EOTA®

EUROPEAN ASSESSMENT DOCUMENT

EAD 330499-00-0601

July 2017

# BONDED FASTENERS FOR USE IN CONCRETE

This European Assessment Document (EAD) has been developed taking into account up-to-date technical and scientific knowledge at the time of issue and is published in accordance with the relevant provisions of Regulation (EU) No 305/2011 as a basis for the preparation and issuing of European Technical Assessments (ETA).

**Contents**

# 1 SCOPE OF THE EAD

## 1.1 Description of the construction product

This EAD covers bonded fasteners (including bonded expansion fasteners) consisting of a bonding material and an embedded metal part placed in pre-drilled holes perpendicular to the surface (maximum deviation 5°) in concrete and anchored therein primarily by means of bond. Bonded fasteners are often used to connect structural elements and non-structural elements to structural components.

The embedded metal part may be a threaded rod, deformed reinforcing bar, internally threaded sleeve or other shape made of carbon steel, stainless steel or malleable cast iron.

If embedded parts are commercial standard rods supplied by a party other than the manufacturer of the bonding component (e.g. manufacturer of standard rods), the following conditions have to be fulfilled:

- Material, dimensions and mechanical properties of the metal parts according to the specifications given in an Annex of the ETA
- Confirmation of material and mechanical properties of the metal part by inspection certificate 3.1 according to EN 10204 [9]; the documents shall be stored
- Marking of the rod with the envisaged embedment depth. This may be done by the manufacturer of the rod or the person on job site.

This EAD covers fasteners with an internal thread with a thread length of at least d + 5 mm.

This EAD applies to fasteners with the following dimensions:

- Minimum thread size of 6 mm (M6);
- Minimum embedment depth $h_{ef,min}$ larger or equal to 40 mm and larger or equal to 4 d; maximum embedment depth $h_{ef,max}$ smaller or equal to 20 d.

Note 1 *The stated limit for the maximum embedment depth of 20 d is in accordance with EN 1992-4. For deeper embedment a constant distribution of bond stress over the embedment depth cannot be readily assumed.*

Bonded fasteners are distinguished according to the operating principles, mixing techniques and installation techniques, which are outlined below.

**Types and operating principles of fasteners**

This EAD covers bonded fasteners with the following mixing and installation techniques:

<u>Mix proportions</u>

Only those bonded fasteners in which the mix proportions are controlled by the packaging of the bonding material are covered. This includes, for example, the following types: glass capsule, soft-skin capsule, pre-packed injection (coaxial or side by side) cartridges or foil pack systems, bulk with mechanical proportioning and bulk where all components are mixed exactly as supplied.

Note 2 *Systems where the mix proportions are controlled by the installer, such as the bulk type where component volumes have to be measured by the installer, are not covered.*

<u>Mixing techniques</u>

- controlled by fastener, e.g. injection cartridge with static mixer nozzle, bulk type with mechanical mixing.
- controlled by the installer - e.g. bulk type mixed in the pot with pre-determined controlled proportioning and mixing of all components.
- controlled during installation - e.g. capsule type

<u>Volume of placed bonding material</u>

- controlled by the fastener, e.g. capsule type.
- controlled by the installer, e.g. injection and bulk types

<u>Drilled hole</u>

- cylindrical hole
- undercut hole

<u>Drilling techniques</u>

- rotary hammer (electric drilling machine or driven by compressed air)
- diamond drilling

Installation techniques

- Capsule placed in the hole and embedded part driven by machine with simultaneous hammering and/or turning (Figure 1.1).
- Bonding material injected into the hole. Embedded part may be inserted manually or mechanically (Figure 1.2).
- Bonding material poured into the hole and embedded part inserted (Figure 1.3).

Installation of the fastener may be independent of torque control or dependent on torque control.

Operating principles

| | |
|---|---|
| - Bonded fastener: | placed in cylindrical hole and anchored by bonding the metal parts to the sides of the drilled hole. |
| - Bonded expansion fastener: | placed into a cylindrical hole; the load transfer is a combination of bonding and expansion, where the expansion is achieved by a special rod. This type of fastener is also known as torque-controlled bonded fastener. |

Examples of installation techniques for bonded fasteners are given in Figure 1.1 to Figure 1.3.

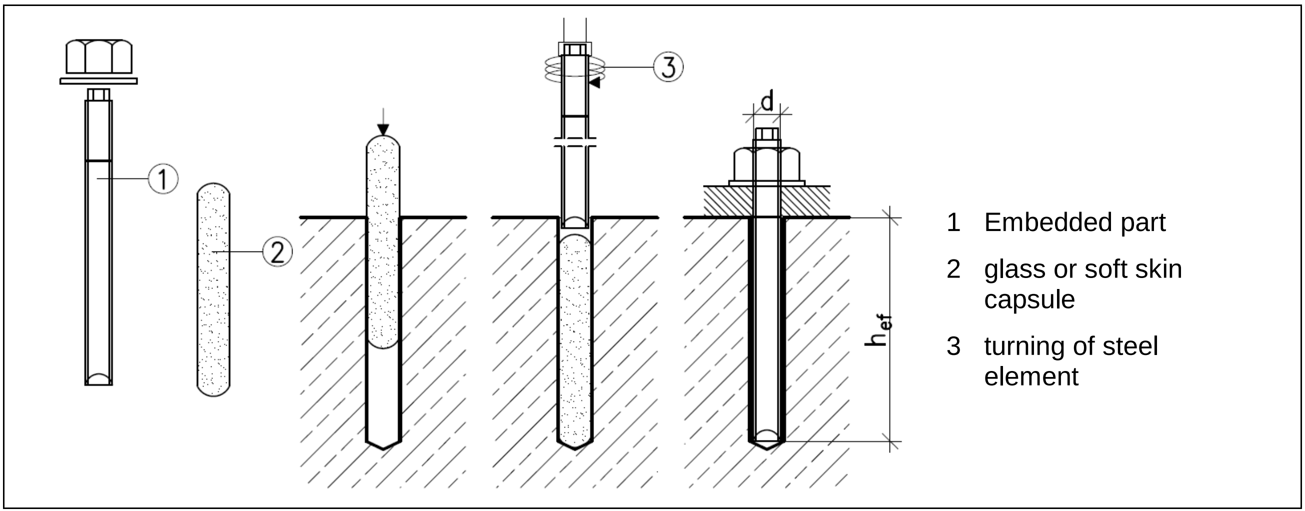


**Figure 1.1 Capsule type**

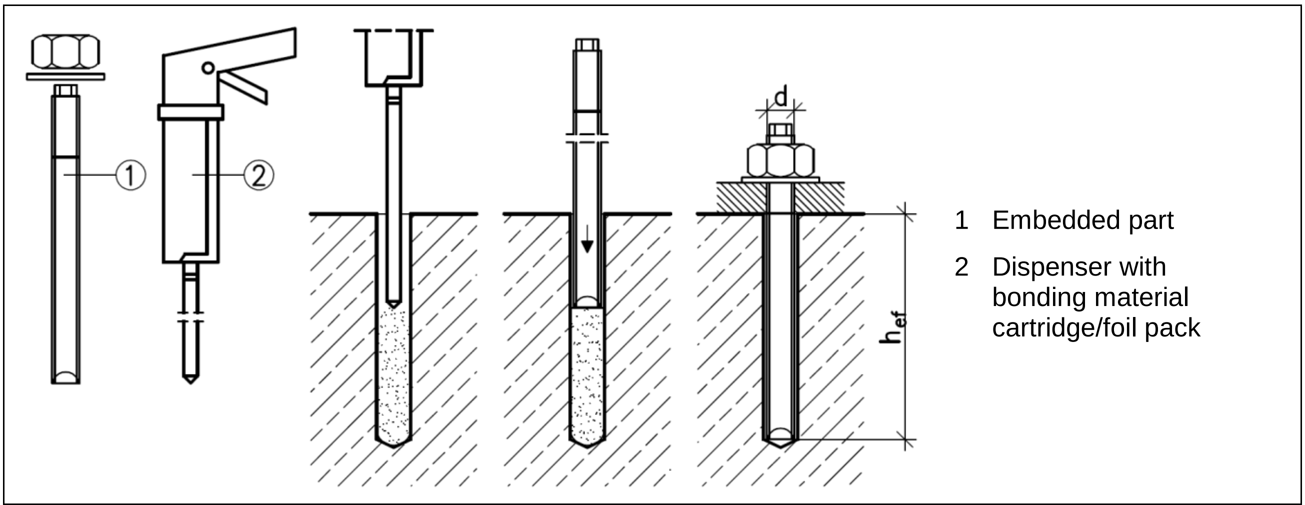


**Figure 1.2 Injection type**

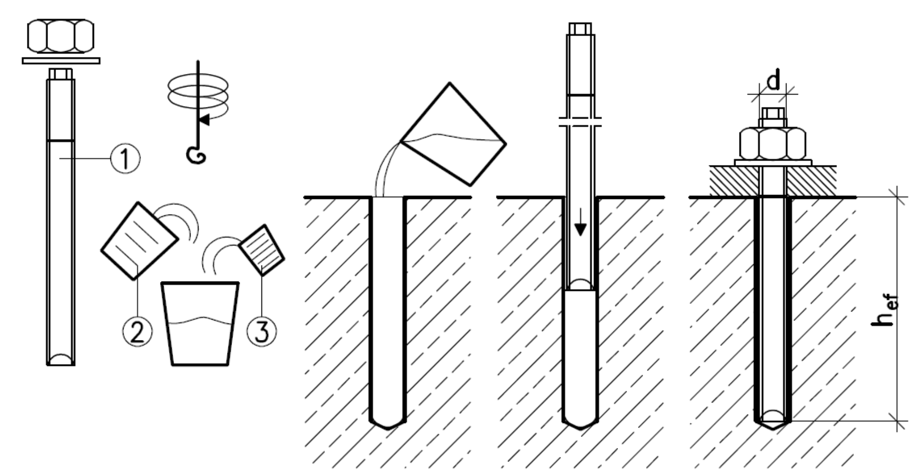


**Figure 1.3 Bulk type**

In this EAD the assessment is made to determine characteristic values of the bonded fastener for design according to EN 1992-4.

*Note 3 For other design provisions additional test series may be required which are not covered by this EAD (such as tests under combined tension and shear load, tests with groups of fasteners for characteristic spacing in tension and shear, etc.).*

*Note 4 The assessment of post-installed rebar connections with bonding material for design according to EN 1992-1-1:2004 [5] and EN 1992-1-2:2004 [6] is covered by EAD 330087-00-0601.*

*Note 5 The assessment of metal injection fasteners for use in masonry is covered by EAD 330076-00-06.04.*

The product is not covered by a harmonised European standard (hEN).

Concerning product packaging, transport, storage, maintenance, replacement and repair it is the responsibility of the manufacturer to undertake the appropriate measures and to advise his clients on the transport, storage, maintenance, replacement and repair of the product as he considers necessary.

It is assumed that the product will be installed according to the manufacturer's product installation instructions MPII or (in absence of such instructions) according to the usual practice of the building professionals.

Relevant manufacturer’s stipulations having influence on the performance of the product covered by this European Assessment Document shall be considered for the determination of the performance and detailed in the ETA.

## 1.2 Information on the intended use of the construction product

### 1.2.1 Intended use

Bonded fastener placed into pre-drilled holes for use in compacted reinforced or unreinforced normal weight concrete without fibres with strength classes in the range C20/25 to C50/60 all in accordance with EN 206 [1].

The fastener is suitable for the use loaded in tension, shear or combined tension and shear

- in uncracked concrete only (Table 1.1, option 7 – 12),
- in cracked and uncracked concrete (Table 1.1, option 1 – 6, max w = 0,3 mm),
- under static or quasi-static actions,
- under seismic actions (category C1: max w = 0,5 mm; C2: max w = 0,8 mm according to Technical Report TR 049).

*Note 6 The loading on the fastener resulting from actions on the fixture (e. g. tension, shear, bending or torsion moments or any combination thereof) will generally be axial tension and/or shear. When the shear force is applied with a lever arm, a bending moment on the fastener will arise.*

*It is presumed, that compressive forces acting in the axis of the fastener are transmitted by the fixture directly to the concrete without acting on the fastener's load transfer mechanism.*

The fastener is suitable for

Concrete condition:

I1 = installation in dry or wet (water saturated) concrete and use in service in dry or wet concrete;

I2 = installation in water-filled drill holes (not sea water) and use in service in dry or wet concrete.

*Note 7 Water-filled holes are pre-drilled holes (with drilling and cleaning according to the MPII), which are afterwards filled with water (e.g. overnight rain in outdoor applications). Underwater installation is different to this condition as the water pressure has to be accounted for and are therefore not covered in this EAD.*

Concrete temperature at installation: $T_{i,min}$ to $T_{i,max}$

*Note 8 The minimum and maximum concrete temperatures at installation, $T_{i,min}$ and $T_{i,max}$, are specified by the manufacturer.*

Installation direction:

D1 = downward only,

D2 = downward and horizontal installation

D3 = downward and horizontal and upwards (e.g. overhead) installation

This EAD covers a range of temperature during installation and curing of the bonding material in the concrete base material between 0 °C and +40°C.

The covered service temperature ranges of the concrete base material (anchorage base) during the working life are

T1: 24°C/40°C = temperature range from -40°C to +40°C, with a maximum long term temperature of +24°C, and a maximum short term temperature of +40°C;

T2: 50°C/80°C = temperature range from -40°C to +80°C, with a maximum long term temperature of +50°C, and a maximum short term temperature of +80°C;

T3: $T_{lt}/T_{st}$ = temperature range from -40°C to $+T_{st}$, with a maximum long term temperature $T_{lt}$ = 0,6 to 1,0 $T_{st}$, and a maximum short term temperature of $T_{st} \geq 40$°C.

*Note 9 The maximum short term temperature $T_{st}$ and the maximum long term temperature $T_{lt}$ are specified by the manufacturer.*

The hardened concrete is at least 21 days old.

The thickness of the concrete member in which the fastener is installed is $h \geq h_{ef} + \Delta h$ and $h \geq 100$ mm, with $\Delta h \geq 2\ d_0$ and $\Delta h \geq 30$ mm.

The performance characteristics are consistent with the design provisions of EN 1992-4 and are based on a design working life of 50 years (see 1.2.2).

*Note 10 Performance characteristics need to be consistent with the design provisions to achieve the required safety of the fastening application. For other design provisions than given in EN 1992-4 modified or additional performance characteristics may be necessary.*

It is assumed that

- the design of an anchorage and the specification of the fastener is under control of an engineer experienced in anchorages and concrete work;
- the fastener installation is executed by trained personnel, ensuring that the MPII and the specifications by the engineer are observed.

*Note 11 Base materials such as screeds or non-structural toppings can have properties that are uncharacteristic of the concrete and/or are excessively weak. Therefore, fastenings in these base materials are not covered in this EAD.*

*Note 12 Fasteners subject to impact loads (e.g. fasteners for the attachment of fall arresting devices) and/or fatigue loads are not covered in this EAD.*

**Assessment options for the intended use**

According to the intended use the manufacturer may choose one of the options given in Table 1.1.

**Table 1.1 Assessment options covered by this EAD**

<table>
<tr><th>Option</th><th>Cracked concrete</th><th>uncracked concrete</th><th>One value for all concrete strength</th><th>Different values for C20/25 to C50/60</th><th>One value for load direction</th><th>Tension and shear capacity</th><th>$c_{cr}$ / $s_{cr}$</th><th>$c_{min}$ / $s_{min}$</th><th>Design method [1)] DM-x</th></tr>
<tr><td>1</td><td rowspan="6">✓</td><td rowspan="6">✓</td><td>×</td><td>✓</td><td rowspan="2">×</td><td rowspan="2">✓</td><td rowspan="4">✓</td><td rowspan="4">✓</td><td rowspan="2">A</td></tr>
<tr><td>2</td><td>✓</td><td>×</td></tr>
<tr><td>3</td><td>×</td><td>✓</td><td rowspan="4">✓</td><td rowspan="4">×</td><td rowspan="2">B</td></tr>
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<tr><td>5</td><td>×</td><td>✓</td><td rowspan="2">✓</td><td rowspan="2">×</td><td rowspan="2">C</td></tr>
<tr><td>6</td><td>✓</td><td>×</td></tr>
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<tr><td>8</td><td>✓</td><td>×</td></tr>
<tr><td>9</td><td>×</td><td>✓</td><td rowspan="4">✓</td><td rowspan="4">×</td><td rowspan="2">B</td></tr>
<tr><td>10</td><td>✓</td><td>×</td></tr>
<tr><td>11</td><td>×</td><td>✓</td><td rowspan="2">✓</td><td rowspan="2">×</td><td rowspan="2">C</td></tr>
<tr><td>12</td><td>✓</td><td>×</td></tr>
</table>

1) Design method according to EN 1992-4

### 1.2.2 Working life/Durability

The assessment methods included or referred to in this EAD have been written based on the manufacturer's request to take into account a design working life of the bonded fastener for the intended use of 50 years when installed in the works (provided that the bonded fastener is subject to appropriate installation (see 1.1). These provisions are based upon the current state of the art and the available knowledge and experience.

When assessing the product the intended use as foreseen by the manufacturer shall be taken into account. The real working life may be, in normal use conditions, considerably longer without major degradation affecting the basic requirements for works[1].

The indications given as to the working life of the construction product cannot be interpreted as a guarantee neither given by the product manufacturer or his representative nor by EOTA when drafting this EAD nor by the TAB issuing an ETA based on this EAD, but are regarded only as a means for expressing the expected economically reasonable working life of the product.

## 1.3 Specific terms used in this EAD

### 1.3.1 Abbreviations

BF = bonded fastener

BEF = bonded expansion fastener (torque-controlled bonded fastener)

MPII = manufacturer's product installation instructions

1 The real working life of a product incorporated in a specific works depends on the environmental conditions to which that works is subject, as well as on the particular conditions of the design, execution, use and maintenance of that works. Therefore, it cannot be excluded that in certain cases the real working life of the product may also be shorter than referred to above.

| | | |
|---|---|---|
| C1 | = | seismic performance category C1 (use in design according to EN 1992-4) |
| C2 | = | seismic performance category C2 (use in design according to EN 1992-4) |
| DM-A | = | design method A according to EN 1992-4 |
| DM-B | = | design method B according to EN 1992-4 |
| DM-C | = | design method C according to EN 1992-4 |
| X1 | = | subject to dry internal conditions |
| X2 | = | subject to dry internal conditions or external atmospheric exposure including industrial and marine environment or permanently damp internal condition, if no particular aggressive conditions exist |
| X3 | = | subject to dry internal conditions or external atmospheric exposure including industrial and marine environment or permanently damp internal condition or permanently damp internal condition and in other particular aggressive conditions<br>*Particular aggressive conditions are e. g. permanent, alternating immersion in seawater or the splash zone of seawater, chloride atmosphere of indoor swimming pools or atmosphere with extreme chemical pollution (e. g. in desulphurization plants or road tunnels where de-icing materials are used).* |

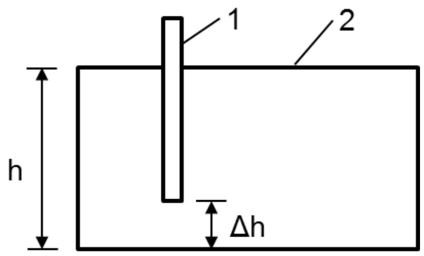
### 1.3.2 Notation

| | | |
|---|---|---|
| $a,b$ | = | constants (tuning factors), evaluated by a regression analysis of the deformations measured during the sustained load tests |
| $A_5$ | = | percentage elongation after fracture (measured over a length of 5d)” |
| $A_s$ | = | relevant stressed cross section of the emdedded metal part |
| $A_{sp}$ | = | Projecting area according to Figure 2.2 |
| $c_{cr}$ | = | characteristic edge distance |
| $c_{cr,N}$ | = | characteristic edge distance for concrete cone failure in tension |
| $c_{cr,sp}$ | = | characteristic edge distance for concrete splitting |
| $c_{cr,V}$ | = | characteristic edge distance for concrete edge failure in shear |
| $c_{min}$ | = | minimum edge distance |
| $cv_F$ ($cv_\delta$) | = | coefficient of variation of failure loads(of displacements) |
| $d$ | = | diameter of embedded part |
| $d_0$ | = | nominal drill hole diameter |
| $d_{cut}$ | = | drill bit diameter |
| $d_f$ | = | diameter of the clearance hole of the fixture |
| $d_{nom}$ | = | effective diameter of fastener for calculation of concrete edge failure |
| $f_c$ | = | concrete compressive strength measured on cylinders |
| $f_{c,cube}$ | = | concrete compressive strength measured on cubes with a side length of 150 mm |
| $f_{c,t}$ | = | compressive strength of concrete at the time of testing |
| $f_{uk}$ | = | characteristic ultimate strength of the metal part [N/mm²] |
| $f_{yk}$ | = | characteristic yield strength of the metal part [N/mm²] |
| $h$ | = | thickness of the concrete member |

| | | |
|---|---|---|
| $h_{nom}$ | = | overall fastener embedment depth in the concrete |
| $h_{ef}$ | = | effective embedment depth |
| $h_{ef,red}$ | = | reduced effective embedment depth according to Figure A2.1 |
| $h_{min}$ | = | minimum thickness of concrete member in which the fastener is installed |
| $h_{sl}$ | = | thickness of slice, measured values |
| $k$ | = | factor for equation (2.15) |
| $k_{cr}$ | = | factor for resistance to concrete failure cracked concrete |
| $k_{ucr}$ | = | factor for resistance to concrete failure uncracked concrete |
| $k_7$ | = | factor for ductility of the fastener |
| $k_8$ | = | factor for calculation of characteristic resistance for pryout failure |
| $\ell_f$ | = | effective length of fastener in shear loading (for calculation resistance for concrete edge failure) |
| $M^0_{Rk,s}$ | = | characteristic resistance for steel failure with lever arm |
| $m$ | = | normalisation exponent taking into account the effect of concrete strength on the resistance |
| $n$ | = | number of tests in a test series |
| $N^0_{Rk,sp}$ | = | characteristic resistance to concrete splitting under tension load |
| $N_{1,3Tinst,m}$ | = | mean values of pre-stressing force of the embedded metal part at 1,3 $T_{inst}$ |
| $N_{1,3Tinst,95\%}$ | = | 95% fractile of pre-stressing force of the embedded metal part at 1,3 $T_{inst}$ |
| $N_{max}$ | = | upper load in repeated load tests |
| $N_{min}$ | = | lower load in repeated load tests |
| $N_p$ ($\tau_p$) | = | load (stress) applied on the fastener during crack cycling tests |
| $N_{p,red}$ ($\tau_{p,red}$) | = | reduced load (stress) applied on the fastener during crack cycling tests |
| $N_{Rk}$ | = | characteristic tension resistance as given in the ETA |
| $N_{Rk,s}$ | = | characteristic tension resistance for steel |
| $N_{sust}$ | = | load applied on a fastener during sustained load test or freeze/thaw test |
| $N_u$ | = | measured maximum ultimate load |
| $N_{u,adh}$ | = | load at loss of adhesion (Figure A2.2) |
| $N_{u,m}$ ($N_{u,5\%}$) | = | mean (5% fractile of) failure loads in tests |
| $N_{u,t}$ | = | maximum load (failure load) in a test |
| $N_{Ru,m,r}$ ($N_{u,5\%,r}$) | = | Mean (5% fractile of) failure load in the corresponding reference test series |
| $N_{Ru,m,mlt}$ ($N_{u,5\%,mlt}$) | = | Mean (5% fractile of) failure load at maximum long term temperature |
| $N_{Ru,m,mst}$ ($N_{u,5\%,mst}$) | = | Mean (5% fractile of) failure load at maximum short term temperature |

| | | |
|---|---|---|
| $s_{cr}$ | = | characteristic spacing |
| $s_{cr,N}$ | = | characteristic spacing for concrete cone failure in tension |
| $s_{cr,sp}$ | = | characteristic spacing for concrete splitting |
| $s_{cr,V}$ | = | characteristic spacing for concrete edge failure in shear |
| $s_{min}$ | = | minimum spacing |
| $s_o$ | = | initial displacement under the sustained load at t=0 (measured directly after applying the sustained load) |
| $max\ t_{fix}$ | = | maximum thickness of the fixture as requested by the manufacturer |
| $max\ T_{fix}$ | = | maximum torque moment for attachment of the fixture |
| $T_{i,min}$ | = | minimum concrete temperature at the time of installation of the fastener as specified by the manufacturer |
| $T_{i,max}$ | = | maximum concrete temperature at the time of installation of the fastener as specified by the manufacturer |
| $T_{inst}$ | = | Required installation torque for bonded expansion fastener specified by the manufacturer |
| $T_{lt}$ | = | maximum long term temperature |
| $T_{st}$ | = | maximum short term temperature |
| $V^0_{Rk,s}$ | = | characteristic shear resistance for steel |
| $V_{Ru,m}$ | = | mean value of failure loads in shear tests |
| $V_{u,5\%}$ | = | 5% fractile of failure loads in shear tests |
| $W_{el}$ | = | elastic section modulus calculated from the stressed cross section of the embedded metal part |
| $\alpha$ | = | reduction factor, see equation (A2.18) |
| $\alpha_{ref}$ | = | factor taking into account sensitivity to different concrete batches according to equation (A2.12) |
| $\alpha_{setup}$ | = | factor taking into account the influence of confined test setup |
| $\alpha_1$ | = | criteria for loss of adhesion, see equation (A2.19) |
| $\alpha_2$ | = | ratio according to equation (2.10), tests at maximum long term temperature |
| $\alpha_3$ | = | ratio according to equation (2.11), tests at maximum short term temperature |
| $\alpha_4$ | = | ratio according to equation (2.12), tests for checking durability of bonding material |
| $\alpha_P$ | = | reduction due to applied tension load during tests |
| rqd. $\alpha$ | = | required value for reduction factor $\alpha$ in the assessment |
| $\beta_{cv}$ | = | Reduction factor for large scatter of failure loads |
| $\delta_0$ | = | displacement of fastener under short term loading |
| $\delta_\infty$ | = | long term displacement of fastener |
| $\delta_{20}$ | = | displacement of the fastener after 20 crack cycles |
| $\delta_{1000}$ | = | displacement of the fastener after 1000 crack cycles |

| | | |
|---|---|---|
| $\delta_{N\infty}$ | = | long term tension displacement |
| $\delta_{m1}$ | = | mean fastener displacement after $10^3$ crack movements |
| $\delta_{m2}$ | = | mean displacement of fastener determined from the repeated load tests after $10^5$ load cycles or the sustained load tests after terminating the tests. |
| $\delta_{u,adh}$ | = | mean displacement in tests at loss of adhesion. |
| $\Delta h$ | = | distance from the embedded end of the fastener (1) to the opposite end of the concrete member (2) |




| | | |
|---|---|---|
| $\Delta w$ | = | crack width (in addition to the width of the hairline crack) |
| $\Delta w_1$ | = | maximum crack width in the crack movement test |
| $\Delta w_2$ | = | minimum crack width in the crack movement test |
| $\tau_{5\%}$ | = | initial characteristic bond strength for equation (2.14) |
| $\tau_p$ | = | acting stress on the fastener in crack cycling tests |
| $\tau_{Rk,cr}$ | = | characteristic bond resistance for cracked concrete C20/25 |
| $\tau_{Rk,ucr}$ | = | characteristic bond resistance for uncracked concrete C20/25 |
| $\tau_{Ru}$ | = | bond strength at normal ambient temperature |
| $\tau_{Ru,m,B18}$ | = | mean bond strength in test series B18 |
| $\tau_{Ru,m,B19}$ | = | mean bond strength in test series B19 |
| $min\,\tau_{Ru,m,r,12}$ | = | Minimum value of average bond strength of all reference test series normalized to minimum concrete strength, according to equation (A2.12) |
| $\tau_{Ru,r,i}$ ($\tau_{u,5\%,r,i}$) | = | mean (5% fractile) of bond resistance of the corresponding reference test carried out in the same slab i or same batch |
| $\tau_{Ru,t,i}$ ($\tau_{u,5\%,t,i}$) | = | mean (5% fractile) of bond strength in test series t in slab i |
| $\tau_{Ru,m,i,12}$ | = | mean bond resistance of reference test with diameter d = 12 mm carried out in the same slab or same batch as those used for the reference tension tests R1 to R4 or A1 to A4 normalized to minimum concrete strength |
| $\tau_{Rk}$ | = | characteristic bond resistance |
| $\gamma_{inst}$ | = | factor accounting for the sensitivity to installation (used in design according to EN 1992-4) |
| $\gamma_{Mc}$ | = | partial factor for concrete failure (to be given in the ETA) |
| $\psi_c$ | = | increasing factor accounting for concrete strength |

### 1.3.3 Indices

| | | |
|---|---|---|
| *cr* | = | cracked concrete |
| *ucr* | = | uncracked concrete |
| *conf* | = | confined test setup |
| *unconf* | = | unconfined test setup |
| *r* | = | reference |
| *t* | = | test |

### 1.3.4 Definitions

| | | |
|---|---|---|
| anchor | = | historically synonymous to fastener |
| component installation temperature range | = | temperature range of the bonding material and embedded part immediately prior to installation. |
| confined test setup | = | close spacing of the support according to Technical Report TR 048 [2], Figure 3.4 |
| curing time | = | the minimum time from the end of mixing to the time when the fastener may be torqued or loaded (whichever is longer). The curing time depends on the concrete temperature. |
| dry concrete | = | concrete cured under normal ambient conditions |
| fastener | = | metal element made of steel or malleable iron post-installed into hardened concrete and used to transmit applied load; as defined in EN 1992-4 [7] |
| fastening | = | assembly of fasteners and fixture used to transmit load to the concrete |
| fixture | = | assembly that transmits loads to the fastener |
| flooded hole | = | used synonymous to water filled hole; this is not synonymous with under water condition (as the pressure of the water is not considered) |
| long term temperature | = | temperature of the concrete within the service temperature range, which will be approximately constant over significant periods of time. Long term temperatures will include constant or near constant temperatures, such as those experienced in rooms that keep a constant temperature or next to heating installations |
| maximum short term temperature | = | upper limit of the service temperature range |
| maximum long term temperature | = | specified by the manufacturer within the range of 0,6 times to 1,0 times the maximum short term temperature. |
| normal ambient temperature | = | temperature of the concrete 21 °C ± 3 °C (for test conditions only) |
| open time | = | maximum time from end of mixing to end of insertion of the metal element into the bonding material (for bulk type fasteners); |
| | = | maximum time from start of injection to end of insertion of the metal element into the bonding material (for injection type fasteners); |
| | = | maximum time for setting (insertion of the metal element) (for capsule type fasteners); |

| | | |
|---|---|---|
| service temperature range | = | range of ambient temperatures in the area of the fastener after installation and during the lifetime of the anchorage. |
| short term temperature | = | temperature of the concrete within the service temperature range which vary over short intervals, e.g. day/night cycles and freeze/thaw cycles. |
| unconfined test setup | = | wide spacing of the support according to Technical Report TR 048, Figure 3.3 |
| working time | = | synonymous to open time or gel time |

# 2 ESSENTIAL CHARACTERISTICS AND RELEVANT ASSESSMENT METHODS AND CRITERIA

## 2.1 Essential characteristics of the product

Table 2.1 shows how the performance of bonded fasteners is assessed in relation to the essential characteristics.

The assessment of bonded expansion fasteners is given in Annex B.

**Table 2.1 Essential characteristics of the product and methods and criteria for assessing the performance of the product in relation to those essential characteristics**

| No | Essential characteristic | Assessment method | Type of expression of product performance<br>*(level, class, description)* |
|---|---|---|---|
| Basic Works Requirement 1: Mechanical resistance and stability | | | |
| Characteristic resistance to tension load (static and quasi-static loading) | | | |
| 1 | Resistance to steel failure (tension) | 2.2.1 | $N_{Rk,s}$ [kN] |
| 2 | Resistance to combined pull-out and concrete failure | 2.2.2 | $\tau_{Rk}$ [N/mm²] |
| 3 | Resistance to concrete cone failure | 2.2.3 | $c_{cr,N}$ [mm] $k_{cr,N}$, $k_{ucr,N}$ [-] |
| 4 | Edge distance to prevent splitting under load | 2.2.4 | $c_{cr,sp}$ [mm] |
| 5 | Robustness | 2.2.5 | $\gamma_{inst}$ [-] |
| 6 | Maximum setting torque moment | 2.2.1.2 | max $T_{fix}$ [Nm] |
| 7 | Minimum edge distance and spacing | 2.2.6 | $c_{min}$, $s_{min}$, $h_{min}$-[mm] |
| Characteristic resistance to shear load (static and quasi-static loading) | | | |
| 8 | Resistance to steel failure (shear) | 2.2.7 | $V^0_{Rk,s}$ [kN], $M^0_{Rk,S}$ [Nm], $k_7$ [-] |
| 9 | Resistance to pry-out failure | 2.2.8 | $k_8$ [-] |
| 10 | Resistance to concrete edge failure | 2.2.9 | $d_{nom}$, $\ell_f$ [mm] |
| Displacements under short term and long term loading | | | |
| 11 | Displacements under short term and long term loading | 2.2.10 | $\delta_0$, $\delta_\infty$ [mm or mm/(N/mm²)] |
| Durability | | | |
| 12 | Durability of metal parts | 2.2.11 | Description |
| Characteristic resistance and displacements for seismic performance categories C1 or C2 (optional) | | | |
| 13 | Resistance to steel failure | TR 049 | $N_{Rk,s,eq}$, $V_{Rk,s,eq}$ [kN] |
| 14 | Resistance to pull-out | | $\tau_{Rk,p,eq}$ [N/mm²] |
| 15 | Fracture elongation | | $A_5$ [%] |
| 16 | Factor for annular gap | | $\alpha_{gap}$ [-], |
| 17 | Displacements | | $\delta_{N,eq}$, $\delta_{V,eq}$ [mm] |
| Basic Works Requirement 3: Hygiene, health and the environment | | | |
| 18 | Content, emission and/or release of dangerous substances | 2.2.12 | Description |

## 2.2 Methods and criteria for assessing for the performance of the product in relation to essential characteristics of the product

An overview of the test program for the assessment of the various essential characteristics of the product is given in Annex A.

Provisions valid for all tests and general aspects of the assessment (determination of 5% fractile values of resistance, determination of reduction factors, criteria for uncontrolled slip, etc.) are also given in Annex A.

Provisions for bonded expansion fasteners are given in Annex B.

### 2.2.1 Resistance to steel failure (tension)

#### 2.2.1.1 Steel capacity (test series N1)

**Purpose of the test**

The characteristic resistance to steel failure may be calculated for steel elements with constant strength over the length of the element as given in equation (2.1). The smallest cross section in the area of load transfer applies.

$$N_{Rk,s} = A_s \cdot f_{uk} \quad [N] \qquad (2.1)$$

If the steel strength differs along the length of the element, calculate the design steel capacity for the specified steel strengths and the corresponding nominal stressed cross sections according to equation (2.1) taking into account the recommended partial factor for steel resistance $\gamma_{M,s}$ according to EN 1992-4, Table 4.1. Take the minimum of these design steel capacities and determine the characteristic resistance to steel failure. The characteristic resistance and the corresponding partial factor $\gamma_{M,s}$ shall be stated in the ETA.

Tests are needed only if

- The steel element is part of the manufacturer's product (CE marking) and
- The calculation of the characteristic resistance to steel failure is not reasonable because the distribution of the steel strength of the finished product along the length of the fastener is not known or cannot easily be determined.

The modulus of elasticity for steel can be taken as $E_s$ = 210 000 N/mm².

**Test conditions**

Perform at least 5 steel tension tests with the finished product.

**Assessment**

Determine the 5%-fractile of the failure loads. This value shall be normalized to the specified nominal strength to account for over-strength of tested samples according to equation (A2.8).

#### 2.2.1.2 Maximum torque moment (test series N2)

**Purpose of the test**

The tests are performed in order to verify that steel failure (yielding) of the steel element may not occur by application of a torque moment, accounting for corresponding tolerances.

**Test conditions**

The tests shall be performed according to Technical Report TR 048, 3.5.

The tests are performed with all diameter sizes of the fastener in uncracked concrete of strength class C50/60.

The holes shall be drilled with a cutting diameter $d_{cut,m}$ of the drill bit according to Technical Report TR 048, Figure 3.5. The diameter of the clearance hole in the fixture shall correspond to the values given in Table 2.5.

**Assessment**

<u>Failure loads</u>

- Determine the mean value of the tension force $N_{1,3Tfix,m}$ [kN] and the 95% fractile of the tension force $N_{1,3Tfix,95\%}$ [kN] at 1,3 $T_{fix}$.

Criteria

All following criteria shall be fulfilled.

1. The 95 %-fractile of the tension force generated in the torque tests at a torque moment T = 1,3 $T_{fix}$ shall be smaller than the nominal yield force ($A_s \cdot f_{yk}$) of the embedded metal part.
2. The 95% of tension force generated in the torque tests at T = 1,3 $T_{fix}$ shall not be larger than the characteristic resistance for pull-out failure for minimum embedment depth.

$$N_{Rk,p} = \pi \cdot d \cdot h_{ef} \cdot \tau_{Rk,ucr} \quad (2.2)$$

3. The tension force generated in the torque test shall be smaller than the concrete cone capacity for concrete C20/25 according to EN 1992-4.
4. At the end of the test, the connection shall be capable of being unscrewed.

### 2.2.2 Resistance to combined pull-out and concrete failure

#### 2.2.2.1 Reference (test series R1 to R4)

**Purpose of test**

These tests are performed to establish a reference for the assessment of the test series for resistance to pull-out failure. These tests may also be used to determine the normalization factor for the normalization to nominal concrete strength. Furthermore, for Options 8, 10 and 12 according to Table 1.1 the test series R2 is used to assess the functioning in high strength concrete.

**Test conditions**

The reference tests shall be carried out with the same diameter of the fastener and in the same slab or same concrete batch as in the corresponding tests for resistance to pull-out failure.

The tests are performed with confined test setup according to Technical Report TR 048.

In addition, reference tension tests (R1) on medium size (M12) as described in A2 have to be performed to take into account the possible influence of different concrete parameters (in various batches) on the failure load.

With the exception of the reference tension tests (R1) on medium size which are needed for the determination of $\tau_{Ru,m,i,12}$, and the reference tests on size s/m/l that are needed for to take account of the influence of certain parameters on the resistance of bonded fasteners, the test series R2 and R4 may be omitted if the characteristics bond strength are determined by unconfined test series A2 and A4.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- If the basic tension tests with unconfined test setup (2.2.2.2) are not performed, determine the increasing factor $\psi_{c,50}$ according to equation (A2.7).
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 15% ($cv_F$ > 15%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- The test results in high strength concrete R2 or R4 may not be smaller than the corresponding test series in low strength concrete R1 or R3 (equation (A2.7): $\psi_{c,xx} \geq 1{,}0$).

Load displacement behaviour

- Determine the reduction factor $\alpha 1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 25 %.

The assessment for Options 8, 10 and 12 according to Table 1.1 regarding the functioning in high strength concrete is performed as follows:

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor α according to Annex A comparing the test results with reference test series according to Table A1.1 line R1.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 1,0 in equation (2.17).

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the mean value of the failure loads $N_{u,m}$ [kN] of the test series.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %."

#### 2.2.2.2 Basic tension tests with unconfined test setup (test series A1 to A4)

**Purpose of the test**

The tests are required for determination of the following characteristics using the factor $\alpha_{setup}$ = 1,0.

- basic characteristic bond strength $\tau_{5\%}$
- the increasing factors accounting for concrete strength $\psi_c$
- short term displacement $\delta_{NO}$

This test series may be omitted if the characteristics given above are determined by confined test series R1 to R4 and using the default reduction factors $\alpha_{setup}$ as follows:

- $\alpha_{setup}$ = 0,75 for confined basic tension tests in uncracked concrete (test series R1 and R2)
- $\alpha_{setup}$ = 0,70 for confined basic tension tests in cracked concrete (test series R3 and R4)

**Test conditions**

The tests are performed with unconfined test setup according to Technical Report TR 048.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the increasing factor $\psi_{c,50}$ according to equation (A2.7).
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 15 % ($cv_F$ > 15 %), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50 % of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 25 %.

#### 2.2.2.3 Increased crack width (test series B10 and B11)

**Purpose of test**

These tests are performed to assess the sensitivity of the fastener to a wide crack in the concrete passing through the location of the fastener. The test series may be omitted for an assessment in uncracked concrete only (option 7-12).

**Test conditions**

The tests are carried out in low strength cracked concrete C20/25 (test series B10) and high strength cracked concrete C50/60 (test series B11), with a crack width of $\Delta w = 0,5$ mm. The tests shall be carried out with confined test setup according to Technical Report TR 048.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R3 for tests in C20/25 and according to Table A1.1 line R4 for tests in C50/60.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 0,8 in equation (2.14).
- If test series R4 has been omitted test series B10 may be used as reference test series for tests B11 with rqd. $\alpha$ = 1,0.

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.4 Repeated loads (test series B12)

**Purpose of the test**

These tests are performed to determine the performance of the fastener under repeated loads simulating service loads that are subject to variation over time.

The tests may be omitted for fasteners qualified for cracked concrete (option 1-6 according to Table 1.1).

**Test conditions**

The tests shall be carried out in uncracked concrete C20/25 according to Technical Report TR 048. The tests are performed as confined tests with medium diameter size M12 or smallest size if that is larger than M12.

The maximum load $N_{max}$ on the fastener shall be calculated as given in equation (2.3) and the minimum load $N_{min}$ is calculated according to equation (2.4).

$$N_{max} = \frac{1{,}1 \cdot \tau_{Rk,ucr} \cdot \pi \cdot d \cdot h_{ef}}{1{,}5 \cdot \gamma_{inst}} \cdot \frac{1}{\alpha_2} \cdot \frac{1}{\alpha_3} \cdot \frac{1}{\alpha_4} \qquad (2.3)$$

$$N_{min} = \max\left(0{,}25\ \tau_{Rk,ucr} \cdot \pi \cdot d \cdot h_{ef};\ N_{max} - A_s \cdot \Delta\sigma_s\right) \qquad (2.4)$$

where

$\Delta\sigma_s$ = 120 N/mm²

**Assessment**

During the repeated load portion of the test no failure is allowed to occur and the increase of displacements during the cycling shall stabilize in a manner that failure is unlikely to occur after some additional cycles. If these requirements are not met, repeat the test with load values $N_{max}$ and $N_{min}$ determined based on a reduced value $N_{max,red}$ until the requirements are met. In this case determine $\alpha_p = N_{max,red} / N_{max}$.

Failure loads in the residual load test

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R3.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 1,0 in equation (2.14).

Load displacement behaviour in the residual load test

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.5 Crack cycling under load (test series B13)

**Purpose of test**

Fasteners intended for use in cracked concrete, in the long term, shall continue to function effectively when the width of the crack is subject to changes in the range covered by this EAD. The test series may be omitted for an assessment in uncracked concrete only (option 7-12).

**Test conditions**

The tests shall be carried out according to Technical Report TR 048 in concrete C20/25. The constant tension load $N_p$ shall be calculated from equation (2.5). The sustained load $N_p$ shall be applied with unconfined test setup.

$$N_p = \frac{0{,}75 \cdot \tau_{Rk,cr} \cdot \pi \cdot d \cdot h_{ef}}{1{,}5 \cdot \gamma_{inst}} \cdot \frac{1}{\alpha_2} \cdot \frac{1}{\alpha_3} \cdot \frac{1}{\alpha_4} \qquad (2.5)$$

The residual load test after crack movements shall be done as a confined test.

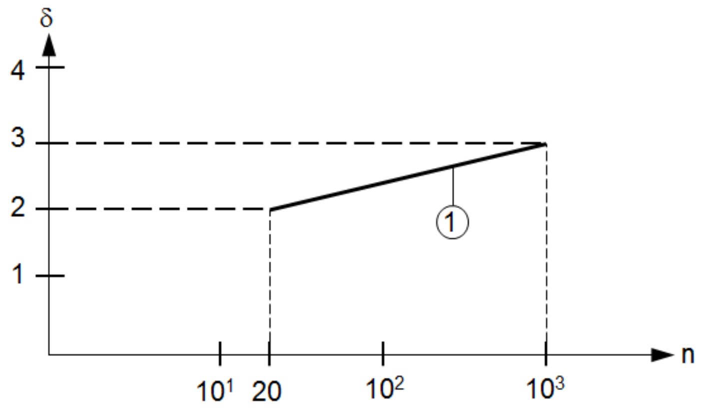
**Assessment**

Displacements during crack cycles

In each test the rate of increase of fastener displacements, plotted in a half-logarithmic scale (see Figure 2.1), shall either decrease or be almost constant: the criteria of the allowable displacement after 20 ($\delta_{20}$) and 1000 ($\delta_{1000}$) cycles of crack opening are graduated as a function of the number of tests as follows:

| | | |
|---|---|---|
| 5 to 9 tests: | $\delta_{20}$ | ≤ 2 mm and $\delta_{1000}$ ≤ 3 mm |
| 10 to 20 tests: | $\delta_{20}$ | ≤ 2 mm; one tests is allowed to 3 mm |
| | $\delta_{1000}$ | ≤ 3 mm; one tests is allowed to 4 mm |
| > 20 tests: | $\delta_{20}$ | ≤ 2 mm; 5% of tests are allowed to 3 mm |
| | $\delta_{1000}$ | ≤ 3 mm; 5% of tests are allowed to 4 mm |

*Note 13 The displacements are considered to be stabilized if the increase of displacements during cycles 750 to 1000 is smaller than the increase of displacements during cycles 500 to 750.*




1 maximum allowable displacement

**Figure 2.1 Criteria for results of tests with variable crack width**

If in the tests the above given requirements on the displacement behaviour, i.e. rate of increase and allowable displacements, are not fulfilled, the test series shall be repeated with a reduced tension load $N_{p,red}$ until the requirements are fulfilled. Calculate the reduction factor according to A2.3.6.

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R3.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 0,9 in equation (2.14).

Load displacement behaviour in the residual load tests

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.2.6 Sustained loads (test series R6, B14 and B15)

**Purpose of the test**

The tests are performed to check the creep behaviour of the loaded fastener at normal ambient temperature (Test series B14) and at maximum long term temperature (test series B15).

**Test conditions**

The tests shall be carried out as confined tests in uncracked concrete C20/25, both at normal ambient temperature and maximum long term temperature with medium diameter size M12 or smallest size if that is larger than M12 as specified by the manufacturer.

The permanent load $N_{sust}$ can be applied by e.g. a hydraulic jack, springs or dead loads (e.g. applied via a lever arm).

a) Tests at normal ambient temperature (test series R6, B14)

Install fasteners at normal ambient temperature (+21°C ±3°C).

Load fastener to $N_{sust}$ according to equation (2.6):

$$N_{sust} = \frac{1{,}1 \cdot \tau_{Rk,ucr,21} \cdot \pi \cdot d \cdot h_{ef}}{1{,}5 \cdot \gamma_{inst}} \cdot \frac{1}{\alpha_2} \cdot \frac{1}{\alpha_3} \cdot \frac{1}{\alpha_4} \qquad (2.6)$$

where

$\tau_{Rk,ucr,21}$ = characteristic bond strength in uncracked concrete for normal ambient temperature as given in the ETA

Maintain the load at $N_{sust}$ and maintain temperature at normal ambient temperature and measure the displacements until they appear to have stabilised, but at least for three months (in special justified cases the TAB may allow a shorter duration for the sustained load test). Temperatures in the room may vary by ± 3 °C due to day/night and seasonal effects but the required test room temperature level shall be achieved as a mean over the test period. The frequency of monitoring displacements shall be chosen so as to demonstrate the characteristics of the fastener. As displacements are greatest in the early stages, the frequency shall be high initially and reduced with time. As an example, the following regime would be acceptable:

| | |
|---|---|
| During first hour: | every 10 minutes |
| During next 6 hours: | every hour |
| During next 10 days: | every day |
| From then on: | every 5-10 days. |

To check the remaining load capacity after the sustained load test, unload the fastener and carry out a confined tension test.

The results of the residual load capacity test shall be compared with the load capacity of reference test series R6.

b) Test at maximum long term temperature (test series B15)

These tests are not needed for temperature range T1, see 1.2.1(-40 °C to +40 °C), because the effect of the maximum long term temperature (+24 °C) is tested under normal ambient temperature.

Install fasteners at normal ambient temperature.

Load fastener to $N_{sust}$ according to equation (2.7):

$$N_{sust} = \frac{1{,}1 \cdot \tau_{Rk,ucr,lt} \cdot \pi \cdot d \cdot h_{ef}}{1{,}5 \cdot \gamma_{inst}} \cdot \frac{1}{\alpha_3} \cdot \frac{1}{\alpha_4} \qquad (2.7)$$

where

$\tau_{Rk,ucr,lt}$ = characteristic bond strength in uncracked concrete for maximum long term temperature as given in the ETA

Raise the temperature of the test chamber to reach the maximum long term temperature at a rate of approximately 20 K per hour or at a rate of 5 K in the concrete in the area of the anchorage.

Maintain the load at $N_{sust}$ and maintain the temperature at the maximum long term temperature. For the duration of the tests, the allowed variation of the temperature of the test chamber and the frequency of monitoring displacements 2.2.2.6 a) applies.

To check the remaining load capacity after the sustained load test, unload the fastener and carry out a confined tension test at the maximum long term temperature.

**Assessment**

The displacements measured in the tests have to be extrapolated according to equation (2.8) (Findley approach) to 50 years (tests at normal ambient temperature), or 10 years (tests at maximum long term temperature), respectively. The trend line according to equation (2.8) may be constructed with data from not less than the last 20 days (minimum of 20 data points) of the sustained load test. The extrapolated displacements shall be less than the mean value of the displacements $\delta_{u,adh}$ in the corresponding reference tests at normal ambient temperature or maximum long term temperature respectively. $\delta_{u,adh}$ is the displacement at $N_{u,adh}$ (loss of adhesion).

$\delta(t) = \delta_o + a \bullet t^b$ (2.8)

where

$\delta_o$: = initial displacement under sustained load at t = 0

a,b: = constants determined by a regression analysis of the deformations measured during the sustained load test

If the test criteria are not fulfilled, the test may be repeated with modified parameters (e.g. reduced load $N_{sust,red}$ or reduced temperature). If the test is repeated with a reduced load calculate the reduction factor $\alpha_p$ according to A2.3.6.

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R6 having the same curing time.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 0,9 in equation (2.14).

Load displacement behaviour in the residual load tests

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.7 Freeze/thaw conditions (test series R7 and B16)

**Purpose of the test**

These tests are performed to determine the performance of the fastener under freeze/thaw conditions simulating varying life conditions.

**Test conditions**

Perform the tests with confined test setup with medium diameter size M12 or smallest size if that is larger than M12. The tests are performed in uncracked freeze-thaw resistant concrete C50/60 in accordance with EN 206 [1]. As test member a cube with side length of 180 mm to 300 mm ~~or~~ (15d to 25d) or a steel encased concrete cylinder shall be used and splitting of concrete shall be prevented.

Cover the top surface of the test member with tap water to a depth of at least 12 mm, other exposed surfaces shall be sealed to prevent evaporation of water.

Load fastener to $N_{sust}$ according to equation (2.9):

$$N_{sust} = \frac{\tau_{Rk,ucr,60} \cdot d \cdot \pi \cdot h_{ef}}{1{,}5 \cdot 1{,}4 \cdot \gamma_{inst}} \quad (2.9)$$

where

$\tau_{Rk,ucr,60}$ characteristic bond strength for concrete strength class C50/60

Carry out 50 freeze/thaw cycles as follows:

- Raise temperature of chamber to (+20 ± 2) °C within 1 hour, maintain chamber temperature at (+20 ± 2) °C for 7 hours (total of 8 hours).
- Lower temperature of chamber to (-20 ± 2) °C within 2 hours, maintain chamber temperature at (-20 ± 2) °C for 14 hours (total of 16 hours).

If the test is interrupted, the samples shall always be stored at a temperature of (- 20 ± 2) °C between the cycles.

The displacements shall be measured during the temperature cycles.

After completion of 50 cycles a confined tension test shall be carried out at normal ambient temperature.

The results of the residual load capacity test shall be compared with the load capacity of reference test series R7.

**Assessment**

The rate of displacement increase shall reduce with increasing number of freeze/thaw cycles to a value almost equal to zero.

If the test criteria are not fulfilled, the test may be repeated with a reduced load $N_{sust,red}$. In this case calculate the reduction factor $\alpha_p$ according to A2.3.6.

Failure loads

- Determine the mean value of failure loads Nu,m [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads Nu,5% [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R7 having the same curing time.
- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 0,9 in equation (2.14).

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.2.8 Installation directions (test series B17)

**Purpose of the test**

The tests are performed to check the performance under unfavourable installation directions. The test series may be omitted for downward installation only (D1).

**Test conditions**

If the manufacturer allows in the MPII all installation directions (D3), tension tests are needed with metal parts installed vertically upwards only. If the manufacturer allows horizontal and vertical downward only (D2), tension tests have to be done with metal parts installed in horizontal direction. Special devices to maintain the fastener in place are used only if stated in the MPII. Such special devices shall also be described in the ETA.

Perform the tests with confined test setup. The tests are performed in low strength concrete C20/25 with largest diameter size applied for by the manufacturer. The tension tests are performed according to Technical Report TR 048.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R1.

- Use the reduction factor $\alpha$ together with rqd. $\alpha$ = 0,9 in equation (2.14).

Load displacement

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.9 Increased temperature (test series B2 and B3)

**Purpose of the test**

These tests are performed to determine the performance of the fastener under increased temperature simulating service conditions that vary within the considered temperature range.

**Test conditions**

The tests shall be carried out with confined test setup in uncracked concrete C20/25 at maximum long term temperature and maximum short term temperature a for each temperature range pplied for.

They may be carried out in slabs or, where space of the heating chamber is restricted, in cubes or cylinders. Splitting of the concrete shall be prevented by means of confinement (dimensions, reinforcement or transverse pressure).

Tests are carried out with fastener M12 (or smallest in range if smallest size is larger than M12).

Install fasteners at normal ambient temperature according to MPII.

Raise test member temperature to required test temperature at a rate of approximately 20 K per hour. Keep the test member at this temperature for 24 hours.

While maintaining the temperature of the test member in the area of the embedded part at a distance of 1 d from the concrete surface at ± 2 K of the required value, carry out confined tension test.

*Note 14 The check that the requirement on the temperature in the test member is fulfilled shall be done once and then the test procedure shall be kept constant.*

Number of tests: n ≥ 5 tests per temperature.

**Assessment:**

The influence of increased temperature is determined based on a comparison of mean failure loads as well as 5%-fractile of failure loads.

**Maximum long term temperature**

From the failure loads measured in the tests at maximum long term temperature the factor $\alpha_2$ shall be calculated according to equation (2.10):

$$\alpha_2 = \min\left(\frac{N_{Ru,m,mlt}}{N_{Ru,m,r}};\frac{N_{u,5\%,mlt}}{N_{u,5\%,r}}\right) \le 1{,}0 \qquad (2.10)$$

**Maximum short term temperature**

From the failure loads measured in the tests at maximum short term temperature the factor $\alpha_3$ shall be calculated according to equation (2.11):

$$\alpha_3 = \min\left(\frac{N_{Ru,m,mst}}{0{,}8 \cdot N_{Ru,m,mlt}};\frac{N_{u,5\%,mst}}{0{,}8 \cdot N_{u,5\%,mlt}}\right) \le 1{,}0 \qquad (2.11)$$

For temperature range T1 according to 1.2.1 the results of tests at normal ambient temperature $\tau_{u,m,mlt}$; $\tau_{u,5\%,mlt}$ may be taken.

The comparison of the 5%-fractile may be omitted for any number of tests in a test series when the coefficient of variation of the test series is smaller than or equal to the coefficient of variation of the reference test series or if the coefficient of variation in both test series is smaller than 15 %.

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.

Load displacement

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.2.10 Minimum installation temperature (test series B4)

**Purpose of the test**

The test is required to check sufficient load bearing capacity at minimum installation temperature after specified minimum curing time.

**Test conditions**

The tests are performed in uncracked concrete C20/25. For test member dimensions, see "Increased temperature" section 2.2.2.9.

Perform the test with medium size M12 (or smallest in range if smallest size is larger than M12).

Drill and clean hole according to MPII then cool test member to the minimum installation temperature specified by the manufacturer and the bonding material and embedded part to the lowest fastener component installation temperature specified by the manufacturer. Install the fastener and maintain the temperature of the test member at the lowest installation temperature for the curing time quoted by the manufacturer at that temperature.

Carry out confined tension test at the end of the curing time while maintaining the temperature of the test member in the area of the embedded part at a distance of 1d from the concrete surface at the specified lowest installation temperature ± 2K.

*Note 15 It may be that some cartridge-in-cartridge systems do not ensure the correct mixing ratio over the full content of the cartridge because of a failure of the seam which cause opening of one of the cartridges especially at low installation temperature. Therefore additional benchmark tests with these systems are recommended; especially at the lowest installation temperature.*

*Note 16 The check that the requirement on the temperature in the test member is fulfilled shall be done once and then the test procedure shall be kept constant.*

Number of tests: $n \geq 5$ tests

**Assessment**

The mean failure loads and the 5% fractile of failure loads measured in tests at the minimum installation temperature and corresponding minimum curing time shall be at least equal to the corresponding values measured in tests at normal ambient temperature and corresponding minimum curing time. These requirements apply also for the tests at other installation temperatures and corresponding minimum curing times.

If the condition is not fulfilled, then the minimum curing time at the minimum installation temperature shall be increased and the tests at minimum installation temperature shall be repeated until the condition is fulfilled.

The comparison of the 5%-fractile may be omitted for any number of tests in a test series when the coefficient of variation of the test series is smaller than or equal to the coefficient of variation of the reference test series or if the coefficient of variation in both test series is smaller than 15 %.

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.

<u>Load displacement</u>

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.11 Minimum curing time at normal ambient temperature (test series B5)

**Purpose of the test**

The test is required to check sufficient load bearing capacity after specified minimum curing time.

**Test conditions**

Perform confined tension tests in uncracked concrete C20/25 at normal ambient temperature at the corresponding minimum curing time specified by the manufacturers. Test with medium diameter size M12 or smallest size if that is larger than M12.

*Note 17 One series of reference tests R1 may be performed at minimum curing time.*

Number of tests: $n \geq 5$ tests

**Assessment**

The mean failure loads and the 5% fractile of failure loads measured in tests at the normal ambient temperature and corresponding minimum curing time shall be at least 0,9 times the values measured in reference tests and basic tension tests according to Table A1.1 with a "long curing time" (24 hours for resins, 14 days for cementitious mortars).

If this condition is not fulfilled, then the minimum curing time at normal ambient temperature shall be increased and the corresponding tests shall be repeated.

The comparison of the 5%-fractile may be omitted for any number of tests in a test series when the coefficient of variation of the test series is smaller than or equal to the coefficient of variation of the reference test series or if the coefficient of variation in both test series is smaller than 15 %.

<u>Failure loads</u>

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength and accounting for concrete batch influence according to paragraphs A2.3.2 and A2.3.4, respectively.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.

<u>Load displacement</u>

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.2.12 Sensitivity to sulphurous atmosphere and high alkalinity (tests series R8, B18 and B19)

**Purpose of the test**

These tests are performed to determine the performance of the fastener under sulphurous atmosphere and high alkalinity.

**Test conditions**

**Test specimen**

Perform the test with medium diameter size M12 or smallest size if that is larger than M12.

The concrete compressive strength class shall be C20/25. The diameter or side length of the concrete specimen shall be equal to or exceed 150 mm. The test specimen may be manufactured from cubes or cylinders or may be cut from a larger slab. They can be cast; it is also allowed to diamond core concrete cylinders from slabs.

One fastener (medium size M12 or smallest size if the smallest size is larger than M12) to be installed per cylinder or cube on the central axis in dry concrete according to the MPII . The embedded part shall be made out of stainless steel.

After curing of the bonding material according to MPII the concrete cylinders or cubes are carefully sawn into 30mm thick slices with a diamond saw. The top slice shall be discarded.

To gain sufficient information from the slice tests, at least 30 slices are necessary (10 slices for every environmental exposure test and 10 slices for the comparison tests under normal climate conditions).

Storage of the test specimen under environmental exposure:

The slices with bonding fasteners are subjected to water with high alkalinity and condensed water with sulphurous atmosphere. For comparison tests slices stored under normal climate conditions (dry / +21 °C $\pm$ 3 °C / relative humidity 50 $\pm$ 5%) for 2000 hours are necessary.

**High Alkalinity (test series B18)**

The slices are stored under standard climate conditions in a container filled with an alkaline fluid (pH = 13,2). All slices shall be completely covered for 2.000 hours. The alkaline fluid is produced by mixing water with KOH (potassium hydroxide) powder or tablets until the pH-value of 13,2 is reached. The alkalinity of pH = 13,2 shall be kept as close as possible to 13,2 during the storage and not fall below a value of 13.0. Therefore the pH-value has to be checked and monitored in regular intervals (at least daily). The producing of alkaline fluid by mixing water with KOH (potassium hydroxide) powder or tablets could be given as an example. If other materials are used then it has to be shown that same results and comparable assessment are achieved.

**Sulphurous atmosphere (test series B19)**

The tests in sulphurous atmosphere shall be performed according to EN ISO 6988 [4]. The slices are put into the test chamber, however in contrast to EN ISO 6988 the theoretical sulphur dioxide concentration shall be 0,67 % at beginning of a cycle. This theoretical sulphur dioxide concentration corresponds to 2 $dm^3$ of $SO_2$ for a test chamber volume of 300 $dm^3$. At least 80 cycles shall be carried out.

**Slice tests**

After removal from storage the thickness of the slices is measured and the metal segments of the bonded fasteners are pushed out of the slice, the slice is placed centrally to the hole of the steel rig plate. If slices are unreinforced then splitting may be prevented by confinement. Care shall be taken to ensure that the loading punch acts centrally on the fastener rod.

The results of at least 10 tests shall be taken for every environmental exposure and for comparison. Results with splitting failure shall be ignored.

**Reference test series (tests series R8)**

The reference test series R8 shall be performed under the same test conditions but the fasteners shall be kept unloaded and stored under normal ambient conditions.

**Assessment**

It shall be shown that the bond strength of the slices stored in an alkaline liquid is at least as high as that of the bond strength of the comparison tests on slices stored under normal conditions. For slices stored in sulphurous atmosphere at least 90% of the bond strength under normal conditions shall be achieved. To show compliance with this requirement the factor $\alpha_4$ shall be calculated according to equation (2.12).

$$\alpha_4 = \min\left(\frac{\tau_{Ru,m,B18}}{\tau_{Rum,r}}; \frac{\tau_{Ru,m,B19}}{0{,}9 \cdot \tau_{Rum,r}}\right) \leq 1{,}0 \qquad (2.12)$$

The reference bond strength $\tau_{um,r}$ is gained in the test series Table A.1, line R8.

The bond strength in the slice tests shall be calculated according to equation (2.13).

$$\tau_u = \frac{N_u}{\pi \cdot d \cdot h_{sl}} \qquad (2.13)$$

### 2.2.2.13 Determination of the characteristic bond resistance

The characteristic bond resistance $\tau_{Rk}$ shall be determined according to equation (2.14).

$$\tau_{Rk} = \tau_{5\%} \cdot \alpha_{setup} \cdot \min ß_{cv} \cdot \min \alpha_p \cdot \min(\min \frac{\alpha}{rqd.\alpha}; \min \alpha_1) \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 \qquad (2.14)$$

For cracked concrete apply min $\alpha_p$ of sustained load tests, freeze thaw tests and crack cycling tests.

For uncracked concrete apply min $\alpha_p$ of sustained load tests, repeated load tests and freeze thaw tests.

If the test data show that the bond strengths vary in a regularly definable way (not randomly) with respect to fastener diameter, then the values $\tau_{Rk}$ may be evaluated as a continuous function of the fastener diameter. Also a function with no more than one extremum is possible if all test results show this product behaviour; e.g. it does not come from the influence of the different concrete batches.

The characteristic bond resistance shall be rounded according to Table 2.2.

The factor $\psi_c$ can be used as an increasing factor to express the bond strength for different concrete strength classes.

**Table 2.2 Rounding steps for characteristic bond resistance**

| $\tau_{Rk}$ [N/mm²] | step $\Delta\tau_{Rk}$ [N/mm²] | example |
|---|---|---|
| ≤ 10 | 0,5 | 4 / 4,5 / 5 / 5,5 … |
| > 10 ≤ 20 | 1,0 | 12 / 13 / 14 / 15… |
| > 20 | 2,0 | 26 / 28 / 30 / 32 … |

### 2.2.3 Resistance to concrete cone failure

### 2.2.3.1 Single Fasteners

The design according to EN 1992-4 needs the factors $k_{ucr,N}$ and $k_{cr,N}$. The following factors can be taken without further testing. They are related to concrete cylinder strength.

$k_{ucr,N}$ = 11

$k_{cr,N}$ = 7,7

$c_{cr,N}$ = 1,5 $h_{ef}$

### 2.2.3.2 Minimum embedment depth (test series A6)

**Purpose of the test**

This test series is performed to check whether a group of 4 fasteners with a minimum embedment depth below the standard default values are consistent with the design provisions in EN 1992-4.

*Note 18 Groups of fasteners with short embedment depth may not create the calculated resistance of concrete cone capacity according to EN 1992-4 with the factors given in 2.2.3.1 which was derived for larger embedment depth.*

The test series may be omitted if the default minimum embedment depth according to Table 2.3 is kept. If the manufacturer applies for smaller embedment depth but still larger or equal to $h_{ef,min}$ = 4d, the test series according to Table A1.1 line A6 are required.

**Table 2.3 Default minimum embedment depth**

| Diameter d | Minimum embedment depth $h_{ef,min}$ | Default minimum embedment depth $h_{ef,min}$ |
|---|---|---|
| [mm] | [mm] | [mm] |
| ≤ 10 | 4 d, > 40 mm | 60 |
| 12 | | 70 |
| 16 | | 80 |
| 20 | | 90 |
| ≥ 24 | | 4 d |

*Note 19 In cases of such lower values of minimum embedment depth (and hence small amount of bonding material) special attention should be paid to the mixing quality of bonding material under various temperature conditions.*

**Test conditions**

The fasteners shall be installed at minimum embedment depth $h_{ef,min}$ as a quadruple group with a spacing $s_{cr,N}$ = 2 $c_{cr,N}$. The tension test until failure shall be carried out as unconfined test setup in uncracked concrete C20/25 in accordance with Technical Report TR 048. At least 20 tests shall be performed with each 5 tests on quadruple fastener groups with the smallest 4 sizes.

**Assessment**

Determine the mean failure load of the quadruple fasteners group in the test series. Determine the theoretical concrete cone capacity $N_{Rk,c}$ according to EN 1992-4 equation (7.1) for the group of fasteners as the reference. For assessment according to section A2.3.7 replace in equation (A2.18) $F_{u.5\%,r}$ by $N_{Rk,c}$.

Criteria:

- $N_{u,m} \geq 0,9\ N_{Rk,c} / 0,75$: min $h_{ef}$ as tested is confirmed
- $N_{u,m} < 0,9\ N_{Rk,c} / 0,75$: min $h_{ef}$ shall be increased and tested again (or shall be increased to the default minimum embedment depth $h_{ef,\ min}$ according to Table 2.3 without further testing)

where

$N_{Rk,c}$ / 0,75 = calculated mean value of concrete cone failure according to EN 1992-4 with

cv = 15%, k = 1,645: (1-0,15*1,1645) = 0,75

### 2.2.4 Edge distance to prevent splitting under load (test series A5)

**Purpose of the test**

The test series is performed to determine the characteristic edge distance at which splitting is not decisive.

**Test conditions**

The tests are required for small, medium and large diameter size and the corresponding minimum embedment depths. Test the fasteners in uncracked concrete C20/25 with unconfined test setup. Install the fasteners in the corner of the test member with minimum thickness $h_{min}$ applied for the fastener at equal edge distances $c_1 = c_2$. Edge distance and minimum thickness of the concrete are proposed by the manufacturer. Perform a tension test according to Technical Report TR 048, section 3.3.1.

**Assessment**

The characteristic edge distance $c_{cr,sp}$ is evaluated from the results of tension tests on single fasteners at the corner ($c_1 = c_2 = c_{cr,sp}$). The mean bond strength in the test series with fasteners at the corner shall be statistically equivalent to a fastener without edge and spacing effects (Table A1.1, line A1) for the same concrete strength. If this condition is not fulfilled, the edge distance shall be increased accordingly.

The characteristic resistance to splitting $N^0_{Rk,sp}$ shall be determined in the design provisions as the minimum of the basic characteristic resistance to pull-out failure $N^0_{Rk,p}$ and the basic characteristic resistance to concrete failure $N^0_{Rk,c}$, i.e. min $\{N^0_{Rk,p}; N^0_{Rk,c}\}$.

In the ETA the value for $N^0_{Rk,sp}$ shall be given as the text "min $\{N^0_{Rk,p}; N^0_{Rk,c}\}$ according to EN 1992-4". For bonded expansion fastener the text should read "min $\{N_{Rk,p}; N^0_{Rk,c}\}$ according to EN 1992-4".

### 2.2.5 Robustness

**Purpose of the test**

These tests are performed to assess the sensitivity of the fastener tension capacity to installation conditions. In this context the sensitivity to the degree of hole cleaning in dry and water saturated concrete, to hole cleaning for applications where the hole contains standing water at the time of installation of the fastener and to mixing effort are considered.

**Test conditions - general**

The tests shall be carried out as confined tension tests in uncracked concrete C20/25. The fasteners are installed with the maximum embedment depth $h_{ef,max}$ defined by the manufacturer. To avoid steel failure but still account properly for the installation aspects for $h_{ef,max}$ the procedure given in section A2 shall be applied.

Additional test conditions for the specific test series B6 to B9 are given below. The following test conditions are defined for drilling the hole with a hammer drilling technique producing drilling dust that has to be removed from the bore hole by blowing (sucking) and brushing. The conditions are also valid for other drilling techniques, which require different methods of bore hole cleaning. However some modifications of the tests might be necessary which shall be agreed by the TAB.

**Assessment**

The assessment for the test series B6 to B9 is carried out according to A2.3.2 accounting for the normalization to the nominal concrete strength. The reduction factor $\alpha$ for each test series is calculated using the corresponding reference test series R5.

Based on the results of these tests the factor $\gamma_{inst}$ accounting for the sensitivity to installation is determined according to 2.2.5.6.

The factor $\gamma_{inst}$ accounting for the sensitivity to installation for all sizes of the fastener shall follow a regular curve.

#### 2.2.5.1 Reference test series (test series R5)

**Purpose of the test**

The test series is needed as reference for comparison of test results in test series B6 to B9.

**Test conditions**

The tests shall be performed with fastener sizes s/m/l (see Table A1.2) with maximum embedment depth in uncracked concrete C20/25. To avoid steel failure see Figure A2.1.The tests shall be performed in dry concrete (equilibrium moisture content).

The test conditions as concrete batch, temperature, drilling method, embedment depth, curing time and setting torque shall be the same as for test series B6 to B9.

Drill downwards to the maximum embedment depth defined by the manufacturer. Clean the drill hole according to the MPII. Place the bonding material and insert the metal part in accordance with the MPII.

Perform a confined tension test according to TR 048.

**Assessment**

<u>Failure loads</u>

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.

<u>Load displacement behaviour</u>

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.5.2 Robustness in dry substrate (test series B6)

**Purpose of the test**

The test series is performed to assess the influence of reduced cleaning effort in dry concrete.

**Test conditions**

The tests shall be performed with fastener sizes s/m/l (see Table A1.2) with maximum embedment depth in uncracked concrete C20/25. To avoid steel failure see Figure A2.1.The tests shall be performed in dry concrete (equilibrium moisture content).

Drill downwards to the maximum embedment depth defined by the manufacturer.

The following cleaning process of the hole has to be carried out in the tests.

Clean the hole with the equipment supplied by the manufacturer using two blowing operations by hand pump or compressed air and one brushing operation, i.e. either blow-brush-blow or blow-blow-brush or brush-blow-blow. The type of blowing and the order of brushing/blowing shall be done as prescribed in the MPII. This test procedure is valid only if the MPII specify hole cleaning with at least four blowing and two brushing operations, meaning twice the operations given above. If the MPII specify less than this, the above requirement (2 blows + 1 brush) shall be reduced proportionately and the number of blows/brushes shall be lowered to the next whole number. Therefore where the MPII recommend two blowing and one brushing operations, the tests shall be carried out without the brushing operation and one blowing only.

If the MPII recommends a vacuum cleaning instead of a blowing operation, the same procedure (including requirements and corresponding reduced operations) applies. If the vacuum cleaning is part of the drilling process, the drilling shall be done without venting (meaning, airing out the dust by periodically moving the drill bit out of the hole) during the drilling process." If the cleaning is performed with suction bit or a hollow drill bit, then the vacuum with the smallest specified maximum flow rate shall be used during the drilling process.

If precise instructions for hole cleaning are not provided by the MPII, the tests are carried out without hole cleaning.

Place the bonding material and insert the metal part in accordance with the MPII.

**Assessment**

<u>Failure loads</u>

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F > 20\%$), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R5.
- Determine the robustness factor $\gamma_{inst}$ according to Table 2.4.
- If $\alpha < 0,70$ use the reduction factor $\alpha$ together with rqd. $\alpha = 0,70$ in equation (2.14) and $\gamma_{inst} = 1,4$.

<u>Load displacement behaviour</u>

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.5.3 Robustness in water saturated (wet) substrate (test series B7)

**Purpose of the test**

The test series is performed to assess the influence of reduced cleaning effort in water saturated concrete.

**Test conditions**

The tests shall be performed with fastener sizes s/m/l (see Table A1.2) with maximum embedment depth in uncracked concrete C20/25. To avoid steel failure see Figure A2.1.

The concrete in the area of anchorage shall be water saturated when the hole is drilled, cleaned and the embedded metal part is installed and tested.

The following procedure may be applied to ensure a water saturated concrete in the area of the anchorage:

1. A pilot hole is drilled in the concrete substrate to the recommended depth.
2. The pilot hole is filled with water and remains flooded for 8 days until water has percolated into the concrete.
3. The water is removed from the pilot hole.
4. The final hole is drilled at the recommended diameter $d_0$.

*Note 20 The diameter of the pilot hole shall be chosen such that sufficient penetration of water into the concrete is achieved. Therefore the diameter of the pilot hole of 0,5 $d_0$ to 0,8 $d_0$ is recommended.*

If methods other than those described above are used it shall be shown by appropriate methods that the concrete in the area of the anchorage is water saturated (e.g. concrete is stored under water immediately after stripping the formwork).

Clean the hole with the equipment supplied by the manufacturer using two blowing operations by hand pump or compressed air and one brushing operation, i.e. either blow-brush-blow or blow-blow-brush or brush-blow-blow. The type of blowing and the order of brushing/blowing shall be done as prescribed in the MPII. This test procedure is valid only if the MPII specify hole cleaning with at least four blowing and two brushing operations, meaning twice the operations given above. If the MPII specify less than this, the above requirement (2 blows + 1 brush) shall be reduced proportionately and the number of blows/brushes shall be lowered to the next whole number. Therefore where the MPII recommend two blowing and one brushing operation, the tests shall be carried out without the brushing operation and one blowing only.

If the MPII recommends a vacuum cleaning instead of a blowing operation, the same procedure (including requirements and corresponding reduced operations) applies. If the vacuum cleaning is part of the drilling process, the drilling shall be done without venting (meaning, airing out the dust by periodically moving the drill bit out of the hole) during the drilling process." If the cleaning is performed with suction bit or a hollow drill bit, then the vacuum with the smallest specified maximum flow rate shall be used during the drilling process.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R5.
- Determine the robustness factor $\gamma_{inst}$ according to Table 2.4.
- If $\alpha < 0,65$ use the reduction factor $\alpha$ together with rqd. $\alpha = 0,65$ in equation (2.14) and $\gamma_{inst} = 1,4$.

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.5.4 Robustness in water-filled hole (test series B8)

**Purpose of the test**

The test series is performed to assess the influence of reduced cleaning effort in water saturated concrete and water filled holes.

These tests are not required for fasteners where the MPII state that water shall be completely removed before fastener installation. Installation instructions shall make it clear that simply inserting a capsule or injecting bonding material does not adequately remove water, and a proper process shall be described to remove water completely.

**Test conditions**

The tests shall be performed with fastener sizes s/m/l (see Table A1.2) with maximum embedment depth in uncracked concrete C20/25. To avoid steel failure see Figure A2.1.

The tests are made in concrete which is water saturated in the area of the anchorage. To ensure a water saturated concrete in the area of the anchorage the procedure of 2.2.5.3 shall be applied.

Clean the hole with the equipment supplied by the manufacturer using two blowing operations by hand pump or compressed air and one brushing operation, i.e. either blow-brush-blow or blow-blow-brush or brush-blow-blow. The type of blowing and the order of brushing/blowing shall be done as prescribed in the MPII. This test procedure is valid only if the MPII specify hole cleaning with at least four blowing and two brushing operations, meaning twice the operations given above. If the MPII specify less than this, the above requirement (2 blows + 1 brush) shall be reduced proportionately and the number of blows/brushes shall be lowered to the next whole number. Therefore where the MPII recommend two blowing and one brushing operations, the tests shall be carried out without the brushing operation and one blowing only.

If the MPII recommends a vacuum cleaning instead of a blowing operation, the same procedure (including requirements and corresponding reduced operations) applies. If the vacuum cleaning is part of the drilling process, the drilling shall be done without venting (meaning, airing out the dust by periodically moving the drill bit out of the hole) during the drilling process." If the cleaning is performed with suction bit or a hollow drill bit, then the vacuum with the smallest specified maximum flow rate shall be used during the drilling process.

After cleaning the hole, fill the hole with water. Without removing the water from the hole, place the bonding material and insert the embedded metal part as described in the MPII.

**Assessment**

<u>Failure loads</u>

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R5.
- Determine the robustness factor $\gamma_{inst}$ according to Table 2.4.
- If $\alpha < 0,65$ use the reduction factor $\alpha$ together with rqd. $\alpha = 0,65$ in equation (2.14) and $\gamma_{inst} = 1,4$.

<u>Load displacement behaviour</u>

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

### 2.2.5.5 Robustness of mixing technique (test series B9)

**Purpose of the test**

The test series is performed to assess the influence of the mixing technique.

Tests are only required for those fastener types where the mixing technique is ensured by the installer, such techniques include:

a) mixing components until a colour change is achieved throughout the material.

b) mixing with recommended equipment for a specified time.

c) carrying out a repetitive mixing operation for a specified number of times.

The test may be omitted if the mixing of the mortar is ensured by use of capsule type systems according to Figure 1.1 or static mixers of injection type systems according to Figure 1.2.

**Test conditions**

Perform the test with medium diameter size M12 or smallest size if that is larger than M12 with maximum embedment depth in uncracked concrete C20/25. To avoid steel failure see Figure A2.1.

Tests shall be carried out on incomplete mixes, i.e. by reducing the specified process by 25 %. For example, in the case of missing technique a) mentioned above, the test is carried out after mixing for 75 % of the time taken to achieve an even colour throughout the material.

**Assessment**

Failure loads

- Determine the mean value of failure loads $N_{u,m}$ [kN], converted to the nominal concrete strength.
- Determine the 5% fractile of the failure loads $N_{u,5\%}$ [kN], converted to the nominal concrete strength.
- Verify the coefficient of variation of failure loads. If the coefficient of variation exceeds 20% ($cv_F$ > 20%), determine the reduction factor for large scatter $ß_{cv}$ according to A2.3.4.
- Determine the reduction factor $\alpha$ according to Annex A comparing the test results with reference test series according to Table A1.1 line R5.
- Determine the robustness factor $\gamma_{inst}$ according to Table 2.4.
- If $\alpha < 0,70$ use the reduction factor $\alpha$ together with rqd. $\alpha = 0,70$ in equation (2.14) and $\gamma_{inst} = 1,4$.

Load displacement behaviour

- Determine the reduction factor $\alpha_1$ according to Annex A.
- Determine the displacements at 50% of the mean failure load $\delta_{0,5Nu,m}$ [mm] in each test.
- Determine the coefficient of variation of the displacements at 50% of the mean failure load $cv_\delta$ [%]. If the displacements at 50% of the failure load are larger than 0,4 mm, $cv_\delta$ shall not exceed 40 %.

#### 2.2.5.6 Assessment of the factor for sensitivity to installation

The factor $\gamma_{inst}$ accounting for the sensitivity to installation is evaluated from the results of the tests for robustness i.e. test series B6 to B9.

For each test series B6 to B9 as applied by the manufacturer the factor $\gamma_{inst}$ shall be determined according to Table 2.4 by comparing the factor α with the value of rqd α for the specific test. The largest resulting factor $\gamma_{inst}$ applies.

**Table 2.4 Values of rqd. $\alpha$ in the sensitivity to robustness tests for bonded fasteners**

| factor $\gamma_{inst}$ | rqd. $\alpha$ for tests according to Table A1.1, respectively | |
|---|---|---|
| | lines B6 and B9 | lines B7 and B8 |
| 1,0 | ≥ 0,95 | ≥ 0,90 |
| 1,2 | ≥ 0,80 | ≥ 0,75 |
| 1,4 | ≥ 0,70 | ≥ 0,65 |

### 2.2.6 Minimum edge distance and spacing (test series B1)

**Purpose of the test**

The tests are performed to check that splitting of the concrete does not occur during the installation of the fastener.

**Test conditions**

The tests are required for small, medium and large diameter size. The tests shall be performed according to Technical Report TR 048, section 3.3.1 in uncracked concrete C20/25 with the embedment depth requested by the manufacturer. For bonded fasteners with several embedment depths (variable embedment depth) the minimum requested embedment depth shall be used. The fasteners shall be placed on an uncast side of the concrete test member with a distance $a \geq 3\, h_{ef}$ between neighbouring groups.

Install two fasteners at minimum edge distance $c_{min}$ and minimum spacing $s_{min}$ in a test member with the minimum thickness $h_{min}$ applied for the fastener.

The minimum edge distance $c_{min}$ and minimum spacing $s_{min}$ of the fasteners are specified by the manufacturer. Edge distance and axial spacing shall be rounded to at least 5 mm. They shall not be smaller than 4 $d_0$ and 35 mm.

**Assessment:**

For applications in cracked concrete it is assumed that reinforcement will be activated once the first crack occurs. Consequently, a lower margin between the applied torque at crack formation and the specified installation torque is accepted. This may lead to different values of ($s_{min}$, $c_{min}$) for applications in cracked or uncracked concrete.

The minimum spacing $s_{min}$ and minimum edge distance $c_{min}$ shall be evaluated from the results of tests with double fastener groups ($c = c_{min}$, $s = s_{min}$). The 5 %-fractile of the torque moments, $T_{5\%}$, calculated according to section A2.3.5) at which a hairline crack has been observed at one fastener of the double fastener group, shall fulfil equation (2.15).

$$T_{5\%} \geq k \cdot \max T_{fix} (f_c / f_{c,t})^{0,5} \quad \text{(for concrete failure)} \qquad (2.15)$$

max $T_{fix}$ is specified by the manufacturer. The following values for k shall be taken:

(a) Scatter of the friction coefficients which determine the magnitude of the splitting forces at the required or recommended torque moment respectively is controlled during production to the values present with the fasteners used in the tests

k = 1,3 fastenings in cracked concrete
= 1,7 fastenings in uncracked concrete.

(b) Scatter of the friction coefficients which determine the magnitude of the splitting forces at the required or recommended torque moment respectively is not controlled during production to the values present with the fasteners used in the tests

k = 1,5 fastenings in cracked concrete
= 2,1 fastenings in uncracked concrete.

The choice of (a) or (b) in the assessment has to be reflected in the FPC.

The splitting forces at the required or recommended torque moment respectively depend on the pre-stressing force generated during torqueing and the ratio splitting force to pre-stressing force. Pre-stressing force and splitting force may be measured in appropriate tests (see Technical Report TR 048).

*Note 21 If steel failure occurs in this test series, increase of the edge distance and spacing will not change the failure mode and the tested edge distance and spacing apply.*

If the criteria are not fulfilled, the minimum edge distance and spacing may be increased without further testing according to the following assessment:

- Calculate the projecting area $A_{sp,t} = (3\ c_{min} + s_{min})(1,5\ c_{min} + h_{ef})$ with edge distances and spacing as tested.
- Calculate k from equation (2.15) as tested
- Calculate $A_{sp}$ with enlarged $c_{min}$ and/or $s_{min}$ and verify $A_{sp}$ > rqd. k / k $A_{sp,t}$.

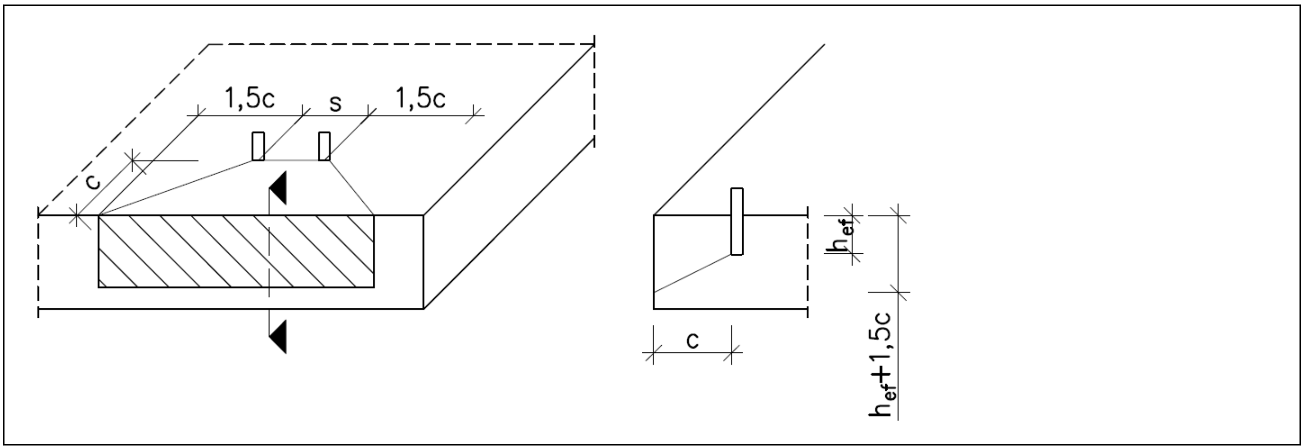



**Figure 2.2 Projecting Area $A_{sp}$**

### 2.2.7 Resistance to steel failure under shear load (test series V1 and V2)

#### 2.2.7.1 Single fastener (test series V1)

The characteristic resistance to steel failure may be calculated for steel elements with constant strength over the length of the element as given below. The smallest cross section of the fastener in the area of load transfer applies.

$$V^0_{Rk,s} = \alpha_v \cdot A_s \cdot f_{uk} = 0{,}5 \cdot A_s \cdot f_{uk} \quad [N] \qquad (2.16)$$

$$M^0_{Rk,S} = 1{,}2 \cdot W_{el} \cdot f_{uk} \quad [Nm] \qquad (2.17)$$

*Note 22 The value $\alpha_V = 0{,}5$ is recommended for carbon steel with an ultimate steel tensile strength up to 1000 N/mm². For ultimate steel strength smaller than 500 N/mm² this value is considered conservative. The design provisions EN 1992-4 are valid for embedded metal parts with a nominal steel tensile strength of $f_{uk} \leq 1000$ N/mm².*

If equation (2.16) is not applicable, the characteristic resistance to steel failure $V_{Rk,S}$ shall be determined by tests.

**Purpose of the test**

These tests are performed to determine the shear capacity of a single fastener without edge influence and thereby establishing the performance characteristics $V_{Rk,s}$ as well as for the determination of the displacement under shear load.

The tests are required only if the fastener has a significantly reduced section along the load transfer zone of the fastener with respect to shear loads or when more than one part of the fastener is used for the transfer of shear loads. For all other fasteners the shear capacity may be determined according to equations (2.16) and (2.17).

The test series is also needed for determination of the displacements $\delta_{V0}$ in section 2.2.10.

**Test conditions**

The tests shall be performed in uncracked concrete C20/25 according to Technical Report TR 048, section 3.6.1. The tests shall be performed with all diameter sizes at minimum embedment depth. The clearance hole in the fixture shall not be larger than specified in Table 2.5.

**Table 2.5 Diameter of clearance hole in the fixture**

| external diameter[1)]<br>d or $d_{nom}$ [mm] | 6 | 8 | 10 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 27 | 30 | > 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| diameter $d_f$ of clearance hole in the fixture [mm] | 7 | 9 | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 30 | 33 | d+3 mm or<br>$d_{nom}$ +3 mm |

1) d if bolt bears against the fixture
$d_{nom}$ if sleeve bears against the fixture

**Assessment**

The following assessment shall be made for each fastener size and for the smallest embedment depth where steel failure occurs:

<u>Failure loads</u>

- Determine the mean value of failure loads $V_{Ru,m}$.
- Determine $V^0_{Rk,s} = V_{u,5\%}$ as the 5% fractile of the failure loads $V_{u,5\%}$ [kN], converted to the nominal steel strength, according to equation (A2.8).

#### 2.2.7.2 Group of fasteners (ductility factor $k_7$)

The characteristic resistance of a group of fasteners in case of steel failure is influenced by the ductility of the fastener. The factor $k_7$ accounts for this influence and is required in EN 1992-4.

The factor $k_7$ may be assumed as follows:

$k_7$ = 1,0 for ductile steel characterized by a rupture elongation $A_5 > 8\%$;

$k_7$ = 0,8 for steel characterized by a rupture elongation $A_5 \leq 8\%$.

### 2.2.8 Resistance to pry-out failure (test series V2)

**Purpose of the test**

The test series is performed to determine the $k_8$ factor for design according to EN 1992-4 for pry-out failure. The test series is optional. If the tests are not performed, the default values for $k_8$ according to Table 2.6 apply.

**Table 2.6 Default values for $k_8$**

| Effective embedment depth $h_{ef}$ [mm] | $k_8$ [-] |
|---|---|
| < 60 mm | 1,0 |
| ≥ 60 mm | 2,0 |

**Test conditions**

The tests shall be performed with a group of 4 fasteners in uncracked concrete C20/25 according to Technical Report TR 048, section 3.6.2. The spacing is selected as $s = s_{cr,N}$ and the edge distance $c \geq c_{cr,N}$. If steel failure occurs, the spacing may be reduced.

**Assessment**

The 5% fractile of failure loads in the test series $V_{u,5\%}$ are compared to the characteristic resistance of the fastener group to tension load in uncracked concrete $N_{Rk,ucr}$ according to equations (2.18) and (2.19).

$$k_8 = \frac{V_{u,5\%}}{N_{Rk,ucr}} \tag{2.18}$$

$$N_{Rk,ucr} = k_{ucr} \cdot h_{ef}^{1,5} \cdot \sqrt{f_{c,t}} \cdot \frac{(s + 3h_{ef})^2}{9{h_{ef}}^2} \tag{2.19}$$

### 2.2.9 Resistance to concrete edge failure

Geometrical data $d_{nom}$ and $\ell_f$ used for design according to EN 1992-4 are given as follows:

$d_{nom}$ outside diameter of the fastener relevant for shear loading

$\ell_f$ effective length of the fastener for transfer of shear load

### 2.2.10 Displacements under short term and long term loading

**Assessment**

As a minimum the displacements under short term loading and long term loading shall be determined for the maximum service load. They may be given as absolute values given in [mm] or relative values either per unit bond stress given in [mm/(N/mm$^2$)] or per unit load given in [mm/kN].

The displacements under short term tension and shear loading ($\delta_{NO}$ and $\delta_{VO}$) are evaluated from the tests on single fasteners without edge or spacing effects. The value derived shall correspond approximately to the 95 %-fractile for a confidence level of 90 %.

The short term tension and shear displacements $\delta_{NO}$ and $\delta_{VO}$ depend on the concrete strength class and state of the concrete (uncracked, cracked). However, it is sufficient to give one value each for the tension and shear displacement which represents the most unfavourable condition and which is valid for all concrete strength classes and cracked and uncracked concrete.

Under shear loading, the displacements might increase due to a gap between fixture and fastener. The influence of this gap is taken into account in design (see EN 1992-4). It shall be stated clearly in the ETA if this gap is taken into account in the assessment.

In the absence of other information $\delta_{N\infty}$ may be calculated as follows:

For fasteners to be used in cracked concrete the long term displacements under tension loading, $\delta_{N\infty}$, shall be calculated from the results of tests with crack cycling under load (see Table A1.1, line B13) according to equation (2.20).

$$\delta_{N\infty} = \frac{\delta_{m1}}{1{,}5} \qquad (2.20)$$

For fasteners to be used in uncracked concrete only, the long term displacements under tension loading, $\delta_{N\infty}$, shall be calculated from the results of sustained load tests (see Table A1.1, line B14 and B15) according to equation (2.21).

$$\delta_{N\infty} = \frac{\delta_{m2}}{2{,}0} \qquad (2.21)$$

The long term shear displacements $\delta_{V\infty}$ may be assumed to be approximately equal to 1,5-times the value $\delta_{VO}$.

### 2.2.11 Durability of metal parts

The assessment/testing required with respect to corrosion resistance will depend on the specification of the fastener in relation to its use. Supporting evidence that corrosion will not occur is not required if the steel parts of the metal fastener are protected against corrosion, as set out below:

(X1) Fastener intended for use in structures subject to dry, internal conditions:

No special corrosion protection is necessary for steel parts as coatings provided for preventing corrosion during storage prior to use and for ensuring proper functioning (zinc coating with a minimum thickness of 5 microns) is considered sufficient.

(X2) Fastener for use in structures subject to external atmospheric exposure (including industrial and marine environments), or exposure in permanently damp internal conditions, if no particular aggressive conditions according to (X3) exist:

Metal parts of the fastener made of stainless steel material 1.4401, 1.4404, 1.4578, 1.4571, 1.4362, 1.4062, 1.4162, 1.4662, 1.4439, 14462 or 1.4539 according to EN 10088:2014 [8] can be used.

These fasteners may also be used in (X1) conditions.

(X3) Fastener for use in structures subject to external atmospheric exposure or exposure in permanently damp internal conditions or particularly aggressive conditions such as permanent or alternate immersion in seawater or the splash zone of seawater, chloride atmosphere of indoor swimming pools or atmosphere with extreme chemical pollution (e.g. in desulfurization plants or road tunnels, where de-icing materials are used):

Metal parts of the fastener of stainless steel material 1.4529, 1.4565 and 1.4547 according to EN 10088:2014 [8] can be used.

These fasteners may also be used in (X1) and (X2) conditions.

### 2.2.12 Content, emission and/or release of dangerous substances

The performance of the hardened bonding material related to the emissions and/or release and, where appropriate, the content of dangerous substances will be assessed on the basis of the information provided by the manufacturer[2] after identifying the release scenarios (in accordance with EOTA TR 034 [12]) taking into account the intended use of the product and the Member States where the manufacturer intends his product to be made available on the market.

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2 The manufacturer may be asked to provide to the TAB the REACH related information which he must accompany the DoP with (cf. Article 6(5) of Regulation (EU) No 305/2011).

The manufacturer is **not** obliged:

- to provide the chemical constitution and composition of the product (or of constituents of the product) to the TAB, or
- to provide a written declaration to the TAB stating whether the product (or constituents of the product) contain(s) substances which are classified as dangerous according to Directive 67/548/EEC and Regulation (EC) No 1272/2008 and listed in the "Indicative list on dangerous substances" of the SGDS.

Any information provided by the manufacturer regarding the chemical composition of the products may not be distributed to EOTA or to TABs.

The identified intended release scenarios for this product and intended use with respect to dangerous substances are:

IA2: Product with indirect contact to indoor air (e.g. covered products) but possible impact on indoor air.

S/W1: Product with direct contact to soil, ground- and surface water.

S/W2: Product with indirect contact to soil, ground- and surface water.

#### 2.2.12.1 SVOC and VOC

For the intended use covered by the release scenario IA2 semi-volatile organic compounds (SVOC) and volatile organic compounds (VOC) are to be determined in accordance with EN 16516 [13]. The loading factor to be used for emission testing is 0,007 $m^2/m^3$.

The preparation of the test specimen is performed by use of a concrete member in which the anchor is installed in accordance with the manufacturer's product installation instructions (MPII) or (in absence of such instructions) the usual practice of anchor installation. The anchor with maximum thread size specified by the manufacturer shall be used. The embedment depth shall be at least 4d.

Once the test specimen has been produced, as described above, it should immediately be placed in the emission test chamber. This time is considered the starting time of the emission test.

The test results have to be reported for the relevant parameters (e.g. chamber size, temperature and relative humidity, air exchange rate, loading factor, size of test specimen, conditioning, production date, arrival date, test period, test result) after 3 and 28 days testing.

The relevant test results shall be expressed in [$mg/m^3$] and stated in the ETA.

#### 2.2.12.2 Leachable substances

For the intended use covered by the release scenario S/W1 the performance of the bonding material concerning leachable substances has to be assessed. A leaching test with subsequent eluate analysis must take place, each in duplicate. Leaching tests of the bonding material are conducted according to CEN/TS 16637-2:2014 [14]. The leachant shall be pH-neutral demineralised water and the ratio of liquid volume to surface area must be (80 ± 10) $l/m^2$.

Cubes of the bonding material with dimensions of 100 mm x 100 mm x 100 mm shall be prepared.

In eluates of "6 hours" and "64 days", the following biological tests shall be conducted:

- Acute toxicity test with Daphnia magna Straus according to EN ISO 6341 [15]
- Toxicity test with algae according to ISO 15799 [16]
- Luminescent bacteria test according to EN ISO 11348-1 [17], EN ISO 11348-2 [18] or EN ISO 11348-3 [19]

For each biological test, EC20-values shall be determined for dilution ratios 1:2, 1:4, 1:6, 1:8 and 1:16.

If the parameter TOC is higher than 10 mg/l, the following biological tests shall be conducted with the eluates of "6 hours" and "64 days" eluates:

- Biological degradation according to OECD Test Guideline 301 part A, B or E.

Determined toxicity in biological tests must be expressed as EC20-values for each dilution ratio. Maximum determined biological degradability must be expressed as "…% within …hours/days". The respective test methods for analysis must be specified.

# 3 ASSESSMENT AND VERIFICATION OF CONSTANCY OF PERFORMANCE

## 3.1 System of assessment and verification of constancy of performance to be applied

For the products covered by this EAD the applicable European legal act is: Decision 1996/582/EC.

The system is: 1.

## 3.2 Tasks of the manufacturer

The corner stones of the actions to be undertaken by the manufacturer of bonded fasteners in the procedure of assessment and verification of constancy of performance are laid down in Table 3.1.

Table 3.1 gives guidance; the control plan depends on the individual manufacturing process and has to be established between notified body and manufacturer for each product.

**Table 3.1 Control plan for the manufacturer; corner stones**

| No | Subject/type of control | Test or control method | Criteria, if any | Minimum number of samples | Minimum frequency of control |
|---|---|---|---|---|---|
| **Factory production control (FPC)<br>[including testing of samples taken at the factory in accordance with a prescribed test plan]** | | | | | |
| **Metal Parts** | | | | | |
| 1 | Dimensions (outer diameter, inner diameter, thread length, etc.) | Caliper and/or gauge | Laid down in control plan | 3 | Every manufacturing batch or 100.000 elements or when raw material batch has been changed *) |
| 2 | Tensile Load or tensile strength | EN ISO 6892-1,<br>EN ISO 898-1,<br>EN ISO 3506-1 | | 3 | |
| 3 | Yield strength | EN ISO 6892-1,<br>EN ISO 898-1,<br>EN ISO 3506-1 | | 3 | |
| 4 | Zinc plating - where relevant | x-ray measurement according to EN ISO 3497, magnetic method according to EN ISO 2178, Phase-sensitive eddy-current method according to EN ISO 21968 | | 3 | |
| 5 | Fracture elongation - where relevant | EN ISO 6892-1<br>EN ISO 898-1 | | 3 | |
| **Bonding material** | | | | | |
| 6 | Batch number and expiry date | visual check | Laid down in control plan | 1 | each batch |
| 7 | Components | check material and the mass of components acc. to recipe | | | |
| 8 | Specific gravity / Density | Standardized method proposed by the manufacturer | | | Every shift or 8 hours of production per machine |
| 9 | Viscosity | | | | |
| 10 | Reactivity (gel time, where relevant: max. reaction temperature, time to max reaction temperature) | | | | Each batch |
| 11 | Properties of raw material | (e.g. by infrared analysis) | | | initial testing and each change of batch |
| 12 | Performance of the cured bonding material | (e.g. tension test to failure) | | 3 | Each batch |

*) The lower control interval is decisive

### 3.3 Tasks of the notified body

The corner stones of the actions to be undertaken by the notified body in the procedure of assessment and verification of constancy of performance for fasteners are laid down in Table 3.2.

**Table 3.2 Control plan for the notified body; corner stones**

| No | Subject/type of control | Test or control method | Criteria, if any | Minimum number of samples | Minimum frequency of control |
|---|---|---|---|---|---|
| **Initial inspection of the manufacturing plant and of factory production control** | | | | | |
| 1 | Ascertain that the factory production control with the staff and equipment are suitable to ensure a continuous and orderly manufacturing of the bonding material. | - | Laid down in control plan | - | 1 |
| **Continuous surveillance, assessment and evaluation of factory production control** | | | | | |
| 2 | Verifying that the system of factory production control and the specified automated manufacturing process are maintained taking account of the control plan. | - | Laid down in control plan | - | 1/year |

## 4 REFERENCE DOCUMENTS

[1] EN 206:2013, Concrete: Specification, performance, production and conformity

[2] EOTA Technical Report TR 048:2016-08 Details of tests for post-installed fasteners in concrete

[3] EOTA Technical Report TR 049:2016-08 Assessment of metal fasteners under seismic action

[4] EN ISO 6988:1994 Metallic and other non-organic coatings – Sulphur dioxide test with general condensation of moisture

[5] EN 1992-1-1:2004 + AC:2010:, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings

[6] EN 1992-1-2:2004 + AC:2008, Eurocode 2: Design of concrete structures - Part 1-2: General rules – Structural fire design

[7] EN 1992-4, Eurocode 2: Design of concrete structures – Part 4: Design of fastenings for use in concrete (expected version 2017)

[8] EN 10088-1: 2014, Stainless steels – Part 1: List of stainless steels, and Part 3: Technical delivery conditions for semi-finished products, bars, rods, wire, sections and bright products of corrosion resisting steels for general purposes

[9] EN 10204: 2004, Metallic products – Types of inspection documents

[10] EN ISO/IEC 17025: 2016, General requirements for the competence of testing and calibration laboratories (ISO/IEC DIS 17025:2016); German and English version prEN ISO/IEC 17025:2016

[11] EN ISO 898-1: 2013, Mechanical properties of fasteners made of carbon steel and alloy steel - Part 1: Bolts, screws and studs with specified property classes - Coarse thread and fine pitch thread (ISO 898-1:2013)

[12] EOTA Technical Report TR 034, General checklist for EADs/ETAs – Content and/or release of dangerous substances in construction products

[13] EN 16516:2017, Construction products – Assessment of release of dangerous substances – Determination of emissions into indoor air

[14] CEN/TS 16637-2:2014, Construction products – Assessment of release of dangerous substances – Part 2: Horizontal dynamic surface leaching test

[15] EN ISO 6341:2013-01, Water quality - Determination of the inhibition of the mobility of Daphnia magna Straus (Cladocera, Crustacea) - Acute toxicity test (ISO 6341:2012)

[16] ISO 15799:2003-11, Soil quality - Guidance on the ecotoxicological characterization of soils and soil materials

[17] EN ISO 11348-1:2009-05, Water quality - Determination of the inhibitory effect of water samples on the light emission of Vibrio fischeri (Luminescent bacteria test) - Part 1: Method using freshly prepared bacteria (ISO 11348-1:2007)

[18] EN ISO 11348-2:2009-05, Water quality - Determination of the inhibitory effect of water samples on the light emission of Vibrio fischeri (Luminescent bacteria test) - Part 2: Method using liquid-dried bacteria (ISO 11348-2:2007)

[19] EN ISO 11348-3:2009-05, Water quality - Determination of the inhibitory effect of water samples on the light emission of Vibrio fischeri (Luminescent bacteria test) - Part 3: Method using freeze-dried bacteria (ISO 11348-3:2007)

## ANNEX A TEST PROGRAM AND GENERAL ASPECTS OF ASSESSMENT

### A1 TEST PROGRAM

The test program for bonded fasteners is given in Table A1.1, which covers fasteners for use in cracked and uncracked concrete and fasteners for use in uncracked concrete only. For bonded fasteners qualified for use in uncracked concrete only, the tests in cracked concrete may be omitted. Detailed information concerning the tests is given in the corresponding sections referred to in these tables.

For bonded fasteners used in cracked and uncracked concrete for which no increase of the performance in high strength concrete is sought (tests according to Table 1.1 option 2, 4, 6 the tests series R2, R4, A2 and A4 may be omitted.

A torque shall not be applied to the-bonded fastener except for torque tests.

The tests shall be performed with the embedment depth requested by the manufacturer (for e.g. capsule type fasteners). If the manufacturer applies for bonded fasteners with several embedment depths (variable embedment depth), the robustness test series according to Table A1.1, lines B6 to B9 shall be done with the maximum embedment depth requested by the manufacturer, while the other test series shall be performed with an embedment depth of $h_{ef}$ = 7 d. To avoid steel failure in the tension tests either the steel strength of the element may be increased or the embedment depth may be modified. Further details are given in A2.

The recommended fastener size as required for tests in Table A1.1 for medium size "m" is d = 12 mm (1/2").

**Table A1.1 Test program for bonded fasteners**

| N° | Purpose of test | concrete | crack width [mm] | size [2)] | $h_{ef}$ | $n_{min}$ | rqd. $\alpha$ | Section |
|---|---|---|---|---|---|---|---|---|
| **Resistance to steel failure** | | | | | | | | |
| N1 | Steel capacity | - | - | All | - | 5 | - | 2.2.1.1 |
| N2 | Maximum torque moment | C50/60 | 0 | All | 7d [1)] | 5 | - | 2.2.1.2 |
| **Reference tests (confined test setup)** | | | | | | | | |
| R1 | Bond strength with confined test setup | C20/25 | 0 | All | 7d [1)] | 5 | - | 2.2.2.1 |
| R2 | | C50/60 | 0 | s/m/l | 7d [1)] | 5 | - | |
| R3 | | C20/25 | 0,3 | s/m/l | 7d [1)] | 5 | - | |
| R4 | | C50/60 | 0,3 | s/m/l | 7d [1)] | 5 | - | |
| R5 | Reference for sensitivity to reduced cleaning effort | C20/25 | 0 | s/m/l | max | 5 | - | 2.2.5 |
| R6 | Reference for sustained load | C20/25 | 0 | m | 7d [1)] | 5 | - | 2.2.2.6 |
| R7 | Reference for freeze/thaw | C50/60 | 0 | m | 7d [1)] | 5 | - | 2.2.2.7 |
| R8 | Reference for slice tests | C20/25 | 0 | m | 30 mm | 10 | - | 2.2.2.12 |
| **Basic tension tests with unconfined test setup** | | | | | | | | |
| A1 | Characteristic resistance for tension loading not influenced by edge and spacing effects | C20/25 | 0 | s/m/l | min | 5 | - | 2.2.2.2 |
| A2 | | C50/60 | 0 | s/m/l | min | 5 | - | |
| A3 | | C20/25 | 0,3 | s/m/l | min | 5 | - | |
| A4 | | C50/60 | 0,3 | s/m/l | min | 5 | - | |
| A5 | Edge distance to prevent splitting under load | C20/25 | 0 | s/m/l | min | 4 | 1,00 | 2.2.4 |
| A6 | Minimum embedment depth | C20/25 | 0 | small | min | 20 | 0,90 | 2.2.3.2 |
| **Resistance to shear load** | | | | | | | | |
| V1 | Characteristic resistance for shear loading not influenced by edge and spacing effects | C20/25 | 0 | All | min | 5 | - | 2.2.7.1 |

| N° | Purpose of test | concrete | crack width [mm] | size 2) | $h_{ef}$ | $n_{min}$ | rqd. $\alpha$ | Section |
|---|---|---|---|---|---|---|---|---|
| V2 | Resistance to pry-out failure | C20/25 | 0 | All | min | 5 | - | 2.2.8 |
| **Resistance to pull-out failure** | | | | | | | | |
| B1 | Minimum edge distance and spacing | C20/25 | 0 | s/m/l | min | 5 | - | 2.2.6 |
| B2 | Maximum long term temperature | C20/25 | 0 | m | min | 5 | - | 2.2.2.9 |
| B3 | Maximum short term temperature | C20/25 | 0 | m | min | 5 | - | 2.2.2.9 |
| B4 | Minimum installation temperature | C20/25 | 0 | m | min | 5 | 1,00 | 2.2.2.10 |
| B5 | Minimum curing time at normal ambient temperature | C20/25 | 0 | m | min | 5 + 5 | 0,90 ref to long curing | 2.2.2.11 |
| B6 | Robustness in dry concrete | C20/25 | 0 | s/m/l | max[2)] | 5 | see Table 2.4 | 2.2.5.2 |
| B7 | Robustness in water saturated concrete | C20/25 | 0 | s/m/l | max[2)] | 5 | | 2.2.5.3 |
| B8 | Robustness in water filled holes (clean water) | C20/25 | 0 | s/m/l | max[2)] | 5 | | 2.2.5.4 |
| B9 | Robustness to mixing technique | C20/25 | 0 | m | max[3)] | 5 | | 2.2.5.5 |
| B10 | Increased crack width | C20/25 | 0,5 | s/m/l | 7d [1)] | 5 | 0,80 | 2.2.2.3 |
| B11 | Increased crack width | C50/60 | 0,5 | s/m/l | 7d [1)] | 5 | 0,80 | 2.2.2.3 |
| B12 | Repeated loads | C20/25 | 0 | m | 7d [1)] | 5 | 1,00 | 2.2.2.4 |
| B13 | Crack cycling under load | C20/25 | 0,1 - 0,3 | All | 7d [1)] | 5 | 0,90 | 2.2.2.5 |
| B14 | Sustained loads (normal ambient temperature) | C20/25 | 0 | m | 7d [1)] | 5 | 0,90 | 2.2.2.6 |
| B15 | Sustained loads (maximum long term temperature) | C20/25 | 0 | m | 7d [1)] | 5 | 0,90 | 2.2.2.6 |
| B16 | Freeze/thaw conditions | C50/60 | 0 | m | 7d [1)] | 5 | 0,90 | 2.2.2.7 |
| B17 | Installation direction | C20/25 | 0 | max | 7d [1)] | 5 | 0,90 | 2.2.2.8 |
| B18 | High alkalinity | C20/25 | 0 | m | 30 mm | 10 | 1,00 (R8) | 2.2.2.12 |
| B19 | Sulphurous atmosphere | C20/25 | 0 | m | 30 mm | 10 | 0,90 (R8) | 2.2.2.12 |

1) This value is valid for injection type and bulk type bonded fasteners. For capsule type bonded fasteners the specified embedment depth associated with the capsule size shall be used. To avoid steel failure the embedment depth modifications may be necessary (see A2).

2) Pull-out test such that steel failure will be avoided. To avoid steel failure the embedment depth modifications may be necessary (see A2).

For certain test series according to Table A1.1 and Table B.1 a reduced range of tested sizes, indicated by "s/m/l", may be used. The number of diameters to be tested in this case depends on the number of requested sizes and is given in Table A1.2.

**Table A1.2 Reduced range of tested sizes s/m/l**

| Number of requested sizes | Number of diameters to be tested |
|---|---|
| Up to 5 | 3 |
| 6 to 8 | 4 |
| 9 to 11 | 5 |
| More than 11 | 6 |

## A2 PROVISIONS FOR ALL TEST SERIES

As far as applicable the Technical Report TR 048 shall be followed with respect to the test members, test setup and performance of the tests. Modifications are addressed in the following sections, which overrule conflicting provisions in the Technical Report TR 048.

It is recommended that handling of tests and calibration items are performed in accordance with EN ISO/IEC 17025 [10].

The failure mode "combined pull-out and concrete cone failure" is characterized by pulling the embedded part (with or without the surrounding bonding material) out of the concrete. Depending on various influencing factors single fasteners and especially fastener groups may show combined pull-out and concrete cone failures starting from any point along the embedment depth.

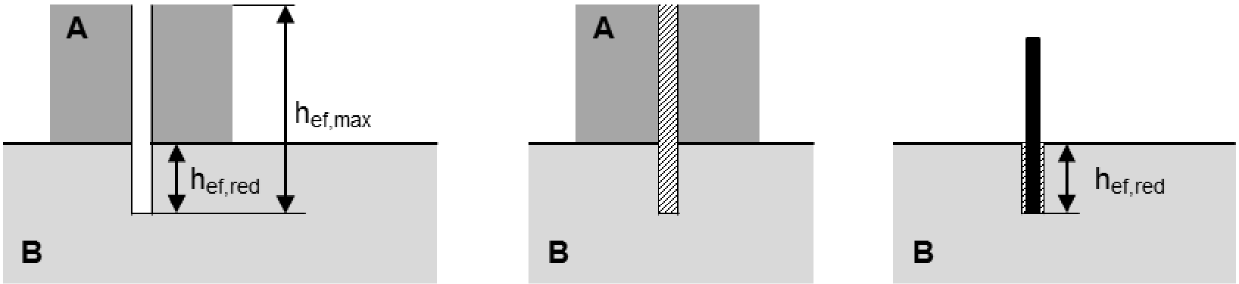
The failure mode "concrete cone failure" is typically characterized by a concrete failure starting from the deepest point of embedment. This failure mode may be observed for single fasteners or fastener groups with or without an influence of edge distances. The concrete cone failure mode shows the highest possible resistance of bonded fasteners and may be predicted according to current experience as given in EN 1992-4 equation (7.1) using the default values for factors $k_{ucr,N}$ = 11,0 and $k_{cr,N}$ = 7,7 related to concrete cylinder strength.

"Steel failure" or "splitting failure" may limit the resistance of bonded fasteners compared to the resistance of "combined pull-out and concrete cone failure" or "concrete cone failure".

To avoid "steel failure" in the tests embedded metal parts of a higher strength than specified by the manufacturer and published in the ETA may be used as long as the functioning of the fastener is not influenced. This condition is fulfilled if the geometry of the embedded part of higher strength steel is identical with the specified embedded part.

In cases where the use of high strength fastener elements (steel strength ≥ 10.9) is insufficient to prevent "steel failure" of the fastener the embedment depth shall be reduced. This principle may overrule the required embedment depth given in Table A1.1 except for the test series concerning robustness (B6 to B9). To avoid steel failure in the tests with maximum embedment depth for injection type systems or nominal embedment depth for capsule type systems the following test procedure may be employed.

Use a test member consisting of two concrete blocks A and B stacked on the top of each other without a permanent connection as shown in Figure A2.1a). Drill the hole in accordance with the procedures described in the MPII. Clean the hole as described below for the specific test. Install the bonding material and the element (for capsule type systems) or the bonding material only (for injection type systems) in each case in accordance with the MPII with the equipment supplied by the manufacturer as shown in Figure A2.1 b). Remove the upper block A and for injection type systems install the metal part (Figure A2.1 c)). After curing perform the confined tension test. In this context $h_{ef,red}$ represents the reduced embedment, for which steel yielding of a high strength metal part is just avoided. For capsule type systems the test setup shall be adapted accordingly.




a) drill & clean b) install bonding material c) insert metal part

**Figure A2.1 Test set up to avoid steel failure**

The unconfined tests with minimum specified embedment depth may show "concrete cone failure". If these results are used for evaluating the characteristic bond resistance (eventually modified by the various influencing factors), the approach is conservative. More precise results may be achieved if the corresponding embedment depth is chosen in a way that bond failure ("combined pull-out and concrete cone failure") is decisive.

Bonded fasteners with a high bond resistance may show only "concrete cone failure" or "steel failure" in unconfined tests. In this case it is recommended to perform all tests as confined tests and to evaluate $\tau_{Rk}$ taking the modification factor $\alpha_{setup}$ into account.

For the assessment of a bonded fastener the overall test programme has to be carried out including at least the following minimum number of different concrete batches within the programme of testing:

| | |
|---|---|
| Assessment for C20/25 | on at least 3 different batches, if the concrete comes from different concrete suppliers. |
| | on at least 4 different batches, if the concrete comes from the same concrete suppliers. |
| Assessment for C50/60 | on at least 2 different batches, if the concrete comes from the same or from different concrete suppliers. |

If concrete batches come from the same concrete supplier, it shall be ensured that each batch is made from a different delivery of either cement or aggregates.

Reference tension tests (R) shall be performed because they are needed for the evaluation of the results of the test series for resistance to pull-out failure and to take account of the influence of certain parameters on the resistance of bonded fasteners to tension load. They shall be made in each batch. All reference tests shall be carried out as follows:

- in dry concrete
- at normal ambient temperature (T = + 21° C ± 3 °C)
- installation in accordance with the MPII
- as confined test;

The reference tests should be made in the same concrete batch as the tests to which they shall be compared. The reference tests shall be made in uncracked concrete (cracked concrete: $\Delta w$ = 0,3 mm), if their results shall be compared with results of tests in uncracked concrete (cracked concrete).

It is necessary to carry out at least 5 reference tests on size M12 in each test series for each concrete batch. The coefficient of variation of the failure loads in one (each) test series of reference tests shall be $cv_F \leq 15$ %. Hence, the number of reference tests may need to be increased until the coefficient of variation meets the requirement.

If the manufacturer applies for embedded parts of bonded fasteners which are geometrically identical but of different material, all tests shall be made with one material. For the other material, only the torque tests according to Table A1.1, line N2 shall be carried out and if the embedded part has a reduced section along the length, shear tests according to Table A1.1, line V1 for the evaluation of the characteristic shear resistance are required.

If the assessment covers more than one drilling technique, all tests shall be done with all drilling techniques. If different sizes of packages, types of nozzles and dispensers will be used for one system, equal mixing of the bonding material components must be proven for all sizes of the packages and with all admissible types of nozzles and dispensers both for coaxial and shuttle cartridges.

The curing time before commencement of the test in test series according to Table A1.1 lines B1 to B19 shall be comparable to the curing time in the corresponding reference test series.

### A2.1 Installation

The fastener shall be installed in accordance with the MPII except for tests according to Table A1.1, lines B6 to B9.

### A2.2 Concrete strength and concrete age

The tests are performed for the assessment in "low strength concrete C20/25" and "high strength concrete C50/60". Therefore the concrete strength at the time of testing the fasteners shall be within the following limits:

C20/25: $25 \leq f_{c,cube} \leq 35$ [N/mm²]

C50/60: $60 \leq f_{c,cube} \leq 70$ [N/mm²]

The concrete test member shall be at least 21 days old at the time of installation of the fastener and testing.

### A2.3 Analysis of ultimate loads

#### A2.3.1 Assessment of the failure mode

The test lab shall identify and report the initial failure mode for any test:

Tension tests:

- concrete cone failure (cc) – give diameter and depth of concrete cone
- splitting (sp) – test condition for tests in uncracked concrete in case when a first crack of the concrete is observed
- bond failure between element and bonding material (be)
- bond failure between bonding material and bore hole (bb) (mixed bond failure between element and bonding material as well as between bonding material and bore hole (bbe) may occur)
- combined bond and concrete failure in unconfined tests (bc)
- steel failure (s) – define position of the steel rupture over length of the fastener

Shear tests:

- steel failure (s) – define position of the steel rupture over length of the fastener
- pry-out (pr) – concrete breakout opposite to the load direction (may occur for shallow embedment)
- concrete edge failure (ce) – may occur when testing close to the edge

If initial failure is not clear, a combination of failure modes may be reported.

### A2.3.2 Conversion of failure loads to nominal strength

The conversion of failure loads shall be done according to Equation (A2.1) to (A2.8) depending on the failure mode.

The increasing factor $\psi_{c,50}$ may be determined separately for cracked and uncracked concrete.

| | | |
|---|---|---|
| **Concrete failure** | $F_{u,c} = F_{u,t} \cdot \left(\frac{f_c}{f_{c,t}}\right)^{0,5}$ with $\frac{f_c}{f_{c,t}} \leq 1,0$ | (A2.1) |
| **Bond failure** | $F_{u,p} = F_{u,t} \cdot \left(\frac{f_c}{f_{c,t}}\right)^{m}$ with $\frac{f_c}{f_{c,t}} \leq 1,0$ | (A2.2) |
| **confined uncracked** | $m = \frac{\log(N_{u,m,R2} / N_{u,m,R1})}{\log(f_{c,R2} / f_{c,R1})} \leq 0,5$ | (A2.3) |
| **confined cracked** | $m = \frac{\log(N_{u,m,R4} / N_{u,m,R3})}{\log(f_{c,R4} / f_{c,R3})} \leq 0,5$ | (A2.4) |
| **unconfined uncracked** | $m = \frac{\log(N_{u,m,A2} / N_{u,m,A1})}{\log(f_{c,A2} / f_{c,A1})} \leq 0,5$ | (A2.5) |
| **unconfined cracked** | $m = \frac{\log(N_{u,m,A4} / N_{u,m,A3})}{\log(f_{c,A4} / f_{c,A3})} \leq 0,5$ | (A2.6) |
| | $\psi_{c,xx} = \left(\frac{f_{ck,xx}}{f_{ck,20}}\right)^{m} > 1,0$ [1)] | (A2.7) |
| **Steel failure** | $F_{u,s} = F_{u,t} \frac{f_u}{f_{u,t}}$ | (A2.8) |

1) If no distinction is made for cracked and uncracked conditions, the factor m shall be determined as the minimum of equations (A2.3) to (A2.6).

### A2.3.3 Conversion of failure load to bond strength

Mean failure loads and 5% fractile of failure loads shall be converted to bond strength related to the nominal diameter of the metal part according to equations (A2.9) and (A2.10).

$$\tau_{\mathrm{Ru}} = \frac{N_{Ru}}{\pi \cdot d \cdot h_{ef}} \quad \text{(A2.9)}$$

$$\tau_{5\%} = \frac{N_{5\%}}{\pi \cdot d \cdot h_{ef}} \quad \text{(A2.10)}$$

### A2.3.4 Conversion of failure load to account for concrete batch influence

When bond failure is observed, the conversion of failure loads for all the tests carried out in the i-batch $F_{u,t,i}$ shall be done according to Equation (A2.11).

$$F_{u,p} = F_{u,t,i} \cdot \alpha_{ref,i} \quad \text{(A2.11)}$$

The factor $\alpha_{ref,i}$ takes into account the sensitivity of each specific concrete batch using the results of reference tests and it shall be calculated according to Equation (A2.12).

$$\alpha_{ref,i} = \frac{\min \tau_{Ru,m,r,12}}{\tau_{Ru,m,i,12}} \leq 1,0 \quad \text{(A2.12)}$$

If the coefficient of variation of the ultimate bond resistance of all results in the reference test series with medium diameter is cv ≤ 15 %, the assessment according to equation (A2.12) may be omitted and $\alpha_{ref} = 1,0$. In this case the characteristic value of the bond resistance in the reference test series and basic tension tests has to be determined with a coefficient of variation of 15 %.

### A2.3.5 Criteria regarding scatter of failure loads

If the coefficient of variation of the failure load in any test series according to Table A1.1, lines R1 to R8 and A1 to V1 exceeds 15 % and is not larger than 30 %, the following reduction shall be taken into account:

$$\beta_{cv} = \frac{1}{1 + 0{,}03(cv - 15)} \leq 1{,}0 \qquad \text{(A2.13)}$$

If the coefficient of variation of the failure load in any test series according to Table A1.1, lines B1 to B19 exceeds 20% and is not larger than 30%, the following reduction shall be taken into account:

$$\beta_{cv} = \frac{1}{1 + 0{,}03(cv - 20)} \leq 1{,}0 \qquad \text{(A2.14)}$$

If the maximum limit for the coefficient of variation of the failure loads of 30% is exceeded the number of tests shall be increased to meet this limit. This EAD does not cover fasteners for which this limit cannot be achieved.

The smallest result min $ß_{cv}$ in any test shall be taken for assessment.

### A2.3.6 Establishing 5 % fractile of bond strength

The 5 %-fractile value of the ultimate bond resistance measured in a test series is to be calculated according to statistical procedures for a confidence level of 90 %. In the case of bonded fasteners, a test series can consist of more than one diameter of the fastener tested under the same conditions. If a precise verification does not take place, a normal distribution and an unknown standard deviation of the population shall be assumed.

$$\tau_{u,5\%} = \tau_{u,m} (1 - k_s \cdot cv_F) \qquad \text{(A2.15)}$$

$$F_{u,95\%} = F_{u,m} (1 + k_s \cdot cv_F) \qquad \text{(A2.16)}$$

e.g. n = 5 tests: $k_s$ = 3,40

n = 10 tests: $k_s$ = 2,57

*Note 23 The confidence level of 90% is defined for characteristic resistance of fasteners in EN 1992-4 and is therefore used for the assessment in this EAD.*

### A2.3.7 Sustained loads, pulsating loads

If the load $N_p$ applied on the fastener during a test series according to Table A1.1, lines B12 to B16 is smaller than the required load, the reduction factor $\alpha_p$ shall be taken into account in the assessment. The smallest value $\alpha_p$ in any of these test series applies for assessment according to (2.14).

$$\alpha_p = \frac{N_{p,t}}{N_p} \leq 1{,}0 \qquad \text{(A2.17)}$$

with

$N_{p,t}$ actual load applied on the fastener in the respective successful test series

$N_p$ load required for the respective test series

### A2.3.8 Failure loads (reduction factors $\alpha$)

For test series B4 to B19 the mean failure loads and 5% - fractile of failure loads shall be compared with the corresponding reference test series of basic tension test series according to Table A1.1:

$$\alpha = \min \{F_{u,m,t} / F_{u,m,r}; F_{u,5\%,t} / F_{u,5\%,r}\} \leq 1{,}0 \qquad \text{(A2.18)}$$

The comparison of the 5%-fractile may be omitted for any number of tests in a test series when the coefficient of variation of the test series is smaller than or equal to the coefficient of variation of the reference test series or if the coefficient of variation in both test series is smaller than 15 %.

With the exception of tests series B6 to B9 (Table A1.1) also the characteristic loads claimed for in the ETA can be used as reference loads.

For tests for sensitivity to installation the reduction factor $\alpha$ is used to determine the factor $\gamma_{inst}$ accounting for the sensitivity to installation.

If the criteria for the required value of $\alpha$ given in equation (A2.18) are not met in one test series, the characteristic resistance shall be reduced by $\alpha$ / rqd. $\alpha$.

### A2.4 Analysis of displacements

#### A2.4.1 Loss of adhesion

With bonded fasteners uncontrolled slip occurs when the bonding material with the embedded part is pulled out of the drilled hole (because then the load displacement behaviour depends significantly on irregularities of the drilled hole). The corresponding load when uncontrolled slip starts is called load at loss of adhesion $N_{u,adh}$.

$N_{u,adh}$ shall be evaluated for every test from the measured load displacement curve. The load at loss of adhesion is characterised by a significant change of stiffness, see Figure A2.2. If the change in stiffness at a defined load is not so obvious, e.g. the stiffness is smoothly decreasing, the load at loss of adhesion shall be evaluated as follows:

1) Compute the tangent to the load-displacement curve at a load 0,3 $N_u$ ($N_u$ = peak load in test). The tangent stiffness can be taken as the secant stiffness between the points 0/0 and 0,3 $N_u/\delta_{0,3}$ ($\delta_{0,3}$: displacement at N = 0,3 $N_u$).
2) Divide the tangent stiffness with a factor of 1,5.
3) Draw a line through the point 0/0 with the stiffness as calculated in 2).
4) The point of intersection between this line and the measured load-displacement curve gives the load $N_{u,adh}$ where the adhesion fails, see Figure A2.3.
5) If there is a peak in the load-displacement curve, to the left side of this line, which is higher than the load at intersection, $N_{u,adh}$ is taken as the peak load, see Figure A2.4.
6) If there is a very stiff load-displacement curve at the beginning ($\delta_{0,3} \leq$ 0,05 mm) the drawing of the line for the calculation can be shifted to the point (0,3 $N_u$ / $\delta_{0,3}$ ), see Figure A2.5.

For tension tests the factor $\alpha_1$ shall be calculated according to equation (A2.19):

$$\alpha_1 = \frac{N_{u,adh}}{N_{Rk,p}} \cdot \frac{1{,}5}{1{,}3} \cdot \gamma_{inst} \leq 1{,}0 \qquad \text{(A2.19)}$$

where

$N_{Rk,p}$ = $\tau_{Rk} \cdot \pi \cdot d \cdot h_{ef}$; characteristic resistance for pull-out failure given in the ETA for concrete strength class and state of concrete (cracked, uncracked) corresponding to the evaluated tension test.

The evaluation of the load at loss of adhesion is not required when failure occurs between bonding material and embedded part along the entire embedment depth. In this case the factor $\alpha_1$ shall be taken as 1,0.

**Examples of load-displacement curves**

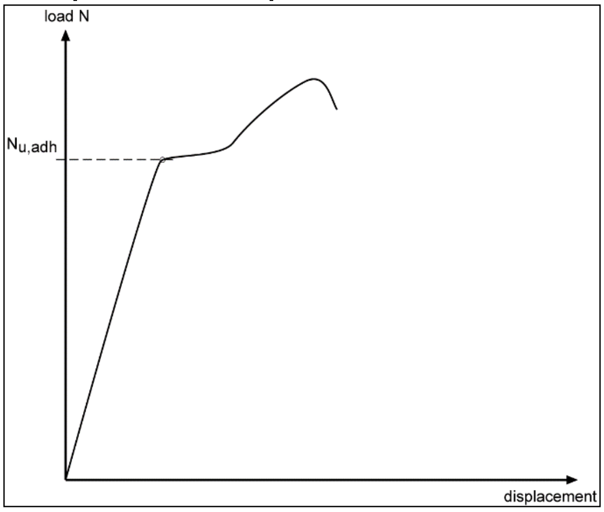



**Figure A2.2 Load at loss of adhesion by a significant change of stiffness**

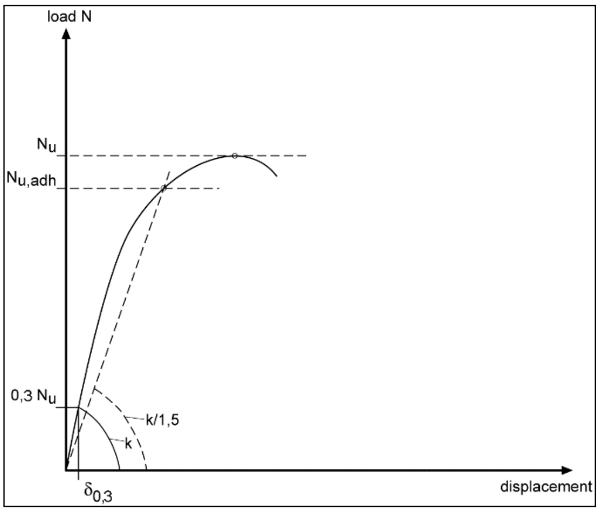



**Figure A2.3 Evaluation of load at loss of adhesion**

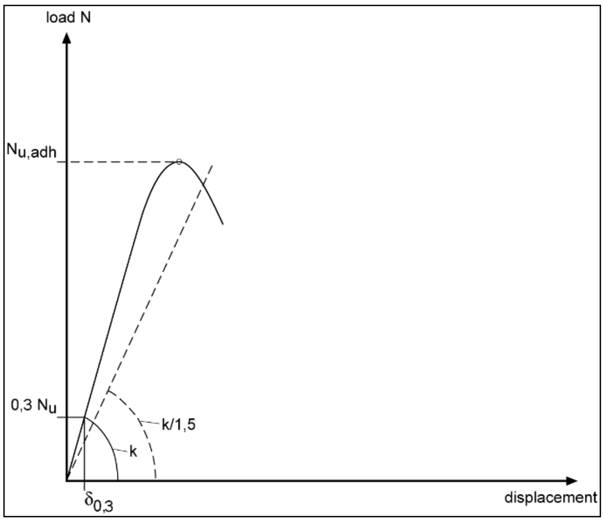



**Figure A2.4 Evaluation of load at loss of adhesion**

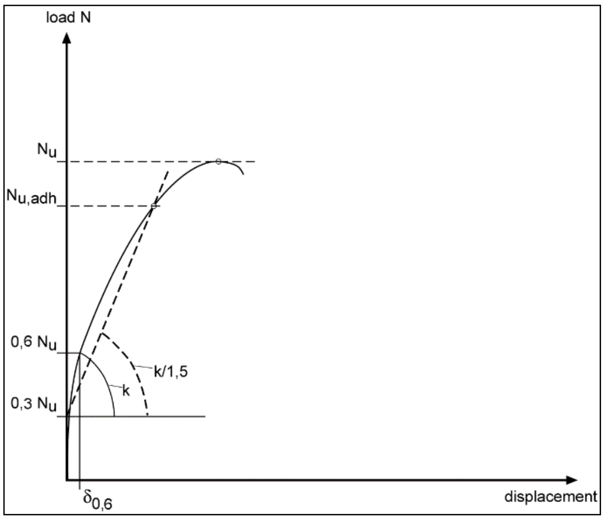



**Figure A2.5 Evaluation of load at loss of adhesion**

### A2.4.2 Limitation of the scatter of displacements

In order to properly activate all fasteners of a fastener group, the displacement behaviour (stiffness) of individual fasteners shall be similar.

The coefficient of variation of the mean displacement at the load level of 0,5 $N_{Ru,m}$ shall fulfil the criteria given in equation (A2.20) and equation (A2.21).

$cv_\delta \leq 0{,}25$ (test series R1 to R8, A1 to A5, B1 to B5) (A2.20)

$cv_\delta \leq 0{,}40$ (test series B4 to B17) (A2.21)

The load displacement curves may be shifted according to Figure A2.6 for determination of the displacement at 0,5 $N_{Ru,m}$.

It is not necessary to observe limitation of the scatter of the load/displacement curves in a test series if in this test series all displacements at a load of 0,5 $N_{Ru,m}$ are smaller than or equal to 0,4 mm.

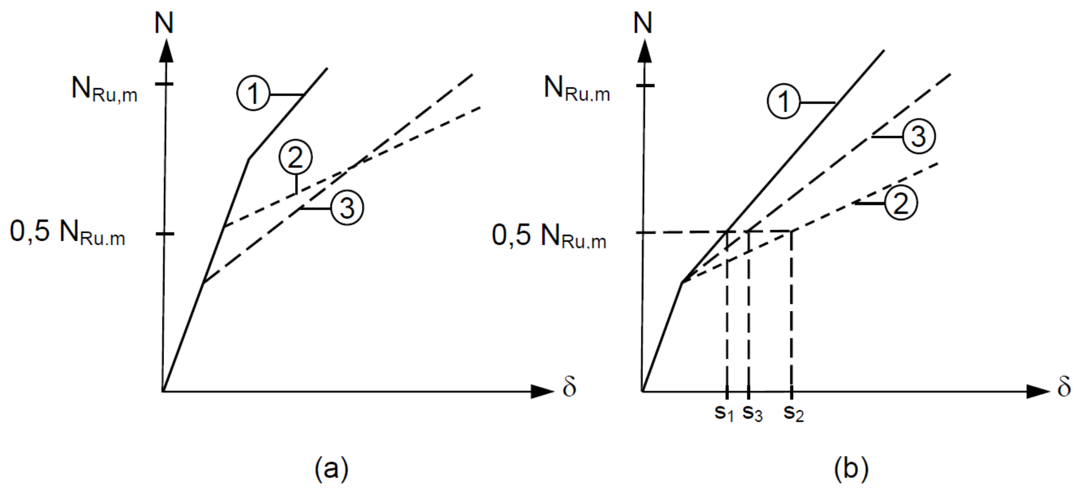



**Figure A2.6 Influence of pre-stressing on load/displacement curves**

a) original curves

b) shifted curves for evaluation of scatter at N = 0,5 $N_{u,m}$

## ANNEX B ASSESSMENT OF BONDED EXPANSION FASTENERS

### B1 General

Bonded expansion fasteners are installed in cylindrical holes, the load transfer is realised e.g. by mechanical interlock of a cone or several cones in the bonding material and then via a combination of bonding- and friction forces in the anchorage ground (concrete).

When a tension force of a certain magnitude is acting in the fastener rod the adhesion between bonding material and fastener rod is destroyed.

After this bonding has been destroyed the expansion areas, due to their geometry, cause expansion forces as in the case of expansion fasteners, which press the bonding material to the wall of the drilled hole; thus the bonding material is expanded or bursts, i.e. it takes over the function of an expansion sleeve of torque-controlled expansions.

In uncracked concrete the loadbearing effect of the bonding by friction is increased due to the expansion forces. In cracked concrete an extensive loss of adhesion between bonding material and concrete is likely to occur.

The function of the fasteners is ensured, if during loading the adhesion between fastener rod and bonding material is destroyed at a level which is lower than the holding capacity of the bond between bonding material and drill hole wall.

The influences of temperature and durability on the bonding material shall be determined according to 2.2.

## B2 Methods of verification

### B2.1 Test Program

The following test series shall be carried out and assessed as bonded fasteners according to 2.2 and Test program for bonded fasteners given in Table A1.1:

- To steel failure (N1 to N2)
- Reference tests (R1 to R8)
- Basic tension tests with unconfined test setup (A1 to A6)
- Resistance to shear load (V1 to V2)

For the test series given in Table B2.1 section 2.2 applies with respect to

- purpose of the test,
- test conditions
- assessment

as far as it is not overruled by Annex B for bonded expansion fasteners.

For testing and assessment of bonded expansion fasteners the setting torque $T_{fix}$ as referenced in section 2.2) shall be replaced by the required installation torque $T_{inst}$ specified by the manufacturer.

**Table B2.1 Test program for bonded expansion fasteners**

| N° | Purpose of test | concrete | crack width [mm] | $T/T_{inst}$ | size 1) 2) | $n_{min}$ | rqd. $\alpha$ |
|---|---|---|---|---|---|---|---|
| E1 | Reduced installation torque in dry concrete | C20/25 | 0,3 | 0,5 | all | 10 | see Table 2.4 |
| E2 | Robustness in dry concrete | C20/25 | 0,3 | 1/0,5 | all | 10 | |
| E3 | Robustness in wet concrete | C20/25 | 0,3 | 1/0,5 | all | 10 | |
| E4 | Robustness in flooded holes (clean water) | C20/25 | 0,3 | 1/0,5 | all | 10 | |
| E5 | Robustness to mixing technique | C20/25 | 0,3 | 1/0,5 | m | 10 | |
| E6 | Increased crack width | C20/25 | 0,5 | 1/0,5 | s/m/l | 10 | 0,80 |
| E7 | Increased crack width | C50/60 | 0,5 | 1/0,5 | s/m/l | 10 | 0,80 |
| E8 | Crack cycling under load | C20/25 | 0,1–0,3 | 1/0,5 | s/m/l | 10 | 0,90 |
| | | | | | interm ediate | 5 | |
| E9 | Sustained loads (normal ambient temperature) | C20/25 | 0 | 1/0,5 | m | 5 | 0,90 |
| E10 | Sustained loads (maximum long term temperature) | C20/25 | 0 | 1/0,5 | m | 5 | 0,90 |
| E11 | Maximum torque moment | C50/60 | 0 | - | all | 5 | - |
| E12 | Freeze/thaw conditions | C50/60 | 0 | 1/0,5 | m | 5 | 0,90 |
| E13 | Installation direction | C20/25 | 0,3 | 1/0,5 | max | 5 | 0,90 |
| E14 | Slip force test | C20/25 | 0,3 | 0 | All | 5 | - |
| E15 | Bond force test | C20/25 | 0,3 | 0 | All | 5 | - |

1) See Table A1.2; m: medium size (12 mm) or smallest size which is larger than 12 mm;
2) The reduced range of tested sizes s/m/l depends on the number of requested sizes and is given in Table A1.2.

### B2.2 General

The required tests for torque-controlled bonded fasteners are given in Table B2.1. In addition the test series according to Table A1.1, lines A1 to A4 are required.

If the slip and bond force tests are carried out and the requirements according to B2.7 are fulfilled, the number of tests given in Table B2.1 lines E1 to E8 may be performed with reduced number of tests $n_{min}$ = 5. If the conditions according to section B2.7 are not fulfilled or the slip and bond force tests are not carried out, the number of tests given in Table B2.1 applies. Therefore, it is recommended that first the tests are carried out according to Table B2.1, line E14 and E15 with checking of the requirements to section B2.7.

The test procedures given in Table B2.1 line E1 to E13 correspond in principle to the required tests for bonded fasteners according to Table A1.1, the necessary modifications and adaptations (including the number of tests) are given in the following.

For bonded fasteners, it is required that the test programme is carried out in concrete made from different concrete batches to take account of the possible influence of different concrete compositions on the bond behaviour.

However, if in a test pull-out failure (pull-out of fastener rod with mortar) occurs, the influence of different concrete batches has to be considered as for bonded fasteners.

In contrast to the assessment of bonded fasteners, all tests in lines E1 to E8 and line E13 shall be carried out as unconfined tests in cracked concrete. The results of these tests shall be compared with the results of tests according to Table A1.1, line A3 (tests in C20/25) or line A4 (tests in C50/60).

The results of tests according to line E9, E10 and E12 shall be compared with confined reference tests performed in the same concrete batch.

In the tests the torque moments $T_{inst}$ specified by the manufacturer in the MPII shall be applied with the exception of the tests according to Table B2.1 E1 and E11. Different requirements on installation torque in test series for robustness E1 and sensitivity to torque moments E11 apply.

Ten minutes after applying the torque moment it shall be reduced to 0,5 $T_{inst}$. If no torque moment is given by the manufacturer, the tests shall be carried out without torque moment.

### B2.3 Robustness

The robustness tests shall be carried out according to Technical Report TR 048 and 2.2.5, however, they shall be performed in cracked concrete ($\Delta w$ = 0,3 mm) as unconfined tests.

In the tests according to line E1 the torque moment of 50% of $T_{inst}$ recommended by the manufacturer shall be applied. The hole shall be cleaned according to the MPII.

For assessment section 2.2.5 applies.

### B2.4 Installation direction

These tests shall be carried out in cracked concrete $\Delta w$ = 0,3 mm as unconfined tests.

### B2.5 Slip force tests

The tests according to Table B2.1, line E14 are carried out to determine the slip force.

The slip force is that force, at which the adhesion between fastener rod and bonding material is destroyed.

The slip force may be determined by a significant change in the stiffness of the load-displacement curve and/or a clear increase of the splitting force.

At least 5 tests per fastener size shall be carried out.

The mean slip force ($F_{slip,m}$) and the 95%-fractile of the slip force ($F_{slip95\%}$) shall be determined for each size with a confidence level of 90 % and by assuming an unknown standard deviation.

The fastener is installed into concrete C20/25 with hole cleaning according to MPII.

No torque moment shall be applied.

After opening of the cracks up to $\Delta w$ = 0,3 mm the fastener is loaded until failure occurs.

The relative displacement of the fastener rod related to the concrete is measured by means of an inductive displacement transducer on the fastener side opposite to the load (unloaded end of the rod).

### B2.6 Bond force tests

The tests according to Table B2.1, line E15, are carried out to determine the bond forces by taking account of the most unfavourable anchorage ground conditions.

The bond force is defined as load at loss of adhesion between bonding material and wall of the drill hole.

The tests are carried out in cracked concrete C20/25 $\Delta w$ = 0,3 mm using a fastener rod which generates no expansion forces (e.g. normal threaded rod with a comparable diameter and length) instead of the fastener rod which is intended for the torque-controlled bonded .

No torque moment is applied.

The hole cleaning is carried out according to robustness test series for bonded fasteners, see (2.2.5).

At least 5 tests per fastener size are required. The most unfavourable condition of robustness tests (E2 to E4) applies.

The determination of the loads at loss of adhesion shall be done according A2.4.1.

The loads shall be converted to nominal concrete strength value of C20/25 according to section A2.3.2.

The mean bond force (min $F_{bond,m}$) and the 5%-fractile of the bond force ($F_{bond5\%}$) shall be determined for each fastener size with a confidence level of 90% by assuming an unknown standard deviation.

### B2.7 Assessment of slip and bond force tests

One of the following criteria shall be fulfilled:

$$F_{bond,m} / F_{slip,m} \geq 3,0 \quad \text{(B2.1)}$$

$$F_{bond5\%} / F_{slip95\%} \geq 1,3 \quad \text{(B2.2)}$$

$F_{bond,m}$ = mean bond force;

$F_{slip,m}$ = mean slip force;

$F_{slip95\%}$ = 95%-fractile of the slip force;

$F_{bond5\%}$ = 5%-fractile of the bond force.

Under the assumption of a normal distribution of the bond forces and slip forces and unknown standard deviation the two conditions ensure that the slip forces will not exceed the bond forces with a probability in the order of $10^{-3}$.

The two conditions given above are considered as being equivalent, if the coefficient of variation of the tests is $\leq$ 15% (tests according to Table B2.1, line E14) and ≤ 10% (tests according to Table B2.1, line E15).

If the coefficient of variation is larger in a test series with a particular fastener sizes, ~~than~~ the number of tests in this series may be increased or the ratios in equations (B2.1) or (B2.2) may be increased.

### B2.8 Load displacement behaviour

Load displacement curves of torque-controlled bonded fasteners in cracked concrete may show a short plateau (max length about 0,5 mm) and also in some cases a very small decrease of the load.

This behaviour indicates the point when the adhesion between bonding material and fastener rod is destroyed. This small plateau in the load displacement curve is acceptable for this kind of fastener in cracked concrete and is not interpreted as uncontrolled slip.

### B2.9 Influence of temperature and durability

The tests for assessing the influence of temperature on the loadbearing behaviour of the fastener shall be assessed according to 2.2.2.9 and 2.2.2.12 with bonded expansion fasteners of medium size applied for.

Reference tests shall be carried out in uncracked concrete of the same batch.

For the assessment of the durability the fastener so-called slice tests with a fastener rod which generates no expansion forces (e.g. with a normal threaded rod) according to 2.2.2.12 shall be carried out.

### B2.10 Determination of the characteristic resistances

The determination of the characteristic resistance shall be given in forces ($N_{Rk}$ in kN) instead of bond strength as for bonded fasteners ($\tau_{Rk}$, in N/mm²) as given in equation (B2.3)

$$N_{Rk} = N_{5\%} \bullet \min ß_{cv} \bullet \min \alpha_p \bullet \left(\min \frac{\alpha}{rqd.\alpha}\right) \bullet \alpha_{ref} \bullet \min \alpha_1 \bullet \alpha_2 \bullet \alpha_3 \bullet \alpha_4 \qquad \text{(B2.3)}$$