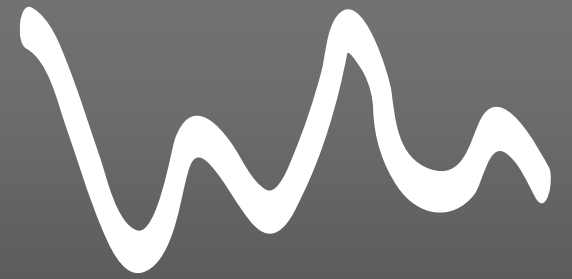


# WIND PROJECT



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# Wind verification of a work of art: the Arc Majeur according Eurocode 1991-1-4

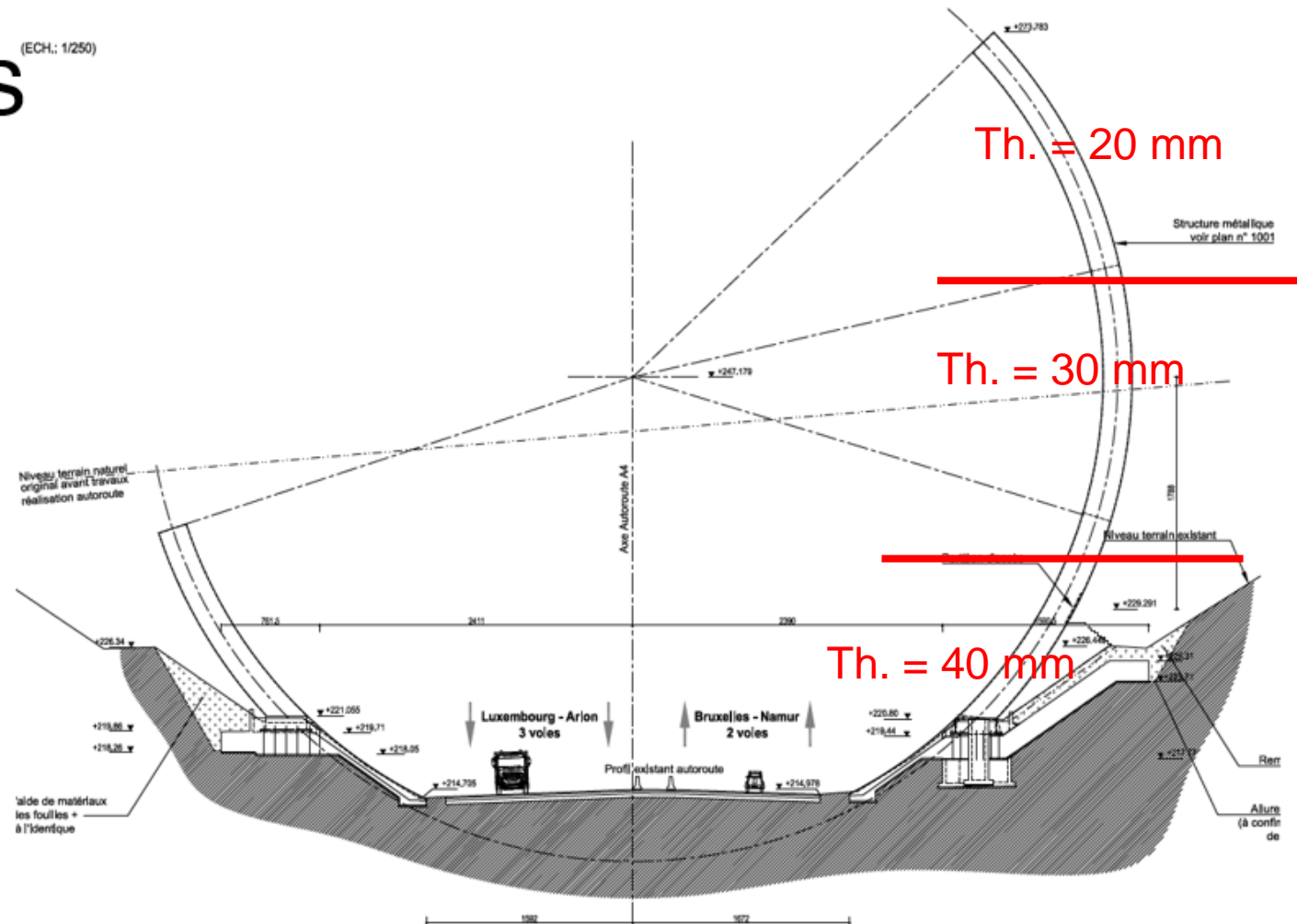
Make the wind verification of the work of art Arc Majeur located on the motorway E411 according to the Eurocode EN 1991-1-4



# Main dimensions

## Main dimensions (ECH: 1/250)

- Angle of 205°
- Radius of 38,5m
- Height : 60m
- Square section 2,25m
- Corten Steel: thk of 20 mm, 30mm and 40mm
- Total mass 147 To + 37 To
- Foundations: 1200 To



# Wind characteristics

- Mean wind speed
- Turbulence intensity
- The peak wind speed
- The peak wind pressure
- Wind distributed loads on the arc

Reference wind speed =  $V_{b,0} = 23\text{m/s}$

Return period = 50 years

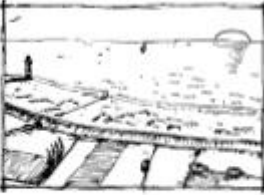
$C_{dir} = C_{seasonal} = C_0 = 1,0$

Terrain Category II  $\rightarrow z_0 = 0.05$  and  $z_{min} = 2\text{m}$

The force coefficient for a square section is taken equal to:  $C_f = 2,0$

## Terrain category 0

Sea, coastal area exposed to the open sea



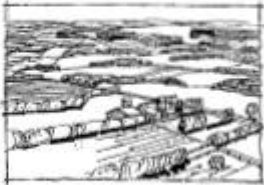
## Terrain category I

Lakes or area with negligible vegetation and without obstacles



## Terrain category II

Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights



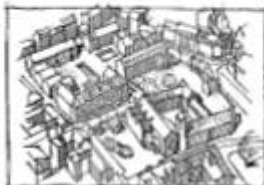
## Terrain category III

Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)



## Terrain category IV

Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m



# Wind characteristics

(2)P The basic wind velocity shall be calculated from Expression (4.1).

$$v_b = c_{dir} \cdot c_{season} \cdot v_{b,0} \quad (4.1)$$

where:

$v_b$  is the basic wind velocity, defined as a function of wind direction and time of year at 10 m above ground of terrain category II

$v_{b,0}$  is the fundamental value of the basic wind velocity, see (1)P

$c_{dir}$  is the directional factor, see Note 2.

$c_{season}$  is the season factor, see Note 3.

## 4.3 Mean wind

### 4.3.1 Variation with height

(1) The mean wind velocity  $v_m(z)$  at a height  $z$  above the terrain depends on the terrain roughness and orography and on the basic wind velocity,  $v_b$ , and should be determined using Expression (4.3)

$$v_m(z) = c_r(z) \cdot c_o(z) \cdot v_b \quad \mathbf{V_{mean,top} = 31 \text{ m/s}} \quad (4.3)$$

# Wind characteristics

## 4.4 Wind turbulence

(1) The turbulence intensity  $I_v(z)$  at height  $z$  is defined as the standard deviation of the turbulence divided by the mean wind velocity.

NOTE 1 The turbulent component of wind velocity has a mean value of 0 and a standard deviation  $\sigma_v$ . The standard deviation of the turbulence  $\sigma_v$  may be determined using Expression (4.6).

$$\sigma_v = k_r \cdot v_b \cdot k_t \quad (4.6)$$

For the terrain factor  $k_r$  see Expression (4.5), for the basic wind velocity  $v_b$  see Expression (4.1) and for turbulence factor  $k_t$  see Note 2.

NOTE 2 The recommended rules for the determination of  $I_v(z)$  are given in Expression (4.7)

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_t}{c_0(z) \cdot \ln(z/z_0)} \quad \text{for} \quad z_{\min} \leq z \leq z_{\max} \quad (4.7)$$
$$I_v(z) = I_v(z_{\min}) \quad \text{for} \quad z < z_{\min}$$

$$I_{v,\text{top}} = 0.141$$

# Wind characteristics

## 4.4 Wind turbulence

(1) The turbulence intensity  $I_v(z)$  at height  $z$  is defined as the standard deviation of the turbulence divided by the mean wind velocity.

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$$\sigma_v = k_r \cdot v_b \cdot k_t \quad (4.6)$$

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$$I_v(z) = I_v(z_{\min}) \quad \text{for} \quad z < z_{\min}$$

## 4.5 Peak velocity pressure

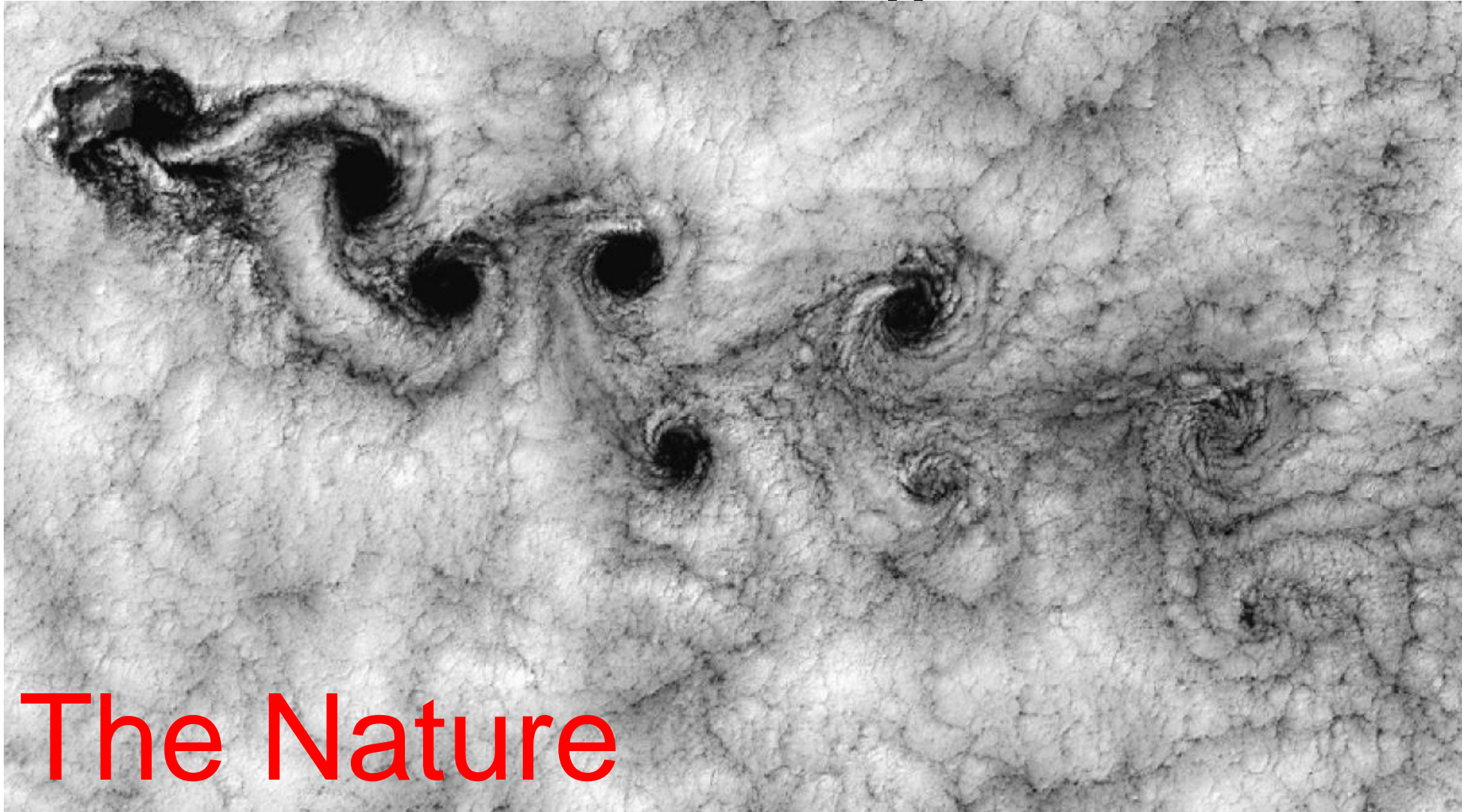
(1) The peak velocity pressure  $q_p(z)$  at height  $z$ , which includes mean and short-term velocity fluctuations, should be determined.

NOTE 1 The National Annex may give rules for the determination of  $q_p(z)$ . The recommended rule is given in Expression (4.8).

$$q_p(z) = [1 + 7 \cdot I_v(z)] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = c_e(z) \cdot q_b$$

**$V_{\text{peak,top}} = 43.7 \text{ m/s}$**   
 **$Q_{\text{p,top}} = 1200 \text{ N/m}^2$**  (4.8)

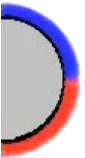
# Vortex Shedding verification



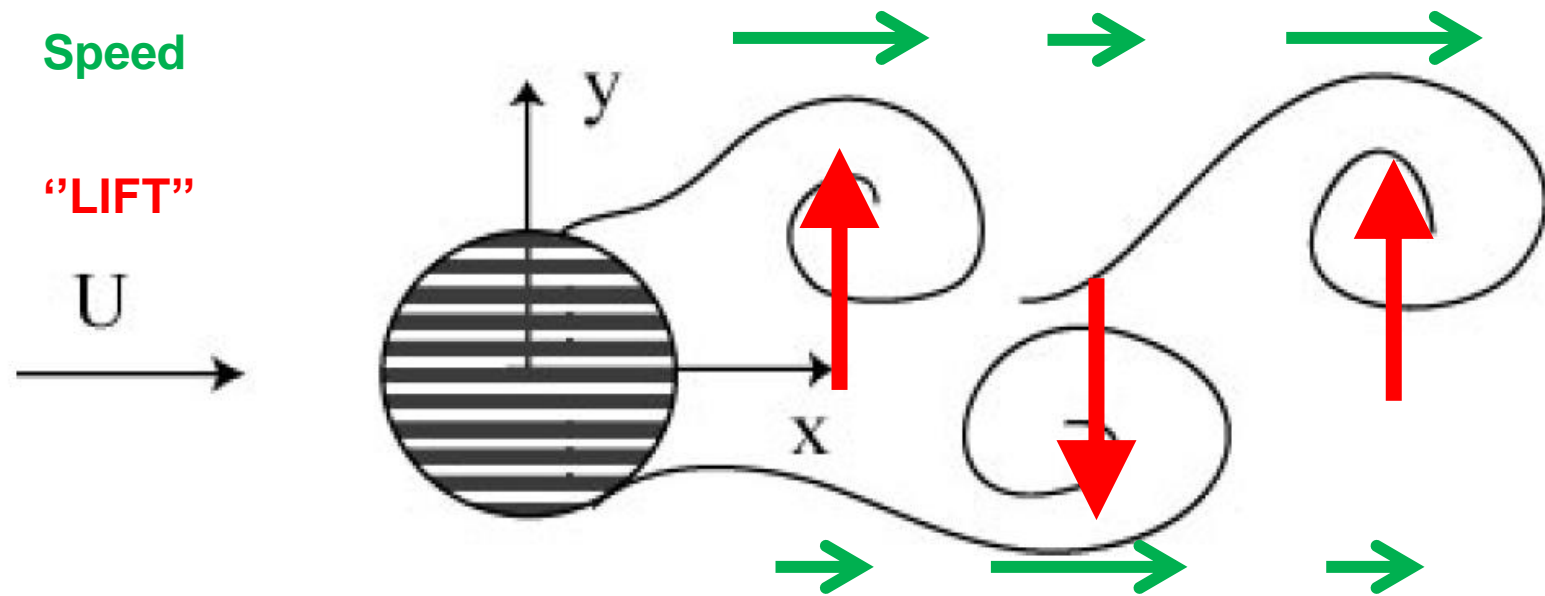
The Nature

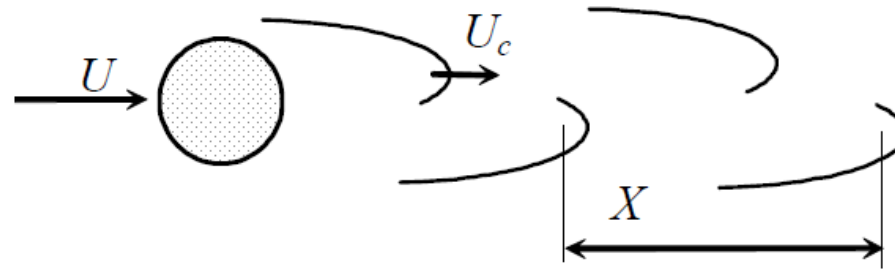


$t = 0.550$



[youtube.com/user/rosikru](https://www.youtube.com/user/rosikru)

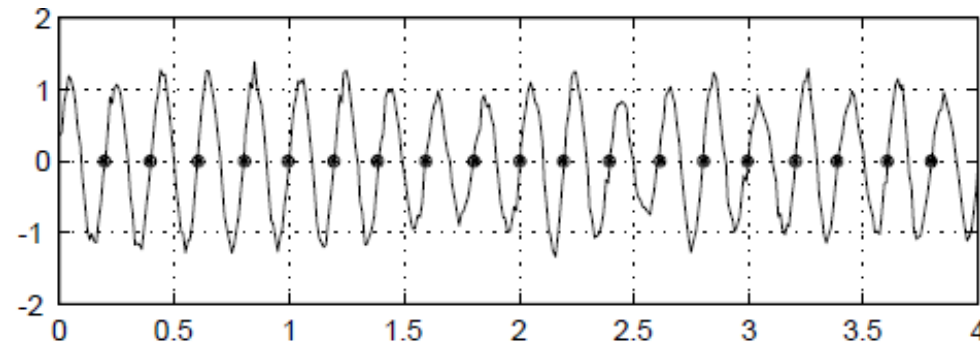




**Vortices generates sinusoidal lateral lift forces**

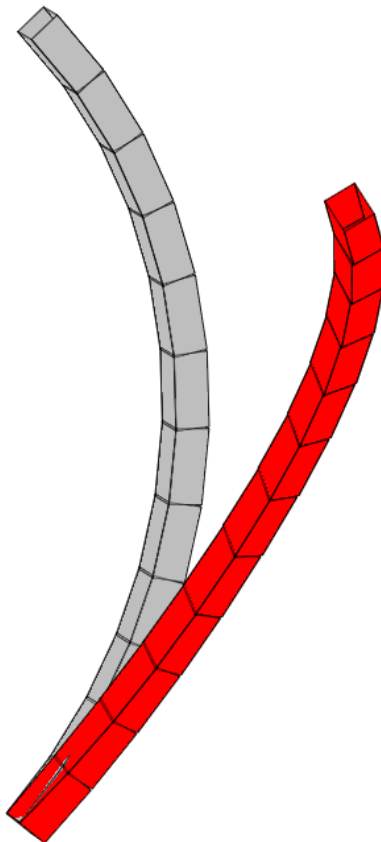
**These alternated vortices**

- **Will create lift forces**
- **Will be more regular if the wind turbulence ( $l_u, l_v$ ) is low**



# Eigen Modes

Beam models



- Compute first eigen modes
- Calculate modal masses

Eigen Modes ( $\Psi$ ) normalized with maximum displacement = 1

With Matlab :  $\Psi^T.M.\Psi = 1$

Matlab value should be corrected:

$$\Psi \rightarrow \Psi / \max(\Psi)$$

$$\text{Modal mass} \rightarrow \Psi^T.M.\Psi / \max(\Psi)^2$$

# Vortex Shedding Verification

BS EN 1991-1-4:2005+A1:2010  
EN 1991-1-4:2005+A1:2010 (E)

**Annex E**  
(informative)

**Vortex shedding and aeroelastic instabilities**

**E.1 Vortex shedding**

# Vortex Shedding Verification

BS EN 1991-1-4:2005+A1:2010  
EN 1991-1-4:2005+A1:2010 (E)

## Annex E (informative)

### Vortex shedding and aeroelastic instabilities

$$V_{\text{crit},i} = \frac{b \cdot n_{i,y}}{St} \quad \mathbf{V_{\text{critic}} = 13.5 \text{ m/s}} \quad (\text{E.2})$$

where:

$b$  is the reference width of the cross-section at which resonant vortex shedding occurs and where the modal deflection is maximum for the structure or structural part considered; for circular cylinders the reference width is the outer diameter

$n_{i,y}$  is the natural frequency of the considered flexural mode  $i$  of cross-wind vibration; approximations for  $n_{1,y}$  are given in F.2

$St$  Strouhal number as defined in E.1.3.2.

# Vortex Shedding Verification

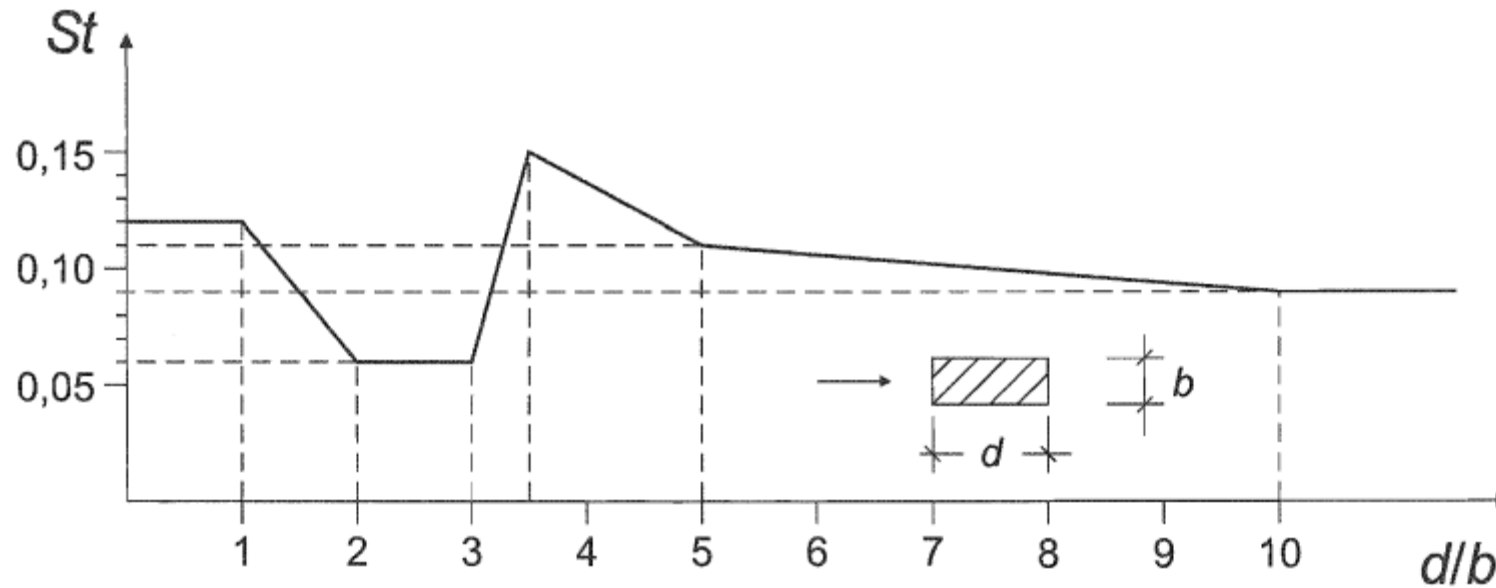


Figure E.1 — Strouhal number ( $St$ ) for rectangular cross-sections with sharp corners

# Vortex Shedding Verification – amplitude approach 2

## E.1.5.3 Approach 2, for the calculation of the cross wind amplitudes

(1) The characteristic maximum displacement at the point with the largest movement is given in Expression (E.13).

$$y_{\max} = \sigma_y \cdot k_p \quad \mathbf{y_{\max} = 1.22 \text{ m}} \quad (\text{E.13})$$

where:

$\sigma_y$  is the standard deviation of the displacement, see (2)

$k_p$  is the peak factor, see (6)

(2) The standard deviation  $\sigma_y$  of the displacement related to the width  $b$  at the point with the largest deflection ( $\phi = 1$ ) can be calculated by using Expression (E.14).

$$\frac{\sigma_y}{b} = \frac{1}{St^2} \cdot \frac{C_c}{\sqrt{\frac{Sc}{4 \cdot \pi} - K_a \cdot \left(1 - \left(\frac{\sigma_y}{b \cdot a_L}\right)^2\right)}} \cdot \sqrt{\frac{\rho \cdot b^2}{m_e}} \cdot \sqrt{\frac{b}{h}} \quad (\text{E.14})$$



# Structural damping

BS EN 1991-1-4:2005+A1:2010  
EN 1991-1-4:2005+A1:2010 (E)

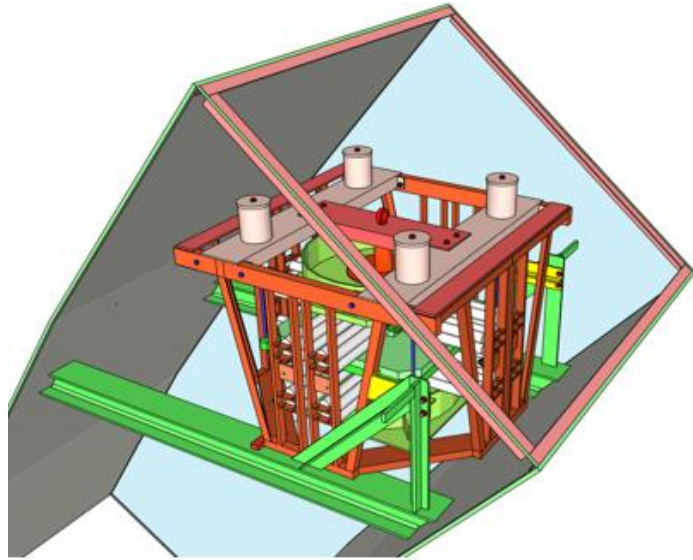
Table F.2 —Approximate values of logarithmic decrement of structural damping in the fundamental mode,  $\delta_s$

Structural type	structural damping, $\delta_s$	
reinforced concrete buildings	0,10	
steel buildings	0,05	
mixed structures concrete + steel	0,08	
reinforced concrete towers and chimneys	0,03	
unlined welded steel stacks without external thermal insulation	0,012	
unlined welded steel stack with external thermal insulation	0,020	
steel stack with one liner with external thermal insulation <sup>a</sup>	$h/b < 18$	0,020
	$20 \leq h/b < 24$	0,040
	$h/b \geq 26$	0,014
steel stack with two or more liners with external thermal insulation <sup>a</sup>	$h/b < 18$	0,020
	$20 \leq h/b < 24$	0,040
	$h/b \geq 26$	0,025
steel stack with internal brick liner	0,070	
steel stack with internal gunite	0,030	
coupled stacks without liner	0,015	
guyed steel stack without liner	0,04	
steel bridges + lattice steel towers	welded	0,02
	high resistance bolts	0,03
	ordinary bolts	0,05
composite bridges	0,04	
concrete bridges	prestressed without cracks	0,04

$$\delta = 0.012$$

$$\xi = \delta / (2 \cdot \pi) = 0.002$$

# Vortex Shedding Verification – TMD design



# Vortex Shedding Verification – TMD design

- Use Den Hartog formulation to optimise the TMD
  - Frequency  $f_{\text{TMD}} = \nu \cdot \text{freq}$       $\nu = \frac{1}{1 + \mu}$       $\mu = m_{\text{TMD}}/\text{modal mass}$
  - Damping ratio TMD  $\xi = ?$       $\xi = \sqrt{\frac{3\mu}{8(1 + \mu)}} = \frac{b}{2\sqrt{km}}$
  - $m_{\text{TMD}} = ?$
- Top displacements reduced by 10
- Plot the Bode diagram of the 1 dof system
- Compare with the 2 dof's (+TMD)

