Design of Post-installed Anchors for Seismic Actions

Gilbert Balbuena  
_Hilti New Zealand._

J. Gramaxo, J. Kunz  
_Hilti Corporation, Liechtenstein._

**ABSTRACT:** 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 these mentioned types of equipment, their adequate design is of crucial importance to guarantee safety and minimize costs associated with seismic events. This paper shows the working principles of different types of anchors, discusses their behaviour under seismic loads, and classifies them according to their suitability for the typical situations occurring in earthquakes such as large cracks in the concrete or alternating directions of the load. 

The primary globally established design concept for anchors under seismic loads can be found in the US codes. This paper will describe the principles of the concept. Specific tests qualify anchors for seismic loads. ACI 318 gives a design method for qualified anchors. 

The final section of this paper will summarize examples of good detailing of anchorage applications leading to a cost-efficient enhancement of the overall safety of buildings and infrastructures in seismic events.

1 INTRODUCTION

1.1 Relevance of seismic anchor design

The awareness of the high risk by which earthquakes threaten lives and goods has resulted in many thorough investigations on the design of structures for seismic actions over the past decades. However, for the global behavior of the structures to perform as designed, it is essential that also the structural connections’ behavior is satisfactory under seismic conditions. Thus the proper behavior and design of post installed anchors may be crucial to guarantee the continuity of the load paths during a seismic event.

Nevertheless, in current practice many structural connections intended to transmit seismic loads are designed on the basis of idealized static loads. Especially in the case of load bearing structures or electromechanical installations such procedures might result in significant social and economic risk.

In addition to the life safety and property loss considerations, there is the additional possibility that non-structural damage will make it difficult or impossible to carry out the functions normally accomplished in a facility. After the serious life safety threats have been dealt with, the potential for post-earthquake downtime or reduced productivity is often the most important risk.
1.2 Seismic action and its implication on structural connections

Earthquakes generate actions on a structure in a variety of ways. These include acceleration of the ground (ground motion), differential settlement of the foundations resulting from liquefaction or other ground phenomena and possible lateral and vertical displacement across a fault trace. From a design perspective, induced structure acceleration represents the most obvious and prevalent loading case to be considered. However, imposed deformations, not inertial forces, are frequently the cause of connection failures in earthquakes, particularly when those connections have not been designed to accommodate large deformations.

Typically, ground accelerations are translated through a structure via the foundations, which interact with the surrounding and supporting soil and rock via a complex interplay of frictional and bearing forces. The input motions from the ground generate varying responses in the structure depending on the magnitude, frequency content and duration of the ground motion, the efficiency of the soil-structure interface and the dynamic characteristics of the structure. As the structure responds to the ground motion, degradation of the primary structure, which serves as the anchorage material, can occur. In reinforced concrete structures this degradation is in large part expressed through cracking in the structural elements. Additionally, the motion of the primary structure will generate actions on secondary structures; such as structural retrofit elements or non-structural equipment. If the secondary structure is connected to the primary structure by anchors, the motion of the primary structure generates tension and shear forces on the anchors. Studies of the US Federal Emergency Management Agency [13] have shown that of the total damage caused by earthquakes, up to 50% may be connected with non-structural elements, especially in urban areas (figure 1)

Figure 1: distribution of earthquake damage between structural and non-structural elements

It is important to note that in addition to the above mentioned direct effects, earthquakes can lead to substantial so called “consequential damage” due to fire, explosions or flooding.

1.3 Plastic deformation capacity

One of the main concerns of seismic building design is to create sufficient ductility in the structure so that in case of a earthquake it is able to produce large deformations without collapsing and with the deformation, to dissipate as much energy as possible. It should be noted that anchors have a very limited energy dissipation capacity; their task should be to transmit forces in a safe way rather than dissipating energy.

2 ANCHOR BEHAVIOR UNDER SEISMIC ACTIONS

2.1 Load transfer principles

Post-installed anchors are usually subdivided into adhesive and mechanical anchors according to the load transfer principle they use. Adhesive anchors use a bonding agent between the base material and the actual anchor and mechanical anchors use friction to transfer load by expansion or keying. Newer anchor types combine different load transfer principles.
Considering the variable nature of seismic forces, it is necessary to clearly subdivide mechanical expansion anchors into so-called torque-controlled expansion anchors and displacement-controlled expansion anchors. A torque-controlled expansion anchor is expanded by applying a torque moment which fixes the anchor in its hole. A distinction is made between a sleeve-type anchor, which mainly consists of a threaded bolt, tapered plug, spacing sleeve as well as expansion sleeve and a stud-type anchor, which has a taper and expansion wedges on its bolt (Fig. 3a). The possibility of applying a torque is a check that the anchor has been set properly. If externally applied tensile loads increase or if cracks appear in the base material, torque-controlled expansion anchors are capable of re-expanding, i.e., so-called follow-up expansion, and thus of transferring higher loads or compensating anchor hole tolerances or crack width variation.

Displacement-controlled expansion anchors have an expansion sleeve and a plug which is hammered into the expansion sleeve (Fig. 3c) or onto which the expansion sleeve is hammered. The magnitude of the expansion force and thus the tensile resistance (loading capacity) depend on the amount of expansion and, in this respect, very high impact energy is generally required for proper expansion. Displacement-controlled expansion anchors cannot re-expand.

Adhesive-expansion anchors generate expansion forces when they are subjected to tensile loading and this makes them suitable for use in cracked concrete. Adhesive-expansion anchors consist of an anchor rod with one or several tapers which are coated to avoid a bond being formed between anchor rod and synthetic resin/adhesive mortar. When a tensile force is applied to the anchor rod, its tapers are pulled into the cured synthetic resin/adhesive mortar which then functions as an expansion wedge. This generates expansion and thus friction forces which are high enough to transfer the tensile load without an adhesive/mortar bond being required.
2.2 **Effects of the cracked concrete**

Structural reinforced concrete is usually cracked due to different reasons. Typically the relevant cracks are caused by tensile stresses induced by applied loads or deformation restrictions (shrinkage, creep, temperature variations). Under seismic actions, additional cracks of substantial width often appear.

During earthquakes, many parts of a structure may see significant plastic deformations, especially those close to plastic hinge areas which can lead to crack openings of several millimeters (figure 5). Evaluations of anchor behavior and the respective approvals do not take into account such extreme situations, since post-installed anchorages should be avoided in plastic hinge areas.

![Figure 5: plastic hinge areas (not recommended for post-installed anchors)](image)

The probability that anchors are in fact located where cracks occur is actually high. This is due to the fact that drilled anchor holds form discontinuities in the concrete base material which result in relatively high stresses under loading (“notch effect”) [1].

The load carrying capacity of post-installed anchors strongly depends on the state of cracking of the concrete base material. Depending on the load transfer principle used by the anchor, the anchor strength in cracked concrete can be reduced to about 50% of the strength in non-cracked concrete, or in some cases the anchor is not suitable for cracked concrete at all.

2.3 **Anchor types suitable for seismic loads**

In seismic load applications, only post-installed anchors qualified for this type of action should be considered. In general, torque controlled expansion anchors, undercut anchors and adhesive expansion anchors can be considered as using appropriate load transfer mechanisms. Some adhesive anchors are also qualified for seismic loads while others are not. Displacement controlled expansion anchors are in general not suitable for seismic load (table 1).

<table>
<thead>
<tr>
<th>Anchor type</th>
<th>Displacement controlled expansion anchors</th>
<th>Not qualified adhesive anchors</th>
<th>Qualified adhesive anchors</th>
<th>Adhesive-expansion anchors</th>
<th>Concrete screws</th>
<th>Torque controlled expansion anchor stud type</th>
<th>Torque controlled expansion anchor type</th>
<th>Undercut anchors</th>
</tr>
</thead>
<tbody>
<tr>
<td>uncracked</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Cracked concrete</td>
<td>Crack width w &lt; 0.5mm</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Crack width 0.5 ≤ w ≤ 1.0mm</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>Crack width w &gt; 1.0mm</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
</tbody>
</table>
Considering the difficulty involved with theoretically predicting the behavior of an anchor, it is of utmost importance to select anchors approved for carrying seismic load. This confirms that anchors have been tested under simulated seismic load and showed satisfactory behavior with respect to resistance and displacement criteria.

2.4 Special aspects of anchor behaviour under shear load

The following special aspects apply to the behavior of anchor fastenings under shear loading and these are also important in the case of seismic 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. If dynamic loading is involved, this stopping against the side of the hole increases the load on the anchor bolt and this can then cause shear failure (Fig. 6a).

· Play, where you have a combination of the hole in the anchoring plate and an anchor bolt that is not well set in the hole, the result will be an anchor stressed in bending and this considerably reduces the loading capacity (ultimate state) (Fig. 6b).

· 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 unfavorable situation, when anchor fastenings are made 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. 6c).

It is possible to considerably improve the behavior of anchor fastenings subjected to shear loading by eliminating the hole play between anchor stud and plate. This also applies to dynamic loads in general and seismic loads in particular. Filling the clearance hole and the anchor hole, virtually excludes any bending of the anchor under shear loading. The fastening resistance (loading capacity) is considerably increased by taking this measure. Filling the plate clearance holes of multiple-anchor fastenings results in a uniform load distribution to all anchors. In the case of a fastening near to a building member edge, this filling prevents the concrete edge from breaking away prematurely which would happen if the anchors closest to the edge were loaded (figures 6 and 7).
2.5 Influence of pre-tensioning fasteners

In general, the behaviour of anchors under dynamic loading can be decisively improved if they are pre-tensioned. This, however, primarily concerns the performance under fatigue relevant loading as the pre-tensioning considerably reduces the range of stress, provided that the upper load limit (max. stress) does not exceed the pre-tensioning force.

During seismic actions, the loading can exceed the pre-tensioning force which results in torque-controlled expansion anchors postexpanding. Under a pulsating or an alternating load, this change from post-expansion and to subsequent release causes a reduction in pre-tensioning force. Due to the possibly high crack width expected in seismic events, the drop in pre-tensioning force must often be assumed to be 100%.

3 DESIGN OF ANCHORS FOR SEISMIC ACTIONS

3.1 Regulations and design methods

In the United States a complete methodology for seismic design of anchors is available. Design provisions are provided by the American Concrete Institute (ACI) in ACI 318 Appendix D (2008) and resistances are available from current Evaluation Service Reports (ESRs) issued by the International Code Council – Evaluation Service, Inc. (ICC-ES). The International Building Code (IBC) has adopted these documents.

As the exact definition of seismic loads requires sophisticated analyses it is current practice to use simplified methods to estimate anchor loads for the fixing of installations or equipments.

3.2 Analysis considering plastification of the attachment

Where ductile elements are fixed, one may assume that the load at which plastification of the attached element occurs is equal to the highest expected anchor load.

3.2.1 equivalent static analysis using amplification factors

In this approach the acceleration of a fixed part is estimated from the ground acceleration as given by national regulations \(a_{\text{ground}}\) and amplification factors describing the most important influence parameters. The value of the seismic load acting at the mass centre of the element to be fixed can be described by:

\[
F = m \cdot a_{\text{ground}} \cdot A_{\text{floor}} \cdot A_{\text{equip}}
\]

\(F\) seismic load acting at the mass centre of the element
\(m\) mass of the element
\(a_{\text{ground}}\) ground acceleration
\(A_{\text{floor}}\) amplification factor for floor
\(A_{\text{equip}}\) amplification factor for fixture

Figure 8: simplified estimation of anchor loads with amplification factors
For buildings of not more than twelve floors, a simplified estimation of the amplification relating the floor acceleration to the ground acceleration, $A_{floor}$, can be given as:

$$A_{floor} = n/8 + 1$$  \hspace{1cm} (2)

Where fixtures are concerned which are not stiff, such as equipment installed on spring damping units or building components which have a comparatively low level of stiffness, the excitation by seismic actions can amplify the equipment acceleration, $a_{equip}$, to the extent that it lies significantly above the floor acceleration, $a_{floor}$. Several sources in literature give an amplification factor $A_{equip} = 2.0$ when the ratio of the natural period of the fixture (incl. the fastening), $T_{equip}$, to the period of the building or floor, $T_{floor}$, satisfies the following condition:

$$0.6 < T_{equip} / T_{piso} < 1.4$$  \hspace{1cm} (3)

Taking this rule as the basis and the floor natural frequency in a standard case $f_{o, floor} = 10$ Hz, it is assumed as a simplification that amplification is relevant for less stiff fixtures and for fastenings with a natural frequency $f_{o, equip} < 15$ Hz:

$$f_{o, equip} \geq 15 \text{Hz} \rightarrow A_{equip} = 1.0$$

$$f_{o, equip} < 15 \text{Hz} \rightarrow A_{equip} = 2.0$$  \hspace{1cm} (4)

### 3.3 Evaluation of the anchor resistance

ICC-ES Evaluation reports give the anchor resistances for the strength design according to ACI 318 appendix D. Anchors qualified for seismic loads according to the above report can be used in strength design according to ACI 318. The procedure is the same as for static loads, except for the following:

- The anchors cannot be used in plastic hinge zones of concrete structures under earthquake forces.
- The pullout strength $N_p$ and steel strength in shear $V_{sa}$ are different from the static values; they are based on the corresponding seismic test defined in AC355.2
- The design strength against concrete related failure modes (cone, combined pullout and concrete cone, splitting, concrete edge, pryout) are reduced by a reduction factor of $\phi_{seismic} = 0.75$.
- In general the anchors have to be designed in such a way that the steel strength of either the anchor or the attachment is governing.
- If an anchor needs to be designed with a concrete related failure mode governing, its design strength needs to be reduced by an additional factor of 0.4.

### 3.4 Detailing for seismic actions

Some consequences to seismic loads can easily and at minor cost be avoided by providing adequate bracings. For the earthquake resistant installation of pipes, equipment or installations it must be ensured that horizontal seismic loads are taken by the fastening. Both transverse and longitudinal braces must be provided. They may be combined with the fastening.

![Practical examples of bracings for installation fastenings](image)
Ceiling paneling and suspended ceilings are damaged extremely often by earthquakes. Although ceiling components often have only a comparatively low weight, the risk to people from falling parts of a ceiling should not be underestimated. Especially in busy public buildings and very tall rooms, ceiling components falling because of an earthquake can be a major hazard for people. The reasons why, comparatively speaking, ceiling paneling and suspended ceilings react very sensitively to the effects of earthquakes are varied. As, in standard cases, ceiling panelling and suspended ceilings are subjected only to their own weight, the load-bearing safety reserves of fastenings and hangers are often too small, on the one hand, and, on the other hand, these fastenings and hangers are not designed for earthquake forces acting dynamically in a horizontal direction in many cases.

Figure 10: Practical examples for earthquake resistant fixing of false ceilings

Furniture, equipment and stored items can basically be expected to move and/or tip over or fall under seismic loading. Suspended items start swinging and can be damaged by hitting something if there is insufficient clearance for the motion to take place freely.

Figure 11: Strategies to avoid movement of furniture, equipment etc.

REFERENCES:
ACI 318 (2008) Building code requirements for structural concrete, Annex D: Anchoring to concrete, American Concrete Institute