# TECHNICAL NOTE

AEFAC
Australian Engineered Fasteners and Anchors Council

AEFAC – TN10

# PREQUALIFICATION & DESIGN REQUIREMENTS FOR FASTENINGS UNDER SEISMIC ACTIONS

Ver. 1.1
October 2021

## Revision Sheet

| Revision Number | Clause/ Figure/ Table | Revision type | Issued on |
|---|---|---|---|
| A1 | Clause 3 | $\phi_c$ is added in notation | 21/10/2021 |
| A1 | Table 5 | Editorial corrections | 21/10/2021 |
| A1 | Clause 10 | Editorial corrections for clause reference in AS 5216 for calculating $N_{Rk,p}$ | 21/10/2021 |
| A1 | Clause 10 | Editorial corrections to definition of $R^0_{k,eq}$ | 21/10/2021 |

## 1. General

This Technical Note outlines the prequalification and design requirements for post-installed fasteners in concrete used to transmit seismic actions by means of tension, shear, or a combination of tension and shear loads between structural connections or non-structural connections. The following connection types are defined as:

- **Structural connections:** These are the connection between structural elements.
- **Non-structural connections:** These are the connection between non-structural parts and components to structural elements.

This Technical Note consists of two parts:

- **Part A (Sections 4-6):** Background information about the prequalification requirements of fasteners for seismic actions.
- **Part B (Sections 7-11):** Design provisions for prequalification requirements and design of fasteners for seismic actions.

The basis for the design requirements of this Technical Note are predominantly from EN 1992-4 (CEN, 2018).

Fasteners used to resist seismic actions shall meet all relevant requirements for non-seismic actions. Fasteners must be prequalified for cracked concrete and where necessary for seismic applications. The level of prequalification for seismic applications is defined via seismic performance categories. The minimum recommended seismic performance categories for fasteners is provided in Section 7. The suitability of the fasteners for cracked concrete and seismic performance categories shall be stated in a prequalification document. The testing and assessment of the fasteners shall be done in accordance with AS 5216 (Standards Australia, 2018) and TR 049 (EOTA, 2016b) for seismic applications.

## 2. Scope

This Technical Note should be considered for structures and non-structural parts and components which are required to be designed for earthquake actions in accordance with AS 1170.4 (Standards Australia, 2007).

Cracked concrete shall be assumed for the determination of design resistance unless proven otherwise in accordance with AS 5216.

Loosening of the nuts or screws shall be prevented. The annular gap between a fastener and its fixture shall be considered in accordance with Section 10.

For the ultimate limit state seismic load combination where the seismic design tension forces in a single fastener or a group of fasteners is not greater than 20% of the total design tension force for the same load combination, it shall be permitted to design the fastener or group of fasteners without following the provisions in Section 8.

For the ultimate limit state seismic load combination where the seismic design shear forces in a single fastener or a group of fasteners is not greater than 20% of the total design shear force for same load combination, it shall be permitted to design the fastener or group of fasteners without following the provisions in Section 8.

Furthermore, the provisions of this Technical Note:

- Do not cover the design of fasteners in region of concrete members where concrete spalling or yielding of reinforcement may take place during seismic actions. These regions are often referred to as plastic hinge regions or zones for flexural concrete members. The length of plastic hinge regions can be determined from analysis of the relevant structure and member. Examples of estimation of the length of plastic hinge regions can be found in EN 1998-1 (CEN, 2004) or ACI 318 (ACI, 2019). Further explanation is provided in Section 4.
- Do not cover seismic design of cast-in fasteners including anchor channels. It is noted that cast-in fasteners which rely on bearing would typically have greater tolerance to crack width and crack opening and closing of the concrete substrate compared to post-installed fasteners. Proprietary capacities of cast-in fasteners for seismic applications would typically be provided by relevant suppliers.
- Do not cover seismic design of power actuated fasteners.
- Do not cover fastenings with shear loads acting on the fastener with a lever arm or with a grout layer with thickness $\geq 0.5d$.

## 3. Notation

| | | |
|---|---|---|
| $N^*$ | = | Design tension force on the fasteners including seismic effects for the corresponding failure modes |
| $N_{Rk,eq,red}$ | = | Reduced characteristic seismic resistance of a fastening under tension loads |
| $N_{Rk,eq}$ | = | Characteristic seismic resistance of a fastening under tension loads |
| $N_{Rk,a}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to anchorage failure of supplementary reinforcement |
| $N_{Rk,c}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to concrete cone failure |

| | | |
|---|---|---|
| $N_{Rk,cb}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to concrete blow-out failure |
| $N_{Rk,i,eq}$ | = | Characteristic resistance of fasteners in seismic tension (*Subscript i represents the different failure modes)* |
| $N_{Rk,p}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to pull-out failure |
| $N_{Rk,re}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to steel failure of supplementary reinforcement |
| $N_{Rk,s}$ | = | Characteristic tensile strength of a fastener to steel failure |
| $N_{Rk,sp}$ | = | Characteristic tensile strength of a fastener or a group of fasteners to concrete splitting failure |
| $R_{d,eq}$ | = | Seismic design resistance of a fastener |
| $R_{k,conc,eq}$ | = | minimum design characteristic seismic resistance for all concrete related failure modes |
| $R_{k,eq}$ | = | Characteristic seismic resistance of a fastener |
| $R^0_{k,eq}$ | = | Basic characteristic seismic resistance for a given failure mode |
| $R_{k,s,eq}$ | = | Minimum characteristic seismic resistance for steel failure |
| $S^*_h$ | = | Designed load in the highest loaded fastener in the group |
| $S^*_g$ | = | Designed load in the group of fasteners |
| $S_p$ | = | Structural performance factor in accordance with AS 1170.4 |
| $V^*$ | = | Design shear force on the fasteners including seismic effects for the corresponding failure modes |
| $V_{Rk,eq,red}$ | = | Reduced characteristic seismic design resistance of a fastening under shear loads |
| $V_{Rk,c}$ | = | Characteristic shear strength of a fastener or a group of fasteners to concrete edge failure |
| $V_{Rk,i,eq}$ | = | Characteristic resistance of fasteners in seismic shear (*Subscript i represents the different failure modes)* |
| $V_{Rk,s}$ | = | Characteristic shear strength of a fastener to steel failure |
| $V_{Rk,cp}$ | = | Characteristic shear strength of a fastener or a group of fasteners to pry-out failure |
| $Z$ | = | Earthquake hazard design factor in accordance with AS 1170.4 |
| $d$ | = | Diameter of fastener bolt or thread diameter of the stud |
| $f_{uf}$ | = | Ultimate tensile strength of fastener |
| $f_{yf}$ | = | Yield tensile strength of fastener |
| $k_p$ | = | The probability factor in accordance with AS 1170.4 |

| | | |
|---|---|---|
| $s_{max}$ | = | Distance between the outermost row of fasteners and opposite edge of the fixture |
| $\alpha_{eq}$ | = | Factor to take into account the influence of seismic actions and associated cracking |
| $\alpha_{gap}$ | = | Reduction factor to take into account for inertia effects due to an annular gap between fastener and fixture in case of shear loading |
| $\gamma_{inst}$ | = | Factor taking in account the sensitivity to installation |
| $\delta_{N,eq(DLS)}$ | = | Displacement of the fastener under tension loading at DLS |
| $\delta_{N,eq}$ | = | Displacement of the fastener under seismic loading |
| $\delta_{N,req(DLS)}$ | = | Required displacement of the fastener under tension loading at DLS |
| $\delta_{V,eq(DLS)}$ | = | Displacement of the fastener under shear loading at DLS |
| $\delta_{V,req(DLS)}$ | = | Required displacement of the fastener under shear loading at DLS |
| $\theta_p$ | = | Rotation of the connection |
| $\phi_c$ | = | Capacity reduction factor for concrete |
| $\phi_i$ | = | Capacity reduction factor for strength of fastener or fastener group for failure mode *i* |
| $\phi_{inst}$ | = | Capacity reduction factor for installation, $\phi_{inst} = \frac{1}{\gamma_{inst}}$ |
| $\mu$ | = | Structural ductility factor in accordance with AS 1170.4 |
| C1 | = | Seismic performance category 1 |
| C2 | = | Seismic performance category 2 |
| DLS | = | Damage limit state |
| ULS | = | Ultimate limit state |

# Part A
# Background Information

## 4. Introduction

Post-installed fasteners in concrete do not have predictable capacities for all possible failure mechanisms and require prequalification which involves tests and assessment procedures to define their performance. Significant research has been conducted internationally, including Europe and the USA, to develop prequalification requirements for fasteners which has resulted in different levels of prequalification based on the application of the fasteners (Eligehausen et al., 2006; Hoehler & Eligehausen, 2008; Hoeler, 2006; Mahrenholtz et al., 2017). Under seismic actions it has been highlighted that the performance of post-installed fasteners is highly dependent on the damage state of the concrete substrate which is related to expected crack widths and the opening and closing nature of the crack.

The requirements discussed in this Technical Note are applicable for fasteners that are located outside of regions where yielding of reinforcement and spalling of concrete may occur. For flexural members this corresponds to the plastic hinge regions. In theory, the length of plastic hinge regions ($l_y$) corresponds to the region for which the yield curvature ($\phi_y$) is exceeded as illustrated in Figure 1. Plastic hinge regions extend for a distance of $l_y$ from beam and column faces, and in other sections such as walls, slabs, and frames where yielding of reinforcement may take place under seismic actions. It's noted that $l_y$ is different to the equivalent plastic hinge length ($l_p$) which is obtained from the idealised curvature distribution for approximating the ultimate displacement capacity of structural elements. The length of plastic hinge regions is highly dependent on the detailing of members. As a guide, the suggested plastic hinge lengths for the purpose of detailing primary seismic components in EN 1998-2 (CEN, 2004) for medium and high levels of ductility are provided in Table 1. Furthermore, the suggested length for positioning fasteners outside of plastic hinge regions in accordance with the commentary of ACI 318 (ACI, 2019) has been provided.

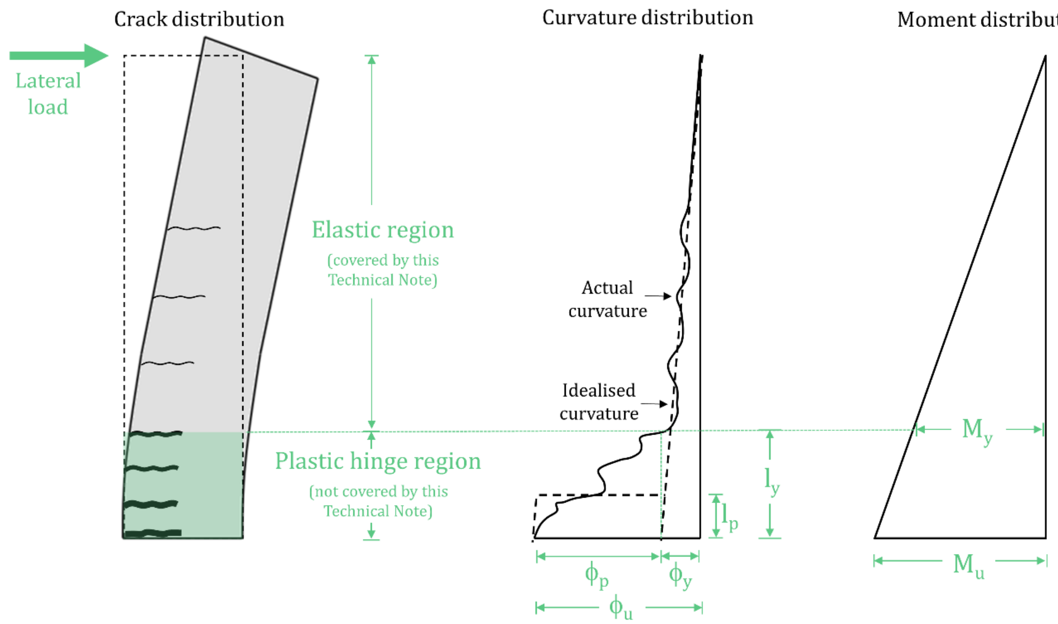



*Figure 1: Plastic hinge formation of a single curvature flexural element ($\phi_y$, $\phi_p$, $\phi_u$ are yield, plastic, and ultimate curvature respectively, $M_y$ and $M_u$ are yield and ultimate moment respectively)*

*Table 1: Recommended plastic hinge lengths for detailing of primary seismic components in EN 1998-1 and for fastener location in ACI 318*

| Member | EN 1998-1 (2004) Medium ductility class | EN 1998-1 (2004) High ductility class | ACI 318 (2019) Commentary |
|---|---|---|---|
| **Beam** | $l_y = h_b$ | $l_y = 1.5h_b$ | $l_y = 2h_b$ |
| | For beams supporting discontinued vertical elements $l_y = 2h_b$ on each side of the supported vertical element | | |
| **Columns** | $l_y = \max\begin{Bmatrix} h_c \\ \frac{l_{cl}}{6} \\ 0.45\text{m} \end{Bmatrix}$ | $l_y = \max\begin{Bmatrix} 1.5h_c \\ \frac{l_{cl}}{6} \\ 0.6\text{m} \end{Bmatrix}$ | $l_y = 2h_c$ |
| | If $\frac{l_c}{3} \leq 3$, $l_y = l_c$ | | |
| **Walls** | $l_y = \max\begin{Bmatrix} l_w \\ \frac{h_w}{6} \end{Bmatrix}$, but $l_y \leq \begin{Bmatrix} 2l_w \\ h_s \text{ for } n \leq 6 \text{ storey} \\ 2h_s \text{ for } n \geq 7 \text{ storey} \end{Bmatrix}$ | | Not specified |

$h_b$ is the beam depth | $h_c$ is the largest cross-sectional dimension of the column | $l_{cl}$ is the clear height of the column | $h_s$ is the clear storey height | $l_w$ is the length of the wall cross-section | $h_w$ is the height of the wall

## 5. Prequalification requirements

In Europe, for static and quasi-static actions, the prequalification tests are conducted for reliability and service-conditions of the structure which are dependent on whether the fasteners are to be used in cracked or uncracked concrete. The prequalification requirements are stated in European Assessment Documents (EAD), including: EAD 330232 (EOTA, 2016a) for mechanical fasteners, EAD 330499 (EOTA, 2017) for bonded fasteners, and EAD 330747 (EOTA, 2018) for fasteners used in redundant non-structural systems. For service-load conditions of the structure, the fasteners are tested in cracked concrete with maximum crack widths of approximately 0.3 mm. This generally corresponds to the maximum crack widths recommended for serviceability requirements.

Since 2013 Europe introduced two seismic performance categories; C1 and C2. The testing procedures and assessment criteria are stated in the Technical Report, TR 049 (EOTA, 2016b). The prequalification tests for C1 involve pulsating tension and alternating shear loading of the fastener in a static crack with a maximum width of 0.5 mm. For C2, in addition to testing the fastener under a pulsating tension and alternating shear loading in a static crack with a maximum width of 0.8 mm, the fastener is loaded in tension in crack cycling conditions to simulate the opening and closing nature of cracks during seismic loading under moment reversals. Furthermore, a fastener exhibiting pull-out or pull-though behaviour is not suitable for C2 performance category. Hence, the prequalification requirements for C2 is more demanding than C1. The crack width limits for seismic applications are based on the requirement that the fasteners will be located outside of the plastic hinge regions of concrete building components. Outside of the plastic hinge region the stress in the longitudinal reinforcement bars is not expected to exceed yielding. Hence, the maximum crack width of 0.8 mm is based on studies which have demonstrated that for flexural members (predominantly frame members) the maximum crack width at yield for a section is approximately 0.8 mm (Hoeler, 2006; Mahrenholtz et al., 2017). The crack widths within the plastic hinge region can be significantly larger as seismic energy is dissipated through yielding of reinforcement and spalling of concrete.

Concurrently, the USA has developed provisions for the prequalification of fasteners in concrete. The requirements are provided in ACI 355.2 (ACI, 2007) and ACI 355.4 (ACI, 2011) for mechanical and chemical fasteners in concrete, respectively. Currently, the prequalification requirements are similar to the European requirements for non-seismic applications and C1 for seismic performance category. The USA is also in the process of introducing a second seismic performance category which will be similar to the C2 category in Europe (ICC-ES, 2020)

# 6. International specification criteria for selection of seismic performance categories

The design specifications for selecting the level of prequalification required for seismic actions varies between international codes and standards. Each nation or region has provided specifications for selecting seismic performance categories based on their own seismicity, design and construction practice.  In general, the criteria are based on one or more of the following factors: seismic demand, design of the structure, and consequence of failure of the structure. The following subsections provide a summary of the specification criteria in Europe, Germany, and the USA.

## 6.1. Eurocode

EN 1992-4:2018 (CEN, 2018) sets the provisions for the design of fastenings for use in concrete structures, however each member state can set their own requirements. The recommended performance categories are provided in Table 2, they are dependent on: the design ground acceleration on rock ground conditions ($a_g$), the soil factor ($S$), and the building importance class.

*Table 2: Recommended seismic performance categories for fasteners in accordance with EN 1992-4:2018*

| Seismicity Class | $a_g S$ (in g's) | Importance class I | II | III | IV |
|---|---|---|---|---|---|
| Very low | $a_g S \leq 0.05$ | No seismic performance category required | | | |
| Low | $0.05 < a_g S \leq 0.1$ | C1 | C1[1] or C2[2] | C1[1] or C2[2] | C2 |
| > Low | $a_g S > 0.1$ | C1 | C2 | C2 | C2 |

[1] For connecting non-structural components to structures | [2] For connecting structural components to structures

## 6.2. German Annex to Eurocode

In Germany, the specification of the prequalification requirement for fasteners is provided in the National Annex to EN 1992-4, DIN EN 1992-4/NA:2019-04 (DIN, 2019). The seismic performance category is specified based on the permissible crack width of the concrete substrate under seismic load conditions. In addition, it is suggested that the behaviour factor ($q$) (i.e., seismic force reduction factor to account for inelastic behaviour) adopted in the design of the structure may be used to estimate the crack widths outside of the plastic hinge regions and discontinuity areas. A summary of the minimum requirements is provided in Table 3.

*Table 3: Minimum seismic performance categories required for fasteners in accordance with DIN EN 1992-4/NA:2019-04*

| Crack width under earthquake design load | Prequalification requirement | Behaviour factor used to estimate crack widths |
|---|---|---|
| $w_k \leq 0.3\, mm$ | No seismic performance category required | $q = 1.0$ |
| $w_k \leq 0.5\, mm$ | C1 | $1.0 < q \leq 1.5$ |
| $w_k \leq 0.8\, mm$ | C2 | $1.5 < q \leq 3.0$ |
| $w_k > 0.8\, mm$ | Fastenings in plastic hinge regions not covered by DIN EN 1992-4 | |

$w_k$ is the characteristic crack width (95 percentile) in accordance with DIN EN 1992-1-1 and DIN 1992-1-1NA

## 6.3. USA standards

The USA seismic design provisions are provided in ASCE/SEI 7 (2016), which sets the minimum design loads and associated criteria for buildings and other structures. ACI 318M-14 (2019) provides the building code requirements for structural concrete, including anchoring into concrete. Seismic design and prequalification requirements are necessary for fasteners in structures which are assigned to Seismic Design Category (SDC) C, D, E, or F. The assignment of SDC is based on seismic demand and risk category of the structure, where seismic demand is defined by the spectral acceleration response in the short period range and at one second. The risk category is similar to the importance level of buildings adopted in the European and Australian codes. Typically, structures in Australia would fall within SDC of B, C and D. A direct comparison between European and USA recommendations for seismic performance categories for various cities in Australia is provided in Lee et al. (2018). It is expected that with the introduction of the second seismic performance category, the USA specifications will be extended to consider the structural ductility demand or to include a performance based approach (ICC-ES, 2020).

# Part B

# Prequalification requirements and design of fasteners in Australia

## 7. Specification criteria for selection of seismic performance categories

Under seismic actions, the prequalification requirements of fasteners are highly dependent on the damage state of the concrete substrate which is related to expected crack widths and the opening and closing nature of the crack. Therefore, the required level of prequalification for the fasteners shall be determined based on the expected damage level of the concrete in which the fasteners are to be installed. The minimum seismic performance category required for fasteners designed for seismic actions as a function of expected crack width is provided in Table 4. The effects of potential opening and closing of the crack under seismic loading on the fastener should also be considered when determining a suitable fastener seismic performance category.

The specification of fastener performance category based on crack width is consistent with the specification in the German Annex, DIN EN 1992-4/NA:2019-04 and the crack width requirements of testing procedures for fasteners in accordance with the European prequalification requirements.  Since outside of the plastic hinge regions it's assumed that the stress and strain in the reinforcement will not exceed yield, the crack widths in these regions may be calculated by using equations which have been developed for service load conditions. Therefore, it is suggested that the crack widths under seismic actions (outside of plastic hinge regions) may be calculated using the equation for maximum crack width ($w$) in accordance with AS 3600.

*Table 4: Minimum required seismic performance categories for fasteners*

| Crack width under design earthquake | Fastener seismic performance category |
|---|---|
| $\boldsymbol{w \leq 0.3mm}$ | Seismic prequalification is not required |
| $\boldsymbol{w \leq 0.5mm}$ | C1 |
| $\boldsymbol{w \leq 0.8mm}$ | C2 |
| $\boldsymbol{w > 0.8mm}$ (plastic hinge region) | Not covered[1] |

[1] For crack widths greater than 0.8 mm special design and alternative solutions may be required.

A simplified approach is also recommended for selecting seismic performance categories especially when it is not feasible or practical to conduct detailed analyses. The suggested criterion is provided in Table 5 and is based on: (i) the earthquake hazard design factor ($Z$), (ii) the probability factor ($k_p$), (iii) the site sub-soil class, and (iv) the importance level of the building. These parameters shall be determined in accordance with the Australian earthquake loading standard, AS 1170.4 and the Australian National Construction Code (NCC).

Table 5 has been developed by conducting a rapid seismic assessment of reinforced concrete buildings in Australia. The assessment has approximated the expected interstorey drift demand of limited-ductile reinforced concrete buildings (typical to Australian building practice) with the consideration of plan asymmetry and higher mode effects. The recommendations are predominantly based on the flexural response of building components assuming that fasteners will be located outside of plastic hinge regions. The suitability of fasteners in shear-controlled components and in buildings with high level of vertical irregularity needs special consideration by the designer. The details of the study are provided in Amirsardari et al. (2020).

*Table 5: Minimum recommended seismic performance categories for fasteners.*

| Importance level | $(k_p Z)$ for site sub-soil class | | | | | Seismic performance category |
|---|---|---|---|---|---|---|
| | E | D | C | B | A | |
| 2 | Not applicable | Not applicable | Not applicable | $\leq 0.1$ | $\leq 0.12$ | Seismic prequalification is not required |
| | Not applicable | 0.08 | $\leq 0.12$ | $> 0.1$ to $\leq 0.18$ | $> 0.12$ to $\leq 0.22$ | C1 |
| | $\geq 0.08$ | $> 0.08$ | $> 0.12$ | $> 0.18$ | $> 0.22$ | C2 |
| 3 | Not applicable | 0.08 | $\leq 0.12$ | $\leq 0.18$ | $\leq 0.22$ | C1 |
| | $\geq 0.08$ | $> 0.08$ | $> 0.12$ | $> 0.18$ | $> 0.22$ | C2 |
| 4 | $\geq 0.08$ | | | | | C2 |

## 8. Design approach

For the design of fasteners under seismic actions, one of the following options shall be fulfilled:

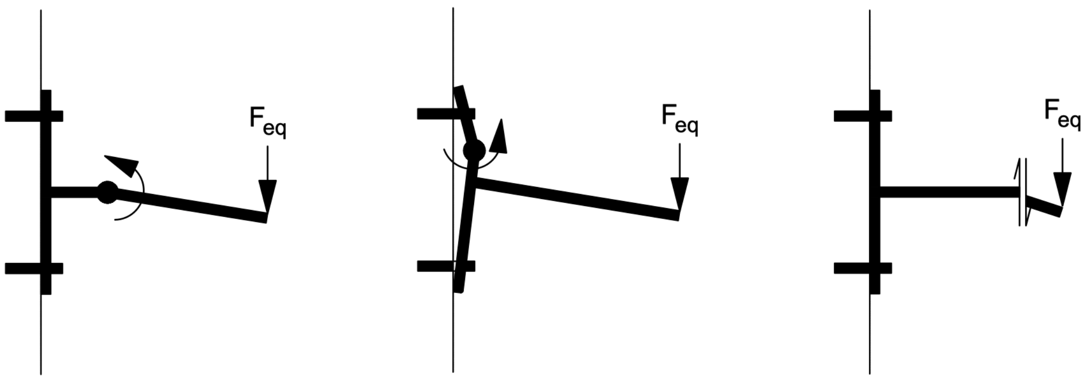
**Option 1 - No ductility requirement**

Fasteners are assumed as non-ductile elements and do not contribute to the ductile behaviour of the structure. The fasteners should be designed using either Option 1a or 1b.

**(1a) Capacity design:** the capacity of non-yielding or yielding fixture or attached element determines the maximum tension and shear load imposed on the connection. The strain hardening and material over-strength of the fixture or attached element shall be considered.

The fastening shall be designed for the maximum tension and/or shear load imposed on the connection based on: (i) development of ductile yield mechanism in the attached element, or (ii) yielding in the base plate, or (iii) capacity of a non-yielding structural or attached element as shown in Figure 2.

**(1b) Elastic design:** elastic behaviour of fastening and structure/element is assumed for the maximum loads obtained from load combinations in accordance with AS 1170.0 at ultimate limit state (ULS) that includes the earthquake component ($E_u$). The design forces shall be determined for structural connections in accordance with AS 1170.4 with $S_p/\mu$=1.0 and for non-structural connections in accordance with AS 1170.4 Section 8.




*(a) Yield mechanism in attached element* *(b) Yield mechanism in fixture (base plate)* *(c) Capacity of non-yielding element*

*Figure 2: Seismic design of fasteners without damaging fasteners*

**Option 2 - Ductility requirement**

The fasteners and steel component shall have sufficient elongation capacity to be considered as ductile. This design option is applicable for the tensile load action on the fastener. The fasteners or group of fasteners is designed for the load combinations including earthquake component ($E_u$) at ULS. The tensile capacity of the fastening related to steel failure shall be smaller than the tensile capacity of fastener related to concrete related failure modes.

It is noted that the fasteners contribution to the energy dissipation in the global structural analysis or non-structural element should not be considered unless appropriate justification is provided, including non-linear time history analysis. The primary structural members could have large non-recoverable displacement of fasteners and this option should not be used in these members.

Furthermore, for the design of fasteners to satisfy Option 2, following additional requirements shall be met:

(i) Fasteners shall be prequalified for seismic performance category C2.

(ii) Steel failure of the fasteners shall be ensured by satisfying following requirements:

(A) For fastenings with one fastener in tension

$$R_{k,s,eq} \leq 0.7\ \phi_{inst} R_{k,conc,eq} \quad \text{Eq. 1}$$

where

$R_{k,s,eq}$ = minimum characteristic seismic resistance for steel failure calculated in accordance with Eq. 4.

$R_{k,conc,eq}$ = minimum design characteristic seismic resistance for all concrete related failure modes (concrete cone, pull-out (mechanical fasteners), concrete blow-out, concrete splitting and combined cone and pull-out (chemical fasteners)) calculated according to Eq. 4.

$\phi_{inst}$ = capacity reduction factor for installation determined in accordance with Appendix A, AS 5216, note: $\phi_{inst} = \frac{1}{\gamma_{inst}}$.

(B) For a group of fasteners with two or more fasteners in tension

$$\frac{R_{k,s,eq}}{S_h^*} \leq 0.7\ \phi_{inst} \frac{R_{k,conc,eq}}{S_g^*} \qquad \text{Eq. 2}$$

where

$R_{k,conc,eq}$ = minimum design characteristic seismic resistance for all concrete related failure modes (concrete cone, concrete blow-out, concrete splitting and combined cone and pull-out (chemical fasteners)) calculated in accordance with Eq. 4.

$S_h^*$ = designed load in the highest loaded fastener in the group.

$S_g^*$ = designed load in the group of fasteners.

For a group of post-installed mechanical fasteners with two or more fasteners in tension, the highest loaded fastener shall be verified for pull-out failure in accordance with Eq. 1 where $R_{k,conc,eq}$ is the seismic pull-out resistance of one fastener.

(iii) All fasteners that are designed to transfer tension load shall be ductile and have stretch length or elongation $\geq 8d$ unless determined otherwise.

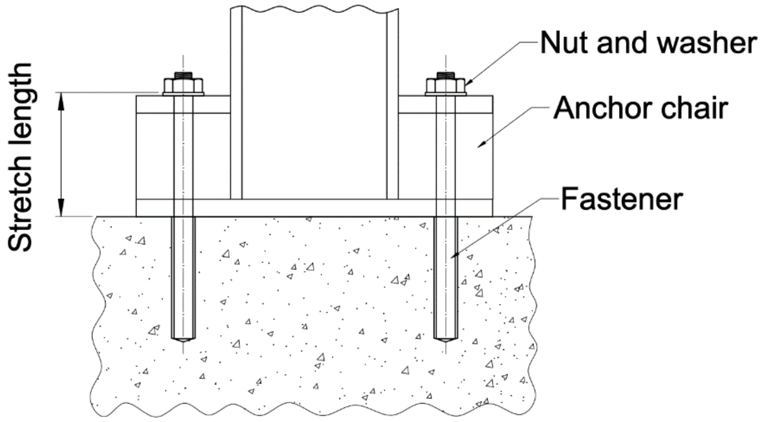
(A) A fastener is considered as ductile if $f_{uf} \leq 800$ N/mm², $\frac{f_{yf}}{f_{uf}} \leq 0.8$ and rupture elongation measured over a length of $5d$ is $\geq 12\%$

where

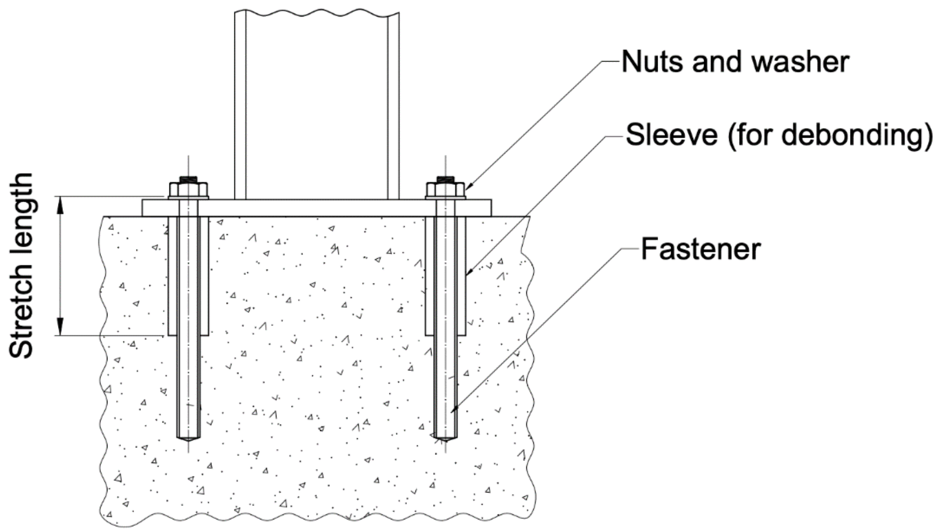
$f_{yf}$ = yield tensile strength of fastener

$f_{uf}$ = ultimate tensile strength of fastener

(B) The characteristic steel resistance of fasteners which incorporate a reduced section, such as threads, over a length less than 8 times the diameter of fasteners at reduced section shall be greater than 1.3 times characteristic yield resistance of the fasteners at the non-reduced section.




*(a) Anchor chair*




*(b) Sleeve or debonded length*

*Figure 3: Illustration of stretch length*

## 9. Derivation of forces acting on fasteners

The design earthquake forces acting on the fixture shall be determined in accordance with AS 1170.4 and Section 8. The maximum value of tension and shear component shall be applied simultaneously when designing the fasteners unless otherwise proved by more accurate analysis.

The distribution of the forces to the individual fasteners of a group shall be undertaken in accordance with AS 5216 (Section 4).

## 10. Determination of resistance

The seismic design resistance of a fastener shall be calculated as follows:

$$R_{d,eq} = \phi_i \, R_{k,eq} \quad \text{Eq. 3}$$

where

$\phi_i$ = capacity reduction factor for strength of fastener or fastener group for failure mode *i* in accordance with AS 5216 (Cl 3.2.1)

The characteristic seismic resistance of a fastener shall be calculated as follows:

$$R_{k,eq} = \alpha_{gap} \, \alpha_{eq} \, R^0_{k,eq} \quad \text{Eq. 4}$$

where

$R_{k,eq}$ = characteristic seismic resistance of a fastener.

$\alpha_{gap}$ = reduction factor to take into account for inertia effects due to an annular gap between fastener and fixture in case of shear loading and determined in accordance with Appendix A, AS 5216.

Following values of $\alpha_{gap}$ may be assumed if further information is not available:

$\alpha_{gap} = 1.0$ if no hole clearance between fastener and fixture;

$\alpha_{gap} = 0.5$ if hole clearance between fastener and fixture is in accordance with AS 5216 (Table 4.2.2.1).

$\alpha_{eq}$ = factor to take into account the influence of seismic actions and associated cracking and determined in accordance with Table 6.

$R^0_{k,eq}$ = basic characteristic seismic resistance for a given failure mode determined as follows:

for steel and pull-out failure under tension load and steel failure under shear load, $R^0_{k,eq}$ shall be determined in accordance with Appendix A, AS 5216 (i.e., $N_{Rk,s,eq}$, $N_{Rk,p,eq}$ and $V_{Rk,s,eq}$);

for combined pull-out and concrete failure for chemical fasteners, $R^0_{k,eq}$ shall be determined according to AS 5216

(Clause 6.2.5, i.e., $N_{Rk,p}$) using characteristic bond resistance ($\tau_{Rk,eq}$) in accordance with Appendix A, AS 5216;

for other failure modes, $R^0_{k,eq}$ shall be determined in accordance with AS 5216 (Chapter 6 and 7, i.e., for tension loads: $N_{Rk,c}$, $N_{Rk,sp}$, $N_{Rk,cb}$, $N_{Rk,re}$, $N_{Rk,a} = \frac{1}{\phi_c} N_{Rd,a}$, and for shear load: $V_{Rk,c}$, $V_{Rk,cp}$, $N_{Rk,re}$, $N_{Rk,a} = \frac{1}{\phi_c} N_{Rd,a}$).

The verification of combined tension and shear forces shall be carried out in accordance with AS 5216 (Clauses 8.1.1, 8.2.1 and 8.3.1). Separate verification shall be carried out for steel failure and failure modes other than steel as follows:

$$\left(\frac{N^*}{\phi_i\, N_{Rk,i,eq}}\right)^{k_{15}} + \left(\frac{V^*}{\phi_i\, V_{Rk,i,eq}}\right)^{k_{15}} \leq 1 \qquad \text{Eq. 5}$$

where

$N^*$ = design tension force on the fasteners including seismic effects for the corresponding failure modes.

$V^*$ = design shear force on the fasteners including seismic effects for the corresponding failure modes.

$N_{Rk,i,eq}$ $V_{Rk,i,eq}$ = characteristic resistance of fasteners in seismic tension and shear (*Subscript i represents the different failure modes*).

Following values shall be used:

for steel failure $N_{Rk,s,eq}$ and $V_{Rk,s,eq}$ for $N_{Rk,i,eq}$ and $V_{Rk,i,eq}$ shall be used, respectively;

for failure modes other than steel failure, largest ratio of $\frac{N^*}{\phi_i\, N_{Rk,i,eq}}$ and $\frac{V^*}{\phi_i\, V_{Rk,i,eq}}$ shall be used.

$k_{15}$ = factor determined in accordance with Appendix A, AS 5216. If detailed information is not available following values may be used:

$k_{15} = 1$ for steel failure;

$k_{15} = 0.67$ for fastenings with supplementary reinforcement to absorb shear loads only;

$k_{15} = 1$ in all other cases.

*Table 6: Reduction factor,* $\alpha_{eq}$ in accordance with EN 1992:4 (2018)

| Design Action | Failure mode | Single fastener[1] | Fastener group |
|---|---|---|---|
| **Tension** | Steel failure | 1.0 | 1.0 |
| | Concrete failure<br>- Undercut fasteners<br>- All other fasteners | <br>1.0<br>0.85 | <br>0.85<br>0.75 |
| | Pull-out failure | 1.0 | 0.85 |
| | Combined pull-out and concrete failure (chemical fastener) | 1.0 | 0.85 |
| | Concrete splitting failure | 1.0 | 0.85 |
| | Concrete blow-out failure | 1.0 | 0.85 |
| | Steel failure of reinforcement | 1.0 | 1.0 |
| | Anchorage failure of reinforcement | 0.85 | 0.75 |
| **Shear** | Steel failure | 1.0 | 0.85 |
| | Concrete pry-out failure<br>- Undercut fasteners<br>- All other fasteners | <br>1.0<br>0.85 | <br>0.85<br>0.75 |
| | Concrete edge failure | 1.0 | 0.85 |
| | Steel failure of reinforcement | 1.0 | 1.0 |
| | Anchorage failure of reinforcement | 0.85 | 0.75 |

[1] This also applies where only one fastener in a group is subjected to tension load

## 11. Displacement requirement of fasteners

For the design of a structure or component, a lower limit state than the ultimate limit state (ULS) may be necessary to maintain the function of the connected components for a certain design seismic event. This is referred to as damage limit state (DLS) in the prequalification document in accordance with Appendix A, AS 5216.

The displacement at the damage limit state under tension and shear loads shall be limited to $\delta_{N,req(DLS)}$ and $\delta_{V,req(DLS)}$ to meet necessary requirements, including functionality and assumed support conditions. These displacement values shall be selected depending upon the requirements of the specific application. If a rigid support is assumed in the analysis, the designer shall establish the limiting displacement compatible to the requirement for the structural behaviour. It is noted that in some cases, the acceptable displacement associated with a rigid support condition is considered to be in the range of 3 mm.

The fastener shall accommodate the deformation or rotation requirements if they are relevant for the design of the connections (for example, the connection to façade elements or structural members not part of the seismic force resisting system).

The rotation of the connection shall be calculated as follows:

$$\theta_p = \frac{\delta_{N,eq}}{s_{max}} \quad \text{Eq. 6}$$

where

$\theta_p$ = rotation of the connection.

$\delta_{N,eq}$ = displacement of the fastener under seismic loading.

$s_{max}$ = distance between the outermost row of fasteners and opposite edge of the fixture as shown in Figure 4.

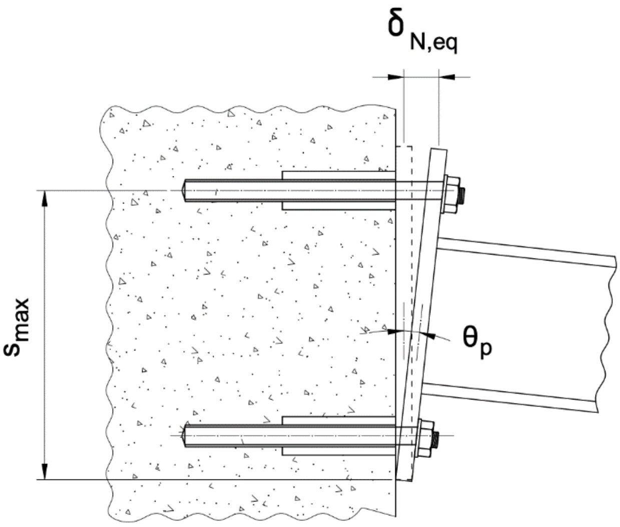



*Figure 4: Illustration of fastening displacement and rotation*

If the fastener displacements under tension and shear loading determined in accordance with Appendix A, AS 5216 are higher than the corresponding required values, the resistance shall be reduced as follows:

$$N_{Rk,eq,red} = N_{Rk,eq} \frac{\delta_{N,req(DLS)}}{\delta_{N,eq(DLS)}} \quad \text{Eq. 7}$$

$$V_{Rk,eq,red} = V_{Rk,eq} \frac{\delta_{V,req(DLS)}}{\delta_{V,eq(DLS)}} \quad \text{Eq. 8}$$

where

$N_{Rk,eq,red}$ = reduced characteristic seismic resistance of a fastening under tension loads.

$V_{Rk,eq,red}$ = reduced characteristic seismic resistance of a fastening under shear loads.

$N_{Rk,eq}$ = characteristic seismic resistance of a fastening under tension loads.

$V_{Rk,eq}$ = characteristic seismic resistance of a fastening under shear loads.

$\delta_{N,req(DLS)}$ = required displacement of the fastener under tension loading at DLS.

$\delta_{N,eq(DLS)}$ = displacement of the fastener under tension loading at DLS determined in accordance with Appendix A, AS 5216.

$\delta_{V,req(DLS)}$ = required displacement of the fastener under shear loading at DLS.

$\delta_{V,eq(DLS)}$ = displacement of the fastener under shear loading at DLS determined in accordance with Appendix A, AS 5216.

If fastenings and attached elements are required to be operational after earthquake, the relevant displacements shall be considered.

## 12. References

ACI (American Concrete Institute). (2007). *ACI 355.2-07: Qualification of post-installed mechanical fasteners in concrete*. ACI

ACI (American Concrete Institute). (2011). *ACI 355.4-11: Qualification of post-installed mechanical fasteners in concrete*. ACI

ACI (American Concrete Institute). (2019). *ACI 318: Building code requirements for structural concrete (ACI 318M-19) and commentary (ACI 318RM-19)*. Michigan: ACI

Amirsardari, A., Pokharel, T., Lee, J., & Gad, E. (2020). *Seismic performance categories for post-installed fasteners in Australia.* Paper presented at the Australian Earthquake Engineering Society Virtual Conference.

ASCE (American Society of Civil Engineers). (2016). *ASCE/SEI 7-16: Minimum design loads and associated criteria for building and other structures*. Virginia: ASCE

CEN (European Committee for Standardization). (2004). *EN 1998-1: Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*. Brussels: CEN

CEN (European Committee for Standardization). (2018). *EN 1992-4: Eurocode 2: Design of concrete structures - Part 4: Design of fastenings for use in concrete*. Brussels: CEN

DIN (German Institute for Standardization). (2019). *DIN EN 1992-4/NA: National Annex - Nationally determined parameters - Eurocode: Deisgn of concrete structures - Part 4: Designing of fastenings for use in concrete, English translastion of DIN EN 1992-4/NA:2019-04*. Berlin: Beuth Verlag GmbH

Eligehausen, R., Mallée, R., & Silva, J. F. (2006). *Anchorage in concrete construction* (First ed.). Berlin, Germany: Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG.

EOTA (European Organisation for Technical Assessment). (2016a). *EAD 330232-00-0601: Mechanical fasteners for use in concrete*.

EOTA (European Organisation for Technical Assessment). (2016b). *TR 049: Post-installed fasteners in concrete under seismic action*.

EOTA (European Organisation for Technical Assessment). (2017). *EAD 330499-00-0601: Bonded fasteners for use in concrete*.

EOTA (European Organisation for Technical Assessment). (2018). *EAD 330747-00-0601: Fasteners for use in concrete for redundant non-structural systems*.

Hoehler, M. S., & Eligehausen, R. (2008). Behaviour and testing of anchors in simulated seismic cracks. *ACI Structural Journal, 105*(5), 348-357.

Hoeler, M. S. (2006). *Behavior and testing of fastenings to concrete for use in seismic applications.* (Doctor of Philosophy Thesis). University of Stuttgart, Stuttgart, Germany.

ICC-ES (International Code Council Evaluation Service). (2020). *AC510-0620-R2: Proposed New Acceptance Criteria for Steel Seismic Qualification of Post-installed Anchors in Concrete*. California, United States of America: https://icc-es.org/wp-content/uploads/2020/04/7-AC510-0620-pre.pdf

Lee, J., Pokharel, T., Tsang, H.-H., & Gad, E. F. (2018). *Requirement for seismic performance of post-installed fastenings in Australia.* Paper presented at the Australian Structural Engineering Conference (ASEC), Adelaide.

Mahrenholtz, P., Wood, R. L., Eligehausen, R., Hutchinson, T. C., & Hoehler, M. S. (2017). Development and validation of European guidelines for seismic qualification of post-installed anchors. *Engineering Structures, 148*, 497-508. doi:http://dx.doi.org/10.1016/j.engstruct.2017.06.048

Standards Australia. (2007). *AS 1170.4-2007 (R2018): Structural design actions - Part 4: Earthquake actions in Australia*. Sydney: SAI Global

Standards Australia. (2018). *AS 5216: Design of post-installed and cast-in fastenings in concrete*. Sydney: SAI Global

AEFAC
Australian Engineered Fasteners and Anchors Council



**www.aefac.org.au**