Metal Structures II

Lecture VI

Tensile structures

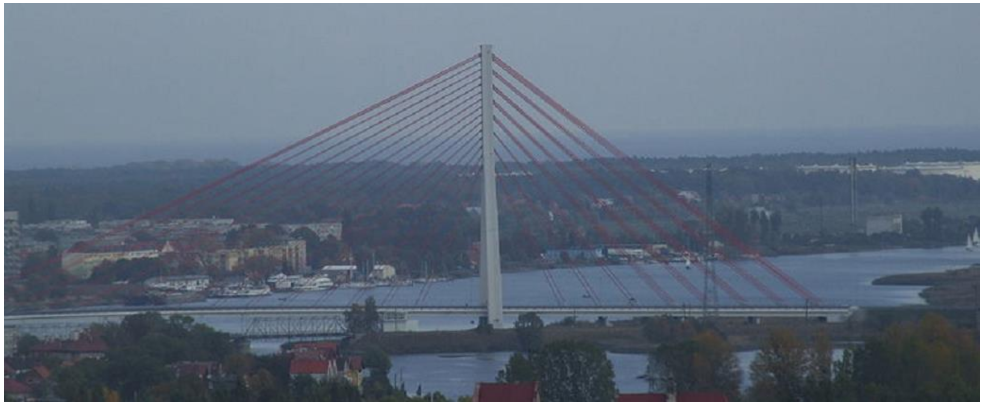
Contents

Introduction

Each strucutres presented previous, on Ist and IInd step of study, are mainly calculated according to EN 1993-1-1 or EN 1993-1-5. For suspension structures is dedicated other Eurocode:

EN 1993-1-11 Design of structures with tension components

Photo: wikipedia



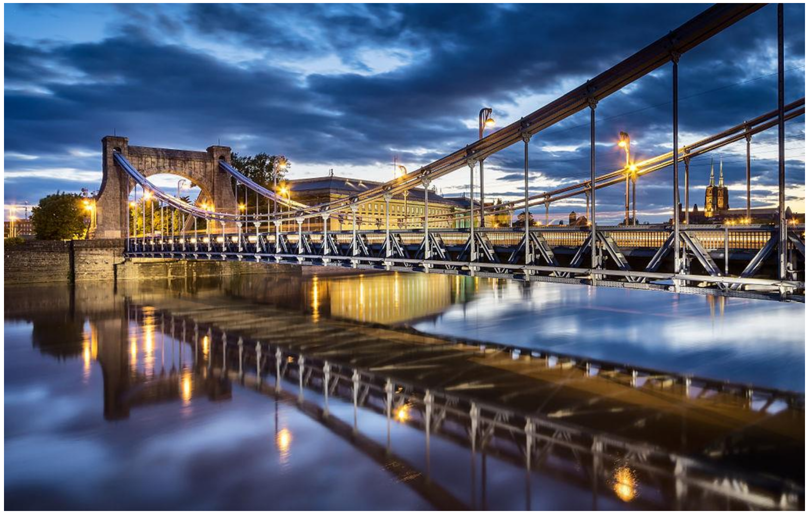


Photo: wikipedia

Bridges (cable-stayed, suspension, ribbon, arch)

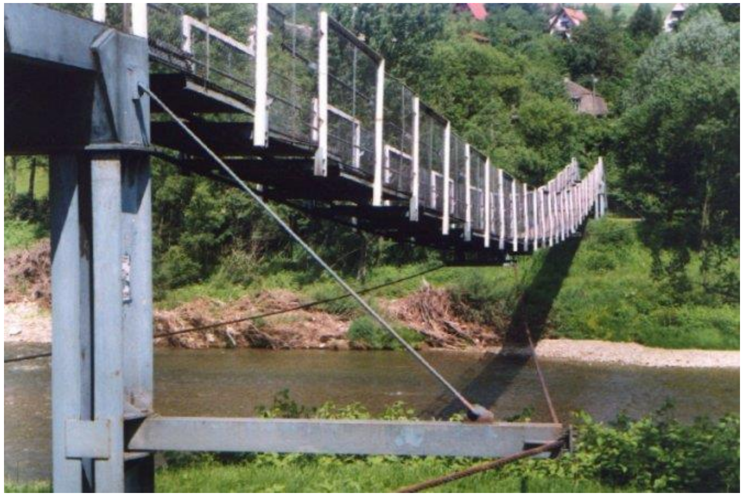


Photo: footbridge.pl

Photo: wikipedia

Suspension roofs

Photo: wikipedia

Photo: gwe24.pl

Photo: greatbritain.pinger.pl

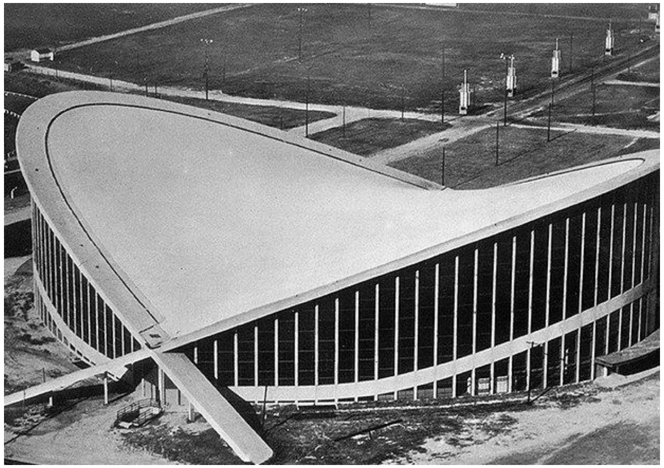


Photo: bryla.pl

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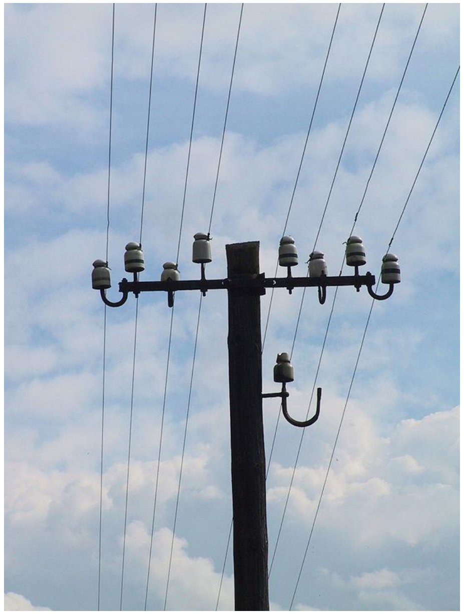


Photo: wikipedia

Power&telephone lines & tractions

Photo: wikipedia

Photo: honigmann.com

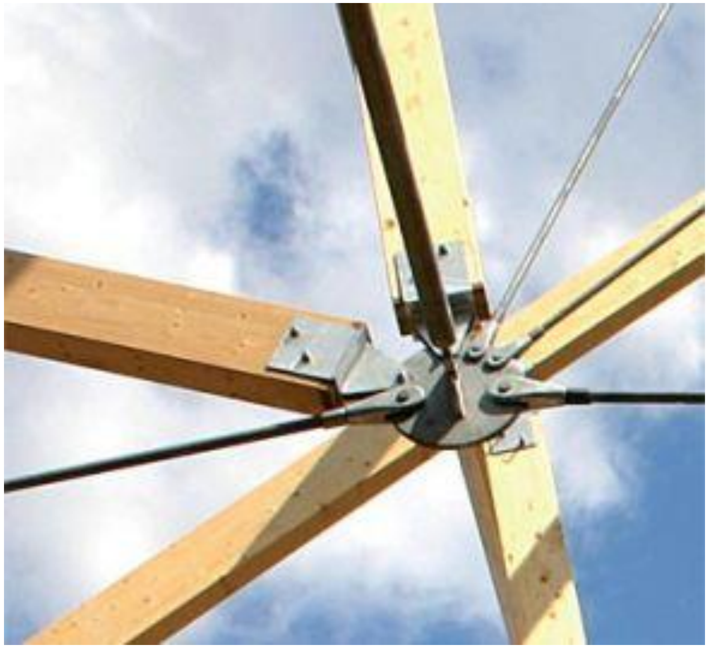
Photo: fompo.com

Photo: radiomap.eu

Guys & stays

Photo: halfen.com

Photo: fachowydekarz.pl



Stays in truss

Transport

Photo: wikipedia

Photo: winda-sc.pl

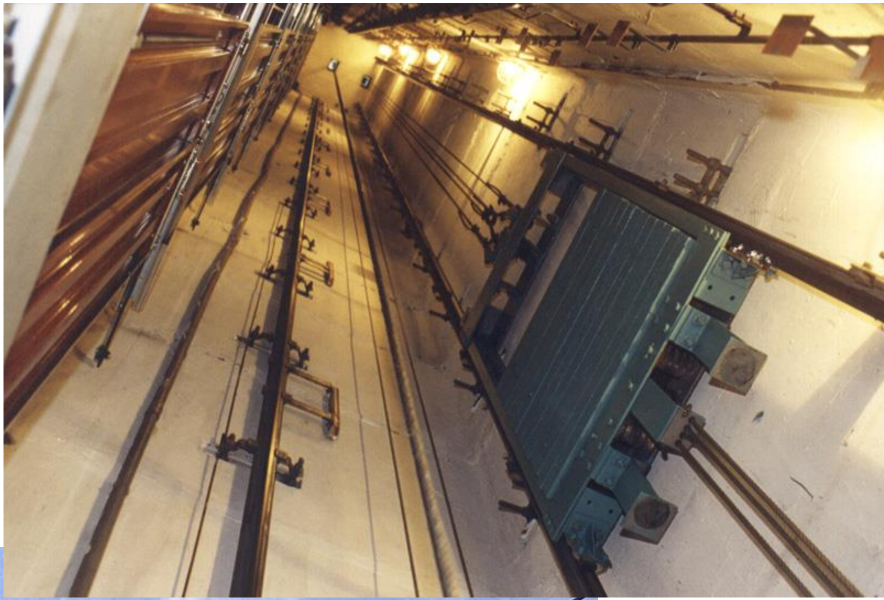


Photo: wikipedia

Photo: wikipedia

Barriers

Photo: krantech.pl

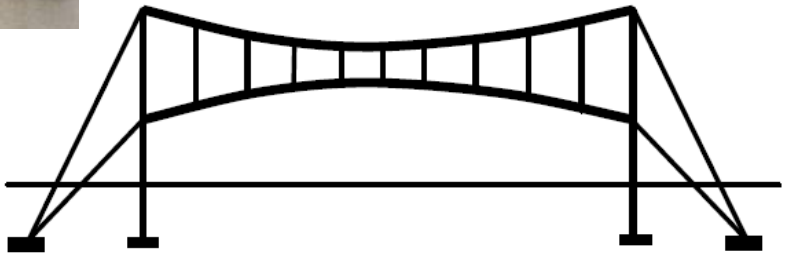
Photo: prowerk.pl

2D & 3D tensile structures

Example of flat tensile structure is Jawerth truss: special type of girder, in which both cords are tension members; web members are classical steel bars.

Photo: footbridge.pl

Photo: chodor-projekt.net



Spatial tensile structure: di-curvature cable nets (roofs).

Photo: us.archello.com

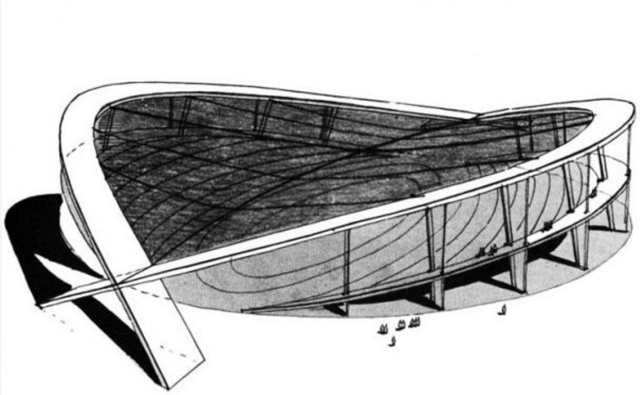


Photo: culture.pl

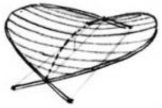


Photo: archiexpo.com

Photo: contractdesign.com

Standards:

EN 1993-1-11 Design of structures with tension components

EN 10 138 Prestressing steels

EN 10 264 Steel wire and wire products. Steel wire for ropes

EN 12 385 Steel wire ropes. Safety

EN 13 411 Terminations for steel wire ropes. Safety

EN 1993-1-11

Design of structures with tension components

Types of tension members → # t / 15 - 21

Structure of tension members → # t / 22 - 29

Grade of steel → # t / 30 - 32

Young modulus → # t / 33 - 34

ULS → # t / 35 - 39

SLS → # t / 40 - 46

Corrosion protection → # t / 47

Anchorages → # t / 48 - 51

Types of tension members

Group	Main tension element	Component
A	Rod (bar)	Tension rod (bar) system, prestressing bar
B	Circular wire	Spiral strand rope
	Circular and Z-wires	Fully locked coil rope
	Circular wire and strand wire	Strand rope
C	Circular wire	Parallel wire strand (PWS)
	Circular wire	Bundle of parallel wires
	Seven wire (prestressing) strand	Bundle of parallel strands

EN 1993-1-11 tab. 1.1

Photo: macalloy.com

A - round bars connected by threads

B - wires; diameter 5 mm - 160 mm; anchored in sockets or other

Photo: linplast.pl

Photo: gkw24.pl

C - need individual or collective anchoring and corrosion protection

Group A:

bracing for roofs, walls, girders;
stays for roof elements, pylons;
tensioning systems for steel-wooden truss and steel structures, space frames

EN 1993-1-11 1.1.(2)

Group B (first part):

Spiral strand ropes are mainly used as:

stay cables for aerials, smoke stacks, masts and bridges;

carrying cables and edge cables for light weight structures;

hangers or suspenders for suspension bridges;

stabilising cables for cable net, anr wood and steel trusses;

hand-rail cables for banisters, balcones, bridge rails and guardrails;

EN 1993-1-11 1.1.(2)

Group B (second part):

Fully locked coil ropes are fabricated in the diameter range of 20 mm to 180 mm and are mainly used as:

stay cables, suspension cables and hangers for bridge construction;

suspension cables and stabilizing cables in cable trusses;

edge cables for cable nets;

stay cables for pylons, masts, aerials;

EN 1993-1-11   1.1.(2)

Group B (third part):

Structural strand ropes are mailny used as:

stay cables for masts, aerials;

hangers for suspension bridges;

damper / spaced tie cables between stay cables;

edge cables for fabric membranes;

rail cables for banisters, balcones, bridge rails and guardrails;

EN 1993-1-11 1.1.(2)

Group C:

Bundles of parallel wires are mainly used as stay cables, main cables for suspension bridges and external tendons;

Bndles of parallel strands are mainly used as stay cables for composite and steel bridges

EN 1993-1-11   1.1.(2)

Group A → EN 1993-1-1 and EN 1993-1-11

Groups B and C → EN 1993-1-11

Group A - rigid elements

Groups B and C - generally limp elements

Group A: horizontal distance between both ends of element ≤ 6,00 m → dead weight of element can be neglected; otherwise - tension with bending.

Groups B and C - small or big deflection → #t / 71

Structure of tension members

Strand

An element of rope normally consisting of an assembly of wires of appropriate shape and dimension laid helically in the same or opposite direction in one or more layers around a centre.

Strand rope (structural strand rope)

An assembly of several strands helically in one or more layers around a core (single layer rope) or centre (rotation-resistant or parallel-closed rope).

Spiral rope

An assembly of a minimum two layers of wires laid helically over a central wire

Spiral strand rope

Spiral rope comprising only round wires.

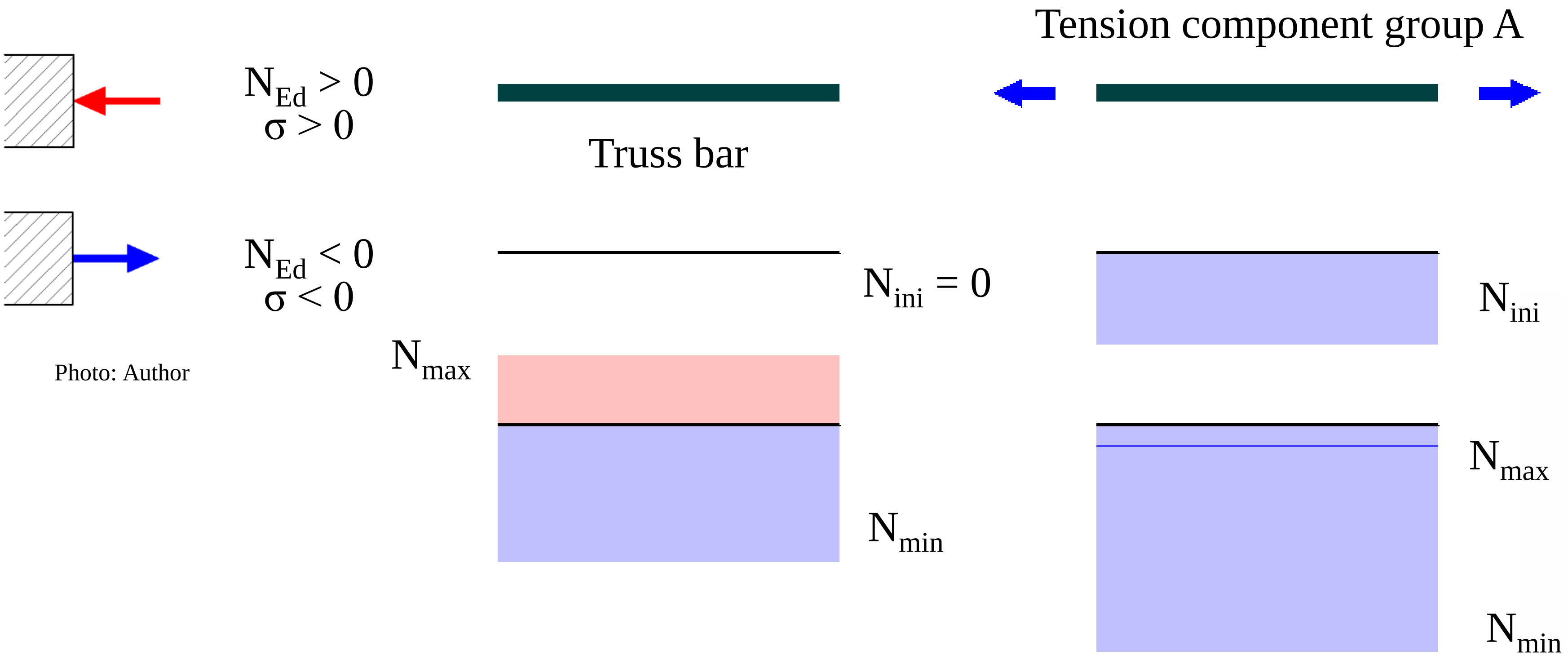
EN 1993-1-11 1.3.1 - 1.3.5

Fully locked coil rope

Spiral rope having an outer layer of fully locked Z-shaped wires.

Truss bar - axial fore (tensile or compressive) is an effect of loads.

Tension component group A - tensile axial force is an effect of initial tensile axial force and loads. Only tensile force is accepted as axial force.



Tension component group A

$N_{Ed} > 0$
$\sigma > 0$

Truss bar

$N_{Ed} < 0$
$\sigma < 0$

$N_{ini} = 0$

N_{ini}

N_{max}

N_{min}

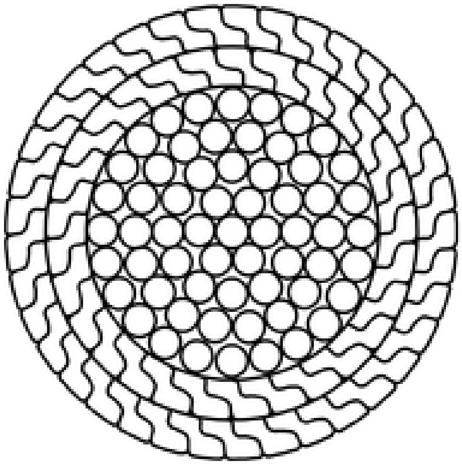
N_{max}

N_{min}

Photo: Author

$$| N_{\text{ini, ten. comp. gr. A}} | > | N_{\text{min, truss bar}} |$$

Wire - basis element of tension components; the most often has O or Z cross-section shape.



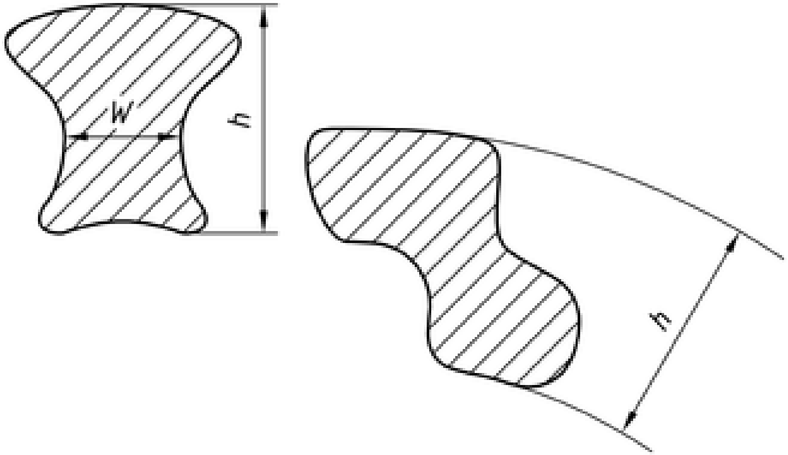
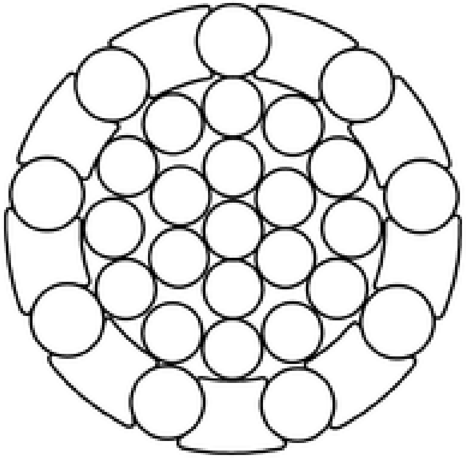


Photo: iso.org



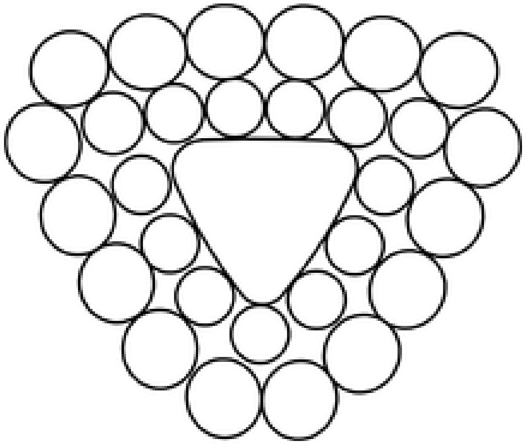
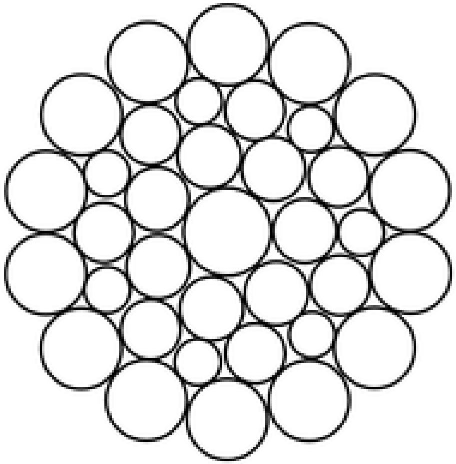


Photo: iso.org

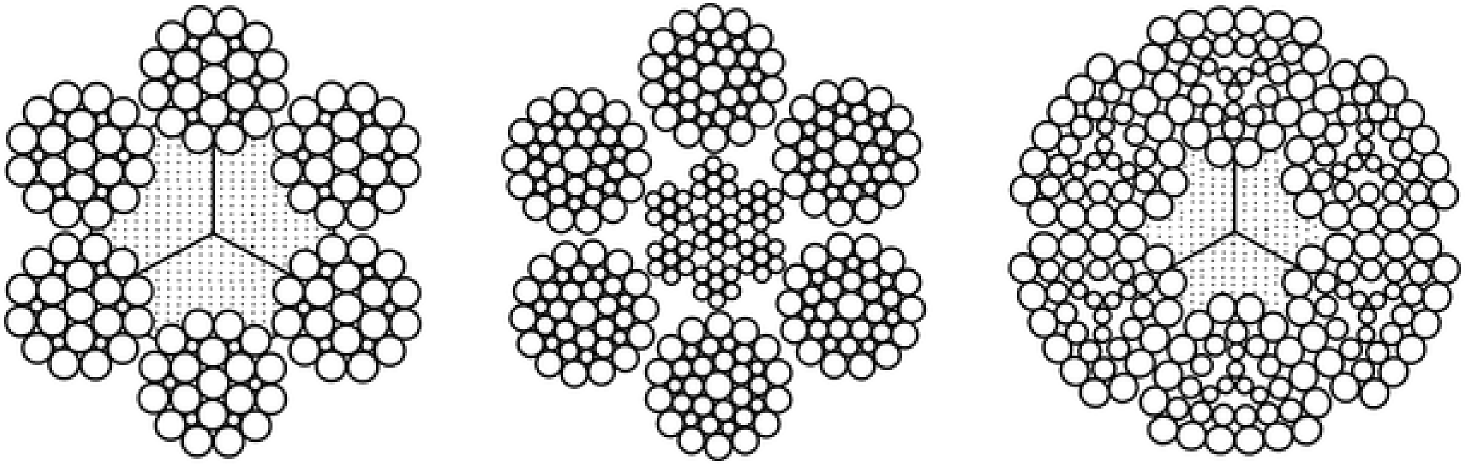


Strand - part of **strand rope**, consist of **wires**

Photo: tmgglobals.com

Strand rope - consist of **strands**

Photo: iso.org



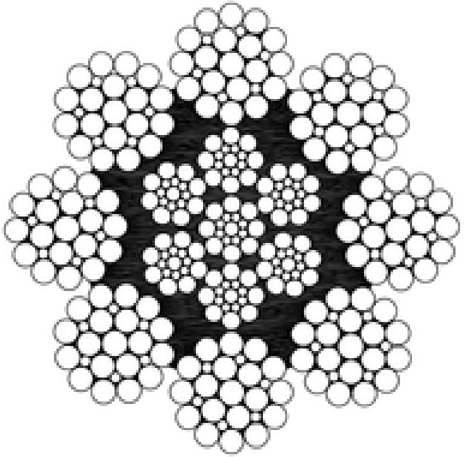


Photo: iso.org

Steel core of fiber core:

Photo: garagejournal.com

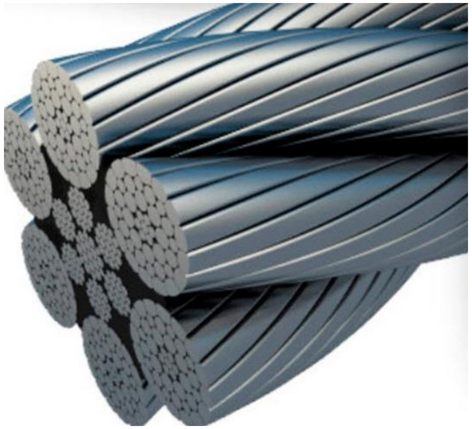
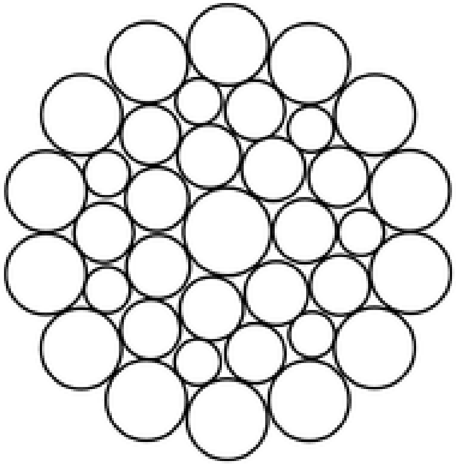


Photo: archiexpo.com

Photo: iso.org



Strand spiral rope

(subtype of **spiral rope)**

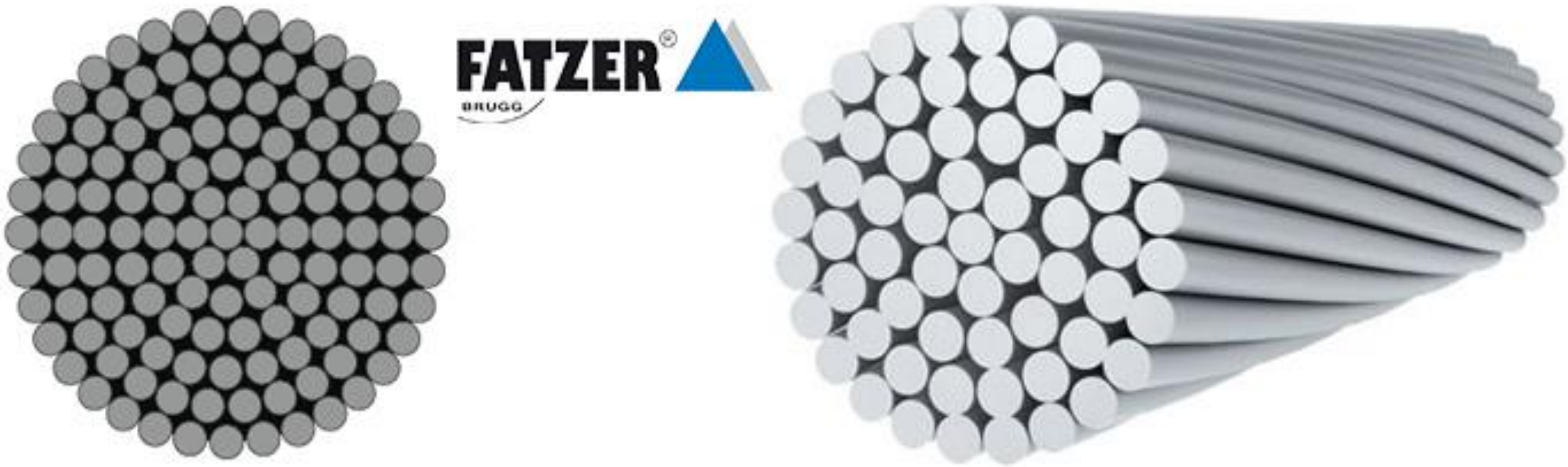


Photo: steelwirerope.com

Fully locked coil rope

(subtype of **spiral rope**)

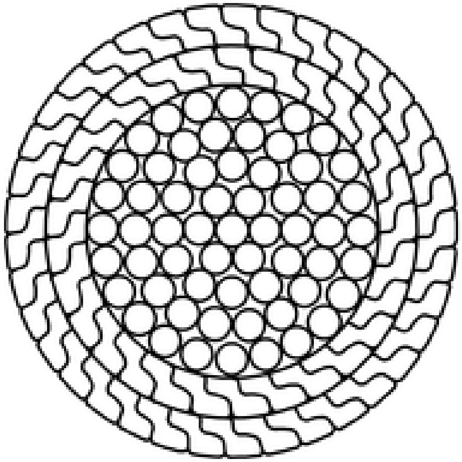


Photo: iso.org

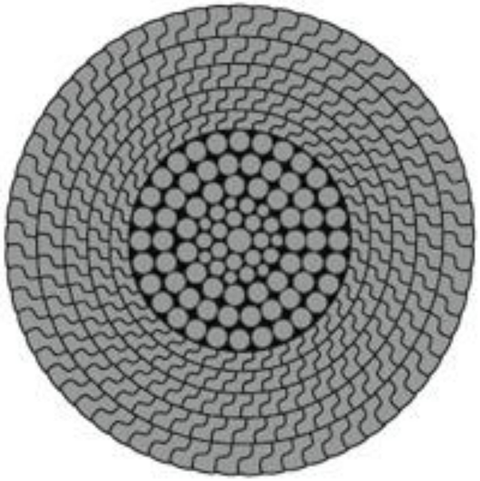


Photo: steelwirerope.com

WIRE

(part of)

STRAND

(part of)

STRAND ROPE

SPIRAL ROPE:

- **strand spiral rope**
  (subtype)
- **fully locked coil rope**
  (subtype)

Component

Self-supporting element

Cross-sections of **strand** and **spiral rope** could look the same.

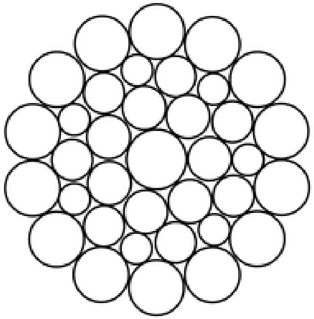


Photo: iso.org

Grade of steel

There is high-strength steel, applied to tension members

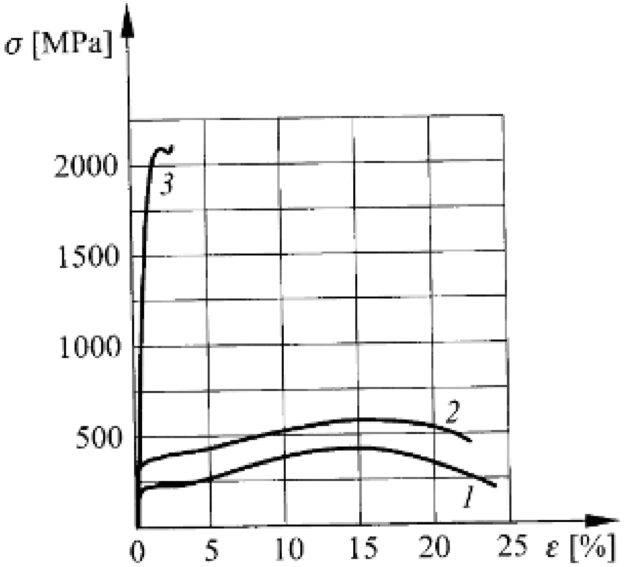


Photo: chodor-projekt.net

1. S235
2. S355
3. Steel for tension members

Type	f_u [MPa]
„Normal" steel, round wire	1 770
„Normal" steel, Z-wire	1 570
Stainless steel, round wire	1 450

EN 1993-1-11 3.1

Besides values f_u recommended by EN 1993-1-11 3.1, strength of steel for ropes can be even higher:

1 960 MPa

2 160 MPa

2 300 MPa

Because of this, the most popular grades of ropes (defined by manufacturers) R_r are as follow:

1 570 MPa

1 770 MPa

1 960 MPa

2 160 MPa

In opposite to "normal" steel, there is no plastic shelf for high strength steel. Because of this, $f_{0,1}$ or $f_{0,2}$ are calculated, based on statistical analysis of results R_e for ε_{pl} = 0,1 % or 0,2 % respectively.

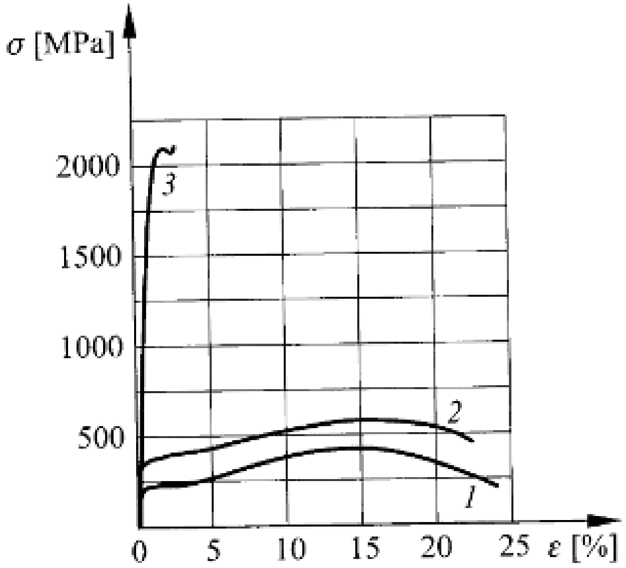


Photo: chodor-projekt.net

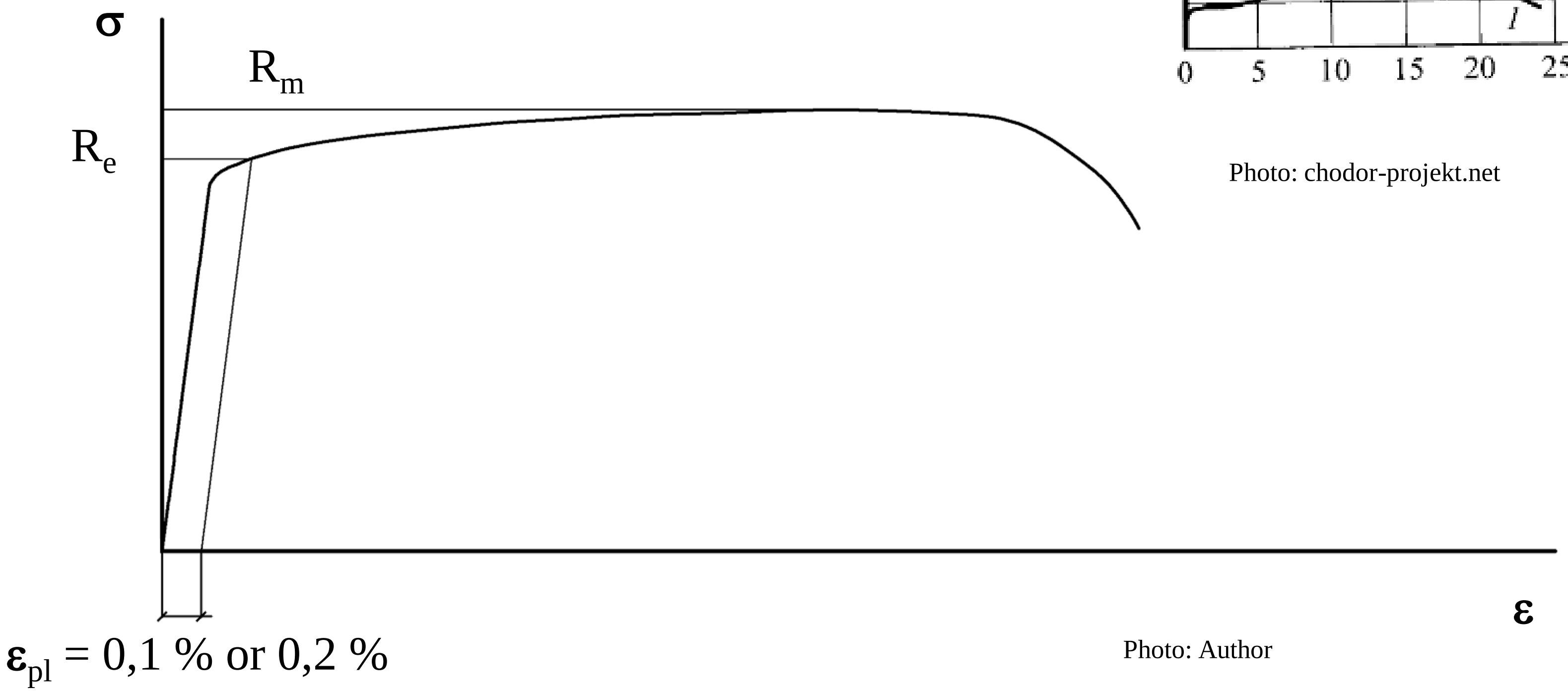


Photo: Author

Young modulus

EN 1993-1-11   3.2

Group A → E = 210 Gpa

Group B, C → EN 1993-1-11   tab. 3.1

	High strength tension component	E_Q [kN / mm^2]	
		„Normal" steel wires	Stainless steel wires
1	Spiral strand ropes	150 +/- 10	130 +/- 10
2	Fully locked coil ropes	160 +/- 10	
3	Strand wire ropes with CWR	100 +/- 10	90 +/- 10
4	Strand wire ropes with CF	80 +/- 10	
5	Bundled of parallel ropes	205 +/- 5	
6	Bundled of parallel strands	195 +/- 5	

CWR / CWS - steel core (rope / strand) → #t / 26

CF - fiber core → #t / 26

Catenary efects (recalculation to effective Young modulus because of catenary)

Photo: personal.strath.ac.uk

$$E_t = E / [\ 1+ w^2\ l^2\ E / (12\ \sigma^3)]$$

EN 1993-1-11 (5.1)

w - unit weight → #t / 38

1 - horizontal span

σ - stress in cable during exploatation

Ultimate Limit State

$$F_{Ed} / F_{Rd} \leq 1{,}0$$

EN 1993-1-11 (6.1), (6.2)

$$F_{Rd} = \min \{ F_{uk} / (1{,}5\, \gamma_R) \quad ; \quad F_k / \gamma_R \}$$

$F_{uk} \rightarrow$ # t / 36

$F_k \rightarrow$ # t / 39

Measures to minimise bending stresses at the anchorage (→ # t / 70)	γ_R
Yes	0,90
No	1,00

EN 1993-1-11 tab. 6.2

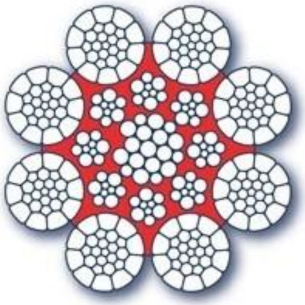


Photo: Author

A = area of metal part only (white)

A_m = area of total cross-section (white + red)

Group	F_{uk}
A	$A\ f_u$
B	$F_{min}\ k_e$
C	$A_m\ f_{uk}$

F_{min} → # t / 37

f_u → #t / 30

f_{uk} → characteristic value of f_u

A → #t / 35

A_m → #t / 35 ; $A_m = \pi\ d^2\ f / 4$

f → #t / 38

EN 1993-1-11 6.2.(3), (4)

EN 1993-1-1 6.2.3

Type of termination (→ #t / 48-49)	Loss factor k_e
Metal filled socket	1,0
Resin filled socket	1,0
Ferrule-secured eye	0,9
Swaged socket	0,9
U-bolt grip	0,8 *)
*) For U-bolt grip a reduction of preload is possible	

EN 1993-1-11 tab. 6.3

EN 1993-1-11 1.3.8, 1.3.9

Minimum breaking force

$F_{min} = d^2 R_r K$

Grade of rope R_r → #t / 31

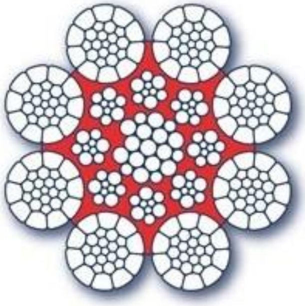
Breaking force factor:

$K = \pi f k / 4$

or

K → EN 12 385

Photo: iso.org



f = (area of metal cross-section) / (area within the circumference of rope) = (white) / (white + red)

f → #t / 38

Spinning loss factor k:

0,75 - 0,80 - strand ropes

0,88-0,90 spiral ropes non fully locked

0,92 - fully locked ropes

Fill factor f

EN 1993-1-11 tab. 2.2

		Fill factor f							Unit weigth w [kN / m^3]
		Core wire + 1 layer z-wires	Core wire + 1 layers z-wires	Core wire + >1 layer z-wires	Number of wire layers around core wire				
					1	2	3 - 6	> 6	
1	Spiral strand ropes (→ # t / 27)				0,77	0,76	0,75	0,73	83
2	Fully locked coil ropes (→ # t / 28)	0,81	0,84	0,88					83
3	Circular wire strand ropes (→ # t / 26)				0,56				93

EN 1993-1-11 tab. 6.1

Group	Relevant standard	F_k
A *)	EN 10 138-1	$F_{0,1k} = A_m f_{0,1}$
B	EN 10 264	$F_{0,2k} = A_m f_{0,2}$
C	EN 10 138-1	$F_{0,1k} = A_m f_{0,1}$
*) For prestressing bars see EN 1993-1-1 and EN 1993-1-4		

$f_{0,1}$, $f_{0,2}$ → # t / 32

A_m → #t / 35 ; $A_m = \pi d^2 f / 4$

f → #t / 38

Serviceability Limit State

Three aspects of SLS must be taken into consideration:

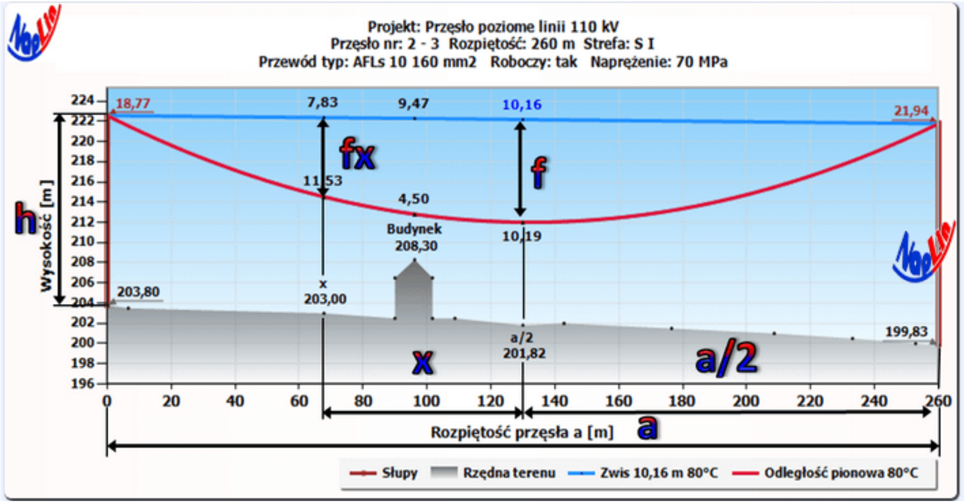


Photo: informs.pl

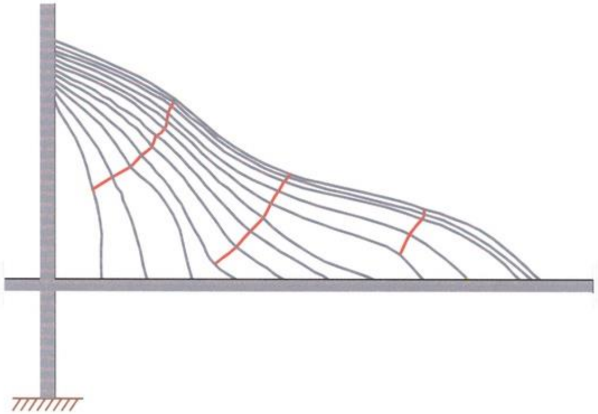


Photo: *R.W. Poston, Evaluation And Mitigation Of Rain Vibration Of Stay Cables*

Deformations, deflections (for example: electro-energetic lines; → #t / 41)

Vibrations (for example: stays in bridges; → #t / 42);

Stresses (→ #t / 43 – 46).

Deformation: electro-energetic line

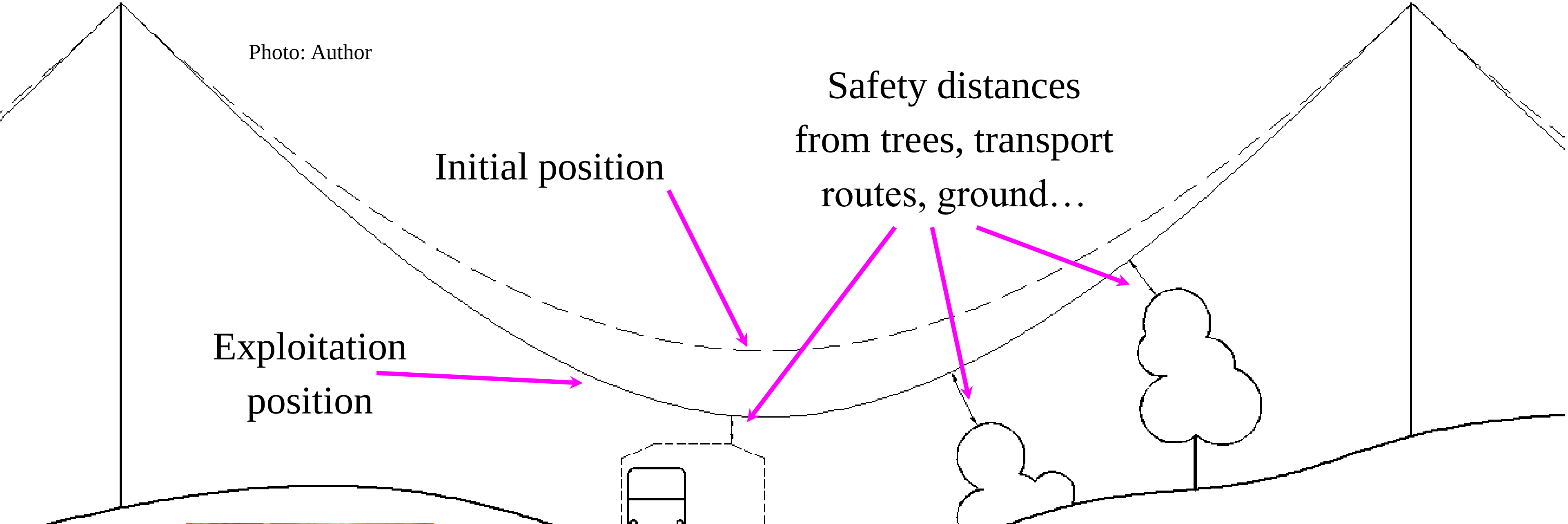


Photo: Author

Initial position

Exploitation position

Safety distances from trees, transport routes, ground…

Photo: kobieta.onet.pl

Summer condition:

high temperature → thermal expansion of cable → bigger deflection in exploitation stage

Photo: ise.pl

Winter condition:

Atmospheric icing (→ #t / 53) → bigger load → bigger deflection in exploitation stage

Vibration: stays in bridge

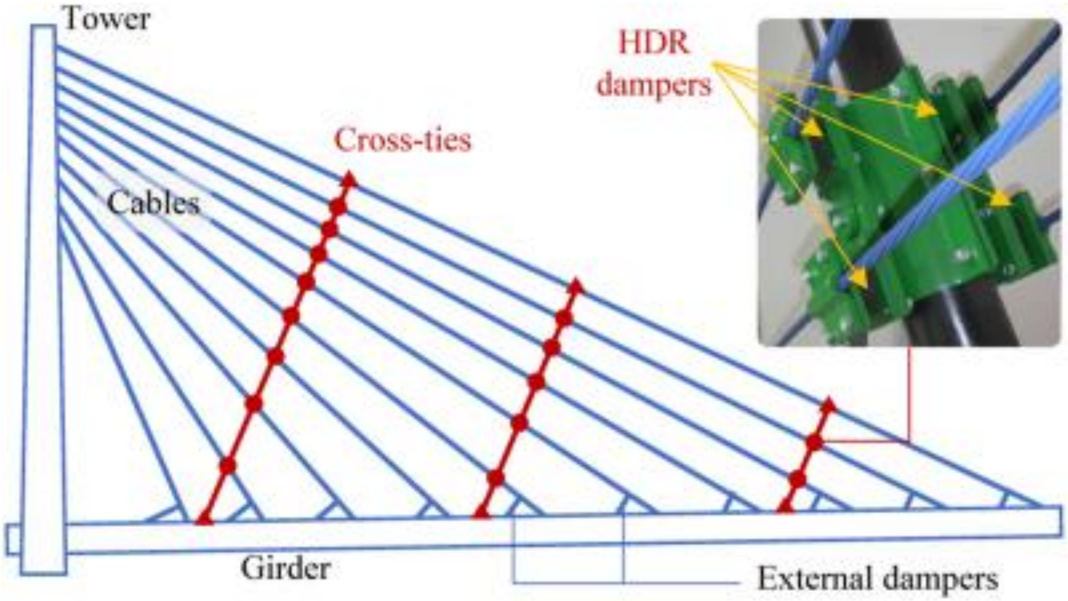


Photo: Stay cable vibration mitigation: A review. L. Sun, L. Chen, H. Huang, Advances in Structural Engineering, Volume 25 Issue 16, December 2022

Vibrations of tendons may be caused by various types of dynamic actions (→ #t / 55 – 68). Vibrations cause unfavorable pulsations of tension forces in cables. Various types of dampers (→ #t / 70) or cross-ties can be used as countermeasures, changing periods (susceptibility to excitation) and amplitudes of vibrations.

Stresses

$$\sigma_{cf\,/\,sc} \,/\, \sigma_{SLS} \leq 1{,}0$$

EN 1993-1-11 (7.1)

$$\sigma_{SLS} = \sigma_{SLS}\,(\sigma_{uk})$$

$$\sigma_{uk} = F_{uk} \,/\, A_m$$

A_m → #t / 35

F_{uk} → #t / 36

This formula must be satisfied for stress in construction phase (σ_{SLS} → #t / 44 - 45) and inservice conditions (σ_{SLS} → #t / 46).

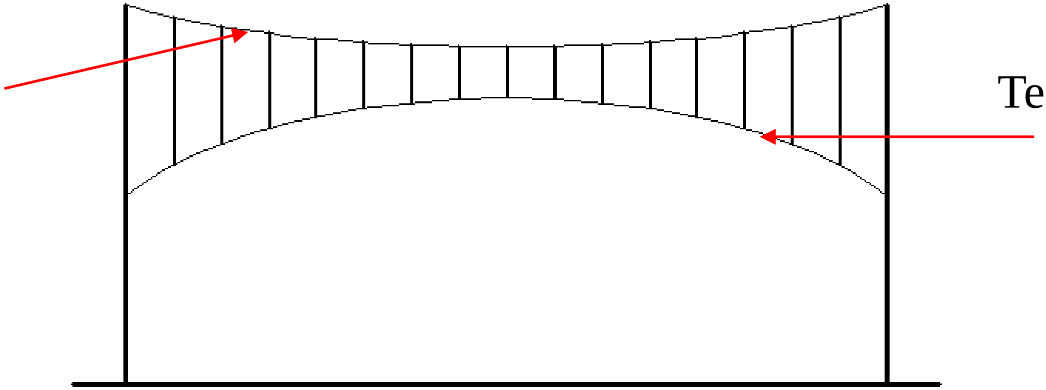
For construction phase:

$\sigma_{SLS} = f_{const} = \sigma_{uk} / (1{,}5\ \gamma_R\ \gamma_F)$ EN 1993-1-11 tab 7.1

Stage of installation	f_{const}	γ_R	γ_F
First tension components for only a few hours	$0{,}60\ \sigma_{uk}$	1,0	1,1
After instalment of other tension components	$0{,}55\ \sigma_{uk}$	1,0	1,2

EN 1993-1-11 tab 7.1

Differentiation („first tension component” – "other tension components”) construction phase into two cases is effect of changes in the tension of the cable during assembly.



Main cable - carries deadweight of structure, snow load and wind pressure

Tensioning cable - carries wind suction

Photo: Author

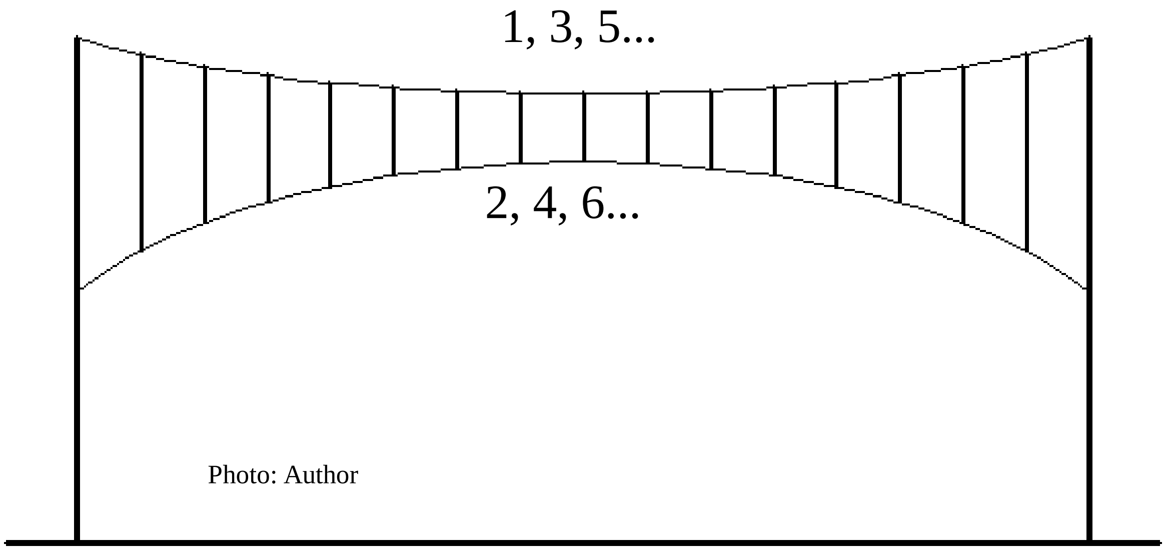


Photo: Author

1. Tension of main cable
2. Tension of tensioning cable - it changes tensile force in main cable
3. Adjustment of force in main cable - it changes tensile force in tensioning cable
4. Adjustment of force in tensioning cable - it changes tensile force in main cable

...

Conclusion - stresses in cables during construction phase change many times and are completely different, than under service condition.

For inservice conditions (exploitation stage):

$\sigma_{SLS} = f_{SLS} = \sigma_{uk} / (1{,}5\ \gamma_R\ \gamma_F)$ EN 1993-1-11 tab 7.1

Loading condition	f_{SLS}	γ_R	γ_F
Fatigue design including bending stresses *)	$0{,}50\ \sigma_{uk}$	0,9	1,5
Fatigue design without bending stresses	$0{,}45\ \sigma_{uk}$	1,0	1,5
*) Bending stresses may be reduced by detailing measures, see 7.1.(2) (→ # t / 70)			

EN 1993-1-11 tab 7.2

Corrosion protection:

exposure classes

Fatilue action	Corrosion action	
	Not exposed externally	Exposed externally
No significant fatigue actions	Class 1	Class 2
Mainly axial fatigue actions	Class 3	Class 4
Axial and lateral fatigue actions (rain & wind)	Not exposed externally + wind & rain is impossible	Class 5

EN 1993-1-11 tab. 2.1

Class 2, 4, 5 → corrosion protection must be very effective

Class 3, 4, 5 → wind fatigue calculation are needed

Anchorages

Type of termination:

Metal filled socket, resin filled socket

Photo: sdj.sagepub.com

Photo: strider-resource.com

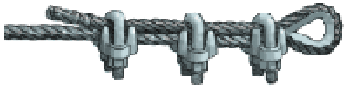
Ferrule-secured eye

Photo: franklin.com.sg

Swaged socket

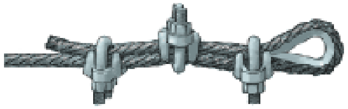
Photo: indiamart.com

U-bolt grip



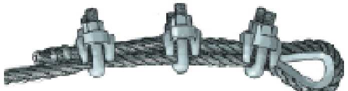
U-Bolt of all clips on dead end of rope.

Correct



Staggered Clips

Incorrect



U-Bolt of all clips on live end of rope.

Incorrect

Photo: e-rigging.com

Photo: mscdirect.com

Generally, there are two cases: anchorage with possibility of regulate tensile force (active anchorage, adjustable anchorage) and without possibilities of regulate tensile force (passive anchorage, fixed anchorage).

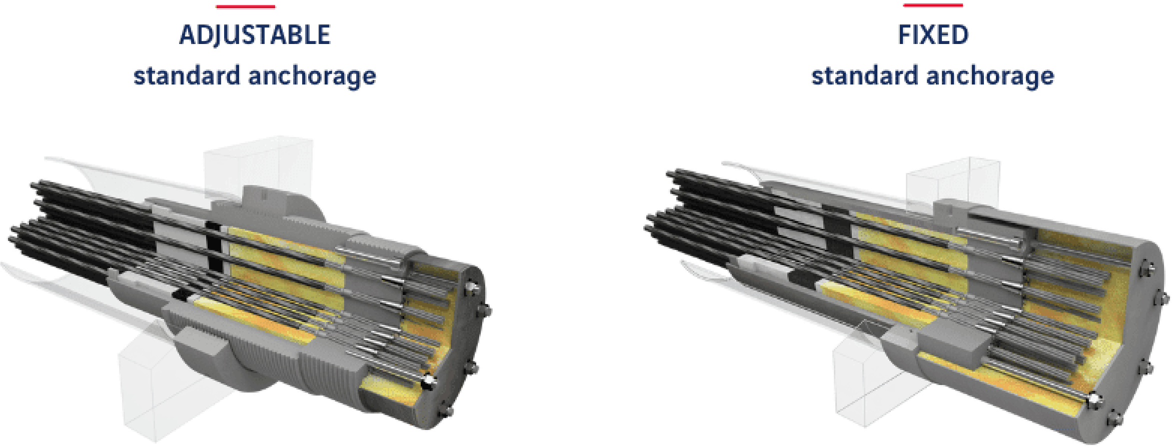


Photo: freyssinet.com

Photo: inzynierbudownictwa.pl

Photo: izbudujemy.pl

Photo: sdj.sagepub.com

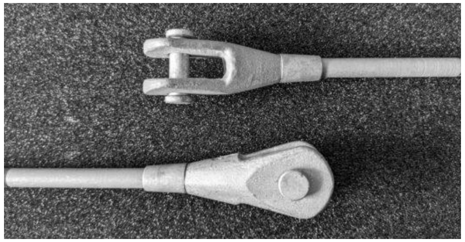


Photo: jordah-pfeifer.pl

Photo: franklin.com.sg

Photo: indiamart.com

Two the most popular solutions for active anchorage:

- by stressing jack;
- by rotation of threaded head;

Photo: prestressed-concrete.paul.eu

Photo: macalloy.com

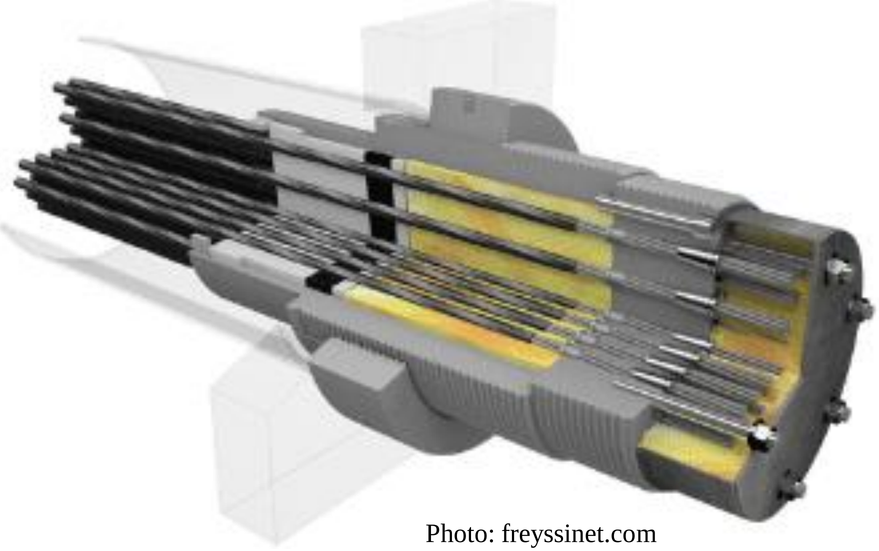


Photo: freyssinet.com

Loads

Dead weight w → #t / 38

Static wind action → EN 1991-1-4

Atmospheric icing → PN B 02013

Thermal action → EN 1991-1-5

Prestressing → EN 1993-1-11

Dynamic loads induced by wind (vibrations, aerodynamic instability) → EN 1991-1-4, literature

Atmospheric icing is one of the most important types of actions for many structures. At now, there is no special Eurocode for this type of load; we use old National Standards (for example PN B 02013, or better PN-EN 50341-2-22:2016).

Photo: iwas.org

According to workers from Chorągwica guyed mast, ice stalactites can have 15 m length and 1 m diamter (~ 3,5 T)

Photo: imgur.com

Photo: hin.no

Atmospheric icing changes three aspects of loads:

- Gravity load (big additional mass);
- Static wind actions (change of dimensions of cross-section; change of cross-section shape → change of aerodynamic factors);
- Dynamic wind actions (change of cross-section shape → possibility of aerodynamic instability, for example galloping for cables → #t / 58)

Vibrations, aerodynamic instability

Buffeting → # t / 56

Bénard – von Kármán vortex → # t / 57

Galloping → # t / 58 - 62

Interferences with neighbour cables → # t / 63

Rain-wind induced vibrations → # t / 64

Aerodynamic divergence → # t / 65

Flexural-torsional flutter → # t / 66

Membrane flutter → # t / 67

Aerodynamic phenomenon dangerous for cables

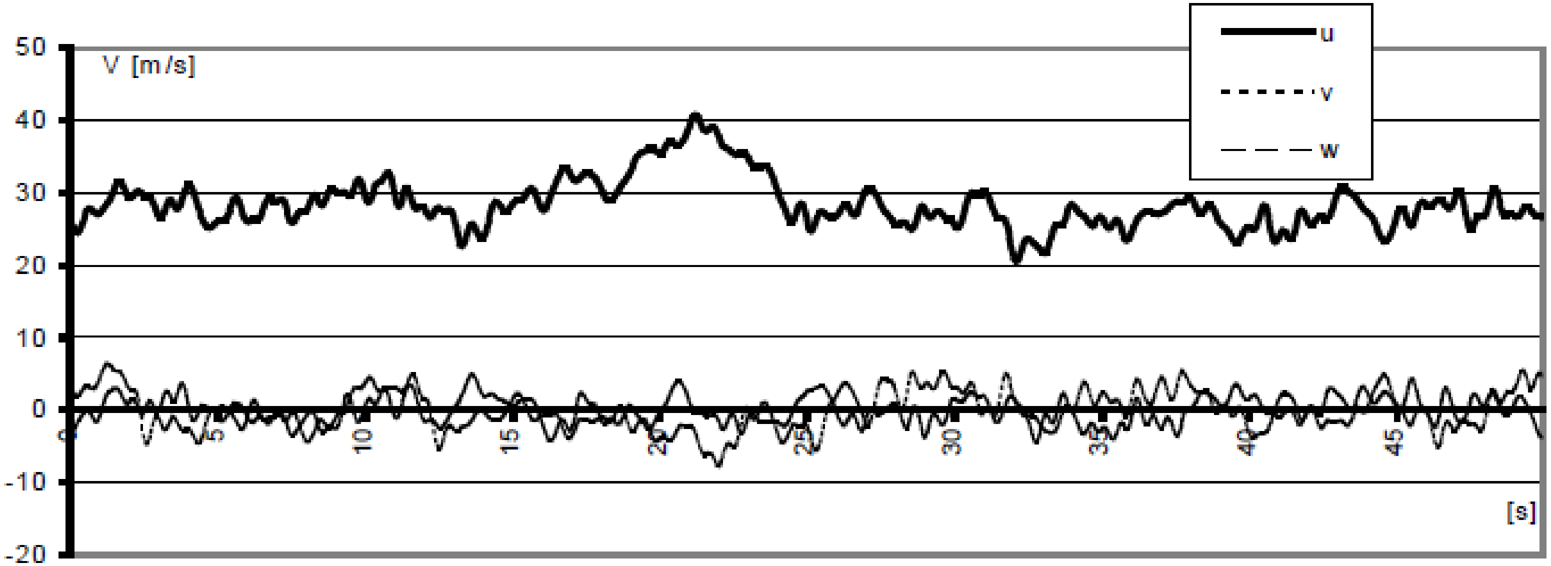
Aerodynamic phenomenon dangerous for tension structures but not dangerous for cables

Aerodynamic phenomenon dangerous for both

Buffeting

3D components of wind velocity

Photo: Author



Non-cyclic pulsations of wind velocity can indicate vibrations of structure as effect of chaotic change of wind pressure. For this one phenomenon important is structural factor $c_s\, c_d$ (EN 1991-1-4)

Photo: odkrywcy.pl

Bénard – von Kármán vortex

(Henri Bénard, Theodore von Kármán)

Unsteady separation of flow of air around round member → cyclic (non-chaotic) change of flow direction → change of pressure → cyclically variable force → resonance with free vibrations of structure

$$V_{cr} = 5\ f\ d$$

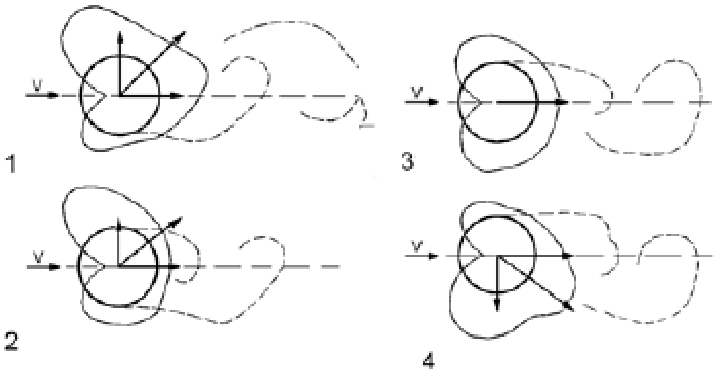


Photo: J. Żurański, "Obciążenie wiatrem budowli i konstrukcji", Arkady Warszawa 1978

Galloping

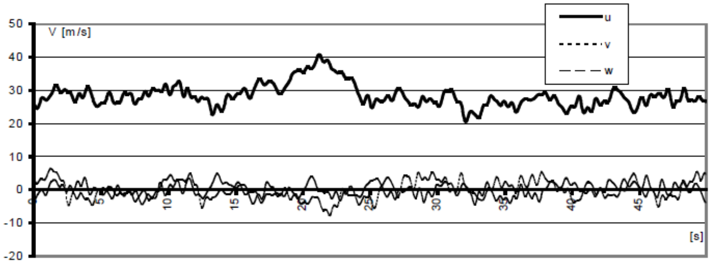


Photo: Author

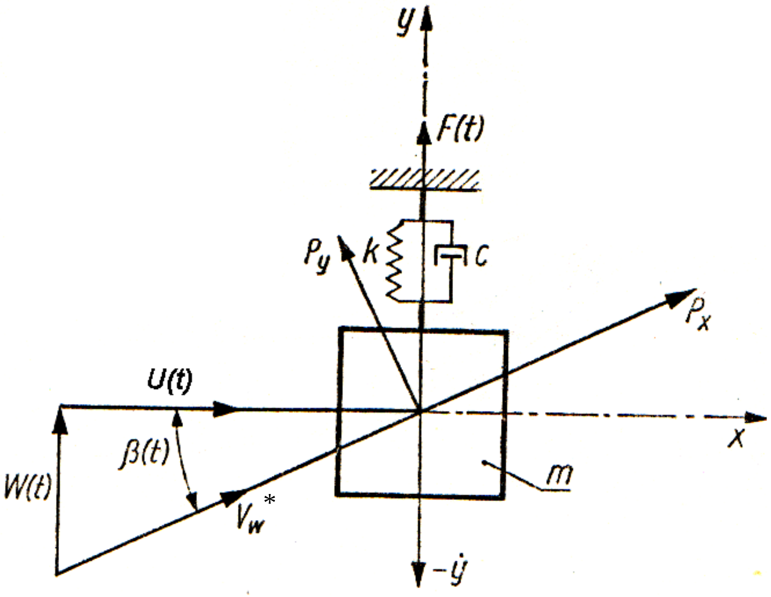


Photo: J. Żurański, "Obciążenie wiatrem budowli i konstrukcji", Arkady Warszawa 1978

Wind velocity in main direction U(t) is dominant. But, as the effect of buffeting, two additional components of wind (V(t), W(t)) must be taken into consideration. Theirs product will be action, applicated to rope in direction perpendicular to main wind direction.

Common effect of U(t) and W(t) is V_w^* . It causes two forces, applicated to rope: P_x (parallel to instantaneous wind direction) and P_y (perpendicular to instantaneous wind direction). Both forces change over time because of changes of U(t) and W(t).

Changes of value W(t) over time causes change rake angle β(t).

$$\beta(t) = \mathrm{arc\,tg}\,[W(t) / U(t)]$$

$$\beta(t) \text{ small} \rightarrow \beta(t) \approx W(t) / U(t)$$

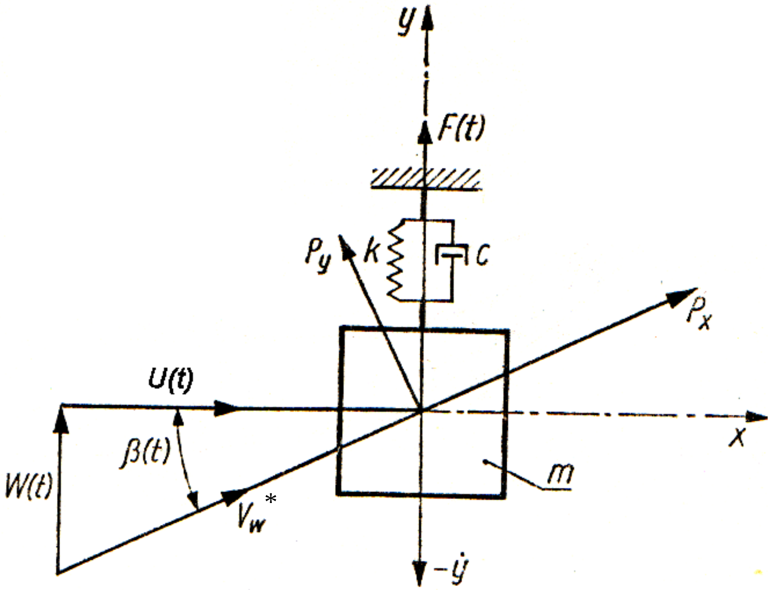


Photo: J. Żurański, "Obciążenie wiatrem budowli i konstrukcji",
Arkady Warszawa 1978

Fundamental formula for vibrations (→ #7 / 25):

$$m\,y'' + c\,y' + k\,y = F(t)$$

$$F(t) = P_y \cos\beta(t) + P_x \sin\beta(t) = F[\beta(t)]$$

First element of the Taylor series:

$$F[\beta(t)] \approx [\partial F / \partial\beta]|_{\beta=0}\,\beta(t) = [\partial F / \partial\beta]\,[W(t) / U(t)]$$

Speed of wind relative to structure is the same as speed of structure relative to air, so:

$$W(t) \approx -y'$$

Longitudinal component of wind has no influence on transverse vibrations

$$U(t) \approx U = \text{const}$$

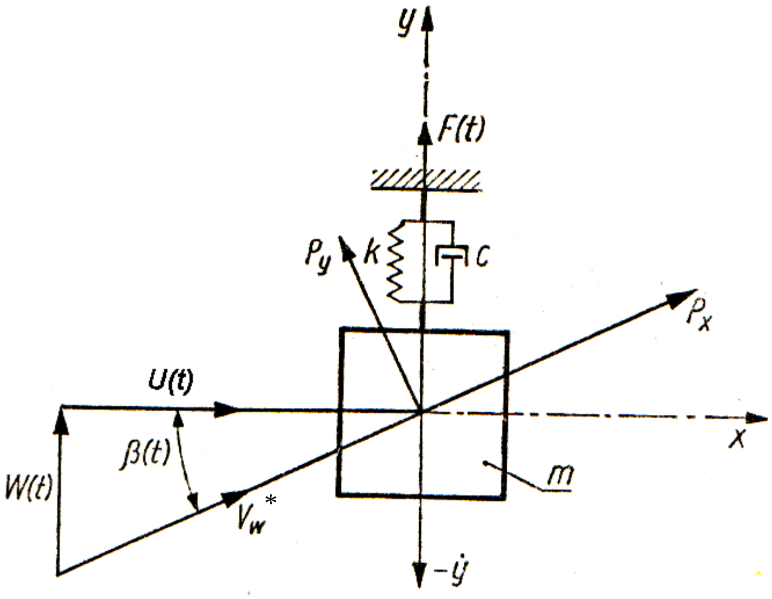


Photo: J. Żurański, "Obciążenie wiatrem budowli i konstrukcji",
Arkady Warszawa 1978

$$F(t) = [\partial F / \partial \beta]\,[W(t) / U(t)] =$$

$$= -\,[\partial F / \partial \beta]\,[y' / U] =$$

$$= -\,y'\,[\partial F / \partial \beta]\,[1 / U]$$

$$m\,y'' + c\,y' + k\,y = -\,y'\,[\partial F / \partial \beta]\,[1 / U]$$

$$m\,y'' + \{c + [\partial F / \partial \beta]\,[1 / U]\}\,y' + k\,y = 0$$

$$m\,y'' + c_1\,y' + k\,y = 0$$

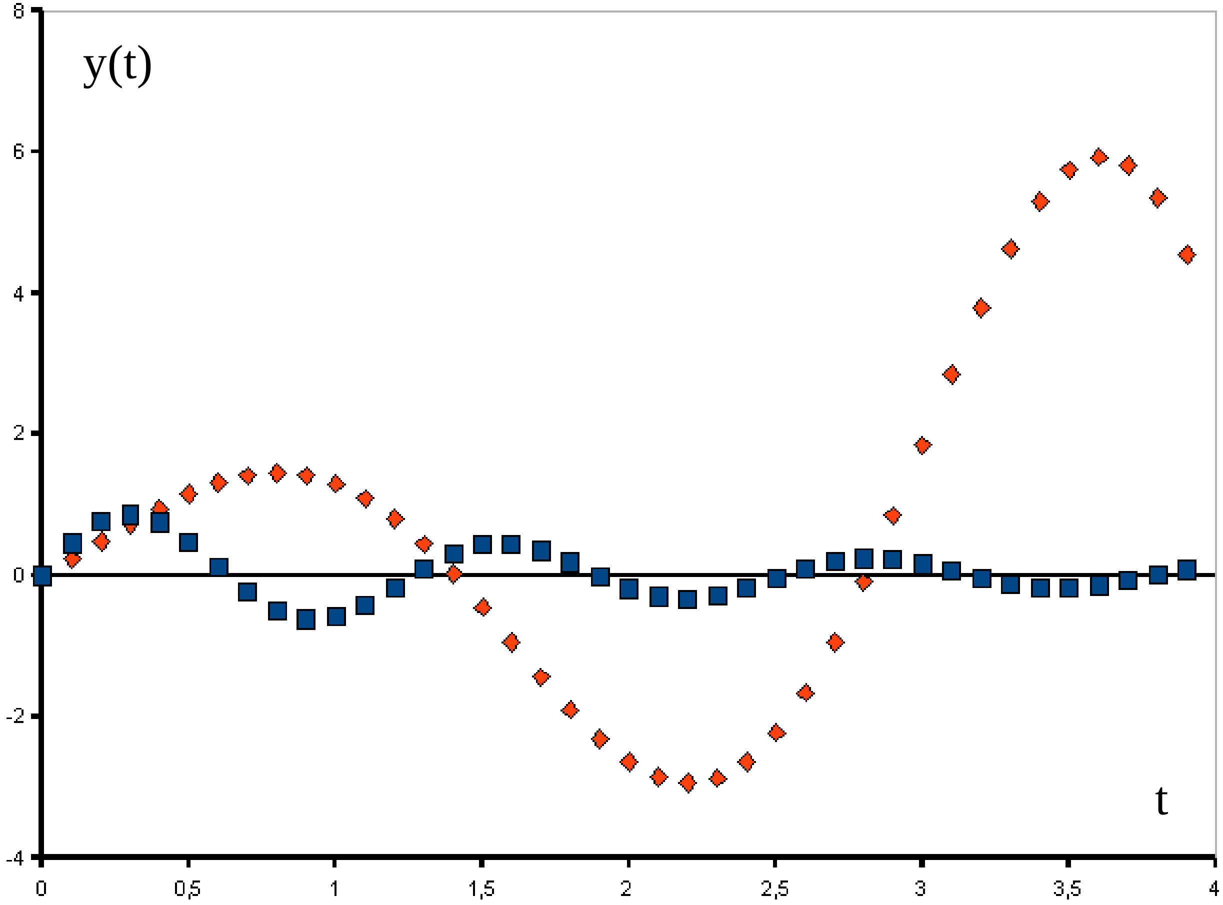
New form of fundamental formula: damping coefficient c_1 contains not only material characteristic, but additionally impact of type of wind flow around cross-section

Photo: Author

$$\omega = \sqrt{(k / m)}$$

$$r = c_1 / (2\,m)$$

$$y(t) = A\, e^{-r\,t} \sin\,[\sqrt{(\omega^2 - r^2)} + \varphi]$$



$$c_1 = \{c + [\partial F / \partial b]\,[1 / U]\} > 0 \text{ (dumped vibrations)}$$

$$c_1 = \{c + [\partial F / \partial b]\,[1 / U]\} < 0 \text{ (galloping)}$$

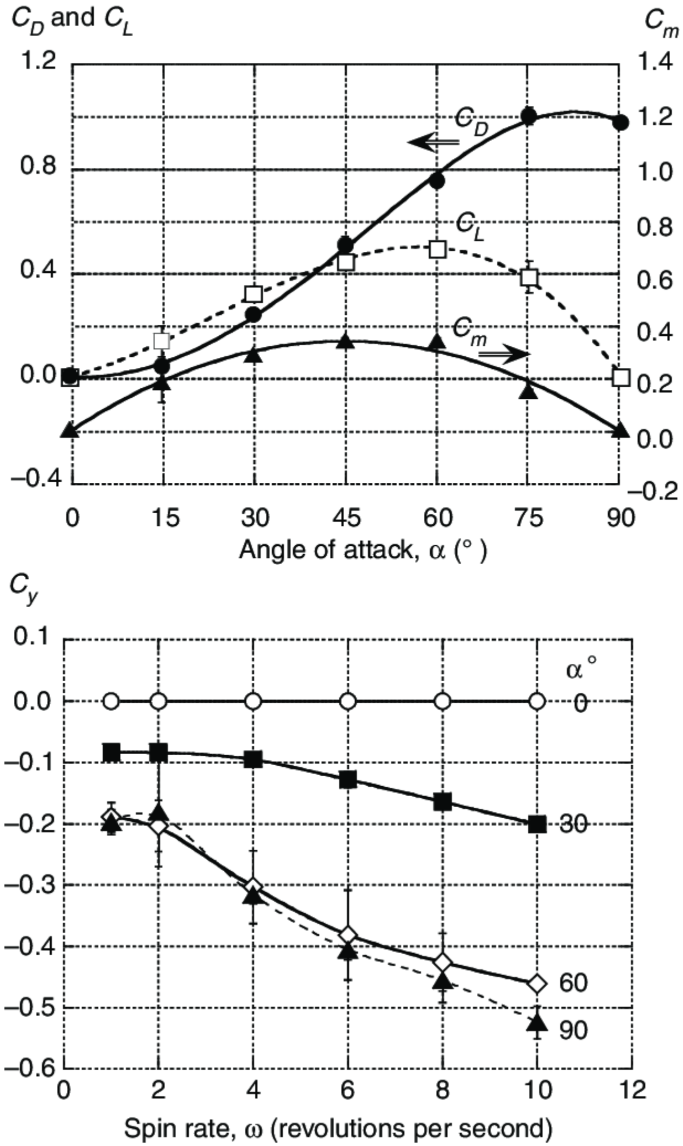


Photo: Flight dynamics of the screw kick in rugby,
K. Seo, O, Kobayashim, M. Murakami

For round cross-section,

$\partial F / \partial \beta = 0 \quad ; \quad c_1 = c$

but for complicated cross-section is possible

$[\partial F / \partial \beta]\,[1 / U] \ll 0$

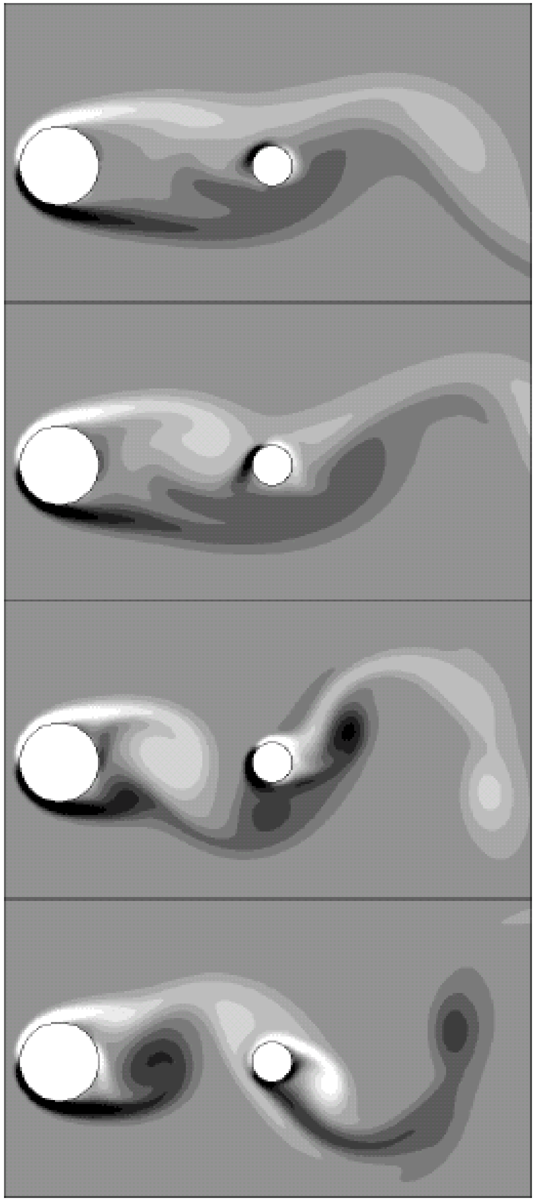
Photo: hin.no

For icing, value of

$[\partial F / \partial \beta]\,[1 / U]$

is hard to predict

Photo: scielo.br



Interferences

Next cable in Bénard – von Kármán vortex street - interactions between vibrations of next cable and vibrations of first cable. For very small distance between cables there is possible feedback from next to first.

Rain-wind induced vibration

Raindrops on the surface of the rope changes the aerodynamic coefficients. As a result there are specific vibrations of cable and, additionally, feedback between vibrations and position of raindrops rivulet.

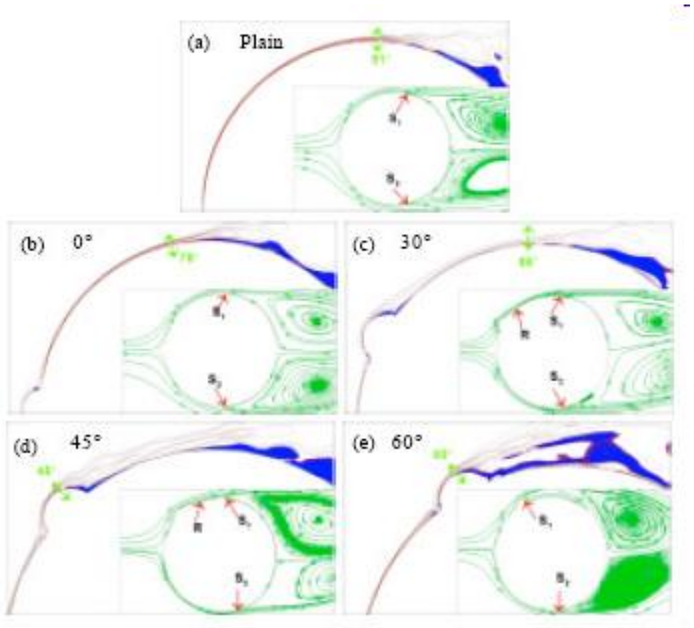


Photo: scialert.net

Aerodynamic divergence

Type of instability (aerodynamic buckling). Due to aerodynamic torsional moment for specific shape of cross-section, structure rapidly changes configuration from one stable position to other (snap-through buckling). Phenomenon danger for bridges (examples: Myślenice footbridge)

Photo: Author

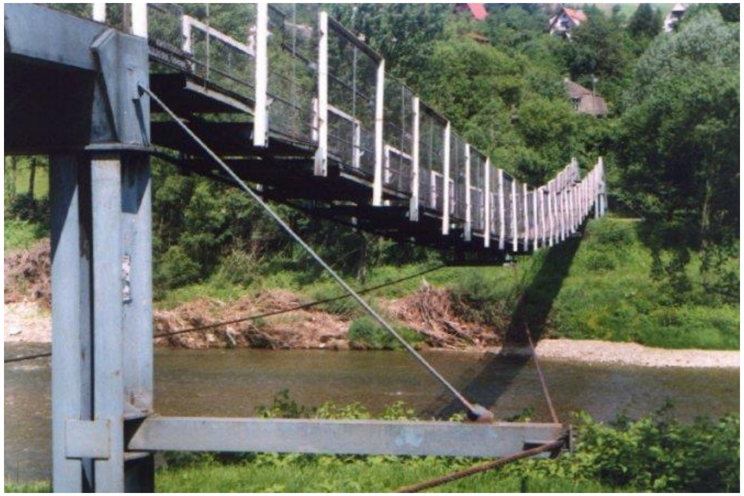


Photo: footbridge.pl

Flexural-torsional flutter

Phenomenon similar to galloping. Due to specific shape of cross-section, there are non-zero values of lift aerodynamicla force (as for galloping) and aerodynamical torsional moment. There is possible positive feedback between amplitudes of both types of vibration (bending and torsional). Amplitudes will increase to destruction of structure. Phenomenon danger for bridges (example: Tacoma Narrow Bridge).

University of Washington Libraries, Special Collections, FAR016

Photo: lib.washington.edu

University of Washington Libraries, Special Collections, FAR017

Photo: lib.washington.edu

Membrane flutter

Vibrations (often resonant and near-resonant vibrations) of roof membranes / cable nest structures due to wind actions. Well-known example of it phenomenon is flag flutter.

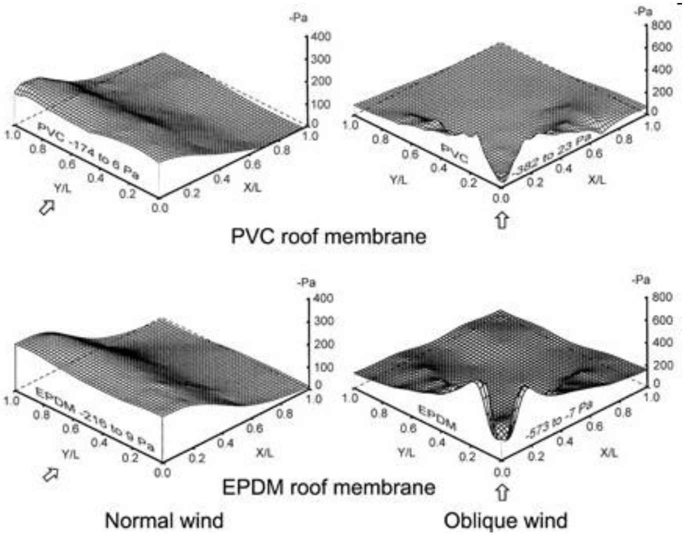


Photo: nrc-cnrc.gc.ca

Photo: wikipedia

Phenomenon	Process
Buffeting	Chaotic vibration along wind, no resonance
Bénard – von Kármán vortex	Cyclic vibration across wind, possibility of resonance
Galloping	Increasing amplitude of vibration to destruction of structure
Interferences	Disturbance of wind flow around object, resulting in vibrations of other very close objects
Rain-wind induced vibrations	Rivulets of water on cables change their aerodynamic characteristics
Aerodynamic divergence	Aerodynamic torsional moment increases with angle of twist of object (positive feedback moment ↔ angle)
Flexural-torsional flutter	Positive feedback (amplitude of vertical vibrations) ↔ (amplitude of torsional vibrations)
Membrane flutter	Positive feedback (deformations) ↔ (forces stimulating deformations)

Prevention

Change of dynamical characteristics of structure by additional mass or additional ropes between main cables;

Additional elements on surface of cables (change flow of wind, reduction galloping and rain-wind induced vibrations)

Photo: wikipedia

Photo: fhwa.dot.gov

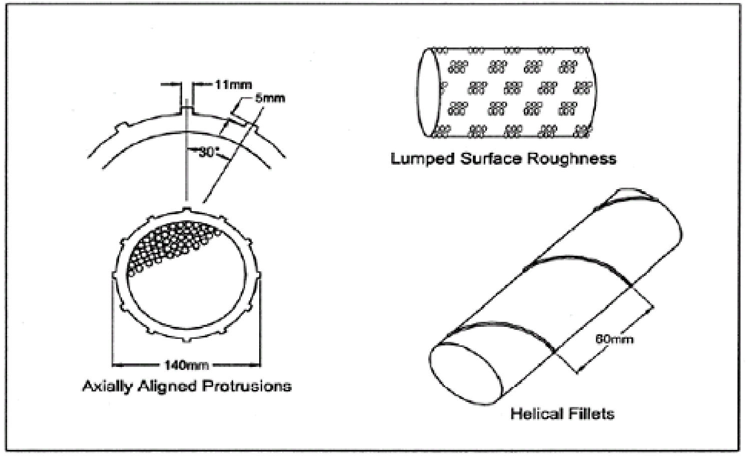


Photo: fhwa.dot.gov

Dumping

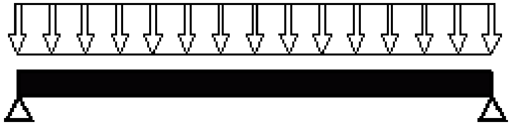
Photo: ravenelbridge.nett

Photo: ravenelbridge.nett

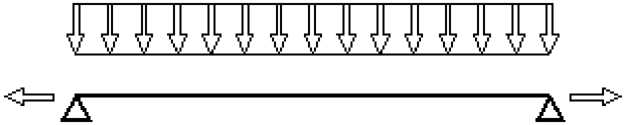
Transversal vibrations dampers are important to minimise bending stresses at the anchorage (→ # t / 35, 46)

Static and dynamic calculations of single tension member

There are many problems with static and dynamic calculations for cables. Complications are presented, based on deflection of cables Δ and first eigenfrequency f in comparison to one-span simple supported beam.

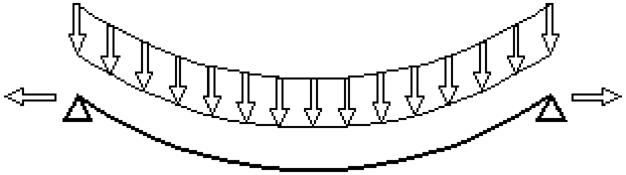


Beam



Tension member

(small deflection)

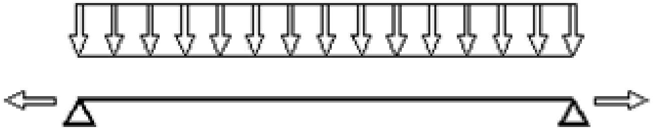


Tension member

(big deflection)

Photo: Author

Photo: Author



Tension member

(small deflection)

Photo: wikipedia

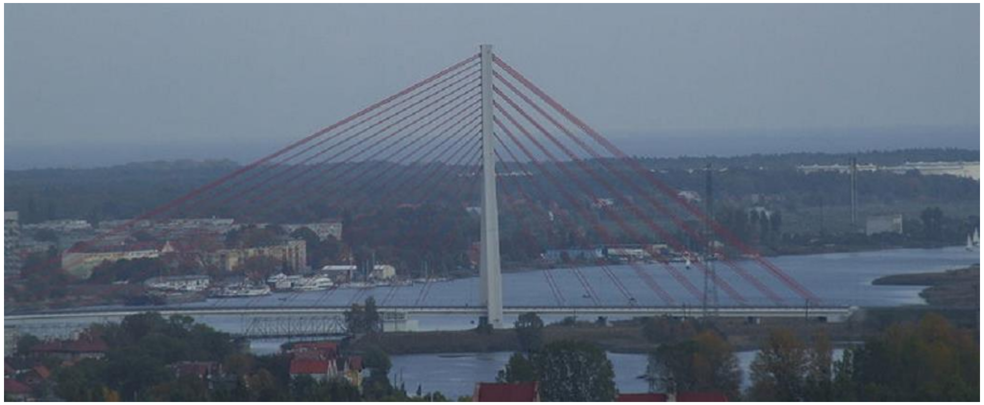


Photo: halfen.com

Stays in truss (tension members gropup A)

Cable-stayed bridges (tension members gropup B, C)

Short guys & stays (tension members gropup B, C)

Photo: radiomap.eu

Photo: Author

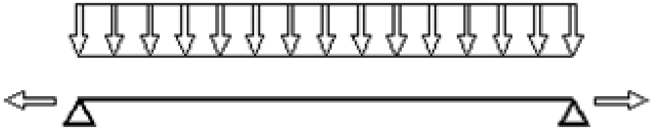


Photo: wikipedia

Generally: rather short members or members with big value of tension force.

Frequently used solution is the use of tensioning devices, e.g. heavy pulleys maintaining a more or less constant tension force. Thanks to this, tendon axis remains almost straight even in case of large perpendicular loads.

Tension member (big deflection – generally tension members gropup B, C)

Photo: Author

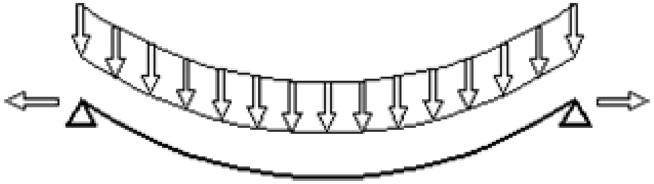


Photo: wikipedia

Suspension bridges

Photo: bryla.pl

Suspension roofs

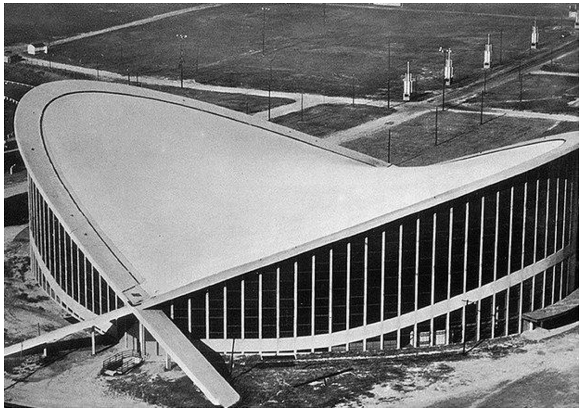
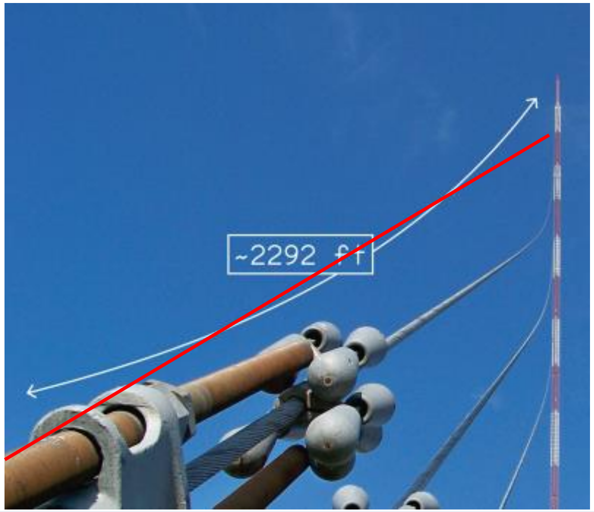


Photo: wired.com

Electro-energetic lines



Long guys & stays

Photo: dgreen.beauty

Photo: wikipedia

Ropeways

Static calculations

Generally, there is relationship between deformation, load and static stiffness of structure:

deformation = load / static stiffness

This relationship derives from fundamental relationship for steel:

$$\varepsilon = \sigma / E$$

ε – effect of deformations, σ – effect of loads, E – stiffness parameter

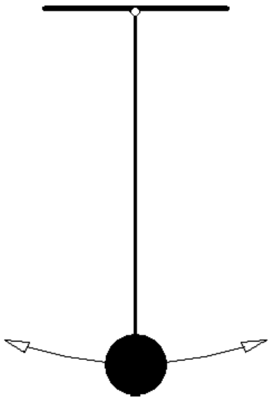


Photo: Author

Dynamic calculations

Basic dynamic characteristics of structures → Lec #7 / 23 - 30

Generally, for one defree of freedom, there is relationship for frequency, mass and dynamic stiffness:

$$\omega_0 = \sqrt{(k / m)}$$

There is possible for both cases calculate specific value:

- static stiffness
- dynamic stiffness

according to formulas:

$$\text{deformation} = \text{load} / \text{static stiffness}$$

$$\text{frequency} = \sqrt{(\text{dynamic stiffness})} / \sqrt{(\text{mass factor})}$$

Beam

Load: g [N / m]

EJ [N m^2]

Mass factor: μ [kg / m]

L [m]

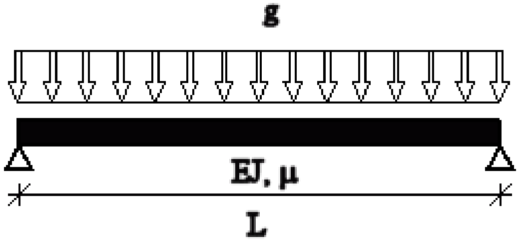


Photo: Author

Parameter	Value		Stiffness (static or dynamic)
Δ [m]	$5\,g\,L^4 / (384\,EJ)$	g / k_{stat}	$384\,EJ / (5\,L^4)$
f [Hz]	$\pi \sqrt{}\,(EJ) / (2L^2 \sqrt{}\,\mu)$	$\sqrt{}\,(k_{dyn}) / \sqrt{}\,(\mu)$	$\pi^2\,EJ / (4\,L^4)$

Both stiffnesses are independent on change of loads g (ice coating or perpendicular loads from wind); they have constant value.

Tension member, small deflection

Load: g [N / m]

H [N]

Mass factor: μ [kg / m]

L [m]

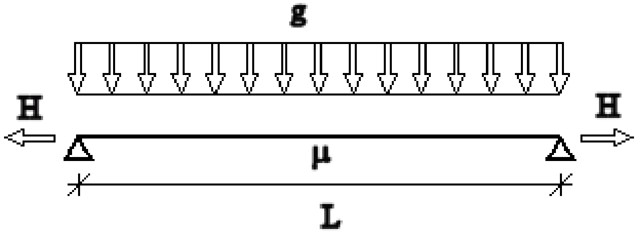


Photo: Author

Parameter	Value		Stiffness (static or dynamic)
Δ [m]	$g L^2 / (8 H)$	g / k_{stat}	$8 H / L^2$
f [Hz]	$0{,}5 \sqrt{(H)} / (L \sqrt{\mu})$	$\sqrt{(k_{dyn})} / \sqrt{(\mu)}$	$0{,}25 H / L^2$

Situation is much more complicated, than for beam. H it’s initial horizontal tension force, which changes due to change of loads (additional ice coating or perpendicular loads from wind). There are nonlinear relationships between ΔH and Δg.

- big H or small Δg → ΔH can be neglegible → linear calculation → there can be defined static and dynamic stiffness of constant value (small deflection);

- small H or big Δg → ΔH can’t be neglegible → nonlinear calculation → static and dynamic stifness depends on type of loads and have various values for various combinations of load (big deflection); this impact can be much more important and much more complicated in comparison to „classical” second-order efect in bar structures.

Tension member, big deflection

Load: g [N / m]

H [N]

Mass factor: μ [kg / m]

L [m]

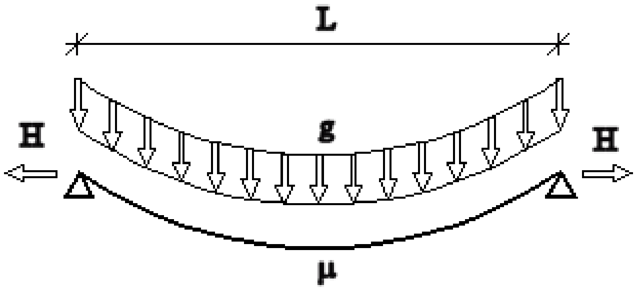


Photo: Author

$k = H / g$

Parameter	Value	Stiffness (static or dynamic)
Δ [m]	$k\,[\cosh(L / 2k) - 1]$	We can't presented formula as g / k_{stat}
f [Hz]	→ #t / 82	We can't presented formula as $\sqrt{(k_{dyn})} / \sqrt{(\mu)}$

Stiffness depends on change of loads **g** (ice coating or perpendicular loads from wind): change of loads changes value of initial force H → change of stiffness → nonlinear calculations.

For big deflection we can't make assumption, that after change of **g**, H = const. → always nonlinear calculations.

$$f = (1 / 2\pi) \sqrt{\{[2(u' + u'') \sin\alpha \cos^2\alpha - (u''' + u'''') \cos^3\alpha] / [\lambda (2u' \operatorname{tg}\alpha + u'' - u)]\}}$$

$u = u(\alpha)$ - normal component of vibrations ; $\lambda = H / g^2$

Solution of this formula depends on L, H, **g**, **μ** in nonlinear way. We need additional calculations for define relationship $u = u(L, H, \mathbf{g}, \boldsymbol{\mu})$

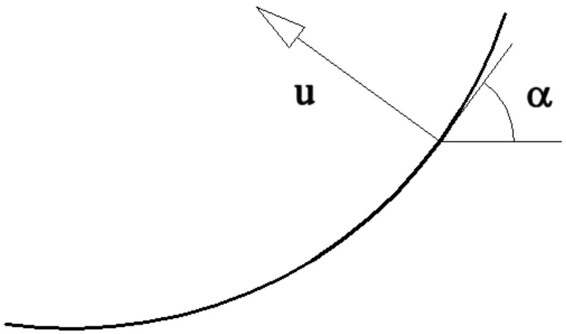


Photo: Author

But, additionally, H depends on change of Δg in strongly nonlinear way. There are two degrees of nonlinearity:

- nonlinear relationships between Δ and $\mathbf{g}$ (by cosh) and between f and $\boldsymbol{\mu}$ (by nonlinear solution of differential equation of the third degree);
- nonlinear relationship between Δg and ΔH for static calculation and nonlinear relationship between λ and $\mathbf{g}$ for dynamic relationship.

There is never possible for big deflection to define values of static and dynamic stiffnesses. This concept – stiffness of constant value – does completely not exist in relation to them. In every second, due to change of wind load, tension member has different „stiffness”.

Conclusions

Member	Static stiffness	Dynamic stiffness	Comments
Beam	$\sim EJ / L^4$	$\sim EJ / L^4$	d.s. $\approx$ s.s.
Tension member, small deflection	◆ linear calculations: $\sim H / L^2$ or ◆ nonlinear calculations, stiffness not defined	◆ linear calculations: $\sim H / L^2$ or ◆ nonlinear calculations, stiffness not defined	◆ linear calculations: d.s. $\approx$ s.s. or ◆ nonlinear calculations, stiffness not defined
Tension member, big deflection	nonlinear calculations only, stiffness is not defined	nonlinear calculations only, stiffness is not defined	◆ nonlinear calculations, stiffness not defined

Examples of structures

- Exhibition halls
- Sport facilities
- Entertainment centres
- Special industrial facilities
- Special transport facilities
- Landmarks
- Bridges

Comparison of dimensions:
Kraków Main Square: 200x200 m;
Hejnalica: 82 m;
Distance: Cracow University of Technology - Wawel Hill: 2 000 m;

Photo: wikipedia

Examples of structures

Stadnion Narodowy,
Warszawa

length 270 m
width 240 m
height 100 m

Suspension roof

Photo: muratorplus.pl

Kraków Main Square: 200x200 m;
Hejnalica: 82 m;

Dorton Arena (Paraboleum), Raleigh

Soprt arena, entertainment center

length 97 m
width 92 m
height 27 m

Suspension roof

Photo: wikipedia

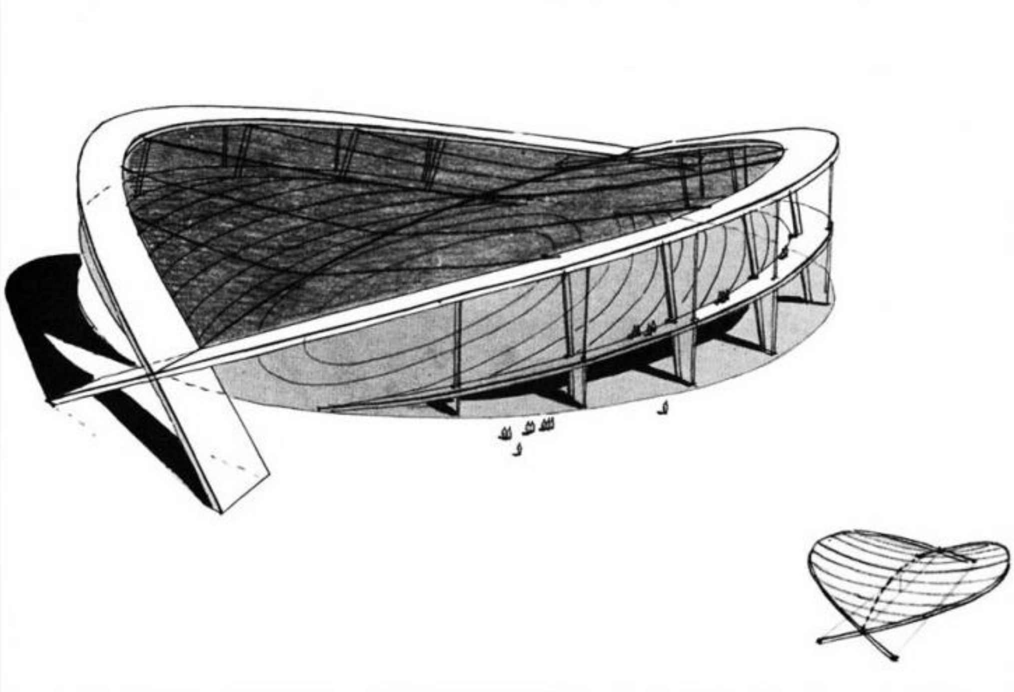


Photo: culture.pl

Kraków Main Square: 200x200 m;

Photo: us.archello.com

Khan Shatyr, Astana

Entertainment center

length 200 m
width 160 m
height 150 m

Suspension roof

Kraków Main Square: 200x200 m;
Hejnalica: 82 m;

Photo: en.tengrinews.kz

Millenium Dome (O2 Arena), London

Entertainment center

diameter 365 m
height 52 m

Suspension roof

Photo: wikipedia

Kraków Main Square: 200x200 m;
Hejnalica: 82 m;

Cooling tower,
Schmehausen

diameter 91 - 84 - 146 m
height 180 m

Cable net

Photo: eng.archinform.net

Kraków Main Square: 200x200 m;
Hejnalica: 82 m;

Ropeway Eibsee, Zugspitze

span 3 213 m

The longest span of ropeway in the world

Photo: tripadvisor.com

Distance: Cracow University of Technology – Krak Mound: 3 850 m

Photo: tripadvisor.com

Photo: forum.skyscraperpage.com

Photo: transmission-line.net

Photo: forum.skyscraperpage.com

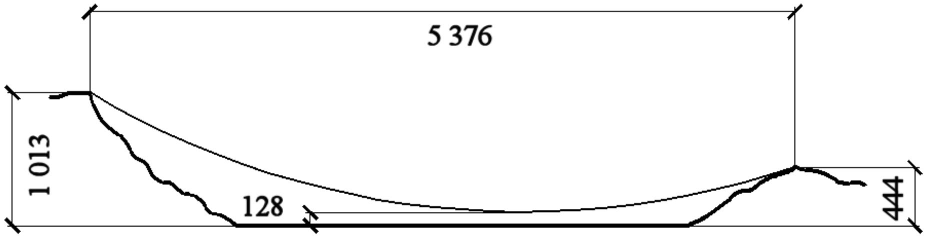
Ameralik Fiord, Greenland

Powerline

span 5 376 m

The longest span of powerline in the world

Photo: Author



Distance: Cracow University of Technology - Wawel Hill: 2 000 m;

Changtai Yangtze River Bridge

main span1 176 m

Distance: Cracow University of Technology – Mariacki Church: 1 150 m;

Photo: siberiantimes.com

Photo: edition.cnn.com

1915 Çanakkale Bridge, Stambuł
main span 2 023 m

Distance: Cracow University of Technology - Wawel Cathedral: 2 000 m;

Examination issues

Types of tension members

Loads and aerodynamical phenomenons, acting on tensile structures

Beam, tension member with small and big deflection - similarities and differences

Tension components - elementy cięgnowe
Suspension - wiszący
Cable-stayed - podwieszony
Ribbon - wstęgowy
Guy - odciąg
Stay - stężenie cięgnowe
Sag - zwis
Wire - drut
Rope - lina
Bundle - wiązka
Stand - splotka
Thread - gwint
Socket - tuleja zaciskowa
Strand - splotka
Strand rope - lina splotkowa wielozwita
Spiral rope - lina spiralna jednozwita
Spiral strand rope - lina splotkowa jednozwita
Fully locked coil rope - lina zamknięta
Minimum breaking force - minimalna siła zrywająca
Breaking force factor - współczynnik siły zrywającej
Fill factor - współczynik wypełnienia
Spinning loss factor - współczynik strat na zwicie

Catenary - zwis
Saddle – siodło
Clamp - zawiesie
Bénard - von Kármán vortex - wiry Bénarda - Kármána
Galloping - galopowanie
Bénard - von Kármán votex street - ścieżka wirowa

Thank you for attention

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