Post-installed anchors prequalification for the seismic environment

Sara Cattaneo – Dept. ABC

Milan, 27th October 2016

Outline

- Fastening: general aspects
- Fastening under seismic action:
  main parameters involved

- European anchors prequalification:
  tests and assessment
- Conclusions

Fastening classifications

Post-installed

Mechanical

Bonded

Rebar

Cast-in

Headed

Anchor channels

Structural

Non-structural

Structural fastening

NTC (Italian Standard) § 11 → R1 – UE 305/2011

‘**construction product’** means any product or kit which is produced and placed on the market for incorporation in a permanent manner in construction works or parts thereof and the performance of which has an effect on the performance of the construction works with respect to the basic requirements for construction works;

‘kit’ means a construction product placed on the market by a single manufacturer as a set of at least two separate components that need to be put together to be incorporated in the construction works;

Product for structural use means any material or construction product which satisfy the basic requirement R1 – **Mechanical resistance and stability**

Basic requirements for construction works - UE 305/2011

Construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and **safety** of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life.

1. Mechanical resistance and stability

The construction works must be designed and built in such a way that the loadings that are liable to act on them during their constructions and use will not lead to any of the following:

(a) collapse of the whole or part of the work;

(b) major deformations to an inadmissible degree;

(c) damage to other parts of the construction works or to fittings or installed equipment as a result of major deformation of the load-bearing construction;

(d) damage by an event to an extent disproportionate to the original cause.

Basic requirements for construction works - UE 305/2011

2. Safety in case of fire

3. Hygiene, health and the environment

4. Safety and accessibility in use

5. Protection against noise

6. Energy economy and heat retention

7. Sustainable use of natural resources

Basic requirements for post-installed fasteners - EAD

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

No	Essential characteristic	Assessment methods	Type of expression of product performance *(level, class, description)*
	Basic Works Requirement 1: Mechanical resistance and stability		
	Characteristic resistance to tension load (static and quasi-static loading)		
1	Resistance to steel failure	2.2.1	$N_{Rk,s}$ [kN]
2	Resistance to pull-out failure	2.2.2	$N_{Rk,p}$ [kN]
3	Resistance to concrete cone failure	2.2.3	$k_{cr,N}$, $k_{ucr,N}$ [-], $c_{cr,N}$ [mm]
4	Robustness	2.2.4	γ_{inst} [-]
5	Minimum edge distance and spacing	2.2.5	c_{min}, s_{min}, h_{min} [mm]
6	Edge distance to prevent splitting under load	2.2.6	$N_{Rk,sp}$ [kN], $c_{cr,sp}$ [mm]
	Characteristic resistance to shear load (static and quasi-static loading)		
7	Resistance to steel failure under shear load	2.2.7	$V_{Rk,s}$ [kN], $M^0_{Rk,s}$ [Nm], k_7 [-]
8	Resistance to pry-out failure	2.2.8	k_8 [-]
9	Displacements under static and quasi-static loading	2.2.9	δ_{N0}, $\delta_{N\infty}$, δ_{V0}, $\delta_{V\infty}$ [mm]
10	Durability	2.2.10	Description
	Characteristic resistance and displacements for seismic performance categories C1 or C2 (optional)		
11	Resistance to steel failure	TR 049	$N_{Rk,s,eq}$, $V_{Rk,s,eq}$ [kN]
12	Resistance to pull-out	TR 049	$N_{Rk,p,eq}$ [kN]
13	Fracture elongation	TR 049	A_5 [%]
14	Factor for annular gap	TR 049	α_{gap} [-],
15	Displacements	TR 049	$\delta_{N,eq}$, $\delta_{V,eq}$ [mm]
	Basic Works Requirement 2: Safety in case of fire		
16	Reaction to fire	-	Class (A1) According EN 13501-1 [19]
	Resistance to fire (optional)		
17	Fire resistance to steel failure (tension load)	2.2.11	$N_{Rk,s,fi}$ [kN]
18	Fire resistance to pull-out failure (tension load)	2.2.12	$N_{Rk,p,fi}$ [kN]
19	Fire resistance to steel failure (shear load)	2.2.13	$V_{Rk,s,fi}$ [kN], $M^0_{Rk,s,fi}$ [Nm]

	Characteristic resistance and displacements for seismic performance categories C1 or C2 (optional)		
11	Resistance to steel failure	TR 049	$N_{Rk,s,eq}$, $V_{Rk,s,eq}$ [kN]
12	Resistance to pull-out		$N_{Rk,p,eq}$ [kN]
13	Fracture elongation		A_5 [%]
14	Factor for annular gap		α_{gap} [-],
15	Displacements		$\delta_{N,eq}$, $\delta_{V,eq}$ [mm]

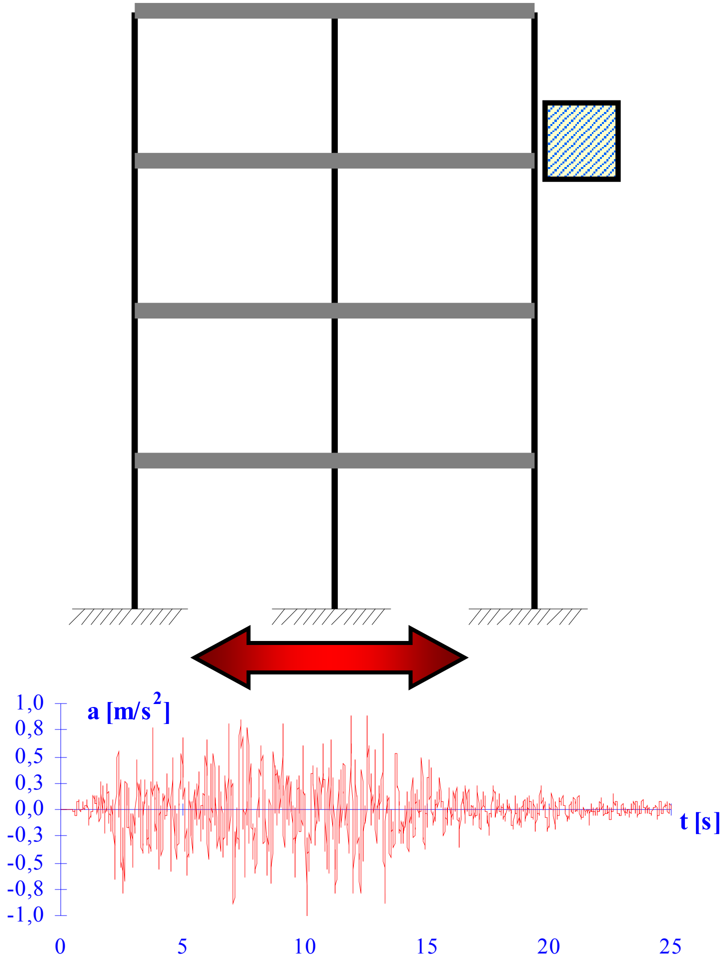
Italian Code NTC 20??

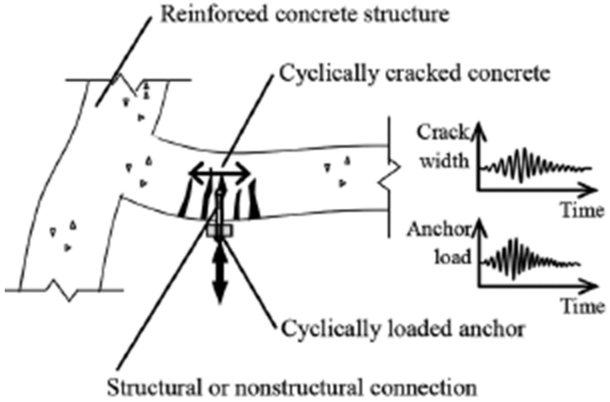
11.4.1. ANCORANTI PER USO STRUTTURALE

Per la qualificazione degli ancoranti per uso strutturale si applica quanto specificato al punto C) del § 11.1, sulla base della Linea guida di benestare tecnico europeo ETAG 001, la quale vale anche per le modalità di esecuzione delle prove di accettazione. Con riferimento alla tabella 1.1 del paragrafo 1.2 dell'Annesso E della citata Linea guida ETAG 001, riguardante le categorie minime raccomandate per la qualificazione degli ancoranti in presenza di azioni sismiche, per tutte le classi d'uso di cui al punto 2.4.2 delle presenti norme, la categoria di prestazione da soddisfare è la C2, definita nella predetta Linea guida.

Fastening for structural use: C2 category

Fastening under seismic action





Anchors behavior is affected by :

Applied action (amplitude, frequency content and duration of the eartquake – direction of application)

Building characteristics

(soil-structure interaction structural stiffness; mass…) → state of the surrounding concrete (cracked….)

Anchor characteristics

Fastening under seismic action: Test protocol

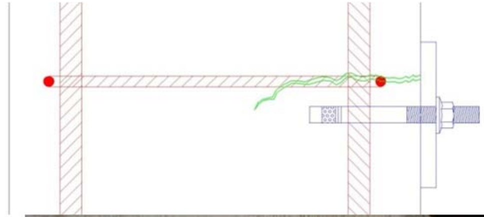
Main parameters to be considered:

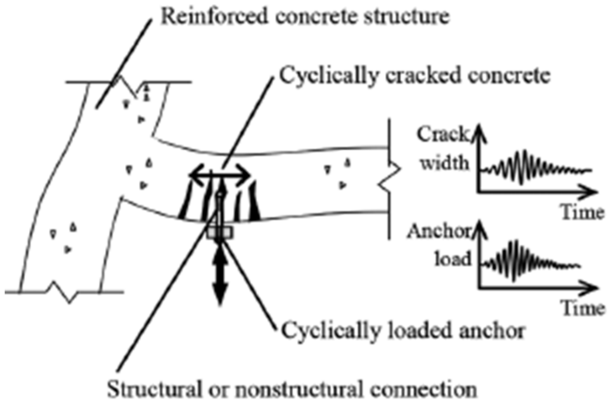
Applied action: Dynamic effect, Load pattern, Crack width

Building characteristics (structural stiffness; reinforcement; mass…)

Anchor characteristics :

- Steel type, steel grade and production method
- Embedment depth
- Head configuration
- Drilling method (core)
- For bonded anchor: type of insert



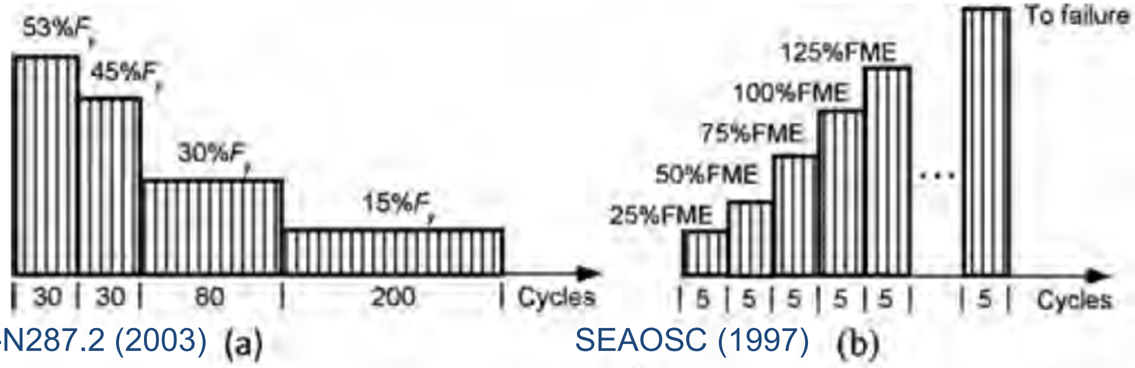


To be defined:

- Load history
- Crack width
- …

Seismic anchor qualification: some protocols

Frequency: 5Hz
Uncracked concrete
Monotonic test
(Residual capacity)



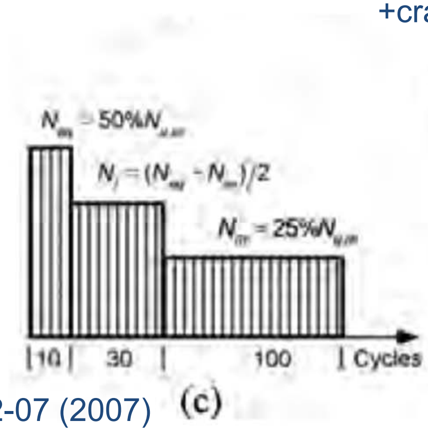
CSA-N287.2 (2003) (a)

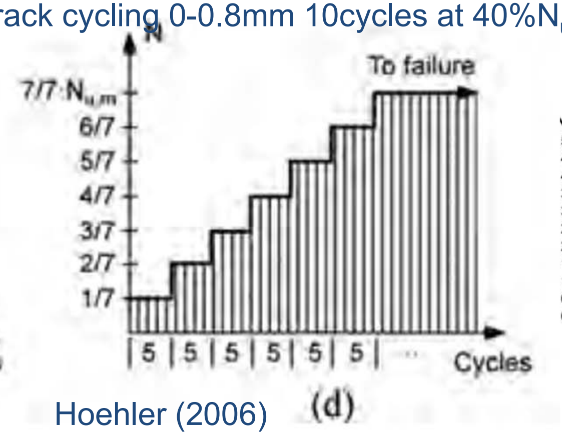
SEAOSC (1997) (b)

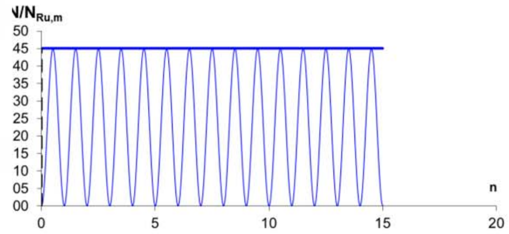
Frequency: 0.1-2Hz Crack width 0.8mm
+crack cycling 0-0.8mm 10cycles at 40%N_{um}

Monotonic test
(Residual capacity)
+ crack cycling 1.0-1.5mm
10cycles at 45%N_{um}

Frequency: 0.1-2Hz
Crack width 0.5mm
Monotonic test
(Residual capacity)







ACI355.2-07 (2007) (c)

Hoehler (2006) (d)

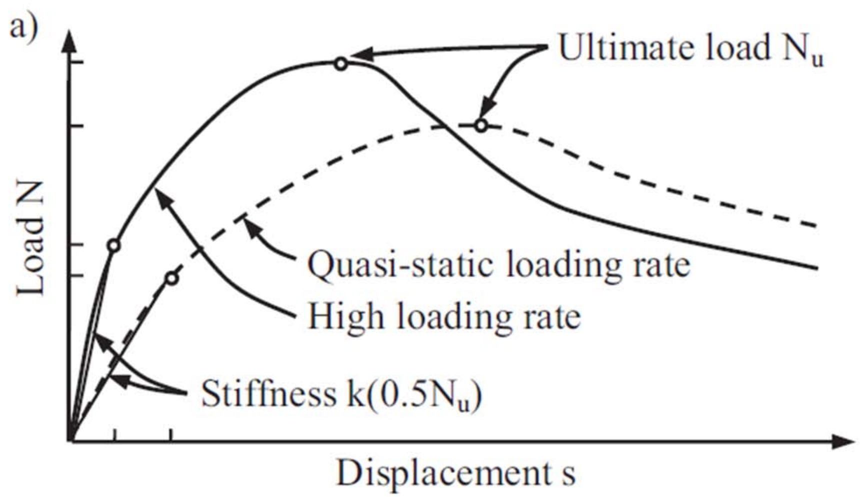
DIBT (1998) (e)

Main differences between protocols:

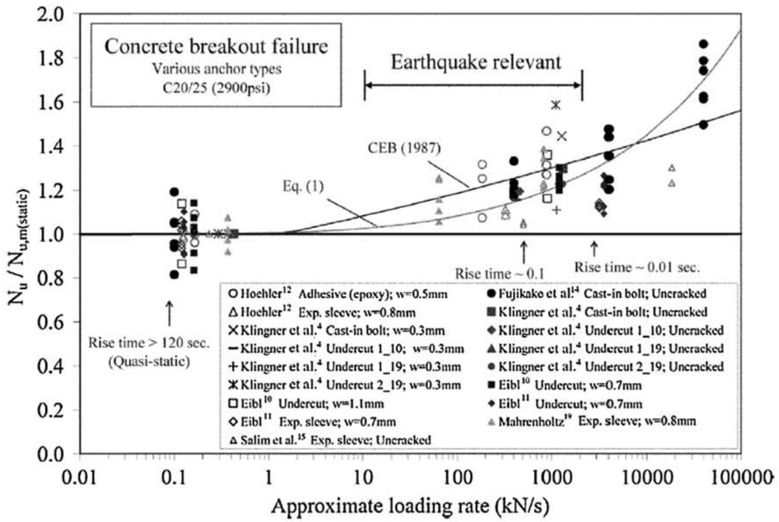
Loading rate
Load pattern: Increasing/decreasing – load level
Crack width
Crack cycling

Applied action: loading rate

Dynamic effect ⟶ Loading rate



Mahrenholtz & Eligehausen (2013)

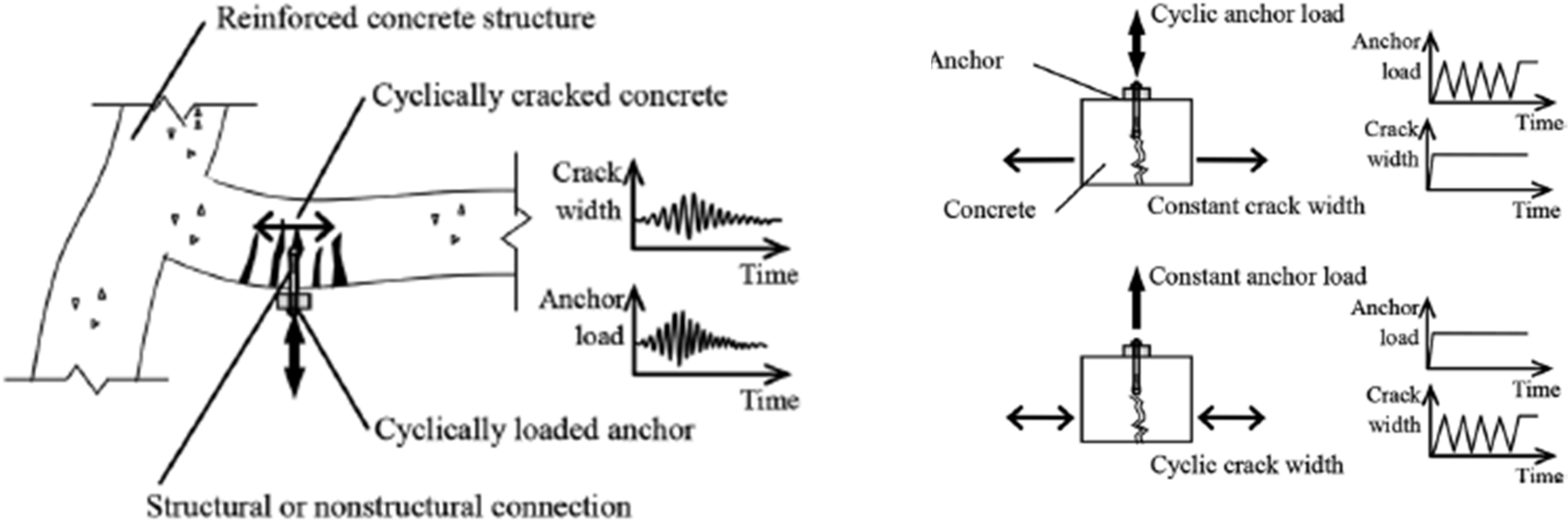


Hoehler et al. (2011)

⬇

Low loading rate are safe side

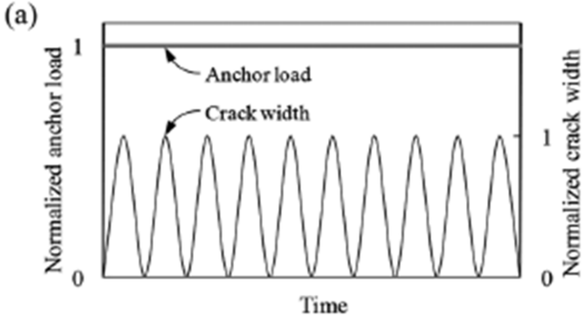
Applied action: load pattern



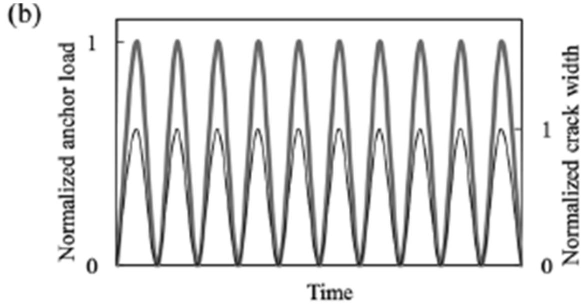
Mahrenholz (2013)

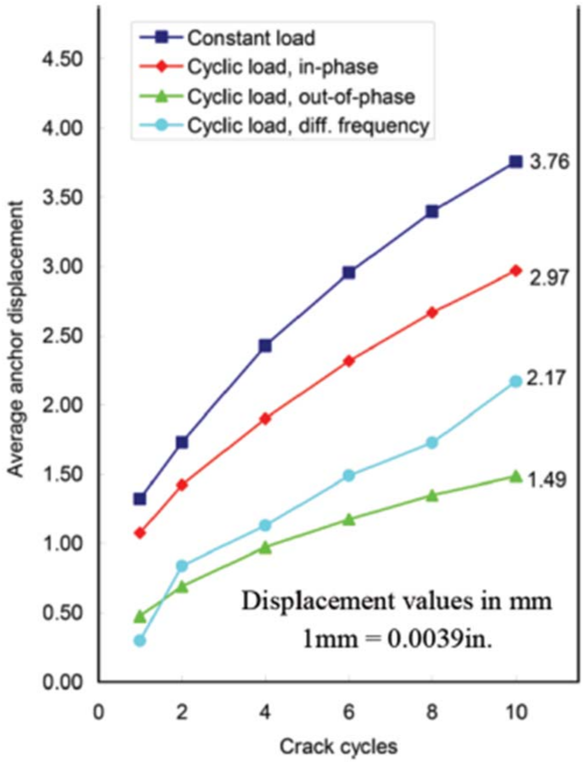
Applied action: load pattern

Cyclic crack and constant load

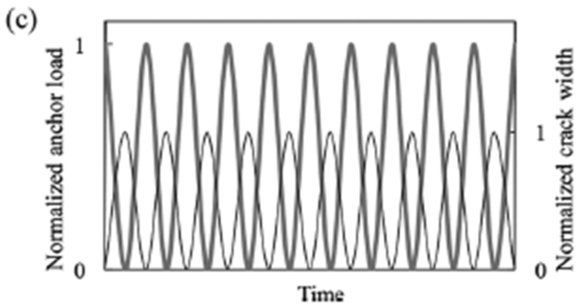


Cyclic crack and load, in phase
(Structural connections)

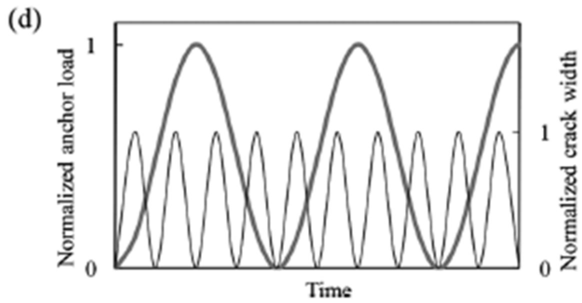




Cyclic crack and load, out of phase
(Non-Structural connections)



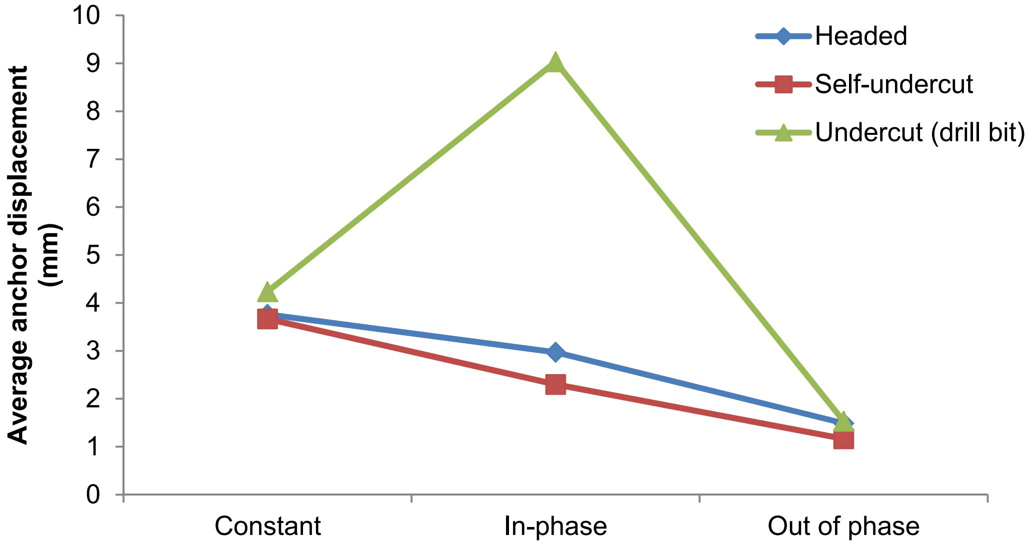
Cyclic crack and load,
different frequencies
(Non-Structural connections)



Headed bolt, max crack width 0.5mm

Mahrenholz (2013)
Mahrenholz& Eligehausen (2016)

Applied action: load pattern

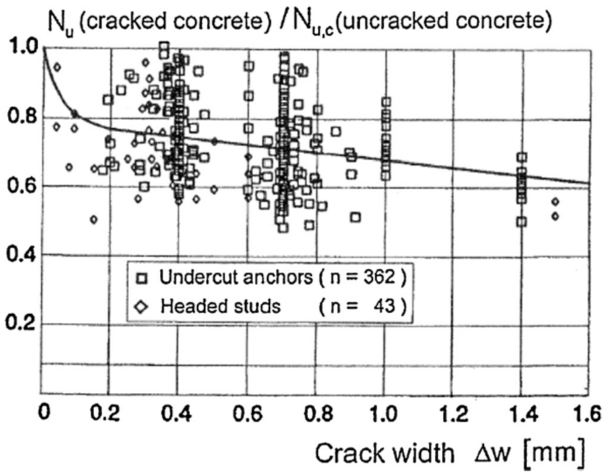


The in-phase pattern is more realistic?

Mahrenholz (2013)
Mahrenholz & Eligehausen (2016)
Sharma et al. (2016)

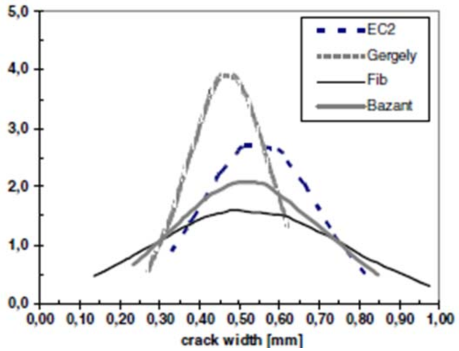
Crack width

Crack width: uncracked – cracked 0.3mm, 0.5mm, 0.8mm,1mm,1.5mm –compressed

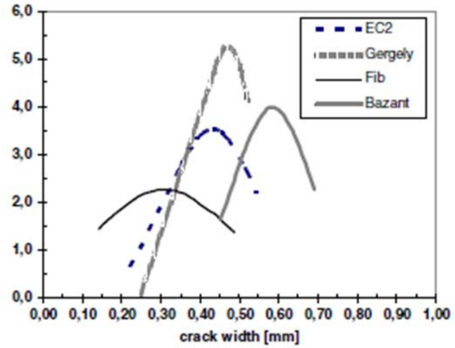


(Eligehausen & Balogh 2005)

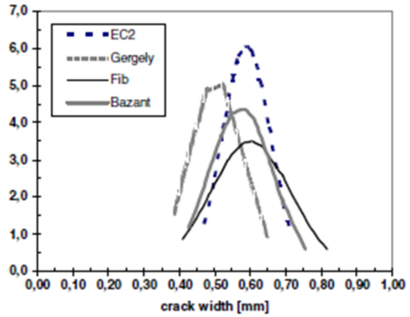
Probability density vs Crack width



Beam-column low ρ_s



Beam high ρ_s



Reinforced concrete walls (Nuti et al. 2008)

Crack width

w=0.8mm is generally accepted as the upper-bound crack width at the onset of yielding of reinforcement just outside the plastic hinge zone

According ACI355 and ETAG001 the maximum crack width under service contition is w=0.5mm
According to EC2 the ratio between yield stress/service stress =1.6
Since the crack width increase linearly up to yielding, the crack width at the onset of yielding results:

w =1.6x0.5 mm =0.8mm

Several studies:
Wood et al.(2009) $w_{max} \rightarrow$ 0.4÷0.6mm
Hoehler (2006) $w_{max} \rightarrow$ 0.4÷1mm

Test protocol: a comprehensive approach

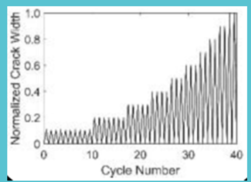
- Earthquake demand → Probabilistic Seismic Hazard Analysis (PSHA)
- Non-linear structural response
- Effect of the building response on the anchorage system

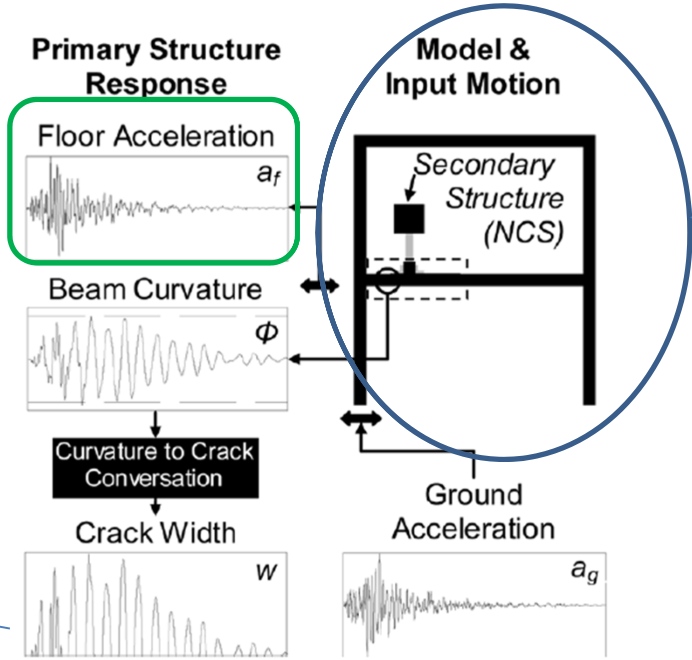
Main researches:
Eligehausen R. Hoehler M, Hutchinson T. Mahrenholtz P., Wood R.

Test protocol: a comprehensive approach

Methodology to obtain crack width and floor acceleration time histories

Crack width protocol

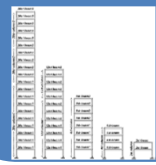


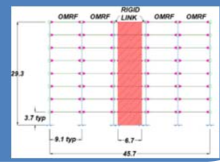


Building simulation: Non linear

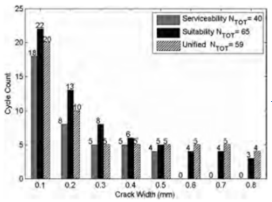
MRF

MRF +shear walls



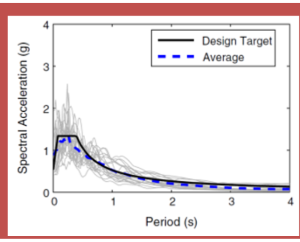


Response statistics



Ground motion selection (Los Angeles, Cittanova)

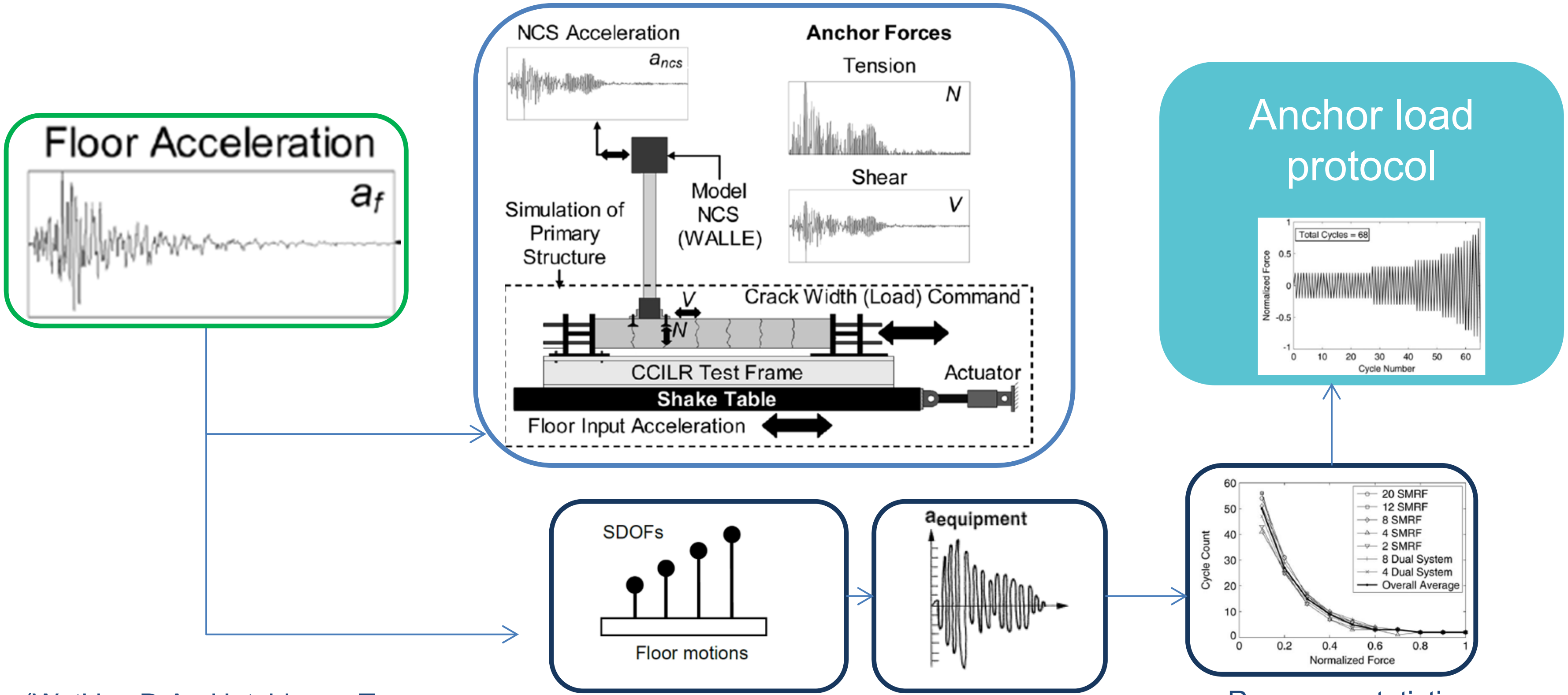
Ground motion Scaling (21)



(Watkins D.A., Hutchinson T, Hoehler M., 2012)

Test protocol: a comprehensive approach

Experimental simulation of primary structure and anchored nonstructural component in laboratory



Numerical analyses

Response statistics

(Watkins D.A., Hutchinson T, Hoehler M., 2012)

Test protocol: a comprehensive approach

Eurocode 8:

Ultimate Limit State (ULS):

Reliable behavior and adequate residual load capacity in extreme events Δw=0.8mm

Target load level: Maximum load in cycling tests corresponds to the characteristic monotonic strength (reference tests in cracked concrete Δw=0.8mm)
By assuming a coefficient of variation v=15% for concrete failure modes and 10% for steel failure it results: $N_{max}= 0.75N_{u,cr,m}$ $V_{max}= 0.85N_{u,cr,m}$
Sustained load during crack cycling $N_w= N_{max} / \gamma_M = 0.5N_{u,cr,m}$

Damage Limitation State (DLS):

Displacement behavior under service conditions Δw=0.5mm

Note: Crack width has a limited influence on shear tests: Δw=0.8mm
γ_F = 1.4 γ_M =1.5   reduction of about 50% of the target load
Sustained load during crack cycling $N_w= 0.8N_{max} / \gamma_M = 0.4N_{u,cr,m}$

Test protocol: a comprehensive approach

Summing up:

Monotonic Tension and shear tests in crack width Δw=0.8mm → $N_{u,cr,m}$, $V_{u,cr,m}$

Test	DLS		ULS	
	Crack width [mm]	Anchor load	Crack width [mm]	Anchor load
Cyclic tension	0.5	$N_{max}= 0.375N_{u,cr,m}$	0.8	$N_{max}= 0.75N_{u,cr,m}$
Cyclic shear	0.8	$V_{max}= 0.425N_{u,cr,m}$	0.8	$N_{max}= 0.85N_{u,cr,m}$
Cyclic crack	0.5	$N_{w}= 0.4N_{u,cr,m}$	0.8	$N_{max}= 0.5N_{u,cr,m}$

Two levels of testing → Unified Protocol

ETAG001

METAL ANCHORS FOR USE IN CONCRETE

ER1 + ER4:

- Part 1: Anchors in general — 1997 – 07/02-11/06-04/13 (Parts 1–2)
- Part 2: Torque-controlled expansion anchors
- Part 3: Undercut anchors — 1997 – 07/02-10/10-04/13
- Part 4: Deformation controlled expansion anchors — 1998 – 07/02-11/06-04/13
- Part 5: Bonded anchors **ER3** — 2002 – 11/06-02/08-04/13
- Part 6: Anchors for multiple use for non-structural applications 2003 – 08/06-01/11

ER4:

- Annex A: Details of tests 1997-10/01-11/06-04/13
- Annex B: Tests for admissible service conditions – Detailed information 1997-10/01-11/06
- Annex C: Design methods for anchorages 1997-10/01-11/06-08/10

- Annex E **ASSESSMENT OF METAL ANCHORS UNDER SEISMIC ACTION 2013**

+ update with WG “Progress file”

Technical Report

TR018 Assessment of torque-controlled bonded anchors (2003)
TR020 Evaluation of Anchorages in Concrete concerning Resistance to Fire (2004)
TR023 Assessment of post-installed rebar connections (2006)
TR029 Design of Bonded Anchors (2007-2010)
TR045 Design of Metal Anchors For Use In Concrete Under Seismic Actions (2013)
TR047 Calculation method for the performance of anchor channels
TR050 Anchor channels under fatigue loading

EAD – European Assessment Document + TR

EAD 330232-00-0601 - MECHANICAL FASTENERS FOR USE IN CONCRETE

EAD 330499-00-0601 - BONDED FASTENERS FOR USE IN CONCRETE

TR048 Details of tests for post-installed fasteners in concrete

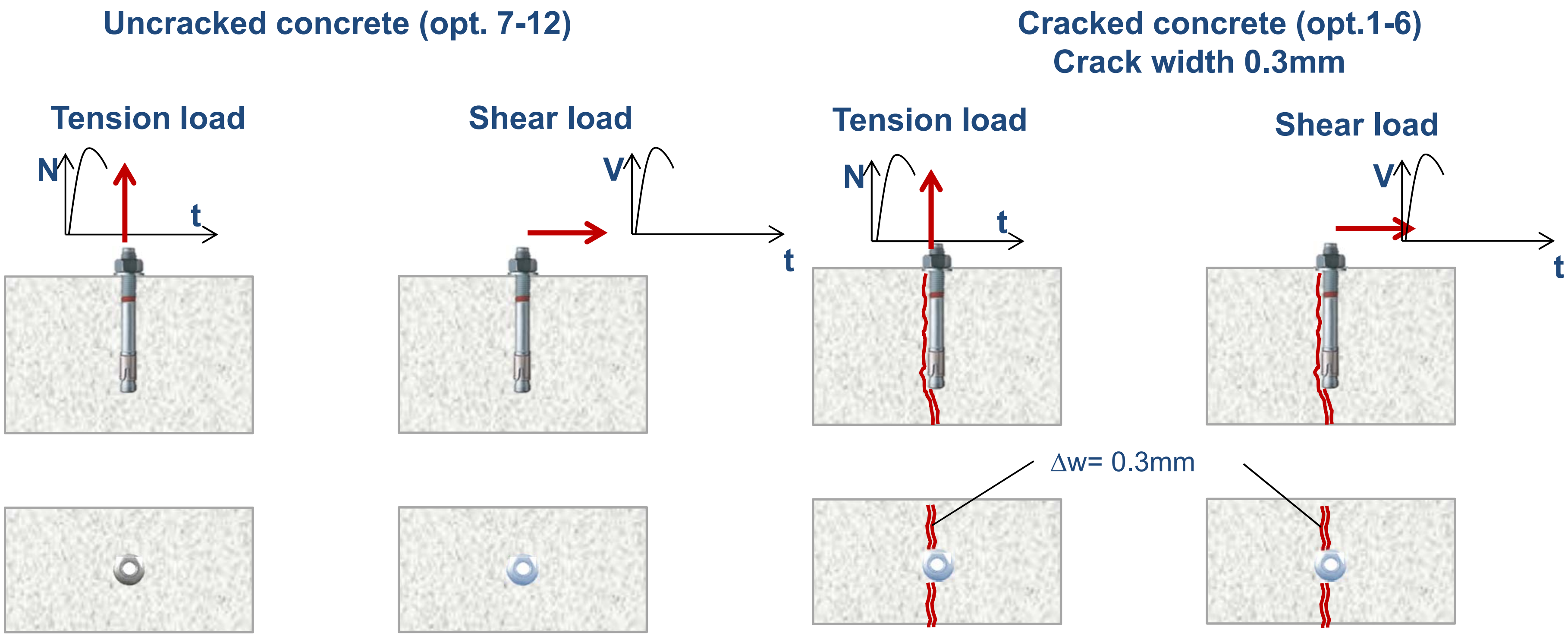
TR049 Post-installed fasteners in concrete under seismic action

Fastening qualification- Europe vs USA

	Europe	USA
Actions	EN 1998-1:2004	ASCE 7
Design Strength	EOTA TR045 pr EN 1992-4	ACI 318 Appendix D AC308
Technical data	ETA	ICC-ESR
Qualification Mechanical/Bonded	ETAG001+ Annex A / E (EAD + TR048+TR049)	ACI355.2 +ACI355.4 ICC-ES AC193/AC308
Anchor channels	EAD only fatigue	AC232
	seismic categories C1,C2	One seismic category

Fastening qualification- Europe

Static



Sensitivity to crack movement (1000 Cycles)
Np ≅ const   Δw= 0.1 ÷0.3mm
Frequency ≅ 0.2Hz

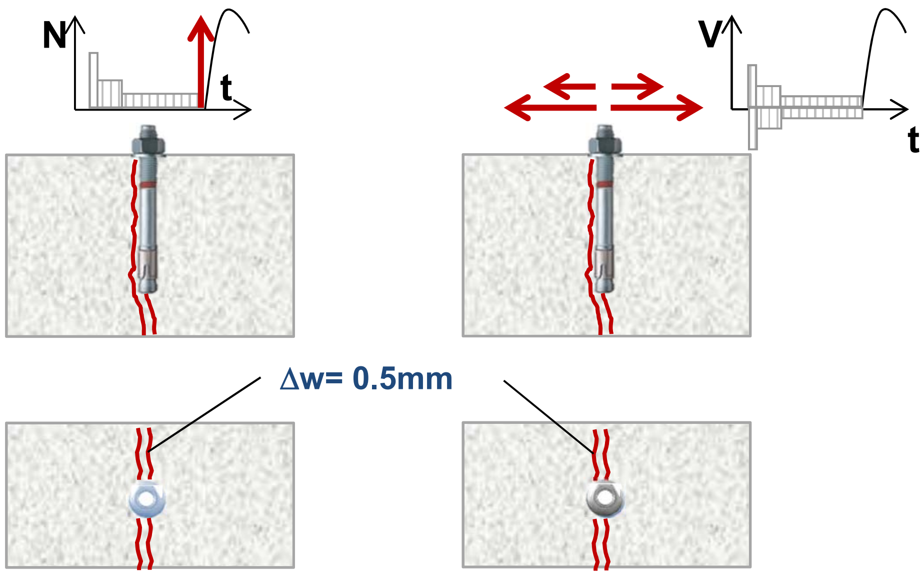
European approach: two seismic categories C1 and C2

C1	C2
Forces	Forces + Displacement
Crack width Δw = 0.5 mm	Crack width Δw = 0.8 mm
Reference tests	Reference tests
Pulsating tension load	Pulsating tension load
Alternating shear load	Alternating shear load
	Crack cycling

C1 category

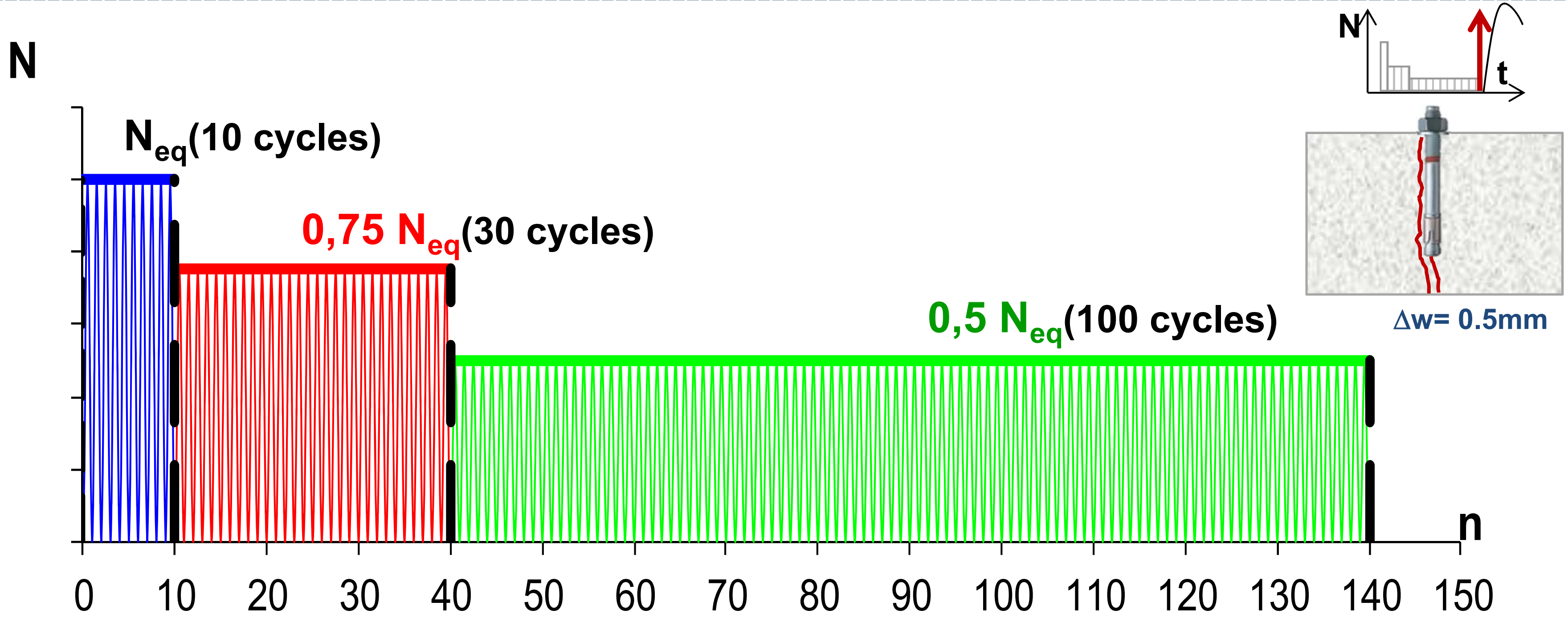
C1.1 Pulsating Tension load

C.1.2 Alternating Shear load



- Cracked concrete (0.5 mm)
- Frequency = 0.1÷2 Hz

C1.1 – Pulsating tension load

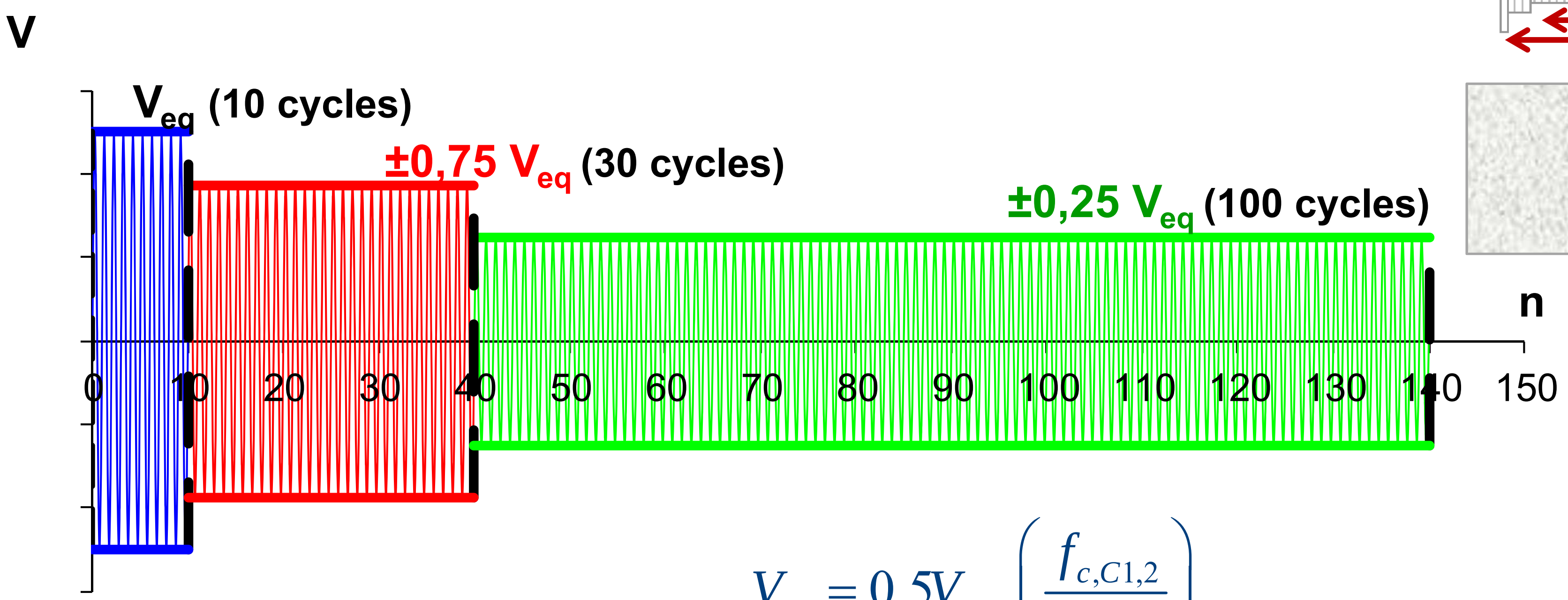


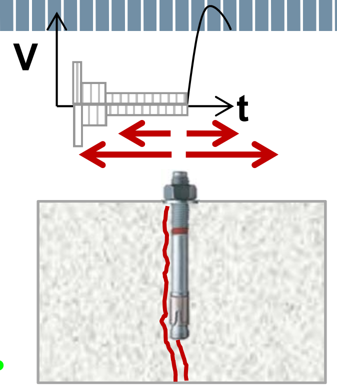
$$N_{eq} = 0.5 N_{u,m} \left(\frac{f_{c,C1,1}}{f_{c,3}} \right)^n$$

$N_{u,m}$ mean characteristic resistance for tension loading not influenced by edge and spacing effects (A3 – C20/25 Δw=0.3mm)

After pulsating tension load residual monotonic test

C1.2 – Alternating shear load





$$V_{eq} = 0.5 V_{u,m} \left(\frac{f_{c,C1,2}}{f_{u,5}} \right)$$

- Load along the crack direction
- $V_{u,m}$ mean shear capacity from test for characteristic resistance to steel failure under shear in non- cracked concrete or $V_{eq} = 0.35 A_s f_{uk}$
- After alternating shear load residual monotonic test

C1.1 assessment

No failure during cycling $N_{u,mC1.1} \geq 1.6 N_{eq}$ $\alpha_{N,C1} = 1.0$

If the fastener fails to fulfil previous requirements repeat the tests at a reduced load level $N_{eq,red}$

$$N_{u,mC1.1} \geq 1.6 N_{red,eq} \qquad \alpha_{N,C1} = \frac{N_{red,eq}}{N_{eq}}$$

$$\Rightarrow \quad N_{u,mC1.1} \geq 1.6 \cdot 0.5 N_{u,m} = 0.8 N_{u,m}$$

C1.2 assessment

No failure during cycling $V_{u,mC1.2} \geq 1.6 V_{eq}$ $\alpha_{V,C1} = 1.0$

If the fastener fails to fulfil previous requirements is not fullfilled repeat the tests at a reduced load level $V_{eq,red}$

$$V_{u,mC1.1} \geq 1.6 V_{red,eq} \qquad \alpha_{V,C1} = \frac{V_{red,eq}}{V_{eq}}$$

$$\Rightarrow \quad V_{u,mC1.1} \geq 1.6 \cdot 0.5 V_{u,m} = 0.8 V_{u,m}$$

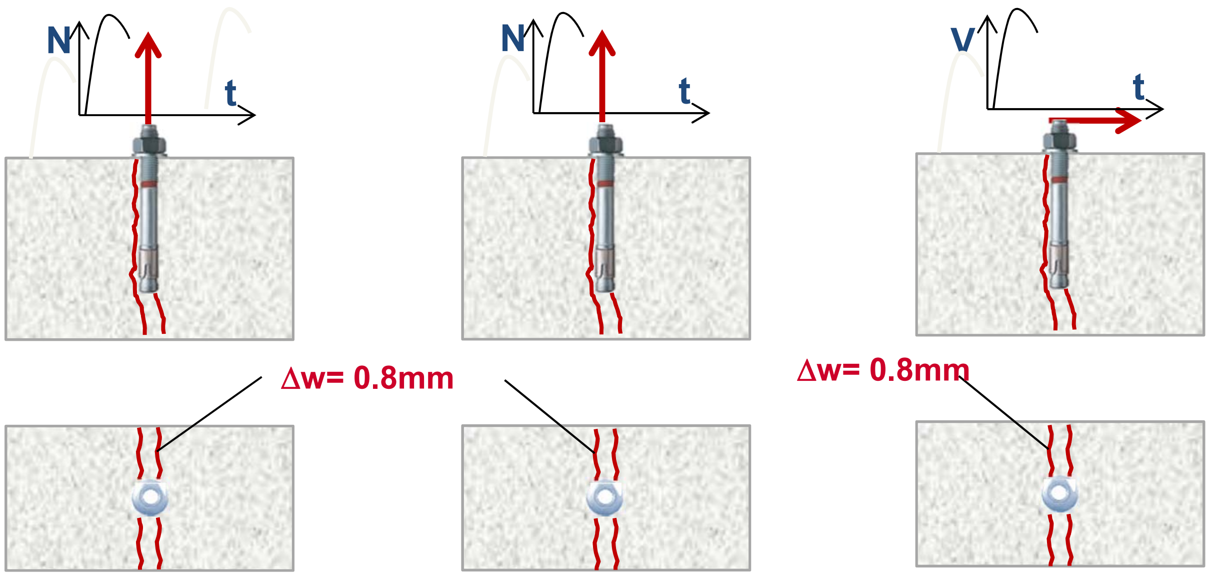
C2 category

- Monotonic load
- Cracked concrete (0.8 mm)

C2.1a Reference
Tension tests C20/25

C.2.1b Reference
Tension tests C50/60

C.2. 2 Reference
Shear tests*

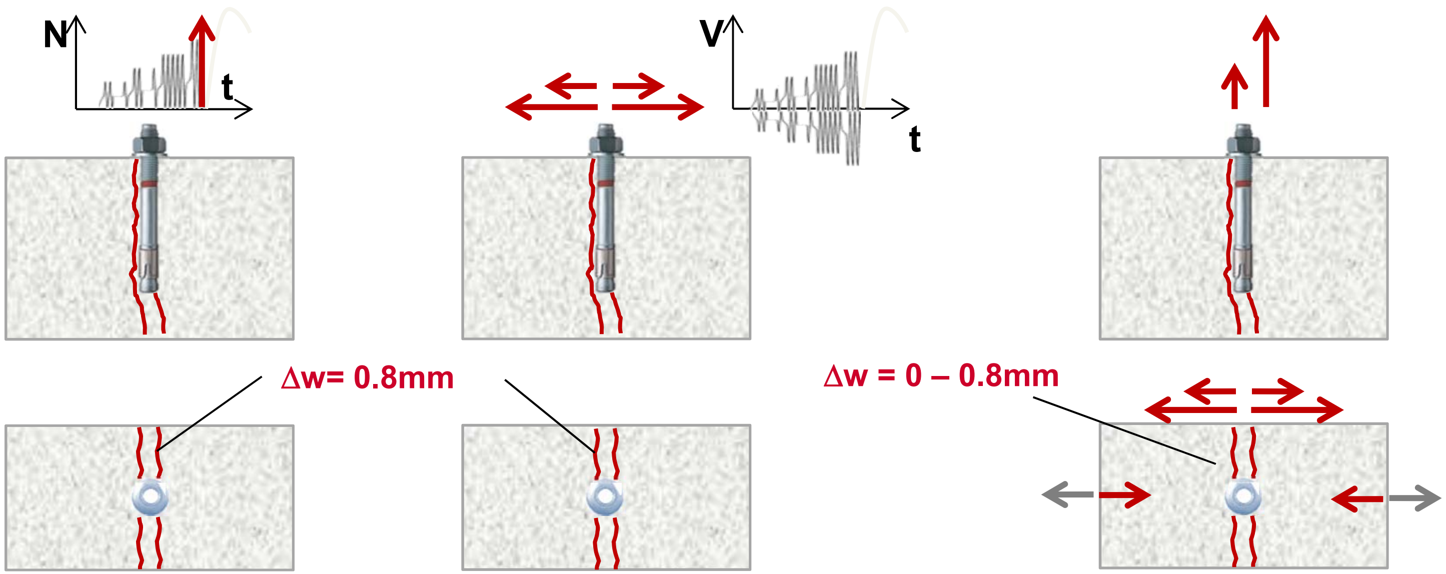


C2 category

C2.3 Pulsating Tension load

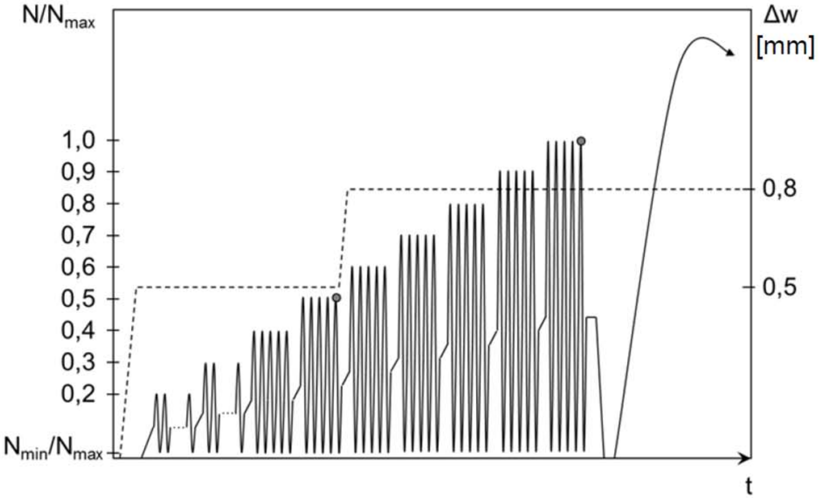
C.2.4 Alternating Shear load

C.2.5 Tension load and varying crack width



- Stepwise Increasing load
- Cracked concrete (0.8 mm)
- Frequency = 0.1÷2 Hz

C2.3 Functioning under Pulsating Tension load



— fastener load
--- crack width
∘ assessment of displacement

N … load
Δw … crack width
t … time

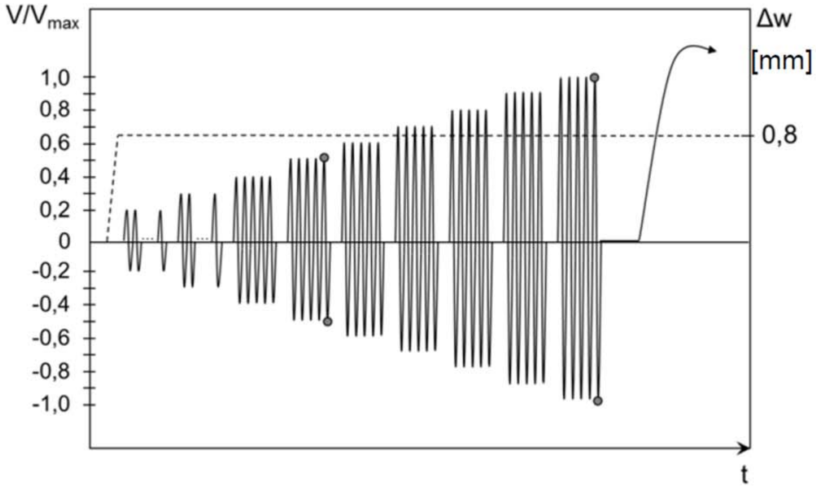
$$N_{\max} = 0.75 N_{u,m,C2.1a} \left(\frac{f_{c,C2,3}}{f_{c,C2.1a}} \right)^n$$

$$N_{\max} = 0.75 N_{u,m,C2.1a} \left(\frac{f_{u,C2,3}}{f_{u,C2.1a}} \right)$$ (Steel failure)

N/N$_{max}$	**Number of cycles**	**Crack width Δ*w* [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	

* Tests may be conducted in Δw=0.8mm at all load level

C2.4 Functioning under Alternating Shear load



— fastener load
- - - crack width
∘ assessment of displacement

V … load
Δw … crack width
t … time

$\pm V/V_{max}$	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	

$$V_{max} = 0.85 V_{u,m,C2.2} \left(\frac{f_{u,C2,4}}{f_{u,C2.2}} \right)$$

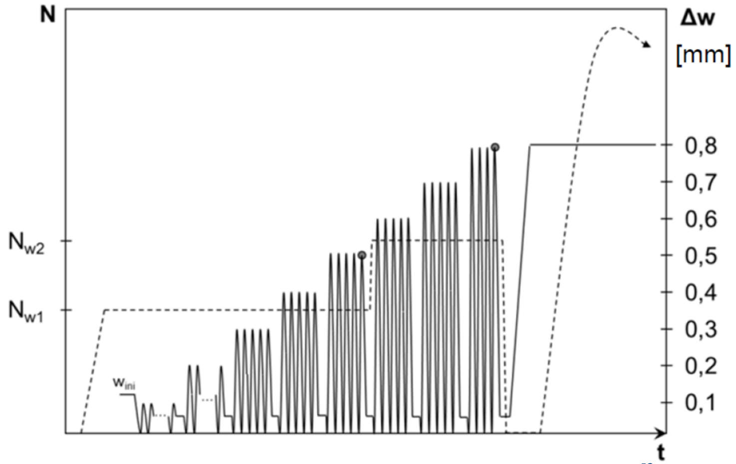
(for details refers to ANNEX E or TR049)

EOTA

C2.5 Functioning under Tension load and varying crack width

Before fastener installation it should be ensured that the compression force is not larger than C_{ini}

$$C_{ini} = 0.01\, f_{c,C2.5} A_g \qquad [N] \qquad A_g = \text{cross section area of the test member } [\text{mm}^2]$$



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

$$N_{w1} = 0.4 N_{u,m,C2.1a} \left(\frac{f_{c,C2,5}}{f_{c,C2.1a}} \right)^n \qquad N_{w2} = 0.5 N_{u,m,C2.1a} \left(\frac{f_{c,C2,5}}{f_{c,C2.1a}} \right)^n$$

$$N_{w1} = 0.4 N_{u,m,C2.1a} \left(\frac{f_{u,C2,5}}{f_{u,C2.1a}} \right) \qquad N_{w2} = 0.5 N_{u,m,C2.1a} \left(\frac{f_{u,C2,5}}{f_{u,C2.1a}} \right)$$

To assure crack closing apply:

$$C_{test} = 0.1\, f_{c,C2.5} A_g \qquad [N]$$

$$C_{test,\max} = 0.15\, f_{c,C2.5} A_g \qquad [N]$$

General

Normalization of test results i.e.

$$N_{u,m}(f_c) = N_{u,m,test}\left(\frac{f_c}{f_{c,test}}\right)^n$$

Load/displacement behavior: load plateau with a corresponding slip greater than 10% of the displacement at the 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.(For C2.1a-C2.1b and initial loading and residual tests C2.3-C2.5). If not fulfilled $\rightarrow$ **not suitable for use in category C2**

Assessment of reference tension tests C2.1

Displacement **cv(δ(0.5$N_{u,m,C2.1}$))≤40%** for δ(0.5$N_{u,m,C2.1}$)≥0.4mm

Load **$N_{u,m,C2.1a}$≥0.8$N_{u,m,3}$** **$N_{u,m,C2.1b}$≥0.8$N_{u,m,4}$**

$N_{u,m,3}$ / $N_{u,m,4}$ mean tension capacity from the tests for "maximum crack width and large/small hole diameter" in cracked concrete C20/25- C50/60 (mechanical fastener)(F1/F2), or tests for "sensitivity to increased crack width (F6/F7)" in concrete C20/25- C50/60 (bonded fastener) (crack width 0.5mm).
It the previous conditions are not fulfilled:

$$\alpha_{\mathrm{C2.1a}} = \frac{N_{u,m,C2.1a}}{0.8N_{u,m,3}} \qquad \alpha_{\mathrm{C2.1b}} = \frac{N_{u,m,C2.1b}}{0.8N_{u,m,4}} \qquad \alpha_{\mathrm{C2.1}} = \min(\alpha_{\mathrm{C2.1a}}, \alpha_{\mathrm{C2.1b}})$$

cv($N_{u,}$)≤20% $\beta_{\mathrm{cv,C2.1a}} = 1$ $\beta_{\mathrm{cv,C2.1b}} = 1$

$$\beta_{\mathrm{cv,C2.1a}} = \frac{1}{1+(cv(N_{u,C2.1a})-20)\cdot 0.03} \qquad \beta_{\mathrm{cv,C2.1b}} = \frac{1}{1+(cv(N_{u,C2.1b})-20)\cdot 0.03})$$

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

cv($N_{u,}$)≤30%

Assessment of reference shear tests C2.2

Failure mode Pull-out and pull-through failure are not allowed. In that case the tests must be repeated with larger embedment depth

Load **$V_{u,m,C2.2} \geq 0.8 V_{u,m,5}$** $\alpha_{C2.2} = 1$

$V_{u,m,5}$ mean shear capacity from the tests for “characteristic resistance to steel failure under shear load
It the previous conditions are not fulfilled:

$$\alpha_{C2.2} = \frac{V_{u,m,C2.2}}{0.8 V_{u,m,5}}$$

$cv(V_{u,}) \leq 15\%$ $\beta_{cv,C2.2} = 1$

$$\beta_{cv,C2.2} = \frac{1}{1 + (cv(V_u) - 15) \cdot 0.03}$$

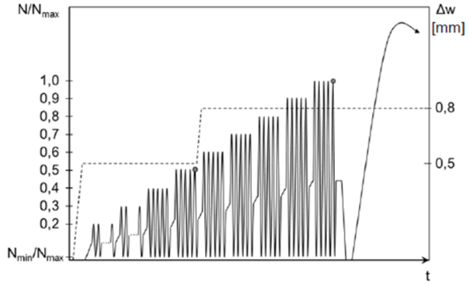
If $cv(N_{u,}) \geq 30\%$ the fastener is not suitable for use in category C2

Assessment of tests under pulsating tension load C2.3

- All fasteners in a test series shall complete the pulsating tension load history

Otherwise the maximum load shall be reduced at $N_{max,red,1}$

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



- Mean displacement shall be assessed during the last cycle at $0.5N/N_{max}$ ($N/N_{max,red,1}$) and at N/N_{max} ($N/N_{max,red,1}$)

To avoid excessive displacement of the fastener

$\delta_m(0.5N/N_{max}) \leq \delta_{N,lim}$=7mm $\qquad$ $\delta_m(0.5N/N_{max,red,1}) \leq \delta_{N,lim}$=7mm

Eventually repeat tests at $N_{max,red,2}$

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

Assessment of tests under pulsating tension load C2.3 (Residual capacity tests)

Displacement **cv(δ(0.5$N_{u,m,C2.3}$))≤40%**

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

Load **$N_{u,m,C2.3}$≥0.9$N_{u,m,C2.1a}$** $\alpha_{C2.3c} = 1$

$$\alpha_{C2.3c} = \frac{N_{u,m,C2.3}}{0.9 N_{u,m,C2.1a}}$$

cv($N_{u,}$)≤20% $\beta_{cv,C2.3} = 1$

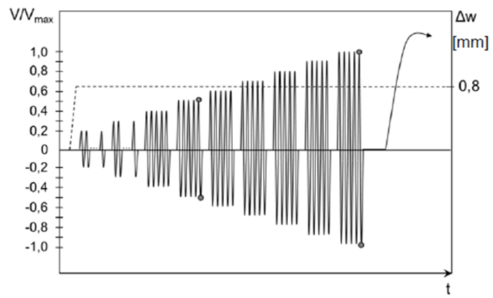
$$\beta_{cv,C2.3} = \frac{1}{1 + (cv(N_{u,C2.3}) - 20) \cdot 0.03}$$

If **cv($N_{u,}$)≥30%** fastener is **not suitable for use in category C2**

$$\alpha_{C2.3} = \min(\alpha_{C2.3a}, \alpha_{C2.3b})\alpha_{C2.3c}$$

Assessment of tests under alternating shear load C2.4

- If a fastener do not complete the alternating shear load history the tests shall be repeated with a reduced value $\mathbf{V_{max,red,1}}$



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

- Mean displacement shall be assessed during the last cycle at $\pm 0.5V/V_{max}$ $(V/V_{max,red,1})$ and at V/V_{max} $(N/N_{max,red,1})$

To avoid excessive displacement of the fastener

$\delta_m(0.5V/V_{max}) \leq \delta_{V,lim}$=7mm $\delta_m(0.5V/V_{max,red,1}) \leq \delta_{V,lim}$=7mm

Eventually repeat tests at $V_{max,red,2}$

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

Assessment of tests under alternating shear load C2.4 (Residual capacity tests)

Failure mode Pull-out and pull-through failure are not allowed. In that case the tests must be repeated with larger embedment depth

Load $\mathbf{V_{u,m,C2.4} \geq 0.95 V_{u,m,C2.2}}$ $\alpha_{\mathrm{C2.4c}} = 1$

$$\alpha_{\mathrm{C2.4c}} = \frac{V_{u,m,C2.4}}{0.95 V_{u,m,C2.2}}$$

$\mathbf{cv(V_{u,}) \leq 15\%}$ $\beta_{\mathrm{cv,C2.4}} = 1$

$$\beta_{\mathrm{cv,C2.4}} = \frac{1}{1 + (cv(V_u) - 20) \cdot 0.03}$$

If $\mathbf{cv(V_{u,}) \geq 30\%}$ fastener is **not suitable for use in category C2**

$$\alpha_{\mathrm{C2.4}} = \min(\alpha_{\mathrm{C2.4a}}, \alpha_{\mathrm{C2.4b}})\alpha_{\mathrm{C2.4c}}$$

Assessment of tests under tension load with varying crack width C2.5

- All fasteners in a test series shall complete the varying crack history under tension load

  Otherwise the test series shall be reduced i.e. $N_{w1,red,1}$ and $N_{w2,red,1}$

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

- Mean displacement shall be assessed during the last cycle at Δw =0.5mm and Δw =0.8mm (N/$N_{max,red,1}$) and at N/N_{max} (N/$N_{max,red,1}$)

  To avoid excessive displacement of the fastener

$$\delta_m(\Delta w = 0.5mm) \le \delta_{N,lim} = 7mm \qquad \delta_m(0.5N/N_{max,red,1}) \le \delta_{N,lim} = 7mm$$

Eventually repeat tests at $N_{w1,red,2}$, $N_{w2,red,2}$ $\longrightarrow$ $\alpha_{C2.3b} = \dfrac{N_{w2,red,2}}{N_{w2}}$

Assessment of tests under tension load with varying crack width C2.5 (Residual capacity tests)

Displacement **cv(δ(0.5N$_{u,m,C2.5}$))≤40%**
If this condition in not fulfilled the fastener is **not suitable for use in category C2**

Load **$N_{u,m,C2.5} \geq 0.9 N_{u,m,C2.1a}$** $\alpha_{C2.5c} = 1$

$$\alpha_{C2.5c} = \frac{N_{u,m,C2.5}}{0.9 N_{u,m,C2.1a}}$$

cv(N$_{u,}$)≤20% $\beta_{cv,C2.5} = 1$

$$\beta_{cv,C2.3} = \frac{1}{1 + (cv(N_{u,C2.5}) - 20) \cdot 0.03}$$

If **cv(N$_{u,}$)≥30%** fastener is **not suitable for use in category C2**

$$\alpha_{C2.5} = \min(\alpha_{C2.5a}, \alpha_{C2.5b}) \alpha_{C2.5c}$$

Seismic performance - Load

Category C1

$N_{Rk,x,C1} = \alpha_{N,C1} N_{Rk,x}$

$N_{Rk,x}$ = characteristic tension resistance for the x mode of failure as reported in the ETA

$V_{Rk,s,C1} = \alpha_{V,C1} V_{Rk,s}$

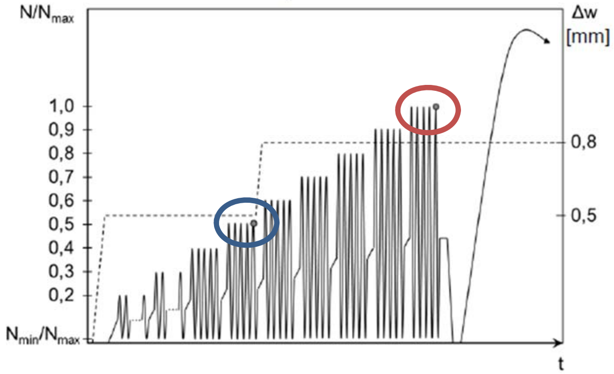
Category C2

$N_{Rk,x,C2} = \alpha_{N,C2} \beta_{cv,N,C2} N_{Rk,x}$

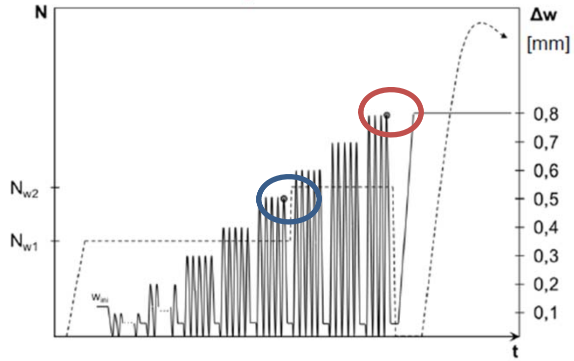
$V_{Rk,s,C2} = \alpha_{V,C2} \beta_{cv,V,C2} V_{Rk,0}$

Seismic performance - Displacement

$\delta_{N,eq}$ (DLS)

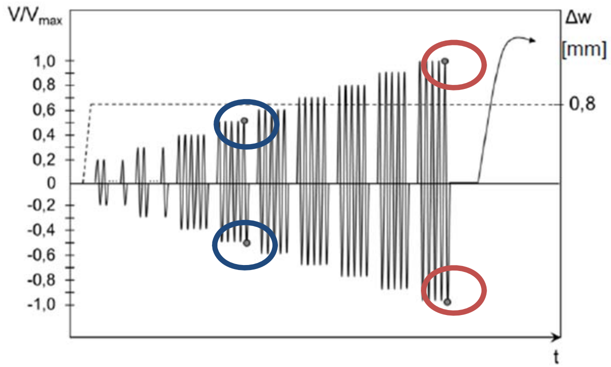


$\delta_{N,eq}$ (ULS)



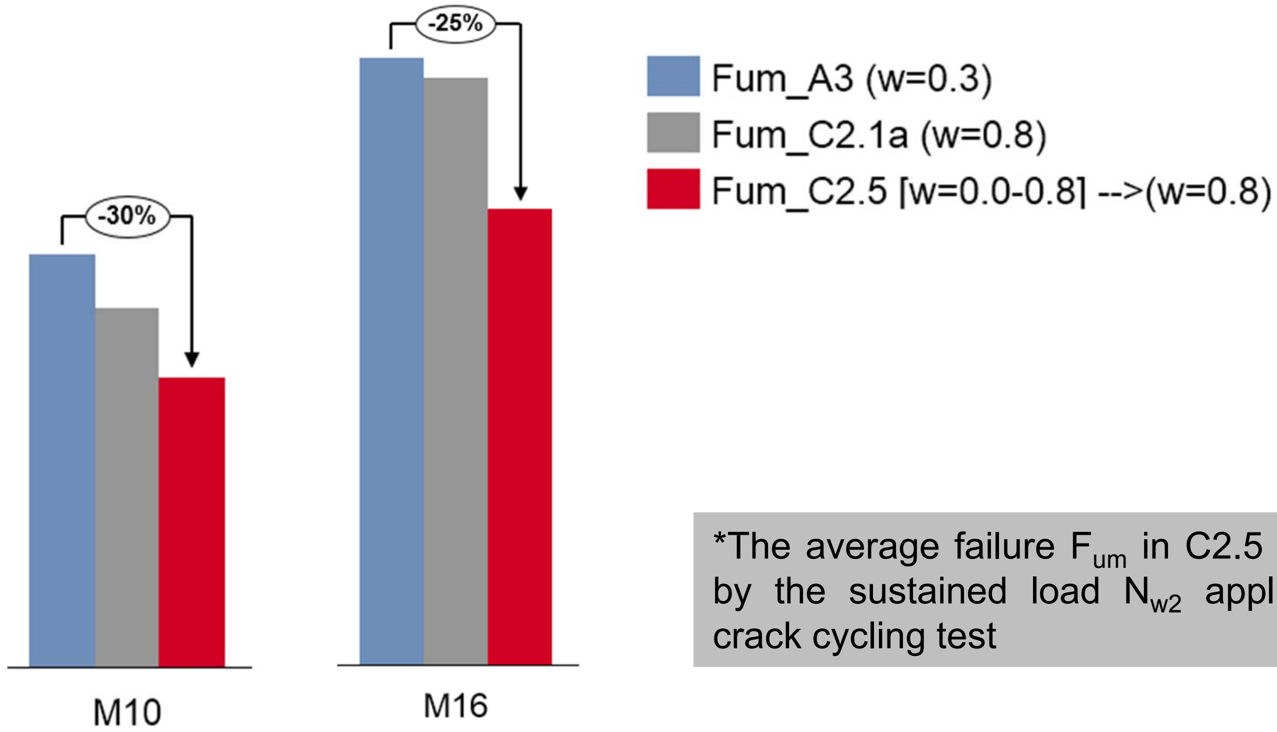
$\delta_{V,eq}$ (DLS)

$\delta_{V,eq}$ (ULS)



Seismic performance – An example

Average failure load in testing C2.5 drop by 30% on M10 and 25% on M16* compared with static test (crack width 0.3mm)



*The average failure F_{um} in C2.5 test is affected by the sustained load N_{w2} applied during the crack cycling test

ETA: an example

Tabella C2: Resistenza caratteristica a trazione per tassello a espansione in metallo Hilti HST3 e HST3-R in calcestruzzo fessurato e non fessurato

			M8	M10	M12	M16	M20	M24
Rottura dell'acciaio								
HST3								
Resistenza caratteristica	$N_{Rk,s}$	[kN]	19,7	32,5	45,1	76,0	124,2	127,0
Fattore di sicurezza parziale	γ_{Ms} 1)	[-]	1,40					1,41
HST3-R								
Resistenza caratteristica	$N_{Rk,s}$	[kN]	17,7	28,7	42,5	69,4	115,8	156,0
Fattore di sicurezza parziale	γ_{Ms} 1)	[-]	1,40					1,56
Rottura per estrazione								
HST3 e HST3-R								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	125
Resistenza caratteristica su calcestruzzo fessurato C20/25	$N_{Rk,p}$	[kN]	7,5	12	20	2)	2)	40
Resistenza caratteristica su calcestruzzo non fessurato C20/25	$N_{Rk,p}$	[kN]	12	20	25	2)	2)	60
Fattore di sicurezza parziale	$\gamma_2 = \gamma_{inst}$	[-]	1,00					
HST3 e HST3-R								
Profondità effettiva di posa	$h_{ef,1}$	[mm]	-	40	50	65	-	-
Resistenza caratteristica su calcestruzzo fessurato C20/25	$N_{Rk,p}$	[kN]	-	2)	2)	2)	-	-
Resistenza caratteristica su calcestruzzo non fessurato C20/25	$N_{Rk,p}$	[kN]	-	2)	2)	2)	-	-
Fattore di sicurezza parziale	$\gamma_2 = \gamma_{inst}$	[-]	1,00					

Tabella C8: Resistenza caratteristica a trazione per carico sismico per tassello a espansione in metallo Hilti HST3 e HST3-R, categoria di prestazione C1

			M8	M10	M12	M16	M20	M24
Rottura dell'acciaio								
HST3								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,s,seis}$	[kN]	19,7	32,5	45,1	76,0	124,2	-
Fattore di sicurezza parziale	$\gamma_{Ms,seis}$ 1)	[-]	1,40					-
HST3-R								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,s,seis}$	[kN]	17,7	28,7	42,5	69,4	115,8	-
Fattore di sicurezza parziale	$\gamma_{Ms,seis}$ 1)	[-]	1,40					-
Rottura per estrazione								
HST3 e HST3-R								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,p,seis}$	[kN]	7,5	12,0	20,0	2)	2)	-
Fattore di sicurezza parziale	$\gamma_2 = \gamma_{inst}$	[-]	1,00					-

Tabella C13: Resistenza caratteristica a trazione per carico sismico per tassello a espansione in metallo Hilti HST3 e HST3-R, categoria di prestazione C2

			M8	M10	M12	M16	M20	M24
Rottura dell'acciaio								
HST3								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,s,seis}$	[kN]	19,7	32,5	45,1	76,0	124,2	-
Fattore di sicurezza parziale	$\gamma_{Ms,seis}$ 1)	[-]	1,40					-
HST3-R								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,s,seis}$	[kN]	17,7	28,7	42,5	69,4	115,8	-
Fattore di sicurezza parziale	$\gamma_{Ms,seis}$ 1)	[-]	1,40					-
Rottura per estrazione								
HST3								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,p,seis}$	[kN]	3,0	10,4	19,5	2)	35,7	-
Fattore di sicurezza parziale	$\gamma_2 = \gamma_{inst}$	[-]	1,00					-
HST3-R								
Profondità effettiva di posa	$h_{ef,2}$	[mm]	47	60	70	85	101	-
Resistenza caratteristica	$N_{Rk,p,seis}$	[kN]	3,4	10,4	19,5	2)	35,7	-
Fattore di sicurezza parziale	$\gamma_2 = \gamma_{inst}$	[-]	1,00					-

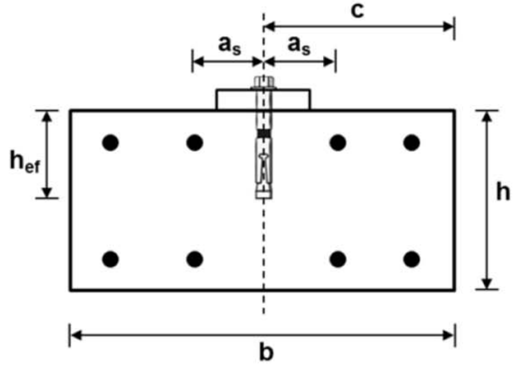
ETA: an example

Tabella C14: Spostamenti sotto carichi a trazione per carico sismico per tassello a espansione di metallo Hilti HST3 e HST3-R, categoria di prestazione C2

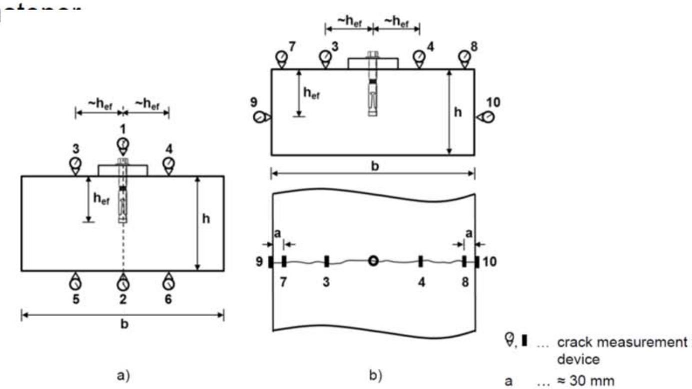
			M8	M10	M12	M16	M20	M24
HST3 e HST3-R								
Spostamento SLD	$\delta_{N,seis}$	[mm]	2,7	3,9	5,2	5,2	6,9	-
Spostamento SLU	$\delta_{N,seis}$	[mm]	10,5	13,7	13,9	11,9	18,4	-

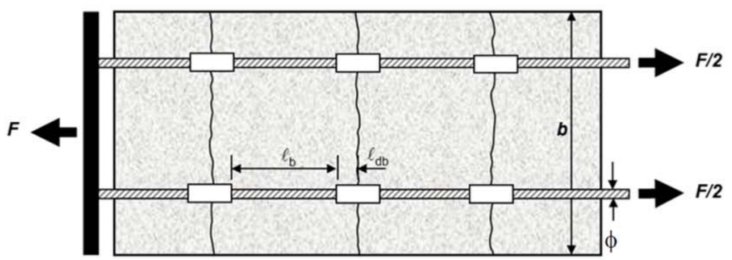
Some additional considerations: crack witdh

The crack width is a fundamental parameter the testing laboratory should assure a proper check during tests



a_s … distance between fastener and reinforcement bar
b … width of test member
c … edge distance
h … height of test member
h_{ef} … embedment depth of fa…



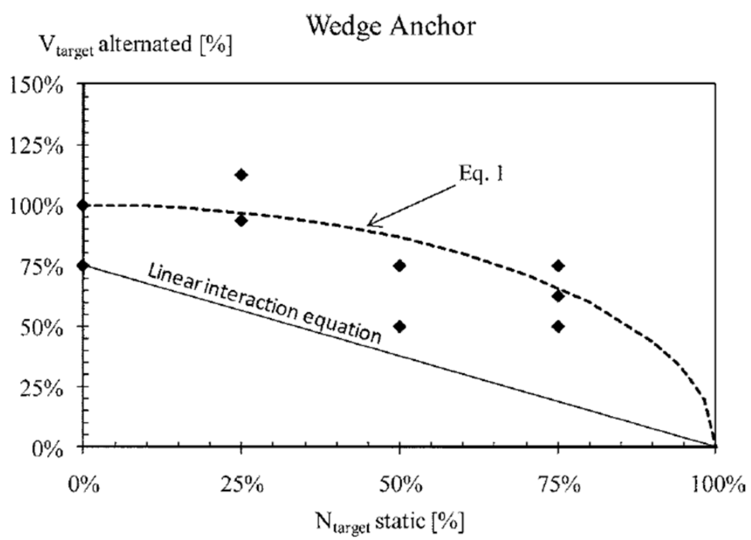


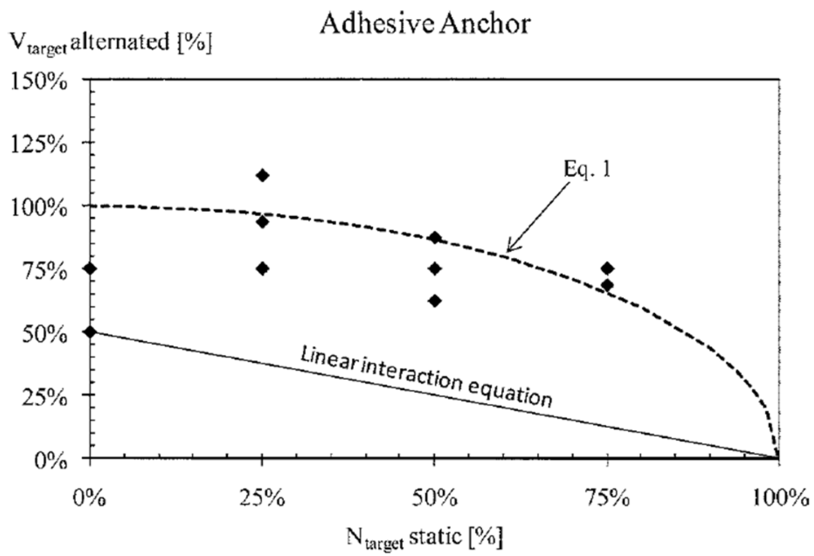
□ = bond breaker
ℓ_b = bond length
ℓ_{bd} = debonding length
ϕ = diameter of rebar
b = width of test member
F = force on test member

Some additional considerations:
tension-shear interaction

The prequalification does not include this aspect

Tests are not necessary if linear interaction curve is adopted (Guillet,2011)





Conclusions

The post-installed prequalification for the seismic environment (opt. C2) is based on a comprehensive scientific and engineering approach.

C2 approach aims to identify anchor suitable/not suitable for highly seismic environments

Still open issues:

The approach is mainly based on the behavior of Non Structural Systems attached to the structure

The constant load applied during cycles seems to be conservative (or not) depending on the type of anchor

THANK YOU
FOR YOUR KIND ATTENTION

References

- ETAG 001. Guideline for European technical approval of metal anchors for use in concrete, Parts 1 – 6. European Organization of Technical Approvals (EOTA), Brussels 1997.
- ETAG Annex E. Guideline for European Technical Approval of metal anchors for use in concrete - Annex E: Assessment of metal anchors under seismic actions. 2013.
- ACI 355.2. Qualification of post-installed mechanical anchors in concrete (ACI 355.2-07) and commentary, American Concrete Institute (ACI), Farmington Hills, Michigan 2007.
- ACI 355.4. Acceptance criteria for qualification of post-installed adhesive anchors in concrete (ACI 355.4-11) and commentary, American Concrete Institute (ACI), Farmington Hills, Michigan 2011.
- CAN/CSA-N287.2-M91. Material requirements for concrete containment structures for CANDU nuclear power plants, Canadian Standards Association (CSA) (517 reaffirmed 2003) 1991.
- SEAOSC. Standard method of cyclic load test for anchors in concrete or grouted masonry, Structural Engineers Association of Southern California (SEAOSC), Whittier, California, April 1997 1997.
- DIBt KKW Leitfaden. Verwendung von Dübeln in Kernkraftwerken und kerntechnischen Anlagen, Leitfaden zur Beurteilung von Dübelbefestigungen bei der Erteilung von Zustimmungen im Einzelfall nach den Landesbauordnung der Bundesländer (Use of anchors in nuclear power plants and nuclear technology installations, guideline for evaluating fastenings for granting permission in individual cases according to the state structure regulations of the federal states of Germany). Deutsches Institut für Bautechnik (DIBt), Berlin (in German) 1998.
- EN 1992. Eurocode 2: Design of concrete structures. European Committee for Standardization (CEN); EN 1992: 2005 2005.
- EN 1998-1. Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. European Committee for Standardization (CEN); EN 1998-1:2004 2004.
- ACI 318-08. Building code requirements for structural concrete (ACI 318-08) and commentary (ACI 318R-08), American Concrete Institute, Farmington Hills, Michigan 2008.

References

- Mahrenholtz P, Eligehausen R. Anchor displacement behavior during simultaneous load and crack cycling. ACI Materials Journal, Vol. 113, No. 5, 645-652, 2016.
- Mahrenholtz P, Eligehausen R, Hutchinson T, Hoehler M. Behavior of anchors tested by stepwise increasing cyclic load protocols in tension and shear. ACI Structural Journal, Vol.113 No.5, 997-1008, 2016.
- Sharma A., Mahadik V., Hofmann J., Influence of crack loading protocol on crack cycling tests on undercut anchors, ACI Structural Journal, Vol.113 No.4, 779-790, 2016.
- Wood R, Hutchinson T. Crack protocols for anchored components and systems. ACI Structural Journal, Vol. 110, No. 3, 391-401, 2013.
- Mahrenholtz C, Eligehausen R, Dynamic performance of concrete undercut anchors for nuclear plants, Nuclear Engineering and Design, 265, 1091-1100, 2013
- Mahrenholtz P. Experimental performance and recommendations for qualification of post-installed anchors for seismic applications. Dissertation, University of Stuttgart 2012.
- Watkins D.A., Hutchinson T, Hoehler M., Cyclic crack and inertial loading System for investigating anchor seismic behavior, Vol.109, No 4, 457-466, 2012.
- Guillet T. Behavior of metal anchors under combined tension and shear cycling loads. ACI Structural Journal, May-June 2011, Vol. 108, No. 3, 315-323 2011.
- Watkins D, Chui L, Hutchinson T, Hoehler M. Survey and characterization of floor and wall mounted mechanical and electrical equipment in buildings. Structural Systems Research Project (SSRP) 2009/11, University of California, San Diego 2009.
- Hoehler M, Eligehausen R. Behavior and testing of anchors in simulated seismic cracks. ACI Structural Journal, May-June 2008, Vol. 105, No. 3, 348-357 2008.
- Nuti C, Santini S. Fastening technique in seismic areas: A critical review. Proceeding of the Conference on Tailor Made Concrete Structures, 899-905, Roma 2008.
- Hoehler M. Behavior and testing of fastenings to concrete for use in seismic applications. Dissertation, University of Stuttgart 2006.
- Eligehausen R, Balogh T. Behavior of fasteners loaded in tension in cracked reinforced concrete. ACI Structural Journal, Vol. 92, No. 3, 365-379 1995.