Metal Structures

Lecture VI

Imperfections

Contents

Introduction

Photo: fishki.pl

Photo: fishki.pl

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Photo: fishki.pl

Photo: prikol.ru

Photo: hourdose.com

Imperfections in steel structures are rather not such picturesque...

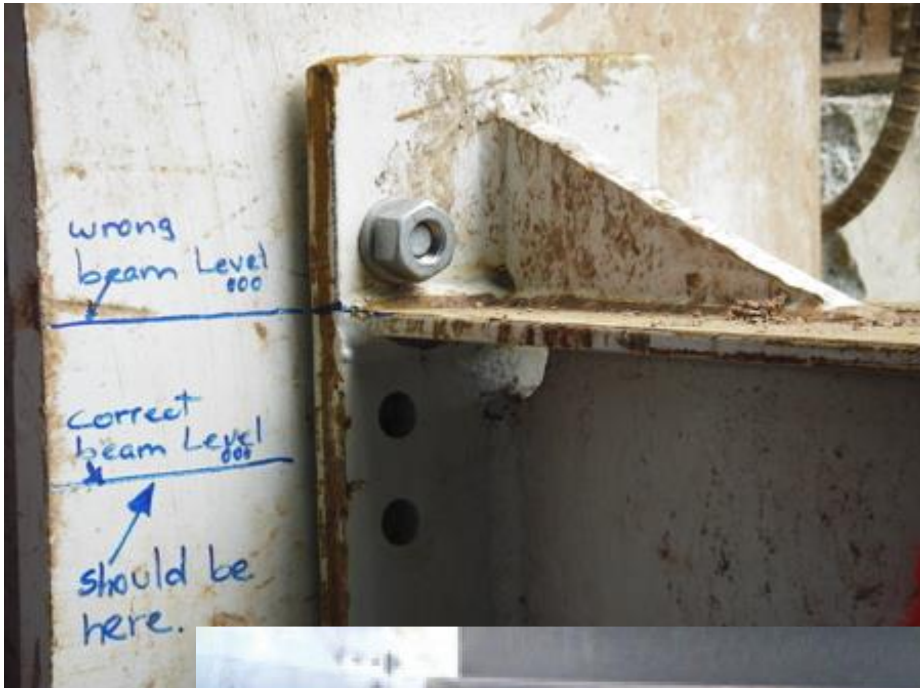

Photo: panama.uela.it

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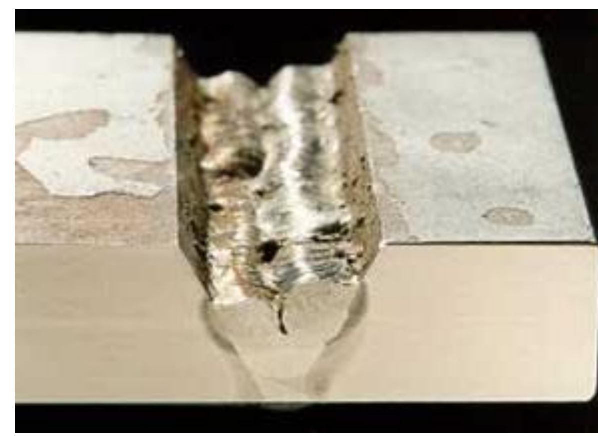


Photo: mig-welding.co.uk

Imperfection

Difference between ideal model of structure (theoretical charateristic of material and ideal geometry) – and real structure (real behavior of material, not ideal geometry)

Photo.: Autor

First labratory, measurements:

524 – 200 – 12 – 2,5

h_I :	b :	t_f :	t_w :
524 mm	198 mm	11,6 mm	2,9 mm
522 mm	202 mm	12,2 mm	3,0 mm
523 mm	199 mm	11,8 mm	3,1 mm
525 mm	200 mm	11,9 mm	2,8 mm
524 mm	199 mm	12,0 mm	2,9 mm
523 mm	200 mm	12,1 mm	2,4 mm
524 mm	201 mm	11,9 mm	2,50 mm
…	…	…	…

Some of these divergences are measurement errors. **But because of imperfection, the actual dimensions of the measured I-beam may differ from the ideal dimensions shown in the design tables.**

We can’t avoid imperfections. In real world not exist ideal structures.

Imperfections origin from microdamages of material, from uncertainly of mathematical models used for calculations and from human factor (confusions, errors).

Part of them we eliminate because of technical requirements for prefabrication process or for erection of structures. Next part of them we can remove by heat treating. Rest of them we must taken into account during calculations.

For calculations, we take ideal geometry (no geometrical imperfections), ideal material (no structural imperfections) and additional load schemes and dimensionless parameters, which represent real imperfections.

Imperfections can be divided into two groups:

structural

geometrical

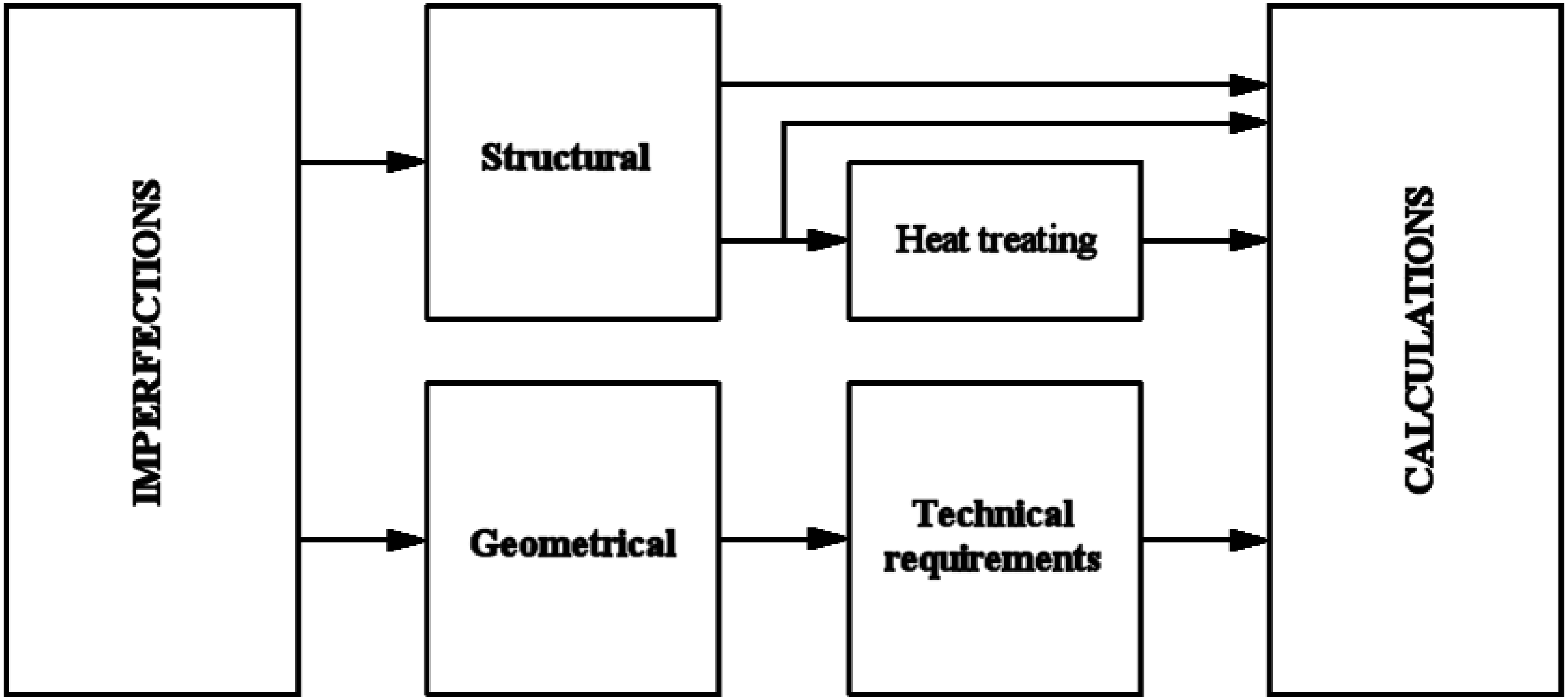


Photo: Author

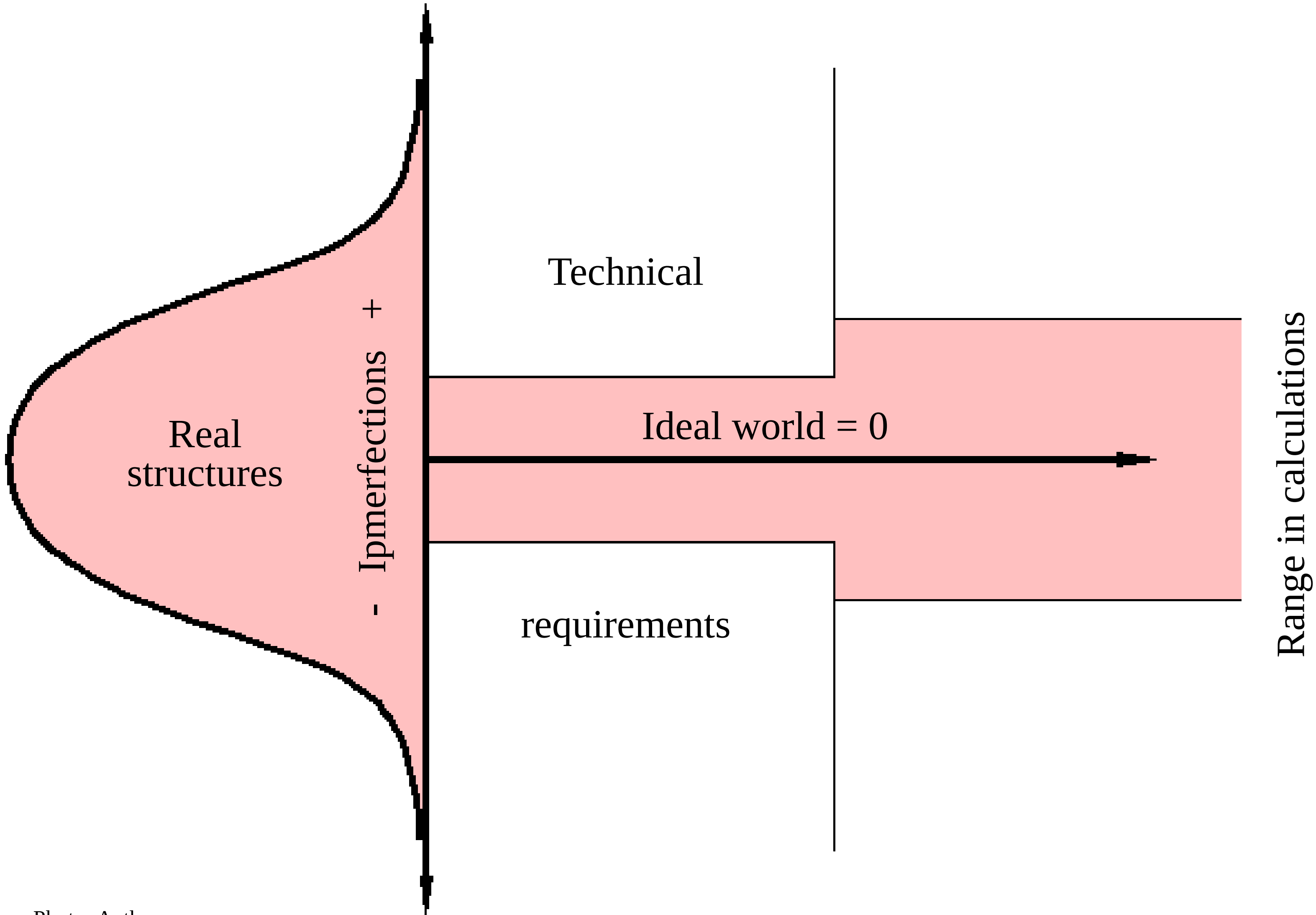


Photo: Author

Structural imperfections

Analysis of material

Structural imperfections can be divided into two kinds:

- natural features of material;
- secondary effects of material processing (hot-rolling, cold-forming, cutting to required dimensions, welding…)

Natural features of material

1. For metals, molecular structure is important. We have no ideal crystals – lack of molecule, shift of molecules, additional molecules, molecules of other chemical elements... Each of these situation changes internal structure of metal and locally decreases its mechanical parameters.

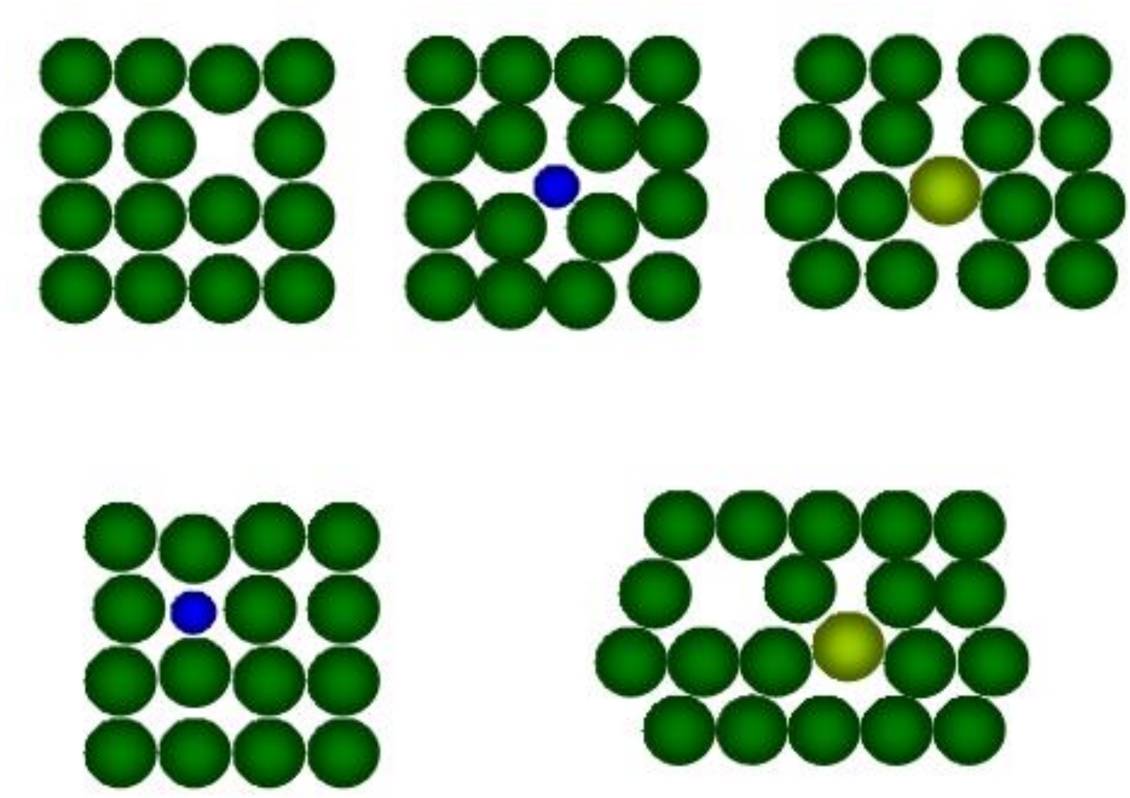


Photo: wikipedia

2. During soldification of steel, crystals start form in random places and in random directions. Their dimensions have random values. Microstresses and microdamages concentrate on borders of crystals.

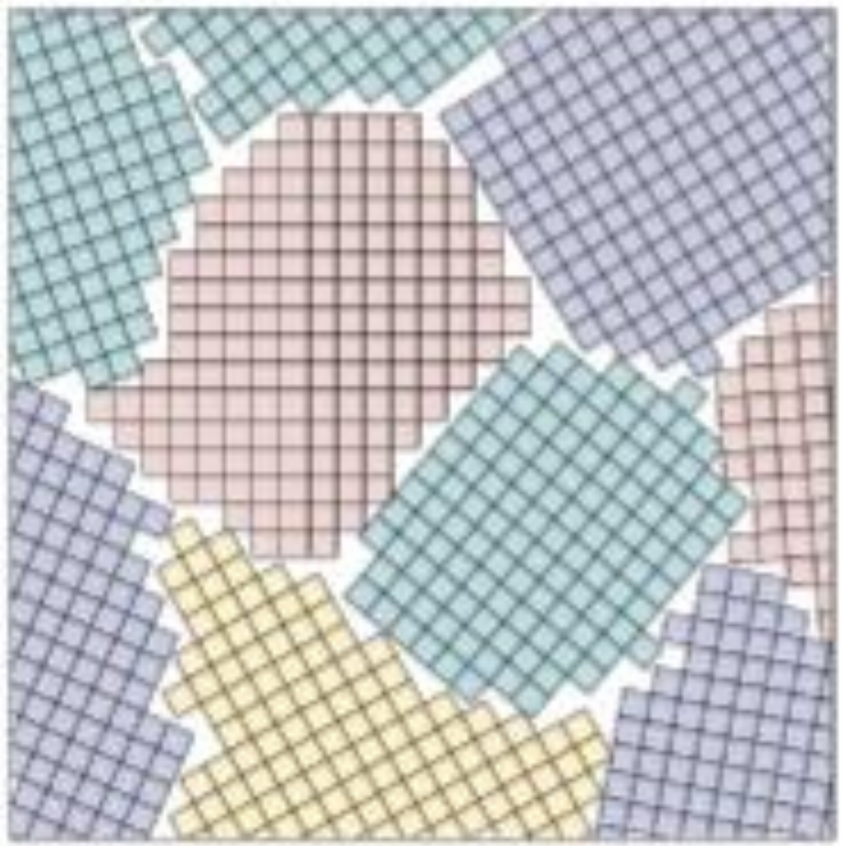


Photo: zasoby.open.agh.edu.pl

Steel consist from iron and carbon – as mixture or chemical compound. Additionally, there are different types of crystals. The effect: various local strength in various points of element.

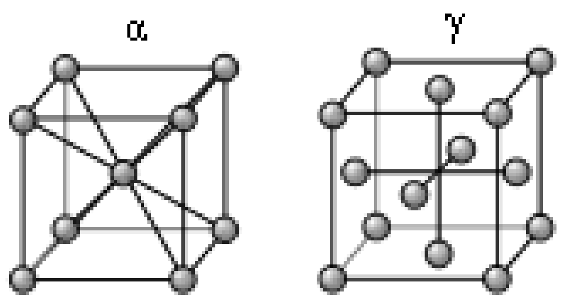


Photo: wikipedia

3. Ferrite, austenite, cementite, ledeburite, pearlite, martensite, bainite, sorbite, spheroidyte – different forms of steel have different mechanical parameters.

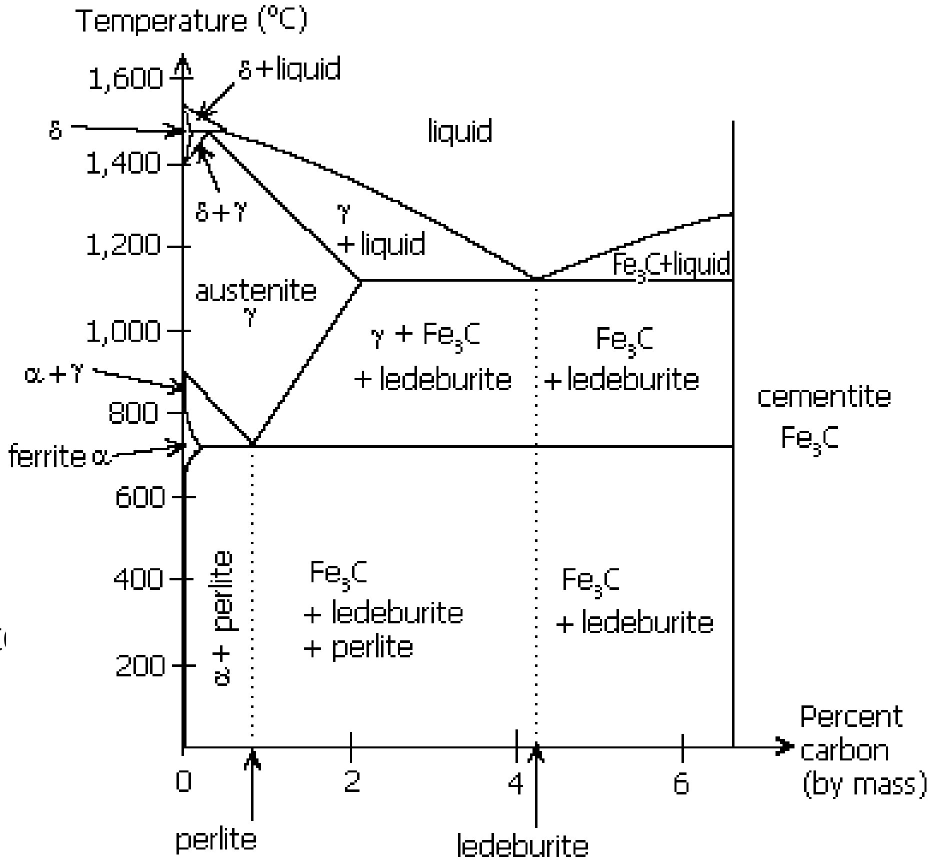


Photo: wikipedia

4. Pollutions

Inside each type of steel exists microscopic impurities of sulphur, phosphorus, gases and slags. They have destructive influence on mechanical parameters of steel (corrosion, microcracking)

S 235 JR [%]

C			Mn	Si	P (max)	S (max)	Cr	Ni	Cu (max)	Al	N (max)
t < 16 mm	16 < t < 40 mm	t > 40 mm									
0,170	0,170	0,200	1,400	0,000	0,035	0,035	0,000	0,000	0,550	0,000	0,012

Effect: different speciments of steel can have different mechanical parameters = different amount of microdamages in different part of material

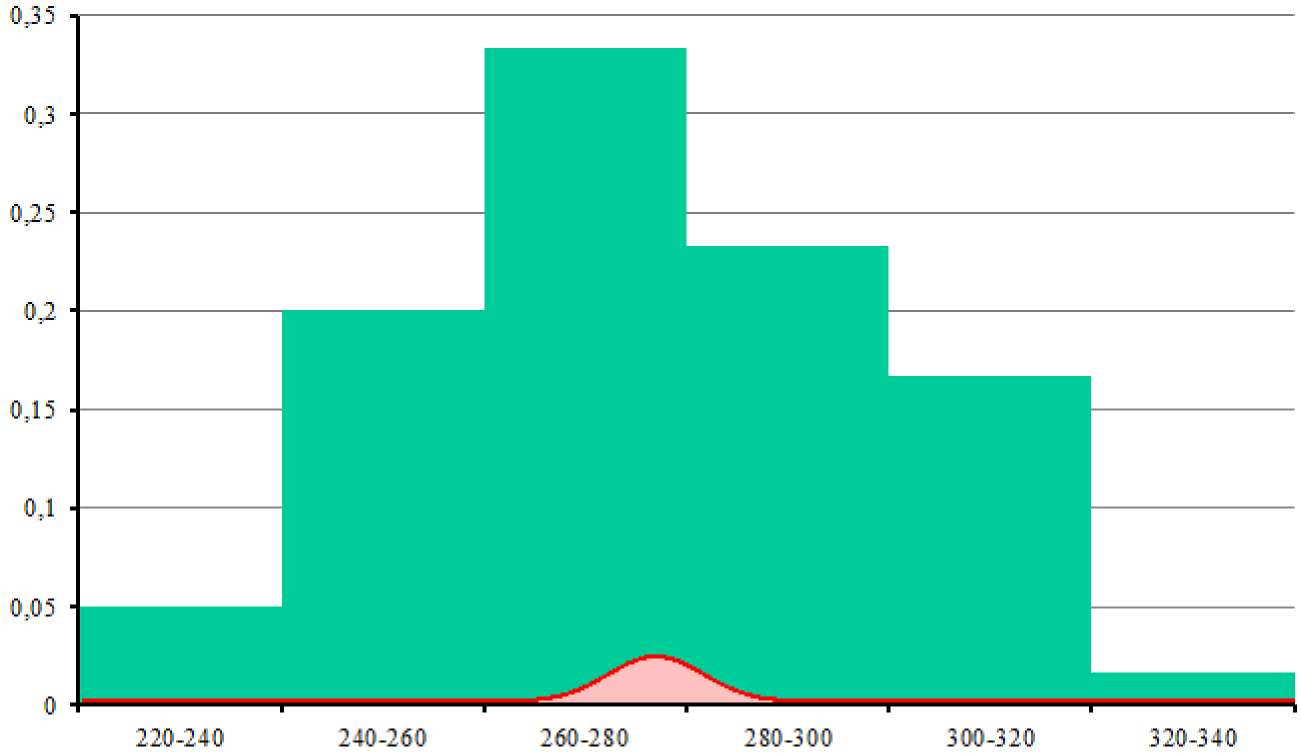


Photo: Author

Influence of imperfections in microstructure:

	f_y [MPa]	f_u [MPa]
„Normal" steel	235 – 355	360 – 470
Stainless steel	210 – 480	380 – 660
High strength steel	500 – 700	590 – 750
Steel for tension members		1 450 – 2 300
Iron monocristal	~ 5 000	
Iron monocristal, no molecular defects (estimation)	~ 18 000	

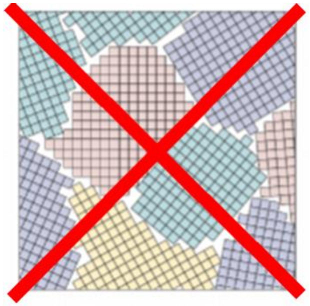
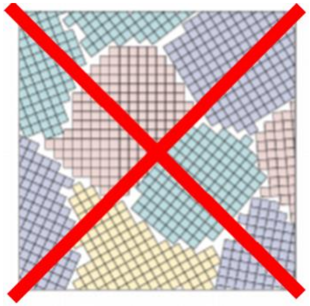


Photo: Author



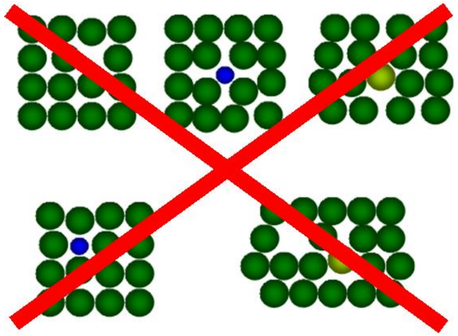
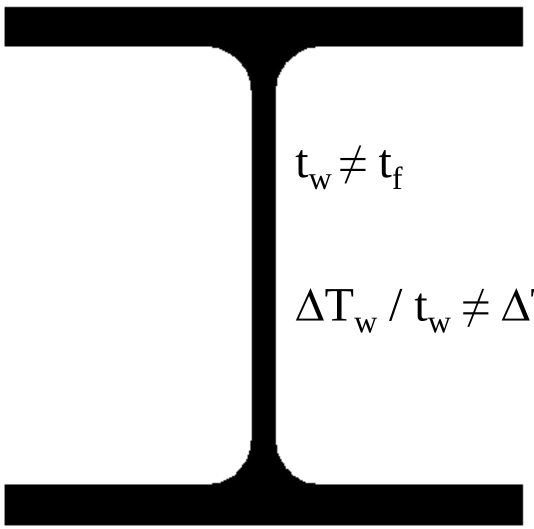


Photo: Author

<u>Secondary effects of material processing</u>

1. Hot-rolled cross-section: different thickness of web and flange, but the same temperature during rolling. Rate of temperature decreasing after rolling is different. Because of this, thermal stresses occur. This is type of residual stresses. Non-zero values of residual stresses change behaviour of member under loads.



$t_w \neq t_f$

$\Delta T_w / t_w \neq \Delta T_f / t_f$ [^{o}C/s mm]

Photo: Author

Photo: preetgroup.com

Residual stresses are self-balanced: each cross-sectional forces caused by them (axial force, bending moment, shear force, torsional moment) are equal 0,00 but their local values could be very big. Their sum with stresses from loads could be locally equal strength of material even for not big value of loads. This phenomenon could significantly decreases resistance of cross-section in comparison to teoretical assumption about lack of stresses in not-loaded element.

Photo: steelconstruction.info

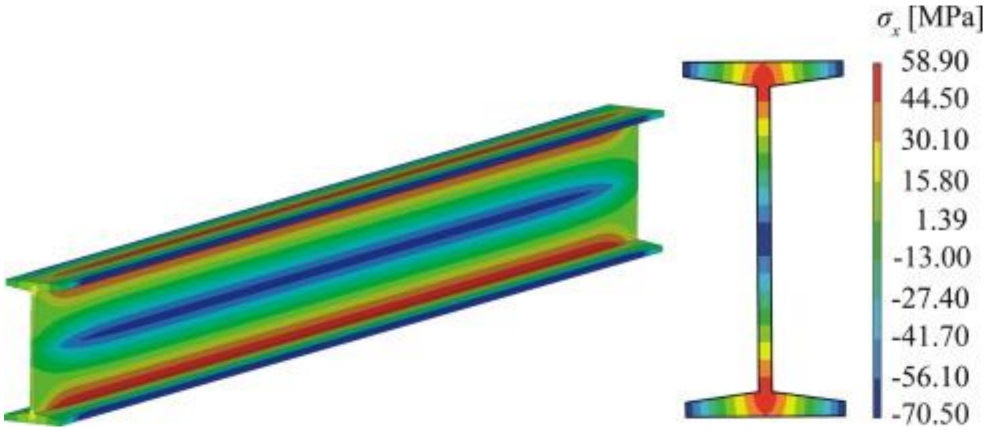


Photo: Global sensitivity analysis of lateral-torsional buckling resistance based on finite element simulations, ZdeněkKala JanValeš

2. Similar situation: cold-formed cross-sections; big deformations during formation of shape of cross-section. The same situation: non-zero values of self-balanced residual stresses.

Photo: ciecieplazma.pl

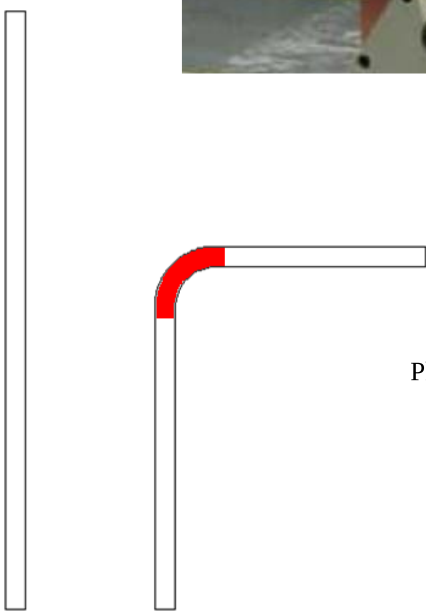


Photo: Author

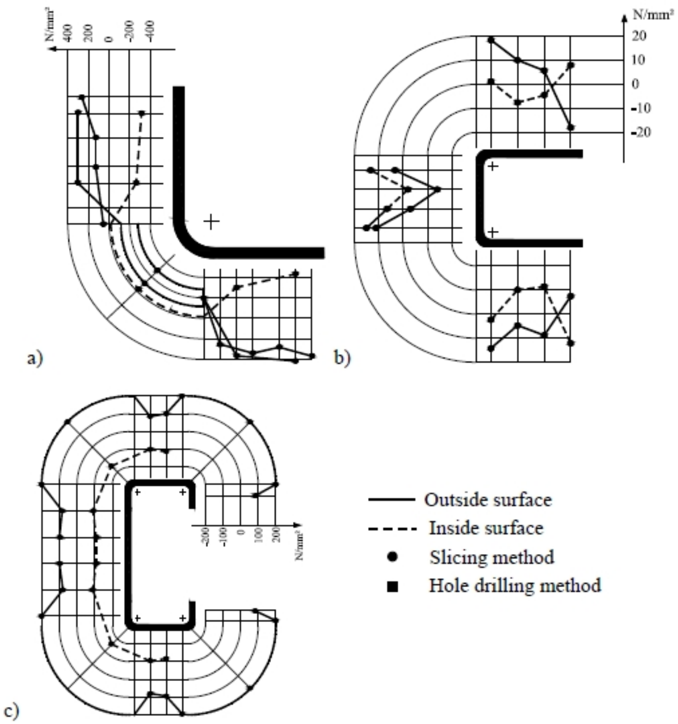


Photo: Design of cold-formed steel structures, D. Dubina, V. Ungureanu, R. Landolfo

Plates and quasi-plates:

Hoop iron (t = 1-5 mm; s = 20-85 mm)

Photo: steelstrap.en.ecplaza.net

Plate in coils

Photo: threadedstainlesssteelpipe.com

Flat steel (t = 6-55 mm; s = 20-150 mm)

→ #1 / 74

Photo: corten.com

Plate sheets

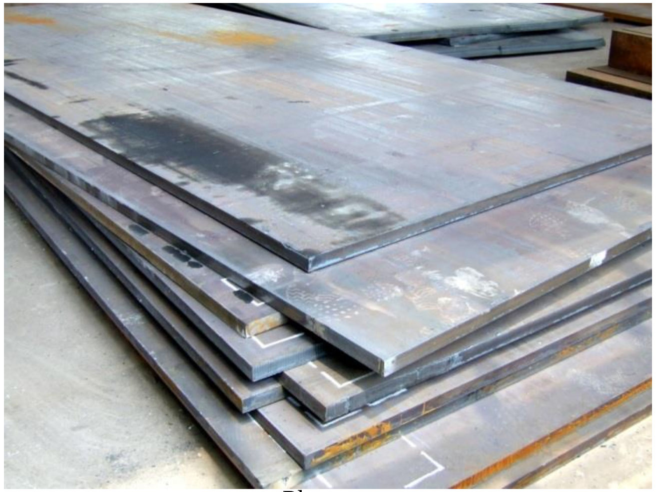


Photo: corten.com

Plate sheetss:

Flat

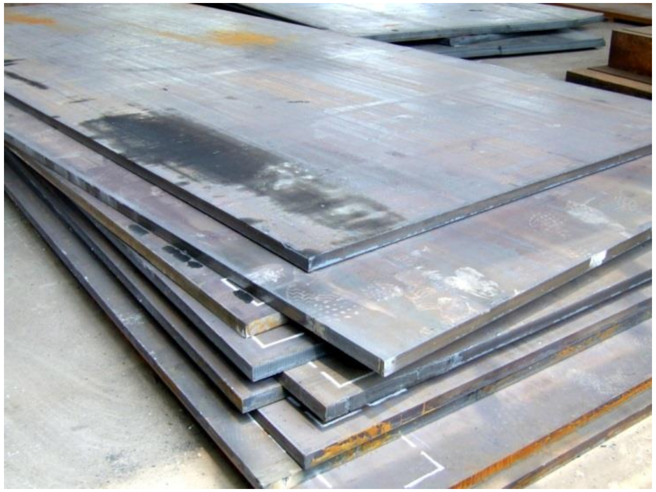


Photo: corten.com

Riffled

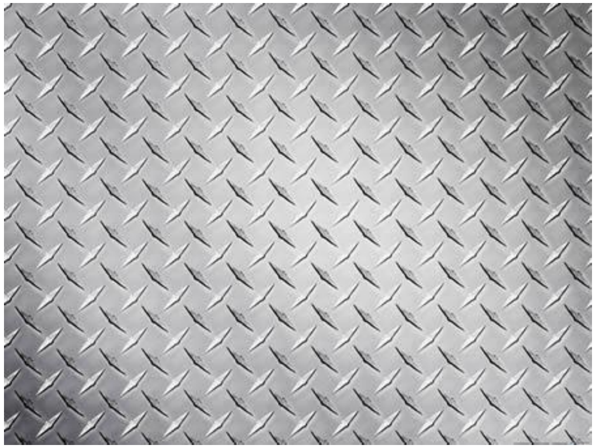


Photo: checker-plate.com

Flat plate sheetss: → #1 / 75

- cut from the coils;
- rolled in one direction;
- rolled in two directions (universal plate);

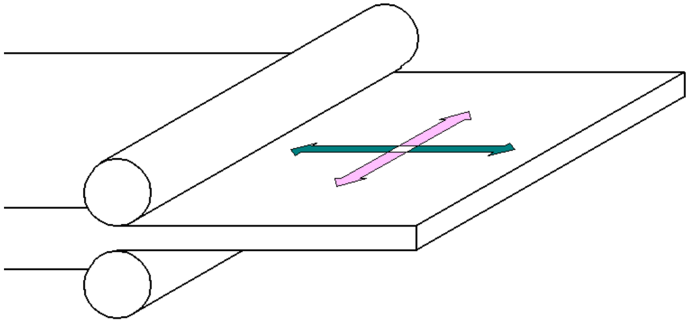


Photo: Author

3. Plate in coils: plates must be straight from the roll after transport. The effect are plastic deformations and residual stresses.

Photo: threadedstainlesssteelpipe.com

4. Crystals are deformated during rolling. This deformation followed by one direction. Steel plates rolled in one direction can have different mechanical characteristics in both directions.

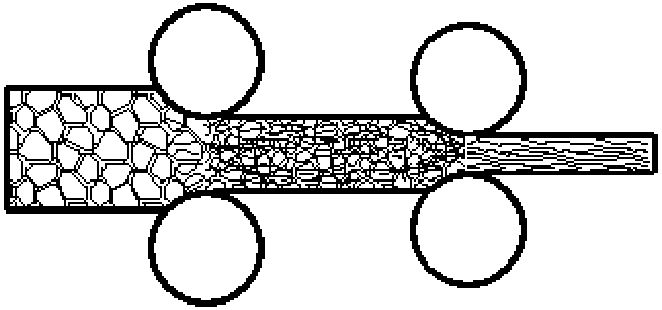


Photo: paws.wcu.edu

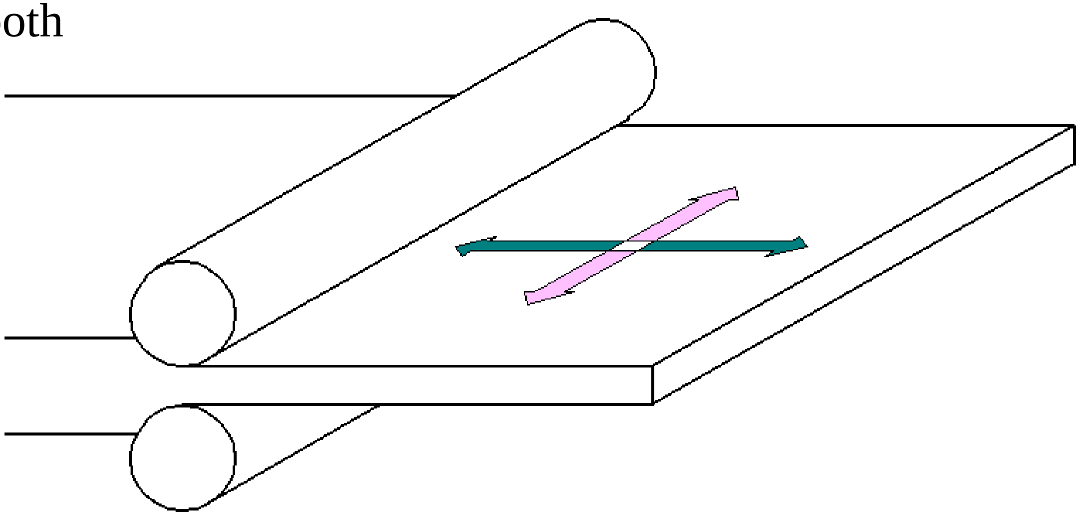
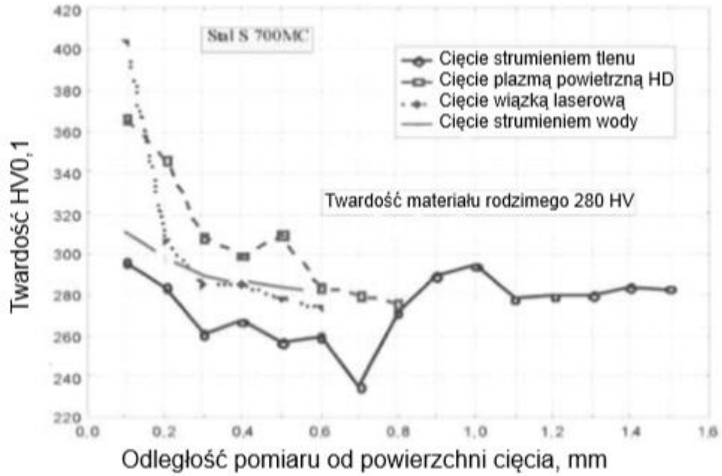


Photo: Author

5. Each type of cutting and drilling steel locally changes its mechanical parameters.

Hardness in function of distance betewwn analised point and edge of steel plate for cutting with oxygen, plasma, laser and water jet; steel S 700 and S 690. Hadrness is effect of local deformation of cristals during cutting.



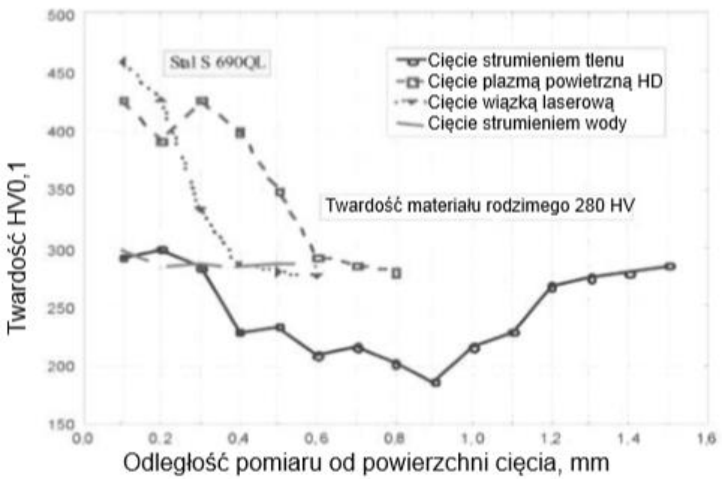


Photo: Wpływ procesów cięcia termicznego i strumieniem wody na właściwości i jakość powierzchni ciętych stali niskostopowych o wysokiej granicy plastyczności, Górka J. Skiba R.

Photo: bth.pl

Photo: ciecieplazma.pl

Photo: sukces-zamocowania.pl

Photo: steelconstruction.info

Initial deformations during cutting (type of plastic deformation) of steel plate – another effect of local deformations of cristals.

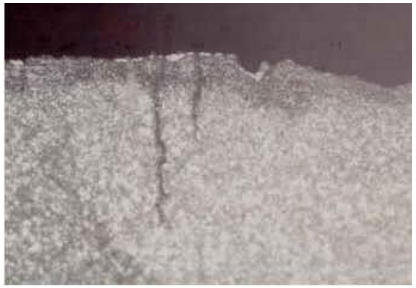


Photo: ndt.net

Hardened steel is very susceptible to brittle fracture. Each element on all cut edges has a certain amount of microcracks.

6. Welded elements: different temperature for different part of elements, different thermal deformations. Non-zero value of residual stresses.

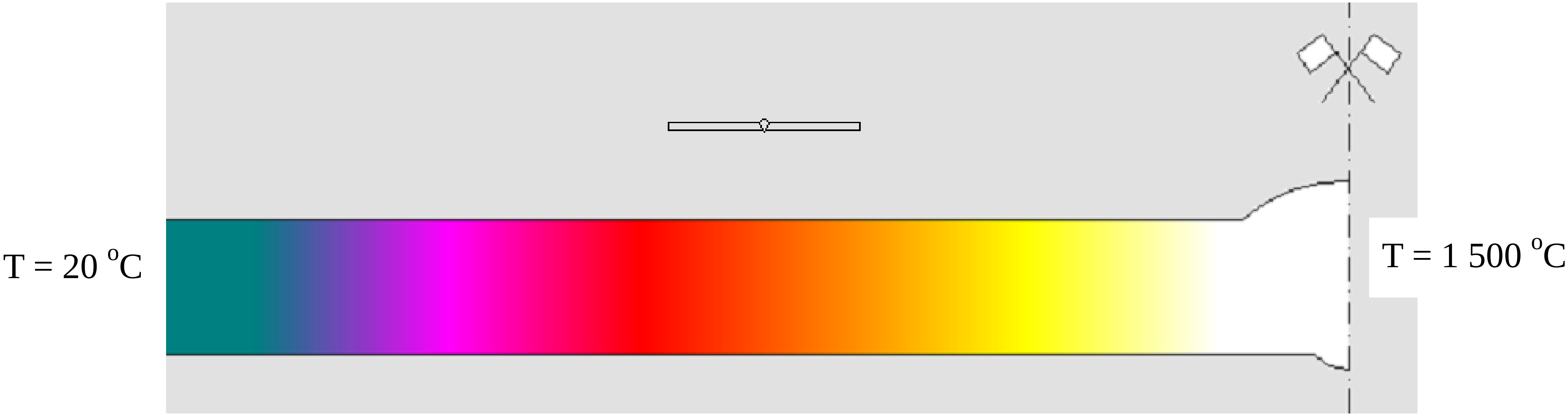
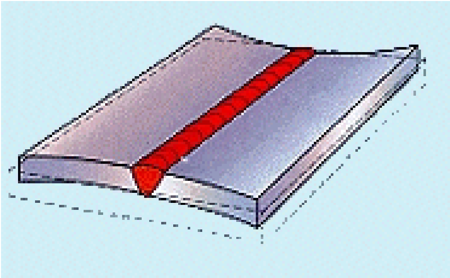
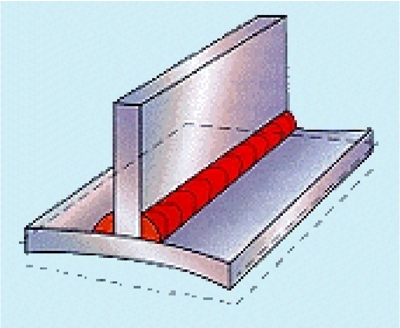


Photo: Author

7. Additionally, there are weldings deformations as a result of residual stresses after weldings. These types of stresses and deformations will be presented on lecture #16.





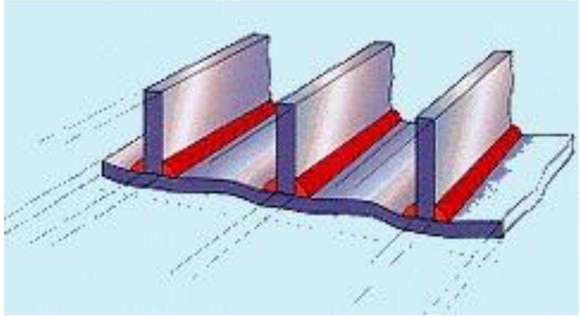


Photo: congnghehan.vn

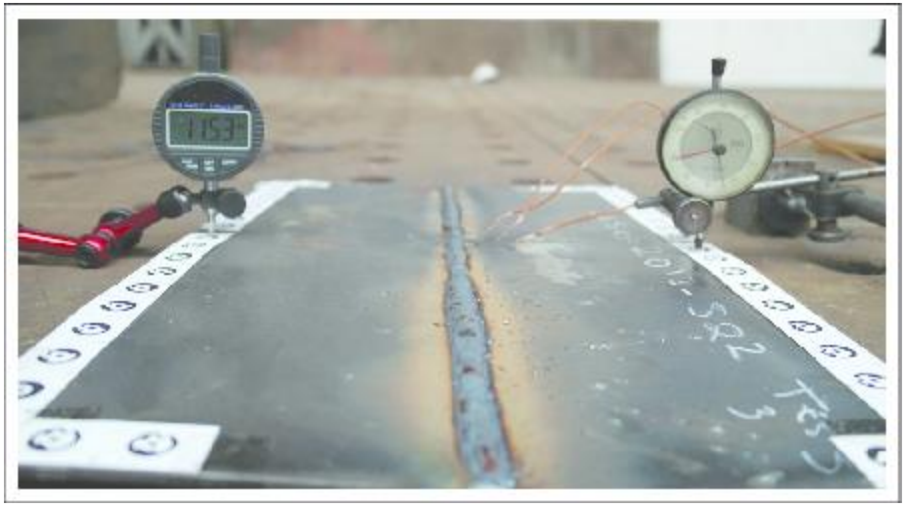


Photo: researchgate.net

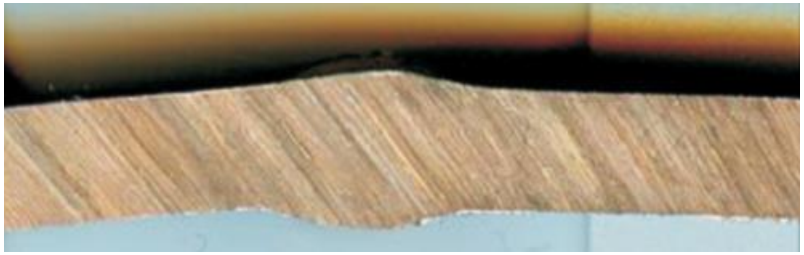


Photo: Analiza numeryczna odkształcenia i naprężenia w strefie złącza spawanego rurociągu przemysłowego, Gliha V Śniezek L Zimmerman J, Biuletyn WAT Vol. LVIII, No. 2, 2009

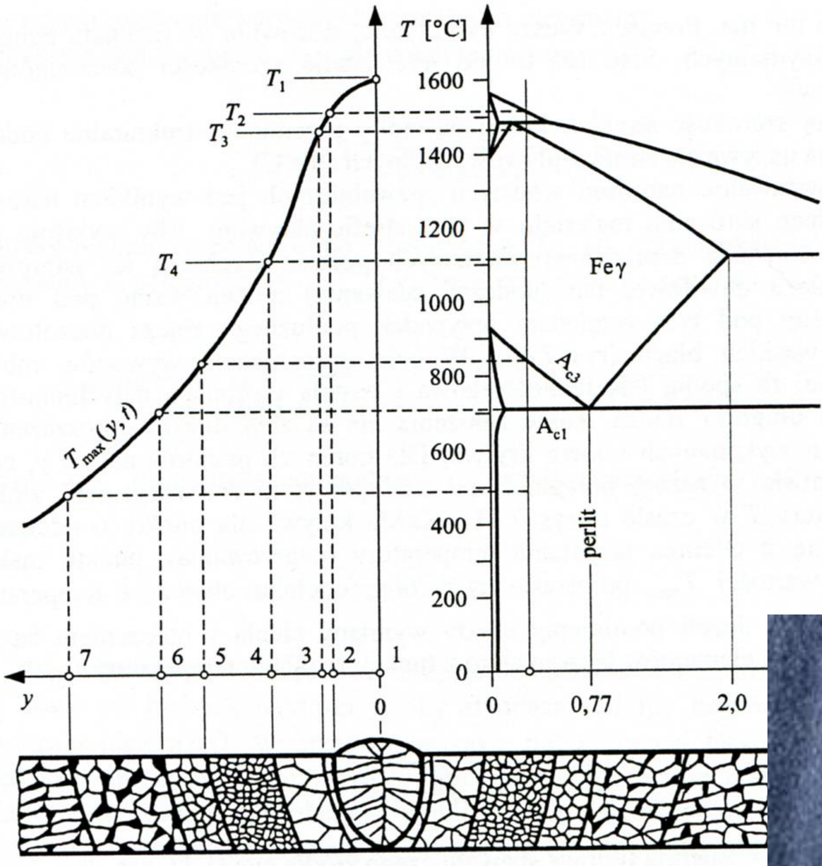


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie Wydawnictwo Edukacyjne Wrocław 2001

8. The side effect of the local remelting of the material is the re-crystallization process. This causes local changes in the mechanical parameters of the material.

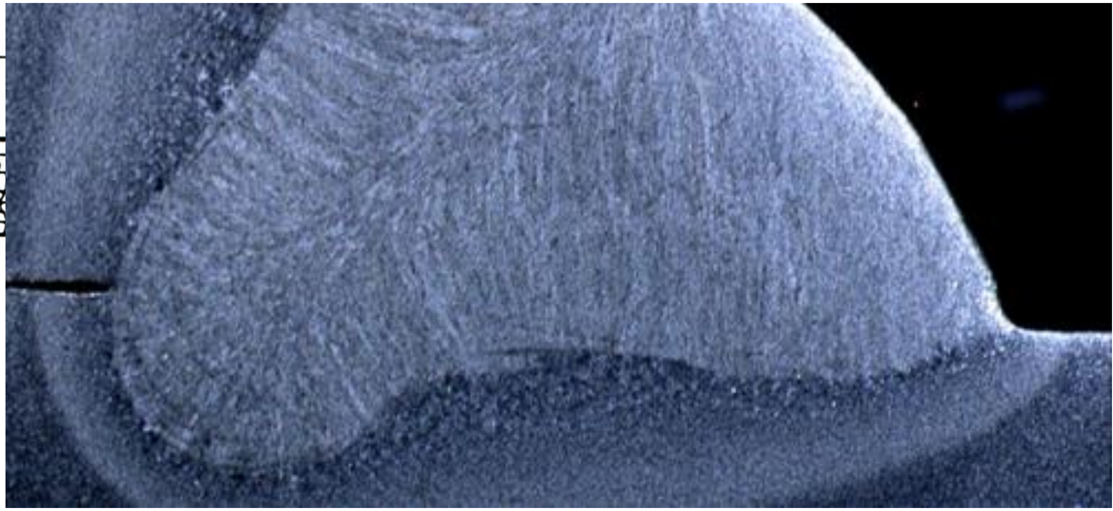


Photo: struers.com

9. Last reason of imperfections during welding process: secondary pollutions and microdamages. This is the reason for the greatest number of imperfections.

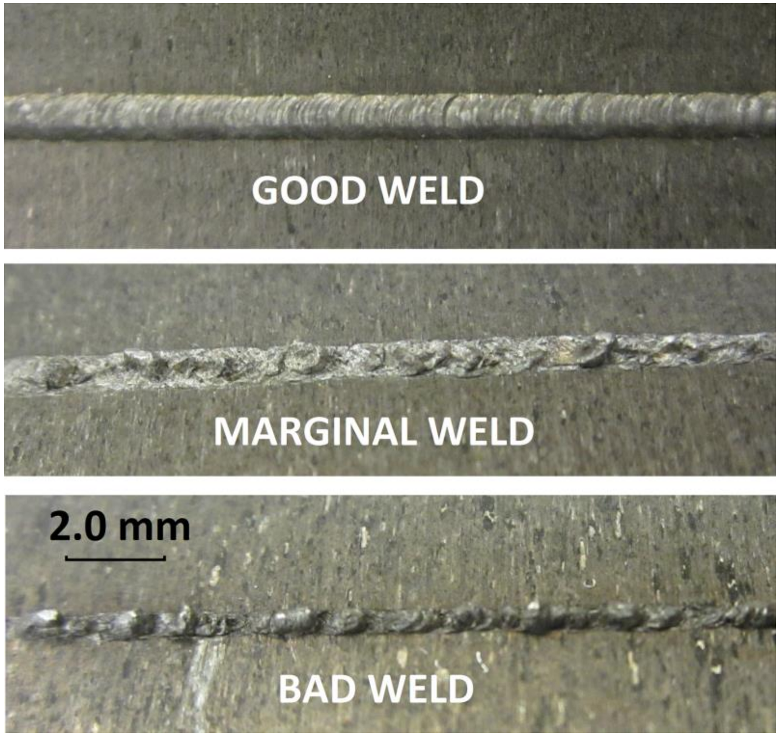


Photo: manufacturingscience.asmedigitalcollection.asme.org

The number of imperfections generated during welding proces is much greater than during other machining processes.

Photo: scottmetals.com.au

Photo: Author

Example: bar bracing with gusset plate

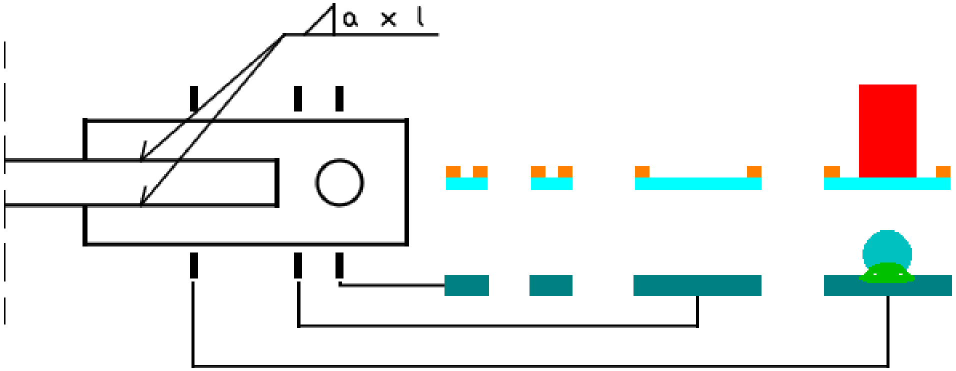


Photo: Author

Approximation: average number of imperfections:

„normal" structural imperfections in steel plate

effect of material processing (cuting, making holes…)

effect of welding process

Structural imperfections in steel plate (#t / 12 – 17)

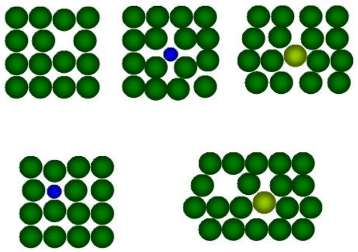


Photo: wikipedia

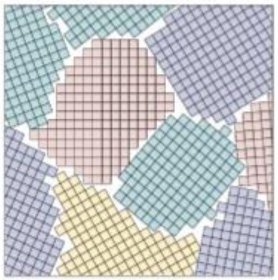


Photo: zasoby.open.agh.edu.pl

Additional effects of material processing (#t / 18 – 25): plastic deformations, local hardening of steel, local cracking…

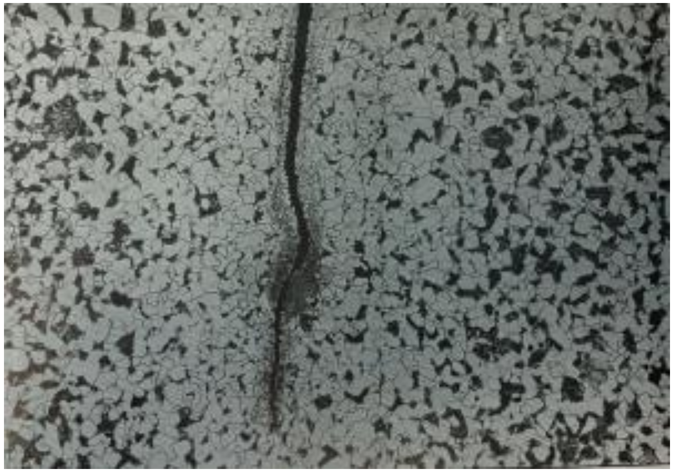
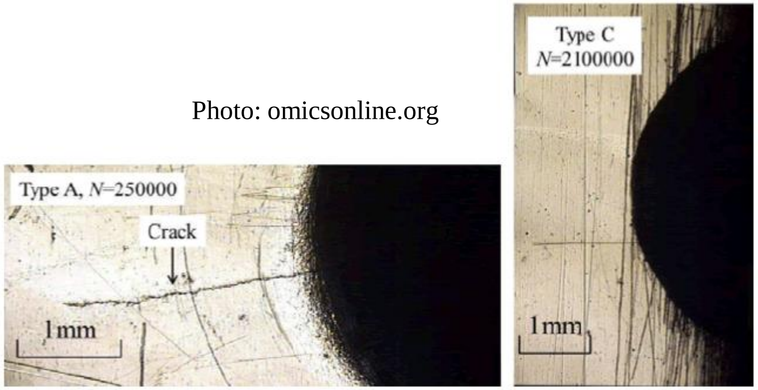


Photo: pmpaspeakingofprecision.com

Photo: omicsonline.org



Additional effects of welding process (#t / 26 – 29): secondary pollutions (gas bubbles, ash) introduced during welding, local deformation of plates, cracks as effect of thermal shrinkage...

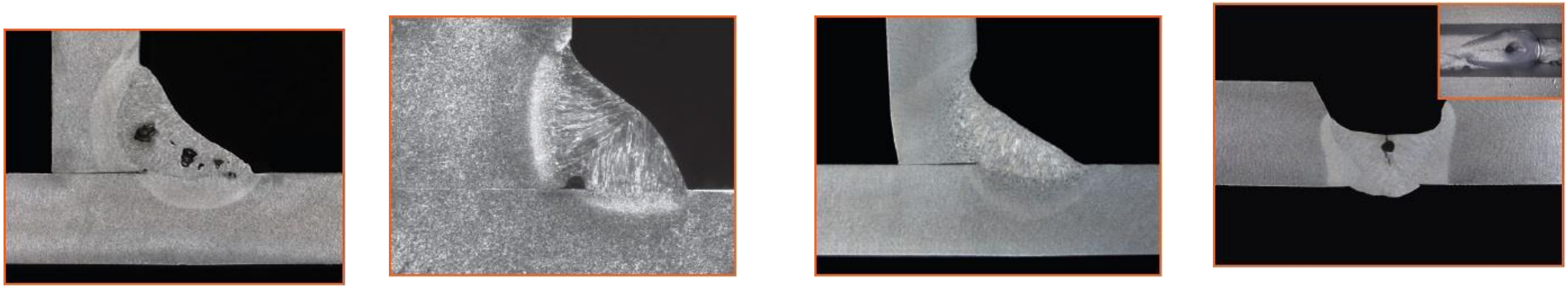


Photo: figel.pl

Ability and experience of worker ↓ → number of welding imperfection ↑ → quality level of welds ↓

Accepted number of welding imperfection is limited by Execution Class. (→ #t / 47).

Annealing – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), very slow decreasing of temperature;

Annealing 1100° C → **<u>homogeneous internal structure (chemical and crystalline), homogenize the mechanical characteristics</u>**;

Annealing 800 - 100° C → **<u>fragmentation of crystals</u>**, increasing strength;

Annealing 500 - 600° C → **<u>reduction of residual stresses</u>**;

Quenching – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), very quick decreasing of temperature → increasing hardness and fragility;

Tempering – increasing of temeprature, keeping element in this temperature for long time (it's need to change internal structure), slow decreasing of temperature;

Tempering 600° C → high strength, **<u>decreasing hardness</u>**;

Tempering 400° C → high strength, high plasticity, **<u>decreasing hardness</u>**;

Tempering 200° C → reduction of quenching stresses and fragility, high hardness;

More information → lab. #5

→ #1 / 89

Geometrical imperfections and technical requirements

How big values of deformations are acceptable?

EN 1090 Execution of steel and aluminum structures:

1090-1 Requirements for conformity assessment of structural components

1090-2 Technical requirements for steel structures

1090-3 Technical requirements for alumnium structures

According to EN 1090, geometrical imperfections are divided as follow:

	Manufacturing	Erection
Essentian	U.L.S.	U.L.S.
Functional	S.L.S. (class 1, class 2)	S.L.S. (class 1, class 2)

Manufacturing – created in assembly room, generally;

Erection – created on construction site, generally;

Essential – basic; for secondary elements;

Functional – important part of structure; avoiding inaccuracies in connections, aesthetic reasons

Examples of Essential – Manufacturing

Photo: EN 1090-2 tab. D.1.1

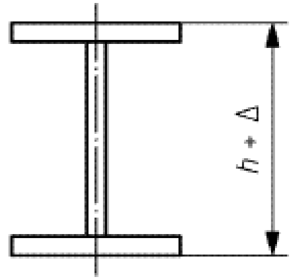
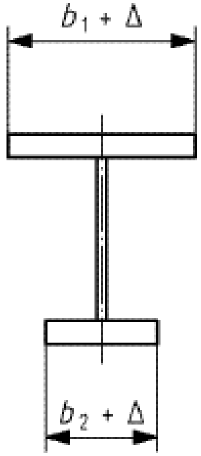
Depth: 	Overall depth h:	$\Delta = - h/50$ (no positive value given)
Flange width: 	Width $b = b_1$ or b_2:	$\Delta = - b/100$ (no positive value given)

Photo: EN 1090-2 tab. D.1.1

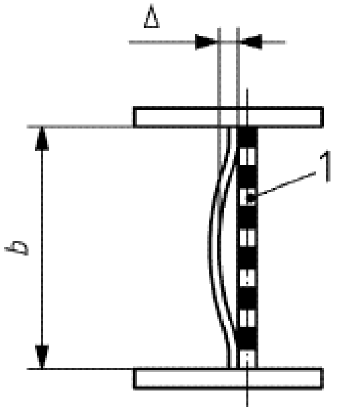
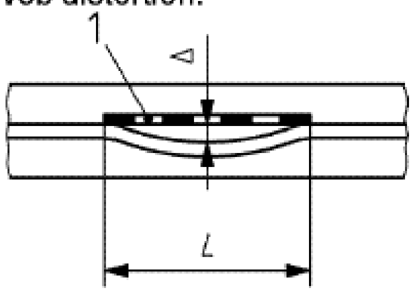
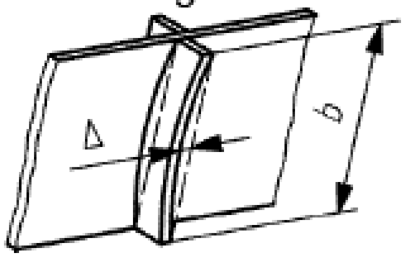
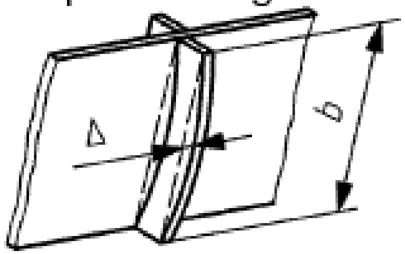
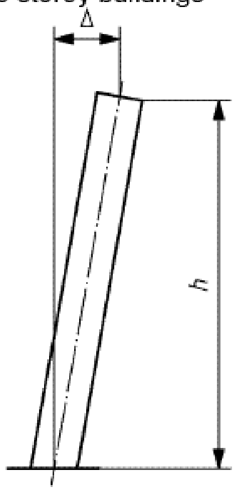
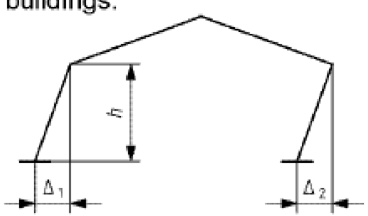
Plate curvature: 	Deviation Δ over plate height b:	$\Delta = \pm b/200$ if $b/t \leq 80$ $\Delta = \pm b^2/(16\,000\,t)$ if $80 < b/t \leq 200$ $\Delta = \pm b/80$ if $b/t > 200$ but $\lvert\Delta\rvert \geq t$ (t = plate thickness)
Web distortion: 	Deviation Δ on gauge length L equal to web height b (see (4))	$\Delta = \pm b/100$ but $\lvert\Delta\rvert \geq t$ (t = plate thickness)

Photo: EN 1090-2 tab. D.1.5

In plane straightness: 	Deviation Δ from straightness in the plane of the web:	$\Delta = \pm b/250$ but $\lvert\Delta\rvert \geq 4$ mm
Out of plane straightness: 	Deviation Δ from straightness normal to the plane of the web:	$\Delta = \pm b/500$ but $\lvert\Delta\rvert \geq 4$ mm

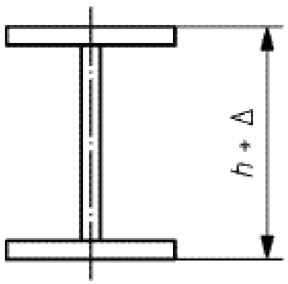
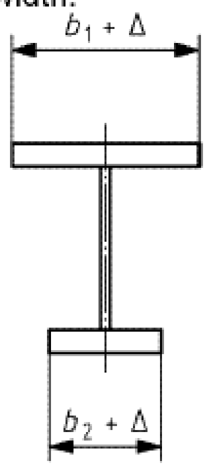
Examples of Essential – Erection

Photo: EN 1090-2 tab. D.1.11

Inclination of columns of single storey buildings 	Overall inclination in storey height *h*:	$\Delta = \pm h/300$
Inclination of single storey columns in portal frame buildings: 	Mean inclination of all the columns in the same frame: [For two columns: $\Delta = (\Delta_1 + \Delta_2)/2$]	$\Delta = \pm h/500$

Examples of Functional – Manufacturing

Photo: EN 1090-2 tab. D.2.1

Depth: 	Overall depth h: $h \leq 900$ mm $900 < h \leq 1\,800$ mm $h > 1\,800$ mm	$\Delta = \pm 3$ mm $\Delta = \pm h/300$ $\Delta = \pm 6$ mm	$\Delta = \pm 2$ mm $\Delta = \pm h/450$ $\Delta = \pm 4$ mm
Flange width: 	Width b_1 or b_2	$+\Delta = b/100$ but $\lvert\Delta\rvert \geq 3$ mm	$+\Delta = b/100$ but $\lvert\Delta\rvert \geq 2$ mm

Examples of Functional – Erection

Photo: EN 1090-2 tab. D.2.23

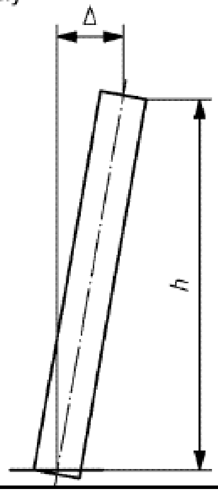
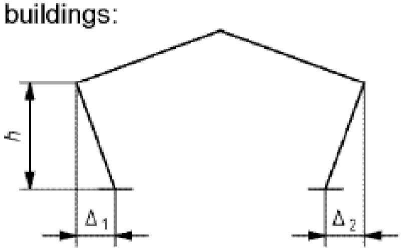
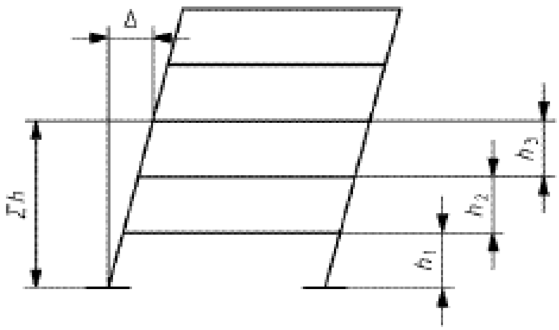
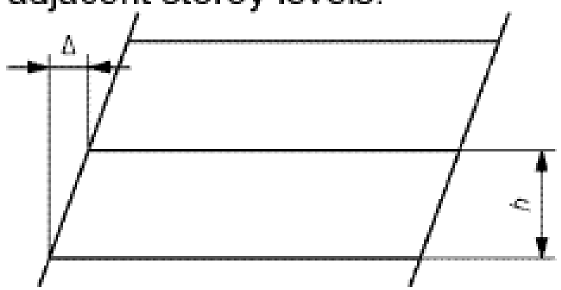
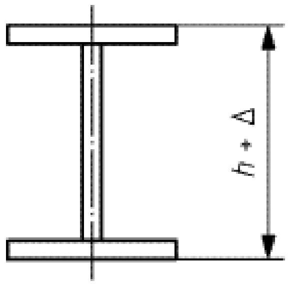
Inclination of columns of single storey buildings generally 	Overall inclination	$\Delta = \pm h/300$	$\Delta = \pm h/500$
Inclination of individual columns in single storey portal frame buildings: 	Inclination Δ of each column: $\Delta = \Delta_1$ or Δ_2	$\Delta = \pm h/150$	$\Delta = \pm h/300$

Photo: EN 1090-2 tab. D.2.24

Location at each storey level, relative to that at the base: 	Location of the column in plan, relative to a vertical line through its centre at base level	$\lvert\Delta\rvert = \Sigma h / (300\sqrt{n})$	$\lvert\Delta\rvert = \Sigma h / (500\sqrt{n})$
Inclination of a column, between adjacent storey levels: 	Location of the column in plan, relative to a vertical line through its centre at the next lower level	$\Delta = \pm h / 500$	$\Delta = \pm h / 1\,000$

Example

Photo: EN 1090-2 tab. D.1.1



h = 800 mm

	Class	Δ	Manufacturing	Erection
Essential	Not applicable	+	<u>0 mm</u>	Not applicable
		-	h / 50 = 16 mm	
Functional	1	+	3 mm	
		-	<u>3 mm</u>	
	2	+	2 mm	
		-	<u>2 mm</u>	

Conclusion: +0mm, -2 mm or -3 mm according to class

Wymiary w milimetrach

Gwint (*d*)				M1,6	M2	M2,5	M3	M4
P[a]				0,35	0,4	0,45	0,5	0,7
(*b*)		b		9	10	11	12	14
		c		15	16	17	18	20
		d		28	29	30	31	33
d_s	nom. = max			1,60	2,00	2,50	3,00	4,00
	Klasa dokładności	A	min.	1,46	1,86	2,36	2,86	3,82
		B		1,35	1,75	2,25	2,75	3,70
e	Klasa dokładności	A	min.	3,41	4,32	5,45	6,01	7,66
		B		3,28	4,18	5,31	5,88	7,50
k	nom.			1,1	1,4	1,7	2	2,8
	Klasa dokładności	A	max	1,225	1,525	1,825	2,125	2,925
			min.	0,975	1,275	1,575	1,875	2,675
	Klasa dokładności	B	max	1,3	1,6	1,9	2,2	3,0
			min.	0,9	1,2	1,5	1,8	2,6
s	nom. = max			3,20	4,00	5,00	5,50	7,00
	Klasa dokładności	A	min.	3,02	3,82	4,82	5,32	6,78
		B		2,90	3,70	4,70	5,20	6,64

Klasa dokładności					l_s i l_g [e, f]									
	A		B											
l					l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g
nom.	min.	max	min.	max	min.	max	min.	max	min.	max	min.	max	min.	max
12	11,65	12,35	–	–	1,2	3							Powyżej grube	
16	15,65	16,35	–	–	5,2	7	4	6	2,75	5			stosowanie ś	
20	19,58	20,42	18,95	21,05			8	10	6,75	9	5,5	8		
25	24,58	25,42	23,95	26,05					11,75	14	10,5	13	7,5	11
30	29,58	30,42	28,95	31,05							15,5	18	12,5	16
35	34,5	35,5	33,75	36,25									17,5	21
40	39,5	40,5	38,75	41,25									22,5	26
45	44,5	45,5	43,75	46,25										
50	49,5	50,5	48,75	51,25										
55	54,4	55,6	53,5	56,5										
60	59,4	60,6	58,5	61,5										
65	64,4	65,6	63,5	66,5										
70	69,4	70,6	68,5	71,5										

The dimensions of the bolts are subject to other standards. The minimum and maximum allowable dimensions are given, for example, in the design tables.

Photo: Tablice do projektowania konstrukcji metalowych, W. Bogucki, M. Żyburtowicz

Imperfections as effect of drilling:

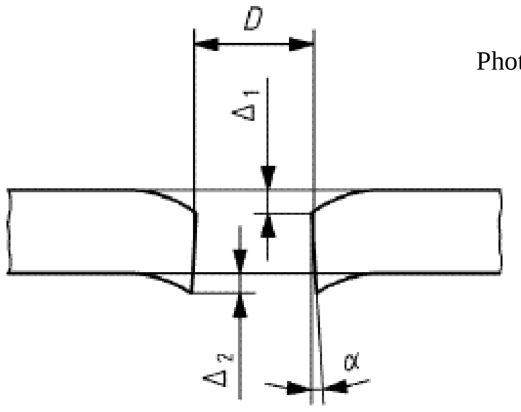


Photo: EN 1090-2 fig. 1.

$$D = (d_{min} + d_{max}) / 2$$

$$\max (\Delta_1 ; \Delta_2) \leq \max (D / 10 ; 1 \text{ mm})$$

$$\alpha \leq 4^o = 7\%$$

EN 1993-1-1 2.4.2 (1)

2.4.2 Design values of geometrical data

(1) Geometrical data for cross-sections and systems may be taken from product standards hEN or drawings for the execution to EN 1090 and treated as nominal values.

If geometrical imperfections do not exceed the permissible values, nominal dimensions are assumed for the calculation (assumed in the design project).

Execution class

There are two classes of imperfections for functional geometrical imperfections. They depend on execution class.

What is the way to determine type of execution class?

Consequences classes		CC1		CC2		CC3	
Service categories		SC1	SC2	SC1	SC2	SC1	SC2
Production categories	PC1	EXC1	EXC2	EXC2	EXC3	EXC3	EXC3
	PC2	EXC2	EXC2	EXC2	EXC3	EXC3	EXC4
Class of imperfection		1			2		

EN 1090-2 tab B.3

If we can't make accurate analysis, we assume EXC2.

Consequences classes - effects of structure destruction

→ #3 / 31

Photo: wikipedia

→ #3 / 32

Consequences calsses	Description	Examples
CC3	**High consequence** for loss of human life or economic, social or environmental consequences **very heavy**	Grandstands; public buildings where consequences of failure are high
CC2	**Medium** for loss of human life or economic, social or environmental consequences **considerable**	Residential; office buildings; public buildings where consequences of failure are medium
CC1	**Low** for loss of human life and economic, social or environmental consequences **small or neglegible**	Agricultural buildings where people do not normally enter; greenhouses

EN 1990 tab B1

Effects for designing and executing; EN 1990, tab. B1 + B4 + B5

Consequences classes	Design Supervision Levels (during designing)	Characteristics	Minimum recommended requirements	Inspection Level (during execution)	Characteristics	Requirements
CC3	DSL3	Extended supervision	Third part checking (performed by an organsation different from that, which has prepared the design)	IL3	Extended inspection	Third party inspection
CC2	DSL2	Normal supervision	Checking by different person, that those originally responsible and in accordance with the procedure of the organisation	IL2	Normal inspection	Inspection in accordance with the procedures of the organisation
CC1	DSL1	Normal supervision	Self-checking (performed by the person, who has prepared the design)	IL1	Normal inspection	Self inspection

Production categories: EN 1090-2 tab. B.2

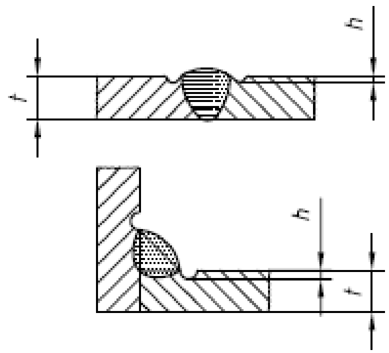
Categories	Criteria
PC1	◆ Non welded components manufactured from any steel grade products; ◆ Welded components manufactures from steel grade products below S355;
PC2	◆ Welded components manufactured from steel grade products from S355 and above; ◆ Components essential for structural integrity that are assembled by welding on construction site; ◆ Components with hot forming manufacturing or receiving thermic treatment during manufacturing; ◆ Components of CHS lattice girders requiring end profile cuts;

Service categories: EN 1090-2 tab. B.1

Categories	Criteria
SC1	◆ Structures and components designed for quasi static actions only (example: buildings); ◆ Structures and components with their connections designed for seismic actions in regions with low seismic activity and in DCL*; ◆ Structures and components designeg for fatigue actions from cranes (class S_0)**;
SC2	◆ Structures and components designed for fatigue actions according to EN 1993 (examples" roads and railway bridges, cranes (class S_1 to S_9)**, structures susceptible to vibrations induced by wind, crowd or rotaring machinery); ◆ Structures and components with their conections designed for seismic actions in regions with medium or risk seismic activity and in DCM* and DCH*;
* DCL, DCM, DCH: ductility calsses according to EN 1998-1; ** For classification of fatigue actions from cranes, see EN 1991-3 and EN 13 001-1	

Welds quality as a function of Execution Class (EN 1090-2 tab 7.6)

Execution classes	Quality level for welded joints
EXC1	D
EXC2	C (generally) D (undercut, overlap, stray arc, end crater pipe)
EXC3	B
EXC4	B+

No.	ISO 6520-1 reference	Imperfection designation	Remarks	t mm	Limits for imperfections for quality levels		
					D	C	B
1.7	5011 5012	Continuous undercut Intermittent undercut	Smooth transition is required. This is not regarded as a systematic imperfection.  	0,5 to 3	Short imperfections: $h \leq 0,2\ t$	Short imperfections: $h \leq 0,1\ t$	Not permitted
				> 3	$h \leq 0,2\ t$, but max. 1 mm	$h \leq 0,1\ t$, but max. 0,5 mm	$h \leq 0,05\ t$, but max. 0,5 mm

EN ISO 5817 tab. 1 - limits of imperfections for quality level

Imperfection designation		Limits for imperfections [a]
undercut (5011, 5012)		not permitted
internal pores (2011 to 2014)	Butt welds	$d \leq 0{,}1\ s$, but max. 2 mm
	Fillet welds	$d \leq 0{,}1\ a$, but max. 2 mm
solid inclusions (300)	Butt welds	$h \leq 0{,}1\ s$, but max. 1 mm $l \leq s$, but max. 10 mm
	Fillet welds	$h \leq 0{,}1\ a$, but max. 1 mm $l \leq a$, but max. 10 mm
linear misalignment (507)		$h < 0{,}05\ t$, but max. 2 mm
root concavity (515)		Not permitted

EN 1090-2 tab. 17 - additional requirement for B+

Type of weld	Shop and site welds		
	EXC2	EXC3	EXC4
Transverse butt welds and partial penetration welds in butt joints subjected to tensile stress:			
$U \geq 0{,}5$	10 %	20 %	100 %
$U < 0{,}5$	0 %	10 %	50 %
Transverse butt welds and partial penetration welds:			
in cruciform joints	10 %	20 %	100 %
in T joints	5 %	10 %	50 %
Transverse fillet welds in tension or shear:			

EN 1090-2 tab. 24 – range of non-destructive tests (NDT), for example X-ray, made for determining the real level of imperfections.

For good-quality weld: real level of imprerfections ≤ limit.

Otherwise weld must be deleted and made once again.

Conclusion: more responsible structure (higher CC) require a greater safety margin in design, more accurate design supervision and more accurate supervision level.

In turn, "troublesome" structure (higher EXC):

due to welding on assembly, use of high-strength steel or a specific method of processing during execution (higher PC),

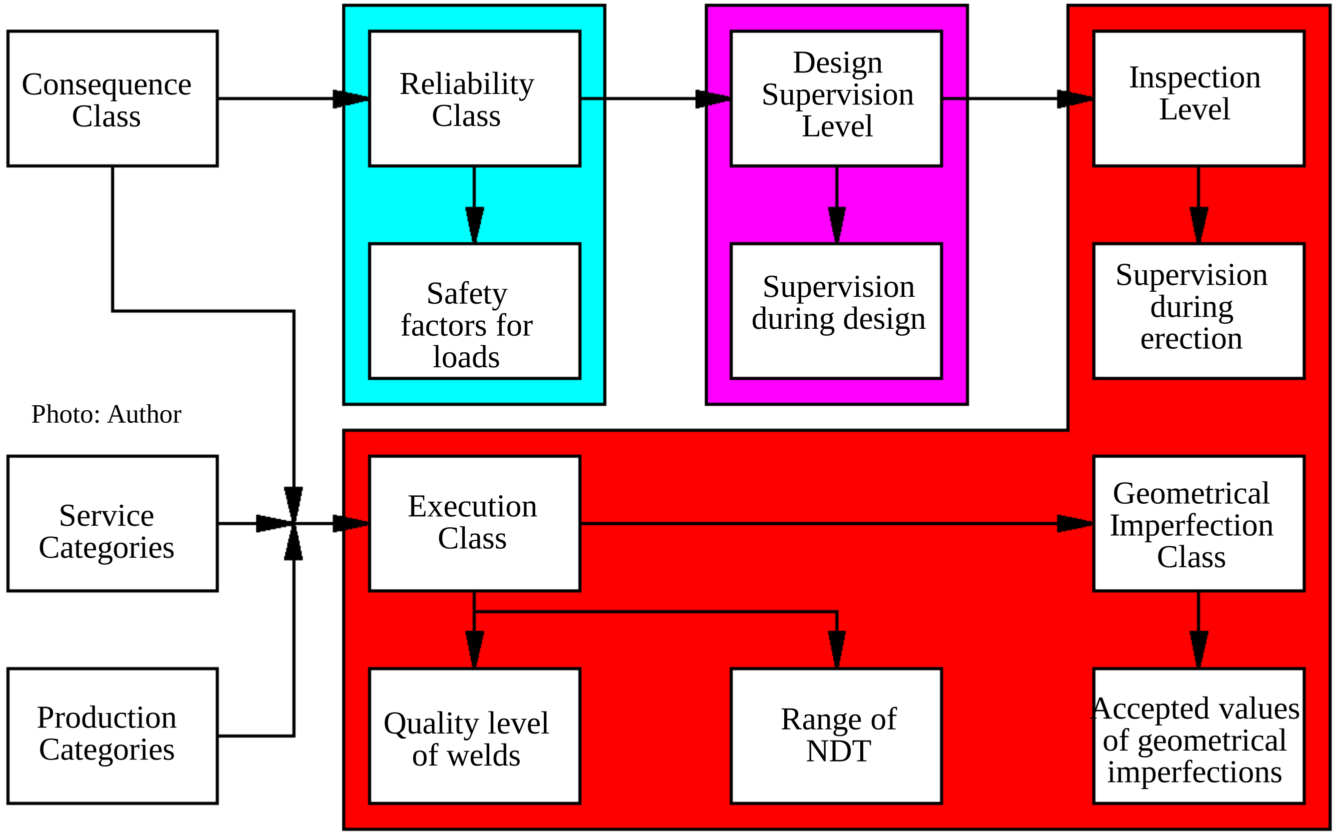
or

significant dynamic load value (higher SC)

or

more responsible (higher CC)

require more accurate execution: they have lower values of acceptable imperfections, require higher quality welds and a greater range of control of their implementation.



Differentiation of loads for more or less important structures

A system to minimize the possibility of error during design proces

A system to minimize the possibility of error during manufacturing and erection

System protection of the structure against errors and imperfections includes design, manufacturing and assembly. For the more responsible structure (CC ↑ SC ↑ PC ↑) high quality of welds, small geometrical imperfections and detailed supervision of design and assembly are necessary.

Welds with too low quality or elements with too big imperfections must be removed and made again.

<u>Design proces</u>

Imperfections are taken into consideration in many various way during design proces. Generally: we analyse <u>ideal geometry</u>, <u>ideal material</u> and <u>effect of imperfections by one of few methods</u>.

These methods can be divided as follows:

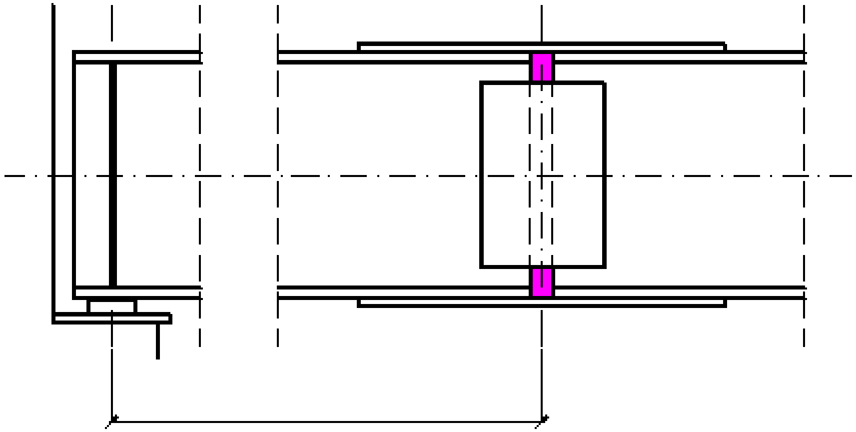
- general principles for design and erection, based on the experience of many generations of engineers;
- additional parameters describing the impact of imperfection on the material;
- indirect consideration of imperfections in calculations;
- equivalent loads from imperfections in calculations.

Equivalent loads base on geometry of structure and cross-sectional forces in elements. The cross-sectional forces are calculated taking into account the safety factors γ for loads. Therefore, equivalent forces do not have to be multiplied once again by the factors γ.

General principles, selected examples (change of dimensions to compensate)

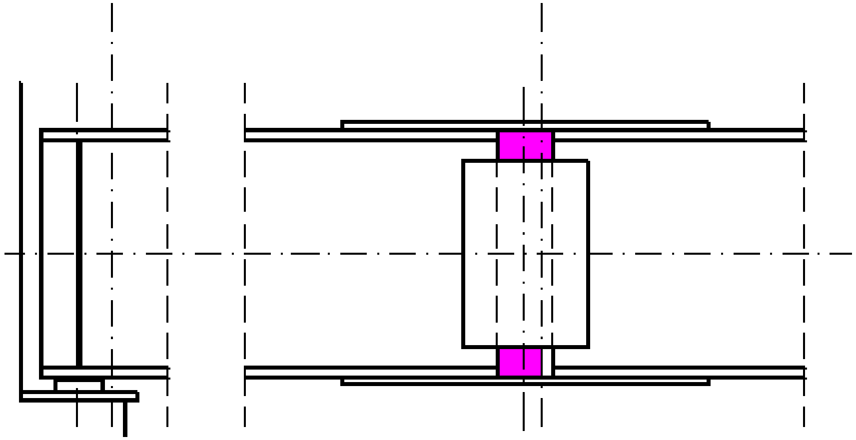
1. Compensation gaps

Theoretical axial distance

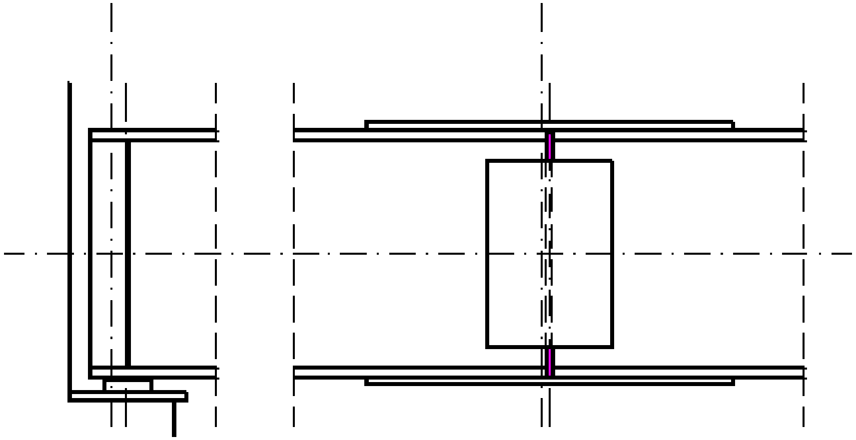


Gap can compensate diference between theoretical and real position of support.

Photo: Author



Bigger axial distance



Smaller axial distance

Effect of compensation: bolts holes in I-beam and plates are in different places.

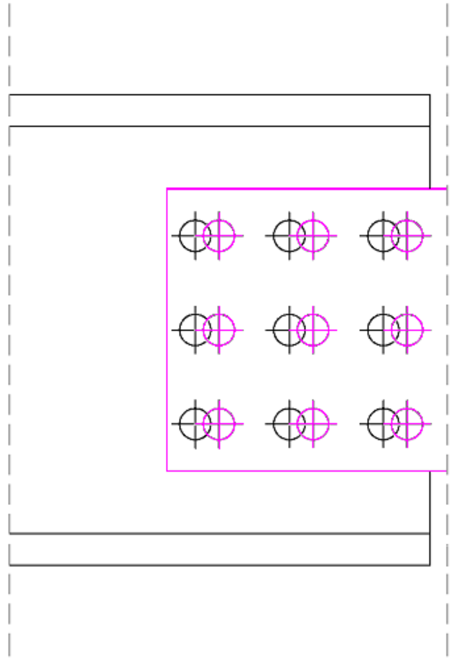


Photo: Author

Because of this, slotted holes are applied in steel structures.

Photo: tekla-detailed-structural-fabrication.com

Oversize and slotted holes are not accepted fot preloaded bolts. Better solution are holes made on construction site, after measuring the actual bolts position.

2. Tension joint: compensation

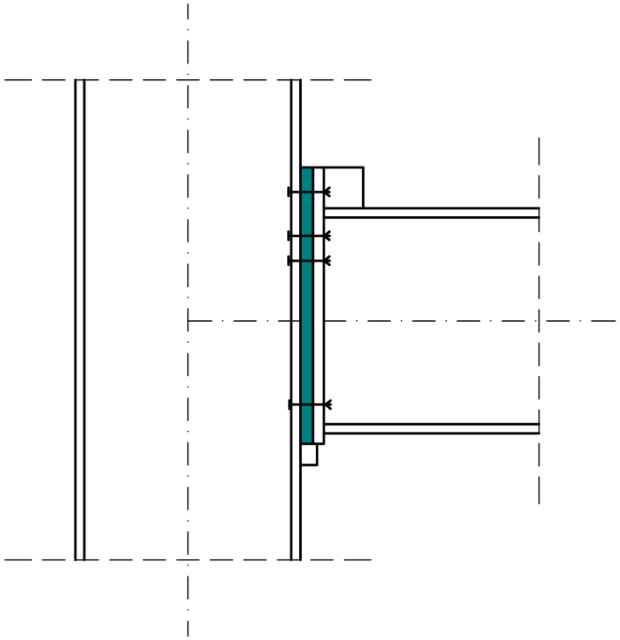


Photo: Author

Photo: uwyo.edu

Length of beams should be a little smaller than theoretical distance between columns. Difference of length is compensate by packing plate.

3. Support of columns

Accuracy for steel structures - to 1 mm. Accuracy for concrete structures (also for position of anchor bolts) - to 10 mm. Diameter of hols for bolts must be very big to enable compensate imperfection for position of anchor bolts.

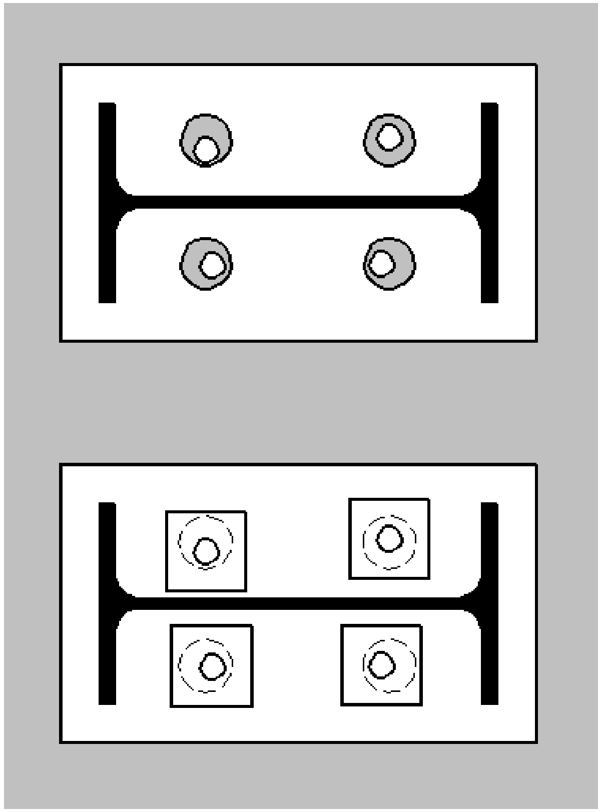


Photo: Author

Photo: nees.org

4. Recommendations for welds

There are zones of residual stress concentration for different types of cross-sections. We should avoid or limit welds on black parts of cross-sections. It's important for geometry of welds.

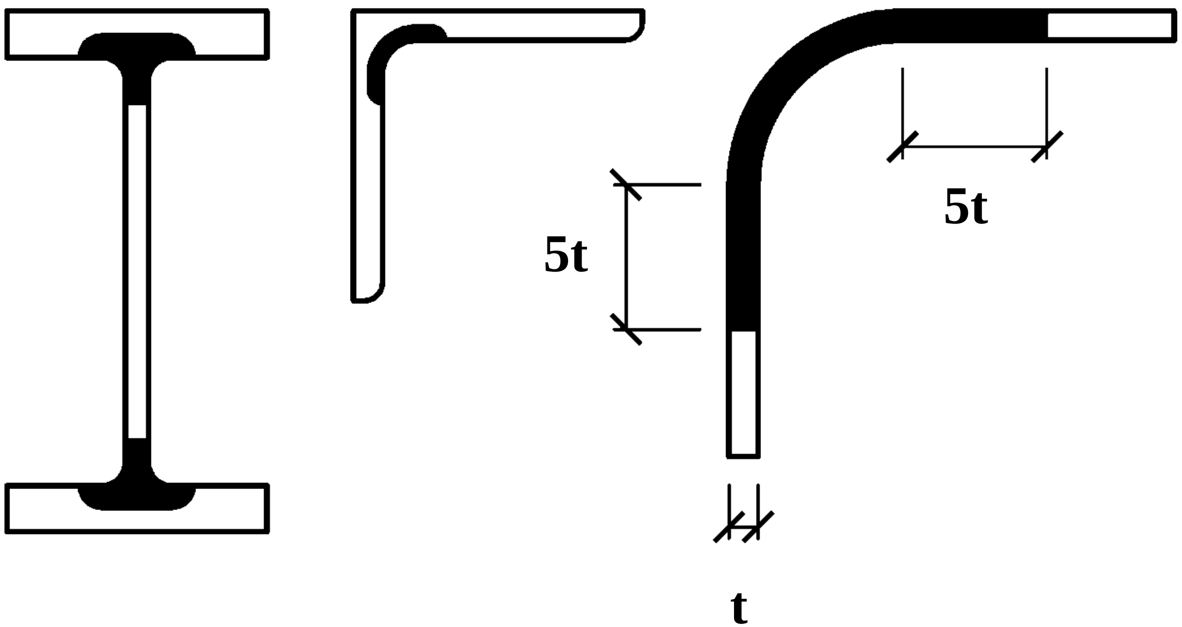
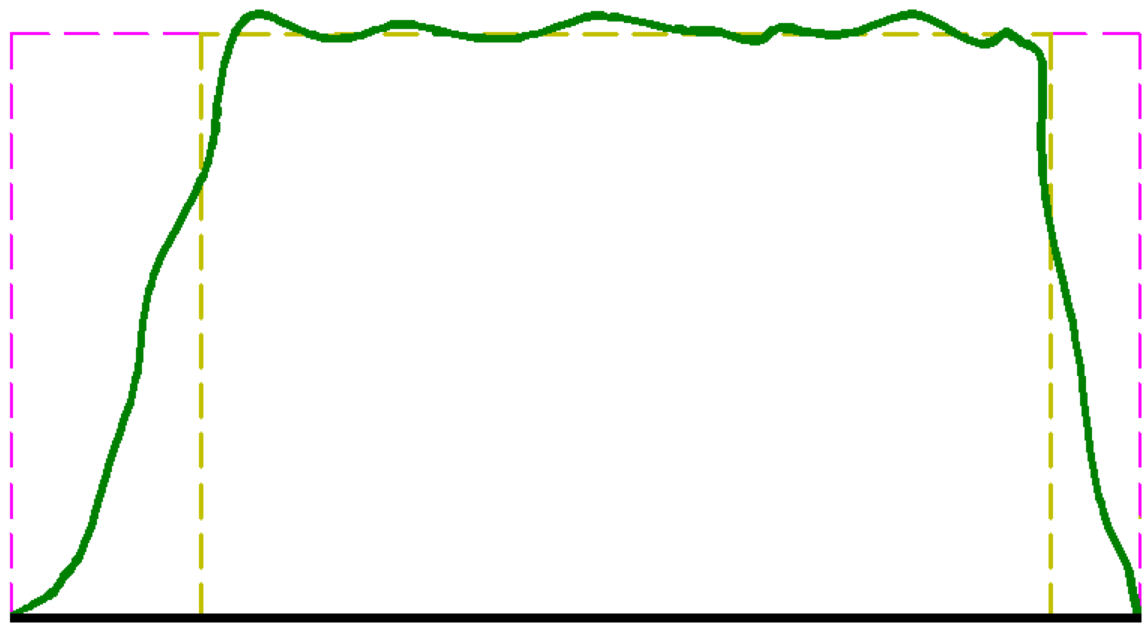


Photo: Author

Photo: Author

Weld quality



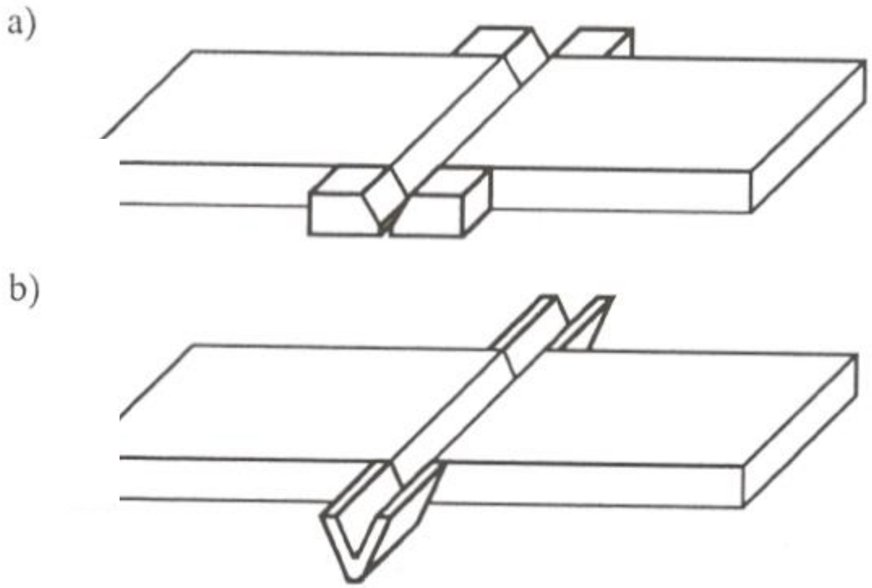
Initial part - launch of the welding machine

Final part - possibility of premature shutdown

Theoretical weld quality by mathematical model

Real weld quality

Real weld quality by mathematical model - too short weld in comparison to load



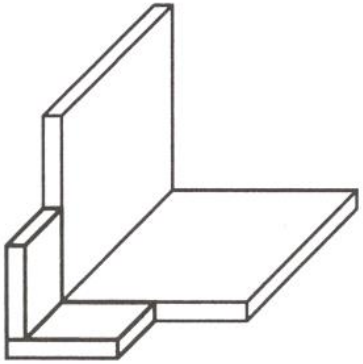
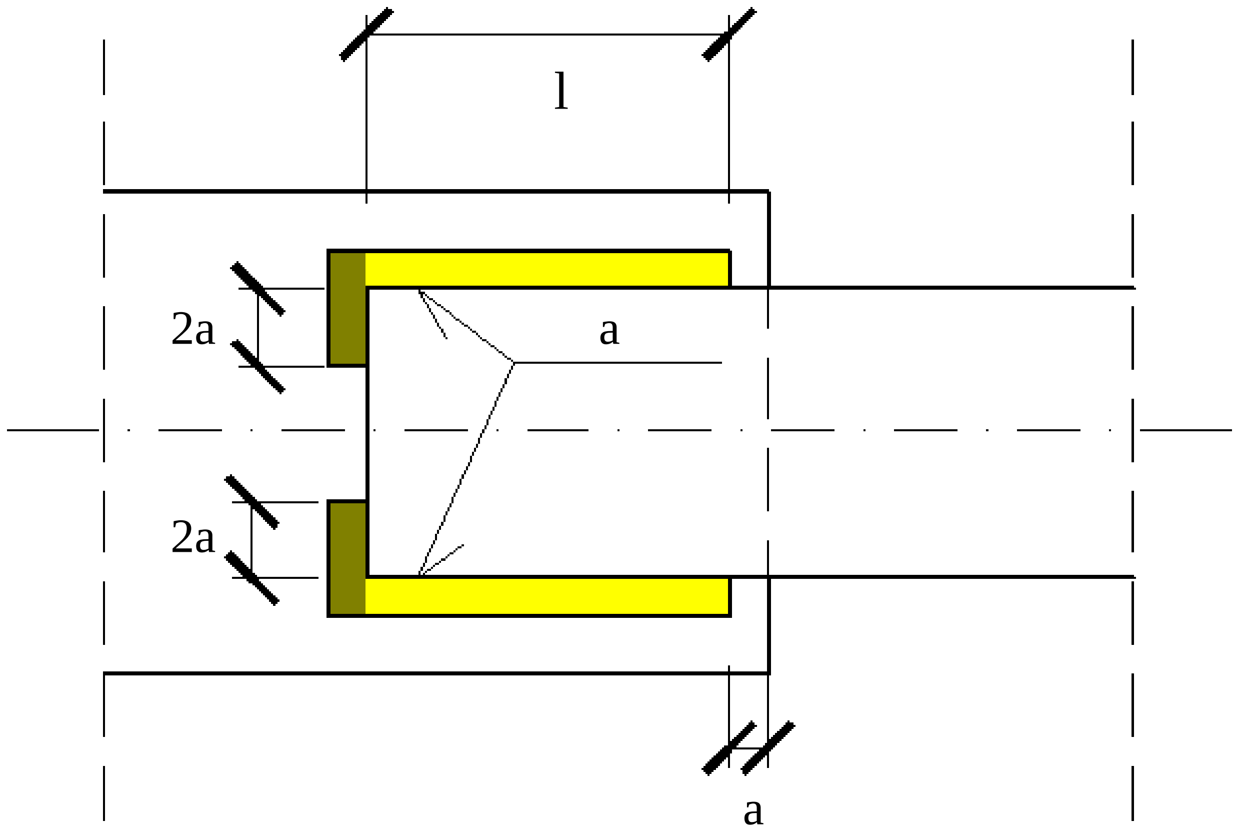


Photo: Konstrukcje stalowe, K. Rykaluk, Dolnośląskie
Wydawnictwo Edukacyjne Wrocław 2001

Run-off plates – initial and final section of the weld are removed

Filled welds – length of welds without run-off plates



$l_{(calculations)} = l$ or $l - 2a$ or $l + 2a - 2a$

Photo: Author

5. Recommendation for cold-formed purlins

Cold-formed purlins are fixed above top surface of girder, with a small gap. This avoids local deformation and collision as effect of imperfection of purlins when pressed against girder. Cold-formed purlin is thin-walled section. Even small deformations could significantly change its cross-section and reduce bending resistance.

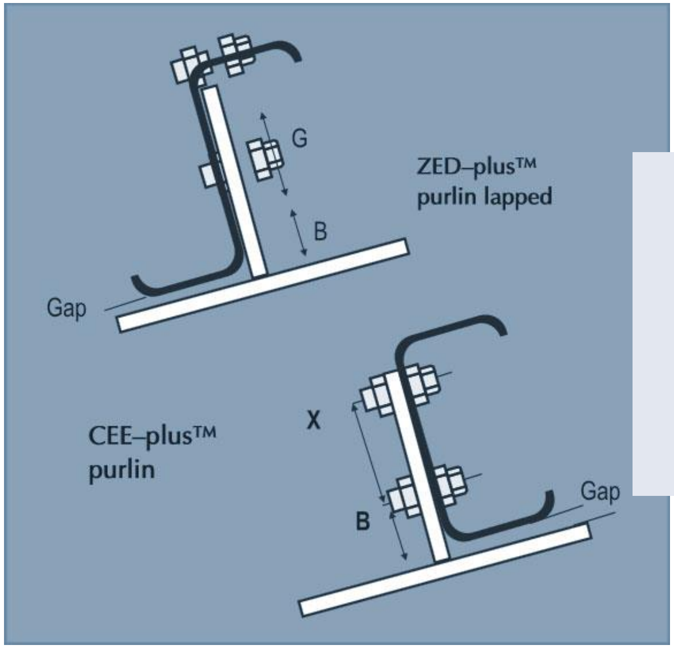


Photo: gscpl.net

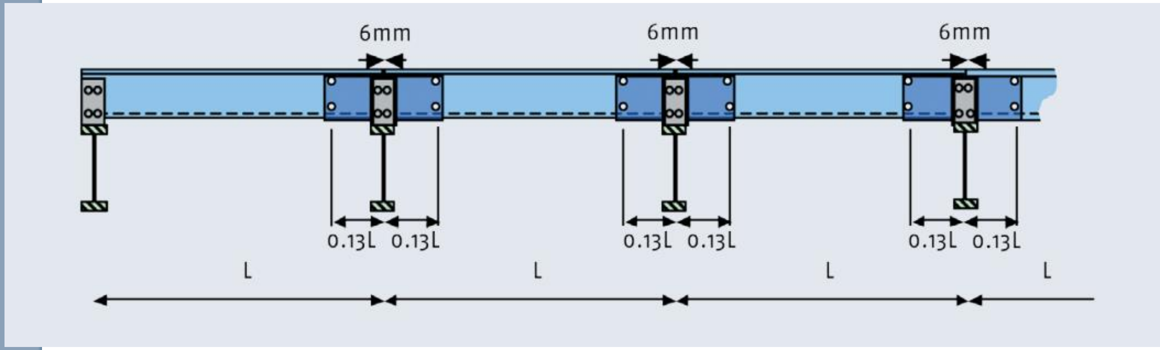
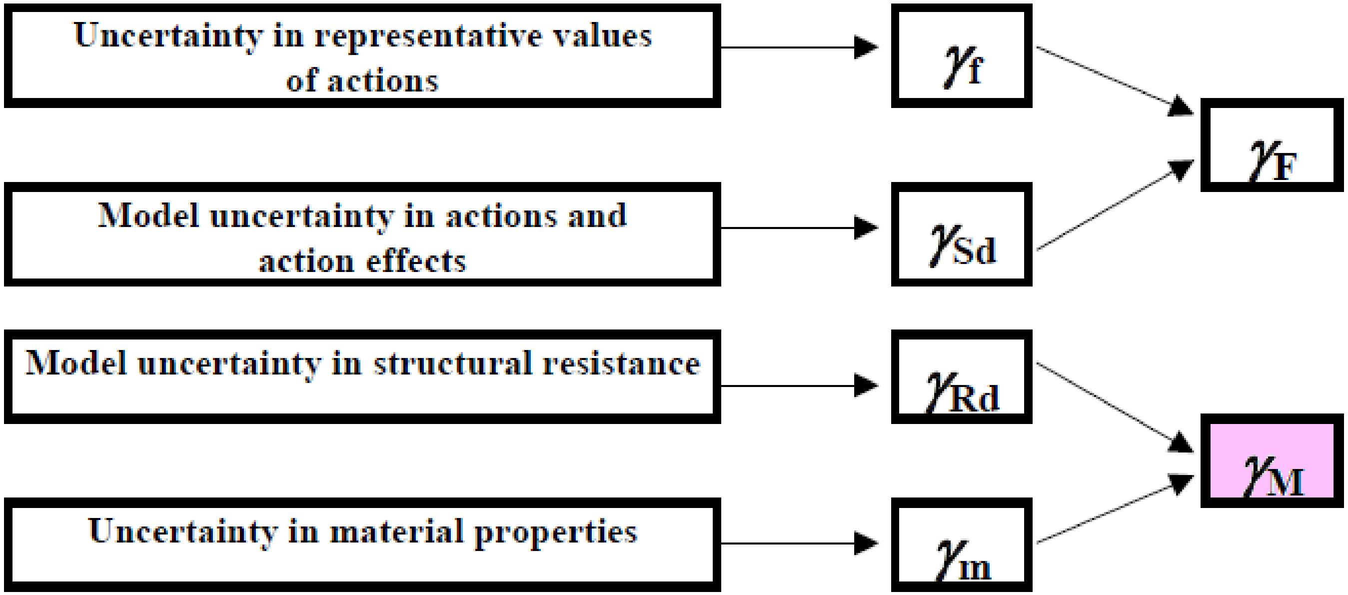


Photo: ruuki.com

Additional parameters

1. Safety factors

Photo: EN 1990 fig. C3



Uncertainty in material propertiws means unknown influence of material imperfections

2. Recalculation from average value to low quantile (structural imperfections):

μ_{Re} (average), σ_{Re} (standard deviation), f_k (lower quantile)

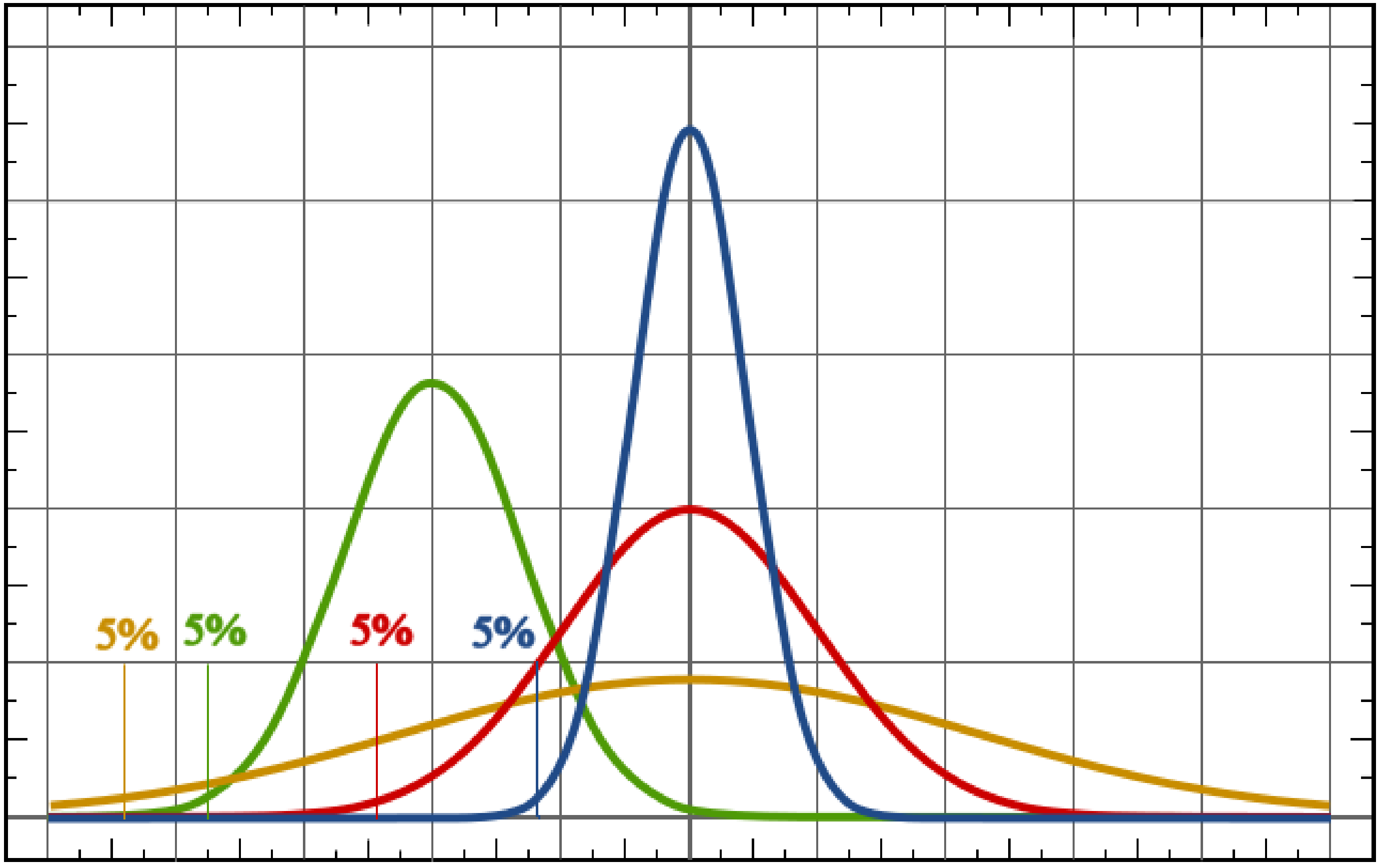
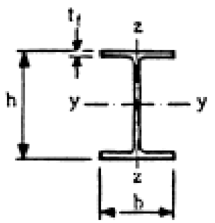
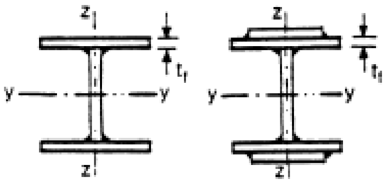
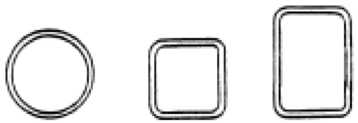


Photo: wikipedia

Cross section	Limits	Buckling about axis	Buckling curve
Rolled I-sections 	h/b > 1,2: $t_f \leq 40$ mm	y – y z – z	a b
	40 mm < $t_f \leq 100$ mm	y – y z – z	b c
	h/b ≤ 1,2: $t_f \leq 100$ mm	y – y z – z	a b
	$t_f > 100$ mm	y – y z – z	d d
Welded I-sections 	$t_f \leq 40$ mm	y – y z – z	b c
	$t_f > 40$ mm	y – y z – z	c d
Hollow sections 	hot rolled	any	a
	cold formed — using f_{yb}*	any	b
	cold formed — using f_{ya}*	any	c

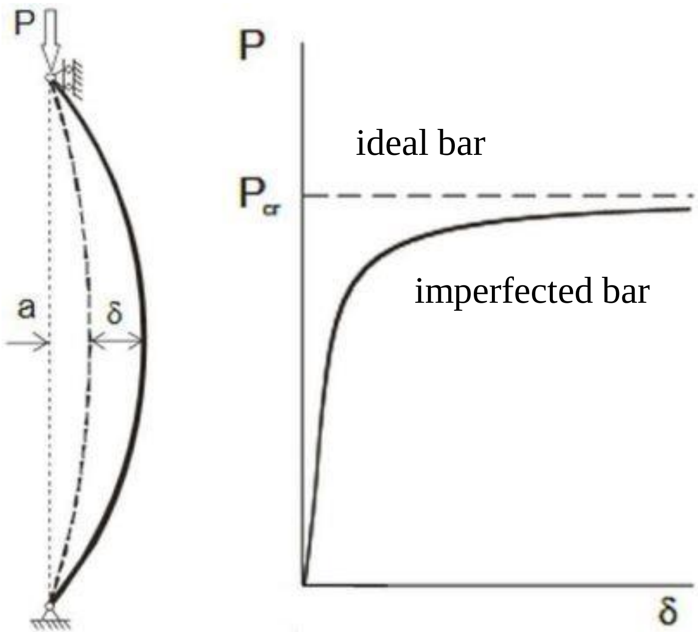
Bucking curve	a	b	c	d
Imperfection factor α	0,21	0,34	0,49	0,76

3. Buckling curves

EN 1993-1-1,
tab. 6.1, 6.2, 6.3, 6.4, 6.5

There are different types of imperfections important for resistance of different types cross-sections.

Photo: chodor-projekt.net



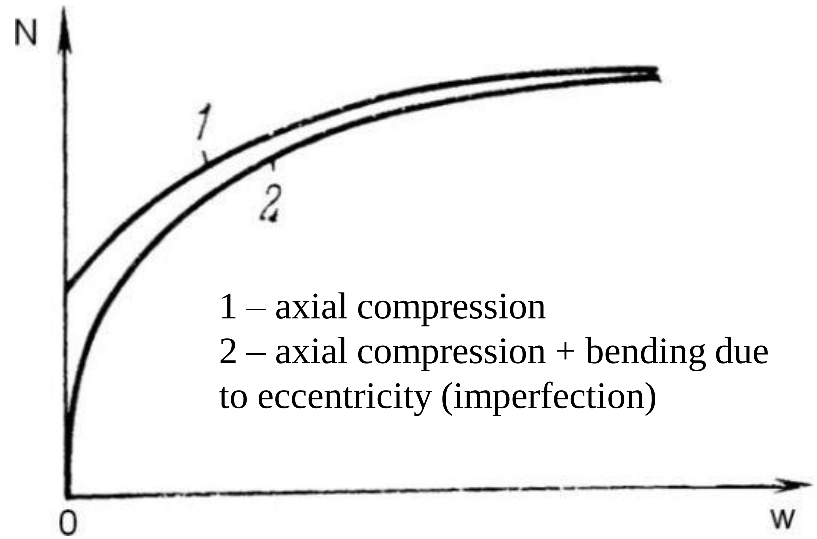


Photo: chodor-projekt.net

Imperfections affect the behavior of the compression bars. Generally: increasing of imperfections makes less critical force and the resistance to instability.

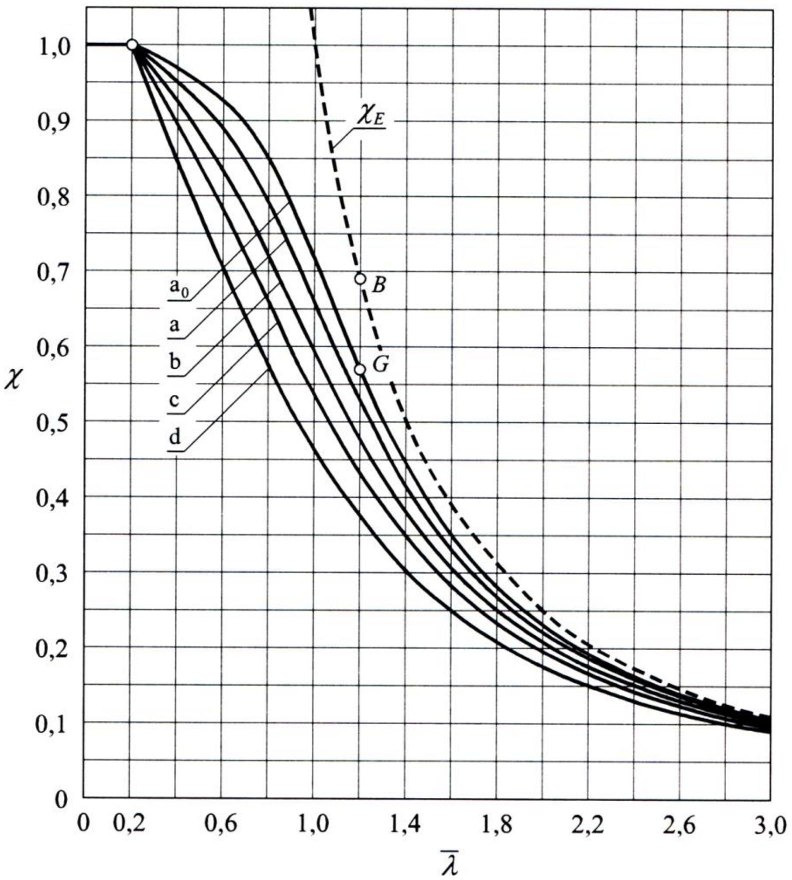


Photo: Zagadnienia stateczności konstrukcji metalowych,
K. Rykaluk, DWE Wrocław 2012

Buckling curves according to Eurocode and for ideal (no geometrical and no material imperfections) compressed bar.

Indirect considerations
(taking into account the influence of imperfection without declaring their value)

1. Different values of yield strength for different thickness of elements: probability of big innoticed internal damage is bigger for thicker element (EN 1993-1-1 tab 3.1):

Standard and steel grade	Nominal thickness of the element t [mm]			
	$t \leq 40$ mm		$40 \text{ mm} < t \leq 80$ mm	
	f_y [N/mm^2]	f_u [N/mm^2]	f_y [N/mm^2]	f_u [N/mm^2]
EN 10025-2				
S 235	235	360	215	360
S 275	275	430	255	410
S 355	355	490	335	470
S 450	440	550	410	550
EN 10025-3				
S 275 N/NL	275	390	255	370
S 355 N/NL	355	490	335	470
S 420 N/NL	420	520	390	520
S 460 N/NL	460	540	430	540
EN 10025-4				
S 275 M/ML	275	370	255	360
S 355 M/ML	355	470	335	450
S 420 M/ML	420	520	390	500
S 460 M/ML	460	540	430	530
EN 10025-5				
S 235 W	235	360	215	340
S 355 W	355	490	335	490
EN 10025-6				
S 460 Q/QL/QL1	460	570	440	550

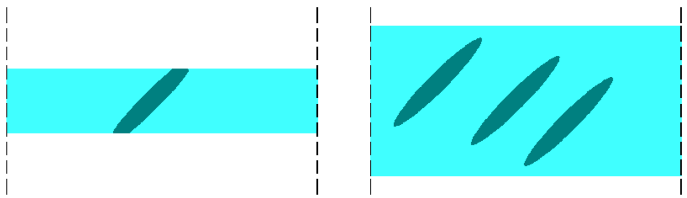


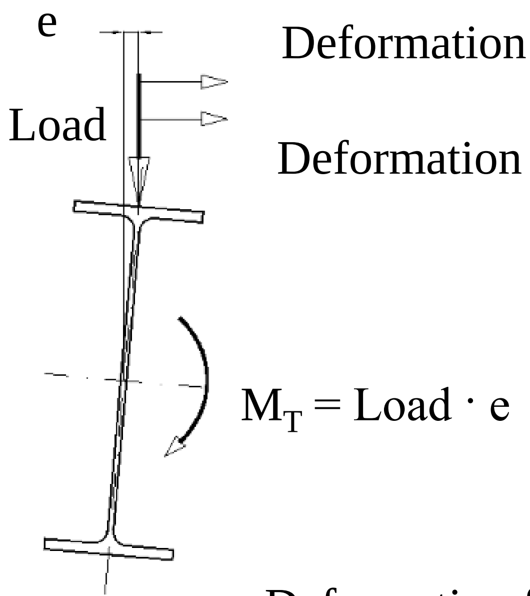
Photo: Author

According to results from Lec #5, critical moment for lateral buckling depends on point of application of load. At the load applied to the upper shelf, the beam loses stability more easily than in the load applied to the bottom shelf.

Application of load	M_{cr} [kNm]	λ_{LT}	χ_{LT}	$\chi_{LT} W_{pl,y} f_y$ [kNm]	M_{Ed} / M_{Rd}
to top flange	91,408	1,271	0,487	71,854	1,113
to centre of shear (= gravity for bi-symmetrical I-beam)	118,515	1,116	0,585	86,323	0,927
to bottom flange	145,635	1,007	0,661	97,509	0,820

Deformation from initial imperfection

Deformation as the result of torsional moment



Initial imperfections make eccentricity e and torsional moment M_T as the secondary effect of load.

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Deformation from initial imperfection

Deformation as the result of torsional moment

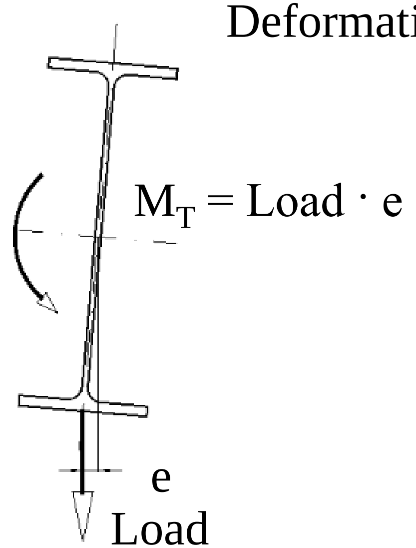


Photo: Author

Various points of load’s application makes various effects of deformations. These deformations from torsional moment can intensify or weaken the impact of initial imperfections. As a result, the cross-section may lose stability more easily (smaller M_{cr}) or more difficult (larger M_{cr})

3. Fatigue calculations

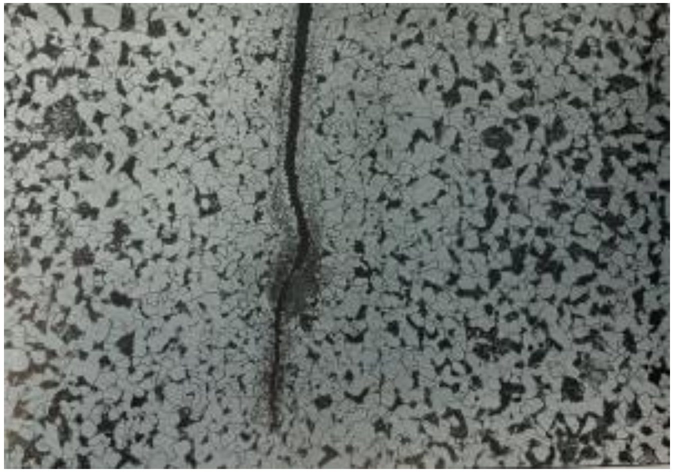


Photo: pmpaspeakingofprecision.com

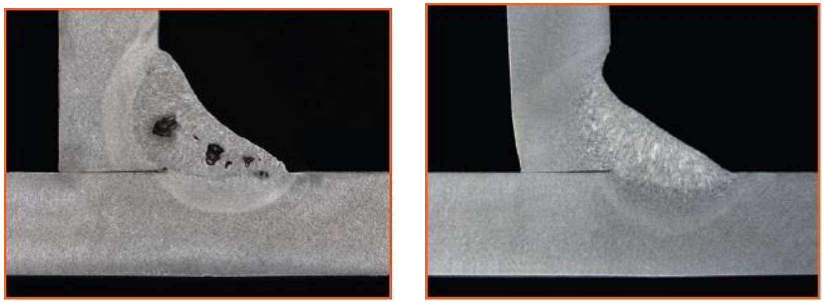
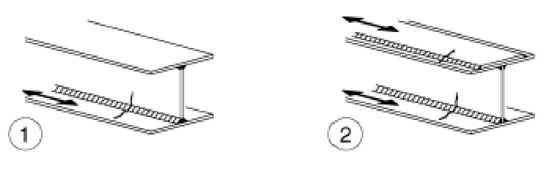
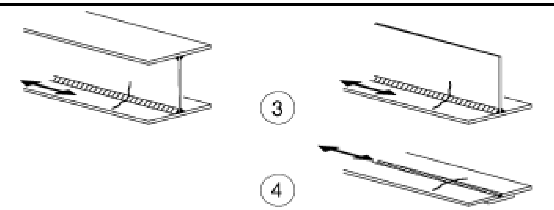
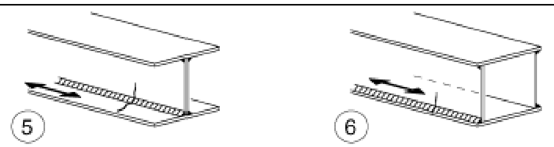
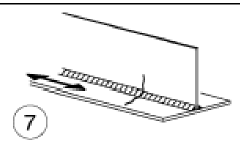


Photo: figel.pl

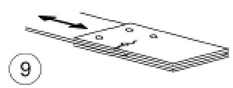
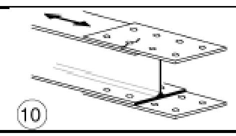
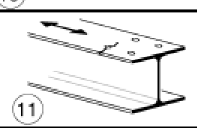
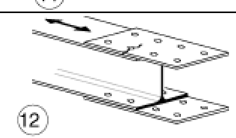
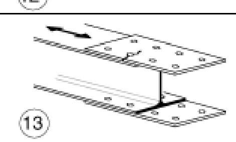
Imperfections originating from machining (cutting, drilling holes) and re-formed during welding, are notches reducing fatigue resistance. They must be taken into account in the case of high-cyclic and dynamic loads. Initial fatigue resistance, depending on the type of notch (i.e. its origin), is described in EN 1993-1-11. Initial fatigue resistance decreases with increasing of load cycles number.

Differen value for different notches

125		Continuous longitudinal welds: 1) Automatic butt welds carried out from both sides. 2) Automatic fillet welds. Cover plate ends to be checked using detail 6) or 7) in Table 8.5.
112		3) Automatic fillet or butt weld carried out from both sides but containing stop/start positions. 4) Automatic butt welds made from one side only, with a continuous backing bar, but without stop/start positions.
100		5) Manual fillet or butt weld. 6) Manual or automatic butt welds carried out from one side only, particularly for box girders
100		7) Repaired automatic or manual fillet or butt welds for categories 1) to 6).

EN 1993-1-9 tab. 8.1 - 8.10

EN 1993-3-2 tab. C-1

		9) Double covered joint with fitted bolts. 9) Double covered joint with non preloaded injection bolts.	9) ... net cross-section. 9) ... net cross-section.
		10) One sided connection with preloaded high strength bolts. 10) One sided connection with preloaded injection bolts.	10) ... gross cross-section. 10) ... gross cross-section.
		11) Structural element with holes subject to bending and axial forces	11) ... net cross-section.
80		12) One sided connection with fitted bolts. 12) One sided connection with non-preloaded injection bolts.	12) ... net cross-section. 12) ... net cross-section.
50		13) One sided or double covered symmetrical connection with non-preloaded bolts in normal clearance holes. No load reversals.	13) ... net cross-section.

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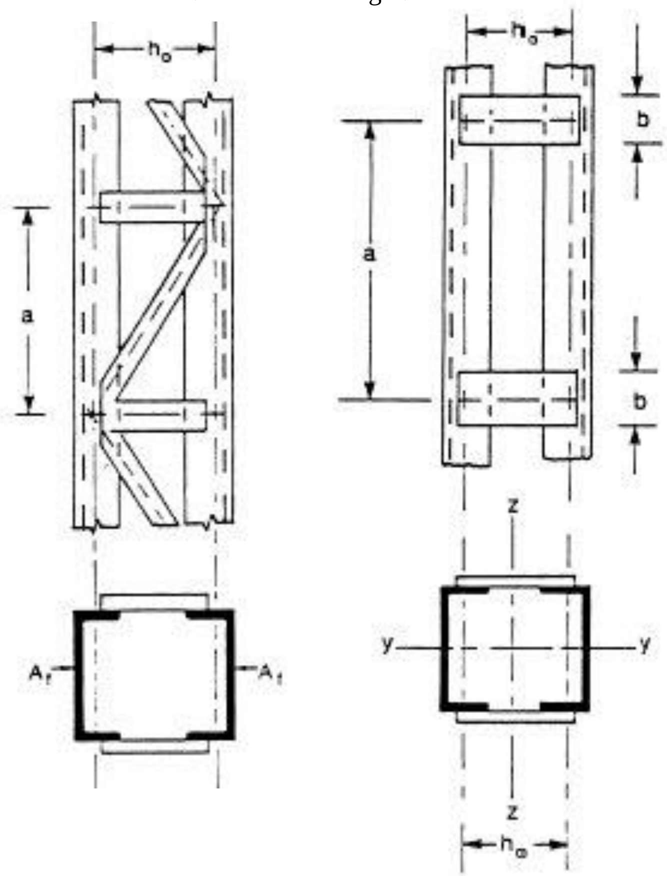
Direct considerations

(equivalent values of imperfections in formulas)

1. We must analysed initial deformations for members with two or more chords (according to EN 1993-1-1 p.6.4). This means, these elements are always bent, even if axial force acts only.

Photo: EN 1993-1-1 fig 6.7



$$M_{Ed}^{II} = e_{imperf} N_{Ed}$$

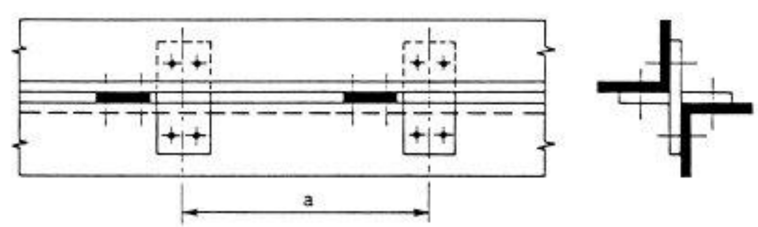
More information will be presented on II step of study

laced compression members,

battened compression members,

closely spaced build-up compression members

Photo: EN 1993-1-1 fig 6.13



2. Stiffeners

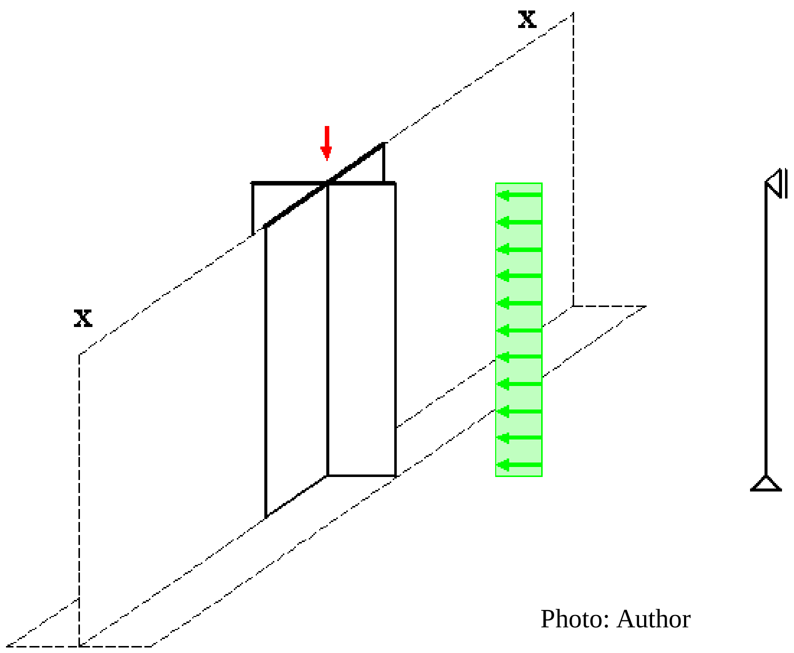


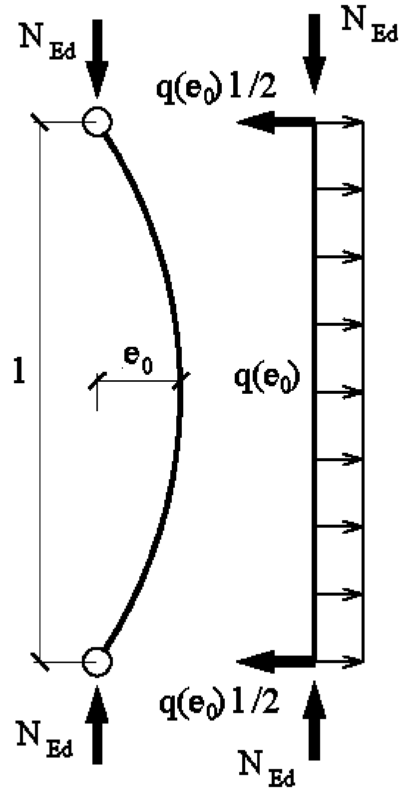
Photo: Author

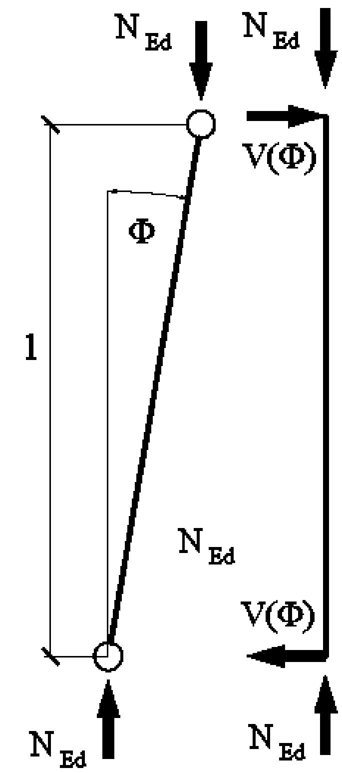
Because of initial imperfections, we increase value of axial force and add prependicular load. Both depend on e_{imperf}

More information will be presented on lecture # 21

Photo: Author

3. Equivalent effects : initial bow imperfection and initial sway imperfection.





For both, we calculated self-balanced loads, corresponded to deformations.

We use different models for different members:

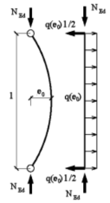
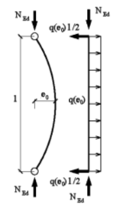
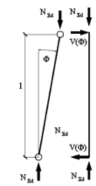
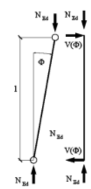
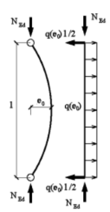
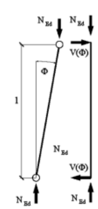
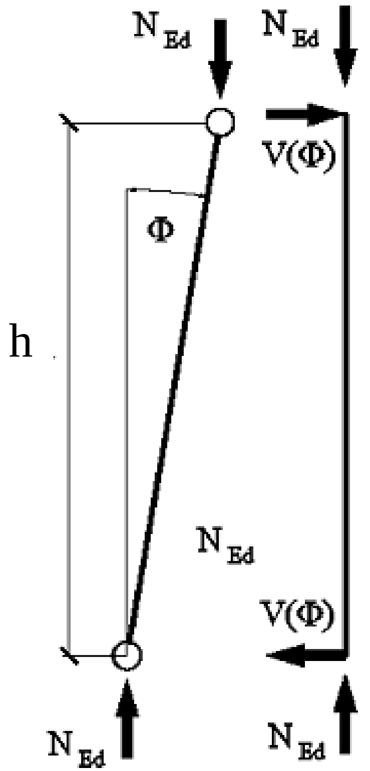
roof girder and horizontal bracing (roof)	
horizontal bracing (ceiling)	 or 
vertical bracing	
column	 and  (mutually exclusive in combinations)

Photo: Author

Sway imperfection



EN 1993-1-1 fig. 5.4

Photo: Author

$\Phi = \Phi_0 \, \alpha_h \, \alpha_m$

$\Phi_0 = 1 / 200$

$\alpha_h = \max\{ 2/3 \; ; \; \min[(2 / \sqrt{h}) \; ; \; 1{,}0]\}$

h – heigh of structure [m]

$\alpha_m = \sqrt{[0{,}5 (1 + 1 / m)]}$

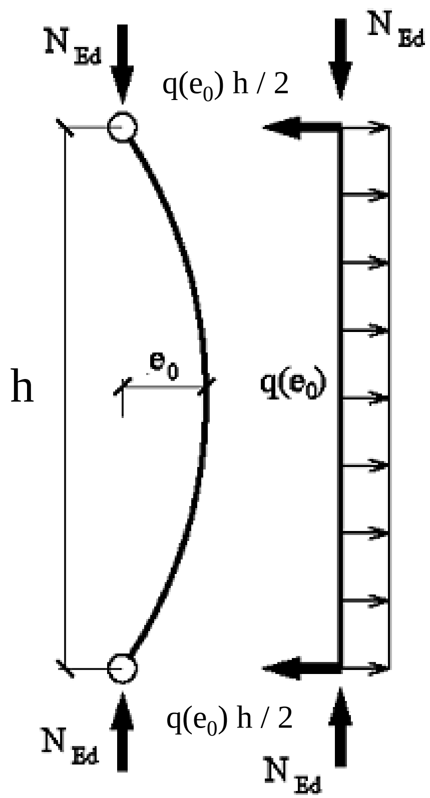
m - number of columns (elements) in a row, including only those columns, which carry a vertical load N_{Ed} not less than 50% of the average value of the column in the vertical plane considered

N_{Ed} – axial force in column or in braced member (chord of truss, etc).

$V(\Phi) \, h = M = N_{Ed} \, h \, \Phi$

$V(\Phi) = N_{Ed} \, \Phi$

Bow imperfection



EN 1993-1-1 fig. 5.4

Photo: Author

e_0 depends on buckling curve (→ Lec #5)

Buckling curve	Elastic analysis	Plastic annalysis
a_0	l / 350	l / 300
a	l / 300	l / 250
b	l / 250	l / 200
c	l / 200	l / 150
d	l / 150	l / 100

N_{Ed} – axial force in column or in braced member (chord of truss, etc).

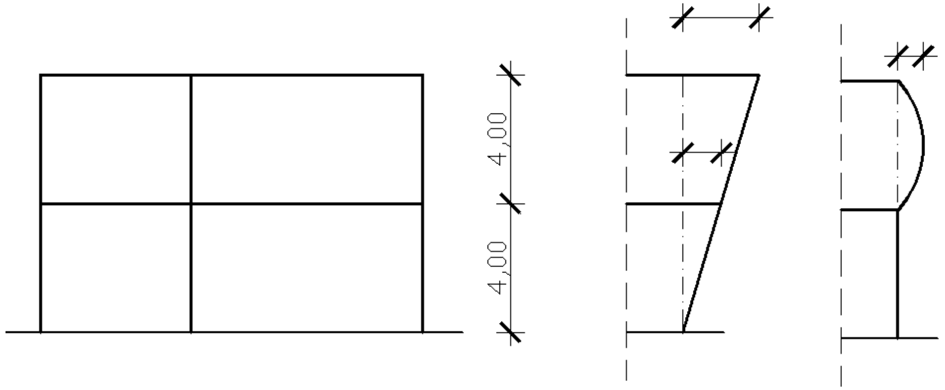
$N_{Ed}\ e_0 = M = q(e_0)\ h^2 / 8$

$q(e_0) = 8\ N_{Ed}\ e_0 / h^2$

Example

Comparision of imperfections values [m]

Photo: Author

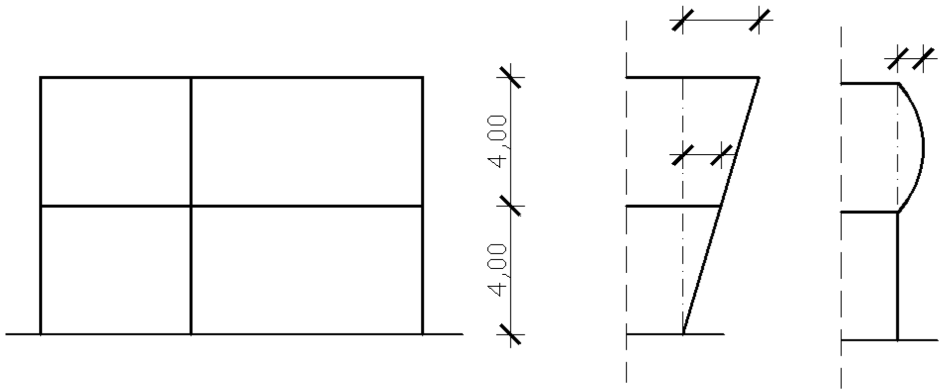


Columns HEB 300, S235, buckling about axis y, elastic analysis

Essentian imperfection - functional imperfection - design imperfection

Sway imperfection for entire structure - sway imperfection for one storey - bow imperfection

Photo: Author

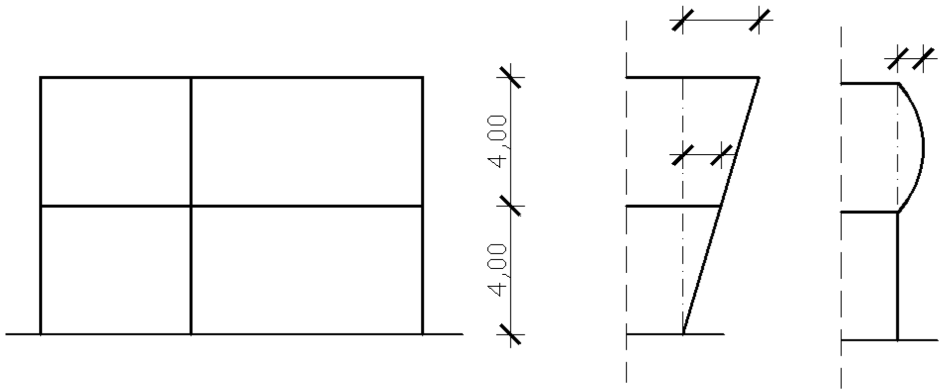


Essential imperfections

Type	Table	Value
Sway imperfection for entire structure	EN 1090-2, tab. D 1-12	$+/- \Sigma h / (300 \sqrt{n}) = +/- 8 / (300 \cdot 1{,}414) =$ $= +/- 0{,}019$ m
Sway imperfection for one storey		$+/- h / 500 = +/- 4 / 500 =$ $= +/- 0{,}008$ m
Bow imperfection		$+/- h / 750 =$ $= +/- 0{,}007$ m

n – number of storey

Photo: Author

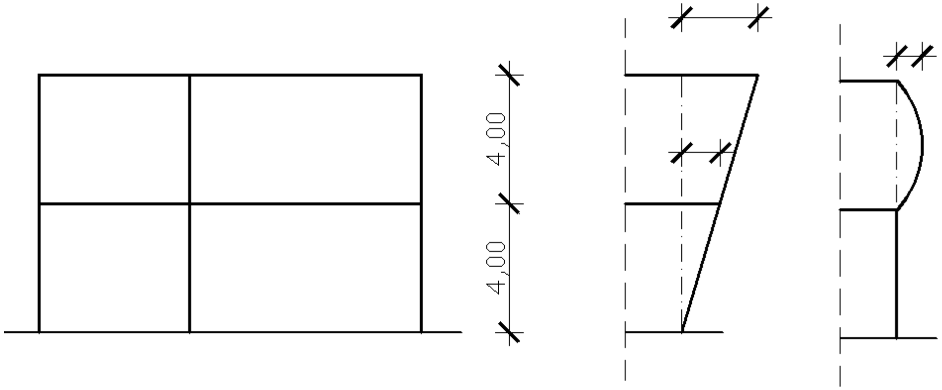


Functional imperfections, Class 1

Type	Table	Value
Sway imperfection for entire structure	EN 1090-2, tab. D 2-24	+/- Σ h / (300 √n) = +/- 8 / (300 · 1,414) = = +/- 0,019 m
Sway imperfection for one storey		+/- h / 500 = +/- 4 / 500 = = +/- 0,008 m
Bow imperfection		+/- h / 750 = = +/- 0,007 m

n – number of storey

Photo: Author

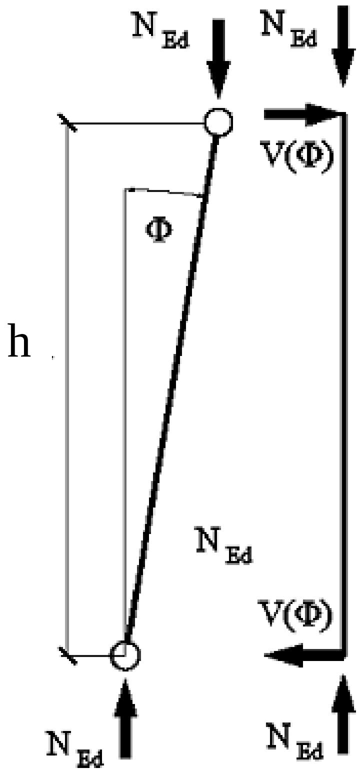


Functional imperfections, Class 2

Type	Table	Value
Sway imperfection for entire structure	EN 1090-2, tab. D 2-24	+/- Σ h / (500 √n) = +/- 8 / (500 · 1,414) = = +/- 0,011 m
Sway imperfection for one storey		+/- h / 1000 = +/- 4 / 1000 = = +/- 0,004 m
Bow imperfection		+/- h / 1000 = = +/- 0,004 m

n – number of storey

Sway imperfection - design



$\Phi = \Phi_0 \, \alpha_h \, \alpha_m$

$\Phi_0 = 1 / 200$

$\alpha_h = \max\{ 2 / 3 \;\; ; \;\; \min[(2 / \sqrt{h}) \;\; ; \;\; 1{,}0]\}$

h – heigh of structure [m]

The maximum possible value of $\alpha_h = 1{,}0$

$\alpha_m = \sqrt{[0{,}5 (1 + 1 / m)]}$

m - number of columns

The maximum possible value of $\alpha_m \rightarrow 1{,}0$

The maximum possible value of $\Phi_{max} = 1 / 200$

Photo: Author

Sway imperfection – design

for entire structure; $h = 8{,}0$ m, $m = 3$ columns
for one storey; $h = 4{,}0$ m, $m = 3$ columns

α	Entire structure	One storey
α_h	$\max\{2/3 \; ; \; \min[(2/\sqrt{h}) \; ; \; 1{,}0]\} =$ $= \max\{2/3 \; ; \; \min[(2/\sqrt{8}) \; ; \; 1{,}0]\} =$ $= \max\{0{,}667 \; ; \; \min[0{,}707 \; ; \; 1{,}0]\} =$ $= \max\{0{,}667 \; ; \; 0{,}707\} =$ $= 0{,}707$	$\max\{2/3 \; ; \; \min[(2/\sqrt{h}) \; ; \; 1{,}0]\} =$ $= \max\{2/3 \; ; \; \min[(2/\sqrt{4}) \; ; \; 1{,}0]\} =$ $= \max\{0{,}667 \; ; \; \min[1{,}0 \; ; \; 1{,}0]\} =$ $= \max\{0{,}667 \; ; \; 1{,}000\} =$ $= 1{,}000$
α_m	$\sqrt{[0{,}5\,(1 + 1/m)]} = \sqrt{[0{,}5\,(1 + 1/3)]} =$ $= \sqrt{0{,}667} =$ $= 0{,}816$	$\sqrt{[0{,}5\,(1 + 1/m)]} = \sqrt{[0{,}5\,(1 + 1/3)]} =$ $= \sqrt{0{,}667} =$ $= 0{,}816$

Sway imperfection – design

for entire structure; h = 8,0 m, m = 3 columns
for one storey; h = 4,0 m, m = 3 columns

Number of storeys	Value	
	For analysed structure	The maximum possible value
Entire structure	+/- $h \Phi_0 \alpha_h \alpha_m$ = = +/- 8 · 0,707 · 0,816 / 200 = + /- 0,023 m	+/- $h \Phi_{max}$ = +/- 8 / 200 = = +/- 0,040 m
One storey	+/- $h \Phi_0 \alpha_h \alpha_m$ = = +/- 4 · 1,000 · 0,816 / 200 = + /- 0,016 m	+/- $h \Phi_{max}$ = +/- 4 / 200 = = +/- 0,020 m

Bow imperfection - design

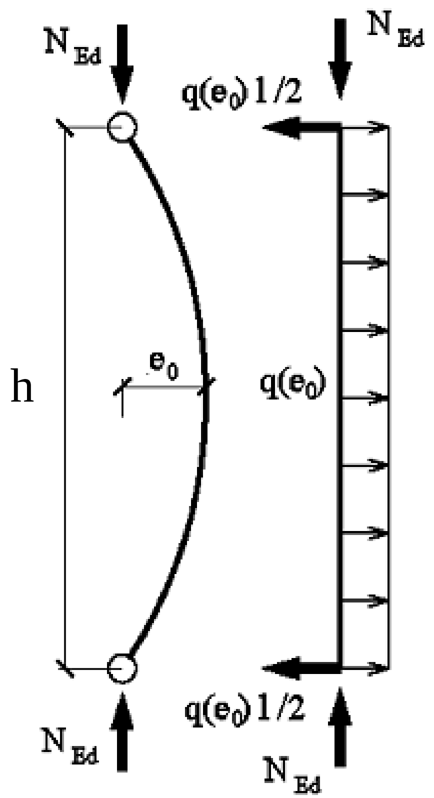


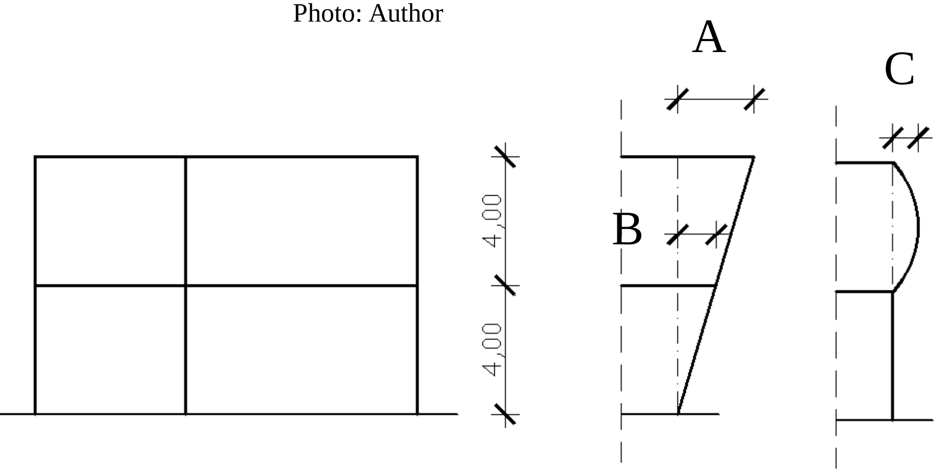
Photo: Author

Buckling curve	Elastic analysis	Plastic annalysis
a_0	l / 350	l / 300
a	l / 300	l / 250
b	l / 250	l / 200
c	l / 200	l / 150
d	l / 150	l / 100

Columns HEB 300, S235, buckling about axis y, elastic analysis → EN 1993-1-1 tab 6.2 → buckling curve b → → +/- h / 250 = +/- 4 / 250 = +/- 0,016 m

The maximum possible value +/- h / 100 = +/- 0,040 m

Photo: Author

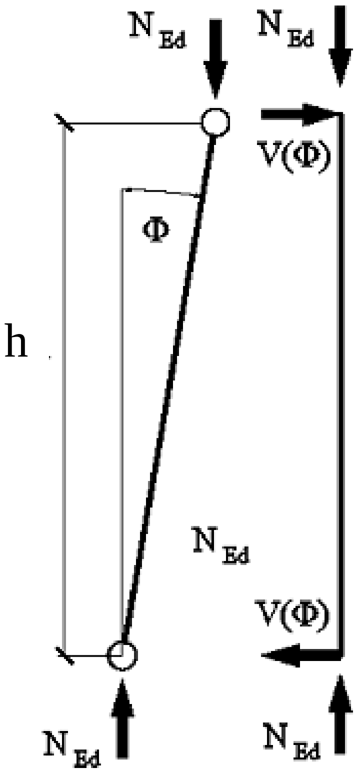


Comparison of imperfections values +/- [mm]

Imperfection	Essential	Functional		Design	
		Class 1	Class 2	For analysed structure	Max possible
A: sway – total	19	19	11	23	40
B: sway – storey	8	8	4	16	20
C: bow	7	7	4	16	40

Technical requirements limit values of imperfection in real structures. Bigger values are not acceptable; structure must be repaired or erected once again.
For design we must take into consideration bigger values of imperfections, than are acceptable in real structures.

Photo: Author

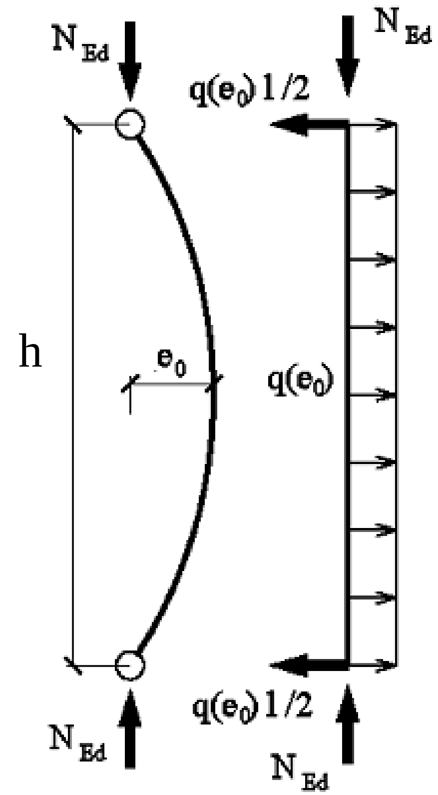


Example: design values of imperfection for sway and bow imperfections for one storey (h = 4,0 m):

B: $h\,\Phi = 0{,}016$ m $\rightarrow \Phi = 0{,}0040$

C: $h\,e_0 = 0{,}016$ m $\rightarrow e_0 = 0{,}0040$

$N_{Ed} = 150$ kN

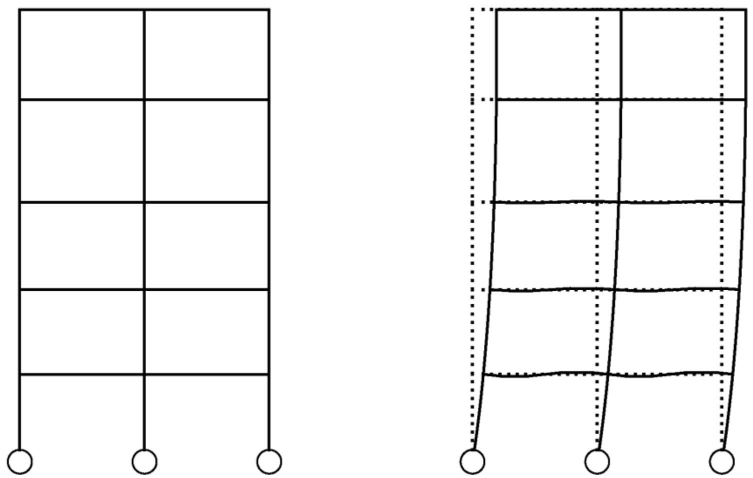


$V(\Phi) = N_{Ed}\,\Phi = 0{,}607$ kN

$q(e_0) = 8\,N_{Ed}\,e_0 / h^2 = 0{,}300$ kN/m

Photo: Author

Multistorey frame - sway imperfections (global)



Global = sway

Equivalent loads should be applied in accordance with the modes of instability.

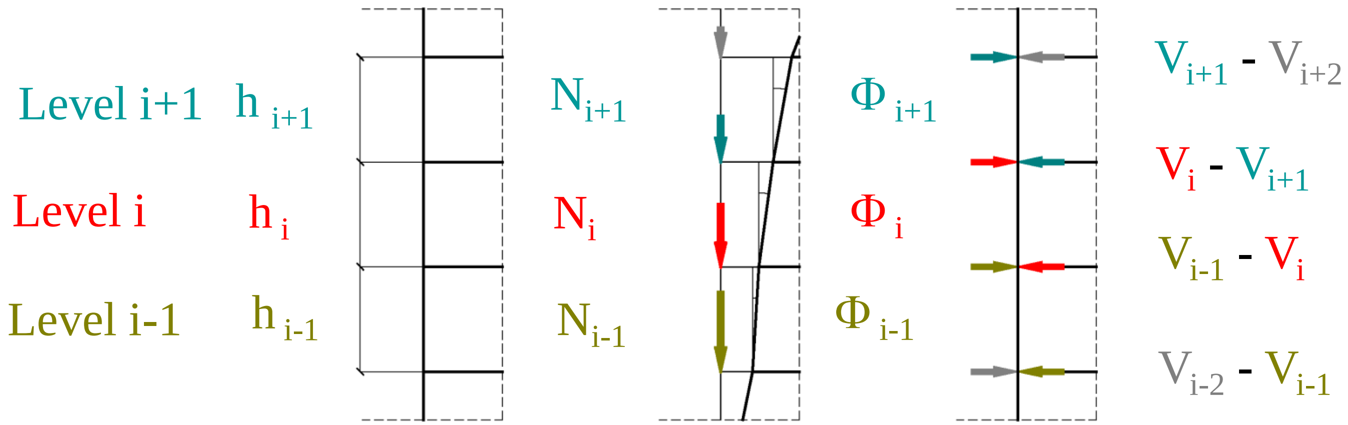
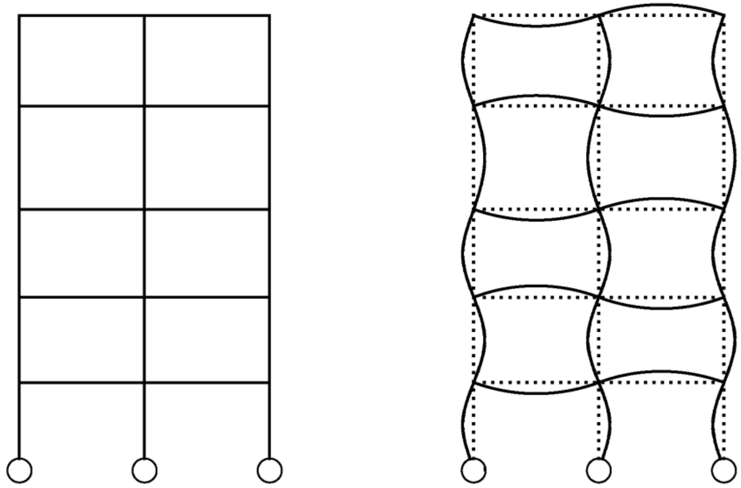


Photo: Author

Multistorey frame - bow imperfections (local)



Local = bow

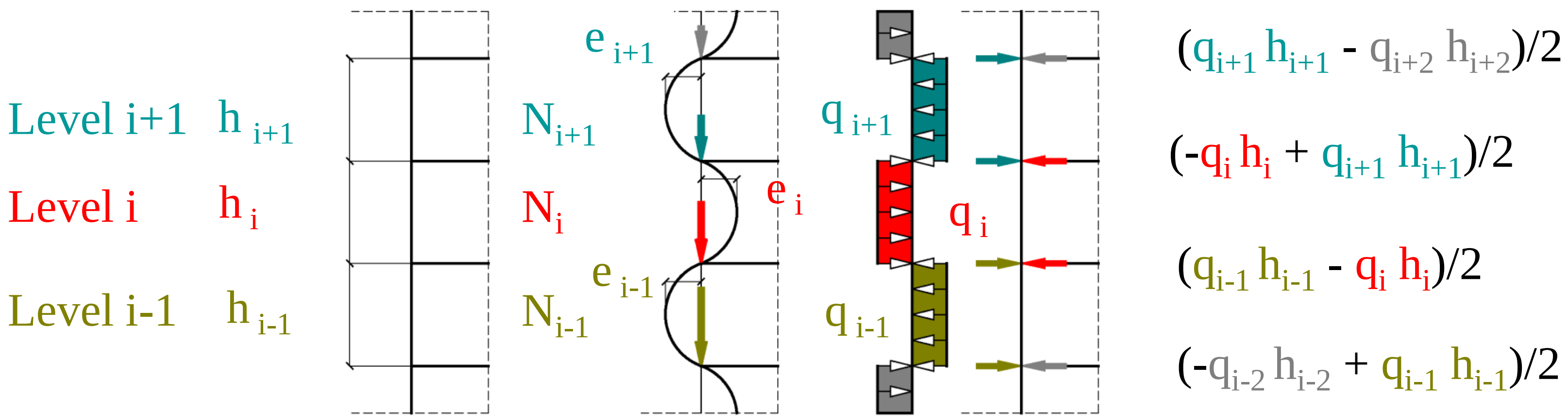


Photo: Author

Examination issues

Types and examples of imperfections

Importance of exectuion class

Equivalent forces of imperfections

Stiffener - żeberko
Footing - stopa fundamentowa
Bracing - stężenie

Thank you for attention

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