Metal Structures II

Lecture VII

Multistorey steel skeletons, high buildings

Contents

Buildings and structures

Building - a man-made structure with a roof and walls standing more or less permanently in one place.

Non-building structure - man-made formations, that does not necessarily have walls;

Structure - each man-made formations (buildings + n-b structures).

Dz.U. 1994 Nr 89 poz. 414

USTAWA

z dnia 7 lipca 1994 r.

Prawo budowlane[1)]

Art. 3.

Ilekroć w ustawie jest mowa o:

1) obiekcie budowlanym – należy przez to rozumieć:

a) budynek wraz z instalacjami i urządzeniami technicznymi,

b) budowlę stanowiącą całość techniczno-użytkową wraz z instalacjami i urządzeniami,

c) obiekt małej architektury;

2) budynku – należy przez to rozumieć taki obiekt budowlany, który jest trwale związany z gruntem, wydzielony z przestrzeni za pomocą przegród budowlanych oraz posiada fundamenty i dach;

3) budowli – należy przez to rozumieć każdy obiekt budowlany niebędący budynkiem lub obiektem małej architektury, jak: obiekty liniowe, lotniska, mosty, wiadukty, estakady, tunele, przepusty, sieci techniczne, wolno stojące maszty antenowe, wolno stojące trwale związane z gruntem urządzenia reklamowe, budowle ziemne, obronne (fortyfikacje), ochronne, hydrotechniczne, zbiorniki, wolno stojące instalacje przemysłowe lub urządzenia techniczne, oczyszczalnie ścieków, składowiska odpadów, stacje uzdatniania wody, konstrukcje oporowe, nadziemne i podziemne przejścia dla pieszych, sieci uzbrojenia terenu, budowle sportowe, cmentarze, pomniki, a także części budowlane urządzeń technicznych (kotłów, pieców przemysłowych, elektrowni wiatrowych, elektrowni jądrowych i innych urządzeń) oraz fundamenty pod maszyny i urządzenia, jako odrębne pod względem technicznym części przedmiotów składających się na całość użytkową;

Buildings

Photo: wikipedia

Structures

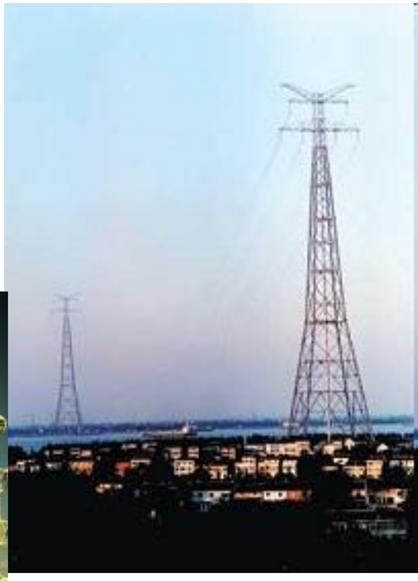


Photo: wikipedia, renewablesintarnational.net, powerengineeringint.com, electrek.co

Main idea:

Multiple storey → increase total floorspace without increasing the size of the building's footprint → good ideal for a congested city where real estate is at a premium.

Photo: wikipedia

Regulation of the Minister of Infrastructure on technical conditions to be met by buildings and their location, 12.04.2002

Rozporządzenie Ministra Infrastruktury z dn. 12 IV 2002 w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie

Height	Symbol
< 12 m; < 4 levels	N
12 - 25 m; 4- 9 levels	SW
25 - 55 m; 9 - 18 levels	W
> 55 m; > 18 levels	WW

According to this document:

4 storeys ↔ 12 m → 3,0 m / storey

9 storeys ↔ 25 m → 2,7 m / storey

18 storeys ↔ 55 m → 3,1 m / storey

But there must be bigger value of storey height for high buildings...

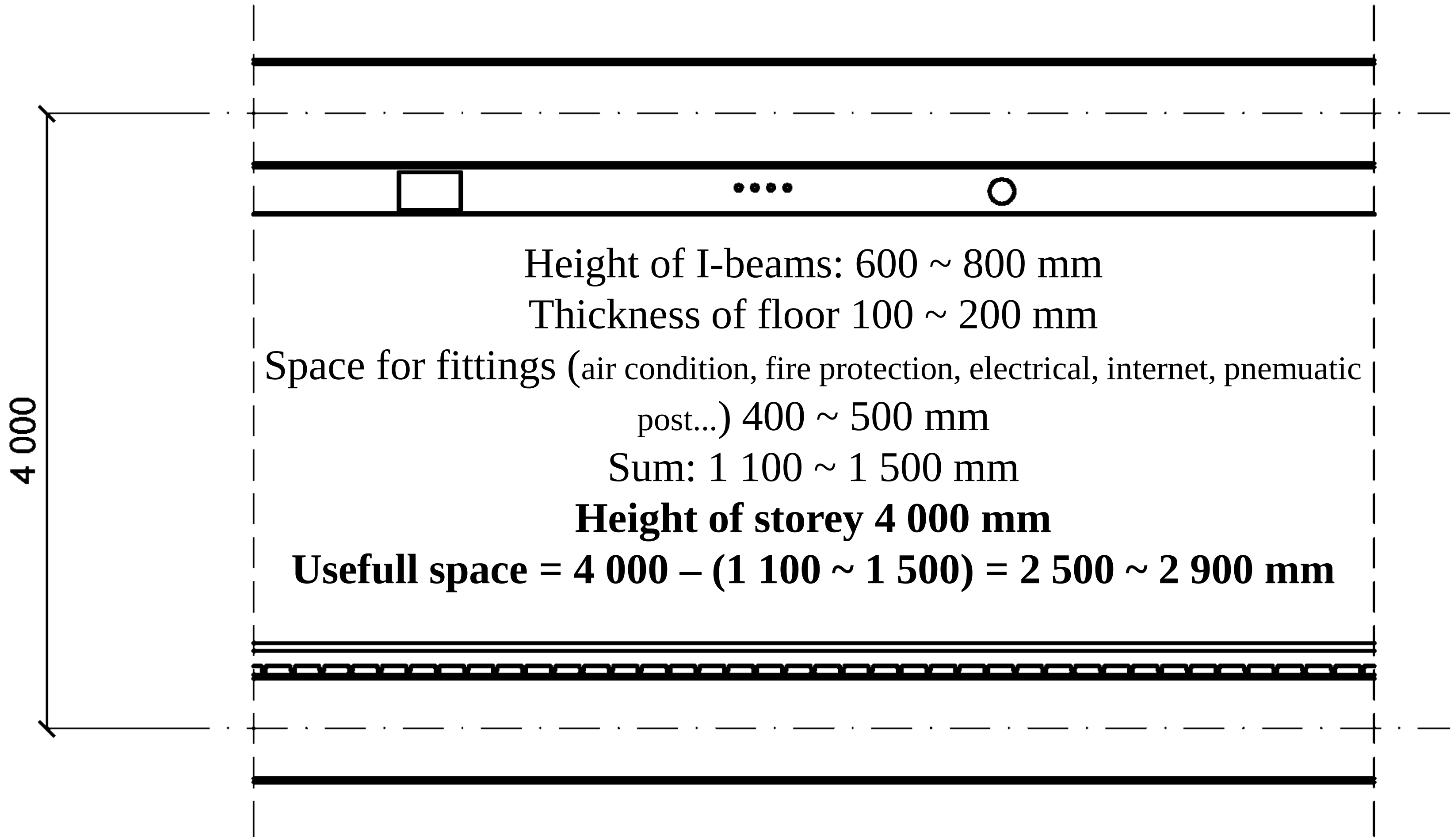


Photo: Author

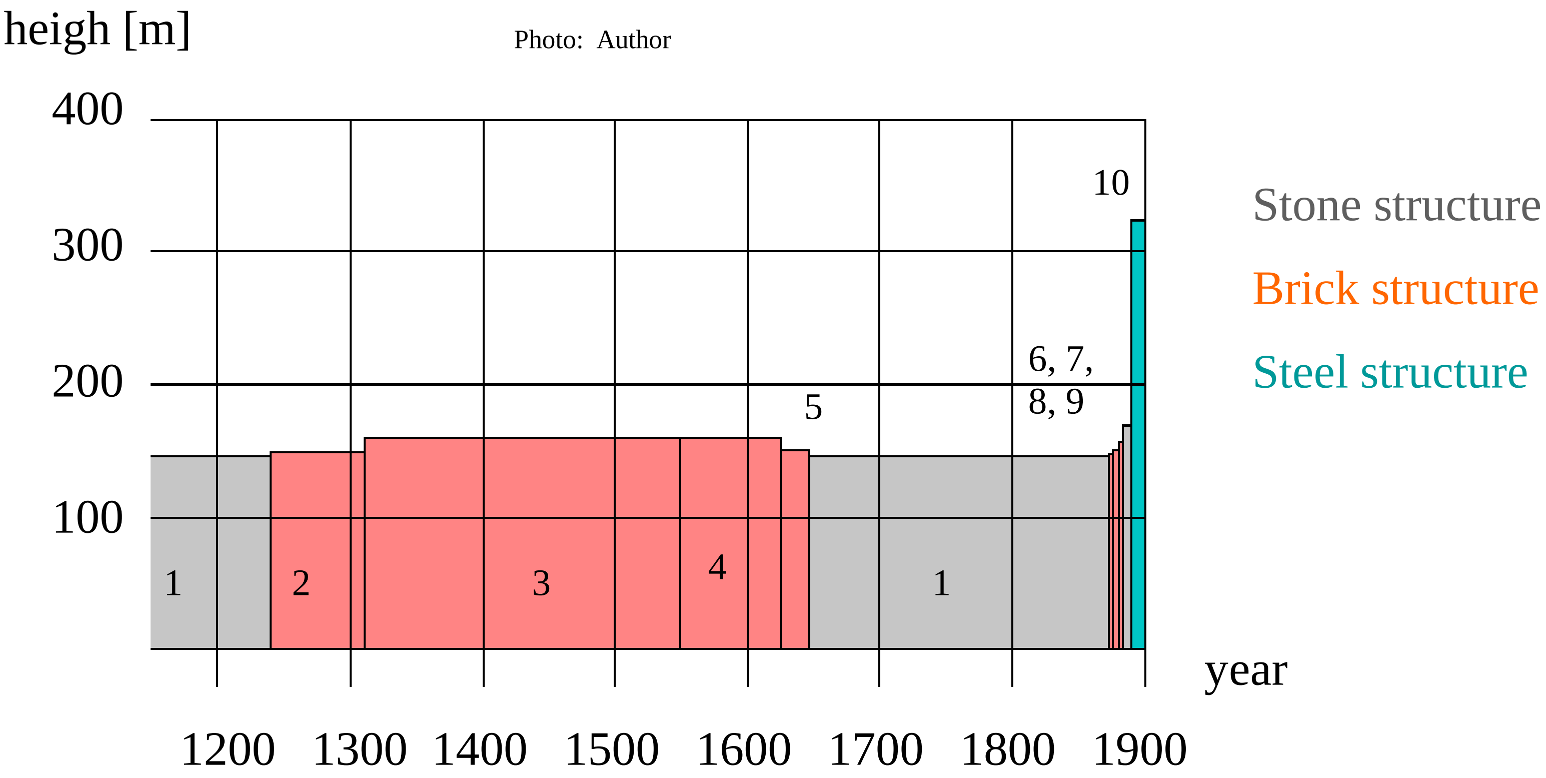
Ranking

The problem: which value is height of buildings?

Photo: wikipedia

Photo: Author

The highest structures for centuries



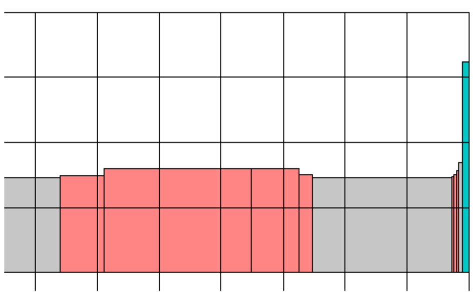
1. Cheops Pyramid 2. Old London Cathedral 3. Lincoln Cathedral 4. St Olaf's Church, Tallin 5. St Mary's Church, Stralsund 1. Cheops Pyramid 6. St Nicholas's Church, Hamburg 7. Rouen Cathedral 8. Cologne Cathedral 9. Washington Monument 10. Eiffel Tower

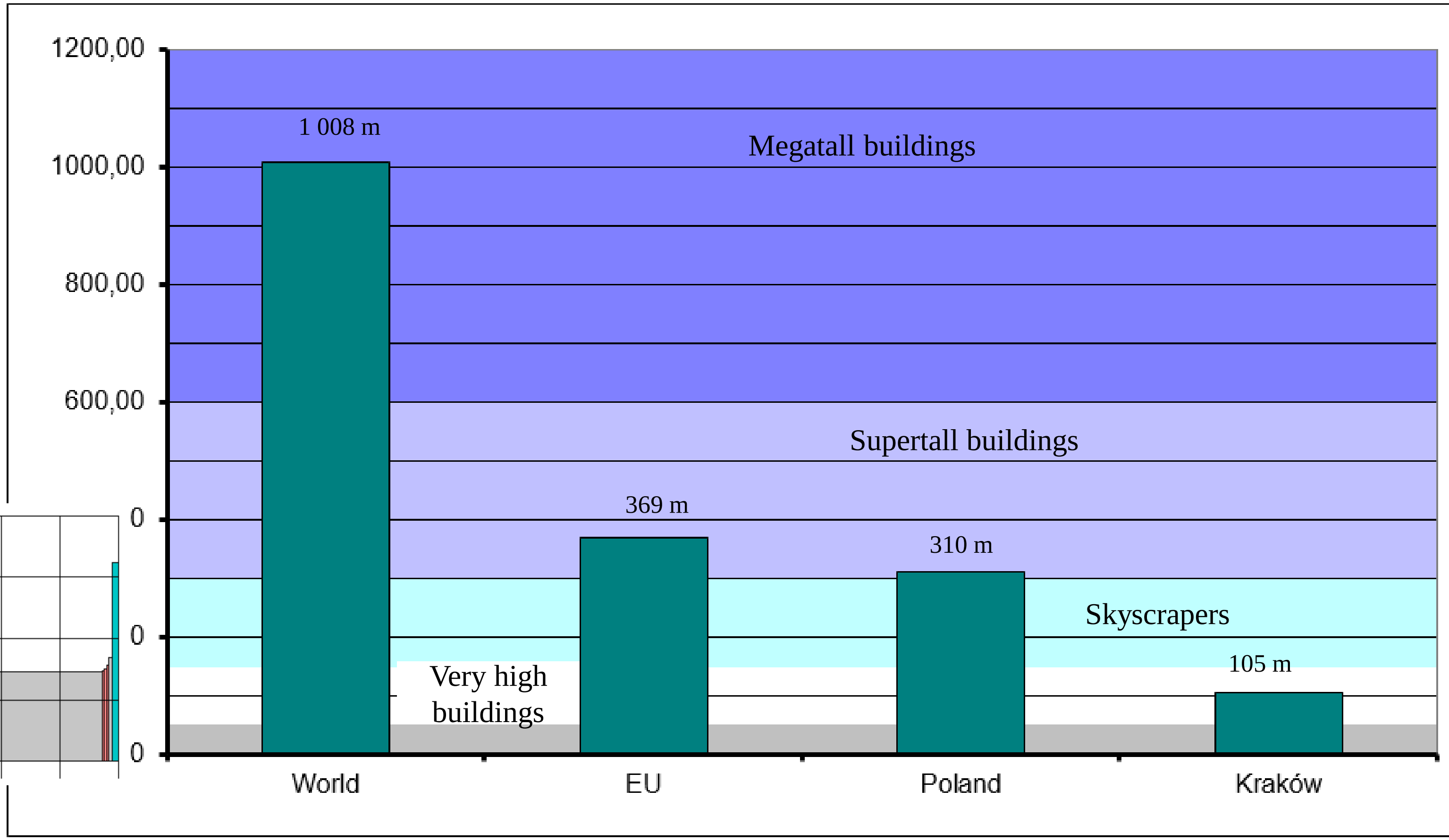
There is no official definition of „skyscraper”. According to unofficial definition (but often used), skyscraper is building that reaches or exceeds the height of 150 metres.

The same for "supertall" and "megatall" buildings; there are only unofficial definitions: h > 300 m and h > 600 m.

Buildings, presented below, can be divided into few groups:

Photo: Author





Megatall buildings (> 600 m) in world (8 objects)

Under construction (2)

1. Jeddah Tower (SA), 1008 m (638); 167 storeys;

Existed (4)

2. Burj Khalifa (UAE), 830 m (585); 163 storeys;

Tower (2)

5. Tokyo Skytree (J), 634 m;

Photo: wikipedia

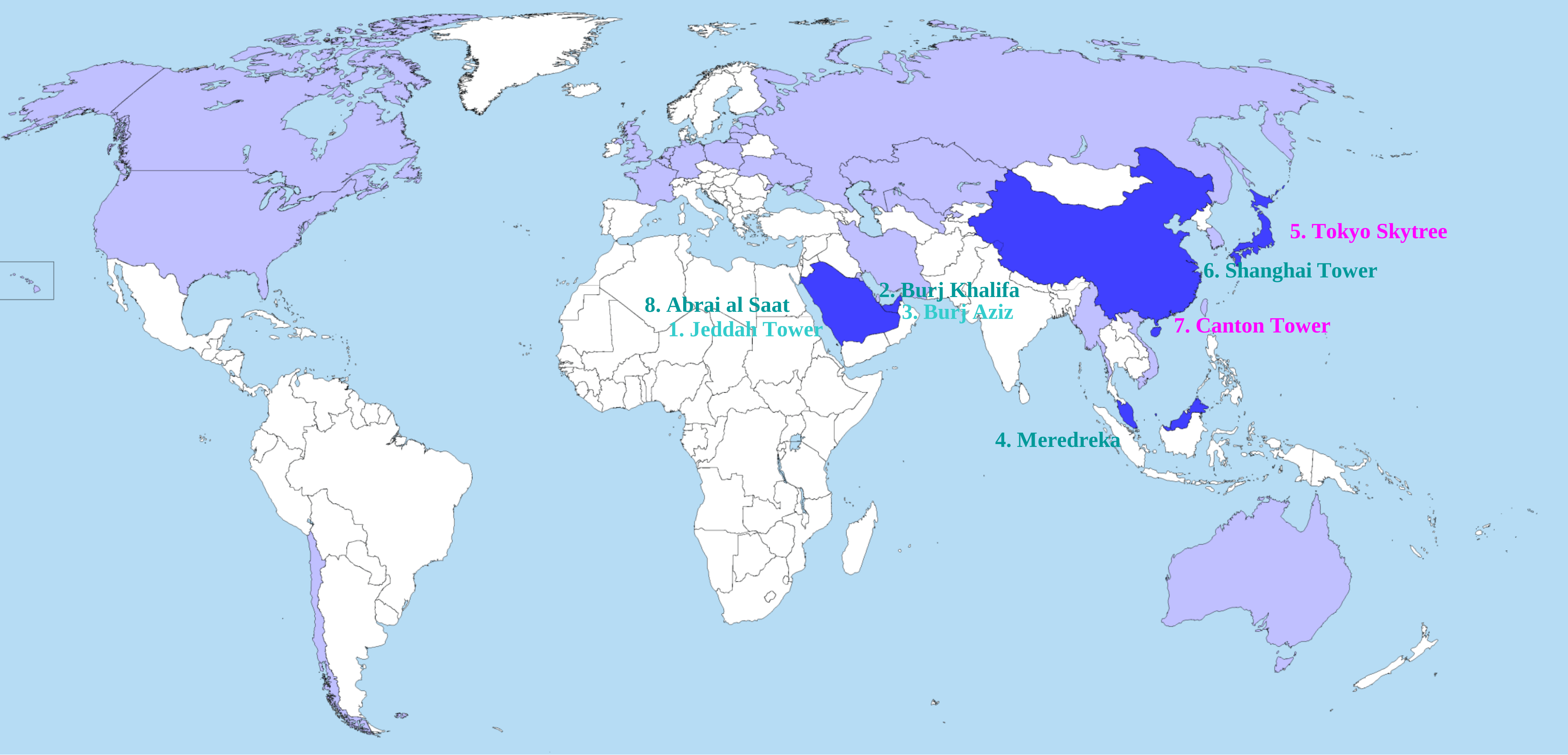


Photo: Author

Existing / under construction megatall (> 600 m; 5 countries)

Existing supertall (300 – 600 m; 23 countries)

Supertall buidings (10) and high skyscraprers in EU
(≥ 200 m; 65 objects)

Tower (32)
1. Riga RTV Tower, Lativa, 369 m

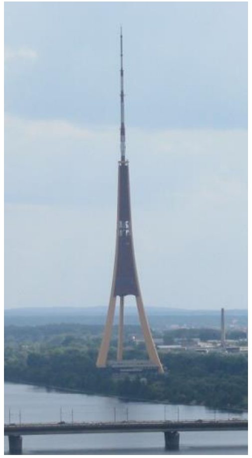


Photo: wikipedia

Existed (28)
8. Varso, Warszawa, 310 m

Photo: natemat.pl

Photo: elbtower.de

Under construction (5)
27. Elbtower Hamburg, Germany, 245 m

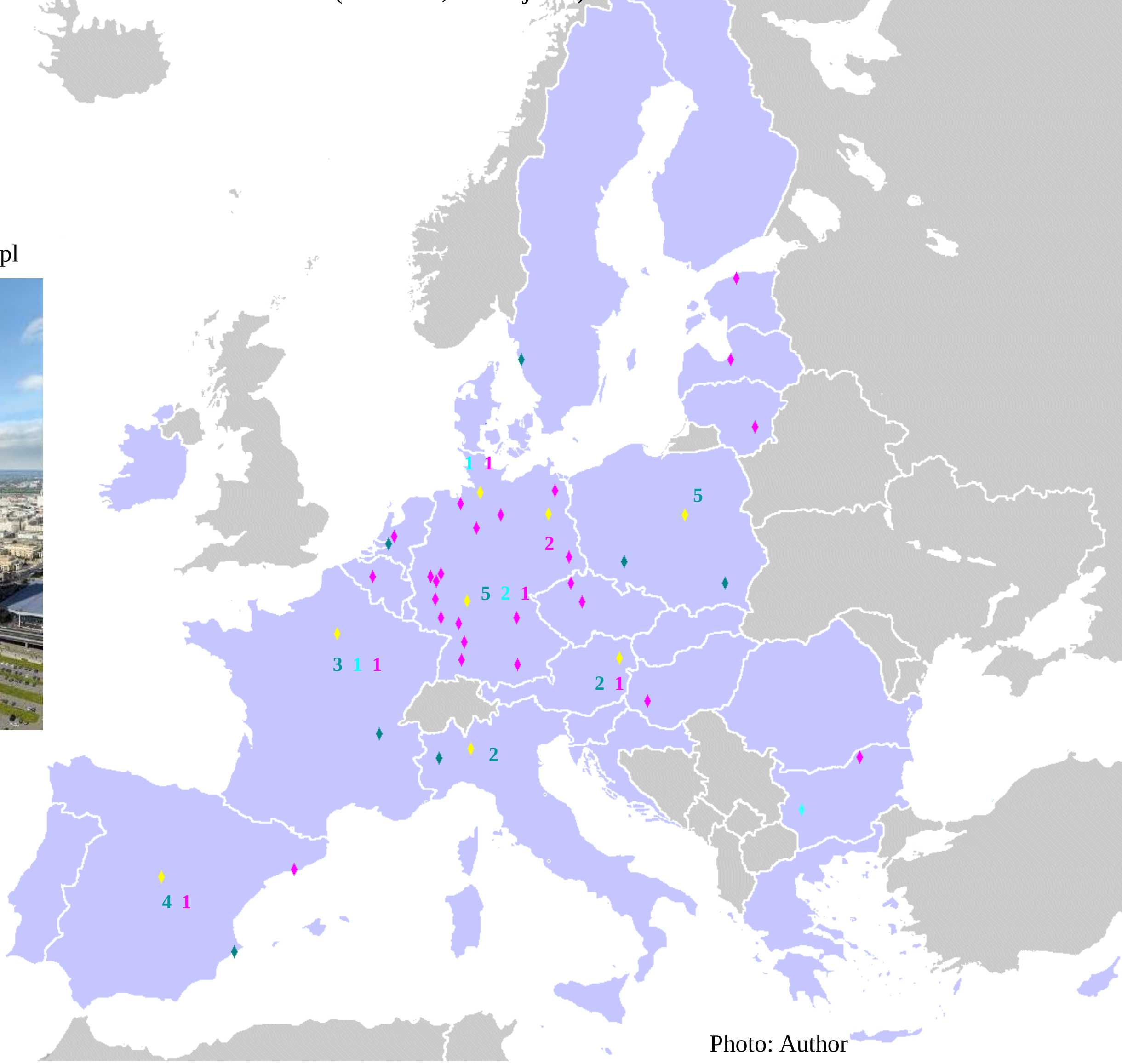


Photo: Author

The highest buildings in Poland
(310 – 100 m; 70 objects)

Photo: natemat.pl

Existed (47)
1. Varso, Warszawa, 310 m

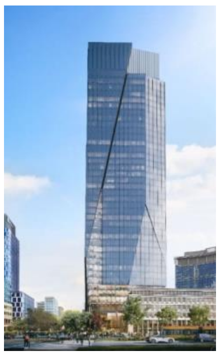


Photo: bryla.pl

Under construction (12)
13. The Bridge, Warszawa, 174 m

Tower (11)
19. Centrum RTV Święty Krzyż, 157 m

Photo: wikipedia

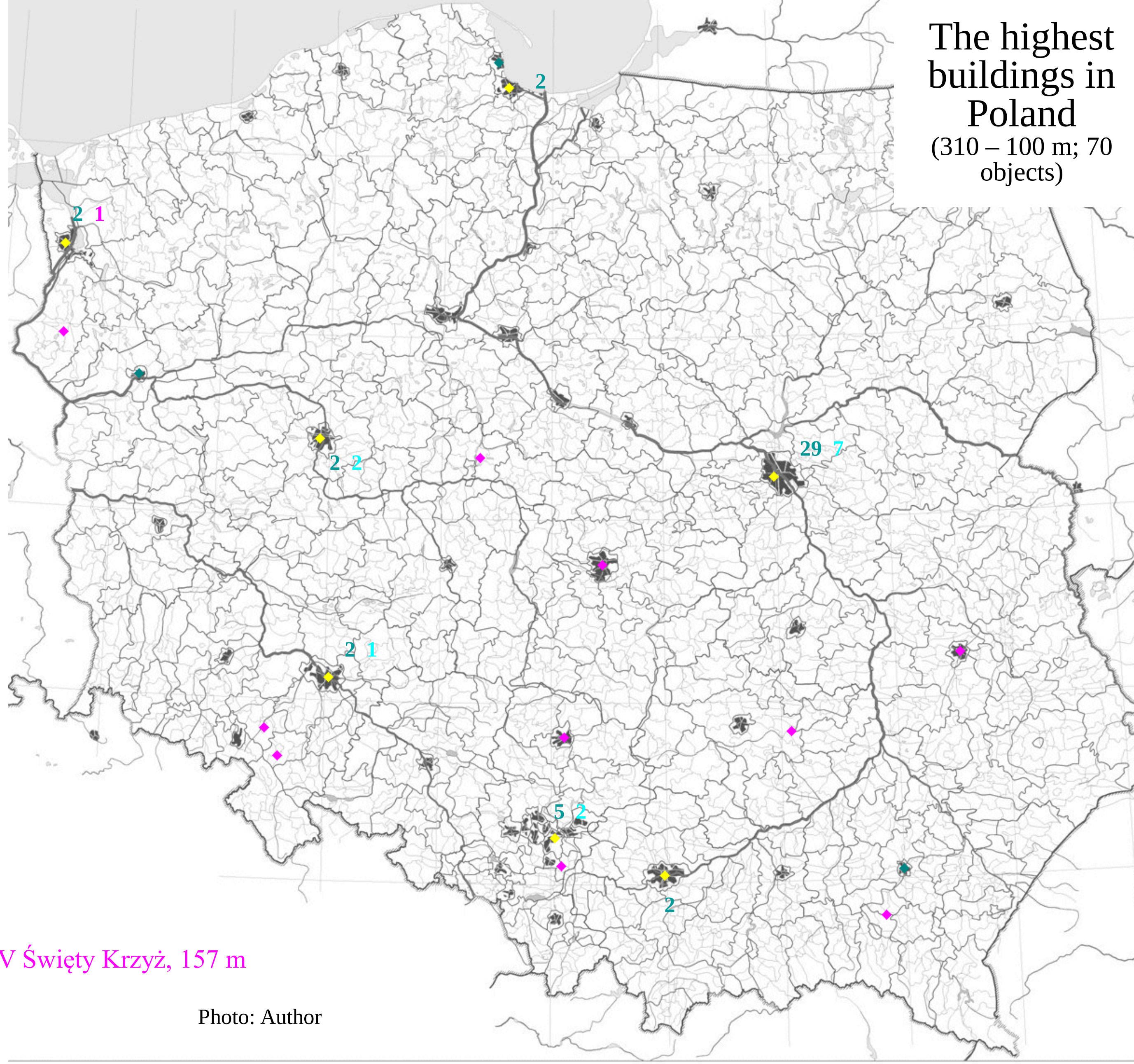
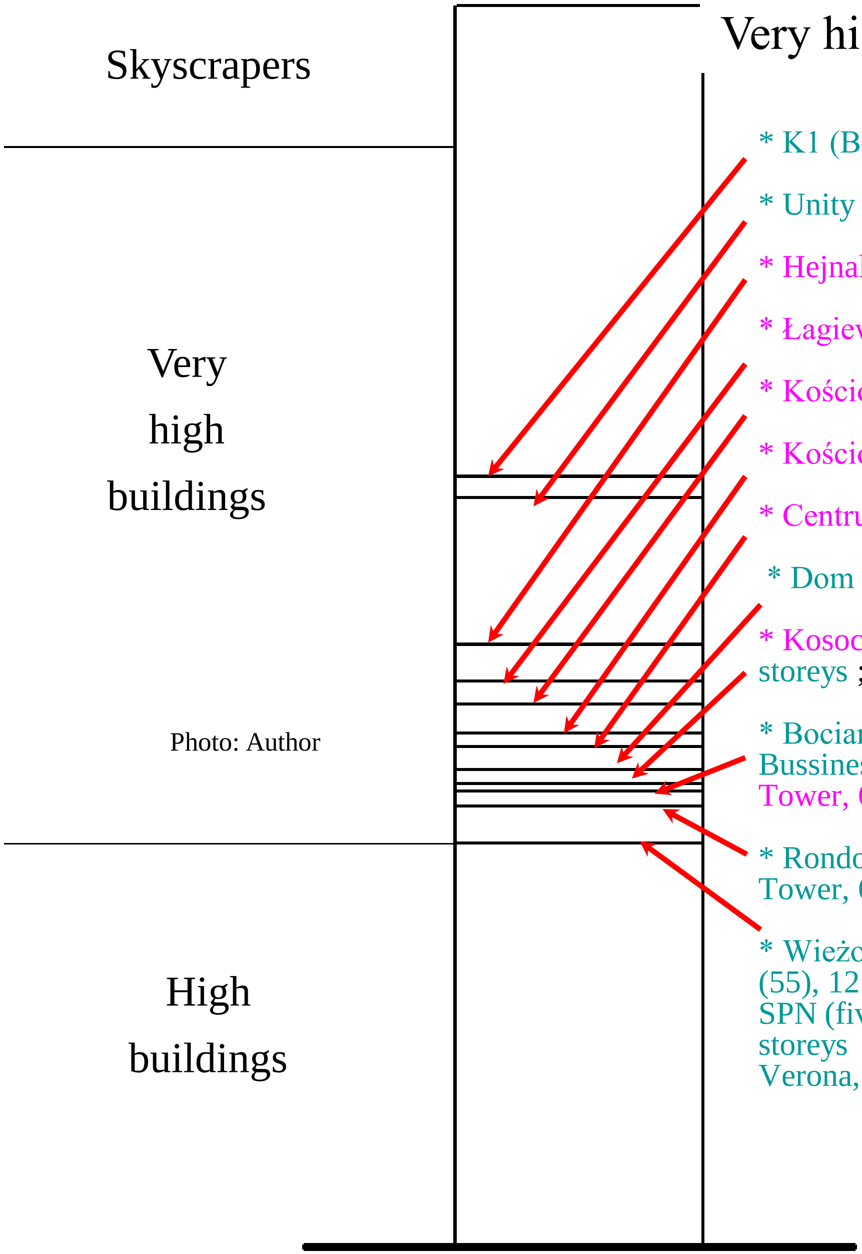


Photo: Author

Very high buildings in Kraków



* K1 (Błękitek), 105 m (88), 20 storeys ;
* Unity Tower, 102 m, 27 storeys ;
* Hejnalica, 82 m ;
* Łagiewniki, 77 m ;
* Kościół św. Józefa, 74 m ;
* Kościół Bożego Ciała, 70 m ; * Ratusz, 70 m;
* Centrum Jana Pawła II, 68 m ;
* Dom Wschodzącego Słońca, 65 m (55), 17 storeys ;
* Kosocice Watertower 63 m ; * Biprostal, 63 m (55), 14 storeys ;
* Bocianie Gniazdo (Okrąglak), 62 m (60), 17 storeys ; * Quattro Bussiness Park, 62 m (55), 14 storeys ; * Krzemionki Radio Tower, 62 m ;
* Rondo Bussiness Park, 60 m (55), 15 storeys ; * Salwator Tower, 60 m (53), 17 storeys ;
* Wieżowiec Kijowska, 55 m (55), 17 storeys ; * Vinci, 55 m (55), 12 storeys ; * Akropol, Babilon, Kapitol, Olimp, wieżowiec SPN (five identical buindings on AGH campus), 55 m (55), 16 storeys ; * Szpital Rydygiera, 55 m (55), 16 storeys ; * Torre Verona, 55 m (55), 15 storeys ;

Photo: wikipedia

Photo: wikipedia

Photo: wikipedia

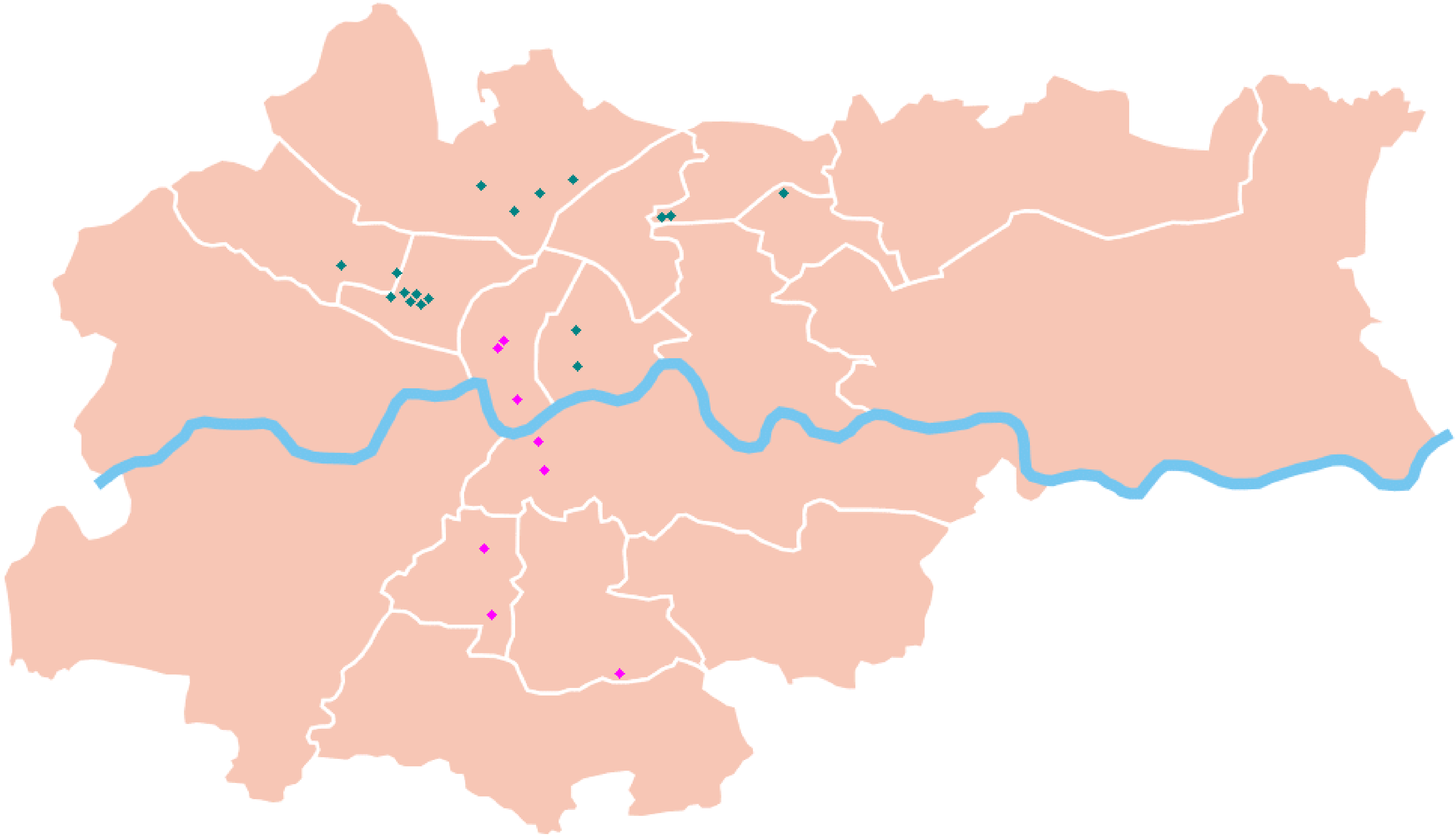
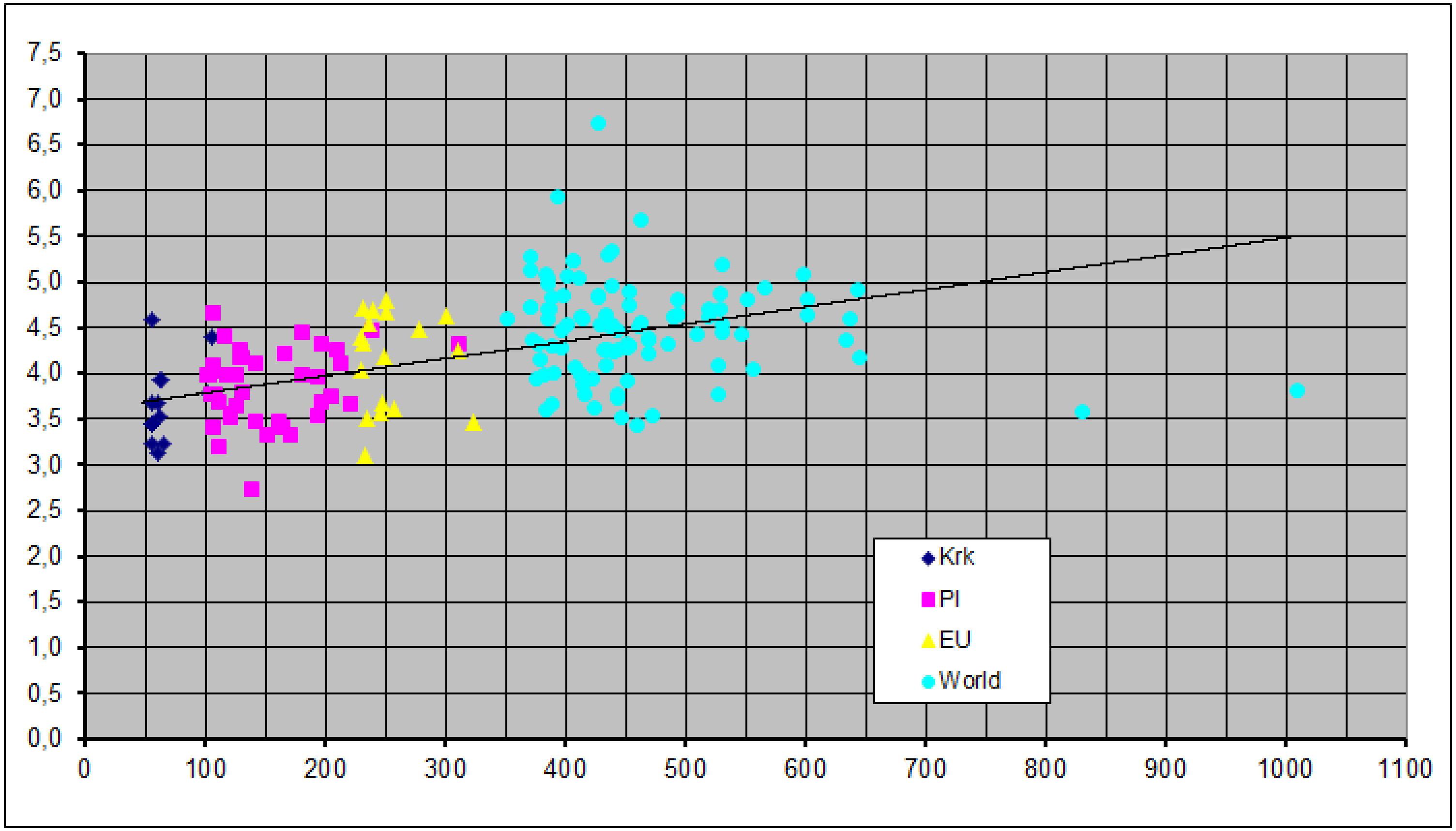


Photo: Author

Total height of building vs average height of storey (existing and under construction)

(4,27 m)

Photo: Author



The tallest structures in the world (photos of others → #t / 6)

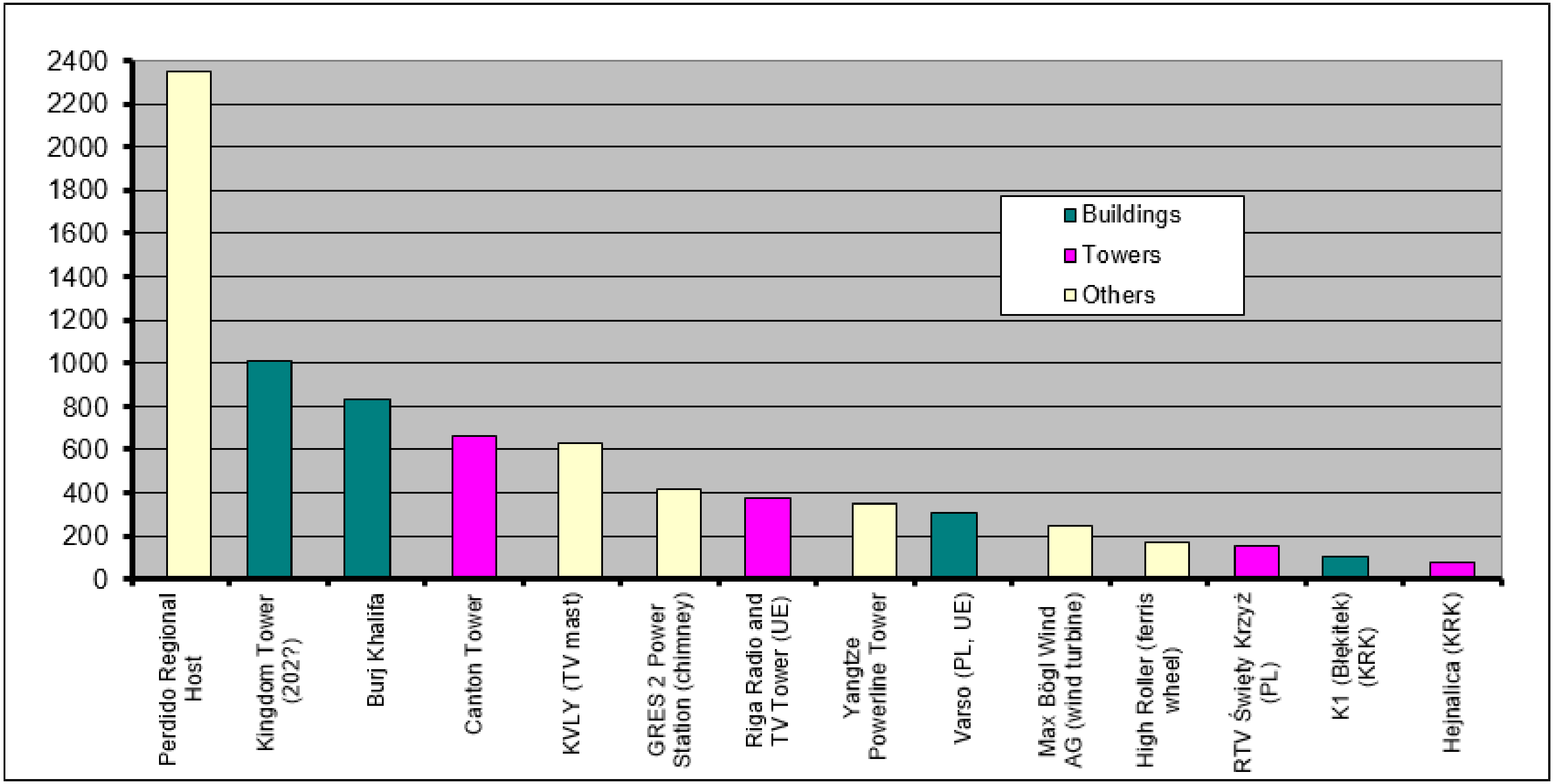


Photo: Author

Perdido Regional Host

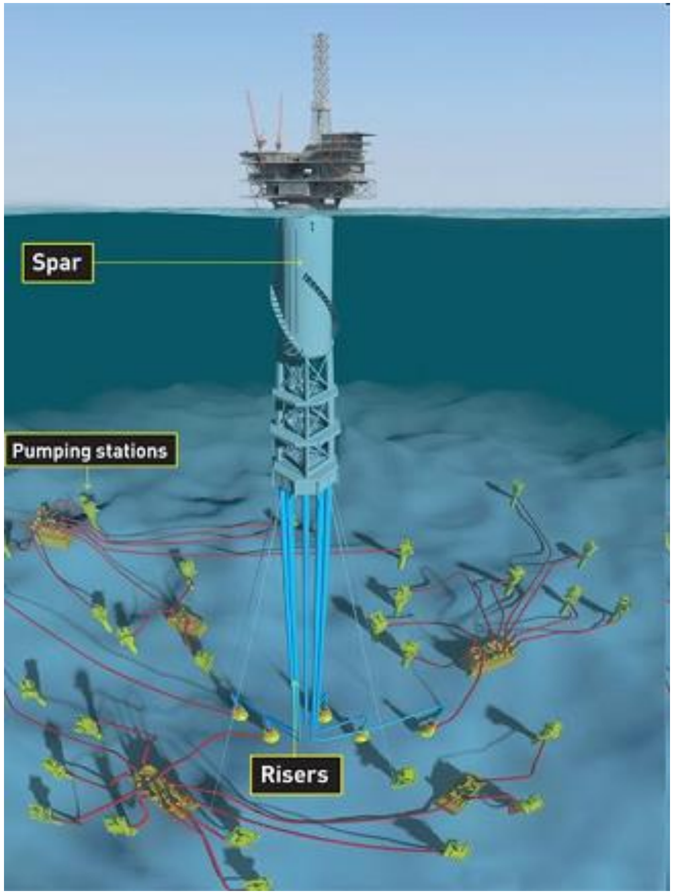


Photo: shell.com, industrytap.com

Dynamic characteristics

Dynamic forces are big problem for very high structures. They behave similar to pendulum. Amplitude of oscillations and perion of oscillations are two very important parameters. Additional problem is value of damping in structures.

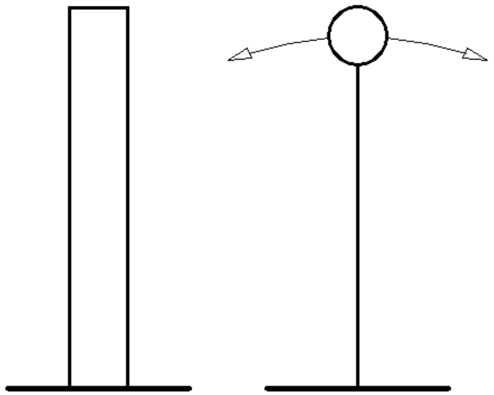


Photo: Author

Generally, for one freedom of degree (for example: pendulum), free oscillations are described as follow:

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

m – mass [kg]

c – damping coefficient [Ns / m]

k – stiffness [N / m]

The solution of this equation is:

$$y(t) = A\, e^{-\beta t} \sin(\omega t + \varphi)$$

A – amplitude of oscillations [m]

β – damping factor [1 / s]

ω – damped angular frequency [rad / s]

φ – phase offfset

ω_0 – angular frequency [rad / s]

ω – damped angular frequency [rad / s]

f – frequency [Hz]

T – period [s]

$$T = 1 / f$$

$$\omega = 2\pi / T = 2\pi f = \sqrt{(\omega_0^2 - \beta^2)}$$

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

β – damping factor [1 / s]

ζ – damping ratio [%]

c – damping coefficient [Ns / m]

Δ – logaritmic decrement of damping

$$\beta = c / 2m$$

$$\Delta = \ln [\, y(t) / y(t + T)] = \beta T$$

$$\zeta = \beta / \omega_0 = c / [2 \sqrt{(k\, m)}] = \Delta / [\sqrt{(4 \pi^2 + \Delta^2)}]$$

There is no information about amplitude for free oscillations:

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

$$y(t) = A\,e^{-\beta t}\sin(\omega t + \varphi)$$

$$A = ?$$

Amplitude can be calculated for excitated vibrations only:

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

There should be taken into consideration many degrees of freedom for high structures:

free vibrations:

$$[M]\,\{y_f''\} + [C]\,\{y_f'\} + [K]\,\{y_f\} = \{0\}$$

excitated vibrations:

$$[M]\,\{y_e''\} + [C]\,\{y_e'\} + [K]\,\{y_e\} = \{F\}$$

[ ] - matrix
{ } - vector

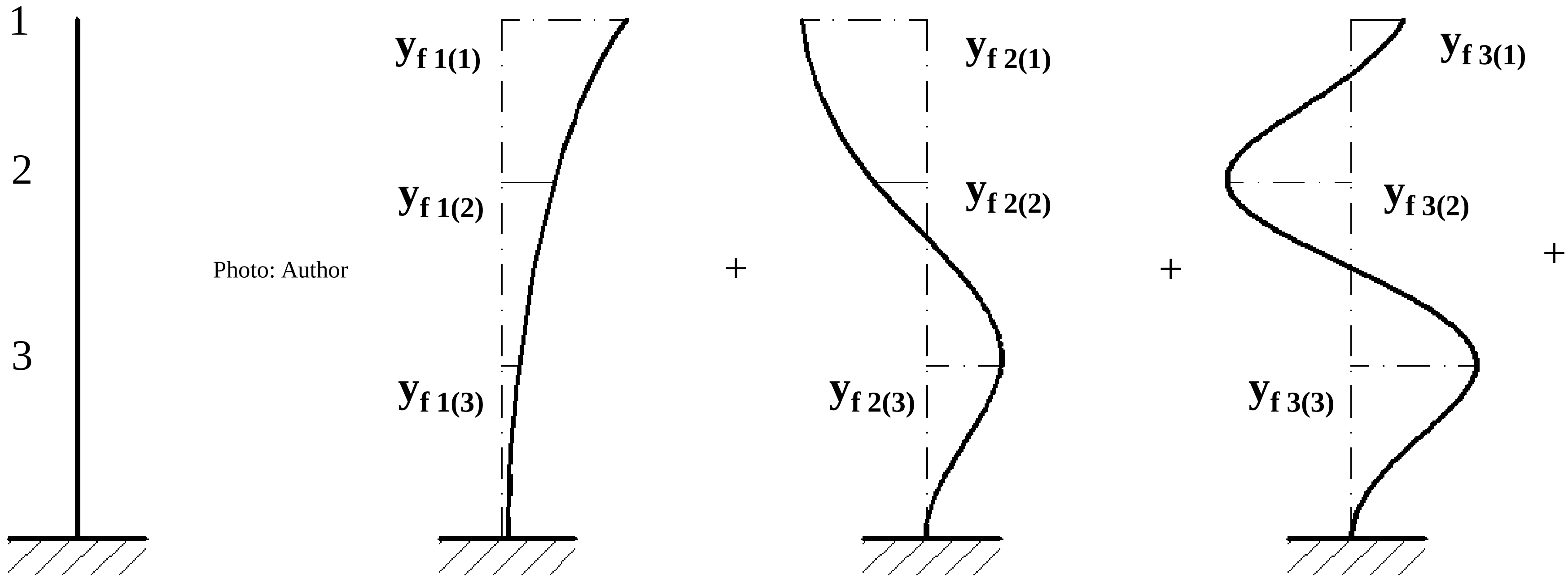


Photo: Author

$\cdot A_1 \sin(\omega_1 t + \varphi_1)$ $\cdot A_2 \sin(\omega_2 t + \varphi_2)$ $\cdot A_3 \sin(\omega_3 t + \varphi_3)$

Vibrations of structure under excitation can be approximated by function series:

$$\{y_e\} = \{y_1\} + \{y_2\} + \ldots + \{y_i\} + \ldots = \Sigma\, [A_i \{y_{f\,i}\} \sin(\omega_i t + \varphi_i)]$$

$$\{y_{f\,i}\} = \{y_{f\,i\,(1)}, y_{f\,i\,(2)}, \ldots\, y_{f\,i\,(j)}, \ldots\, y_{f\,i\,(n)}\}$$

$y_{f\,i\,(j)}$ – free vibration, i-eigenvalue, j-point

A_i - amplitude

$$\{y_e\} = \Sigma [A_i \{y_{f\,i}\} \sin(\omega_i t + \varphi_i)]$$

$$\{y_e'\} = \Sigma [A_i \{y_{f\,i}\} \omega_i \cos(\omega_i t + \varphi_i)]$$

$$\{y_e''\} = \Sigma [- A_i \{y_{f\,i}\} \omega_i^2 \sin(\omega_i t + \varphi_i)]$$

$$[M] \{y_e''\} + [C] \{y_e'\} + [K] \{y_e\} = \{F\}$$

$$[M] \Sigma [- A_i \{y_{f\,i}\} \omega_i^2 \sin(\omega_i t + \varphi_i)] + [C] \Sigma [A_i \{y_{f\,i}\} \omega_i \cos(\omega_i t + \varphi_i)] +$$

$$+ [K] \Sigma [A_i \{y_{f\,i}\} \sin(\omega_i t + \varphi_i)] = \{F\}$$

Known: $[M]$, $[K]$, $\{F\}$, $\{y_{f\,i}\}$, ω_i

Estimated: $[C]$, φ_i (φ_i colud be 0)

Unknown: A_i

A_i are calculated by numerical by numerical integration of above formula. After that, all parameters (forces, deformations) are known.

The biggest problem is assumption of damping. Formula

$c\ y'$

or

$[C]\ \{y'\}$

is only aproximation: viscotic damping, proportional to velocity of vibrations. It is good approximation for dissipation of vibrational energy in material. But, generally, this process is rather in proportion to $(y')^2$ or $(\{y'\})^2$. For joints (especially bolted joints) dissipation of vibrational energy is in proportion to y, {y} or, sometimes, to m, [M].

Generally, for real structures, value of damping can be different for various modes of vibrations. Additionally, is possible, that for any mode of vibration, damping changes in proportion to amplitude of vibration.

But "natural" damping has very small value. Generally, for high building, $\zeta \approx 1 \div 5\%$. Because of this, there can be assumed for calculations, one constant value for total structure for each mode of vibration and for each value of amplitude.

In case of each dynamic excitation, it is very important whether its frequency coincides with natural vibration frequency of structure. If excitation is in resonance range, vibration amplitudes and dynamic forces increase rapidly. This can easily lead to destruction of structure (ULS exceeded, → #t / 31). Outside resonance range, excitation may lead to exceeding SLS (→ #t / 32).

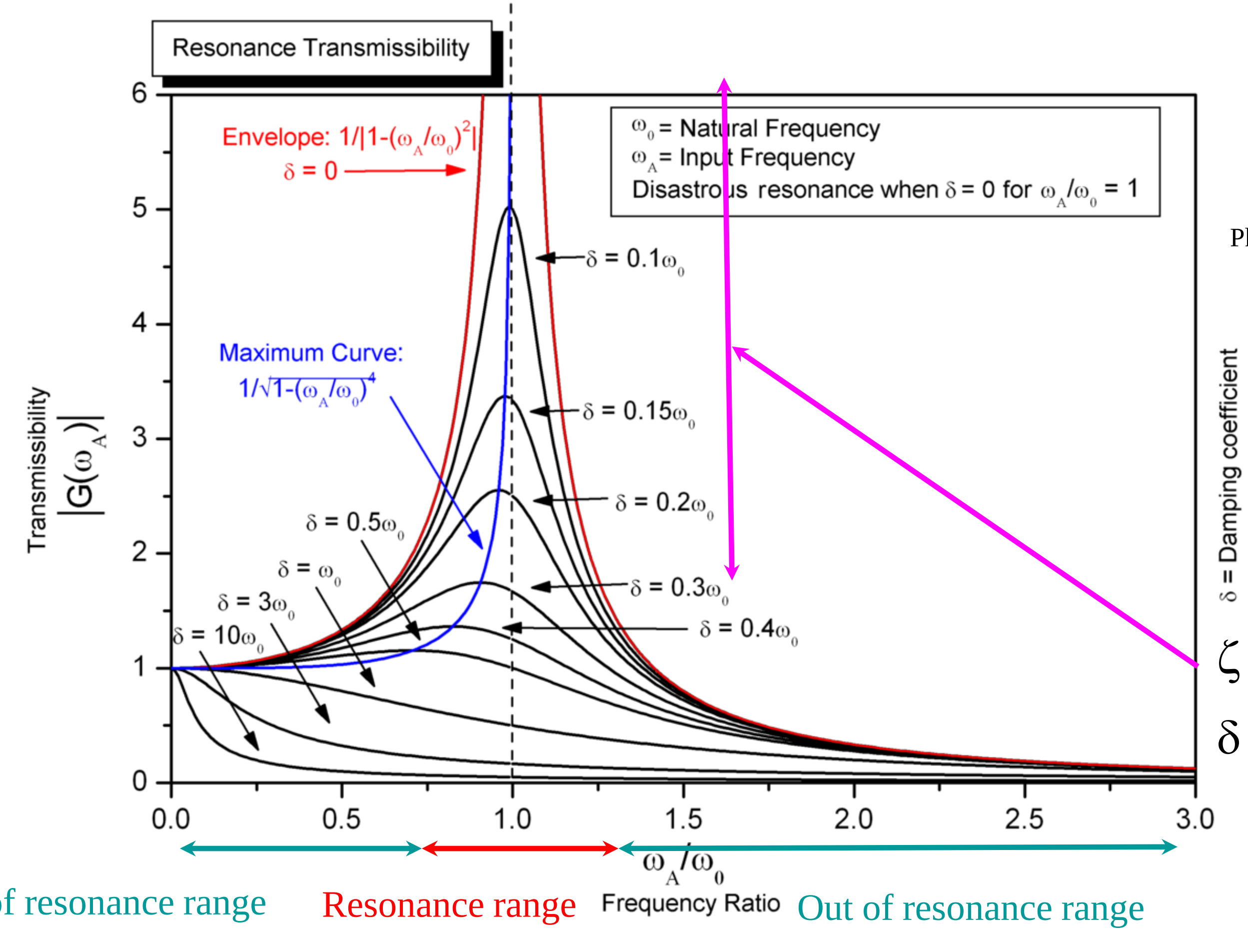


Photo: wikipedia

$\zeta \approx 1 \div 5\%$ means

$\delta \approx 0{,}05 \div 0{,}30\ \ \omega_0$

so, dynamic effects ≥ 1,7 · static effects

Exceeding ULS: danger of damage, destruction and collapse, because of too big values of inertia forces, caused by earthquake or pressure caused by hurricane.

Photo: sanandreasfault.org

Photo: shine.cn

Photo: eu.gainesville.com

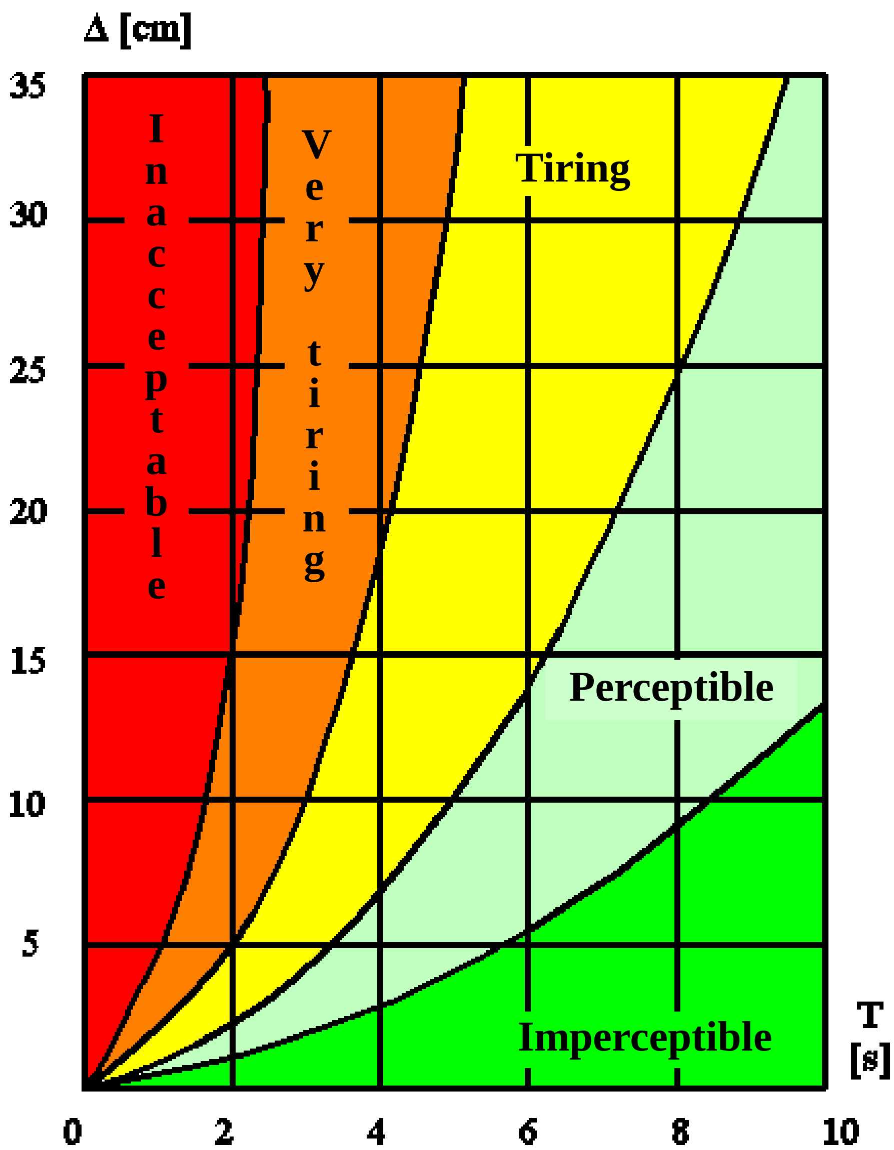


Photo: "Konstrukcje metalowe, tom II", M. Łubiński, W. Żółtowski, A. Filipowicz

Exceeding SLS: there is no special information and requirements in Eurocodes for amplitudes and frequencies of vibrations in context of peoples feeling. It could be found in literature.

d - static deformation
(equilibrium state; colud be 0)
Δ - vibrations around equilibrium state

Photo: Author

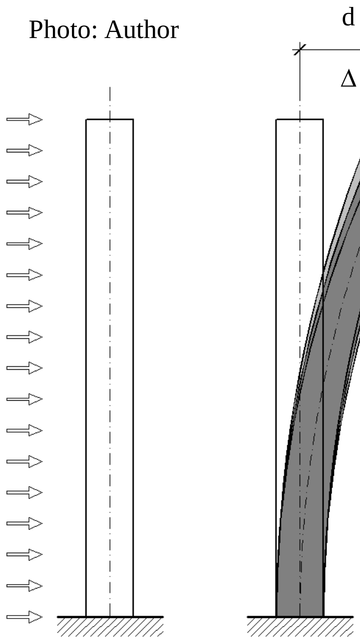


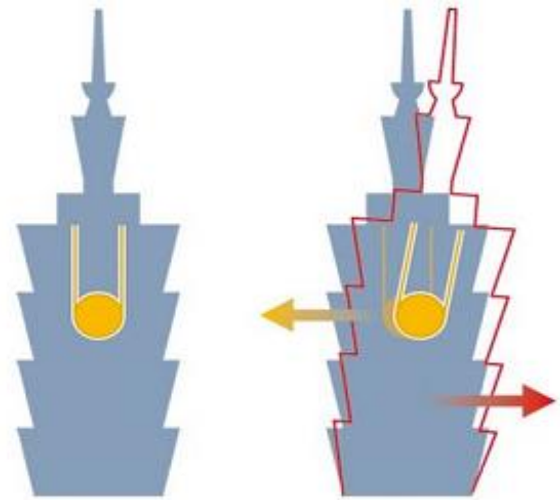
Photo: tightwadcruises.wordpress.com

Sometimes there are installed specific structures and machines, increase "natural" damping of building.

There is special structures on the top of Taipei 101 – massive steel sphere (mass = 1 / 1000 mass of building). Sphere hangs on 16 steel ropes ϕ 10 cm.

Photo: wikipedia

Dynamic characteristics of building and pendulum are, that displacements of pendulum are always on the opposite direction than displacements of buildings.

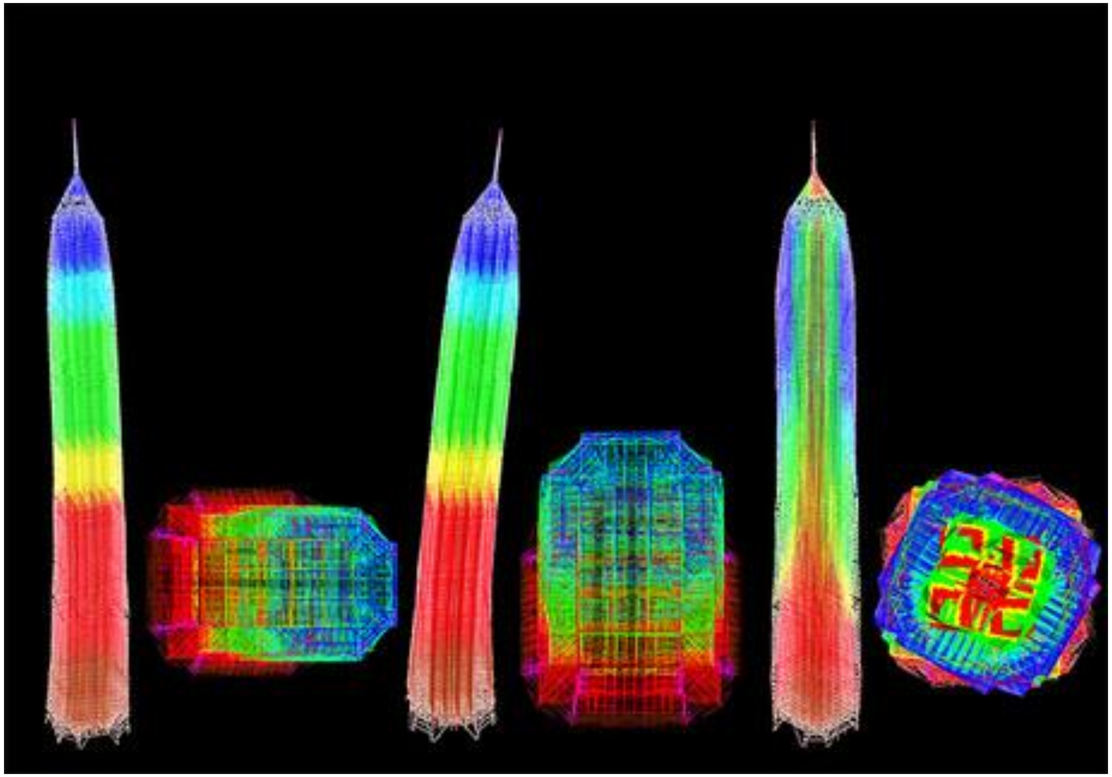


Thank this, oscillations of building from earthquake or wind are reduced by 45 %.

Photo: wikipedia

There is very important first natural frequency for analyse of structure for advanced types of calculations. It can be calculated, based on full 3D dynamical computer calculations, or based on few approximated formulas, presented as follow.

Photo: skyscrapercity.com



1. Geiger's formula, transversal vibrations:

$f = (1 / 2\pi) \sqrt{(g / \Delta)}$; Δ - as for horizontal cantilever; deflection under dead weight

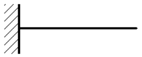


Photo: Author

2. First transversal frequency of cantilever:

$EJ = const$, μ [kg / m] = const:

$f = 0{,}560 \sqrt{(EJ / \mu)} / H^2$

3. T. Tatara, "Odporność dynamiczna obiektów budowlanych w warunkach wstrząsów górniczych", Kraków, PK 2012, (transversal vibrations):

$f = 1 / (A\,n)$; $A = 0{,}045$ [s], n – number of storeys

4. PN / B 2011, (transversal vibrations):

$f = (A \sqrt{B}) / H$; $A = 10$ [Hz $\sqrt{m}$], B - width of building || to wind direction

5. EN 1991-1-4: (transversal vibrations):

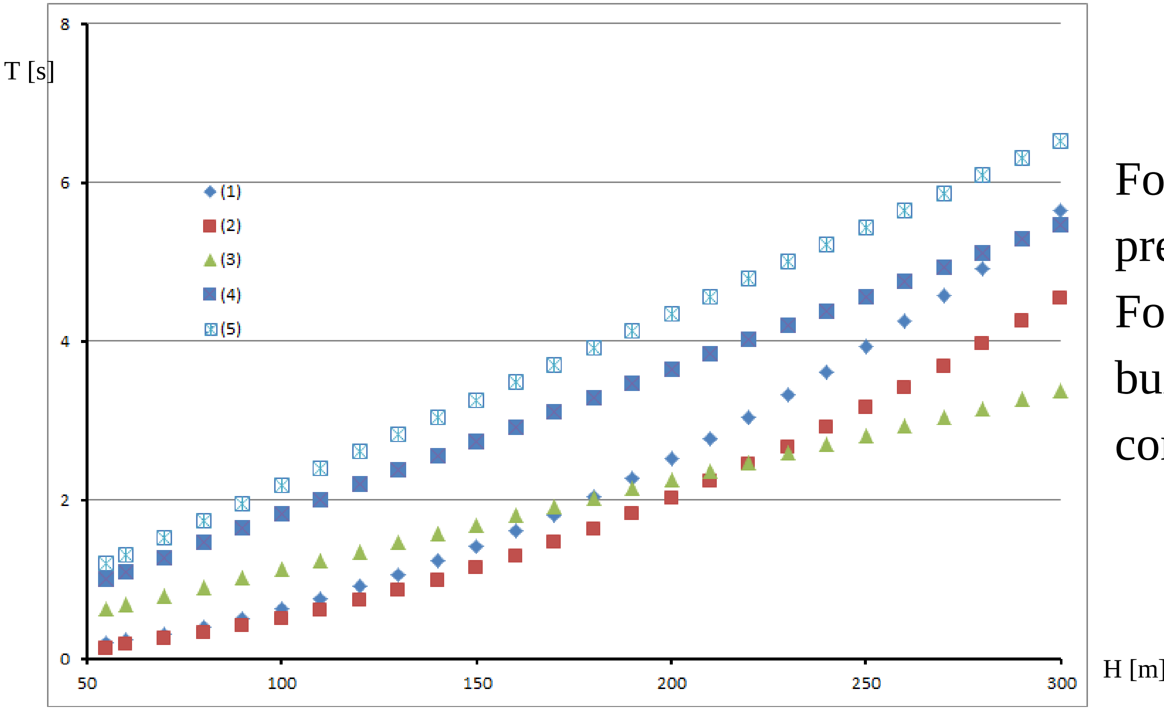
$f = A / H$; $A = 46$ [Hz m]

The most accurate is, of course, FEM model.

Method **1** is simplified, but the most complicated amongs other simplified. It allows take into consieration various distribution of mass and stiffness along building.

Method **2** allows to obtain various results for various buildings of the same geometry but various constant distribution of mass and stiffness along building. If distribution of mass or stiffness along building is strongly non=constant, this formula has got only rought results.

Methods **3**, **4**, **5** ale the fastest and the simplest. Frequency of oscillation is function olny geometry, but result will be the same for various buildings of the same geometry.



For methods **1** and **2**, structure presented on #t / 53 is analysed.

For method **4**, square footprint of building = 30x30 m is taken into consideration (the same as for **1** and **2**).

Photo: Author

Apart from transversal vibrations, longitudinal vibrations could be important. For example, for cantilever in case of EJ = const, EA = const, μ [kg / m] = const, (method **2**):

$$f_{transv} = 0,560 \sqrt{(EJ / \mu)} / H^2$$

$$f_{long} = 0,250 \sqrt{(EA / \mu)} / H$$

Structure presented on #t / 53 is analysed:

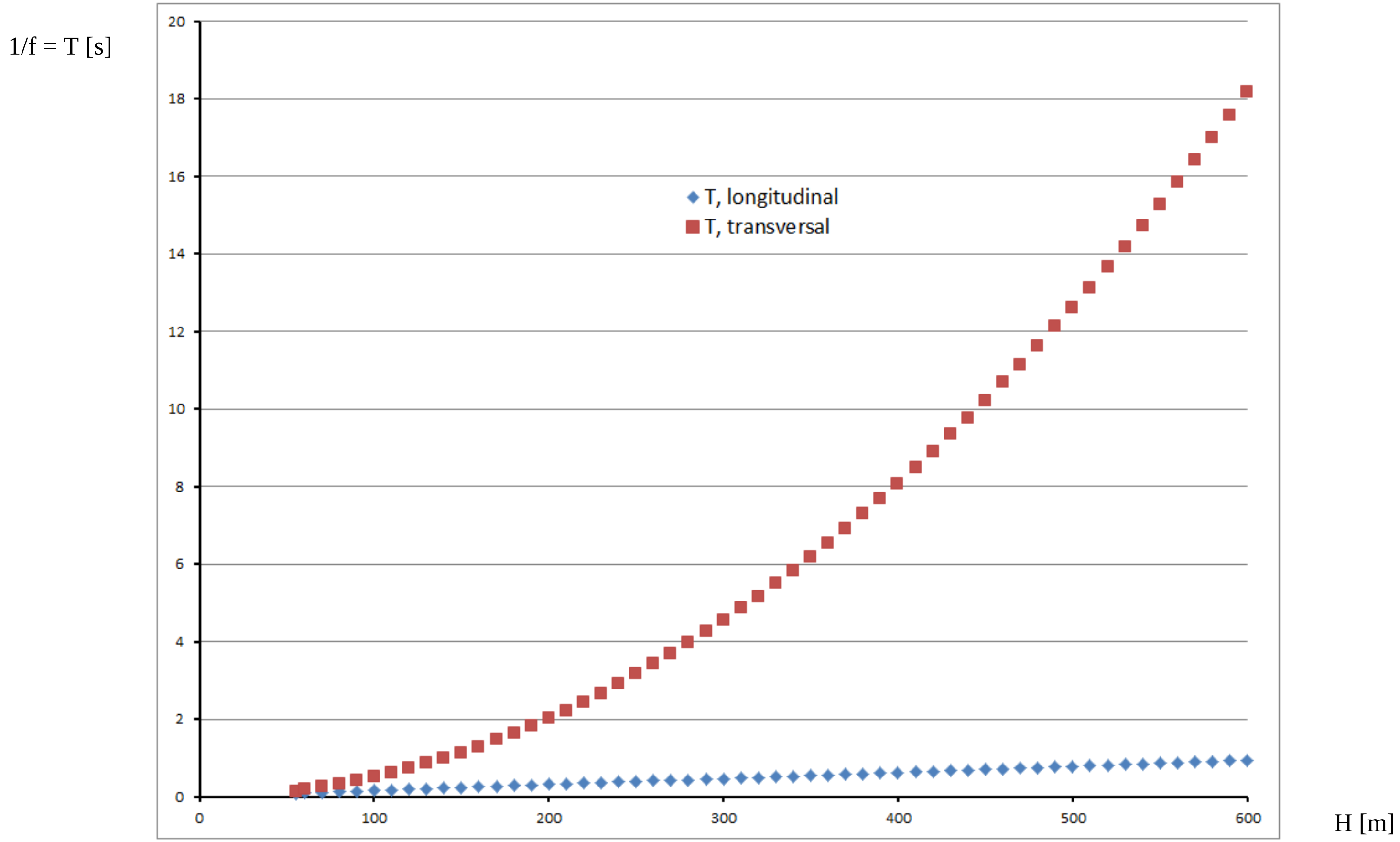
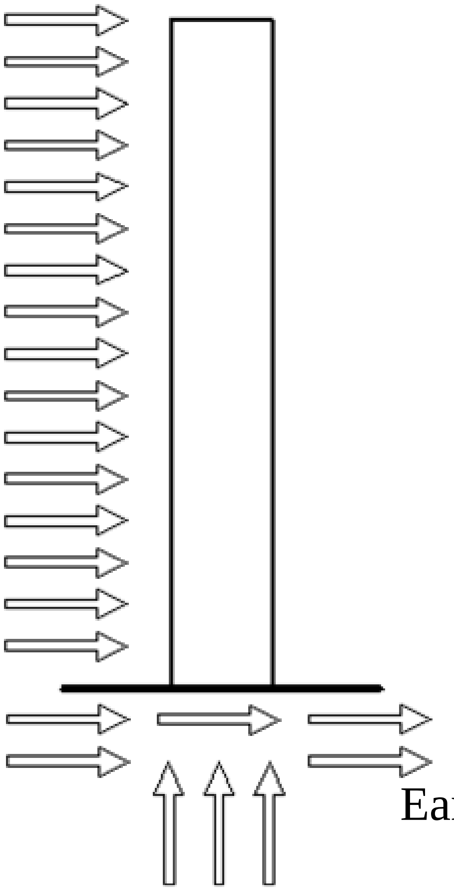


Photo: Author

Wind action v.s. earthquake

There are two most important types of excitation for very high buildings: wind action and earthquakes.

Wind action: excitation by dynamic loads



Earthquakes: excitation by ground motion

Photo: Author

Both types of excitations have chaotic character. Both can be presented as Fourier series:

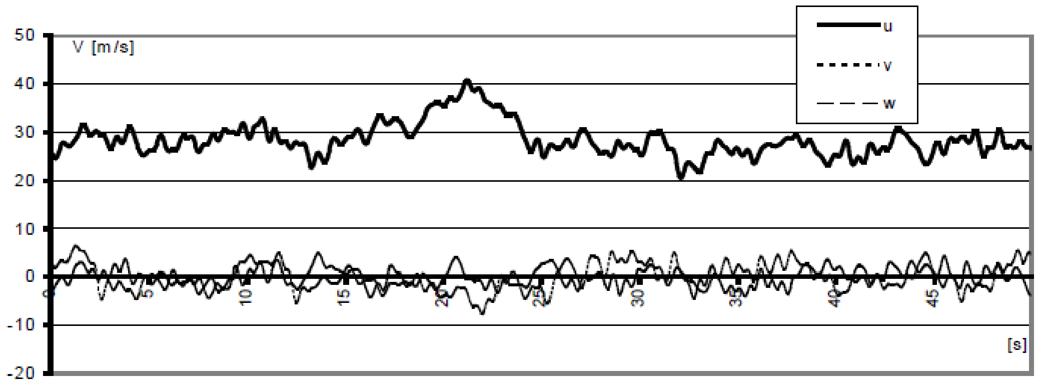


Photo: Author

$$E(t) = \Sigma\,(A_i \sin \psi_i), \quad i = 1, 2, \ldots$$

Effect of chaotic wind action is buffeting (→ #6 / 56)

ψ_i - dominant excitation frequencies

ω_n - frequencies of natural vibration

If

$\psi_i \approx \omega_n$

there is resonans

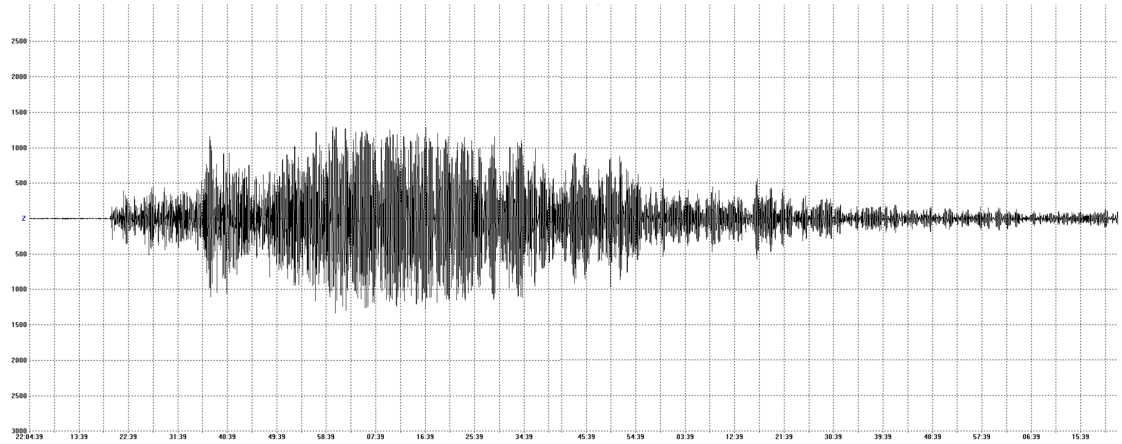


Photo: geosci.ipfw.edu

Generally, for wind, three components of loads should be taken into consideration:

- horizontal, parallel to average direction of wind (u);
- horizontal, perpendicular to average direction of wind (v);
- vertical (w);

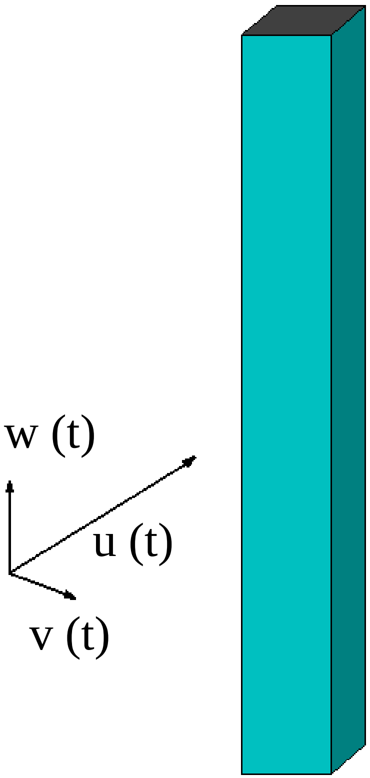
Vertical can be neglected during analysis of high buildings.

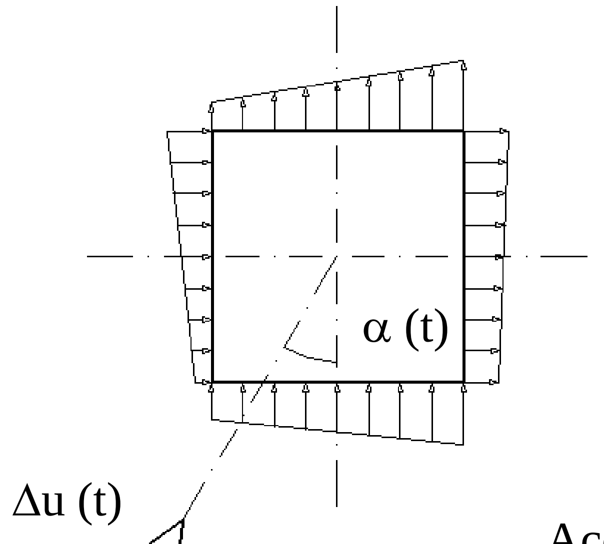
During earthquake, four types of waves in ground must be be taken into consideration:

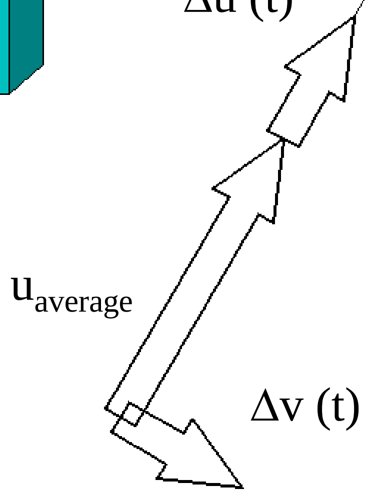
- longitudinal (in total volume of Earth);
- transversal (in total volume of Earth);
- **Rayleigh's** (longitudinal-transversal surface wave - exists only near surface of Earth, disappearing at a depth of few length of wave);
- **Love's** (transversal surface wave - exists only near surface of Earth, disappearing at a depth of few length of wave);

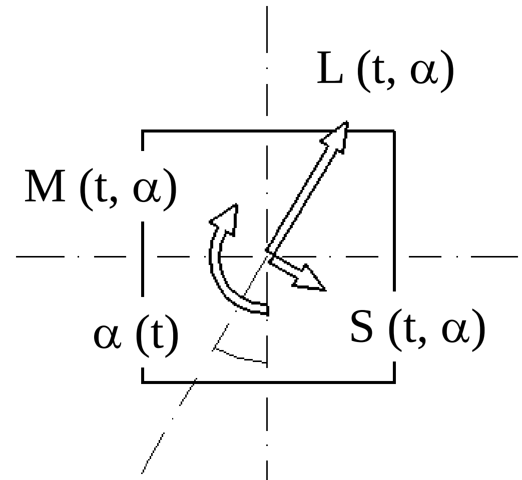
Both surface waves are the most dangerous for structures.

Photo: Author









According to information in EN 1991-1-4, there can be possbile to calculate only static (average) part of wind load.

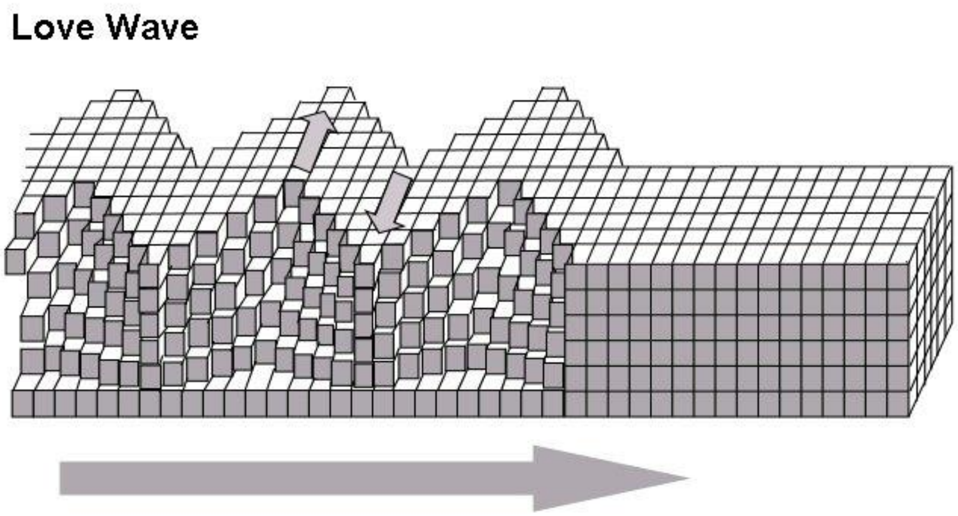
$$u(t) = u_{average} + \Delta u(t)$$

$$v(t) = 0 + \Delta u(t)$$

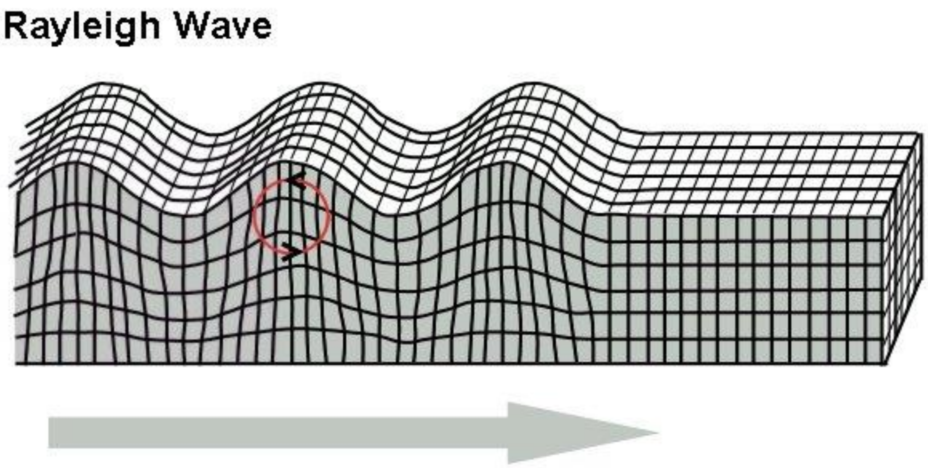
$$\alpha(t) = \alpha_{average} + \Delta \alpha(t)$$

$$\Delta \alpha(t) = \text{arc tg} \{ \Delta u(t) / [u_{average} + \Delta u(t)] \}$$

Photo: wikipedia



Horizontal excitation → **horizontal** vibrations.



Horizontal and vertical excitation → **horizontal** and **vertical** vibrations.

For wind action - type of load - very useful is spectral analysis of wind. Spectral analysis presents information about strucutre of wind (Fourier serie):

$$E(t) = \Sigma (A_i \sin \psi_i), \quad i = 1, 2, ...$$

what is proportion between A_i for different ψ_i - frequency of wind oscillations. Value of A_i shows big (big A_i) or small (small A_i) impact on structure in case of resonance ($\omega_i \approx \psi_i$).

For earthquake - type of kinematic excitation – the same, spectral analysi is possible. But more useful is spectral analysis of behaviour of structure under excitation. This is analysis of behaviour of many different buildings under seismic and paraseismic excitations. Result is information about acceleration of structure in function of its free vibration (in case of resonans with waves in ground). Loads applied to structure is calculated as:

$$F = a\, m$$

a - acceleration of structure

m - mass of structure

For analysis of seismic (paraseismic) excitation are dedicated Eurocodes series 1998.

Effect of wind

Various analysis of wind spectrum show, that wind excitation reaches maximum for period T = 60 ÷ 120 s (resonance for structure with first period of oscillation 60 ÷ 120 s). Information presented on #t / 37, 38 shows, that for high buildings theirs free vibration period is lower than 15 s. **In resonant range of high buildings, wind excitation is very small**. **There is no impact on ULS, only on SLS**.

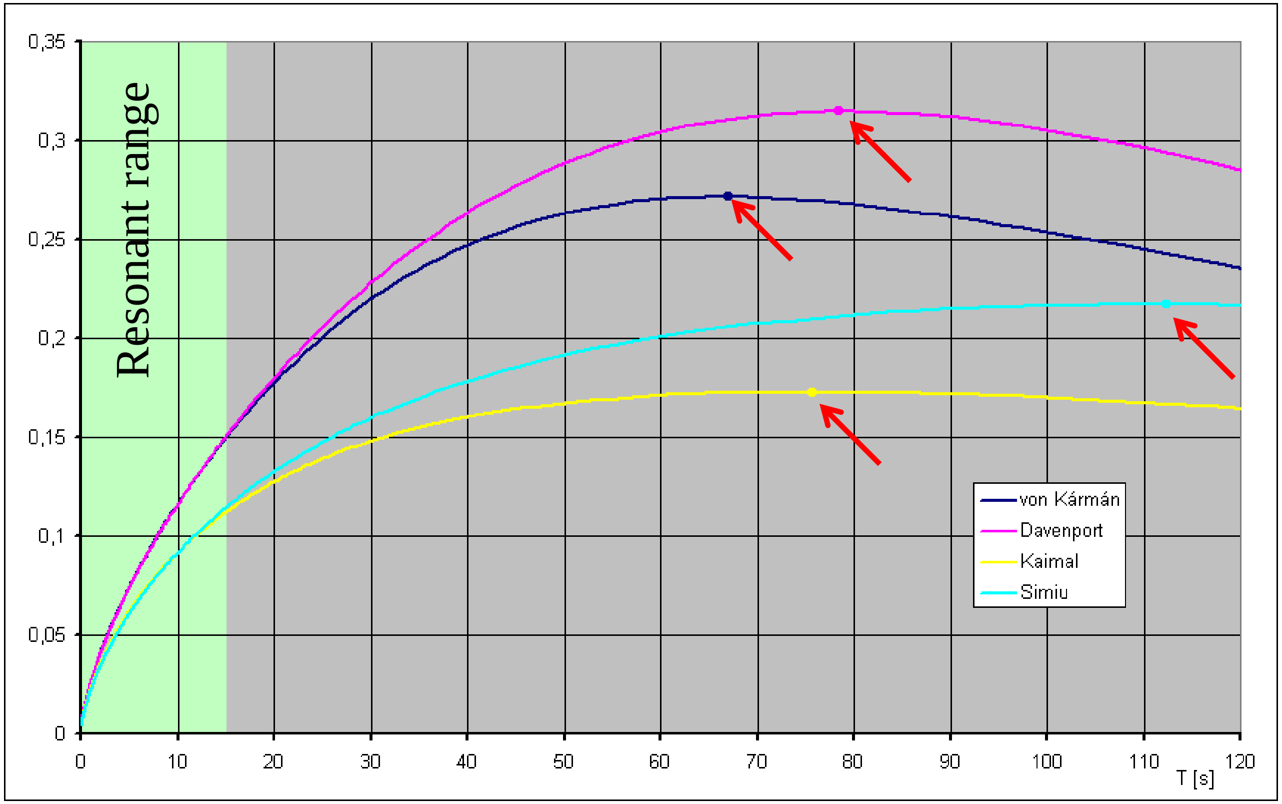
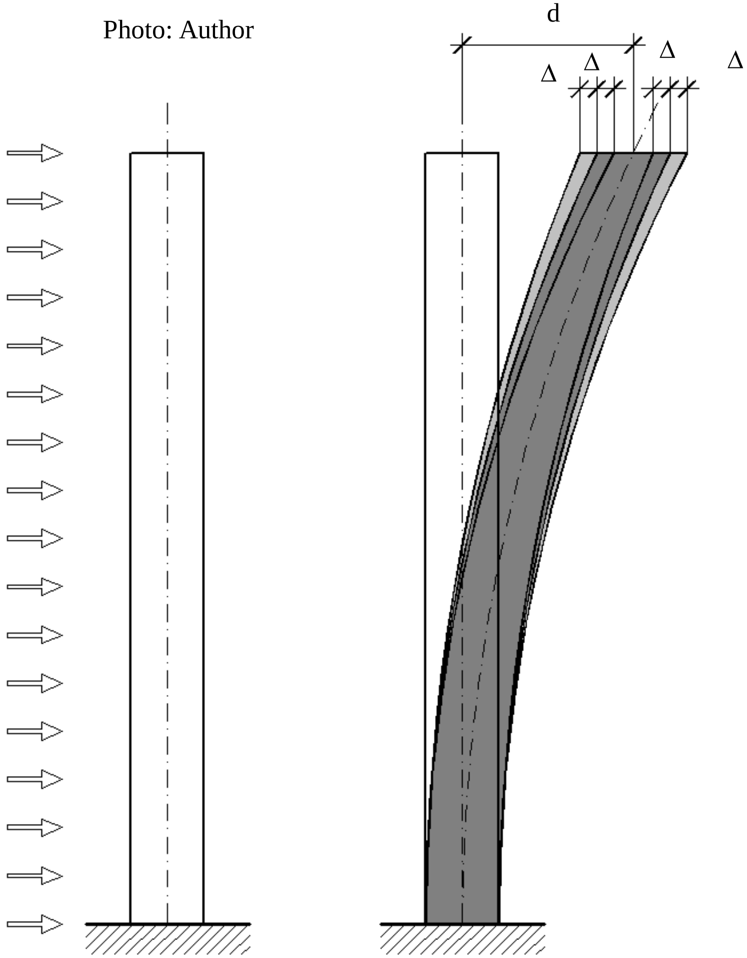


Photo: Author

Photo: Author



Analysis of wind SLS (period-amplitude analysis).

d is effect of load by average value of wind.

Value of d is calculated according to EN 1993-1-4.

Calculation of Δ is much more complicated. It is the effect of resolving formulas:

$$[M]\ \{y_e''\} + [C]\ \{y_e'\} + [K]\ \{y_e\} = \{F\}$$

Value of dynamic coefficient $c_s c_d$ (EN 1991-1-4 p. 6.1, 6.2, 6.3) can be used as rough approximation of Δ:

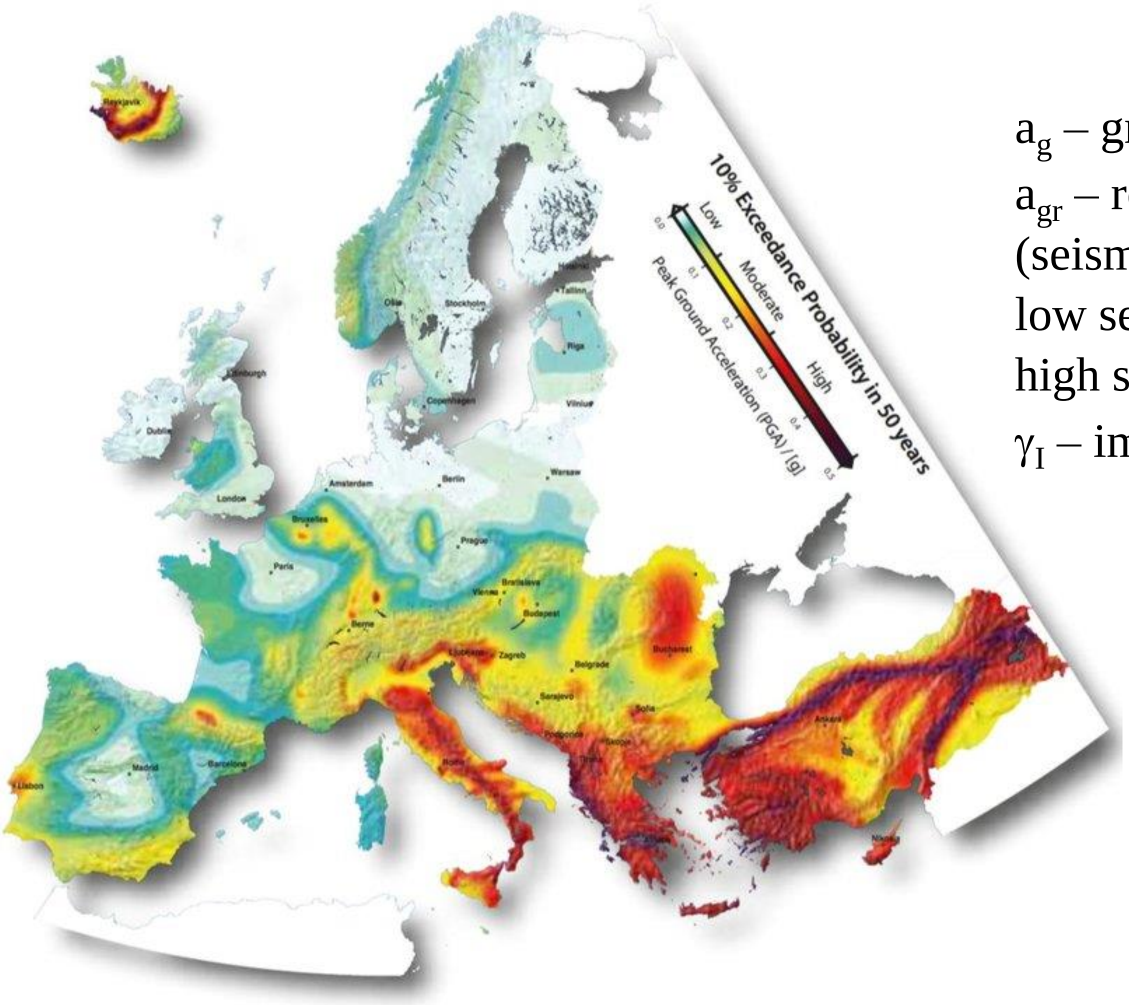
If $c_s c_d > 1{,}0$ then

$$c_s c_d \approx (d + \Delta) / d \rightarrow \Delta = d\ (c_s c_d - 1{,}0)$$

Based on T (perion of oscillations) from dynamic analysis and amplitude Δ, analysis of peoples feeling inside building (→ #t / 32) is possible.

Effect of earthquake

Photo: Seismic Hazard Model 2015 for Switzerland , S. Wiemer & all.



$$a_g = a_{gr} \gamma_I$$

a_g – ground acceleration

a_{gr} – refference ground acceleration (seismic zone; from 0,0 [m / s^2] in very low seismic activity to 3,0 [m / s^2] in high seismic activity region

γ_I – importance of structure factor

γ_I could be related to Consequences Classes:

0,8 for CC1;

1,0 for CC2

1,2 for „low” CC3

1,4 for „high” CC3

Seismic excitations are very rare and of very small activity in Poland. On the other hand, very often can occur para-seismic excitations from human activity in mines (crumps).

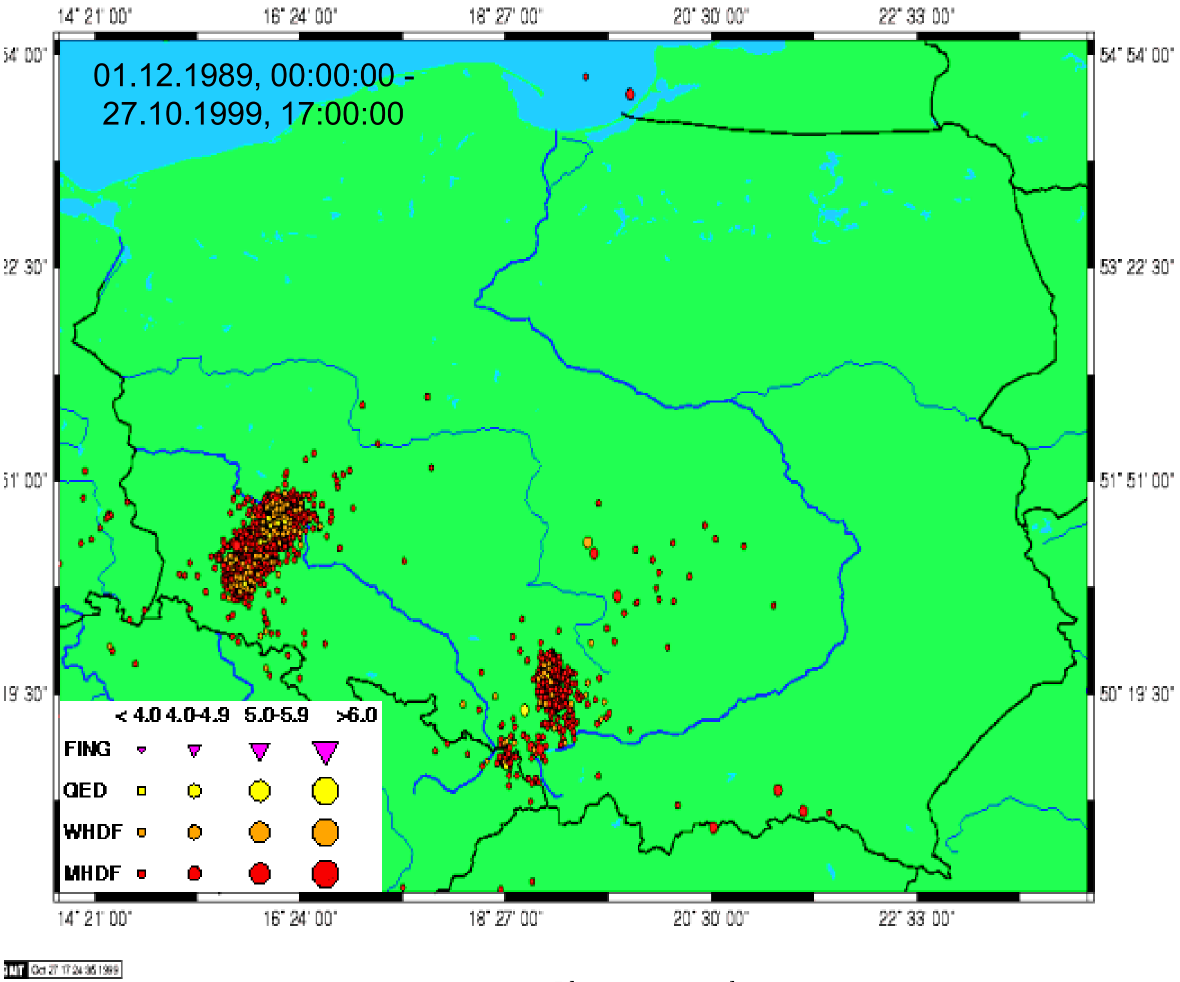


Photo: sgp.org.pl

There are three regions: in GZW (Upper Silesian Coal Basin), ROW (Rybnik Coal Area) and LGOM (Legnica-Głogów Copper District).

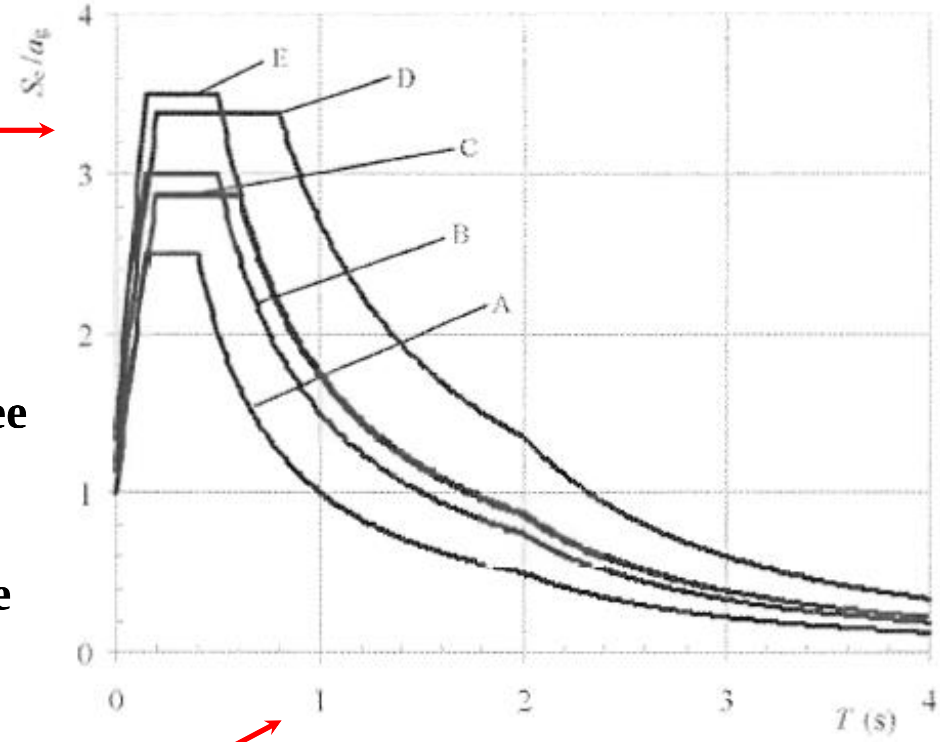
Para-seismi excitations are characterised specific values of refference ground acceleration a_{gr} ; other than in case of seismic excitations.

Impact of ground acceleration on structure:

A, B, C, D, E – ground conditions (A – rock; E – alluvium)

Photo: EN 1998-1 fig. 3.2

Proportion between acceleration of structure and acceleration of ground



The biggest impact is for structures with first perion of free vibration < 2,5 s. Information presented on #t / 37, 38 shows, that for high buildings theirs free vibration period is mostly in this range.

First perion of free vibrtation of structure

(Example diagram for transversal seismic vibrations; for seismic longitudinal and for both para-seismic, other diagrams must be analysed).

Max values of parameter S_c / a_g (→ #t / 49) are various for both direction of seismic and para-seismic excitations and can reach values 1,35 ÷ 4,50.

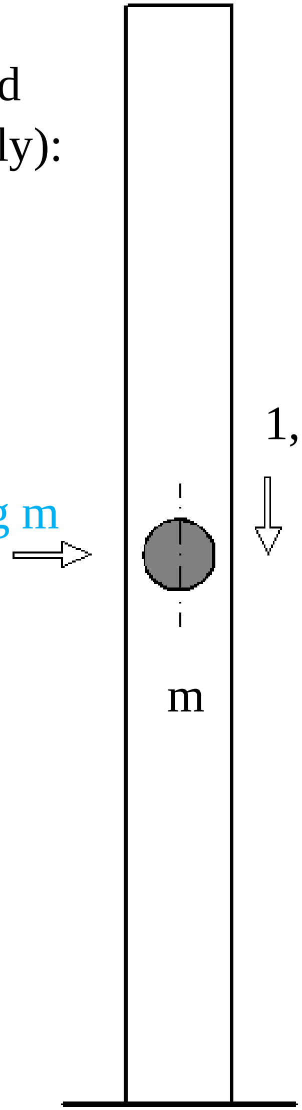
Example:
a_{gr} = 0,50 [m / s^2] (low seismic activity);
γ_I = 1,0 (CC2);
S_c / a_g = 3,0
Acceleration, applicated to structure (in horizontal and in vertical direction), is equal
0,50 ·1,0 · 3,0 = 1,50 [m / s^2]
In comparison to g (gravitional acceleration, 9,81 [m / s^2]), it is 15% (0,153 of g – this means 0,153 dead-weight)

To better understand importance of this fact, it is worth comparing it with wind action. For Kraków, for example, wind action 10 m above ground (characteristic value) is equal 0,186 kPa; 600 m above ground is equal 0,497 kPa. For structure, presented on slide #/t / 53 (4,0 m height of level, footprint 30,0 x 30,0 m) total value of wind action for one level (4,0 · 30,0) is from 22,320 kN to 59,640 kN. Characteristic value of dead-weight of one level is 4 493,686 kN.

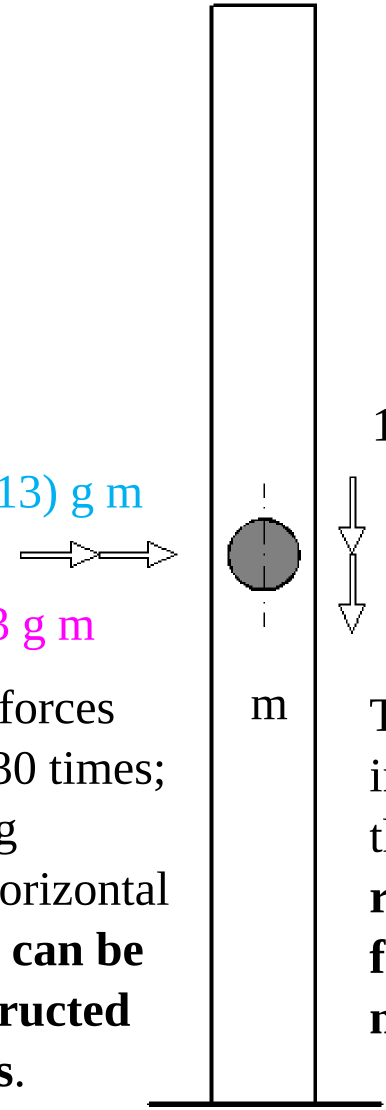
(22,320 kN ÷ 59,640 kN) / 4 493,686 kN = 0,005 ÷ 0,013

So, effect of wind action colud be presented as 0,5 ÷ 1,3% of dead-weight.

No earthquake (wind action and dead-weight only):



Earthquake (wind action and dead-weight and inertia forces), **low** seismic activity:



Total horizontal forces increasing 12 ÷ 30 times; the same bending moments from horizontal actions; **buiding can be completely destructed by inertia forces**.

Total vertical forces increasing up only 15%; there is possible than **resistance of columns for vertical force still is not exceeding**.

Photo: Author

Conclusions

- Both phenomenon (wind, earthquake) have chaotic character;
- Both can be presented by Fourier serie;
- Wind is excitation by load, earthquake - kinematic excitation;
- Wind could be analysed by spectrum of load, earthquake by spectrum of structure answer.

- Wind action no make resonant excitation of buildings;
- Longitudinal excitation of buildings from wind is neglegible;
- Transversal excitation (shear forces, bending moments) of buildings from wind could be important for SLS of buildings;
- In specific cases, secondary elements (facades) could be damaged by wind action.

- Earthquake can destruct structure by transversal inertia forces;
- Impact of longitudinal inertia forces on resistance could be neglegible;
- Earthquake is too short phenomenon (several secont) to make SLS analysis in case out of resonant range.

Effects of wind actions

Photo: wikipedia

Wind, location: Kraków
Office building

First model (structure similar to K1)

Live load 2,50 kN / m^2

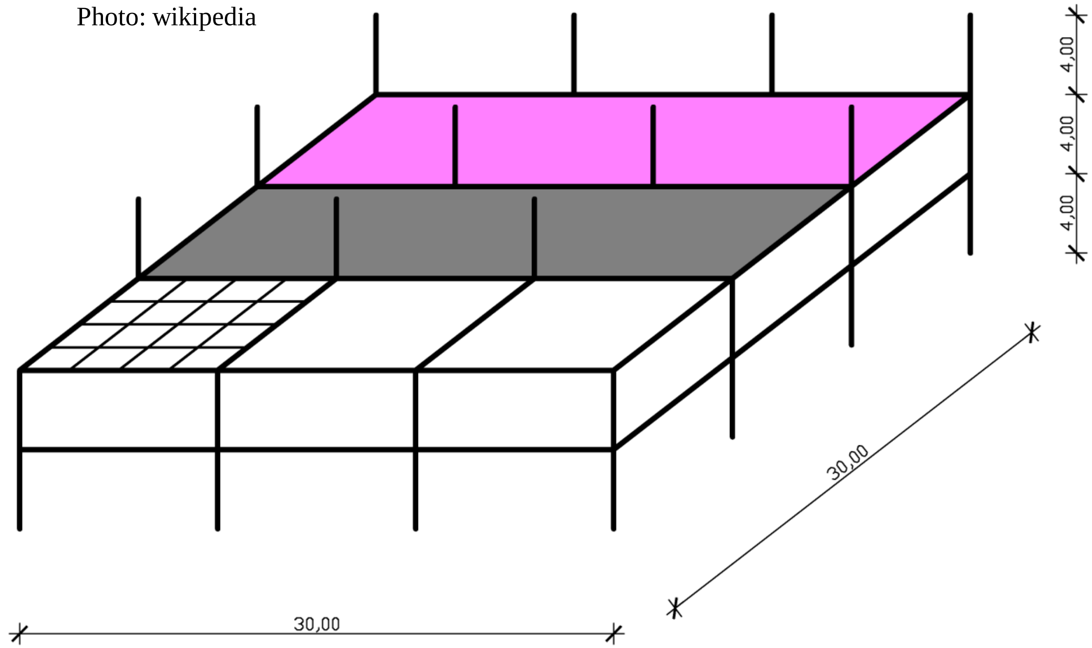
Concrete plate 10 cm

Columns: 2x HLR^+ 1100

Girders: HEA 700

Secondary beams: IPE 500

Photo: Author



Columns: 2x HLR$^+$ 1100

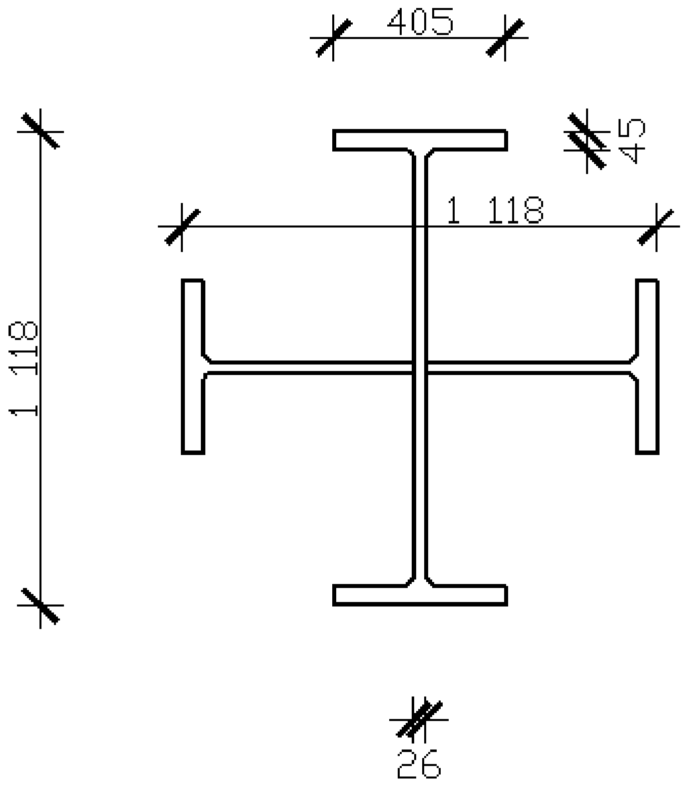


Photo: Author

Reactions

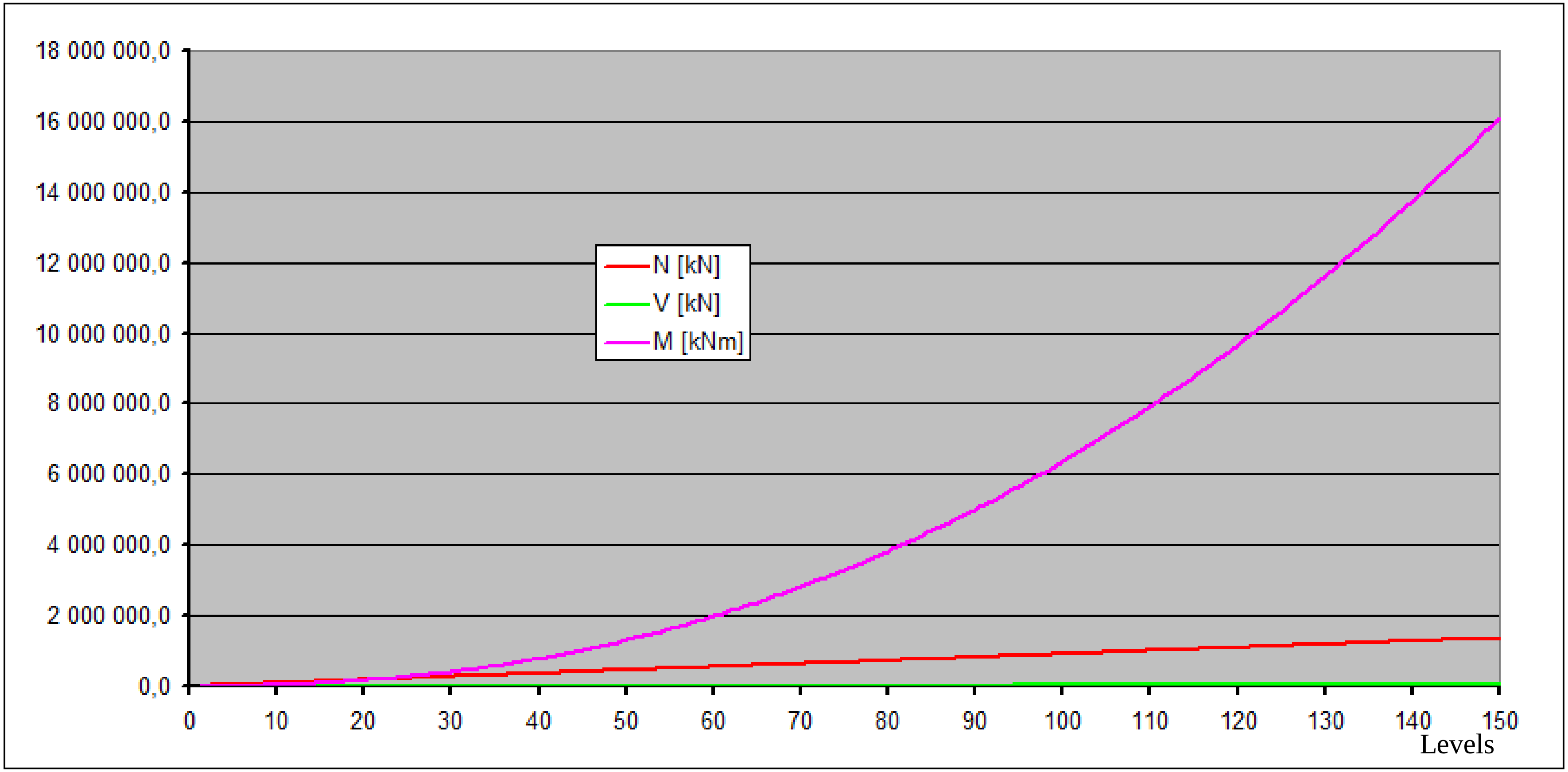


Photo: Author

Axial forces in columns

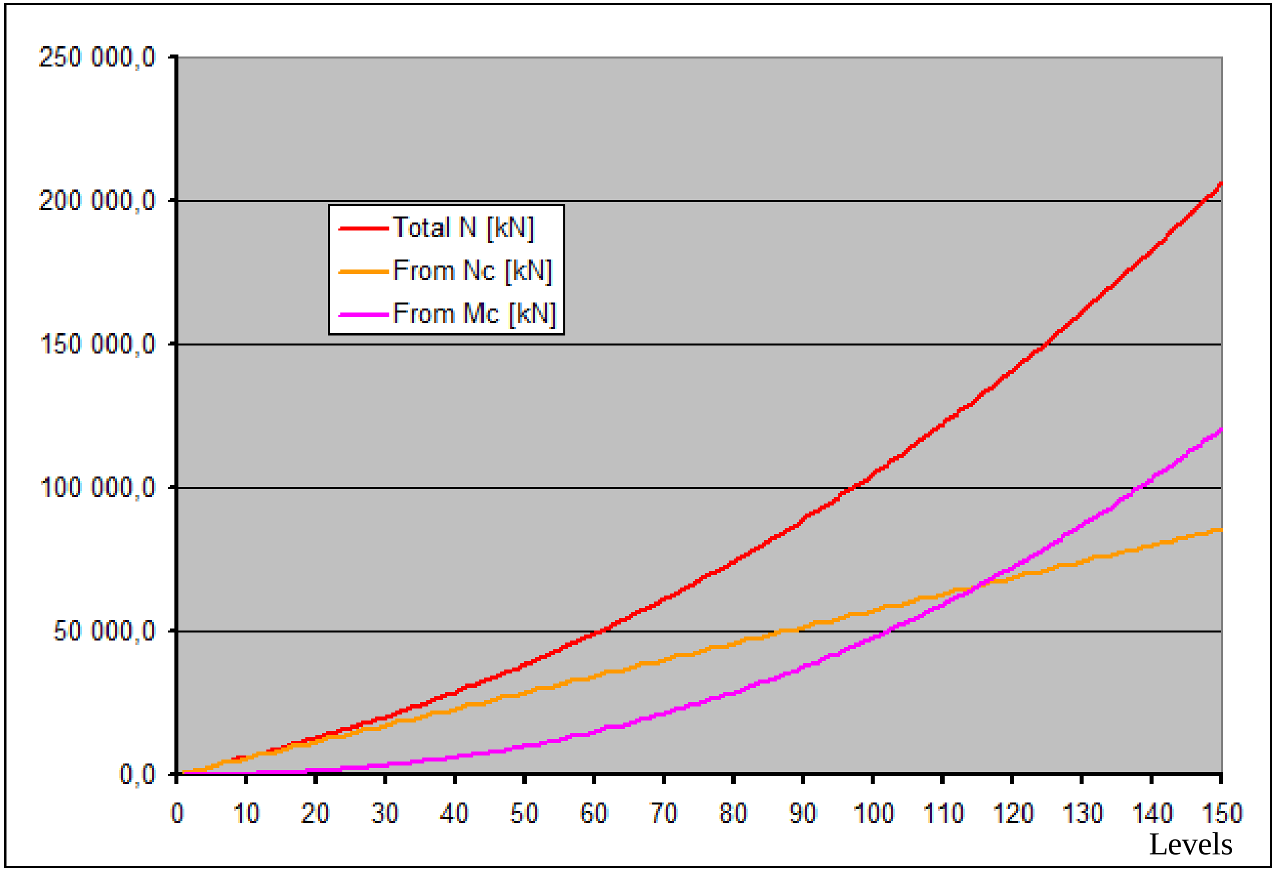


Photo: Author

Axial force in column vs resistance (without buckling) of column

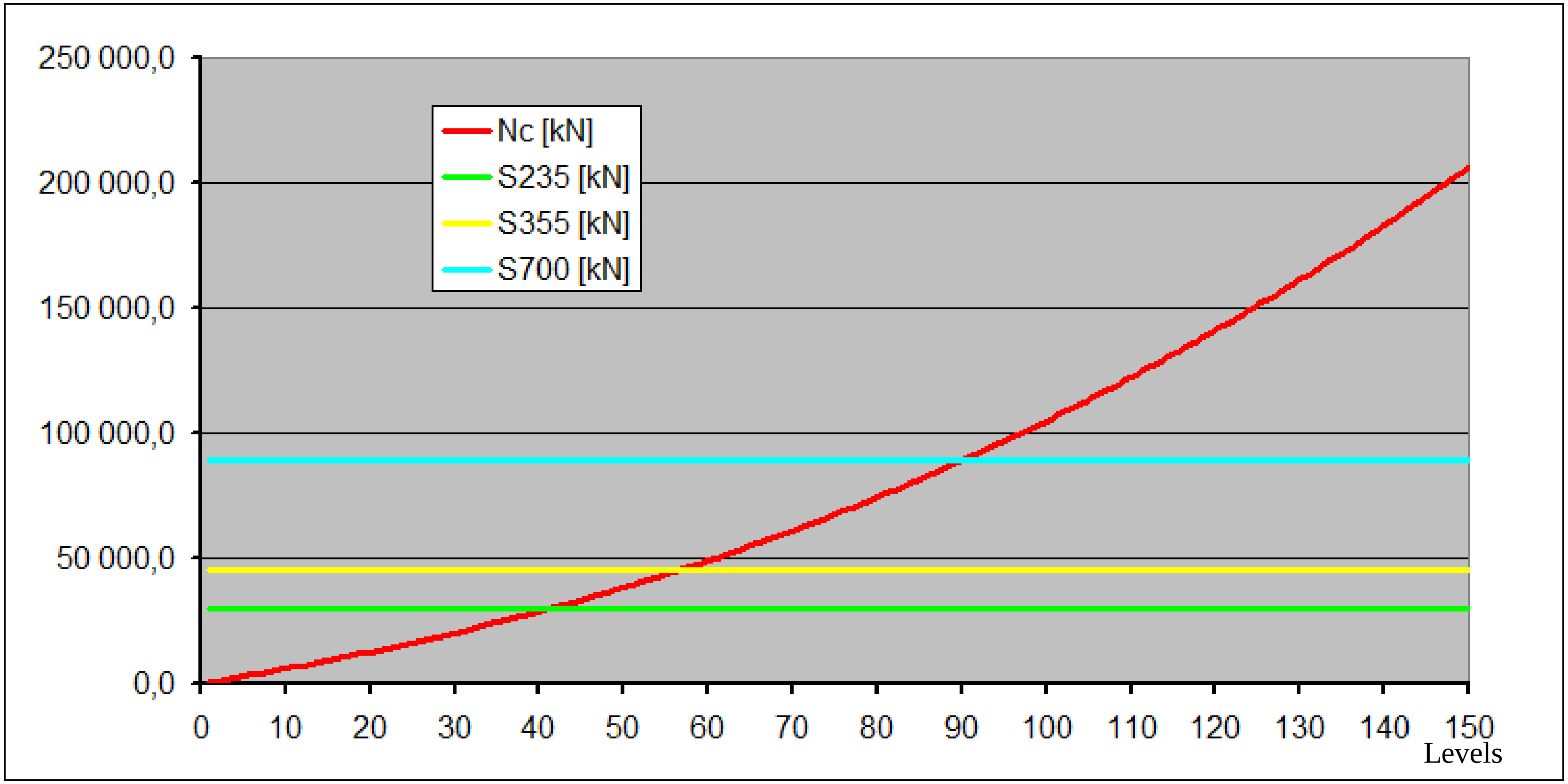


Photo: Author

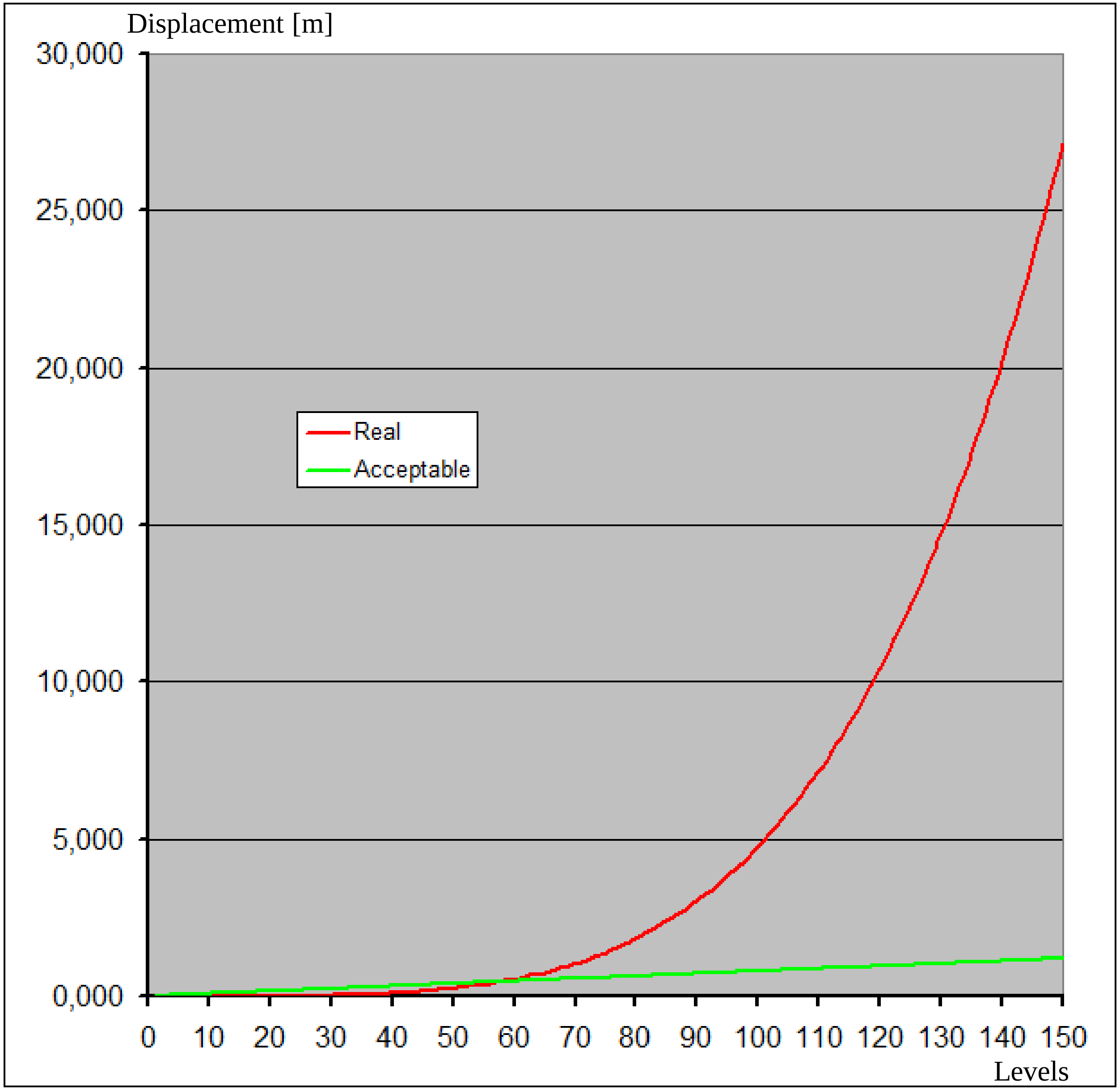


Photo: Author

Horizontal displacements of building's top end

Acceptable: H / 500

EN 1993-1-1 NA.23

Vibrations of building’s top end

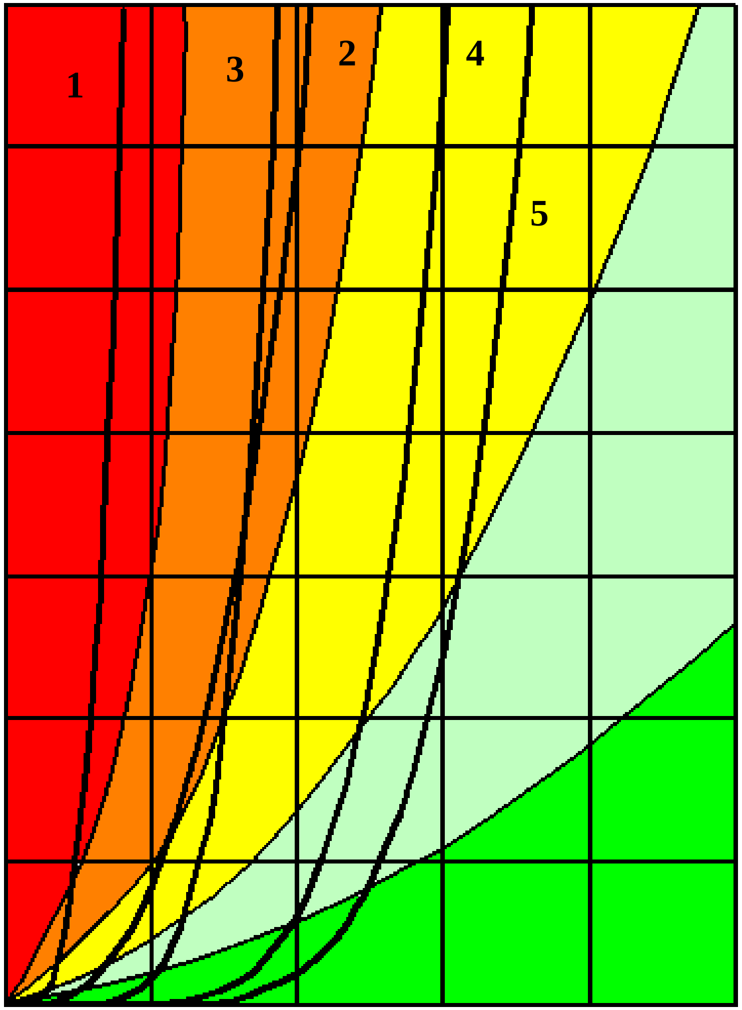


Photo: Author

1. Geiger (max 37 levels);
2. Cantilever (max 40 levels);
3. Tatara (max 45 levels);
4. Old standard (max 55 levels);
5. New standard (max 58 levels);

Average 47 levels

Conclusions

This type of structure can satisfy ULS and SLS for a limited numbef of levels only:

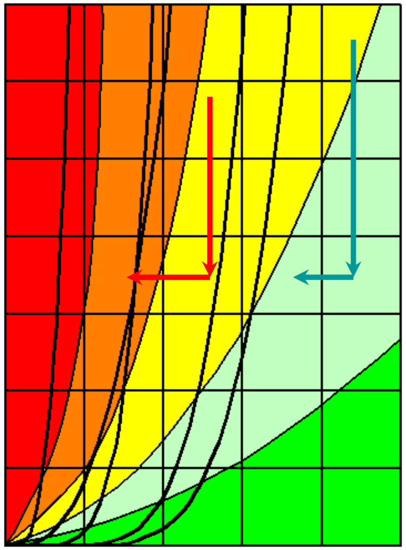
Condition	Max number of levels
Resistane for axial force in columns (S700)	89
Horizontal displacements of top	57
Vibrations under wind (approximation)	47

For bigger number of levels we must use other types of structure.

Dynamic calculations are the most complicated part of designing. There is good idea to increase stiffness of structure (more massive columns) for reduction horizontal displacements and increase resistance for axial force. But as the effect of stiffness change, period of oscillations change. Additionally, application of more massive columns increases stifness, but, the same, increases of mass. As the effect, we have change of dynamic characteristics ($T \approx \sqrt{(m / EJ)}$; $\Delta \approx 1 / EJ$) to the values which we can't predict by simple way (very nonlinear relations). Is possile, that relation $\Delta \leftrightarrow T$ could be worse than without application more massive columns.

Additionally, in case of seismic or paraseismic loads, we should rather decrease stiffness of structure.

Photo: Author



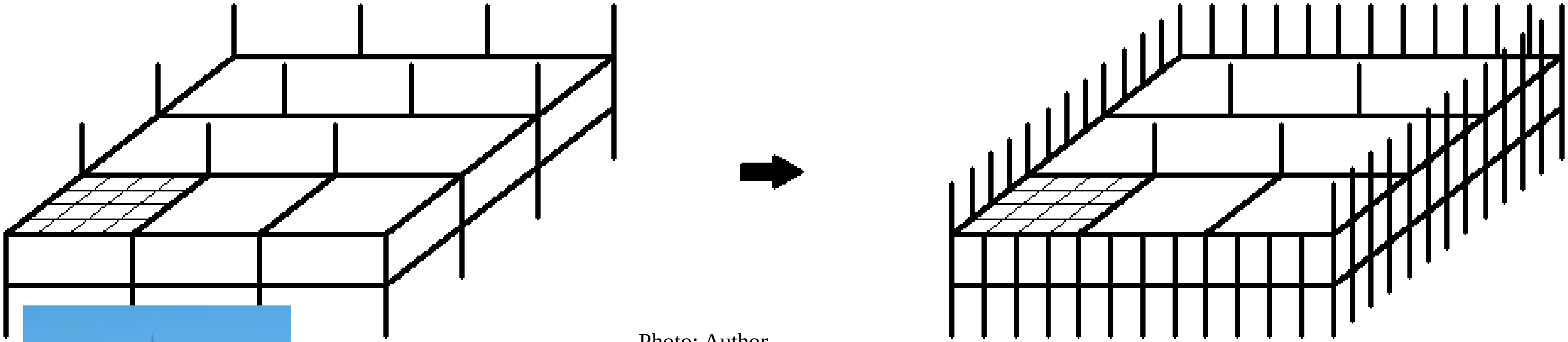


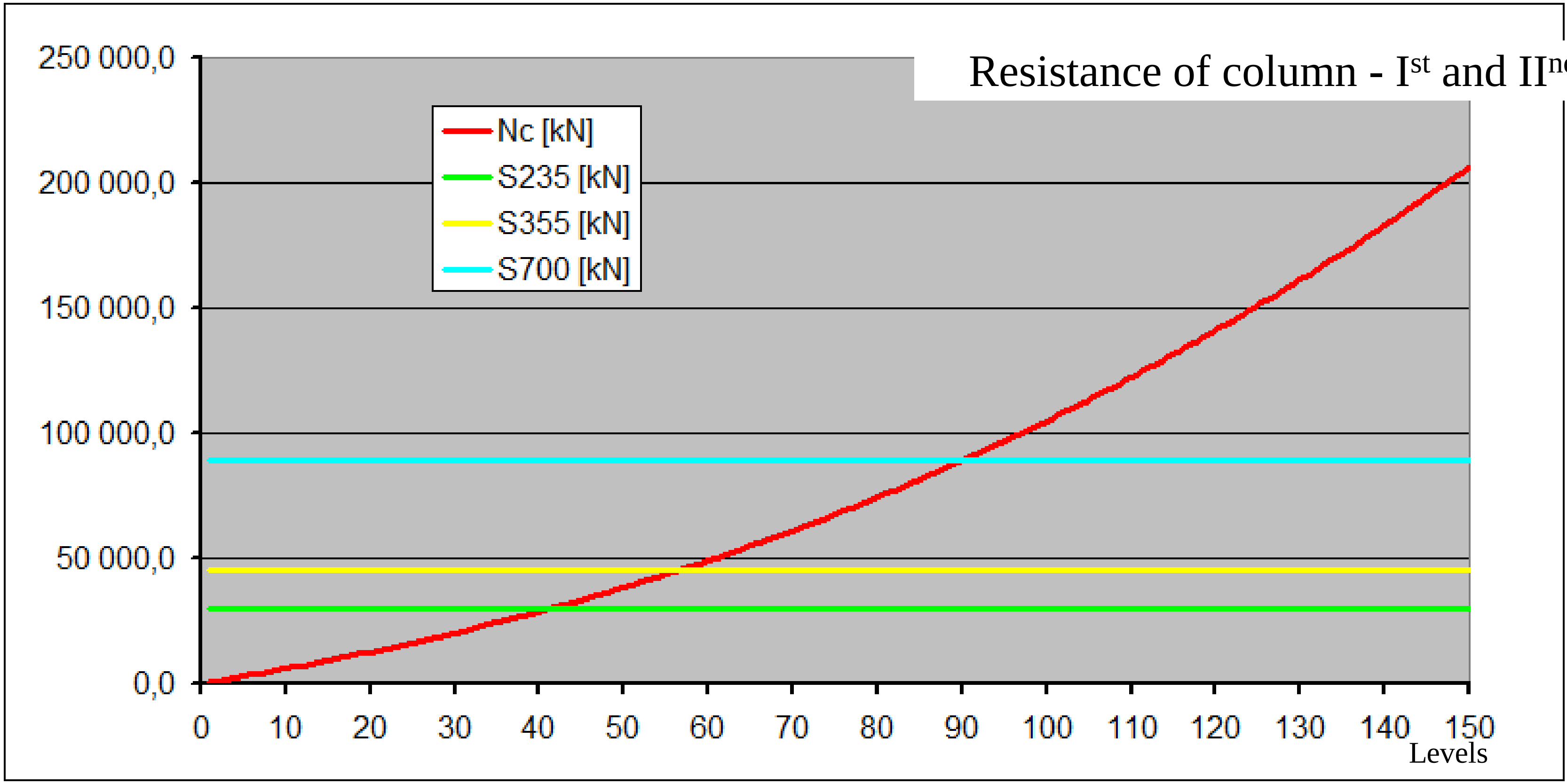
Photo: Author

Second model: columns on outline of building are every 2,5 m; in central part of building, as on previous example, every 10 m.

Structure similar to Empire State Building.

Photo: wikipedia

Resistance of column - Ist and IInd structure



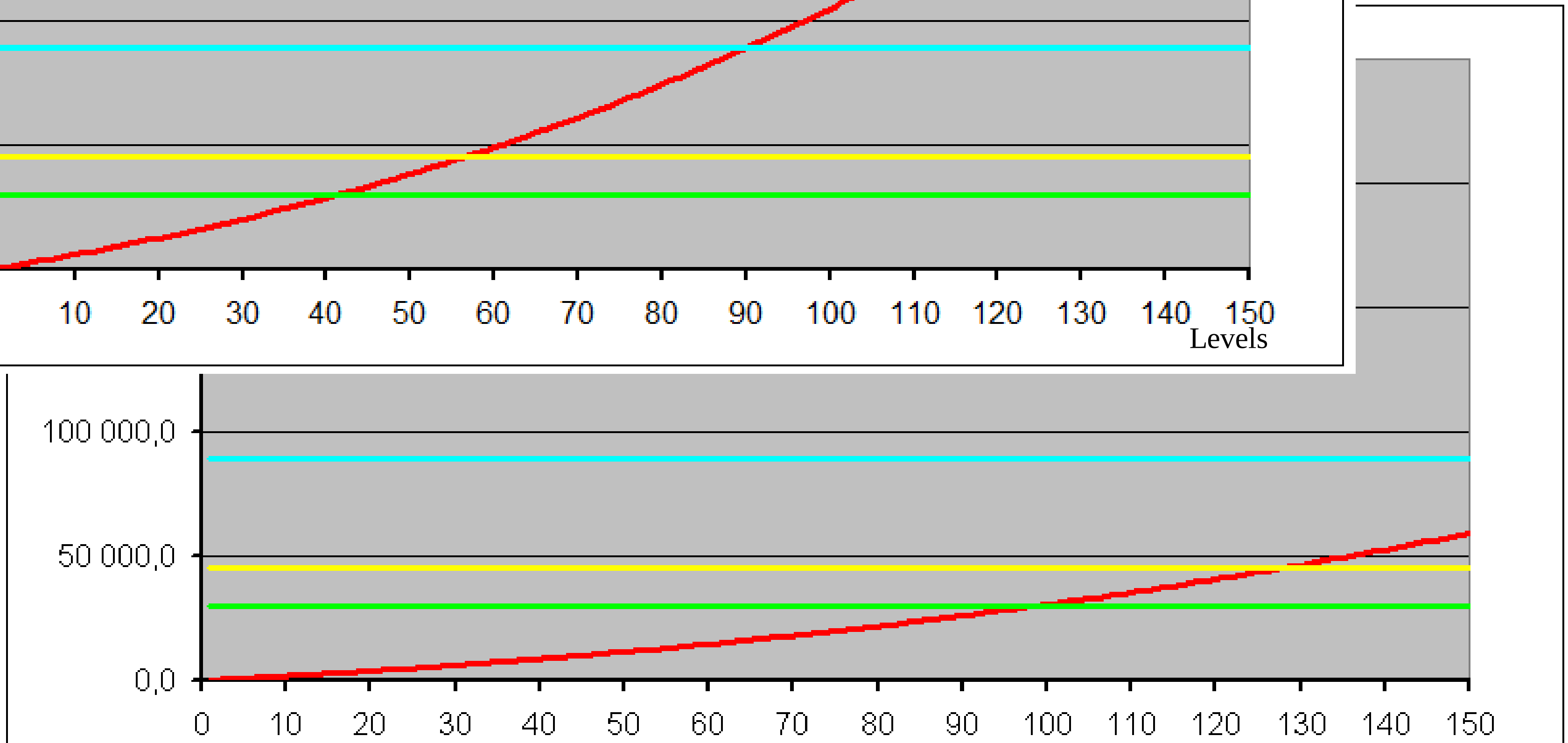


Photo: Author

Displacement of top - II[nd] and I[st] structure

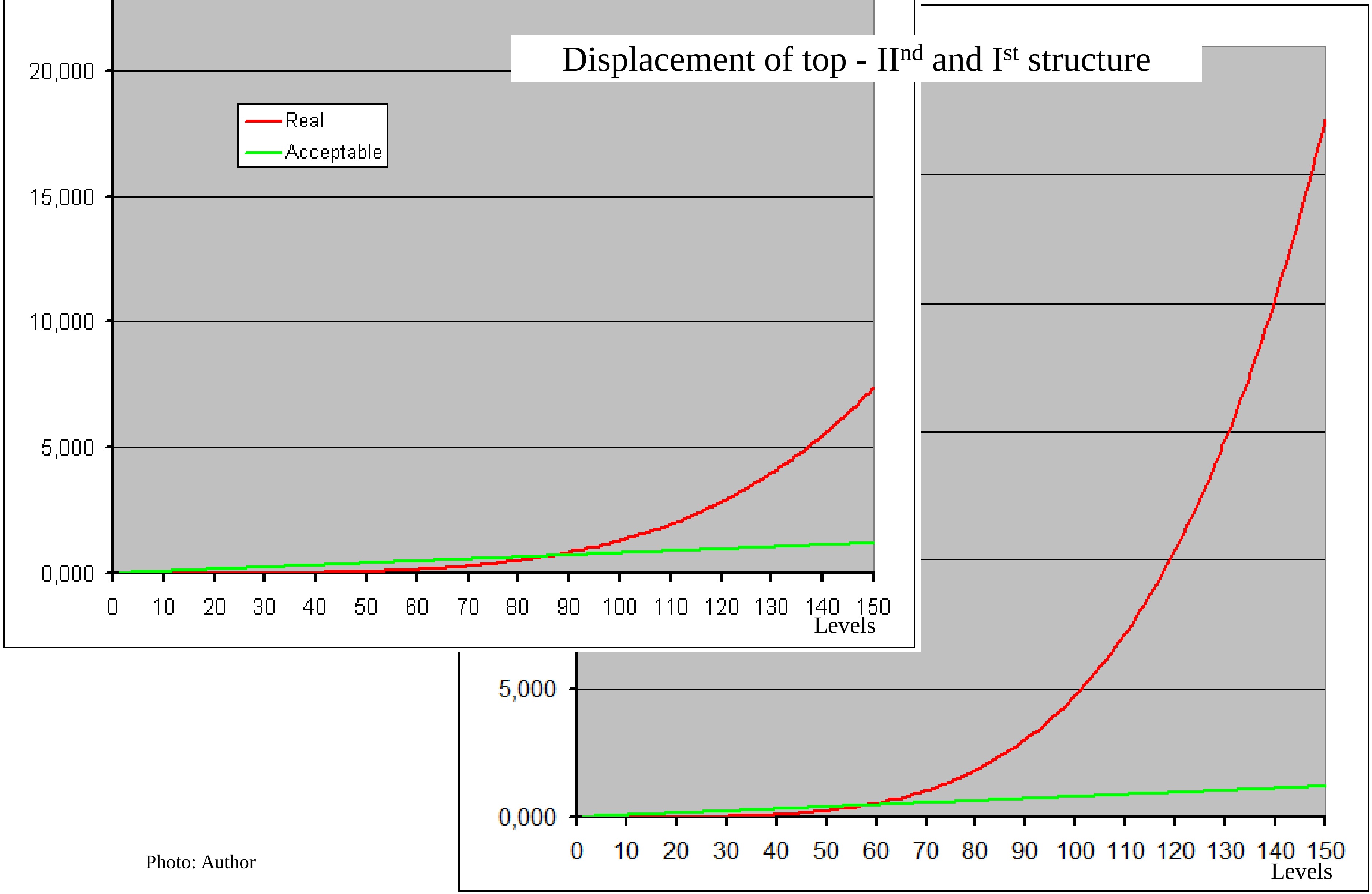


Photo: Author

Vibrations of building’s top end
- Ist and IInd structure

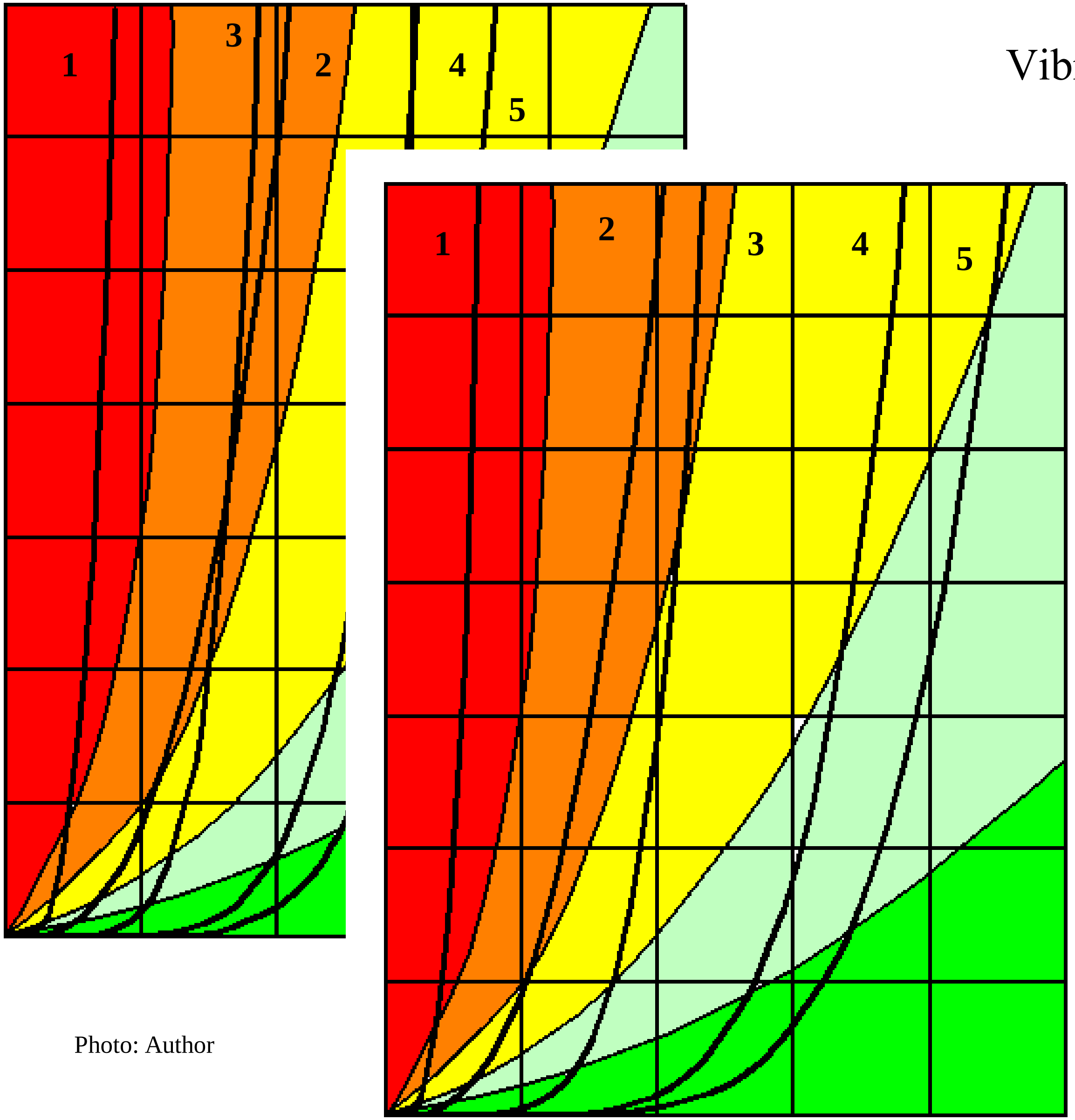


Photo: Author

1. Geiger (max 45 levels);
2. Cantilever (max 52 levels);
3. Tatara (max 71 levels);
4. Old standard (max 61 levels);
5. New standard (max 81 levels);

Average 62 levels

Condition	Max accepted number of levels	
	Ist model	IInd model
Resistane for axial force in columns (S700)	89	> 150
Horizontal displacements of top	57	86
Vibrations under wind (approximation)	47	62

Additional problem is torsional stiffness of buildings (aerodynamical torsional moment → #t / 42). Stiffness in the plane of floors is provided by reinforced concrete slabs or theirs support members. We need additional bracings against mutual rotation of neighboring storeys.

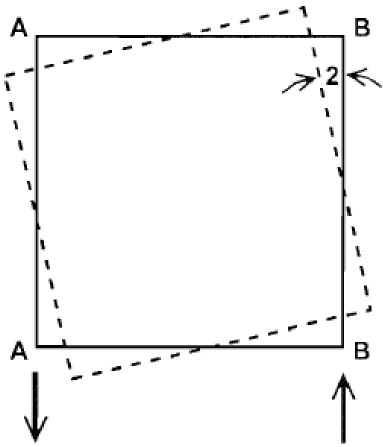


Photo: EN 1993-1-1 fig 5.5

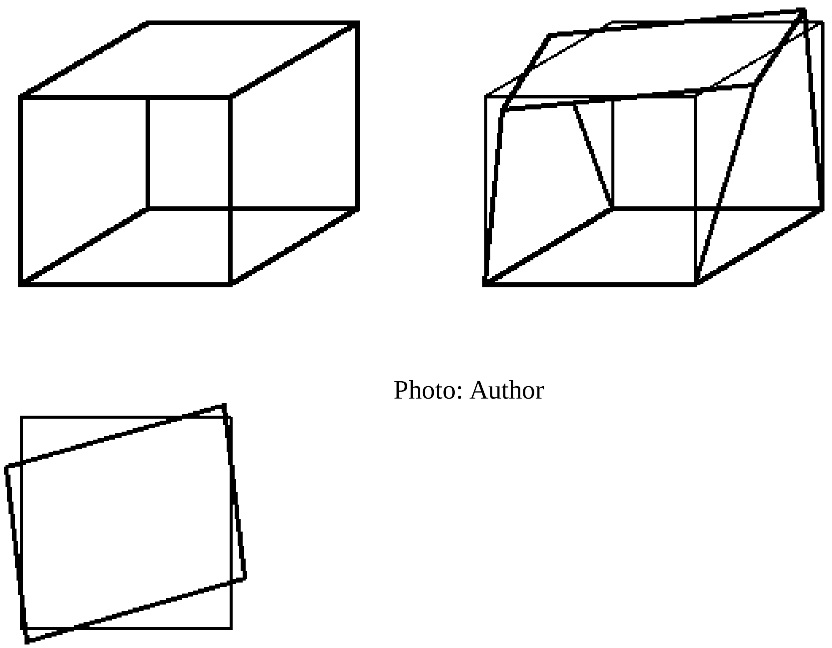


Photo: Author

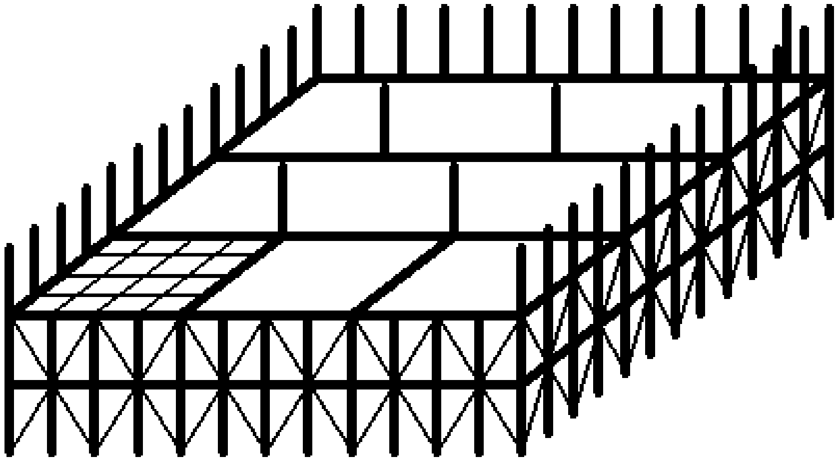


Photo: Author

Third model: massive bracings on elevation. Increasing of stiffeness, prevention from torsional deformations.

Structure similar to John Hancock Center.

Photo: wikipedia

Structure

Structure of high building can be conventionally divided into two parts:

gravitational system - transfers vertical loads (dead weight, live loads, snow...);

horizontal system – transverse horizontal forces, forces from torsional moments and from bending moments;

Gravitational system = columns

Horizontal system = many different ways

Generally, there are two main horizontal systems:

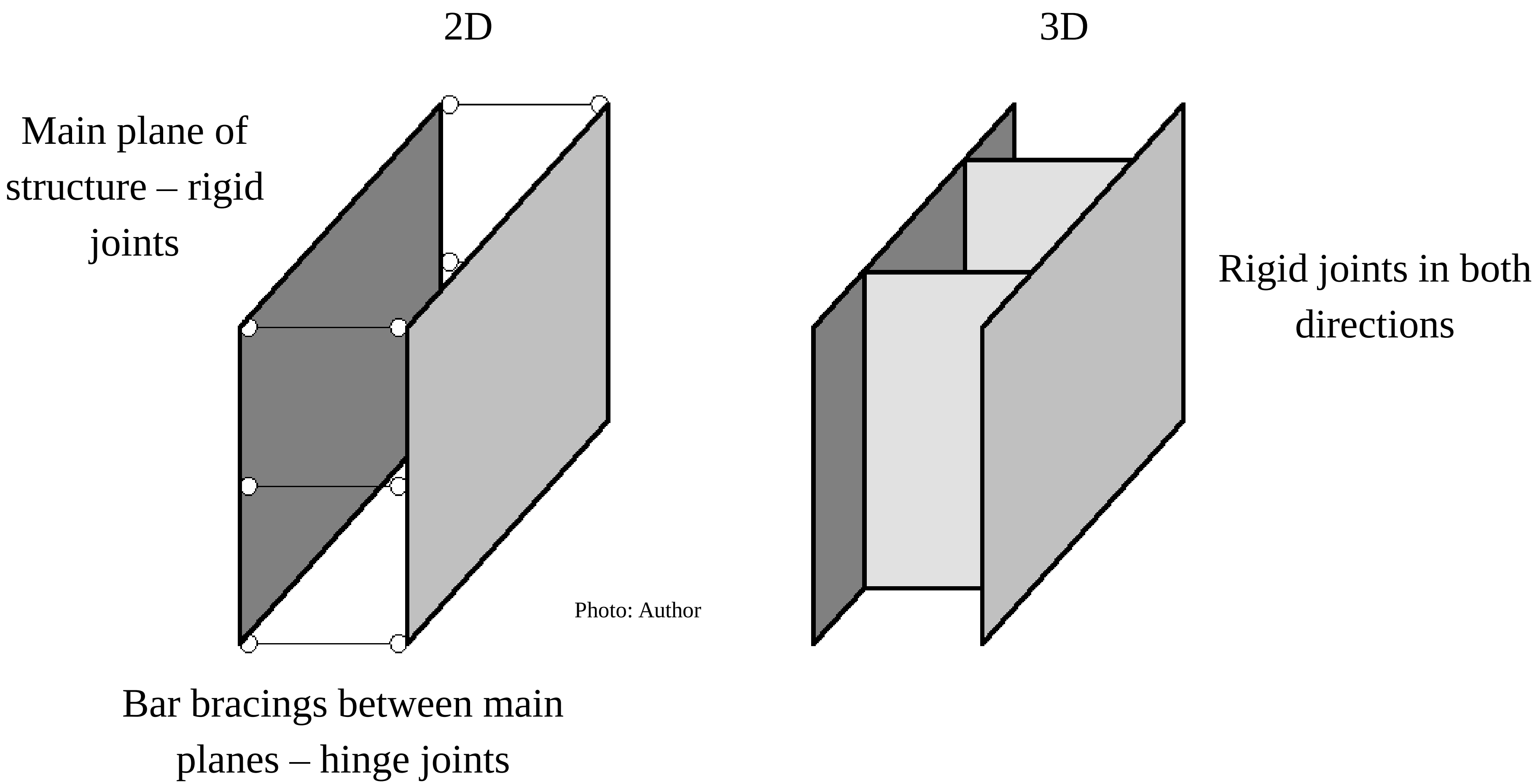
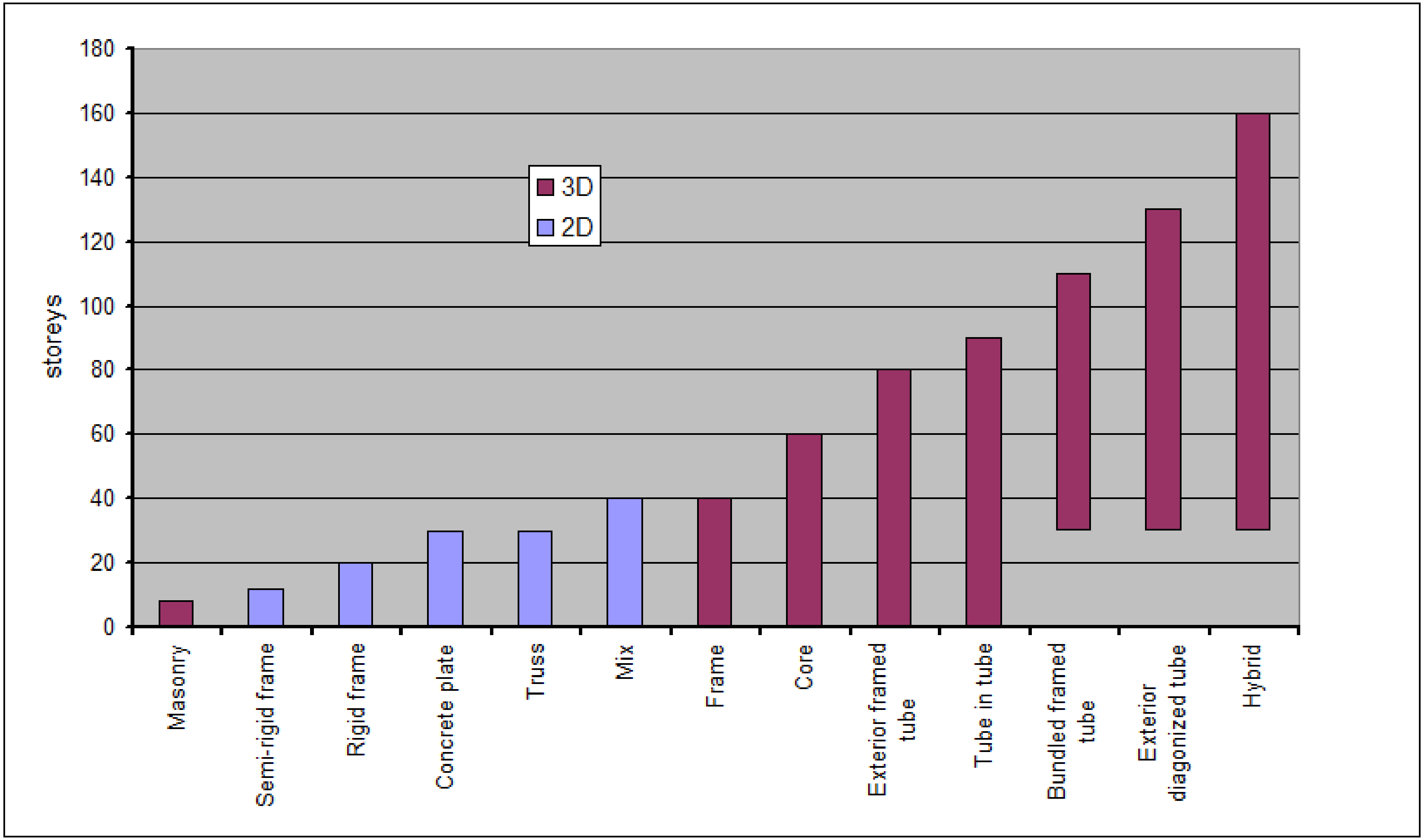


Photo: Author

Photo: Author



Different ways to ensure adequate stiffness of buildings.

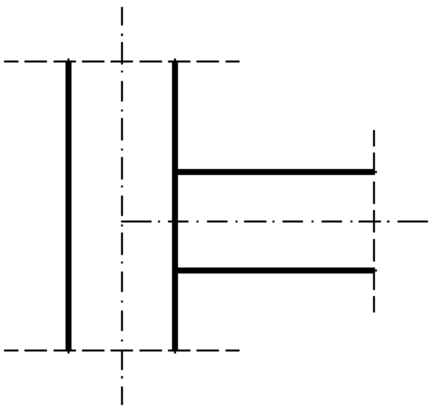
Masonry walls

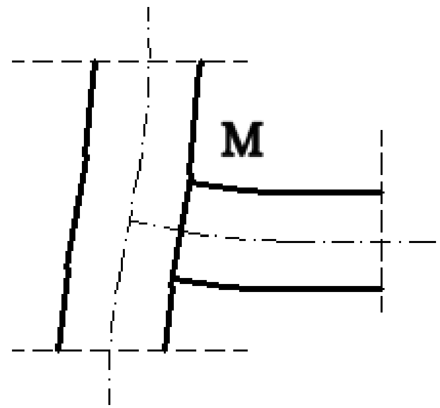
The oldest type of structure in high building. Masonry walls intersect each other in perpendicular direction; it can be treated as 3D system.

Philadelphia City Hall, the tallest masonry building in the world, 167 m.
Maximum thickness of wall: 6,7 m.

Photo: wikipedia

2D Semi-rigid frame





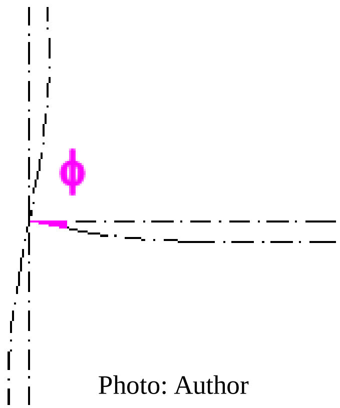
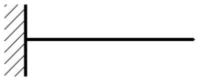
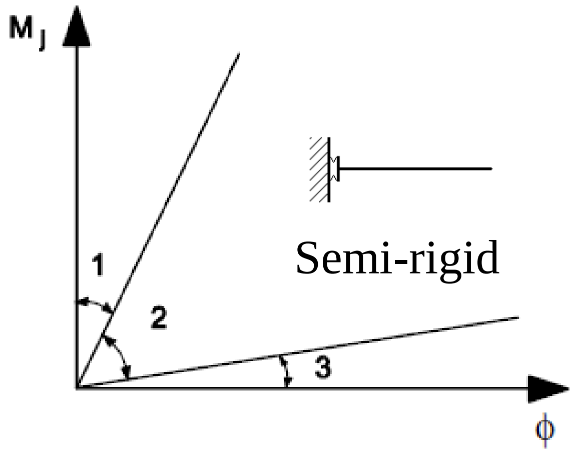


Photo: Author

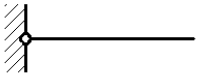


Rigid



Semi-rigid

Pinned



Main plane of structure = plane of frame

Photo: EN 1993-1-8 fig 5.4

2D Rigid frame

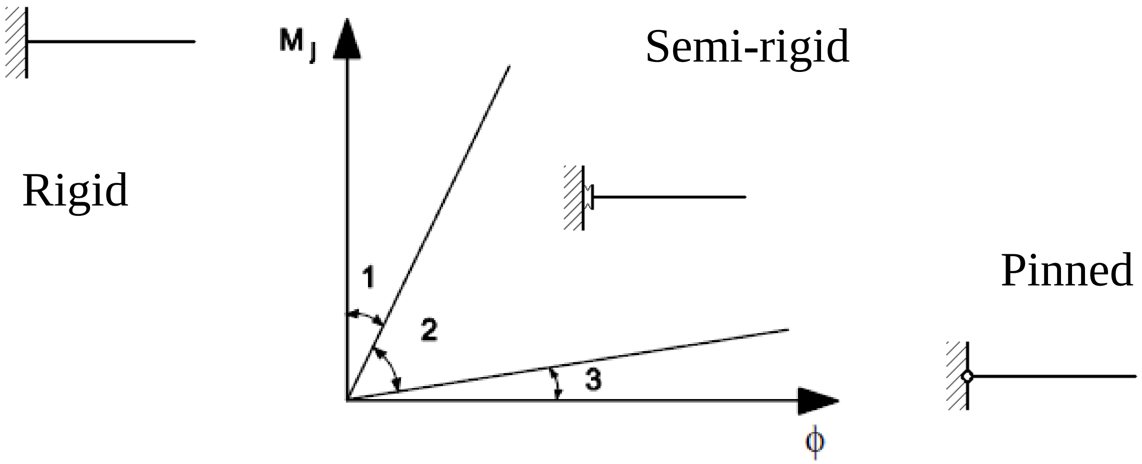


Photo: Author

Main plane of structure =
plane of frame

2D Concrete plate

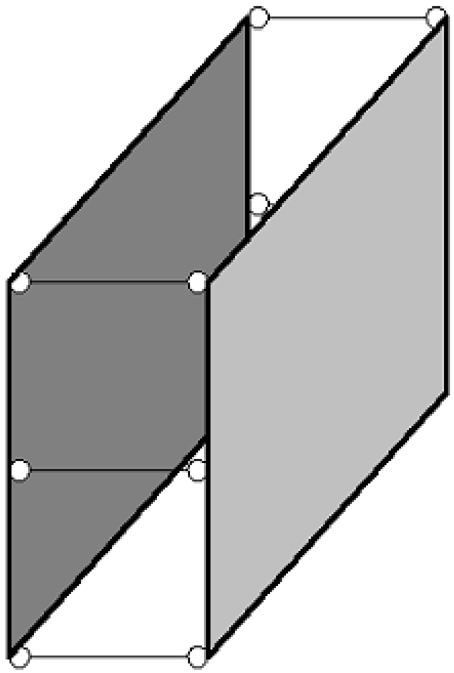
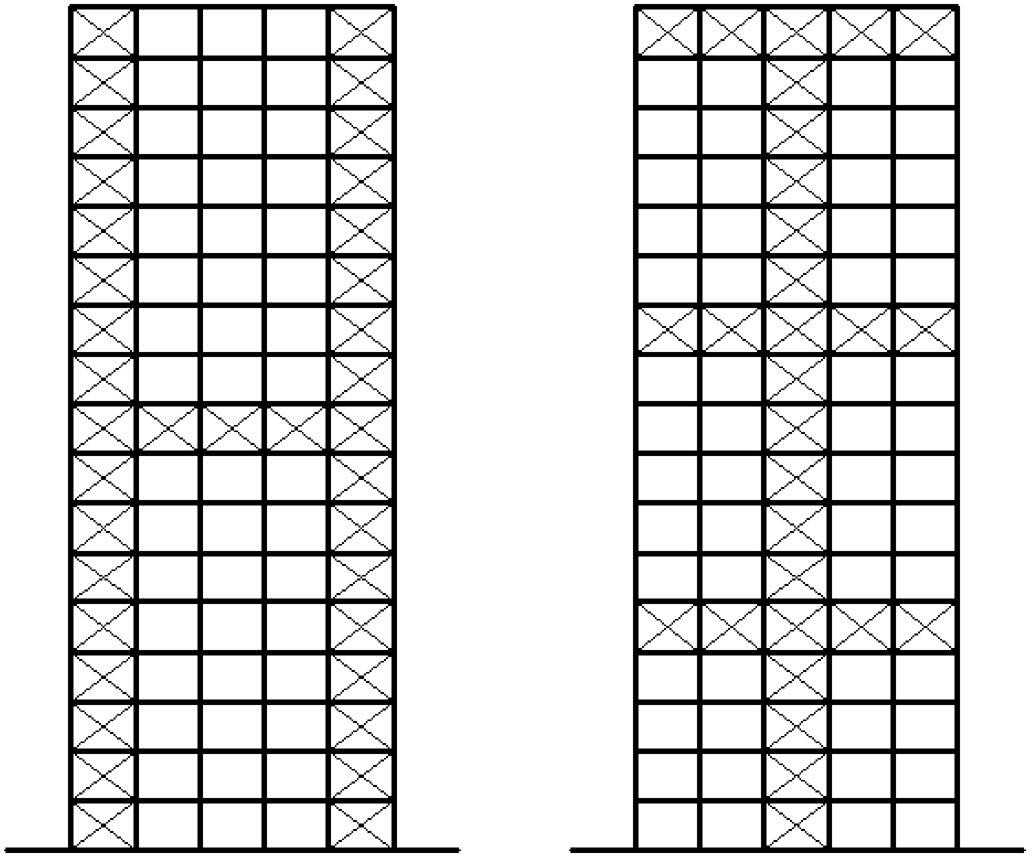


Photo: Author

Main plane of structure =
concrete plat

2D Truss = frame with bracings in-plane



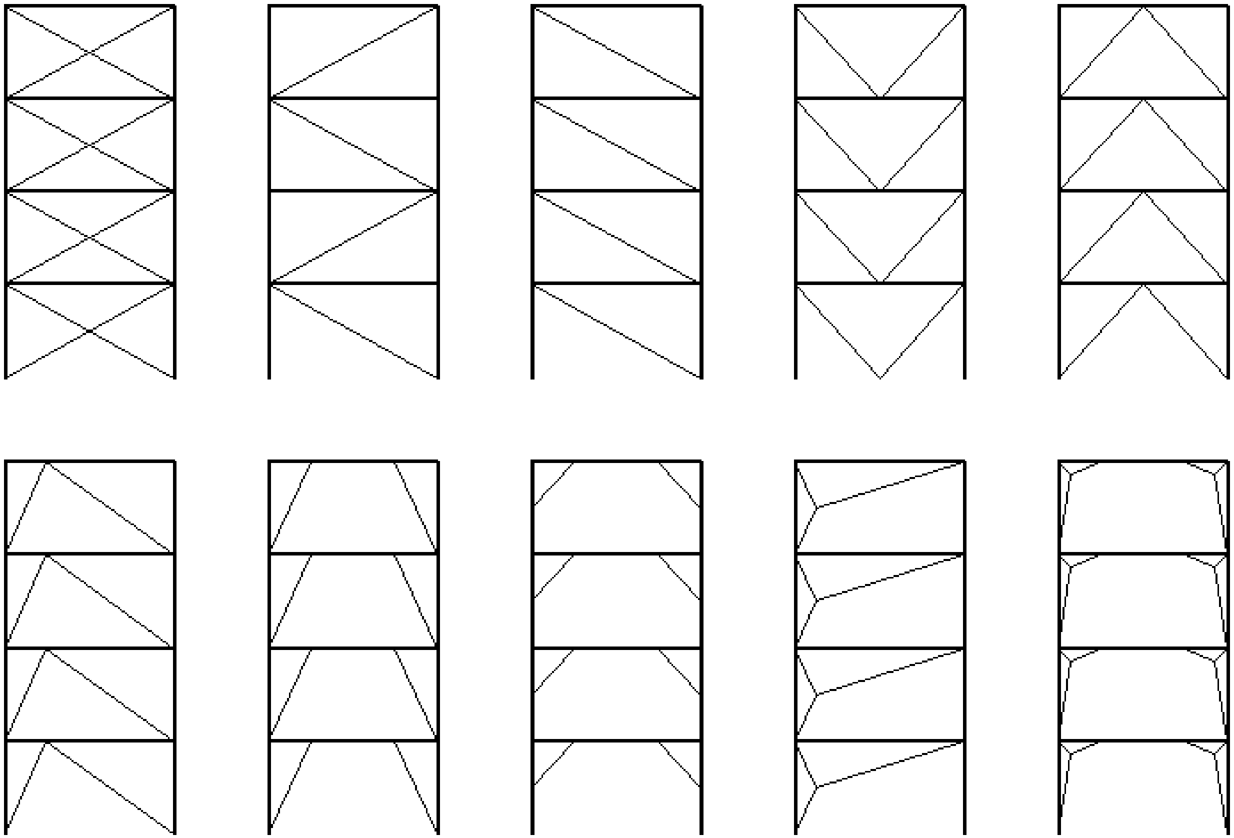
Main plane of structure = plane of braced frame

Photo: Author

2D Mix

Combination of different methods (concrete plate + truss, concrete plate + rigid frame)

Additionally, there need bracings between main planes of structure. These bracings should not cause troubles with internal communication.



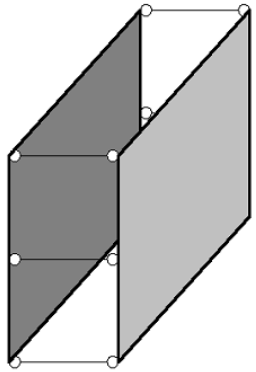


Photo: Author

Bracings **between** main planes of structure can't be confused with trusses **in** main plane.

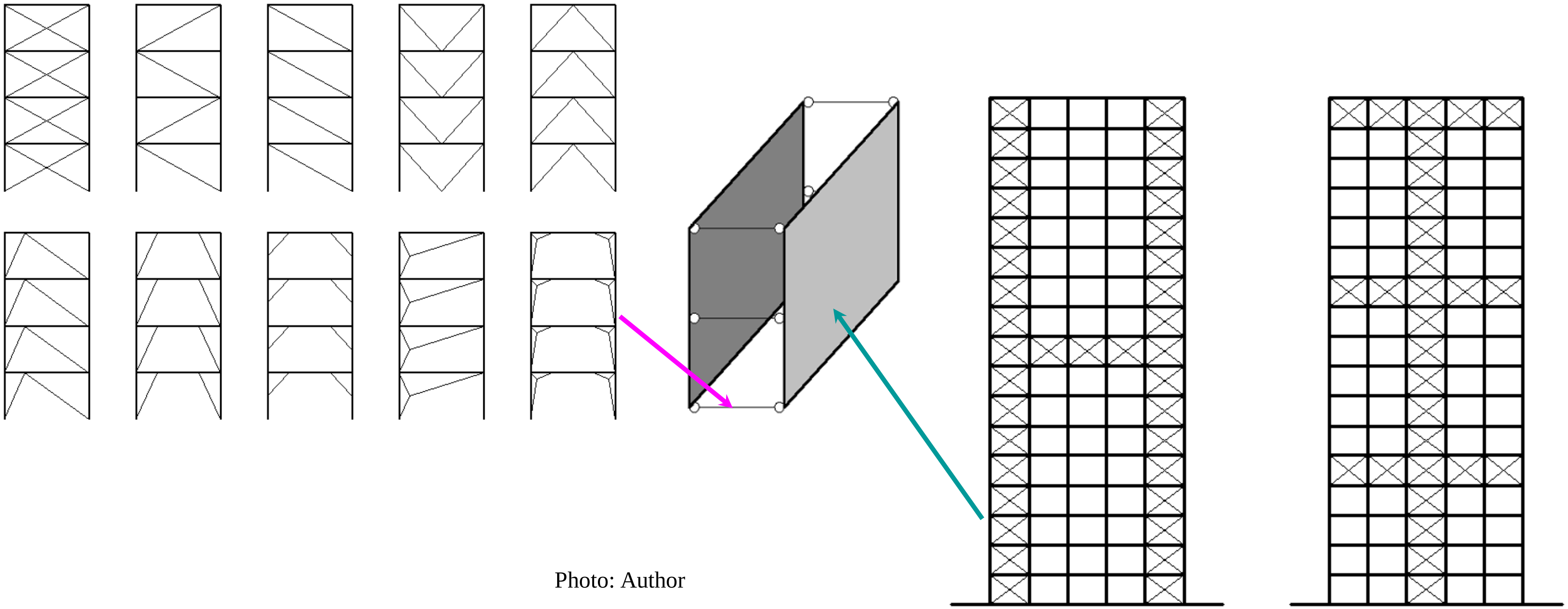


Photo: Author

It's good idea to put each bracings in position that would not require communication: around external walls, around internal walls of elevator shafts, staircases and toilets.

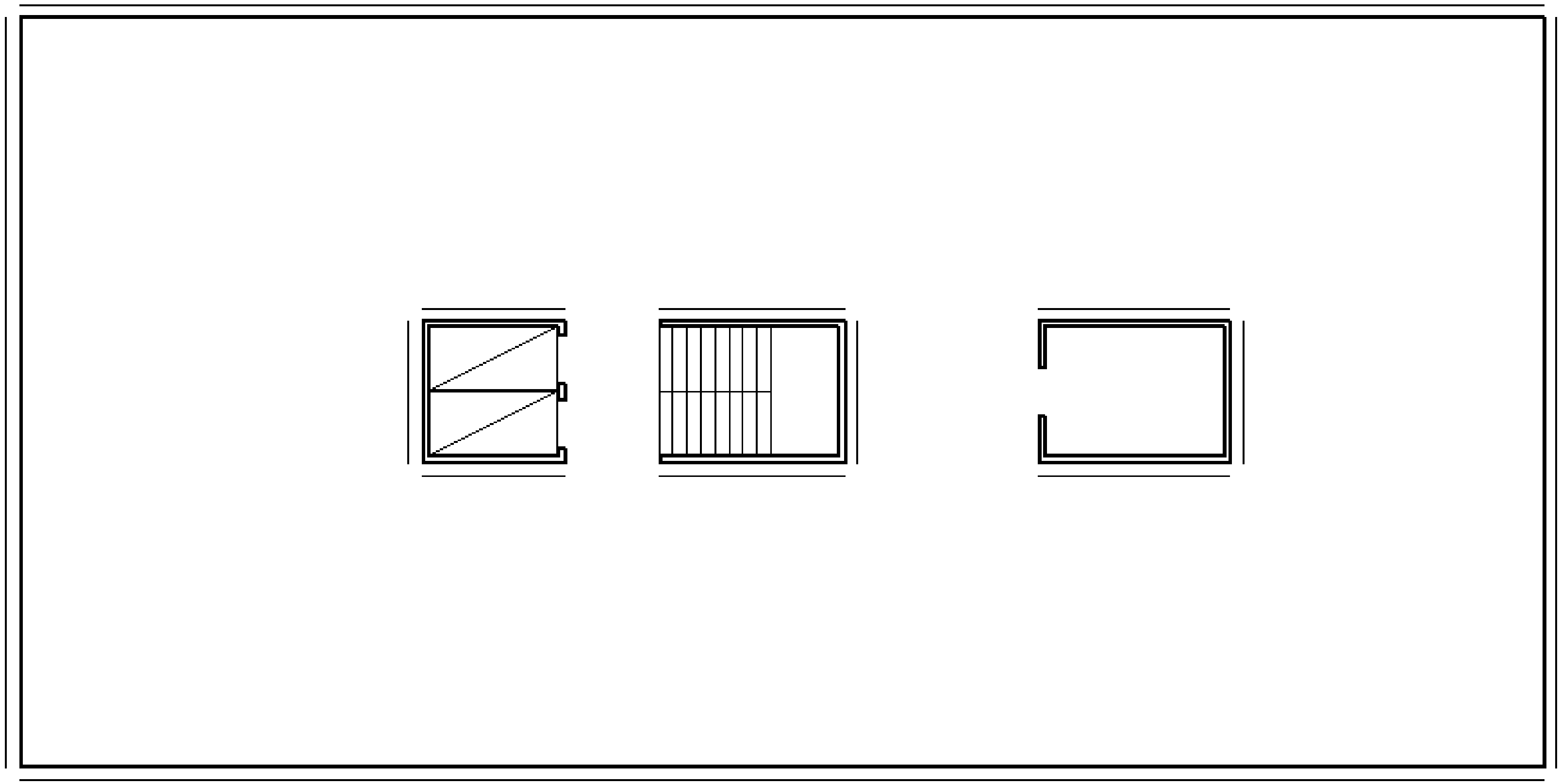


Photo: Author

Bracings in high buildings are exposed to parasitic stresses from big values of axial forces in columns and shortening of columns. They should work only on the lateral forces, theoretically.

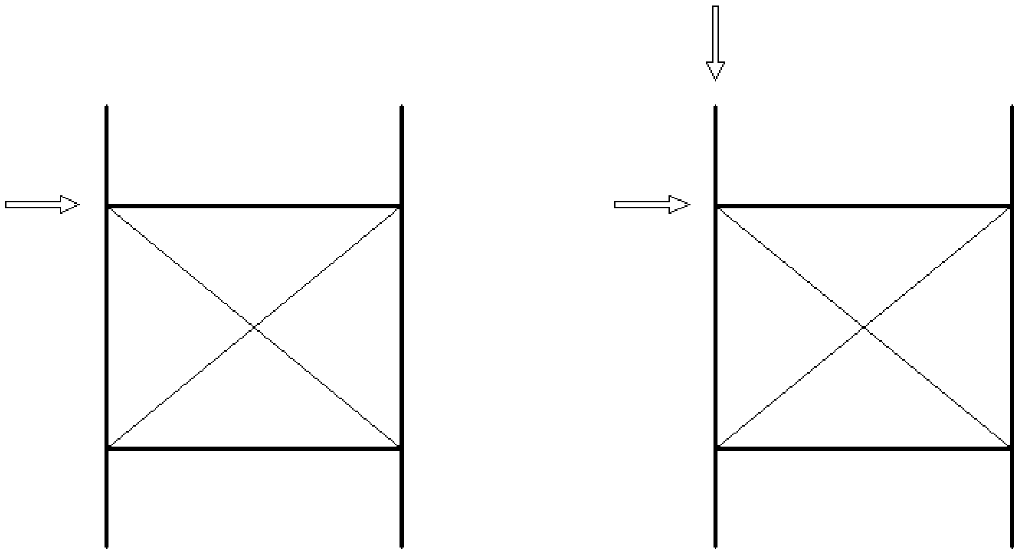
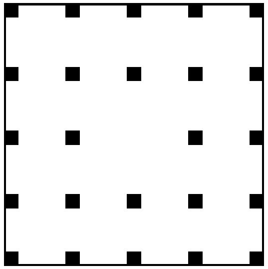
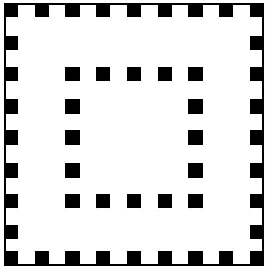


Photo: Author



1

3D



5

1. Frame (→ Ist model, #t / 53)

2. Core

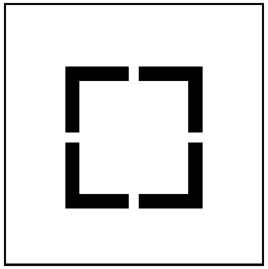
3. Framed interion tube

4. Framed exterior tube (→ IInd model, #t / 62)

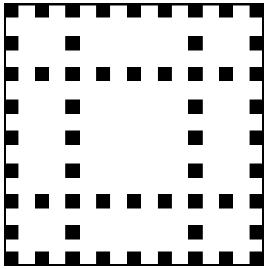
5. Tube in tube

6. Bundled framed tube

7. Hybrid



2



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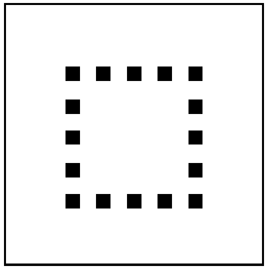

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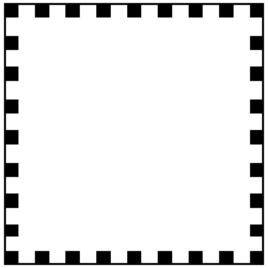

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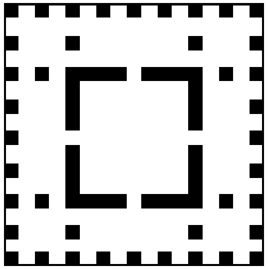


7

Photo: Author

3D frame means, that girders are connected with columns in both direction by rigid joints. Two technical solution are applicated.

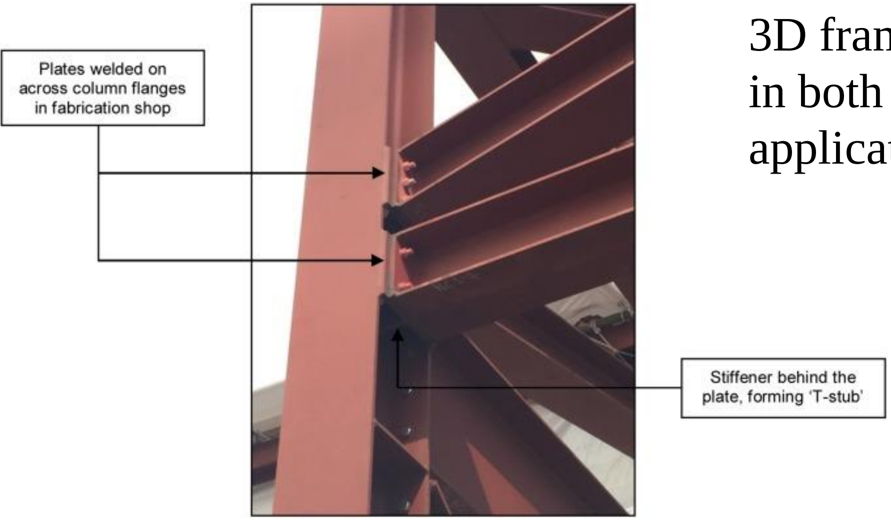


Photo: Current UK trends in the use of simple and/or semi-rigid steel connections, M. Kidd, R. Judge, S.W. Jones, Case Studies in Structural Engineering 6 / 2016

Photo: prefabmarket.com

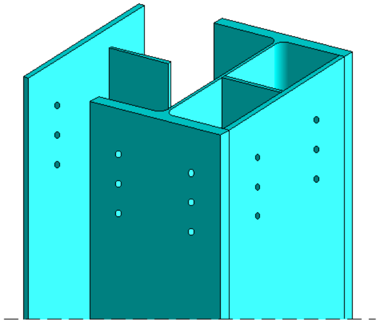


Photo: Autor

Photo: resources.scia.net

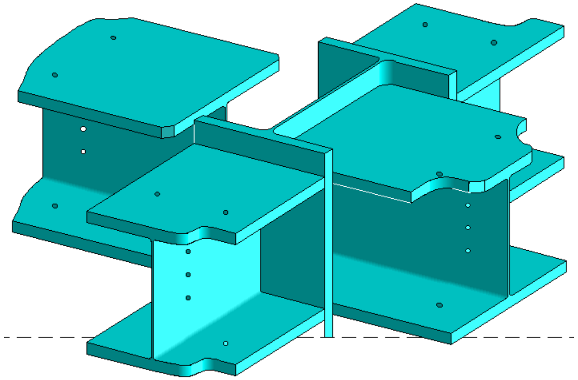


Photo: Autor

Top fifteen existed:

Burj Khalifa	Hybrid
Shanghai Tower	Hybrid
Abraj Al Bait	Hybrid
Ping An International Finance	Hybrid
Lotte World Premium Tower	Hybrid
One World Trade Center	Hybrid
CTF Finacial Centre	Hybrid
Willis Tower	Bundled tube
Taipei 101	Hybrid
World Finansial Centre	Hybrid
International Commerce Centre	Hybrid
Tianjin R&F Guangdong Tower	Hybrid
John Hancock Centre	Diagonized tube
Petronas Tower 1	Tube in tube
Petronas Tower 2	Tube in tube

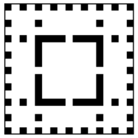
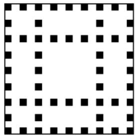
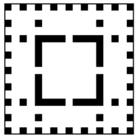
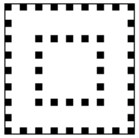


Photo: Author







Construction materials

Steel
Concrete

Steel building – main vertical and lateral structural elements (and floor systems) are constructed from steel (until recently, the most popular system).

Concrete building – main vertical and lateral structural elements (and floor systems) are constructed from concrete (at now, the most popular system).

Composite building – combination of both steel and concrete acting compositely in main structural elements.

Mixed-structure building – steel and concrete part of building above or below each other, no compositely acting (the most unpopular system).

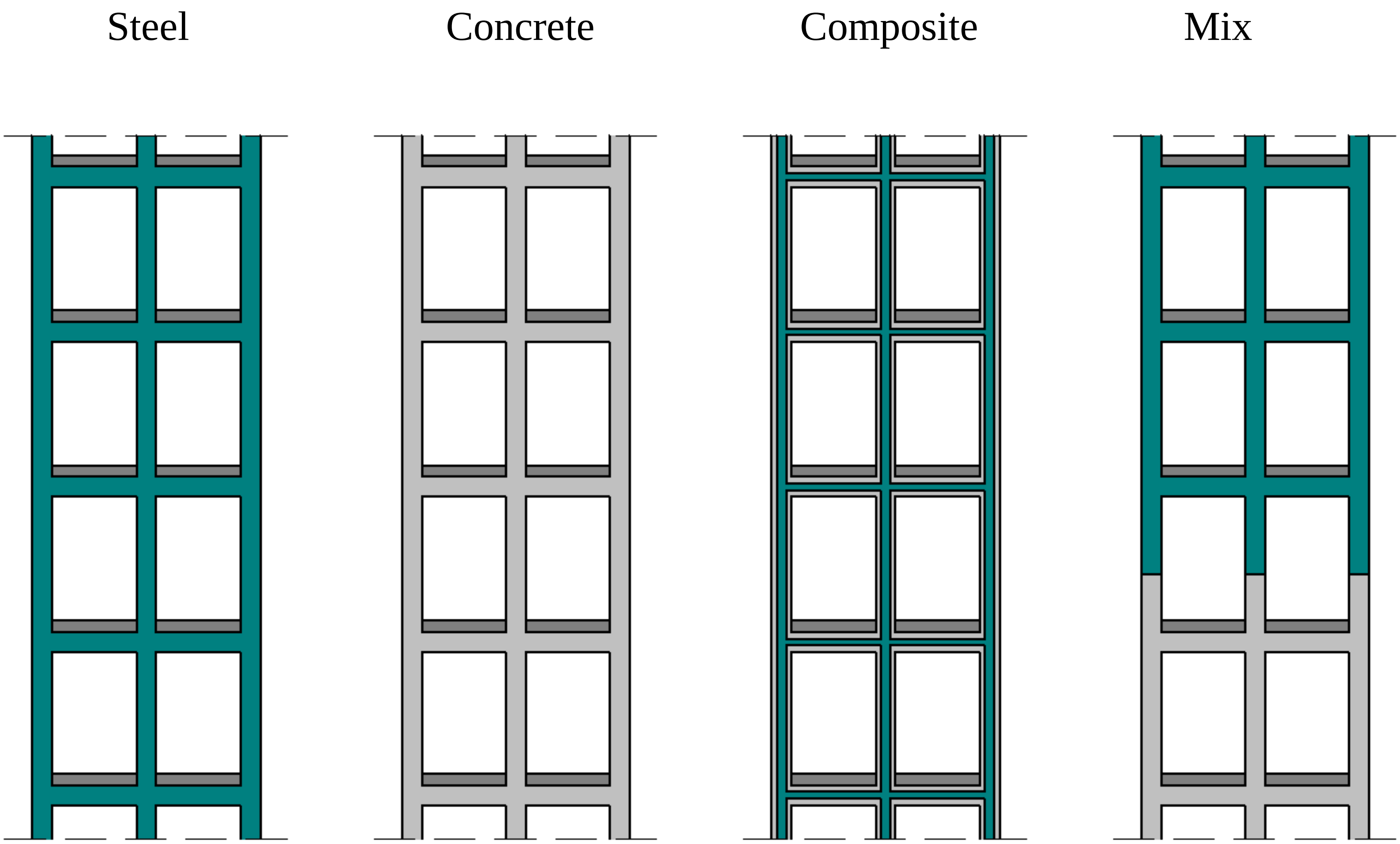


Photo: Author

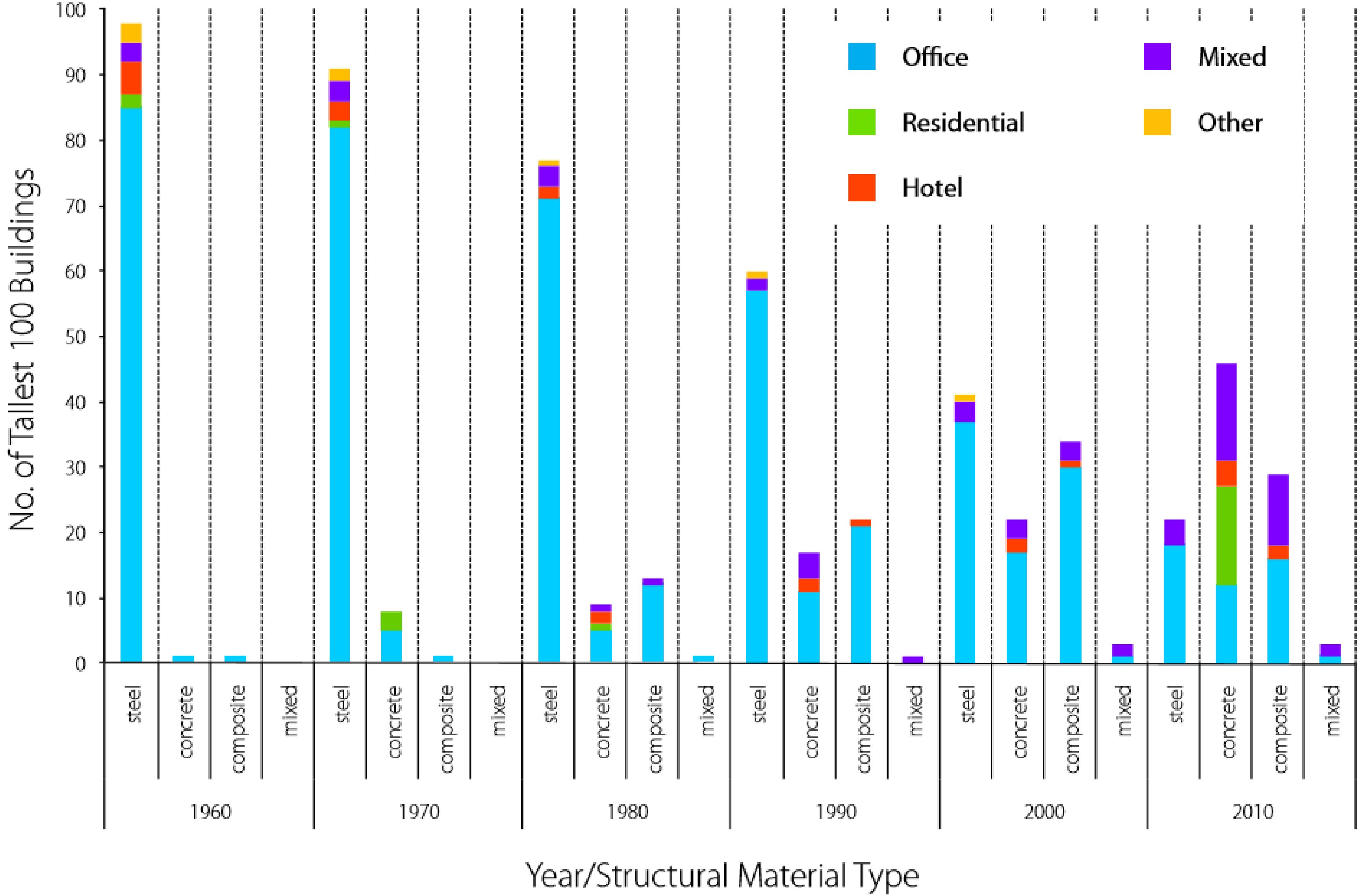


Photo: ctbuh.org

Top fifteen existed:

Burj Khalifa	Mix
Shanghai Tower	Composite
Abraj Al Bait	Mix
Ping An International Finance	Composite
Lotte World Premium Tower	Composite
One World Trade Center	Composite
CTF Finacial Centre	Composite
Willis Tower	Steel
Taipei 101	Composite
World Finansial Centre	Composite
International Commerce Centre	Composite
Tianjin R&F Guangdong Tower	Composite
John Hancock Centre	Steel
Petronas Tower 1	Concrete
Petronas Tower 2	Concrete

Requirements for joints and members

There is presented, based on experience, few additional requirements for columns and theirs connections in high buildings.

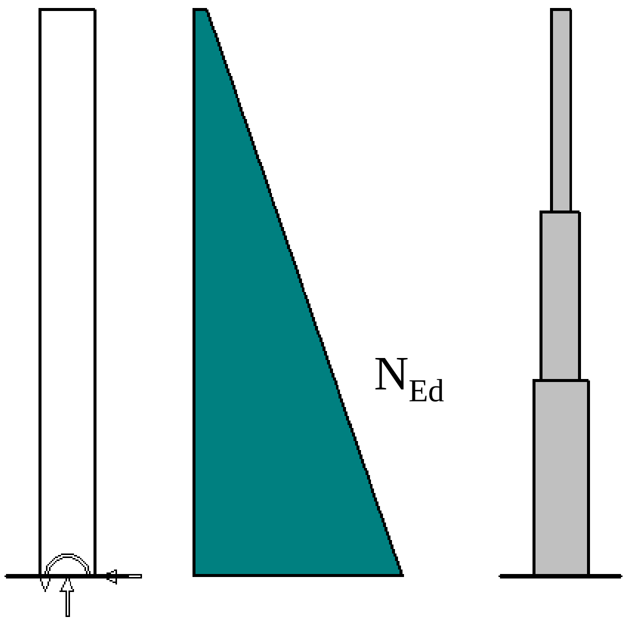


Photo: Author

Axial force rapidly increase along columns. There is good idea to change cross-section of column. Length of transport member can’t be longer than 12 m (tansport limits).

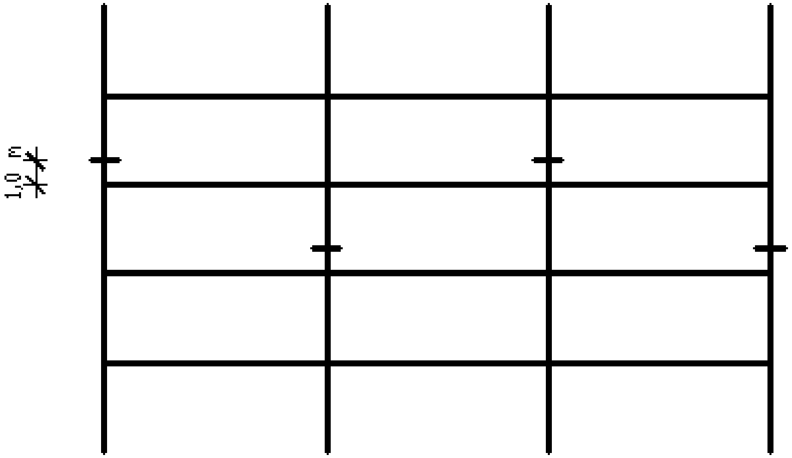


Photo: Author

Joints in columns should be placed about 1,0 m over level of floor-board. Joints in adjacent columns should be placed in different storeys.

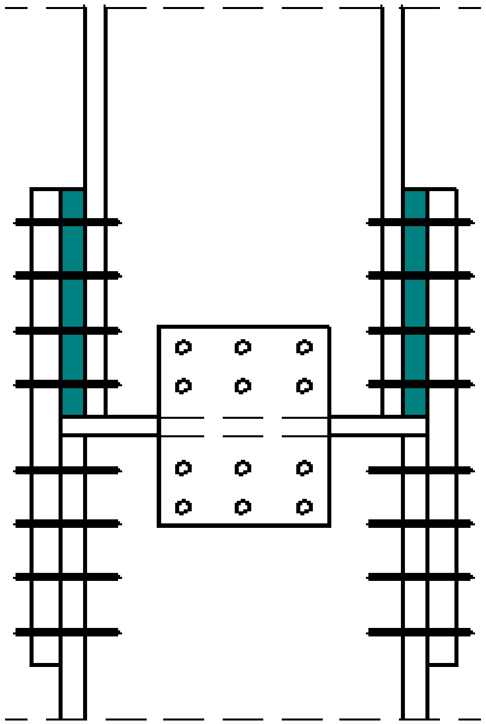


Photo: Author

In case of not very big difference (to 30 mm) between deep two different part of column, joint can be made as classical shear joint with packing plate.

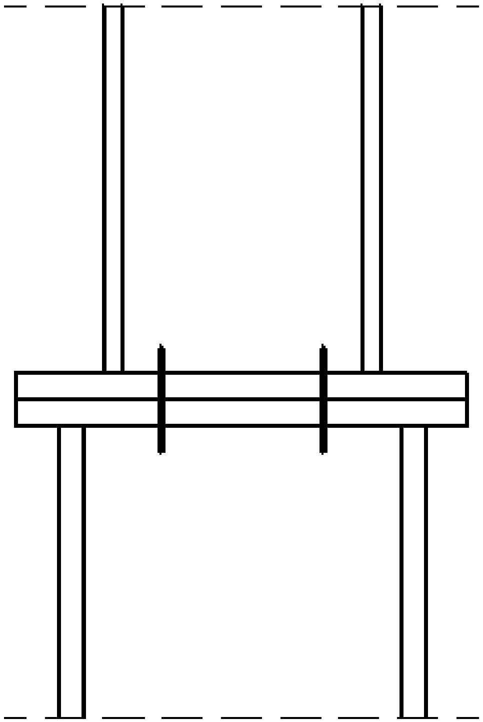


Photo: Author

For bigger difference it should be rather tension joint.

Photo: hoverdale.com

Both surfaces must be grinded smoothly to ensure full contact in compressed part of joint.

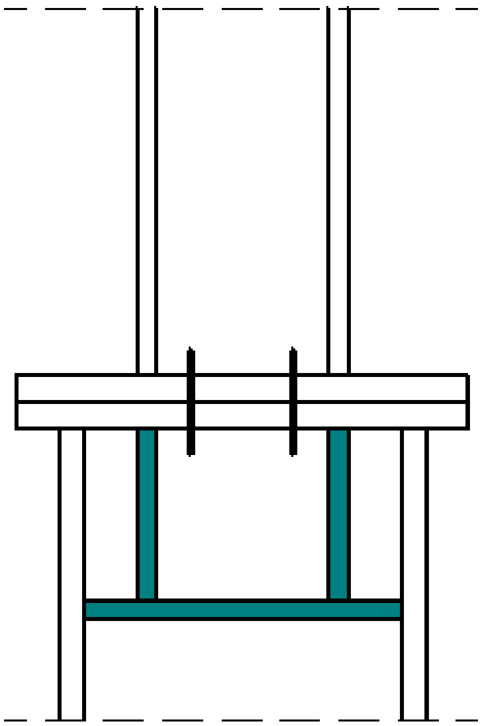


Photo: Author

For very big difference, there are needed additional plates to make web of lower part more stiff.

Way of calculations depends on shape of stresses in joint.

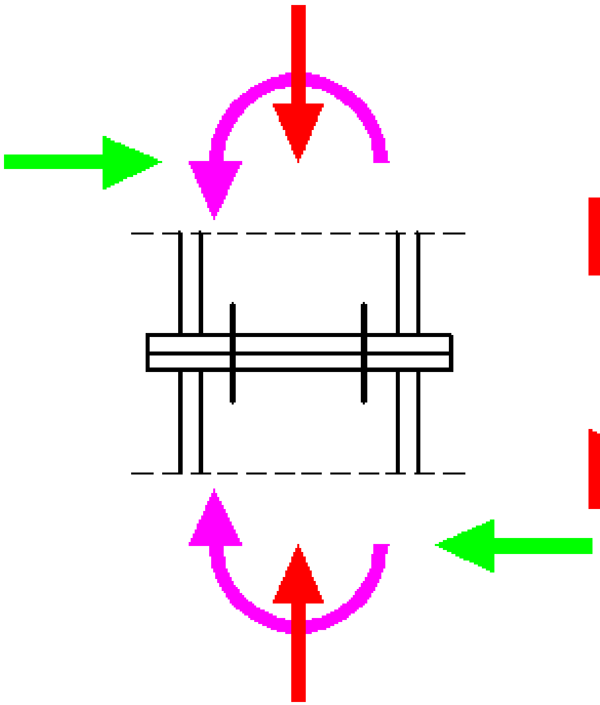
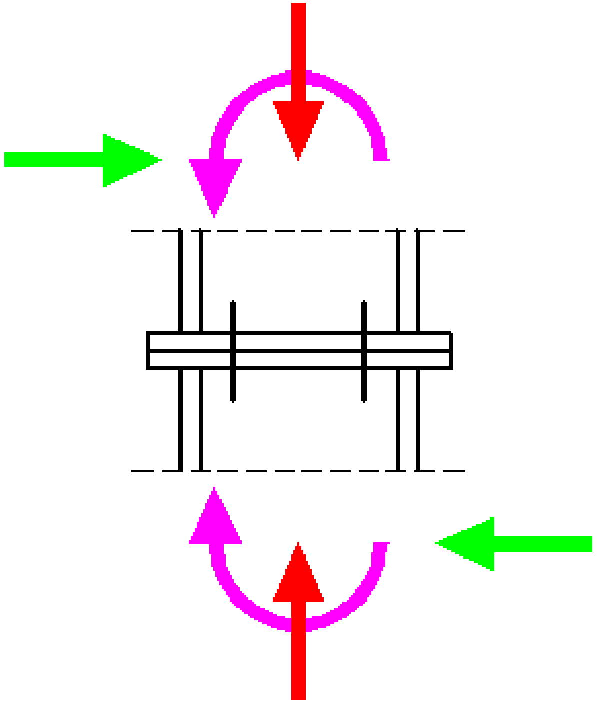


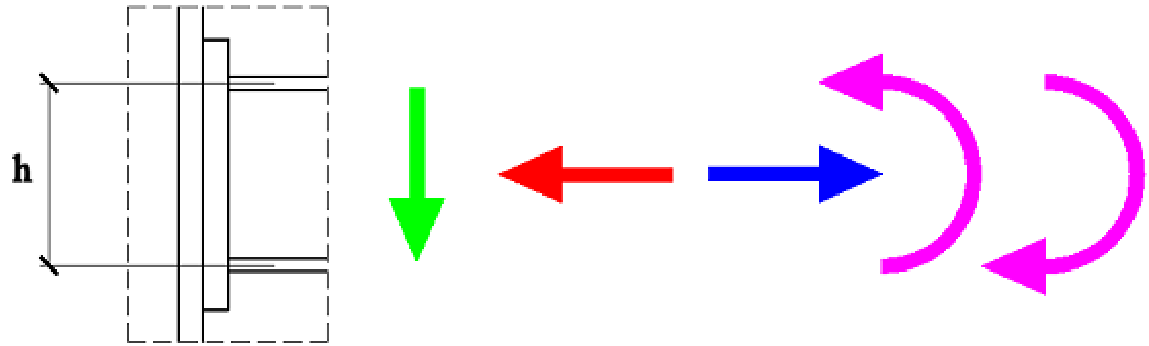
Photo: Author

Relatively small bending moment to compressive axial force → compression only → bolts calculated only for shear force.

Relatively big bending moment to compressive axial force → compression and tension → classical tension joint → bolts calculated for tensile force and shear force.

Cross-sectional forces are applied to joint of column in the same manner as to beam in classical tension joint: stresses from axial force and bending moment are paralell to axis of member.

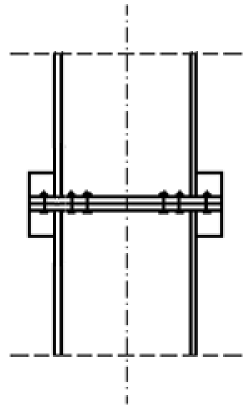


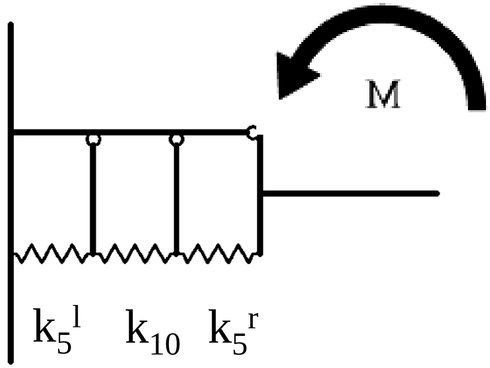


Because of this, during calculation of column joint, formulas for beam in classical tension joint must be applied.

Photo: Author

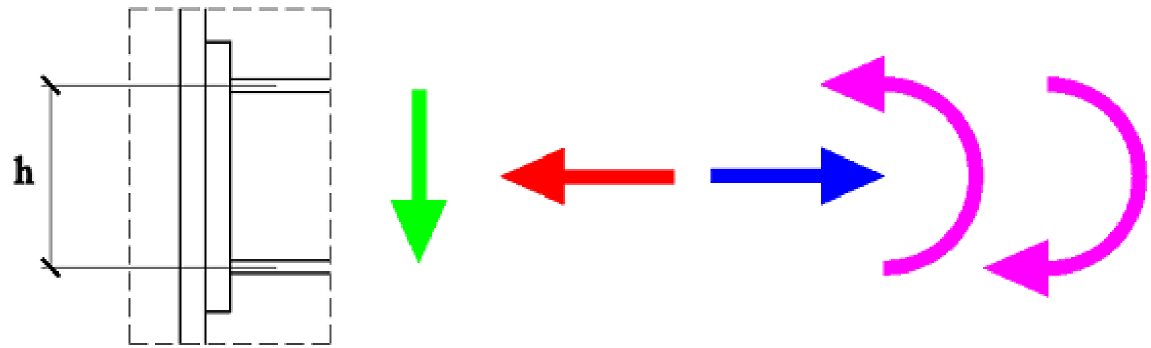
Photo: Author





Stiffness of joint should be analised:

- top end plate under bending;
- shank of bolt;
- bottom end plate under bending;



Resistance of joint should be analised:

- compressive flange as for flange of beam;
- tensile part of web as for web of beam;
- local bending for end plate;

Examination issues

Real dumping and its idealisation

Way of calculation in case of dynamic excitation

Wind excitation and para- / seismic excitation, similiarities and differences

Horizontal systems in high buildings

Angular frequency - częstość kołowa
Frequency - czestotliwość
Period - okres
Damping factor - współczynnik tłumienia
Damping ratio - ułamek tłumienia krytycznego
Damping coefficient - współczynnik proporcjonalności
Logaritmic dekrement of damping - logarytmiczny dekrement tłumienia drgań
Eigenvalue – wartość własna
Spectral analysis - analiza spektralna (widmowa)
Core - trzon
Framed tube - konstrukcja ramowo-powłokowa
Tube in tube - pęk ramowo-powłokowy
Diagonized tube - konstrukcja ramowo-powłokowa ze stężeniami

Thank you for attention

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