1. Design Principles

1.1. General

This chapter is intended to provide the reader with the design principles related to the anchorage of structural and non-structural elements to structural components through fasteners. Fasteners, mechanical or bonded, are designed to transmit actions to concrete by different mechanisms depending on their type and mode of action.

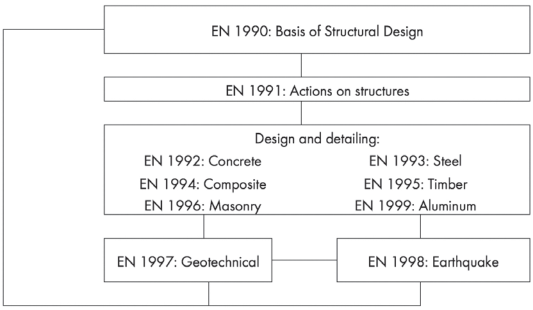

Figure 1: The Eurocodes

The design principles are primarily based on the European Standards of the Eurocode EN 1992-4, which is a European standard for the design of fastenings for use in concrete.
The Eurocode EN 1992-4 uses the fastener design theory, which applies to single fasteners and group of fasteners, on condition that the fasteners are of equal type and size and on the condition that they are joined through a common fixture.

1.2. Partial factor method

This design manual uses the partial factor method according to the European Norm EN 1990. When using the partial factor method, it shall be verified that, in all relevant design situations, no relevant limit state is exceeded when design values for actions (E_d) or effects of actions and resistances (R_d) are used in the design models.

$$E_d \leq R_d$$

For the selected design situations and the relevant limit states, the individual actions for the critical load cases should be combined.
Design values should be obtained by using the characteristic, or other representative values, in combination with partial and other factors (γ_f, γ_M) as defined in EN 1991 to EN 1999, the design guides for post-installed anchors and the relevant approval of the chosen anchor.

$$R_d = \frac{R_k}{\gamma_M}$$

The respective approval number is given in the relevant chapter of the anchor's design tables. Actual design requirements for post-installed anchors are published in the EN 1992-4. This Design Manual uses a simplification of these norms to allow manual verifications for anchorages.
The characteristic values and partial factors of the anchors are derived by assessments of the results of tests described in EN 1992-4. This guideline requires to meet the respective criteria of its suitability tests and tests for admissible service conditions.

1.3. Base material

The Würth anchor assortment is manufactured for a range of different base materials such as lightweight and normal weight concrete, masonry and plasterboards. The anchors presented in the following chapters are for use in normal weight concrete of different strength classes. The compressive strength is an important material property for calculating the load transmitting capacity. It is e.g. in Europe denoted by concrete strength classes which relate to the characteristic cylinder strength f_{ck} or the cube strength $f_{ck,cube}$ in accordance with EN 206. The suitable strength class for each individual anchor is given in the relative European Technical Assessment (ETA).
Table 1 shows the different concrete strength classes according to EN 206.

Table 1: Concrete strength classes

Concrete strength classes (EN 206:2000)			**C12/15**	**C16/20**	**C20/25**	**C25/30**	**C30/37**	**C35/45**	**C40/50**	**C45/55**	**C50/60**
Characteristic compressive strength of concrete determined by testing cylinders of 150 mm diameter by 300 mm height at 28 days	f_{ck}	[N/mm²]	12	16	20	25	30	35	40	45	50
Characteristic compressive strength of concrete determined by testing cubes of 150 mm side length at 28 days	$f_{ck,cube}$	[N/mm²]	15	20	25	30	37	45	50	55	60

1.4. Partial safety factors

Table 2: Partial safety factors for post-installed fasteners according to EN 1992-4

Failure modes	**Partial factor**		
	Permanent and transient design situations		**Accidental design situation**
Steel failure - fasteners			
Tension	γ_{Ms}	$= 1.2 \cdot f_{uk}/f_{yk} \geq 1.4$	$= 1.05 \cdot f_{uk}/f_{yk} \geq 1.25$
Shear with and without level arm		$= 1.0 \cdot f_{uk}/f_{yk} \geq 1.25$ when $f_{uk} \leq 800$ N/mm² and $f_{yk}/f_{uk} \leq 0.8$	$= 1.0 \cdot f_{uk}/f_{yk} \geq 1.25$ when $f_{uk} \leq 800$ N/mm² and $f_{yk}/f_{uk} \leq 0.8$
		$= 1.5$ when $f_{uk} > 800$ N/mm² or $f_{yk}/f_{uk} > 0.8$	$= 1.3$ when $f_{uk} > 800$ N/mm² or $f_{yk}/f_{uk} > 0.8$
Steel failure – supplementary reinforcement			
Tension	$\gamma_{Ms,re}$	= 1.15 [a]	= 1.0
Concrete related failure			
Concrete cone failure, concrete edge failure, concrete blow-out failure, concrete pry-out failure	γ_{Mc}	$= \gamma_c \cdot \gamma_{inst}$	$= \gamma_c \cdot \gamma_{inst}$
	γ_c	= 1.5 [a]	= 1.2 [a]
	γ_{inst}	≥ 1.0 for post-installed fasteners in tension, see relevant ETA	
		= 1.0 for post-installed fasteners in shear	
Concrete splitting failure	γ_{Msp}	$= \gamma_{Mc}$	
Pull-out and combined pull-out and concrete failure	γ_{Mp}	$= \gamma_{Mc}$	

[a] The values are in accordance with EN 1992-1-1. For seismic repair and strengthening of existing structures see EN 1998.

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1.5. Würth simplified anchor design method

The Würth Simplified Anchor Design Method is based on the design concept of the EN 1992-4 and offers the engineer a convenient way of verifying the load capacity of a Würth anchor.

1.6. Failure modes

The following failure modes are considered:

Failure in Tension Loading
1. Steel failure
2. Concrete cone failure
3. Pull-out failure
4. Combined pull-out and concrete failure of bonded fasteners
5. Concrete splitting failure
Failure in Shear Loading
1. Steel failure without lever arm
2. Steel failure with lever arm
3. Concrete pry-out failure
4. Concrete edge failure

When both tension and shear are present, interaction effects are also considered. With above verifications and the interaction effects, it is sufficiently proven that the anchorage is able to transmit the acting loads into the concrete member.
Post-installed anchors do not always substitute e.g. falsely placed cast-in steel elements for which the load transmitting concrete member was already structurally verified. In many cases, post-installed anchors are used to add attachments in order to refurbish even new construction as well as for repair and strengthening work. Therefore, it is strongly recommended to verify if the concrete member is able to transmit the additional concentrated loads.

1.6.1. Failure due to tension loading

1.6.1.1. Steel failure

Steel failure of a fastener in tension loading occurs when the tension load exceeds the characteristic steel resistance of the fastener. The resistance is directly proportional to the governing cross sectional area of the fastener and the ultimate steel strength f_{uk}. The characteristic resistance for steel failure can be found in the relevant European Technical Assessment ETA.

1.6.1.2. Concrete cone failure

Concrete cone failure occurs when the fastening system fails due to the failure of the concrete base material of the system. Concrete failure in this case takes up the shape of a conical breakout, and it is directly proportional to the effective anchorage depth of the fastener. The following is the concrete cone failure design resistance equation according to the Würth Simplified Method:

$$N_{Rd,c} = N^0_{Rd,c} \cdot f_{b,N} \cdot f_{sx} \cdot f_{sy} \cdot f_{cx,1} \cdot f_{cx,2} \cdot f_{cy}$$

The figure below demonstrates a typical conical breakout in concrete:

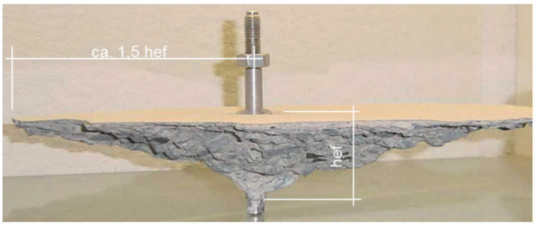

Figure 2: Concrete cone failure of a Fixanchor W-FAZ

1.6.1.3. Pull-out failure

Pull-out failure of a fastener occurs when the applied tension load exceeds the resistance induced by the expansion elements of a fastener on the wall of the drilled hole. In the case of torque-controlled expansion anchors, pull-out failure can occur when the follow-up expansion is not achieved. In case of displacement-controlled expansion anchors, this can occur when the expansion cone is not properly driven into the expansion sleeve. The following is the pull-out design resistance equation according to the Würth Simplified Method:

$$N_{Rd,p} = N^0_{Rd,p} \cdot f_{b,N}$$

1.6.1.4. Combined pull-out and concrete failure of bonded fasteners

Combined pull-out and concrete failure occurs when the tension load is higher than the resistance created by the bond between the mortar or bonding agent and the concrete. As a result of this failure, the anchor rod is pulled out from the concrete and consequently pulls out a small concrete cone in the process. The bond resistance is directly proportional to the bond strength τ_{Rk} of the selected chemical mortar. Additionally, and after the introduction of the new EN 1992-4, an additional influence factor fsus has been introduced to the combined pull-out and concrete failure of bonded fasteners to take into account long-term loading and creep effects on the bonded anchor. The following is the combined pull-out and concrete cone design resistance equation according to the Würth Simplified Method:

$$N_{Rd,p} = N^0_{Rd,p} \cdot f_{b,N} \cdot f_{hef} \cdot f_{sx,p} \cdot f_{sy,p} \cdot f_{cx,1,p} \cdot f_{cx,2,p} \cdot f_{cy,p} \cdot f_{sus}$$

1.6.1.5. Concrete splitting failure

Splitting failure occurs typically under tension loading when the fastener or group of fasteners are located near an edge or a corner and when the minimum edge distance, spacing, and concrete thickness requirements are not met. The following is the concrete splitting failure design resistance equation according to the Würth Simplified Method:

$$N_{Rd,sp} = N^0_{Rd,sp} \cdot f_{b,N} \cdot f_{sx,sp} \cdot f_{sy,sp} \cdot f_{cx,1,sp} \cdot f_{cx,2,sp} \cdot f_{cy,sp} \cdot f_h$$

1.6.2. Failure due to shear loading

1.6.2.1. Steel failure with/without lever arm

When the building components are sufficiently large (edge distance, spacing, and material thickness), steel failure occurs when the loading of the fastener in shear exceeds maximum resistance capacity. Steel failure resistance values are taken from the relevant fastener ETA.

1.6.2.2. Concrete pry-out

Concrete pry-out failure usually occurs in fasteners or group of fasteners with a small embedment depth in concrete. The following is the concrete pry-out design resistance equation according to the Würth Simplified Method:

$$V_{Rd,c} = N_{Rd,c} \cdot k$$

1.6.2.3. Concrete edge failure

Concrete edge failure occurs when the fastener or group of fasteners are located near an edge or corner and loaded in the direction of the edge. The following is the concrete edge failure design resistance equation according to the Würth Simplified Method:

$$V_{Rd,c} = V^0_{Rd,c} \cdot f_{b,V} \cdot f_{s,V} \cdot f_{c2,V} \cdot f_a \cdot f_h$$

1.7. Influence factors

The following is a table of the general influence factors in the design resistance equations above. Tables for specific values are found in the anchor selection chapter.

Table 3: Influence factors

Factor	Description
f_b	Influence of concrete strength
f_{sx}, f_{sy}	Influence of spacing
f_{cx}, f_{cy}	Influence of edge distances
f_h	Influence of concrete member thickness
f_{hef}	Influence of the effective anchorage depth
f_a	Influence of load direction on edge resistance
f_{sus}	Influence of sustained loads for bonded anchors

1.8. Required verifications

1.8.1. In tension

Table 4: Required verifications for post-installed fasteners in tension

	Failure mode	Single fastener	Group of fasteners	
			Most loaded fastener	Group
1	Steel failure of fastener	$N_{Ed} \leq N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms}}$	$N_{Ed}^{h} \leq N_{Rd,s} = \frac{N_{Rk,s}}{\gamma_{Ms}}$	
2	Concrete cone failure	$N_{Ed} \leq N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}}$		$N_{Ed}^{g} \leq N_{Rd,c} = \frac{N_{Rk,c}}{\gamma_{Mc}}$
3	Pull-out failure of fastener [a]	$N_{Ed} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$	$N_{Ed}^{h} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$	
4	Combined pull-out and concrete failure [b]	$N_{Ed} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$		$N_{Ed}^{g} \leq N_{Rd,p} = \frac{N_{Rk,p}}{\gamma_{Mp}}$
5	Concrete splitting failure	$N_{Ed} \leq N_{Rd,sp} = \frac{N_{Rk,sp}}{\gamma_{Msp}}$		$N_{Ed}^{g} \leq N_{Rd,sp} = \frac{N_{Rk,sp}}{\gamma_{Msp}}$

[a] Not required for post-installed bonded fasteners

[b] Not required for post-installed mechanical fasteners

1.8.2. In shear

Table 5: Required verifications for post-installed fasteners in shear

	Failure mode	Single fastener	Group of fasteners	
			Most loaded fastener	Group
1	Steel failure of fastener without lever arm	$V_{Ed} \leq V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms}}$	$V_{Ed}^{h} \leq V_{Rd,s} = \frac{V_{Rk,s}}{\gamma_{Ms}}$	
2	Steel failure of fastener with lever arm	$V_{Ed} \leq V_{Rd,s,M} = \frac{N_{Rk,s,M}}{\gamma_{Ms}}$	$V_{Ed}^{h} \leq V_{Rd,s,M} = \frac{N_{Rk,s,M}}{\gamma_{Ms}}$	
3	Concrete pry-out failure	$V_{Ed} \leq V_{Rd,cp} = \frac{V_{Rk,cp}}{\gamma_{Mc}}$		$V_{Ed}^{g} \leq V_{Rd,cp} = \frac{V_{Rk,cp}}{\gamma_{Mc}}$
4	Concrete edge failure	$V_{Ed} \leq V_{Rd,c} = \frac{V_{Rk,c}}{\gamma_{Mc}}$		$V_{Ed}^{g} \leq V_{Rd,c} = \frac{V_{Rk,c}}{\gamma_{Mc}}$

1.8.3. Combined tension and shear loading

In the new EN 1992-4, combined tension and shear are separately evaluated for steel and concrete. This gives the designer a better and more accurate estimation of the interaction effects on the materials.

Table 6: Required verifications for post-installed fasteners without supplementary reinforcement subjected to a combined tension and shear load

	Failure mode	Verification
1	Steel failure of fastener [a]	$\left(\frac{N_{Ed}}{N_{Rd}}\right)^2 + \left(\frac{V_{Ed}}{V_{Rd}}\right)^2 \leq 1$ If N_{Ed} and V_{Ed} are different for the individual fasteners of the group, the interaction shall be verified for all fasteners.
2	Failure modes other than steel failure	$\left(\frac{N_{Ed}}{N_{Rd,i}}\right)^{1.5} + \left(\frac{V_{Ed}}{V_{Rd,i}}\right)^{1.5} \leq 1$ or $\left(\frac{N_{Ed}}{N_{Rd,i}}\right) + \left(\frac{V_{Ed}}{V_{Rd,i}}\right) \leq 1.2$ With $N_{Ed} / N_{Rd,i} \leq 1$ and $V_{Ed} / V_{Rd,i} \leq 1$ The largest value of $N_{Ed} / N_{Rd,i}$ and $V_{Ed} / V_{Rd,i}$ for the different failure modes shall be taken.

[a] This verification is not required in case of shear load with lever arm

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1.9. Geometry of anchorage

When installing post-installed anchors, the consideration of geometrical constraints is very important. The thickness of the concrete member in which the anchor has to be post-installed to later decides how deep the installer can drill a hole into the concrete, and finally the maximum effective anchorage depth of the anchor. As the anchor's pull-out resistance depends on the effective anchorage depth, the thickness of the concrete member determines the maximum load which can be transferred in almost all cases. On the other hand, the projecting length of the anchor has to be selected in order to cover tolerances of the construction and the thickness of the attachment itself.

1.9.1. The effective anchorage depth

The effective anchorage depth h_{ef} is one of the most important dimensions as it determines the so called concrete capacity of each anchor.

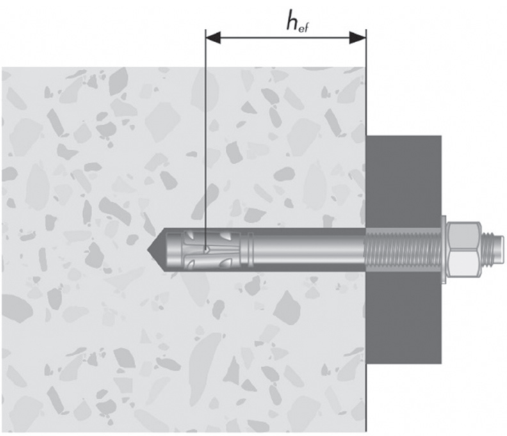

Figure 3: Effective anchorage depth of fastener

Advanced anchors normally generate concrete cone failure as this failure is the limit of each post-installed fastening system. The concrete cone failure depends on the compressive strength of concrete and on the anchorage depth h_{ef}:

$$N^0_{Rk,c} = k_1 \cdot \sqrt{f_{ck}} \cdot h^{1.5}$$

With $k_9 = k_{cr,N} = 7.7$ for cracked concrete and $k_9 = k_{ucr,N} = 11$ for verified non-cracked concrete

The engineer is responsible to verify if the acting tensile load is smaller than the concrete cone capacity of the anchor. From a structural design point of view, the engineer has to mention the anchor's effective anchorage depth in his or her detailed drawings. Only this value guarantees that suppliers provide anchors with the respective performance.

1.9.2. Anchor diameter

The diameter is important for calculating the steel capacity due to shear loading, but gives also information on the required diameter d_0 of the drill hole in the concrete member and on the maximum clearance hole diameter d_f in the fixtures.

1.9.3. Fixture thickness

The thickness of the fixture has to be verified by the structural engineer for adequate load capacity. Minimum values can be found in the relevant product ETA. Considering the stand-off fixture below, the projecting length of the anchor rod has to cover the gap between concrete surface and anchor plate, the thickness of the anchor plate itself and in addition have to exceed the anchor plate by the thickness of washer and nut.

Figure 4: Column fixing with stand-off fixture

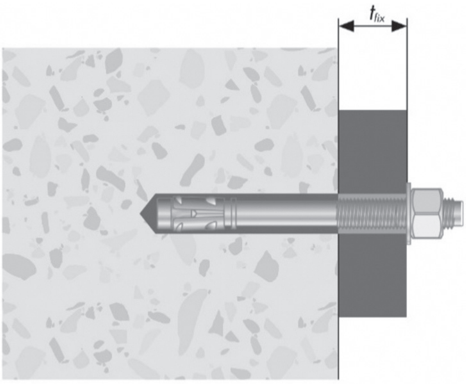

Figure 5: Fixture thickness

The maximum fixture thickness t_{fix} which represents the maximum useful length is difficult to decide during the designing stage, because the real conditions on building site differ mostly from the drawings. Most suppliers provide anchors with a wide range of useful lengths at same effective anchorage depth. This allows the installer to select a proper anchor in agreement with the responsible structural engineer.

1.9.4. Anchor length

The anchor length l depends on the effective anchorage depth and the useable length. In general, the anchor is longer than the sum of both, because it should consider additional length for the washer and nut. For safety reasons, the anchor should project at least one pitch of the threaded bolt. On the other hand, that part which exceeds the effective anchorage depth depends on the manufacturers developing ability to provide economic fastening systems.

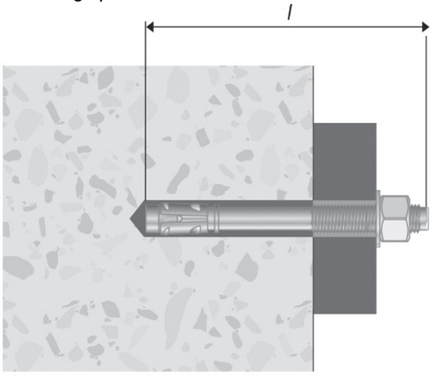

Figure 6: Anchor length

1.9.5. Concrete member thickness and the drill hole depth

The drill hole depth depends on the type of anchor. Figure 7 below shows the depth of the drill hole h_1 in case of a through fixing. This means that the anchor is installed through the bracket into the concrete. The sufficient depth of the drill hole is important to generate the correct functioning of the anchors in order to achieve the designed performance on the one hand, but on the other hand it determines the minimum concrete member thickness.

According to guidelines, the minimum component thickness in which anchors are installed is h ≥ 80 mm.

If the thickness of the concrete member is smaller than required above, then the resistance can be reduced because of a premature splitting failure or a reduction of the shear resistance for anchorages at the edge. Furthermore, the minimum values for edge distance and spacing might not be sufficient because a splitting failure can occur during installation. Therefore, a smaller thickness of the concrete member is allowed only if the above-mentioned effects are taken into account in the design and installation of the anchorage.
The minimum member thickness is given in the relevant product European Technical Approval.

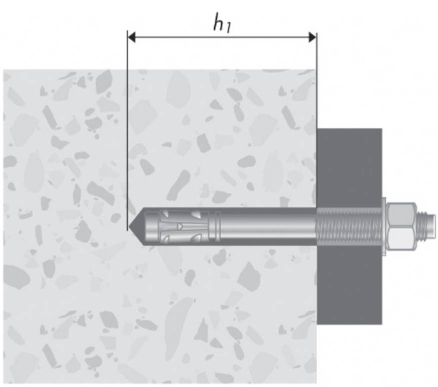

Figure 7: Drill-hole depth

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The used symbols are listed below:

Symbol	Description
ETA CE	European Technical Assessment Key document for the calculation. It contains the performance parameters of the anchor
ICC ES	International Code Council ICC Evaluation Service Inc. (ICC ES) issues evaluation reports based on the Uniform Building Code and related codes in the USA and Canada.
	The anchor may also be used under seismic action according to ETA and/or ICC-ESR
	Fire resistance classification
LEED tested	LEED certified The system looks at numerous factors that were divided into five categories, which relate to and include the health of humans and the environment
VOC conforming solvent reduced	VOC Emissions class label In the context of analyzing the air a group of pollutants is analyzed, which can have serious health effects on humans. The term VOC (volatile organic compounds) is grouped together, a plurality of volatile organic compounds
NSF	NSF International The National Sanitation Foundation (NSF) is a nonprofit organization that ensures the safety of public health and environmental protection. It ensures that the materials and additives used in food, water or air are not harmful to health
THIRD-PARTY VERIFIED EPD ISO 14025 and EN 15804 Institut Bauen und Umwelt e.V.	An EPD (Environmental Product Declaration) is a multipage document that serves to provide transparency to the public regarding the environmental influences of building products. It is the basis for the ecological evaluation of buildings
	For sprinkler systems