The Second Generation Eurocodes

Key changes and benefits through design examples

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EN 1999 ‘Eurocode 9: Design of aluminium structures’

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EN1999-1-5 Design example

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General features of a 1MW wind turbine (*)

Tower height = 60÷80m;

Tower diameter = 2,80÷3,20m

Rotor diameter = 60÷70m;

Weight of nacelle and rotor assemblage ≅ 600KN;

Weight of the tower ≅ 300KN, for t = 20mm;

Vertical load at the tower base N ≅ 1000KN;

Maximum horizontal action due to wind V = 150KN

Wind tower in Frigento (Italy) - Wikipedia

Design forces at the base of the tower

Assuming:

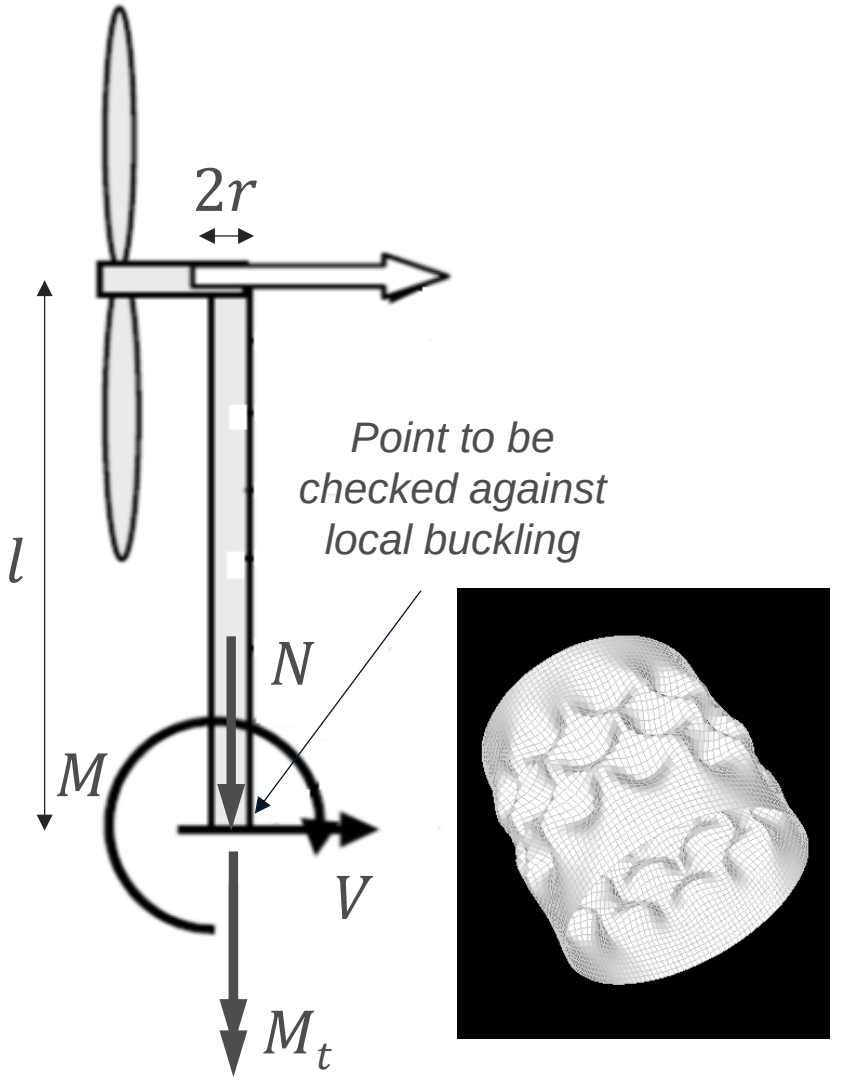
l = 60m, r = 1,5m, t = 20mm

the following design values of the forces at the base of the tower are obtained:

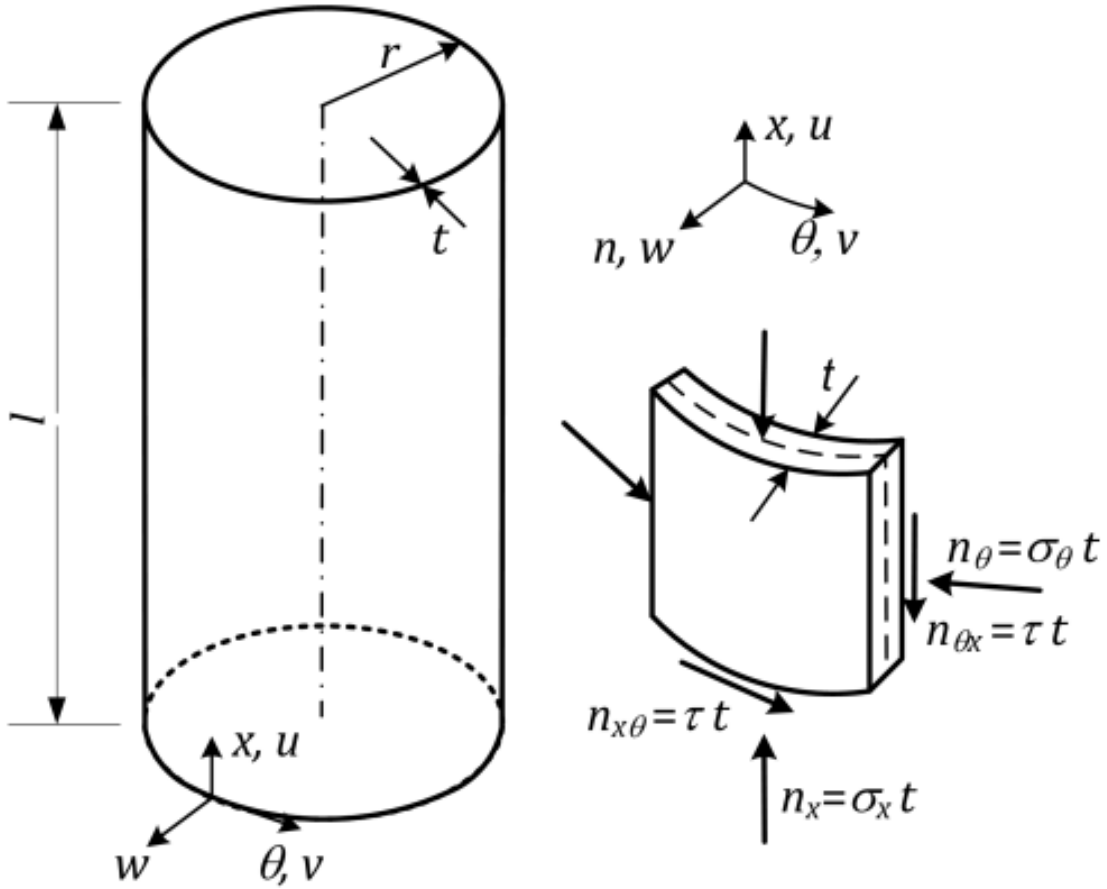
Axial load N = 1500KN (γ_g = 1.5);

Bending moment M = 13500KNm (γ_q = 1.5);

Torque from jaw effects M_t = 1500KNm ($\cong$ 10 ÷ 15% of M).



General shell and material data



l = 60m, r = 1,5m, t = 20mm

$$\omega = \frac{l}{\sqrt{rt}} = 346{,}4$$

$$\frac{r}{t} = 75$$

Selected alloy:

EN AW6082 T6

f_0 = 240 N/mm^2; f_u = 295 N/mm^2;
(for 12,5 < t < 100mm);

ρ_{HAZ} = 0,52; BC = A.

Calculation of the buckling factor

(2) The reduction factor due to buckling in a perfect shell should be taken as given by Formulae (8.14) and (8.15):

$$\chi_{i,perf} = \frac{1}{\varphi_i + \sqrt{\varphi_i^2 - \bar{\lambda}_i^2}} \text{ but } \chi_{i,perf} \leq 1{,}00$$

with:

$$\varphi_i = 0{,}5\left(1 + \mu_i(\bar{\lambda}_i - \bar{\lambda}_{i,0}) + \bar{\lambda}_i^2\right)$$

where

μ_i is a parameter depending on the alloy and loading case, from Annex A

$\bar{\lambda}_{i,0}$ is the squash limit relative slenderness, from Annex A;

i is subscript standing for x, θ or τ, depending on the loading type.

$$\bar{\lambda}_x = \sqrt{\frac{f_o}{\sigma_{x,cr}}}$$

$$\bar{\lambda}_\theta = \sqrt{\frac{f_o}{\sigma_{\theta,cr}}}$$

$$\bar{\lambda}_\tau = \sqrt{\frac{f_o}{\sqrt{3}\tau_{cr}}}$$

Calculation of the meridional buckling stress

(3) The critical meridional buckling stress, using values of C_x from Table A.1, should be obtained from Formula (A.3):

$$\sigma_{x,cr} = 0{,}605EC_x t/r = 409{,}6\text{N/mm}^2 \text{ where } C_x = 0{,}725 \text{ (Long cylinder with BC1 \& BC1)} \qquad \text{(A.3)}$$

Table A.1 — Factor, C_x, for critical meridional buckling stress

Cylindrical shell	$\omega = \frac{l}{\sqrt{rt}}$	Factor C_x
Short	$\omega \le 1{,}7$	$C_x = 1{,}36 - 1{,}83/\omega + 2{,}07/\omega^2$
Medium-length	$1{,}7 < \omega < 0{,}5r/t$	$C_x = 1$
Long	$\omega \ge 0{,}5r/t$	$C_x = 1 - \frac{0{,}2}{C_{xb}}\left(2\omega\frac{t}{r} - 1\right)$ but $C_x \ge 0{,}6$ where C_{xb} is given in Table A.2

Table A.2 — Parameter, C_{xb}

Case	Cylinder end	Boundary condition	C_{xb}
1	end 1 end 2	BC 1 BC 1	6
2	end 1 end 2	BC 1 BC 2	3
3	end 1 end 2	BC 2 BC 2	1
NOTE	BC 1 includes both BC1f and BC1r, see Table 7.1.		

Meridional imperfection factor

A.3.2.3 Meridional buckling parameter

(1) The meridional imperfection factor should be obtained from Formula (A.6):

$$\alpha_x = \frac{1}{1 + 0{,}6\left(\frac{1}{Q^{0{,}7}}\sqrt{\frac{r}{t}}\right)^{1{,}6}} \text{ but } \alpha_x \leq 1{,}00 \qquad \text{(A.6)}$$

where

$\bar{\lambda}_{x,0}$ is the meridional squash limit slenderness parameter;

Q is the meridional compression tolerance parameter.

(2) The tolerance parameter, Q, should be taken from Table A.3 for the specified tolerance class. For tolerance class 4 tolerance parameter, Q, depends also on boundary conditions as defined in Table 7.1.

(3) The alloy factor and the meridional squash limit slenderness parameter defined in 8.2.3.2 should be taken from Table A.4, according to the material buckling class as defined in EN 1999-1-1.

Calculation of the buckling factor $\chi_{x,perf}$

Table A.3 — Tolerance parameter, *Q*, for Formula (A.6)

Tolerance class	Value of *Q* for boundary conditions	
	BC1r, BC2r	BC1f, BC2f
Class 1	16	
Class 2	25	
Class 3	40	
Class 4	60	50

Q = 25 (Class 2)

$\alpha_x = 0{,}660$

$\bar{\lambda}_x = 0{,}765$

$\chi_{x,perf} = 0{,}906$

Table A.4 — Values of $\bar{\lambda}_{x,0}$ and μ_x for meridional compression

Material buckling class	$\bar{\lambda}_{x,0}$	μ_x
A	0,6	0,3
B	0,65	0,35
C	0,7	0,4

Calculation of the shear buckling stress

(3) The critical shear buckling stress, using values of C_τ from Table A.9, should be obtained from Formula (A.18):

$$\tau_{cr} = 0,75EC_\tau\sqrt{\frac{1}{\omega}}\frac{t}{r} = 26,9\text{N/mm}^2 \text{ where } C_\tau = 1 \text{ (Medium-length cylinder)} \qquad \text{(A.18)}$$

Table A.9 — Factor, C_τ in Formula (A.18) for critical shear buckling stress

Cylindrical shell	$\omega = \frac{l}{\sqrt{rt}}$	**Factor C_τ**
Short	$\omega \le 10$	$C_\tau = \sqrt{1+\frac{42}{\omega^3}}$
Medium-length	$10 < \omega < 8,7r/t$	$C_\tau = 1$
Long	$\omega \ge 8,7r/t$	$C_\tau = \frac{1}{3}\sqrt{\frac{\omega t}{r}}$

Calculation of the buckling factor $\chi_{\tau,perf}$

(1) The shear imperfection factor should be obtained from Formula (A.19):

$$\alpha_\tau = \alpha_{\tau,\mathrm{ref}} + (1 - \alpha_{\tau,\mathrm{ref}})e^{-0{,}002r/t} \text{ but } \alpha_\tau \leq 1{,}00 \qquad \text{(A.19)}$$

(2) The shear imperfection factor, $\alpha_{\tau,\mathrm{ref}}$, should be taken from Table A.10 for the specified tolerance class.

Table A.10 — Factor, $\alpha_{\tau,\mathrm{ref}}$, in Formula (A.19) based on tolerance

Tolerance class	Factor $\alpha_{\tau,\mathrm{ref}}$
Class 1	0,50
Class 2	0,65
Class 3 and 4	0,75

Q = 25 (Class 2)

$\alpha_\tau = 0{,}95$

$\bar{\lambda}_\tau = 1{,}92$

$\chi_{\tau,perf} = 0{,}226$

Table A.11 — Values of $\bar{\lambda}_{\tau,0}$ and μ_τ for shear

Material buckling class	$\bar{\lambda}_{\tau,0}$	μ_τ
A	0,5	0,4
B	0,55	0,35
C	0,6	0,3

Buckling checks

Buckling resistances

$$\sigma_{x,Rd} = \frac{\alpha_x \chi_{x,perf} f_0}{\gamma_m} = 130{,}5 N/mm^2;$$

$$\tau_{Rd} = \frac{\alpha_\tau \chi_{\tau,perf} f_0}{\sqrt{3}\gamma_m} = 27{,}1 N/mm^2;$$

Design stresses

$$\sigma_{x,EdN} = \frac{N}{2\pi r t} = 8{,}0 N/mm^2;$$

$$\sigma_{x,EdM} = \frac{M}{\pi r^2 t} = 95{,}5 N/mm^2;$$

$$\sigma_{max} = \sigma_{x,EdN} + \sigma_{x,EdM} = 103{,}5 N/mm^2;$$

$$\tau = \frac{M_t}{2\pi r^2 t} = 5{,}3 N/mm^2$$

Buckling strength verification

8.2.3.3 Buckling strength verification

(1) Although buckling is not a purely stress-initiated failure phenomenon, the buckling strength verification may be represented by limiting the design values of membrane stresses or stress resultants. The influence of bending stresses on buckling strength may be neglected, provided they arise as a result of boundary compatibility effects. Special consideration should be given to bending stresses from local loads or from thermal gradients.

(2) Depending on the loading and stressing situation, one or more of the verifications given by Formulae (8.21) to (8.23) for the key values of single membrane stress components should be carried out:

$$\sigma_{x,Ed} \leq \sigma_{x,Rd} \tag{8.21}$$

$$\sigma_{\theta,Ed} \leq \sigma_{\theta,Rd} \tag{8.22}$$

$$\tau_{Ed} \leq \tau_{Rd} \tag{8.23}$$

Interaction formulas

(3) If more than one of the three buckling-relevant membrane stress components are present in the design situation under consideration, the interaction given by Formulae (8.24) and (8.25) for the combined membrane stress state should be carried out:

$$\left(\frac{\sigma_{x,\mathrm{Ed}}}{\sigma_{x,\mathrm{Rd}}}\right)^{k_x} + \left(\frac{\sigma_{\theta,\mathrm{Ed}}}{\sigma_{\theta,\mathrm{Rd}}}\right)^{k_\theta} - k_{\mathrm{i}}\left(\frac{\sigma_{x,\mathrm{Ed}}}{\sigma_{x,\mathrm{Rd}}}\right)\left(\frac{\sigma_{\theta,\mathrm{Ed}}}{\sigma_{\theta,\mathrm{Rd}}}\right) + \left(\frac{\tau_{\mathrm{Ed}}}{\tau_{\mathrm{Rd}}}\right)^{k_\tau} \leq 1{,}00 \qquad (8.24)$$

where $\sigma_{\mathrm{x,Ed}}$, $\sigma_{\mathrm{\theta,Ed}}$ and τ_{Ed} are the interaction-relevant groups of the significant values of compressive and shear membrane stresses in the shell. The interaction parameters, k_{x}, k_{θ}, k_{τ} and k_{i}, should be taken as:

$$k_{\mathrm{x}} = 1{,}25 + 0{,}75\chi_{\mathrm{x}}$$
$$k_{\theta} = 1{,}25 + 0{,}75\chi_{\theta}$$
$$k_{\tau} = 1{,}75 + 0{,}25\chi_{\tau}$$

$$\left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}}\right)^{k_x} + \left(\frac{\tau_{Ed}}{\tau_{Rd}}\right)^{k_\tau} = 0{,}692 < 1; \qquad (A.24)$$

$$k_{\mathrm{i}} = (\chi_{\mathrm{x}}\chi_{\theta})^2 \qquad (A.25)$$

where χ_{x}, χ_{θ} and χ_{τ} are the buckling reduction factors defined in 8.2.3.2, using the buckling parameters given in A.3.2 to A.3.4.

Thank you!