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Post-installed concrete anchors in nuclear power plants: Performance and qualification

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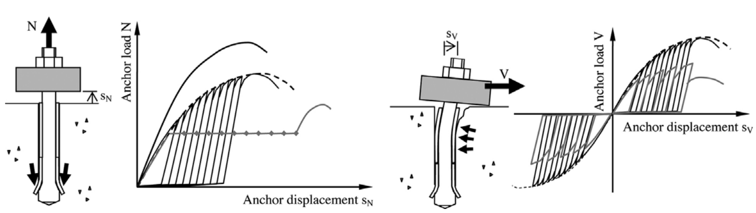
HIGHLIGHTS

- Review of qualification and design regulations for anchors in nuclear power plants.
- First complete set of nuclear anchor load–displacement data and its evaluation ever.
- Demonstration of robust test behavior of a qualified post-installed anchor product.

GRAPHICAL ABSTRACT



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ABSTRACT

In nuclear power plants (NPPs), post-installed anchors are widely used for structural and non-structural connections to concrete. In many countries, anchor products employed for safety relevant applications have to be approved by the authorities. For the high safety standards in force for NPPs, special requirements have to be met to allow for extreme design situations. This paper presents an experimental test program conducted to evaluate the performance of anchors according to the German Guideline for Anchorages in Nuclear Power Plants and Nuclear Technology Installations (DIBt KKW Leitfaden, 2010). After a brief introduction to anchor behavior and the regulative context, the results of tension and shear tests carried out on undercut anchors are discussed. Robust load capacities and relatively small displacements determined for demanding load and crack cycling tests demonstrated the suitability of anchors qualified according to a state-of-the-art qualification guideline.

1. Introduction

1.1. Anchor types and general behavior

Post-installed anchors are used to connect structural elements with each other or to fix non-structural components and systems to the structure. Post-installed anchors are easy to install and provide more flexibility than cast-in anchors like headed studs. On the other hand, post-installed anchors are in general technically sophisticated products which are more sensitive to the boundary conditions than cast-in anchors. Most of the commercially available anchor products can be assigned to one of the major anchor types which are categorized according to their load transfer mechanism. Anchor types relevant in the context of this paper are shown in Fig. 1.

Each anchor type shows individual performance characteristics and failure modes. Undercut anchors function similar to headed bolts by mechanical interlock at the anchor base, allowing a deep concrete cone to develop with a large plane area. For larger embedment depths, steel failure may occur. Due to its pronounced bearing area, undercut anchors are less sensitive to concrete cracking effects than other post-installed anchor types. Expansion anchors transfer the load by friction between anchor body and expansion elements, and by friction between expansion elements and concrete. Torque-controlled expansion anchors are pulled further into

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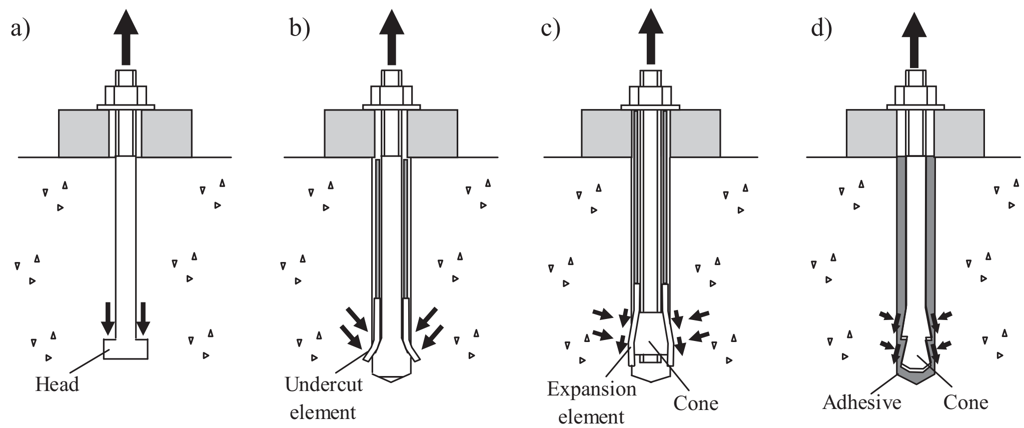

Fig. 1. Anchor types: (a) headed bolt; (b) undercut anchor; (c) expansion anchor; (e) bonded expansion anchor.

their expansion elements (follow-up expansion) when the load or crack width is increased, resulting in relatively large displacements. Expansion anchors fail either by concrete breakout or, particularly in case of thin expansion elements or installation in cracked concrete, when their body is completely pulled through the expansion elements. In case of bonded expansion anchors, the tension load is transferred from the hardened adhesive to the concrete by bond and, due to the geometric imperfection of the drilled hole, also by micro-interlock. The bond between the adhesive and the cone shaped steel element is broken during initial loading and the hardened adhesive then serves as an expansion sleeve allowing follow-up expansion. In principle, this anchor develops the same failure modes like expansion anchors. Anchors loaded in shear generally fail in steel failure mode provided that they are long enough to exclude pryout failure and installed far from any edges to exclude concrete edge failure. Further details on anchors and their load–displacement behavior can be found in Eligehausen et al. (2006).

Since cracks in the concrete base material have a significant negative influence on the anchor performance, the assumption that the anchor is situated in a crack is conservative. The diagrams in Fig. 2 depict the tension and shear load–displacement curves of anchors tested in cracked and uncracked concrete. Anchors used in seismic applications are subjected to cyclic actions. For load cycling, the backbone curve of the load–displacement path generally follows the monotonic mean of quasi-static pullout tests (Fig. 2). While by the limited number of load cycles assumed for seismic events, the performance of anchors loaded in tension is in general not adversely affected (Fig. 2a), anchor loaded in shear may fail by low cycle fatigue (Fig. 2b). The driving performance aspect for anchors loaded in tension is crack cycling which occurs when the structure response to the earthquake motion. In this case the anchor experiences substantial axial displacement in which course the embedment depth and thus the remaining anchor capacity is reduced, ultimately resulting in pullout failure. In-depth discussion of seismic anchor performance is given in Mahrenholtz (2012).

1.2. *Design and qualification*

NPP concrete structures including anchorages are designed in the US according to ACI 349 (2006) and in Canada according to CAN3-A23.3-04 (2010) in conjunction with CSA N287.3-14 (2014). In Europe, concrete structures are designed according to EN 1992 (2011), which is currently amended by another part for anchor design (prEN 1992-4, 2013), and according to EN 1998 (2006) for additional seismic design provisions. Further national guidelines are effective and superior to the Eurocodes for the design of NPP structures and their components, e.g. (ETC-C, 2010) in France or (DIN 25449, 2008) and (KTA 2201, 2011) in Germany.

Anchor design data are derived from qualification tests which all post-installed anchor products need to pass since these products are not standardized. For NPPs in US, ACI 349 (2006) references ACI 355.2 (2007) as an acceptable anchor qualification standard. The Canadian guideline CAN/CSA-N287.2-M91 (1991) defines a similar test protocol. In Europe, European Technical Approvals (ETAs) are issued on the basis of the ETAG 001 (2013) qualification guideline which was just amended by the ETAG Annex E (2013) for seismic qualification. There are two performance categories C1 and C2, with C1 qualification tests corresponding to the simulated seismic tests given in ACI 355.2 (2007) and C2 tests representing a more demanding test protocol for highest seismic performance. Anchors used in German NPPs have to hold an ETA for static application and in addition have to be qualified according to the DIBt KKW

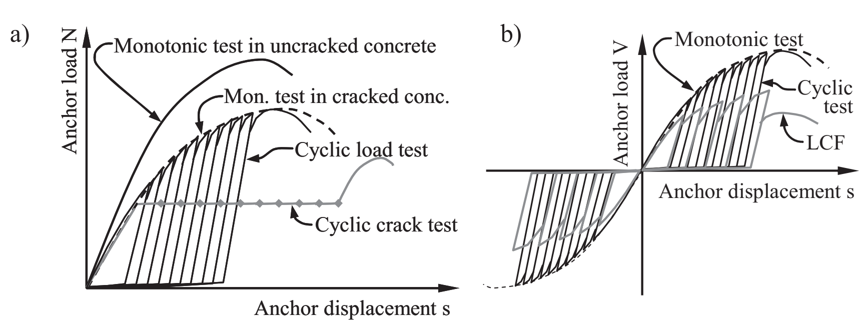

Fig. 2. Load–displacement behavior of anchors: (a) schematic load–displacement curves for anchor loaded in tension, effect of cracking as well as load or crack cycling; (b) schematic load–displacement curves for anchor loaded in shear, and the effect of load cycling and low cycle fatigue (LCF).