ArcelorMittal

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Durability

B. Technical manual

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1. Purpose of the software

The key objective of the design engineer is to choose the most cost-effective sheet pile solution considering the different aspects that influence the structure safety during its lifetime.

Durability is a software that simplifies the choice of a steel sheet pile section taking into account the durability of steel in different environnement and the service life of the sheet pile structure. Only “regular” hot rolled sheet piles Z-type and U-type are handled.

Durability proposes many interesting features as listed below:

- Loads on the sheet pile wall sections can be defined throughout the sheet pile length
- Different corrosion zones may be defined as well as protection zones
- Water level may be different in front and at the back of sheet pile
- A complete project can be verified by defining the Head wall and Anchor wall
- Explicit numerical checks are presented for each level according to the calculation method chosen
- Several “Scenarios” may be tested and compared in the same project
- All sheet piles from ArcelorMittal catalogue may be checked automatically for the same loading conditions
- Anchor rods, plates and waling are also checked for several cases
- Imperial and metric unit system are implemented
- Available filters allow to easily find the valid sheet piles for the defined project
- Numerous input data controls are integrated in the software to avoid inconsistencies

Durability proposes two different calculations:

- Sheet pile verification
- Anchor rods, plates and waling verifications for several cases

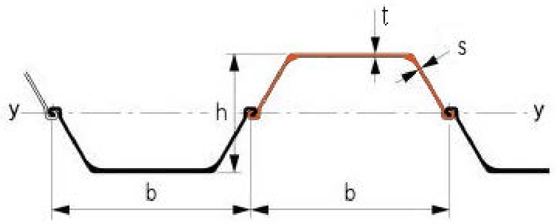
Sheet pile section may be checked by two different design approaches:

- **Eurocode 3 – Part 5** (EC3-5)
- **Allowable Stress Design** (ASD)

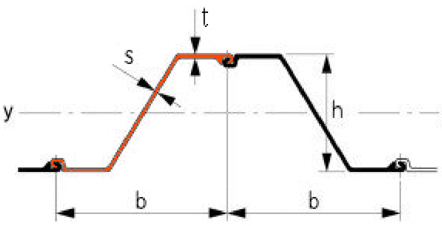
The first part of this technical manual deals with the sheet pile verification.

The second part deals with anchor system verification.

Following chapters will show the different options and assumptions that have been implemented in the software for each calculation method.



U piles geometry



Z piles geometry

2. Symbols

This chapter aims to include all needed parameters in calculations proposed by Durability.

Metric (SI) an Imperial units and description are provided.

2.1. Sheet pile check

Sheet pile properties

Property	Metric (SI)	Imperial	Description
Name	-	-	Sheet pile name
Steel grade	-	-	Different available steel grades
f_y	MPa	ksi	Different available yield strength of steel
W_{el}	cm³/m	in³/ft	Elastic section modulus
W_{pl}	cm³/m	in³/ft	Plastic section modulus
I	cm⁴/m	in⁴/ml	Moment of inertia
A	cm²/m	in²/ft	Cross-sectional area
$t_{f,ini}$	mm	in	Nominal flange thickness of a steel sheet pile (initial)
$t_{w,ini}$	mm	in	Nominal web thickness of the steel sheet pile (initial)
h	mm	in	Height of cross-section
α	°	°	Inclination of the web
b	mm	in	Nominal flange width
$c=\left(h_{ini}-t_{f,ini}\right)/\sin\alpha$ for Z-piles $c=\left(h_{ini}-t_{f,ini}\right)/\left(2\sin\alpha\right)$ for Upile	mm	in	Slant height of the web of steel sheet piles
b_d	mm	in	Double sheet pile width
b_s	mm	in	Single sheet pile width
A_v	cm²/m	in²/ft	Projected shear area of the web
G_{ssp}	kg/m²	lb/ft²	Mass of the steel sheet piling wall

Following parameters will be calculated automatically:

Parameter	Metric (SI)	Imperial	Description
Initial class	-	-	Section class (initial), defined in EC3-5 Table 5.1
Reduced class	-	-	Section class (reduced), defined in EC3-5 Table 5.1
$\varepsilon=\sqrt{235/f_y}$	-	-	Parameter as function of f_y
h_{red}	mm	in	Reduced height of cross-section
$t_{f,red}$	mm	in	Reduced nominal flange thickness of a steel sheet pile
$t_{w,red}$	mm	in	Reduced nominal web thickness of the steel sheet pile
$A_{v,red}=\frac{\left(h_{red}-t_{f,red}\right)}{b_s}\cdot t_{w,red}$	cm²/m	in²/ft	Reduced projected shear area of the web

Additional constant parameters:

Parameter	Metric (SI)	Imperial Unit	Description
E	kN/m²	ksf	Modulus of elasticity (210E+6 kN/m²)
ρ	kg/m³	lb/ft³	Unit mass (7850 kg/m³)

Loads, geometry and partial safety factors:

Parameter	Metric (SI)	Imperial Unit	Description
N_{Ed}	kN/m	kip/ft	Design axial force derived from a calculation
V_{Ed}	kN/m	kip/ft	Design shear force derived from a calculation
M_{Ed}	kNm/m	kip*ft/ft	Design bending moment derived from a calculation
l	m	ft	Buckling length (please, refer to EC3-5 Figure 5.8)
$z_{w,front}$	m	ft	Water level in front of the sheet pile
$z_{w,front}$	m	ft	Water level at the back of the sheet pile
Profile	-		Sheet pile section
f_y	MPa	ksi	Yield strength of steel
β_B	-	-	Factor accounting for the possible reduction of the section modulus of U-piles due to insufficient shear force transmission in the interlocks
β_D	-	-	Factor accounting for the possible reduction of the bending stiffness of U-piles due to insufficient shear force transmission in the interlocks
γ_{M0}	-	-	Partial safety factor according to EC3-5 §5.1.1 (4)
γ_{M1}	-	-	Partial safety factor according to EC3-5 §5.1.1 (4)
Service life	Years	Years	Service life
p_{front}	Years	Years	Protection on the front side
p_{back}	Years	Years	Protection at the back side
L_{wall}	m	ft	Wall length
L_{ssp}	m	ft	Sheet pile length

ASD parameters:

Result	Metric (SI)	Imperial Unit	Description
$\sigma_{applied}$	MN/m²	ksi	Stress applied or generated by the loads (M, N)
$\sigma_{allowable}$	MN/m²	ksi	Maximum value of allowable stress
$S_{f,ini}$	-	-	Safety factor without taking into account the loss of steel thickness
$S_{f,red}$	-	-	Safety factor taking into account the loss of steel thickness

Eurocode 3 – Part 5 results:

Check	Result	Metric (SI)	Imperial Unit	Description
1	$M_{c,Rd}$	kNm/m	ksf/ft	Design moment resistance of the cross-section
	ρ_P	-	-	Reduction parameter of yield strength
	$f_{y,red}$	MN/m²	ksft	Reduced yield strength
2	$V_{pl,Rd}$	kN/m	kips/ft	Design shear resistance of the cross-section
	ρ	-	-	Reduction factor of bending moment
	$M_{V,Rd}$	kNm/m	ksf/ft	Reduced design moment resistance
3	$c/t_w > 72\varepsilon$	-	-	Web slenderness
	$\overline{\lambda}$	-	-	Relative web slenderness
	f_{bv}	MN/m²	ksft	Shear buckling strength
	$V_{b,Rd}$	kN/m	kips/ft	Shear buckling resistance
4	N_{cr}	kN/m	kips/ft	Critical axial load regarding buckling effect
	$N_{pl,Rd}$	kN/m	kips/ft	Plastic design resistance of the cross-section
	α	-	-	Imperfection factor
	$\overline{\lambda}$	-	-	Non-dimensional slenderness
	Φ	-	-	Numerical function
	χ	-	-	Buckling coefficient
	$\frac{N_{Ed}}{\chi N_{pl,Rd}} + 1{,}15 \frac{M_{Ed}}{M_{c,Rd}}$	-	-	Buckling numerical check
5	$N_{pl,Rd}$	kN/m	kips/ft	Design axial load resistance of the cross-section
	$\frac{N_{Ed}}{N_{pl,Rd}}$	-	-	Axial loads relation
	k_1	-	-	Parameter equal to 0.10 or 0.25 depending on profile type and its class
	k_2	-	-	Parameter equal to 1.00, 1.11 or 1.33 depending on profile type and its class
	$M_{N,Rd}$	kNm	ksf/ft	Maximum bending moment
	$M_{N,Rd} \leq M_{c,Rd}$	-	-	True or False
6	$V_{pl,Rd}$	kN/m	kips/ft	Design shear resistance of the cross-section
	ρ	-	-	Numerical parameter
	$f_{y,red}$	MN/m²	ksf	Reduced yield strength
	$M_{c,Rd,red}$	kNm/m	ksf/ft	Reduced design moment resistance of the cross-section
	$M_{N,Rd,red}$	kNm	ksf/ft	Reduced maximum bending moment

2.2. Anchor system check

Result	Metric (SI)	Imperial Unit	Description
F_{anchor}	kN	kips	ULS axial anchor reaction per anchor
F_{Ed}	kN	kips	ULS axial anchor reaction per unit length
$F_{t,ser}$	kN	kips	SLS axial anchor reaction per unit length
F_{bolt}	kN	kips	ULS axial bolt reaction per bolt
Sp	m	ft	Anchor spacing
n	-	-	Number of sheet pile system between anchors
b_{sys}	m	ft	Sheet pile system width
A_g	cm²	in²	Initial gross cross sectional area of anchor
A_s	cm²	in²	Initial tensile stress area of thread
$A_{g,red}$	cm²	in²	Reduced gross cross sectional area of anchor
$A_{s,red}$	cm²	in²	Reduced tensile stress area of thread
A_{net}	cm²	in²	Gross cross-sectional area of the bolt
f_{ua}	MPa	ksi	Tensile strength of the steel anchor
k_t	-	-	Reduction factor allowing for combined bending and tension in the thread
n_{waling}	-	-	Number of waling channels equals to 2 by default

Additional partial safety factors:

Result	Metric (SI)	Imperial Unit	Description
γ_{M2}	-	-	Partial safety factor according to the EC3-5 7.1 (4)
$\gamma_{Mt,ser}$	-	-	Partial safety factor according to Eurocode 3 -5 7.1 (4)
$S_{f,waling}$	-	-	Safety factor on waling steel grade

Plates, swivel and nuts geometry parameters:

Result	Metric (SI)	Imperial Unit	Description
b_a	mm	in	Plate width
h_a	mm	in	Plate height
t_a	mm	in	Plate thickness
d'	mm	in	Load spread diameter
d	mm	in	Diameter of hole in bearing plate
b_{sp}	mm	in	Swivel plate width
h_{sp}	mm	in	Swivel plate height
t_{sp}	mm	in	Swivel plate thickness
w_{sp}	mm	in	Diameter of round part of swivel plate
d_{sp}	mm	in	Diameter of hole in swivel plate
d_{sg}	mm	in	Diameter across flats of nut

Loads

Result	Metric (SI)	Imperial Unit	Description
F	kN	kips	Horizontal component of anchor load (ULS value)
F_P	kN	kips	Load supported by the pile
F_W	kN	kips	Load supported by the waling

3. Sheet pile section verification

3.1. Design approaches

Sheet pile section may be verified by two different design approaches:

- **Eurocode 3 – Part 5** (EC3-5)
- **Allowable Stress Design** (ASD)

3.1.1. Allowable Stress Design approach (ASD)

This method compares stress generated by the loads on the corroded sheet section to the maximum stress allowed.

$$\sigma_{applied} = \frac{M}{W_{el,red}} + \frac{N \cdot e}{W_{el,red}} + \frac{N}{A_{red}} \leq \sigma_{allowable} = \frac{f_y}{S_f}$$

Where:

$\sigma_{applied}$	Stress applied or generated by the loads (M, N) on the sheet pile section
$\sigma_{allowable}$	Maximum value of allowable stress
N	Compression load applied on the section
M	Bending moment applied on the section
e	Eccentricity of compression load
$W_{el,red}$	Reduced elastic section modulus of the sheet pile section
A_{red}	Reduced cross-section area of the sheet pile section
f_y	Yield strength of steel
S_f	Safety factor

This calculation method may be used in two ways:

- S_f will be calculated for a sheet pile section chosen by the user (see Results tab) and for all sheet piles included in ArcelorMittal catalogue (see Sf summary tab)
- For S_f defined by the user, software may provide all possible sheets piles that reach the criteria. For that, active “*Only valid sheet pile”* in Sheet pile tab.

Output parameters are summarized in the following table:

3.1.2. Eurocode 3 – Part 5

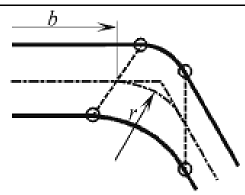
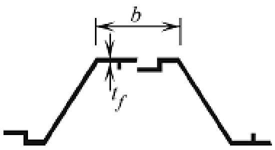
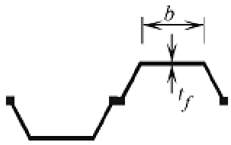
Eurocode 3 – Part 5 calculates first the class of the sheet pile section.

All checks require comparing design values of loads and their maximum allowable values. Sometimes, it is necessary to check the interaction among loads.

3.1.2.1. Section classification

Eurocode 3 – Part 5 requires section classification before numerical checks. Section pile section is classified according to the Table 5-1:

Table 5-1: Classification of cross-sections

Classification	Z-profile	U-profile
		
Class 1	- the same boundaries as for class 2 apply - a rotation check has to be carried out	
Class 2	$\frac{b/t_f}{\varepsilon} \leq 45$	$\frac{b/t_f}{\varepsilon} \leq 37$
Class 3	$\frac{b/t_f}{\varepsilon} \leq 66$	$\frac{b/t_f}{\varepsilon} \leq 49$

$\varepsilon = \sqrt{\frac{235}{f_y}}$	f_y [N/mm²]	240	270	320	355	390	430
	ε	0,99	0,93	0,86	0,81	0,78	0,74

Key:

b: width of the flat portion of the flange, measured between the corner radii, provided that the ratio r/t_f is not greater than 5,0; otherwise a more precise approach should be used;
t_f: thickness of the flange for flanges with constant thickness;
r: midline radius of the corners between the webs and the flanges;
f_y: yield strength.

Note: For class 1 cross-sections it should be verified that the plastic rotation provided by the cross-section is not less than the plastic rotation required in the actual design case. Guidance for this verification (rotation check) is given in Annex C.

It's important to note that Durability doesn't handle class 4 section. If $(b/t_f)/\varepsilon > k$, section will be classified as class 4, but will be considered as Class 3 using Eurocode 3-1-1 §5.5.2 (9) with reduced grade $f_{y,red}$:

> (9) Except as given in (10) Class 4 sections may be treated as Class 3 sections if the width to thickness ratios are less than the limiting proportions for Class 3 obtained from Table 5.2 when ε is increased by $\sqrt{\frac{f_y/\gamma_{M0}}{\sigma_{com,Ed}}}$, where $\sigma_{com,Ed}$ is the maximum design compressive stress in the part taken from first order or where necessary second order analysis.

Consequently, reduced grade will be calculated as:

$$f_{y,red} = \frac{235 \cdot k^2 \cdot t_f^2}{b^2} \text{ with } k = 66 \text{ for Z-piles and } k = 49 \text{ for U-piles}$$

3.1.2.2. Numerical checks

3.1.2.2.1. Bending moment [EC3-5 5.2.2: (1) (2)]

In absence of shear force and axial force, the design value of the bending moment M_{Ed} should satisfy:

$$M_{Ed} \leq M_{c,Rd}$$

Where:

M_{Ed} Design bending moment, derived from a calculation

$M_{c,Rd}$ Design moment resistance of the cross-section

$M_{c,Rd}$ should be determined from the following expressions:

- Class 1 or 2 cross-sections: $M_{c,Rd} = \beta_B W_{pl} f_y / \gamma_{M0}$
- Class 3 cross-sections: $M_{c,Rd} = \beta_B W_{el} f_y / \gamma_{M0}$
- Class 4 cross-sections: reduced yield strength $f_{y,red}$ and then section fulfils class 3 criteria $f_{y,red} = \frac{235 \cdot k^2 \cdot t_f^2}{b^2}$ where $k = 66$ for Z-piles and $k = 49$ for U-piles according to EC3-5 Table 5.1.

Where:

W_{el} Elastic section modulus

W_{pl} Plastic section modulus

γ_{M0} Partial safety factor equals to 1.0 by default according to 5.1.1 (4) (customizable by user)

β_B Factor that takes account a possible lack of shear force transmission in the interlocks and has the following values:

$\beta_B = 1.0$ for Z-piles and triple U-piles

$\beta_B \leq 1.0$ for single and double U-piles

Utilization factor: $U_f = \frac{M_{Ed}}{M_{c,Rd}}$

3.1.2.2.2. Bending moment and shear interaction [EC3-5 5.2.2: (3) (4) (5) (8) (9)]

The design value of the shear force V_{Ed} at each cross-section should satisfy:

$$V_{Ed} \leq V_{pl,Rd}$$

Where:

V_{Ed}	Design shear, derived from a calculation
$V_{pl,Rd} = \dfrac{A_v f_y}{\sqrt{3}\gamma_{M0}}$	Design plastic shear resistance for each web
A_v	Projected shear area for each web, acting in the same direction as V_{Ed}

One has to check:

- If $V_{Ed} \leq 0.50 \cdot V_{pl,Rd}$, no reduction need to be made in the design moment resistance $M_{c,Rd}$.
- If $V_{Ed} > 0.50 \cdot V_{pl,Rd}$, the design moment resistance of the cross-section should be reduced to $M_{V,Rd}$, the reduced design plastic moment resistance allowing for the shear force, is obtained as follows:

$$M_{V,Rd} = \frac{1}{b_d} \cdot \left[\beta_B W_{pl} b_d - \frac{\rho (A_v \cdot b_d)^2}{4(2 \cdot t_w) \sin \alpha} \right] \frac{f_y}{\gamma_{M0}} \qquad \text{but} \qquad M_{V,Rd} \leq M_{c,Rd}$$

Where $\rho = (2V_{Ed} / V_{pl,Rd} - 1)^2$

t_w Web thickness

α Inclination of the web

Utilization factor:

$$U_f = \frac{V_{Ed}}{V_{pl,Rd}} \qquad \text{if } V_{Ed} \leq 0.50 \cdot V_{pl,Rd}$$

$$U_f = max\left(\frac{V_{Ed}}{V_{pl,Rd}}, \frac{M_{Ed}}{M_{V,Rd}}\right) \qquad \text{if } V_{Ed} > 0.50 \cdot V_{pl,Rd}$$

3.1.2.2.3. Web shear buckling [5.2.2: (6) (7)]

If $c / t_w > 72\varepsilon$, the shear buckling resistance of the webs of sheet piles should be verified.

The shear buckling resistance should be obtained from $V_{b,Rd} = \dfrac{(h - t_f) t_w f_{bv}}{\gamma_{M0} b_s}$

Where f_{bv} is the shear buckling strength according to Table 6-1 of EN 1993-1-3 for a web without stiffening at the support and for a relative web slenderness given by $\bar{\lambda} = 0.346 \dfrac{c}{t_w} \sqrt{\dfrac{f_{yb}}{E}}$ with $f_{yb} = f_y$.

Utilization factor:

$$U_f = \frac{V_{Ed}}{V_{b,Rd}}$$

Table 6.1: Shear buckling strength f_{bv}

Relative web slenderness	Web without stiffening at the support	Web with stiffening at the support [1]
$\bar{\lambda}_w \leq 0{,}83$	$0{,}58 f_{yb}$	$0{,}58 f_{yb}$
$0{,}83 < \bar{\lambda}_w < 1{,}40$	$0{,}48 f_{yb} / \bar{\lambda}_w$	$0{,}48 f_{yb} / \bar{\lambda}_w$
$\bar{\lambda}_w \geq 1{,}40$	$0{,}67 f_{yb} / \bar{\lambda}_w^2$	$0{,}48 f_{yb} / \bar{\lambda}_w$

[1] Stiffening at the support, such as cleats, arranged to prevent distortion of the web and designed to resist the support reaction.

3.1.2.2.4. Buckling: bending and axial force [EC3-5 5.2.3: (1) (2) (3) (4)]

First check to be done: $$N_{Ed} \le N_{pl,Rd}$$ [Criterion 1]

Member buckling doesn't need to be taken into account if:

$$\frac{N_{Ed}}{N_{cr}} \le 0.04$$ [Criterion 2]

N_{Ed} Design value of the compression force

N_{cr} Elastic critical load of the sheet pile, calculated with following expression:

$$N_{cr} = EI\beta_D \pi^2 / l^2$$

In which l is the buckling length.

$$N_{Ed} \le N_{cr}$$

If the criterion 2 is not satisfied, the buckling resistance should be verified as follows for class 1, 2 and 3 sections:

$$\frac{N_{Ed}}{\chi N_{pl,Rd}} + 1{,}15 \frac{M_{Ed}}{M_{c,Rd}} \le \frac{\gamma_{M0}}{\gamma_{M1}}$$ [Criterion 3]

$N_{pl,Rd}$ Plastic design resistance of the cross-section equals to $\frac{Af_y}{\gamma_{M0}}$

$M_{c,Rd}$ Design moment resistance of the cross-section

N_{cr} Elastic critical load

A Cross-sectional area

γ_{M0} Partial safety factor

γ_{M1} Partial safety factor

χ Buckling coefficient factor from 6.3.1.2 of EN 1993-1-1, using curve "d" and a non-dimensional slenderness given by:

$$\chi = \min\left\{1.0; \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}\right\}$$

$$\Phi = 0.5 \cdot \left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}}$$

α Imperfection factor equals to 0.76 (curve "d")

For class 4 section, reduced yield strength $f_{y,red}$ is considered and then section fulfils class 3 criteria:

$$f_{y,red} = \frac{235 \cdot k^2 \cdot t_{r,red}^2}{b^2}$$

$k = 66$ for Z-piles and $k = 49$ for U-piles according to EC3-5 Table 5.1

Utilization factor:

- $U_f = \frac{N_{Ed}}{N_{pl,Rd}}$ if $N_{Ed} \le N_{pl,Rd}$ and $\frac{N_{Ed}}{N_{cr}} \le 0.04$
- $U_f = \max\left(\frac{N_{Ed}}{N_{pl,Rd}}, \frac{\frac{N_{Ed}}{\chi N_{pl,Rd}} + 1.15\frac{M_{Ed}}{\chi M_{c,Rd}}}{\gamma_{M0}/\gamma_{M1}}\right)$ if $N_{Ed} \le N_{pl,Rd}$ and $\frac{N_{Ed}}{N_{cr}} > 0.04$

3.1.2.2.5. Bending and axial force [EC3-5 5.2.3: (9) (10) (11)]

For members subject to axial force, the design value of the axial force N_{Ed} at each cross-section should satisfy:

$$N_{Ed} \leq N_{pl,Rd}$$

$N_{pl,Rd}$ Plastic design resistance of the cross-section equals to $\dfrac{Af_y}{\gamma_{M0}}$

The effects of axial force on the plastic moment resistance of the cross-section of class 1, 2 and 3 sheet piles may be neglected if:

$$\frac{N_{Ed}}{N_{pl,Rd}} \leq k_1$$

- For Z-profiles of class 1 and 2: $k_1 = 0.10$
- For U-profiles of class 1 and 2: $k_1 = 0.25$
- For class 3 profiles: $k_1 = 0.10$

If the axial force exceeds these limiting values, the following criteria should be satisfied in the absence of shear force:

$$M_{N,Rd} = k_2 M_{c,Rd}\left(1 - \frac{N_{Ed}}{N_{pl,Rd}}\right) \text{ but } M_{N,Rd} \leq M_{c,Rd}$$

- For class 1 and 2 cross-sections:
  - For Z-profiles: $k_2 = 1.00$
  - For U-profiles: $k_2 = 1.33$
- For class 3 cross-sections: $k_2 = 1.00$
- For class 4 cross-sections: reduced yield strength $f_{y,red}$ and then section fulfils class 3 criteria
  $f_{y,red} = \dfrac{235 \cdot k^2 \cdot t_f^2}{b^2}$ where $k = 66$ for Z-piles and $k = 49$ for U-piles according to EC3-5 Table 5.1

Where: $M_{N,Rd}$ Reduced design moment resistance allowing for the axial force

Utilization factor: $U_f = \dfrac{N_{Ed}}{N_{pl,Rd}}$

3.1.2.2.6. Bending, shear and axial force [EC3-5 5.2.3: (12)]

If the axial force exceeds the limiting value, the combined presence of bending, axial and shear force should be considered as follows:

a) Provided that the design value of the shear force V_{Ed} does not exceed 50% of the design plastic shear resistance $V_{pl,Rd}$ no reduction need to be made in combinations of moment and axial force.

b) When V_{Ed} exceeds 50% of $V_{pl,Rd}$ the design resistance of the cross-section should be calculated using a reduced yield strength $f_{y,red} = (1-\rho) f_y$ for the shear area, where $\rho = (2V_{Ed}/V_{pl,Rd} - 1)^2$.

$$M_{Ed} \leq M_{N,Rd,red(f_y=f_{y,red})} = k_2 M_{c,Rd,red(f_y=f_{y,red})}\left(1 - \frac{N_{Ed(f_y=f_{y,red})}}{N_{pl,Rd,red(f_y=f_{y,red})}}\right)$$

3.1.2.3. Local effects of water pressure [EC3-5 5.2.4]

When the differential water pressure exceeds 5 m head for Z-piles and 20 m head for U-piles, the effects of water pressure on transverse local plate bending should be taken into account to determine the overall bending resistance by using a reduced yield strength.

$$f_{y,red} = \rho_P f_y$$

With ρ_P taken from following table:

Table 5-2: Reduction factors ρ_P for Z-piles due to differential water pressure

w	$(b/t_{min})\ \varepsilon = 20{,}0$	$(b/t_{min})\ \varepsilon = 30{,}0$	$(b/t_{min})\ \varepsilon = 40{,}0$	$(b/t_{min})\ \varepsilon = 50{,}0$
5,0	1,00	1,00	1,00	1,00
10,0	0,99	0,97	0,95	0,87
15,0	0,98	0,96	0,92	0,76
20,0	0,98	0,94	0,88	0,60

Key:

b is the width of the flange, but b should not be taken as less than $c/\sqrt{2}$, where c is the slant height of the web

t_{min} is the lesser of t_f or t_w

t_f is the flange thickness

t_w is the web thickness

w is the differential head in m

$\varepsilon = \sqrt{\dfrac{235}{f_y}}$; f_y is the yield strength in N/mm².

Notes:

1) $\rho_P = 1{,}0$ may be used if the interlocks of Z-piles are welded.

2) Intermediate values may be interpolated linearly.

A welded option will allow the use of ρ_P =1 for welded Z-piles.

Since the EC3-5 doesn't provide ρ_P values for U piles, Durability will not allow to consider U-piles with w > 20 m, and an alert message will be displayed in this case.

3.1.2.4. Corrosion rates

Loss of thickness (mm) due to corrosion of sheet piles will be provided by the following tables and the reduced sheet pile properties will be calculated accordingly.

- **EC3-5 Tables 4.1and 4.2**

Table 4-1: Recommended value for the loss of thickness [mm] due to corrosion for piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils (sand, silt, clay, schist, ...)	0,00	0,30	0,60	0,90	1,20
Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00
Aggressive natural soils (swamp, marsh, peat, ...)	0,20	1,00	1,75	2,50	3,25
Non-compacted and non-aggressive fills (clay, schist, sand, silt, ...)	0,18	0,70	1,20	1,70	2,20
Non-compacted and aggressive fills (ashes, slag, ...)	0,50	2,00	3,25	4,50	5,75

Notes:

1) Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.

2) The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

Table 4-2: Recommended value for the loss of thickness [mm] due to corrosion for piles and sheet piles in fresh water or in sea water

Required design working life	5 years	25 years	50 years	75 years	100 years
Common fresh water (river, ship canal, ...) in the zone of high attack (water line)	0,15	0,55	0,90	1,15	1,40
Very polluted fresh water (sewage, industrial effluent, ...) in the zone of high attack (water line)	0,30	1,30	2,30	3,30	4,30
Sea water in temperate climate in the zone of high attack (low water and splash zones)	0,55	1,90	3,75	5,60	7,50
Sea water in temperate climate in the zone of permanent immersion or in the intertidal zone	0,25	0,90	1,75	2,60	3,50

Notes:

1) The highest corrosion rate is usually found in the splash zone or at the low water level in tidal waters. However, in most cases, the highest bending stresses occur in the permanent immersion zone, see Figure 4-1.

2) The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

- **EC3-5 NAD UK (2010) Tables 4.1and 4.2**

Table 4.1 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years	125 years
Undisturbed natural soils (sand, silt, clay, schist…)	0,00	0,30	0,60	0,90	1,20	1,50
Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00	3,75
Aggressive natural soils (swamp, marsh, peat…)	0,20	1,00	1,75	2,50	3,25	4,00
Non-compacted and non-aggressive fills (clay, schist, sand, silt…)	0,18	0,70	1,20	1,70	2,20	2,70
Non-compacted and aggressive fills (ashes, slag…)	0,50	2,00	3,25	4,50	5,75	7,00

NOTE 1 Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.

NOTE 2 The values given for 5 years and 25 years are based on measurements, whereas the other values are extrapolated.

Table 4.2 – Loss of thickness (mm) per face due to corrosion of bearing piles and sheet piles in fresh water or seawater

Required design working life	5 years	25 years	50 years	75 years	100 years	125 years
Common fresh water (river, ship canal) in the zone of high attack (water line)	0,15	0,55	0,90	1,15	1,40	1,65
Brackish or very polluted fresh water (sewage, industrial effluent…) in the zone of high attack (water line)	0,30	1,30	2,30	3,30	4,30	5,30
Sea water in temperate climates in the high tide splash zone or in the low water zone (see Note 3)	0,55	1,90	3,75	5,60	7,50	Protection system required
Sea water in temperate climates in the zone of permanent immersion or in the intertidal zone	0,25	0,90	1,75	2,60	3,50	4,40

NOTE 1 The highest corrosion rate is usually found in the splash zone or at the low water level in tidal waters. However, in most cases, the highest bending stresses occur in the permanent immersion zone (see BS EN 1993-5:2007, Figure 4-1).

NOTE 2 The values given for 5 years and 25 years are based on measurements, whereas the other values are extrapolated.

NOTE 3 The values in this table for corrosion loss in the low water zone apply to situations where the effects of Accelerated Low Water Corrosion (ALWC) are not a design requirement. ALWC is a particularly aggressive form of corrosion associated with bacterial activity at low water level in marine conditions. Attack is random both within and between locations and typically at or just above the lowest astronomical tide (LAT) level. Due to the high rate of steel loss when ALWC occurs, the life expectancy of a pile will be short and it is recommended that a protection system is used to control the situation rather than reliance on sacrificial steel. Suitable options may be painting or cementitious coating but it is also recommended that consideration is given to installation of a cathodic protection system either immediately or at a later date if necessary. Whilst this phenomenon might not affect every location, if ignored, this rapid form of attack can result in costly repair and maintenance works at an unexpectedly early stage in the life of a structure.

- **Custom**: defined by the user.

4. Anchor system verification

4.1. Cases classification

4.1.1. Central Anchor

Four different cases are considered:

- Case 7.4 Anchoring with a waling behind the sheet pile wall
- Case 7.5a Anchoring without a waling (anchor located in an in-pan of the sheet pile wall)
- Case 7.5b Anchoring without a waling (anchor located on an out-pan of the sheet pile wall)
- Case 7.6 Anchoring with waling in front of the sheet pile wall

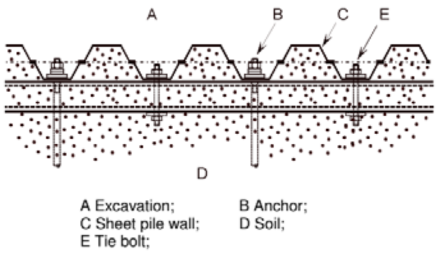


Figure 7-4: Example of anchoring with a waling behind the sheet pile wall

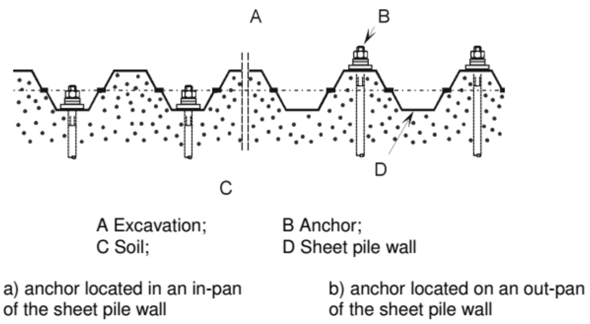


Figure 7-5: Examples of anchoring without a waling

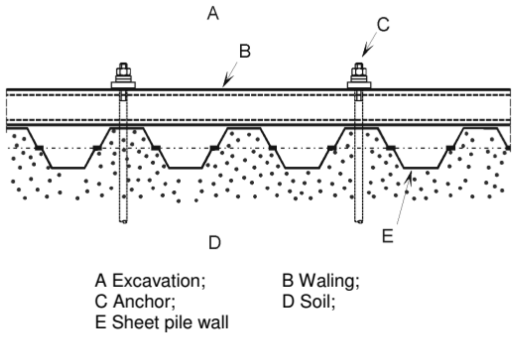


Figure 7-6: Example of a waling in front of the sheet pile wall

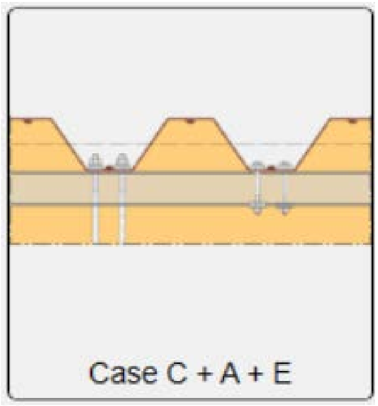
Case	Checks to be done according to EC3-5
7.4	• Plate dimensions • Shear resistance of flange EC3-5 §7.4.3 (3a) • Tensile resistance of webs EC3-5 §7.4.3 (3b)
7.5a	• Plate dimensions • Shear resistance of flange EC3-5 §7.4.3 (3a) • Tensile resistance of webs EC3-5 §7.4.3 (3b)
7.5b	• Plate dimensions • Shear resistance to the local transverse force EC3-5 §7.4.3 (4)
7.6	• Plate dimensions • Shear resistance to the local transverse force EC3-5 §7.4.3 (4)

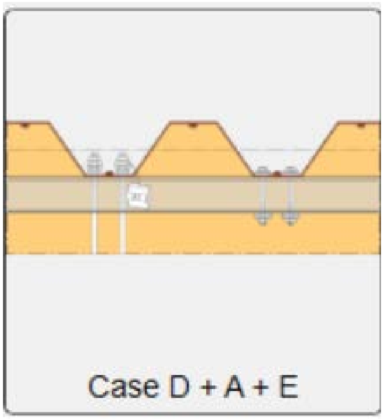
4.1.2. Double centric anchor

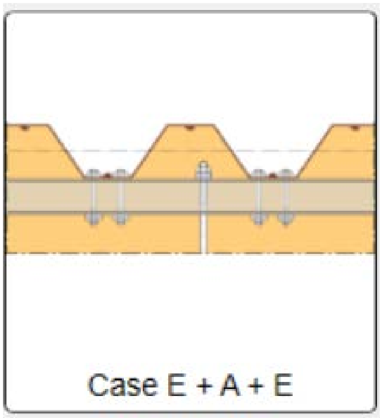
According to specific conditions provided by ArcelorMittal (cf. *"AZ-Stahlspundwände Exzentrische Verankerung"*"), AZ-piles should be specifically verified when they are submitted to a double centric anchor reaction.

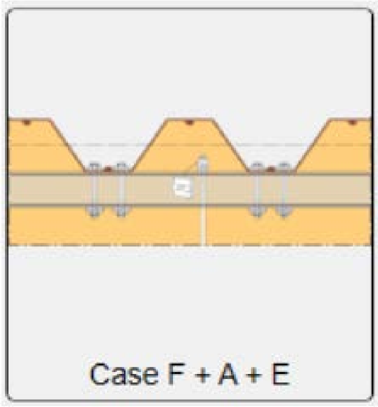
There are four cases:

- **Case C+A+E:** with waling, 2 anchors/bolts and without swivel
  - The tie-rod is checked according to Table 6.13 (cf. 4.5.1.2.2.2)
  - The bolts are checked according to Table 6.3 (cf. 4.5.1.2.2.2)
- **Case D+A+E:** with waling, 2 anchors/bolts and with swivel
  - The tie-rod is checked according to Table 6.14 (cf. 4.5.1.2.2.2)
  - The bolts are checked according to Table 6.3 (cf. 4.5.1.2.2.2)
- **Case E+A+E:** with waling, 1 anchor on waling, 2 bolts and without swivel
  - The tie-rod is checked according to Case E from eccentric brochure (cf. 4.5.2)
  - The bolts are checked according to Table 6.3 (cf. 4.5.1.2.2.2)
- **Case F+A+E:** with waling, 1 anchor on waling, 2 bolts and with swivel
  - The tie-rod is checked according to Case F from eccentric brochure (cf. 4.5.2)
  - The bolts are checked according to Table 6.3 (cf. 4.5.1.2.2.2)









4.2. Anchor

4.2.1. ASD method

Load per anchor is calculated from the following expression:

$$F_{anchor,ULS} = F_{Ed,ULS}Sp = F_{Ed,ULS}nb_{sys}$$

Where:

$F_{anchor,ULS}$	ULS axial anchor reaction per anchor (kN or kips)
$F_{Ed,ULS}$	ULS axial anchor reaction per unit length (kN/m or kips/ft)
Sp	Anchor spacing (m or ft)
n	Number of sheet pile system between anchors (no unit)
b_{sys}	Sheet pile system width (m or ft)

ASD calculation method depends on anchor type:

- If the anchor chosen is ASDO type

  Allowable stresses:

$$\sigma_{allowable,shaft} = \frac{kf_y}{S_{f,shaft}}$$
$$\sigma_{allowable,thread} = \frac{kf_y}{S_{f,thread}}$$

  Allowable loads:

$$F_{allowable,shaft} = \sigma_{allowable,shaft}A_{g,red}$$
$$F_{allowable,thread} = \sigma_{allowable,thread}A_{s,red}$$
$$F_{anchor,ULS} \leq min(F_{allowable,shaft}, F_{allowable,thread})$$

  Where:

  - k is a factor equal to 1.15 for seismic conditions, otherwise it is equal to 1.0.
  - $A_{g,red}$ is the reduced gross cross sectional area of anchor
  - $A_{s,red}$ is the reduced tensile stress area of thread

- If the anchor chosen is AMTB type:

  Allowable stress:

$$\sigma_{allowable,thread} = \frac{kf_y}{S_{f,thread}}$$

  Allowable load:

$$F_{allowable,thread} = \sigma_{allowable,thread}A_{s,red}$$

$$F_{anchor,ULS} \leq F_{allowable,thread}$$

  Where k is a factor equal to 1.15 for seismic conditions, otherwise it is equal to 1.0.

4.2.2. Eurocode method

4.2.2.1. Ultimate limit state verification (ULS)

According to EC3-5 §7.2.3, the tensile resistance $F_{t,Rd}$ of anchors should be taken as the lesser of $F_{tt,Rd}$ and $F_{tg,Rd}$.

$$F_{Ed} \leq F_{t,Rd}$$

$$F_{t,Rd} = \min(F_{tt,Rd}, F_{tg,Rd})$$

$$F_{tt,Rd} = k_t \frac{f_{ua} A_s}{\gamma_{M2}} \qquad F_{tg,Rd} = \frac{A_g f_y}{\gamma_{M0}}$$

Where:

- A_s Tensile stress area at the threads
- f_{ua} Tensile strength of the steel anchor
- γ_{M2} Partial safety factor
- k_t Reduction factor allowing for combined bending and tension in the thread
- A_g Gross cross-sectional area of the anchor rod

4.2.2.2. Serviceability limit state verification (SLS)

According to EC3-5 §7.2.4, for serviceability limit state verifications, the cross-section of the anchor shall be designed to prevent deformations due to yielding of the tie rod under the characteristic load combination.

$$F_{Ed} \leq F_{t,ser}$$

$$F_{t,ser} = \frac{A_s f_y}{\gamma_{Mt,ser}}$$

Where:

- A_s Tensile stress area of the threaded portion or the gross cross-sectional area of the shaft, whichever is smaller.
- $F_{t,ser}$ SLS axial anchor force under characteristic loading
- $\gamma_{Mt,ser}$ Partial safety factor according to Eurocode 3 -5 7.1 (4)

4.3. Bolt

4.3.1. ASD method

Load per bolt is calculated from the following expression:

$$F_{bolt,ULS} = F_{Ed,ULS} b_{sys}$$

Where:

$F_{bolt,ULS}$	ULS axial bolt reaction per bolt (kN or kips)
$F_{Ed,ULS}$	ULS axial bolt reaction per unit length (kN/m or kips/ft)
b_{sys}	Sheet pile system width (m or ft)

Allowable stress:

$$\sigma_{allowable,net\ area} = \frac{k f_y}{S_{f,net\ area}} = \frac{k f_y}{1.67}$$

Allowable load:

$$F_{allowable,net\ area} = \sigma_{allowable,net\ area} A_{net}$$

$$F_{bolt,ULS} \leq F_{allowable,net\ area}$$

Where:

- k is a factor equal to 1.15 for seismic conditions, otherwise it is equal to 1.0.
- A_{net} is the gross cross-sectional area of the bolt

4.3.2. Eurocode method

4.3.2.1. Ultimate limit state verification (ULS)

According to EC3-5 §7.2.3, the tensile resistance $F_{t,Rd}$ of bolts should be taken as the lesser of $F_{tt,Rd}$ and $F_{tg,Rd}$.

$$F_{Ed} \leq F_{t,Rd}$$

$$F_{t,Rd} = \min(F_{tt,Rd}, F_{tg,Rd})$$

$$F_{tt,Rd} = k_t \frac{f_{ua} A_s}{\gamma_{M2}} \qquad F_{tg,Rd} = \frac{A_g f_y}{\gamma_{M0}}$$

Where:

A_s	Tensile stress area at the threads
f_{ua}	Tensile strength of the steel bolt
γ_{M2}	Partial safety factor
k_t	A reduction factor allowing for combined bending and tension in the thread
A_g	Gross cross-sectional area of the bolt

4.3.2.2. Serviceability limit state verification (SLS)

According to EC3-5 §7.2.4, for serviceability limit state verifications, the cross-section of the bolt shall be designed to prevent deformations due to yielding of the bolt under the characteristic load combination.

$$F_{Ed} \leq F_{t,ser}$$

$$F_{t,ser} \leq \frac{A_s f_y}{\gamma_{Mt,ser}}$$

Where:

A_s	Tensile stress area of the threaded portion or the gross cross-sectional area
$F_{t,ser}$	SLS axial force of the bolt under characteristic loading
$\gamma_{Mt,ser}$	Partial safety factor

4.4. Waling

It is important to note that the waling is considered as a continuous beam.

Bending moment applied on waling is calculated as follows:

$$M_{applied} = R * \frac{s^2}{10}$$

Where:

- R ULS anchor reaction per unit length (KN/m or kips/ft)
- s Anchor spacing (m or ft)

Allowable stress:

$$\sigma_{allowable} = \frac{k f_y}{S_{f,waling}}$$

$$W_{el,eq} = n_{waling} W_{el,profil}$$

$$M_{allowable} = W_{el,eq} \sigma_{allowable}$$

$$M_{applied} \leq M_{allowable}$$

Where:

$\sigma_{allowable}$	Allowable stress (MN/m² or ksi)
k	Factor equal to 1.30 for seismic conditions, otherwise it is equal to 1.0
n_{waling}	Number of waling channels equals to 2 by default
f_y	Waling steel grade (MN/m² or ksi)
$S_{f,waling}$	Safety factor on waling steel grade (no unit)
$W_{el,eq}$	Equivalent elastic section modulus for 2 waling channels
$M_{allowable}$	Allowable bending moment (kNm or kips*ft)

4.5. Plates

4.5.1. Centric anchor

Calculation method proposed for ASD and Eurocode depends on the defined case and type of the sheet pile considered (U-pile or Z-pile).

It's important to note that Durability is able to suggest plate dimensions (b_a, h_a, t_a) in order to satisfy all required conditions.

4.5.1.1. Structural verification

For each Eurocode case (except when we have a bolt), we have the choice between a standard plate or a plate with a swivel plate.

For the case 7.4 (EC3-5), the user have to choose between a bolt or tie rod (anchor)

→ For standard plate : $d' = \frac{1}{2}(d + d_{SG})$

→ For plate + swivel plate : $d' = \frac{1}{2}(d_{SP} + d_{SG})$

Where:

d' Load spread diameter

d Diameter of hole in bearing plate

d_{sp} Diameter of hole in swivel plate

d_{sg} Diameter across flats of nut

4.5.1.2. Loads calculation

In case of a waling (cases 7.4 and 7.6), load distribution has to be considered:

$F = F_P + F_W$ Horizontal component of anchor load (ULS value)

$F_P = \frac{F}{n}$ Load supported by the pile

$F_W = F\frac{n-1}{n}$ Load supported by the waling

Where "n" number of systems between 2 anchors

- AZ piles → number of double sheet piles
- U piles → number of simple sheet piles

4.5.1.2.1. U sheet pile

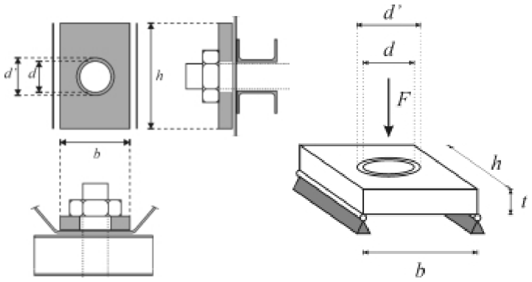
In case of U-piles, all plates have to satisfy following geometry conditions:

$$b_a \geq 0.8 b_f$$

$$h_a \leq 1.5 b_a$$

$$t_a \geq max[\frac{d_A}{3}; 2t_f]$$

- **Case 7.4 (Bolt) – Standard plate**

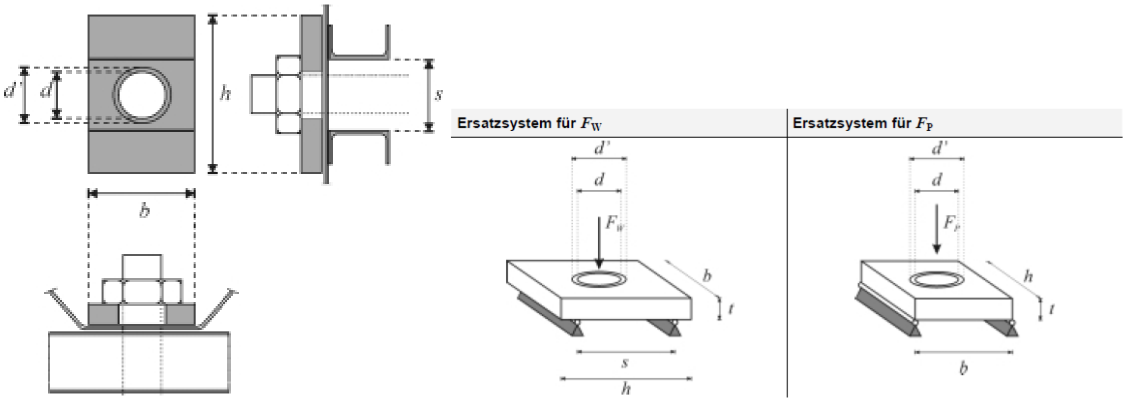


$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(b_a - d') + \sqrt{(b_a - d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}} < F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

- **Case 7.4 (Anchor) – Standard plate**



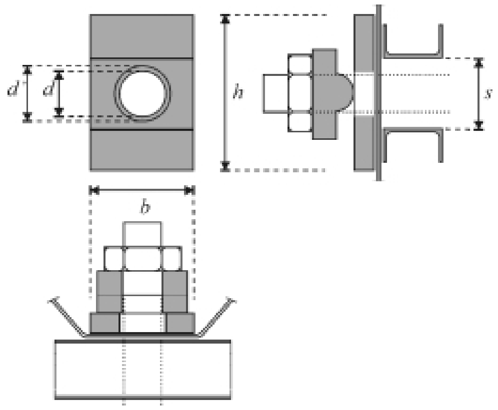
$$F_{P,Ed} \leq F_{P,M,V,Rd} = \frac{2}{3}[-(b_a - d') + \sqrt{(b_a - d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

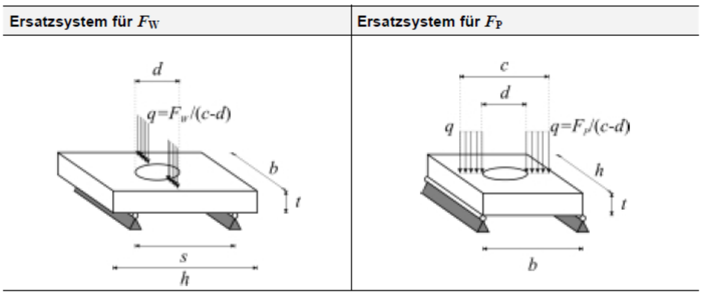
$$F_{W,Ed} \leq F_{W,M,V,Rd} = \frac{2}{3}[-(s - d') + \sqrt{(s - d')^2 + 3t_a^2}](b_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

- **Case 7.4 (Anchor) - Swivel plate**



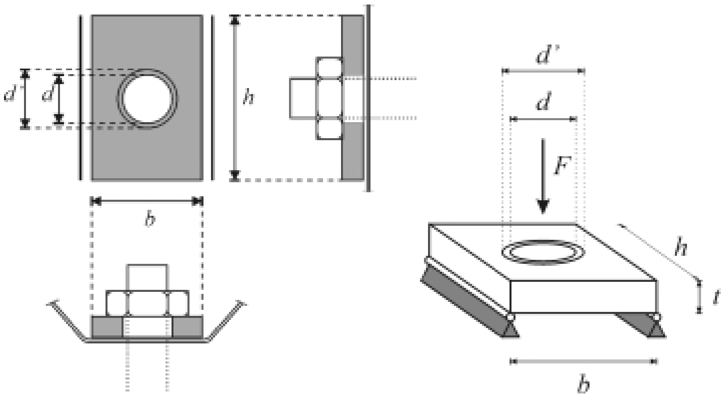


$$F_{P,Ed} \leq F_{P,M,Rd} = 2t_a^2 \frac{h_a - d}{2b_a - c - d} \frac{f_y}{\gamma_{M0}}$$

$$F_{P,Ed} \leq F_{P,V,Rd} = \frac{2}{\sqrt{3}} h_a t_a \frac{f_y}{\gamma_{M0}}$$

$$F_{W,Ed} \leq F_{W,M,V,Rd} = \frac{2}{3}[-s + \sqrt{s^2 + 3t_a^2}](b_a - d) \frac{f_y}{\gamma_{M0}}$$

- **Case 7.5 (Anchor) – Standard plate**



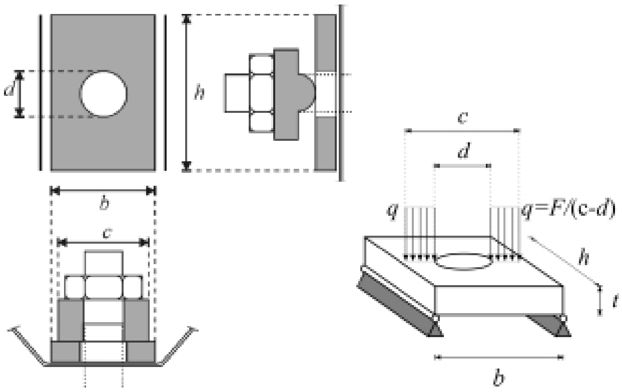
$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(b_a - d') + \sqrt{(b_a - d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}} < F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

In case 7.5b, $b_a \geq max(b, b + 2r_0)$ to ensure that width is long enough in order that the extremities end at the area of load application into the web.

- **Case 7.5 (Anchor) – Swivel plate**



Please, note that the plate steel grade should be at least equal to the swivel plate steel grade.

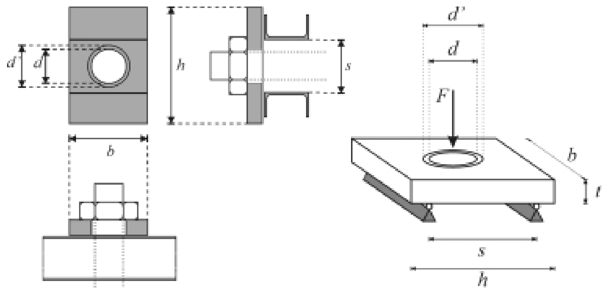
$$F_{Ed} \leq F_{M,Rd} = 2t_a^2 \frac{h_a - d}{2b_a - c - d}\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{V,Rd} = \frac{2}{\sqrt{3}} h_a t_a \frac{f_y}{\gamma_{M0}}$$

$$c = b_{SP}$$

In case 7.5b, $b_a \geq max(b, b + 2r_0)$ to ensure that width is long enough in order that the extremities end at the area of load application into the web.

- **Case 7.6 – Standard plate**



$b_a \leq 1.5h_a$

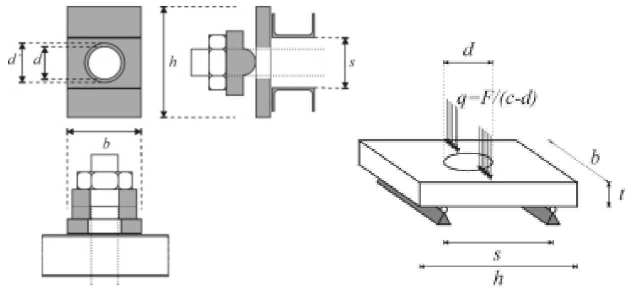
$t_a \geq \frac{d_A}{3}$

$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(s-d') + \sqrt{(s-d')^2 + 3t_a^2}](b_a - d)\frac{f_y}{\gamma_{M0}}$

$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$

$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$

- **Case 7.6 – Swivel plate**



$b_a \leq 1.5h_a$

$t_a \geq \frac{d_A}{3}$

$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-s + \sqrt{s^2 + 3t_a^2}](b_a - d)\frac{f_y}{\gamma_{M0}}$

4.5.1.2.2. Z sheet pile

4.5.1.2.2.1. Single centric anchor

In case of Z-piles, all plates have to satisfy following geometry conditions:

$$b_a \geq 0.8 b_f$$

$$h_a \leq 1.5 b_a$$

$$t_a \geq max[\frac{d_A}{3}; 2t_f]$$

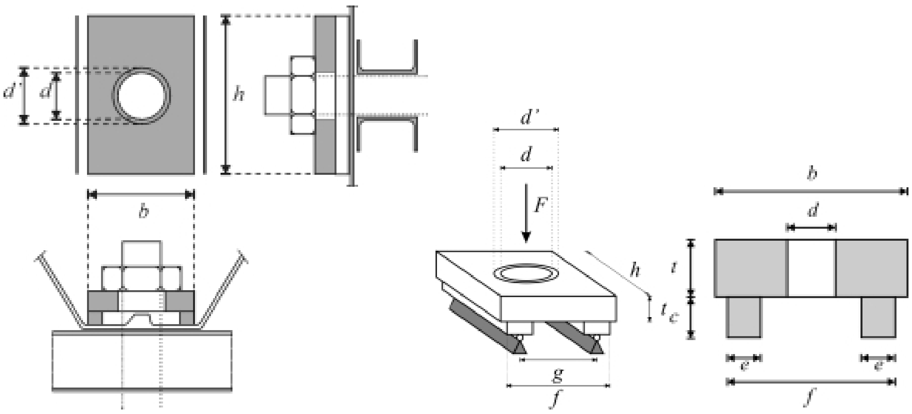
$$e = \begin{cases} 30mm for ASDO \\ 40mm for AMTB \end{cases}$$

$$c = \begin{cases} 30mm for ASDO \\ 50mm for AMTB \end{cases}$$

$$f = b$$

$$g = f - e$$

- **Case 7.4 (Bolt)**

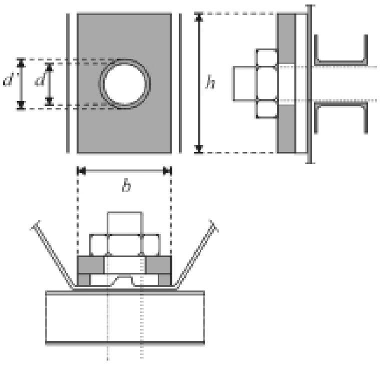


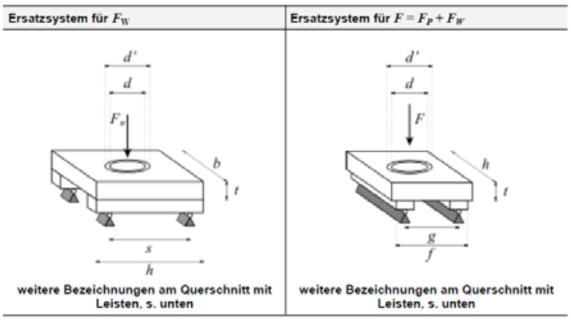
$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(g-d') + \sqrt{(g-d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

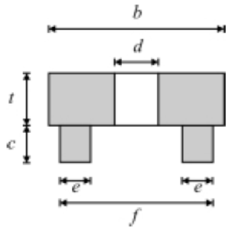
$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

- **Case 7.4 (Anchor) – Standard plate**







$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(g-d') + \sqrt{(g-d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

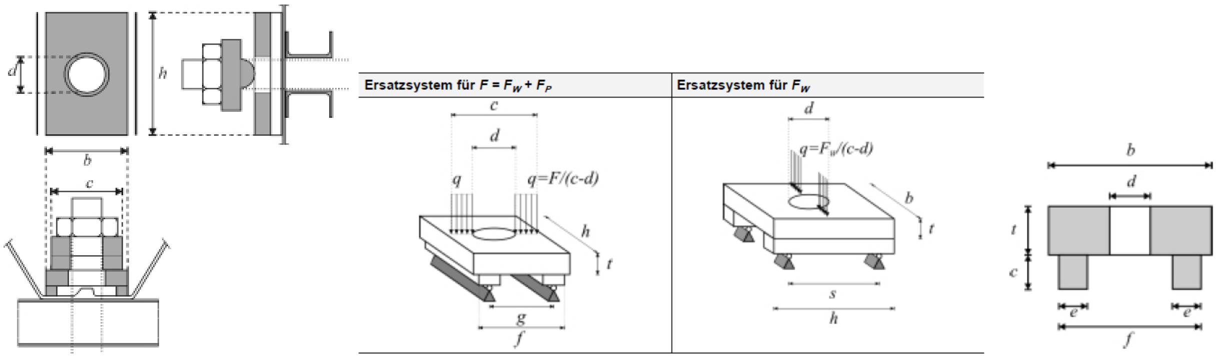
$$M_{Ed} = \frac{1}{4}F_{W,Ed}(s - d')$$

$$M_{Ed} \leq M_{pl,Rd} = W_{pl,Rd}\frac{f_y}{\gamma_{M0}} = [\frac{1}{4}(b_a - d)t_a^2 + ce(t_a - \frac{ce}{b_a - d} + c)]\frac{f_y}{\gamma_{M0}}$$

$$V_{Ed} = \frac{1}{2}F_{W,Ed}$$

$$V_{Ed} \leq 0.5V_{pl,Rd} = \frac{A_v}{2\sqrt{3}}\frac{f_y}{\gamma_{M0}} = [(b_a - d)t_a + 2ec]\frac{f_y}{\gamma_{M0}}$$

- **Case 7.4 (Anchor) – Swivel plate**



$$c = b_{SP}$$

- If $[c \leq g]$ or $[c > gandg - d \geq \sqrt{2}(c - g)]$:

$$F_{Ed} \leq F_{M,Rd} = 2t_a^2 \frac{h_a - d}{2g - c - d} \frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{V,Rd} = \frac{2}{\sqrt{3}} h_a t_a \frac{f_y}{\gamma_{M0}}$$

- If $[c > gandg - d < \sqrt{2}(c - g)]$:

$$F_{Ed} \leq F_{M,V,Rd} = \frac{1}{3}\frac{(c-g)^2}{c-d}\left(-1 + \sqrt{1 + 12t_a^2 \frac{(c-d)^2}{(c-g)^4}}\right)\frac{h_a f_y}{\gamma_{M0}}$$

For all cases:

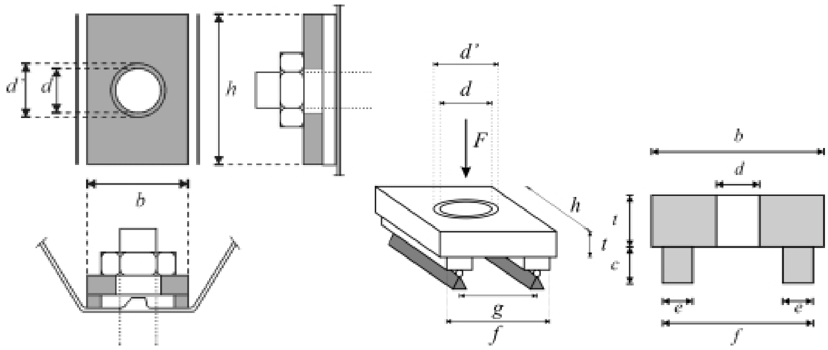
$$M_{Ed} = \frac{1}{4} F_{W,Ed} s$$

$$M_{Ed} \leq M_{pl,Rd} = W_{pl,Rd} \frac{f_y}{\gamma_{M0}} = \left[\frac{1}{4}(b_a - d)t_a^2 + ce\left(t_a - \frac{ce}{b_a - d} + c\right)\right]\frac{f_y}{\gamma_{M0}}$$

$$V_{Ed} = \frac{1}{2} F_{W,Ed}$$

$$V_{Ed} \leq 0.5 V_{pl,Rd} = \frac{A_v}{2\sqrt{3}} \frac{f_y}{\gamma_{M0}} = [(b_a - d)t_a + 2ec]\frac{f_y}{\gamma_{M0}}$$

- **Case 7.5 (Anchor) – Standard plate**



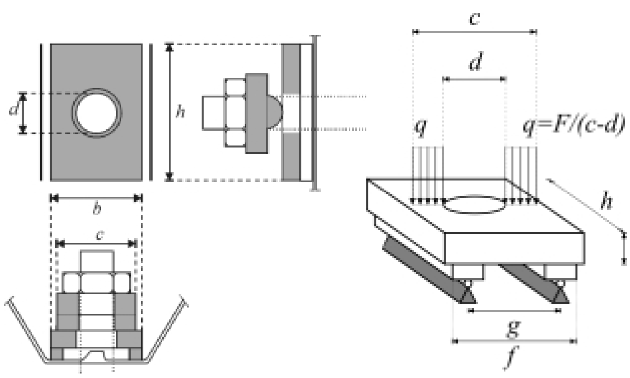
$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(g-d') + \sqrt{(g-d')^2 + 3t_a^2}](h_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

In case 7.5b, $b_a \geq max(b, b + 2r_0)$ to ensure that width is long enough in order that the extremities end at the area of load application into the web.

- **Case 7.5 (Anchor) – Swivel plate**



- If $[c \leq g]$ or $[c > g \; and \; g - d \geq \sqrt{2}(c-g)]$:

$$F_{Ed} \leq F_{M,Rd} = 2t_a^2 \frac{h_a - d}{2g - c - d}\frac{f_y}{\gamma_{M0}}$$

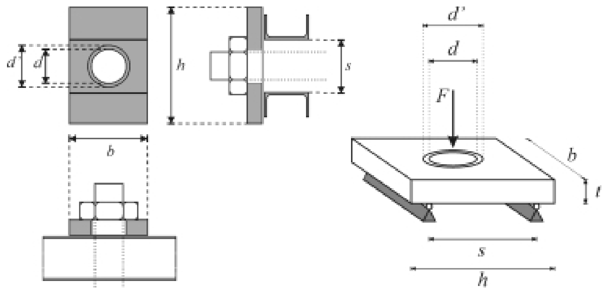
$$F_{Ed} \leq F_{V,Rd} = \frac{2}{\sqrt{3}} h_a t_a \frac{f_y}{\gamma_{M0}}$$

- If $[c > g \; and \; g - d < \sqrt{2}(c-g)]$

$$F_{Ed} \leq F_{M,V,Rd} = \frac{1}{3}\frac{(c-g)^2}{c-d}(-1 + \sqrt{1 + 12t_a^2 \frac{(c-d)^2}{(c-g)^4}})\frac{h_a f_y}{\gamma_{M0}}$$

In case 7.5b, $b_a \geq max(b, b + 2r_0)$ to ensure that width is long enough in order that the extremities end at the area of load application into the web.

- **Case 7.6 – Standard plate**



$$b_a \leq 1.5h_a$$

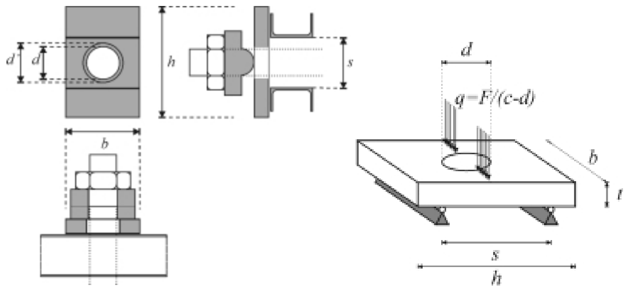
$$t_a \geq \frac{d_A}{3}$$

$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-(s-d') + \sqrt{(s-d')^2 + 3t_a^2}](b_a - d)\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_a \frac{f_y}{\gamma_{M0}}$$

- **Case 7.6 – Swivel plate**



$$b_a \leq 1.5h_a$$

$$t_a \geq \frac{d_A}{3}$$

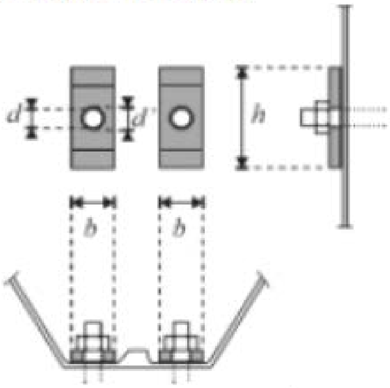
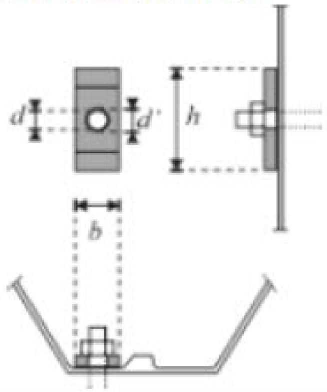
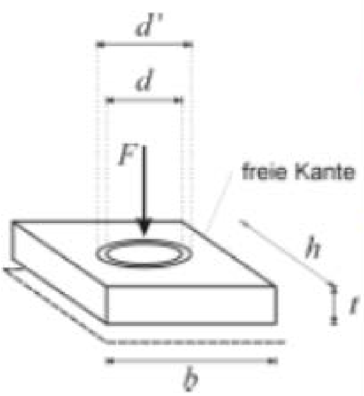
$$F_{Ed} \leq F_{M,V,Rd} = \frac{2}{3}[-s + \sqrt{s^2 + 3t_a^2}](b_a - d)\frac{f_y}{\gamma_{M0}}$$

4.5.1.2.2.2. Double centric anchor

Standard plates:

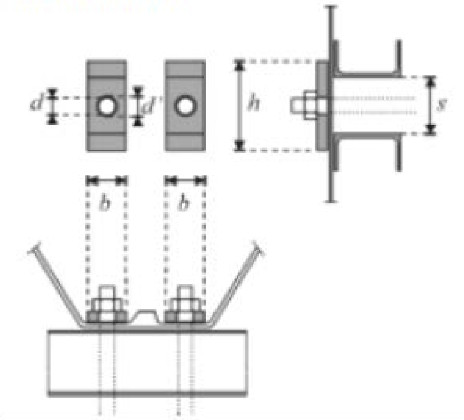
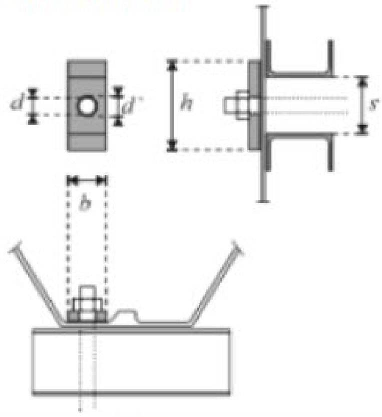
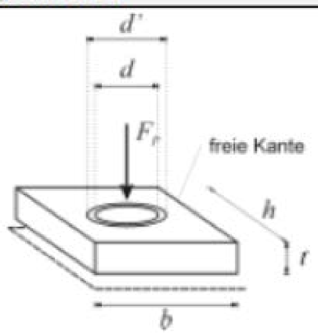
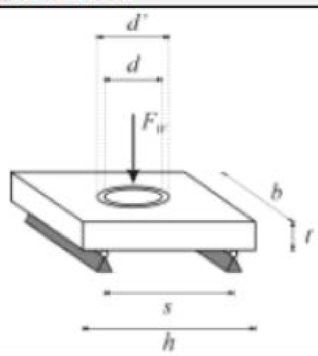
- “Table 6-3” (no waling)

Tabelle 6-3: Ankerplatten bei doppelt und exzentrisch verankerten Z-Bohlen ohne Gurtung und vordere Bolzenplatten

<table>
<tr><th colspan="2">Nachweise von Ankerplatten bei doppelt und exzentrisch verankerten Z-Bohlen ohne Gurtung (Typ 12)</th></tr>
<tr><td>AdZoG - Ankerplatten für doppelt verankerte Z-Bohlen ohne Gurtung
BdZmG - vordere Bolzenplatten für doppelt verankerte Z-Bohlen mit Gurtung

</td><td>AeZoG - Ankerplatten für exzentrisch verankerte Z-Bohlen
BeZmG - vordere Bolzenplatten für exzentrisch verankerte Z-Bohlen mit Gurtung

</td></tr>
<tr><th>Ersatzsystem</th><th>Nachweise</th></tr>
<tr><td>
</td><td>*M-V-Interaktion:*
$F_{Ed} \le F_{MV,Rd} = \frac{4}{3}\left(-(h-d') + \sqrt{(h-d')^2 + 3t^2}\right)(b-d)\frac{f_y}{\gamma_M}$
Lokale Lasteinleitung:
$F_{Ed} \le F_{Rd,l} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_M} < \frac{1}{\sqrt{3}}\pi d t \frac{f_y}{\gamma_M}$
Weitere Anforderungen:
- die Ankerplattenbreite muss mind. 80% der Flanschbreite betragen (s. EC 3 Teil 5) bei exzentrischer Lasteinleitung mindestens 90 %
- $h \le 2.5b$
- $t \ge 2.0t_f$ und $t \ge d_A/3$</td></tr>
</table>

- Table 6-13 (with waling)

Tabelle 6-13: Ankerplatten bei doppelt und exzentrisch verankerten Z-Bohlen mit Gurtung

Nachweise von Ankerplatten bei doppelt und exzentrisch verankerten Z-Bohlen mit Gurtung (Typ 12 und Typ 2)	
AdZmG – Ankerplatten für doppelt verankerte Z-Bohlen mit Gurtung 	AeZmG – Ankerplatten für exzentrisch veranker-te Z-Bohlen mit Gurtung 
Ersatzsystem für F_P	*Ersatzsystem für F_W*
	

Nachweis

M-V-Interaktion:

$$F_{Ed} \leq F_{M,V,Rd} = \frac{4}{3}\frac{n}{(2n-1)^2}\left(-X + \sqrt{X^2 + 3t^2(2n-1)^2}\right)(b-d)\frac{f_y}{\gamma_M}$$

mit $X = (h-d') + 2(s-d')(n-1)$

Lokale Lasteinleitung:

$$F_{Ed} \leq F_{Rd,l} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - d^2)\frac{f_y}{\gamma_M} < \frac{1}{\sqrt{3}}\pi\, d\, t\frac{f_y}{\gamma_M}$$

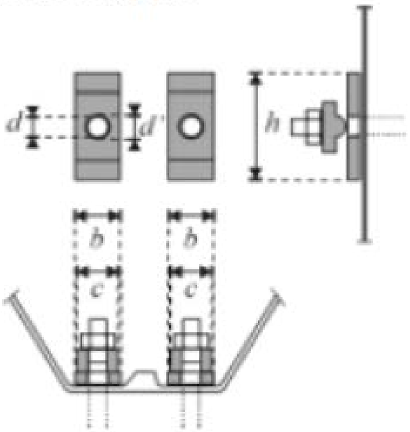
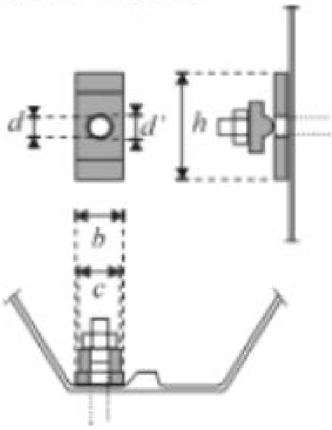
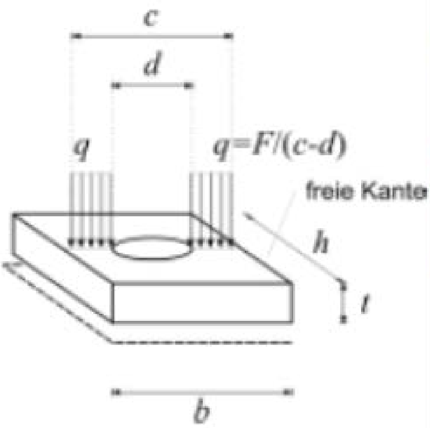
Weitere Anforderungen:

- die Ankerplattenbreite muss mind. 80% der Flanschbreite betragen (s. EC 3 Teil 5) bei exzentri-scher Lasteinleitung mindestens 90 %
- $h \leq 2.5\,b$
- $t \geq 2.0\,t_f$ und $t \geq d_A / 3$

Plate + Swivel plate:

- “Table 6-6” (no waling):

Tabelle 6-6: Ankerplatten mit Gelenkplatte bei doppelt und exzentrisch verankerten Z-Bohlen ohne Gurtung

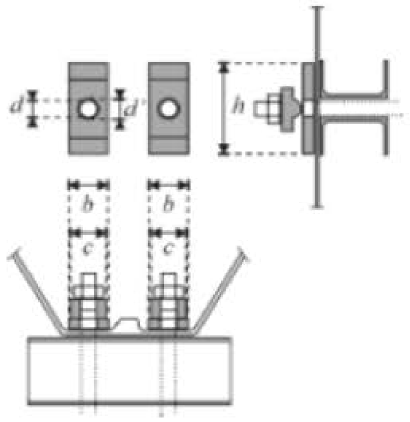
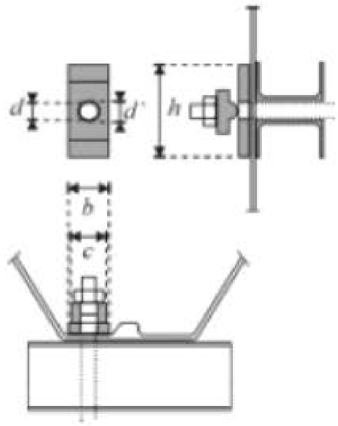
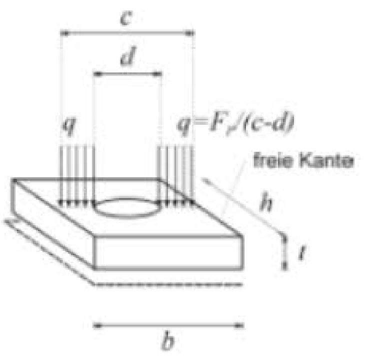
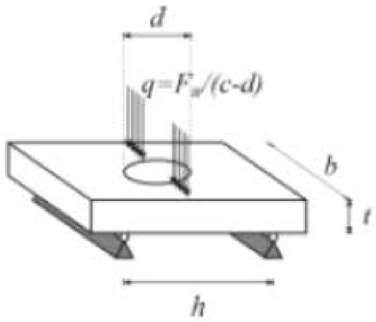
<table>
<tr><th colspan="2">Nachweise von Ankerplatten mit Gelenkplatte bei doppelt und exzentrisch verankerten Z-Bohlen ohne Gurtung (Typ 13)</th></tr>
<tr><td>AdZoGG - Ankerplatten für doppelt verankerte Z-Bohlen mit Gelenkplatte

</td><td>AeZoGG - Ankerplatten für exzentrisch verankerte Z-Bohlen mit Gelenkplatte

</td></tr>
<tr><th>Ersatzsystem</th><th>Nachweise</th></tr>
<tr><td>
</td><td>M-V-Interaktion:
$F_{Ed} \le F_{M,V,Rd} = \frac{4}{3}\left(-h+\sqrt{h^2+3t^2}\right)(b-d)\frac{f_y}{\gamma_M}$

Lokale Lasteinleitung:
mind. die Stahlgüte der Gelenkplatte (s. Gelenkplatte)

Weitere Anforderungen:
- die Ankerplattenbreite muss mind. 80% der Flanschbreite betragen (s. EC 3 Teil 5) bei exzentrischer Lasteinleitung mindestens 90 %
- $h \le 2.5b$
- $t \ge 2.0t_f$ und $t \ge d_A/3$</td></tr>
</table>

- “Table 6-14” (with waling)

Tabelle 6-14: Ankerplatten mit Gelenkplatten bei doppelt und exzentrisch verankerten Z-Bohlen mit Gurtung

Nachweise von Ankerplatten bei doppelt und exzentrisch verankerten Z-Bohlen mit Gurtung und Gelenkplatte (Typ 13 und Typ 5)	
AdZmGG – Ankerplatten für doppelt verankerte Z-Bohlen mit Gelenkplatte und Gurtung	AeZmGG - Ankerplatten für exzentrisch verankerte Z-Bohlen mit Gelenkplatte und Gurtung
	
Ersatzsystem für F_P	**Ersatzsystem für F_W**
	

Nachweise

M-V-Interaktion:

$$F_{Ed} \le F_{M,V,Rd} = \frac{4}{3}\frac{n}{(2n-1)^2}\left(-\left(h+2s(n-1)\right)+\sqrt{\left(h+2s(n-1)\right)^2+3t^2(2n-1)^2}\right)(b-d)\frac{f_y}{\gamma_M}$$

Lokale Lasteinleitung:

mind. die Stahlgüte der Gelenkplatte (s. Gelenkplatte)

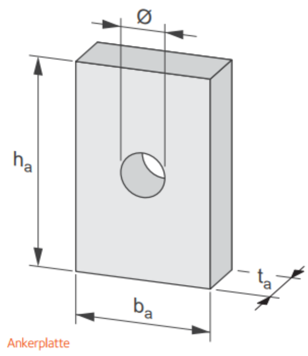
Weitere Anforderungen:

- die Ankerplattenbreite muss mind. 80% der Flanschbreite betragen (s. EC 3 Teil 5) bei exzentrischer Lasteinleitung mindestens 90 %
- $h \le 2.5b$
- $t \ge 2.0t_f$ und $t \ge d_A/3$

4.5.2. Double centric anchor

4.5.2.1. Plate dimensions

$$b_a \begin{cases} \leq b_c \\ \geq 0.9 \times b_c \end{cases} \qquad h_a \leq 2.5 \times b_a \qquad t_a \left| \begin{array}{l} \geq 40\ mm \\ \geq 2 \times t_f \\ \geq d_A/3 \end{array} \right.$$



4.5.2.2. Resistance check

4.5.2.2.1. Check of plate resistance to local force

Anchorage with waling:

Case E (nuts): $X = s - d'$

Case F (swivel plate): $X = s$

$$F_{M,V,Rd} = \frac{2}{3}(b_a - d)X\left[\sqrt{1 + 3\left(\frac{t_a}{X}\right)^2} - 1\right]\frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{M,V,Rd}$$

Where “s” is the distance between waling profiles.

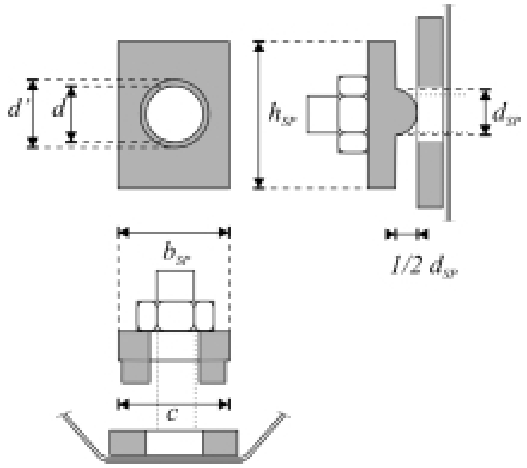
4.5.2.2.2. Punching check

$$F_{Rd,l1} = \frac{\pi}{2\sqrt{2}}(d^2{}_{SG} - d^2)\frac{f_y}{\gamma_{M0}} \qquad F_{Rd,l2} = \frac{1}{\sqrt{3}}\pi d t_a \frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l} = min\{F_{Rd,l1}, F_{Rd,l2}\} \qquad F_{Ed} \leq F_{Rd,l}$$

4.6. Swivel plate

4.6.1. Centric Anchor



Geometrical conditions to be satisfied:

$$b_{SP} =\leq d_{SG} + 2t_{SP}$$

$$h_{SP} \leq d_{SG} + 2t_{SP}$$

$$d_{SG} + 2t_{SP} \geq e$$

$$t_{SP} \geq \frac{d_A}{2}$$

$$c = min(b_a, b_{SP})$$

Loads conditions to be satisfied:

$$F_{Ed} \leq F_{Rd,l,1} = \frac{\pi}{2\sqrt{2}}(d_{SG}^2 - w_{SP}^2)\frac{f_y}{\gamma_{M0}}$$

$$F_{Rd,l,1} \leq F_{Rd,l,2} = \frac{1}{\sqrt{3}}\pi d_{SG} t_{SP} \frac{f_y}{\gamma_{M0}}$$

$$F_{Ed} \leq F_{loc} = w_{SP}(c - d)\frac{f_y}{\gamma_{M0}}$$

4.7. Sheet pile

4.7.1. Eurocode

Case	Checks to be done according to EC3-5
7.4	• Shear resistance of flange EC3-5 §7.4.3 (3a) • Tensile resistance of webs EC3-5 §7.4.3 (3b)
7.5a	• Shear resistance of flange EC3-5 §7.4.3 (3a) • Tensile resistance of webs EC3-5 §7.4.3 (3b)
7.5b	• Shear resistance to the local transverse force EC3-5 §7.4.3 (4)
7.6	• Shear resistance to the local transverse force EC3-5 §7.4.3 (4)

4.7.1.1. Shear resistance of flange EC3-5 §7.4.3 (3a)

$$F_{Ed} \leq R_{Vf,Rd}$$

F_{Ed} Design value of the local transverse force applied through the flange

$R_{Vf,Rd}$ Design value of the shear resistance of the flange under the washer plate, given as

$$R_{Vf,Rd} = 2(b_a + h_a)t_f \frac{f_y}{\sqrt{3}\gamma_{M0}}$$

b_a Width of the washer plate

h_a Height of the washer plate

t_f Flange thickness of the washer plate, but $t_f \leq 1.5b_a$

f_y Yield strength of the sheet pile

4.7.1.2. Tensile resistance of webs EC3-5 §7.4.3 (3b)

$$F_{Ed} \leq R_{tw,Rd}$$

F_{Ed} Design value of the local transverse force applied through the flange

$R_{tw,Rd}$ Design value of the tensile resistance of 2 webs, given as

$$R_{tw,Rd} = 2h_a t_w \frac{f_y}{\gamma_{M0}}$$

t_w Web thickness

4.7.1.3. Shear resistance to the local transverse force EC3-5 §7.4.3 (4)

One has to check:

$F_{Ed} \leq 0.5R_{c,Rd} \rightarrow$ No further verification necessary

$F_{Ed} > 0.5R_{c,Rd} \rightarrow \frac{F_{Ed}}{R_{c,Rd}} + 0.5\frac{M_{Ed}}{M_{c,Rd}} \leq 1.0$

Where:

F_{Ed} Design value of the local transverse force per web applied through the waling

M_{Ed} Design value of the bending moment at the location of the anchor force or strut force

$M_{c,Rd}$ Design bending resistance of the sheet pile from EC3-5 §5.2.2(2).

$R_{c,Rd}$ Design resistance to the local transverse force, minimum value of $R_{e,Rd}$ and $R_{p,Rd}$ for each web, given by

$$R_{e,Rd} = \frac{\varepsilon}{4e}(s_s + 4s_{ec})\sin\alpha\left(t_w^2 + t_f^2\right)f_y/\gamma_{M0}$$

$$R_{p,Rd} = \chi R_{P0}/\gamma_{M0}$$

With:

$\chi = 0.06 + \frac{0.47}{\lambda} <= 1.0$

$\lambda = \sqrt{\frac{R_{p0}}{R_{cr}}}$

$R_{cr} = 5.42E\frac{t_w^3}{c}\sin\alpha$

$R_{p0} = \sqrt{2}\varepsilon f_y t_w \sin\alpha\left(s_s + t_f\sqrt{\frac{2b\sin\alpha}{t_w}}\right)$

b Width of the flange

c Slant height of the web

$e = max\left(5mm\,;\; r_0 tan\left(\frac{\alpha}{2}\right) - \frac{t_W}{2\sin\alpha}\right)$ Eccentricity of the force introduced into the web

f_y Yield strength of the sheet pile

r_0 Outside radius of the corner between flange and web

$s_{ec=2\pi r_0}\frac{\alpha}{180}$ with α in degrees

s_s Length of stiff bearing, determined from 6.3 of EN 1993-1-5. If the waling consists of two parts, e.g. two channel-sections, $s_s$is the sum of both parts plus the minimum of the distance between the two parts or the length s_{ec}

- Case 7.5b (no waling): $s_s = h_a$
- Case 7.6 (there is a waling): $s_s = 2 * s' + s_{ec}$ if $s \geq s_{ec}$; $s_s = 2 * s' + s$ if $s < s_{ec}$

Where:

s is the distance between 2 profiles of the waling (mm)

$s' = t_{w,waling} + r_{waling} + t_{f,waling}$

t_f Flange thickness

t_w Web thickness

α inclination of the web

$\varepsilon = \sqrt{\frac{235}{f_y}}$

5. LCA calculation

Durability allows to calculate Environmental Product Declaration (EPD) for the selected section in *Sheet pile* tab. Up to five scenarios may be examined.

Hot rolled sheet piles EPD will be considered for GU sheet piles and EcoSheetPiles EPD for the AZ and the other sheet pile sections.

Durability propose 3 calculation methods:

- Business practice
- Reuse/recycle %
- Number of cycles

Those methods are used to calculate the % of reuse, the % of recycle and the % of landfill.

5.1. Business practice method

Initial length

Initial length can be taken from *Sheet pile* tab if it's already defined.

ΔL is the increment of length to define the real length delivered in situ (input value).

Minimum length

It corresponds to the minimum length that remains at the end life of the sheet pile.

Percentages calculation

The length of the sheet pile is reduced by the cutting length until it reaches the minimum length.

The number of uses can be deduced as:

Number of uses = (Initial length – minimum length) / cutting length

Each time the cutting length is subtracted from the initial length, we can deduce the following values:

Reuse = length of the sheet pile - cut length

Recycle = cut length x recycling rate

Landfill = cut length x (100 – recycling rate)

We can then deduce the final % reuse, % recycle and % landfill based on the initial length.

5.2. Reuse/recycle % method

The % reuse and the % recycle is directly inputted.

The % landfill is deduced from both of them.

5.3. Number of cycles

In this case, percentages are deduced as follows:

% **Reuse =** 100 ***** (number of cycles– 1) / number of cycles

% **Recycle** = (100 - % Reuse) x Recycling rate / 100

% **Landfill** = 100 - % Reuse - % Recycle

5.4. LCA values calculation

Net scrap calculation

Net scrap = Manufacturing + Reuse + Recycle

Where:

Manufacturing = either -909 kg/t (for GU) or -1140 kg/t for EcoSheetPiles Plus

Reuse = - Manufacturing x % Reuse

Recycle = % Recycle * 1000

Then, columns A1-A3 (Raw material supply, transport and manufacturing), C3 (Waste processing) and D (Reuse recovery recycling potential) will be calculated:

A1-A3 is taken from EPD

C3 = column C3 from EPD x % Landfill

D = - (A1-A3) x % Reuse + Scrap (from Database) x Net Scrap / 1000

Finally, these values are multiplied by the sheet pile mass.

5.5. Transport calculation

Column A4 values are obtained as a product of the value from database and distance (input value).

5.6. Total calculation

Total value will be calculated in absolute and per use:

- Total = A1-A3 + C3 + D + A4
- Total per use = (A1-A3 + C3 + D + A4) / times SSP is used