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Development and validation of European guidelines for seismic qualification of post-installed anchors

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ABSTRACT

This paper presents the technical background for seismic qualification procedures for post-installed anchors in the European Technical Approval Guideline (ETAG 001) seismic annex issued in 2013. We discuss requirements for a comprehensive guideline and reference supporting research. Numerical studies to generate new simulated seismic protocols for anchors are summarized with a focus on their application to Europe. To reduce the time and cost of anchor product qualification testing, while fulfilling the requirement of European building codes to assess two performance categories, we combine the results of our numerical studies to generate novel testing protocols that allow for the assessment of anchor behavior at multiple levels in a unified protocol. Validation tests demonstrate that the unified protocol results in anchor performance comparable with that achieved in multiple, single-performance-level tests.

1. Introduction

Many parts of the world are subject to earthquakes and Europe is no exception. In addition to direct losses from damaged infrastructure and tragic human losses, indirect losses resulting from disruption of operations can have lasting impacts on a community following an earthquake. This risk depends not only on the magnitude of the seismic hazard, but also on the vulnerability of the built environment. Historically, inadequate anchorage to concrete, in particular of nonstructural components and systems, has been identified as a significant contributor to direct and indirect losses during earthquakes [e.g., [1–5]]. Proper seismic anchorage requires (1) the availably of and adherence to sound seismic anchorage design provisions and (2) anchor products qualified to remain functioning under seismic conditions. In this paper, the focus is on the latter of these requirements.

In the course of European harmonization of building codes and standards, national level documents for post-installed anchors were replaced by a European Technical Approval Guideline (ETAG) beginning in 1997 [6]. However, prior to the release of ETAG 001 Annex E in 2013 [7], the scope of the guideline did not include seismic applications. This new Annex E includes two performance categories for anchors (denoted as C1 and C2). Category C1 testing procedures and assessment criteria closely resemble those currently used in the United States [American Concrete Institute (ACI) 355.2 [8], ACI 355.4 [9]]. In contrast, the C2 anchor performance category, which is more demanding, is required for applications in safety-critical infrastructure (higher building importance class) or when increased seismic demands are anticipated.

This paper outlines the technical basis for the test procedures in the C2 performance category. We briefly summarize the history of developments in seismic anchorage qualification guidelines and the technical requirements for a comprehensive seismic anchorage qualification. We then synthesize our numerical and experimental investigations to develop a new seismic anchorage testing protocol and discuss its applicability to Europe, as well as the unification of multi-level demands (*serviceability* and *suitably*) for use in ETAG 001 Annex E [7]. Finally, we present the results of exploratory tests to validate the equivalence of post-installed anchor performance tested using the unified protocol and multiple, single-performance-level protocols.

2. Brief history of seismic anchorage qualification

In the United States, prior to 1997, qualification of post-installed anchors for seismic performance was not common practice outside of the nuclear and telecommunications industries

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[10]. At that time, post-installed anchors were routinely listed by the International Conference of Building Officials Evaluation Service (ICBO ES) as suitable for seismic conditions based on static tests in uncracked concrete. Anchor connection failures observed during the 1994 Northridge Earthquake in California prompted a review of this practice. After a temporary ban, the ICBO ES adopted acceptance criteria based on the Canadian standard CAN/CSA-N287.2 [13] and listing of mechanical anchors for seismic loading resumed in 1998 [10]. As an alternate means of qualification for seismic loading, the ICBO ES adopted load cycling tests developed by the Structural Engineers Association of Southern California (SEAOSC) [14]. Both these tests (CAN/CSA-N287.2 and SEAOSC) are performed in uncracked concrete, which are less demanding then tests in cracked concrete.

Test programs and evaluation requirements for post-installed mechanical anchors in cracked concrete were introduced in the United States in 2001 in ACI 355.2 [15]. Shortly thereafter, the ICC-ES[1] developed new acceptance criteria AC193 [16] for mechanical anchors based on ACI 355.2. Subsequently, ACI and ICC-ES extended these criteria to include adhesive anchors in cracked concrete [ACI 355.4 [9], AC308 [17]]. It is worth noting that ACI 355.2 and ACI 355.4 are based on ETAG 001 [6] with the exception of the *simulated seismic tests*, which are cyclic load tests and did not exist in the European standard prior to 2013. The seismic testing procedures and acceptance criteria in these documents include tension and shear load cycling in a static crack. They are based on the state-of-the-art as practiced in 2001 and continue today to serve as the basis for issuing post-installed anchor approvals in the United States.

Parallel to developments in the United States, in Germany, the *Deutsches Institut für Bautechnik* (DIBt) issued a guideline for the use and testing of post-installed anchors in German nuclear facilities under extreme load conditions [DIBt KKW Guideline [18]]. The guideline requires tension and shear load cycling in a static crack as well as tests of the anchor in large crack opening and closing cycles, which in this guideline is called *crack movement tests*.

Important load cycling parameters and assessment criteria for the above-mentioned simulated seismic tests are summarized in Table 1. The number of load cycles, their amplitude pattern, and the target load values (load factors) applied in tension (N) or shear (V) at each level of cycling vary significantly between the standards. It is further notable that in current standards used in the United States [7,8,9], anchor performance is evaluated in a crack width (w) of 0.5 mm. This crack width is also used to evaluate anchor performance for non-seismic applications; i.e., the crack width represents service conditions, rather than seismic conditions. The DIBt KKW Guideline [18] also requires verification of performance in 1.0 mm and 1.5 mm wide cracks. These large crack widths assume that anchors are located where the reinforcement in the concrete has undergone a strain of 0.5 % when it yields.

In crack movement tests, an anchor is installed in a closed hairline crack and loaded by a sustained tension load (N_w) that is a fraction of the ultimate strength of the anchor. Crack opening (w_1) and closing (w_2) is typically achieved by applying an external load to the reinforced concrete specimen. In guidelines developed prior to 2013, a pulsating tension load is applied to the anchorage component and the initial crack closing width is allowed to increase as cycling progresses (due to the splitting force developed by the anchor and degradation of the reinforcement bond) provided a minimum specified difference w_1 - w_2 is maintained. Key crack movement test parameters and assessment criteria are summarized in Table 2. It is important to note that the small crack widths (smaller than 0.3 mm) and large number of cycles (1000) used in the U.S. guidelines are not intended to represent seismic conditions. Only the DIBt KKW Guideline [18] attempts to simulate conditions during an earthquake, however, since the guidelines allow for yielding of the reinforcement steel, which is outside the scope of design provisions in most building codes, they are overly stringent in many cases. Details regarding the historical seismic anchorage qualification guidelines can be found in [19].

[1] In 2002, the three major model code bodies the Unites States – including the ICBO – merged under the umbrella of the International Code Council (ICC). For this reason, in this paper ICBO documents reaffirmed subsequent to 2002 are referenced hereafter as ICC-ES documents.

3. Requirements for a comprehensive seismic anchorage qualification

Post-installed and cast-in-place anchors are commonly used in construction to secure nonstructural components and systems (NCSs), such as mechanical, electrical and plumbing systems, as well as to connect structural members to concrete. In reinforced concrete structures, the deformation induced during an earthquake result in cracking of concrete beams, columns, walls and floors. These cracks open and close depending on the amplitude, frequency content and duration of the earthquake motion and the dynamic characteristics of the structure. Since the structural system often serves as the base material for concrete anchorages, these cracks will influence anchor performance. Additionally, the structural system filters the earthquake input motion, influencing acceleration demands throughout the structure. Anchors used to attach nonstructural components are loaded according to the component's dynamic characteristics and the acceleration at the point of attachment, resulting in simultaneous cyclic tension and shear forces. In contrast, the loads on anchors used in structural connections are directly governed by the response of the primary structure that is the columns, beams and walls that comprise the gravity and lateral load resistance systems. Although considerations in this section pertain to both cast-in-place and post-installed anchors used in any structural system, the focus is on post-installed anchors used to secure nonstructural components within buildings, because they represent the largest volume of anchorage applications and, as discussed later, are conservative with respect to the number of load cycles.

A brute-force approach to qualify anchors for seismic applications would be to require dynamic testing of all anchored systems, e.g. by shake table testing according to AC156 [20]. Since this is not practical or economically feasible, and the application in which the anchor will be used is unknown at the time the anchor undergoes seismic qualification, generic testing provisions that cover a range of service conditions are required. As discussed in Section 2 of this paper, previous seismic anchorage qualification guidelines have applied various combinations of tension load cycling, shear load cycling and crack movement tests independently. In actuality, during a seismic event, anchors in concrete will simultaneously be subjected to tension and shear load cycling at dynamic rates, while experiencing cyclic crack opening and closing in the base material. However, there is mounting evidence from full-scale dynamic experiments that separation of actions leads to indicative seismic performance for anchors [21–25]. In the remainder of this section, we synthesize evidence from numerous investigators that inform the development of the new seismic anchorage testing protocols presented in Section 4.

3.1. Dynamic effects

Although earthquakes are dynamic processes involving inertial effects, none of the existing anchor qualification standards summarized in Section 2 require verification of anchor performance at rapid loading or crack cycling rates. Typical anchor loading rates