Engineering judgement on the use of American's anchor performance provisions along with the European seismic action definition

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SUMMARY:
Under seismic loading the performance of an anchored connection is crucial either to the stability of a structure or in order to avoid major casualties and/or economic impacts consequence of non-structural elements collapse. In Europe the seismic action definition is available through the EN 1998:2004 and the anchor performance can be defined by the CEN/TS 1992-4:2009. However, the anchor's seismic pre-qualification testing description is still under development. As such, the European framework is not yet harmonized in order to allow the design of a post-installed anchorage under seismic conditions. To allow in Europe the design of anchors subjected to seismic action, the resistance evaluation can attend to the provisions and technical reports existing in the United States (ACI 355.2 with ICC-ES AC193 and AC308).

Keywords: Anchor design, Seismic codes, ICC-ESR

1. AWARNESS AND BACKGROUND

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. 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.

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.

1.1. Influence of earthquake resulting cracks in the anchor's concrete base material

As a structure responds to earthquake ground motion it experiences displacement and consequently deformation of its individual members. This deformation leads to the formation and opening of cracks in 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 cracks in the concrete will cycle open and closed for the duration of the ground motion.

Parts of the structures may be subjected to extreme inelastic deformation as exposed in Fig. 1.1. 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 this region where plastic hinging is expected to occur, such as the base of shear wall and joint regions of frames, should be avoided unless apposite design measures are taken.

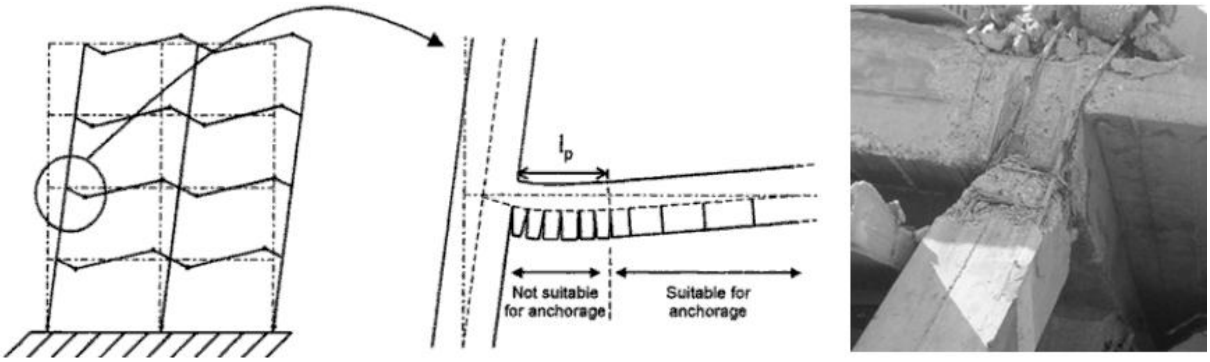

Figure 1.1. Member cracking assuming a strong-column, weak girder design (l_p = plastic hinge length)

1.2. Suitability and use of anchors under seismic

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 of the 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 and concrete screws. Furthermore, some specific chemical anchors have also been recognized good performance to resist seismic actions. Displacement controlled anchors, having an expansion sleeve and a plug which is hammered into the expansion sleeve, should be avoided at all cost considering that their performance under seismic is proven unsuitable.

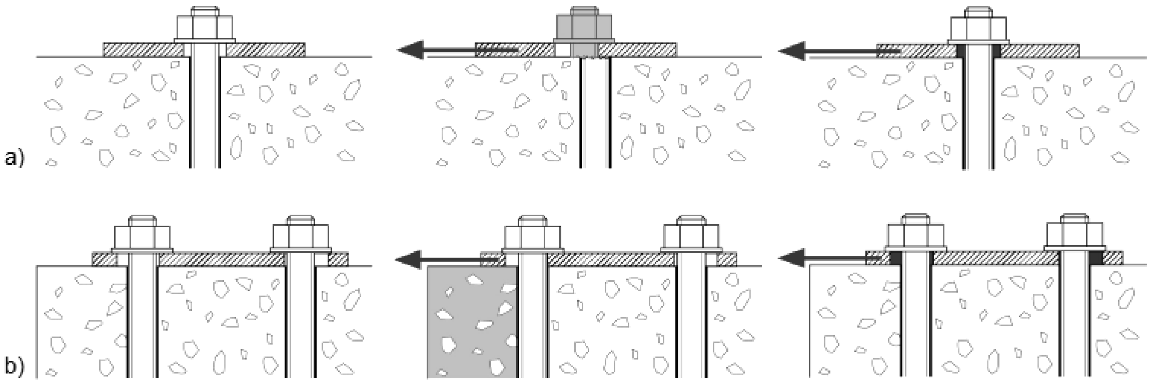

Figure 1.2. Influence of the hole play in the anchorage bearing under shear loading

If the shear load exceeds the friction between the concrete and the anchoring plate, the consequence will be slip of the fixture by an amount equal to the hole play. This stopping against the side of the hole increases the load on the anchor bolt and this can then cause shear failure (Fig. 1.2.a). Moreover, where multiple-anchor fastenings are concerned, it must be assumed that due to play of the hole on the plate a shear load is not distributed 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 are loaded and this can result in failure of the concrete edge before the anchors furthest from the edge can also participate in the load transfer (Fig. 1.2.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.

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) and the resistance evaluation can be defined by the CEN/TS 1992-4:2009. However, the anchor's seismic pre-qualification testing description is still under development. As such, the European framework is not yet harmonized in order to allow the design of a post-installed anchorage under seismic conditions.

As a summary, Table 2.1. display the application ranges of the different guidelines or codes mentioned above. The compared design codes represent the state of the art for the testing of fasteners and the design of fastenings in concrete worldwide.

Table 2.1. 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	CEN-TS 1992-4:2009
Technical data	ICC-ESR	To be derived based on pre-qualification criteria
Pre-qualification criteria	ACI 355.2 with ICC-ES AC193/AC308	Under development by EOTA

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 very low seismicity is observed 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 associated with 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. 2.1.). Note that the design response spectrum according to ASCE7 does not contemplate the influence of the building importance (being considered later in the design flow) and as such the comparison was made considering the resulting spectrum accordantly scaled by this factor.

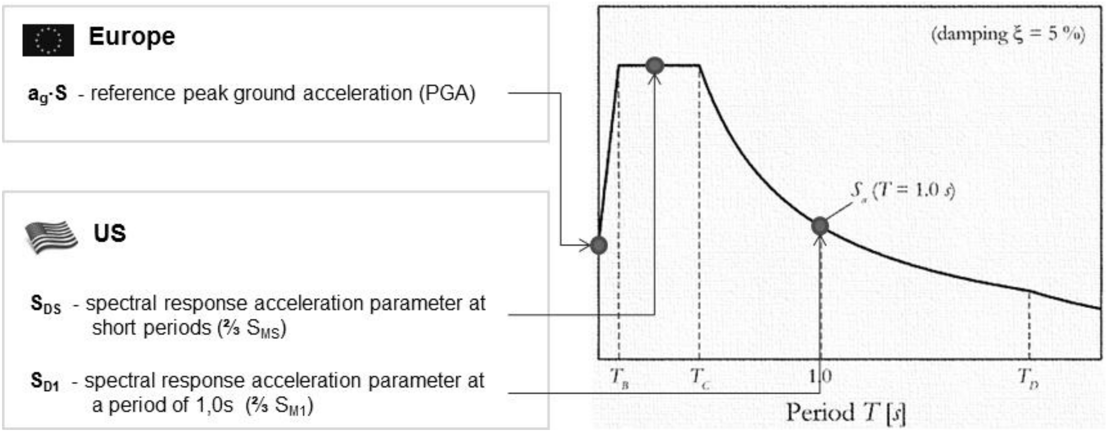

Figure 2.1. Design response spectrum according to Eurocode 8 and ASCE 7

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.

2.2. Anchors seismic design resistance

Design provisions for the anchor seismic design is provided by the ACI 318 Appendix D or the recent CEN/TS 1992-4:2009. Both design codes 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 (Eqn. 2.1.). All codes factor the characteristic action E_k with partial safety factors γ (Eqn. 2.2.). For the characteristic resistance there is a conceptual difference since the European codes divide the characteristic resistance R_k 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.

$$\mathrm{E}_d \leq \mathrm{R}_d \qquad (2.1)$$
$$\mathrm{E}_d = E_k \cdot \gamma \qquad (2.2)$$
$$\mathrm{R}_d = R_k/\gamma \qquad (2.3)$$
$$\mathrm{R}_d = \phi \cdot R_k \qquad (2.4)$$

For the design three main approaches are presented by both codes. Note that all three of these provisions are acceptable design cases. The anchorage can then be governed by ductile anchor yielding, ductile fixture yielding or a non-ductile limit established by any of the concrete failure modes. Since it's clear that a non-ductile failure in seismic event is clearly undesired based on this option a very significant reduction is applied to the concrete related resistances.

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 the crack 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. 2.2. The maximum seismic tension and shear test load is equal to 50% of the mean tension capacity in cracked concrete from reference tests.

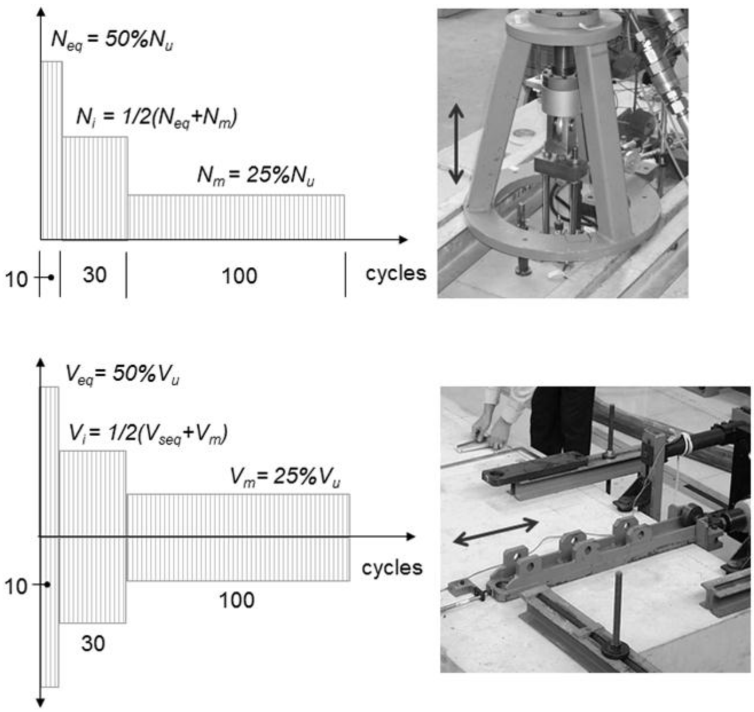

Figure 2.2. Loading pattern for simulated seismic tension and shear tests according to ACI355.2

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 3). The ETAG 001 covers only anchors under static and quasi static loading; fatigue loadings and seismic loadings are not covered.

3. APPROACH FOR ANCHOR SEISMIC DESIGN IN EUROPE

Under seismic loading the performance of an anchored connection is crucial either to the stability of a structure or in order to avoid major casualties and/or economic impacts consequence of non-structural elements collapse. Therefore, to allow in Europe the design of anchors subjected to seismic action, the resistance evaluation should attend to the provisions and ICC-ESR technical reports existing in the United States.

As above mentioned the expressions to determine the seismic base shear force are very much similar. 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 3.1.

Table 3.1. European seismicity rating relation to seismic design category (SDC) for importance class I, II, III

EN 1998-1:2004 (Eurocode 8)		ASCE7
Seismicity rating	Design repercussion	SDC
Very low $ag \leq 0.04 \cdot g$ $ag \cdot S \leq 0.05 \cdot g$	No seismic specific provisions need to be observed	A
Low $ag \leq 0.08 \cdot g$ $ag \cdot S \leq 0.1 \cdot g$	Reduced or simplified design procedures may be used	B
$ag > 0.08 \cdot g$ $ag \cdot S > 0.1 \cdot g$	Seismic design must be attend to all the elements	C to F

As the only yet important exception to the Table 3.1, 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 the design should consider all the seismic specific provisions.

In practical terms, in the process of determining the seismic actions, it's straightforward for a designer to recognize according to the design ground acceleration (a_g) when it is required to consider the seismic provisions. According to ACI 318 Appendix D the anchors should be design considering the seismic provisions in case the Seismic Design Category is assigned as C or above. Therefore, every time the seismicity rating is above low only seismically approved anchors should be used and the design should be performed considering the seismic provisions presented by ACI 318.

Considering the above and the seismic design framework for fastenings in concrete, the seismic design of anchors in Europe can use the framework presented by Table 3.2 where the loads are defined per the EN 1998-1:2004 and the resistance derives from the United States anchor performance provisions. The mentioned practice is presently the only available combining seismic pre-qualification with European guidelines being fully operational and can as such be considered a state-of-the-art approach.

Table 3.2. European anchor seismic design framework in the absence of seismic tech. data and pre-qualification

	United States	Europe
Load definition	ASCE 7	EN 1998-1:2004
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