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NEW EUROPEAN SEISMIC REGULATIONS FOR THE QUALIFICATION AND DESIGN OF POST-INSTALLED ANCHORING

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ABSTRACT

Under seismic loading, the performance of a connection in a structure is crucial either to its stability or in order to avoid casualties and major economic impacts, due to the collapse of non-structural elements.

In the United States the anchor seismic resistance shall be evaluated in accordance with ACI 318 Appendix D. Created in accordance with the ACI 355.2 regulated testing procedures and acceptance criteria ICC-ES AC193 and AC308, pre-qualification reports provide sound data in a proper design format.

With the release of the ETAG 001 Annex E in the first half of 2013, the seismic pre-qualification of anchors became regulated in Europe. Anchors submitted to these new test procedures will now also incorporate in the ETA (European Technical Approval) all the required technical data for seismic design. Until the release of the EN 1992-4, planned for 2015, EOTA TR045 (Technical Report) will set the standard for the seismic design of steel to concrete connections.

Therefore, the design framework for the seismic design of anchors is already available through both the U.S. and European regulations.

1. INTRODUCTION

In all parts of the world, seismic design methodologies not only for primary structures, but also including equipment, installation and other non-structural element supports have significantly gained in importance over the past years. This does not apply solely to "classical" earthquake regions, but also to Central Europe where, for example, the threat from earthquakes has been underestimated in the past. As the tragic 1999 İzmit earthquake and the seismicity distribution shown in Fig. 1, large earthquakes in Europe are not just historical references.

In fact the economic and social costs associated with the failure or interruption of certain services and equipments such as water, energy or telecommunication supply systems and traffic lines are of comparable magnitude to the costs associated with structural failures, if not greater.

As post-installed anchors are often used to fix structural members and non-structural components, their adequate design and selection is of crucial importance to guarantee safety and minimize costs associated with seismic events. The connections should then be clearly detailed during design phase in order to allow a common understanding of the project specifications by contractors and building inspectors. Ultimately, this practice avoids the high risk of leaving the responsibility to subcontractors.

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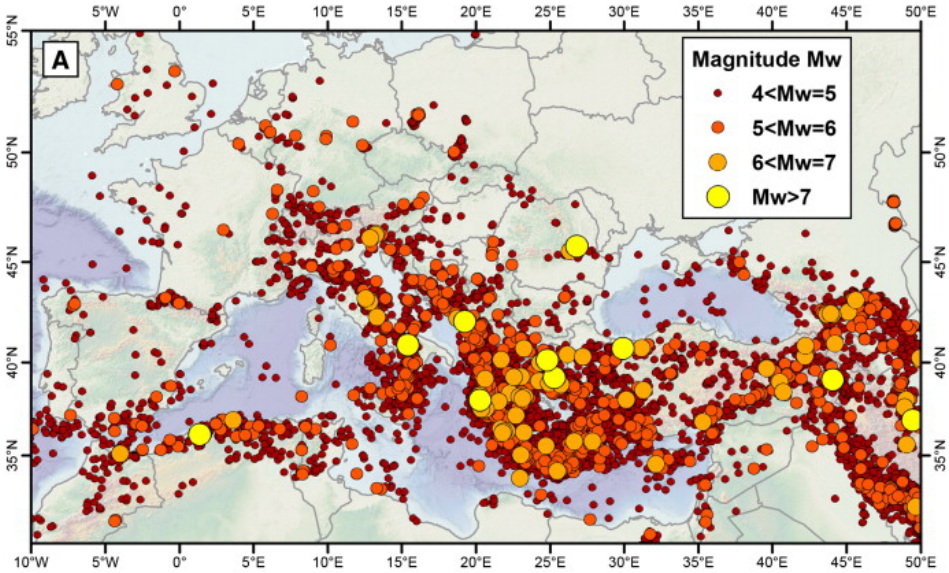


Figure 1. European seismicity distribution for the 1976–2009 period (NEIC catalog)

1.1. Influence of earthquake resulting cracks in concrete base material

As a structure responds to earthquake ground motion it experiences displacement and consequently deformation of its individual members. These deformations lead to the formation and opening of cracks in the concrete members. Consequently all anchorages intended to transfer earthquake loads should be suitable for use in cracked concrete and their design should be predicted on the assumption that concrete cracks will open and closed for the duration of the ground motion.

Parts of the structures may however be subjected to extreme inelastic deformation as exposed in Fig. 2. In the reinforced areas yielding of the reinforcement and cycling of cracks may result in cracks width of several millimetres, particularly in regions of plastic hinges. Qualification procedures for anchors do not currently anticipate such large crack widths. For this reason, anchorages in these regions where plastic hinging is expected to occur should be avoided unless apposite design measures are taken.

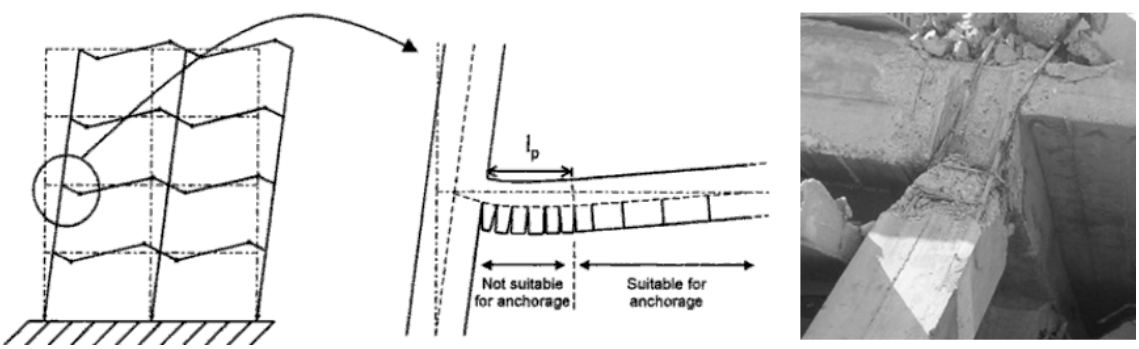


Figure 2. Member cracking assuming a strong-column, weak girder design (lp = plastic hinge length)

1.2. Suitability of anchors under seismic loading

An anchor suitable (approved) to perform in a commonly defined cracked concrete, about 0.3 mm, is not consequently suitable to resist seismic actions, it's just a starting point.

During an earthquake, cyclic loading of the structure and fastenings is induced simultaneously. Due to this the width of the cracks will vary between a minimum and a maximum value and the fastenings will be loaded cyclically. Specific testing programs and evaluation requirements are then

necessary in order to evaluate the performance of an anchor subjected to seismic actions. Only the anchors approved after the mentioned procedure shall be specified for any safety relevant connection.

Anchors generally suitable for taking up seismic actions are those which can be given a controlled and sustained pre-tensioning force and are capable of re-expanding when cracking occurs. Also favourable are anchors which have an anchoring mechanism based on a keying (mechanical interlock) as it is the case for undercut anchors. Furthermore, some specific chemical anchors have also been recognized good performance to resist seismic actions. Displacement controlled expansion anchors should be avoided considering that their performance under seismic is proven unsuitable.

The following Table 1 provides a rough overview of the suitability of various types of anchors to resist seismic actions. This suitability depends to a great extent on how badly the concrete has cracked and how large the cracks are in the event of an earthquake. The classifications presented are based on a generic assessment of the anchor types not reflecting a particular evaluation of any product or anchor manufacture.

Table 1. Suitability of anchors under seismic loading (- unsuitable, + suitable, ++ very suitable)

Type of anchor		Displacement controlled expansion anchors	Adhesives anchors	Concrete screws	Torque-controlled expansion anchors	Adhesive-expansion anchors	Sleeved torque-controlled expansion anchors	Undercut anchors
Cracked concrete with crack width, w	small (w < 0.5mm)	-	++	++	++	++	++	++
	medium (0.5 ≤ w ≤ 1.0mm)	-	+	+	+	+	++	++
	large (w > 1.0mm)	-	-	-	-	+	+	++

Note that the precise understanding of an anchor ability to tackle seismic loading should always be checked by consulting the anchor approvals being Table 1 a guidance for a general understanding of the different anchor type capacities and limitations, independently from any anchor manufacture.

1.3. Influence of annular gaps in the anchorage resistance under shear loading

Under shear loading, if the force exceeds the friction between the concrete and the anchoring plate, the consequence will be slip of the fixture by an amount equal to the annular gap. The forces on the anchors are amplified due to a hammer effect on the anchor resulting from the sudden stop against the side of the hole (Fig. 3.a). This justifies the new European seismic design guideline recommendation for annular gaps between the anchors and the fixture to be avoided in seismic design situations.

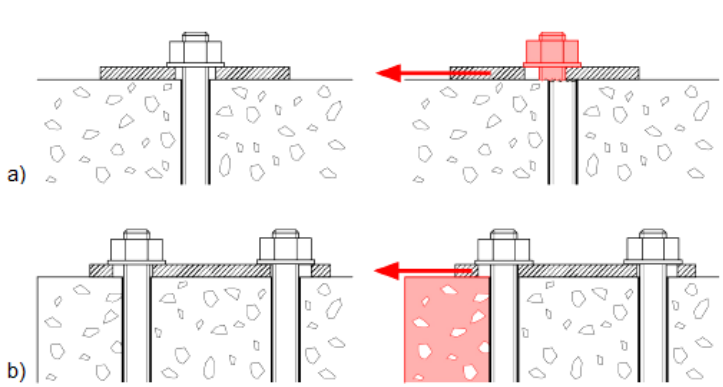


Figure 3. Main consequences possibility resulting from annular gaps between the anchor and fixture

Moreover, where multiple-anchor fastenings are concerned, it must be assumed that due to play of the hole on the steel plate a shear load may not be distributed equally among all anchors. In an unfavourable situation, when anchor fastenings are positioned near to the edge of a building member, only the anchors closest to the edge should be assumed loaded and as such this could result in an early failure of the concrete edge before the anchors furthest from the edge can also participate in the load transfer (Fig. 3.b).

By eliminating the hole play, filling the clearance hole with an adhesive mortar e.g., the effects mentioned above are controlled with great benefit to the anchorage performance. The use of Hilti Dynamic Set (Fig. 4) will ensure a professional approach for a controlled filling of the annular gaps as well as it will prevent the loosening of the nut since it also comprehends a lock nut, effect that also complies with a European seismic design guideline clear recommendation. Also according to the same guideline, in case it can be ensured that there is no hole clearance between the anchor and the fixture, the anchor seismic resistance for shear loading is doubled compared to connections with hole clearances.

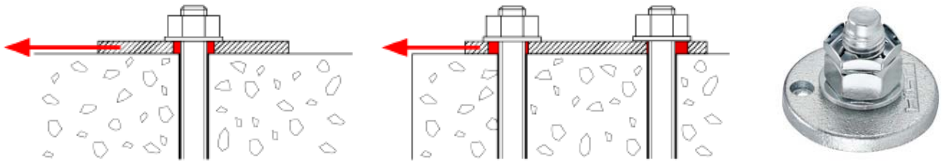


Figure 4. Benefits of filled annular gaps and Hilti Dynamic Set: Filling washer, conical washer, nut and lock-nut

2. UNITED STATES AND EUROPEAN SEISMIC REGULATIONS

For a sound seismic design of a post-installed anchorage the first step begins with the correct definition of the acting loads. In the United States ASCE 7 establishes the provisions for the definition of the seismic action and the anchor performance shall be evaluated in accordance with ACI 318 Appendix D and AC308 in case of chemical anchors. Pre-qualification reports, created in accordance with published testing procedures and acceptance criteria, (ACI 355.2 with ICC-ES AC193 and AC308) provide sound data in a proper format for design.

Following the same design flow, in Europe the action definition is available through the EN 1998:2004 (Eurocode 8). Until the release of the EN 1992-4, planned for 2015, EOTA TR045 (Technical Report) sets the standard for the seismic design of steel to concrete connections. This regulation is in full alignment with ETAG 001 Annex E, the new European guideline for the anchor's seismic pre-qualification testing. As such, the European framework is also already harmonized in order to allow the design of a post-installed anchorage under seismic conditions.

As an overview, Table 2 display the application ranges of the different guidelines or codes mentioned above. The presented design codes represent the state of the art for the testing of fasteners and the design of fastenings in concrete worldwide. Note that even if not all, most of the countries in the world refer to one of these frameworks for the design of anchors.

Table 2. Seismic design framework for fastenings in concrete

	United States	Europe
Load definition	ASCE 7	EN 1998-1:2004
Design resistance	ACI 318 Appendix D AC308	EOTA TR045
Technical data	ICC-ES report (ESR)	ETA
Pre-qualification criteria	ACI 355.2 with ICC-ES AC193/AC308	ETAG 001, Annex E

2.1. Seismic load definition

The starting point for the definition of the seismic actions is the seismic design spectrum. In the case of the US a seismic design category (SDC) is endorsed and the seismic design spectrum is obtained by the mapped maximum (short period, 0.2s) and 1.0s period acceleration whereas in Europe the seismic hazard is defined by the peak ground acceleration (PGA) and no SDC is established. There is however a clear definition for low and very low seismicity, based on the design ground acceleration, and in case of very low seismicity no specific seismic provisions need to be observed.

The influence of the soil type is considered in both codes by a site coefficient which is based on matching ground classifications, considering the shear wave velocity limits and soil descriptions. Based on the risk of an eventual improper seismic performance, the categorization of buildings is placed in the same way by both codes and the correspondent importance factor is assigned with similar values (even if at different phase in the design flow).

Considering the above mentioned, the equations to derive the seismic design spectrum are expected to be different between the codes but, considering equivalent importance class and ground type, the resulting shape and spectral acceleration are very much similar. In simple terms, it can be said that mathematically the two codes are just pointing different coordinates of the design spectrum (Fig. 5). Note that the design response spectrum according to ASCE7 does not contemplate the influence of the building importance (being considered later in the design) and as such the comparison was made considering the resulting spectrum accordantly scaled by this factor.

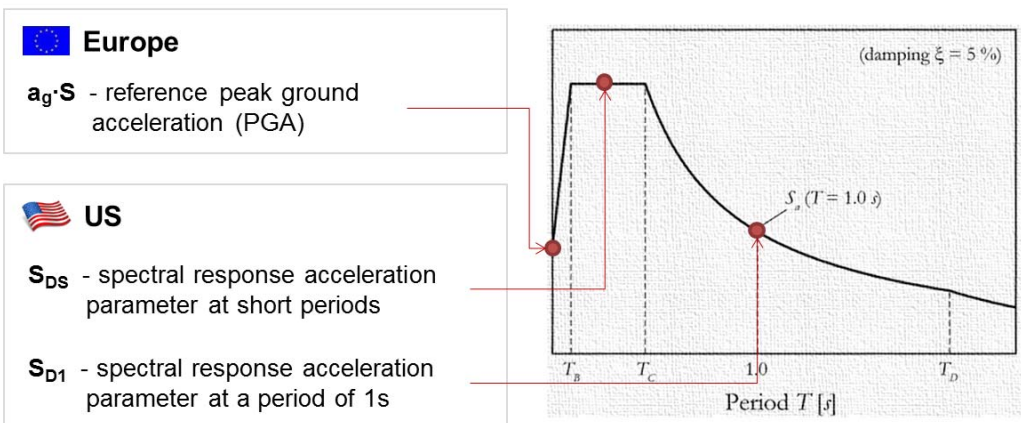


Figure 5. Design response spectrum according to Eurocode 8 and ASCE 7

A comparison was also established between the seismic base shear force using the EN1998-1:2004 and the ASCE7. Evaluating the different expressions as well as some practical applications of the codes we can conclude that the values are decidedly coincident. From the seismic base shear force different well-known methods can be used to determine the load acting at each level of the structure.

As such, comparing the resulting seismic design spectrums with equivalent importance classes and ground types (S being the soil factor), it's possible to correlate the European seismicity rating with the United States seismic design category, as expressed in Table 3.

As the only yet important exception to the Table 3, in case of a building with an importance class IV and a seismicity rating of low or above the corresponding seismic design category is C or above. This means that in the case of buildings that in the event of a failure could pose a substantial hazard to the environment or community (e.g. hospitals, fire stations, power plants) the design should consider all the seismic specific provisions.

Table 3. Eurocode 8 seismicity rating compared to ASCE7 seismic design category (SDC), for building importance class I, II, III

EN 1998-1:2004 (Eurocode 8)		ASCE7	
Seismicity rating	Design repercussion	SDC	Design repercussion
Very low $ag \cdot S \leq 0.05 \cdot g$	No seismic specific provisions need to be observed	A	No seismic specific provisions need to be observed
Low $ag \cdot S \leq 0.1 \cdot g$	Reduced or simplified design procedures may be used	B	
$ag \cdot S > 0.1 \cdot g$	Seismic design must be attend to all the elements	C to F	Seismic design must be attend to all the elements

2.2. Anchors seismic design resistance

Design provisions for the anchor seismic design are provided by the ACI 318 Appendix D or the recent EOTA TR045. Both design regulations work with the CC-method (concrete capacity method) to calculate the characteristic resistances of fastenings. Differences between the codes occur in the basic assumptions for the design equations which partially result in different factors. According to the CC-method the design resistances are calculated for tension loading and shear loading considering all possible failure modes.

All discussed safety concepts calculate resistance and actions based on partial safety factors. The main requirement for design of the discussed codes is that the factored action E shall be smaller or equal to the factored resistance R (Eq. 1). All codes factor the characteristic action E_k with partial safety factors γ (Eq. 2).

$$E_d \leq R_d \tag{1}$$
$$E_d = E_k \cdot \gamma \tag{2}$$

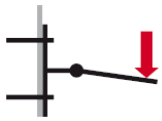
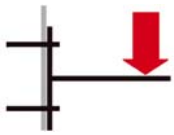
For the characteristic resistance there is a conceptual difference since the European codes divide the characteristic resistance Rk by a partial safety factor γ (Eqn. 2.3.) whereas the United States codes factor the characteristic resistance R_k with a strength reduction factor ϕ (Eqn. 2.4.). The effect of these factors is however the same reducing the characteristic value to design level. The design resistance R_d is generally very similar for all the evaluated failure modes independently on the adopted code.

$$R_d \leq R_k / \gamma \tag{3}$$
$$R_d = \phi \cdot R_k \tag{4}$$

As per the new European design guideline, EOTA TR045, the design incorporates three design approaches which are described below. Note that all three of these approaches are acceptable within their application conditions. Table 4 provides an overview of these different design options.

Note that the ACI 318 also considers thee design approaches that are conceptually the same as the ones presented by the EOTA TR045. The main difference, that nevertheless has the same background intention, comes from the fact that the “Elastic design” defined as per European guideline has a different approach in the U.S. regulations. In the ACI 318 this design option consider the loads resulting from a regular seismic design (not elastic) and introduces a reduction factor (recommended as 0.4) directly applied on all concrete failure modes. It is the authors’ opinion that the new European regulations have made the different design approaches more clear compared to the ACI 318 interpretation.

Table 4. Seismic design options per European seismic guideline

	**a1) Capacity design** The anchorage is designed for the force corresponding to the yield of a ductile component or, if lower, the maximum force that can be transferred by the fixture or the attached element.
	**a2) Elastic design** The fastening is designed for the maximum load assuming an elastic behaviour of the fastening and of the structure.
	**b) Design with requirements on the ductility of the anchors** This requires an anchor classified as ductile and this approach is applicable only for the tension component. Additional provisions are required to be observed in order to ensure the anchor steel resistance is governing the resistance.

2.3. Evaluation of the anchor seismic performance

For testing of fastenings in concrete three different basic guidelines must be considered. In the United States ACI 355.2 covers testing of post-installed mechanical anchors under static and seismic loading and prescribes testing programs and evaluation requirements for post-installed mechanical anchors intended for use in concrete under the design provisions of ACI 318. This guideline is the basis for the acceptance criteria AC193 and AC308 by the International Code Council (ICC). While AC193 covers testing of mechanical anchors, AC308 covers testing and design of adhesive anchors.

Referring the main testing procedures, the anchors are installed in a closed crack that then is open to 0.5mm. The anchors under testing are afterwards subject to the sinusoid varying loads specified, using a loading frequency between 0.1 and 2Hz as exposed in Fig. 6. The maximum seismic tension and shear test load is equal to 50% of the mean capacity in cracked concrete from ref. tests.

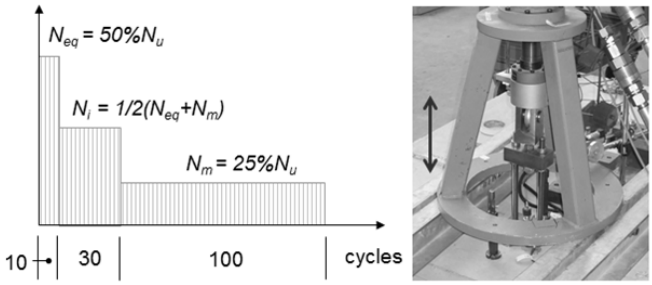


Figure 6. Loading pattern for simulated seismic tension tests according to ACI355.2

After the simulated seismic-tension and seismic-shear cycles have been run, the anchors are tested to failure in static-tension and static-shear. The mean residual tension and shear capacities shall be assessed according the guideline defined limits.

In Europe the ETAG 001 is valid for testing of post- installed mechanical (Part 1 to Part 4) and bonded anchors (Part 5). With the release of the ETAG 001 Annex E in the first half of 2013, the seismic pre-qualification of anchors became regulated in Europe. Two different testing programs are presented to assess the anchor's suitability to seismic loading resulting in two seismic performance categories classified as follows:

- Seismic category C1: similar to the US seismic pre-qualification procedure and only suitable for non-structural applications.
- Seismic category C2: very demanding seismic crack movement tests classify an anchor as suitable for structural and non-structural applications.

While seismic category C1 is identical to the U.S. seismic pre-qualification procedure, seismic category C2 involves a set of quite more demanding seismic load and/or crack cycle tests especially considering that for assessing the tension seismic performance one of the tests involves the cycling of the cracks until a width of 0.8mm.

In practical terms, according to the EOTA TR045 and for ag·S above 0.05g, anchors intended for connections between structural elements of primary or secondary seismic members should always have a seismic category C2. For anchors used in the attachment of non-structural elements, if the acceleration ag·S is between 0.05g and 0.10g then a seismic category C1 can be used. Please note that these are the generic recommendations that member states can locally adjust.

3. CONCLUSIONS

Considering all the exposed above, the design framework for the seismic design of anchors is already available through both the U.S. and European regulations. This means that there it is no longer a need for an engineering judgement on the use of U.S. anchor performance provisions along with the European seismic action definition, solution suggested by one of the authors during the last years in the absence of European seismic regulations to assess and design anchors.

It's now the responsibility of the anchoring manufactures to provide designers and the building industry with seismic design data according to the new European testing procedures. Hilti has been at the forefront of anchoring related seismic projects and investigations, Hilti has already approved for seismic performance category C2 both the chemical anchor HIT-HY 200 + HIT Z and mechanical anchor HST.

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