Guide on

Design of post-installed anchor bolt systems

in Hong Kong

Dr. S.S.H Cho and Ir Prof. SL Chan
Department of Civil and Environmental Engineering,
The Hong Kong Polytechnic University

published by
The Hong Kong Institute of Steel Construction
www.hkisc.org

香港
鋼結構學會
Hong Kong Institute of
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Contents

Preface

This book is published by The Hong Kong Institute of Steel Construction for the benefit of the construction industry via technology advancement. The authors acknowledge the supports by the Research Grant Council of the Hong Kong SAR Government on the projects " Second-Order Analysis of Flexible Steel Cable Nets Supporting Debris (PolyU 152008/15E)" and "Second-order and Advanced Analysis of Arches and Curved Structures (PolyU 152012/14E)" and the Innovative Technology Fund for the project "Advanced design of flexible barrier systems by large deflection theory (ITS/032/14)".

Disclaimer

1 Introduction

1.1 Scope of this book

Anchor bolts have been extensively used over the world for connecting steel structures to concrete structures. They can be either cast-in or post-installed. However, in many cases, such as in Alteration and Addition (A&A) works in Hong Kong, the concrete has already been cast and set and therefore the anchor bolts are normally post-installed.

In European countries, the European Organisation of Technical Assessment (EOTA) published the Guideline for European Technical Approval of Metal Anchors for Use in Concrete (ETAG 001) [1]. Anchor bolts which acquire European Technical Assessments or formerly known as European Technical Approvals (ETAs) must fulfill the requirements given in ETAG 001 [1]. On the other hand, the European Committee for Standardization (CEN) published Design of Fastenings for Use in Concrete (CEN/TS 1992-4) [2] which provides technical specifications on anchor bolt design which is based on the limit state approach.

In Hong Kong, the authority provides a list of approved anchor bolts in the Central Data Bank (CDB) [3] which have been tested in accordance with outdated BS 5080 [4] and ETAG 001 [1]. However, the current construction regulations do not provide specific design codes of anchor bolts so advanced system can hardly be demonstrated to be sufficient. Instead of the limit state design approach, authorities widely accept using a global factor of safety of 3.0 to the characteristic resistance of the anchor bolt to obtain its design resistance. This method has been adopted for decades and is considered obsolete and lack of transparency because the true failure mode of the anchor bolt or the bolt group cannot be reflected. Therefore, a design guide making references to latest technologies appears to be necessary.

This handbook is aimed to set out the design guidelines for post-installed anchor bolt design subject to mainly static loads making references to ETAG 001, Annex C [1], TR029 [5] and CEN/TS 1992-4 [2]. The design guidelines can be applied to both single anchor bolts and bolt groups.

This handbook shall be used in conjunction with the Code of Practice for the Structural Use of Steel [6] and the Code of Practice for Structural Use of Concrete

[7] or other relevant design codes for design of other steel elements such as base plate or checking of existing structural elements which is not covered in this handbook.

1.2 Aim of anchor bolt design

The aim of anchor bolt design is to produce an anchor bolt connection analysis and design of adequate safety and serviceable level in its design life, both at a sufficiently and acceptably low probability of violating the limit states. The anchor bolt connection should be fit for its purpose of construction during the design life of a structure.

1.3 Limit state design

The limit state design (LSD) was first introduced and became widely used around early 80's and it is aimed to make sure the factored resistance greater than factored design load as:

$$\gamma_f \cdot F \leq \frac{R}{\gamma_m} \tag{1.1}$$

in which γ_f and γ_m are respectively the load and resistance factors. The load effects, F, shall be determined by normal structural analysis methods for axial, bending, shear or torsion and/or other actions in structural members and components, multiplied by a partial load factor (γ_f) to give an upper bound estimate for load effects. Resistance effects, R, shall be determined by normal strength of materials, geometry of member and other material properties. The material yield strength shall be divided by a resistance factor or partial material factor (γ_m) to give a lower bound estimate for material properties.

There are mainly two limit states, namely the ultimate and the serviceability limit states. While this handbook covers mainly the ultimate limit state of strength, other examples of limit states relevant to steel structures are given in Table 1.1.

Table 1.1 Examples of limit states

Ultimate limit states (ULS)	Serviceability limit states (SLS)
Strength (including general yielding, rupture, buckling and forming a mechanism)	Deflection
Stability against overturning, sliding, uplift and sway stability	Vibration
Fire resistance	Wind induced oscillation
Brittle fracture and fracture caused by fatigue	Durability

1.4 Resistance and load factors

1.4.1 Resistance factors

1.4.1.1 Partial safety factor for steel

The partial safety factor of steel γ_{Ms} depends on the characteristic steel ultimate strength f_{uk} and the characteristic steel yield strength f_{yk}. For galvanized steel as well as stainless steel, the value of γ_{Ms} for tension is given by:

$$\gamma_{Ms} = 1.2\frac{f_{uk}}{f_{yk}} \geq 1.4 \quad (1.2)$$

For shear, the value of γ_{Ms} is given by:

$$\gamma_{Ms} = 1.0\frac{f_{uk}}{f_{yk}} \geq 1.25 \qquad \text{for } f_{uk} \leq 800\text{N/mm}^2 \text{ and } \frac{f_{yk}}{f_{uk}} \leq 0.8 \quad (1.3a)$$

$$\gamma_{Ms} = 1.5 \qquad \text{for } f_{uk} > 800\text{N/mm}^2 \text{ or } \frac{f_{yk}}{f_{uk}} > 0.8 \quad (1.3b)$$

Therefore, as an example, for an anchor bolt with $f_{uk} = 800\text{N/mm}^2$ and $f_{yk} = 640\text{N/mm}^2$, the value of γ_{Ms} is taken as 1.5 for failure modes due to tension and 1.25 for failure modes due to shear.

1.4.1.2 Partial safety factor for concrete

The partial factor γ_{Mc} covers concrete break-out failure modes (i.e. cone failure, edge failure and pry-out failure).

The value of γ_{Mc} is determined by:

$$\gamma_{Mc} = \gamma_c \cdot \gamma_2 \quad (1.4)$$

where

γ_c = partial factor for concrete under compression = 1.5

γ_2 = partial factor taking into account the installation safety of the fastening system

For tension:

γ_2 = 1.0 for systems with high installation safety
= 1.2 for systems with normal installation safety
= 1.4 for systems with low but still acceptable installation safety

For shear:

γ_2 = 1.0

The level of installation safety can be found in the relevant approval documents and depends largely on the anchor bolt size. For an anchor bolt with normal installation safety ($\gamma_2 = 1.2$) as an example, the value of γ_{Mc} is taken as 1.8 for failure modes due to tension and 1.5 for failure modes due to shear.

The partial factor for pull-out failure γ_{Mp} is given in the relevant approval documents. In general, for the partial factors for splitting failure γ_{Msp} and the pull-out failure γ_{Mp}, the value for γ_{Mc} is recommended.

1.4.2 Load factors

As mentioned in Section 1.1, in Hong Kong, an overall factor of safety of 3.0 is widely used in anchor bolt design. Since the required resistance factors vary among different failure modes, the load factor will be given in Equation (1.5) so that the overall factor of safety remains 3.0.

$$\gamma_f = \frac{3.0}{\gamma_m} \qquad (1.5)$$

For example, if the anchor bolt design is governed by concrete cone failure with $\gamma_{Mc} = 1.5$, the load factor will be given by $\gamma_f = 3.0/1.5 = 2.0$.

1.5 Major symbols

N	normal force (positive = tension, negative = compression)
V	shear force
M	moment
T	torsion
N_{Rk} (V_{Rk})	characteristic resistance of normal force (shear force) of a single anchor bolt or a bolt group

N_{Rd} (V_{Rd})	design resistance of normal force (shear force) of a single anchor bolt or a bolt group
N_{Sd} (V_{Sd})	design normal force (shear force)
c	edge distance from the anchor bolt centre
c_1 (c_2)	edge distance in direction 1 (direction 2)
c_{cr}	characteristic edge distance for ensuring the transmission of the characteristic resistance of anchor bolt
c_{min}	minimum allowable edge distance
d	diameter of anchor bolt or threaded diameter
d_{nom}	outside diameter of anchor bolt
d_0	nominal diameter of drilled hole
f_{cu}	characteristic compressive cube strength of concrete
f_{yk}	characteristic steel yield strength or steel proof strength
f_{uk}	characteristic steel ultimate strength
h	thickness of concrete in which the anchor bolt is installed
h_{ef}	effective embedment depth
h_{min}	minimum allowable thickness of concrete
n	number of anchor bolts in a group
s	centre to centre spacing of anchor bolts in a group
s_1 (s_2)	centre to centre spacing of anchor bolts in a group in direction 1 (direction 2)
s_{cr}	characteristic spacing for ensuring the transmission of the characteristic resistance of anchor bolt
s_{min}	minimum allowable spacing

2 Anchor Bolts and Base Materials

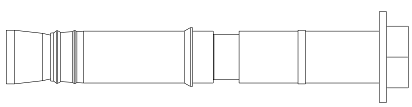
2.1 Anchor bolts

2.1.1 Types of anchor bolts

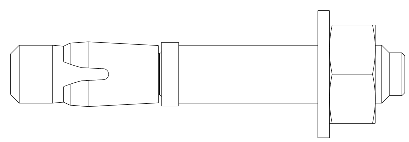
To suit different needs and the conditions of the base materials, there are many types of anchor bolts as shown in Figure 2.1 such as:

(a) Torque-controlled expansion anchor (sleeve type and wedge type)
(b) Deformation-controlled expansion anchor
(c) Undercut anchor
(d) Concrete screw
(e) Chemical anchor
(f) Expansion chemical anchor

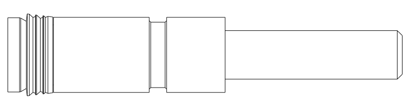
The above anchors can be classified into two broad systems, namely the mechanical systems and the chemical systems which will be explained briefly in Section 2.1.1.1 and 2.1.1.2.



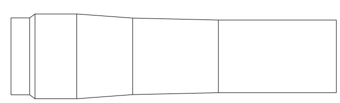
(a1) Torque-controlled expansion anchor (sleeve type)



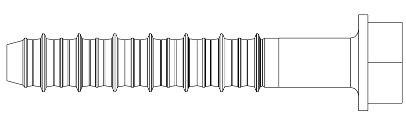
(a2) Torque-controlled expansion anchor (wedge type)



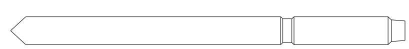
(b) Deformation-controlled expansion anchor



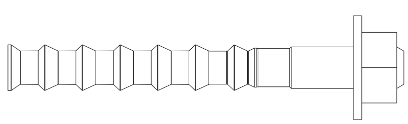
(c) Undercut anchor



(d) Concrete screw



(e) Chemical anchor



(f) Expansion chemical anchor

Figure 2.1 Different types of post-installed anchors

In Hong Kong, generally design engineers shall use anchor bolts listed in the CDB [3] which were previously approved in other projects. Sometimes these anchor bolts were approved with conditions which are shown in the “remarks / comments” column of the reference list table. Therefore, design engineers shall take the remarks or comments into consideration in their design. Otherwise, if anchors bolts not listed in the CDB [3] are used, test reports in accordance with BS 5080 [4] or ETAG 001 [1] shall be submitted to the Building Departments (BD) or other relevant authorities for approval. Anchor bolts are commonly available in galvanized steel and stainless steel. If the anchor bolt application is exposed to external condition, such as fixings at external walls and canopies, stainless steel anchors shall be used.

2.1.1.1 Mechanical systems

Mechanical anchors include types (a), (b), (c) and (d). For torque-controlled anchor, the “sleeve” or the “wedge” of the anchor bolts will expand in the drilled hole through applying a torque. Similarly, for deformation-controlled anchor, the “sleeve” of the anchor bolt will expand through movement of an internal plug in the “sleeve”. The tensile resistance of an expansion type anchor bolt is developed by friction between the “sleeve” or “wedge” of the anchor bolt and the base material.

Undercut anchors develop mechanical interlock between anchor and base material. The undercutting can be achieved by a special drilling tool or by the anchor itself during installation. Then the expansion “sleeve” will fill the undercut hole and develop a tensile resistance.

Concrete screws are screwed into pre-drilled holes by a special screwdriver. The threads will cut into the concrete and create mechanical interlock between screw and concrete.

2.1.1.2 Chemical systems

Types (e) and (f) are chemical anchors also known as adhesive anchors or bonded anchors. A chemical anchor is an anchor placed into a hole in concrete with the gap between anchor and the concrete filled with a bonding compound. After the bonding compound is set, a tensile resistance is developed by means of chemical interlock.

An expansion chemical anchor works like a combination of chemical anchor and expansion anchor. After the bonding compound is set, a torque is applied and the bonding compound around the “sleeve” is split and creates additional friction between the “sleeve” and the concrete.

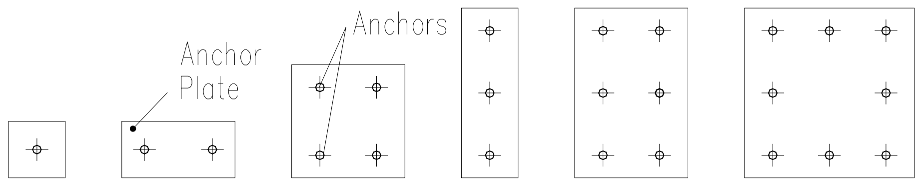
2.1.2 Anchor bolts in a group

The design guidelines of this handbook can also be applied to groups of anchor bolts. In this case, only anchor bolts of the same type and size shall be considered and the following conditions are satisfied.

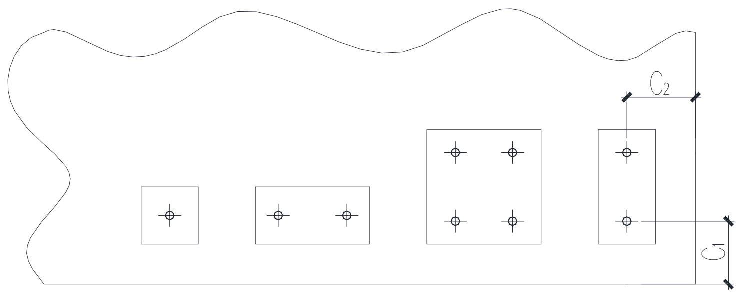
2.1.2.1 Bolt configurations

Figure 2.2 and Figure 2.3 show the configurations of post-installed anchor bolts covered in this handbook. The allowable configurations depend on which design code the anchor bolt design is based on. If the anchor bolts are designed in accordance with ETAG 001, Annex C [1] for mechanical anchors or TR029 [5] for chemical anchors, the bolt configurations shall follow Figure 2.2. Figure 2.2(a) shows the allowable configuration of anchor bolts situated far from concrete edges for all loading directions or close to concrete edges for tension force only while Figure 2.2(b) shows the allowable configurations of anchor bolts situated close to a concrete edge subject to shear force. If the anchor bolts are designed in accordance with CEN/TS 1992-4 [2], the bolt configurations shall follow Figure 2.3. Figure 2.3(a) shows the allowable configuration of anchor bolts without hole clearance situated at all edge distances; Figure 2.3(b) shows the allowable configurations of anchor bolts with hole clearance situated far from concrete edges and Figure 2.3(c) show allowable configurations of anchor bolts with hole clearance situated close to a concrete edge.

If the anchor bolt is too close to a concrete edge, it will be susceptible to concrete edge failure. Therefore, in ETAG 001, Annex C [1], TR029 [5] and CEN/TS 1992-4 [2], bolt configurations for bolts close to edge will have a more stringent requirement. In the case of $c < \max(10h_{ef}, 60d_{nom})$, only configurations with single anchor bolts or groups with two and four anchor bolts are accepted as shown in Figure 2.2(b) and Figure 2.3(c). Configurations other than those shown in Figure 2.2 and Figure 2.3 shall also be allowed based on engineering judgment or other design methods according to the manufacturers. Those methods shall be developed based on current design standards (e.g. ETAG 001, Annex C [1], TR029 [5], CEN/TS 1992-4 [2] and FIB [8]) and supported by a series of test data.

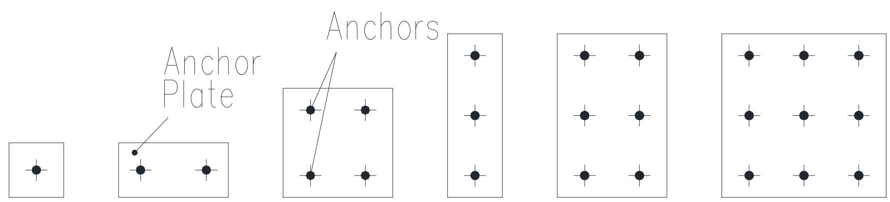


(a) All loading directions, if anchors are situated far from edges or tension force only, if anchors are situated close to edges

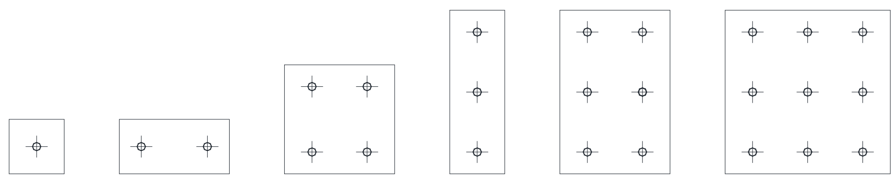


(b) Shear force, if anchors are situated close to an edge

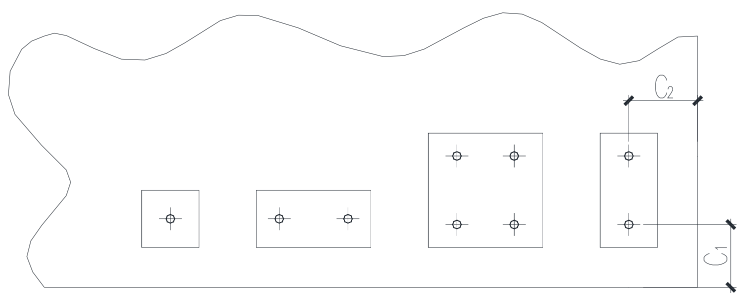
Figure 2.2 Configurations allowed in ETAG 001, Annex C and TR029



(a) Anchor bolts without hole clearance, far from concrete edge



(b) Anchor bolts with hole clearance, far to concrete edge



(c) Anchor bolts with hole clearance, close to concrete edge

Figure 2.3 Configurations allowed in CEN/TS 1992-4

2.1.2.2 Minimum bolt spacing and edge distance requirements

Design engineers shall refer to manufacturer design manual for minimum bolt spacing requirement s_{min} and minimum edge distance requirement c_{min} which are normally determined by tests and mentioned in the relevant approval documents.

2.2 Base Materials

2.2.1 Concrete

The concrete structures shall be of normal weight concrete with grades ranging from C25 to C60 (i.e. characteristic cube strength of concrete ranging from 25N/mm^2 to 60N/mm^2. For other concrete grades, Section 2.2.2 shall be referred. Depending on the type of anchor bolts, the base concrete may be cracked or non-cracked. Cracks exist in tension zone of concrete and will affect the resistance of the anchor bolt. Non-cracked concrete may be assumed if under service load conditions the anchor with its entire anchorage depth is located in non-cracked concrete (i.e. compression zone).

According to CEN/TS 1992-4 [2], non-cracked concrete may be assumed if the following equation is observed:

$$\sigma_L + \sigma_R \leq \sigma_{adm} \tag{2.1}$$

where

σ_L	=	stress in the concrete induced by external loads including fastener loads (compressive stresses are negative)
σ_R	=	stress in the concrete due to restraint of intrinsic imposed deformations (e.g. shrinkage of concrete) or extrinsic imposed deformations (e.g. due to displacement of support or temperature variations). If no detailed analysis is conducted, assume $\sigma_R = 3.0$ N/mm^2.
σ_{adm}	=	admissible tensile stress for the definition of non-cracked concrete. The recommended value is $\sigma_{adm} = 0$ N/mm^2.

As a conservative approach, cracked concrete shall be assumed for anchor bolt design if the condition of concrete is not known.

2.2.2 Other base materials

The following base materials are also common in practice but not covered in this handbook.

(a) Low strength concrete (f_{cu} < 25 N/mm2)
(b) high strength concrete (f_{cu} > 60N/mm2)
(c) Lightweight concrete
(d) Masonry
(e) Brick wall
(f) Drywall, etc

The characteristic resistances of anchor bolts in the above base materials shall be determined by laboratory tests or based on engineering judgments. It is advised to consult the manufacturers for design of anchor bolts in the above base materials.

2.2.3 Grout

Grout is not a base material. However, it is commonly used as a levelling layer. The design strength of grout should be the same as for concrete of equivalent cube strength f_{cu} but greater than 30 N/mm^2. The effect of grout as a levelling layer will be described in Section 3.3.1.

3 Static analysis of anchor bolts

3.1 General

A fastening can be subject to tension, compression, shear forces, moments, torsion, or the combination of above. These forces are resolved into shear and tension of individual bolts. Therefore, an anchor bolt can be subject to the following loading conditions:

(a) Tension force only
(b) Shear force only
(c) Combined tension and shear

In general, elastic analysis may be used for calculating the loads on individual anchor bolts both at ultimate and serviceability limit states.

3.2 Tension force per anchor bolt

According to the theory of elasticity a linear distribution of strains across the base plate and a linear relationship between strains and stresses exists (Figure 3.1). This assumption is valid only if the base plate is rigid and does not deform significantly. The base plate should remain elastic under design forces and its deformation should be compatible with the displacement of the anchor bolts.

For the determination of forces of the anchor bolts the following assumptions may be used:

1. The axial stiffness $E_s A_s$ of all fasteners is equal. The anchor bolt threaded area A_s shall follow the manufacturer specifications and the modulus of elasticity of steel E_s shall follow the Code of Practice for the Structural Use of Steel [6] and is taken as 205 000 N/mm^2.
2. The modulus of elasticity of the concrete E_c depends on the concrete grade and shall follow the Code of Practice for Structural Use of Concrete [7].
3. Anchor bolts in the zone of the base plate under compression do not take forces. The compression force is taken by the base plate and transferred to base concrete.

The compressive stress in the concrete and the tension force in the anchor bolts can be solved by finding the neutral axis of the base plate under axial force and moments. The neutral axis can be found by solving a cubic equation by numbers of iteration. Therefore, it is best to use design software to obtain the tension force in the anchor bolts. However, under some simple loading conditions as in the following sections, the tension forces of individual anchor bolts can be solved by simple hand calculation.

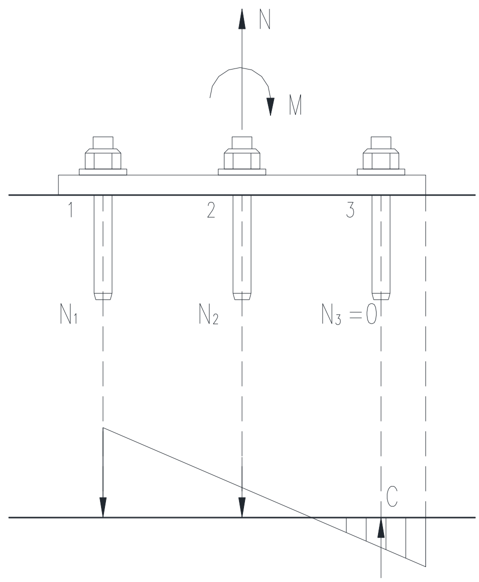


Figure 3.1 Stress-strain diagram of fastening under tension force and bending moment

3.2.1 Fastenings subject to tension only

If the fastening is under tension only, the tension force of individual anchor bolts can be calculated simply by dividing the total design tension by the number of bolts.

3.2.2 Fastenings subject to uni-axial bending moment only

If the fastening is under uniaxial bending moment only as shown in Figure 3.2, the maximum design tension of single anchor bolt can be calculated by the following steps.

The stress-strain relationships of steel and concrete are respectively:

$$E_s = \frac{\sigma_s}{\varepsilon_s} \tag{3.1}$$

$$E_c = \frac{\sigma_c}{\varepsilon_c} \tag{3.2}$$

From the strain diagram in Figure 3.2, the relationship between strain in concrete and strain in anchor bolt is given by:

$$\frac{\varepsilon_c}{x} = \frac{\varepsilon_{s1}}{d-x} = \frac{\varepsilon_{s2}}{d-x-s} \tag{3.3}$$

The tension force of anchor bolts (T_1 and T_2) and compression force at concrete (C) can be expressed below:

$$T_1 = \sigma_{s1}A_s = \varepsilon_{s1}E_sA_s = \varepsilon_c\frac{d-x}{x}mE_cA_s \tag{3.4}$$

$$T_2 = \sigma_{s2}A_s = \varepsilon_{s2}E_sA_s = \varepsilon_c\frac{d-x-s}{x}mE_cA_s \tag{3.5}$$

$$C = \frac{\sigma_c bx}{2} = \frac{\varepsilon_c E_c bx}{2} \tag{3.6}$$

where

m = modular ratio $= \frac{E_s}{E_c}$

b = width of anchor plate

At equilibrium,

$$T_1 + T_2 - C = 0 \tag{3.7}$$

$$T_1(d-x) + T_2(d-x-s) + C\frac{2x}{3} = M \tag{3.8}$$

After substituting Equations (3.4), (3.5) and (3.6) into Equation (3.7) and rearranging terms, Equation (3.7) can be rewritten as the following quadratic equation.

$$\frac{b}{2}x^2 + 2mA_sx - mA_s(2d-s) = 0 \tag{3.9}$$

Therefore, the location of neutral axis, x, can be found by solving Equation (3.9). Once x is solved, the compressive strength of concrete and the anchor bolt tension forces can be solved by substituting Equations (3.4), (3.5) and (3.6) back into Equation (3.8).

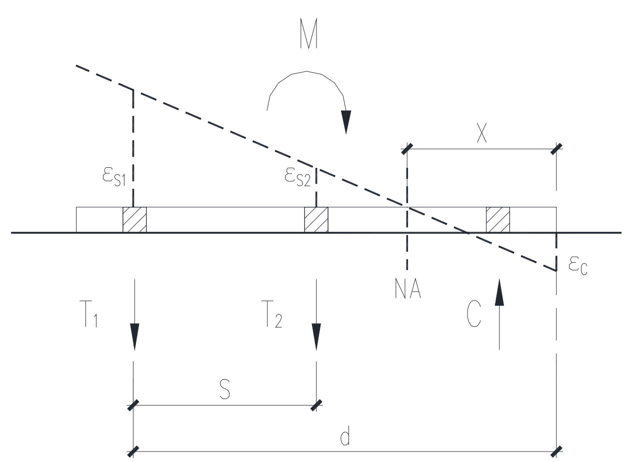


Figure 3.2 Fastening under uni-axial bending moment only

3.2.3 Fastenings subject to tension and significant uniaxial bending moment

If the fastening is under tension and a significant uniaxial bending moment, it is recommended that the design tension of anchor bolts should be solved by design software. Alternatively, it can be calculated by assuming the location of the neutral axis first. Then iterations are performed until the equilibrium of force ($\sum N = 0$) and moment ($\sum M = 0$) is reached by shifting the neutral axis.

3.3 Shear force per anchor bolt

It should be noted that standard hole size should always be used; otherwise the anchor bolts are not considered to take up any shear force as only small deformation of fixture is assumed unless they are properly filled with mortar. The calculation of shear forces of individual anchor bolts depends very much on their failure modes.

Figure 3.3 shows examples of shear force distribution under the failure modes of steel failure and concrete pry-out. If the fastening is subject to shear only as shown in Figure 3.3(a) and (b), the shear forces of individual anchor bolts are calculated by dividing the design shear force by the number of anchor bolts. In case of torsion as shown in Figure 3.3(c), the shear load is determined by resolving the torsion into a group of shear forces perpendicular to the line between the anchor bolts and the centre of gravity of the bolt group as in Equation (3.10).

$$V_T = \frac{T \cdot r_{max}}{\sum(x_i^2 + y_i^2)} \tag{3.10}$$

where

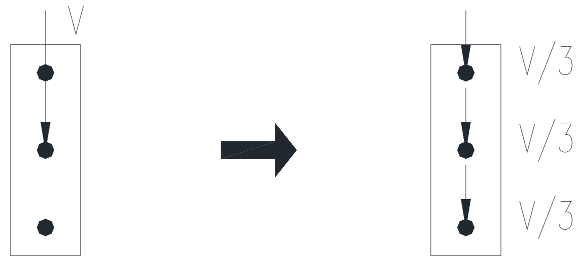
V_T	=	shear due to torsion
T	=	torsion
r_{max}	=	distance between the outmost anchor bolt and the centre of gravity of the bolt group
x_i	=	distance of the i-th column of bolt from the centre of gravity of the anchor bolt group in x-direction
y_i	=	distance of the i-th row of bolt from the centre of gravity of the anchor bolt group in y-direction

If the fastening is subject to both shear and torsion as shown in Figure 3.3(d), the resultant shear force V_R can be calculated by Equation (3.11).

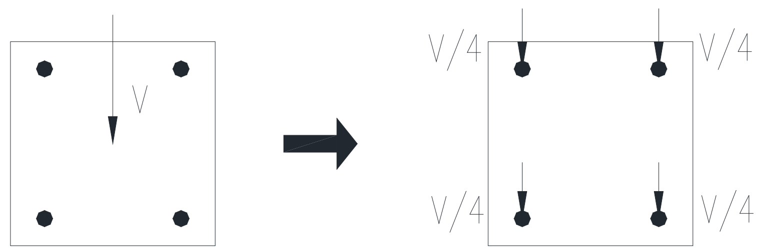
$$V_R = \sqrt{(V_x/n + V_T \cdot \sin\theta)^2 + \left(V_y/n + V_T \cdot \cos\theta\right)^2} \tag{3.11}$$

where

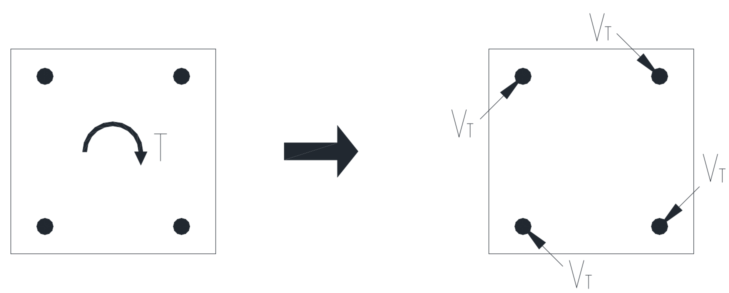
V_x = total shear force in x-direction
V_y = total shear force in y-direction
n = number of bolts



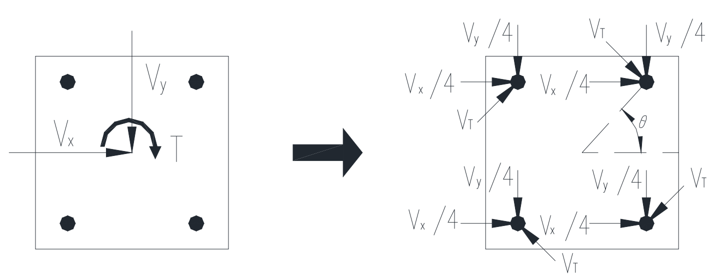
(a) 3 anchor bolts subject to shear in one direction only



(b) 4 anchor bolts subject to shear in one direction only



(c) 4 anchor bolts subject to torsion only



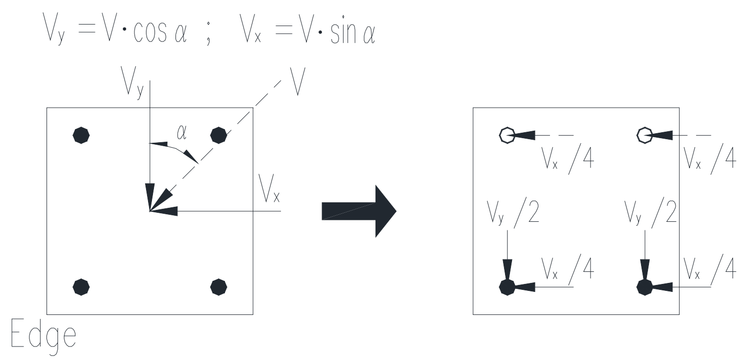
(d) 4 anchor bolts subject to both shear and torsion

Figure 3.3 Fastening under concrete pry-out and steel failure modes

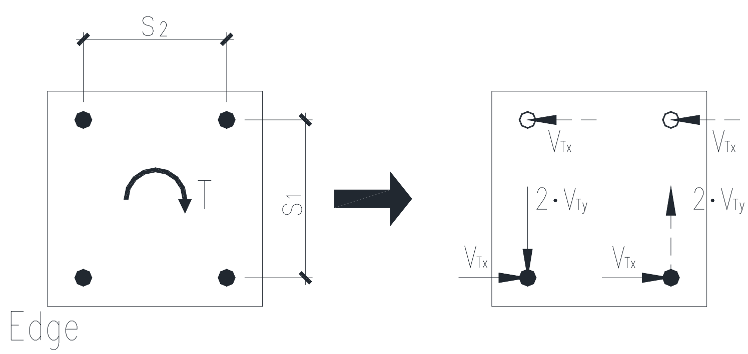
Figure 3.4 shows shear force distribution when the failure mode is concrete edge failure. When anchor bolts are close to the concrete edge subject to a shear force perpendicular to the edge, they might fail by concrete edge failure. Since the displacements are relatively small in the state of failure, because the concrete is brittle, it is not sure whether the deformations of the fasteners are sufficient to guarantee a load transfer to all post-installed anchor bolts before concrete edge failure occurs. Therefore it is assumed that in a group of anchor bolts only the anchor bolts close to the edge take all shear forces. In Figure 3.4(a), the shear force acting parallel to the concrete edge is distributed evenly to all anchor bolts. If the shear force is inclined to the edge, component parallel to the edge will be taken up evenly by all anchor bolts, while the component perpendicular to the concrete edge is taken up only by the anchor bolts close to the edge as shown in Figures 3.4(b) and (c).

For anchor bolts with oversized holes close to an concrete edge, if the gap between anchor bolt and anchor plate is properly filled with mortar as shown in Figure 3.5(a), when checking concrete edge resistance, according to design methods given in ETAG 001 [1], Annex C, TR029 [5] and CEN/TS 1992-4 [2], only the first row of the anchor bolts closest to the concrete edge are assumed to be effective in taking shear force. However, some manufacturer suggests that the design shear force for checking concrete edge failure for the first row of the anchor bolts closest to the concrete edge could be taken as $V/2$. This suggestion is also valid for non-standard bolt arrangement as shown in Figure 3.5(b).

(a) 2 anchor bolts subject to shear in x-direction only

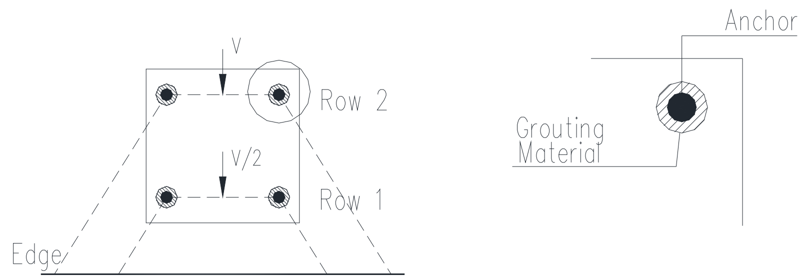


(b) 4 anchor bolts subject to inclined shear only

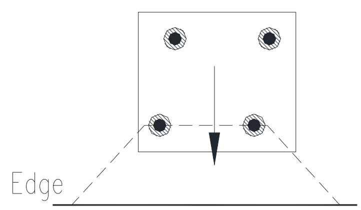


(c) 4 anchor bolts subject to torsion only

Figure 3.4 Anchor bolt groups under concrete edge failure mode



(a) Standard bolt arrangement



(b) Non-standard bolt arrangement

Figure 3.5 Fastening with oversized holes filled with mortar

3.3.1 Shear force without lever arm

In the above considerations it is assumed that the base plate or fixture is laid directly or with a thin layer of levelling grout on the concrete surface. Shear forces acting on anchor bolt may be assumed to act without a lever arm if all of the following conditions are fulfilled:

- The fixture must be made of metal and in the area of the fastening be fixed directly to the concrete without an intermediate layer or with a levelling layer of mortar with a compressive strength larger than 30 N/mm^2 and a thickness smaller than d/2.
- The fixture is in contact with the anchor over its entire thickness if the design is in accordance with ETAG 001 [1], Annex C or TR029 [5] or at least half of its entire thickness if the design is in accordance with CEN/TS 1992-4 [2].

3.3.2 Shear force with lever arm

If a thicker grout layer exists between concrete and base plate or if the fastening is mounted in standoff installation, in other words, the conditions given in Section 3.3.1 are not satisfied, shear load acting with a lever arm shall be considered and this will result an additional bending moment. This might result in steel failure.

As shown in Figure 3.6, the effective lever arm of the shear force shall be taken as,

$$l = a_3 + e_1 \tag{3.12}$$

where

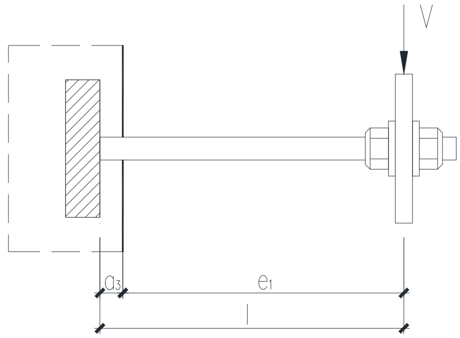
a_3 = $0.5d$ for general cases (Figure 3.6(a))
= 0 if a washer and a nut are directly clamped to the concrete surface (Figure 3.6(b)), or if a leveling grout layer with a compressive strength larger than 30 N/mm^2 and a thickness larger than d/2 is present (Figure 3.6(c))
d = outside diameter of the anchor bolt
e_1 = distance between shear force and concrete surface

The value a_3 takes into account during the bore drilling process concrete spalling occurs on the concrete surface which increases the lever arm of the shear load. The concrete spalling does not have to be taken into consideration if the anchor bolt is clamped to the concrete surface by a nut and a washer (Figure 3.6(b)) or if the gap is filled with grout (Figure 3.6(c)).

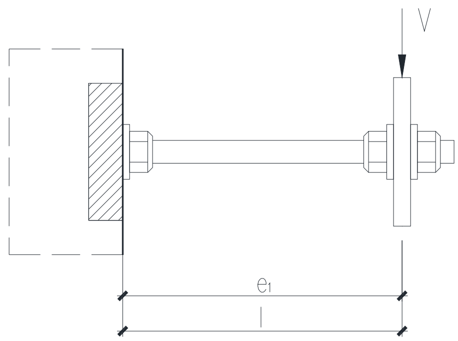
The moment acting on the fastening due to shear force is calculated according to Equation (3.13).

$$M = V \cdot \frac{l}{\alpha_m} \tag{3.13}$$

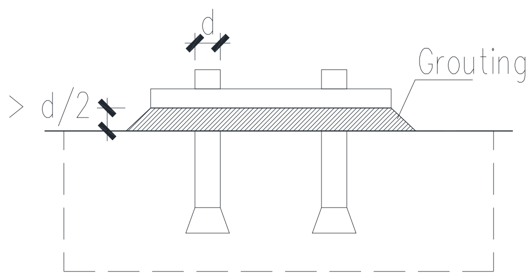
α_m takes into account the degree of restraint of the fastener in the fixture (Figure 3.7). No restraint ($\alpha_m = 1.0$) should be assumed if the fixture can rotate freely (Figure 3.7(b)). Full restraint ($\alpha_m = 2.0$) may be assumed only if the fixture cannot rotate and the fixture is clamped to the fastening by a nut and washer (Figures 3.7(c) and 3.7(d)). In case of doubt it is recommended to use $\alpha_m = 1.0$.



(a) $a_3 = 0.5d$

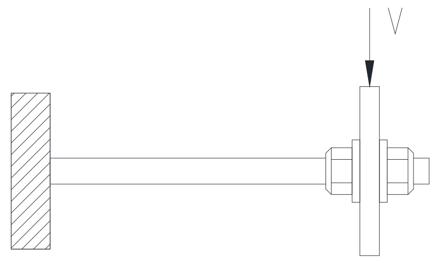


(b) $a_3 = 0$

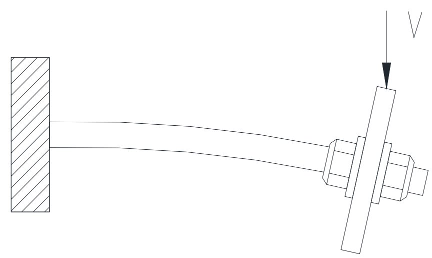


(c) $a_3 = 0$

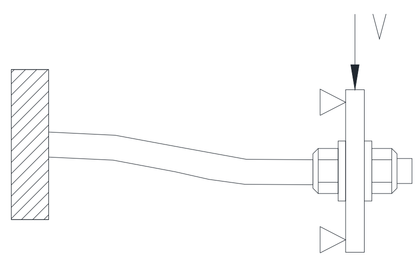
Figure 3.6 Definition of lever arm



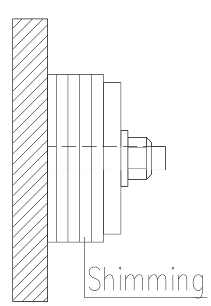
(a) Underformed system



(b) Deformed system without restraint ($\alpha_m = 1.0$)



(c) Deformed system with full restraint ($\alpha_m = 2.0$)



(d) Deformed system with shimming ($\alpha_m = 2.0$)

Figure 3.7 Fastenings without and with restraint in the fixture

4 Failure modes and design resistance of mechanical anchors

4.1 General

The failure modes of mechanical anchors under tension forces include:

- Steel failure
- Pull-out failure
- Concrete cone failure
- Splitting failure

The failure modes of mechanical anchor under shear forces include:

- Steel failure
- Concrete edge failure
- Concrete pry-out failure

Table 4.1 shows a list of requirements that shall be fulfilled for single anchor bolt or anchor bolts in group under tension or shear.

It is almost impossible to predict the failure mode of an anchor bolt or a bolt group which governs the resistance as it depends on a couple of factors such as the magnitude and direction of forces, anchor bolt grade, concrete condition and grade, embedment depth, edge distance, bolt spacing, etc. Therefore, it is necessary to calculate the resistance of each failure mode. In fact, manufacturers will provide all the values of design resistance under different failure modes of a single anchor bolt and design guidelines in a design manual. Design engineers only need to follow the design manual to calculate the ultimate design resistance of an anchor bolt group. However, very often, these design guidelines are simplified and only applicable to simple bolt configuration such as double bolts. The following sections will go into more details about the calculation of mechanical anchor bolt resistance.

Table 4.1 Design resistance check requirements for mechanical anchor bolts

Loading	Failure mode	Single anchor	Anchor group
Tension	Steel failure	$N_{Sd} \leq N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms}}$	$N_{Sd}^{h} \leq N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms}}$
	Pull-out failure	$N_{Sd} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$	$N_{Sd}^{h} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$
	Concrete cone failure	$N_{Sd} \leq N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}}$	$N_{Sd}^{g} \leq N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}}$
	Splitting	$N_{Sd} \leq N_{Rd,sp} = \frac{N_{Rk,sp}}{\gamma_{Msp}}$	$N_{Sd}^{g} \leq N_{Rd,sp} = \frac{N_{Rk,sp}}{\gamma_{Msp}}$
Shear	Steel failure	$V_{Sd} \leq V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms}}$	$V_{Sd}^{h} \leq V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms}}$
	Concrete edge failure	$V_{Sd} \leq V_{Rd,c} = \frac{V_{Rk,c}}{\gamma_{Mc}}$	$V_{Sd}^{g} \leq V_{Rd,c} = \frac{V_{Rk,c}}{\gamma_{Mc}}$
	Concrete pry-out failure	$V_{Sd} \leq V_{Rd,cp} = \frac{V_{Rk,cp}}{\gamma_{Mc}}$	$V_{Sd}^{g} \leq V_{Rd,cp} = \frac{V_{Rk,cp}}{\gamma_{Mc}}$

Note:

N_{sd} (V_{sd}) = design tension (shear) acting on the single anchor bolt

N_{sd}^{h} (V_{sd}^{h}) = design tension (shear) acting on the most stressed anchor of an anchor group calculated according to Section 3.2 (Section 3.3)

N_{sd}^{g} (V_{sd}^{g}) = design value of the sum of the tension forces (shear forces) acting on the tensioned anchors of a group calculated according to Section 3.2 (Section 3.3)

$N_{Rd,s}$ ($N_{Rk,s}$) = design (characteristic) resistance of steel failure under tension

$N_{Rd,p}$ ($N_{Rk,p}$) = design (characteristic) resistance of pull-out failure

$N_{Rd,c}$ ($N_{Rk,c}$) = design (characteristic) resistance of concrete cone failure

$N_{Rd,sp}$ ($N_{Rk,sp}$) = design (characteristic) resistance of splitting failure

$V_{Rd,s}$ ($V_{Rk,s}$) = design (characteristic) resistance of steel failure under shear

$V_{Rd,c}$ ($V_{Rk,c}$) = design (characteristic) resistance of concrete edge failure

$V_{Rd,cp}$ ($V_{Rk,cp}$) = design (characteristic) resistance of concrete pry-out failure

4.2 Resistance to tension force

4.2.1 Steel failure

Steel failure is the most straightforward failure mode. It is observed by fracture in the shaft or the thread area as shown in Figure 4.1. The design tensile resistance of anchor bolt can be found in manufacturer design manual; otherwise the characteristic value of bolt resistance $N_{Rk,s}$ to tension of an anchor bolt can be calculated directly by:

$$N_{Rk,s} = A_s \cdot f_{uk} \tag{4.1}$$

where

A_s = threaded area of an anchor bolt and given in manufacturer specifications

f_{uk} = the ultimate tensile strength of bolt

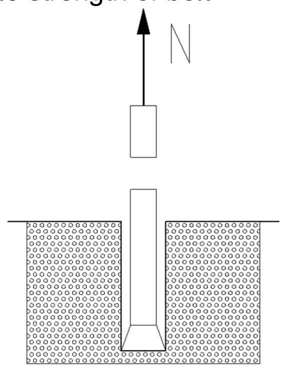


Figure 4.1 Steel tension failure

4.2.2 Pull-out failure

Pull-out failure is a failure mode where the complete anchor bolt is pulled out of the hole as shown in Figure 4.2. The pull-out resistance $N_{Rk,p}$ is determined by repetitive laboratory tests fulfilling the requirements in ETAG 001 [1] and engineers shall refer to manufacturer specifications for design values. However, in some cases, pull-out failure may not occur as the anchor bolts is failed by other failure mode such as concrete cone failure or steel failure. In this case, check against pull-out failure is not required.

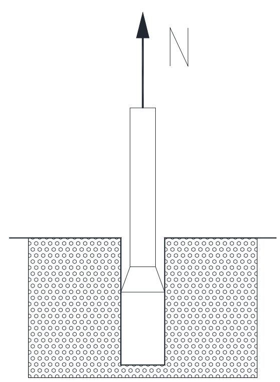


Figure 4.2 Pull-out failure mode

4.2.3 Concrete cone failure

Concrete cone failure occurs when a cone-shaped break-out body is separated from the base concrete. As an engineering practice, a dispersion angle of approximately between 30° and 40° is commonly assumed. As shown in Figure 4.3, provided that the cone area is unaffected by the edge distance, the idealized cone area $A_{c,N}^{0}$ of a single anchor bolt is defined as the area of a square with each side equal to $s_{cr,N}$. Therefore, $A_{c,N}^{0}$ is given by:

$$A_{c,N}^{0} = {s_{cr,N}}^{2} \tag{4.2}$$

The actual values of $s_{cr,N}$ is given in the relevant approval documents. However, according to current experience, $s_{cr,N}$ is widely taken as $3h_{ef}$.

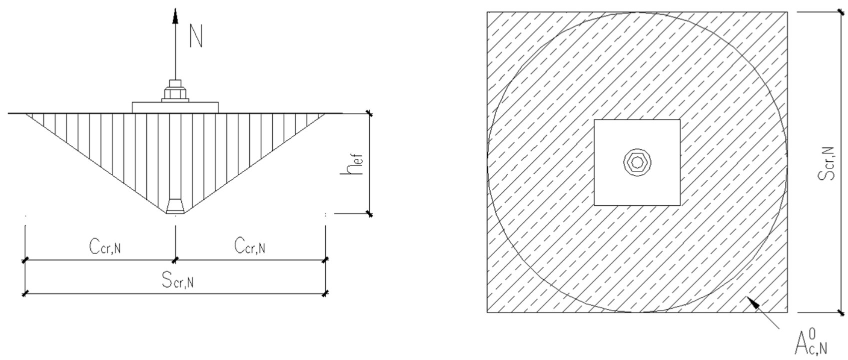


Figure 4.3 Concrete cone failure mode

The concrete cone resistance depends on a couple of factors such as the condition of concrete (cracked or non-cracked), concrete strength and embedment depth. The design concrete cone resistance $N_{Rd,c}^{0}$ of a single anchor bolt can be found in the manufacturer design manual. Alternatively, the characteristic concrete cone resistance $N_{Rk,c}^{0}$ of the above-mentioned idealized concrete cone can be calculated empirically by the following equation.

$$N_{Rk,c}^{0} = k_c \cdot \sqrt{f_{cu}} \cdot {h_{ef}}^{1.5} \tag{4.3}$$

where

k_c	=	factor specified by the manufacturer and dependent on the condition of the concrete
f_{cu}	=	concrete characteristic cube strength in N/mm^2
h_{ef}	=	embedment depth of the anchor bolt in mm

The values of k_c commonly range from 7.0 to 7.2 for cracked concrete and 9.8 to 10.1 for non-cracked concrete. The actual value is given in the relevant approval documents.

However, the actual characteristic concrete cone resistance of a single anchor bolt or an anchor bolt group is further affected by the following factors.

- The actual cone area is limited by edge distance and / or bolt spacing.
- The anchor bolt is too close to the existing reinforcement
- The applied load is eccentric.

Therefore, the actual characteristic concrete cone resistance $N_{Rk,c}$ shall be corrected by the following equation.

$$N_{Rk,c} = N_{Rk,c}^{0} \cdot \frac{A_{c,N}}{A_{c,N}^{0}} \cdot \psi_{s,N} \cdot \psi_{re,N} \cdot \psi_{ec,N} \tag{4.4}$$

where

$A_{c,N}$	=	actual concrete cone area limited by bolt spacing and edge distance
$\psi_{s,N}$	=	edge distance coefficient
$\psi_{re,N}$	=	shell spalling coefficient
$\psi_{ec,N}$	=	eccentricity coefficient

The effects due to bolt spacing and edge distance, existing reinforcement and the load eccentricity will be further explained in the following sections.

4.2.3.1 Effect due to edge distance and bolt spacing

If an anchor bolt is too close to the edge, the concrete actual cone area might be constrained by the edge distance. Take Figure 4.4 as an example, if the edge distance c of one side of the concrete block is smaller than $c_{cr,N}$ which is equal to $0.5s_{cr,N}$ as shown in Figure 4.3, the idealized cone area cannot be formed and the actual cone area is given by:

$$A_{c,N} = \left(c + c_{cr,N}\right) \cdot s_{cr,N} \tag{4.5}$$

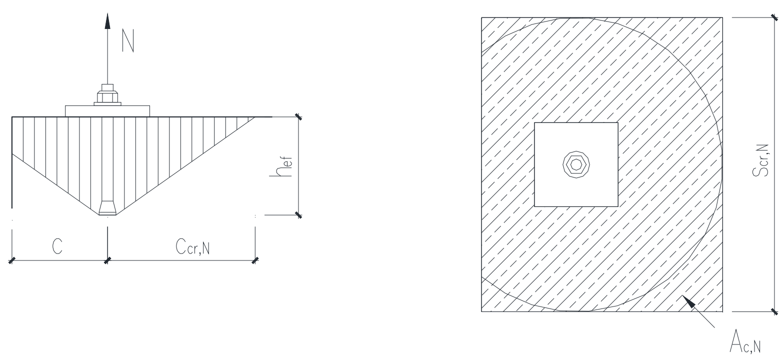
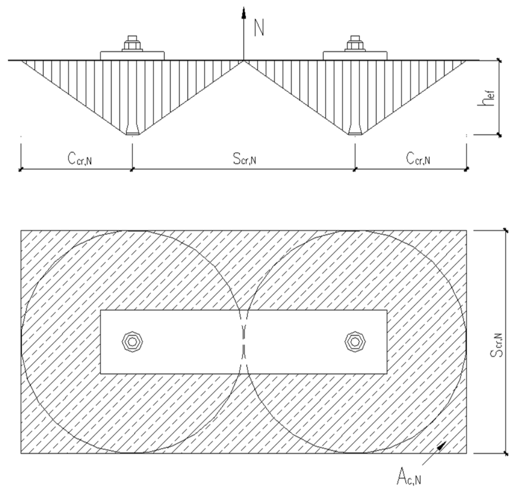


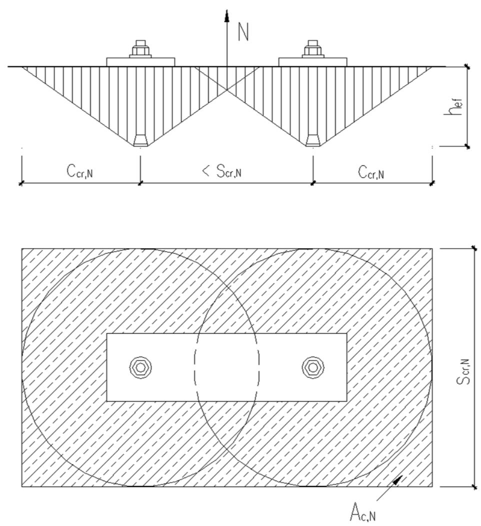
Figure 4.4 Concrete cone area affected by edge distance

The actual cone area of an anchor bolt group is limited by the edge distance as well as the bolt spacing. Figure 4.5 shows bolt groups with double anchor bolts which are far from concrete edge. As shown in Figure 4.5(a), if the bolt spacing is larger than or equal to $s_{cr,N}$, the actual cone area is unaffected by the bolt spacing and is equal to $2A_{c,N}^{0}$. Otherwise, as shown in Figure 4.5(b), if the bolt spacing s is smaller than $s_{cr,N}$, the two idealized concrete cone areas overlap. Thus, the actual concrete cone area is given by:

$$A_{c,N} = \left(s_{cr,N} + s\right) \cdot s_{cr,N} \tag{4.6}$$



(a) Concrete cone area unaffected by bolt spacing



(b) Concrete cone area affected by bolt spacing

Figure 4.5 Concrete cone areas of double anchors

Similarly, for a 2×2 anchor bolt group with arrangement as shown in Figure 4.6, provided that $c_1, c_2 \leq c_{cr,N}$ and $s_1, s_2 \leq s_{cr,N}$, the actual concrete cone area is given by:

$$A_{c,N} = \left(c_1 + s_1 + c_{cr,N}\right) \cdot \left(c_2 + s_2 + c_{cr,N}\right) \tag{4.7}$$

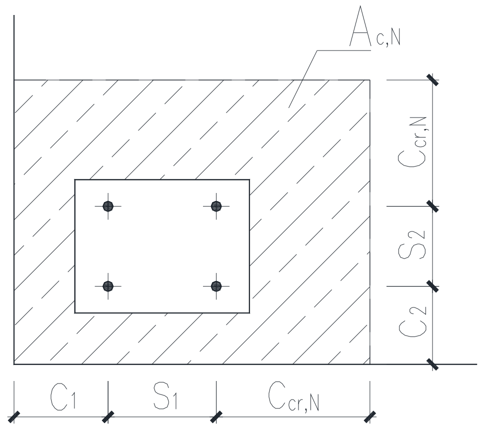


Figure 4.6 Concrete cone area of a group of 2x2 anchor bolts

The actual concrete cone area of other anchor bolt configuration can be found in a similar manner. In addition, if the edge distance of an anchor bolt is smaller than $c_{cr,N}$, an edge distance coefficient has to be considered and is given by:

$$\psi_{s,N} = 0.7 + 0.3\frac{c}{c_{cr,N}} \leq 1.0 \tag{4.8}$$

If more than one of the edge distances are smaller than $c_{cr,N}$, the smallest one should be used in Equation (4.8).

4.2.3.2 Effect due to existing reinforcement

If the anchor bolt is too close to the existing reinforcement, spalling of concrete might occur. To account for this, a shell spalling coefficient has to be considered which is given by:

$$\psi_{re,N} = 0.5 + \frac{h_{ef}}{200} \leq 1.0 \tag{4.9}$$

However, shell spalling coefficient needs not to be considered if:

- the embedment depth of the anchor bolt larger than 100mm, or
- the reinforcement is provided at a spacing larger than or equal to 150mm, or
- the reinforcement with a diameter of 10mm or less is provided at a spacing larger than 100mm.

4.2.3.3 Effect due to load eccentricity

If the applied load is eccentric, the concrete cone resistance is further reduced by the eccentricity factor which is given by:

$$\psi_{ec,N} = \frac{1}{1 + \frac{2e_N}{s_{cr,N}}} \leq 1.0 \tag{4.10}$$

where e_N is the eccentricity of the resulting tension force acting on the anchor bolts in tension to the centre of gravity of the tensioned anchor bolts. If the eccentricity is in two directions, then $\psi_{ec,N}$ has to be calculated separately for each axis and the product of the two coefficients is adopted.

For simplicity, $\psi_{ec,N} = 1.0$ may be assumed, provided that the most stressed anchor bolt is checked according to Equation (4.11)

$$N_{Sd}^h \leq \frac{N_{Rk,c}^h}{\gamma_{mc}} \tag{4.11}$$

and the resistance of this anchor bolt is taken as:

$$N_{Rk,c}^h = \frac{N_{Rk,c}}{n} \tag{4.12}$$

4.2.3.4 Effect due to narrow members

It is not uncommon to have anchor bolt application with three or more edge distances $c < c_{cr,N}$. In this case the characteristic resistance calculated according to Equation (4.4) may lead to a conservative result. A more precise result can be obtained if in the case of single angle bolts the value of h_{ef} is replaced by:

$$h'_{ef} = \frac{c_{max}}{c_{cr,N}} \cdot h_{ef} \tag{4.13a}$$

Or in the case of anchor bolts in groups h_{ef} is limited to the larger of:

$$h'_{ef} = \frac{c_{max}}{c_{cr,N}} \cdot h_{ef} \quad \text{or} \quad h'_{ef} = \frac{s_{max}}{s_{cr,N}} \cdot h_{ef} \tag{4.13b}$$

The values of critical spacing $s_{cr,N}$ and critical edge distance $c_{cr,N}$ are respectively calculated by

$$s'_{cr,N} = s_{cr,N} \frac{h'_{ef}}{h_{ef}} \tag{4.14}$$

$$c'_{cr,N} = c_{cr,N} \frac{h'_{ef}}{h_{ef}} \tag{4.15}$$

The values of h'_{ef}, $s'_{cr,N}$ and $c'_{cr,N}$ are then inserted into Equations (4.2), (4.3), (4.5), (4.6), (4.7), (4.8) and/or (4.10) for a more precise characteristic concrete cone resistance.

4.2.4 Splitting failure

Splitting failure is a failure mode where the concrete component splits completely as shown in Figure 4.7(a) or the concrete fractures along the fastening and the edge of the concrete element as shown in Figure 4.7(b). If the edge distance is adequate, splitting cracks might develop between closely spaced anchor bolts during installation as shown in Figure 4.7(c).

Splitting failure due to installation can be avoided if the minimum requirements of edge distance c_{min}, spacing s_{min} and the concrete thickness h_{min} are met. Engineers shall refer to the manufacturer design manual for the minimum requirements of edge distance c_{min}, bolt spacing s_{min} and concrete thickness h_{min} for installation.

Splitting failure due to loading can also be avoided if at least one of the following conditions is satisfied.

a) If the anchor bolt design is in accordance with ETAG 001 [1], Annex C, the edge distance in all directions $c \geq 1.2\, c_{cr,sp}$ with concrete thickness $h \geq 2h_{ef}$; if the anchor bolt design is in accordance with CEN/TS 1992-4 [2], the edge distance in all directions $c \geq c_{cr,sp}$ for single anchor bolts and $c \geq 1.2c_{cr,sp}$ for anchor bolt groups where $c_{cr,sp}$ is given in manufacturer specifications and for both cases the concrete thickness $h \geq h_{min}$.
b) The characteristic resistance for concrete cone failure and pull-out failure is calculated for cracked concrete and reinforcement resists the splitting forces and limit the crack width to smaller than 0.3mm.

Otherwise, the characteristic splitting resistance $N_{Rk,sp}$ of a single anchor bolt or an anchor bolt group shall be calculated by:

$$N_{Rk,sp} = N_{Rk}^{0} \cdot \frac{A_{c,N}}{A_{c,N}^{0}} \cdot \psi_{s,N} \cdot \psi_{re,N} \cdot \psi_{ec,N} \cdot \psi_{h,sp} \tag{4.16}$$

where

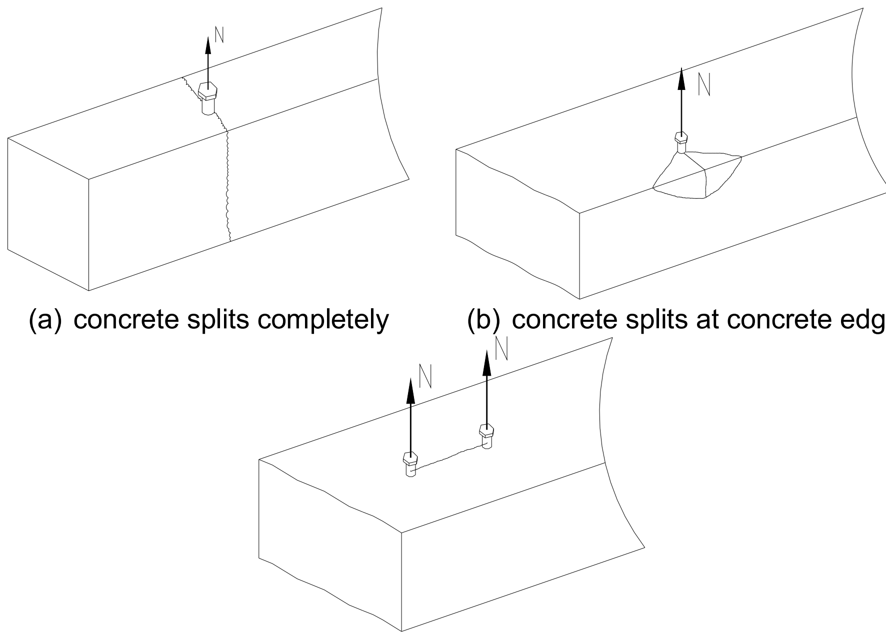
$N_{Rk}^{0} \quad = \quad \min\left(N_{Rk,p}, N_{Rk,c}^{0}\right)$

$\psi_{h,sp} \quad = \quad \left(\frac{h}{h_{min}}\right)^{2/3} \leq 1.5$ for ETAG 001 [1], Annex C

$\quad = \quad \left(\frac{h}{h_{min}}\right)^{2/3} \leq \left(\frac{2h_{ef}}{h_{min}}\right)^{2/3}$ for CEN/TS 1992-4 [2]

$\psi_{h,sp}$ is the thickness coefficient which accounts for the positive effect of the actual concrete thickness to the splitting resistance.

Except the additional thickness coefficient $\psi_{h,sp}$, Equation (4.16) is almost identical to Equation (4.4) except the values of $c_{cr,N}$ and $s_{cr,N}$ shall be replaced by $c_{cr,sp}$ and $s_{cr,sp}$ when calculating $\psi_{s,N}$ and $\psi_{ec,N}$ according to Equation (4.8) and (4.10).



(a) concrete splits completely (b) concrete splits at concrete edge

(c) splitting crack develops

Figure 4.7 Splitting failure modes

4.3 Resistance to shear force

4.3.1 Steel failure

4.3.1.1 Shear force without lever arm

The design shear resistance of the anchor bolt can be found directly from the manufacturer design manual. Alternatively, except for anchor bolts with significantly reduced section, the characteristic shear resistance can be calculated directly by:

$$V_{Rk,s} = 0.5A_s \cdot f_{uk} \tag{4.17}$$

4.3.1.2 Shear force with lever arm

The design moment capacity of a single anchor bolt can be found in the manufacturer's design manual. Alternatively, the characteristic moment capacity can be calculated by:

$$M_{Rk,s}^{0} = 1.2W_{el} \cdot f_{uk} \tag{4.18}$$

where W_{el} is the elastic section modulus of the anchor bolt and given in manufacturer design manual.

If tension force co-exists with moment, the section capacity of the bolt is given by

$$\frac{N_{sd}}{N_{Rd,s}} + \frac{M_{Rk,s}}{M_{Rk,s}^{0}} \leq 1.0 \tag{4.19}$$

where $N_{Rd,s}$ is the design bolt tension resistance

$M_{Rk,s}$ is the characteristic value of reduced moment capacity under tension

Rearranging terms in Equation (4.19) gives an expression of $M_{Rk,s}$:

$$M_{Rk,s} = M_{Rk,s}^{0}\left(1 - \frac{N_{sd}}{N_{Rd,s}}\right) \tag{4.20}$$

After $M_{Rk,s}$ is known, the equivalent shear resistance with lever arm can be calculated by rearranging terms in Equation (3.13) as follows.

$$V_{Rk,s} = \frac{\alpha_m M_{Rk,s}}{l} \tag{4.21}$$

where α_m and l are given in Section 3.3.2

4.3.2 Concrete edge failure

Concrete edge failure mode is also similar to concrete cone failure mode except it occurs at the lateral surface instead of the top surface of the concrete. It should be noted that concrete edge failure needs not be checked for groups with not more than 4 anchors when the edge distance in all directions fulfills the following conditions:

- $c > 10h_{ef}$
- $c > 60d_{nom}$

The concrete edge resistance is calculated in a similar approach of calculating the concrete cone resistance. Figure 4.8 shows the area of an idealized concrete edge break-out body and is given by:

$$A_{c,V}^{0} = 4.5{c_1}^2 \tag{4.22}$$

where c_1 is the edge distance in the direction of the shear force

The concrete edge resistance depends on a couple of factors such as the anchor bolt size and length, condition of concrete (cracked or non-cracked), concrete strength and edge distance, etc. The design value of concrete edge resistance $V_{Rd,c}^{0}$ of the above-mentioned idealized concrete edge break-out body can be found directly from the manufacturer's design manual. Alternatively, the characteristic value of concrete edge resistance $V_{Rk,c}^{0}$ can be calculated empirically by Equation (4.23).

$$V_{Rk,c}^{0} = k_1 {d_{nom}}^{\alpha} {l_f}^{\beta} \sqrt{f_{cu}} \cdot {c_1}^{1.5} \tag{4.23}$$

where

d_{nom}	=	outside diameter of the anchor bolt $\leq 60\text{mm}$
l_f	=	effective length of the anchor bolt = $h_{ef} \leq 8d_{nom}$
c_1	=	edge distance in the direction of the shear force
α	=	$0.1\left(\frac{l_f}{c_1}\right)^{0.5}$
β	=	$0.1\left(\frac{d_{nom}}{c_1}\right)^{0.2}$

The values of k_1 commonly range from 1.35 to 1.7 for cracked concrete and 1.6 to 2.4 for non-cracked concrete. The actual value of k_1 is given in the relevant approval documents.

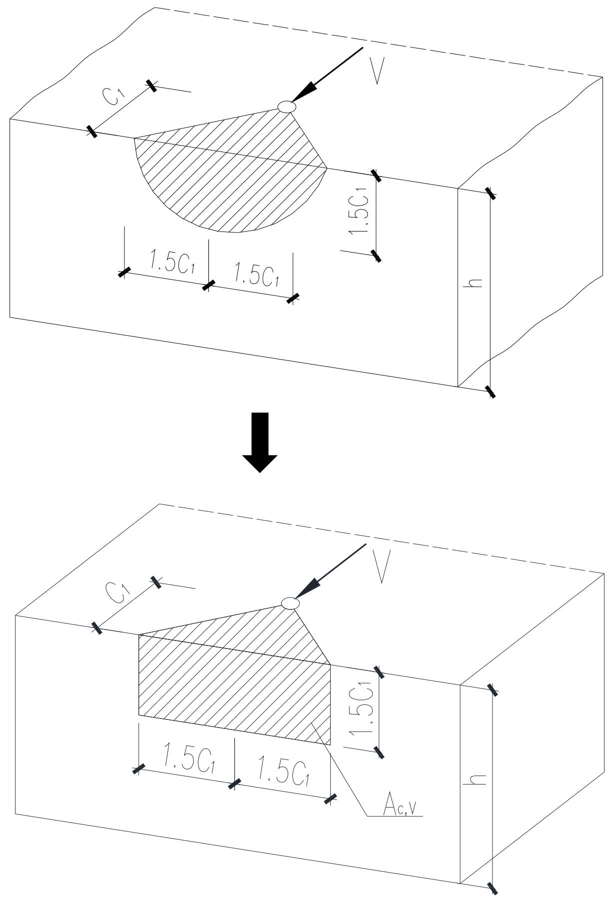


Figure 4.8 Concrete edge failure mode

Similar to concrete cone failure, the actual characteristic value of concrete edge resistance of a single anchor bolt or a bolt group is further affected by the following reasons.

- The actual concrete break-out body is limited by edge distance, bolt spacing and / or the concrete thickness
- The applied shear force is eccentric.
- The direction of the applied shear force is inclined to the line perpendicular to the concrete edge.
- The anchor bolt is located near to the existing reinforcement.

Therefore, the actual characteristic value of concrete edge resistance $V_{Rk,c}$ shall be corrected by the following equation.

$$V_{Rk,c} = V_{Rk,c}^{0} \cdot \frac{A_{c,V}}{A_{c,V}^{0}} \cdot \psi_{s,V} \cdot \psi_{h,V} \cdot \psi_{ec,V} \cdot \psi_{\alpha,V} \cdot \psi_{re,V} \tag{4.24}$$

where

$A_{c,V}$	=	actual concrete edge break-out area
$\psi_{s,V}$	=	edge distance coefficient
$\psi_{h,V}$	=	thickness coefficient
$\psi_{ec,V}$	=	eccentricity coefficient
$\psi_{\alpha,V}$	=	force inclination coefficient
$\psi_{re,V}$	=	reinforcement coefficient

The effects due to anchor bolt spacing, edge distance and concrete thickness, shear force eccentricity, direction of shear force application and existing reinforcement will be further explained in the following sections.

4.3.2.1 Effect due to edge distance, bolt spacing and concrete thickness

If a single anchor bolt is too close to the concrete edge, the actual edge break-out body area might be constrained by the edge distance. Take Figure 4.9(a) as an example, if the edge distance c_2 of one side of the concrete block is smaller than $1.5c_1$, the idealized concrete edge break-out body cannot be formed and the actual edge break-out body area is given by:

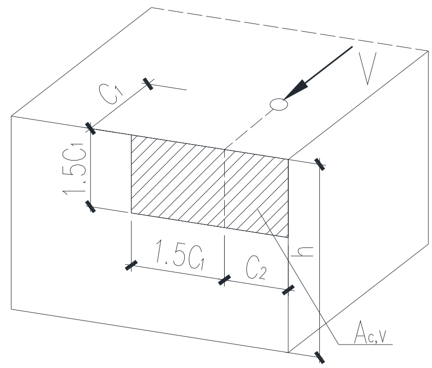
$$A_{c,V} = (1.5c_1 + c_2) \cdot 1.5c_1 \tag{4.25}$$

Similarly, the actual edge break-out area of an anchor bolt group is limited by the edge distance as well as the bolt spacing. Figure 4.9(b) shows a bolt group with double anchor bolts with spacing s smaller than $3c_1$. The actual edge break-out area is overlapped by the bolt spacing and is given by:

$$A_{c,V} = (3c_1 + s) \cdot 1.5c_1 \tag{4.26}$$

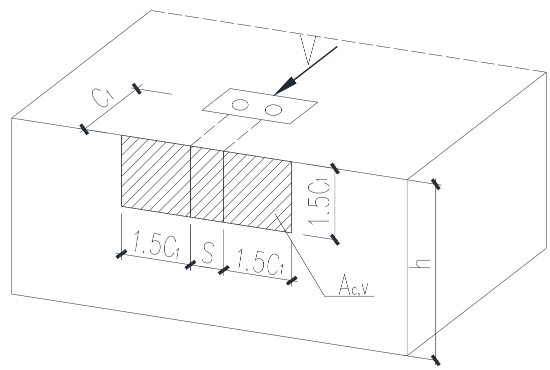
If the concrete thickness is not adequate, the edge break-out area of a single anchor bolt or an anchor bolt group will also be affected. Figure 4.9(c) shows a bolt group with 2×2 anchor bolts with edge distance c_2 of one side of the concrete block smaller than $1.5c_1$, spacing s smaller than $3c_1$ and concrete thickness h smaller than $1.5c_1$. The actual concrete edge break-out area is equal to:

$$A_{c,V} = (1.5c_1 + s + c_2) \cdot h \tag{4.27}$$



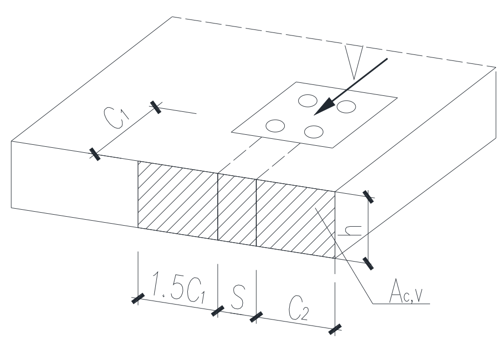
$\boxed{c_2 \leq 1.5c_1; h \geq 1.5c_1}$

(a) Concrete edge break-out area affected by edge distance



$\boxed{s \leq 3c_1; h \geq 1.5c_1}$

(b) Concrete edge break-out area affected by bolt spacing



$\boxed{c_2 \leq 1.5c_1; s \leq 3c_1; h < 1.5c_1}$

(c) Concrete edge break-out area affected by edge distance, bolt spacing and concrete thickness

Figure 4.9 Concrete edge break-out areas

The actual concrete edge break-out area of other bolt configuration can be found in a similar manner. In additional, if the edge distance c_2 or the concrete thickness h is smaller than $1.5c_1$ as shown in Figure 4.9(a) and Figure 4.9(c), an additional coefficient has to be considered.

For $c_2 < 1.5c_1$

$$\psi_{c,V} = 0.7 + 0.3\frac{c_2}{1.5c_1} \leq 1.0 \tag{4.28}$$

In case of both edge distance are smaller than $1.5c_1$, the smaller value of c_2 is used in Equation (4.28)

The coefficient $\psi_{h,V}$ takes into account that the shear resistance does not decrease proportionally to the member thickness as assumed by the ratio $A_{c,V}/A^0_{c,V}$. For $h < 1.5c_1$

$$\psi_{h,V} = \left(\frac{1.5c_1}{h}\right)^{0.5} \geq 1.0 \tag{4.29}$$

4.3.2.2 Effect due to load eccentricity

If the applied shear force is not aligned with the centre of gravity of the anchor bolt group, the eccentricity coefficient has to be considered.

$$\psi_{ec,V} = \frac{1}{1 + \frac{2e_V}{3c_1}} \leq 1.0 \tag{4.30}$$

where e_V is the shear force eccentricity and is determined from the resultant shear of the anchor bolt group

4.3.2.3 Effect due to direction of shear force application

If the applied shear force is inclined to the line perpendicular to the concrete edge, the force inclination coefficient has to be considered.

$$\psi_{\alpha,V} = \sqrt{\frac{1}{(\cos\alpha_v)^2 + (0.4\sin\alpha_v)^2}} \geq 1.0 \tag{4.31}$$

where α_v is the angle between the shear force application and the line perpendicular to the concrete edge

The resultant shear force calculation follows the rules given in Section 3.3.

4.3.2.4 Effect due to existing reinforcement

The existing reinforcement will have a positive effect on the concrete edge resistance. The values of the reinforcement coefficient are taken as follows.

- $\psi_{re,V} = 1.2$ for anchor bolts in cracked concrete with straight edge reinforcement (ϕ ≥ 12mm)
- $\psi_{re,V} = 1.4$ for anchor bolts in cracked concrete with straight edge reinforcement (ϕ ≥ 12mm) and closely spaced stirrups or wire mesh with a spacing ≤ 100mm and $2c_1$ or anchor bolts in non-cracked concrete.

4.3.2.5 Effect due to narrow members

It is not uncommon to have anchor bolt application with two edge distances perpendicular to the load direction ($c_{2,1}, c_{2,2}$) smaller than $1.5c_1$ and the concrete thickness h smaller than $1.5c_1$. In this case the characteristic resistance calculated according to Equation (4.24) may lead to a conservative result. A more precise result can be obtained if in the case of single angle bolts the value of c_1 is replaced by the larger of:

$$c_1' = \frac{\max(c_{2,1}, c_{2,2})}{1.5} \quad \text{or} \quad c_1' = \frac{h}{1.5} \tag{4.32a}$$

Or in the case of anchor bolts in groups c_1 is limited to the largest of:

$$c_1' = \frac{\max(c_{2,1}, c_{2,2})}{1.5} \quad \text{or} \quad c_1' = \frac{h}{1.5} \quad \text{or} \quad c_1' = \frac{s}{3} \tag{4.32b}$$

The values of c_1' is then inserted into Equations (4.22), (4.23), (4.25), (4.26), (4.27), (4.28), (4.29) and/or (4.30) for a more precise characteristic concrete cone resistance.

4.3.3 Concrete pry-out failure

The concrete pry-out failure mode is to certain extent similar to the concrete cone failure mode as shown in Figure 4.10.

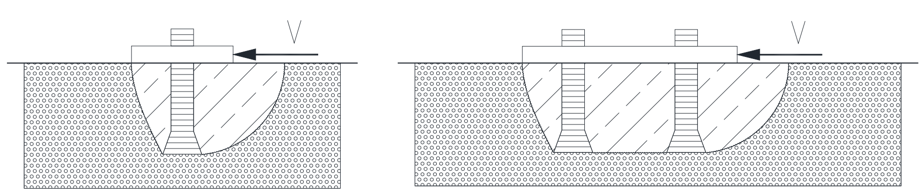


Figure 4.10 Concrete pry-out failure mode

Therefore the characteristic value of concrete pry-out resistance can be calculated in a similar manner as:

$$V_{Rk,cp} = k_3 \cdot N_{Rk,c} \tag{4.33}$$

where

k_3	=	pry-out factor given in the relevant approval documents
$N_{Rk,c}$	=	characteristic value of concrete cone failure resistance calculated for anchor bolts resisting shear forces

By engineering experience, $k_3 = 1.0$ for post-installed anchor with $\mathrm{h_{ef}} < 60\mathrm{mm}$ and $k_3 = 2.0$ for post-installed anchor with $h_{ef} \geq 60\mathrm{mm}$. Alternatively, the design value of concrete pry-out resistance $V_{Rd,cp}$ can be found in manufacturer design manual.

4.4 Resistance to combined tension and shear forces

For anchor bolts subject to both tension and shear, Table 4.1 shall be fulfilled and in addition the combined effect of tension and shear shall be checked as in Equation (4.34).

$$\left(\frac{N_{sd}}{N_{Rd}}\right)^2 + \left(\frac{V_{sd}}{V_{Rd}}\right)^2 \leq 1.0 \tag{4.34a}$$

$$\left(\frac{N_{sd}}{N_{Rd}}\right)^{1.5} + \left(\frac{V_{sd}}{V_{Rd}}\right)^{1.5} \leq 1.0 \tag{4.34b}$$

Equation (4.34a) shall be used if the failure mode is steel failure. Otherwise, Equation (4.34b) shall be used.

4.5 Design procedure of mechanical anchor bolts

The design procedure of a single anchor bolt or an anchor bolt group is presented as follows.

1. Determine the design forces of the anchor bolt / bolt group. Identify design requirements, e.g. seismic, crack / non-cracked concrete, strength of concrete, corrosion and fatigue, etc.

2. Select an anchor based on design requirements. Determine the preliminary anchor bolt size, the anchor bolt layout, the dimensions of the base plate, the spacing and edge distances, etc.

3. Resolve the design forces into tension and shear of individual anchor bolt according to Section 3.2 and 3.3.

4. Calculate the design tension resistances of the anchor bolt according to Section 4.2.

5. Calculate the design shear resistances of the anchor bolt according to Section 4.3.

6. Compare the design anchor bolt forces to the design resistances according to Sections 4.1 and 4.4.

7. If the design resistances are larger than the design anchor bolts force, OK!
   If not, repeat the procedure from Step 2.

5 Failure modes and design resistance of chemical anchors

5.1 General

Chemical anchors exhibit very similar failure modes of mechanical anchors. Therefore, this chapter shall be read in conjunction with Chapter 4 of this handbook.

The failure modes of chemical anchors under tension forces include:

- Steel failure
- Combined pull-out and concrete cone failure
- Concrete cone failure
- Splitting failure

The failure modes of mechanical anchor under shear forces include:

- Steel failure
- Concrete edge failure
- Concrete pry-out failure

Table 5.1 shows a list of requirements that shall be fulfilled for single anchor bolt or anchor bolts in group under tension or shear.

Table 5.1 Design resistance check requirements for chemical anchor bolts

Loading	Failure mode	Single anchor	Anchor group
Tension	Steel failure	$N_{Sd} \leq N_{Rd,s} = \dfrac{N_{Rk,s}}{\gamma_{Ms}}$	$N_{Sd}^{h} \leq N_{Rd,s} = \dfrac{N_{Rk,s}}{\gamma_{Ms}}$
	Combined pull-out and concrete cone failure	$N_{Sd} \leq N_{Rd,p} = \dfrac{N_{Rk,p}}{\gamma_{Mp}}$	$N_{Sd}^{g} \leq N_{Rd,p} = \dfrac{N_{Rk,p}}{\gamma_{Mp}}$
	Concrete cone failure	$N_{Sd} \leq N_{Rd,c} = \dfrac{N_{Rk,c}}{\gamma_{Mc}}$	$N_{Sd}^{g} \leq N_{Rd,c} = \dfrac{N_{Rk,c}}{\gamma_{Mc}}$
	Splitting	$N_{Sd} \leq N_{Rd,sp} = \dfrac{N_{Rk,sp}}{\gamma_{Msp}}$	$N_{Sd}^{g} \leq N_{Rd,sp} = \dfrac{N_{Rk,sp}}{\gamma_{Msp}}$
Shear	Steel failure	$V_{Sd} \leq V_{Rd,s} = \dfrac{V_{Rk,s}}{\gamma_{Ms}}$	$V_{Sd}^{h} \leq V_{Rd,s} = \dfrac{V_{Rk,s}}{\gamma_{Ms}}$
	Concrete edge failure	$V_{Sd} \leq V_{Rd,c} = \dfrac{V_{Rk,c}}{\gamma_{Mc}}$	$V_{Sd}^{g} \leq V_{Rd,c} = \dfrac{V_{Rk,c}}{\gamma_{Mc}}$
	Concrete pry-out failure	$V_{Sd} \leq V_{Rd,cp} = \dfrac{V_{Rk,cp}}{\gamma_{Mc}}$	$V_{Sd}^{g} \leq V_{Rd,cp} = \dfrac{V_{Rk,cp}}{\gamma_{Mc}}$

Note:

N_{sd} (V_{sd})	=	design tension (shear) acting on the single anchor bolt
N_{sd}^{h} (V_{sd}^{h})	=	design tension (shear) acting on the most stressed anchor of an anchor group calculated according to Section 3.2 (Section 3.3)
N_{sd}^{g} (V_{sd}^{g})	=	design value of the sum of the tension forces (shear forces) acting on the tensioned anchors of a group calculated according to Section 3.2 (Section 3.3)
$N_{Rd,s}$ ($N_{Rk,s}$)	=	design (characteristic) resistance of steel failure under tension
$N_{Rd,p}$ ($N_{Rk,p}$)	=	design (characteristic) resistance of combined pull-out and concrete cone failure
$N_{Rd,c}$ ($N_{Rk,c}$)	=	design (characteristic) resistance of concrete cone failure
$N_{Rd,sp}$ ($N_{Rk,sp}$)	=	design (characteristic) resistance of splitting failure
$V_{Rd,s}$ ($V_{Rk,s}$)	=	design (characteristic) resistance of steel failure under shear
$V_{Rd,c}$ ($V_{Rk,c}$)	=	design (characteristic) resistance of concrete edge failure
$V_{Rd,cp}$ ($V_{Rk,cp}$)	=	design (characteristic) resistance of concrete pry-out failure

The following sections will go into more details about the calculation of chemical anchor bolt resistance.

5.2 Resistance to tension force

5.2.1 Steel failure

Section 4.2.1 applies.

5.2.2 Combined pull-out and concrete cone failure

Figure 5.1 shows the combined pull-out and concrete cone failure of a single anchor bolt. The idealized bond influence area $A_{p,N}^{0}$ is defined as the area of a square with each side equal to $s_{cr,Np}$. The value of $s_{cr,Np}$ is given by:

$$s_{cr,Np} = 7.3d\sqrt{\tau_{Rk,ucr}} \leq 3h_{ef} \tag{5.1}$$

where $\tau_{Rk,ucr}$ is the characteristic bond strength of the anchor bolt in non-cracked concrete, given in the relevant approval documents

The combined pull-out and concrete cone resistance depends on a couple of factors such as the condition of concrete (cracked or non-cracked), concrete strength, anchor bolt size and embedment depth. The design combined pull-out and concrete cone resistance $N_{Rd,p}^{0}$ of a single anchor bolt can be found in the manufacturer's design manual. Alternatively, the characteristic concrete cone resistance $N_{Rk,p}^{0}$ of the above-mentioned idealized bond influence area can be calculated by the following equation.

$$N_{Rk,p}^{0} = \tau_{Rk} \cdot \pi \cdot d \cdot h_{ef} \tag{5.2}$$

where τ_{Rk} is the characteristic bond strength of the anchor bolt depending on the concrete strength and condition (i.e. cracked or non-cracked), given in the relevant approval documents

Combined pull-out and concrete failure only needs to be checked when the value of τ_{Rk} is smaller than the value of $\tau_{Rk,max}$. The value of $\tau_{Rk,max}$ is calculated by equating the characteristic combined pull-out and concrete cone resisting given in Equation (5.2) and the characteristic concrete cone resistance given in Equation (4.3) and is given by:

$$\tau_{Rk,max} = \frac{k_c \cdot \sqrt{f_{cu} \cdot h_{ef}}}{\pi \cdot d} \tag{5.3}$$

where

k_c = factor specified by the manufactured and dependent on the condition of the concrete (refer to Section 4.2.2)

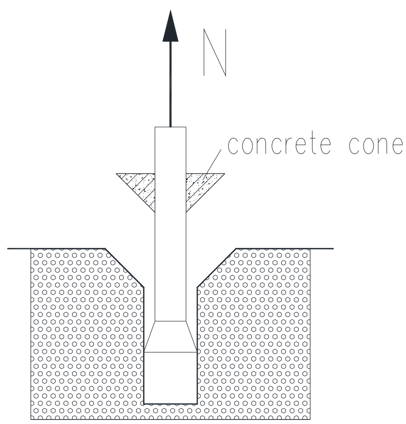


Figure 5.1 Combined pull-out and concrete cone failure mode

Similar to concrete cone failure, the actual resistance of a single anchor bolt or an anchor bolt group depends on a couple of factors as follows.

- The actual bond influence area is limited by edge distance and / or bolt spacing.
- The anchor bolts are closely spaced.
- The anchor bolt is too close to the existing reinforcement.
- The applied load is eccentric.

Therefore, the actual characteristic value of the combined pull-out and concrete cone resistance $N_{Rk,p}$ shall be corrected by the following equation.

$$N_{Rk,p} = N^0_{Rk,p} \cdot \frac{A_{p,N}}{A^0_{p,N}} \cdot \psi_{s,Np} \cdot \psi_{g,Np} \cdot \psi_{re,N} \cdot \psi_{ec,Np} \tag{5.4}$$

where

$A_{p,N}$ = actual bond influence area limited by bolt spacing and edge distance

$\psi_{s,Np}$	=	edge distance coefficient
$\psi_{g,Np}$	=	group coefficient
$\psi_{re,N}$	=	shell spalling coefficient
$\psi_{ec,Np}$	=	eccentricity coefficient

The effects due to spacing and edge distance, closely spaced anchors, existing reinforcement and the load eccentricity will be further explained in the following sections.

5.2.2.1 Effect due to edge distance and bolt spacing

The actual bond influence area $A_{p,N}$ and the edge distance coefficient $\psi_{s,Np}$ are determined in a manner similar to determining $A_{c,N}$ and $\psi_{s,N}$ in Section 4.2.3 except the characteristic bolt spacing $s_{cr,N}$ is replaced by $s_{cr,Np}$ and characteristic edge distance $c_{cr,N}$ is replaced by $c_{cr,Np}$ which is given by:

$$c_{cr,Np} = s_{cr,Np}/2 \quad (5.5)$$

5.2.2.2 Effect due to closely spaced anchors

If the anchor bolts are closely spaced, there will be a positive effect to the resistance of the combined pull-out and concrete cone failure. This group effect is taken into account by the group coefficient $\psi_{g,Np}$ which is given by:

$$\psi_{g,Np} = \psi_{g,Np}^{0} - \left(\frac{s}{s_{cr,Np}}\right)^{0.5} \cdot \left(\psi_{g,Np}^{0} - 1\right) \geq 1.0 \quad (5.6)$$

where

$\psi_{g,Np}^{0}$	=	$\sqrt{n} - \left(\sqrt{n} - 1\right) \cdot \left(\frac{\tau_{Rk}}{\tau_{Rk,max}}\right)^{1.5} \geq 1.0$
n	=	number of bonded anchors of a group

5.2.2.3 Effect due to existing reinforcement

Section 4.2.3.2 applies.

5.2.2.4 Effect due to load eccentricity

Section 4.2.3.3 applies except $s_{cr,N}$ is replaced by $s_{cr,Np}$.

5.2.2.5 Effect due to narrow members

Section 4.2.3.4 applies except $s_{cr,N}$ is replaced by $s_{cr,Np}$ and $c_{cr,N}$ is replaced by $c_{cr,Np}$.

5.2.3 Concrete cone failure

Section 4.2.3 applies.

5.2.4 Splitting failure

Section 4.2.4 applies except if the anchor bolt design is in accordance with TR029 [5], the concrete thickness requirement $h \geq 2h_{ef}$ in condition a) is changed to $h \geq 2h_{min}$ and the value of $\psi_{h,sp}$ is given by:

$$\psi_{h,sp} = \left(\frac{h}{h_{min}}\right)^{2/3} \leq \left(\frac{2h_{ef}}{h_{min}}\right)^{2/3} \tag{5.7}$$

5.3 Resistance to shear force

5.3.1 Steel failure

Section 4.3.1 applies.

5.3.2 Concrete edge failure

Section 4.3.2 applies.

5.3.3 Concrete pry-out failure

The characteristic concrete pry-out resistance is given by:

$$V_{Rk,cp} = min\left(k_3.N_{Rk,p}, k_3.N_{Rk,c}\right) \tag{5.8}$$

5.4 Resistance to combined tension and shear forces

Section 4.4 applies.

5.5 Design procedure of chemical anchor bolts

The design procedure of a single anchor bolt or an anchor bolt group is presented as follows.

1. Determine the design forces of the anchor bolt / bolt group. Identify design requirements, e.g. seismic, crack / non-cracked concrete, strength of concrete, corrosion and fatigue, etc.

2. Select an anchor based on design requirements. Determine the preliminary anchor bolt size, the anchor bolt layout, the dimensions of the base plate, the spacing and edge distances, etc.

3. Resolve the design forces into tension and shear of individual anchor bolt according to Section 3.2 and 3.3.

4. Calculate the design tension resistances of the anchor bolt according to Section 5.2.

5. Calculate the design shear resistances of the anchor bolt according to Section 5.3.

6. Compare the design anchor bolt forces to the design resistances according to Sections 5.1 and 5.4.

7. If the design resistances are larger than the design anchor bolts force, OK! If not, repeat the procedure from Step 2.

6 Seismic Design Consideration

6.1 General

Although the chance of significant earthquake in Hong Kong is rare because it is geographically located far away from the earthquake active zone and currently there is no statutory seismic design requirements for new building structures as well as A&A works in existing buildings in Hong Kong, there is an increasing awareness of seismic hazards. This chapter is aimed to introduce design methods of anchor bolts subject to seismic loads now widely used in European countries.

As mentioned in Chapter 1, EOTA published ETAG 001 [1] which provides technical approval guidelines of metal anchors used in concrete. In Annex E, assessment methods of metal anchors under seismic loads are provided. In the meantime, EOTA published a technical report on Design on Metal Anchors for Use in Concrete under Seismic Actions (TR045) [9] which provides design methods for metal anchors which have acquired ETA in accordance with ETAG 001 [1], Annex E. This chapter is written by making reference to TR045 [9].

6.2 Seismic performance categories

The performance of anchor bolts subject to seismic loads is categorized into C1 and C2. Seismic performance category C1 provides anchor bolt capacities only in terms of resistances at ultimate limit state, while seismic performance category C2 provides anchor bolt capacities in terms of both resistances at ultimate limit state and displacements at damage limitation state and ultimate limit state. In other words, the requirements for seismic performance category C2 are more stringent than those for seismic performance category C1.

The recommended seismic performance categories for structural and non-structural elements in Hong Kong simplified from Table 5.1 of TR045 [9] are shown in Table 6.1.

Table 6.1 Recommended seismic categories for structural and non-structural elements in Hong Kong

Seismicity Level[1]		Importance Class[2]		
Class	Seismic Acceleration $a_g \cdot S$	I	II & III	IV
> Low	> 0.1g	C1	C2	

Notes for Table 6.1:

(1) The seismicity level is defined as the product $a_g \cdot S$ where a_g is the design ground acceleration on Type A group and S is the soil factor both in accordance with EN 1998-1 [10]

(2) Importance classes are defined as follows.

Importance Class I: Buildings of minor importance for public safety, e.g. agricultural buildings, etc.

Importance Class II: Ordinary buildings, not belonging in the other categories

Importance Class III: Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institution etc.

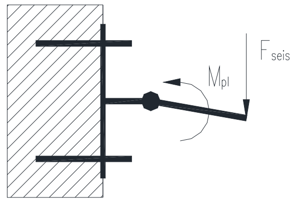
Importance Class IV: Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire station, power plant, etc.

6.3 Design options

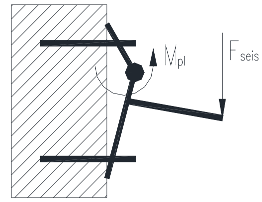
For seismic design of anchor bolts, one of the following options a1), a2) for design without requirements on the ductility of the anchors or b) for design with requirements on the ductility of the anchors, shall be satisfied.

6.3.1 Design Option a1) – capacity design

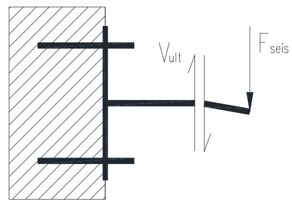
The anchor or anchor group for both structural and non-structural element connections is designed for the maximum forces that can be transmitted to the fastening based on either yielding of a ductile steel component (Figure 6.1(a) and 6.1(b)) taking the effects of material over-strength into account, or the capacity of a non-yielding attached element (Figure 6.1(c)).



(a) Yielding in attached element



(b) Yielding in base plate



(c) Capacity of attached element

Figure 6.1 Seismic design by protecting the anchors

6.3.2 Design Option a2) – elastic design

The anchor or anchor bolt group is designed for the maximum load obtained from the design load combinations that include seismic load $\mathrm{E_{E,d}}$ corresponding to the ultimate limit state (EN 1998-1 [10]) assuming an elastic behaviour of the fastening and of the structure. For structural element connection, the load effects shall be derived according to EN 1998-1 [10] with a behaviour factor $\mathrm{q} = 1.0$. For non-structural element connections the load effects shall be derived to EN 1998-1 [10] with a behaviour factor $\mathrm{q_a} = 1.0$ for the attached element.

6.3.3 Design Option b)

The anchor or anchor group is designed for ductile steel failure. This approach is only applicable for the tension component of the load acting on the anchor. Unless shear forces acting on the fastening are resisted by additional means, additional anchors should be provided and designed in accordance with option a1) or a2).

To ensure ductile steel failure, the following requirements shall be fulfilled.

a. The anchor shall have an ETA that acquires a qualification for seismic performance category C2.
b. To ensure ductile steel failure, for single anchor in tension the following equation shall be satisfied.

$$R_{k,s,seis} \leq 0.7 \frac{R_{k,conc,seis}}{\gamma_2} \tag{6.1}$$

For anchor bolt groups, the following equation shall be satisfied.

$$\frac{R_{k,s,seis}}{N_{Sd}^{h}} \leq 0.7\frac{R_{k,conc,seis}}{N_{Sd}^{g} \cdot \gamma_2} \quad (6.2)$$

where

$R_{k,s,seis}$	=	characteristic seismic resistance for steel failure calculated according to Section 6.4
$R_{k,conc,seis}$	=	minimum characteristic seismic resistance for all concrete related failure modes calculated according to Section 6.4
γ_2	=	partial safety factor for installation safety given in the relevant approval documents
N_{Sd}^{h}	=	design tension acting on the most stressed anchor of a bolt group
N_{Sd}^{g}	=	design tension acting on the tensioned anchors as a group

c. The nominal steel ultimate strength of the load transferring section of the anchor bolt does not exceed $f_{uk} = 800$ MPa, the ratio of nominal yield strength to nominal ultimate strength does not exceed $f_{yk}/f_{uk} = 0.8$ and and the rupture elongation (measured over a length of 5d) is at least 12%.

d. The steel strength of an anchor bolt with reduced cross-section over a length smaller than $8d$ where d is the diameter of the reduced section shall be greater than 1.3 the yield strength of the unreduced section.

It should be noted that due to the possible large non-recoverable displacements of the anchor bolt, Design Option b) is recommended only for the fastening of secondary seismic members.

6.4 Design resistance

Tables 6.2a and 6.2b respectively show a list of requirements that shall be fulfilled for seismic design for mechanical anchor bolts and chemical anchor bolts.

Table 6.2a Seismic design resistance check requirements for mechanical anchor bolts

Loading	Failure mode	Single anchor	Anchor group
Tension	Steel failure	$N_{Sd,seis} \leq N_{Rd,s,seis}$	$N^h_{Sd,seis} \leq N^h_{Rd,s,seis}$
	Pull-out failure	$N_{Sd,seis} \leq N_{Rd,p,seis}$	$N^h_{Sd,seis} \leq N^h_{Rd,p,seis}$
	Concrete cone failure	$N_{Sd,seis} \leq N_{Rd,c,seis}$	$N^g_{Sd,seis} \leq N^g_{Rd,c,seis}$
	Splitting	$N_{Sd,seis} \leq N_{Rd,sp,seis}$	$N^g_{Sd,seis} \leq N^g_{Rd,sp,seis}$
Shear	Steel failure	$V_{Sd,seis} \leq V_{Rd,s,seis}$	$V^h_{Sd,seis} \leq V^h_{Rd,s,seis}$
	Concrete edge failure	$V_{Sd,seis} \leq V_{Rd,c,seis}$	$V^g_{Sd,seis} \leq V^g_{Rd,c,seis}$
	Concrete pry-out failure	$V_{Sd,seis} \leq V_{Rd,cp,seis}$	$V^g_{Sd,seis} \leq V^g_{Rd,cp,seis}$

Table 6.2b Seismic design resistance check requirements for chemical anchor bolts

Loading	Failure mode	Single anchor	Anchor group
Tension	Steel failure	$N_{Sd,seis} \leq N_{Rd,s,seis}$	$N^h_{Sd,seis} \leq N^h_{Rd,s,seis}$
	Combined pull-out and concrete cone	$N_{Sd,seis} \leq N_{Rd,p,seis}$	$N^g_{Sd,seis} \leq N^g_{Rd,p,seis}$
	Concrete cone failure	$N_{Sd,seis} \leq N_{Rd,c,seis}$	$N^g_{Sd,seis} \leq N^g_{Rd,c,seis}$
	Splitting	$N_{Sd,seis} \leq N_{Rd,sp,seis}$	$N^g_{Sd,seis} \leq N^g_{Rd,sp,seis}$
Shear	Steel failure	$V_{Sd,seis} \leq V_{Rd,s,seis}$	$V^h_{Sd,seis} \leq V^h_{Rd,s,seis}$
	Concrete edge failure	$V_{Sd,seis} \leq V_{Rd,c,seis}$	$V^g_{Sd,seis} \leq V^g_{Rd,c,seis}$
	Concrete pry-out failure	$V_{Sd,seis} \leq V_{Rd,cp,seis}$	$V^g_{Sd,seis} \leq V^g_{Rd,cp,seis}$

The seismic design resistance $R_{d,seis}$ $(N_{Rd,seis}, V_{Rd,seis})$ is given by:

$$R_{d,seis} = \frac{R_{k,seis}}{\gamma_{M,seis}} \tag{6.3}$$

where the partial safety factor for seismic resistance $\gamma_{M,seis}$ should be identical to the corresponding values for static loading according to ETAG 001 [1], Annex C.

The characteristic seismic resistance $R_{k,seis}$ $(N_{Rk,seis}, V_{Rk,seis})$ of a fastening shall be calculated for each failure mode according to the following equation.

$$R_{k,seis} = \alpha_{gap} \cdot \alpha_{seis} \cdot R^0_{k,seis} \tag{6.4}$$

where

α_{gap}	=	reduction factor to take into account inertia effects due to an annular gap between anchor and fixture only applicable to shear and given in the relevant approval documents
α_{seis}	=	reduction factor to take into account the influence of large cracks and scatter of load-displacement curves
$R^0_{k,seis}$	=	basic characteristic seismic resistance

For simplification, α_{gap} can be taken as 1.0 in case of no hole clearance between anchor and fixture and 0.5 in case of connections with hole clearance.

The values of α_{seis} for different loadings and failure modes are given in Table 6.3

Table 6.3 Reduction factor α_{seis}

Loading	Failure mode	Single anchor	Anchor group
Tension	Steel failure	1.00	1.00
	Pull-out failure	1.00	0.85
	Concrete cone failure • undercut anchors • all other anchors	 1.00 0.85	 0.85 0.75
	Combined pull-out and concrete cone failure	1.00	0.85
	Splitting	1.00	0.85
Shear	Steel failure	1.00	0.85
	Concrete edge failure	1.00	0.85
	Concrete pry-out failure • undercut anchors • all other anchors	1.00 0.85	0.85 0.75

For steel and pull-out failure under tension and steel failure under shear, $R^0_{k,seis}$ (i.e. $N_{Rk,s,seis}$, $N_{Rk,p,seis}$, $V_{Rk,s,seis}$) shall be taken from the relevant approval documents. For combined pull-out and concrete cone failure, $R^0_{k,seis}$ (i.e. $N_{Rk,p,seis}$) shall be determined in accordance with TR029 [5], however, based on the characteristic bond resistance under seismic loading $\tau_{Rk,seis}$ given in the relevant approval documents. For other failure modes, $R^0_{k,seis}$ (i.e. $N_{Rk,c,seis}$, $N_{Rk,sp,seis}$, $V_{Rk,c,seis}$, $V_{Rk,cp,seis}$) shall be determined in accordance with ETAG 001 [1], Annex C or TR029 [5].

For anchor bolts subject to both tension and shear, the following equations shall be satisfied.

$$\frac{N_{Sd}}{N_{Rd,seis}} + \frac{V_{Sd}}{V_{Rd,seis}} \leq 1.0 \quad (6.5)$$

In Equation (6.5), the largest values of $N_{Sd}/N_{Rd,seis}$ and $V_{Sd}/V_{Rd,seis}$ for different failure modes shall be inserted.

7 Anchor Bolt Qualification

7.1 General

As mentioned in Chapter 1, ETAG 001 [1] sets out the basis for assessing anchors bolts to be used in in both cracked and non-cracked concrete. It consists of the following parts and annexes.

Part 1	Anchors in general
Part 2	Torque-controlled expansion anchors
Part 3	Undercut anchors
Part 4	Deformation-controlled expansion anchors
Part 5	Bonded anchors
Part 6	Anchors for multiple use for non-structural applications
Annex A	Details of test
Annex B	Tests for admissible service conditions – detailed information
Annex C	Design methods for anchorages

To acquire ETA by EOTA, an anchor bolt must be tested repeatedly in accordance with ETAG 001 [1]. The general test conditions and acceptance criteria for all types of anchor bolts are given in Part 1 of ETAG 001 [1] while the specific requirements (e.g. number of tests required) for each type of anchor bolt are given in the subsequent parts (Part 2 to 6). The detailed test procedures are given in ETAG 001 [1], Annex A.

7.2 Anchor bolt assessment

The assessment requirements for anchor bolts to be used in (1) cracked and non-cracked concrete or (2) non-cracked concrete only fall into the following 2 main categories

1. Suitability
2. Admissible service conditions

The following sections will describe briefly the requirements of each category.

7.2.1 Tests for suitability

The suitability tests are to examine whether an anchor bolt is capable of safe and effective behaviour in service including consideration of adverse conditions during both installation and in service. The following aspects of behaviours shall be tested.

1. Installation safety (e.g. effect of diameter of drilled hole, cleaning of the

hole, water in the hole, intensity of anchorage and striking the reinforcement during drilling)

2. Functioning in low strength concrete (C25)
3. Functioning in high strength concrete (C60)
4. Functioning in crack movements (for cracked concrete only)
5. Functioning under repeated loading
6. Functioning under sustained loading
7. Effect of torque moment on tension force

The suitability tests for anchor to be used in cracked and non-cracked concrete are summarized in Table 7.1a (reproduced from Table 5.1 of ETAG 001 Part 1) and for anchor bolts to be used in non-cracked concrete only in Table 7.1b (reproduced from Table 5.2 of ETAG 001 Part 1).

Table 7.1a Suitability tests for anchors to be used in cracked and non-cracked concrete

	Purpose of test	Concrete	Crack width Δw (mm)	Criteria		Test procedure described in ETAG 001 Annex A
				Load displacement behaviour described in ETAG 001 Part 1	Ultimate load req. $\alpha^{(3)}$	
1	Installation safety	(1)	0.3	6.1.1.1	(4)	5.2.1
2	Installation safety – contact with reinforcement(2)	C25	0.3	6.1.1.1	(4)	5.8
3	Functioning in low strength concrete	C25	0.5	6.1.1.1	≥ 0.8	5.2.1
4	Functioning in high strength concrete	C60	0.5	6.1.1.1	≥ 0.8	5.2.1
5	Functioning in crack movements	C25	0.1 to 0.3	6.1.1.1 and 6.1.1.2(a)	≥ 0.9	5.5
6	Functioning under repeated loads	C25	0	6.1.1.1 and 6.1.1.2(b)	$1.0^{(5)}$	5.6
7	Torque test	C60	0	-	6.1.2 (d)	5.10

Table 7.1b Suitability tests for anchors to be used in non-cracked concrete only

	Purpose of test	Concrete	Criteria		Test procedure described in ETAG 001 Annex A
			Load displacement behaviour described in ETAG 001 Part 1	Ultimate load req. α (3)	
1	Installation safety	(1)	6.1.1.1	(4)	5.2.1
3	Functioning in low strength concrete	C25	6.1.1.1	≥ 0.8	5.2.1
4	Functioning in high strength concrete	C60	6.1.1.1	≥ 0.8	5.2.1
6	Functioning under repeated loads	C25	6.1.1.1 and 6.1.1.2(b)	1.0(5)	5.6
7	Torque test	C60	-	6.1.1.2 (d)	5.10

Notes for Tables 7.1a and 7.1b:

(1) Dependent on anchor bolt type (refer to ETAG 001 Part 2 to 6)

(2) Necessary only for anchor bolts with h_{ef} < 80mm to be used in concrete with a reinforcement of spacing < 150mm

(3) α = lesser value of $\frac{N^t_{Ru,m}}{N^r_{Ru,m}}$ and $\frac{N^t_{Rk}}{N^r_{Rk}}$

where

$N^t_{Ru,m}$, N^t_{Rk} = mean value and 5%-fractile respectively of the ultimate loads in a test series

$N^r_{Ru,m}$, N^r_{Rk} = mean value and 5%-fractile respectively of reference ultimate loads for the concrete strength present in the evaluated test series

Equations for calculating $N^r_{Ru,m}$ and N^r_{Rk} are given in ETAG 001 Annex B.

(4) The values of req. α in the installation tests are dependent on the partial safety factor γ_2 and are summarized below.

Partial safety factor γ_2	Req. α for tests according to Tables 7.1a and 7.1b	
	Line 1	Line 2
1.0	≥ 0.95	≥ 0.85
1.2	≥ 0.8	≥ 0.7
1.4	≥ 0.7	≥ 0.6

(5) The failure loads shall fall into the same scatter band as the results of reference tensile tests.

7.2.2 Tests for admissible service conditions

The admissible service conditions for anchors in concrete are influenced by the following factors.

1. Type of anchor bolt (e.g. expansion, undercut and bonded, etc)
2. Design and material specification of the anchor bolt (e.g. embedment depth, diameter of drilled hole, cross-section of steel parts and strength of anchor material, etc)

3. Direction of loading of the anchor bolt (e.g. tension, oblique tension, shear and combined tension and shear, etc)
4. Condition of concrete (cracked or non-cracked)
5. Concrete grade (C25 to C60)
6. Arrangement of anchor bolts (e.g. spacing and edge distance, etc)

In general, the applicant will choose one of the available options set out in Table 7.2 (reproduced from Table 5.3 of ETAG 001 Part 1) based on the following conditions of use.

- The anchor is for use in both cracked and non-cracked concrete (Options 1 to 6); or
- The anchor is for use in non-cracked concrete only (Options 7 to 12).

- The characteristic resistance is given as a function of the concrete strength (Options 1, 3, 5 for cracked concrete and Options 7, 9, 11 for non-cracked concrete). Tests are performed in concrete of strengths C25 and C60; or
- The influence of concrete strength on the characteristic resistance is neglected. In this case all tests are performed with concrete at strength C25 and tests with concrete at strength C60 are not required. Hence a single characteristic resistance is valid for all classes for strength ≥ C25 (Options 2, 4, 6 for cracked concrete and Options 8, 10, 12 for non-cracked concrete).

- The characteristic resistance is given as a function of the load direction (Options 1 and 2 for cracked concrete and Options 7 and 8 for non-cracked concrete); or
- Only one characteristic resistance is given for all load directions (Options 3 to 6 for cracked concrete and Option 9 to 12 for non-cracked concrete).

- Both values for distance between anchors s_{cr} and s_{min}, and for the edge distance c_{cr} and c_{min} are determined (Options 1 to 4 for cracked concrete and Options 7 to 10 for non-cracked concrete); or
- The distance between anchors s_{cr} and distance from an edge c_{cr} are determined by applicant. These values cannot be reduced (Options 5 and 6 for cracked concrete and Options 11 and 12 for non-cracked concrete).

Table 7.2 Assessment options covered by ETAG 001

Option	Cracked and	Non-cracked	C25 only	C25 to	F_{Rk} one	F_{Rk} function	c_{cr}	s_{cr}	c_{min}	s_{min}	Design method

	non-cracked	only		C60	value	of direction					according to Annex C
1	✓			✓		✓	✓	✓	✓	✓	A
2	✓		✓			✓	✓	✓	✓	✓	
3	✓			✓	✓		✓	✓	✓	✓	B
4	✓		✓		✓		✓	✓	✓	✓	
5	✓			✓	✓		✓	✓			C
6	✓		✓		✓		✓	✓			
7		✓		✓		✓	✓	✓	✓	✓	A
8		✓	✓			✓	✓	✓	✓	✓	
9		✓		✓	✓		✓	✓	✓	✓	B
10		✓	✓		✓		✓	✓	✓	✓	
11		✓		✓	✓		✓	✓			C
12		✓	✓		✓		✓	✓			

The extent of the test programme will depend on the applicant's request with respect to the range of conditions of use to be assessed for each anchor type. As an example, the tests required for Option 1 are summarized in Appendix B. The number of tests may be reduced if the anchor's behaviour conforms to the current experience.

7.3 Assessing the resistances of an anchor bolt

When an anchor bolt is tested according to ETAG 001 [1], a range of tests are carried out to determine the resistances of the anchor bolt. The mean ultimate resistance $N_{Ru,m}^{t}$ is defined as the average of all the ultimate loads N_{Ru} from the test results, i.e.

$$N_{Ru,m}^{t} = \frac{\sum N_{Ru}}{n} \tag{7.1}$$

If the test results are plotted onto a graph where the x-axis is the ultimate load and the y-axis is the number of tests that failed at that ultimate load, it will form a bell-shaped curve also known as a standard distribution curve as shown in Figure 7.1.

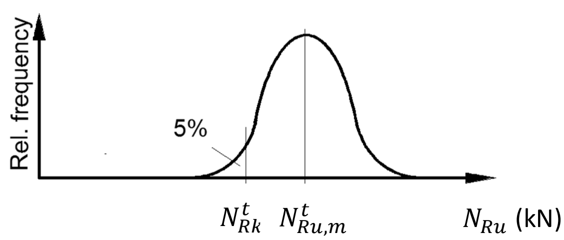


Figure 7.1 A typical standard distribution curve

The standard deviation σ in statistics is a measure that is used to quantify the amount of variation of a set of data and is given by:

$$\sigma = \sqrt{\frac{\sum\left(N_{Ru} - N_{Ru,m}^{t}\right)^2}{N - 1}} \tag{7.2}$$

The characteristic resistance is the 5%-fractile of the ultimate loads measured in a test series which means 95% of the actual failure loads are expected to be above this value. The 5%-fractile of the ultimate loads can be calculated from limited test data according to statistical procedures assuming a confidence level of 90% with and an unknown standard deviation using Equation (7.3).

$$N_{Rk}^{t} = N_{Ru,m}^{t} - k \cdot \sigma \tag{7.3}$$

where k is a factor to determine the characteristic resistance and is dependent on the number of tests performed. The more the number of tests, the smaller the value of k it will be because of the higher reliability. Table 7.3 summarizes the values of k factor against the number of tests.

Table 7.3 k factor against the number of tests
(confidence level = 90%, unknown σ)

No of Tests	3	5	10	20	40	∞
k factor	5.312	3.400	2.569	2.208	2.011	1.645

Note: for other number of tests k factors refer to BS ISO 16269 Part 6:2005 [11]

8 Design Examples

8.1 2×2 anchor bolt group with tension and shear

Figure 8.1 shows a 2×2 anchor bolt group subject to a design tension force of 20kN and a design shear force of 6kN. The design information is shown in Table 8.1.

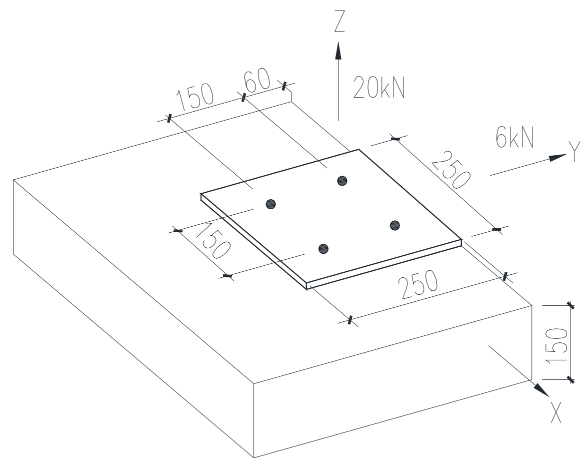


Figure 8.1 2×2 anchor bolt group with tension and shear

Table 8.1 Design information of the anchor bolt group

Concrete		
Concrete grade		C35
Concrete condition		Cracked
Reinforcement spacing	(mm)	150
Anchor bolt		
Anchor bolt type: undercut anchor		
Bolt size		M12
Characteristic ultimate strength f_{uk}	(N/mm^2)	800
Characteristic yield strength f_{yk}	(N/mm^2)	640
Stressed cross-sectional area A_s	(mm^2)	84.3
External diameter of anchor d_{nom}	(mm)	18
Effective anchorage depth h_{ef}	(mm)	60
Minimum base thickness h_{min}	(mm)	130
Minimum spacing s_{min}	(mm)	60
Minimum edge distance c_{min}	(mm)	60
Critical spacing for concrete cone failure $s_{cr,N}$	(mm)	180
Critical edge distance for concrete cone failure $c_{cr,N}$	(mm)	90
Critical spacing for splitting failure $s_{cr,sp}$	(mm)	180
Critical edge distance for splitting failure $c_{cr,sp}$	(mm)	90

The design of anchor bolt is tabulated as follows.

Tension		
Design Force		
N_{Sd}^{g} (kN)	$= 20$	
N_{Sd}^{h} (kN)	$= 5$	
Design Steel Resistance		
$N_{Rk,s}$ (kN)	$= 84.3 \times 800$ $= 67.44$	*(4.1)*
γ_{Ms}	$= 1.5$	
$N_{Rd,s}$ (kN)	$= 44.96$	
	$> N_{Sd}^{h}$	OK
Design Pull-out Resistance		
$N_{Rd,p}$ (kN)	No pull-out failure	(given)
Design Concrete Cone Resistance		
k_c	$= 7.2$	(given)
$N_{Rk,c}^{0}$ (kN)	$= 7.2 \times \sqrt{35} \times 60^{1.5}$ $= 19.80$	*(4.3)*
$A_{c,N}^{0}$ (mm²)	$= 180 \times 180$ $= 32400$	*(4.2)*
$A_{c,N}$ (mm²)	$= (2 \times 90 + 150)(90 + 150 + 60)$ $= 99000$	*(4.7)*
$\psi_{s,N}$	$= 0.7 + 0.3\dfrac{60}{90}$ $= 0.9$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,N}$	$= 1.0$	*(4.10)*
$N_{Rk,c}$ (kN)	$= 19.80 \times \dfrac{99000}{32400} \times 0.9 \times 1 \times 1$ $= 54.44$	*(4.4)*
γ_{Mc}	$= 1.5$	
$N_{Rd,c}$ (kN)	$= 36.29$	
	$> N_{Sd}^{g}$	OK
Design Splitting Resistance		
N_{Rk}^{0} (kN)	$= 19.80$	
$A_{c,N}^{0}$ (mm²)	$= 180 \times 180$ $= 32400$	*(4.2)*
$A_{c,N}$ (mm²)	$= (2 \times 90 + 150)(90 + 150 + 60)$ $= 99000$	*(4.7)*
$\psi_{s,N}$	$= 0.7 + 0.3\dfrac{60}{90}$ $= 0.9$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,N}$	$= 1.0$	*(4.10)*
$\psi_{h,sp}$	$= \left(\dfrac{150}{130}\right)^{2/3} \leq 1.5$ $= 1.10 \leq 1.5$	
$N_{Rk,sp}$ (kN)	$= 19.80 \times \dfrac{99000}{32400} \times 0.9 \times 1 \times 1 \times 1.1$ $= 59.90$	*(4.16)*
γ_{Msp}	$= 1.5$	

$N_{Rd,sp}$ (kN)	$= 39.93$	
	$> N_{Sd}^{g}$	OK

Shear		
Design Force		
N_{Sd}^{g} (kN)	$= 6$	
N_{Sd}^{h} (kN)	$= 1.5$	
Design Steel Resistance		
$V_{Rk,s}$ (kN)	$= 0.5 \times 84.3 \times 800$	*(4.17)*
	$= 33.72$	
γ_{Ms}	$= 1.25$	
$V_{Rd,s}$ (kN)	$= 26.98$	
	$> V_{Sd}^{h}$	OK
Design Concrete Edge Resistance		
k_1	$= 1.7$	(given)
α	$= 0.1\left(\frac{60}{60}\right)^{0.5}$ $= 0.1$	
β	$= 0.1\left(\frac{18}{60}\right)^{0.2}$ $= 0.0786$	
$V_{Rk,c}^{0}$ (kN)	$= 1.7 \times 18^{0.1} \times 60^{0.0786} \times \sqrt{35} \times 60^{1.5}$ $= 8.61$	*(4.23)*
$A_{c,V}^{0}$ (mm^2)	$= 4.5 \times 60^2$ $= 16200$	*(4.22)*
$A_{c,V}$ (mm^2)	$= (3 \times 60 + 150)(1.5 \times 60)$ $= 29700$	*(4.26)*
$\psi_{c,V}$	$= 1.0$	*(4.28)*
$\psi_{h,V}$	$= 1.0$	*(4.29)*
$\psi_{ec,V}$	$= 1.0$	*(4.30)*
$\psi_{\alpha,V}$	$= 1.0$	*(4.31)*
$\psi_{re,V}$	$= 1.0$	
$V_{Rk,c}$ (kN)	$= 8.61 \times \frac{29700}{16200} \times 1 \times 1 \times 1 \times 1 \times 1$ $= 15.78$	*(4.24)*
γ_{Mc}	$= 1.5$	
$V_{Rd,c}$ (kN)	$= 10.52$	
	$> V_{Sd}^{g}$	OK
Design Concrete Pry-out Resistance		
$N_{Rk,c}$ (kN)	$= 54.44$	
k_3	$= 2.0$	(given)
$V_{Rk,cp}$ (kN)	$= 2.0 \times 54.44$ $= 108.88$	*(4.33)*
γ_{Mc}	$= 1.5$	
$V_{Rd,cp}$ (kN)	$= 72.59$	
	$> V_{Sd}^{g}$	OK

Combined Tension and Shear		
Design Force		
N_{Sd}^{g} (kN)	$= 20$	
V_{Sd}^{g} (kN)	$= 6$	
Critical Design Resistance		
$N_{Rd,c}$ (kN)	$= 36.29$	
$V_{Rd,c}$ (kN)	$= 10.52$	
Interaction		
$\left(\frac{N_{Sd}^{g}}{N_{Rd,c}}\right)^{1.5} + \left(\frac{V_{Sd}^{g}}{V_{Rd,c}}\right)^{1.5}$	$= \left(\frac{20}{36.29}\right)^{1.5} + \left(\frac{6}{10.52}\right)^{1.5}$ $= (0.55)^{1.5} + (0.57)^{1.5}$ $= 0.84$	*(4.34b)*
	≤ 1.0	OK

8.2 Double anchor bolt group with shear and torsion

Figure 8.2 shows a double anchor bolt group subject to a design shear force of 5kN and a design torsion of 1kNm. The design information is shown in Table 8.2.

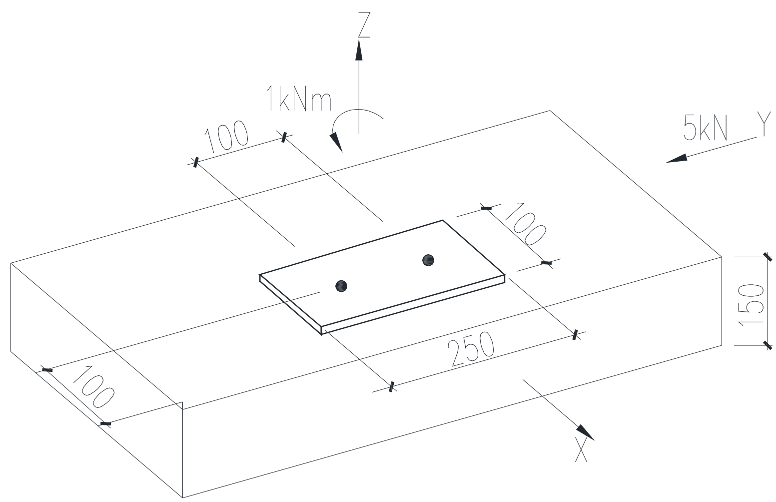


Figure 8.2 Double anchor bolt group with shear and torsion

Table 8.2 Design information of the anchor bolt group

Concrete		
Concrete grade		C30
Concrete condition		Non-cracked
Reinforcement spacing	(mm)	150
Anchor bolt		
Bolt type: torque-controlled expansion anchor		
Bolt size		M10
Characteristic ultimate strength f_{uk}	(N/mm^2)	650
Characteristic yield strength f_{yk}	(N/mm^2)	520
Stressed cross-sectional area A_s	(mm^2)	58.0
External diameter of anchor d_{nom}	(mm)	10
Effective anchorage depth h_{ef}	(mm)	40
Minimum base thickness h_{min}	(mm)	100
Minimum spacing s_{min}	(mm)	50
Minimum edge distance c_{min}	(mm)	50
Critical spacing for concrete cone failure $s_{cr,N}$	(mm)	120
Critical edge distance for concrete cone failure $c_{cr,N}$	(mm)	60
Critical spacing for splitting failure $s_{cr,sp}$	(mm)	190
Critical edge distance for splitting failure $c_{cr,sp}$	(mm)	95

The design of anchor bolt is tabulated as follows.

Shear		
Design Force		
V_y/n (kN)	$= 5/2$ $= 2.5$	
V_T (kN)	$= 1/0.1$ $= 10$	
V_{Sd}^h (kN)	$= \sqrt{2.5^2 + 10^2}$ $= 10.31$	
V_{Sd}^g (kN)	$= \sqrt{5^2 + 10^2}$ $= 11.18$	
e_v (mm)	$= 10 \times 50/11.18$ $= 44.72$	
α_v (°)	$= \tan^{-1}\left(\frac{5}{10}\right)$ $= 26.57$	
Design Steel Resistance		
$V_{Rk,s}$ (kN)	$= 0.5 \times 58 \times 650$ $= 18.85$	*(4.17)*
γ_{Ms}	$= 1.25$	
$V_{Rd,s}$ (kN)	$= 15.08$	
	$> V_{Sd}^h$	OK
Design Concrete Edge Resistance		
k_1	$= 2.4$	(given)
α	$= 0.1\left(\frac{40}{100}\right)^{0.5}$ $= 0.0632$	
β	$= 0.1\left(\frac{10}{100}\right)^{0.2}$ $= 0.0631$	
$V_{Rk,c}^0$ (kN)	$= 2.4 \times 10^{0.06\ 32} \times 60^{0.06\ 31} \times \sqrt{30} \times 100^{1.5}$ $= 19.19$	*(4.23)*
$A_{c,V}^0$ (mm²)	$= 4.5 \times 100^2$ $= 45000$	*(4.22)*
$A_{c,V}$ (mm²)	$= (3 \times 100 + 100)(1.5 \times 100)$ $= 60000$	*(4.26)*
$\psi_{c,V}$	$= 1.0$	*(4.28)*
$\psi_{h,V}$	$= 1.0$	*(4.29)*
$\psi_{ec,V}$	$= \frac{1}{1 + \frac{2 \times 44.72}{3 \times 100}}$ $= 0.770$	*(4.30)*
$\psi_{\alpha,V}$	$= \sqrt{\frac{1}{(\cos 26.57)^2 + (0.4 \sin 26.57)^2}}$ $= 1.096$	*(4.31)*
$\psi_{re,V}$	$= 1.0$	
$V_{Rk,c}$ (kN)	$= 19.19 \times \frac{60000}{45000} \times 1 \times 1 \times 0.77 \times 1.096 \times 1$ $= 21.59$	*(4.24)*
γ_{Mc}	$= 1.5$	

$V_{Rd,c}$ (kN)	$= 14.39$	
	$> V_{Sd}^{g}$	OK
Design Concrete Pry-out Resistance		
k_c	$= 10.1$	(given)
$N_{Rk,c}^{0}$ (kN)	$= 10.1 \times \sqrt{30} \times 40^{1.5}$ $= 13.99$	*(4.3)*
$A_{c,N}^{0}$ (mm²)	$= 120 \times 120$ $= 14400$	
$A_{c,N}$ (mm²)	$= (60 + 100/2) \times 120$ $= 13200$	*(4.5)*
$\psi_{s,N}$	$= 1.0$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,N}$	$= 1.0$	*(4.10)*
$N_{Rk,c}$ (kN)	$= 13.99 \times \frac{13200}{14400} \times 1 \times 1 \times 1$ $= 12.82$	
k_3	$= 2.4$	(given)
$V_{Rk,cp}$ (kN)	$= 2.4 \times 12.82$ $= 30.77$	*(4.33)*
γ_{Mc}	$= 1.5$	
$V_{Rd,p}$ (kN)	$= 20.51$	
	$> V_{Sd}^{h}$	OK

8.3 2×2 anchor bolt group with shear and uniaxial moment

Figure 8.3 shows a 2×2 anchor bolt group subject to a design tension force of 80kN and a design moment of 6kNm. The design information is shown in Table 8.3.

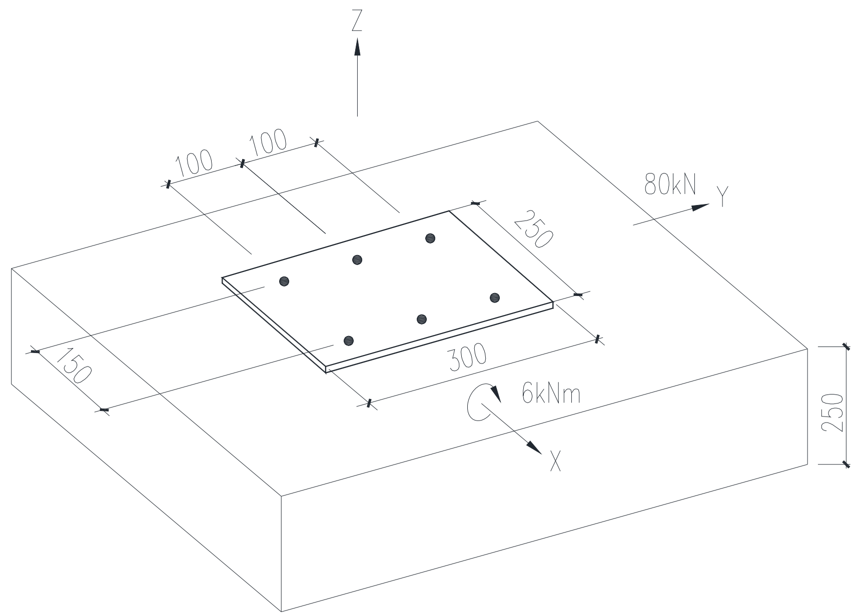


Figure 8.3 2×2 anchor bolt group with shear and uniaxial moment

Table 8.3 Design information of the anchor bolt group

Concrete		
Concrete grade		C25
Concrete condition		Cracked
Modulus of elasticity, E_c	(N/mm^2)	20500
Reinforcement spacing	(mm)	150
Anchor bolt		
Anchor bolt type: chemical anchor		
Bolt size		M16
Characteristic ultimate strength f_{uk}	(N/mm^2)	800
Characteristic yield strength f_{yk}	(N/mm^2)	640
Stressed cross-sectional area A_s	(mm^2)	157
External diameter of anchor d_{nom}	(mm)	18
Effective anchorage depth h_{ef}	(mm)	125
Minimum base thickness h_{min}	(mm)	161
Minimum spacing s_{min}	(mm)	80
Minimum edge distance c_{min}	(mm)	80
Critical spacing for concrete cone failure $s_{cr,N}$	(mm)	375
Critical edge distance for concrete cone failure $c_{cr,N}$	(mm)	187.5
Critical spacing for splitting failure $s_{cr,sp}$	(mm)	250
Critical edge distance for splitting failure $c_{cr,sp}$	(mm)	125
Characteristic bond resistance, non-cracked concrete $\tau_{Rk,ucr}$	(N/mm^2)	18
Characteristic bond resistance, cracked concrete $\tau_{Rk,cr}$	(N/mm^2)	8.5

The design of anchor bolt is tabulated as follows.

Tension		
Design Force		
N_{Sd}^{g} (kN)	$= 30.86$	*(Section 3.2.2)*
N_{Sd}^{h} (kN)	$= 10.88$	
e_N (mm)	$= 2 \times 10.88 \times \dfrac{100}{30.86} - 50$ $= 20.51$	
Design Steel Resistance		
$N_{Rk,s}$ (kN)	$= 157 \times 800$ $= 125.6$	*(4.1)*
γ_{Ms}	$= 1.5$	
$N_{Rd,s}$ (kN)	$= 83.73$	
	$> N_{Sd}^{h}$	OK
Design Combined Pull-out and Concrete Cone Resistance		
$s_{cr,Np}$ (mm)	$= 7.3 \times 16 \times \sqrt{18} \leq 3 \times 125$ $= 495.54 \leq 375$ $= 375$	*(5.1)*
$N_{Rk,p}^{0}$ (kN)	$= 8.5 \times \pi \times 16 \times 125$ $= 53.41$	*(5.2)*
$A_{p,N}^{0}$ (mm²)	$= 375 \times 375$ $= 140625$	*(4.2)*
$A_{p,N}$ (mm²)	$= (375 + 150)(375 + 100)$ $= 249375$	*(4.7)*
$\psi_{s,Np}$	$= 1.0$	*(4.8)*
$\psi_{g,Np}^{0}$	$= 1.0$	
$\psi_{g,Np}$	$= 1.0$	*(5.6)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,Np}$	$= \dfrac{1}{1 + \dfrac{2 \times 20.51}{375}}$ $= 0.901$	*(4.10)*
$N_{Rk,p}$	$= 53.41 \times \dfrac{249375}{140625} \times 1 \times 1 \times 1 \times 0.901$ $= 85.34$	*(5.4)*
γ_{Mp}	$= 1.5$	
$N_{Rd,p}$ (kN)	$= 56.89$	
	$> N_{Sd}^{g}$	OK
Design Concrete Cone Resistance		
k_c	$= 7.2$	(given)
$N_{Rk,c}^{0}$ (kN)	$= 7.2 \times \sqrt{25} \times 125^{1.5}$ $= 50.31$	*(4.3)*
$A_{c,N}^{0}$ (mm²)	$= 375 \times 375$ $= 140625$	*(4.2)*
$A_{c,N}$ (mm²)	$= (375 + 150)(375 + 100)$ $= 249375$	*(4.7)*
$\psi_{s,N}$	$= 1.0$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*

$\psi_{ec,N}$	$= \cfrac{1}{1 + \cfrac{2 \times 20.51}{375}}$ $= 0.901$	*(4.10)*
$N_{Rk,c}$ (kN)	$= 50.31 \times \frac{249375}{140625} \times 1 \times 1 \times 0.901$ $= 80.38$	*(4.4)*
γ_{Mc}	$= 1.5$	
$N_{Rd,c}$ (kN)	$= 53.59$	
	$> N_{Sd}^{g}$	OK
Design Splitting Resistance		
N_{Rk}^{0} (kN)	$= 50.31$	
$A_{c,N}^{0}$ (mm²)	$= 250 \times 250$ $= 62500$	*(4.2)*
$A_{c,N}$ (mm²)	$= (250 + 150)(250 + 100)$ $= 140000$	*(4.7)*
$\psi_{s,N}$	$= 1.0$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,N}$	$= \cfrac{1}{1 + \cfrac{2 \times 20.51}{250}}$ $= 0.859$	*(4.10)*
$\psi_{h,sp}$	$= \left(\frac{250}{161}\right)^{2/3} \leq 1.5$ $= 1.341 \leq 1.5$	
$N_{Rk,sp}$	$= 50.31 \times \frac{140000}{62500} \times 1 \times 1 \times 0.859$ $\times 1.341$ $= 129.81$	*(4.16)*
γ_{Msp}	$= 1.5$	
$N_{Rd,sp}$ (kN)	$= 86.54$	
	$> N_{Sd}^{g}$	OK

Shear		
Design Force		
V_{Sd}^{g} (kN)	$= 80$	
V_{Sd}^{h} (kN)	$= 80/6$ $= 13.33$	
Design Steel Resistance		
$V_{Rk,s}$ (kN)	$= 0.5 \times 157 \times 800$ $= 62.8$	*(4.17)*
γ_{Ms}	$= 1.25$	
$V_{Rd,s}$ (kN)	$= 50.24$	
	$> V_{Sd}^{h}$	OK
Design Concrete Pry-out Resistance		
$N_{Rk,c}^{0}$ (kN)	$= 50.31$	
$A_{c,N}^{0}$ (mm²)	$= 375 \times 375$ $= 140625$	
$A_{c,N}$ (mm²)	$= (375 + 150) \times (375 + 100 + 100)$ $= 301875$	
$\psi_{s,N}$	$= 1.0$	*(4.8)*
$\psi_{re,N}$	$= 1.0$	*(4.9)*
$\psi_{ec,N}$	$= 1.0$	*(4.10)*
$N_{Rk,c}$ (kN)	$= 50.31 \times \frac{301875}{140625} \times 1.0 \times 1.0 \times 1.0$ $= 108.00$	
k_3	$= 2.0$	(given)
$V_{Rk,cp}$ (kN)	$= 2.0 \times 108.00$ $= 216.00$	*(4.33)*
γ_{Mc}	$= 1.5$	
$V_{Rd,cp}$ (kN)	$= 144.00$	
	$> V_{Sd}^{g}$	OK

Combined Tension and Shear		
Design Force		
N_{Sd}^{g} (kN)	$= 30.86$	
V_{Sd}^{g} (kN)	$= 80$	
Critical Design Resistance		
$N_{Rd,c}$ (kN)	$= 53.59$	
$V_{Rd,cp}$ (kN)	$= 144$	
Interaction		
$\left(\frac{N_{Sd}^{g}}{N_{Rd,c}}\right)^{1.5} + \left(\frac{V_{Sd}^{g}}{V_{Rd,cp}}\right)^{1.5}$	$= \left(\frac{30.86}{53.59}\right)^{1.5} + \left(\frac{80}{144}\right)^{1.5}$ $= (0.58)^{1.5} + (0.56)^{1.5}$ $= 0.86$	*(4.34b)*
	≤ 1.0	OK

9 References

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[6] Code of Practice for the Structural Use of Steel, 2011. Buildings Department, HKSAR.

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[11] BS ISO 1626-6:2005. Statistical Interpretation of Data – Part 6: Determination of Statistical Tolerance Intervals, 2005. BSI.

Appendix A Installation Procedure

A.1 Installation procedure of mechanical anchor bolts

A.1.1 Installation procedure of torque-controlled expansion anchor

1. Drill hole into the concrete to the required depth by hammer drilling or diamond drilling.
2. Clear debris from the hole with wire brush and compressed air, etc, following manufacturer's instruction.
3. Install anchor with washer and nut into the concrete through the fixture's hole by hammer setting or machine setting.
4. Turn the nut clockwise by hand as tight as possible.
5. Further tighten the nut by applying a torque with a special tool until it fits closely.

A.1.2 Installation procedure of displacement-controlled expansion anchor

1. Drill hole into the concrete to the required depth by hammer drilling or diamond drilling.
2. Clear debris from the hole with wire brush and compressed air, etc, following manufacturer's instruction.
3. Drive anchor into the concrete until it is flush with the concrete surface.
4. Use a setting tool to expand the anchor in the concrete.
5. Place the fixture over the anchor and fasten the bolt through the fixture and into the anchor by applying a torque.

A.1.3 Installation procedure of undercut anchor

1. Drill hole into the concrete to the required depth by hammer drilling or diamond drilling.
2. Clear debris from the hole with wire brush and compressed air, etc, following manufacturer's instruction.
3. Drive anchor into the concrete until the cone sits on the bottom on the drilled hole.
4. Use a setting tool to form the undercut in the concrete.
5. Place the fixture over the anchor and fasten the bolt through the fixture and into the anchor by applying a torque.

A.2 Installation procedure of chemical anchor bolts

A.2.1 Installation procedure of bonded anchor

1. Drill hole into the concrete to the required depth by hammer drilling or diamond drilling.
2. Clear debris from the hole with wire brush and compressed air, etc, following manufacturer's instruction.
3. Inject adhesive into the drilled hole.
4. Set the element to the required embedment depth until the working time is elapsed.
5. Place the fixture over the element and fasten the nut by applying a torque.

A.2.2 Installation procedure of bonded expansion anchor

The procedure set out in Section A.2.1 applies except no cleaning is required for hammer drilled hole.

Appendix B Testing of Anchor Bolts of Admissible Service Conditions

Table B.1 (reproduced from Table 5.4, ETAG 001, Part 1) shows the tests required for Option 1 which requires the widest range of tests. The test procedures are described in ETAG 001, Annex A, while the details of the test conditions and the number of tests required for different options are given in ETAG 001, Annex B.

Table B.1 Tests for admissible service conditions (Option 1)

	Purpose of test	Concrete grade	Crack width Δw (mm)	Load direction	Spacing and edge distance	Member thickness h	Remarks	Test procedure described in ETAG 001 Annex A	Note
1	Characteristic resistance for tension not influenced by spacing and edge effects	C25	0	N	$s > s_{cr,N}$ $c > c_{cr,N}$	$\geq h_{min}$	Test with single anchors	5.2.1	-
2		C60	0	N					(4)
3		C25	0.3	N					-
4		C60	0.3	N					(4)
5	Characteristic resistance for shear not influenced by spacing and edge effects	C25	0	V	$s > s_{cr,N}$ $c > c_{cr,N}$	$\geq h_{min}$	Test with single anchors	5.3.1	(7)
6		C60	0	V					(4)
7		C25	0.3	V					-
8		C60	0.3	V					(4)
9	Characteristic resistance for combined tension and shear not influenced by spacing and edge effects	C25	0	45°				5.4	-
10		C60	0	45°					(4)
11		C25	0.3	30° 60°					-
12		C60	0.3	30° 60°					(4)
13	Spacing for characteristic tension resistance	C25	0	N	$s_1 = s_2 = s_{cr,N}$ $c > c_{cr,N}$		Quadruple anchor group	5.2.2	-
14	Edge distance for characteristic tension resistance	C25	0	N	$s > s_{cr,sp}$ $c_1 = c_2 = c_{cr,sp}$	$= h_{min}$	Test with single anchors at corner	5.2.1	-
15	Characteristic shear resistance in non-cracked concrete for pry-out failure	C25	0	V	$s = s_{cr,N}$ $c \geq c_{cr,N}$	$\geq h_{min}$	Quadruple anchor group	5.3.3	(5), (6)
16	Characteristic shear resistance in non-cracked concrete close to an edge	C25	0	V	c_1 for concrete failure $c_2 \geq c_{cr,V}$ $s \geq s_{cr,V}$		Tests with single anchors at the edge loading in direction 1	5.3.1	(2)
17		C60	0	V					(2), (3)
18	Characteristic shear resistance in cracked concrete close to an edge	C25	0.3	V	c_1 for concrete failure $c_2 \geq c_{cr,V}$ $s \geq s_{cr,V}$		Tests with single anchors at the edge loading in direction 1	5.3.1	(2), (3)
19	Spacing and edge distance for characteristic shear resistance	C25	0	V	c_1 for concrete failure $c_2 = c_{cr,V}$ $s = s_{cr,V}$		Double anchor group at corner loading in direction 1	5.3.2	(2), (3)
20	Minimum spacing and edge distance	C25	0	(1)	$s = s_{min}$ $c = c_{min}$	$= h_{min}$	Double anchor group at the edge at uncast side of test member	5.9	-

The grey shaded test series above may be omitted if the design model of ETAG 001, Annex C is used.

Note:

(1) Torque moment increased in steps of 0.2 T_{inst}

(2) The value of c_1 shall be chosen such that the concrete edge failure occurs rather than steel failure or pry-out failure.

(3) The tests may be omitted, if the test results according to line 16 agree with current experience (refer to ETAG 001, Annex B for details).

(4) The tests may be omitted, if failure of tests in concrete of grade C25 is caused by rupture of steel.

(5) If steel failure occurs, the spacing may be reduced (refer to ETAG 001, Annex A, Cl. 5.3.3 for details)

(6) If different types of anchors of one anchor size are available, the stiffest anchor with the highest steel capacity shall be chosen.

(7) Tests according to line 5 are required only if the anchor has a significant reduced section along the length of the bolt or the sleeve of a sleeve type anchor should be considered or for internal threaded parts.