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α_{gap} factor in seismic anchor design: Closing the gap of understanding

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Abstract

For seismic anchor design, European Technical Assessments (ETA) provide the α_{gap} factor which reduces the seismic shear strength in case there is an annular gap between anchor and fixture. Though presented in the ETA as a capacity reduction factor, it is actually an amplification factor intended to account for the increased load demand acting on the anchor. Design standards outside of Europe do not stipulate the α_{gap} factor, therefore Evaluation Service Reports (ESR) in the US do not report this factor. If the design data published in any ESR is compared to that published in a similar ETA, the α_{gap} reduction factor makes the performance of the ETA product appearing lower than that of the ESR product. This discrepancy causes confusion among design professionals particularly in regions outside of Europe.

Keywords: post-installed anchor; gap factor; hammer effect; seismic qualification and design.

1 Introduction

Amplification plays an important role in seismic design. Figure 1 shows the acceleration of an attachment and that of the concrete structure it is attached to, recorded during a shake table test. It clearly illustrates the amplified acceleration acting on the attachment. The amplification occurs due to various reasons, the gap between anchor and attachment is one of them as will be discussed in this paper. Increased accelerations also mean increased inertia loads acting on the attachment and the anchors connecting it to the concrete. The European anchor design standard EN 1992-4 (2018) takes this effect into account by the α_{gap} factor (Clause C.5 (2)).

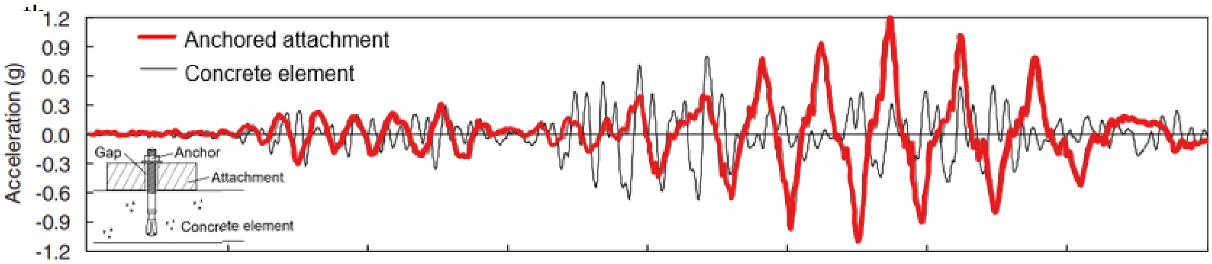


Figure 1. Acceleration record of the concrete element and anchored attachment during earthquake shaking (example for an expansion anchor after Mahrenholtz, Hutchinson, et al. (2016)).

The annular gap between anchor and attachment is the hole clearance which is provided by standard to allow for installation tolerances. During earthquake induced vibrations, any remaining pretension in the anchor after initial loss clamping the attachment down onto the concrete surface vanishes and the attachment starts to slip within the clearance. The slipping mass of the attachment experiences a phase shift to the concrete structure acting as its vibration exciter, resulting in amplified accelerations and inertia loads. As the gap only influences the amplification in lateral direction but not in axial direction, the α_{gap} factor is only applicable when designing the anchor for shear loads but not when designing the anchor for tension load. Without a gap between the anchor and attachment, there is no load increasing effect for the anchored attachment.

2 Background

Seismic loading is one of the most demanding load types acting on structures and nonstructural components and systems (NCS) attached to them. Yet it is a very complex design situation considered by relatively simple qualification tests of components involved. Post-installed anchors connecting structural or nonstructural elements to the concrete structure are designed according to standards like the EN 1992-4 in Europe, the ACI 318 (2019) in the US, or the AS 5216 (2021) in Australia. These design standards require product qualifications of mechanical and chemical anchors in accordance with the ACI 355.2 (2019) and ACI 355.4 (2019) for the design according to the ACI 318, or the EAD 330232-01-0601 (2021) and EAD 330499-01-0601 (2020) for the design according to the EN 1992-4 as well as AS 5216. The product qualification results in technical approvals like the European Technical Assessments (ETAs) and the Evaluation Service Reports (ESRs) typically issued by the Evaluation Service of the International Code Council (ICC-ES) in the US. The ETAs and ESRs are also acknowledged in other countries, either respectively, e.g. Australia and New Zealand, or equitably, e.g. Taiwan and Korea.

The α_{gap} factor was introduced in Europe with the publication of the EN 1992-4 in 2018. The ETAs give a default value of $\alpha_{gap} = 0.5$ if an annular gap is present between anchor and attachment, meaning that the design resistance is reduced by 50%. For anchor products that allow the injection of chemical adhesive to close the annular gap (Figure 2), the factor can be altered to $\alpha_{gap} = 1.0$ as any amplification effects by the gap is precluded. Since the α_{gap} factor is provided in the ETA, it is often mistaken as a performance factor depending on the resistance i.e. load capacity of the assessed anchor itself. In fact, it is a factor which considers the effects of increased load demand acting on the anchor due to the presence of an annular gap. If the anchor product provides the option to reliably close the gap with adhesive with minimum compressive strength of 30MPa or higher, the increased load demand is not applicable.

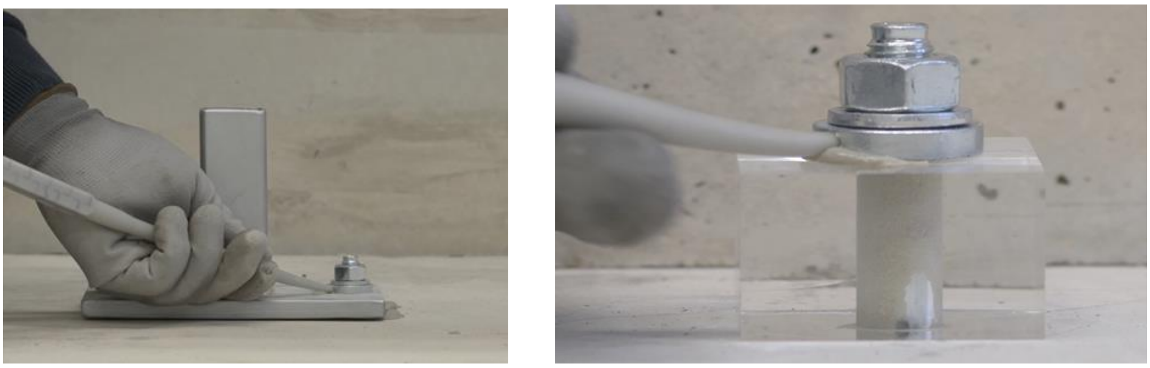


Figure 2. The annular gap of an expansion anchor (MKT BZ3) is injected by chemical adhesive with a compressive strength of 40 MPa (MKT VMH) through a special washer (left), closeup of a mockup where the steel fixture is replaced by acrylic glass to visualise how the adhesive is filling the gap (right).

The ACI 318 does not take into account the phenomenon of gap induced amplification and as a consequence, the ESRs do not have the reduction factor α_{gap}. The discrepancy in both approval types, ETA and ESR, regarding the design data of the same or similar anchor product causes confusion among design professionals. Particularly in countries where both approval types are accepted, designers may be encouraged to specify ICC-ES certified products due to the absence of the α_{gap} factor. Without consideration of the α_{gap} factor the full performance of the anchor under shear is assumed to be achieved without gap filling. Whilst, for the same product with an equivalent ETA, the gap has either to be filled in a separate installation step or a 50% strength reduction has to be accepted; both options coming with a disadvantage.

Another erroneous approach is to reduce the characteristic capacities and nominal capacities given in ETAs and ESRs, respectively, to account for the gap effect in the case of no information on α_{gap} is given. The information may be missing because the respective ETA was issued before the introduction of EN 1992-4 in 2018 or because ESRs do not specify α_{gap} factors. While there might be some rationale behind this approach, there is no justification for it per se. For this argument, it is important to understand how anchors are loaded during product qualification tests and how they are loaded under realistic conditions.

3 Seismic tests on installed anchors

3.1 Component-level testing for product qualification

For product qualification, the installed anchors are loaded to evaluate strength data which is later reported in ETAs and ESRs. The performance of an isolated anchor is tested, i.e. the tests are run on a component level. Qualification test programs consist of many test series including simulated seismic tests if an approval for earthquake loads is sought, to ensure the anchor performs safely for its intended use. During these simulated tests, single anchors are loaded via a fixture according to defined load protocols at quasi-static loading rates, i.e. without any acceleration and dynamic effects (Figure 3). The basic load capacity for static and seismic applications is tested without gap filling. The gap between anchor and fixture is manifested in the anchor load-displacement curve as a plateau near zero load when the fixture transecting the hole clearance between reversed load cycles.

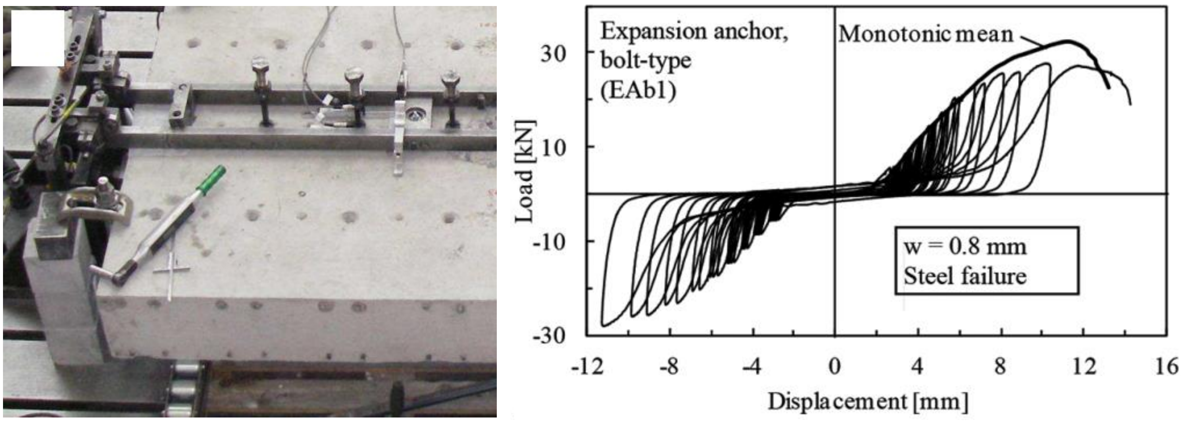


Figure 3. Component-level qualification test on an anchor installed in concrete for simulated seismic loading following a load protocol (left) and measured load-displacement curve of the anchor (right) (Mahrenholtz, Eligehausen, et al., 2016).

The manufacturer may decide to run additional qualification tests with gap filling. Due to its restraining effect on the anchor bolt, some additional shear capacity can be observed. This beneficial effect results in higher seismic load capacities given in the ETA as an alternative to load capacities applicable for installations without gap filling (e.g. ETA-19/0619). For clarity it is noted that this increase of the characteristic capacity is independent of the impact of the α_{gap} factor on the design capacity discussed in this paper.

3.2 System-level testing for realistic conditions

To test anchors under realistic conditions, shake table tests are run on a test setup where single or multiple anchors are installed to connect structural or nonstructural elements to the concrete, i.e. the tests are run on a system level. During shaking, dynamic action comes into play and the inertia of the connected attachment creates the earthquake load acting on each anchor (Figure 4). With the mass being fixed, the acceleration of the input motion determines the anchor load which can be adjusted by scaling the input acceleration. If there is a gap between the anchor and attachment, the anchor load-displacement curve shows a plateau similar to that observed for qualification tests. However, the gap also influences the response of the system to the acceleration and by this the achieved anchor load during shaking.

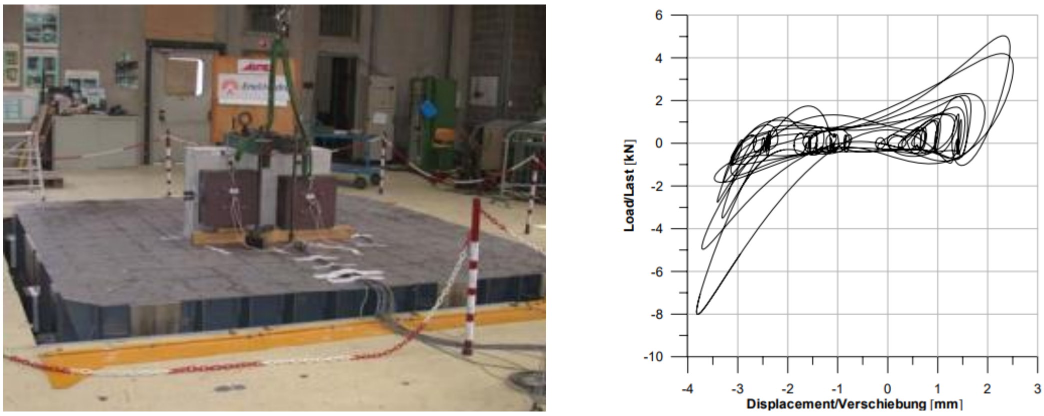


Figure 4. System-level shake table test on anchors installed in a mounted concrete block, loaded by weights and their inertia when accelerated by real earthquake input motions (left), load-displacement curve of the anchors (right) (Rieder, 2009).

While shake table tests are used to qualify NCS equipment for seismic applications, they are not used for qualification testing on anchor products according to ACI 355.2 / ACI 355.4 or EAD 330232 / EAD 330499. It is noted, however, that industry and academia run shake table tests on anchor products for research, and the outcome impacts the development of design and qualification standards.

4 Seismic design of concrete anchors

4.1 Gap induced load amplification

For tests at component and at system level, similar load hysteresis can be observed with the annular gap creating a plateau near zero load. The difference between these tests is that for system-level tests, the gap influences the load acting on the anchor as the gap amplifies the acceleration acting on the attachment. Figure 5 depicts a schematic of a structure subjected to strong ground motion during an earthquake. The structure serves as a filter which amplifies the ground acceleration near the natural frequencies of the structure. Any NCS acts as an oscillator which behaviour and acceleration depends on its natural frequency. These phenomena are well studied and considered in seismic design procedures.

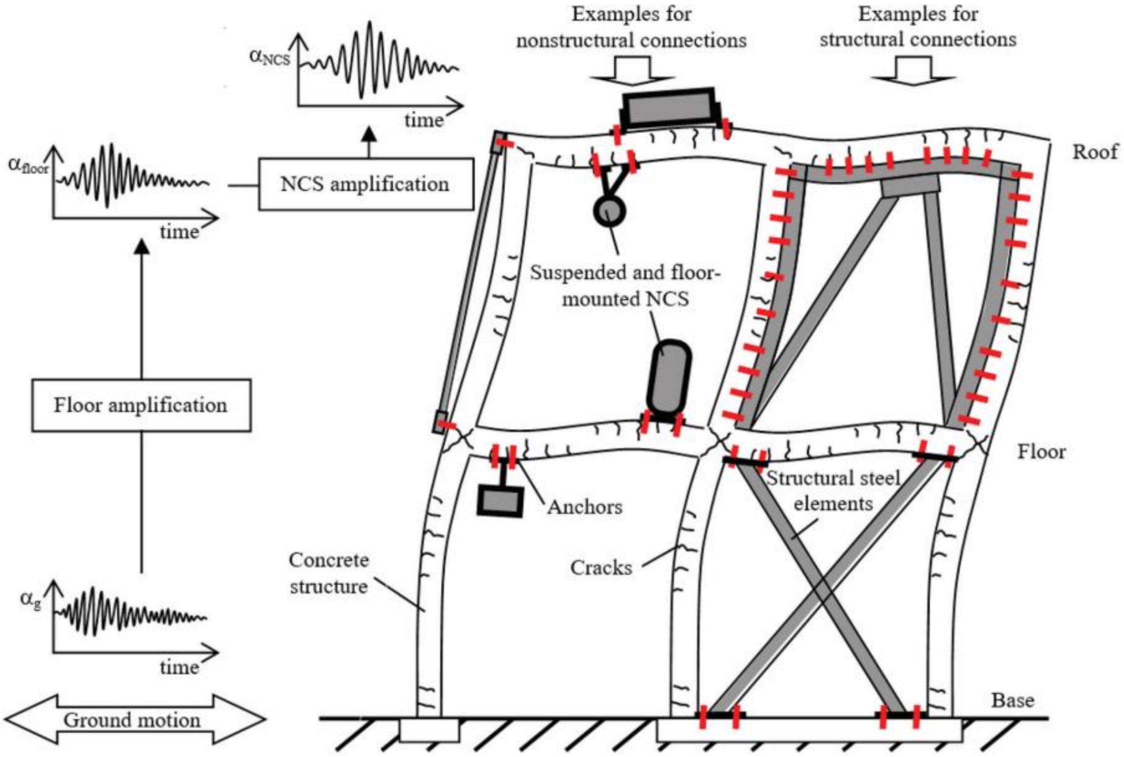


Figure 5. Schematic of structure during shaking with indicated acceleration and amplification (Mahrenholtz and Wood, 2020).

The anchor load develops according to the inertial response of the system, but the displacement response of the anchor, in turn, feeds back the behaviour of the attachment it is connecting to the structure (Mahrenholtz, 2012). Any slip created by the annular gap between anchor and attachment potentially results in a phase shift to the concrete structure and further amplification. Rieder (2009) ran numerical and experimental tests to investigate the acceleration amplification caused by the annular gap. Depending on the width of the gap, the acceleration of the slipping attachment and by this the load acting on the anchor is increased by a mean factor of up to 2 if compared to a connection without gap (Figure 6).

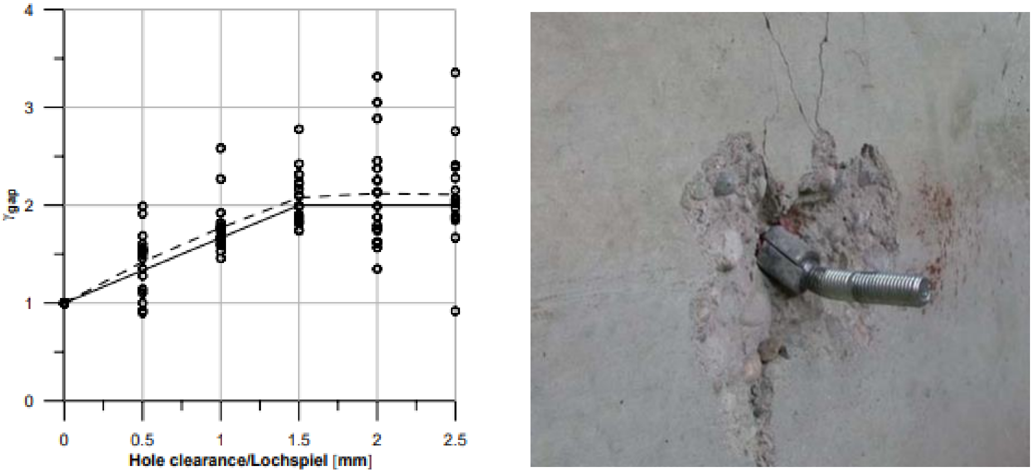
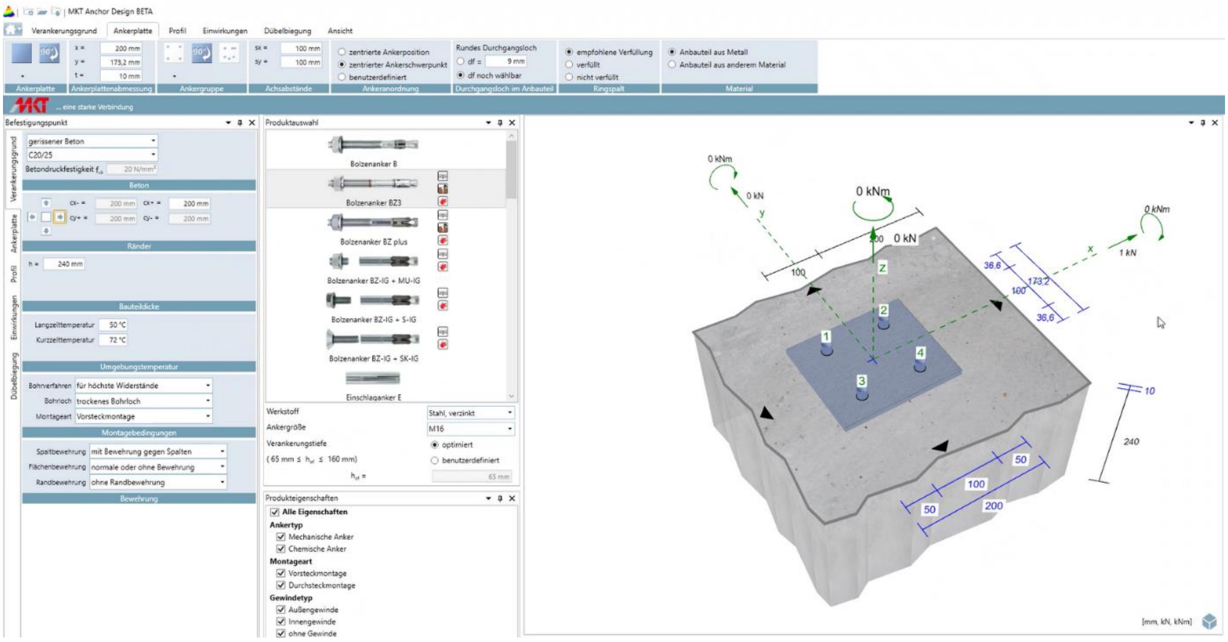


Figure 6. Increase of the acceleration and seismic load expressed by the gap dependent amplification factor γ_{gap} plotted against the hole clearance i.e. annular gap width (left), anchor failure due to overloading (right) (Rieder, 2009).

4.2 Resistance reduction factor α_{gap} given in the ETA

For Europe, the initial plan was to account for the gap induced amplification in anchor design by introducing a safety factor of γ_{gap} = 2 as proposed by Rieder (2009) which increases the acting design load. However, this would have required adjustments in the existing design standard for general load assumptions EN 1991 (2002) and/or in the standard for earthquake design EN 1998 (2006). Hence it was later decided to introduce it reciprocally as a resistance reduction factor of 1/2 = 0.5 in the anchor design standard EN 1992-4 drafted at that time. If the manufacturer can offer a gap filling feature, i.e. a washer through which adhesive can be injected after installation, α_{gap} = 1.0 is reported in the ETA. Otherwise, or in addition, α_{gap} = 0.5 is reported for design cases without gap filling. Design professionals can consider these options best by using anchor design software which is freely available and easy to use (an example is shown in Figure 7).



x = 200 mm
y = 173,2 mm
t = 10 mm
sx = 100 mm
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○ zentrierte Ankerposition
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○ df = 9 mm
● df noch wählbar
● empfohlene Verfüllung
○ verfüllt
○ nicht verfüllt
● Anbauteil aus Metall
○ Anbauteil aus anderem Material

gerissener Beton
C20/25
Betondruckfestigkeit f_{ck} 20 N/mm²
cx- = 200 mm
cx+ = 200 mm
cy+ = 200 mm
cy- = 200 mm
h = 240 mm
Langzeittemperatur 50 °C
Kurzzeittemperatur 72 °C
Bohrverfahren für höchste Widerstände
Bohrloch trockenes Bohrloch
Montageart Vorsteckmontage
Spaltbewehrung mit Bewehrung gegen Spalten
Flächenbewehrung normale oder ohne Bewehrung
Randbewehrung ohne Randbewehrung

Werkstoff Stahl, verzinkt
Ankergröße M16
Verankerungstiefe ● optimiert
(65 mm ≤ h_{ef} ≤ 160 mm) ○ benutzerdefiniert
h_{ef} = 65 mm

☑ **Alle Eigenschaften**
Ankertyp
☑ Mechanische Anker
☑ Chemische Anker
Montageart
☑ Vorsteckmontage
☑ Durchsteckmontage
Gewindetyp
☑ Außengewinde
☑ Innengewinde
☑ ohne Gewinde

Figure 7. Example of seismic design accounting for the gap factor in the MKT software (MKT Software, 2024).

The gap factor α_{gap} = 0.5 applies if no gap is filled. Knowing that the basic load capacity reported in the ETA is derived from qualification testing on anchors without gap filling by default, a reduction factor for design situations with the same installation condition may seem counter-intuitive. However, it is important to remember that qualification testing is conducted on anchors tested at component level, whereas the anchor design is meant to represent real conditions at system level. Therefore, to avoid adverse effects and to ensure the design capacity is not compromised by an increased demand, EN 1992-4 requires that the gap is filled if α_{gap} = 1.0 is assumed. This requirement has been adopted by the AEFAC TN-10 (2021), the technical note complementing AS 5216 requirements for the qualification and design of anchors for seismic applications. To date, α_{gap} is not stipulated in any other anchor design code, particularly not in ACI 318.

5 Summary and conclusions

In seismic design, amplification effects increase the acceleration, thereby increasing the load acting on the structure and any attachments anchored to it. The annular gap between anchor and attachment is the source of additional amplification during shaking. Injecting adhesive through a special washer closes the gap and after hardening, any slip and thus amplification can be avoided. Without gap filling, the load can be amplified to double its original value. This is considered by the α_{gap} factor in the European design standard and the European Technical Assessment (ETA) of anchor products.

The gap induced amplification is a phenomenon which increases the load demand. For reasons of practicability, however, it is considered in anchor design as a capacity reducing factor. If the anchor product does not allow any gap filling or the gap filling is skipped to keep the installation effort low, the design strength is reduced by a factor of $\alpha_{gap} = 0.5$ which therefore can be interpreted as a default value. This approach often creates confusion even among design professionals who are familiar with anchor design and qualification as the annular gap is generally not filled during tests on anchors for product qualification according to US or European standards. The reason for this apparent contradiction lies in the fact that the anchor products are tested quasi-statically on component level where the gap does not influence the load demand but their application is then on system level where the gap results in the described load amplification.

The situation is particularly confusing in countries outside Europe where ETAs are recognised, probably as equivalent to other product approvals e.g. ESRs from the US. Design professionals are potentially discouraged to use ETA approved products where they face a massive design strength reduction by the α_{gap} factor. However, whether the amplification effect of annular gaps is to be considered by the α_{gap} factor or not depends in the first place on the design standards used locally. It is not meaningful to compare the design strength of an ETA approved product which accounts for the α_{gap} factor of 0.5 to that of an ESR approved product without applying an α_{gap} factor, while using a local design code that does not specify the α_{gap} factor. As an example for this design situation, Figure 8 depicts a newly built data center in Korea where NCS equipment is laterally braced and anchored into the concrete floor, using ETA approved expansion anchors. The anchorage was designed according to the local design standard KDS 14 20 50 (2022) without applying a strength reducing α_{gap} factor that is not specified in KDS 14 20 50.

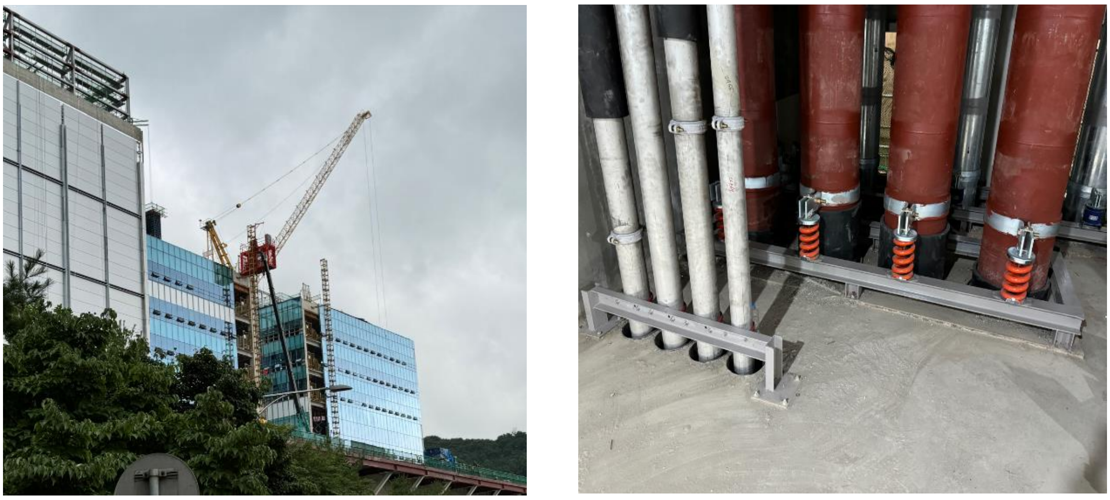

Figure 8. Data center project in Korea (left); detail of expansion anchors (MKT BZ3) connecting seismic bracing to the concrete structure (right).

Opinions , conclusions, and recommendations expressed in this paper are those of the authors only and do not necessarily reflect those of the authors' affiliations or other sponsoring agencies.

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