European Commission

Eurocodes
Background and Applications

Design of **Steel Buildings**
with worked examples

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Brussels, Belgium

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European Commission
DG Enterprise and Industry
Joint Research Centre
European Convention for Constructional Steelwork
European Committee for Standardization
CEN/TC250/SC3

Basis of Design, a case study building

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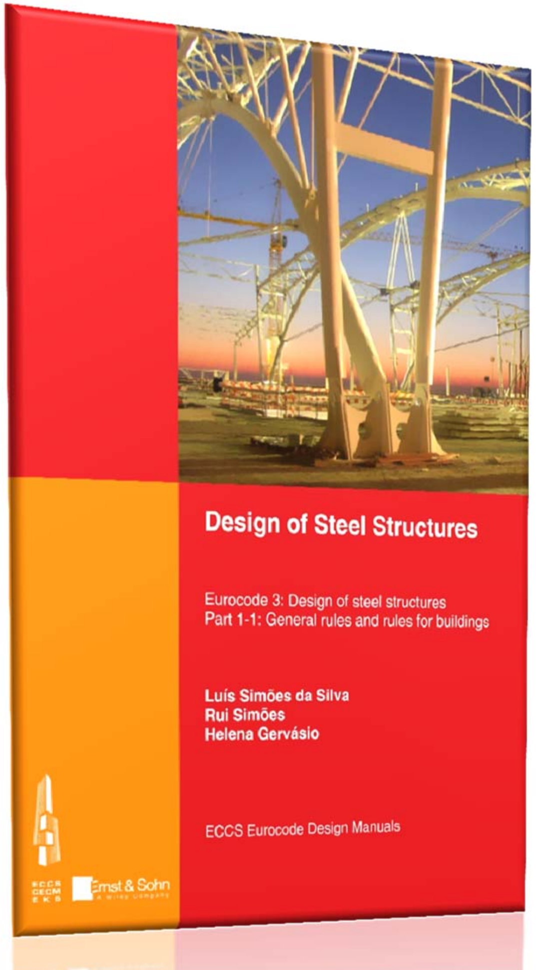
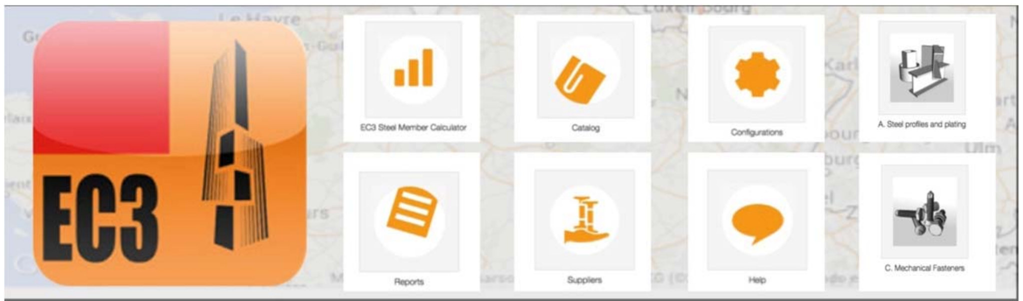
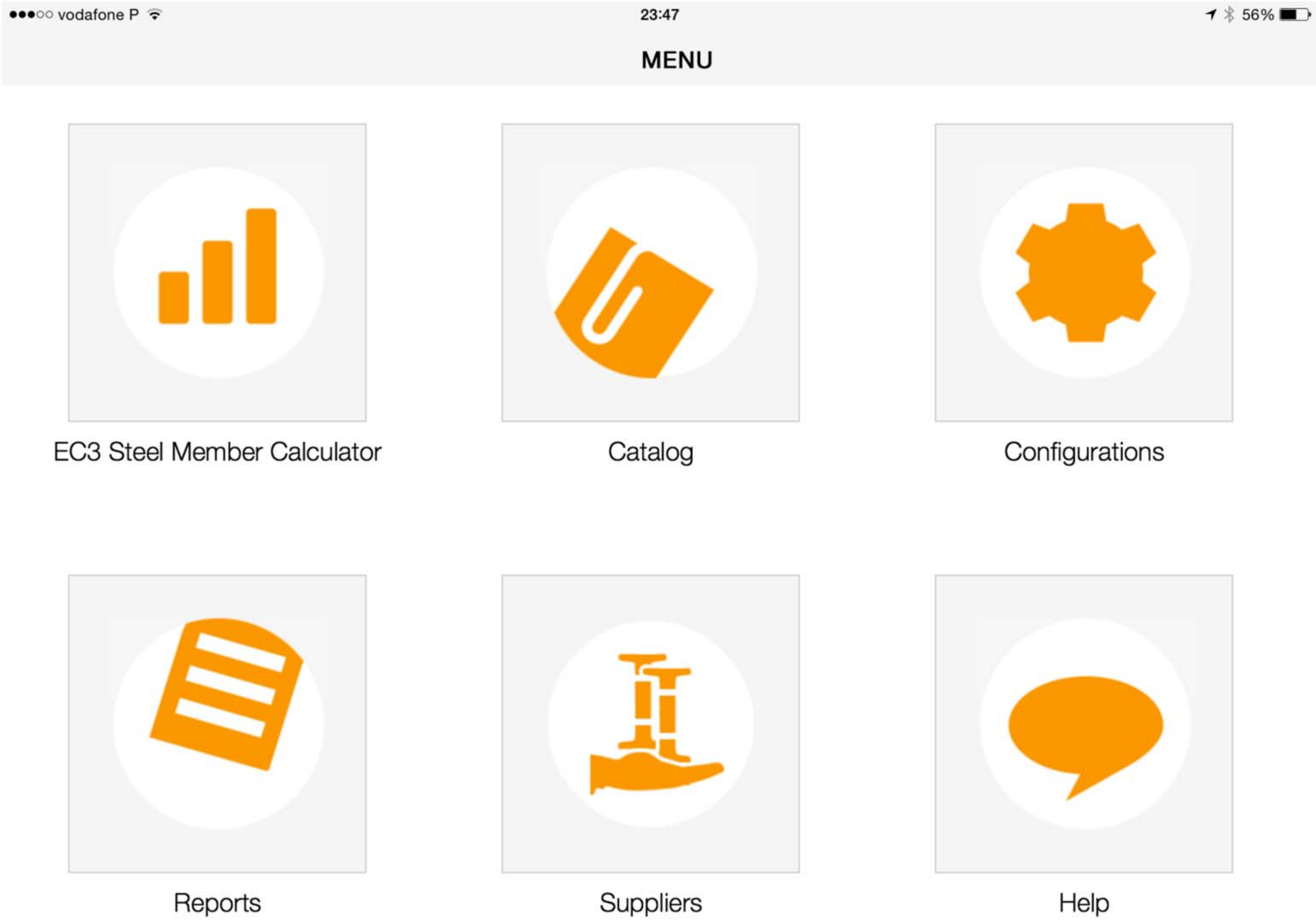
Joint Research Centre

Contents

Support material from ECCS



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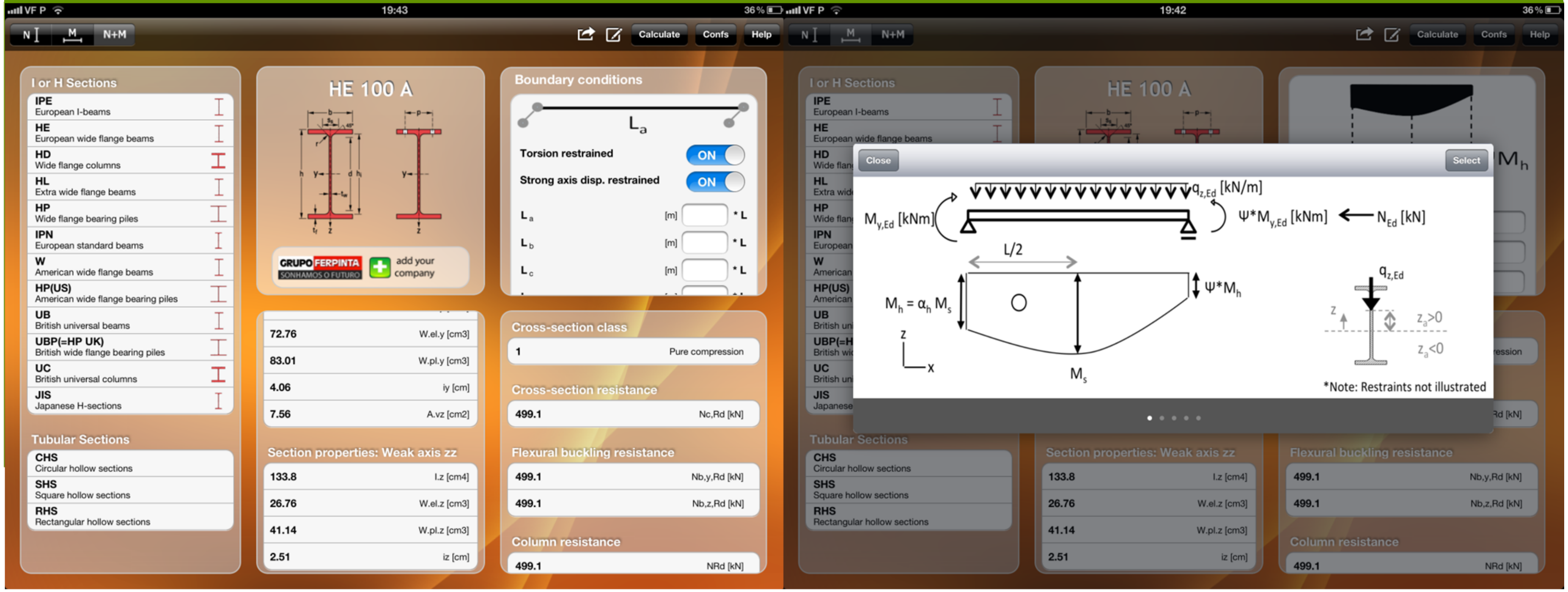
EC3 Steel Member Calculator
Catalog
Configurations
Reports
Suppliers
Help

VERSION 3.0 (May 2014):

- Tubular sections
- Beam-columns
- Geo referencing

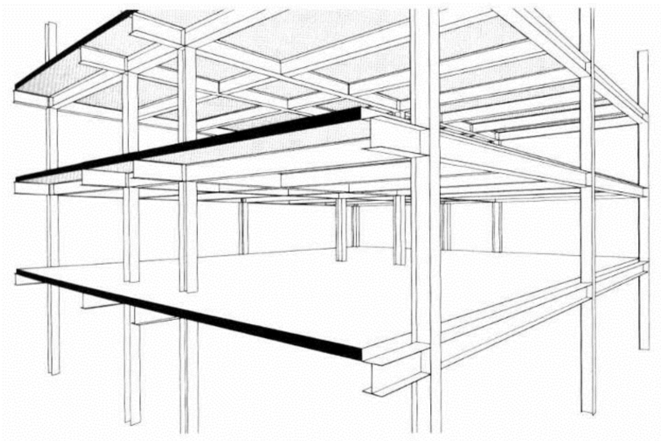


Definitions and Basis of Design

- ✓ Conceptual Aspects
- Codes of Practice and Standardization
- Basis of Design
- Materials
- Geometric Characteristics and Tolerances

The conceptual of design of a steel building includes:

- **geometry** and **structural scheme** – isostatic/hyperstatic systems, trusses/portal frame, type of connections (rigid, hinged,…), type of floor systems, type and section orientation (hot-rolled, welded,…), bracing systems, type of supports (built-in, hinges,…), expansion joints, etc…, taking into account the loading (vertical loads, wind, seismic, ΔT, settlement of supports, etc...)
- **definition of materials** – strength grades and steel quality, bolts, etc…;
-



Conceptual aspects

<u>In addition, it must take into account:</u>

- architecture project, installation of equipments and functional requirements (thermal and acoustic);
- safety checks;
- serviceability checks;
- durability of the structure;
- cost and construction time (e.g. bolted connections instead of welded connections);
- fabrication, transport and erection;
- sustainability (e.g. ease of disassembly).

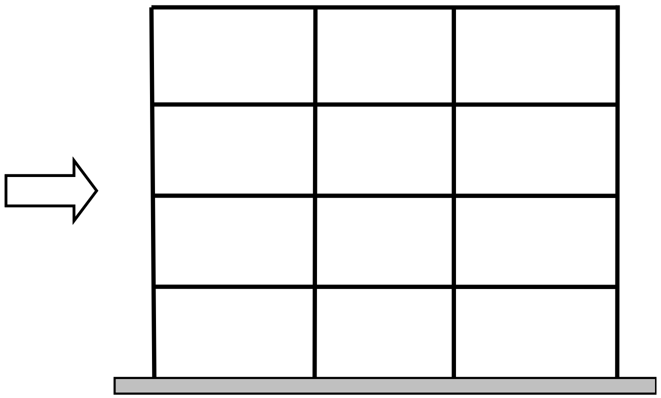
Braced and unbraced buildings

- Braced systems - strength and stiffness to horizontal actions and global stability (2nd order sway effects).
- Strength and stiffness (wind, seismic, etc…) may be achieved by:

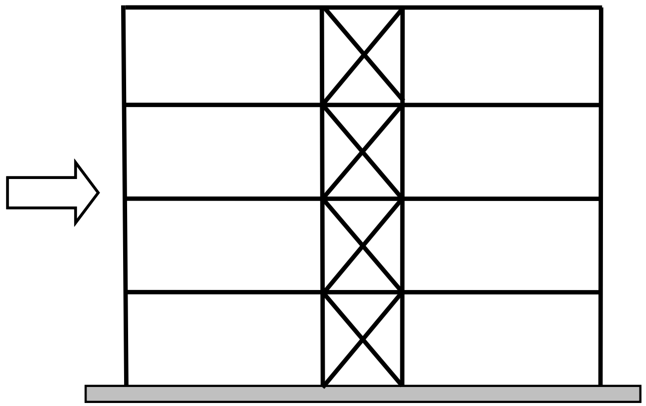
  i) triangular systems;

  ii) rigid walls or pavements;

  iii) stiffness of the structure (rigid connections).

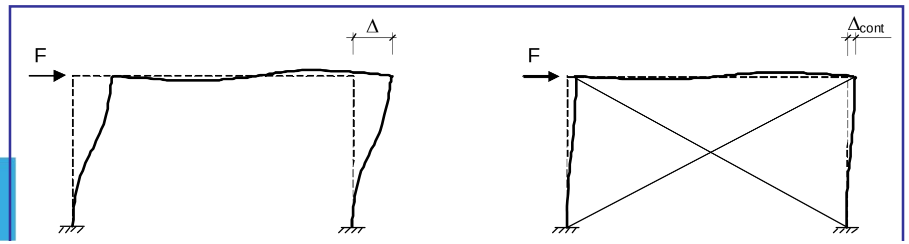


a) Unbraced structure



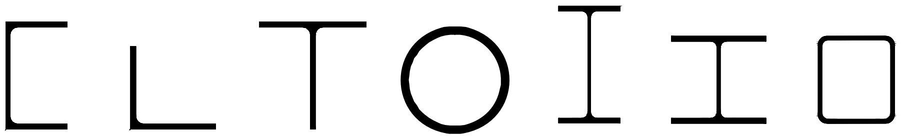
b) Braced structure

Criteria for effective bracing – bracing system reduces the lateral flexibility by at least 80%



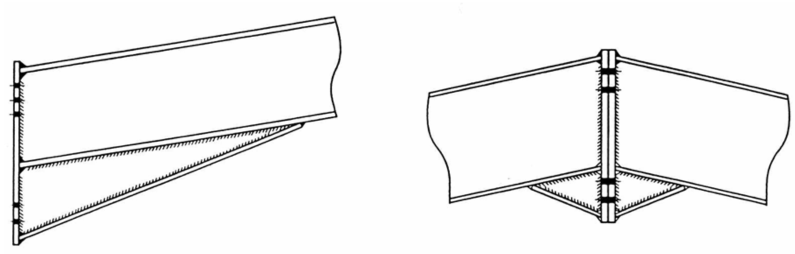
Conceptual aspects

Type of sections



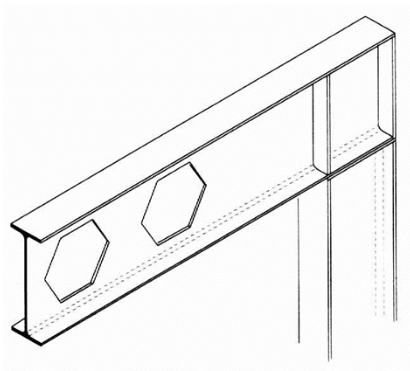
Hot-rolled sections

Type of connections

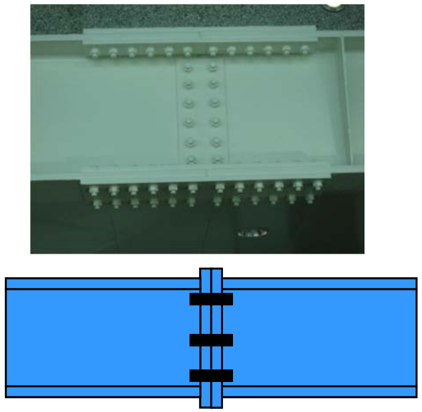


Bolted beam-to-column and beam-to-beam joints

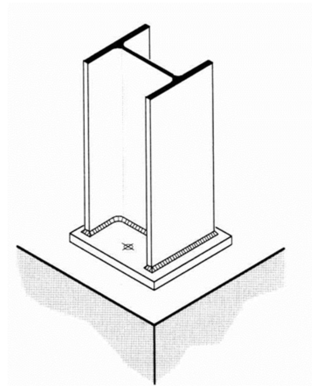
Tapered members



Castellated beams

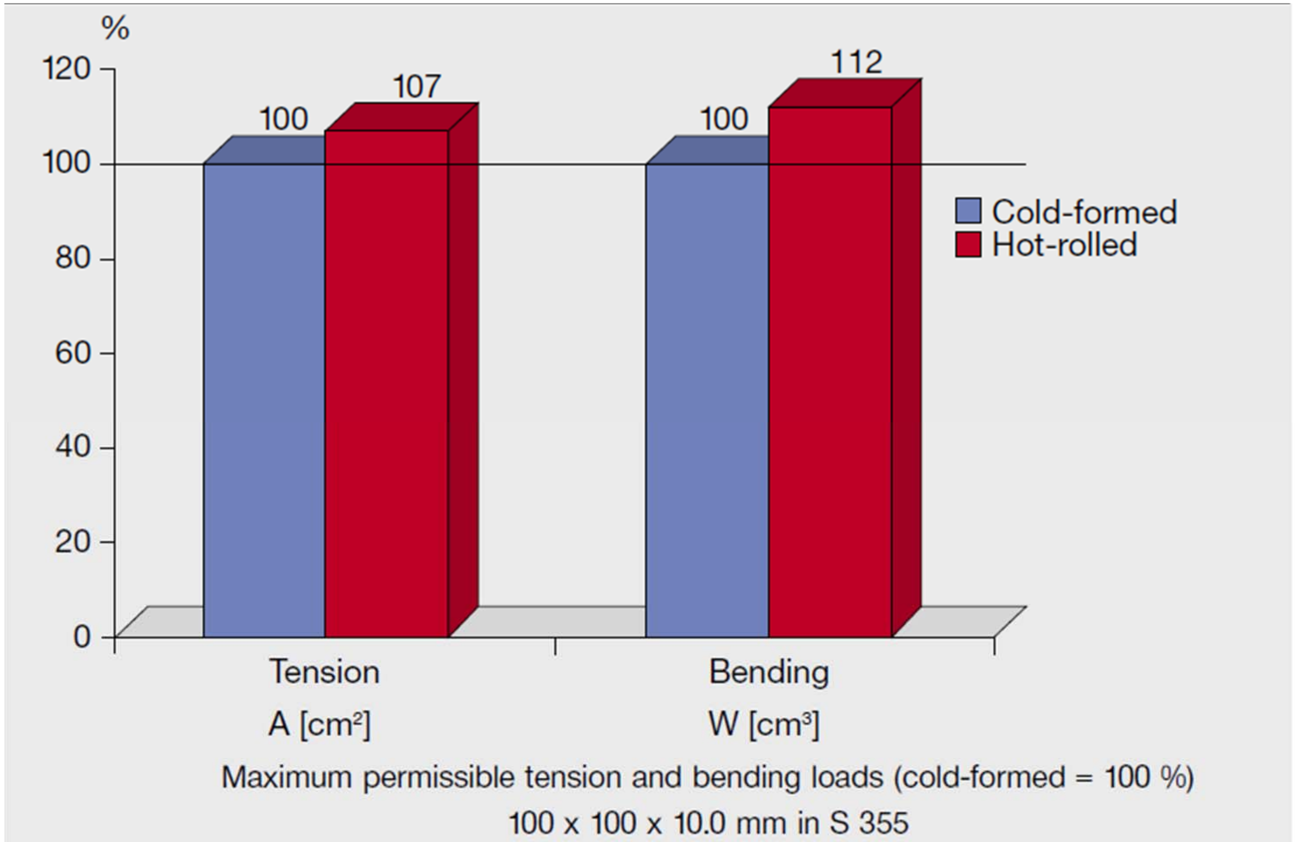


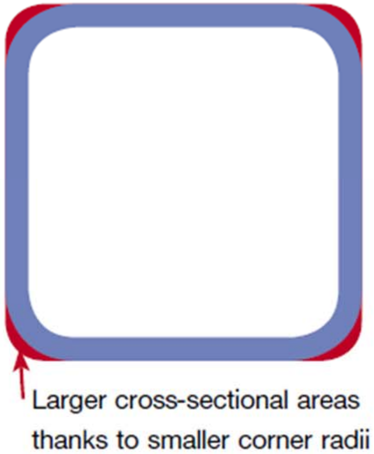
Beam splices



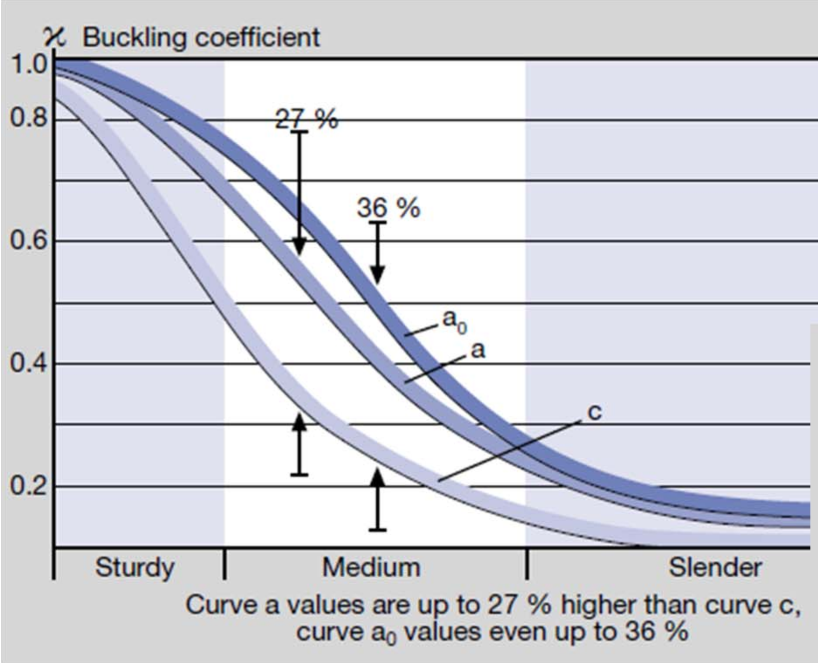
Column bases

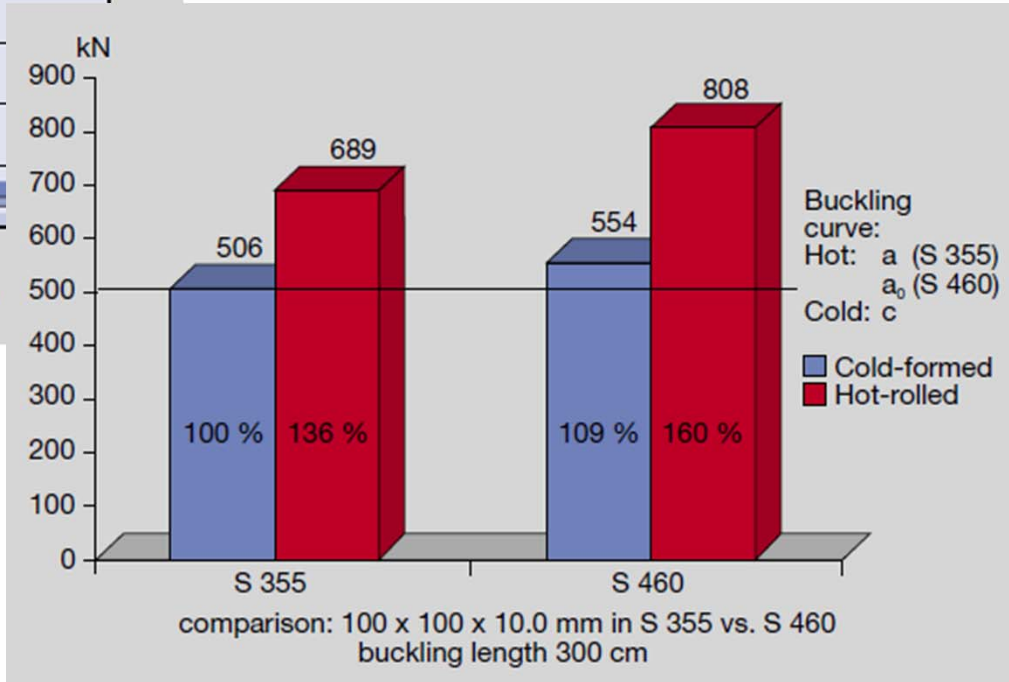
Difference between hot finished and cold formed





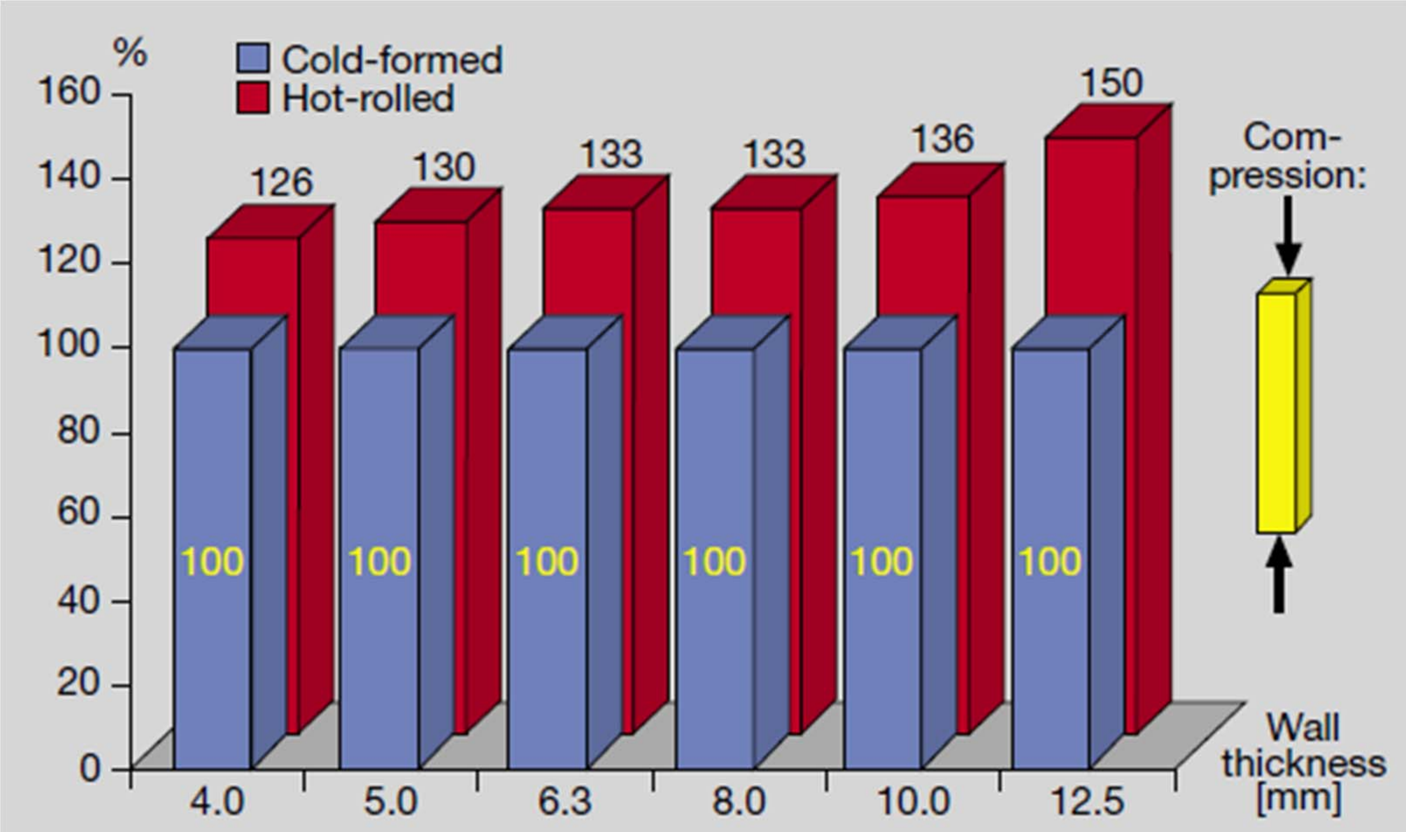
Hot finished vs. cold formed in compression





Is difference in the resistance between HF and CF profiles decreasing with increase of the thickness? Why?

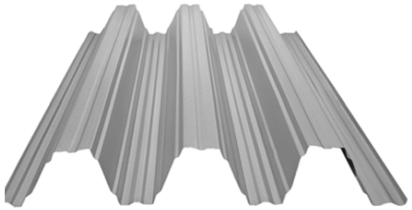
Answer:

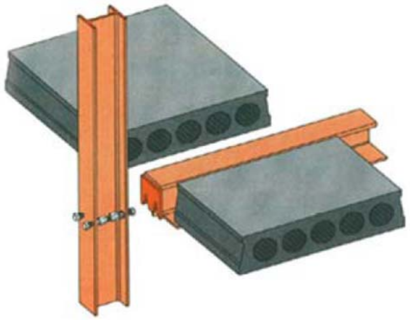


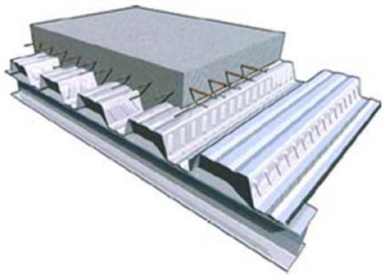
Comparison of maximum permissible compression loads (cold-formed = 100 %)
100 x 100, Grade S 355, buckling length 300 cm

Conceptual aspects

Steel products (flat products)







Definitions and Basis of Design

- Conceptual Aspects
- ✓ Codes of Practice and Standardization
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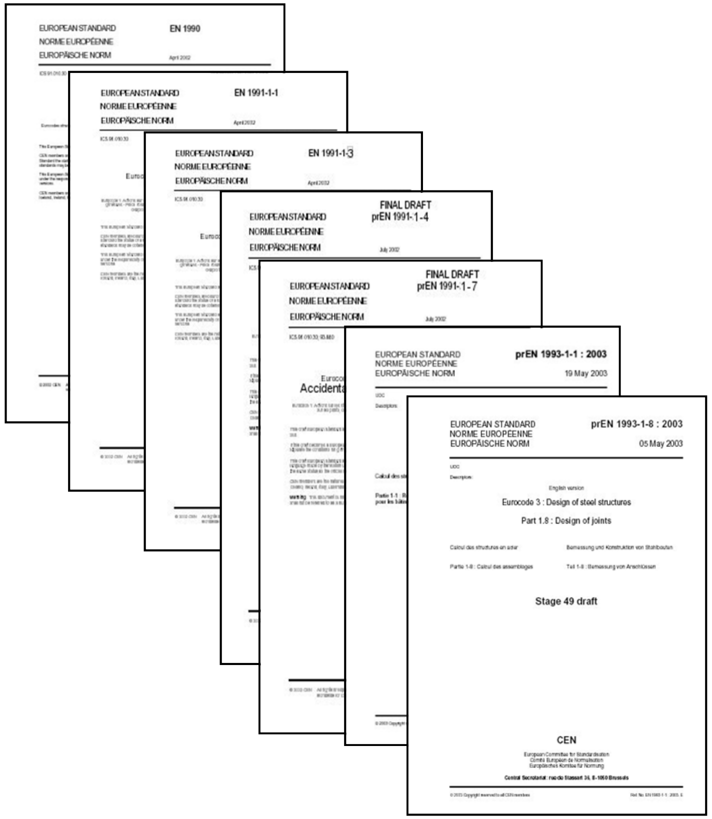
Codes of Practice and Standardization

- EN 1990 Eurocode: Basis of Structural Design
- EN 1991 Eurocode 1: Actions on Structures
- EN 1992 Eurocode 2: Design of Concrete Structures
- EN 1993 Eurocode 3: Design of Steel Structures
- EN 1994 Eurocode 4: Design of Composite Steel and Concrete Structures
- EN 1995 Eurocode 5: Design of Timber Structures
- EN 1996 Eurocode 6: Design of Masonry Structures
- EN 1997 Eurocode 7: Geotechnical Design
- EN 1998 Eurocode 8: Design of Structures for Earthquake Resistance
- EN 1999 Eurocode 9: Design of Aluminium Structures

EN 1993-1 General rules and rules for buildings
EN 1993-2 Steel bridges
EN 1993-3 Towers, masts and chimneys
EN 1993-4 Silos, tanks and pipelines
EN 1993-5 Piling
EN 1993-6 Crane supporting structures

EN 1993-1-1 General rules and rules for buildings
EN 1993-1-2 Structural fire design
EN 1993-1-3 Cold-formed thin gauge members and sheeting
EN 1993-1-4 Stainless steels
EN 1993-1-5 Plated structural elements
EN 1993-1-6 Strength and stability of shell structures
EN 1993-1-7 Strength and stability of planar plated structures transversely loaded
EN 1993-1-8 Design of joints
EN 1993-1-9 Fatigue strength of steel structures
EN 1993-1-10 Selection of steel for fracture toughness and through-thickness properties
EN 1993-1-11 Design of structures with tension components made of steel
EN 1993-1-12 Supplementary rules for high strength steel



EC0 87 p.
EC1 174 p.
EC3 211+53=264 p.

EC 0	**87 p.**
EC 1-1-1	**44 p.**
EC 1-1-3	**43 p.**
EC 1-1-4	**52 p.**
EC 1-1-7	**35 p.**
EC 3-1-1	**82 p.**
EC 3-1-8	**129 p.**
Totalt	**525 p.**

EC 3-1-5 53 p.

CE Marking (01 July 2014)

CPR imposes the following ‘<u>basic requirements for construction works</u>’:

1. Mechanical resistance and stability;

2. Safety in case of fire;

3. Hygiene, health and the environment;

4. Safety and accessibility in use;

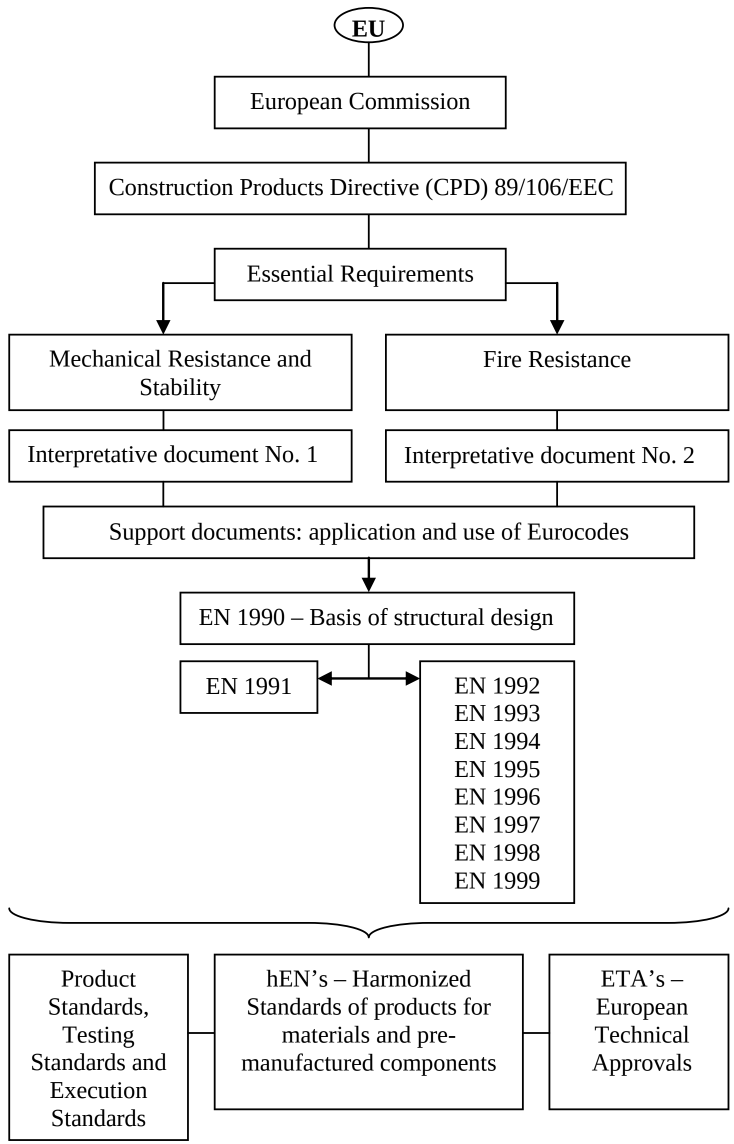
5. Protection against noise,

6. Energy economy and heat retention;

7. Sustainable use of natural resources.

For steel products the main **harmonized product standards** are:

- Steel sections and plates – EN 10025-1;
- Hollow sections – EN 10210-1 and EN 10219-1;
- Preloadable bolts – EN 14399-1;
- Non-preloadable bolts – EN 15048-1;
- Fabricated structural steelwork – EN 1090-1



CE Marking – warranty by the manufacturer that its products meet specified performance characteristics that are defined as essential to the application of the products in the field of construction. In order to do this the manufacturer needs to:

- Know the requirements in terms of defined essential performance characteristics and required values to be met. For structural steel components these **requirements** are defined in clause 4 of EN 1090-1.
- Use specified test methods that can evaluate whether products conform to the specified requirements. For structural steel components these **evaluation methods** are defined in clause 5 of EN 1090-1.
- Implement a system for controlling regular production. For structural steel components the system for **evaluation of conformity** is defined in clause 6 of EN 1090-1.
- Mark its products in the correct way using a suitable classification and designation system. For structural steel components the **marking system** is defined in clauses 7 and 8 of EN 1090-1.

Definitions and Basis of Design

Conceptual Aspects

Codes of Practice and Standardization

✓ Basis of Design

Materials

Geometric Characteristics and Tolerances

Basis of Design

Basic Requirements (EN 1990) - structure must be designed and executed so as to perform the functions for which it was conceived, for a pre-determined service life**.**

- Conditions that prevent failure (ultimate limit states);
- Conditions that guarantee proper performance in service (serviceability limit state);
- Conditions related to durability (among others, protection against corrosion).

Verification of the limit sates (EN 1990) requires:

- quantification and combination of **actions**;
- Definition of the mechanical properties of **materials**;
- Definition of the **geometry** of the structure and components.

Basic variables

Calculation of load effects requires appropriate methods of analysis (section 5 of EN 1990), including design assisted by testing (Annex D).

Basis of Design

ULTIMATE LIMIT STATES

$$E_d \leq R_d$$

- loss of static equilibrium;
- internal failure of the structure or its members and joints;
- failure or excessive deformation of the ground (EN 1997);
- fatigue failure (EN 1993-1-9).

Combinations according to EN 1990 (Annex A): fundamental, accidental and seismic.

SERVICEABILITY LIMIT STATES

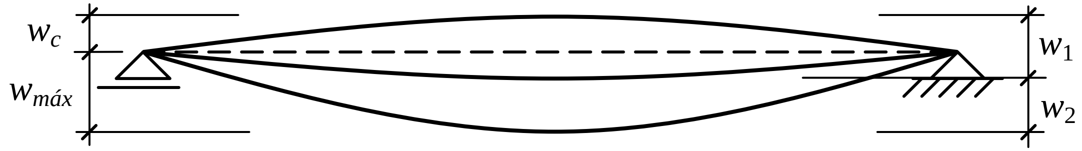
$$E_d \leq C_d$$

- deformation,
- vibration.

Combinations according to EN 1990 (Annex A): characteristic; frequent e quasi-permanent.

Basis of Design

SERVICEABILITY LIMIT STATES:
NCCI: Non-conflicting Complementary Information



	$w_{máx}$	w_2
Roofs in general	$L/200$	$L/250$
Roofs often used by people	$L/250$	$L/300$
Floors in general	$L/250$	$L/300$
Floors and roofs supporting plaster or other fragile finishes or non-flexible partition walls	$L/250$	$L/350$
Floors that bear columns (unless the displacement has been included in the global analysis for the ultimate limit state)	$L/400$	$L/500$
When $w_{máx}$ may affect the appearance of the building	$L/250$	-
Cantilever beam ($L = 2\ L_{cantiliver}$)	Previous limits	

Definitions and Basis of Design

Conceptual Aspects

Codes of Practice and Standardization

Basis of Design

✓ Materials

Geometric Characteristics and Tolerances

Materials: properties

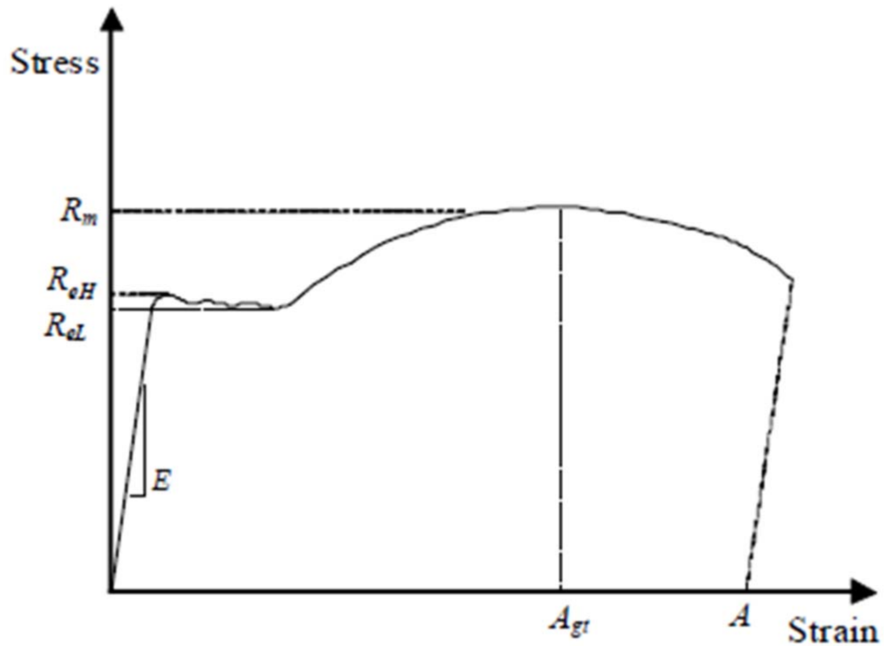
Design values (e.g. yield stress) are obtained from characteristic values/nominal values dividing by partial safety coefficients γ_M.

Recommended values (EN 1993-1-1):

$$\gamma_{M0} = 1.00;\ \gamma_{M1} = 1.00 \text{ e } \gamma_{M2} = 1.25.$$

Ductility properties

- $f_u / f_y \geq 1.1$;
- Failure strain > 15%;
- $\varepsilon_u \geq 15\ \varepsilon_y$.



- Modulus of elasticity $E = 210\ GPa$;
- Poisson's ratio in elastic range $\nu = 0.3$;
- Coefficient of linear thermal expansion $\alpha = 12\text{x}10^{-6}\ /°C$;
- Volumetric mass $\rho = 7850\ kg/m^3$.

Materials: properties

Table 1.6 – Hot-rolled steel grades and qualities according to EN 10025-2.

Steel grades and qualities	Minimum yield strength R_{eH} (MPa)				Tensile strength R_m (MPa)		Minimum percentage elongation after fracture $L_o = 5.65\sqrt{S_0}$		
	Nominal thickness (mm)				Nominal thickness (mm)		Nominal thickness (mm)		
	≤ 16	>16 ≤ 40	>40 ≤ 63	>63 ≤ 80	< 3	≥3 ≤ 100	≥3 ≤ 40	>40 ≤ 63	>63 ≤ 100
S235JR	235	225	215	215	360 to 510	360 to 510	26	25	24
S235J0	235	225	215	215	360 to 510	360 to 510			
S235J2	235	225	215	215	360 to 510	360 to 510	24	23	22
S275JR	275	265	255	245	430 to 580	410 to 560	23	22	21
S275J0	275	265	255	245	430 to 580	410 to 560			
S275J2	275	265	255	245	430 to 580	410 to 560	21	20	19
S355JR	355	345	335	325	510 to 680	470 to 630	22	21	20
S355J0	355	345	335	325	510 to 680	470 to 630			
S355J2	355	345	335	325	510 to 680	470 to 630			
S355K2	335	345	335	325	510 to 680	470 to 630	20	19	18
S450J0	450	430	410	390	-	550 to 720	17	17	17

EN 10025

Steel Grade

S235 to S960

Steel Qualities

JR, J0, J2, K2

Table 2.1 of EN 1993-1-10 ensures adequate behaviour against brittle fracture.

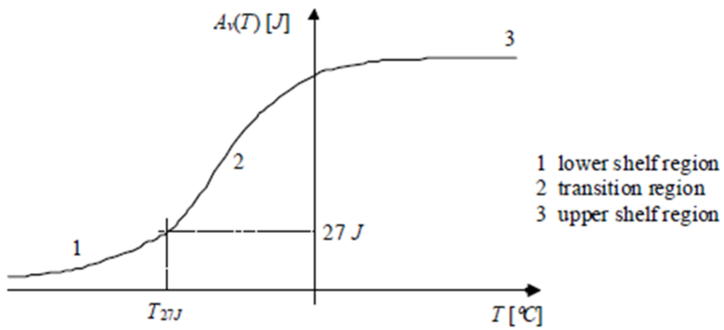


Figure 1.8 – Relationship between impact energy and temperature

Definitions and Basis of Design

Conceptual Aspects

Codes of Practice and Standardization

Basis of Design

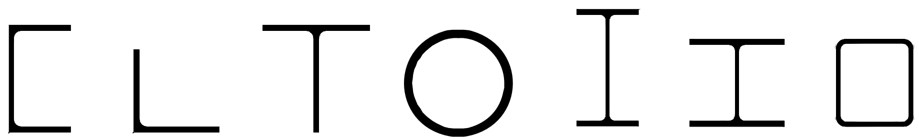
Materials

✓ Geometric Characteristics and Tolerances

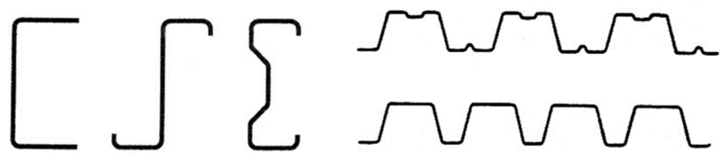
Geometric characteristics and tolerances

Geometric Data

Dimensions, shape, ... - Characteristic or nominal values.



Hot-rolled sections



Cold-formed sections

EN 1090 (and product standards) establishes two types of tolerances:

- Fundamental tolerances – required to ensure resistance and stability of the structure;
- Functional tolerances – required to ensure aesthetical appearance of the structure.

Table 1.11 – Essential manufacturing tolerances – welded sections (EN 1090-2)

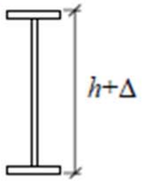
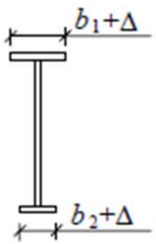
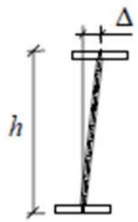
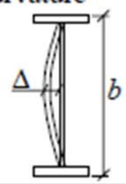
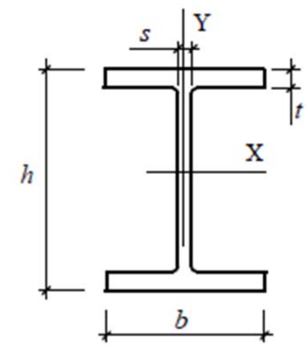
Criterion	Parameter	Tolerance Δ
Depth 	Overall depth h	$\Delta = -h/50$ No positive value given
Flange width 	Width $b = b_1$ or b_2	$\Delta = -b/100$
Squareness at bearings 	Verticality of web at supports for components without bearing stiffeners	$\Delta = \pm 200$ but $\Delta \geq t_w$ (t_w = web thickness)
Plate curvature 	Deviation Δ over plate height b	$\Delta = \pm b/100$ but $\Delta \geq t$ (t = plate thickness)

Table 1.8 – Dimensional tolerances for structural steel I and H sections (EN 10034)

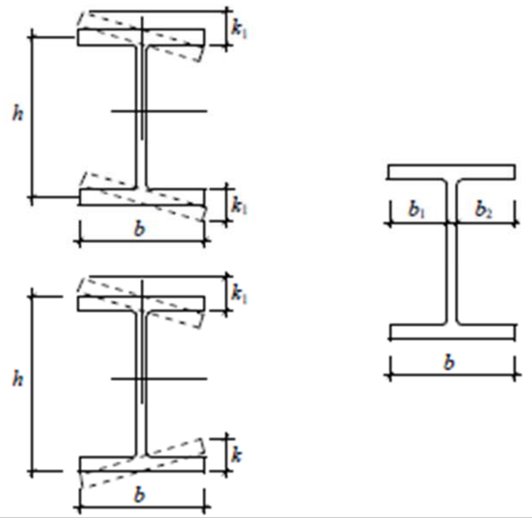
Section height h (*mm*)	Tol. (*mm*)	Flange width b (*mm*)	Tol. (*mm*)	Web thickness s (*mm*)	Tol. (*mm*)	Flange thickness t (*mm*)	Tol. (*mm*)
$h \leq 180$	+3.0 -3.0	$b \leq 110$	+4.0 -1.0	$s < 7$	+0.7 -0.7	$t < 6.5$	+1.5 -0.5
$180 < h \leq 400$	+4.0 -2.0	$110 < b \leq 210$	+4.0 -2.0	$7 \leq s < 10$	+1.0 -1.0	$6.5 \leq t < 10$	+2.0 -1.0
$400 < h \leq 700$	+5.0 -3.0	$210 < b \leq 325$	+4.0 -4.0	$10 \leq s < 20$	+1.5 -1.5	$10 \leq t < 20$	+2.5 -1.5
$h > 700$	+5.0 -5.0	$b > 325$	+6.0 -5.0	$20 \leq s < 40$	+2.0 -2.0	$20 \leq t < 30$	+2.5 -2.0
				$40 \leq s < 60$	+2.5 -2.5	$30 \leq t < 40$	+2.5 -2.5
				$s \geq 60$	+3.0 -3.0	$40 \leq t < 60$	+3.0 -3.0
					--	$t \geq 60$	+4.0 -4.0



h – Height measured at the centre line of web thickness
b – Flange width
s – Web thickness measured at the mid-point of dimension h
t – Flange thickness measured at the quarter flange width point

Table 1.9 – Tolerances on out-of-square and web off-centre of structural steel I and H sections (EN 10034)

Out-of-square $k+k_1$	Tol. (mm)	Web off-centre e		Tol. (mm)
$b \leq 110$	1.50	$t < 40mm$	$b \leq 110$	2.50
			$110 \leq b < 325$	3.5
			$b > 325$	5.0
$b > 110$	2 % of b (max. 6.5 mm)	$t \geq 40mm$	$110 < b \leq 325$	5.0
			$b > 325$	8.0



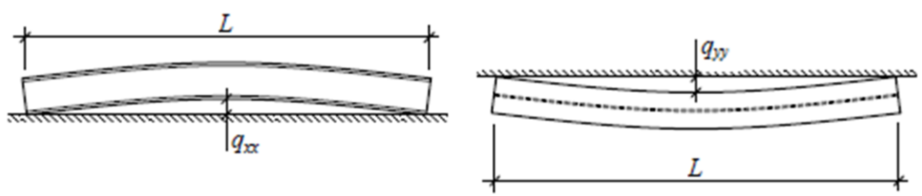
b – Flange width

t – Flange thickness

$$e = \frac{b_1 - b_2}{2}$$

Table 1.10 – Tolerances on straightness of structural steel I and H sections (EN 10034)

Section height h (mm)	Tolerance on straightness q_{xx} and q_{yy} on length L (%)
$80 < h < 180$	0.30 L
$180 < h \leq 360$	0.15 L
$h > 360$	0.10 L



Global Analysis

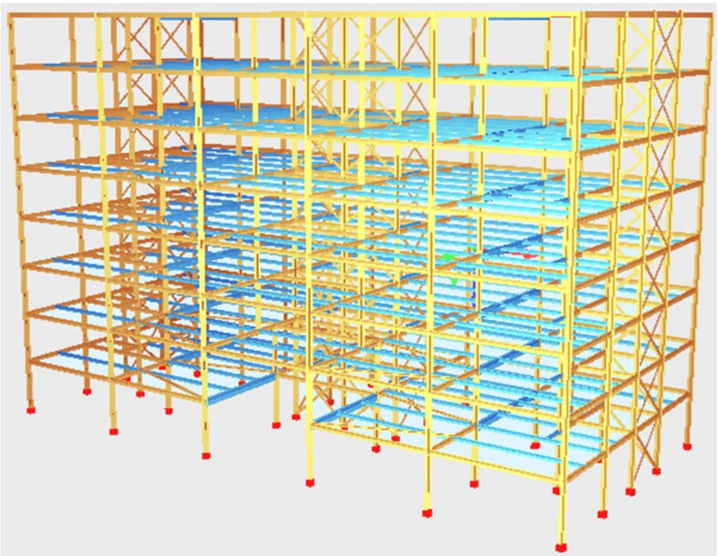
- ✓ Structural modeling
- Structural analysis
- Case-study building

Global Analysis: structural modeling

The model should simulate real conditions (structural elements, connections, loading, supports, ...).

i) Type of element

- Modeling with linear, two-dimensional or three-dimensional elements.



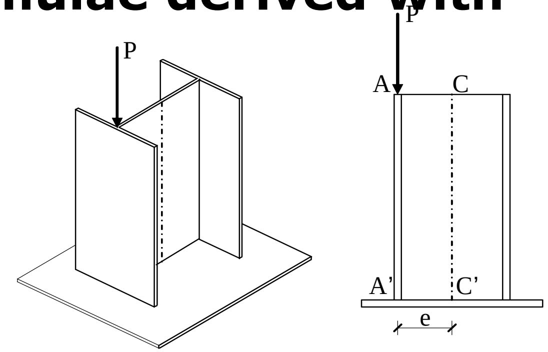
Beam elements

Alternative ways of modeling floors (stiffness in its own plan) in the behaviour of the structure

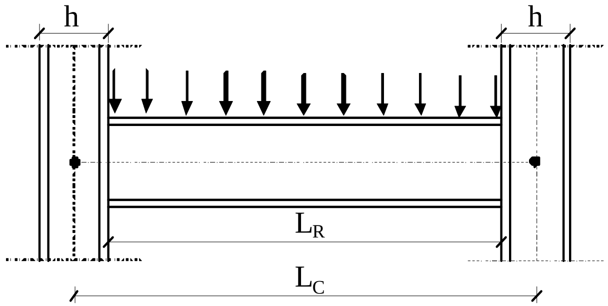
Plate or shell elements

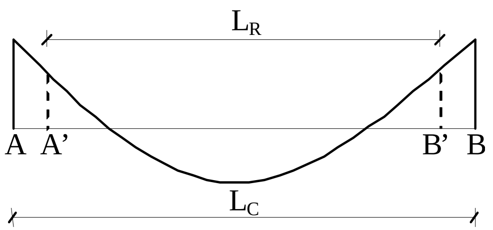
Global Analysis: structural modeling

ii) Influence of member axis (resistance formulae derived with respect to the centroid of the section)

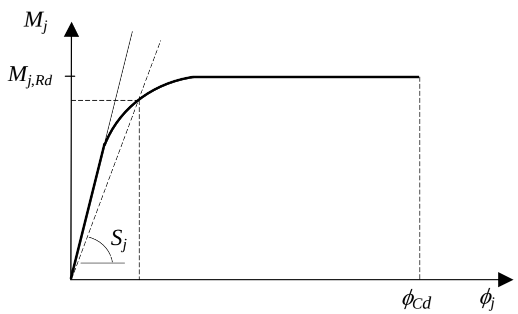


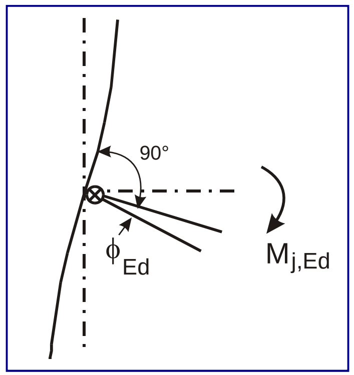
iii) Influence of eccentricities and supports.

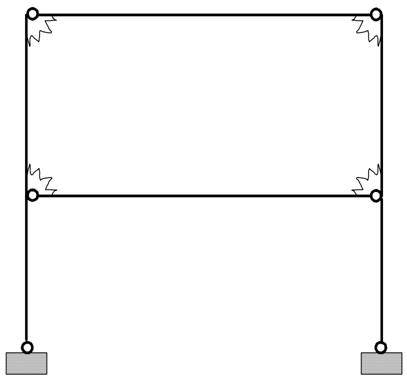




iv) Influence of joints







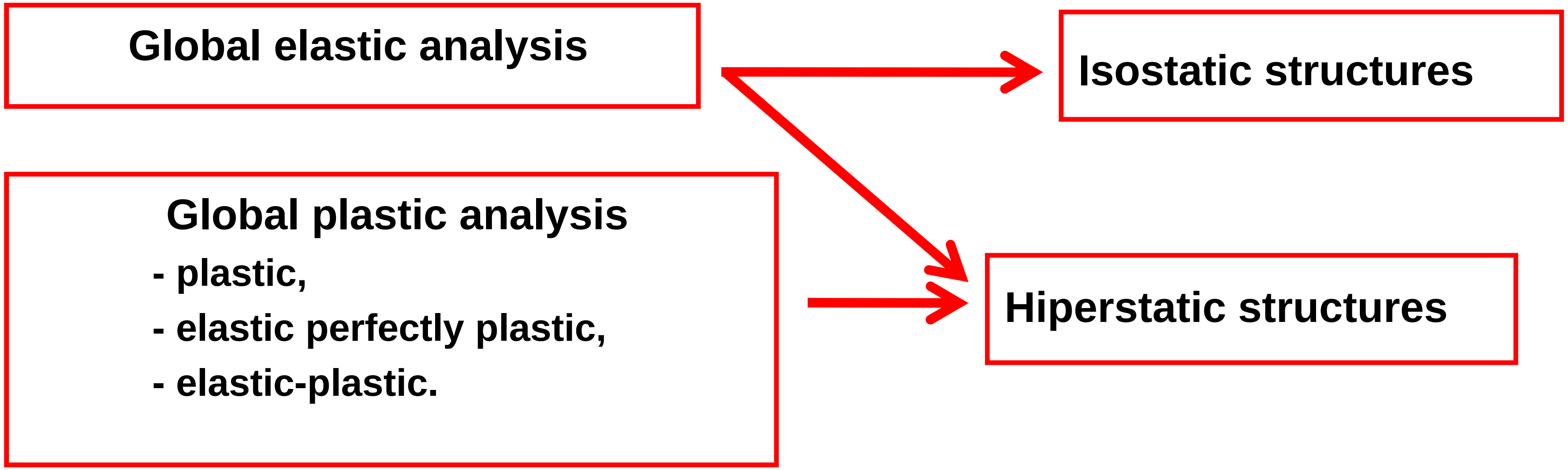
Global Analysis

Structural modeling

✓ Structural analysis

Case-study building

Global Analysis: structural analysis



NOTES (EC3-1-1, Cl. 5.4)**:**

- Although internal forces may be obtained from a **global elastic analysis**, the design resistance may be quantified based on the plastic resistance of the section (depending on the class of the section).

- Re-distribution of internal forces is allowed in **global elastic analysis**.

- **Global plastic analysis** – entails the capacity for re-distribution of forces - requirements: ductile material, compact sections, braced and symmetric.

Global Analysis: structural analysis

Effects to consider in global analysis:

i) deformability and stiffness of the structure and supports;

ii) stability of the structure (global, members and local);

iii) behaviour of cross-sections (classification of sections);

iv) behaviour of joints (strength and stiffness);

v) imperfections (global and in members).

Global Analysis: structural analysis

1st order analysis vs. 2nd order analysis

1st order analysis – Internal forces and displacements are evaluated in relation to the undeformed structure (EC3-1-1, cl. 5.2.1(1)).

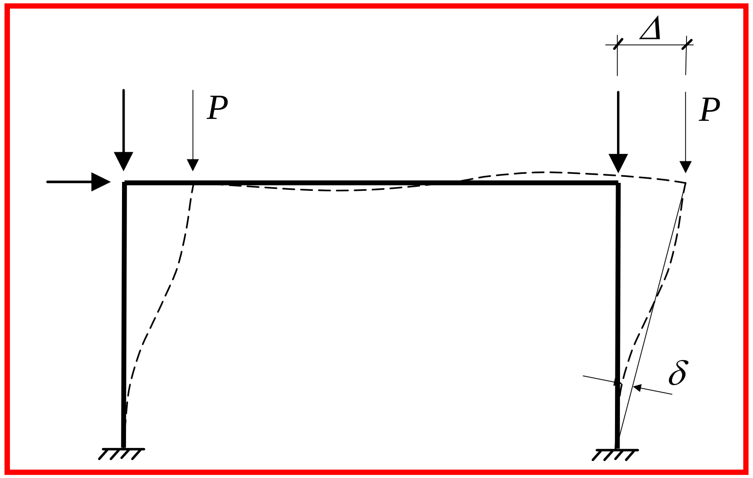
2nd order analysis – The deformation of the structure is considered in the evaluation of internal forces and displacements (iterative procedure).

Structures sensitive to 2nd order effects – structures with high compressed members and structures with low stiffness (e.g.: structures with cables).

2nd order effects

***P*-δ effects** (local effects).

***P*-Δ effects** (global effects).



Global Analysis: structural analysis

Need to consider 2ª order analysis - EC3-1-1 - cl. 5.2.1(3):

$$\alpha_{cr} = F_{cr} / F_{Ed} \leq 10$$ (elastic analysis

$$\alpha_{cr} = F_{cr} / F_{Ed} \leq 15$$ (plastic analysis)

F_{Ed}: design loading for a given load combination;

F_{cr}: elastic critical load.

Global Analysis: structural analysis

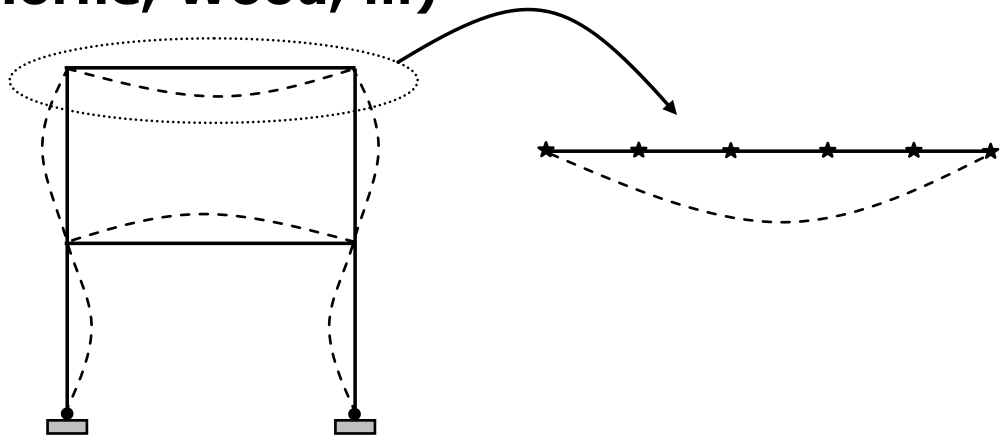
i) Analytical evaluation

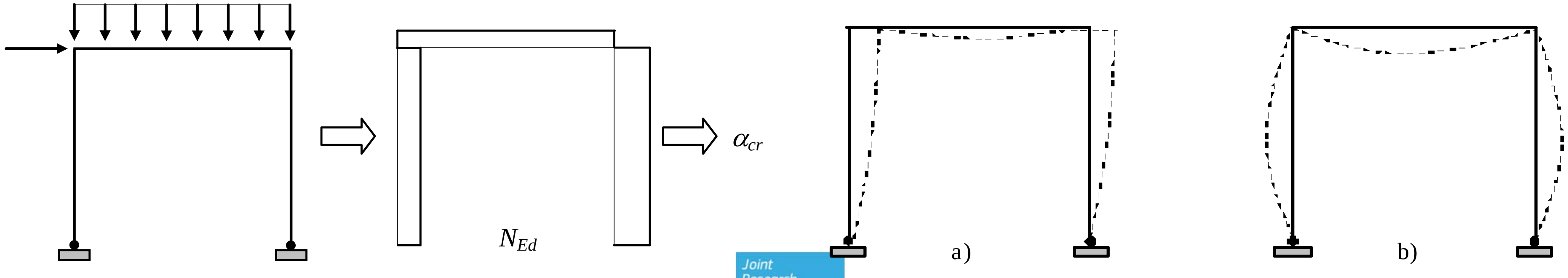
ii) Numerical calculation

iii) Approximate methods (Horne, Wood, …)

ELASTIC CRITICAL LOAD

ii) NUMERICAL CALCULATION: Linear eigenvalue analysis





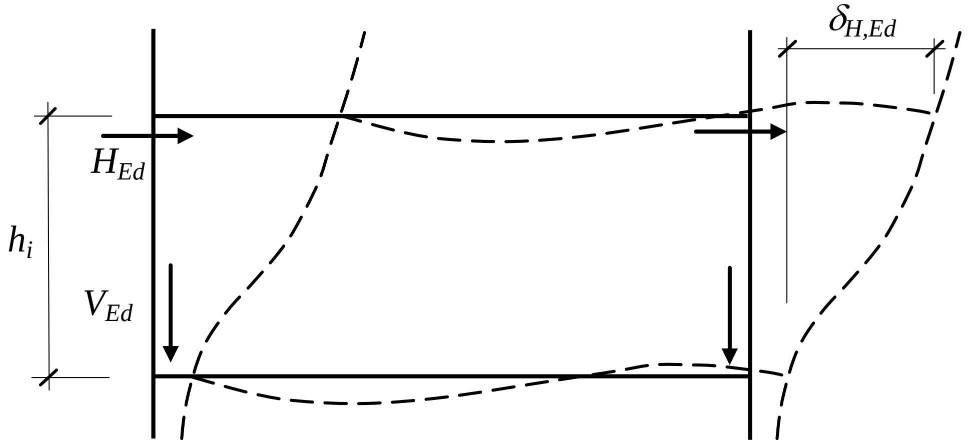
Global Analysis: structural analysis

iii) APPROXIMATE METHODS (EC3, cl.5.2.1(4)B) (Horne, Wood,...)

HORNE's METHOD

Applicable for plane frames and one-storey frames with low inclination of the beams ($\leq 26^{o}$), unbraced and with low axial force ($\bar{\lambda} \leq 0{,}3\sqrt{\frac{A\,f_y}{N_{Ed}}}$):

$$\alpha_{cr} = \left(\frac{H_{Ed\,(top)}}{V_{Ed\,(base)}} \frac{h_i}{\delta_{H,Ed}} \right)$$



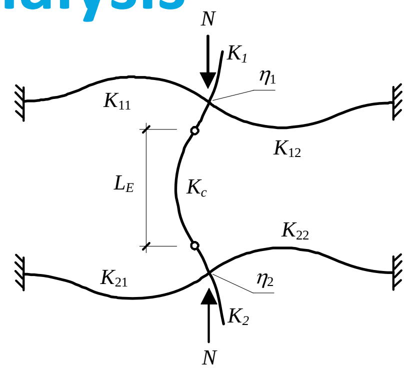
Global Analysis: structural analysis

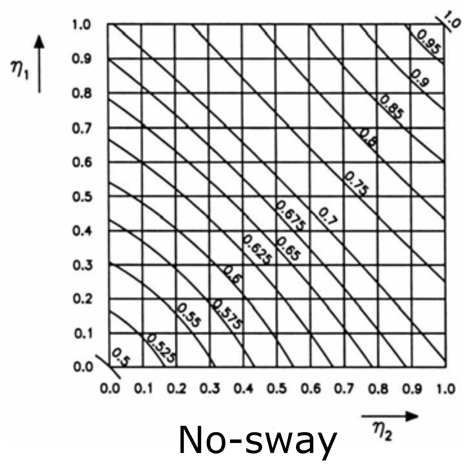
WOOD's METHOD

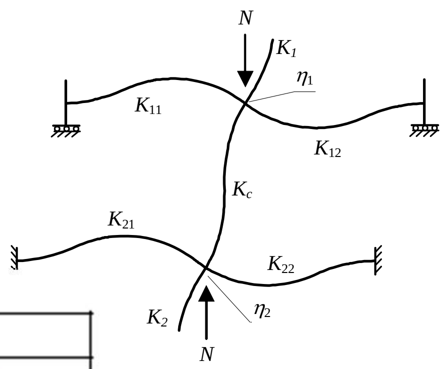
$$\eta_1 = \frac{K_c + K_1}{K_c + K_1 + K_{11} + K_{12}}$$

$$\eta_2 = \frac{K_c + K_2}{K_c + K_2 + K_{21} + K_{22}}$$

$$N_{cr} = \frac{\pi^2 EI}{L_e^2} \qquad \alpha_{cr} = \frac{N_{cr}}{N_{Ed}}$$







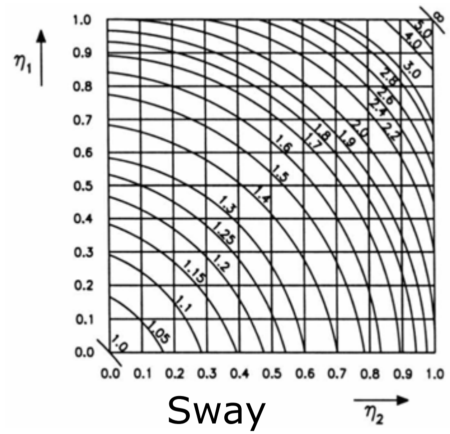


Table 2.19 – K_{ij} stiffness coefficients in beams

Restriction to rotation at the opposite end	K_{ij}
Fixed	1.0 I/L
Pinned	0.75 I/L
Equal rotation (single curvature)	0.5 I/L
Equal rotation but in the opposite way (double curvature)	1.5 I/L
General case (θ_a next to the column and θ_b at the opposite end)	$1+0.5(\theta_b/\theta_a))I/L$

Global Analysis: structural analysis

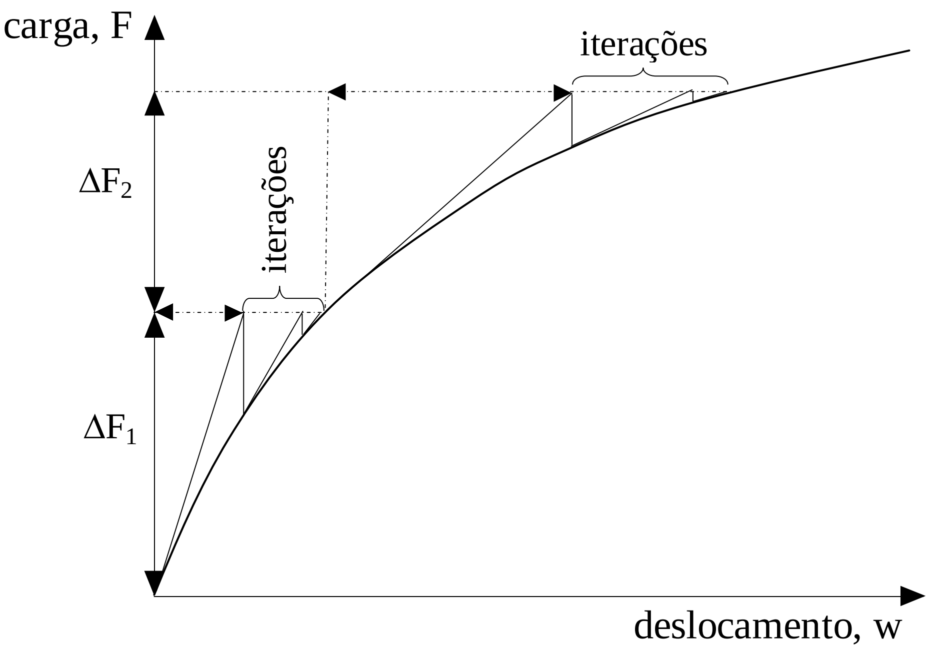
2nd ORDER ANALYSIS

i) Numerical methods (iterative procedures)

ii) Simplified methods

NUMERICAL METHODS ("EXACT")

- **Modeling**
- **Convergence**
- **Validation**



Global Analysis: structural analysis

SIMPLIFIED METHODS (APPROX)

- **Amplified sway moment method (clause 5.2.2(4));**
- **Sway-mode buckling length method (clause 5.2.2(8)).**

Amplified sway moment method

$$M_{ap}^{II} = M_{NS}^{I} + \frac{1}{1-\frac{1}{\alpha_{cr.S}}} M_{S}^{I} \qquad N_{ap}^{II} = N_{NS}^{I} + \frac{1}{1-\frac{1}{\alpha_{cr.S}}} N_{S}^{I} \qquad d_{ap}^{II} = d_{NS}^{I} + \frac{1}{1-\frac{1}{\alpha_{cr.S}}} d_{S}^{I}$$

- For regular structures, EC3-1-1 (clause 5.2.2), allows the inclusion of secon-order effects associated with vertical loads in a **simplified way**. Amplification of first-order effects associated with horizontal actions (including imperfections), by:

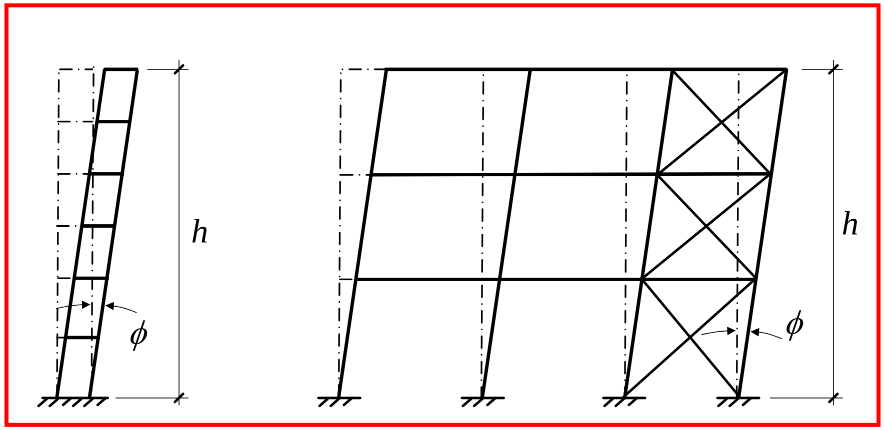
$$1/\left(1-1/\alpha_{cr}\right) \qquad \text{if} \quad \alpha_{cr} >= 3.0$$

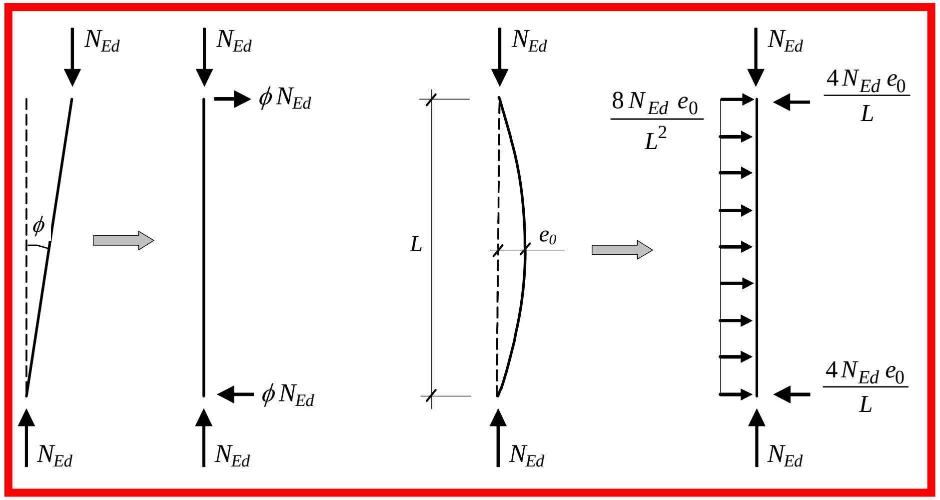
Global Analysis: structural analysis

IMPERFECTIONS

Equivalent horizontal forces

Global imperfections: lack of verticality





$$\phi = \phi_0 \, \alpha_h \, \alpha_m$$

Equivalent geometrical imperfections

Local imperfections: initial curvature

e_0/L

Table 2.20 – Initial local bow imperfections

Buckling curve	Elastic analysis e_0/L	Plastic analysis e_0/L
a_0	1/350	1/300
a	1/300	1/250
b	1/250	1/200
c	1/200	1/150
d	1/150	1/100

Global Analysis: structural analysis

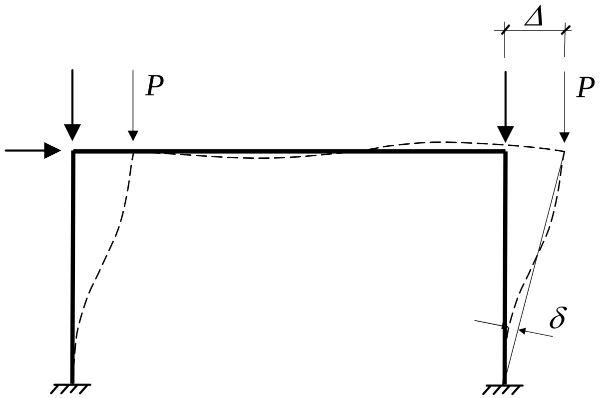
GLOBAL FRAME ANALYSIS

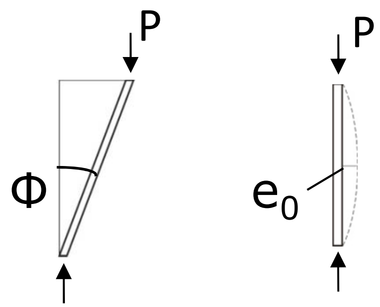
→ Choice between frame analyses regarding the kind of member design:

- Design by member buckling checks
- Design by 2nd order moments + cross-section checks

→ Methods depend on the accounting of

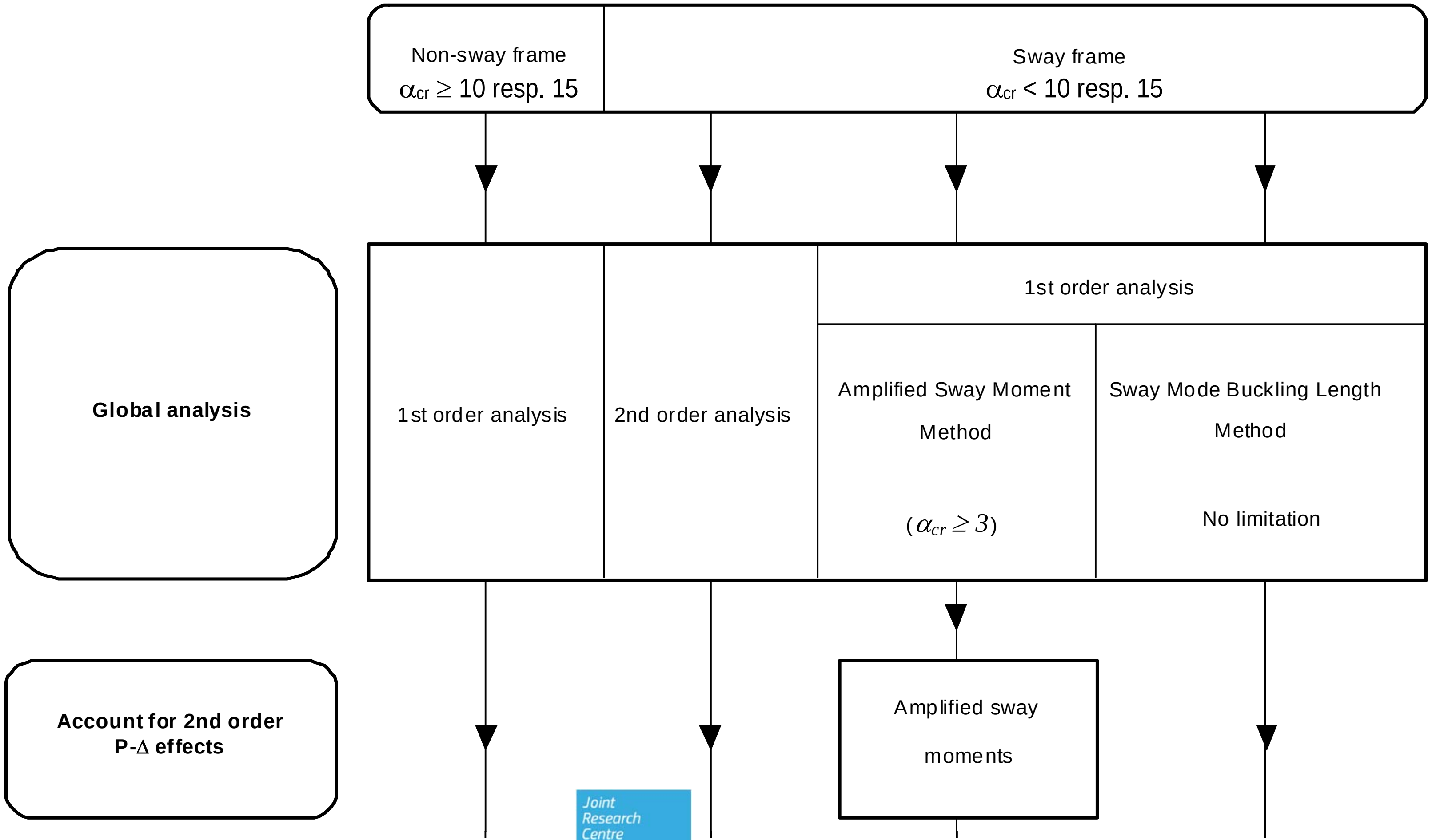
- 2nd order effects
- imperfections: global **Φ** and/or member $\mathbf{e_0}$





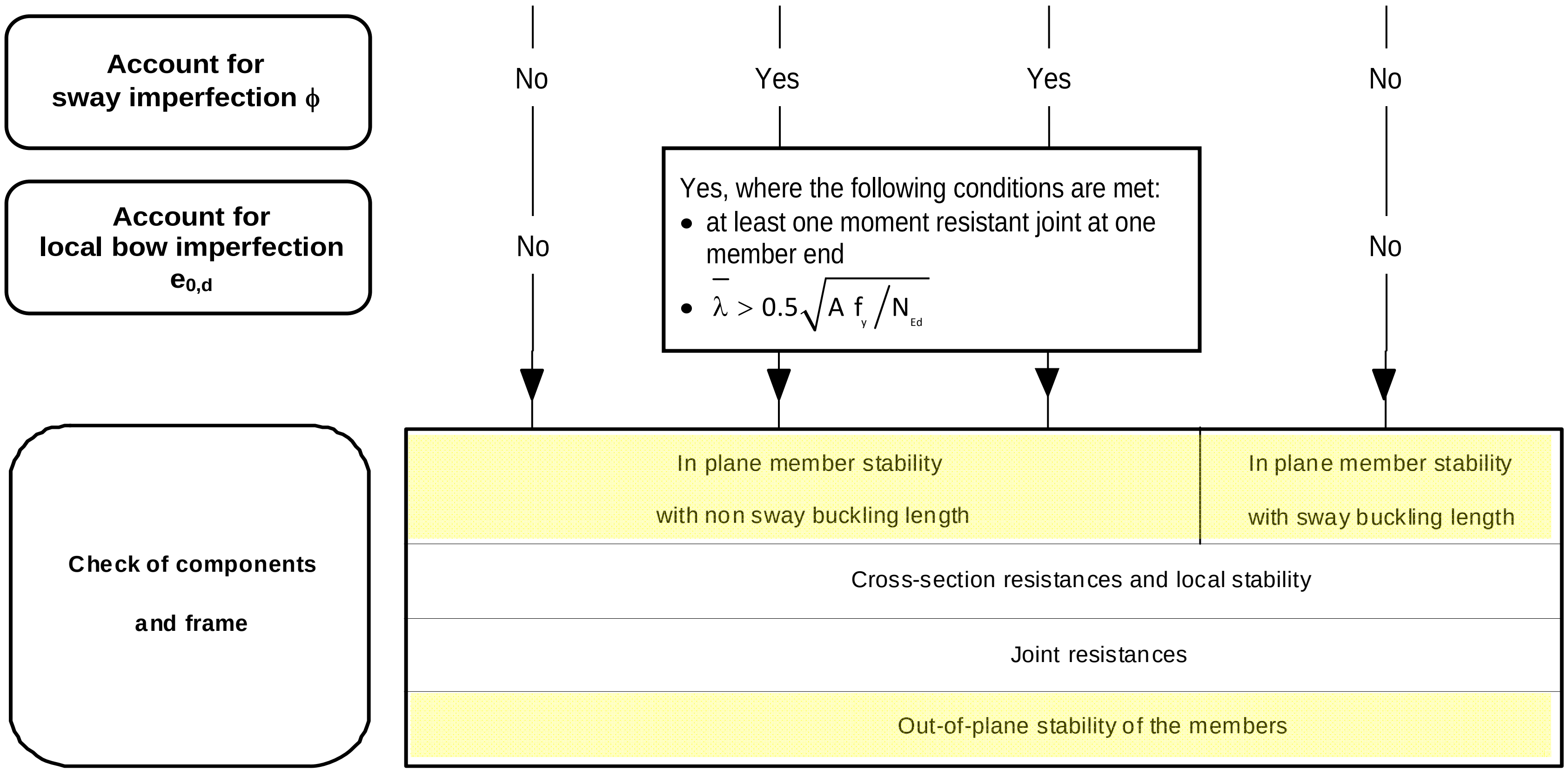
Global Analysis: structural analysis

GOBAL ANALYSIS AND DESIGN WITH MEMBER BUCKLING CHECKS



Global Analysis: structural analysis

GOBAL ANALYSIS AND DESIGN WITH MEMBER BUCKLING CHECKS



FRAME DESIGN WITH "FULL" 2. ORDER MOMENTS + CS-CHECKS