EAD 330924-01-0601-v01

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European Assessment Document for

Variant: Cast-in anchor bolts under fatigue or seismic actions

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Contents

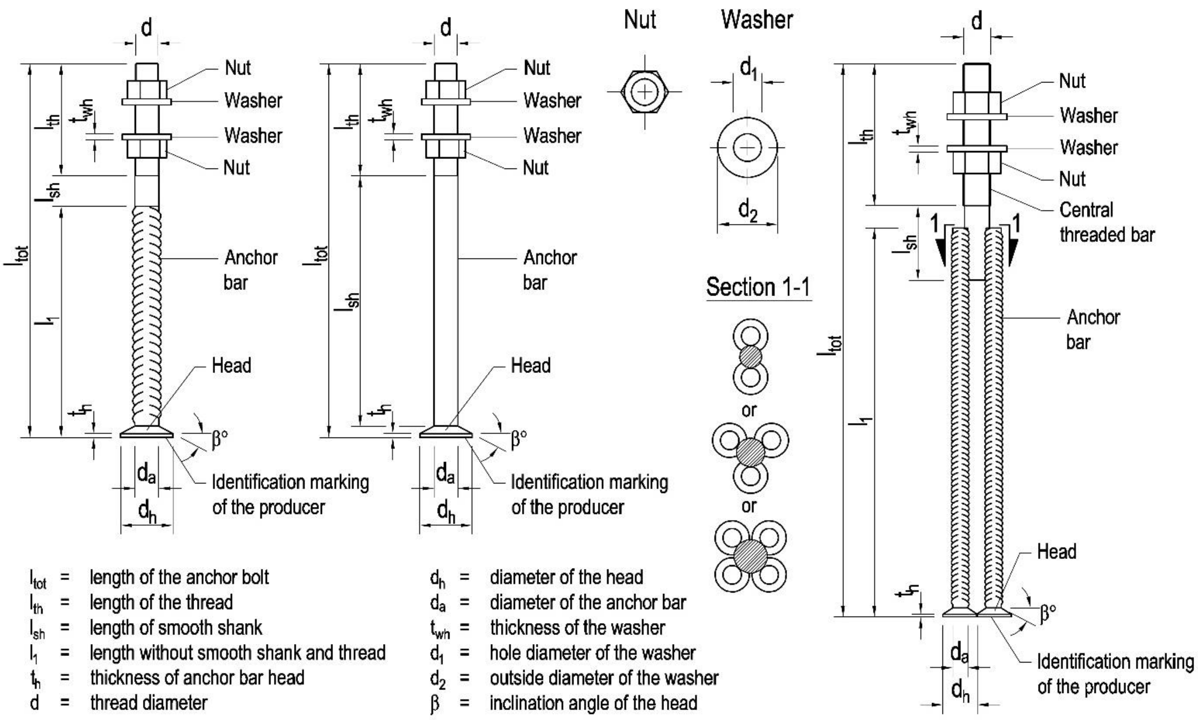
1 SCOPE OF THE EAD

1.1 Description of the construction product

EAD 330924-01-0601 [1], clause 1.1, applies with following amendments.

In addition to EAD 330924-01-0601 [1], clause 1.1, for anchor bolt type 1 anchor bars can be made of smooth steel in accordance with EN 10263-4 [2][1] with the following characteristics:

yield strength:	f_{yk}	≥	640 N/mm²
tensile strength:	f_{uk}	≥	800 N/mm².



anchor bar made of ribbed reinforcing steel	anchor bar made of smooth steel	anchor bar made of ribbed reinforcing steel
a) anchor bolt type 1		b) anchor bolt type 2

Figure 1.1.1: Example for anchor bolt with typical dimensions

This EAD is a variant to EAD 330924-01-0601 [1] due to the additional assessment of cast-in anchor bolts type 1 under fatigue cyclic loading and under seismic actions.

This EAD covers anchor bolts under fatigue cyclic loading that are secured against turning of the nut under fatigue cyclic loading, e.g., by the use of lock nuts or counter nuts as specified in the Manufacturers Product Installation Instruction (MPII).

1 All undated references to standards in this EAD are to be understood as references to the dated versions listed in chapter 4.

1.2 Information on the intended use(s) of the construction product

1.2.1 Intended use

EAD 330924-01-0601 [1], clause 1.2.1, applies.

In addition to EAD 330924-01-0601 [1], the cast-in anchor bolt type 1 is intended to be used:

- under seismic actions (category C1, category C2).

  The behaviour of anchor bolts in regions of reinforced concrete structures, where plastic steel strains are expected (e.g., in plastic hinge zones) and thus, the placing of the anchors in such regions is not covered in this EAD.

- under fatigue cyclic loads in combination with or without static or quasi-static loads.

  The anchor bolt is intended to be used to transmit tension loads ($+N$), shear loads ($\pm V$) without lever arm or any combination of these loads into the concrete.

In addition to EAD 330924-01-0601 [1], in this EAD the assessment for fatigue cyclic loading is made to determine the characteristic values of the anchor bolt for calculation in accordance with EOTA TR 061 [3], assessment method C.

This EAD covers anchor bolts under fatigue cyclic shear loads only without an annular gap between the hole in the fixture and the anchor bolt. Under fatigue cyclic tension loading a gap is possible.

Note: The annular gap can be filled with injection mortar.

A stand-off installation of anchor bolts under fatigue cyclic loading is not covered, i.e., the conditions of EN 1992-4 [4], 6.2.2.3 (1) b), are fulfilled.

The effective embedment depth is h_{ef} ≥ min (60 mm; 4 d).

1.2.2 Working life/Durability

EAD 330924-01-0601 [1], clause 1.2.2, applies.

1.3 Specific terms used in this EAD

EAD 330924-01-0601 [1], clause 1.3, applies.

The notations and symbols frequently used in this EAD Variant are given below. Further particular notation and symbols are given in the text.

Essential resistances in axial and transverse direction regarding the relevant failure modes under fatigue cyclic loading

n	Number of load cycles
$\Delta N_{Rk,s,0,n}$ (n = 1 to n = ∞)	Characteristic steel fatigue resistance under tension loading with origin load (F_{lo} = 0) in axial direction and n load cycles
$N_{Rk,c,0,n}$ (n = 1 to n = ∞)	Characteristic concrete cone fatigue resistance under tension loading with origin load (F_{lo} = 0) in axial direction and n load cycles
$\Delta N_{Rk,sp,0,n}$ (n = 1 to n = ∞)	Characteristic splitting fatigue resistance under tension loading with origin load (F_{lo} = 0) in axial direction and n load cycles
$\Delta N_{Rk,cb,0,n}$ (n = 1 to n = ∞)	Characteristic blow out fatigue resistance under tension loading with origin load (F_{lo} = 0) in axial direction and n load cycles
$\Delta N_{Rk,p,0,n}$ (n = 1 to n = ∞)	Characteristic pull-out fatigue resistance under tension loading with origin load (F_{lo} = 0) in axial direction and n load cycles
$\Delta V_{Rk,s,0,n}$ (n = 1 to n = ∞)	Characteristic steel fatigue resistance under shear loading with origin load (F_{lo} = 0) in transverse direction and n load cycles
$\Delta V_{Rk,c,0,n}$ (n = 1 to n = ∞)	Characteristic concrete edge fatigue resistance under shear loading with origin load (F_{lo} = 0) in transverse direction and n load cycles
$\Delta V_{Rk,cp,0,n}$ (n = 1 to n = ∞)	Characteristic concrete pry-out fatigue resistance under shear loading with origin load (F_{lo} = 0) in transverse direction and n load cycles
a_s	Exponent for combined tension and shear verification regarding steel failure under static and cyclic loading
ψ_{FN}	Load transfer factor for tension loading
ψ_{FV}	Load transfer factor for shear loading

Essential resistances in axial and transverse direction regarding the relevant failure modes under seismic performance

$N_{Rk,s,C1}$	Characteristic steel resistance to tension load for seismic performance category C1
$N_{Rk,p,C1}$	Characteristic pull-out resistance to tension load for seismic performance category C1
$N_{Rk,s,C2}$	Characteristic steel resistance to tension load, displacements for seismic performance category C2
$N_{Rk,p,C2}$	Characteristic pull-out resistance to tension load, displacements for seismic performance category C2
$\delta_{N,C2}$	Displacements under tension load for seismic performance category C2
$V_{Rk,s,C1}$	Characteristic steel resistance to shear load for seismic performance category C1
$V_{Rk,s,C2}$	Characteristic steel resistance to shear load for seismic performance category C2
$\delta_{V,C2}$	Displacements under shear load for seismic performance category C2
α_{gap}	Factor for annular gap

2 ESSENTIAL CHARACTERISTICS AND RELEVANT ASSESSMENT METHODS AND CRITERIA

2.1 Essential characteristics of the product

Table 2.1.1 shows how the performance of the product is assessed in relation to the essential characteristics.

Table 2.1.1: 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
Basic Works Requirement 1: Mechanical resistance and stability			
Characteristic resistance under static and quasi-static tension load			
1	Characteristic resistance to steel failure under static and quasi-static tension load	EAD 330924-01-0601, 2.2.1	Level $N_{Rk,s}$ [kN]
2	Characteristic resistance to pull-out failure under static and quasi-static tension load	EAD 330924-01-0601, 2.2.2	Level $N_{Rk,p}$ [kN]
3	Characteristic resistance to concrete cone failure under static and quasi-static tension load	EAD 330924-01-0601, 2.2.3	Level $k_{cr,N}$, $k_{ucr,N}$ [-], h_{ef}, $c_{cr,N}$, $s_{cr,N}$ [mm]
4	Edge distance to prevent splitting failure	EAD 330924-01-0601, 2.2.4	Level $c_{cr,sp}$, $s_{cr,sp}$ [mm]
5	Minimum edge distance, spacing and thickness of concrete member	EAD 330924-01-0601, 2.2.5	Level c_{min}, s_{min}, h_{min} [mm]
6	Maximum installation torque	EAD 330924-01-0601, 2.2.6	Level T_{inst} [Nm]
Characteristic resistance under static and quasi-static shear load			
7	Resistance to steel failure under static and quasi-static shear load	EAD 330924-01-0601, 2.2.7	Level $V_{Rk,s}$ [kN], k_7 [-], $M^0_{Rk,s}$ [Nm]
8	Resistance to concrete edge failure under static and quasi-static shear load without supplementary reinforcement	EAD 330924-01-0601, 2.2.8	Level l_f, d_{nom} [mm]
9	Resistance to pry-out failure under static and quasi-static shear load	EAD 330924-01-0601, 2.2.9	Level k_8 [-]
Characteristic resistance under static and quasi-static tension and shear load			
10	Combined tension and shear load under static and quasi-static load	EAD 330924-01-0601, 2.2.10	Level k_{11} [-]
Displacement under static and quasi-static tension or shear load			
11	Displacement under static and quasi-static tension or shear load	EAD 330924-01-0601, 2.2.11	Level δ_{N0}, $\delta_{N\infty}$, δ_{V0}, $\delta_{V\infty}$ [mm]
Characteristic resistance under fatigue cyclic loading			
12	Characteristic steel fatigue resistance under tension loading	2.2.1	Level $\Delta N_{Rk,s,0,n}$ (n = 1 to n = ∞)

No	Essential characteristic	Assessment method	Type of expression of product performance
13	Characteristic concrete cone, splitting and blow out fatigue resistance under tension loading	2.2.2	Level $\Delta N_{Rk,c,0,n}$ $\Delta N_{Rk,sp,0,n}$ $\Delta N_{Rk,cb,0,n}$ (n = 1 to n = ∞)
14	Characteristic pull-out fatigue resistance under tension loading	2.2.3	Level $\Delta N_{Rk,p,0,n}$ (n = 1 to n = ∞)
15	Characteristic steel fatigue resistance under shear loading	2.2.4	Level $\Delta V_{Rk,s,0,n}$ (n = 1 to n = ∞)
16	Characteristic concrete edge fatigue resistance under shear loading	2.2.5	Level $\Delta V_{Rk,c,0,n}$ (n = 1 to n = ∞)
17	Characteristic concrete pry-out fatigue resistance under shear loading	2.2.6	Level $\Delta V_{Rk,cp,0,n}$ (n = 1 to n = ∞)
17	Characteristic steel fatigue resistance under tension and shear	2.2.7	Level α_s
18	Load transfer factor for tension and shear loading	2.2.8	Level ψ_{FN} , ψ_{FV}
Characteristic resistance and displacements for seismic performance categories C1 and C2			
19	Characteristic resistance to tension load for seismic performance category C1	2.2.9	Level $N_{Rk,s,C1}$, $N_{Rk,p,C1}$ [kN]
20	Characteristic resistance to tension load, displacements for seismic performance category C2	2.2.10	Level $N_{Rk,s,C2}$, $N_{Rk,p,C2}$ [kN], $\delta_{N,C2}$ [mm]
21	Characteristic resistance to shear load for seismic performance category C1	2.2.11	Level $V_{Rk,s,C1}$ [kN
22	Characteristic resistance to shear load, displacements for seismic performance category C2	2.2.12	Level $V_{Rk,s,C2}$ [kN], $\delta_{V,C2}$ [mm]
23	Factor for annular gap	2.2.13	Level α_{gap} [-]
Basic Works Requirement 2: Safety in case of fire			
24	Reaction to fire	EAD 330924-01-0601, 2.2.12	Class
25	Resistance to fire	EAD 330924-01-0601, 2.2.13	Level $N_{Rk,s,fi}$, $N_{Rk,p,fi}$, $V_{Rk,s,fi}$ [kN], $M^0_{Rk,s,fi}$ [Nm]

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

2.2.1 Characteristic steel fatigue resistance under tension loading

Purpose of assessment

Determination of the characteristic steel fatigue resistance function under cyclic tension loading for steel failure as a linearised function of the number of load cycles n.

Assessment method

For the determination of the linearised characteristic fatigue resistance function, $\Delta N_{Rk,s,0,n}$, test series FA.1 to FA.4 in accordance with Table A.1.1.1 shall be performed.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The characteristic fatigue resistance shall be determined as follows:

$$\Delta N_{Rk,s,0,n} = k \cdot \frac{\Delta F_{k,n} \cdot N_{Rk,s}}{F_{k,Ref}} \tag{2.2.1.1}$$

where:

$\Delta F_{k,n}$	in accordance with equation (A.3.2.8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.2 (for uncracked concrete) and FA.4 (for cracked concrete)
$F_{k,Ref}$	in accordance with A.3.1, characteristic value of static resistance determined from reference test series FA.1 (for uncracked concrete) and FA.3 (for cracked concrete)
$N_{Rk,s}$	characteristic value of static resistance as determined in static tension tests in accordance with EAD 330924-01-0601 [1], 2.2.1
k	inclination factor

= 1,0 for tests performed with inclination of 3°
or if the installation instructions describe how to prevent skewing of the anchor effectively by suitable measures when installing the anchor (securing the installation position perpendicular to the surface of the concrete member, e.g., by installation templates, counter nuts etc.)

= 0,75 for tests performed without inclination of 3°
and no installation instructions for preventing skewing of the anchor

If the fatigue tests of different sizes are evaluated using a joint evaluation with at least 20 tests in total (based on the stress at the cross section), the characteristic fatigue resistance shall be calculated as follows:

The assessment in accordance with A.3.2 is done for the stress ($\Delta\sigma_k$) at the cross section instead of ΔF_k. The characteristic fatigue resistance for each size shall be calculated in accordance with following Equation:

$$\Delta N_{Rk,s,0,n} = k \cdot \frac{\Delta \sigma_{k,n} \cdot A_s \cdot \sigma_{Rk,s}}{\sigma_{k,Ref}} \tag{2.2.1.2}$$

where:

$\Delta\sigma_{k,n}$	in accordance with A.3.2, characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.2 (for uncracked concrete) and FA.4 (for cracked concrete), result of the joint evaluation
A_s	stressed cross section of the relevant anchor bolt size
$\sigma_{Rk,s}$	= $N_{Rk,s}$ / A_s (stress in the cross section)
$\sigma_{k,Ref}$	= $F_{k,ref}$ / A_s (stress in the cross section), $\sigma_{k,Ref} \geq \sigma_{Rk,s}$
$N_{Rk,s}$, $F_{k,ref}$, k	see Equation (2.2.1.1)

<u>Expression of results</u>: $\Delta N_{Rk,s,0,n}$ with (n = 1 to n = ∞) ,e.g., Figure A.3.2.1

2.2.2 Characteristic concrete cone, splitting and blow-out fatigue resistance under tension loading

<u>Purpose of assessment:</u>

Determination of the characteristic fatigue resistance function for concrete cone, splitting and blow out failure under cyclic tension loading as a linearised function of the number of load cycles n

<u>Assessment method</u>

The characteristic fatigue resistances to concrete cone failure, pull-out failure, splitting and blow out failure shall be calculated as follows:

$$\Delta N_{Rk,c,0,n} = \eta_{k,c,N,fat,n} \cdot N_{Rk,c} \tag{2.2.2.1}$$

$$\Delta N_{Rk,sp,0,n} = \eta_{k,sp,N,fat,n} \cdot N_{Rk,sp} \tag{2.2.2.2}$$

$$\Delta N_{Rk,cb,0,n} = \eta_{k,cb,N,fat,n} \cdot N_{Rk,cb} \tag{2.2.2.3}$$

where:

$N_{Rk,c}$ characteristic value of static resistance to concrete cone failure in accordance with EN 1992-4 [4], Equation (7.1)

$N_{Rk,sp}$ characteristic value of static resistance to splitting failure in accordance with EN 1992-4 [4], Equation (7.23)

$N_{Rk,cb}$ characteristic value of static resistance to blow out failure of mechanical fasteners in accordance with EN 1992-4 [4], Equation (7.25)

$\eta_{k,c,N,fat,n}$ reduction factor for concrete cone failure
determined without tests in accordance with Equation (2.2.2.4) or
determined by tests in accordance with Equation (2.2.2.5)

$\eta_{k,sp,N,fat,n} = \eta_{k,cb,N,fat,n} = \eta_{k,c,N,fat,n}$

If no tests are performed the reduction factor $\eta_{k,c,N,fat,n}$ for fatigue resistances shall be calculated as a function of the number of cycles n on the safe side as follows:

$$1{,}0 \geq \eta_{k,c,N,fat,n} = 1{,}1 \cdot n^{-0{,}055} \geq 0{,}5 \tag{2.2.2.4}$$

When a manufacturer wishes to get more favourable values, they shall be determined by tests of series FA.5 to series FA.8 in accordance with Table A.1.1.1.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The reduction factor $\eta_{k,c,N,fat,n}$ shall be calculated as follows:

$$\eta_{k,c,N,fat,n} = \frac{\Delta F_{k,n}}{F_{k,Ref}} \tag{2.2.2.5}$$

where:

$\Delta F_{k,n}$ in accordance with equation (A.3.2 .8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.6 (for uncracked concrete) and FA.8 for cracked concrete)

$F_{k,Ref}$ in accordance with A.3.1, characteristic value of reference static resistance as determined from tests series FA.5 (for uncracked concrete) or FA.7 (for cracked concrete)

<u>Expression of results</u>

$\Delta N_{Rk,c,0,n}$, $\Delta N_{Rk,sp,0,n}$, $\Delta N_{Rk,cb,0,n}$ with (n = 1 to n = ∞), e.g., Figure A.3.2.1

2.2.3 Characteristic pull-out fatigue resistance under tension loading

Purpose of assessment:

Determination of the characteristic fatigue resistance function for pull-out failure under cyclic tension loading as a linearised function of the number of load cycles n

Assessment method

The characteristic fatigue resistances to pull-out failure shall be calculated as follows:

$$\Delta N_{Rk,p,0,n} = \eta_{k,p,N,fat,n} \cdot N_{Rk,p} \quad (2.2.3.1)$$

where:

$N_{Rk,p}$ characteristic value of static resistance to pull-out failure of the anchor bolt as assessed on the basis of EAD 330924-01-0601 [1], clause 2.2.2

$\eta_{k,p,N,fat,n}$ determined without tests in accordance with Equation (2.2.2.4) with $\eta_{k,p,N,fat,n} = \eta_{k,c,N,fat,n}$ or determined by tests in accordance with Equation (2.2.3.2)

If no tests are performed the reduction factor $\eta_{k,p,N,fat,n}$ for fatigue resistances shall be calculated on the safe side in accordance with Equation (2.2.2.4).

When a manufacturer wishes to get more favourable values they shall be determined by tests of series FA.9 to series FA.12 in accordance with Table A.1.1.1.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The reduction factor $\eta_{k,p,N,fat,n}$ shall be calculated as follows:

$$\eta_{k,p,N,fat,n} = \frac{\Delta F_{k,n}}{F_{k,Ref}} \quad (2.2.3.2)$$

where:

$\Delta F_{k,n}$ in accordance with equation (A.3.2 .8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.10 (for uncracked concrete) and FA.12 for cracked concrete)

$F_{k,Ref}$ in accordance with A.3.1, characteristic value of reference static resistance as determined from tests series FA.9 (for uncracked concrete) or FA.11 (for cracked concrete)

Expression of results

$\Delta N_{Rk,p,0,n}$ with (n = 1 to n = ∞), e.g., Figure A.3.2.1

2.2.4 Characteristic steel fatigue resistance under shear loading

Purpose of assessment:

Determination of the characteristic fatigue resistance function for steel failure as a linearised function of the number of load cycles n.

Assessment method

Required tests: For the determination of the linearised characteristic fatigue resistance function, $\Delta V_{Rk,s,0,n}$, test series FA.13 to FA.16 in accordance with Table A.1.1.1 shall be performed.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The characteristic fatigue resistance shall be determined as follows:

$$\Delta V_{Rk,s,0,n} = \frac{\Delta F_{k,n} \cdot V_{Rk,s}}{F_{k,Ref}} \qquad (2.2.4.1)$$

where:

$\Delta F_{k,n}$ in accordance with equation (A.3.2 .8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.14 (for uncracked concrete) and FA.16 for cracked concrete)

$F_{k,Ref}$ in accordance with A.3.1, characteristic value of static resistance determined from reference test series FA.13 (for uncracked concrete) and FA.15 (for cracked concrete)

$V_{Rk,s}$ characteristic value of static resistance as determined in static tension tests in accordance with EAD 330924-01-0601 [1], 2.2.7

If the fatigue tests of different sizes are evaluated using a joint evaluation with at least 20 tests in total (based on the stress at the cross section), the characteristic fatigue resistance shall be calculated as follows:

The assessment in accordance with A.3.2 shall be done for the stress ($\Delta\sigma_k$) at the cross section instead of ΔF_k. The characteristic fatigue resistance for each size shall be calculated in accordance with following Equation:

$$\Delta V_{Rk,s,0,n} = \frac{\Delta\sigma_{k,n} \cdot A_s \cdot \sigma_{Rk,s}}{\sigma_{k,Ref}} \qquad (2.2.4.2)$$

where:

$\Delta\sigma_{k,n}$ in accordance with A.3.2, characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.14 (for uncracked concrete) and FA.16 (for cracked concrete), result of the joint evaluation

A_s stressed cross section of the relevant anchor bolt size

$\sigma_{Rk,s}$ $V_{Rk,s}$ / A_s (stress in the cross section)

$\sigma_{k,Ref}$ $F_{k,ref}$ / A_s (stress in the cross section), $\sigma_{k,Ref} \geq \sigma_{Rk,s}$

$V_{Rk,s}$, $F_{k,ref}$ see Equation (2.2.4.1)

Expression of results: $\Delta V_{Rk,s,0,n}$ (n = 1 to n = ∞) ,e.g., Figure A.3.2.1

2.2.5 Characteristic concrete edge fatigue resistance under shear loading

Purpose of assessment:

Determination of the characteristic fatigue resistance function for concrete edge failure as a linearised function of the number of load cycles n.

Assessment method

The characteristic fatigue resistance to concrete edge failure shall be calculated as follows:

$$\Delta V_{Rk,c,0,n} = \eta_{k,c,V,fat,n} \cdot V_{Rk,c} \quad (2.2.5.1)$$

where:

$V_{Rk,c}$ characteristic value of static resistance to concrete edge failure in accordance with EN 1992-4 [4], Equation (7.40)

$\eta_{k,c,V,fat,n}$ reduction factor for concrete edge failure

determined without tests in accordance with Equations (2.2.5.2) or

determined by tests in accordance with Equation (2.2.5.3)

If no tests are performed the reduction factor $\eta_{k,c,V,fat,n}$ for fatigue resistances shall be calculated as a function of the number of cycles n on the safe side as follows:

$$1{,}0 \geq \eta_{k,c,V,fat,n} = 1{,}2 \cdot n^{-0{,}08} \geq 0{,}5 \quad (2.2.5.2)$$

When a manufacturer wishes to get more favourable values, they shall be determined by tests of series FA.17 to series FA.18 in accordance with Table A.1.1.1.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The reduction factor $\eta_{k,c,V,fat,n}$ shall be calculated as follows:

$$\eta_{k,c,V,fat,n} = \frac{\Delta F_{k,n}}{F_{k,Ref}} \quad (2.2.5.3)$$

where:

$\Delta F_{k,n}$ in accordance with equation (A.3.2 .8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.18 (for uncracked concrete)

$F_{k,Ref}$ in accordance with A.3.1, characteristic value of reference static resistance as determined from tests series FA.17 (for uncracked concrete)

Expression of results: $\Delta V_{Rk,c,0,n}$ (n = 1 to n = ∞),e.g., Figure A.3.2.1

2.2.6 Characteristic concrete pry-out fatigue resistance under shear loading

Purpose of assessment:

Determination of the characteristic fatigue resistance function for concrete pry-out failure under cyclic shear loading as a linearised function of the number of load cycles n.

Assessment method

The characteristic fatigue resistance to concrete pry-out failure shall be calculated as follows:

$$\Delta V_{Rk,cp,0,n} = \eta_{k,cp,V,fat,n} \cdot V_{Rk,cp} \quad (2.2.6.1)$$

where:

$V_{Rk,cp}$ characteristic value of static resistance to concrete edge failure in accordance with EN 1992-4 [4], Equation (7.39c) or (7.39d)

$\eta_{k,cp,V,fat,n}$ reduction factor for concrete edge failure
determined without tests in accordance with Equations (2.2.5.2) with $\eta_{k,cp,V,fat,n} = \eta_{k,c,V,fat,n}$,
or determined by tests in accordance with Equation (2.2.6.2)

If no tests are performed the reduction factor $\eta_{k,cp,V,fat,n}$ for fatigue resistances shall be calculated on the safe side in accordance with Equation (2.2.5.2).

When a manufacturer wishes to get more favourable values they shall be determined by tests of series FA.19 to series FA.20 in accordance with Table A.1.1.1.

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The reduction factor $\eta_{k,cp,V,fat,n}$ shall be calculated as follows:

$$\eta_{k,cp,V,fat,n} = \frac{\Delta F_{k,n}}{F_{k,Ref}} \quad (2.2.6.2)$$

where:

$\Delta F_{k,n}$ in accordance with equation (A.3.2.8), (A.3.2.11) and (A.3.2.12), characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.20 (for uncracked concrete)

$F_{k,Ref}$ in accordance with A.3.1, characteristic value of reference static resistance as determined from tests series FA.19 (for uncracked concrete)

Expression of results

$\Delta V_{Rk,cp,0,n}$ (n = 1 to n = ∞) ,e.g., Figure A.3.2.1

2.2.7 Characteristic steel fatigue resistance under combined tension and shear loading

Purpose of assessment

Determination of the characteristic fatigue resistance function for steel failure as a linearised function of the number of load cycles n and determination of the a_{sn}-values for combined tension and shear verification.

Assessment method

Characteristic steel fatigue resistance under combined tension and shear is only given if after tests of test series FA.2 and FA.4 no failure on the concrete surface is observed. If this condition is not fulfilled, it shall be stated in the ETA that steel fatigue resistance under combined tension and shear loading = 0.

Under combined tension and shear verification the following exponents shall be given on the safe side for anchor bolts made of carbon steel and stainless steel:

$\alpha_s = \alpha_{sn}$ = 0,5 for thread size smaller than M16

$\alpha_s = \alpha_{sn}$ = 0,7 for thread size M16 and larger where:

α_s exponent for verification of steel failure in accordance with EN 1992-4 [4] Equation (8.1)

α_{sn} exponent for verification of steel failure in accordance with TR 061 [3] Table 2.5

When a manufacturer wishes to get more favourable values, they shall be determined by tests of series FA.21 and FA.22 in accordance with Table A.1.1.1.

For all tests of series FA.21 and FA.22 one angle β between the axis of the anchor bolt and load direction shall be chosen in accordance with the relation between fatigue tension resistance $\Delta N_{Rk,s,0,\infty}$ and fatigue shear resistance $\Delta V_{Rk,s,0,\infty}$:

β = 30°: $\Delta N_{Rk,s,0,\infty}$ / $\Delta V_{Rk,s,0,\infty}$ > 1,33 (2.2.7.1)

β = 45°: 0,75 ≤ $\Delta N_{Rk,s,0,\infty}$/ $\Delta V_{Rk,s,0,\infty}$≤ 1,33 (2.2.7.2)

β = 60°: $\Delta N_{Rk,s,0,\infty}$ / $\Delta V_{Rk,s,0,\infty}$< 0,75 (2.2.7.3)

where:

$\Delta N_{Rk,s,0,\infty}$ characteristic value of fatigue limit resistance as determined from tests series FA.2 (for uncracked concrete) or FA.4 (for cracked concrete)

$\Delta V_{Rk,s,0,\infty}$ characteristic value of fatigue limit resistance as determined from tests series FA.14 (for uncracked concrete) or FA.16 (for cracked concrete)

The tests shall be performed in accordance with A.1 and A.2.

The assessment shall be performed in accordance with A.2 and A.3.

The following Equation shall be solved to a_{sn} to determine a_{sn} as a function of the number of cycles.

$$\left(\frac{\cos(\beta)\cdot\Delta F^{\beta}_{Rk,s,n}}{\Delta N_{Rk,s,n}}\right)^{a_{sn}} + \left(\frac{\sin(\beta)\cdot\Delta F^{\beta}_{Rk,s,n}}{\Delta V_{Rk,s,n}}\right)^{a_{sn}} = 1{,}0 \qquad (2.2.7.4)$$

where:

$\Delta F^{\beta}_{Rk,s,n}$ in accordance with A.3.2, characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.21 (for uncracked concrete) and FA.22 (for cracked concrete)

$\Delta N_{Rk,s,n}$ in accordance with A.3.2, characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.2 (for uncracked concrete) and FA.4 (for cracked concrete)

$\Delta V_{Rk,s,n}$ in accordance with A.3.2, characteristic value of fatigue resistance after n load cycles determined from fatigue test series FA.14 (for uncracked concrete) and FA.16 (for cracked concrete)

The α_{sn}-values shall be determined by interactive steps with calculation the Equation in such a way that the graph connects the resistances $\Delta N_{Rk,s,n}$, $\Delta F^{\beta}_{Rk,s,n}$ and $\Delta V_{Rk,s,n}$ (see Figure 2.2.7.1) for each given number of cycles n.

The lowest value α_{sn} shall be given in the ETA as value α_s.

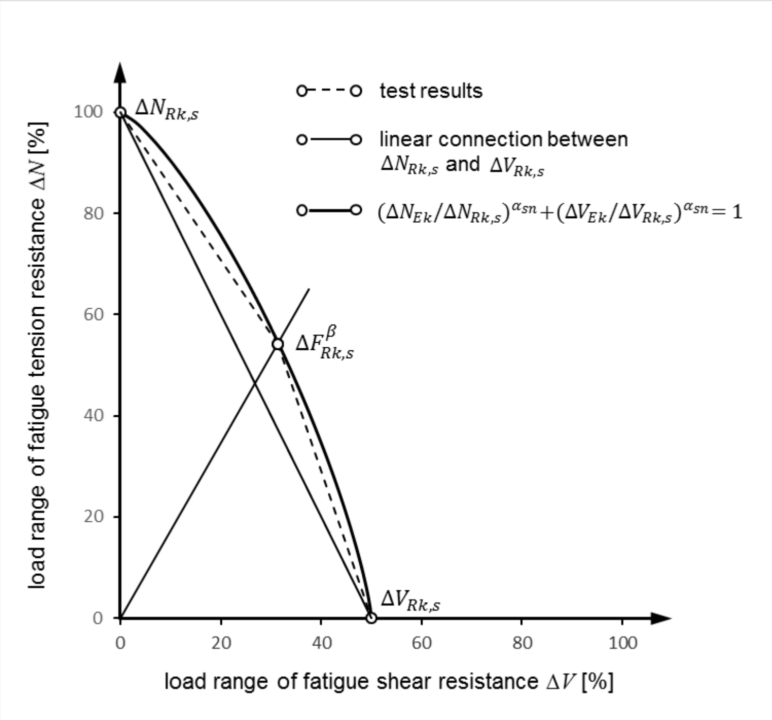


Figure 2.2.7.1: Example for an interaction diagram for combined tension and shear loads

Expression of results: a_s

2.2.8 Load transfer factor for tension and shear loading

Purpose of assessment

The purpose of the assessment is to determine the influence of non-equally loaded anchor bolts within a group on the fatigue resistance under shear (ψ_{FV}) and tension (ψ_{FN}) loading.

Assessment method

No tests are required if the load transfer factors ψ_{FN} = ψ_{FV} = 0,5 are applied on the safe side.

When a manufacturer wishes to get more favourable values, they shall be determined by tests in accordance with Table A.1.1.1, test series FA.2 and FA.4 for tension and test series FA.14 and FA.16 for shear and assessment in accordance with EAD 330250-00-0601 [5], Annex C, C.3.2 and C.3.3.

The determination shall be done only with the smallest and largest anchor size if the resulting load transfer factors are applied to all other anchor sizes specified by the manufacturer. The smallest load transfer factors ψ_{FN} and ψ_{VN} shall be applied.

For assessment of the parameters a_{cr}, a_{ucr}, b_{cr} and b_{ucr} in accordance with EAD 330250-00-0601 [5], C.3.2 and C.3.3, the single values F_{up} and Δs of each test shall be used to determine the power function in cracked and non-cracked concrete as given in EAD 330250-00-0601 [5], Figure C.3.

$F_{up,ucr}$ = upper load level tested in uncracked concrete
(for tension from test series FA.2 and for shear from test series FA.14)

Δs_{ucr} = displacements of a test results in uncracked concrete
(for tension from test series FA.2 and for shear from test series FA.14)

$F_{up,cr}$ = upper load level tested in cracked concrete
(for tension from test series FA.4 and for shear from test series FA.16)

Δs_{cr} = displacements of a test results in cracked concrete
(for tension from test series FA.4 and for shear from test series FA.16)

The test results shall be used for the determination of the load transfer factor (see EAD 330250-00-0601 [5], Annex C, for additional details):

ψ_{FN} = ψ_F in accordance with EAD 330250-00-0601 [5], Equation (C.26) for tension

ψ_{FV} = ψ_F in accordance with EAD 330250-00-0601 [5], Equation (C.26) for shear

Expression of results

ψ_{FN}, ψ_{FV}

2.2.9 Resistance to tension for seismic performance category C1 (Series C.1.1)

Purpose of assessment

These tests are intended to evaluate the performance of anchor bolts under simulated seismic tension loading, including the effects of cracks, and without edge effects for seismic performance category C1.

Assessment method

Tests in accordance with Table B.1.1, test series C1.1 shall be performed.

The general test conditions are given in B.2 and B.3.1.

Explanations for anchor bolt types to be tested are given in B.3.2.

Specific tests conditions are given in EAD 330232-01-0601 [6], clause C.3.3.1.

The assessment of test series is given in EAD 330232-01-0601 [6], clause C.4.1.

The reduction factor $\alpha_{N,C1}$ shall be determined in accordance with EAD 330232-01-0601 [6], clause C.4.1.1.

The characteristic resistance to tension load for seismic performance category C1 shall be calculated in accordance with EAD 330232-01-0601 [6], clause C.4.3.1.1.

For steel failure caused reduction:

$N_{Rk,s,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.70)

$N_{Rk,p,C1}$ shall be calculated in accordance with EAD 330232-01-0601 6], Equation (C.71)

$N_{Rk,p,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.72), if no pull-out failure occurs for static loading

For pull-out failure caused reduction:

$N_{Rk,s,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.73)

$N_{Rk,p,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.74)

$N_{Rk,p,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.75), if no pull-out failure occurs for static loading

Expression of results

$N_{Rk,s,C1}$, $N_{Rk,p,C1}$ [kN]

2.2.10 Resistance to tension for seismic performance category C2 (Series C.2.1, C2.3, C2.5)

Purpose of assessment

These tests are intended to evaluate the performance of anchor bolts under simulated seismic tension loading, including the effects of cracks, and without edge effects for seismic performance category C2.

Assessment method

Tests in accordance with Table B.1.1, test series C2.1, C2.3 and C2.5 shall be performed with the same embedment depths and test set-up (confinement conditions).

The general test conditions are given in B.2 and B.3.1.

Explanations for anchor bolt types to be tested are given in clause B.3.2.

Specific tests conditions are given in EAD 330232-01-0601 [6]:

- clause C.3.4.1 for reference test series C.2.1,
- clause C.3.4.2 for tests under pulsating tension loading (test series C2.3) and

- clause C.3.4.4 for tests with tension load and varying crack width (test series C2.5).

The assessment of test series is given in EAD 330232-01-0601 [6], clause C.4.2.

The reduction factor $\alpha_{N,C2}$ shall be determined in accordance with EAD 330232-01-0601 [6], Equation (C.66).

The reduction factor $\beta_{cv,N,C2}$ shall be determined in accordance with EAD 330232-01-0601 [6], Equation (C.67).

The characteristic resistance to tension load for seismic performance category C2 shall be calculated in accordance with EAD 330232-01-0601 [6], clause C.4.3.2.1.

For steel failure caused reduction:

$N_{Rk,s,C2}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.77)

$N_{Rk,p,C2}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.78)

For pull-out failure caused reduction:

$N_{Rk,s,C2}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.79)

$N_{Rk,p,C2}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.80)

The displacements $\delta_{N,C2}$ shall be assessed in accordance with EAD 330232-01-0601 [6], clause C.4.3.2.3, Table C.6.

Expression of results

$N_{Rk,s,C2}$, $N_{Rk,p,C2}$ [kN], $\delta_{N,C2}$ [mm]

2.2.11 Resistance to shear load for seismic performance categories C1 (Series C1.2)

Purpose of assessment

These tests are intended to evaluate the performance of anchor bolts under simulated seismic shear loading, including the effects of cracks, and without edge effects for seismic performance category C1.

Assessment method

Tests in accordance with Table B.1.1, test series C1.2 shall be performed.

The general test conditions are given in B.2 and B.3.1.

Explanations for anchor bolt types to be tested are given in clause B.3.2.

Specific tests conditions are given in EAD 330232-01-0601 [6], clause C.3.3.2.

The assessment of test series is given in EAD 330232-01-0601 [6], clause C.4.1.

The reduction factor $\alpha_{V,C1}$ shall be determined in accordance with EAD 330232-01-0601 [6], clause C.4.1.2.

The characteristic resistance to shear load for seismic performance category C1 shall be calculated in accordance with EAD 330232-01-0601 [6], clause C.4.3.1.2.

$V_{Rk,s,C1}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.76)

Expression of results

$V_{Rk,s,C1}$ [kN]

2.2.12 Resistance to shear load for seismic performance categories C2 (Series C2.2, C2.4)

Purpose of assessment

These tests are intended to evaluate the performance of anchor bolts under simulated seismic shear loading, including the effects of cracks, and without edge effects for seismic performance category C2.

Assessment method

Tests in accordance with Table B.1.1, test series C2.2 and C2.4 shall be performed with the same embedment depths and test set-up (confinement conditions).

The general test conditions are given in B.2 and B.3.1.

Explanations for anchor bolt types to be tested are given in clause B.3.2.

Specific tests conditions are given in EAD 330232-01-0601 [6]:

- clause C.3.4.1 for reference test series C.2.2,
- clause C.3.4.3 for tests under alternating shear loading (test series C2.4).

The assessment of test series is given in EAD 330232-01-0601 [6], clause C.4.2.

The reduction factor $\alpha_{V,C2}$ shall be determined in accordance with EAD 330232-01-0601 [6], Equation (C.68).

The reduction factor $\beta_{cv,V,C2}$ shall be determined in accordance with EAD 330232-01-0601 [6], Equation (C.69).

The characteristic resistance to tension load for seismic performance category C2 shall be calculated in accordance with EAD 330232-01-0601 [6], clause C.4.3.2.2.

$V_{Rk,s,C2}$ shall be calculated in accordance with EAD 330232-01-0601 [6], Equation (C.81)

The displacements $\delta_{V,C2}$ shall be assessed in accordance with EAD 330232-01-0601 [6], clause C.4.3.2.3, Table C.6.

Expression of results

$V_{Rk,s,C2}$ [kN], $\delta_{V,C2}$ [mm]

2.2.13 Factor for annular gap for seismic performance categories C1 and C2

Purpose of assessment

When an annular gap is present between anchor bolt and fixture, the forces on the anchor bolt are amplified under shear loading due to a hammer effect on the anchor bolt. In EN 1992-4 [4] this effect is considered in the resistance of the fastening by introducing the reduction factor α_{gap}.

Assessment method

The factor for annular gap α_{gap} for seismic performance categories C1 and C2 shall be determined in accordance with EAD 330232-01-0601 [6], clause C.4.3.4.

Expression of results

α_{gap} [-]

3 ASSESSMENT AND VERIFICATION OF CONSTANCY OF PERFORMANCE

3.1 System(s) of assessment and verification of constancy of performance to be applied

EAD 330924-01-0601, clause 3.1, applies.

3.2 Tasks of the manufacturer

EAD 330924-01-0601, clause 3.2, applies.

For characteristic steel fatigue resistance EAD 330250-00-0601, clause 3.2, Table 3.1, Line 3 applies.

3.3 Tasks of the notified body

EAD 330924-01-0601, clause 3.3, applies.

4 REFERENCE DOCUMENTS

[1]	EAD 330924-01-0601	Cast-in anchor bolts
[2]	EN 10263-4:2017	Steel rod, bars and wire for cold heading and cold extrusion – Part 4: Technical delivery conditions for steels for quenching and tempering
[3]	EOTA TR 061:2018-01, amended 2020-09, amended 2023-02	Design methods for fasteners in concrete under fatigue cyclic loading
[4]	EN 1992-4:2018	Eurocode 2 – Design of concrete structures – Part 4: Design of fastenings for use in concrete
[5]	EAD 330250-00-0601	Post-installed fasteners in concrete under fatigue cyclic loading
[6]	EAD 330232-01-0601	Mechanical fasteners for use in concrete

ANNEX A: TEST METHOD TO DETERMINE THE LINEARISED CHARACTERISTIC FATIGUE RESISTANCE

A.1 Test programme and test details

A.1.1 Test programme

The characteristic fatigue resistance function shall be determined by testing performed in accordance with Table A.1.1. All tests are performed in concrete of strength class C20/25.

Table A.1.1.1: Required tests under static and fatigue cyclic loading for anchor bolts

N°	Tests in accordance with clauses	Crack width Δw [mm]	Load direction	Min. number of tests	Anchor Size 3)	Embedment depth h_{ef}	Remarks
	Tension						
FA.1	2.2.1 Reference tests for steel failure	0	0°	5	all	max	single anchor
FA.2	2.2.1 Fatigue tests for steel failure	0	0°	15	all	max	single anchor
FA.3	2.2.1 Reference tests for steel failure	0,3	0°	5	all	max	single anchor
FA.4	2.2.1 Fatigue tests for steel failure	0,3	0°	15	all	max	single anchor
FA.5	2.2.2 Reference tests for concrete failure 1)	0	0°	5	all	min	group of 4 anchors
FA.6	2.2.2 Fatigue tests for concrete failure 1)	0	0°	15	all	min	group of 4 anchors
FA.7	2.2.2 Reference tests for concrete failure 1)	0,3	0°	5	all	min	group of 4 anchors
FA.8	2.2.2 Fatigue tests for concrete failure 1)	0,3	0°	15	all	min	group of 4 anchors
FA.9	2.2.3 Reference tests for pull-out failure 1)	0	0°	5	all	min	single anchor
FA.10	2.2.3 Fatigue tests for pull-out failure 1)	0	0°	15	all	min	single anchor
FA.11	2.2.3 Reference tests for pull-out failure 1)	0,3	0°	5	all	min	single anchor
FA.12	2.2.3 Fatigue tests for pull-out failure 1)	0,3	0°	15	all	min	single anchor
	Shear						
FA.13	2.2.4 Reference tests for steel failure	0	90°	5	all	max	single anchor
FA.14	2.2.4 Fatigue tests for steel failure	0	90°	15	all	max	single anchor
FA.15	2.2.4 Reference tests for steel failure	0,3	90°	5	all	max	single anchor
FA.16	2.2.4 Fatigue tests for steel failure	0,3	90°	15	all	max	single anchor
FA.17	2.2.5 Reference tests for concrete edge failure 2)	0	90°	5	Min4)	min	group of 2 anchors
FA.18	2.2.5 Fatigue tests for concrete edge failure 2)	0	90°	15	Min4)	min	group of 2 anchors
FA.19	2.2.5 Reference tests for concrete pry-out failure 2)	0	90°	5	Min4)	min	group of 2 anchors
FA.20	2.2.5 Fatigue tests for concrete pry-out failure 2)	0	90°	15	Min4)	min	group of 2 anchors
	Combined tension and shear						
FA.21	2.2.6 Fatigue tests for steel failure	0	β	10	all	max	single anchor
FA.22	2.2.6 Fatigue tests for steel failure	0,3	β	10	all	max	single anchor

Footnotes to Table A.1.1.1:

1) No tests are required, if the reduction factor for characteristic fatigue resistance for concrete cone failure is calculated in accordance with Equation (2.2.2.4).

2) No tests are required, if the reduction factor for characteristic fatigue resistance for concrete edge failure is calculated in accordance with Equation (2.2.5.2).

3) Anchor size may be reduced if statistically equivalence is given.

4) Minimum size without steel failure

The total number of tests of anchors having a uniform cross section with variable embedment depths can be reduced, if the resulting fatigue resistance of the smallest embedment depth is applied to all other anchor embedment depths specified by the manufacturer.

If the anchor is produced with different steel qualities as specified by the manufacturer, the tests summarized in Table A.1.1.1 shall be performed with the steel of lowest rupture elongation and strength. Otherwise, the tests summarized in Table A.1.1.1 shall be performed for all steel qualities. The number of tests can be reduced if the results fit within the other tests.

Tests summarized in Table A.1.1.1 shall be performed for all coatings specified by the manufacturer. The number of tests can be reduced if the results fit within the other tests.

<u>Distribution of the tests:</u>

The test shall be performed in a way that the fatigue test fails between n = 10000 and n = $1 \cdot 10^6$ load cycles for carbon steel and between n = 10000 and n = $1 \cdot 10^7$ load cycles for stainless steel.

The fatigue tests shall be distributed in a way that 6 to 8 tests shall fail between 10^4 and 10^5 load cycles, about 6 to 8 tests shall fail between 10^5 and $1 \cdot 10^6$ under tension load and between 10^5 and $5 \cdot 10^5$ under shear load. For stainless steel 2 tests shall fail between $2 \cdot 10^6$ and $1 \cdot 10^7$.

<u>Reduction of the necessary test numbers of fatigue tests:</u>

If the fatigue tests regarding steel failure for different sizes are statistical equivalent (based on the stress at the cross section) the number of tests for the other sizes can be reduced to 5. The results can be assessed using a joint evaluation with at least 20 tests in total. For the joint evaluation the assessment in accordance with A.3.2 shall be done for the stress at the cross section $\Delta\sigma_k$ instead of ΔF_k.

If the test results in crack concrete are statistically equivalent with the test results in uncracked concrete the number of tests in cracked concrete can be reduced to 5. Minimum 20 tests in total shall be performed. For cracked and uncracked concrete minimum 5 tests for each size shall be performed.

<u>Determine statistically equivalence:</u>

The determination of statistically equivalence shall be performed using the quantiles-lines and the 90% confidence levels. Statistically equivalence is sufficient if the results of different diameters or the results in cracked and uncracked concrete are within the range between the 5%-quantile-line and the 95%-quantile-line (prediction band) of the unfavourable or leading investigated size (largest amount of test results) in uncracked concrete.

The lowest 5%-quantile level shall be taken at the unfavourable condition with respect to size or cracked and uncracked concrete. Therefore, the scatter band of the test results shall be taken into account and the comparison of the different sizes or concrete state (cracked / uncracked) can be done using stresses instead of forces.

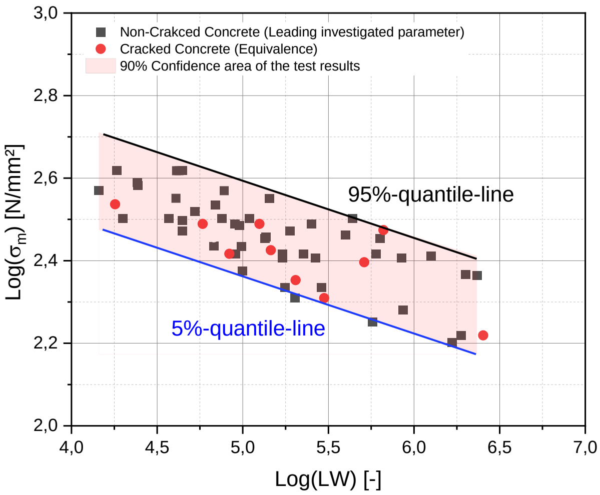
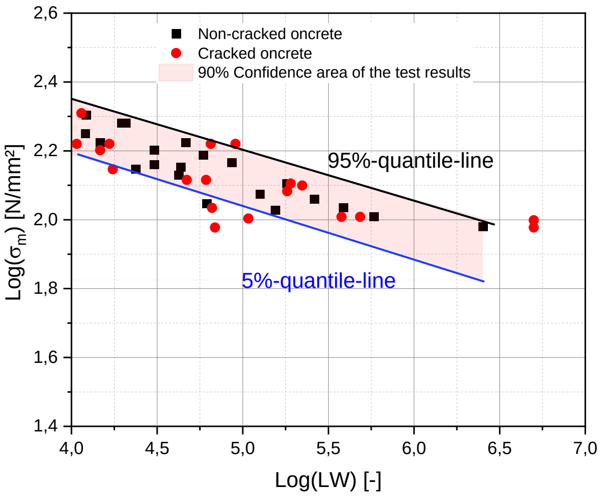
Statistically equivalence is given	
Statistically equivalence is not given	

Figure A.1.1.1 Example for statistically equivalence or no statistically equivalence

A.1.2 Test details

The tests shall be performed in accordance with EAD 330250-00-0601 [5], Annex D, with following amendments:

- the anchor bolt is not a post-installed fastener, but a cast-in anchor in accordance with EAD 330924-01-0601 [1],
- EAD 330250-00-0601 [5], clause D.4.2 (Confined test setup), does not apply,
- EAD 330250-00-0601 [5], clause D.5 (Details for Installation of the fastener), does not apply – modifications are given in clause A.1.2.1
- EAD 330250-00-0601 [5], clause D.6 (Details for tests in cracked concrete), does not apply – modifications are given in clause A.1.2.2

A.1.2.1 Details for the installation of the anchor bolts

The tested anchor bolts shall be installed in a concrete surface that has been cast against a form of the test member.

When testing in cracked concrete, anchor bolts shall be placed in the middle of hairline cracks. It shall be verified that the anchor bolt is placed over the entire anchoring zone in the crack by suitable methods as described in the following.

To guarantee that the entire anchoring zone of the anchor bolts is located in the crack, aluminium foil shall be applied to the crack plates before concreting (see Figures A.1.2.1.1, A.1.2.1.2 and A.1.2.1.3). The crack plates and aluminium foil shall be at the level of the installed anchors. Thus, it can be guaranteed before the test that the installed anchors are in the crack course when the cracks were opened. Directly before concreting, formwork panels shall be placed on both sides of the anchors. These panels serve to protect the aluminium foil before and while concreting. The concrete shall then successively be placed carefully into the formwork and immediately compacted in layers so that a mass balance can be established around the foil. While the filling of the concrete, the additional formwork panels shall slowly be pulled upwards, so that the concrete can flow slowly and evenly to the foil from both sides. If these formwork panels would not be in place, the aluminium foil would be torn apart by the concrete pressure. During the hardening process of the concrete test specimen, the aluminium foil is dissolving due to the high alkalinity of the fresh concrete. This guarantees that the aluminium foil is not affecting the load bearing behaviour of the anchors.

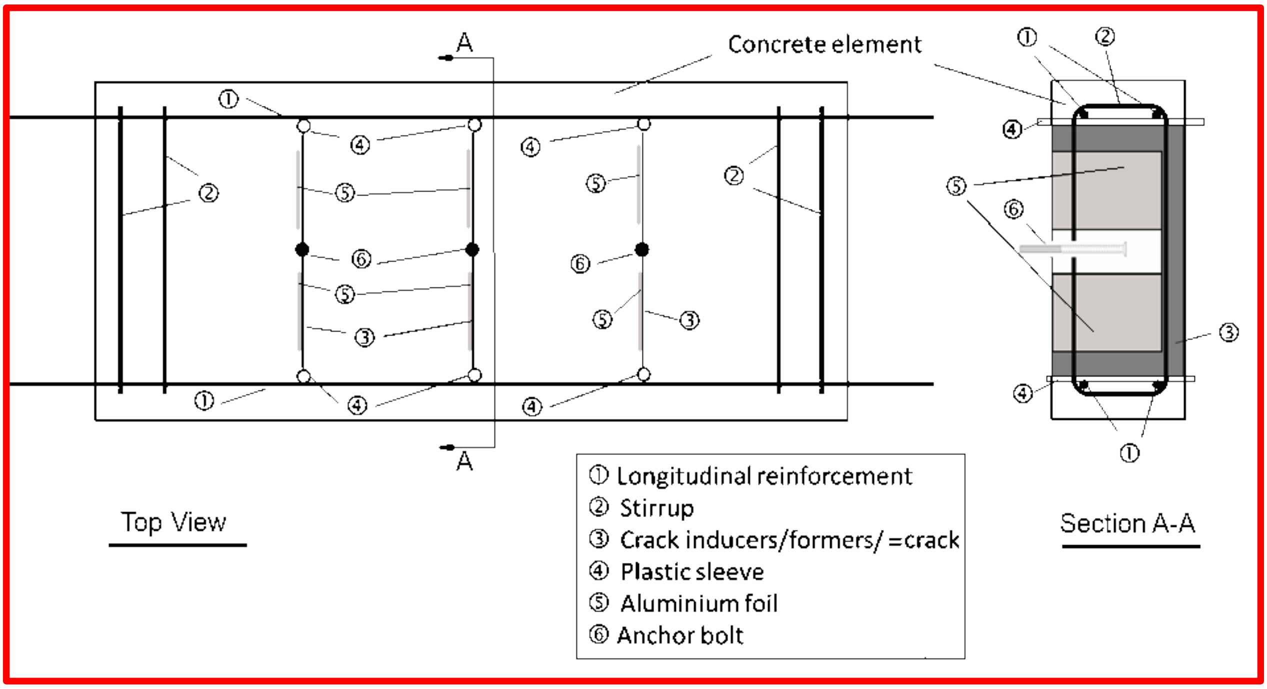


Figure A.1.2.1.1: Example for placing the aluminium foil within the test specimen

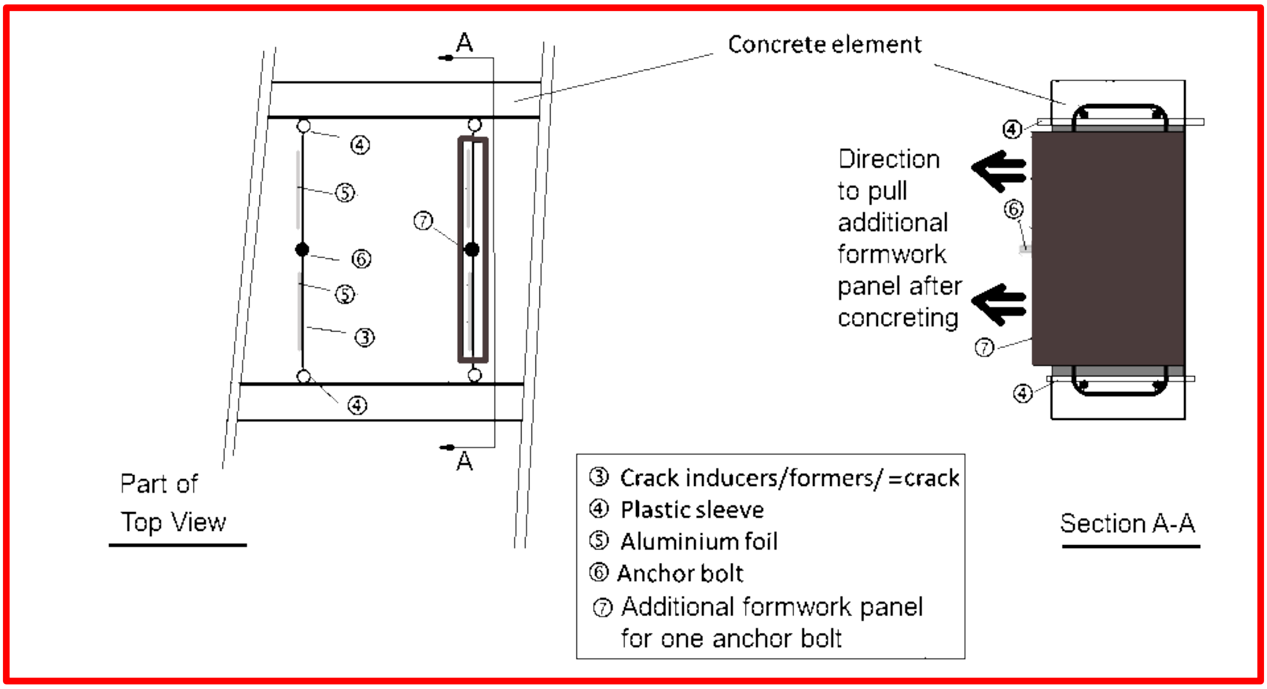


Figure A.1.2.1.2: Example for additional formwork for one anchor bolt and pulling direction

Figure A.1.2.1.3: Example for additional formwork panels

A.1.2.2 Details for tests in cracked concrete

The tests in cracked concrete shall be undertaken in unidirectional cracks. The required crack width Δw is given in Table A.1.1.1 or Table B.1.1. Δw is the difference between the crack width when loading the anchor bolt and the crack width of the hairline crack. The crack shall be widened to the required crack width with wedges or rebar according Figure B.3.1.1.2 while the anchor bolt is unloaded. The initial crack width shall be set to within +10 % of the specified value. However, the mean value of a series shall reflect the specified value.

Use one-sided tolerance for crack width.

Then the anchor bolt shall be subjected to load while the crack width is controlled, either

- at a constant width, for example, by means of a servo system, or

- limited to a width close to the initial value by means of appropriate reinforcement and depth of the test member.

In both cases the crack width at the face opposite to that through which the anchor bolt is installed shall be maintained at a value larger than or equal to the specified value.

A.2 Basics

In fatigue tests the force-controlled periodic loading with sinusoidal course shall be used as the most disadvantageous case (practical application) of the test specimen (see Figure A.2.1).

The repeated loads consist of a constant lower stress level and an upper stress level with same algebraic sign (no alternating actions) and shall be applied on the specimen until fatigue failure.

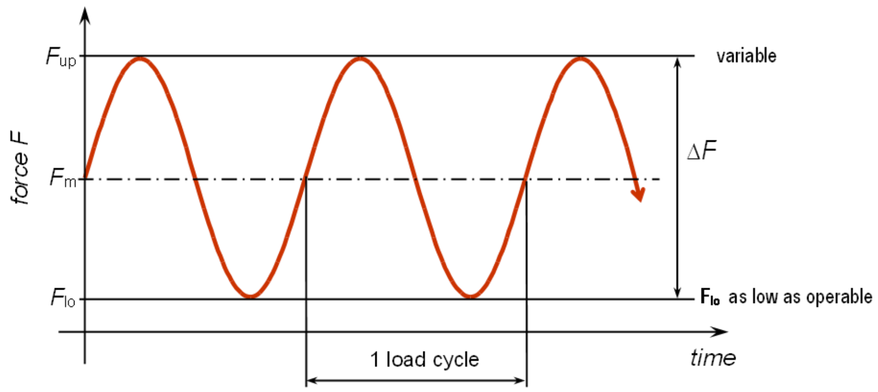


Figure A.2.1: Example of fatigue cyclic loading protocol

Tests which are stopped without failure shall not be included in the final evaluation.

Only tests failed after 10^6 load cycles (carbon steel) and after 10^7 (stainless steel) under tension and after 500000 load cycles (carbon steel) and after 10^7 (stainless steel) under shear shall be taken into account if the regression curve is unfavourable under this assumption.

Tests failed before 10000 load cycles under tension or shear load shall be taken into account if the regression curve is unfavourable under this assumption.

The total linearised function consists of 4 lines (see also Figure A.3.2.1):

- The upper horizontal level is the characteristic fatigue resistance ΔF_k (n = $1 \cdot 10^4$).
- The first slope m_1 (up to n = $5 \cdot 10^6$) shall be determined as given in clause A.3.
- The second slope m_2 (between n = $5 \cdot 10^6$ and n = $1 \cdot 10^8$) shall be calculated as given in clause A.3. The slope shall be reduced depending on the slope m_1.
- The lower horizontal level is the limit characteristic resistance $\Delta F_{k,\infty}$ ($n = \infty$).

The used capital letter F in this Annex shall be replaced by the letter N for tension loads, V for shear loads and F^β for combined tension and shear loads, σ for stress at the cross section.

A.3 Procedure steps

A.3.1 Determination of the characteristic static resistance

For the determination of the characteristic static resistance S_k five tests ($n \geq 5$) are required.

For the determination of the static and fatigue resistances testing shall be done on the identical product regarding batch, geometry, material etc.

The characteristic value S_k is equivalent to the 5%-quantile $(\mathrm{p} = 0{,}05)$, determined on a level of confidence of 90% $(1 - \alpha = 0{,}9)$ and unknown standard deviation by using the normal distribution.

The value shall be determined as follows:

$$S_k = \overline{S} - k_{n-u,p,1-\alpha} \cdot \hat{s} \qquad \text{(A.3.1.1)}$$

where

$k_{n-u,p,1-\alpha}$	statistic factor in accordance with Table A.3.1.1, for values $(n - u)$ not given in Table A.3.1.1, see also [12]
n	degrees of freedom, equal to the number of static test results
u	known condition of the mean value $(u = 1)$

$$\hat{s} = \sqrt{\frac{\sum_{i=1}^{n}(\overline{S}-S_i)^2}{n-1}}\text{, standard deviation} \qquad \text{(A.3.1.2)}$$

Table A.3.1.1: Statistic factor $k_{n-u,0,05,0,9}$ with 5%-quantile and confidence level of 90%

$n-u$	2	3	4	5	6	7	8
$k_{n-u,0,05,0,9}$	5,311	3,957	3,400	3,092	2,894	2,754	2,650
$n-u$	10	12	14	16	20	24	28
$k_{n-u,0,05,0,9}$	2,503	2,402	2,329	2,272	2,190	2,132	2,089

The characteristic static resistance shall be determined in accordance with following Equation:

$$F_{k,ref} = S_k \qquad \text{(A.3.1.3)}$$

where: S_k in accordance with Equation (A.3.1.1)

A.3.2 Determination of the characteristic fatigue resistance

The number of cycles to failure n for each range of force ΔF shall be determined through testing. The test results shall be used for the determination of the fatigue resistance function.

The characteristic fatigue resistance function shall be determined by statistical evaluation based on the 5%-quantile with a confidence level of 90%

The procedure is summarized as given:

1. Linear regression of the test data on log-log scale shall be performed employing the method of least squares. The regression line is given with Equation (A.3.2.1):

$$y_i = a_m + b_m \cdot x_i \qquad \text{(A.3.2.1)}$$

where:

y_i	Variable of the regression curve as the logarithm applied fatigue load range for test result i $= \log \Delta F_i$
x_i	Variable of the regression curve as the number of observed load cycles for test result i $= \log n_i$
a_m, b_m	Regression parameter for the average function, see Equations (A.3.2.2) and (A.3.2.3)
n_i	Number of cycles for test result i
ΔF_i	Load range of fatigue resistance for test result i

The parameters a_m and b_m shall be obtained from the condition that the sum of the squares of residuals is minimum:

$$b_m = \frac{\sum x_i\, y_i - m \cdot (\sum \bar{x})\,(\sum \bar{y})}{\sum x_i^2 - m \cdot \sum(\bar{x})^2} \qquad \text{(A.3.2.2)}$$

$$a_m = \bar{y} - b_m \cdot \bar{x} \qquad \text{(A.3.2.3)}$$

where:

$a_m, b_m,\ x_i, y_i$ see Equation (A.3.2.1)

m Number of test results

$\bar{y}$ and $\bar{x}$ Mean values of y_i and x_i respectively

2. The standard deviation shall be estimated as:

$$s = \sqrt{\frac{S_{yy} - b_m \cdot S_{xy}}{m-2}} \tag{A.3.2.4}$$

where:

$$S_{yy} = \sum y_i^2 - \frac{1}{m}\left(\sum y_i\right)^2 \tag{A.3.2.5}$$

$$S_{xy} = \sum x_i\, y_i - \frac{1}{m}\left(\sum x_i \sum y_i\right) \tag{A.3.2.6}$$

x_i, y_i see Equation (A.3.2.1)

b_m Regression parameter for the average function, see Equation (A.3.2.2)

m Number of test results

3. The lower confidence limit shall be evaluated using the 5%-quantile value of the regression line.

The characteristic fatigue resistance shall be calculated using the following Equation:

$$log\left(\Delta F_{k,n}\right) = a_m + b_m \cdot log\,(n) - k \cdot s \tag{A.3.2.7}$$

where:

$\Delta F_{k,n}$ characteristic fatigue resistance for n load cycles

n Number of load cycles

a_m, b_m see Equation (A.3.2.2) and (A.3.2.3)

k statistical factor for a confidence level of 90% and unknown standard deviation

= $k_{n-u,p,1-\alpha}$ in accordance with Table A.3.1.1

s standard deviation, see Equation (A.3.2.4)

If a test result is below the calculated characteristic regression curve the curve shall be shifted in a way that the curve runs through the lowest value.

4. The assessment of the characteristic resistance for fatigue loading shall be performed using a four-linear curve in the double logarithmic scale (see Figure A.3.2.1).

4a. The characteristic fatigue resistances for n = $1 \cdot 10^4$ to n < $5 \cdot 10^6$ load cycles shall be derived from test results as follows:

$$\Delta F_{k.n} = 10^{\left(a + b \cdot \log(\mathrm{n})\right)} \tag{A.3.2.8}$$

where:

$$a = \left(\frac{k \cdot s - a_m}{b_m}\right) \tag{A.3.2.9}$$

$$b = \left(\frac{1}{b_m}\right) \tag{A.3.2.10}$$

$\Delta F_{k,n}$ characteristic fatigue resistance for n load cycles

n Number of load cycles

a_m, b_m see Equation (A.3.2.2) and (A.3.2.3)

k, s see Equation (A.3.2.7)

4b. For n = 5 · 10^6 load cycles the characteristic resistance shall be calculated as follows:

$$\Delta F_{k.n} = \Delta F_{k.5\cdot10^6} = 10^{\left(a + b \cdot \log\left(5 \cdot 10^6\right)\right)} \quad \text{(A.3.2.11)}$$

where

a, b = see Equation (A.3.2.9) and (A.3.2.10)

4c. For $n > 5 \cdot 10^6$ load cycles the slope of the curve shall be reduced depending on the slope of the determined curve up to 5 million cycles. The slope shall be expressed as m_1 up to $n = 5 \cdot 10^6$ cycles and as m_2 for $n > 5 \cdot 10^6$ cycles.

The characteristic fatigue resistances for $n > 5 \cdot 10^6$ load cycles and $n < 1 \cdot 10^8$ cycles shall be calculated as follows:

$$\Delta F_{k.n} = 10^{\left(\log \Delta F_{k.5\cdot10^6} + \frac{\log(n) - 6.7}{m_2}\right)} \quad \text{(A.3.2.12)}$$

where:

$$m_2 = 2 \cdot m_1 - 1 = \frac{2}{b} - 1 \quad \text{(A.3.2.13)}$$

$$m_1 = \frac{1}{b} \quad \text{(A.3.2.14)}$$

b see Equation (A.3.2.10)

$\Delta F_{k,n}$ characteristic fatigue resistance for n load cycles

n Number of load cycles

m_1 slope up to $5 \cdot 10^6$ load cycles

m_2 slope for more than $5 \cdot 10^6$ load cycles and less than 10^8 load cycles

4d. For $n > 1 \cdot 10^8$ a horizontal line shall be applied using the value that was calculated for $n = 1 \cdot 10^8$.

4e. For $n < 1 \cdot 10^4$ a horizontal line shall be applied using the value that was calculated for $n = 1 \cdot 10^4$.

An example of the determination is given in following figure.

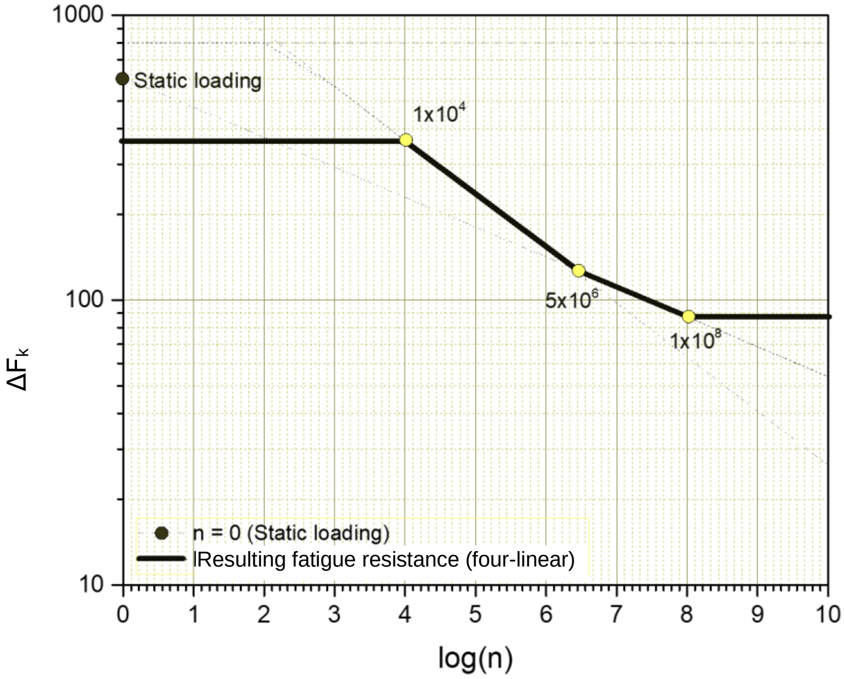


Figure A.3.2.1: Schematic four-linear fatigue resistance ΔF_k for log(n) number of cycles

ANNEX B: ANCHOR BOLTS IN CONCRETE UNDER SEISMIC ACTION

B.1 Test programme

Table B.1.1 Test programme

Series	Purpose of test	Concrete	Crack width Δw [1] [mm]	n_{min} [2]	Sizes	EAD 330232-01-0601 [6], clause
Characteristic resistance for seismic performance category C1						
C1.1	Functioning under pulsating tension load	C20/25	0,5	5	All	C.3.3.2 C.4.1.1
C1.2	Functioning under alternating shear load	C20/25	0,5	5	All	C.3.3.3 C.4.1.2
Characteristic resistance for seismic performance category C2						
C2.1a	Reference tension tests in low strength concrete	C20/25	0,8	5	All	C.3.4.1 C.4.2.1, C.4.2.2
C2.1b	Tension tests in high strength concrete	C50/60	0,8	5	All	C.3.4.1 C.4.2.1, C.4.2.2
C2.2	Reference shear tests	C20/25	0,8	5	All	C.3.4.1 C.4.2.1, C.4.2.3
C2.3	Functioning under pulsating tension load	C20/25	0,5 / 0,8 [3]	5	All	C.3.4.2 C.4.2.1, C.4.2.4
C2.4	Functioning under alternating shear load	C20/25	0,8	5	All	C.3.4.3 C.4.2.1, C.4.2.5
C2.5	Functioning with tension load under varying crack width	C20/25	Δw_1=0,0 Δw_2=0,8	5	All	C.3.4.4 C.4.2.1, C.4.2.6

1) Crack width added to the hairline crack width before loading of anchor bolt.

2) Test all anchor bolt diameters to be assessed for use in seismic applications. For different anchor bolt types to be tested see B.3.2.

3) 0,5 ($\leq$ 0,5·N/N_{max}); 0,8 ($>$ 0,5·N/N_{max}). The tests may also be conducted in Δw = 0,8 mm at all load levels (N/N_{max}).

B.2 General

The compressive strength of concrete $f_{c,test}$ used in the various equations in this document shall consistently represent the value measured with standard cylinders or standard cubes, unless specifically required otherwise. If necessary, the concrete compressive strength may be converted accordingly.

Seismic performance categories C1 and C2 in accordance with EAD 330232-01-0601 [6], C.1.2, for post-installed mechanical fasteners apply also for cast-in anchor bolts.

B.3 Test Methods

B.3.1 General testing requirements

As far as applicable EAD 330232-01-0601 [6], Annex C, and EAD 330924-01-0601 [1], Annex A, shall be followed for test members, test setup and details of tests. Modifications are addressed in Clause B.3 of this document, which overrules conflicting provisions in EAD 330232-01-0601 [6], Annex C, and EAD 330924-01-0601 [1], Annex A.

B.3.1.1 Test members

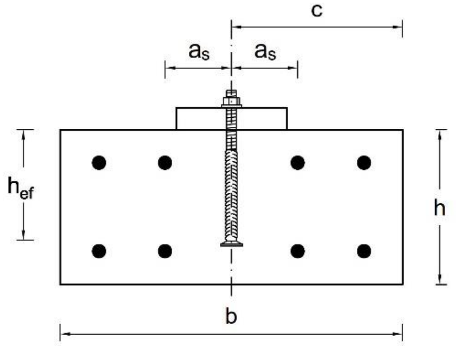
The thickness of the test member shall be at least the maximum of 1,5 h_{ef} and the minimum member thickness requested by the manufacturer which is given in the ETA. The width of the test member shall be large enough to avoid any influence of the edges on the anchor bolt behaviour. The test member shall be designed such that the crack width is approximately constant throughout the thickness of the test member during the test (including crack cycling (for crack widths ≥ 0,3 mm), load cycling and peak load). This requirement is considered to be fulfilled if

a) the crack width Δw_{hef} at the level of the embedment depth h_{ef} is equal to or greater than the required value, and

b) the crack width Δw_{top} at the top side of the test member (i.e., the side in which the anchor bolt is installed) is equal to or larger than Δw_{hef} for $\Delta w_{hef} \geq 0{,}3$ mm.

The reinforcement shall be of equal size and placed symmetrically (see Figure B.3.1.1.1). The spacing of the reinforcement in the test member shall be ≤ 400 mm. The capacity of the anchor bolt shall not be affected by the reinforcement. The reinforcement shall remain well in the elastic range during each test. Buckling of the reinforcement shall be avoided. The bond length ℓ_b between possible crack planes and at both ends of the specimen (see Figure B.3.1.1.2) shall be large enough to introduce the tension force into the concrete.

To facilitate the opening of the crack by Δw = 0,8 mm a bond breaker shall be applied at both sides of the crack (see Figure B.3.1.1.2). A plastic pipe with an inner diameter of ≈ 1,2 d_s shall be used for this purpose, where d_s denotes the diameter of the reinforcing bar. When using bond breakers, the de-bonding length ℓ_{db} shall be ≤ 5 d_s.



a_s … distance between anchor bolt and reinforcement bar

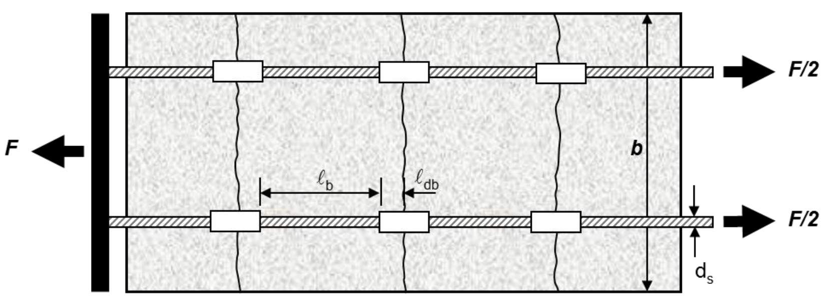
b … width of the test member

c … edge distance

h … height of test member

h_{ef} … embedment depth of the anchor bolt

Figure B.3.1.1.1 Example cross section of test member



… bond breaker

ℓ_b … bond length

ℓ_{db} … de-bonding length

d_s … diameter of rebar

b … width of test member

F … force on test member

Figure B.3.1.1.2 Example for test member with bond breaking pipes on rebar (plan view)

The requirement that the anchor bolt behaviour is not influenced by the edges of the test member is considered to be fulfilled if for unconfined testing the concrete breakout body (see EN 1992-4 [4], Figure 7.1 b) does not intersect with an edge or the edge distance of the anchor bolt in all directions is $c \geq 2{,}0\ h_{ef}$.

The requirement that the capacity of the anchor bolt is not affected by the reinforcement is considered to be fulfilled for unconfined tests if the distance a_s between the anchor bolt and the nearest reinforcement bar (see Figure B.3.1.1.1) is at least 75 mm and $\geq 0{,}60\ h_{ef}$. If for large embedment depths this distance requirement and the spacing requirement of the reinforcement ≤ 400 mm cannot be fulfilled at the same time an expertise is required showing that the nearest reinforcement bar does not affect the capacity of the anchor bolt.

Note The above requirement for a_s is based on the consideration that the reinforcement does not intersect the portion of the concrete breakout cone that has developed at peak load and on the following two assumptions:

1. *The crack length at ultimate load is approximately 0,4 times the side length of the final cone. The slope of the cone as measured from the horizontal is on the average about 35°.*
2. *The spacing of the reinforcement used to create and control the crack width is not less than 150 mm.*

The fulfilment of the requirements regarding the constant crack width shall be demonstrated for each test member design for the anchor bolt with the highest ultimate load to be tested in this test member for the crack width required for the specific test (see Table B.1.1) and for crack width Δw = 0,3 mm to 0,8 mm for test series C2.5. At least 3 test members shall be tested for each test member design and in each test the conditions given above shall be fulfilled. The results of this assessment shall be recorded. There are two options for the assessment shown in Figure B.3.1.1.3a) and Figure B.3.1.1.3b).

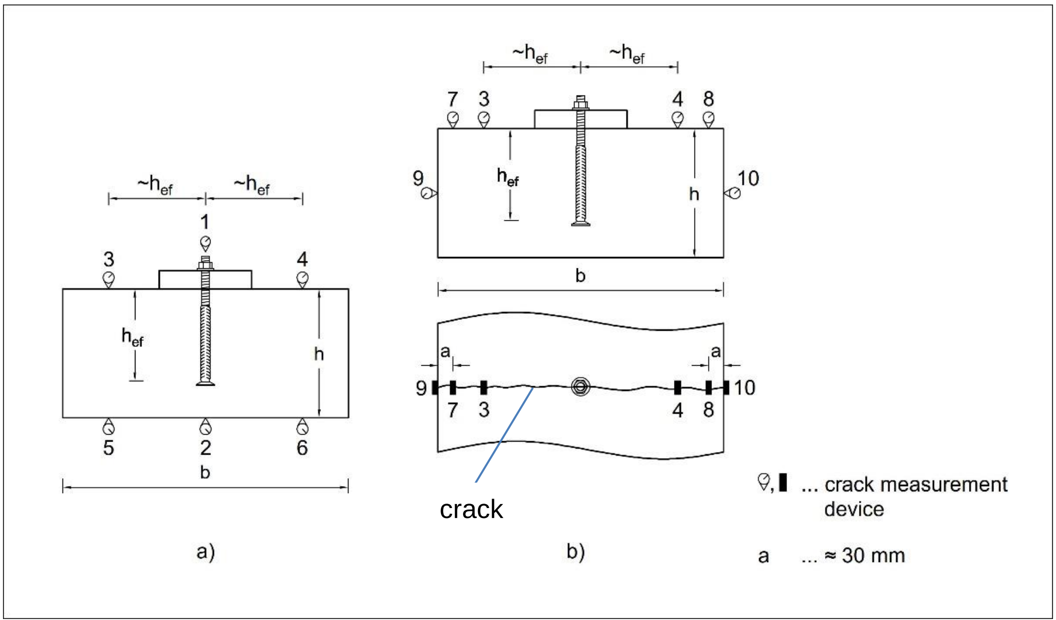


Figure B.3.1.1.3 Measurements for one crack at one anchor bolt to show fulfilment of the constant crack width requirement (for crack inducing with crack inducer and aluminium foil see Figure A.1.2.1.1)

Crack measurement and tolerance on crack width

The crack width shall be measured continuously during the test with a measuring error not greater than 0,02 mm.

In tension tests the crack width Δw_{hef} shall be determined by either one of the following two approaches:

a) Linear interpolation of crack measurements at the top Δw_{top} and bottom Δw_{bot} of the test member (see Figure B.3.1.1.3a). In this case the crack width shall be measured either at the location of the anchor bolt (i.e., locations 1 (Δw_{top}) and 2 (Δw_{bot}) in Figure B.3.1.1.3a) or on both sides of the anchor bolt (i.e., locations 3 & 4 (for Δw_{top}) and 5 & 6 (for Δw_{bot}) in Figure B.3.1.1.3a) with the two mean values of the measurements at the top and bottom representing Δw_{top} and Δw_{bot}, respectively.

b) Measuring the crack width at the side of the test member at the embedment depth level h_{ef} (i.e., locations 9 and 10 in Figure B.3.1.1.3b). In this case the mean value of the measurements at the side of the test member shall be determined to represent Δw_{hef}.

For both approaches in unconfined tension tests the measurement devices shall be placed as shown in Figure B.3.1.1.3.

In shear tests the crack width shall be measured within a distance of approximately 1,0 h_{ef} in front of and behind the anchor bolt (and the mean value shall be determined) or directly at the anchor bolt location where possible.

The mean of the measured crack widths Δw_{hef} for each test series determined for each anchor bolt shall be equal to or greater than the specified crack width for the test series. Individual crack widths shall be within the following tolerance:

- for Δw < 0,3 mm: 20% of crack width specified for the test series.
- for Δw ≥ 0,3 mm: minimum of 10% of the crack width specified for the test series and 0,04 mm.

B.3.1.2 Installation of a fixture to the anchor bolt

The installation torque T_{inst} required by the manufacturer shall be applied to the anchor bolt by a torque wrench (which has a documented calibration). The measuring error shall not exceed 5 % of the applied torque throughout the whole measurement range. After about 10 minutes of applying T_{inst} to the anchor bolt, the torque shall be reduced to 0,5 T_{inst} to account for relaxation of the pre-stressing force with time.

If no torque is specified by the manufacturer’s product installation information (MPII), finger-tighten the anchor bolt prior to testing.

B.3.1.3 Test setup

The crack shall be located over the entire effective load transfer zone of the anchor bolt (see h_{lz} in accordance with Figure B.3.1.3.1). For crack inducing see Figure A.1.2.1.1 and clause A.1.2.1.

All tension tests shall be performed as unconfined tests (see EAD 330924-01, Figure A.5.1 [1]).

In shear tests uplift of the fixture (steel plate) shall be restrained such that no significant friction forces are induced. Such friction forces are avoided if for example a setup as shown in Figure B.3.1.3.2 is used, which prevents the uplift, limits friction by roller bearing and does not actively apply a compression force. Furthermore, the maximum allowed annular gap of the clearance hole in accordance with EN 1992-4 [4], Table 6.1, shall be selected in the shear tests. For anchor bolts with a specified smaller gap or without an annular gap, both of which shall be stated in the ETA, the specific anchor bolt system may be tested.

Note *The effect of high loading rates on the anchor bolt behaviour is conservatively neglected.*

In accordance with Figure B.3.1.1.3a) the crack widths shall be measured at the top and bottom of the test member either at the anchor bolt location (locations 1 and 2 in Figure B.3.1.1.3a) or at a distance of approximately h_{ef} on both sides of the anchor bolt (locations 3 and 4 and locations 5 and 6 in Figure B.3.1.1.3a). The mean value of the crack width measurements at locations 3 and 4 represents Δw_{top} and the mean value of the crack width measurements at locations 5 and 6 represents Δw_{bot}. The crack width Δw_{hef} shall be obtained by linear interpolation of the top and bottom crack widths, i.e., Δw_{top} and Δw_{bot}, respectively.

Equally, the approach shown in Figure B.3.1.1.3b) may be pursued if it is shown that the width of the crack remains approximately constant across the width of the test member. This condition is considered to be fulfilled if the ratio of the mean value of the crack width measurements at locations 7 and 8 to the mean value of the measurements at locations 3 and 4 is ≤ 1,05. The mean value of the crack width measurements at locations 3 and 4 represents Δw_{top} and the mean value of the crack width measurements at locations 9 and 10 represents Δw_{hef}.

For test series C2.5 only one anchor bolt shall be located in a crack at the time of testing.

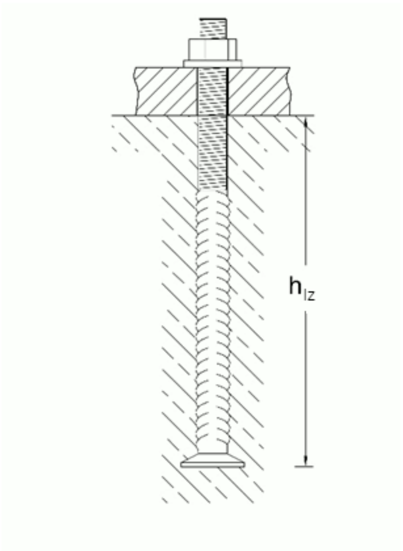


Figure B.3.1.3.1 Effective load transfer zone (h_{lz})

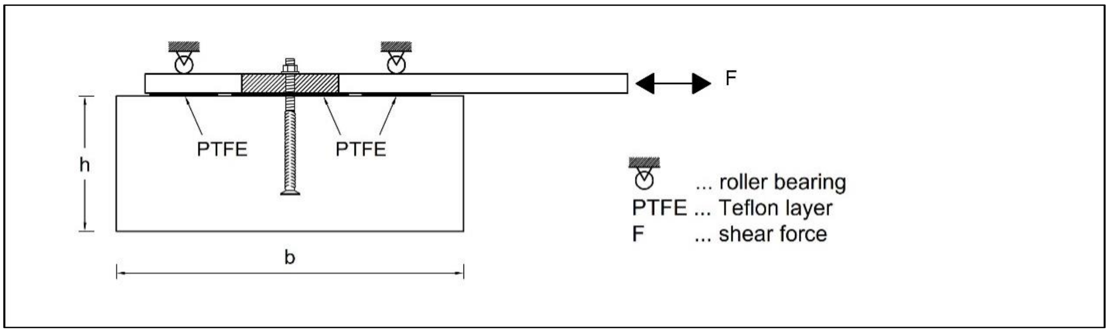


Figure B.3.1.3.2 Sketch of example for shear test setup with no significant friction forces

<u>Control of crack width</u>

In the tests to failure (monotonic tests and residual capacity tests) the anchor bolt shall be subjected to load while the crack width is controlled, either

a) at a constant width taking into account the requirements given in clause B.3.1.1, for example, by means of a servo system, or

b) limited to a width close to the specified value by means of the reinforcement and test member dimensions (see B.3.1.1).

B.3.2 Anchor bolt types to be tested

In general, the tests shall be performed with all anchor bolt diameters, embedment depths, steel types (galvanized steel, stainless steel, high corrosion resistant steel) and grades (strength classes and lowest rupture elongation), production methods, head configurations to be assessed for use in seismic applications. The number of variants to be tested may be reduced as described below. It shall be allowed to perform additional tests beyond the minimum number of tests described below to verify anchor bolt characteristics for additional parameters to meet manufacturer's wishes and expectations (e.g., tests at different embedment depths).

If certain reference tension tests, which are required in the context of this assessment, have not been performed in the non-seismic part of the assessment, these tests shall be performed. Equally, it shall be permitted that the corresponding resistance under ultimate load is calculated from the data obtained in the non-seismic assessment for cracked concrete.

It shall be permitted that the tests are conducted with the smallest anchor diameter. In this case the obtained test results with regard to loads may be used for larger anchor diameters without changes.

B.3.2.1 Steel type, steel grade and production methods

Tension tests

If the load bearing area of the head is identical in all models, only anchor bolts of one steel type, the highest steel grade and one production method shall be tested. The measured displacements shall be applied to all steel types, steel grades and production methods.

Shear tests

Only anchor bolts of the highest grade and lowest rupture elongation shall be tested if the reduction of the characteristic steel shear resistance due to simulated seismic shear testing as compared to the characteristic steel shear resistance under static loading is accepted for all steel types and steel grades. Otherwise, all steel types and steel grades shall be tested. The measured displacements shall be applied to the anchor bolts made from other steel types, steel grades or by other production methods.

B.3.2.2 Head configuration

The specific test series shall be performed with the most adverse head configuration of the product in respect to functioning and ultimate load. If the most adverse head configuration is not obvious all head configurations shall be tested.

B.3.2.3 Embedment depth

Tension tests

a) Anchor bolts under category C1 (test series C1.1):

   If multiple embedment depths are specified and the reduction factor for seismic loading $\alpha_{N,C1}$ shall be evaluated for all embedment depths, minimum and maximum embedment depths shall be tested. If the same reduction factor for seismic loading $\alpha_{N,C1}$ is accepted for all embedment depths, only the maximum embedment depth needs to be tested.

b) Anchor bolts under category C2 (test series C2.1, C2.3 and C2.5):

   If multiple embedment depths are specified, it is allowed to only perform tests at the maximum embedment depth. If only the maximum embedment depth is tested, the reduction factors $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ for the maximum embedment depth shall be applied to anchor bolts with smaller embedment depths and the displacements measured for anchor bolts with the maximum embedment shall be applied to anchor bolts with smaller embedment depths.

Shear tests

a) Anchor bolts under category C1 (test series C1.2):

   If there is more than one embedment depth specified for an anchor bolt, tests shall be performed for the minimum and maximum embedment depth only. If in the tests with minimum embedment depth steel failure occurs tests at the maximum embedment depth may be omitted if the reduction factor $\alpha_{V,C1}$ is applied to all embedment depths.

b) Anchor bolts under category C2 (test series C2.2, C2.4):

   Only the minimum embedment depth shall be tested if the reduction factor for seismic loading $\alpha_{V,C2}$ is accepted for all embedment depths. If at the minimum embedment depth pry-out failure is encountered, select a larger embedment depth avoiding pry-out failure. The displacements measured in the tests with the minimum embedment depth shall be applied to anchor bolts with a larger embedment depth.