

EOTA[®]

TECHNICAL REPORT

**Post-installed fasteners
in concrete
under seismic action**

**TR 049
AUGUST 2016**

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1 SCOPE

This Technical Report (TR) covers metal fasteners for use in concrete under seismic actions. The assessment of metal fasteners under seismic actions is optional. The TR deals with the preconditions, assumptions, required tests and assessment for metal fasteners under seismic actions. Fasteners qualified for multiple use for non-structural applications are not covered by this document.

This TR does not address the use of fasteners under fatigue loads and/or impact loads.

1.1 General

The tests in this TR are intended to evaluate the performance of fasteners under simulated seismic tension and shear loading, including the effects of cracks, and under simulated seismic crack cycling conditions. The behaviour of fasteners in regions of reinforced concrete structures, where plastic steel strains are expected (e.g. in plastic hinge zones) is not covered in the requirements of this annex; fasteners shall be placed outside of these regions.

A precondition for qualification in fastener seismic performance categories C1 and C2 is the complete assessment for use in cracked and non-cracked concrete (option 1 to 6).

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.

1.2 Categories

For the evaluation of the performance of fasteners subjected to seismic loading two seismic performance categories, i.e. C1 and C2, with C2 being more stringent than C1, are distinguished. The recommended use of the performance categories C1 and C2 as they relate to the design of fastenings in concrete is given in TR 045 [5] and prEN1992-4 [3].

Performance category C1 provides fastener capacities in terms of strength (forces), while performance category C2 provides fastener capacities in terms of both strength (forces) and displacements. In both cases, the effect of concrete cracking is taken into account. The maximum crack width considered in C1 is $\Delta w = 0,5$ mm and in C2 it is $\Delta w = 0,8$ mm, where Δw is additive to the hairline crack width in the concrete member after fastener installation but before fastener loading.

Qualification of fasteners for category C1 comprises tests under pulsating tension load (2.3.2) and tests under alternating shear load (2.3.3). Qualification of fasteners for category C2 includes reference tests up to failure (2.4.2), tests under pulsating tension load (2.4.3), tests under alternating shear load (2.4.4) as well as tests under crack cycling (2.4.5). In these tests forces and displacements are measured either continuously or at certain intervals. Qualification of fasteners for category C2 places higher demands on the performance of fasteners under seismic action as compared to category C1.

Based on the respective load histories and crack widths, which are different for the two categories C1 and C2, the design information for C1 contains values of tension and shear resistance of the fastener, while for C2 it contains values of tension and shear resistance as well as fastener displacement.

Detailed information regarding the various testing protocols and assessment criteria for both seismic performance categories is given in Chapters 2 and 3.

2 METHODS OF VERIFICATION

2.1 General testing requirements

As far as applicable the TR 048 [6] shall be followed for test members, test setup and details of tests. Modifications are addressed in Section 2 of this document, which overrule conflicting provisions in the TR 48 [6].

2.1.1 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 fastener 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 $\geq 0,3$ 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 fastener 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 2.1). The spacing of the reinforcement in the test member shall be ≤ 400 mm. The capacity of the fastener 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 2.2) shall be large enough to introduce the tension force into the concrete.

To facilitate the opening of the crack by $\Delta w = 0,8$ mm a bond breaker may be applied at both sides of the crack (see Figure 2.2). A plastic pipe with an inner diameter of $\approx 1,2 d_s$ may 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} is recommended to be $\leq 5 d_s$.

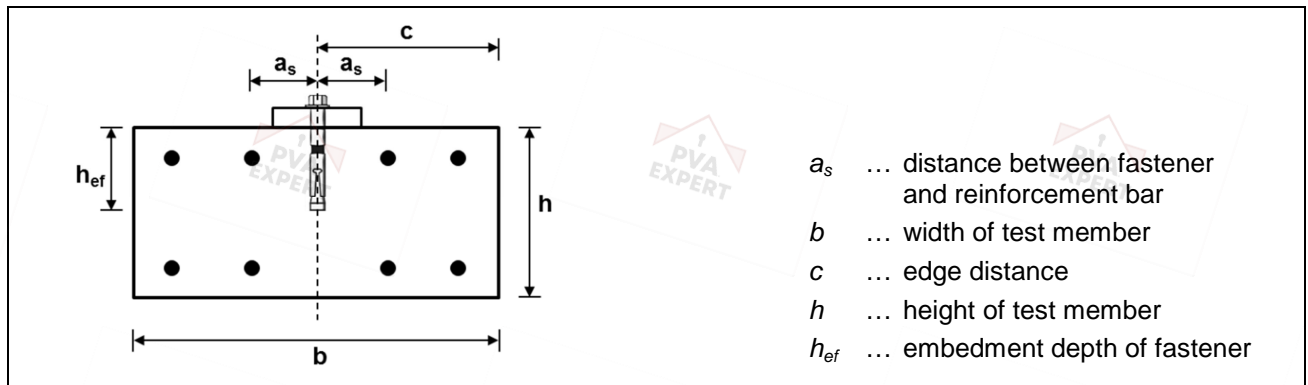


Figure 2.1 Example cross section of test member

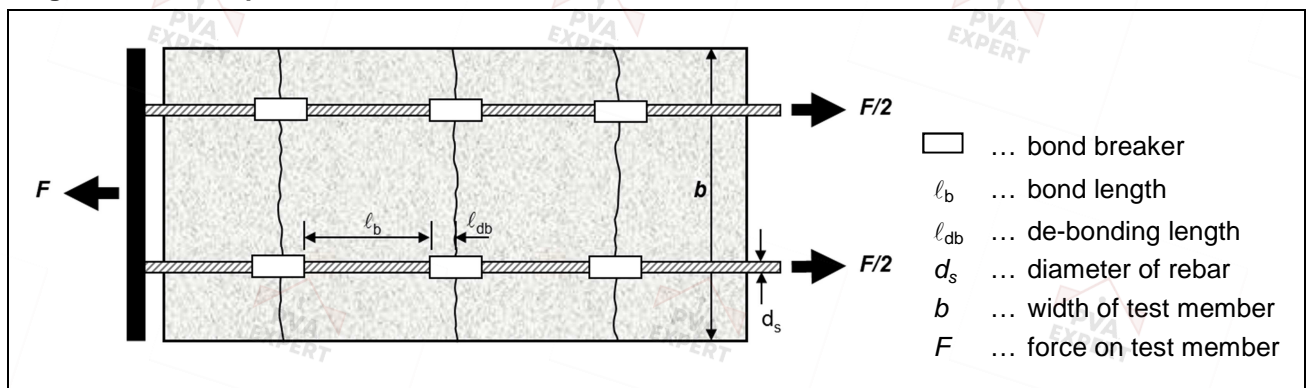


Figure 2.2 Example for test member with bond breaking pipes on rebar (plan view)

The requirement that the fastener behaviour is not influenced by the edges of the test member is considered to be fulfilled if for unconfined testing the concrete breakout body does not intersect with an edge or the edge distance of the fastener in all directions is $c \geq 2,0 h_{ef}$.

The requirement that the capacity of the fastener is not affected by the reinforcement is considered to be fulfilled for unconfined tests if the distance a_s between the fastener and the nearest reinforcement bar (see Figure 2.1) 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 fastener.

For confined tests the distance requirements between fastener and nearest reinforcement as stated in the previous paragraph do not apply.

Note 1: 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 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 typically 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 fastener with the highest ultimate load to be tested in this test member for the crack width required for the specific test (see Table 2.1 and Table 2.4) and for crack width $\Delta w = 0,3$ 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 verification shall be reported in the test report. There are two options for the verification shown in Figure 2.3a) and Figure 2.3b).

According to Figure 2.3a) the crack widths are measured at the top and bottom of the test member either at the fastener location (locations 1 and 2 in Figure 2.3a) or at a distance of approximately h_{ef} on both sides of the fastener (locations 3 & 4 and 5 & 6 in Figure 2.3a). 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} is obtained by linear interpolation of the top and bottom crack widths, i.e. Δw_{top} and Δw_{bot} , respectively.

Alternatively, the approach shown in Figure 2.3b) 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 $\leq 1,05$. 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 fastener shall be located in a crack at the time of testing.

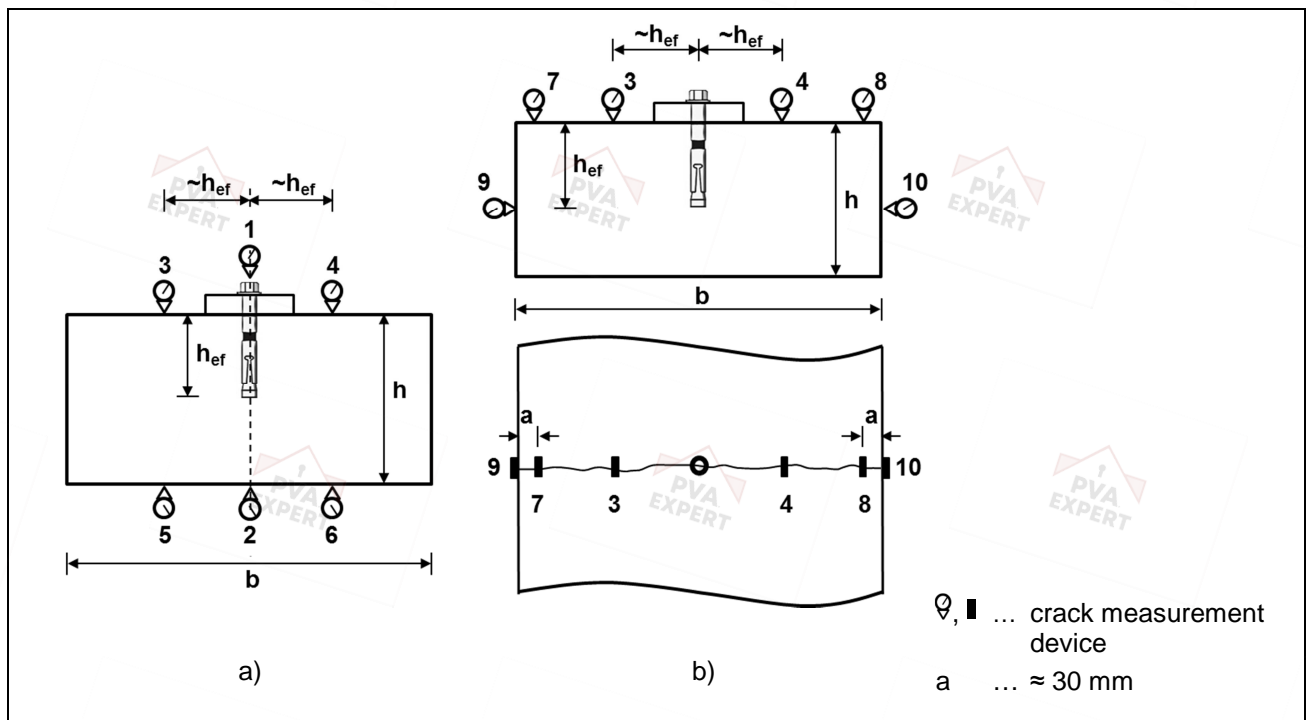


Figure 2.3 Measurements to show fulfilment of the constant crack width requirement

2.1.2 Installation of fasteners

Install the fastener in a hairline crack according to TR 048 [6], and the manufacturer's printed installation instructions (MPII) except for tests described in 2.4.5, where a compression load is applied to the test member before installation of the fastener. Use drill bits with a diameter $d_{cut,m}$ (medium).

The installation torque T_{inst} required by the manufacturer shall be applied to the fastener by a torque wrench (which has a documented calibration) except in cases where the fastener is installed using a tool (such as e.g. an impact screw driver) specified in the MPII. 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 fastener, the torque moment shall be reduced to $0,5 T_{inst}$ to account for relaxation of the pre-stressing force with time. This reduction of the installation torque does not apply to concrete screws.

If no torque is specified by the manufacturer's printed installation instructions, finger-tighten the fastener prior to testing. Test internally threaded fasteners with the bolt specified by the manufacturer and report the bolt type in the test report.

2.1.3 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:

- Linear interpolation of crack measurements at the top Δw_{top} and bottom Δw_{bot} of the test member (see Figure 2.3a). In this case the crack width shall be measured either at the location of the fastener (i.e. locations 1 (Δw_{top}) and 2 (Δw_{bot}) in Figure 2.3a) or on both sides of the fastener (i.e. locations 3 & 4 (for Δw_{top}) and 5 & 6 (for Δw_{bot}) in Figure 2.3a) with the two mean values of the measurements at the top and bottom representing Δw_{top} and Δw_{bot} , respectively.
- Measuring the crack width at the side of the test member at the embedment depth level h_{ef} (i.e. locations 9 & 10 in Figure 2.3b). 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 2.3. In confined tension tests the measuring devices 3, 4, 5 and 6 in Figure 2.3a and 3 & 4 in Figure 2.3b shall be placed as close as possible to the fastener but not further away than 150 mm from the fastener.

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

The mean of the measured crack widths Δw_{hef} for each test series determined for each fastener 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 $\Delta w < 0,3$ mm: 20% of crack width specified for the test series
- for $\Delta w \geq 0,3$ mm: minimum of 10% of the crack width specified for the test series and 0,04 mm.

2.1.4 Test setup

The fastener shall be located in the crack over the entire effective load transfer zone, $h_{l_{tz}}$ of the fastener (meaning, e.g. over the entire embedment depth for a bonded fastener or a concrete screw, over 1,5 times the length of the interaction zone h_{iz} of a torque-controlled expansion fastener or undercut fastener or bonded expansion fastener, see Figure 2.4).

Note 2: One way to achieve this, at least for larger fastener diameters, is to drill the fastener hole at the desired position prior to initiating the cracking.

It shall be verified that the fastener is located in the crack over the length defined above, e.g. by use of a borescope.

All tension tests shall be performed as unconfined tests according to TR 048 [6] unless specified otherwise in the specific test section below.

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 2.5 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 (see TR 048 [6]) shall be selected in the shear tests. For fasteners with a specified smaller gap or without an annular gap, both of which have to be stated in the ETA, the specific fastener system may be tested.

All tests with bonded fasteners shall be performed at normal ambient temperature ($21^{\circ}\text{C} \pm 3^{\circ}\text{C}$).

Note 3: The effect of high loading rates on the fastener behaviour is conservatively neglected.

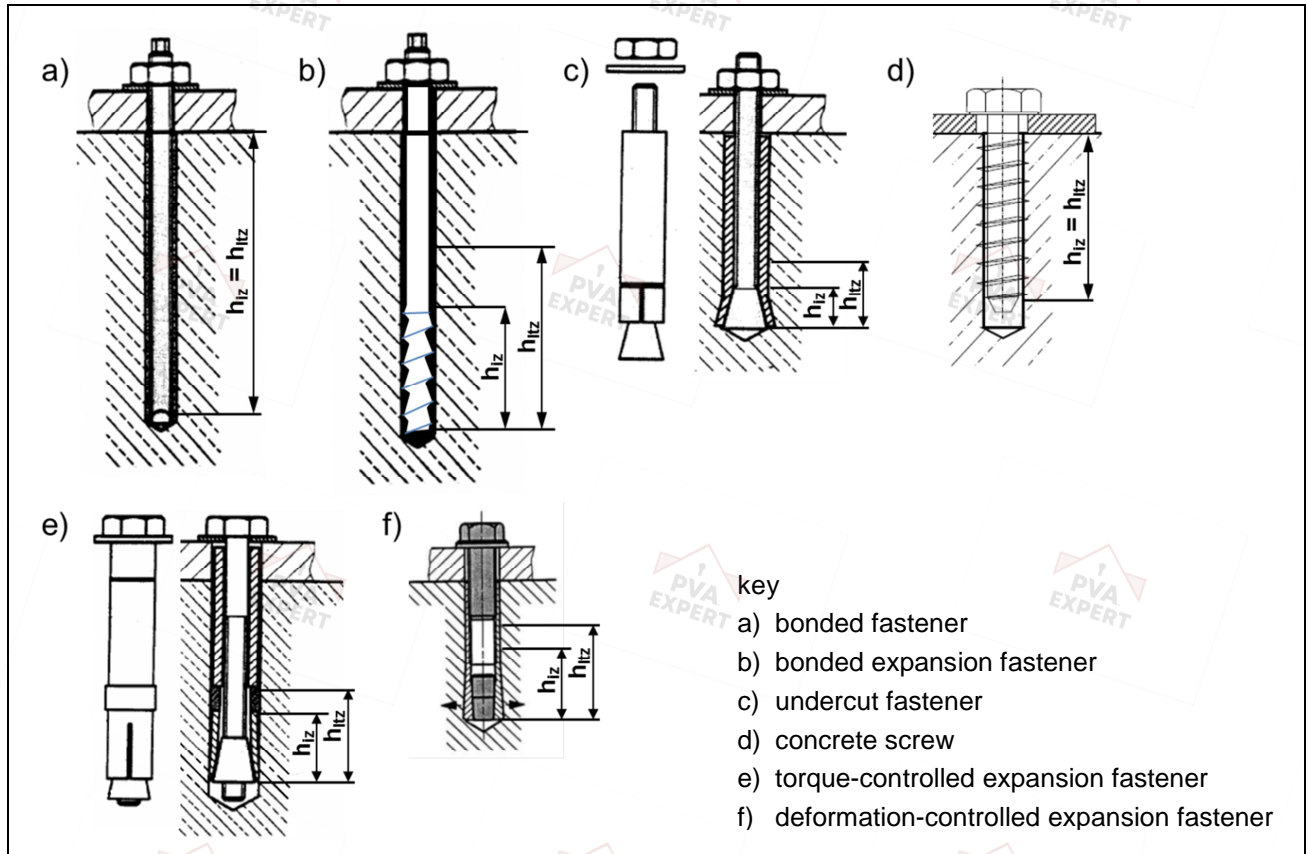


Figure 2.4 Effective load transfer zone

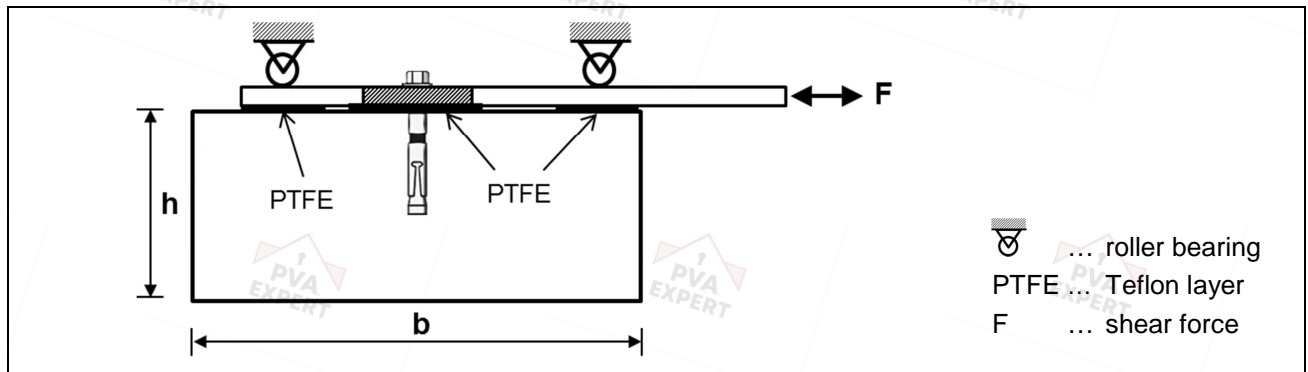


Figure 2.5 Sketch of example for shear test setup with no significant friction forces

2.1.5 Control of crack width

In the tests to failure (monotonic tests and residual capacity tests) the fastener is subjected to load while the crack width as defined in 2.1.3 is controlled, either

- a) at a constant width taking into account the requirements given in section 2.1.1, for example, by means of a servo system, or
- b) limited to a width close to the specified value by means of appropriate reinforcement and test member dimensions (see 2.1.1).

2.2 Fastener types to be tested

In general, the tests described in 2.2.6 and 2.4 shall be performed with all fastener diameters, embedment depths, steel types (galvanised steel, stainless steel, high corrosion resistant steel) and grades (strength classes and lowest rupture elongation), production methods, head configurations (mechanical fasteners), types of inserts (threaded rod, threaded sleeve or rebar for bonded fasteners), different mortar versions of bonded fasteners as well as drilling methods to be qualified 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 fastener characteristics for additional parameters (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 prequalification, these tests shall be performed. Alternatively, it shall be permitted that the corresponding resistance under ultimate load is calculated from the data obtained in the non-seismic prequalification for cracked concrete.

2.2.1 Torque controlled expansion fasteners

2.2.1.1 Steel type, steel grade and production methods

2.2.1.1.1 Tension tests

If all of the following conditions are fulfilled, and the eventual reduction factor is accepted for all fasteners, only fasteners of one steel type, the highest steel grade and one production method need to be tested. Otherwise fasteners of all steel types, steel grades and production methods shall be tested. Meaning, if all conditions are fulfilled for all steel types and steel grades but not for different production methods, the fasteners of different production methods shall be tested.

- The geometry of the fastener is identical.
- The pre-stressing forces at torque $T = 0,5 T_{inst}$ as well as at $T = 1,0 T_{inst}$ are statistically equivalent for the different steel types, steel grades and production methods. The installation torque T_{inst} may be different for different steel types and steel grades.
- The friction between cone and sleeve (internal friction) and the friction between sleeve and concrete (external friction) are identical for the different steel types, steel grades and production methods. This condition shall be considered to be fulfilled if the fasteners are made out of the same material, and any coatings are the same, and the surface roughness and hardness of the cone and the sleeve are statistically equivalent. For fasteners made out of different materials (e.g. galvanized and corrosion resistant steel) this condition shall be considered to be fulfilled if the coating is identical, and the internal friction between cone and sleeve depends mainly on the coating, and the surface roughness and hardness of the cone and the sleeve are statistically equivalent.

If the geometry is not identical but almost identical (similar) and the above conditions b) and c) are fulfilled, the seismic qualification tests for the other steel type, steel grade or production method may be omitted if all of the following requirements are met. In this context "fast 1" is the fastener for which the tests have been performed and "fast 2" is the fastener for which the tests are omitted.

- The geometrical data of the two fasteners, i.e. "fast 1" and "fast 2", are compared with each other and the comparison including the identified differences are documented and submitted for the assessment.
- The fastener "fast 2" has an ETA for cracked concrete for static loading conditions.
- The performance of "fast 2" is better or equal to the performance of "fast 1", which has to be shown in terms of
 - $N_{Rk,p,fast\ 2} \geq N_{Rk,p,fast\ 1}$ (where $N_{Rk,p}$ is the characteristic value given in the ETA);
 - reference tension tests in cracked concrete C20/25 and C50/60 according to EAD 330232 [1]: performance of fastener "fast 2" \geq performance of fastener "fast 1";
 - tests for "maximum crack width and large hole diameter" and "maximum crack width and small hole diameter" according to EAD 330232 [1]: performance of fastener "fast 2" \geq performance of fastener "fast 1";
 - tests for "crack cycling under load" according to EAD 330232 [1]: sustained load for which fastener "fast 2" passes the criteria is larger than or equal to the corresponding load for fastener "fast 1";
 - in the load/displacement curves fasteners "fast 1" and "fast 2" show the same stiffness
 - the ductility in terms of the A_5 -value of fastener "fast 2" \geq ductility for fastener "fast 1".
- The seismic resistance for "fast 2" is determined as $\min(N_{Rk,p,fast\ 1} \cdot \alpha_{N,Cx,fast\ 1}; N_{Rk,p,fast\ 2} \cdot \alpha_{N,Cx,fast\ 1})$.

Note 4: In case the highest steel grade is tested pull-out failure might be decisive and steel failure does not occur. For lower steel grades steel failure may become decisive and the corresponding seismic performance may be relevant.

The measured displacements shall be applied to the fasteners made from other steel types, steel grades or by other production methods.

2.2.1.1.2 Shear tests

Only fasteners made of galvanized steel of the highest grade and lowest rupture elongation (percentage of elongation after fracture, A, see ISO 898-1 [5]) need to 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 fasteners made from other steel types, steel grades or by other production methods.

2.2.1.2 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.

2.2.1.3 Embedment depth

2.2.1.3.1 Tension tests

- a) Fasteners under category C1 (test series C1.1):
If multiple embedment depths are specified, in general, minimum and maximum embedment depths shall be tested. However, only the maximum embedment depth needs to be tested if the reduction factor for seismic loading $\alpha_{N,C1}$ according to Equation (3.1) is accepted for all embedment depths.
- b) Fasteners 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 $\beta_{cv,N,C2}$ according to Equation (3.48) and Equation (3.49), respectively, for the maximum embedment depth shall be applied to fasteners with shallower embedment depths and the displacements measured for fasteners with the maximum embedment shall be applied to fasteners with shallower embedment depths.

2.2.1.3.2 Shear tests

- a) Fasteners under category C1 (test series C1.2):
If there is more than one embedment depth specified for a fastener diameter, tests need to 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 $\alpha_{V,C1}$ according to Equation (3.2) is applied to all embedment depths.
- b) Fasteners under category C2 (test series C2.2, 2.4):
Only the minimum embedment depth needs to be tested if the reduction factor for seismic loading $\alpha_{V,C2}$ according to Equation (3.50) 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 fasteners with a larger embedment depth.

If for a specified embedment depth deeper setting is allowed, the embedment depth for the tests shall be selected such that the most unfavourable position with regard to the shear plane is accounted for. For example, fasteners may consist of a smooth shaft and a threaded part. Depending on the thickness of the fixture the shear plane may pass through the smooth portion or the threaded part (see Figure 2.6).

Note 5: For mechanical fasteners a single embedment depth h_{ef} is frequently specified for each diameter (e.g. M12, $h_{ef} = 70$ mm). Different lengths of the fastener for the same diameter may account for different thicknesses of the fixture t_{fix} . It may therefore be allowed to set the fastener deeper than the specified value (as long as all other requirements such as for example h_{min} are met) for ease of use to avoid extensive projection of the fastener above the fixture. This may result in an unfavourable position with regards to shear loading.

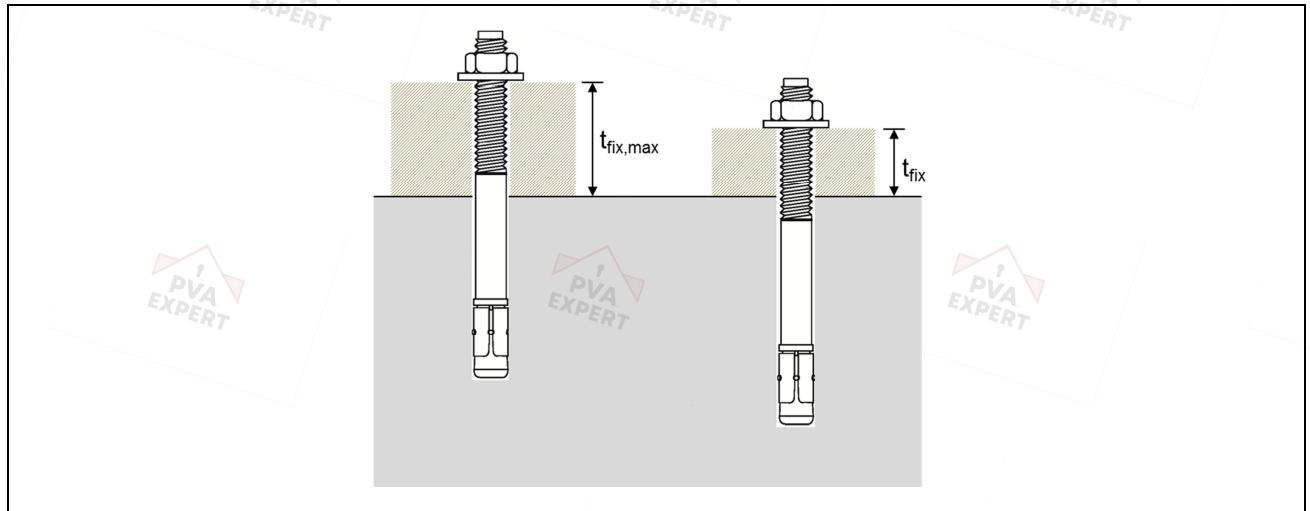


Figure 2.6 Shear test with unfavourable position with regard to shear plane

2.2.1.4 Drilling method

A reduction of number of drilling methods to be tested is only allowed for shear tests. In this case the hole shall be drilled with the most adverse drilling method, which in many cases will be diamond coring.

2.2.2 Undercut fasteners (not including concrete screws)

2.2.2.1 Steel type, steel grade and production method

2.2.2.1.1 Tension tests

If the undercut of the concrete is identical in all models for full expansion and partial expansion during the tests for “robustness to installation” according to EAD 330232 [1], only fasteners of one steel type, the highest steel grade and one production method need to be tested. The measured displacements shall be applied to all steel types, steel grades and production methods. If this condition is not fulfilled, test all fasteners; however, only fasteners with the minimum undercut for full expansion need to be tested if the reduction factor due to simulated seismic tension testing $\alpha_{N,C1}$ according to Equation (3.1) and $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ according to Equation (3.48) and Equation (3.49), respectively, are accepted for all fasteners.

In addition, an undercut fastener that shows a follow-up expansion during loading shall comply with the requirements for torque-controlled expansion fasteners in 2.2.1.1.1.

2.2.2.1.2 Shear tests

See 2.2.1.1.2.

2.2.2.2 Head configuration

See 2.2.1.2.

2.2.2.3 Embedment depth

See 2.2.1.3.

2.2.2.4 Drilling method

See 2.2.1.4.

2.2.3 Concrete screws

2.2.3.1 Tension tests

The seismic qualification tests for the other steel type, steel grade or production method may be omitted if all of the following requirements are met. In this context “fast 1” is the fastener for which the tests have been performed and “fast 2” is the fastener for which the tests are omitted.

- The fastener “fast 2” has an ETA for cracked concrete for static loading conditions.

- The performance of fastener “fast 2” is better or equal to the performance of fastener “fast 1”, which has to be shown in terms of
 - $N_{Rk,p,fast\ 2} \geq N_{Rk,p,fast\ 1}$ (where $N_{Rk,p}$ is the characteristic value given in the ETA);
 - tests for “crack cycling under load” according to EAD 330232 [1]: sustained load for which fastener “fast 2” passes the criteria is larger than or equal to the corresponding load for fastener “fast 1”;
 - the ductility in terms of the A_5 -value of fastener “fast 2” \geq ductility for fastener “fast 1”;
 - the seismic resistance for fastener “fast 2” is determined as $\min(N_{Rk,p,fast\ 1} \cdot \alpha_{N,Cx,fast\ 1}; N_{Rk,p,fast\ 2} \cdot \alpha_{N,Cx,fast\ 1})$.

2.2.3.2 Shear tests

A reduction of number of variants to be tested is only allowed for shear tests with respect to the embedment depth as given in 2.2.1.3.2 and the drilling method as given in 2.2.1.4.

2.2.4 Bonded fasteners

2.2.4.1 Type of insert

2.2.4.1.1 Tension tests:

If the bond strength is equal for bonded fasteners with different types of inserts (threaded rod, rebar, internal threaded sleeve etc.) tests can be performed with the most adverse type of insert and the results shall be applied to all other types of inserts. If the bond strength is different, all types of inserts shall be tested.

2.2.4.1.2 Shear tests:

For fasteners under category C1 shear tests (test series C1.2) need to be performed for the smallest, medium and largest diameters only. For intermediate sizes the smaller performance $\alpha_{V,C1}$ of the neighbouring tested sizes shall be used.

2.2.4.2 Steel type, steel grade and production method

2.2.4.2.1 Tension tests

For bonded fasteners only one steel type needs to be tested. The steel type with the highest strength shall be selected. The measured displacements shall be applied to fasteners of all steel types and grades.

2.2.4.2.2 Shear tests

See 2.2.1.1.2.

2.2.4.3 Embedment depth

2.2.4.3.1 Tension tests:

- a) Fasteners under category C1 (test series C1.1):
If multiple embedment depths are specified only the minimum and maximum embedment depths need to be tested.
- b) Fasteners under category C2:
If multiple embedment depths are specified, test series C2.1, C2.3 and C2.5 may only be performed with an embedment depth of $h_{ef} = 7d$ as confined test in accordance with TR 048 [6] to ensure bond failure. In this case the reduction factors $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ according to Equation (3.48) and Equation (3.49), respectively, at this embedment depth shall be applied to all embedment depths and the displacements measured at this embedment depth shall be applied to all embedment depths. If for $h_{ef} = 7d$ steel failure occurs, the test shall be performed with a steel element having the same geometry but a higher steel strength than specified. In case steel failure does also occur in this situation the embedment depth shall be reduced such that bond failure is observed.

In addition the steel behaviour under pulsating tension load shall be captured. The corresponding tests may be carried out in uncracked concrete as confined or unconfined tests. Perform test series C2.3 in uncracked concrete (ie. $\Delta w = 0,0\text{mm}$) with the highest steel strength for use in seismic applications and an embedment depth ensuring steel failure. Determine the mean tension capacity of

the steel element $N_{u,m,C2.1a}$ used for the definition of N_{max} and for the assessment of this C2.3 test series as given in Equation (2.1).

$$N_{u,m,C2.1a} = A_s \cdot f_{u,C2.3} \quad (2.1)$$

with

A_s = [mm²] - effective stressed cross-section area of steel element

$f_{u,C2.3}$ = [N/mm²] ultimate mean steel strength of fasteners used in the test series C2.3

An assessment of the displacements for this C2.3 test series may be omitted as the displacements in case of combined pull-out and concrete cone failure are considered decisive and are to be reported as the displacement behaviour of the fastener.

The resulting reduction factors $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ according to Equation (3.48) and Equation (3.49), respectively, for this steel strength shall be applied to all lower steel strengths. When calculating $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ it shall be assumed that the reduction factors associated with the test series C2.5, which is not required in this case, are set equal to 1,0, i.e. $\alpha_{C2.5} = 1,0$ and $\beta_{cv,C2.5} = 1,0$.

Testing to capture the steel failure for a given steel class to be qualified may be omitted if it is demonstrated that the maximum force corresponding to the combined pull-out and concrete failure mode at maximum embedment depth is lower than 80% of the force corresponding to yielding of the insert.

2.2.4.3.2 Shear tests:

See 2.2.1.3.2.

2.2.4.4 Drilling method

See 2.2.1.4.

2.2.5 Bonded expansion fasteners

2.2.5.1 Steel type, steel grade and production method

2.2.5.1.1 Tension tests

If all of the following conditions are fulfilled, and the eventual reduction factor is accepted for all fastener types, only fasteners of one steel type, the highest steel grade and one production method need to be tested. Otherwise fasteners of all steel types, steel grades and production methods shall be tested. Meaning, if all conditions are fulfilled for all steel types and steel grades but not for different production methods, fasteners of different production methods shall be tested.

- The geometry of the fastener is identical.
- The pre-stressing forces at torque $T = 0,5 T_{inst}$ as well as at $T = 1,0 T_{inst}$ are statistically equivalent for the different steel types, steel grades and production methods. The installation torque T_{inst} may be different for different steel types and grades.
- Both the slip force as well as the bond force, as defined in EAD 330499 [2], are statistically equivalent for the different steel types, steel grades and production methods. This condition shall be considered to be fulfilled if the fasteners are made out of the same material, any coatings are the same, and the surface roughness of the fastener in the load transfer zone is statistically equivalent. For fasteners made out of different materials (e.g. galvanized and corrosion resistant steel) this condition shall be considered to be fulfilled if the coating is identical, and the slip force depends mainly on the coating, and the surface roughness of the fastener in the load transfer zone is statistically equivalent.

The measured displacements shall be applied to the fasteners made from other steel types, steel grades or by other production methods.

2.2.5.1.2 Shear tests

See 2.2.1.1.2.

2.2.5.2 Head configuration

See 2.2.1.2.

2.2.5.3 Embedment depth

See 2.2.1.3.

2.2.5.4 Drilling method

See 2.2.1.4.

2.2.6 Deformation controlled expansion fasteners

No reduction of number of variants to be tested is allowed for this type of fasteners.

2.3 Tests for category C1

2.3.1 Tests program

The additional tests for category C1 are shown in Table 2.1.

Table 2.1 Additional tests for qualification of fasteners under category C1

	Purpose of test	Concrete	Crack width Δw ¹⁾ [mm]	Minimum number of tests ²⁾	Test procedure see Section	Assessment criteria see Section
C1.1	Functioning under pulsating tension load ³⁾	C20/25	0,5	5	2.3.2	3.1.1
C1.2	Functioning under alternating shear load ⁴⁾	C20/25	0,5	5	2.3.3	3.1.2

¹⁾ Crack width added to the hairline crack width after fastener installation but before loading of fastener.
²⁾ Test all fastener diameters to be qualified for use in seismic applications. For different fastener types to be tested see 2.2.
³⁾ For bonded fasteners: for each type of insert with the same mechanical properties the number of tested sizes can be reduced in accordance with EAD 330499 [2], Table 2.7.
⁴⁾ For bonded fasteners: test smallest, medium and largest diameter

All tests shall be performed with fasteners with a steel strength not smaller than the nominal value f_{uk} .

2.3.2 Tests under pulsating tension load (test series C1.1)

Purpose:

These tests are intended to evaluate the performance of fasteners under simulated seismic tension loading, including the effects of cracks, and without edge effects.

General test conditions:

The test shall be performed with an unconfined test setup according to TR 048 [6] with the following modifications for bonded fasteners.

In general, bonded fasteners shall be tested with a confined test setup in accordance with TR 048 [6]. If multiple embedment depths are specified, an embedment depth of $h_{ef} = 7d$ is recommended for tests with the minimum embedment depth. Alternatively, tests with an unconfined test set-up may be performed. In this case the minimum embedment depth shall be selected such that pull-out failure is ensured.

Note 6: In order to select the proper embedment depth for pull-out failure for bonded fasteners it shall be demonstrated that Equation (2.2) is fulfilled for the embedment depth h_{ef} used. If Equation (2.2) is not fulfilled with the chosen embedment depth, the embedment depth shall be increased until Equation (2.2) is fulfilled, where steel failure is avoided. If Equation (2.2) cannot be fulfilled in unconfined tests, confined tests shall be conducted (see above).

$$7 \cdot h_{ef,test}^{1,5} \cdot \sqrt{f_{c,C1.1}} \leq N_{u,m} \cdot \left(\frac{f_{c,C1.1}}{f_{c,3}} \right)^n \leq 10 \cdot h_{ef,test}^{1,5} \cdot \sqrt{f_{c,C1.1}} \quad (2.2)$$

where

$N_{u,m}$ = [N] - mean tension capacity from service condition tests "characteristic resistance for tension loading not influenced by edge and spacing effects" in cracked concrete

C20/25 performed with an unconfined test set-up according to EAD 330499 [2], Table 2.5;

- $h_{ef,test}$ = [mm] - effective embedment depth;
- $f_{c,C1.1}$ = [N/mm²] - mean compressive strength of concrete measured with cubes used for the test series C1.1 at the time of testing;
- $f_{c,3}$ = [N/mm²] - mean compressive strength of concrete measured with cubes used for the service condition test series "characteristic resistance for tension loading not influenced by edge and spacing effects" in concrete C20/25 according to EAD 330499 [2], Table 2.5 at the time of testing;
- n = normalization exponent; see EAD 330499 [2].

In addition tests with the maximum embedment depth are required.

For all types of fasteners the pulsating tension load tests shall be executed as described in the following:

Open the crack by $\Delta w = 0,5$ mm. Subject the fasteners to sinusoidal tension loads with the levels and cycle counts specified in Table 2.2 and Figure 2.7, where N_{eq} is given in Equation (2.3) in case of concrete or bond failure and in Equation (2.4) in case of steel failure, N_i is given in Equation (2.5), and N_m is given in Equation (2.6). The cycling frequency shall be between 0,1 and 2 Hz. The bottom of the tension load pulses may be taken to be slightly greater than zero to avoid servo control problems but shall not exceed N_{min} , with N_{min} being the maximum of 3% of N_{eq} and 200 N.

$$N_{eq} = 0,5 \cdot N_{u,m} \cdot \left(\frac{f_{c,C1.1}}{f_{c,3}} \right)^n \quad [\text{N}] \text{ (concrete, pull-out or bond failure)} \quad (2.3)$$

where

- $N_{u,m}$ = [N] - all fasteners except bonded fasteners:
mean tension capacity from "reference tension tests" in cracked concrete C20/25 according to EAD 330232 [1], for the considered embedment depth;
- [N] - bonded fasteners with unconfined test setup in test series C1.1:
mean tension capacity from service condition tests "characteristic resistance for tension loading not influenced by edge and spacing effects" according to EAD 330499 [2], Table 2.5 for the considered embedment depth
- bonded fasteners with confined test setup in test series C1.1:
mean tension capacity from service condition tests "characteristic resistance for tension loading not influenced by edge and spacing effects" according to EAD 330499 [2], for the considered embedment depth [N];
- $f_{c,C1.1}$ = [N/mm²] - mean compressive strength of concrete used for the test series C1.1 at the time of testing;
- $f_{c,3}$ = [N/mm²] - mean compressive strength of concrete used for the "reference tension tests" according to EAD 330232 [1], and tests for "characteristic resistance for tension loading not influenced by edge and spacing effects" according to EAD 330499 [2], Table 2.5 or (as applicable) at the time of testing;
- n = normalization exponent; see EAD 330232 [1], and EAD 330499 [2]

$$N_{eq} = 0,5 \cdot N_{u,m} \cdot \left(\frac{f_{u,C1.1}}{f_{u,3}} \right) \quad [\text{N}] \text{ (steel failure)} \quad (2.4)$$

where

- $N_{u,m}$ = [N] - mean tension steel capacity from "reference tension tests" in cracked concrete C20/25 according to EAD 330232 [1], and tests for "characteristic resistance for tension loading not influenced by edge and spacing effects" according to EAD 330499 [2];
- $f_{u,C1.1}$ = [N/mm²] - ultimate mean steel strength of fasteners used for test series C1.1;
- $f_{u,3}$ = [N/mm²] - ultimate mean steel strength of fasteners used for "reference tension tests" according to EAD 330232 [1], and tests for "characteristic resistance for tension loading not influenced by edge and spacing effects" according to EAD 330499 [2];

Adjustment for different steel strengths in Equation (2.4) is not required if the fasteners used in test series C1.1 and “reference tension tests” according to EAD 330232 [1], and tests for “characteristic resistance for tension loading not influenced by edge and spacing effects” according to EAD 330499 [2] are taken from the same production lot.

If mixed failure modes occur in the “reference tension tests” according to EAD 330232 [1], and tests for “characteristic resistance for tension loading not influenced by edge and spacing effects” according to EAD 330499 [2], the load N_{eq} shall be determined assuming that the failure mode, which was observed in the majority of tests in the test series, occurred in all tests.

$$N_i = 0,75 \cdot N_{eq} \quad [\text{N}] \quad (2.5)$$

$$N_m = 0,5 \cdot N_{eq} \quad [\text{N}] \quad (2.6)$$

Table 2.2 Required loading history for test series C1.1

Load level	N_{eq}	N_i	N_m
Number of cycles (n_{cyc})	10	30	100

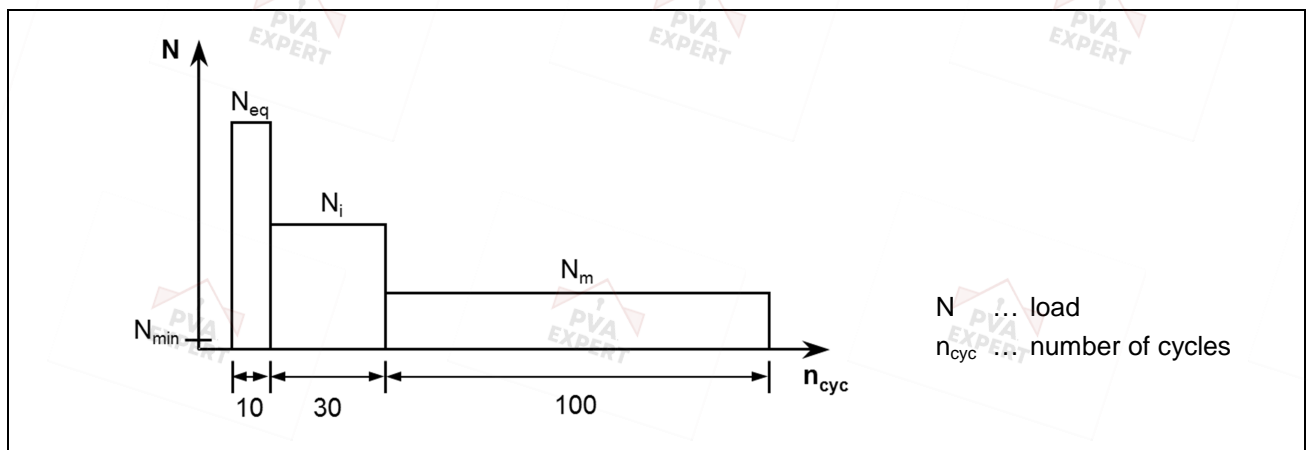


Figure 2.7 Required loading history for test series C1.1

Record the crack width, fastener displacement and applied tension load. Following completion of the simulated seismic tension cycles, open the crack by $\Delta w = 0,5$ mm, but not less than the crack opening width as measured at the end of the cyclic test and load the fastener in tension to failure. Record the maximum tension load (residual tension capacity), the corresponding displacement, the crack width, and plot the load-displacement response.

If the fastener fails to fulfil the requirements given in the corresponding assessment (see 3.1.1) it shall be permitted to conduct the tests with a reduced load level.

2.3.3 Tests under alternating shear load cycling (test series C1.2)

Purpose:

These tests are intended to evaluate the performance of fasteners under simulated seismic shear loading, including the effects of concrete cracking.

General test conditions:

The test shall be performed according to TR 048 [6] with the following modifications.

Open the crack by $\Delta w = 0,5$ mm. Subject the fasteners to sinusoidal shear loads in the direction of the crack with the levels and cycle counts specified in Table 2.3 and Figure 2.8, where V_{eq} is given in Equation (2.7), Equation (2.8), or Equation (2.9) as applicable, V_i is given in Equation (2.10) and V_m is given in Equation (2.11). The cycling frequency shall be between 0,1 and 2 Hz.

$$V_{eq} = 0,5 \cdot V_{u,m} \cdot \left(\frac{f_{u,C1.2}}{f_{u,5}} \right) \quad [\text{N}] \text{ (fasteners without sleeve in shear plane)} \quad (2.7)$$

where

- $V_{u,m}$ = [N] - mean shear capacity from tests for "characteristic resistance to steel failure under shear load" in non-cracked concrete C20/25 (see EAD 330232 [1]);
- $f_{u,C1.2}$ = [N/mm²] - mean ultimate tensile strength of steel fastener elements used in test series C1.2;
- $f_{u,5}$ = [N/mm²] - mean ultimate tensile strength of steel fastener elements used in tests for "characteristic resistance to steel failure under shear load" in non-cracked concrete C20/25 according to EAD 330232 [1].

For fasteners with a sleeve in the shear plane V_{eq} shall be calculated according to Equation (2.8).

$$V_{eq} = 0,5 \cdot V_{u,m} \cdot \left(\frac{f_{u,bol,C1.2}}{f_{u,bol,5}} \cdot \frac{A_{s,bol}}{A_{s,fas}} + \frac{f_{u,sle,C1.2}}{f_{u,sle,5}} \cdot \frac{A_{s,sle}}{A_{s,fas}} \right) \text{ [N]} \quad (2.8)$$

where

- $V_{u,m}$ = [N] - as defined in Equation (2.7);
- $f_{u,bol,C1.2}$ = [N/mm²] - mean ultimate tensile strength of bolt used in test series C1.2;
- $f_{u,sle,C1.2}$ = [N/mm²] - mean ultimate tensile strength of sleeve used in test series C1.2;
- $f_{u,bol,5}$ = [N/mm²] - mean ultimate tensile strength of bolt used in in tests for "characteristic resistance to steel failure under shear load" in non-cracked concrete C20/25 according to EAD 330232 [1];
- $f_{u,sle,5}$ = [N/mm²] - mean ultimate tensile strength of sleeve used in in tests for "characteristic resistance to steel failure under shear load" in non-cracked concrete C20/25 according to EAD 330232 [1];
- $A_{s,bol}$ = [mm²] - effective cross section of bolt
- $A_{s,sle}$ = [mm²] - effective cross section of sleeve;
- $A_{s,fas}$ = [mm²] - $A_{s,bol} + A_{s,sle}$;

Adjustment for different steel strengths in Equations (2.7) and (2.8) is not required if the fasteners tested in C1.2 and in in tests for "characteristic resistance to steel failure under shear load" in non-cracked concrete C20/25 according to EAD 330232 [1], are taken from the same production lot.

If tests for "characteristic resistance to steel failure under shear load" have not been performed according to EAD 330232 [1], (which is allowed only for fasteners with no significantly reduced section along the length of the bolt and no sleeve in the shear plane, that is taken into account in the shear resistance), V_{eq} shall be permitted to be calculated in accordance with Equation (2.9).

$$V_{eq} = 0,35 \cdot A_s \cdot f_{uk} \text{ [N]} \quad (2.9)$$

where

- A_s = [mm²] - effective stressed cross section area of steel element in the shear plane;
- f_{uk} = [N/mm²] - characteristic steel ultimate tensile strength (nominal value) of the finished product;

$$V_i = 0,75 \cdot V_{eq} \text{ [N]} \quad (2.10)$$

$$V_m = 0,5 \cdot V_{eq} \text{ [N]} \quad (2.11)$$

Table 2.3 Required loading history for test series C1.2

Load level	$\pm V_{eq}$	$\pm V_i$	$\pm V_m$
Number of cycles (n_{cyc})	10	30	100

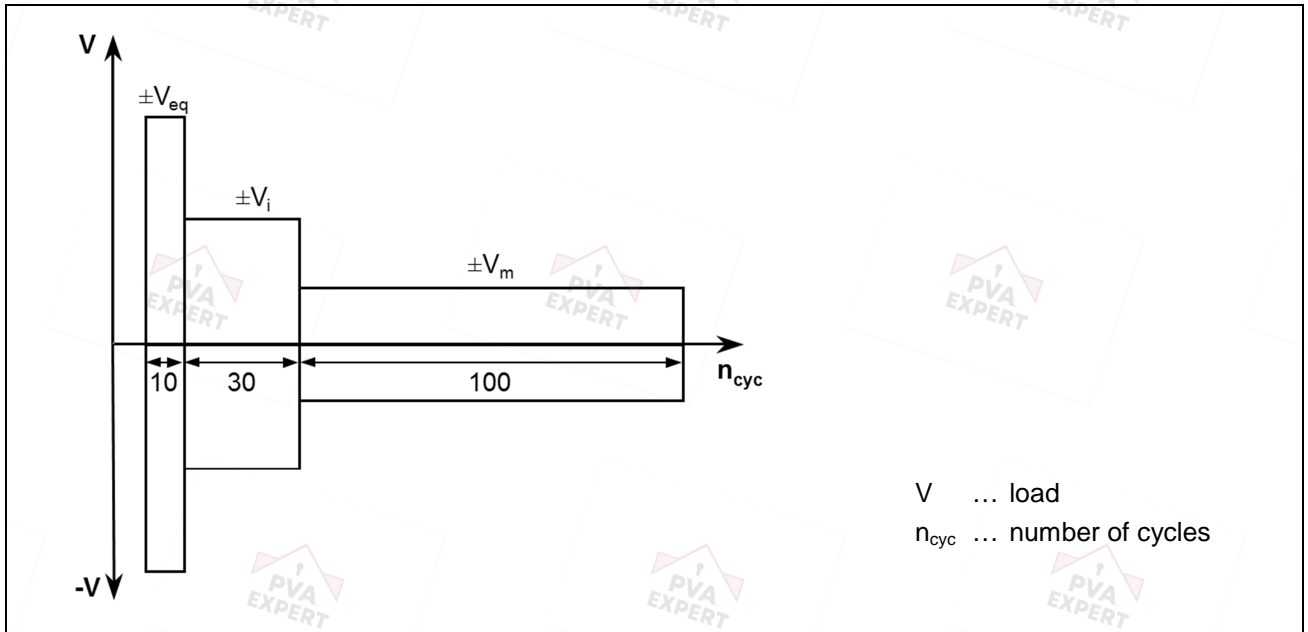


Figure 2.8 Required load history for test series C1.2

To reduce the potential for uncontrolled slip during load reversal, the alternating shear loading (Figure 2.9a) is permitted to be approximated by two half-sinusoidal load cycles at the required frequency connected by a reduced speed, ramped load as shown in Figure 2.9b, or by simply triangular loading cycles as shown in Figure 2.9c.

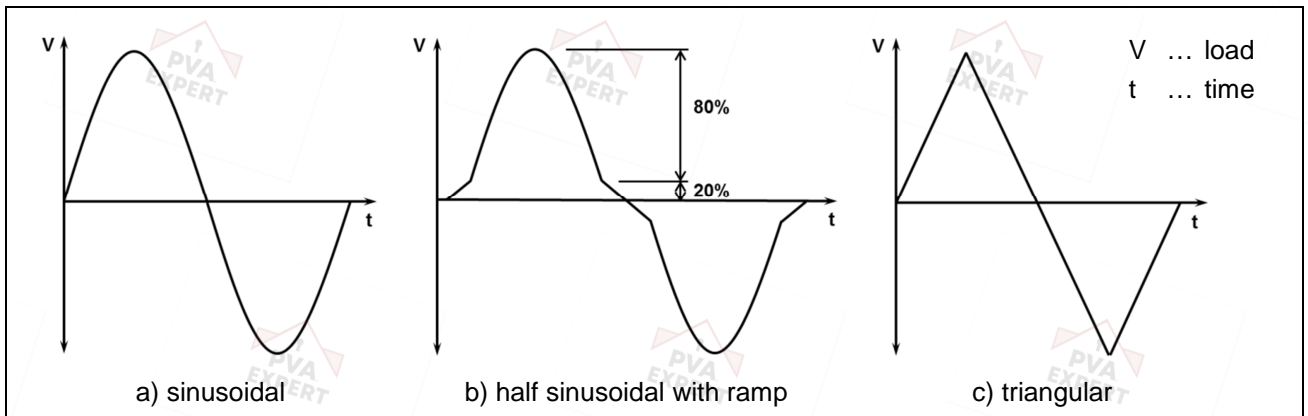


Figure 2.9 Permitted seismic shear cycle C1.2

Record the crack width, fastener displacement and applied shear load. Plot the load-displacement history in the form of hysteresis loops.

Following completion of the simulated seismic shear cycles, open the crack by $\Delta w = 0,5 \text{ mm}$, but not less than the crack opening width as measured at the end of the cyclic shear test and load the fastener in shear to failure. Record the maximum shear load (residual shear capacity), the corresponding displacement, the crack width, and plot the load-displacement response.

If the fastener fails to fulfil the requirements given in the corresponding assessment (see 3.1.2) it shall be permitted to conduct the tests with a reduced load level.

2.4 Tests for category C2

2.4.1 Test program

The required additional tests for fasteners of category C2 are given in Table 2.4.

Table 2.4 Additional tests for qualification of fasteners under category C2

Test no.	Purpose of test	Concrete	Crack width Δw ¹⁾ [mm]	Minimum number of tests ²⁾	Test procedure see Section	Assessment criteria see Section
C2.1a	Reference tension tests in low strength concrete	C20/25	0,8	5	2.4.2	3.2.1, 3.2.2
C2.1b	Tension tests in high strength concrete	C50/60	0,8	5	2.4.2	3.2.1, 3.2.2
C2.2 ³⁾	Reference shear tests	C20/25	0,8	5	2.4.2	3.2.1, 3.2.3
C2.3	Functioning under pulsating tension load	C20/25	$0,5 (\leq 0,5 \cdot N/N_{max})$ ⁴⁾ $0,8 (> 0,5 \cdot N/N_{max})$	5	2.4.3	3.2.1, 3.2.4
C2.4	Functioning under alternating shear load	C20/25	0,8	5	2.4.4	3.2.1, 3.2.5
C2.5	Functioning with tension load under varying crack width	C20/25	$\Delta w_1 = 0,0$ ⁵⁾ $\Delta w_2 = 0,8$	5	2.4.5	3.2.1, 3.2.6

¹⁾ Crack width Δw added to the width of hairline crack after fastener installation but before loading of fastener.

²⁾ Test all fastener diameters for which the fastener is to be qualified for use in seismic applications. For fasteners with different steel types, steel grades, production methods, head configurations (mechanical fasteners), types of inserts (bonded fasteners), multiple embedment depths and drilling methods see 2.2.

³⁾ See 2.4.2

⁴⁾ The tests may also be conducted in $\Delta w = 0,8$ mm at all load levels (N/N_{max}).

⁵⁾ $\Delta w_1 = 0,0$ mm is defined in 2.4.5.

Test series C2.1, C2.3 and C2.5 shall be performed with the same embedment depths and test set-up (confinement conditions). This requirement is also valid for test series C2.2 and C2.4.

Test series C2.1, C2.3 and C2.5:

Bonded fasteners shall be tested with a confined test setup in accordance with TR 048 [6] with an embedment depth and steel strength as defined in 2.2.4.3. All other fasteners shall be tested with an unconfined test setup.

All tests shall be performed with fasteners with a steel strength not smaller than the nominal value f_{uk} .

2.4.2 Reference tension and shear tests (test series C2.1 and C2.2)

The tension test series C2.1 and shear test series C2.2 shall be performed in accordance with TR 048 [6], with a crack width as specified in Table 2.4.

The test series C2.2 may be omitted if the results of the service condition tests “characteristic under shear load (V1)” in uncracked concrete C20/25 according to EAD 330232 [1], ($\Delta w = 0,0$ mm) are accepted as $V_{u,m,C2.2}$. In this case the steel properties of the samples in the tests for “characteristic resistance to steel failure under shear load” in non-cracked concrete C20/25 according to EAD 330232 [1], have to be used for the normalization in the context of the C2.4 test series.

If in the test series C2.2 failure is caused by pull-out or pull-through of the fastener the test may be repeated with a larger embedment depth avoiding these failure modes (compare 3.2.3).

2.4.3 Tests under pulsating tension load (test series C2.3)

The tests shall be performed according to TR 048 [6] and 2.1.1 with the following modifications:

Open the crack by $\Delta w = 0,5$ mm (see exception in Footnote 4 of Table 2.4). Subject the fastener to the sinusoidal tension loads specified in Table 2.5 and Figure 2.10 with a cycling frequency no greater than 0,5 Hz, where N_{max} is given by Equation (2.12) to Equation (2.14). Triangular loading cycles may be used in

place of sinusoidal cycles. The bottom of the tension load pulses may be taken to be slightly greater than zero to avoid servo control problems but shall not exceed N_{min} , with N_{min} being the maximum of 2% of N_{max} and 200 N. Crack width shall be controlled during load cycling. The crack shall be opened to $\Delta w = 0,8$ mm after the load cycles at $0,5 N/N_{max}$ have been completed.

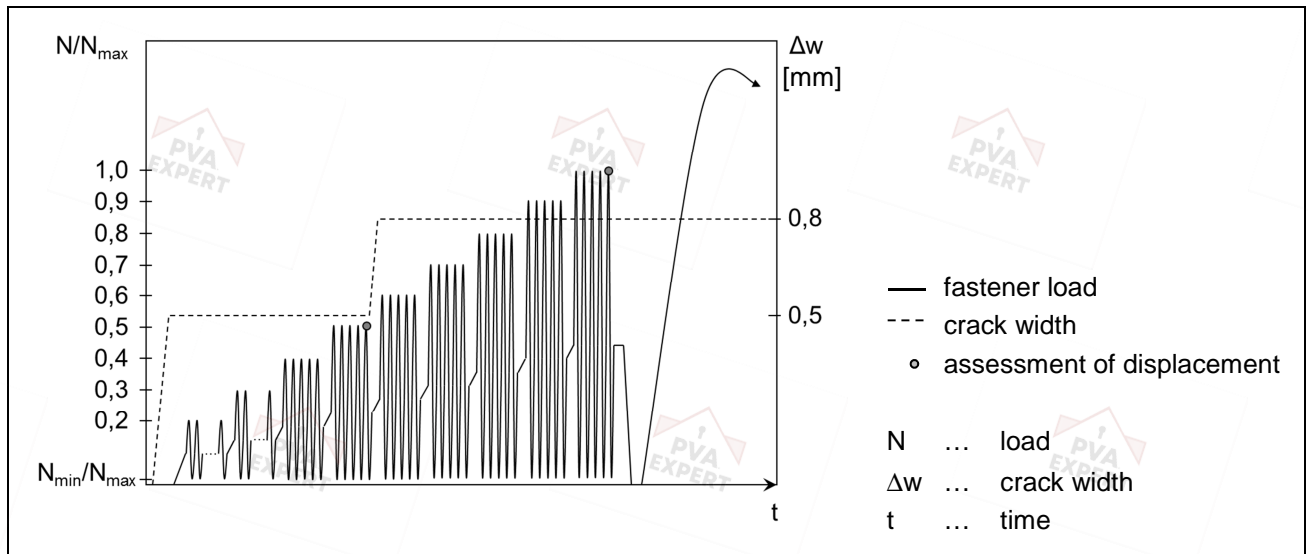


Figure 2.10 Schematic test procedure C2.3

Table 2.5 Required load amplitudes for test series C2.3

N/N_{max}	Number of cycles	Crack width Δw [mm]
0,2	25	0,5
0,3	15	0,5
0,4	5	0,5
0,5	5	0,5
0,6	5	0,8
0,7	5	0,8
0,8	5	0,8
0,9	5	0,8
1	5	0,8
SUM	75	

Depending on the failure mode observed in test C2.1a, N_{max} is determined as follows:

Steel failure

$$N_{max} = 0,75 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{u,C2.3}}{f_{u,C2.1a}} \right) \quad [\text{N}] \quad (2.12)$$

Bond failure of bonded fasteners

$$N_{max} = 0,75 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.3}}{f_{c,C2.1a}} \right)^n \quad [\text{N}] \quad (2.13)$$

All other failure modes

$$N_{\max} = 0,75 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.3}}{f_{c,C2.1a}} \right)^{0,5} \quad [\text{N}] \quad (2.14)$$

where

$N_{u,m,C2.1a}$ = [N] - mean tension capacity from the reference test series C2.1a [N];

$f_{u,C2.3}$ = [N/mm²] - ultimate mean steel strength of fasteners used in the test series C2.3;

$f_{u,C2.1a}$ = [N/mm²] - ultimate mean steel strength of fasteners used in the test series C2.1a

$f_{c,C2.3}$ = [N/mm²] - mean compressive strength of concrete at the time of testing of the test series C2.3;

$f_{c,C2.1a}$ = [N/mm²] - mean compressive strength of concrete at the time of testing of the test series C2.1a;

n = normalization factor to account for concrete strength; EAD 330499 [2].

If mixed failure modes occur in test series C2.1a, the largest value of Equations (2.12) and (2.14) shall be applied.

Adjustment for different steel strengths in Equation (2.12) is not required if the fasteners tested in C2.1a and C2.3 are taken from the same production lot.

Record the crack width, fastener displacement and applied tension load continuously during the simulated seismic tension cycles. Report the displacements at minimum and maximum load and the crack width as a function of the number of load cycles.

Following completion of the simulated seismic tension cycles unload the fastener. During the unloading of the fastener the crack width may get smaller. For the residual capacity test open the crack to $\Delta w = 0,8$ mm, but not less than the crack opening width as measured at the end of the cyclic test, and load the fastener in tension to failure. Record the maximum tension load (residual tension capacity), the corresponding displacement, the crack width, and plot the load-displacement response.

If the fastener fails to fulfil the requirements given in the corresponding assessment (see 3.2.4) it shall be permitted to conduct the tests with a reduced load level.

If the fastener meets the requirements given in the corresponding assessment but a smaller displacement at the first assessment point (i.e. at the end of load cycling at level $0,5 \cdot N/N_{\max}$; see 3.2.4 and Figure 2.10) is intended it shall be permitted to conduct the test with a reduced load level.

2.4.4 Tests under alternating shear load (test series C2.4)

The tests shall be performed according to TR 048 [6] and 2.1.1 with the following modifications:

Open the crack by $\Delta w = 0,8$ mm. Subject the fastener to the sinusoidal shear loads specified in Table 2.6 and Figure 2.11 with a cycling frequency no greater than 0,5 Hz, where V_{\max} is given by Equation (2.15) or Equation (2.16) as applicable.

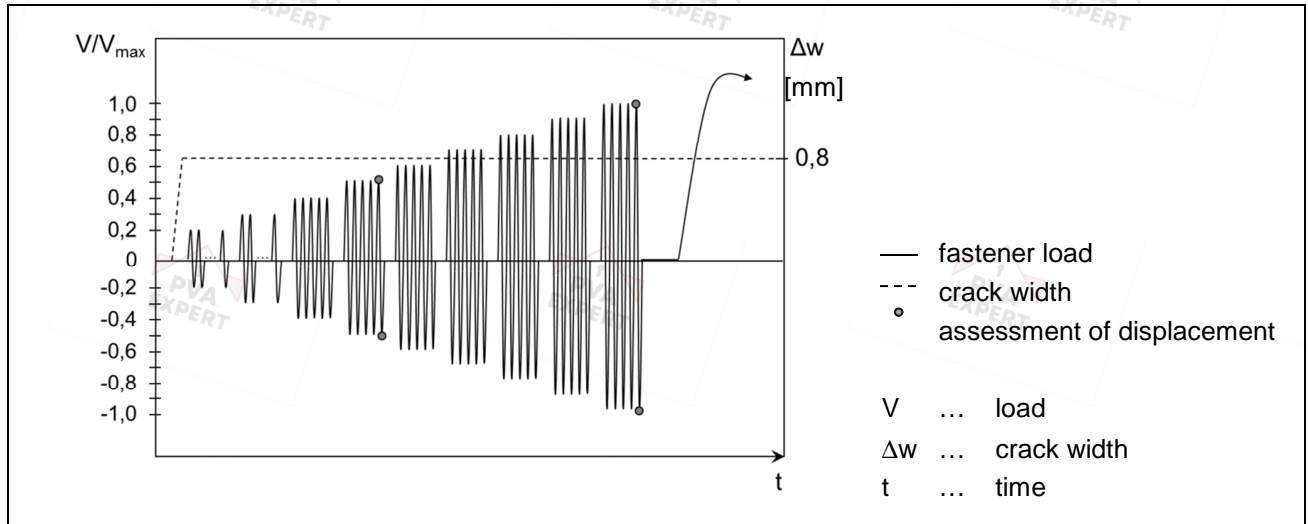


Figure 2.11 Schematic test procedure C2.4

Table 2.6 Required load amplitudes for test series C2.4

$\pm V/V_{max}$	Number of cycles	Crack width Δw [mm]
0,2	25	0,8
0,3	15	0,8
0,4	5	0,8
0,5	5	0,8
0,6	5	0,8
0,7	5	0,8
0,8	5	0,8
0,9	5	0,8
1	5	0,8
SUM	75	

$$V_{max} = 0,85 \cdot V_{u,m,C2.2} \left(\frac{f_{u,C2.4}}{f_{u,C2.2}} \right) \quad [\text{N}] \quad (\text{fasteners without sleeve in shear plane}) \quad (2.15)$$

where

$V_{u,m,C2.2}$ = [N] - mean shear capacity from the reference test series C2.2;

$f_{u,C2.4}$ = [N/mm²] - ultimate mean steel strength of fasteners used in the test series C2.4;

$f_{u,C2.2}$ = [N/mm²] - ultimate mean steel strength of fasteners used in the test series C2.2.

For fasteners with a sleeve in the shear plane V_{eq} shall be calculated according to Equation (2.16).

$$V_{max} = 0,85 \cdot V_{u,m,C2.2} \cdot \left(\frac{f_{u,bol,C2.4}}{f_{u,bol,C2.2}} \cdot \frac{A_{s,bol}}{A_{s,fas}} + \frac{f_{u,sle,C2.4}}{f_{u,sle,C2.2}} \cdot \frac{A_{s,sle}}{A_{s,fas}} \right) \quad [\text{N}] \quad (2.16)$$

where

$V_{u,m,C2.2}$ = [N] - as defined in Equation (2.15);

$f_{u,bol,C2.4}$ = [N/mm²] - mean ultimate tensile strength of bolt used in test series C2.4;

$f_{u,sle,C2.4}$ = [N/mm²] - mean ultimate tensile strength of sleeve used in test series C2.4;

$f_{u,bol,C2.2}$ = [N/mm²] - mean ultimate tensile strength of bolt used in test series C2.2;

$f_{u,sle,C2.2}$ = [N/mm²] - mean ultimate tensile strength of sleeve used in test series C2.2;

$A_{s,bol}$ = [mm²] - effective cross section of bolt;

$$A_{s,sle} = [\text{mm}^2] - \text{effective cross section of sleeve};$$

$$A_{s,fas} = [\text{mm}^2] - A_{s,bol} + A_{s,sle}$$

Adjustment for different steel strengths in Equations (2.15) and (2.16) is not required if the fasteners tested in C2.2 and C2.4 are taken from the same production lot.

The load shall be applied parallel to the direction of the crack. To reduce the potential for uncontrolled slip during load reversal, an approximation by two half-sinusoidal load cycles at the required frequency connected by a reduced speed, ramped load (see Figure 2.12b) or simply triangular loading cycles (see Figure 2.12c) may be used in place of sinusoidal cycles (see Figure 2.12a). The crack width shall be controlled during load cycling.

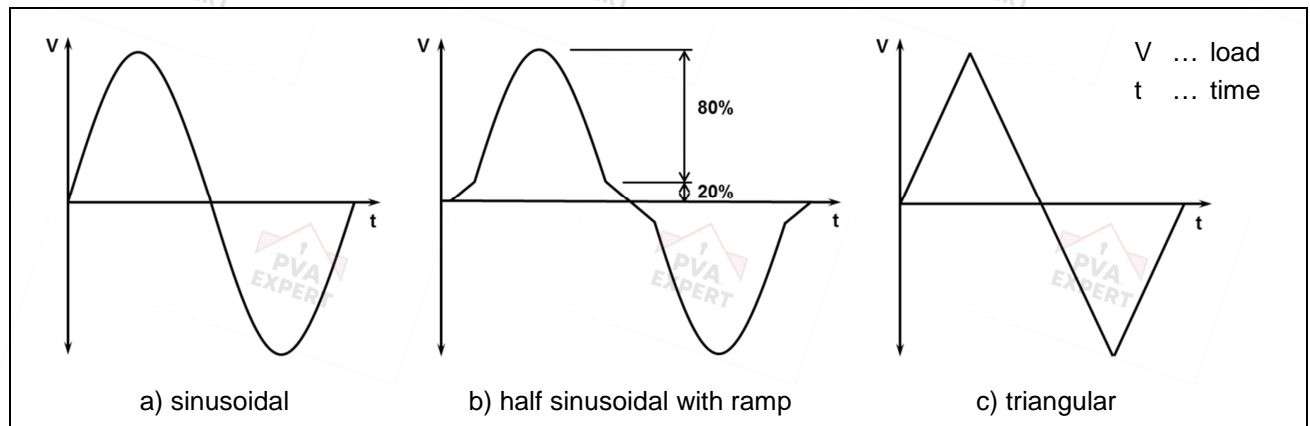


Figure 2.12 Permitted seismic shear cycle C2.4

Record the crack width, fastener displacement and applied shear load continuously during the simulated seismic shear cycles. Report the displacements at minimum and maximum load and the crack width as a function of the number of load cycles.

Following completion of the simulated seismic shear cycles unload the fastener. During the unloading of the fastener the crack width may get smaller. For the residual capacity test open the crack to $\Delta w = 0,8 \text{ mm}$, but not less than the crack opening width as measured at the end of the cyclic test, and load the fastener in shear to failure. Record the maximum shear load (residual shear capacity), the corresponding displacement, the crack width, and plot the load-displacement response.

If the fastener fails to fulfil the requirements given in the corresponding assessment (see 3.2.5) it shall be permitted to conduct the tests with a reduced load level.

If the fastener meets the requirements given in the corresponding assessment but a smaller displacement at the first assessment point (i.e. at the end of load cycling at level $0,5 \cdot V/V_{max}$; see 3.2.5 and Figure 2.11) is intended it shall be permitted to conduct the test with a reduced load level.

If in the test series C2.4 failure is caused by pull-out or pull-through the test may be repeated with a larger embedment depth avoiding these failure modes (compare 3.2.5).

Note 7: During the shear load cycling test failure may occur in the embedded portion of the fastener. If such a failure occurs close to the embedded end of the fastener the residual capacity may not be significantly affected. Hence, in this case failure of the fastener during cycling may easily be overlooked. Attention should be paid to this aspect.

2.4.5 Tests with tension load and varying crack width (test series C2.5)

The tests shall be performed according to TR 048 [6] and 2.1.1 with the following modifications:

Tests shall be carried out on one fastener at a time with no other fasteners installed in the same crack.

Prior to installing fasteners in the test member, loading cycles as required to initiate cracking and to stabilise the relationship between crack width and applied load may be applied to the test member. This loading shall not exceed the elastic limit of the test member.

In order to create similar starting conditions when using a test member with one crack plane and a test member with multiple crack planes the initiated hairline crack may be closed by applying a centric compression force. Before installation of the fastener it shall be ensured that the compression force is not larger than C_{ini} according to Equation (2.17).

$$C_{ini} = 0,01 \cdot f_{c,C2.5} \cdot A_g \text{ [N]} \tag{2.17}$$

where

- A_g = [mm²] - cross section area of the test member;
= $b \cdot h$, with b and h being the width and thickness of the test member, respectively;
- $f_{c,C2.5}$ = [N/mm²] - mean compressive strength of concrete measured on cubes at the time of testing of the test series C2.5.

Install the fastener in the hairline crack according to 2.1.2. When C_{ini} is applied for testing bonded fasteners and bonded expansion fasteners the following procedure may be applied: remove the compression force C_{ini} , install the fastener according to 2.1.2 and after curing again apply C_{ini} on the concrete test member.

Place crack measurement displacement transducers according to 2.1.3 and zero the devices. Following application of load to the fastener sufficient to remove any slack in the loading mechanism, begin recording the fastener displacement and increase the tension load on the fastener to N_{w1} as given by Equation (2.19) to Equation (2.21). With the fastener load N_{w1} held constant, begin the crack cycling program specified in Table 2.7 and Figure 2.13 with a cycling frequency no greater than 0,5 Hz. The first crack movement is in the direction of crack closure by applying a compression load on the test member.

Note 8: The initial crack width w_{ini} after applying N_{w1} may exceed $\Delta w = 0,1$ mm. In this case the first crack movement in the direction of crack closure will close the crack and the crack cycling program is performed starting with $\Delta w = 0,1$ mm (see Figure 2.13).

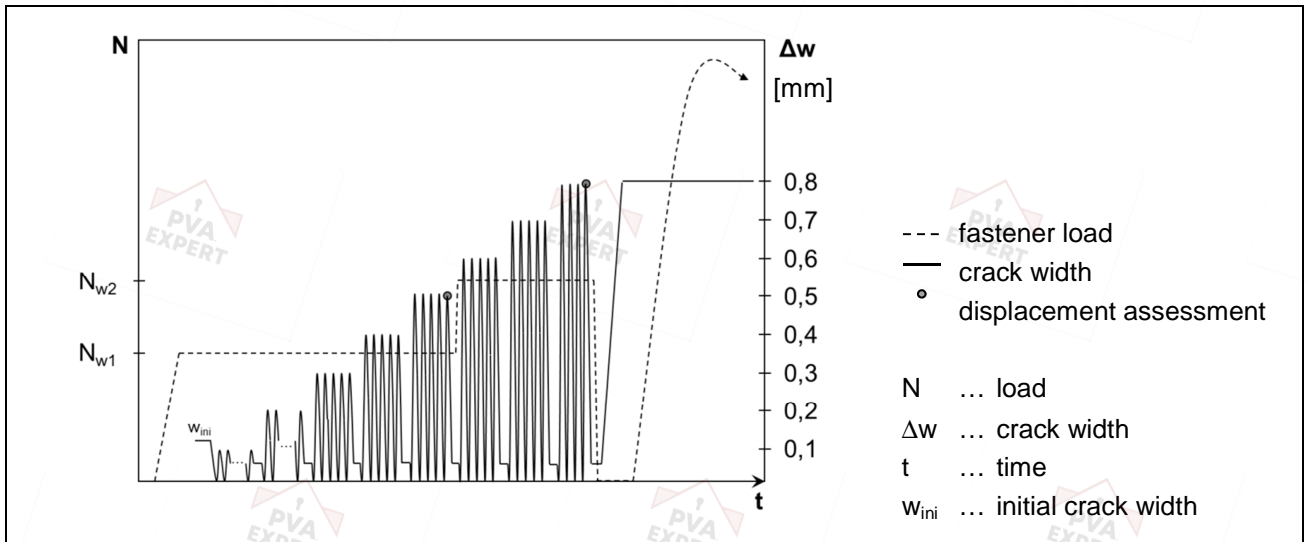


Figure 2.13 Schematic test procedure C2.5

Table 2.7 Required crack widths for test series C2.5

Fastener load	Number of cycles	Crack width Δw [mm]
N_{w1}	20	0,1
N_{w1}	10	0,2
N_{w1}	5	0,3
N_{w1}	5	0,4
N_{w1}	5	0,5
N_{w2}	5	0,6
N_{w2}	5	0,7
N_{w2}	4	0,8
	59	SUM

In each cycle the crack shall be closed by applying a centric compression force C_{test} according to Equation (2.18)

$$C_{test} = 0,1 \cdot f_{c,C2.5} \cdot A_g \quad [\text{N}] \quad (2.18)$$

where

A_g = $[\text{mm}^2]$ - cross section area of the test member;

= $b \cdot h$, with b and h being the width and thickness of the test member, respectively;

$f_{c,C2.5}$ = $[\text{N/mm}^2]$ - mean compressive strength of concrete measured on cubes at the time of testing of the test series C2.5

If the crack is not closed to $\Delta w \leq 0,1$ mm when applying C_{test} according to Equation (2.18), the compression force shall be increased until either $\Delta w \leq 0,1$ mm is achieved or the compression force reaches the maximum value of $C_{test,max} = 0,15 \cdot f_{c,C2.5} \cdot A_g$. This procedure fulfils the requirement of $\Delta w_1 = 0$ mm (see Table 2.4).

Depending on the failure mode observed in the test series C2.1a, N_{w1} is determined as follows:

Steel Failure

$$N_{w1} = 0,4 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{u,C2.5}}{f_{u,C2.1a}} \right) \quad [\text{N}] \quad (2.19)$$

Bond Failure of bonded fasteners

$$N_{w1} = 0,4 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.5}}{f_{c,C2.1a}} \right)^n \quad [\text{N}] \quad (2.20)$$

All other failure modes

$$N_{w1} = 0,4 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.5}}{f_{c,C2.1a}} \right)^{0,5} \quad [\text{N}] \quad (2.21)$$

where

$N_{u,m,C2.1a}$ = $[\text{N}]$ - mean tension capacity from the test series C2.1a $[\text{N}]$;

$f_{u,C2.5}$ = $[\text{N/mm}^2]$ - ultimate mean steel strength of fasteners used in the test series C2.5;

$f_{u,C2.1a}$ = $[\text{N/mm}^2]$ - ultimate mean steel strength of fasteners used in the test series C2.1a;

$f_{c,C2.5}$ = $[\text{N/mm}^2]$ - mean compressive strength of concrete used at the time of testing in the test series C2.5;

$f_{c,C2.1a}$ = $[\text{N/mm}^2]$ - mean compressive strength of concrete used at the time of testing in the test series C2.1a;

n = normalization factor to account for concrete strength; EAD 330499 [2]

If mixed failure modes occur in the test series C2.1a, the largest value of Equations (2.19) and (2.21) shall be applied.

After completion of the crack cycles at crack width $\Delta w = 0,5$ mm, increase the tension load on the fastener to N_{w2} as given by Equation (2.22) to Equation (2.24) and then continue the crack cycling sequence to completion.

Depending on the failure mode observed in the test series C2.1a, N_{w2} is determined as follows:

Steel Failure

$$N_{w2} = 0,5 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{u,C2.5}}{f_{u,C2.1a}} \right) \quad [\text{N}] \quad (2.22)$$

Bond Failure of bonded fasteners

$$N_{w2} = 0,5 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.5}}{f_{c,C2.1a}} \right)^n \quad [\text{N}] \quad (2.23)$$

All other failure modes

$$N_{w2} = 0,5 \cdot N_{u,m,C2.1a} \cdot \left(\frac{f_{c,C2.5}}{f_{c,C2.1a}} \right)^{0,5} \quad [\text{N}] \quad (2.24)$$

with $N_{u,m,C2.1a}$, $f_{u,C2.5}$, $f_{u,C2.1a}$, $f_{c,C2.5}$, $f_{c,C2.1a}$, and n as defined in Equation (2.19) to Equation (2.21).

If mixed failure modes occur in the test series C2.1a, the largest value of Equations (2.22) and (2.24) shall be applied.

Adjustment for different steel strengths in Equation (2.19) and Equation (2.22) is not required if the fasteners tested in C2.1 and C2.5 are taken from the same production lot.

Record the crack width, fastener displacement and applied tension load continuously during the simulated seismic crack cycles. Report the displacements at minimum and maximum crack width and the applied tension load as a function of the number of crack cycles.

Following completion of the simulated seismic crack cycles unload the fastener. During the unloading of the fastener the crack width may get smaller. For the residual capacity test open the crack to $\Delta w = 0,8$ mm, but not less than the crack opening width as measured at the end of the cyclic test, and load the fastener in tension to failure. Record the maximum tension load (residual tension capacity), the corresponding displacement, the crack width, and plot the load-displacement response.

If the fastener fails to fulfil the requirements given in the corresponding assessment (see 3.2.6) it shall be permitted to conduct the tests with a reduced load level.

If the fastener meets the requirements given in the corresponding assessment but a smaller displacement at the first assessment point (i.e. at the end of crack width cycling at level $\Delta w = 0,5$ mm; see 3.2.6 and Figure 2.13) is intended it shall be permitted to conduct the test with a reduced load level.

3 ASSESSMENT OF TEST RESULTS

3.1 Assessment for category C1

3.1.1 Assessment of tests under pulsating tension load (test series C1.1)

All fasteners in a test series shall complete the simulated seismic tension load history specified in Table 2.2 and Figure 2.7. Failure of a fastener to develop the required resistance in any cycle prior to completing the load history specified in Table 2.2 and Figure 2.7 shall be recorded as an unsuccessful test. The mean residual capacity of the fasteners in the test series shall be equal to or greater than 160% of N_{eq} as given by Equation (2.3) or Equation (2.4), as applicable.

Successful completion of the cyclic loading history and fulfilment of the residual tension capacity requirement of this section shall be reported. In this case the seismic reduction factor for tension loading according to Equation (3.1) is $\alpha_{N,C1} = 1,0$.

If the fastener fails to fulfil one of the above requirements at N_{eq} , it shall be permitted to conduct the test with reduced cyclic loads $N_{eq,red}$ until the requirements are met. The loading history specified in Table 2.2 and Figure 2.7 shall be applied, where $N_{eq,red}$, $N_{i,red}$ and $N_{m,red}$ are substituted for N_{eq} , N_i and N_m , respectively. All fasteners in a test series shall complete the simulated seismic tension load history. Failure of a fastener to develop the required tension resistance in any cycle prior to completing the loading history given in Table 2.2 and Figure 2.7 shall be recorded as an unsuccessful test. The mean residual capacity of the fasteners in the test series shall be at least 160% of the reduced load $N_{eq,red}$. Successful completion of the cyclic loading history with reduced load values and fulfilment of the residual tension capacity requirement of this section shall be recorded together with the type of failure mode causing the reduced load values and the reduction factor $\alpha_{N,C1}$, which is calculated as given in Equation (3.1).

$$\alpha_{N,C1} = \frac{N_{eq,red}}{N_{eq}} \quad (3.1)$$

If the fastener successfully completes the cyclic loading history but does not fulfil the residual capacity requirement, a linear reduction (in the extent of actual residual capacity divided by required residual capacity) may be applied in terms of $\alpha_{N,C1}$ without repeating the test series.

The reduction factor $\alpha_{N,C1}$ is then valid for fasteners with the tested embedment depth and all smaller embedment depths.

If fasteners with more than one embedment depth have been tested and different failures are observed in these tests, different reduction factors for steel and pull-out (bond) failure may be obtained.

The reduction factor $\alpha_{N,C1}$ shall be used to determine the characteristic resistances under seismic loading according to 3.3.1.

3.1.2 Assessment of tests under alternating shear load (test series C1.2)

All fasteners in a test series shall complete the simulated seismic shear load history specified in Table 2.3 and Figure 2.8. Failure of a fastener to develop the required resistance in any cycle prior to completing the loading history specified in Table 2.3 and Figure 2.8 shall be recorded as an unsuccessful test. The mean residual capacity of the fasteners in the test series shall be at least 160% of V_{eq} given by Equation (2.7), Equation (2.8) or Equation (2.9), as applicable.

Successful completion of the cyclic loading history and fulfilment of the residual shear capacity requirement of this section shall be reported. In this case the seismic reduction factor for shear loading according to Equation (3.2) is $\alpha_{V,C1} = 1,0$.

If the fastener fails to fulfil one of the above requirements at V_{eq} , it shall be permitted to conduct the test with reduced cyclic loads $V_{eq,red}$ until the requirements are met. The loading history specified in Table 2.3 and Figure 2.8 shall be applied, where $V_{eq,red}$, $V_{i,red}$ and $V_{m,red}$ are substituted for V_{eq} , V_i and V_m , respectively. All fasteners in a test series shall complete the simulated seismic shear load history. Failure of a fastener to develop the required shear resistance in any cycle prior to completing the loading history given in Table 2.3 and Figure 2.8 shall be recorded as an unsuccessful test. The mean residual capacity of the fasteners in the test series shall be at least 160% of the reduced load $V_{eq,red}$. Successful completion of the cyclic history with reduced load values and fulfilment of the residual capacity requirement of this section shall be recorded together with a corresponding reduction factor $\alpha_{V,C1}$, which is calculated as given in Equation (3.2).

$$\alpha_{V,C1} = \frac{V_{eq,red}}{V_{eq}} \quad (3.2)$$

If the fastener successfully completes the cyclic loading history but does not fulfil the residual capacity requirement, a linear reduction (in the extent of actual residual capacity divided by required residual capacity) may be applied in terms of $\alpha_{V,C1}$ without repeating the test series.

The reduction factor $\alpha_{V,C1}$ shall not exceed the value $\alpha_{V,C1} = 0,7$ for commercial standard rods or standard reinforcing bars which are not produced and subjected to factory production control by the manufacturer of the bonded fastener system.

The reduction factor $\alpha_{V,C1}$ shall be used to determine the characteristic resistance for seismic loading according to 3.3.1.

The reduction factor $\alpha_{V,C1}$ according to Equation (3.2) is valid for all embedment depths greater than the tested embedment depth. If more than one embedment depth has been tested the reduction factor $\alpha_{V,C1}$ for an intermediate embedment depth may be determined by linear interpolation.

3.2 Assessment for category C2

3.2.1 General requirements

3.2.1.1 Normalization of test results

The test results shall be normalised as follows:

Steel Failure

$$N_{u,m}(f_u) = N_{u,m,test} \cdot \left(\frac{f_u}{f_{u,test}} \right) \quad [\text{N}] \quad (3.3)$$

$$V_{u,m}(f_u) = V_{u,m,test} \cdot \left(\frac{f_u}{f_{u,test}} \right) \quad [\text{N}] \quad (3.4)$$

For fasteners with a sleeve in the shear plane the normalization shall be calculated as follows:

$$V_{u,m}(f_u) = V_{u,m,test} \cdot \left(\frac{f_u}{f_{u,test}} \cdot \frac{A_{s,bol}}{A_{s,fas}} + \frac{f_{u,sle}}{f_{u,sle,test}} \cdot \frac{A_{s,sle}}{A_{s,fas}} \right) [\text{N}] \quad (3.5)$$

Bond Failure of bonded fasteners

$$N_{u,m}(f_c) = N_{u,m,test} \cdot \left(\frac{f_c}{f_{c,test}} \right)^n \quad [\text{N}] \quad (3.6)$$

All other failure modes

$$N_{u,m}(f_c) = N_{u,m,test} \cdot \left(\frac{f_c}{f_{c,test}} \right)^{0.5} \quad [\text{N}] \quad (3.7)$$

where

$A_{s,bol}$ = [mm²] - effective cross section of bolt;

$A_{s,sle}$ = [mm²] - effective cross section of sleeve;

$A_{s,fas}$ = [mm²] - $A_{s,bol} + A_{s,sle}$.

$N_{u,m}$ = [N] - normalized mean tension capacity;

$N_{u,m,test}$ = [N] - mean tension capacity from the test series;

$V_{u,m}$ = [N] - normalized mean shear capacity;

$V_{u,m,test}$ = [N] - mean shear capacity from the test series;

f_c = [N/mm²] - mean compressive strength of concrete to which the capacity is to be normalized;

$f_{c,test}$ = [N/mm²] - mean compressive strength of concrete used at the time of testing;

f_u = [N/mm²] - mean ultimate steel strength of bolt, threaded rod or insert to which the capacity is to be normalized;

$f_{u,sle}$ = [N/mm²] - mean ultimate steel strength of the sleeve to which the capacity is to be normalized;

$f_{u,sle,test}$ = [N/mm²] - ultimate steel strength of the sleeve of fasteners used in the tests ;

$f_{u,test}$ = [N/mm²] - ultimate mean steel strength of bolt, threaded rod or insert of fasteners used in the tests;

n = normalization factor to account for concrete strength; EAD 330499 [2].

Adjustment for different steel strengths in Equation (3.3) to Equation (3.5) is not required if the fasteners in all tests are taken from the same production lot.

If mixed failure modes occur in the test series C2.1, C2.3 and C2.5 the normalization shall be performed assuming that the failure mode, which was observed in the majority of tests in the test series, occurred in all tests.

3.2.1.2 Load/displacement behaviour

In the load/displacement curve for each fastener tested, a load plateau with a corresponding slip greater than 10% of the displacement at ultimate load, and/or a temporary drop in load of more than 5% of the ultimate load is not acceptable up to a load of 70% of the ultimate load in the single test.

This requirement shall be fulfilled in the test series C2.1a and C2.1b, and in the initial loading as well as in the residual capacity tests of test series C2.3 and C2.5. If this requirement is not fulfilled, the fastener is not suitable for use in category C2.

3.2.2 Assessment of reference tension tests (test series C2.1)

The following conditions apply:

1. Scatter of displacements:

$$cv(\delta(0,5 \cdot N_{u,m,C2.1})) \leq 40\% \quad (3.8)$$

with

cv = [%] - coefficient of variation;

$\delta(0,5 \cdot N_{u,m,C2.1})$ = [mm] - displacement of the fastener at 50% of mean ultimate load of test series C2.1a and b, i.e. $N_{u,m,C2.1a}$ and $N_{u,m,C2.1b}$, respectively .

If this condition is not fulfilled for one of the test series, the fastener is not suitable for use in category C2. It is allowed to increase the number of tests to fulfil this requirement. Note that if in a test series displacements of all fasteners at the load $0,5 N_{u,m}$ are smaller than or equal to 0,4 mm the above condition on the scatter of the displacement does not apply.

2. Ultimate load:

a. Test series C2.1a in low strength concrete C20/25:

$$N_{u,m,C2.1a} \geq 0,8 \cdot N_{u,m,3} \quad (3.9)$$

with

$N_{u,m,C2.1a}$ = [N] - mean ultimate tension load from test series C2.1a;

$N_{u,m,3}$ = [N] - mean tension capacity from the tests for “maximum crack width and large hole diameter” in cracked concrete C20/25 according to EAD 330232 [1], or tests for “sensitivity to increased crack width (F6)” in concrete C20/25 according to EAD 330499 [2], Table 2.5;

If this condition is fulfilled, $\alpha_{C2.1a} = 1,0$. If the condition is not fulfilled, the reduction factor $\alpha_{C2.1a}$ is determined for the test series C2.1a according to Equation (3.10).

$$\alpha_{C2.1a} = \frac{N_{u,m,C2.1a}}{0,8 \cdot N_{u,m,3}} \quad (3.10)$$

In Equations (3.9) and (3.10) the resistances from the tests for “maximum crack width and large hole diameter” in cracked concrete C20/25 according to EAD 330232 [1], or suitability tests “sensitivity to increased crack width (F6)” in concrete C20/25 according to EAD 330499 [2], Table 2.5 shall be normalized according to Equation (3.3), Equation (3.6) or Equation (3.7), as applicable, to the strength in test series C2.1a.

b. Test series C2.1b in high strength concrete C50/60:

$$N_{u,m,C2.1b} \geq 0,8 \cdot N_{u,m,4} \quad (3.11)$$

with

$N_{u,m,C2.1b}$ = [N] - mean ultimate tension load from test series C2.1b;

$N_{u,m,4}$ = [N] - mean tension capacity from the tests for “maximum crack width and small hole diameter” in cracked concrete C50/60 according to EAD 330232 [1], or suitability tests “sensitivity to increased crack width (F7)” in concrete C50/60 according to EAD 330499 [2], Table 2.5.

If this condition is fulfilled, $\alpha_{C2.1b} = 1,0$. If the condition is not fulfilled, the reduction factor $\alpha_{C2.1b}$ is determined for the test series C2.1b according to Equation (3.12).

$$\alpha_{C2.1b} = \frac{N_{u,m,C2.1b}}{0,8 \cdot N_{u,m,4}} \quad (3.12)$$

In Equations (3.11) and (3.12) the resistances from the tests for “maximum crack width and small hole diameter” in cracked concrete C50/60 according to EAD 330232 [1], or suitability tests “sensitivity to increased crack width (F7)” in concrete C50/60 according to EAD 330499 [2], Table 2.5 shall be normalized according to Equation (3.3), Equation (3.6) or Equation (3.7), as applicable, to the strength in test series C2.1b.

The reduction factor $\alpha_{C2.1}$ is determined according to Equation (3.13).

$$\alpha_{C2.1} = \min(\alpha_{C2.1a}; \alpha_{C2.1b}) \quad (3.13)$$

3. Scatter of ultimate loads:

$$cv(N_u) \leq 20\% \quad (3.14)$$

If this condition is fulfilled for both test series C2.1a and C2.1b, $\beta_{cv,C2.1a} = \beta_{cv,C2.1b} = 1,0$. If this condition is not fulfilled in a test series, the factors $\beta_{cv,C2.1a}$ and/or $\beta_{cv,C2.1b}$ shall be calculated according to Equation (3.15) and Equation (3.16), respectively.

$$\beta_{cv,C2.1a} = \frac{1}{1 + (cv(N_{u,C2.1a}) - 20) \cdot 0,03} \quad (3.15)$$

$$\beta_{cv,C2.1b} = \frac{1}{1 + (cv(N_{u,C2.1b}) - 20) \cdot 0,03} \quad (3.16)$$

where $cv(N_{u,C2.1a})$ and $cv(N_{u,C2.1b})$ are the coefficients of variation of the ultimate loads in test series C2.1a and C2.1b, respectively.

The factor $\beta_{cv,C2.1}$ is determined as given in Equation (3.17):

$$\beta_{cv,C2.1} = \min(\beta_{cv,C2.1a}; \beta_{cv,C2.1b}) \quad (3.17)$$

If $cv(N_u)$ is larger than 30% in one test series, the fastener is not suitable for use in category C2. It shall be allowed to increase the number of tests in a test series to possibly fulfil this requirement.

3.2.3 Assessment of reference shear tests (test series C2.2)

If calculated values or results of tests for “characteristic resistance to steel failure under shear load” according to EAD 330232 [1], are taken as reference tests, this section does not apply. If test series C2.2 are performed for reference shear values the following conditions apply:

1. Failure mode:

If failure is caused by pull-out or pull-through the fastener is not suitable for use in category C2. The test may be repeated with a larger embedment depth avoiding these failure modes.

2. Ultimate load:

$$V_{u,m,C2.2} \geq 0,8 \cdot V_{u,m,5} \quad (3.18)$$

with

$V_{u,m,C2.2}$ = [N] - mean ultimate shear load from test series C2.2;

$V_{u,m,5}$ = [N] - mean shear capacity from the tests for “characteristic resistance to steel failure under shear load” according to EAD 330232 [1].

If this condition is fulfilled, $\alpha_{C2.2} = 1,0$. If this condition is not fulfilled, the factor $\alpha_{C2.2}$ shall be determined according to Equation (3.19).

$$\alpha_{C2.2} = \frac{V_{u,m,C2.2}}{0,8 \cdot V_{u,m,5}} \quad (3.19)$$

In Equations (3.18) and (3.19) the resistances from the tests for “characteristic resistance to steel failure under shear load” according to EAD 330232 [1], shall be normalized according to Equation (3.4) or Equation (3.5), as applicable, to the strength in test series C2.2.

3. Scatter of ultimate loads:

$$cv(V_u) \leq 15\% \quad (3.20)$$

If this condition is fulfilled, $\beta_{cv,C2.2} = 1,0$. If this condition is not fulfilled, the factor $\beta_{cv,C2.2}$ shall be determined according to Equation (3.21).

$$\beta_{cv,C2.2} = \frac{1}{1 + (cv(V_u) - 15) \cdot 0,03} \quad (3.21)$$

where $cv(V_u)$ is the coefficient of variation of the ultimate loads in test series C2.2.

If $cv(V_u)$ is larger than 30%, the fastener is not suitable for use in category C2.

3.2.4 Assessment of tests under pulsating tension load (test series C2.3)

The following conditions apply:

1. All fasteners in a test series shall complete the pulsating tension load history specified in Figure 2.10 and Table 2.5. Failure of a fastener to develop the required resistance in any cycle prior to completing the loading history specified in Table 2.5 shall be recorded as an unsuccessful test. In case of an unsuccessful test, the test series shall be repeated with a reduced value $N_{max,red,1}$ until the requirement is fulfilled. In this case the reduction factor $\alpha_{C2.3a}$ shall be calculated according to Equation (3.22).

$$\alpha_{C2.3a} = \frac{N_{max,red,1}}{N_{max}} \quad (3.22)$$

with

N_{max} = [N] - maximum tension load according to Equation (2.12) to Equation (2.14).

$N_{max,red,1}$ = [N] - reduced tension load to fulfil the requirement.

2. Displacements are assessed during the last cycle at $0,5 \cdot N/N_{max}$ and at $1,0 \cdot N/N_{max}$ or at $0,5 \cdot N/N_{max,red,1}$ and at $1,0 \cdot N/N_{max,red,1}$, respectively, (refer to Figure 2.10). Displacements shall be reported in terms of the mean value.

To avoid excessive displacement of the fastener a displacement limit at the end of load cycling at $0,5 \cdot N/N_{max}$ or $0,5 \cdot N/N_{max,red,1}$ (i.e. after 50 load cycles (see Figure 2.10 and Table 2.5)) is introduced for the assessment of fasteners. Due to lack of sufficient test data this limit is assumed as $\delta_{N,lim} = 7$ mm. The following condition shall be fulfilled:

$$\delta_m(0,5 \cdot N/N_{max}) \leq \delta_{N,lim} \quad (3.23)$$

with

$\delta_m(0,5 \cdot N/N_{max})$ = [mm] - mean value of displacements of the fastener after load cycling at $0,5 \cdot N/N_{max}$ or $0,5 \cdot N/N_{max,red,1}$ of test series C2.3;

$\delta_{N,lim}$ = 7 mm.

If this condition is not fulfilled repeat the tests with a reduced value $N_{max,red,2}$ until the requirement is fulfilled and calculate the reduction factor $\alpha_{C2.3b}$ according to Equation (3.24).

$$\alpha_{C2.3b} = \frac{N_{max,red,2}}{N_{max}} \quad (3.24)$$

with

N_{max} = [N] - maximum tension load according to Equation (2.12) to Equation (2.14);

$N_{max,red,2}$ = [N] - reduced tension load to fulfil the requirement.

If the condition according to Equation (3.23) is fulfilled but a smaller displacement is intended it shall be permitted to repeat the tests with a reduced value $N_{max,red}$.

3. Residual capacity tests (all three conditions apply):

a. Scatter of displacement:

$$cv(\delta(0,5 \cdot N_{u,m,C2.3})) \leq 40\% \quad (3.25)$$

with

$\delta(0,5 \cdot N_{u,m,C2.3})$ = [mm] - displacement of the fastener at 50% of the mean ultimate tension load from the residual capacity tests of test series C2.3. Only the displacement in the residual capacity test is taken, i.e., the displacement that occurred during the cyclic loading is neglected.

$$N_{u,m,C2.3} = [N] - \text{mean ultimate tension load from residual capacity tests of test series C2.3.}$$

If this condition is not fulfilled, the fastener is not suitable for use in category C2.

b. Ultimate load:

$$N_{u,m,C2.3} \geq 0,9 \cdot N_{u,m,C2.1a} \quad (3.26)$$

with

$N_{u,m,C2.1a}$ = [N] - mean ultimate tension load from test series C2.1a;

$N_{u,m,C2.3}$ = [N] - mean ultimate tension load from residual capacity tests of test series C2.3.

If this condition is fulfilled, $\alpha_{C2.3c} = 1,0$. If this condition is not fulfilled, the factor $\alpha_{C2.3c}$ shall be determined according to Equation (3.27).

$$\alpha_{C2.3c} = \frac{N_{u,m,C2.3}}{0,9 \cdot N_{u,m,C2.1a}} \quad (3.27)$$

In Equations (3.26) and (3.27) the resistances from test series C2.1a shall be normalized according to Equation (3.3), Equation (3.6) or Equation (3.7), as applicable, to the strength in test series C2.3.

Alternatively, the test series C2.3 may be repeated with a reduced value of N_{max} until the requirement given in Equation (3.26) is fulfilled.

c. Scatter of ultimate loads:

$$cv(N_u) \leq 20\% \quad (3.28)$$

If this condition is fulfilled, $\beta_{cv,C2.3} = 1,0$. If this condition is not fulfilled, $\beta_{cv,C2.3}$ shall be determined according to Equation (3.29).

$$\beta_{cv,C2.3} = \frac{1}{1 + (cv(N_u) - 20) \cdot 0,03} \quad (3.29)$$

where $cv(N_u)$ is the coefficient of variation of the ultimate loads in the residual capacity tests in test series C2.3.

If $cv(N_u)$ is larger than 30%, the fastener is not suitable for use in category C2.

The reduction factor $\alpha_{C2.3}$ resulting from the pulsating tension test series C2.3 is determined according to Equation (3.30).

$$\alpha_{C2.3} = \min(\alpha_{C2.3a}; \alpha_{C2.3b}) \cdot \alpha_{C2.3c} \quad (3.30)$$

Report the displacements after successful completion at $0,5 \cdot N/N_{max}$ and $1,0 \cdot N/N_{max}$ or at $0,5 \cdot N/N_{max,red}$ and $1,0 \cdot N/N_{max,red}$ in case the tests are repeated with a reduced load value, as applicable.

3.2.5 Assessment of tests under alternating shear load (test series C2.4)

The following conditions apply:

1. All fasteners in a test series shall complete the alternating shear load history specified in Figure 2.11 and Table 2.6. Failure of a fastener to develop the required resistance in any cycle prior to completing the loading history specified in Table 2.6 shall be recorded as an unsuccessful test. In case of an unsuccessful test, the test series shall be repeated with a reduced value $V_{max,red,1}$ until the requirement is fulfilled. In this case the reduction factor $\alpha_{C2.4a}$ shall be calculated according to Equation (3.31).

$$\alpha_{C2.4a} = \frac{V_{max,red,1}}{V_{max}} \quad (3.31)$$

with

V_{max} = [N] - maximum shear load according to Equation (2.15) or Equation (2.16);

$V_{max,red,1}$ = [N] - reduced shear load to fulfil the requirement.

2. Displacements are assessed during the last cycle at $\pm 0,5 \cdot V/V_{max}$ and $\pm 1,0 \cdot V/V_{max}$ or $\pm 0,5 \cdot V/V_{max,red,1}$ and $\pm 1,0 \cdot V/V_{max,red,1}$ (refer to Figure 2.11). Displacements shall be reported as the maximum of the mean of the absolute values in the positive loading direction and the mean of the absolute values in the negative loading direction.

To avoid excessive displacement of the fastener a displacement limit at the end of load cycling at $\pm 0,5 \cdot V/V_{max}$ (i.e. at load cycle 50 (see Figure 2.11 and Table 2.6)) is introduced for the assessment of fasteners. Due to lack of sufficient test data this limit is assumed as $\delta_{V,lim} = 7$ mm. The following condition shall be fulfilled:

$$\delta_m(0,5 \cdot V/V_{max}) \leq \delta_{V,lim} \quad (3.32)$$

with

$$\delta_m(0,5 \cdot V/V_{max}) = [\text{mm}] - \max(|\delta_m(+0,5 \cdot V/V_{max})|; |\delta_m(-0,5 \cdot V/V_{max})|); \text{ maximum of the mean value of displacements of the fastener after load cycling at } +0,5 \cdot V/V_{max} \text{ and the mean value of displacements of the fastener after load cycling at } -0,5 \cdot V/V_{max} \text{ of test series C2.4; if the tests have been performed with } V_{max,red,1} \text{ replace } V_{max} \text{ by } V_{max,red,1};$$

$$\delta_{V,lim} = 7 \text{ mm.}$$

If the condition is not fulfilled repeat the tests with a reduced value $V_{max,red,2}$ until the requirement is fulfilled. Determine the corresponding reduction factor $\alpha_{C2.4b}$ in accordance with Equation (3.33).

$$\alpha_{C2.4b} = \frac{V_{max,red,2}}{V_{max}} \quad (3.33)$$

with

$$V_{max} = [\text{N}] - \text{maximum shear load according to Equation (2.15) or Equation (2.16);}$$

$$V_{max,red,2} = [\text{N}] - \text{reduced shear load to fulfil the requirement.}$$

If the condition according to Equation (3.32) is fulfilled but a smaller displacement is intended it shall be permitted to repeat the tests with a reduced value $V_{max,red}$.

3. Residual capacity tests (both conditions apply):

- a. Failure mode:

If failure is caused by pull-out or pull-through the fastener is not suitable for use in category C2. The tests may be repeated with a larger embedment depth avoiding these failure modes.

- b. Ultimate load:

$$V_{u,m,C2.4} \geq 0,95 \cdot V_{u,m,C2.2} \quad (3.34)$$

with

$$V_{u,m,C2.4} = [\text{N}] - \text{mean ultimate shear load from residual capacity tests of test series C2.4.}$$

$$V_{u,m,C2.2} = [\text{N}] - \text{mean ultimate shear load from residual capacity tests of test series C2.2.}$$

If this condition is fulfilled, $\alpha_{C2.4c} = 1,0$. If this condition is not fulfilled, the factor $\alpha_{C2.4c}$ shall be determined according to Equation (3.35).

$$\alpha_{C2.4c} = \frac{V_{u,m,C2.4}}{0,95 \cdot V_{u,m,C2.2}} \quad (3.35)$$

In Equations (3.34) and (3.35) the resistances from test series C2.2 shall be normalized according to Equation (3.4) or Equation (3.5), as applicable, to the strength in test series C2.4.

Alternatively, the test series C2.4 may be repeated with a reduced value of V_{max} until the requirement given in Equation (3.34) is fulfilled.

- c. Scatter of ultimate loads:

$$cv(V_u) \leq 15\% \quad (3.36)$$

If this condition is fulfilled, $\beta_{cv,C2.4} = 1,0$. If this condition is not fulfilled, $\beta_{cv,C2.4}$ shall be determined according to Equation (3.37).

$$\beta_{cv,C2.4} = \frac{1}{1 + (cv(V_u) - 15) \cdot 0,03} \quad (3.37)$$

where $cv(V_u)$ is the coefficient of variation of the ultimate loads in the residual capacity tests in test series C2.4.

If $cv(V_u)$ is larger than 30%, the fastener is not suitable for use in category C2.

The reduction factor $\alpha_{C2.4}$ resulting from the alternating shear load test series C2.4 is determined according to Equation (3.38).

$$\alpha_{C2.4} = \min(\alpha_{C2.4a}; \alpha_{C2.4b}) \cdot \alpha_{C2.4c} \quad (3.38)$$

Report the displacements after successful completion at $\pm 0,5 \cdot V/V_{max}$ and $\pm 1,0 \cdot V/V_{max}$ or at $\pm 0,5 \cdot V/V_{max,red}$ and $\pm 1,0 \cdot V/V_{max,red}$ in case the tests are repeated with a reduced shear load, as applicable.

3.2.6 Assessment of tests under tension load with varying crack width (test series C2.5)

The following conditions apply:

1. All fasteners in the test series shall complete the varying crack width history under tension load specified in Figure 2.13 and Table 2.7. Failure of a fastener to develop the required resistance in any cycle prior to completing the crack cycling history specified in Table 2.7 shall be recorded as an unsuccessful test. In case of an unsuccessful test, the test series shall be repeated with proportionally reduced values of N_{w1} and N_{w2} , i.e. $N_{w1,red,1}$ and $N_{w2,red,1}$, respectively, until the requirement is fulfilled. The corresponding reduction factor $\alpha_{C2.5a}$ shall be calculated according to Equation (3.39).

$$\alpha_{C2.5a} = \frac{N_{w2,red,1}}{N_{w2}} \quad (3.39)$$

with

N_{w2} = [N] - tension load according to Equation (2.22) to Equation (2.24) as applicable;

$N_{w2,red,1}$ = [N] - reduced tension load to fulfil the requirement.

2. Displacements are assessed during the last cycle at $\Delta w = 0,5$ mm and $\Delta w = 0,8$ mm (see Figure 2.13). Displacements shall be reported in terms of the mean value.

To avoid excessive displacement of the fastener a displacement limit at the end of cycling at $\Delta w = 0,5$ mm (i.e. at the end of cycle 45 (see Figure 2.13 and Table 2.7)) is introduced for the assessment of fasteners. Due to lack of sufficient test data this limit is assumed as $\delta_{N,lim} = 7$ mm. The following condition shall be fulfilled:

$$\delta_m(\Delta w = 0,5) \leq \delta_{N,lim} \quad (3.40)$$

with

$\delta_m(\Delta w = 0,5)$ = [mm] - mean value of displacements of the fastener at the end of cycling at $\Delta w = 0,5$ mm of test series C2.5;

$\delta_{N,lim}$ = 7 mm.

If this condition is not fulfilled repeat the tests with proportionally reduced values of N_{w1} and N_{w2} , i.e. $N_{w1,red,2}$ and $N_{w2,red,2}$, respectively, until the requirement is fulfilled and calculate the reduction factor $\alpha_{C2.5b}$ according to Equation (3.41).

$$\alpha_{C2.5b} = \frac{N_{w2,red,2}}{N_{w2}} \quad (3.41)$$

with

N_{w2} = [N] - tension load according to Equation (2.22) to Equation (2.24);

$N_{w2,red,2}$ = [N] - reduced tension load to fulfil the requirement.

If the condition according to Equation (3.40) is fulfilled but a smaller displacement is intended it shall be permitted to repeat the tests with proportionally reduced values $N_{w1,red,2}$ and $N_{w2,red,2}$.

3. Residual capacity tests (all three conditions apply):

a. Scatter of displacement:

$$cv(\delta(0,5 \cdot N_{u,m,C2.5})) \leq 40\% \quad (3.42)$$

with

$\delta(0,5 \cdot N_{u,m,C2.5})$ = [mm] - displacement of the fastener at 50% of the mean ultimate tension load from the residual capacity tests of test series C2.5; displacement in the residual capacity test only, i.e., neglecting the displacement that occurred during the crack cyclic.

$N_{u,m,C2.5}$ = [N] - mean ultimate tension load from residual capacity tests of test series C2.5.

If this condition is not fulfilled, the fastener is not suitable for use in category C2.

b. Ultimate load:

$$N_{u,m,C2.5} \geq 0,9 \cdot N_{u,m,C2.1a} \quad (3.43)$$

with

$N_{u,m,C2.1a}$ = [N] - mean ultimate tension load from test series C2.1a

$N_{u,m,C2.5}$ = [N] - mean ultimate tension load from residual capacity tests of test series C2.5.

If this condition is fulfilled, $\alpha_{C2.5c} = 1,0$. If this condition is not fulfilled, the factor $\alpha_{C2.5c}$ shall be determined according to Equation (3.44).

$$\alpha_{C2.5c} = \frac{N_{u,m,C2.5}}{0,9 \cdot N_{u,m,C2.1a}} \quad (3.44)$$

In Equations (3.43) and (3.44) the resistances from test series C2.1a shall be normalized according to Equation (3.3), Equation (3.6) or Equation (3.7), as applicable, to the strength in test series C2.5.

Alternatively, the test series C2.5 may be repeated with a reduced value of N_{max} until the requirement given in Equation (3.43) is fulfilled.

c. Scatter of ultimate loads:

$$cv(N_u) \leq 20\% \quad (3.45)$$

If this condition is fulfilled, $\beta_{cv,C2.5} = 1,0$. If this condition is not fulfilled, $\beta_{cv,C2.5}$ shall be determined according to Equation (3.46).

$$\beta_{cv,C2.5} = \frac{1}{1 + (cv(N_u) - 20) \cdot 0,03} \quad (3.46)$$

If $cv(N_u)$ is larger than 30%, the fastener is not suitable for use in category C2.

The reduction factor $\alpha_{C2.5}$ resulting from the varying crack width test series C2.3 is determined according to Equation (3.47).

$$\alpha_{C2.5} = \min(\alpha_{C2.5a}; \alpha_{C2.5b}) \cdot \alpha_{C2.5c} \quad (3.47)$$

Report the displacements after successful completion at the end of crack cycling at $\Delta w = 0,5$ mm and $\Delta w = 0,8$ mm.

3.2.7 Determination of decisive reduction factors for seismic category C2

3.2.7.1 Tension

The reduction factors $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ are determined according to Equations (3.48) and (3.49), respectively.

$$\alpha_{N,C2} = \alpha_{C2.1} \cdot \min(\alpha_{C2.3}; \alpha_{C2.5}) \quad (3.48)$$

where

$$\begin{aligned}
 \alpha_{C2.1} &= \text{reduction factor } \alpha \text{ according to 3.2.2;} \\
 \alpha_{C2.3} &= \text{reduction factor } \alpha \text{ according to 3.2.4;} \\
 \alpha_{C2.5} &= \text{reduction factor } \alpha \text{ according to 3.2.6.} \\
 \beta_{cv,N,C2} &= \min(\beta_{cv,C2.1}; \beta_{cv,C2.3}; \beta_{cv,C2.5}) \\
 &\text{where} \\
 \beta_{cv,C2.1} &= \text{reduction factor } \beta_{cv} \text{ accounting for large scatter according to 3.2.2;} \\
 \beta_{cv,C2.3} &= \text{reduction factor } \beta_{cv} \text{ accounting for large scatter according to 3.2.4;} \\
 \beta_{cv,C2.5} &= \text{reduction factor } \beta_{cv} \text{ accounting for large scatter according to 3.2.6.}
 \end{aligned} \tag{3.49}$$

The reduction factors according to Equation (3.48) and Equation (3.49) are valid for fasteners with the tested embedment depth and all smaller embedment depths.

If fasteners with more than one embedment depth have been tested and different failure modes are observed in these tests, different reduction factors for steel and pull-out (bond) failure may be obtained.

The reduction factors $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ shall be used to determine the characteristic resistances under seismic loading according to 3.3.2.1.

3.2.7.2 Shear

The reduction factors $\alpha_{V,C2}$ and $\beta_{cv,V,C2}$ are determined according to Equations (3.50) and (3.51), respectively.

$$\alpha_{V,C2} = \alpha_{C2.2} \cdot \alpha_{C2.4} \tag{3.50}$$

where

$$\begin{aligned}
 \alpha_{C2.2} &= \text{reduction factor } \alpha \text{ according to 3.2.3;} \\
 \alpha_{C2.4} &= \text{reduction factor } \alpha \text{ according to 3.2.5.}
 \end{aligned}$$

$$\beta_{cv,V,C2} = \min(\beta_{cv,C2.2}; \beta_{cv,C2.4}) \tag{3.51}$$

where

$$\begin{aligned}
 \beta_{cv,C2.2} &= \text{reduction factor } \beta_{cv} \text{ accounting for large scatter according to 3.2.3;} \\
 \beta_{cv,C2.4} &= \text{reduction factor } \beta_{cv} \text{ accounting for large scatter according to 3.2.5;}
 \end{aligned}$$

The reduction factors according to Equation (3.50) and Equation (3.51) are valid for fasteners with the tested embedment depth and all larger embedment depths. If more than one embedment depth has been tested the reduction factors $\alpha_{V,C2}$ and $\beta_{cv,V,C2}$ for an intermediate embedment depth may be determined by linear interpolation.

The reduction factors $\alpha_{V,C2}$ and $\beta_{cv,V,C2}$ shall be used to determine the characteristic resistances under seismic loading according to 3.3.2.2.

3.3 Characteristic values for seismic design

In this assessment it is assumed that the characteristic resistances under seismic action for concrete failure modes (concrete cone breakout in tension and concrete edge breakout and pry-out failure in shear) are covered in the design method by applying reduction factors to the corresponding characteristic resistances under non-seismic loading conditions.

3.3.1 Seismic performance category C1

3.3.1.1 Tension

The characteristic resistances as determined below are valid for fasteners with the tested embedment depth and all smaller embedment depths.

3.3.1.1.1 All fasteners except bonded fasteners

a. Steel failure caused reduction:

The characteristic resistances for steel tension and pull-out under seismic loading, i.e. $N_{Rk,s,C1}$ and $N_{Rk,p,C1}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C1} = \alpha_{N,C1} \cdot N_{Rk,s} \quad [N] \quad (3.52)$$

$$N_{Rk,p,C1} = \alpha_{N,C1} \cdot N_{Rk,p} \quad [N] \quad (3.53)$$

$$N_{Rk,p,C1} = \alpha_{N,C1} \cdot N_{Rk,c} \quad [N] \quad (\text{if no pull-out failure occurs for static loading}) \quad (3.54)$$

where

$N_{Rk,s}$ = [N] - characteristic steel tension resistance as reported in the ETA for static loading;

$N_{Rk,p}$ = [N] - characteristic pull-out resistance in cracked concrete as reported in the ETA for static loading;

$N_{Rk,c}$ = [N] - characteristic concrete cone resistance in cracked concrete for static loading;

$\alpha_{N,C1}$ = reduction factor α according to 3.1.1.

b. Pull-out failure caused reduction:

The characteristic resistances for steel tension and pull-out under seismic loading, i.e. $N_{Rk,s,C1}$ and $N_{Rk,p,C1}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C1} = N_{Rk,s} \quad [N] \quad (3.55)$$

$$N_{Rk,p,C1} = \alpha_{N,C1} \cdot N_{Rk,p} \quad [N] \quad (3.56)$$

$$N_{Rk,p,C1} = \alpha_{N,C1} \cdot N_{Rk,c} \quad [N] \quad (\text{if no pull-out failure occurs for static loading}) \quad (3.57)$$

For $N_{Rk,s}$, $N_{Rk,p}$, $N_{Rk,c}$ and $\alpha_{N,C1}$ see a.

3.3.1.1.2 Bonded fasteners:

a. Steel failure caused reduction:

The characteristic resistances for steel tension and pull-out (bond) under seismic loading, i.e. $N_{Rk,s,C1}$ and $\tau_{Rk,C1}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C1} = \alpha_{N,C1} \cdot N_{Rk,s} \quad [N] \quad (3.58)$$

$$\tau_{Rk,C1} = \alpha_{N,C1} \cdot \tau_{Rk,base} \quad [N] \quad (3.59)$$

where

$N_{Rk,s}$ = [N] - characteristic steel tension resistance as reported in the ETA for static loading;

$\tau_{Rk,base}$ = [N/mm²] - characteristic bond resistance for cracked concrete ($\tau_{Rk,cr}$) as reported in the ETA for static loading;

$\alpha_{N,C1}$ = reduction factor α according to 3.1.1.

b. Pullout failure caused reduction:

The characteristic resistances for steel tension and pull-out (bond) under seismic loading, i.e. $N_{Rk,s,C1}$ and $\tau_{Rk,C1}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C1} = N_{Rk,s} \quad [N] \quad (3.60)$$

$$\tau_{Rk,C1} = \alpha_{N,C1} \cdot \tau_{Rk,base} \quad [N] \quad (3.61)$$

with $N_{Rk,s}$, $\tau_{Rk,base}$ and $\alpha_{N,C1}$ as defined in Equation (3.58) and Equation (3.59).

3.3.1.2 Shear

The characteristic shear resistance for steel under seismic loading, $V_{Rk,s,C1}$, to be reported in the ETA is determined as follows:

$$V_{Rk,s,C1} = \alpha_{V,C1} \cdot V_{Rk,s} \quad [N] \quad (3.62)$$

where

$V_{Rk,s}$ = [N] - characteristic shear resistance as reported in the ETA for static loading;

$\alpha_{V,C1}$ = reduction factor α according to 3.1.2.

The value $V_{Rk,s,C1}$ according to Equation (3.62) is valid for all embedment depths greater than the tested embedment depth. If more than one embedment depth has been tested the value $V_{Rk,s,C1}$ for an intermediate embedment depth may be determined by linear interpolation.

3.3.2 Seismic performance category C2

The characteristic values reported in the ETA are calculated as follows:

3.3.2.1 Tension loading

The characteristic resistances as determined below are valid for fasteners with the tested embedment depth and all smaller embedment depths.

The characteristic resistance for seismic actions as given in the following shall be limited by the values for static and quasi-static loading.

3.3.2.1.1 All fasteners except bonded fasteners

a) Steel failure caused reduction:

The characteristic resistances for steel tension and pull-out under seismic loading, i.e. $N_{Rk,s,C2}$ and $N_{Rk,p,C2}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C2} = \alpha_{N,C2} \cdot \beta_{cv,N,C2} \cdot N_{Rk,s} \quad [\text{N}] \quad (3.63)$$

$$N_{Rk,p,C2} = \alpha_{N,C2} \cdot \beta_{cv,N,C2} \cdot N_{Rk,0} \quad [\text{N}] \quad (3.64)$$

where

$N_{Rk,0}$ = [N] - characteristic value of tests for “maximum crack width and large hole diameter (F1)”-and “maximum crack width and small hole diameter (F2)” according to EAD 330232 [1], (normalized according to Equation (3.3) to Equation (3.7) to the compressive strength of concrete (measured on cylinders) of $f_c = 20 \text{ N/mm}^2$);

Note 9: The characteristic value $N_{Rk,0}$ may be determined as follows:

- (1) determine the characteristic value of the test series F1 and F2 separately and take the minimum of the two;
- (2) determine the characteristic value of the combined test data of the test series F1 and F2;
- (3) take the maximum of (1) and (2), i.e. $N_{Rk,0} = \max(\min(F1;F2);(F1 \cup F2))$.

$N_{Rk,s}$ = [N] - characteristic steel tension resistance as reported in the ETA for static loading;

$\alpha_{N,C2}$ = reduction factor α as determined in Equation (3.48);

$\beta_{cv,N,C2}$ = reduction factor β_{cv} accounting for large scatter as determined in Equation (3.49).

b) Pullout failure caused reduction:

The characteristic resistances for steel tension and pullout under seismic loading, i.e. $N_{Rk,s,C2}$ and $N_{Rk,p,C2}$, respectively, to be reported in the ETA are determined as follows:

$$N_{Rk,s,C2} = N_{Rk,s} \quad [\text{N}] \quad (3.65)$$

$$N_{Rk,p,C2} = \alpha_{N,C2} \cdot \beta_{cv,N,C2} \cdot N_{Rk,0} \quad [\text{N}] \quad (3.66)$$

with $N_{Rk,0}$, $N_{Rk,s}$, $\alpha_{N,C2}$ and $\beta_{cv,N,C2}$ as given in Equation (3.63) and Equation (3.64).

3.3.2.1.2 Bonded fasteners

a) Steel failure:

The characteristic resistance for steel tension $N_{Rk,s,C2}$ to be reported in the ETA is determined as follows:

$$N_{Rk,s,C2} = \alpha_{N,C2} \cdot \beta_{cv,N,C2} \cdot N_{Rk,s} \quad [\text{N}] \quad (3.67)$$

where

$N_{Rk,s}$ = [N] - characteristic steel tension resistance as reported in the ETA for static loading;

$\alpha_{N,C2}$ = reduction factor α as determined in Equation (3.48) for tests in which steel failure occurred;

$\beta_{cv,N,C2}$ = reduction factor β_{cv} accounting for large scatter as determined in Equation (3.49) for tests in which steel failure occurred.

b) Pullout (bond) failure:

If pullout (bond) failure for bonded fasteners is given in terms of a characteristic bond resistance the corresponding resistance under seismic loading $\tau_{Rk,C2}$ is determined as follows:

$$\tau_{Rk,C2} = \alpha_{N,C2} \cdot \beta_{cv,N,C2} \cdot \tau_{Rk,base} \quad [\text{N/mm}^2] \quad (3.68)$$

with

$\tau_{Rk,base}$ = [N/mm²] - basic bond strength τ_{Rk}^0 from tests “sensitivity to increased crack width (F6)” in concrete C20/25 according to EAD 330499 [2], Table 2.5 applying α_1 to α_4 and α_{setup} (i.e. reduction factors regarding “uncontrolled slip”, maximum long term temperature, maximum short term temperature, and durability) as defined in EAD 330499 [2], section 2.2.2 and the reduction resulting from tests “sensitivity to sustained loads” according to EAD 330499 [2], Table 2.5 (i.e. reduction resulting from sustained load); however, the reduction resulting from tests “sensitivity to crack movements (F8)” according to EAD 330499 [2], Table 2.5 (i.e. reduction resulting from functioning in crack movement) may not be applied.

$\alpha_{N,C2}$ = reduction factor α as determined in Equation (3.48) for tests in which pull-out (bond) failure occurred;

$\beta_{cv,N,C2}$ = reduction factor β_{cv} accounting for large scatter as determined in Equation (3.49) for tests in which pull-out (bond) failure occurred.

3.3.2.2 Shear loading

Under shear loading only steel failure is considered in the evaluation. Pry-out and concrete edge failure are taken into account in the design provisions.

The characteristic steel shear resistance under seismic shear loading, $V_{Rk,s,C2}$, to be reported in the ETA is determined as follows:

$$V_{Rk,s,C2} = \alpha_{V,C2} \cdot \beta_{cv,V,C2} \cdot V_{Rk,0} \quad [\text{N}] \quad (3.69)$$

where

$V_{Rk,0}$ = [N] - characteristic resistance for steel failure given in the ETA for static loading;

$\alpha_{V,C2}$ = reduction factor α according to Equation (3.50);

$\beta_{cv,V,C2}$ = reduction factor β_{cv} accounting for large scatter according to Equation (3.51).

The characteristic resistance according to Equation (3.69) is valid for fasteners with the tested embedment depth and all larger embedment depths. If more than one embedment depth has been tested the characteristic resistance for an intermediate embedment depth may be determined by linear interpolation.

3.3.2.3 Displacements

The displacement values reported in the ETA are determined as given in Table 3.1.

Table 3.1 Displacement information

Displacement ¹⁾	Obtained from
$\delta_{N,eq}(DLS)$	Maximum of the mean value of displacements reported at $0,5 \cdot N/N_{max}$ or $0,5 \cdot N/N_{max,red}$ (as applicable) of C2.3 tests and the mean value of displacements reported at $\Delta w = 0,5$ mm of C2.5 tests.
$\delta_{N,eq}(ULS)$	Maximum of the mean value of displacements reported at $1,0 \cdot N/N_{max}$ or $1,0 \cdot N/N_{max,red}$ (as applicable) of C2.3 tests and the mean value of displacements reported at $\Delta w = 0,8$ mm of C2.5 tests.
$\delta_{V,eq}(DLS)$	Mean value of displacements reported at $0,5 \cdot V/V_{max}$ or $0,5 \cdot V/V_{max,red}$ (as applicable) of C2.4 tests.
$\delta_{V,eq}(ULS)$	Mean value of displacements reported at $1,0 \cdot V/V_{max}$ or $1,0 \cdot V/V_{max,red}$ (as applicable) of C2.4 tests.
¹⁾ DLS – Damage Limitation State (see EN 1998-1 [1], 2.2.1) ULS – Ultimate Limit State (see EN 1998-1 [1], 2.2.1)	

3.3.3 Partial safety factor $\gamma_{M,eq}$

The recommended partial safety factors under seismic action ($\gamma_{M,eq}$) are the same as for static loading.

3.3.4 Reduction factor α_{gap}

When an annular gap is present between fastener and fixture, the forces on the fasteners are amplified under shear loading due to a hammer effect on the fastener.

In the design approach of prEN 1992-4 [3] this effect is considered in the resistance of the fastening by introducing the reduction factor α_{gap} .

The factor α_{gap} is taken as equal to 0,5 for fasteners with hole clearance according to prEN 1992-4 Table 6.1 or equal to 1,0 if the product specifications and or the MPII require a proper filling of the annular gap and shear tests were carried out accordingly. The TAB shall check proper filling of the annular gap using the procedure given in the MPII for single fasteners as well as for groups of fasteners.

The value of α_{gap} is reported in the ETA as a product performance of the fastener as a function of the installation instructions.

When different performances are reported for installation with or without filling of the annular gap, consequently different values of α_{gap} have to be reported, respectively.

3.3.5 Content of the European Technical Assessment (ETA)

In the ETA the characteristic resistance for seismic performance category C1 or C2 for which the fastener has been assessed shall be reported. The design method for which the characteristic resistance applies shall be referred to.

An example of the information for characteristic values for design of fasteners under seismic action is shown in Table 3.2 and Table 3.3.

Table 3.2 Sample ETA seismic design information for seismic performance category C1

Fastener type		M...	...	M...
<i>(static design information)</i>				
		XX		XX
Seismic design information				
$N_{Rk,s,eq}$	[kN]	XX		XX
$\gamma_{Ms,eq}$ ¹⁾	[-]	XX		XX
$N_{Rk,p,eq}$ ($\tau_{Rk,C1}$ for bonded fasteners)	[kN] [N/mm ²]	XX		XX
$\gamma_{Mp,eq}$ ¹⁾	[-]	XX		XX
$V_{Rk,s,eq}$	[kN]	XX		XX
$\gamma_{Ms,eq}$ ¹⁾	[-]	XX		XX

¹⁾ The recommended partial safety factors under seismic action ($\gamma_{M,eq}$) are the same as for static loading.

Table 3.3 Sample ETA seismic design information for seismic performance category C2

Fastener type		M...	...	M...
<i>(static design information)</i>				
		XX		XX
Seismic design information				
$N_{Rk,s,eq}$ ²⁾	[kN]	XX		XX
$\gamma_{Ms,eq}$ ³⁾	[-]	XX		XX
$N_{Rk,p,eq}$ ($\tau_{Rk,eq}$ for bonded fasteners)	[kN] [N/mm ²]	XX		XX
$\gamma_{Mp,eq}$ ³⁾	[-]	XX		XX
$\delta_{N,eq}(DLS)$ ^{1) 2)}	[mm]	XX		XX
$\delta_{N,eq}(ULS)$ ¹⁾	[mm]	XX		XX
$V_{Rk,s,eq}$ ²⁾	[kN]	XX		XX
$\gamma_{Ms,eq}$ ³⁾	[-]	XX		XX
$\delta_{V,eq}(DLS)$ ^{1) 2)}	[mm]	XX		XX
$\delta_{V,eq}(ULS)$ ¹⁾	[mm]	XX		XX

DLS – Damage Limitation State (see EN 1998-1 [1], 2.2.1)

ULS – Ultimate Limit State (see EN 1998-1 [1], 2.2.1)

¹⁾ The listed displacements represent mean values.

²⁾ A smaller displacement may be required in the design provisions stated in section “Design of Anchorage”, e.g. in the case of displacement sensitive fastenings or “rigid” supports. The characteristic resistance associated with such smaller displacement may be determined by linear interpolation or proportional reduction.

³⁾ The recommended partial safety factors under seismic action ($\gamma_{M,eq}$) are the same as for static loading.

4 TEST REPORT

In addition to the minimum requirements listed in TR 048 [6], the report shall include at least the following information regarding the optional seismic tests:

Test member

- Reinforcement ratio
- Drawing of test member (including dimensions and position of reinforcement)

Test setup

- Loading device
- Type and positioning of crack measurement device(s)
- Particulars concerning restraining uplift in shear tests (where applicable)
- Verification method for fastener being located in crack over required length
- Method of crack creation
- Verification of approximately constant crack width throughout thickness of test member (where applicable)

Measured values

- Frequency of load cycling (where applicable)
- (hairline) crack width before and after fastener installation
- Minimum and maximum loads in each cycling sequence of load cycling tests
- Annular gap of clearance hole for shear tests
- Crack width for residual capacity tests
- Alternating shear load cycling procedure
- Reduced load levels and reason for reduction (where applicable)
- Location of failure (e.g. in shaft portion, threaded part, neck of fastener)
- Particulars of tests for category C1
 - Crack width Δw
 - Fastener displacement as a function of number of load cycles
 - Constant load levels N_{eq} , N_i and N_m on fastener and method of applying the load in test series C1.1
 - Constant load levels V_{eq} , V_i and V_m on fastener and method of applying the load in test series C1.2
- Particulars of tests for category C2
 - Maximum loads N_{max} and V_{max} in test series C2.3 and C2.4, respectively
 - Type of loading cycles (sinusoidal or triangular) in test series C2.3
 - Fastener displacements at minimum and maximum load and crack width as a function of number of load cycles in test series C2.3 and C2.4
 - Fastener displacements at 0,5 N/N_{max} and 1,0 N/N_{max} in test series C2.3
 - Fastener displacements at 0,5 V/V_{max} and 1,0 V/V_{max} in test series C2.4
 - Constant load levels N_{w1} and N_{w2} on fastener and method of applying the load in test series C2.5
 - Frequency of crack cycling in test series C2.5
 - Initial compression force C_{ini} in test series C2.5
 - Compression force C_{test} in test series C2.5
 - Fastener displacements at minimum and maximum crack width and applied tension load as a function of number of crack cycles in test series C2.5
 - Fastener displacements at the end of crack cycling at level $\Delta w = 0,5$ mm and $\Delta w = 0,8$ mm in test series C2.5.

5 ABBREVIATION AND NOTATION

5.1 Abbreviation

- C1, C2 = seismic performance categories for prequalification of fasteners
 cv = coefficient of variation
 DLS = Damage Limitation State (see EN 1998-1 [1], 2.2.1)
 MPII = Manufacturer printed installation instructions
 ULS = Ultimate Limit State (see EN 1998-1 [1], 2.2.1)

5.2 Notation

- A = percentage elongation after fracture
 A_g = cross section area of test member
 a_s = distance between fastener and nearest reinforcement bar (see Figure 2.1)
 A_s = effective stressed cross section area of steel element
 A_5 = Fracture elongation
 b = width of test member (see Figure 2.1 and Figure 2.2)
 c = edge distance (see Figure 2.1)
 C_{ini} = initial centric compression force on concrete test member in test series C2.5
 C_{test} = centric compression force on concrete test member during crack cycling in test series C2.5
 $d_{cut,m}$ = medium cutting diameter of hard metal hammer-drill bits
 d = diameter of fastener
 d_s = diameter of the reinforcing bar (see Figure 2.2)
 $f_{c,i}$ = mean compressive strength of concrete in test series i
 f_u = mean ultimate steel strength
 f_{uk} = characteristic steel ultimate tensile strength (nominal value)
 F = force
 h = thickness of test member (see Figure 2.1)
 h_{ef} = effective embedment depth of fastener
 h_{iz} = interaction zone between fastener and concrete
 h_{ltz} = effective load transfer zone of fasteners
 h_{min} = minimum thickness of concrete member
 ℓ_b = bond length (see Figure 2.2)
 ℓ_{db} = de-bonding length (see Figure 2.2)
 n = normalization factor to account for concrete strength (EAD 330232 [1] and EAD 330499 [2])
 n_{cyc} = number of cycles
 N = tension load
 N_{eq} = maximum tension load to be applied in the seismic tension test series C1.1
 N_i = intermediate tension load to be applied in the seismic tension test series C1.1
 N_m = minimum tension load to be applied in the seismic tension test series C1.1
 N_{max} = maximum tension load to be applied in the pulsating tension load test series C2.3
 N_{min} = lower bound of tension load pulses in test series C2.3
 $N_{Rk,c}$ = characteristic concrete cone resistance in cracked concrete given in the ETA for static loading
 $N_{Rk,p}$ = characteristic tension pull-out resistance given in the ETA for static loading
 $N_{Rk,s}$ = characteristic steel tension resistance given in the ETA for static loading
 $N_{Rk,p,Cx}$ = characteristic tension pull-out resistance under seismic action reported in the ETA for seismic performance category C1, C2
 $N_{Rk,s,Cx}$ = characteristic steel tension resistance under seismic action reported in the ETA for seismic performance category C1, C2

$N_{u,m}$	= mean tension capacity
N_{w1}	= tension load to be applied in the serviceability range ($\Delta w \leq 0,5$ mm) of the varying crack width test series C2.5
N_{w2}	= tension load to be applied in the suitability range ($0,5$ mm $< \Delta w \leq 0,8$ mm) of the varying crack width test series C2.5
t	= time
t_{fix}	= thickness of fixture
T	= torque
T_{inst}	= installation torque
V	= shear load
V_{eq}	= maximum shear load to be applied in the seismic shear test series C1.2
V_i	= intermediate shear load to be applied in the seismic shear test series C1.2
V_m	= minimum shear load to be applied in the seismic shear test series C1.2
V_{max}	= maximum shear load to be applied in the alternating shear load test series C2.4
$V_{Rk,s}$	= characteristic steel shear resistance given in the ETA for static loading
$V_{Rk,s,Cx}$	= characteristic steel shear resistance under seismic action reported in the ETA for seismic performance category C1, C2
$V_{u,m}$	= mean shear capacity
w_{ini}	= initial crack width after applying N_{w1} in test series C2.5
Δw	= crack width, which is additive to the width of the hairline crack after fastener installation but before fastener loading
Δw_{hef}	= crack width at embedment depth h_{ef}
Δw_{top}	= crack width at the top side of the test member in which the fastener is installed
Δw_{bot}	= crack width at the bottom side of the test member in which the fastener is installed
$\alpha_{C2,x}$	= reduction factor resulting from assessment of test series C2.x
$\alpha_{N,Cx}$	= seismic reduction factor for tension resistance for seismic performance category C1, C2
$\alpha_{V,Cx}$	= seismic reduction factor for shear resistance for seismic performance category C1, C2
$\beta_{cv,C2,x}$	= reduction factor resulting from large coefficients of variation in test series C2.x
$\beta_{cv,N}$	= reduction factor for tension resistance resulting from large coefficients of variation
$\beta_{cv,V}$	= reduction factor for shear resistance resulting from large coefficients of variation
$\delta(N)$	= displacement of the fastener measured at tension load value N
$\delta_{N,lim}$	= displacement limit corresponding to excessive displacement of the fastener in the assessment of the results of test series C2.3 and C2.5
$\delta_{N,eq}$	= displacement of the fastener associated with the seismic test series C2.3 and C2.5
$\delta_{V,lim}$	= displacement limit corresponding to excessive displacement of the fastener in the assessment of the results of test series C2.4
$\delta_{V,eq}$	= displacement of the fastener associated with the seismic test series C2.4
$\gamma_{M,eq}$	= partial factor for material under seismic loading
$\gamma_{Mp,eq}$	= partial factor for pull-out failure mode (combined pull-out and concrete cone failure mode for bonded fasteners) under seismic loading
$\gamma_{Ms,eq}$	= partial factor for steel under seismic loading
$\tau_{Rk,Cx}$	= characteristic seismic bond resistance reported in the ETA for seismic performance category C1, C2

5.3 Definitions

non-structural element	= Building element, the failure of which results in medium consequence for loss of human life and considerable economic, social or environmental consequences, but does not result in the failure of the structure or part of the structure; examples: façade element, piping (PM)
structural element	= Building element, the failure of which may result in the failure of the

structure or part of the structure; examples: column, beam, slab

6 REFERENCES

- [1] EAD 330232-00-0601: Mechanical fasteners for use in concrete
- [2] EAD 330499-00-0601: Bonded fasteners for use in concrete
- [3] prEN 1992-4:2015 Eurocode 2: Design of concrete structures – Part 4: Design of fastenings for use in concrete
- [4] EN 1998-1:2004 + AC 2009, Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings.
- [5] EOTA TR 045: Design of Metal Anchors for Use in Concrete Under Seismic Actions, Edition February 2013
- [6] EOTA TR 048:2016-08 Details of tests for post-installed fasteners in concrete
- [7] ISO 898-1, Mechanical properties of fasteners made of steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread