EN4103 – Renewable Energy Design
a.y. 2018/19
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Wind Turbine Tower Design

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Scheme of an offshore wind turbine

teproduced courtesy of Siemens Wind Power

References

- **Books**

  Hau (2006) Wind Turbine Fundamentals

  Burton et al (2014) Wind Energy Handbook

- **Standards**

  Eurocode 3, National Annex (BS EN 1993)

  DNV-GL code of practice/guidelines on wind turbines

- **Software**

  Bladed 4.4 Educational, Garrad Hassan

- **Reports**

  Rawlinson-Smith (2004) Load calculations for a generic 1.5 MW wind turbine…

Design Constraints

- **Ultimate limit state (ULS)**
  - **Plastic limit (tower, joints)**
  - **Buckling (tower)**
  - **Fatigue (tower, joints)**
- **Serviceability limit state (SLS)**
  - **Slip resistance check (joint)**
- **Avoidance of resonance (vibration frequency)**
- **Blade clearance**
- **Transportability**

Standards

- **EN 1993-1-6:2007** DESIGN OF STEEL STRUCTURES – STRENGTH AND STABILITY OF SHELL STRUCTURES

- **EN 1993-1-8:2007** DESIGN OF STEEL STRUCTURES – DESIGN OF JOINTS

- **EN 1993-1-9:2007** DESIGN OF STEEL STRUCTURES – FATIGUE

- See National Annexes

Load Analysis

- **Wind Turbine Loads**

  Inertia and gravity loads

  Aerodynamic loads

  Operational loads

  Other loads (wake, impact, ice …)

- **Load Analysis**

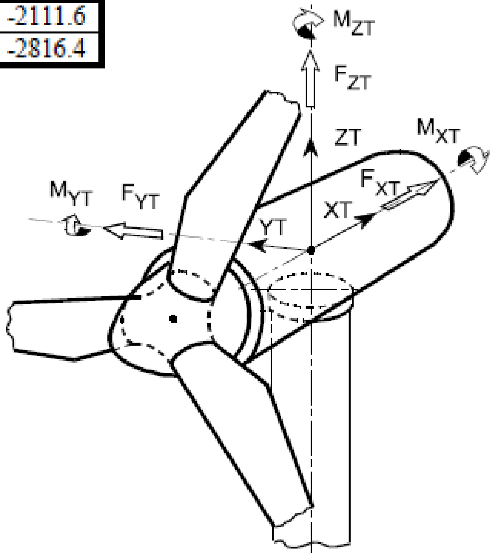
  Bladed Software

  Indications can be suggested also by scaling from other WT designs

Load Analysis

		Load case	Mx kNm	My kNm	Mxy kNm	Mz kNm	Fx kN	Fy kN	Fxy kN	Fz kN
Mx	Max	6.1k	59022	10049	59871	1061.2	230.2	-808.5	840.6	-2600.2
Mx	Min	6.1o	-49749	15133	52000	-1126.2	263.3	672.8	722.5	-2689.1
My	Max	1.5c	1173.3	37424	37442	291.3	482.6	0.50	482.6	-2778.2
My	Min	1.3f	-7170.6	-44470	45044	-313.5	-509.2	100.5	519.1	-2707.4
Mxy	Max	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Mxy	Min	1.1a	3.5	7.0	7.8	38.8	19.3	2.3	19.4	-2731.9
Mz	Max	2.2a	3670.0	4567.6	5859.4	3254.4	76.8	-30.6	82.7	-2267.6
Mz	Min	1.1f	-8139.8	1158.2	8221.8	-2713.1	48.2	128.3	137.1	-2714.7
Fx	Max	6.1h	-17442	32747	37102	35.6	616.3	251.1	665.5	-2653.8
Fx	Min	1.3f	-7170.6	-44470	45044	-313.5	-509.2	100.5	519.1	-2707.4
Fy	Max	6.1o	-49749	15133	52000	-1126.2	263.3	672.8	722.5	-2689.1
Fy	Min	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Fxy	Max	6.1k	58988	11721	60141	1295.1	284.3	-817.2	865.2	-2600.5
Fxy	Min	1.1a	64.7	-1255.6	1257.2	15.3	0.17	0.21	0.27	-2740.9
Fz	Max	7.1c70	1844.8	12494	12629	-44.5	254.5	11.9	254.7	-2111.6
Fz	Min	1.1e	3070.6	12526	12897	-112.6	188.2	-31.2	190.8	-2816.4

Table 5.4 - Ultimate Loads: Tower at 0.00m



Materials

Table 1 – Steel properties

Element	Standard and steel grade	Nominal thickness of the element t [mm]			
		$t \leq 40$ mm		40 mm $< t \leq 80$ mm	
		f_y	f_u	f_y	f_u
		[MPa]	[MPa]	[MPa]	[MPa]
Flange	S355	355	510	335	470
Tower	S355	355	510	335	470

According to EN1993-1-8:2005 [5] bolt class and relevant properties are reported below:

Table 2 – Bolt properties

Bolt class	f_{yb}	f_{ub}
	[MPa]	[MPa]
8.8	640	800

Partial Factors

- **EC-3: Ultimate LS**

$\gamma_{G_1} = 1,35$ Permanent loads

$\gamma_{Q_1} = 1,50$ Variable loads

Material, resistance	γ_{M0}	1,00
Mat., buckling	γ_{M1}	1,10
Mat., bolts	γ_{M2}	1,25

- **EC-3: Serviceability LS**

$\gamma_{G_1} = 1,00$

$\gamma_{Q_1} = 1,00$

Mat., bolts	$\gamma_{M3,res}$	1,10

- **DNV-GL guidelines**

Type	PSFL
Abnormal safety factor Load case 2.2 and 7.1	1.10
Normal and extreme safety factor All other load cases	1.35
Transport and erection safety factor Load case 8.1	1.5

ULS: Plastic limit (tower)

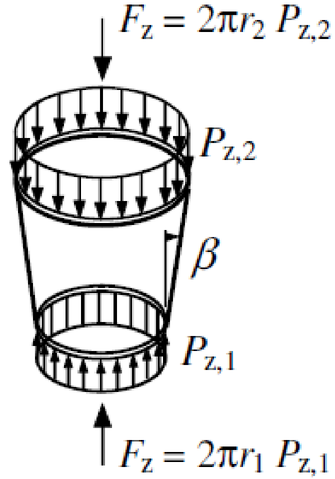
Reference: **EC3-1-6**, sect 4.1 etc (tower),

Annex A

$$\sigma_{eq,Ed} = \sqrt{\sigma_{z,Ed}^2 + 3\tau_{z\theta,Ed}^2}$$

$$\sigma_{\mathrm{eq,Ed}} \leq f_{\mathrm{eq,Rd}}$$

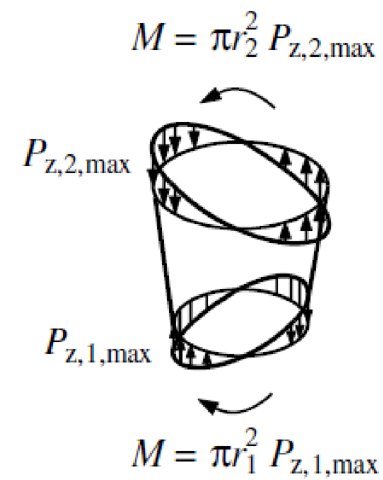
A.3.1 Uniform axial load



$$\sigma_x = -\frac{F_z}{2\pi r t \cdot \cos\beta}$$

$$\sigma_\theta = 0$$

A.3.2 Axial load from global bending



$$\sigma_{x,\max} = \pm\frac{M}{\pi r^2 t \cdot \cos\beta}$$

$$\sigma_\theta = 0$$

ULS: Plastic limit (joints)

Reference: **EC3-1-8**

Table 3.2: Categories of bolted connections

Category	Criteria	Remarks
Shear connections		
A bearing type	$F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used.
B slip-resistant at serviceability	$F_{v,Ed,ser} \leq F_{s,Rd,ser}$ $F_{v,Ed} \leq F_{v,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at serviceability see 3.9.
C slip-resistant at ultimate	$F_{v,Ed} \leq F_{s,Rd}$ $F_{v,Ed} \leq F_{b,Rd}$ $F_{v,Ed} \leq N_{net,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. For slip resistance at ultimate see 3.9. $N_{net,Rd}$ see 3.4.1(1) c).
Tension connections		
D non-preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	No preloading required. Bolt classes from 4.6 to 10.9 may be used. $B_{p,Rd}$ see Table 3.4.
E preloaded	$F_{t,Ed} \leq F_{t,Rd}$ $F_{t,Ed} \leq B_{p,Rd}$	Preloaded 8.8 or 10.9 bolts should be used. $B_{p,Rd}$ see Table 3.4.
The design tensile force $F_{t,Ed}$ should include any force due to prying action, see 3.11. Bolts subjected to both shear force and tensile force should also satisfy the criteria given in Table 3.4.		

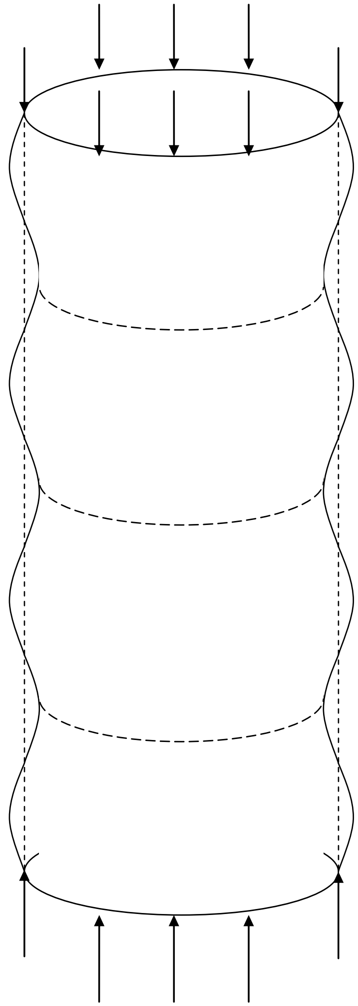
ULS: Buckling

For a **perfect** cylindrical shell under axial load,

$$\sigma_{cr} = 0.605\ E\ (t/R)$$

E = Modulus of elasticity,

t = Wall thickness, R = Shell radius



Imperfections

- are magnified by applied compression
- result in earlier onset of yield (on concave surfaces)

ULS: Buckling

Reference: **EC3-1-6**, sect 8 etc (tower)

Imperfections

First step: Decide the “fabrication tolerance quality class” – A, B or C

These correspond to % deviations of 0.6%, 1% and 1.6% respectively

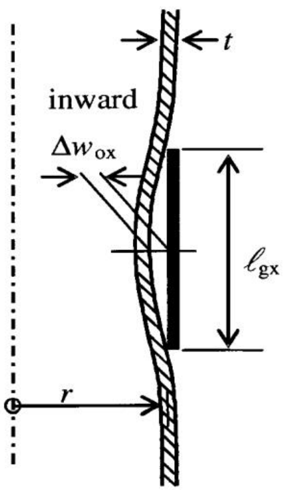
ULS: Buckling

The % imperfections of the finished tower section will be checked, using

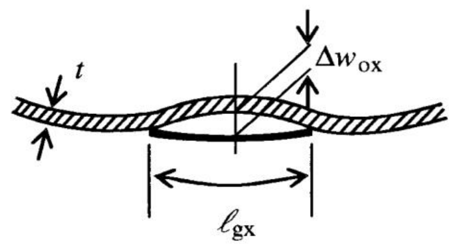
a) a straight rod of length L = $4(Rt)^{0.5}$ placed vertically anywhere

b) a curved gauge of same length placed circumferentially

c) a straight rod of length L = 25t placed vertically across horizontal welds

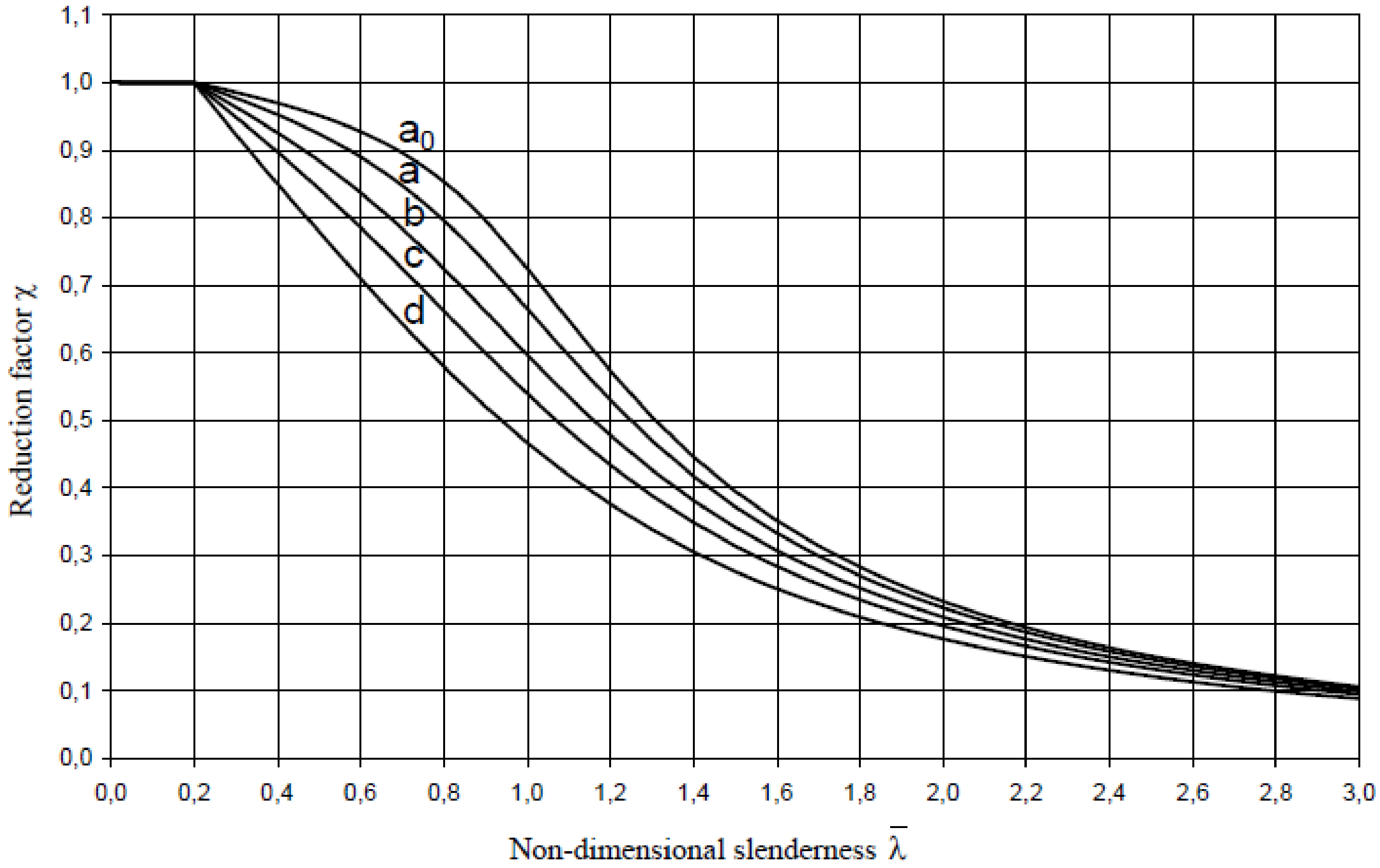


a) Measurement on a meridian (see 8.4.4(2)a)



b) First measurement on a circumferential circle (see 8.4.4(2)a)

ULS: Buckling



Buckling curves (Euler hyperbola)

ULS: Buckling

The elastic critical buckling stress determines the relative shell slenderness, $\lambda = (f_y/\sigma_{cr})^{0.5}$

The buckling strength is then determined as a proportion of the yield strength, according to

- The relative shell slenderness, λ
- The fabrication tolerance quality class
- The balance of axial stresses and bending stresses

A low proportion of axial stress – as normally found on WTG towers – results in a relatively higher buckling strength.

ULS: Buckling

Resistance buckling stress

$$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_{M1}, \quad \sigma_{\theta,Rd} = \sigma_{\theta,Rk}/\gamma_{M1}, \quad \tau_{x\theta,Rd} = \tau_{x\theta,Rk}/\gamma_{M1}$$

where

$$\sigma_{x,Rk} = \chi_x f_{yk}, \quad \sigma_{\theta,Rk} = \chi_\theta f_{yk}, \quad \tau_{x\theta,Rk} = \chi_\tau f_{yk} / \sqrt{3}$$

Buckling reduction factor
(slenderness, imperfections, …)

Checks

$$\sigma_{x,Ed} \le \sigma_{x,Rd}, \quad \sigma_{\theta,Ed} \le \sigma_{\theta,Rd}, \quad \tau_{x\theta,Ed} \le \tau_{x\theta,Rd}$$

+ combined loading check

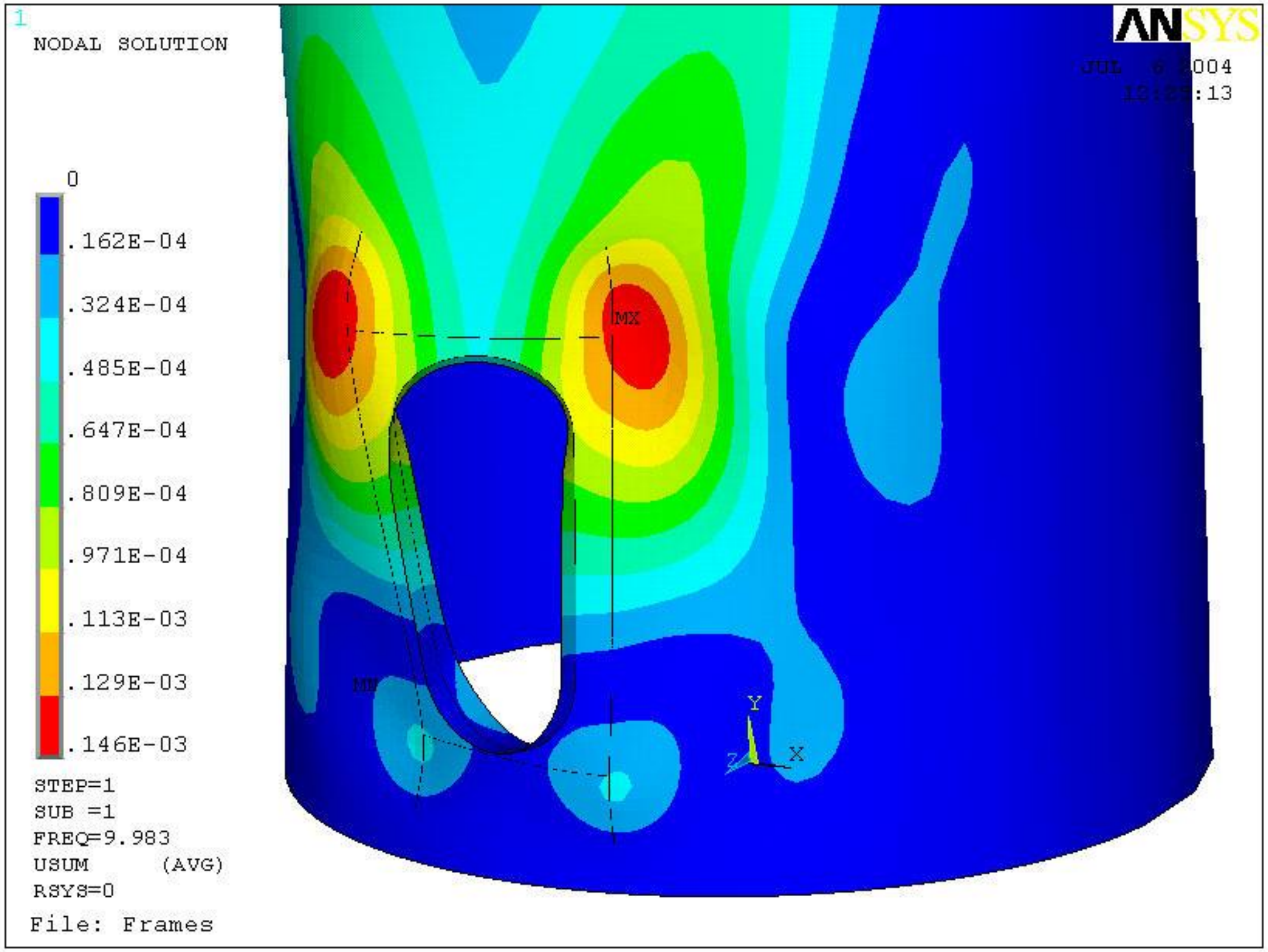
ULS: Buckling

Tower doorways

Tower doorways are always stiffened round the edge, but standard rules for a cylindrical shell no longer apply. FE analysis can be used.

ULS: Buckling

Analysis of buckling using finite elements



first buckling mode

ULS: Fatigue

A WTG tower may see 1,000,000,000 loading cycles in its life

No. of load cycles = No. of blade passes
For 20 rpm 3 bladed machine operating continuously, this gives
20 x 3 x 60 x 8760 x25 = ca 800,000,000 cycles

The turbine manufacturer describes these loads in terms of **fatigue load spectra**.

These are tables of load ranges (eg tower base bending moment or TBOM) against numbers of cycles.

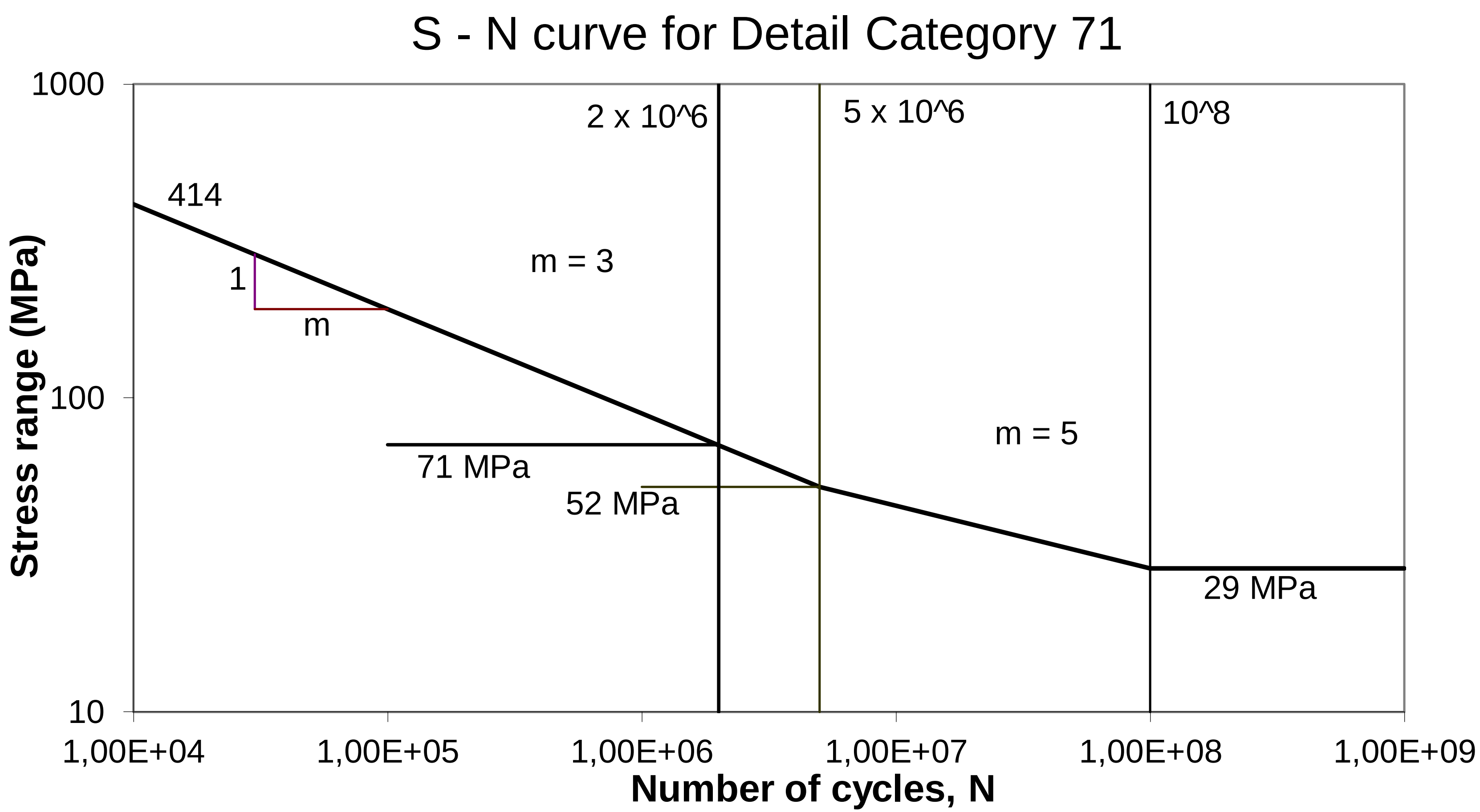
ULS: Fatigue

Fatigue bending moment ranges are converted to stress ranges using $\sigma = M/Z$.

[Load safety factor = Material safety factor = 1.0]

S/N curves give the number of constant amplitude load cycles permitted for each stress range.

ULS: Fatigue



S - N curve for Detail Category 71
1000
100
10
Stress range (MPa)
414
1
m
m = 3
2 x 10^6
5 x 10^6
10^8
m = 5
71 MPa
52 MPa
29 MPa
1,00E+04
1,00E+05
1,00E+06
1,00E+07
1,00E+08
1,00E+09
Number of cycles, N

Avoidance of resonance

Sources of Tower Excitation

A. Blade passing frequency

Stochastic wind loading (gust slicing)
Each blade "slices through" a localised gust in turn. Dominant effect.

Tower shadow
Load on each blade drops off sharply as it passes behind tower

Wind shear, yaw, shaft tilt
Largely averaged out over three blades – 2^{nd} order

Avoidance of resonance

Sources of Tower Excitation

B. Rotational frequency

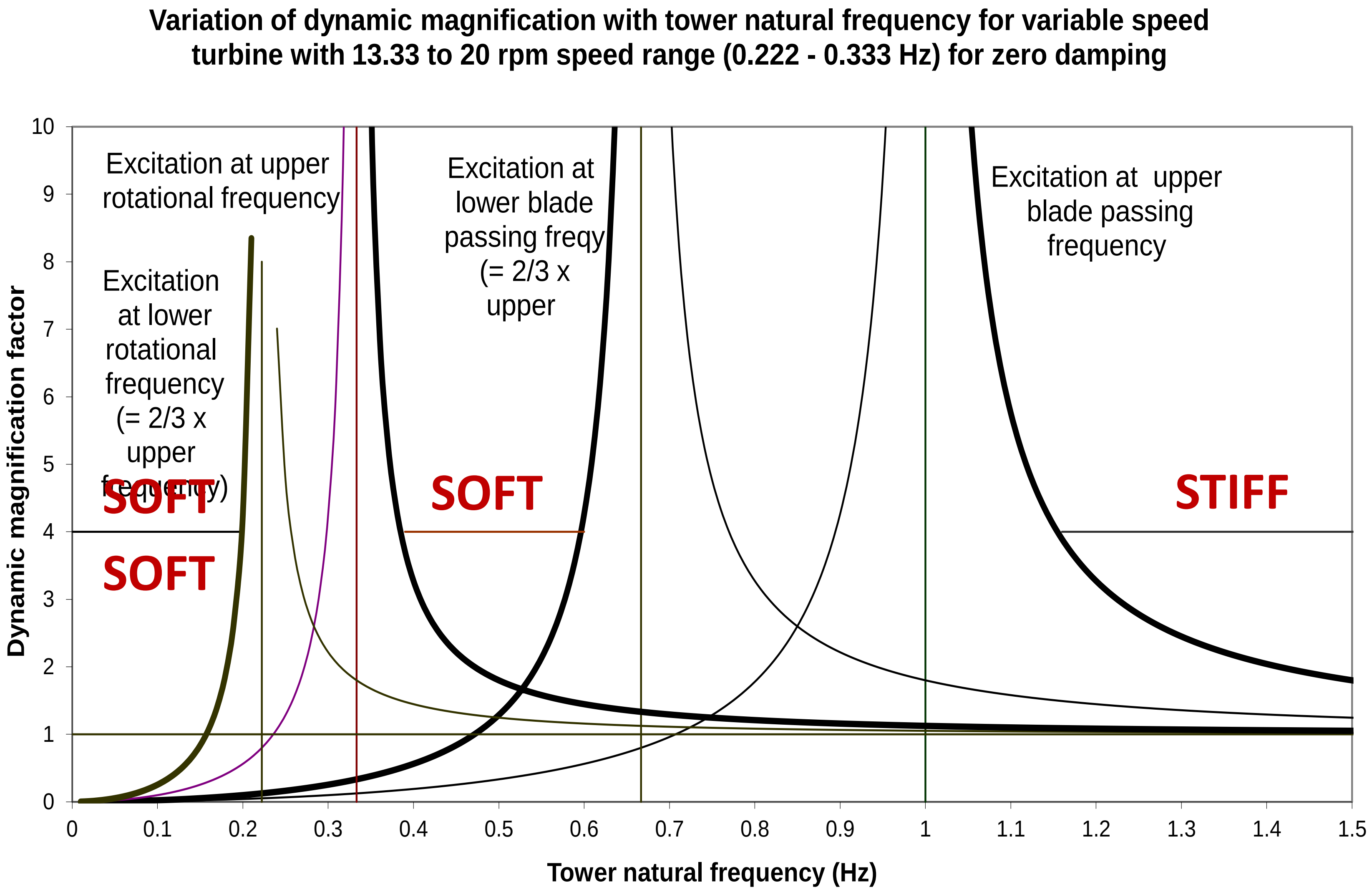
Blade pitch error

+/- 0.3 degrees specified in 2003 GL rules
=> thrust variation of ~+/- 1% of steady thrust

Rotor mass imbalance

0.005R eccentricity specified in 1999 GL rules
=> moment variation of ~+/-1% of max thrust x R

Avoidance of resonance

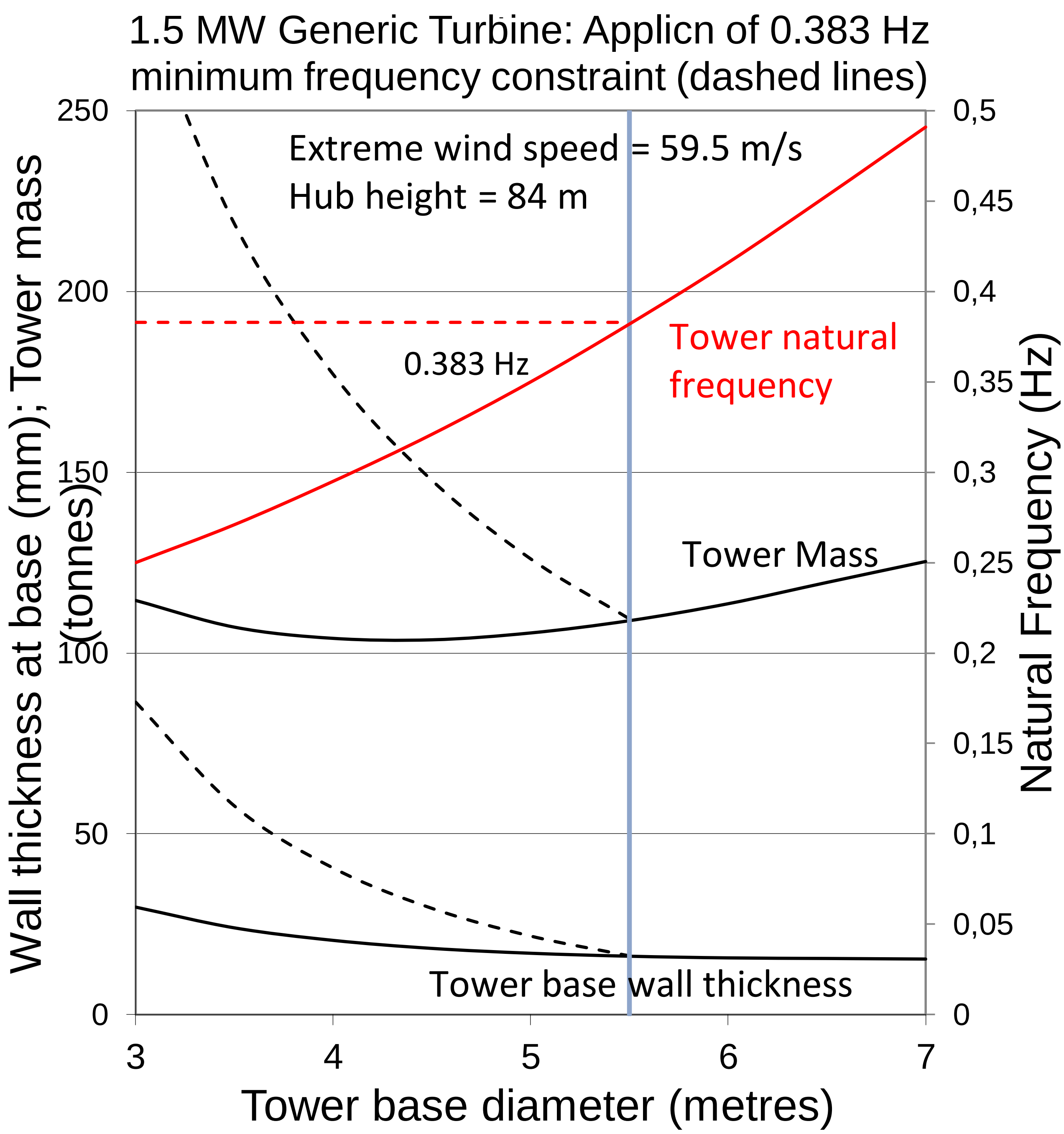


Avoidance of resonance

Design options

Second moment of area ($\pi R^3 t$) restricted by natural frequency limitations.

Initially, increasing the R/t ratio gives more efficient use of material, but at high R/t the buckling reduction factor penalty increases.



1.5 MW Generic Turbine: Applicn of 0.383 Hz minimum frequency constraint (dashed lines)
Extreme wind speed = 59.5 m/s
Hub height = 84 m
0.383 Hz
Tower natural frequency
Tower Mass
Tower base wall thickness
Wall thickness at base (mm); Tower mass (tonnes)
Natural Frequency (Hz)
Tower base diameter (metres)
250
200
150
100
50
0
0,5
0,45
0,4
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
3
4
5
6
7

Blade Clearance

Blades bending close to tower

Image: Vestas