Metal Structures I

Lecture XXII

Steel halls & skeletons

Contents

Types of halls

Steel hall: repetitive arrangement of flat steel frames of rigid joints, interrelated by roof bracings and walls bracings by hinge joints.

Photo: traskostal.pl

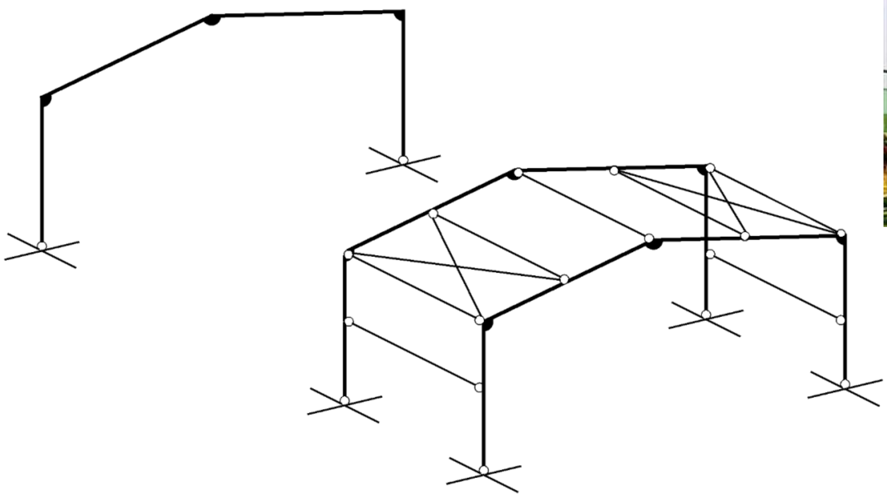


Photo: Author

Photo: weldon.pl

Halls: industrial, warehouse, trade, cooler, garage, hangar, office, agricultural, sport, exhibition…

Photo: steel.com.au

Photo: easyhalls.com

Photo: ekbud.lublin.pl

Photo: pebsteel.com

Photo: toiowo.eu

Photo: aviationbuildingsystem.com

Photo: internationalsteelspan.com

Photo: sztuka-architektury.pl

Based on types of loads, there are two possibilities for steel hall:

- "heavy" hall with cranes act on hall structure;
- "light" hall without crane act on hall structure;

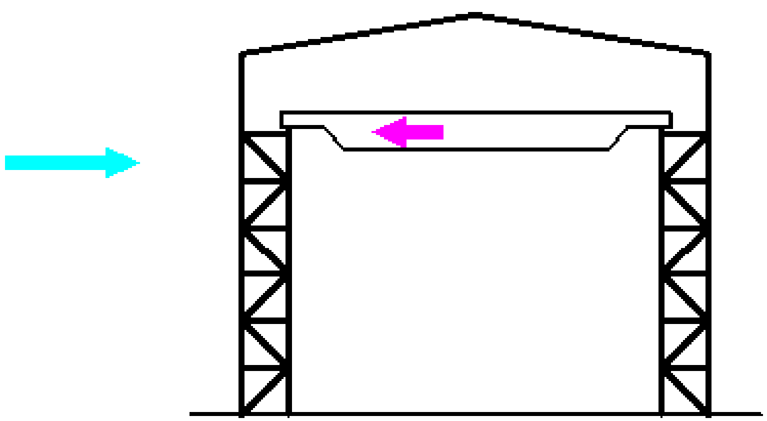
Photo: eci.com.pl

Photo: spawstal.pl

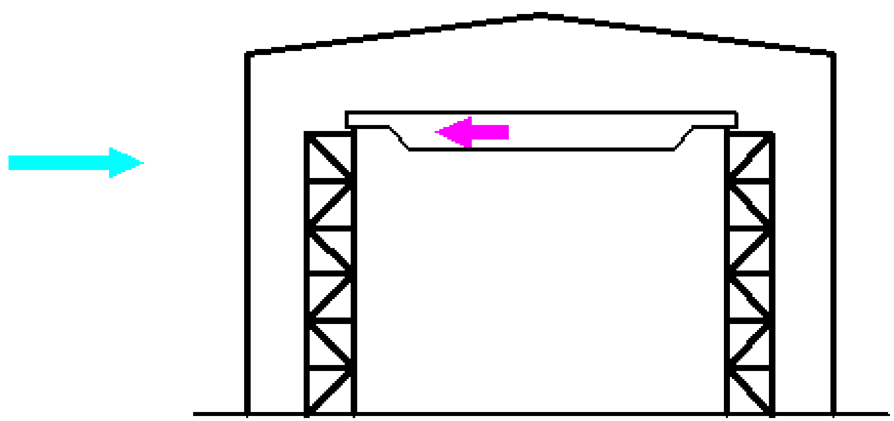
Photo: weldon.pl

Photo: Author

A



B



Case	Crane supporting structure	Hall structure
A	Dead weight Climatic actions Crane actions	
B	Dead weight Crane actions	Dead weight Climatic actions

According to situation A, B, there are three possibilities:

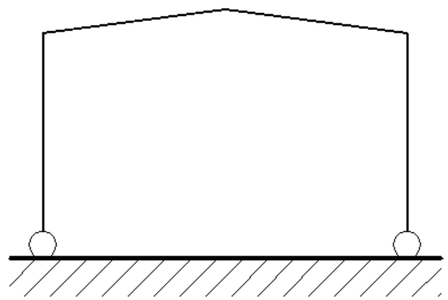
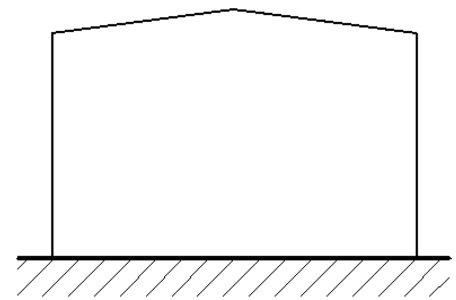
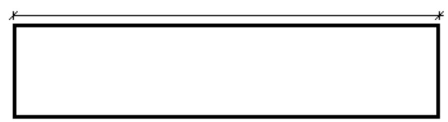
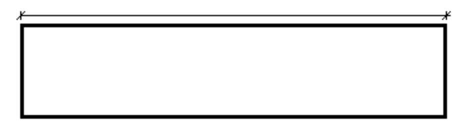
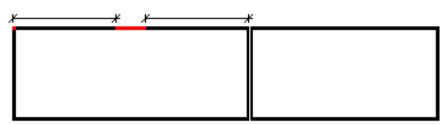
Situation	Type of hall
A	"Heavy"
B	"Light"
Hall without crane	"Light"

„Heavy" – loads from crane could be bigger than all rest type of loads (dead-weight + snow + wind + …)

Loads and actions for „heavy" halls will be presented on II^{nd} step of study.

General rules

Photo: Author

	"Light" hall	"Heavy" hall
Static scheme		
Max length of building / max distance between dilatations	150 m 	120 m 
Max longitudinal distance between front wall / dilatation and vertical wall bracing	60 m 	

Examples of "heavy" and "light" halls

Photo: stabud.eu

Photo: pebsteel.com

Generally, "heavy" halls are various types of industrial halls.

"Light" halls could have various destiny of various architecture.

Photo: ekbud.lublin.pl

Photo: toiowo.eu

Photo: internationalsteelspan.com

Idea of flat frames transversaly connected gives great possibilities for shaping structures.

Photo: steel.com.au

Photo: roof-care.com

Photo: sztuka-architektury.pl

Skeletons

The second - less popular - construction scheme is steel skeleton. In case of a frame, rigid joints appear only in one plane. Elements in perpendicular direction are connected to frame by hinge joints. Rigid joints only are in both directions in skeleton.

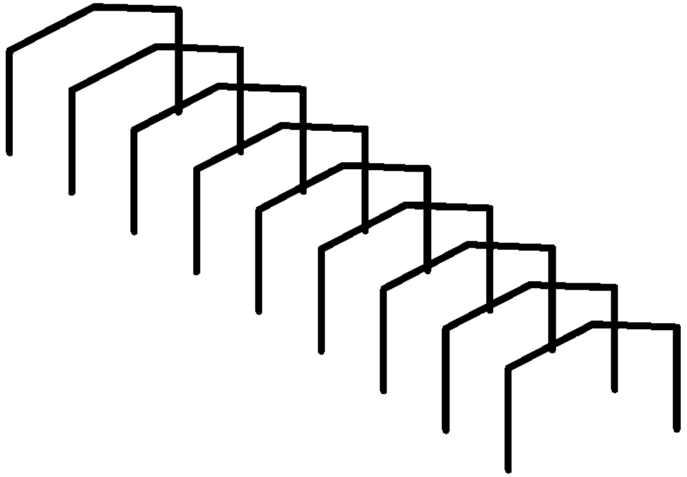
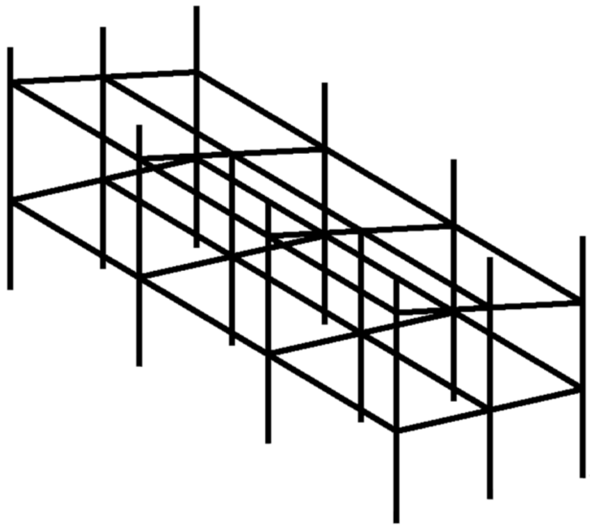


Photo: Author



Rigid joint in both directions can be based on classic solution of tension joint. Relative to strong axis of column cross-section, bolts connect column flange and end plate. Relative to weak axis, bolts connect end plate and additional plate welded to the column flanges.

Photo: resources.scia.net

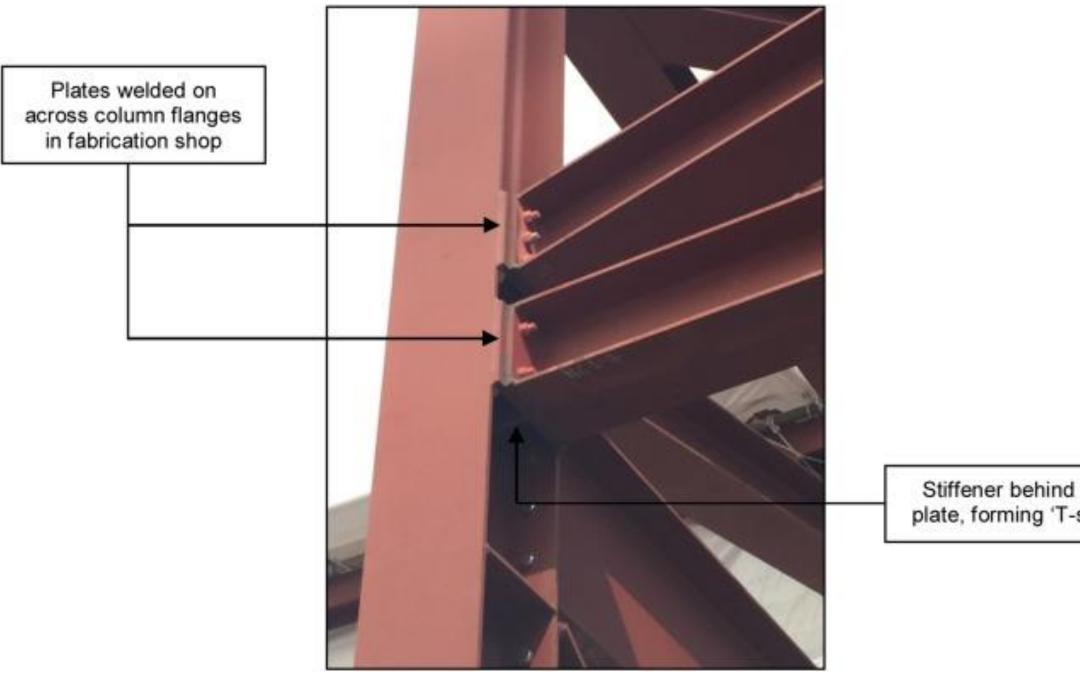
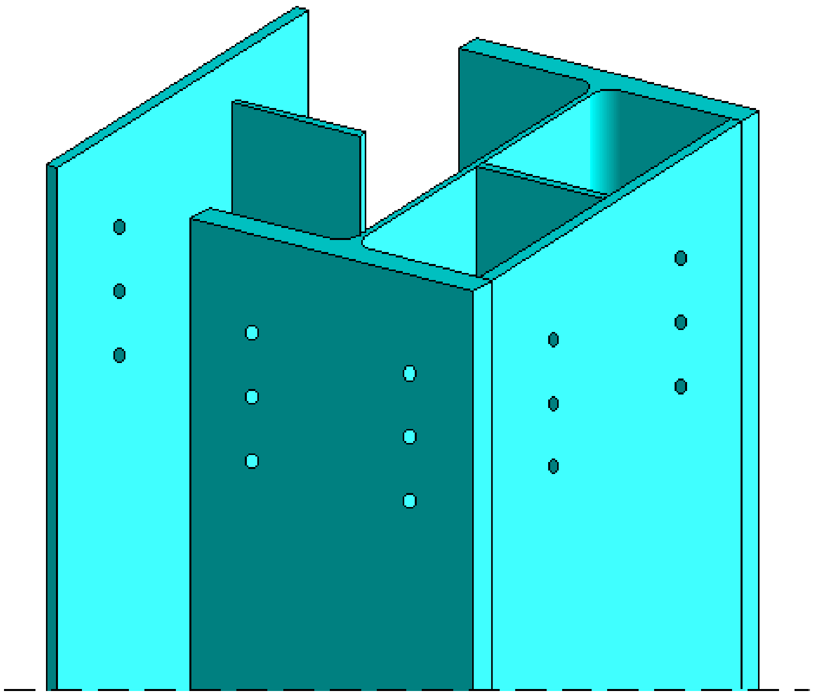


Photo: Current UK trends in the use of simple and/or semi-rigid steel connections, M. Kidd, R. Judge, S.W. Jones, Case Studies in Structural Engineering 6 / 2016

Photo: Author



Another solution is offset universal joint, connecting beams to I-stub welded to flange and web of column.

Photo: prefabmarket.com

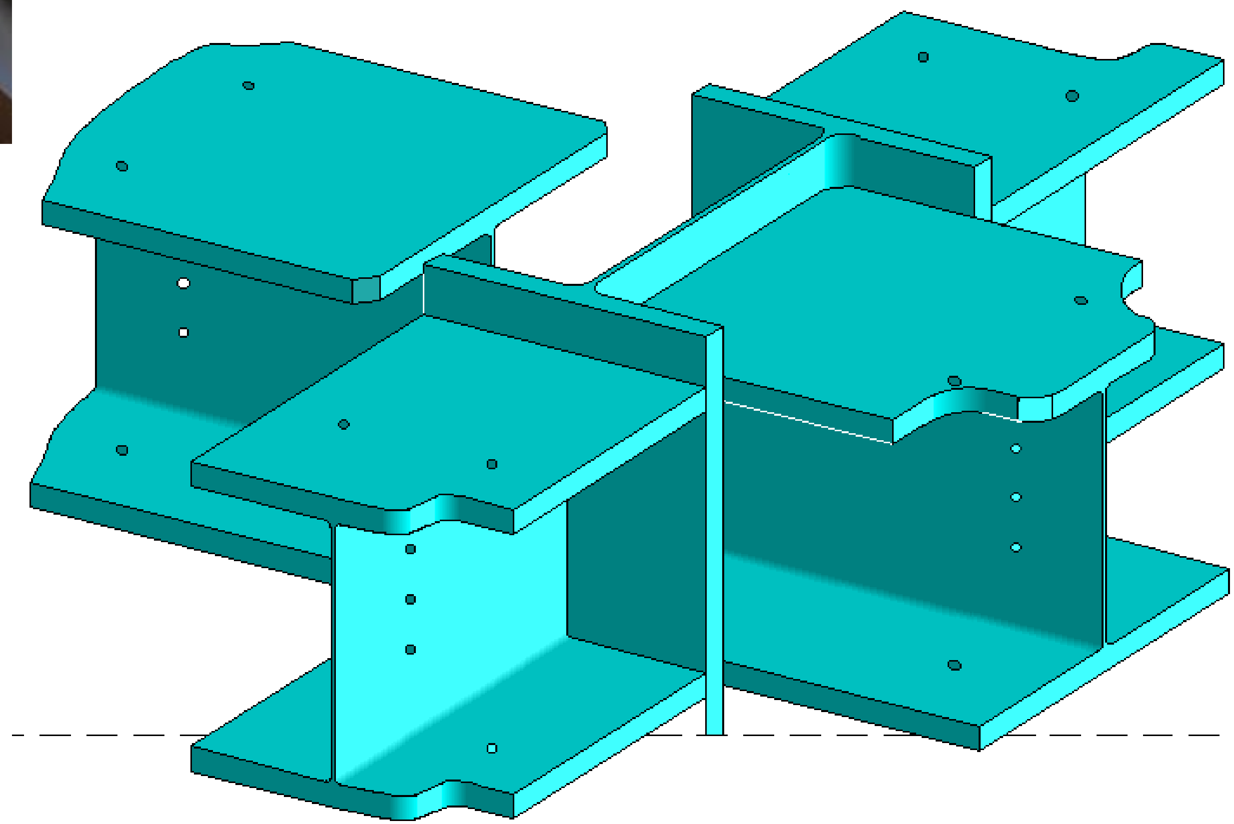


Photo: Author

Stiffness and resistance of these solutions must be checked.

For left one, formulas from Eurocode for both characteristics can be applied in both directions (in both directions joint can be analised as beam to column of I-cross-secions). Additionally welds must be calculated.

Right one is more complicated. Part beam-column flange can be analised as welded joint beam-column. No formulas for stiffness and resistance for part beam-column web are presented in Eurocode. This part bases on supposition „if resistance of welds is ok, everythink is ok".

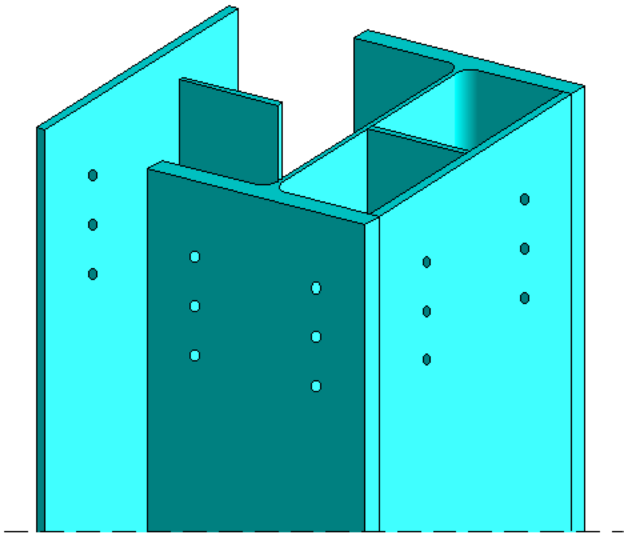


Photo: Author

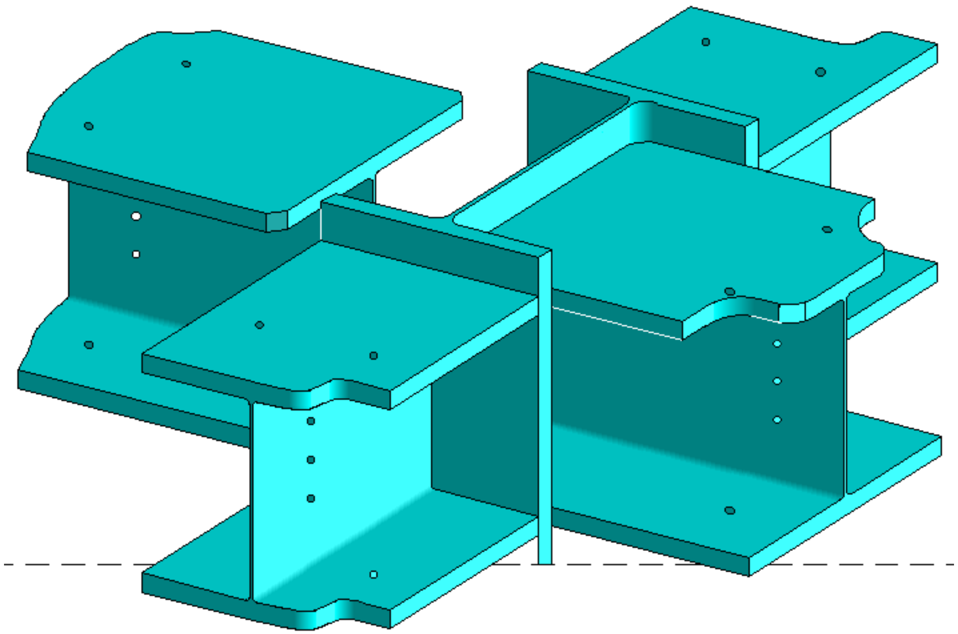


Photo: wallsviews.co

Steel skeletons are preferred to few-storeys offices buildings. Small number of bracings is applicated thanks to big stiffness of joint and – in horizontal direction – floors.

Photo: ekbud.lublin.pl

Photo: rccconcrete.com

Photo: wikipedia

Photo: noizz.pl

Such solution is recommended the same for tall buildings. According to economical analysis, this solution is good up to about 40 storeys (≈ 160 m).

For higher buildings, cooperation between skeleton and central massive concrete core is recommended. More information will be presented on II[nd] step of study.

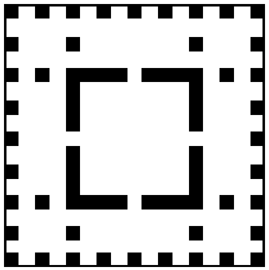


Photo: Author

Frames	Skeletons
Rigid joint in plane only	Rigid join in both directions
Columns bended in one direction	Bi-axial bending in columns
Bracings in side walls and roof	Small number of bracings, cooperation with floors
Critical length of columns: in plane effect of cooperation between column and girders (→ #13 / 35-71); out of plane it distance between vertical bracings	Critical length of columns: in both directions effect of cooperation between column and girders (→ #13 / 35-71) or – if horizontal stiffness of floor is big (concrete plate for example) – it is distance between floors
Sandwich panels, cladding panels, glass fasades as housing	
The most often solution: one-storey; possible up to 20 storeys	Up to 40 storeys

Sub-structures

Regardless the presence of cranes, there are the same sub-strucrutures for each situation – **hall and skeleton**.

Examples in drawings and photos will refer to hall, as structure used much more often.

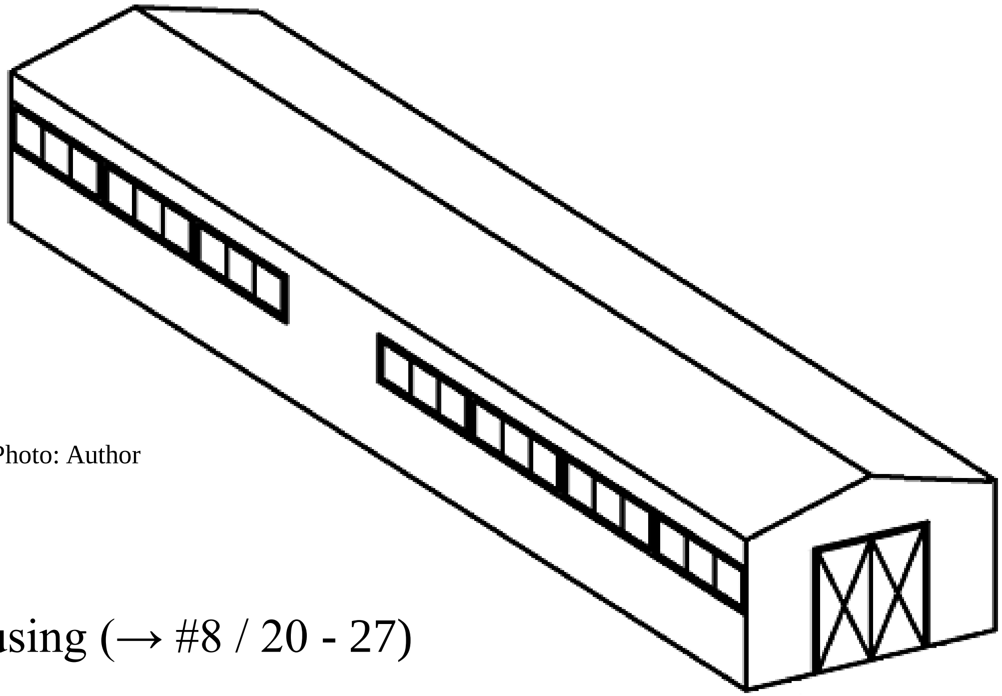
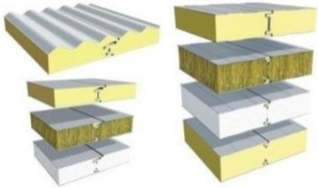
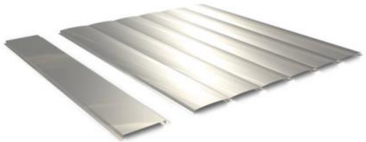
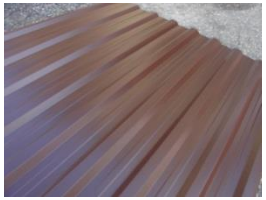


Photo: Author

The outer part - roofing and housing (→ #8 / 20 - 27)

→ #8 / 21	Thermal isolation	Factory-made connecting latch	Anti-buckling protection for purlins according to EN
 Photo: steelprofil.pl	☺	☺	☹
 Photo: pruszynski.com.pl	☹	☺	☹
 Photo: amarodachy.pl	☹	☹	☺ (per 5 - 10 years from erection)
 Photo: building.co.uk	Separated problems (generally: responsible of manufacturer)		

Roofing and housing can be calculated as one of three levels of accuracy:

→ #8 / 22

Accuracy of calculations	Comments
Dead weight only	The simples and most popular way of calculations (each type)
Dead weight + anti-buckling protection	According to EN 1993-1-3 (corrugated sheet only ; → Lecture #10) or FEM calculations according to results of tests and experiments (sandwich panels, cladding panels)
Dead weight + anti-buckling protection + cooperation with structure in bearing of loads	FEM calculations according to results of tests and experiments (each type);

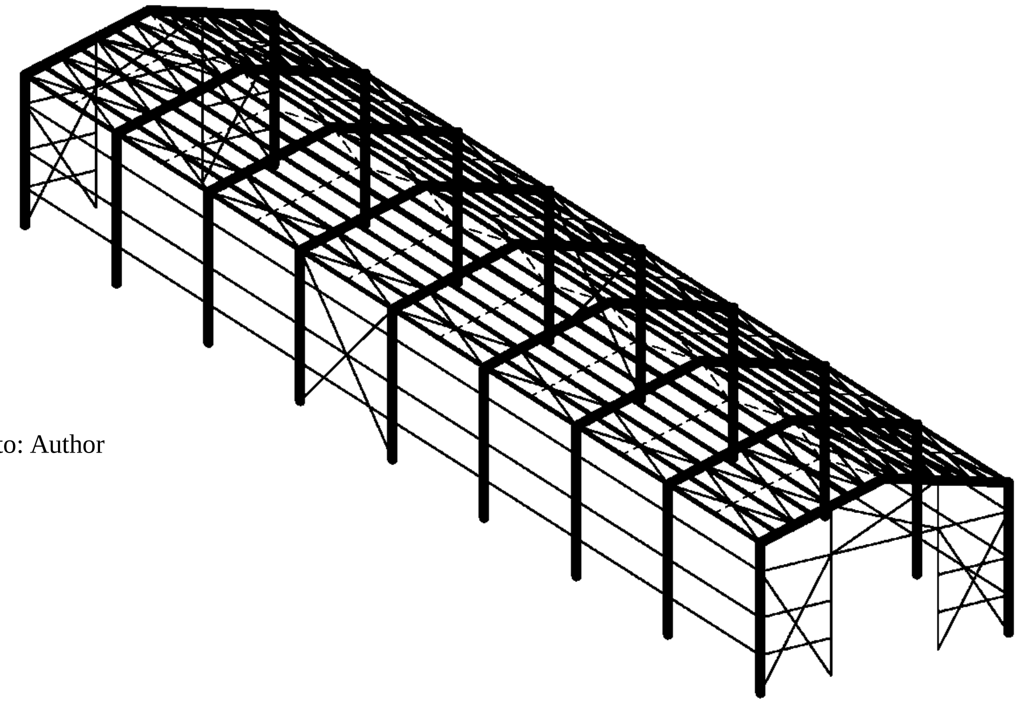


Photo: Author

Main structure

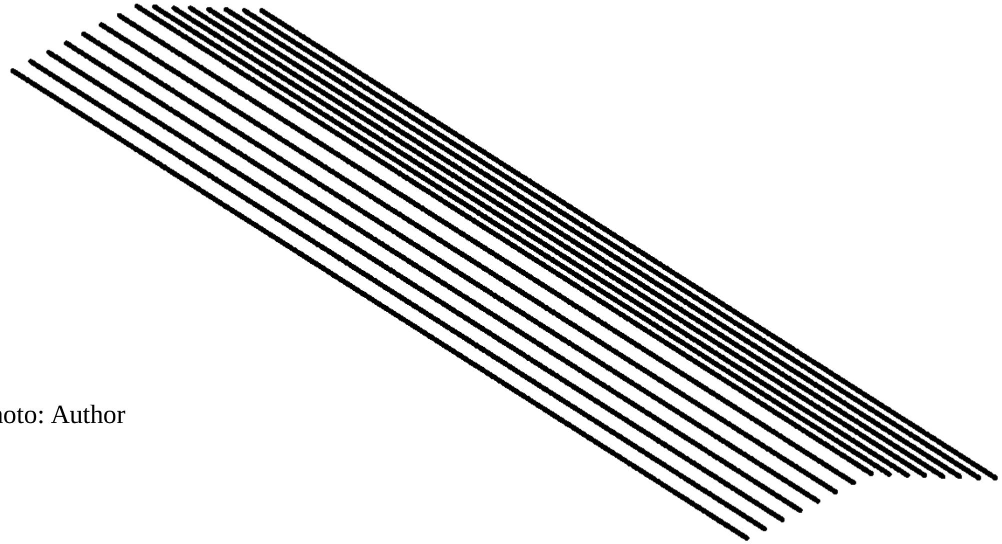


Photo: Author

Purlins (the same – hall and skeleton):

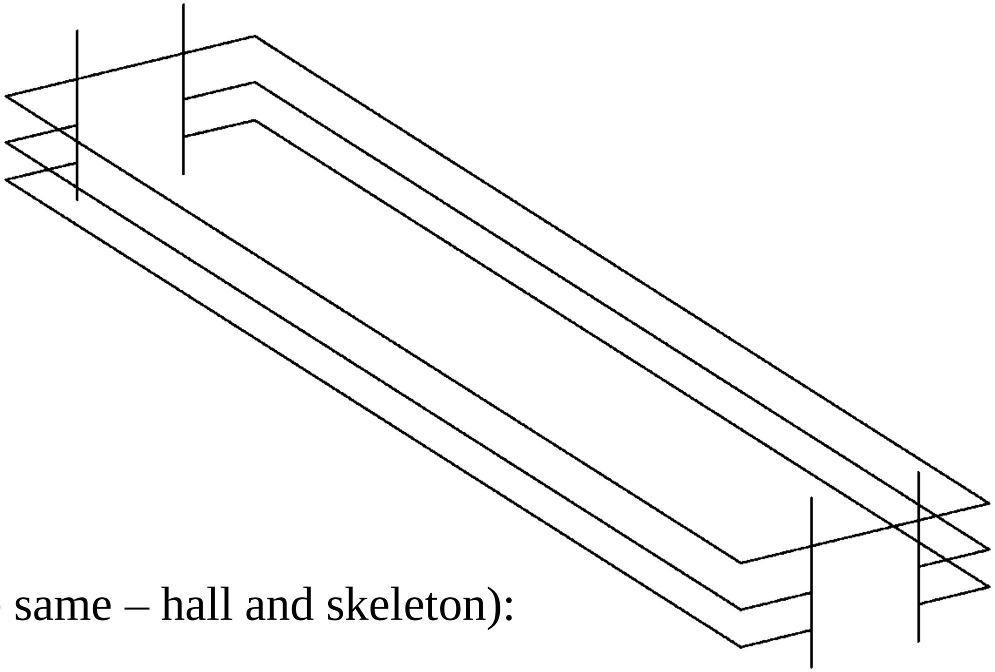
- General information → #8 / 28 – 41;
- Truss prulins #9;
- Hot-rolled beams #11;
- Castellated beams #12 / 57 – 73.

Recommended types of purlins for different length of span (distance betwen supports):

→ #8 / 38

<table>
<tr><th>Lenght</th><th>Continous, cold-formed</th><th>Continous, suspended, cold formed</th><th>One-span, hot-rolled</th><th>One-span, castellated</th><th>One-span, truss</th></tr>
<tr><td>< 3</td><td rowspan="3">👍</td><td rowspan="2">👎</td><td>👎</td><td rowspan="2">👎</td><td rowspan="4">👎</td></tr>
<tr><td>3 – 4</td><td rowspan="3">👍</td></tr>
<tr><td>4 – 6</td><td rowspan="2">👍</td><td rowspan="3">👍</td></tr>
<tr><td>6 – 8</td><td rowspan="3">👎</td></tr>
<tr><td>8 – 12</td><td rowspan="2">👎</td><td rowspan="2">👎</td><td rowspan="2">👍</td></tr>
<tr><td>12 – 18</td><td>👎</td></tr>
</table>

Photo: Author



Housing structure (the same – hall and skeleton):
(→ #8 / 42 – 47)

There is no snow load for girts; cross-sections of girts is much more lighter than for purlins.

Photo: newsteelconstruction.com Photo: everfaithsteel.cn Photo: calgor.com.pl

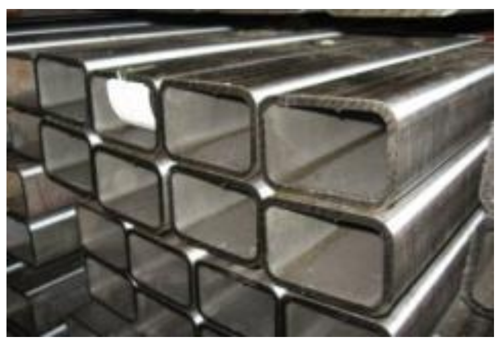
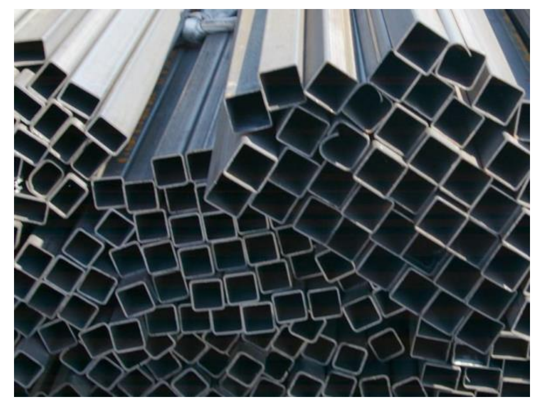
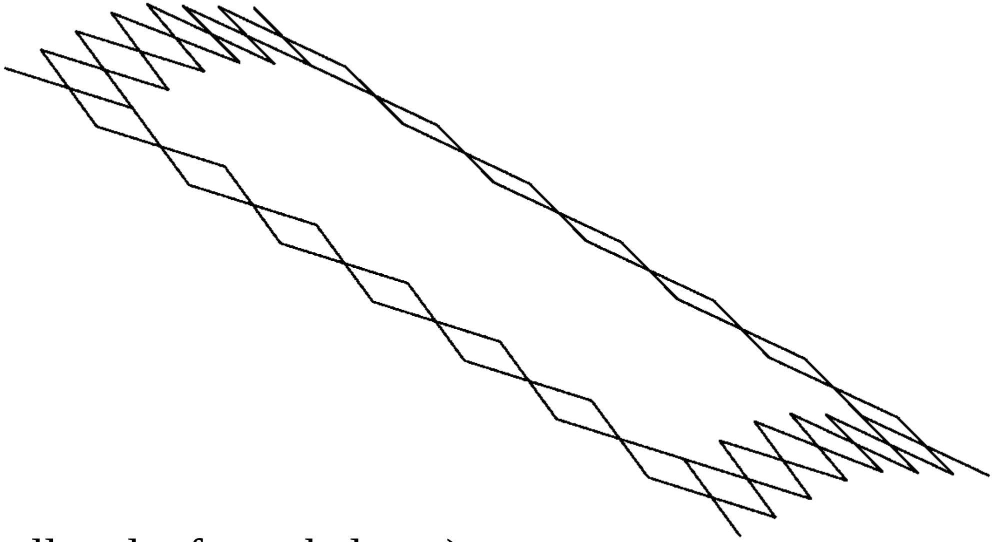
Horizontal elements	  
Vertical elements (for example additional columns)	 

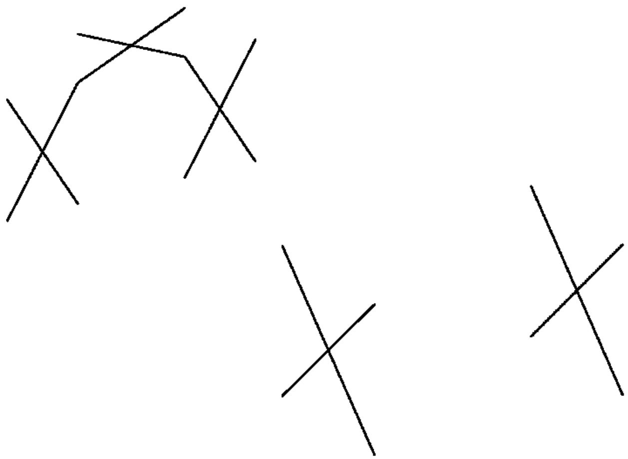
Photo: wggstal.pl Photo: wistal.pl

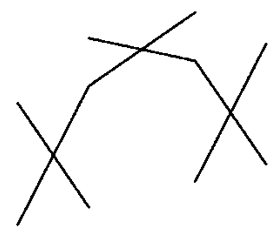
Photo: Author



Roof bracing (hall and, often, skeleton):
(→ #8 / 48, #10)

Photo: Author





Wall bracing (hall and, often, skeleton):
(→ #8 / 48, #10)

Bracings - recommended cross-sections (→ Lec # 10)

Photo: calgor.com.pl

Photo: rafstal-inox.pl

Photo: rafstal-inox.pl

→ #8 / 48

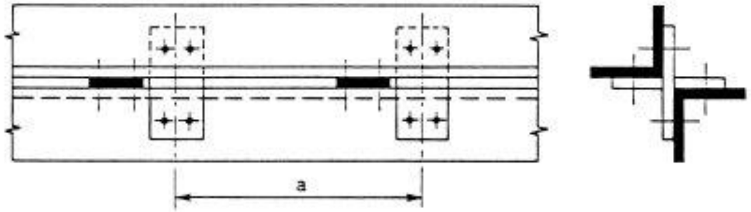


Photo: EN 1993-1-1 fig. 6.13

Photo: stalhart.pl

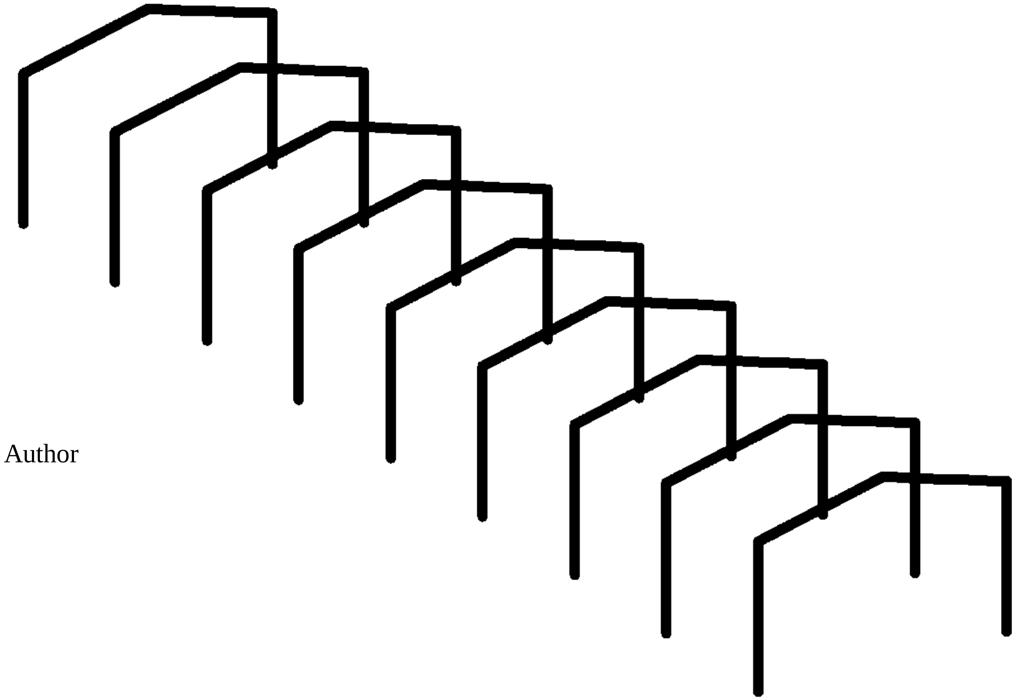


Photo: Author

Main frames (roof truss, roof girders and columns) (hall – flat, skeleton – 3D)
(→ #9, #11, #12, #13)

Hall may be built of full-walled elements (hot-rolled or welded I-beams) or truss members.

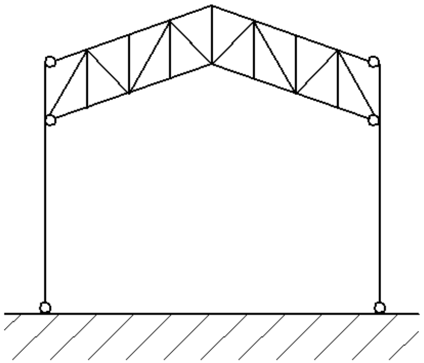
Photo: setrometalgroup.com

Photo: traskostal.pl

Photo: waldenstructures.com

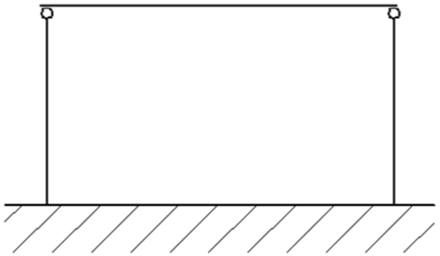
Photo: wikipedia

Directions of support

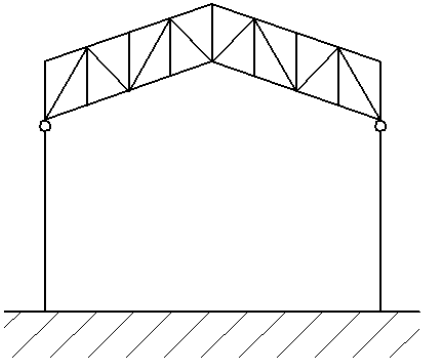


Truss: side supports

Photo: Author



Beam: support from below only



Truss: support from below

→ #20 / 57

Support from below → #20 / 58 - 84

Side supports → #20 / 85 - 87

Ways of analysis

According to the information presented in Lecture # 3, the most important issues related to calculations of structure, are:

- first or second order effects;
- 2D or 3D modeling;
- elastic or plastic analysis.

These issues are independent of each other - choosing one of alternatives in any of them does not limit choices in others.

Calculations:	Handmade	By computer
2 D	**Acceptable**	Acceptable
3 D	Acceptable	**Recommended**

Calculations:	Handmade	By computer
Elastic analysis: linear dependence **σ–ε**	**Conditionally acceptable (II – IV class c-s)**	Acceptable (linear model of material)
Plastic analysis: nonlinear dependence **σ–ε**	**Conditionally acceptable (I class c-s)**	**Recommended (nonlinear model of material)**

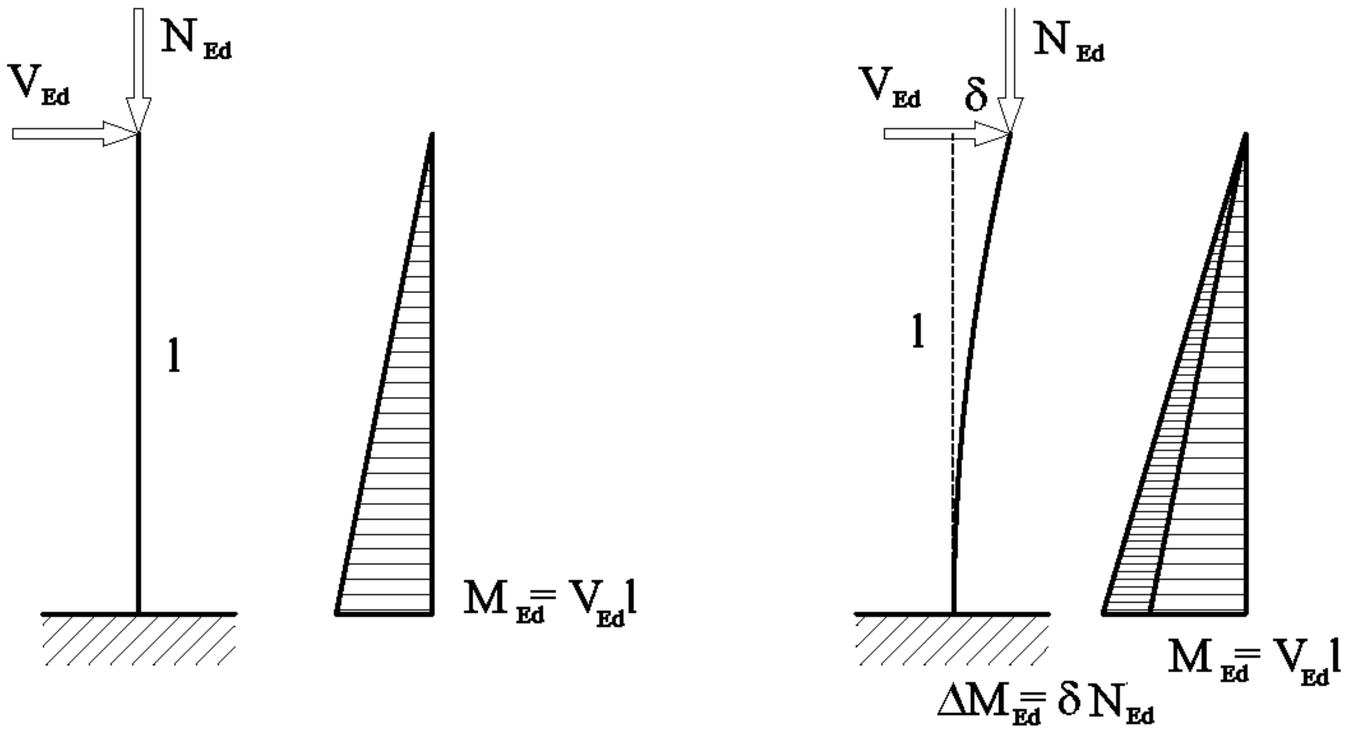
→ #3 / 90

Calculations:	Handmade	By computer
I[st] order effects	**Conditionally acceptable (→ #3 / 86)**	Acceptable (smal deformations)
II[nd] order effects	**Conditionally acceptable (→ #3 / 86)**	**Recommended (large deformations)**

→ #3 / 86

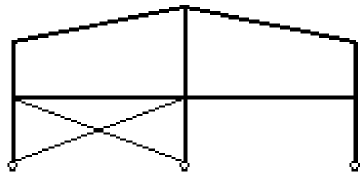
There is additional bending moment from axial force for very flexible structures

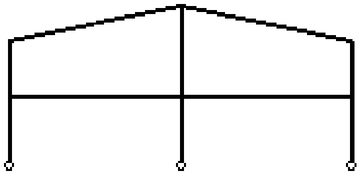
Photo: Author



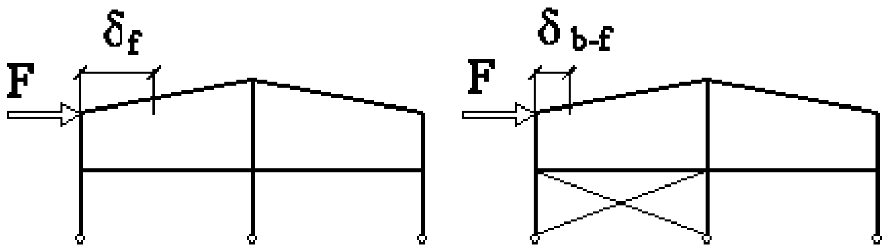
For calculations, new value of horizontal force is applied: $V_{Ed}^* = V_{Ed}\ \alpha^*$

Wall with in-plane bracing





↓ ↓



$\delta_f / \delta_{b-f} \le 5$ → Non-braced frame

↓

$\delta_f / \delta_{b-f} > 5$

↓

Braced frame - no need second-order analysis

Second-order analysis

Photo: Author

→ #13 / 47

When we must make second-order analysis (PN B 03200)

For non-braced frame:

$\alpha_{cr} \approx (H_{Ed}\ h) / (V_{Ed}\ \delta_{H,Ed})$

$\alpha_{cr} = F_{cr} / F_{ed}$ α_{cr} – „distance" between cross-sectional force from external loads and critical force for instability		
$\alpha_{cr} > 10$	$10 \geq \alpha_{cr} \geq 3$	$\alpha_{cr} < 3$
No need analysis	Simple analysis	Advanced analysis

Simple analysis:

$Q_{Ed}{}^{*} = Q_{Ed}\ \alpha^{*}$

$\alpha^{*} = 1 / (1 - 1 / \alpha_{cr})$

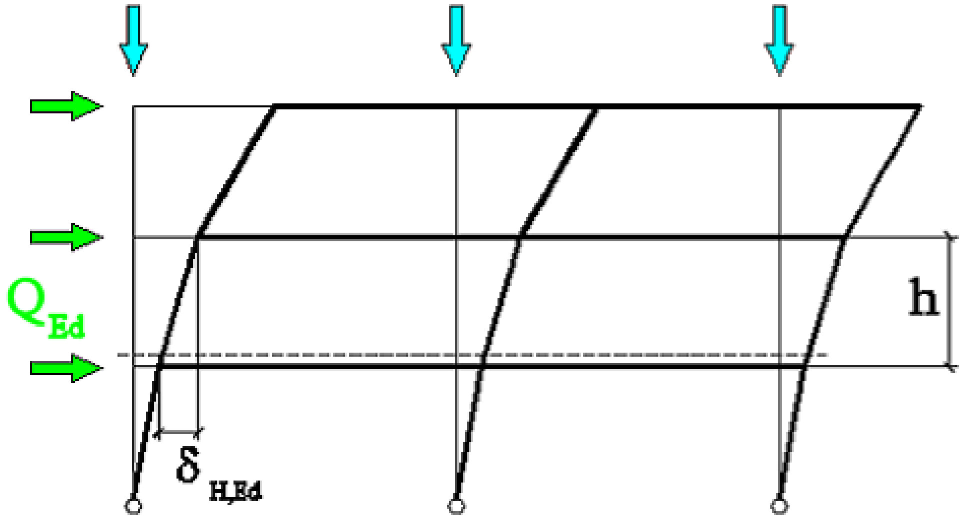
Q_{Ed}, H_{Ed} , V_{Ed} – from one analysed storey only

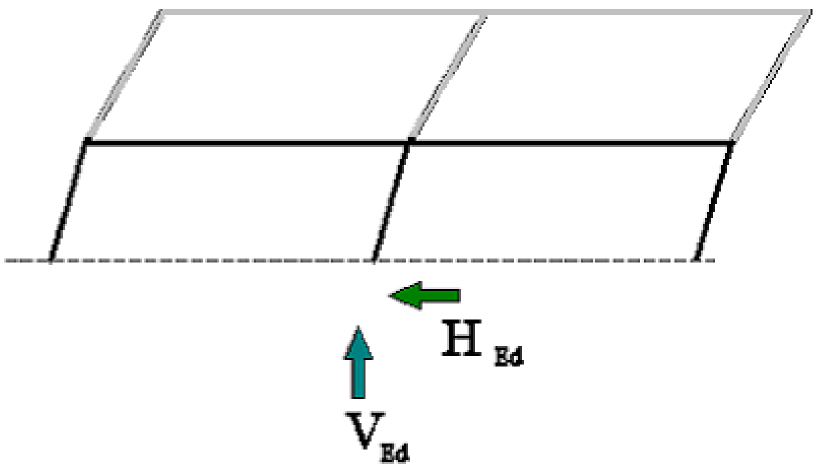
EN 1993-1-1 5.2.1.(3),
EN 1993-1-1 5.2.2.(5)B

→ #13 / 48

EN 1993-1-1 (5.1), (5.2), (5.4)

Photo: Author





Of course, α_{cr} can be also calculated by computer programme

→ #13 / 49

$$\alpha_{cr} = F_{cr} / F_{Ed} \rightarrow F_{cr} = \alpha_{cr} F_{Ed}$$

α_{cr}	α^*
20	1,053
15	1,071
10	1,111
7	1,167
5	1,250
4	1,333
3	1,500
2	2,000
1	$\rightarrow \infty$

Based on F_{cr}, computer programme can analyses stabilities of column.

α_{cr} increases when:

there is big difference between critical buckling force and load
or
there are low horizontal forces and displacements.

Simple analysis - linear statical calculations with enlarged value of horizontal loads α^*.

Advanced analysis - nonlinear statical calculations (computer programmes with geometrical nonlinearity = lagre displacement range) without enlarged value of horizontal loads.

Analysis of second order effect is important during calculation stability of column in frames. It is not mandatory, it is possible to carry out calculations in the range of first order effects (procedure „C" - IInd order effects important for μ_y - distinction betwen sway and non-sway structure).

	Procedure "A"	Procedure "B"	Procedure "C"
Loads	• „normal" • **from IInd order effects** • from sway imperfections • from bow imperfections	• „normal" • from sway imperfections	• „normal"
Calculations	• Resistance	• Resistance • $\mu_y = 1,0$ • Stability	• Resistance • **Value of μ_y** • Stability
Notes	Big amount of calculations for loads.	Medium amount of calculations for loads, medium amount of calculations for stability.	Small amount of calculations for loads, big amount of calculations for stability.

2D and 3D model

Structure can be calculated as separated flat part with equivalent effects from load perpendicular to main plane, or as full 3D model of structure. Effects of loads perpendicular to main plane are automatically taken into account in 3D.

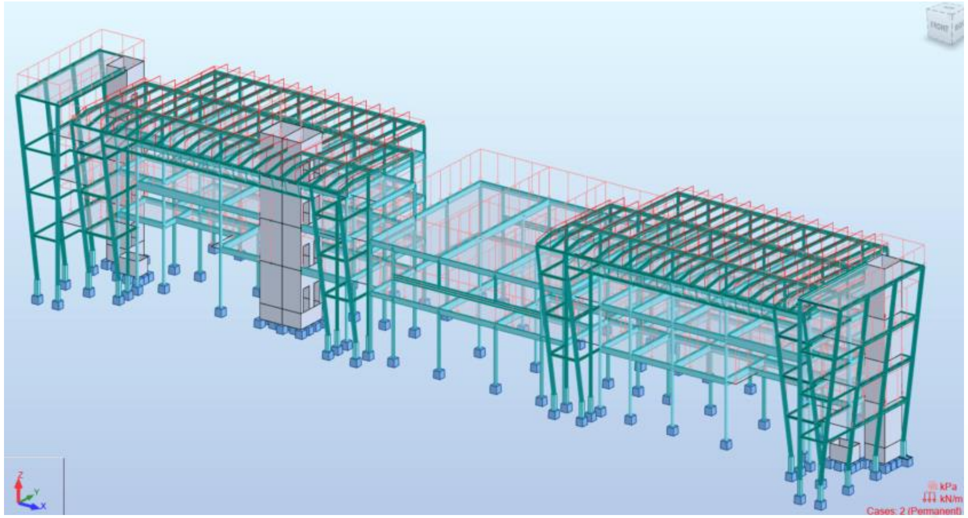
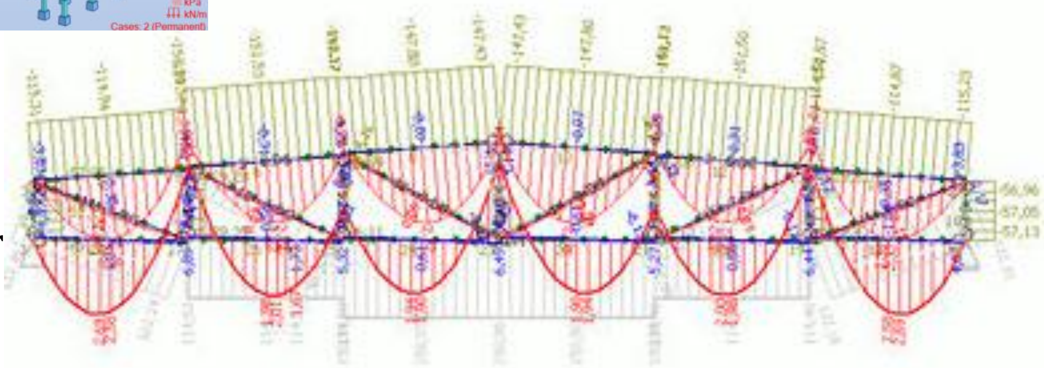


Photo: blogs.autodesk.com

3D model is closer to real behavior of structure - transfer of loads between elements occurs in all directions.

Photo: archiexpo.com



2D model is simpler to make and easier to calculate (small number of elements).

Simple 2D models have been used by many generations of engineers to design structures. 3D models, which have many times more degrees of freedom, appeared on a larger scale only with development of computing power of computers.

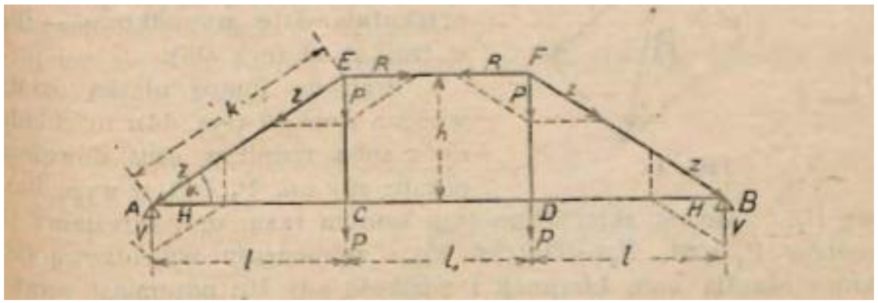
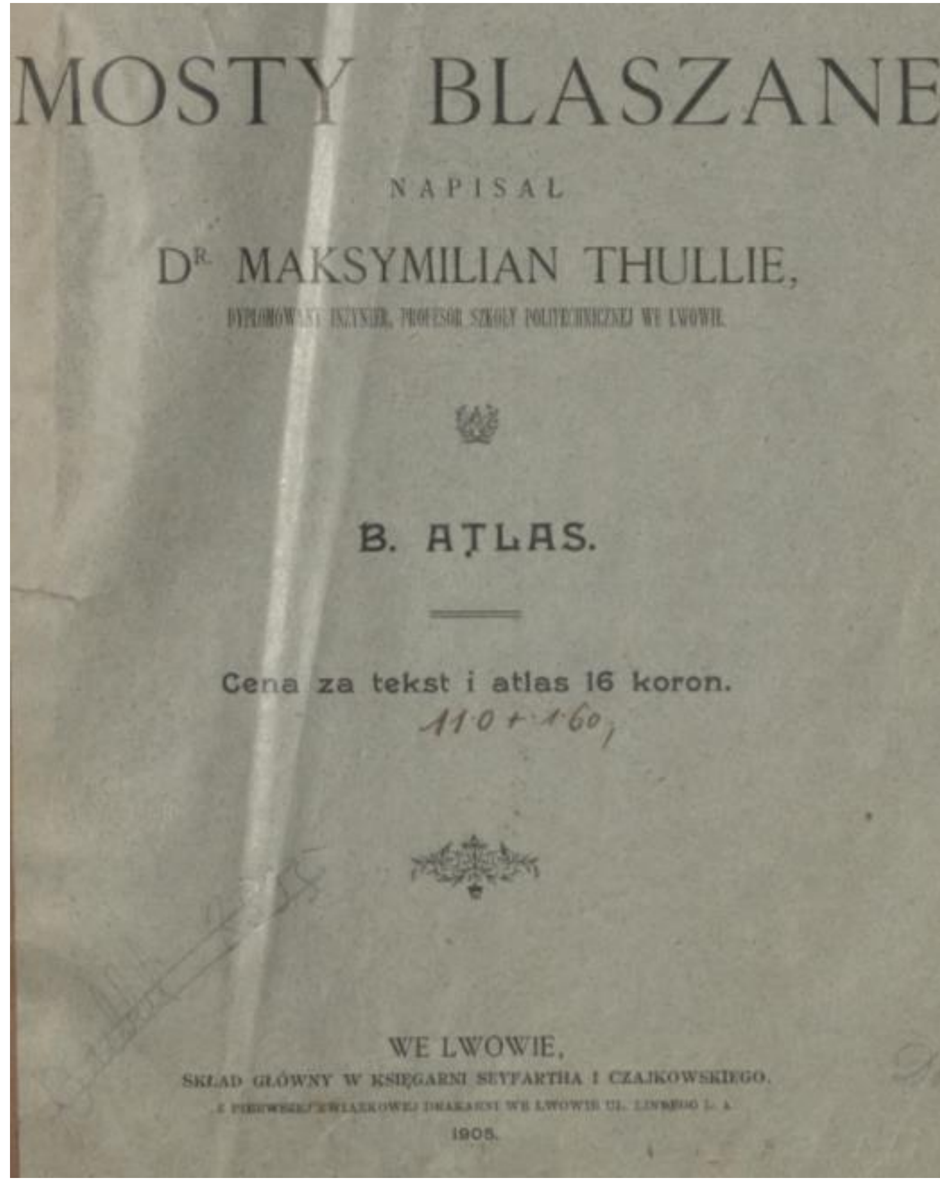


Photo: bcpw.bg.pw.edu.pl

From this period there are many recommendations regarding shaping of structures and simplified calculation models for loads perpendicular to main plane.
3D model requires more work during modeling. In 2D, more work will be required , for example, to analyze roof bracing.



MOSTY BLASZANE

NAPISAŁ

Dr MAKSYMILIAN THULLIE,

DYPLOMOWANY INŻYNIER, PROFESOR SZKOŁY POLITECHNICZNEJ WE LWOWIE.

B. ATLAS.

Cena za tekst i atlas 16 koron.

11.0 + 1.60

WE LWOWIE,

SKŁAD GŁÓWNY W KSIĘGARNI SEYFARTHA I CZAJKOWSKIEGO.

1905.

Photo: repozytorium.biblos.pk.edu.p

→ #8 / 44

Photo: steelconstruction.info

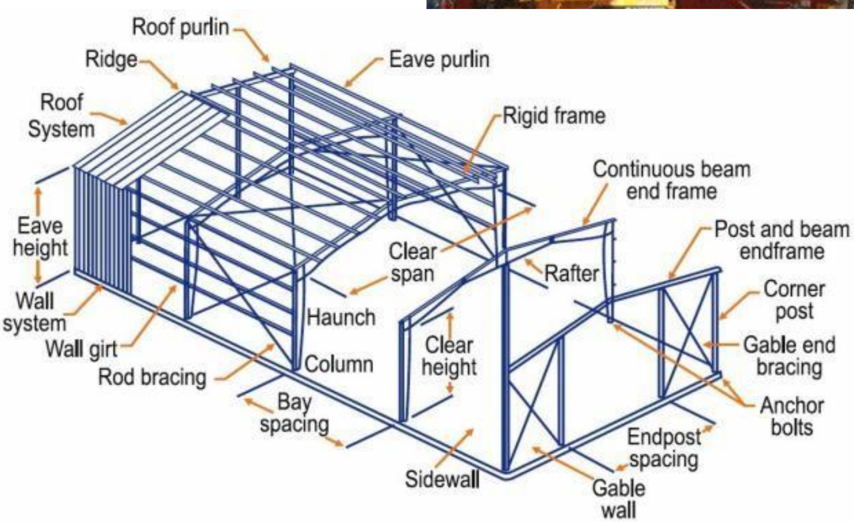
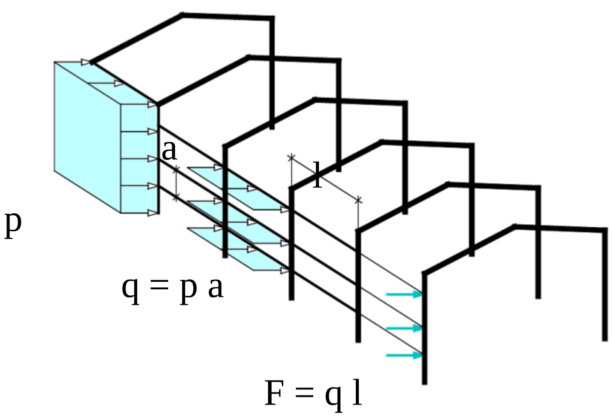


Photo: greenterrahomes.com

Wall girts, purlins, roof bracings and side wall bracings make specific system for wind action. Front wall housing columns must be connected with purlins and roof bracings at one point. The same, girts on front and side walls.

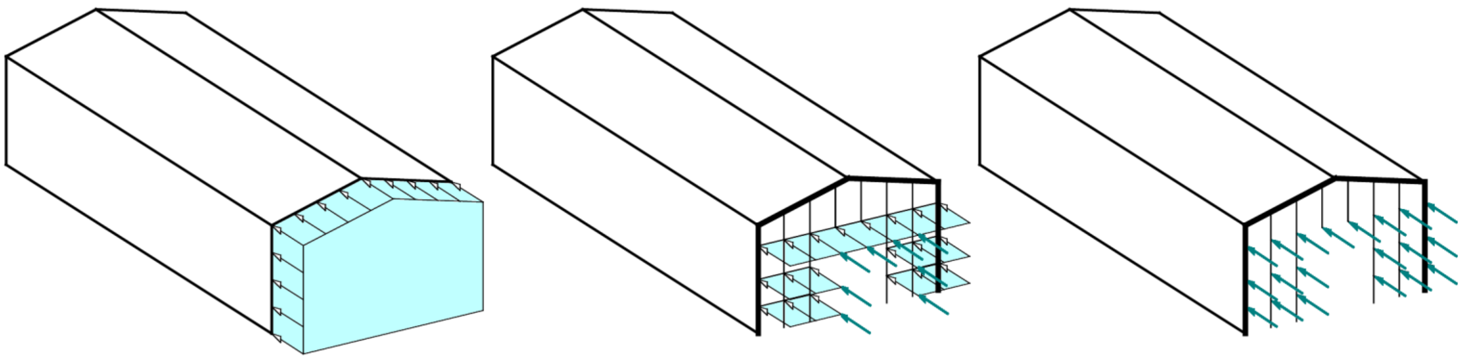
Photo: Author



Wind acts on housing (p, [kN / m^2]). Housing is support on wall girts; loads from housing act on girts as continous loads (q, kN / m). Girts are under bending (mono- or bi-axial). Loads from girts act on main frames as forces, applied in points of connection girts - main columns.

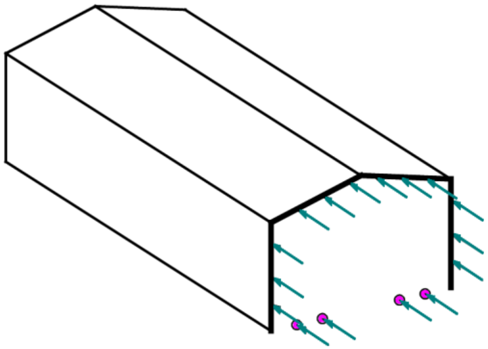
→ #8 / 45

Photo: Author

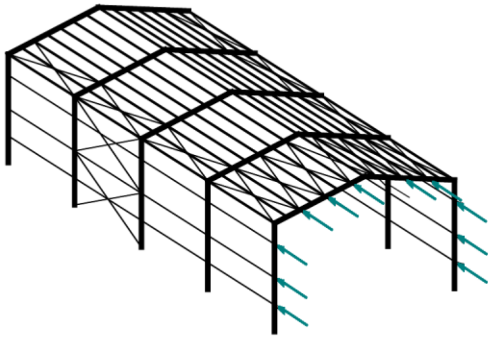


Wind acts on front wall: the same way of recalculation p → q → F. Forces are applied to main frames (perpendiculary to theirs plane) and to housing columns. In case of doors (in front / side wall), wind action from door is applied to girts and housing columns around doors.

Photo: Author

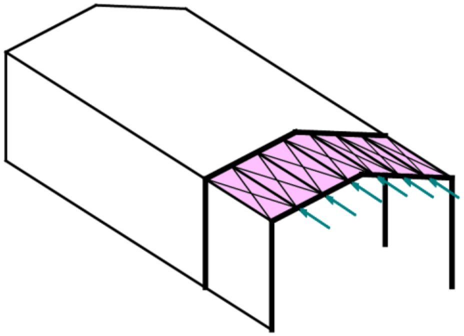


Loads from housing columns finally act on bases of housing column and main frames (main columns, roof girders), perpendiculary to theirs planes. It potentially makes bi-axial bending in main frames.



Main frames are supported in perpendicular direction by bracings, purlins and side wall girts. It prevent from bi-axial bending.

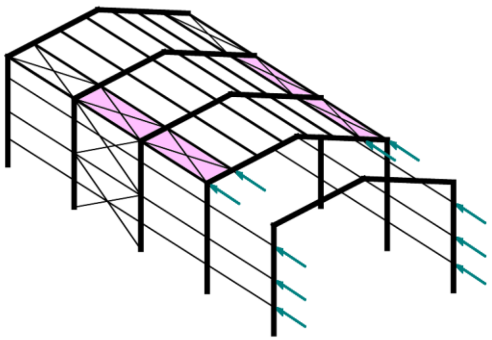
Photo: Author



Roof bracings and purlins make horizontal truss. Roof girders are chords of truss. The effect is, that loads perpendicular to main frames make additional axial forces in roof girders. Additionally, there are axial forces in purlins.

→ #8 / 46

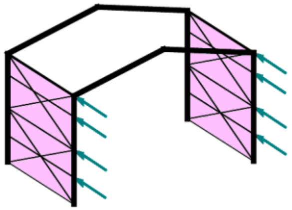
Photo: Author



Roof: loads are transported through longitudinal broof bracings.

Wall: loads are transported by side wall girts.

Photo: Author



Finally, loads act on vertical bracings on side walls, vertical trusses. Main columns are chords of truss. Depending on location of girts on side walls, there is possible bi-axial bending in these four of columns (loads out of nodes of truss).

→ #8 / 47

Way of calculation - 2D vs. 3D - is very important for algorithm.

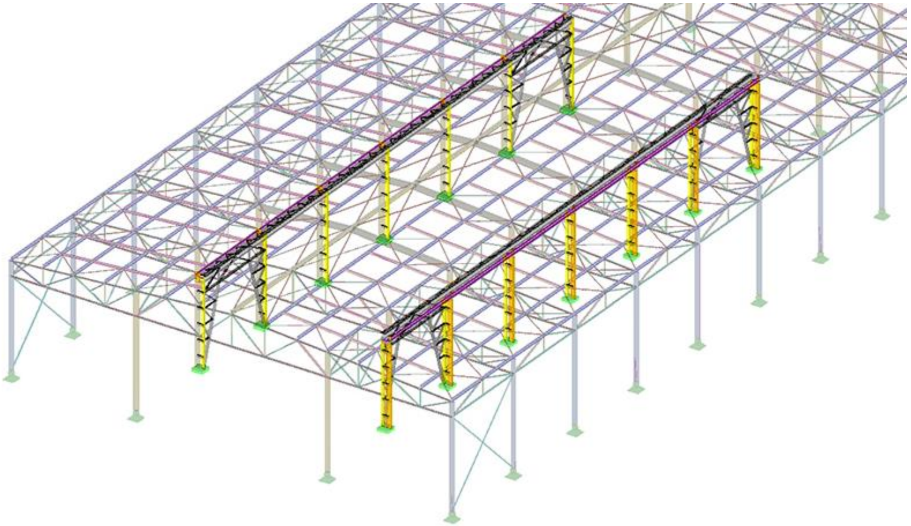


Photo: mesilo.pl

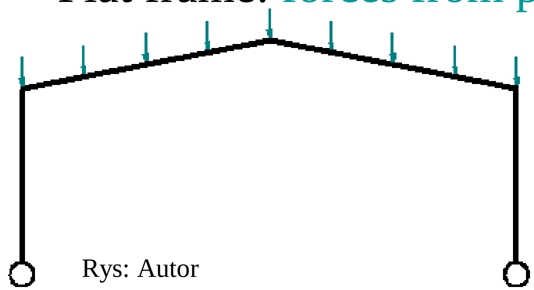
3D model in FEM calculations: we have full information about cooperation between trusses, purlins and bracing bars right away. Calculation is made in two steps:

- Initial calculation: dead weight, climatic actions, live loads etc.
- Equivalent forces in analysis of imperfections of roof griders and instability of roof girdres are calculated, based on value of compressive force in roogf girders from first step.

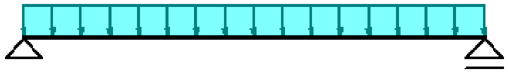
→ Des 1 examp / 53

2D model (method of equivalent flat frames) is much more complicated:

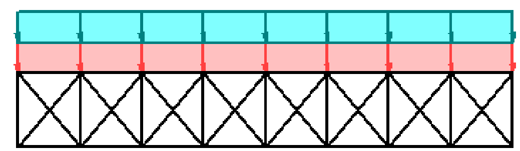
Flat frame: forces from purlins



Purlin: bi-axial bending



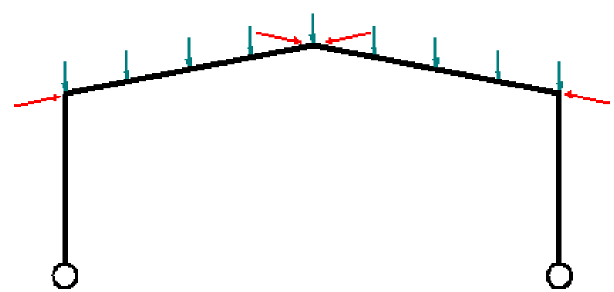
Roof bracings:
horizontal truss

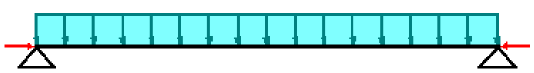


Wind acrion
Equivalent forces from
instability and imperfection

Cooperation frame-bracings:
additional forces in purlins,
additional forces in frame.

→ Des #1 / 69





Purlin: bi-axial bending +
compressive axial force
(recalculation)

Frame: additional axial forces
from cooperation with
bracings (recalculation)

Elastic and plastic analysis

EN 1993-1-1 is dedicated, first of all, to elastic calculations. There is only few information about calculation by plastic analysis: 5.4.1, 5.4.3, 5.6, BB.3. Additionally, few information is presented in EN 1993-1-8 5.1.

- Plastic analysis can be used only for members of I^{st} or II^{nd} class of cross-section, and axis of symmetry in plane of bending moment;
- Plastic hinge occurs in a joint: the joint should have sufficient strength to ensure the hinge remains in the member or should be able to sustain the plastic resistance for a sufficient rotation;
- Members are protected from lateral buckling;
- Where a transverse force that exceeds 10 % of the shear resistance of the cross section, is applied to the web at the plastic hinge location, web stiffeners should be provided within a distance along the member of h/2 from the plastic hinge location, where h is the height of the cross section.

Examples of elastic and plastic analysis in design project:

Design project	Elastic analysis	Plastic analysis
I (steel truss)	Everything	Nothing
II (floor girder)	Majority	Primary beam, redistribution of bending moments
III (steel hall)	Everything	Nothing

Plastic analysis – as more economical – should be always used for multispan continous beams of I^{st} class of cross-section.

In case of frames, situation is more complicated.

Caculations of steel frame	Elastic (simpler)	Plastic (more economical)
Design of new structure	Recommended	Possible
Recalculation of existing structure (expertise or change of load)	Possible	Recommended

Global plastic analysis should be also used for important values of accidental actions.

Members: EN 1993-1-1 5.4.3.(1) defines three possible types of global plastic analysis:

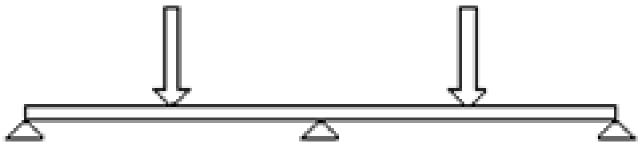
- elastic-plastic analysis with plastified sections and/or joints as plastic hinges,
- non-linear plastic analysis considering the partial plastification of members in plastic zones,
- rigid-plastic analysis neglecting elastic behaviour between hinges.

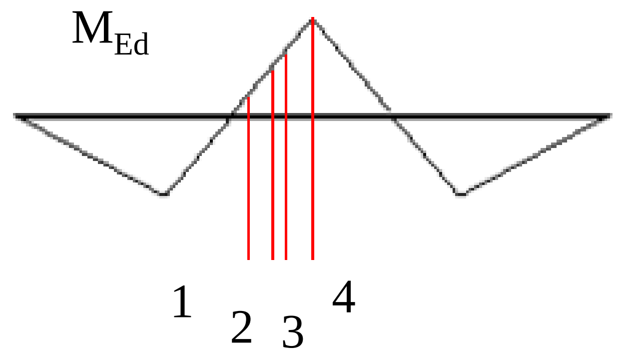
Joints: EN 1993-1-8 5.1 defines only two types:

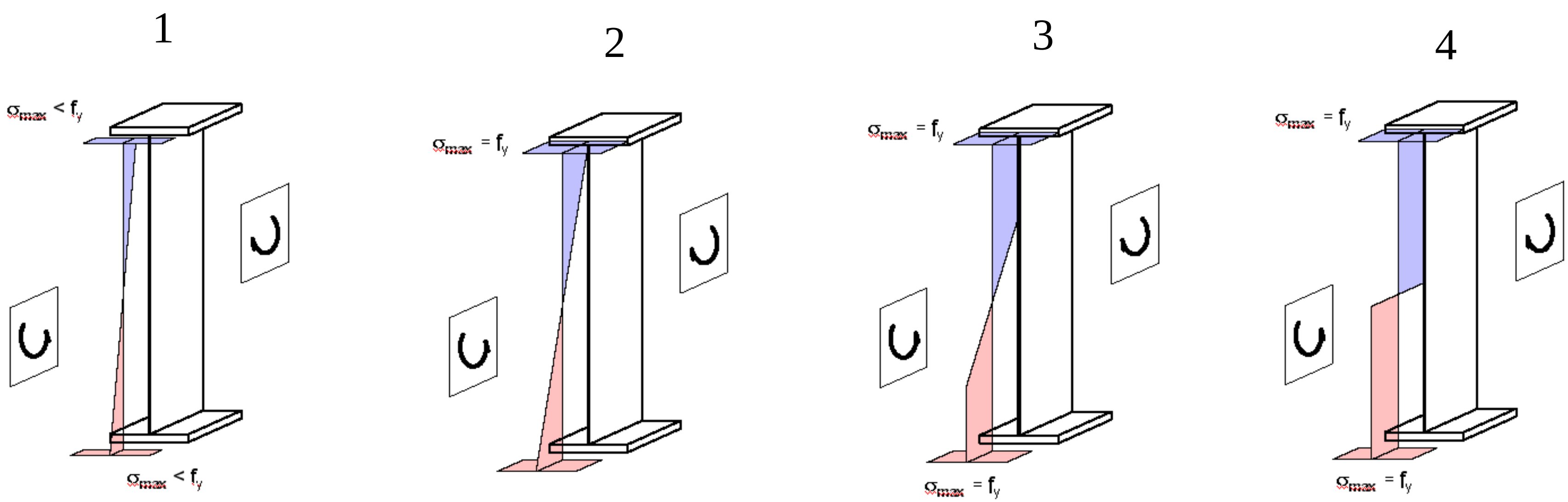
- elastic-plastic global analysis;
- rigid-plastic global analysis.

Elastic-plastic analysis takes into account elastic behavior of material in members. Depending on value of bending moment, elastic, elastic-plastic or full plasticizing stress distribution may appear in various cross-section.

Photo: Author

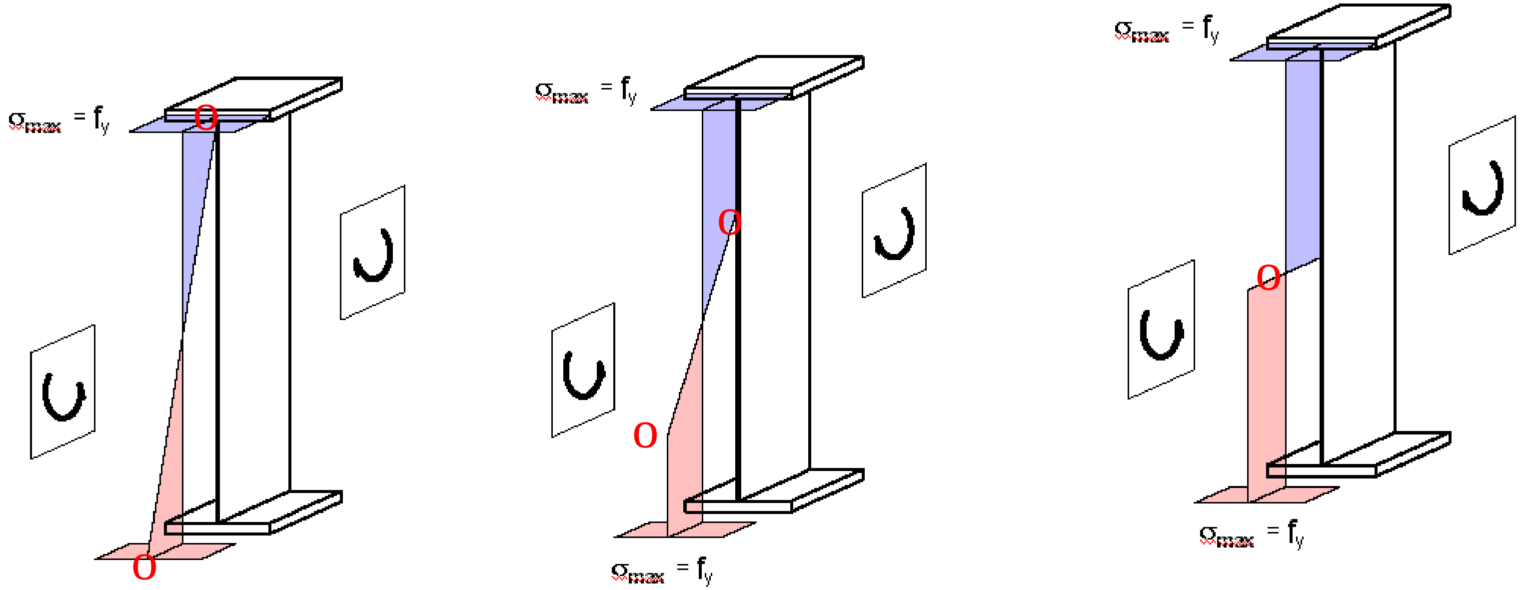






Points o at which elastic state ends and plastic state begins ($\sigma_{max} = f_y$), create a specific shape along length of beam, named „plastic front”.

Photo: Author



Shape of plastic front is specific for type of external load.

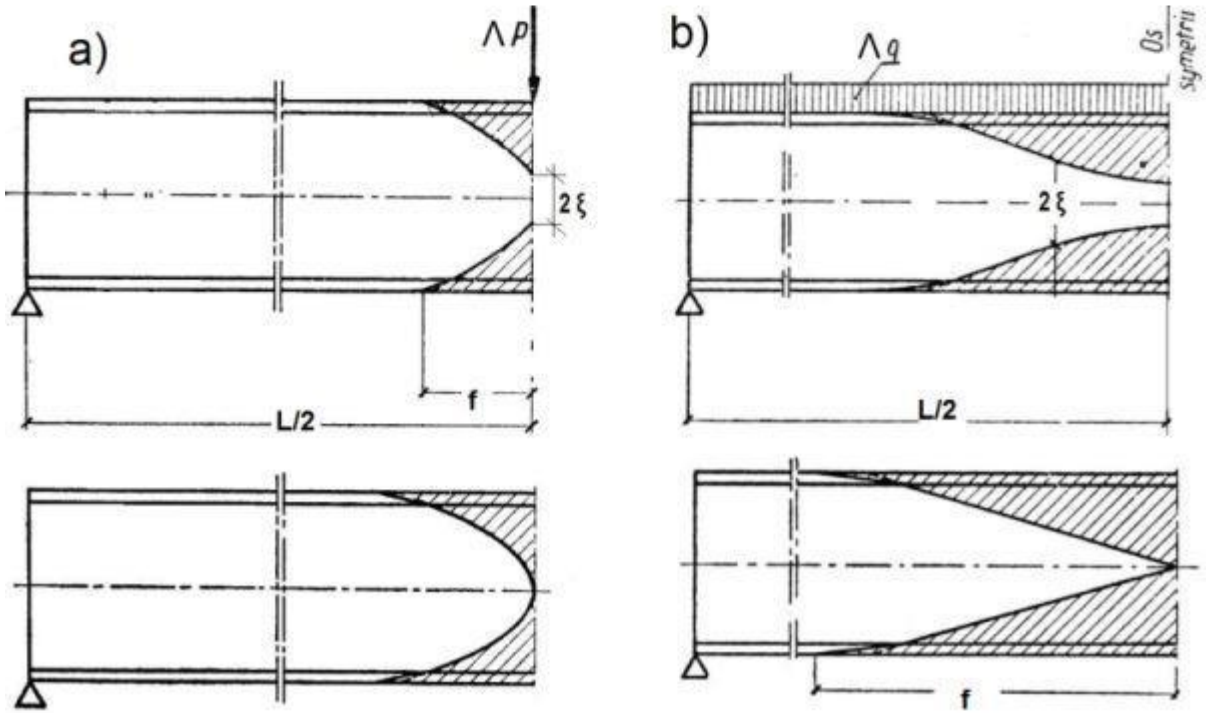


Photo: chodor-projekt.net

Taking into account elastic and elastic-plastic zone causes that plastic hinge should be treated as an area, not a point. Additional effects of elasticity and plastic elasticity should be taken into account (e.g. deflection values are different than in rigid-plastic method).

Non-linear plastic analysis is the most complex type of analysis. It includes not only development of plastic front as a function of applied load, but also issue of impact of deformation on distribution of cross-sectional forces (second order effects) and issue of forms of loss of stability.

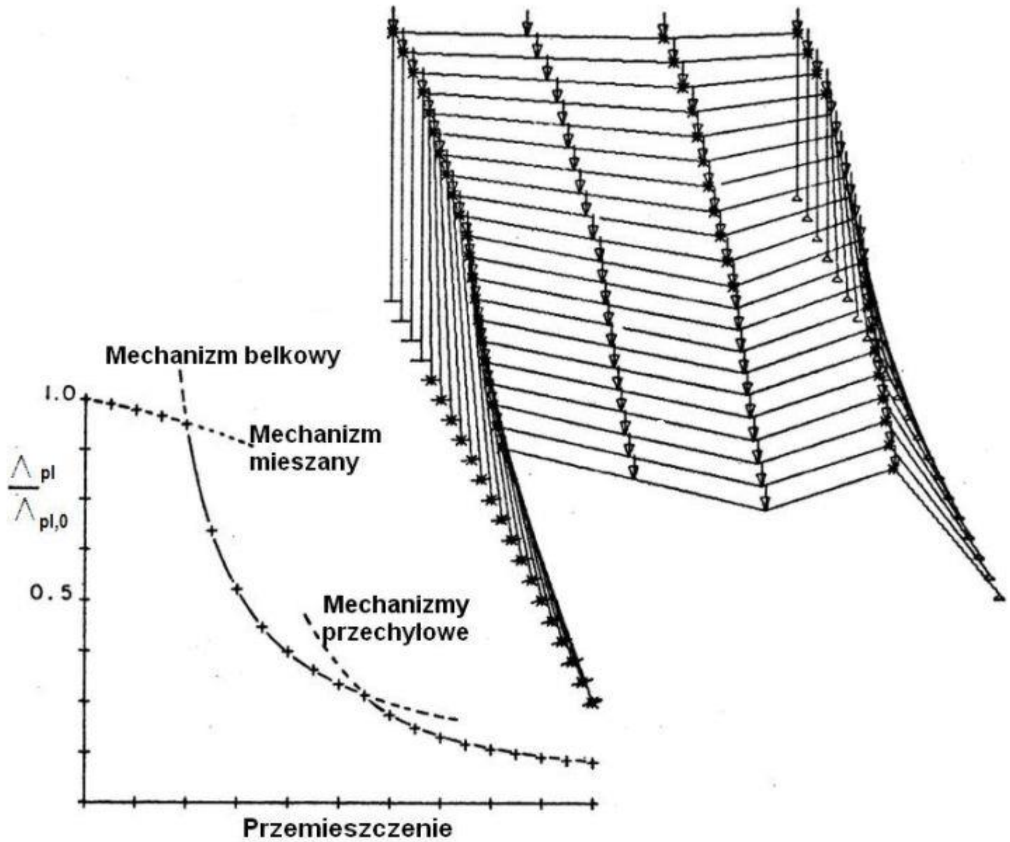


Photo: chodor-projekt.net

For example: a complex equilibrium path, taking into account fact of increasing compressive forces in girder due to deformation of frame and secondary effects from compressive forces.

Rigid-plastic analysis (the simplest) assumes that structure consists of segments with infinite stiffness, connected by joints existing in structure from the beginning or by plastic hinges. Joints and hinges are simplified to a points. This method is used in calculation of redistribution of bending moments in beams.

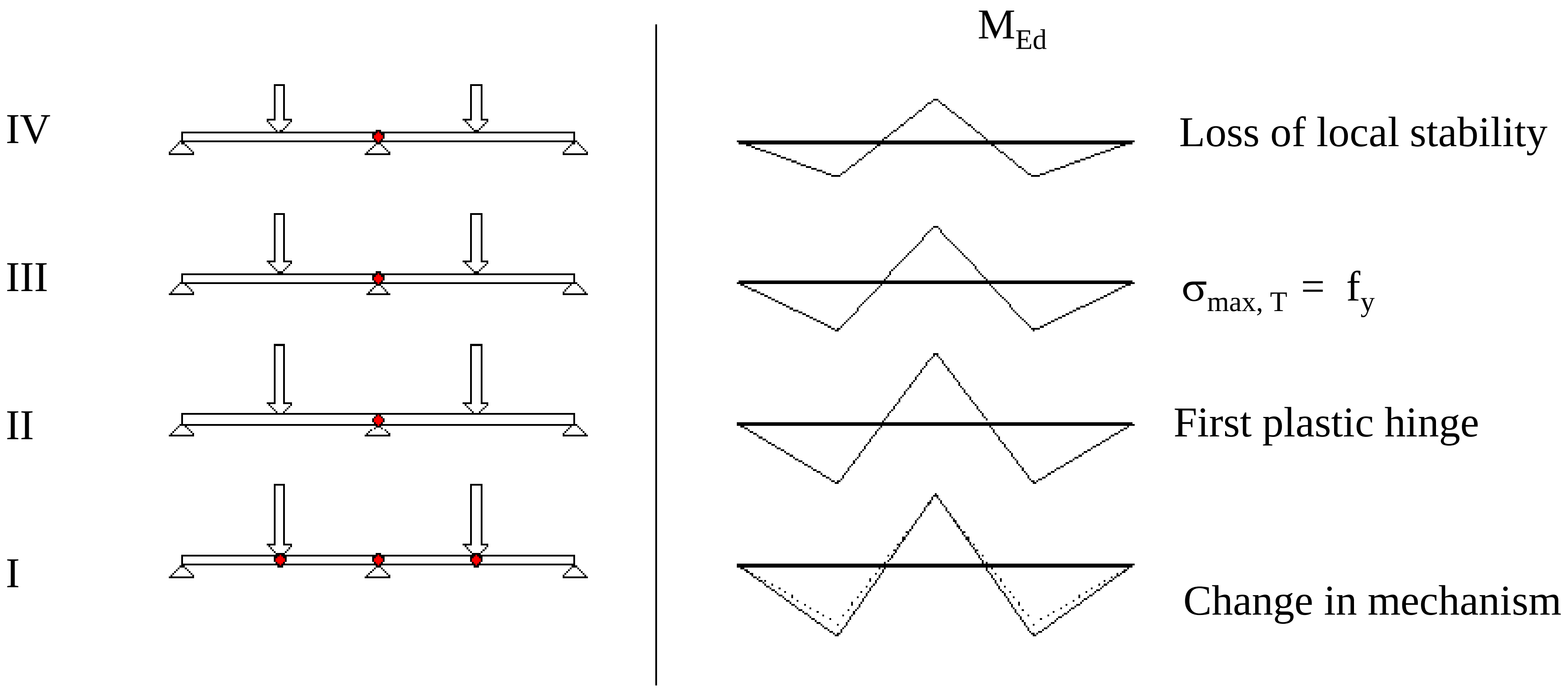
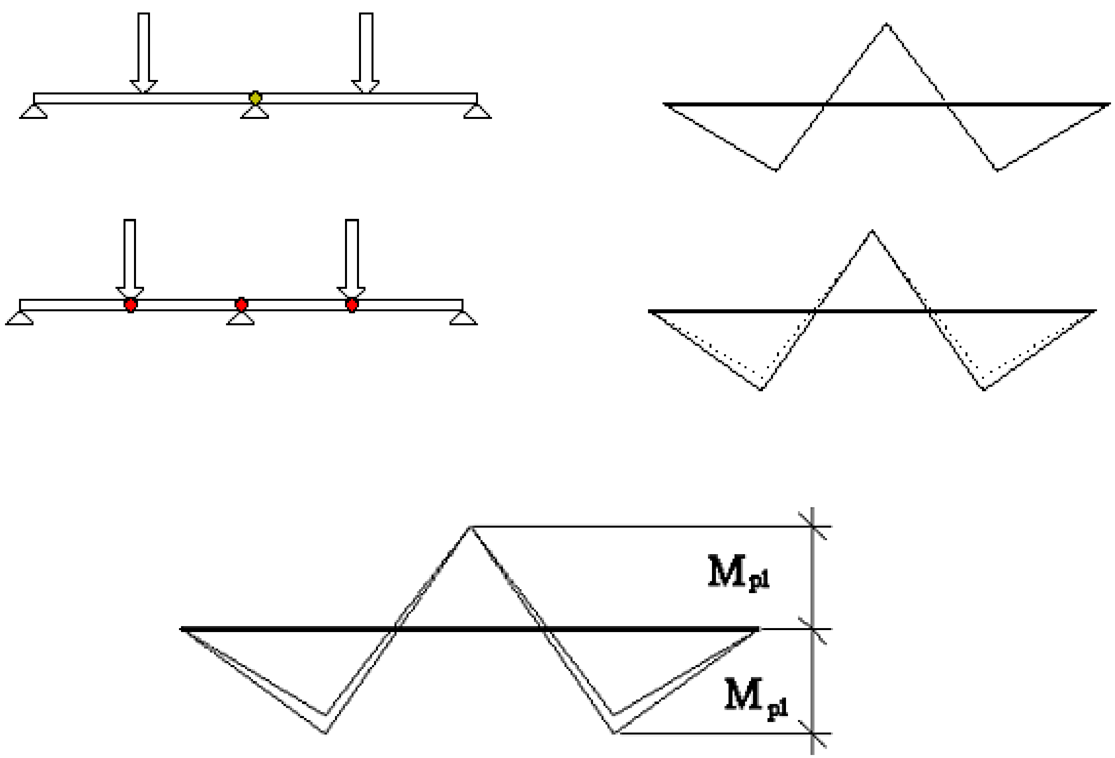


Photo: Author

Rigid-plastic analysis (the last of above) is usually sufficient to perform calculation. An example would be analysis of redistribution of bending moments on a multi-span beam and formation of subsequent plastic hinges. Each creation of hinge changes static scheme and loading of beam (plastic hinge and plastic moments in hinge). Destruction occurs when there are so many hinges that the beam turns into a mechanism.



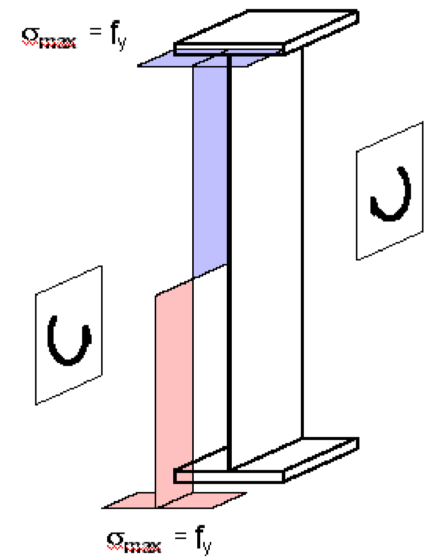


Photo: Author

It is analogous in case of frames - only that here it is not always easy to determine order and places of creation of plastic hinges. An easy case is the symmetrical load on the symmetrical frame.

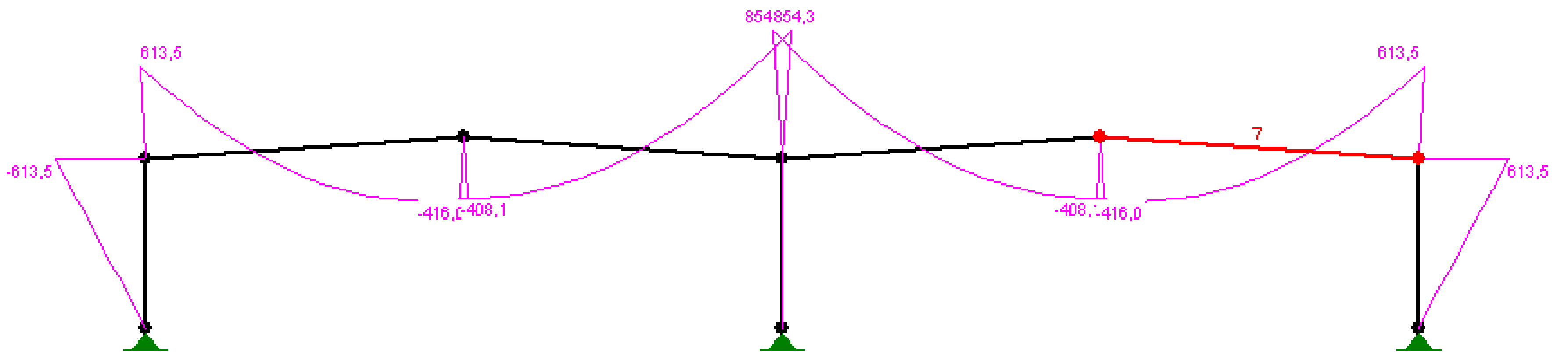
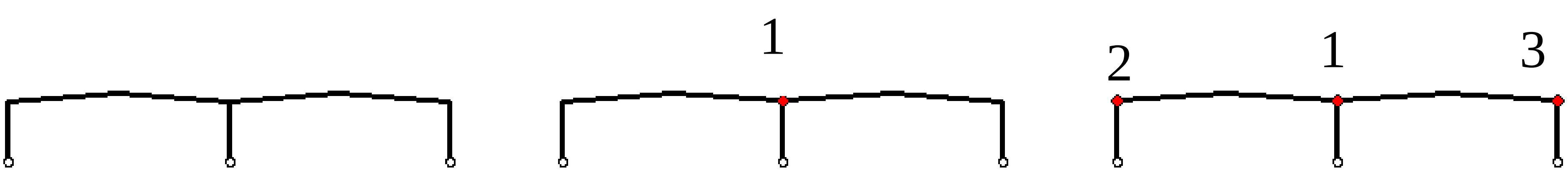


Photo: Author

Before redistribution: $M_{Ed.,\,1} = W_{pl}\, f_y > M_{Ed.,\,2} = M_{Ed.,\,3}$



After full redistribution (change in mechanism): $M_{Ed.,\,1} = M_{Ed.,\,2} = M_{Ed.,\,3} = W_{pl}\, f_y$

Rotation capacity of joint is sufficent for create plstic hinge, when (EN 1993-1-8 6.4):

- Rotation capacity $\geq 1{,}5^{\Psi} M_{j,Rd} / S_{j,ini}$
- Joint is full-strength

Joint	$M_{j,Rd}$ govered by	Additional requirement	Rotation capacity ϕ_{Cd} [rad]
Bolted	Web column in shear	$d_w / t_w \leq 69\,\varepsilon$	Sufficient for plastic analysis, if additional requirements are satisfied
	Flange column in bending or end-plate or flange cleat / flange plate	$t_p \leq 0{,}36\, d \sqrt{(f_{ub} / f_y)}$	
Welded		No horisontal stiffeners on column	$\geq 0{,}015$
	NO web column in shear	Horisontal stiffener only in compression part of column	$\geq 0{,}025\, h_c / h_b$

In case of beams, it is not necessary to check rotation capability. It is enough, if multi-span cnotinous beam is Ist class of crosss-ection.

Classification of joints according to various methods:

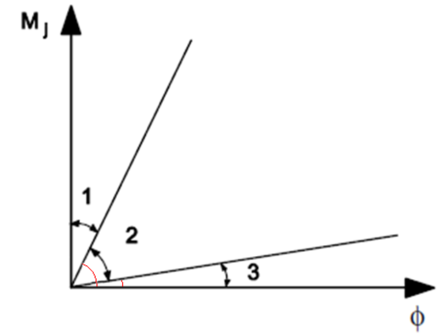
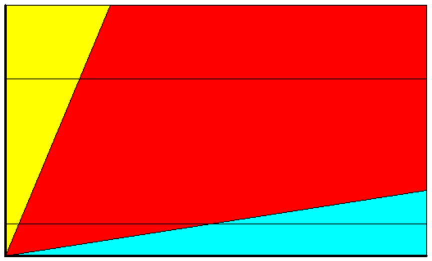
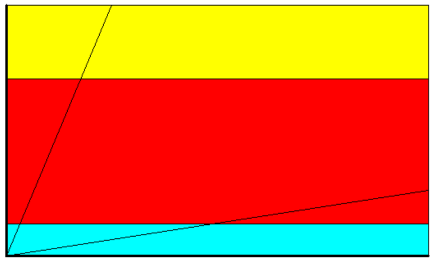
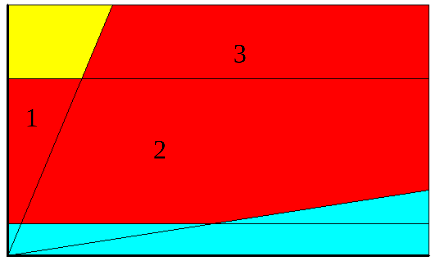


Photo: EN 1993-1-8 fig 5.4

Photo: Author







Elastic ($S_{j,\ ini}$, Lec #14, #15):

Pinned

Semi-rigid

Rigid

Rigid-plastic ($M_{j,\ Rd}$):

Nominally pinned

Partial-strength

Full-strength

Elastic-plastic ($M_{j,Rd}$):

Nominally pinned

1. rigid and partial-strength
2. semi-rigid and partial-strength
3. semi-rigid and full-strength

Full-strength

Elastic and plastic analysis for stiffness of joint:

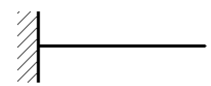
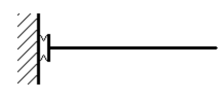
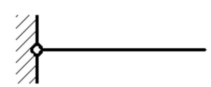
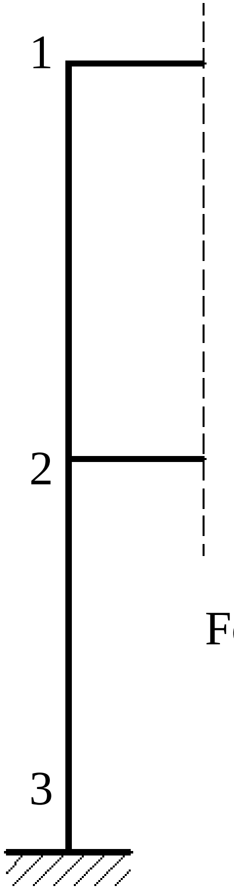
Analysis	Elastic	Model of joint	Plastic
Joints cassified according to	$S_{j,\ ini}$		$M_{j,\ Rd}$ and ϕ_j
Types of joint	Rigid		Full-strength
	Semi-rigid		Partial-strength
	Pinned (hinge)		Nominally-pinned

Photo: Author

→ #14 / 81

Photo: Author

Classification of joints according to rigid-plastic method (proportion between resistance of beam/column and joint).



$M_{full\text{-}strength}$ = (function of resistance of beam and column)		
	1	min ($M_{c,\ pl,\ Rd}$; $M_{b,\ pl,\ Rd}$)
	2	min (2 $M_{c,\ pl,\ Rd}$; $M_{b,\ pl,\ Rd}$)
	3	$M_{c,\ pl,\ Rd}$

For each joints we calculate resistance $M_{j,\ Rd}$

Type of joint:	$M_{j,\ Rd}$ (resistance of joint)
Full-strength	$\geq M_{full\text{-}strength}$
Partial-strength	0,25 $M_{full\text{-}strength}$ - $M_{full\text{-}strength}$
Nominally-pinned	$\leq$ 0,25 $M_{full\text{-}strength}$

EN 1993-1-8 5.2.3.2, 5.2.3.3

If

$$M_{j,\,Rd} \geq 1{,}2\; M_{full\text{-}strength}$$

plastic hinge occurs in beam or column, not in joint. There is no need to calculate rotation capacity of joint.

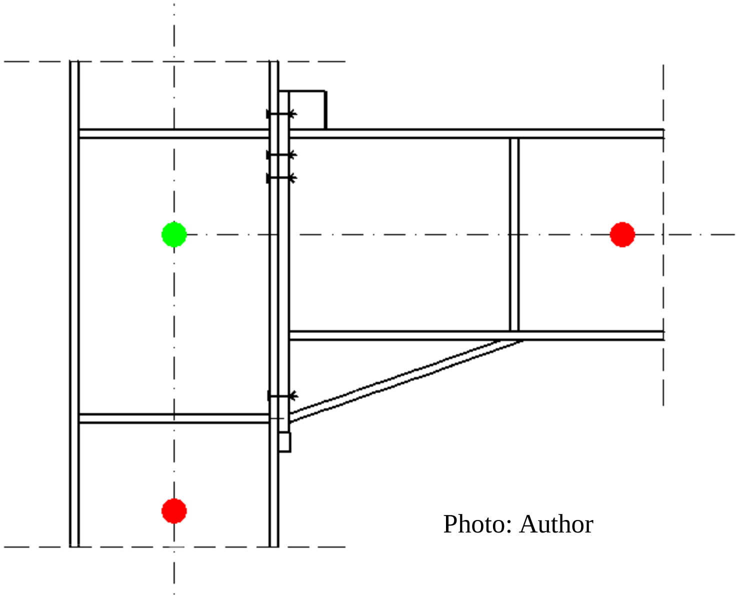
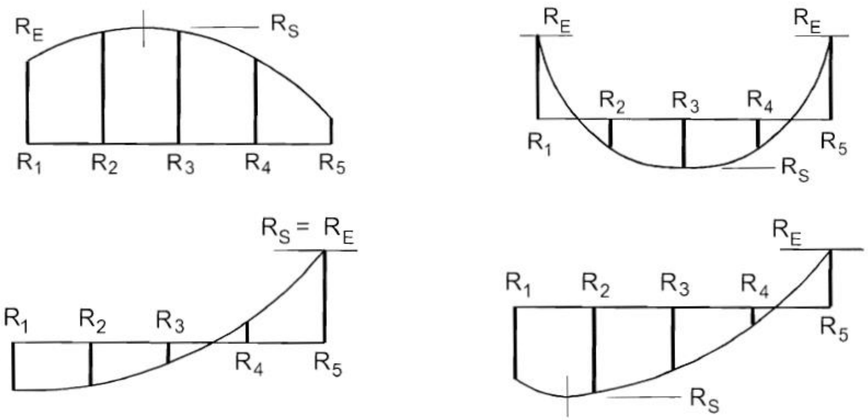


Photo: Author



EN 1993-1-1 fig BB.5

Tests and experiments on full-scale models and nummerical analysis show, than behavior of structure in plastic range looks differently in the case of loss of stability, and differently without loss of stability. Rules presented in Eurocode concern situation without loss of stability. Many additional requirements for max distance between plastic hinge and bracing are presented EN 1993-1-1 app. BB3. Satisfying of there requirements prevent structure from loss of stability in plastic range.

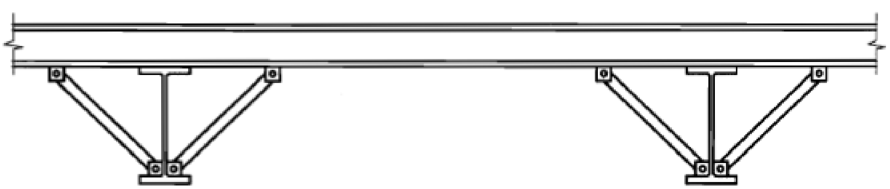
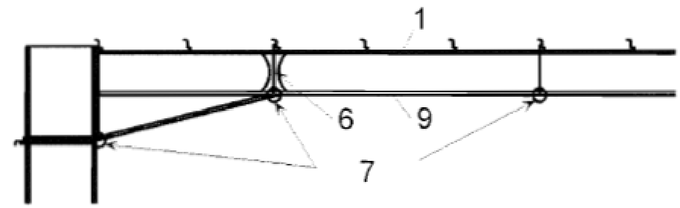
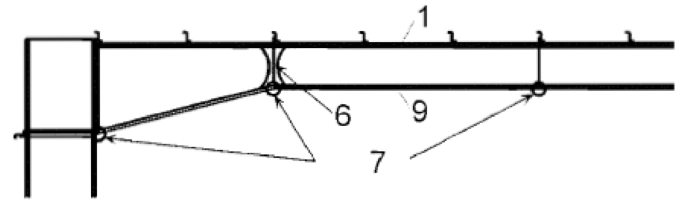


Photo: EN 1993-1-1 fig 6.5



EN 1993-1-1 fig BB.2



For multi-span and multi-level frame and for many various combinations of loads, there can be not clear, what is order of occuring plastic hinge. In this case we should take into consideration two theorems:

1. Kinematic Theorem: *the structure becomes a mechanism (destroyed), if the kinematically admissible displacement fields increase the work of external forces is equal to the growth of the work of the internal forces (upper limit of plastic resistance).*

2. Static Theorem: *the structure will not be destroyed if for a given load can be found statically admissible stress field (lower limit of plastic resistance).*

These Theorems allow estimation of plastic resistance from below and above. We are not always able to provide exact value of plastic resistance.

Photo: Author

Way of calculation: based on Principle of Virtual Works, we determine destruction scheme at which virtual work is the lowest and corresponding destructive load (kinematic upper estimation).

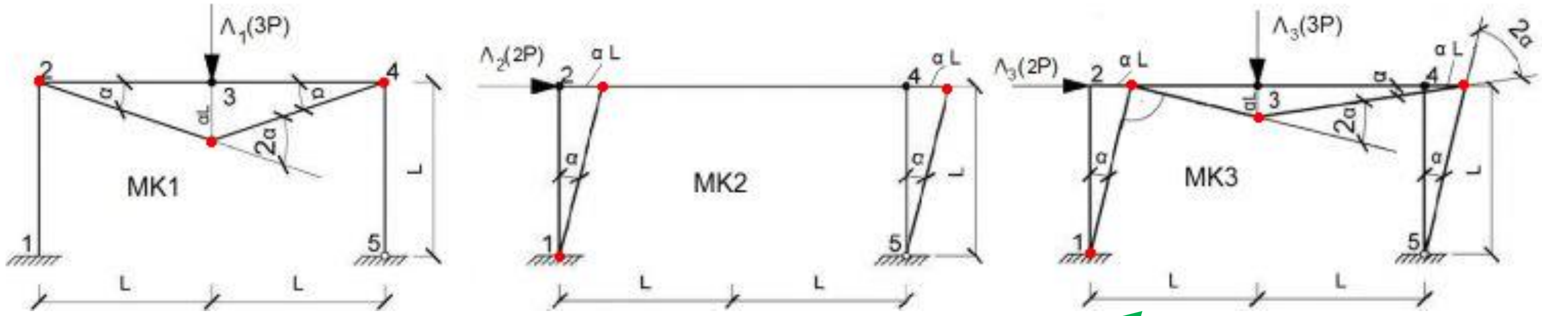


Photo: chodor-projekt.net

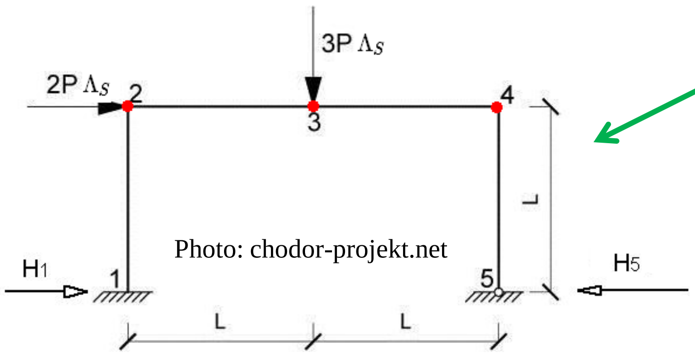


Photo: chodor-projekt.net

Then, for previously determined destruction scheme, we analyze balance of loads and reactions (static lower estimation). After taking into account plastic hinges, scheme is statically determinate

Example:

L = 5 m,   P = 90 kN

Horizontal force = 180 kN (2x90 kN)

Vertical force = 270 kN (3x90 kN)

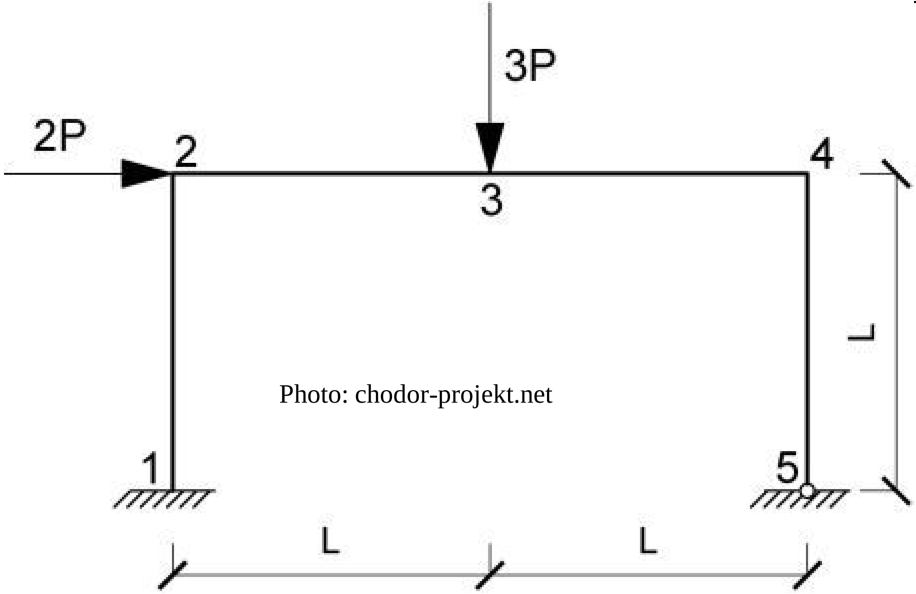


Photo: chodor-projekt.net

Global analiysis	Cross-section of columns and girder	Mass of one frame	Conclusion
Elastic („classical" calculation)	IPEO 450	1848 kg	
Plastic (static and kinematic estimation)	IPEA 500	1588 kg	Frame is 14% lighter

Construction details

In steel structure, specific solutions are sometimes found, different from the most common ones presented previously. They concern shape of building, static scheme and types of nodes.

Photo: bryla.pl

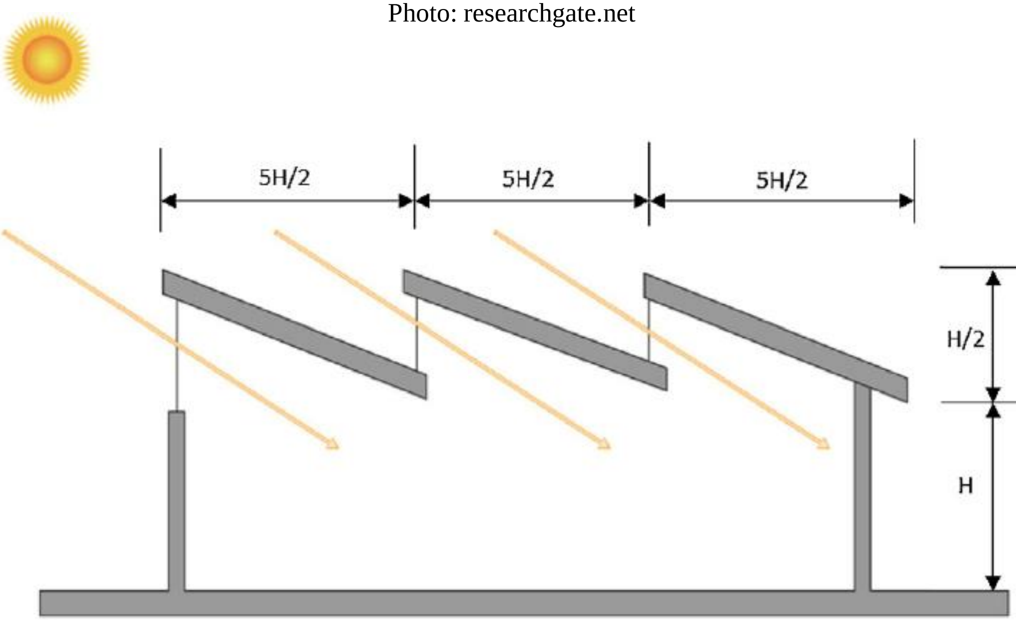
Photo: rosahale.pl

Photo: konar.eu

Light inside building

Photo: globalprayers.info

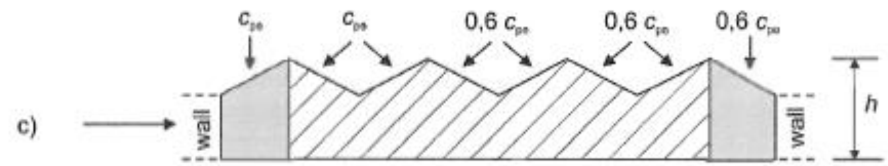
Photo: researchgate.net



One of problems with using large spans halls is lack of light. To avoid costs related to electric lighting, halls are illuminated with sunlight by means of skylights or windows in saw-tooth roofs.

Specific type of snow and wind action must be analised in case of saw-tooth roof.

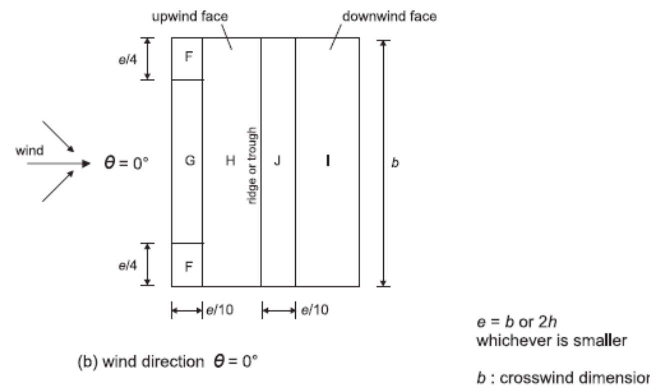
Photo: bryla.pl

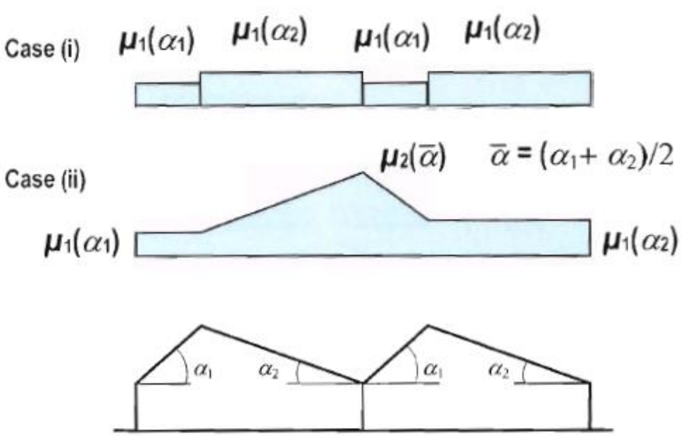


Wind

EN 1991-1-7 fig. 7.10

"Prependicular" wind - the same for first, second and third roof slope, 60% for next.





Snow

Photo: EN 1991-1-3 fig. 5.4

"Parallel" wind - no difference for one-span and multi-span roof

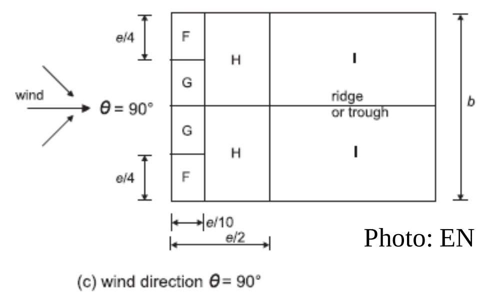


Photo: EN 1991-1-4 fig. 7.7


Photo: pl.all.biz


Photo: euroexport.pl

Modern skylights are system solutions.

In case of ridge skylight, additional bracings mus te mouted unfer edges of skylight.


Photo: euroexport.pl

Photo: imagecomtech.com

Photo: wascoskylights.com

Skylights allow you to get interesting architectural solutions.

Photo: kingspan.com

Photo: skyspec.com

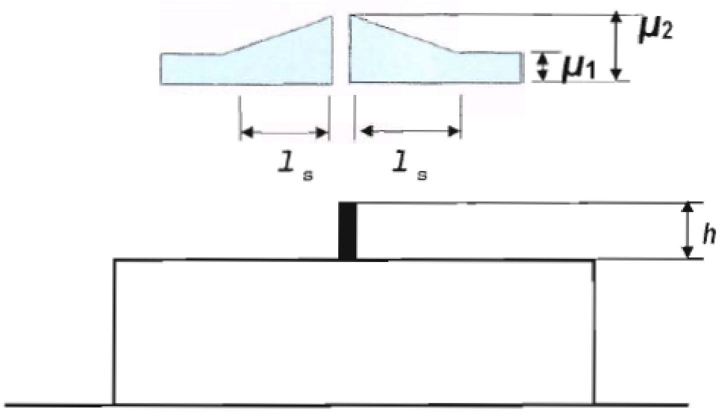


Photo: EN 1991-1-3 fig. 6.1

Of course, skylights are obstrucles, which can make collection of snow drifts on roof.

Photo: coastalengineeringcompany.com

Prefabricated systems of halls

According to information, presented on #t / 6, there are only deadweight and climatic load act on „light" halls. In many cases there is no other type of loads and actions.

Idea of prefabricated system: hall consists of a repetitive system parts of modular sizes. Calcuated is for the worst climatic action in country. Various dimensions of hall are obtained by using various sizes of components.

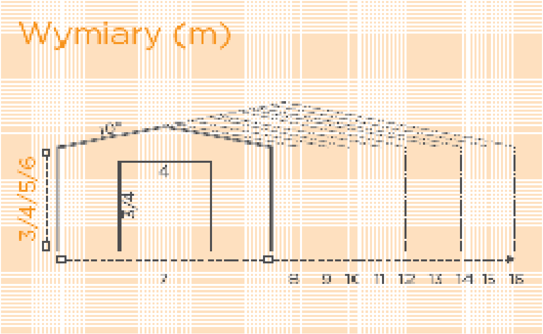


Photo: frisomat.pl

Photo: tgpolska.com

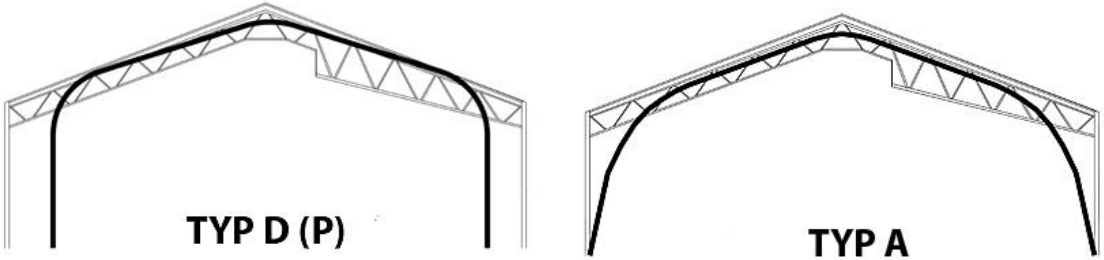


Photo: tgpolska.com

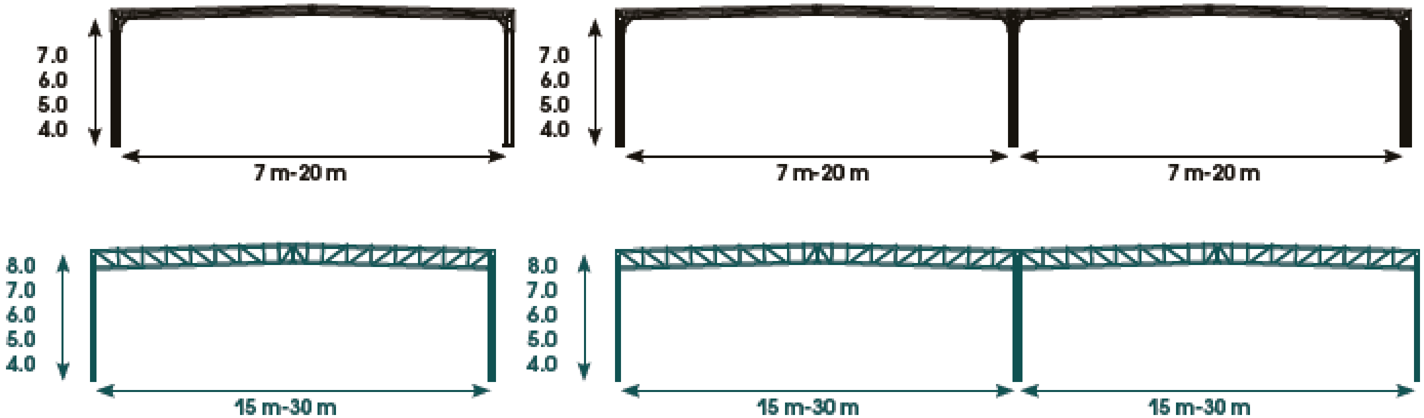
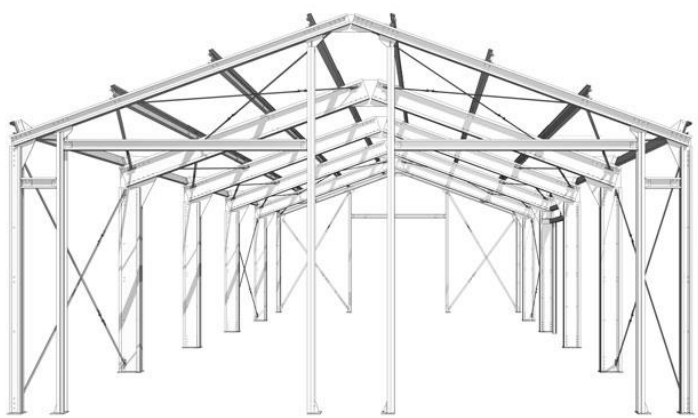


Photo: frisomat.pl



Prefabricated hall systems allow a good adaptation of hall size to needs and size of plot.

Photo: besta-hale.pl

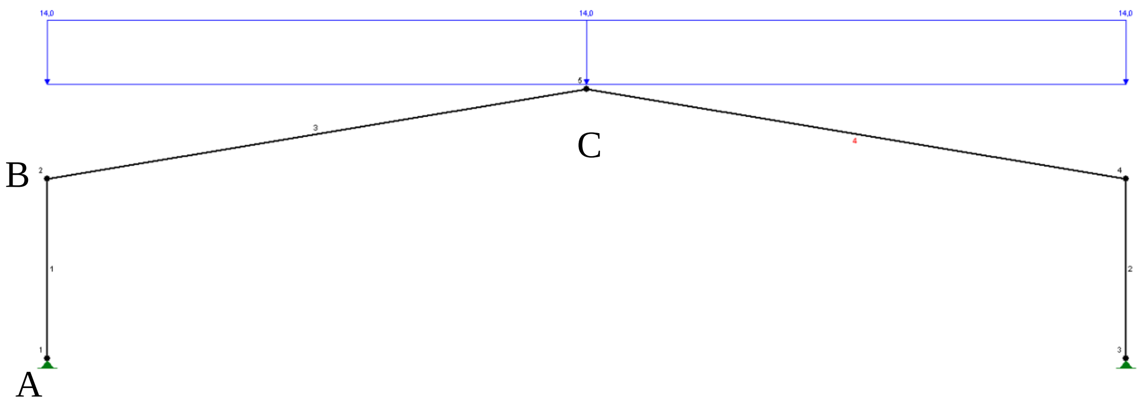
Tied portal frame

Enormous reduction of bending moments in roof girders and columns, enoromus tensile force in tie-beams

Photo: lindab.com

Portal frame vs. tied portal frame

Two frames, span 2 x 15,00 m, height 5,00 + 2,50 m, continous load 14 kN / m:



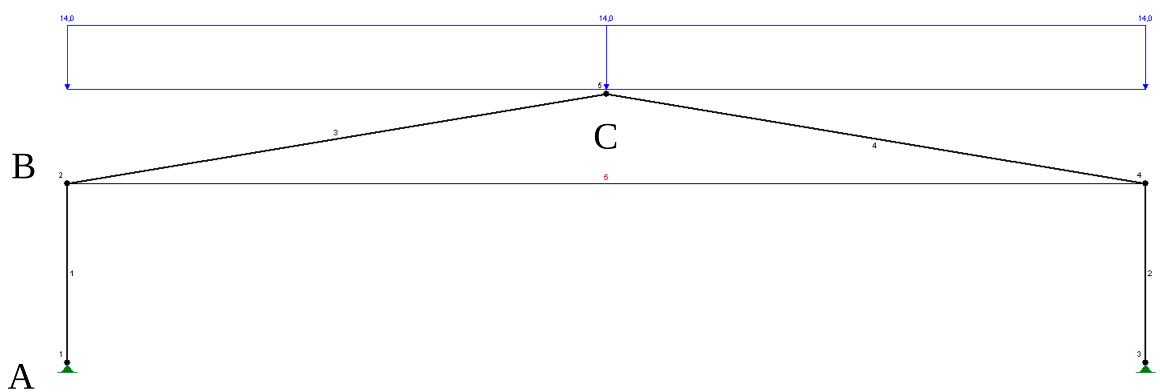


Photo: Author

Member	Point	Portal frame			Tied portal frame		
		M_{Ed} [kNm]	V_{Ed} [kN]	N_{Ed} [kN]	M_{Ed} [kNm]	V_{Ed} [kN]	N_{Ed} [kN]
Roof girder	C	375,8	28,4	170,2	271,1 (0,721)	112,0 (3,944)	708,6 (4,163)
	$M_{opposite}$	-403,6			-163,2 (0,404)		
	B	862,6	191,2	206,8	237,7 (0,276)	107,6 (0,563)	672,0 (3,250)
Column	B	862,6	172,5	222,6	237,7 (0,276)	47,5 (0,275)	222,6 (1,000)
	A	0,0	172,5	226,8	0,0	47,5 (0,275)	226,8 (1,000)
Tie beam							- 633,7

Cooling halls

Photo: rosahale.pl

Photo: traskostal.pl

Photo: obud.pl

In most cases, main structure of hall is hidden under housing. Opposite in case of cooling halls - main structure is very often visible outside.

Photo: miesiecznik.murator.pl

This is result of fundamental principle: thermal insulation between main structure and low temperature.

In most cases, structure must be protected from outside from cold winter temperatures. For cooling halls, low temperature is indoors, regardless of season. In such situation, thermal insulation is placed inside, main structure – outside.

Roofs witout purlins

Purlins are not always used in roof structure. It is possible to use corrugated sheets with high fold height. They are rigid enough to support external loads (dead weight, climatic loads) if are arranged perpendicular to the axis of the girders.

Photo: cobouw.pl

Photo: g-5.pl

Photo: Author

Other example of such solution could be concrete channel slabs, supported by girders.

Also self-stable arch roofs made by corrugated sheet.

Photo: elbet.pl

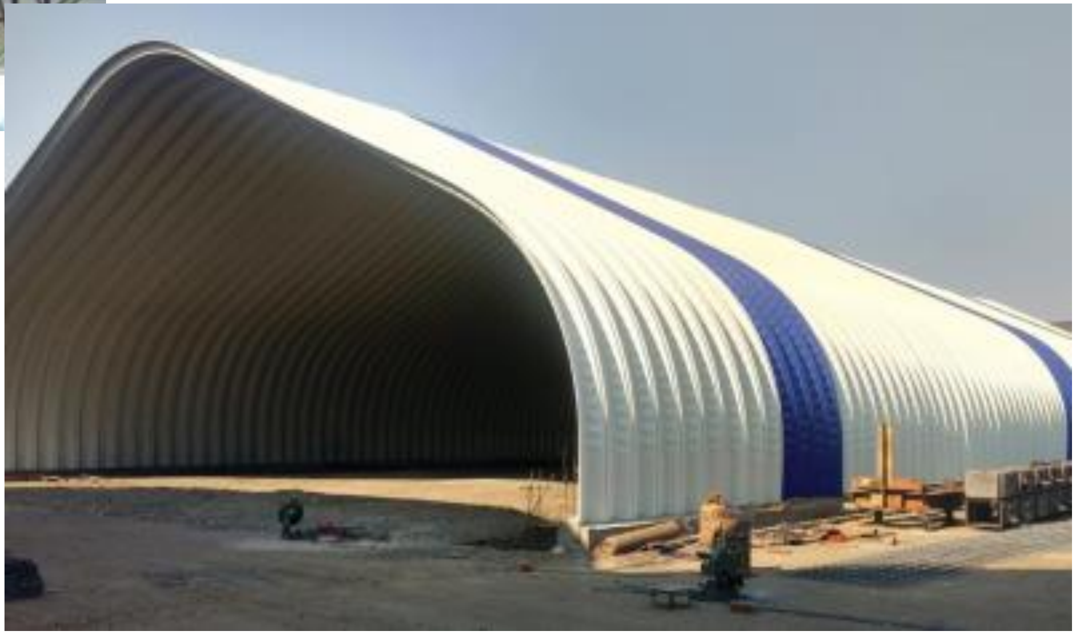


Photo: surfacesreporter.com

Mix structure

Photo: bca.gov.sg

Photo: deltabi.it

Some economical analysis suggest, that system "steel girder - concrete column" is cheaper than both steel girder and column.

Front wall

Vertical loads applied to roof girder depend on distance between girders. For this reason, load on front frame is half load compared to others. It is possible to use a smaller front frame or completely eliminate it.

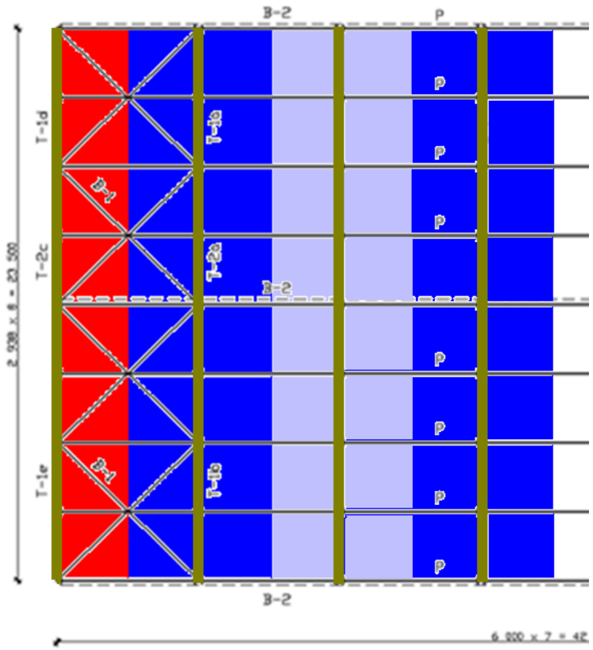


Photo: Author

Photo: konar.eu

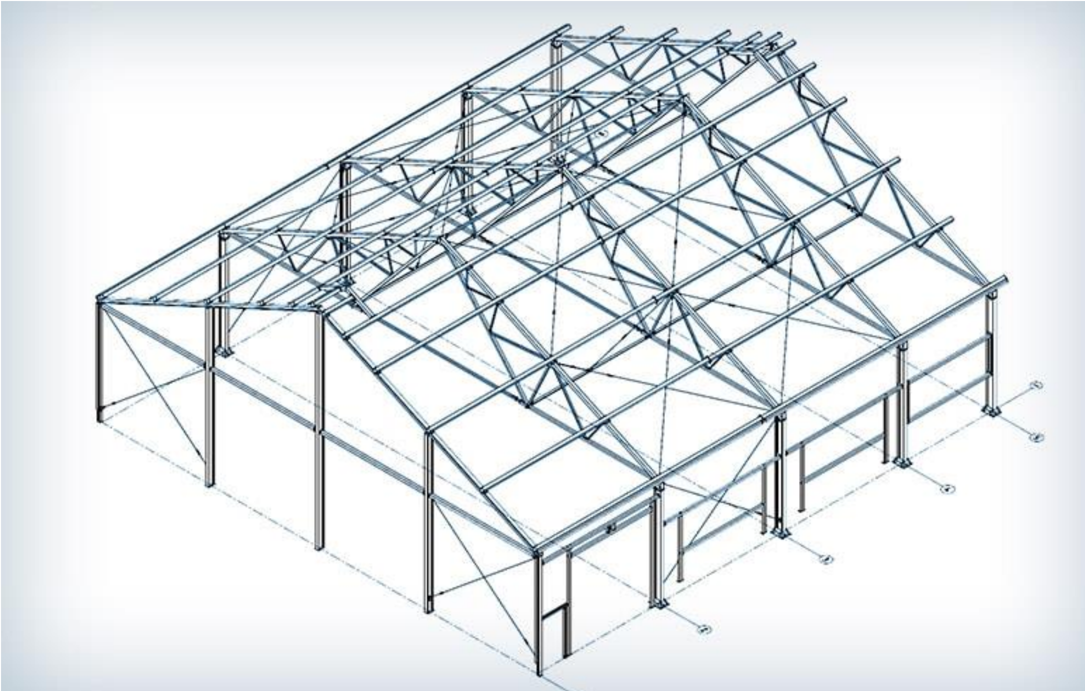


Photo: budvision.pl

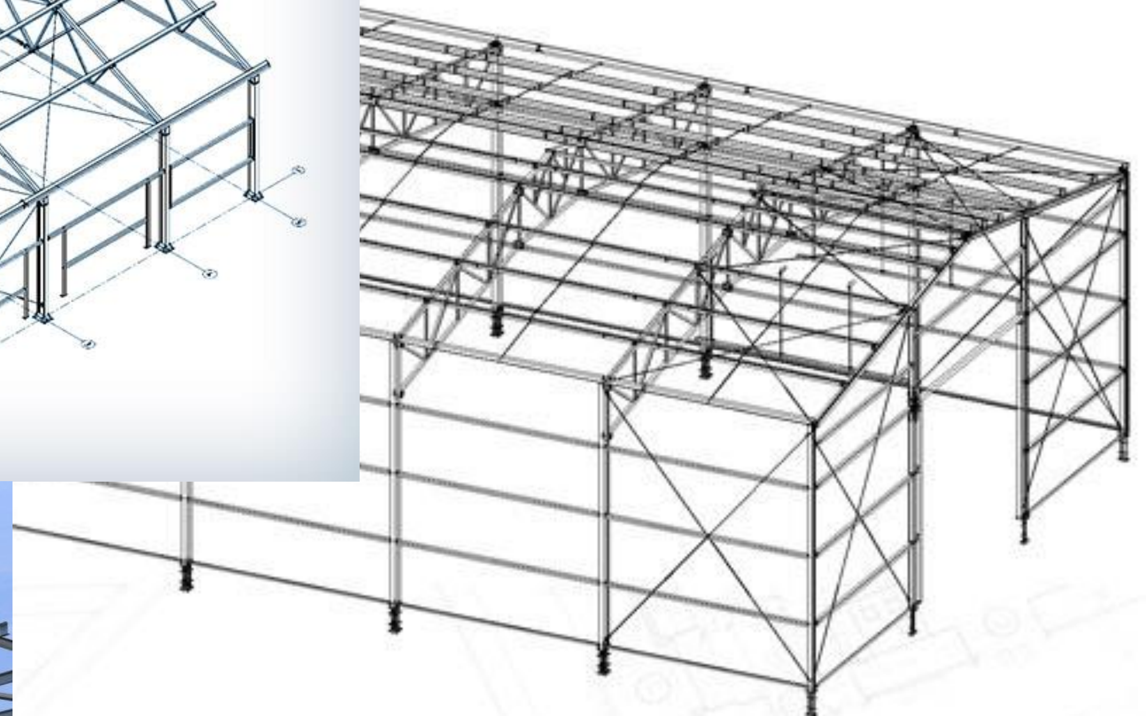


Photo: cobouw.pl

Photo: biznes-mentor.pl

This solution is one of only few cases when vertical bracing will be need in front wall.

Super-light hall

Photo: besta-hale.pl

Photo: metalfach.com.pl

Super-light hall means hall made of cold-formed sections. Often It is a solution of a prefabricated hall.

Structure looks like made by „normal” I-beams. In real they are couples of cold-formen C-sections.

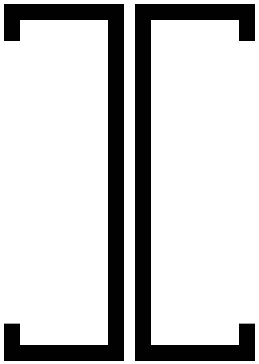


Photo: Author

Photo: skeleton.pl

Obtaining sufficient stiffness and resistance of rigid joints in this case can be problematic. Therefore, a specific static scheme of structure is often used.

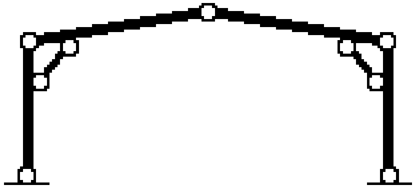


Photo: Author

Ridge joint

Photo: steelgram.co.uk

Photo: thorndell.com

Two parts of roof girder connected in ridge of hall.

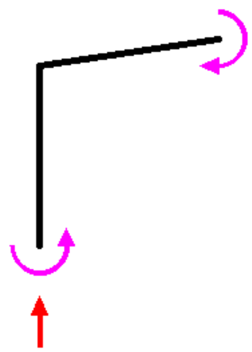
For stiffness: parameters k_i for left and right beam and end-plate.

For resistance: left and right end-plate in local bending, left and right web of beam into local tension, left and right top flange of beam in local compression.

Horizontal tension bolted joint

Photo: konar.eu

Rare solution there is a horizontal tension bolted joint. In such joint we deal with a completely different distribution of forces and completely different phenomena in comparizon to vertical tension bolted joint.



Beam: bending moment, neglected value of axial force

Column: bending moment, important value of compressive axial force

Photo: Author

Photo: uwyo.edu

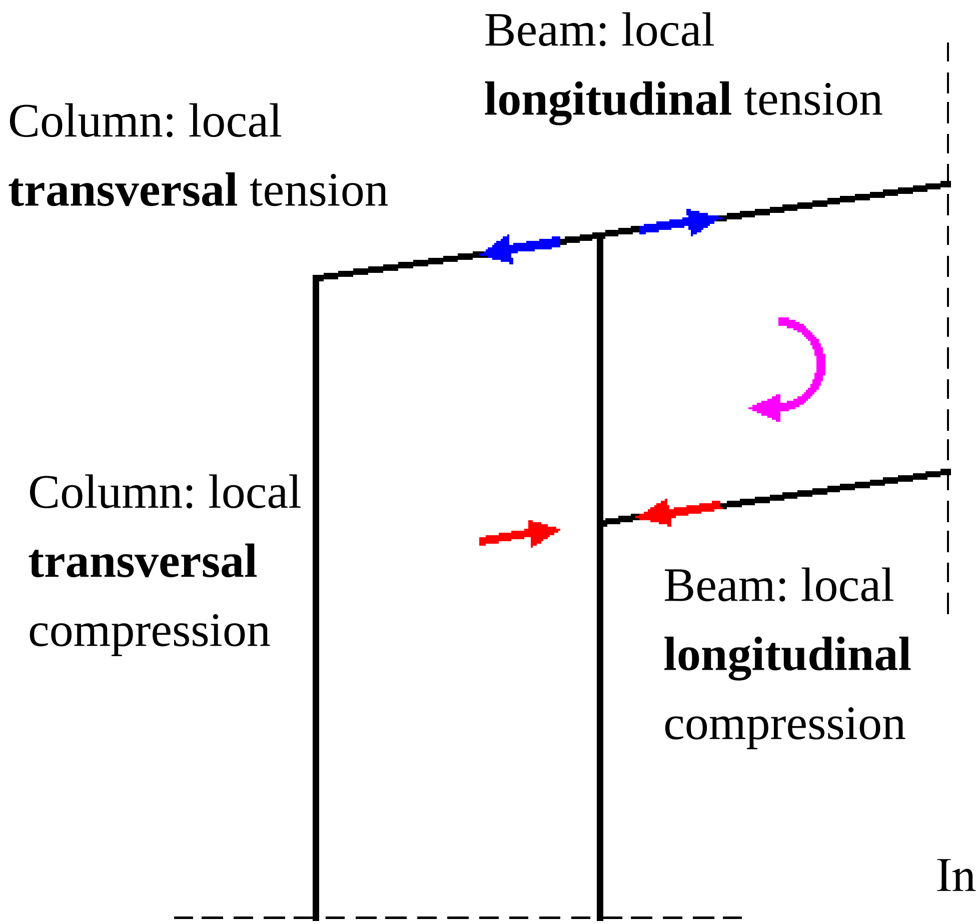


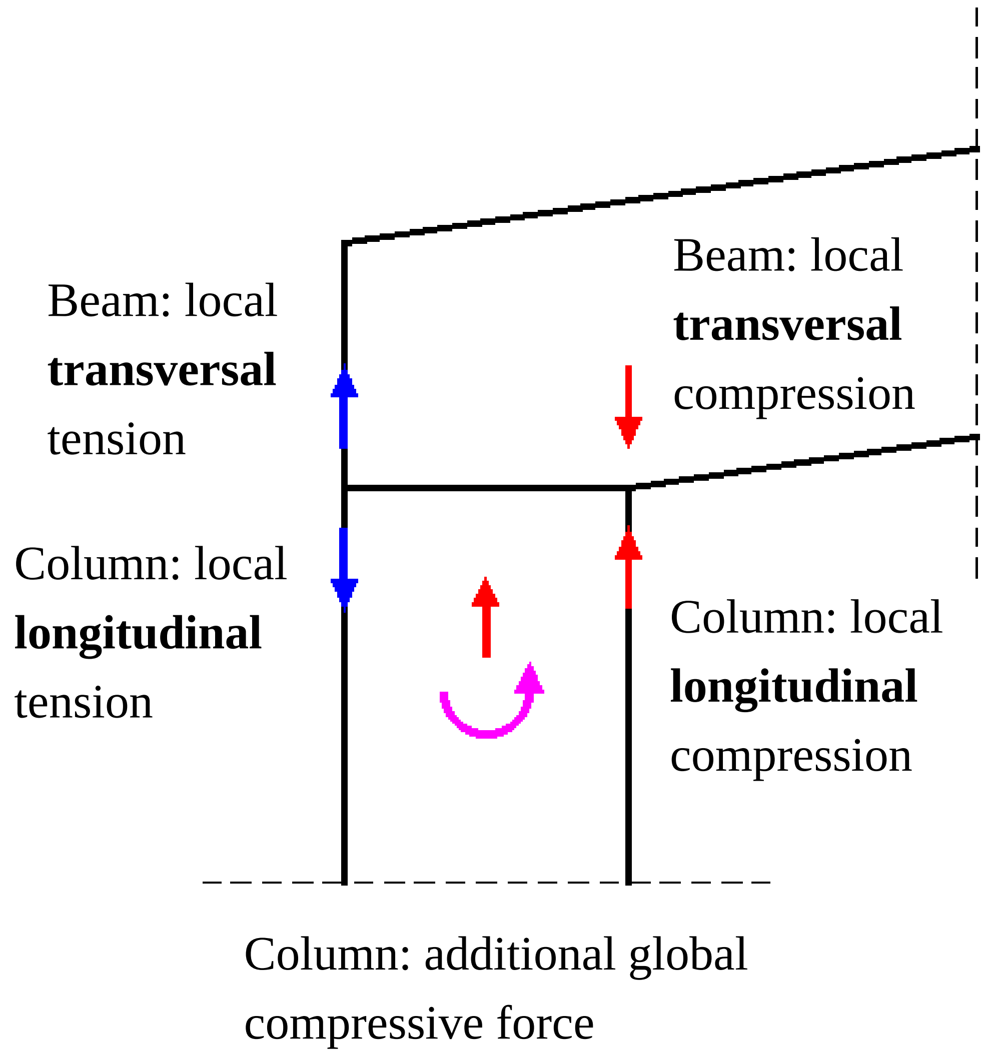
Photo: Author

Photo: uwyo.edu

In „classical" (vertical) tension joint, local loads in column are transversal, in beam are longitudinal.

Photo: wymiar.eu

Photo: Author



In horizontal tension joint, oppisite to vertical, local loads in column are longitudinal, in beam are transversal.

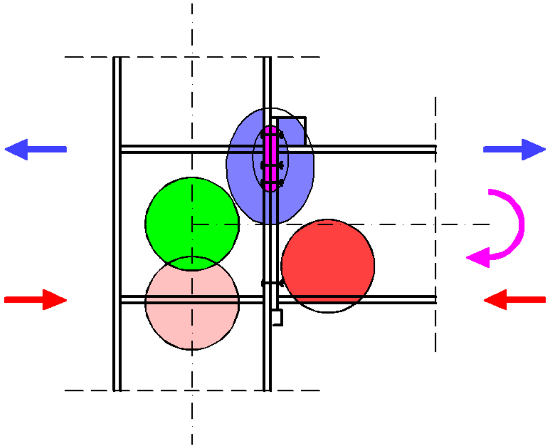


Photo: Author

Calculation for vertical tension joint:

- column for transversal phenomena;
- plate for bending;
- beam for longitudinal phenomena.

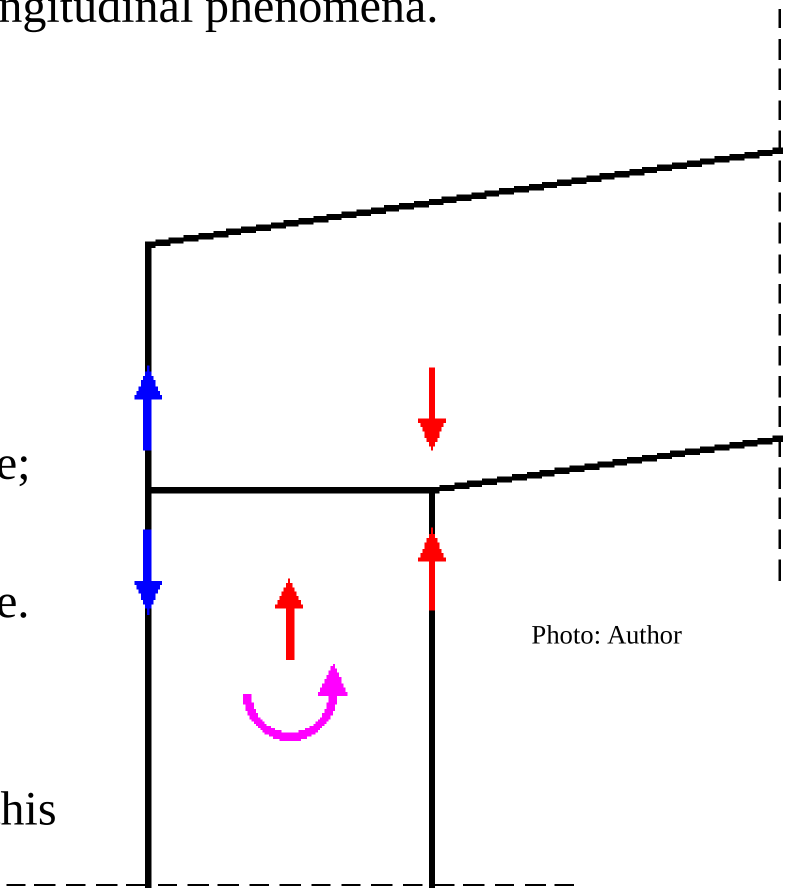


Photo: Author

Calculation for horizontal tension joint:

- column for formulas according to beam in vertical one;
- plate for bending;
- beam for formulas according to column in vertical one.

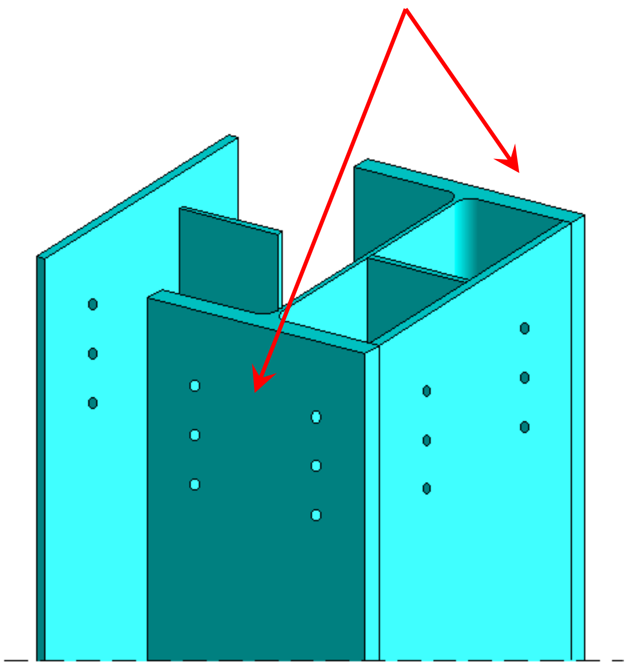
Additional problem is globa laxial force in column.
Formmulas presented in eurocode could be applied, if this force is no greater than 5% resistance.

Rigid joints in skeletons

For rigid joint, stiffness and resistance must be checked.

Tension bolted joint, "classical" calculation on web's face:
stiffness (→ #14 / 85-91, #15, proj #3)
resistance (→ #19, proj #3)

Tension welded joint, calculation on web's face:
stiffness (→ #14 / 85-91, #15)
resistance (→ #19)



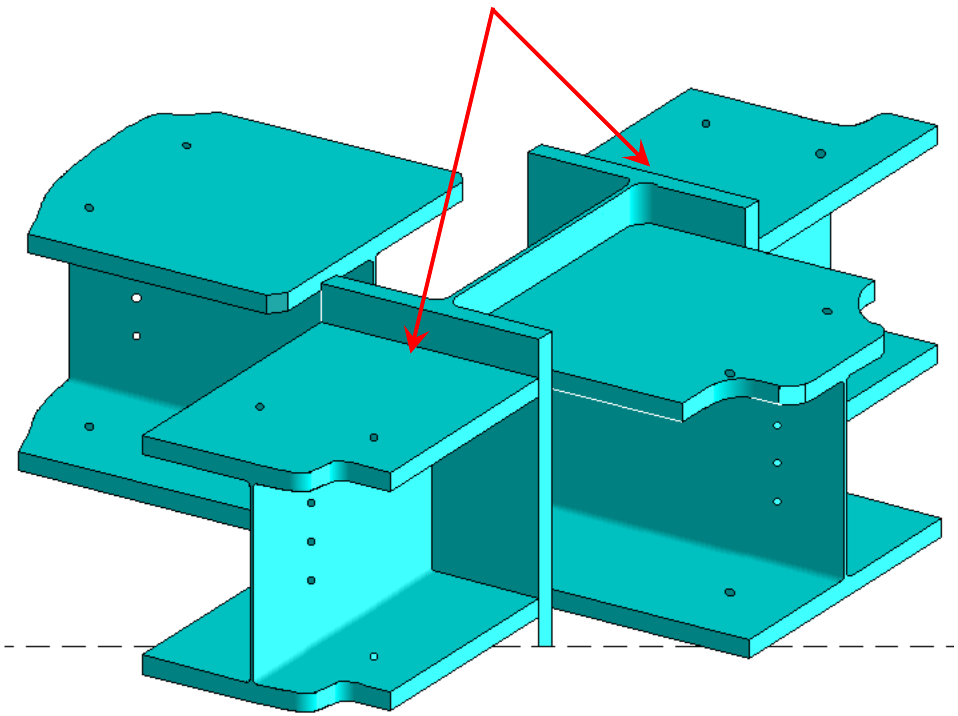


Photo: Author

Flanges are horizontal stffeners on column's web, webs could be treated as diagonal stiffener on column's web.

Perpendicular direction: no detailed information in Eurocode.

Direct welding of column and beam flanges on inside of the column flanges – ideal rigid joint is assumed without detailed verification.

Welded joint - no loaded parts of column to verify resistance (→ #19 / 54); resistence results only from welds strength.

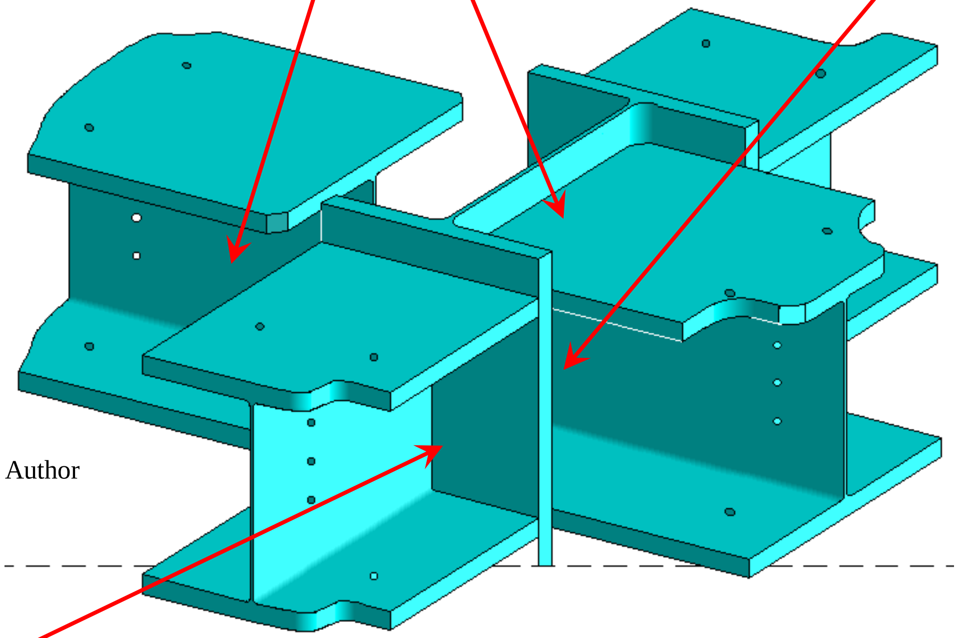
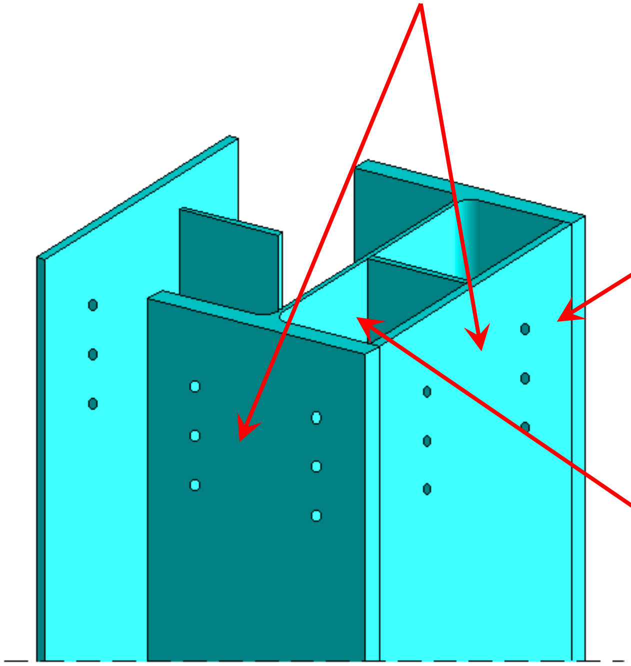


Photo: Author

Stiffness of joint with horizontal and diagolan stiffeners on column's web: ideal rigid without checking (→ #15 / 65, 66); resistance as fot joint with stiffeners on column's web; checking of welds strength.

The same calculation on both sides: tension bolted joint beam-column, contact between end plate and column's flange. The same calculation for stiffness and resistance.



No free flange edge, probably stiffness and resistance greater than would result from Eurocode formulas.

Troublesome welding process and bolts installation - small space available.

Photo: Author

Examination issues

"Light" hall and "heavy" hall, similiarities and differences

Impact of IInd order effects on calculation of steel hall

2D and 3D models, similiarities and differences

Elastic and plastic analysis, similiarities and differences

Main assumptions of plastic analysis

Sub-types of plastic analysis, characteristics

Hall and skeleton, similiarities and differences

Roofing - poktycie dachu
Housing - obudowa ścian
Tie-beam - ściąg
Tied frame - rama ze ściągiem
Ridge - kalenica
Eaves - okap
Drifting - zaspy
Multi-bay hall - hala wielonawowa
Multi-span roof - dach wieloprzesłowy (wielopołaciowy)
Saw-tooth roos - dach pilasty, dach szedowy

Thank you for attention

tmichal@pk.edu.pl