard to be removed later. Post-installed undercut anchors (Fig. 1b) provide maximum flexibility and are suitable for adding new components at a later stage and may be used for versatile retrofit solutions as well. During installation, the expansion elements either extends into an undercut predrilled by a special drilling apparatus or they create the undercut by a self-cutting action of the anchor. Detailed description of the load-bearing behavior of the anchor types can be found in the literature (Eligehausen et al., 2006).

Though post-installed anchors have been used in Nuclear Power Plants (NPP) already in the 1960s and 1970s, their use was not regulated in the beginning and the design approaches varied significantly. In 1979, structural failure of supports of safety related piping systems in the US and questions concerning the performance of expansion anchors led to the issuance of the Inspection and Enforcement Bulletin (IEB 79-02, 1979). Thereafter, in 1980, the American Concrete Institute (ACI) codified the design methodology

* Corresponding author. Present address: Buesingstraße 6, 12161 Berlin, Germany. Tel.: +49 172 6577516.
E-mail address: christoph@mahrenholtz.net (C. Mahrenholtz).

0029-5493/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nucengdes.2013.09.038

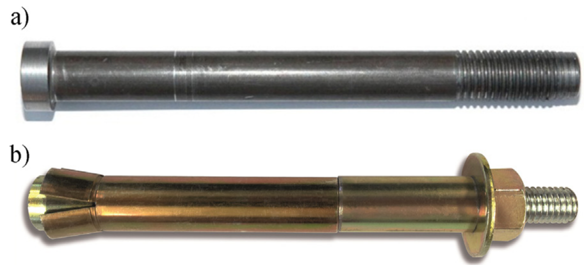


Fig. 1. Examples for anchors suitable to sustain extreme actions: (a) cast-in-place headed stud; (b) post-installed undercut anchor.

of anchors based on limited amount of available test data and developed the ACI 349 (ACI 349, 1980) for the design of nuclear safety related concrete structures. Since then, extensive research has been done on anchorages to concrete structures and many clauses have been updated in the latest edition (ACI 349, 2006). The provisions in ACI 349 were reassessed for their applicability to post-installed anchors in the early 1990s and have been harmonized with the provisions of ACI 318 Appendix D, "Anchoring to Concrete" which are incorporated since 2002 (ACI 318, 2002). Nowadays, Appendix D of ACI 318 (ACI 318, 2011) is the most widely accepted provision for the seismic design of fastenings in the US and presumably worldwide. In Europe, the design of concrete structures for NPPs is generally covered by the provisions given in the reinforced concrete design code Eurocode 2 (EN 1992, 2011). Additional provisions for the design of structures for earthquake resistance are given in the Eurocode 8 (EN, 1998:2006) as well as in national codes like DIN 24449 and KTA2201 in Germany. To date, no European code contains anchor design provisions. Therefore, anchor design is generally carried out according to Annex C of the European Technical Approval Guideline ETAG 001 (ETAG 001, 2013) or the CEN Technical Specification CEN/TS 1992-4 of the European Committee for Standardization (CEN/TS 1992-4, 2009). It is expected that the CEN/TS 1992-4 will be transferred into a harmonized standard as Part 4 of the Eurocode 2 until 2014.

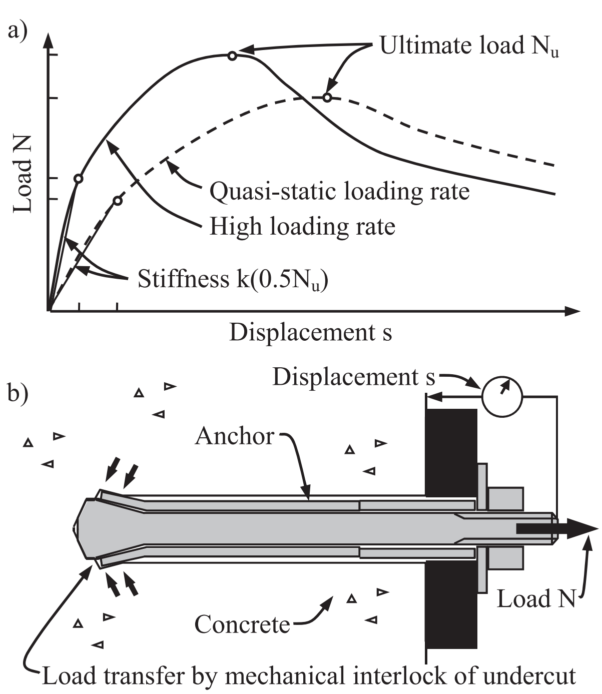


Fig. 2. Schematic to illustrate (a) the influence of loading rate on the load–displacement behavior of (b) concrete anchors (undercut anchor shown as an example).

Qualified anchors have to be used for safety relevant connections in the US and Europe. The qualification of concrete anchors is conducted according to the qualification guidelines ACI 355.2 (ACI 355.2, 2007) and ETAG 001 (ETAG 001, 2013) in the US and Europe, respectively. These guidelines provide test conditions and acceptance criteria which must be met prior to issuing an Evaluation Service Report (ESR) in the US or a European Technical Approval (ETA). The ACI 355.2 includes seismic approval testing which, however, is based only on load cycling tests with relatively moderate test conditions. Until recently, ETAG 001 did not cover seismic loading. Only in 2013, Annex E of ETAG 001 (ETAG 001, 2013) was published which covers the qualification of post-installed anchors for seismic loading. For the high safety demands of NPPs including extreme loading caused by earthquakes, airplane impacts or explosions, the German Institute for Civil Engineering (DIBt) published the German Guideline for Anchorages in NPP in 1998 (DIBt KKW Leitfaden, 1998). This guideline recognizes the most demanding tension and shear load cycling as well as crack cycling tests worldwide. In general, qualification tests are always carried out at quasi-static loading rates which are considered to be conservative. It is noteworthy that ACI 355.2 qualified anchors have to be used in many countries as their concrete design codes either refer to or originate from Appendix D of ACI 318 (e.g. Chile, Korea, New Zealand, Taiwan).

2. Motivation and research significance

As reinforced concrete structures are subjected to dynamic actions such as seismic excitations, concrete members and concrete anchors embedded therein experience different kinds of cyclic loadings at high rates. As known from general material sciences and in particular from concrete testing, high loading rates generally influence the concrete properties in a positive way (Malvar and Ross, 1998; Sharma et al., 2010; Wesche and Krause, 1972; Zielinski, 1982). Accordingly, concrete anchors subjected to dynamic loading are expected to develop higher peak load capacities and smaller displacements at peak load, but also an increased initial stiffness if compared to quasi-static loading (Fig. 2).

Any experimentally measured reduction of anchor displacement and increase of anchor capacity as a result of realistic high loading rates would give evidence that the qualification testing at quasi-static rates contains reserves of resistance and would allow relaxing the test conditions or assessment criteria. To this end, monotonic and cyclic tests in shear and tension as well as crack cycling tests were carried out at earthquake relevant rates and frequencies to quantify the dynamic effects on the anchor load and displacement capacities.

3. Literature review

There is a high probability that anchors are located in *cracks* caused by external loading or thermal constraints exceeding the low tensile strength of concrete (Bergmeister, 1988; Eligehausen et al., 1986; Lotze, 1987). For shear loads, the influence of cracks on the load–displacement behavior of anchors is relatively small (Fuchs and Eligehausen, 1989; Vintzeleou and Eligehausen, 1991). For headed studs, the reduction of shear capacity due to a 0.4 mm crack is smaller than 10%. For tension loads, however, cracks have a significant impact on the behavior of anchors (Cannon, 1981; Eligehausen and Balogh, 1995). Though undercut anchors and headed studs are less crack sensitive than any other anchor type, e.g. screw or expansion anchors, 0.4 mm cracks reduce the tension capacity by about 25% (Fig. 3). In conclusion, it is important that anchors are tested in realistic crack widths. For reinforced concrete structures responding to seismic loads, large crack widths in the