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TECHNOLOGIECAMPUS DE NAYER SINT-KATELIJNE-WAVER

Structural Stainless Steel Designing with stainless steel

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Outline

- Corrosion resistance
- Chemical composition and grades
- Examples of structural applications
- Grade selection
- Material mechanical characteristics
- Design according to Eurocode 3
- Alternative methods
- Deflections
- Additional information
- Resources for engineers

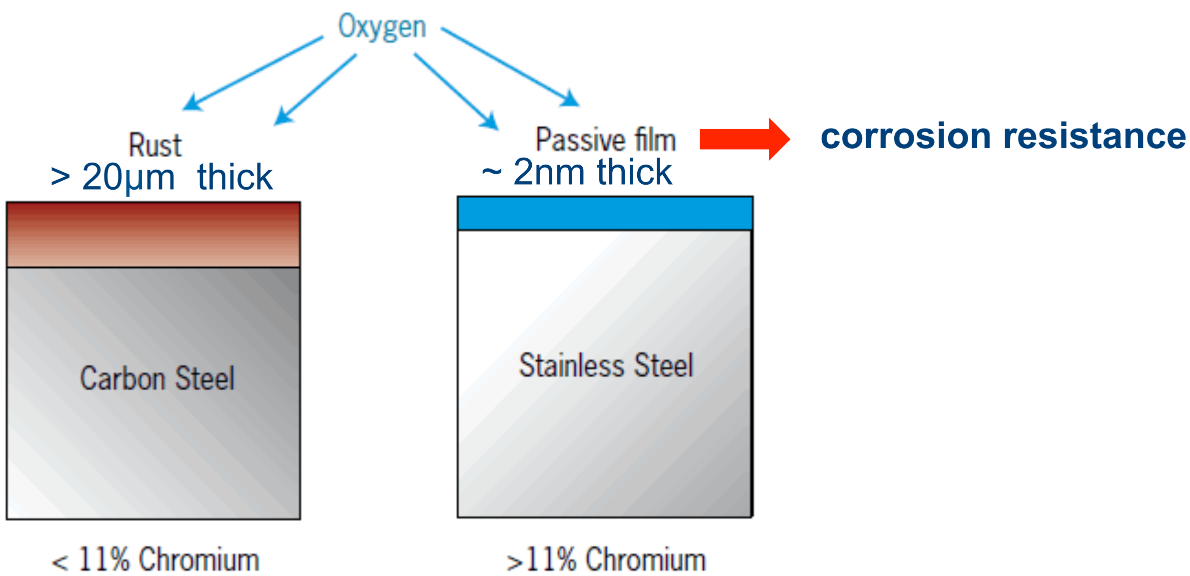
Section 1

Corrosion resistance

Stainless Steel

Stainless steels are corrosion-resistant iron alloys that contain a minimum of 10.5% chromium (Cr).

Other present alloying elements:
carbon (C), nickel (Ni), manganese (Mn), molybdenum (Mo), copper (Cu), silicon (Si), sulphur (S), phosphorus (P) and nitrogen (N).



Passive layer

The natural formation of a passive surface film is the key to the corrosion resistance of stainless steels.

Properties of the passive film:

- Chromium Rich Oxide (Oxy-hydroxides of Fe and Cr)
- Very thin, ~ 20-30 Ångströms (2-3 nm)
- Extremely adherent
- Passive
- Self Repairing (within minutes)

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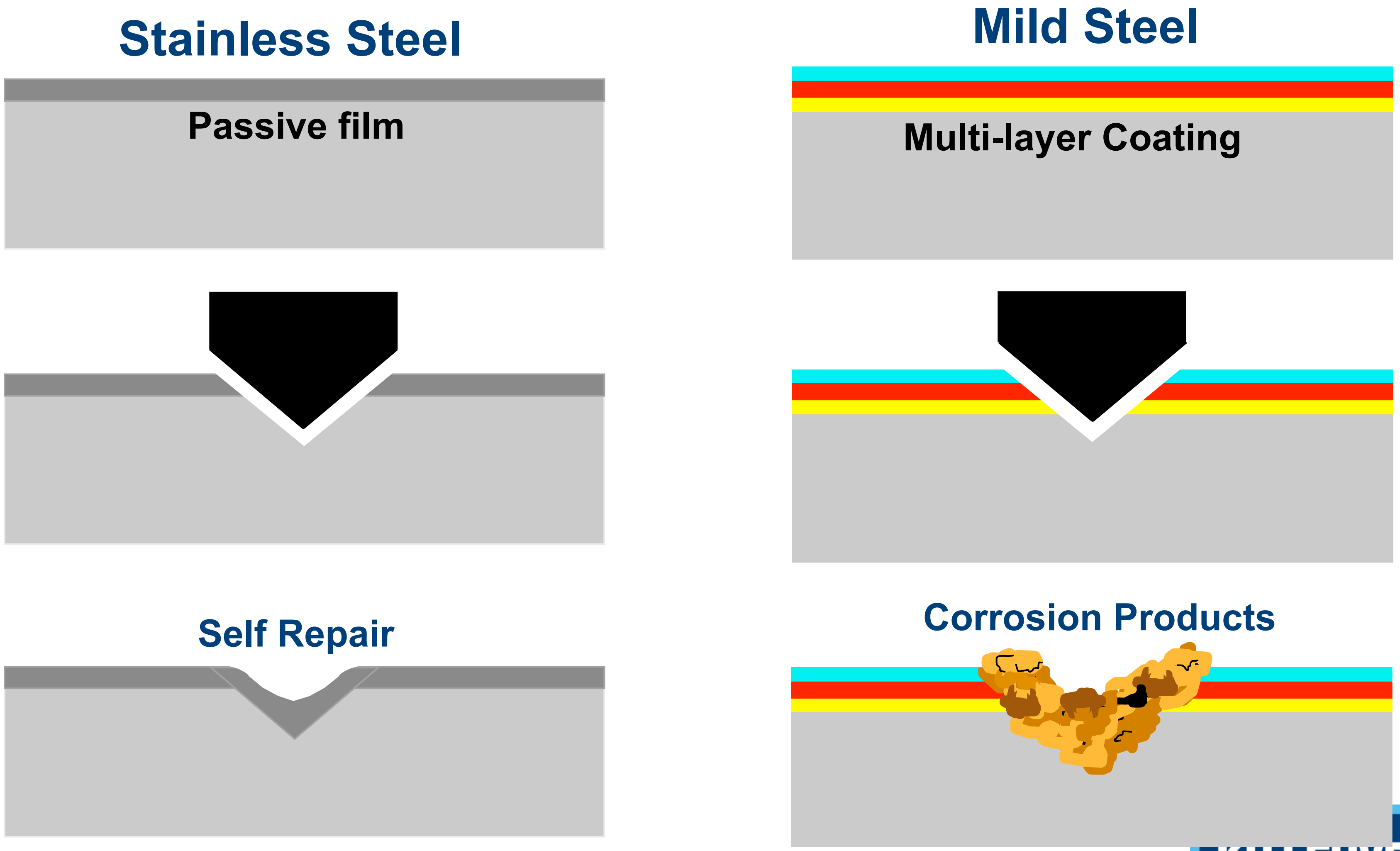
Damage to protective layer



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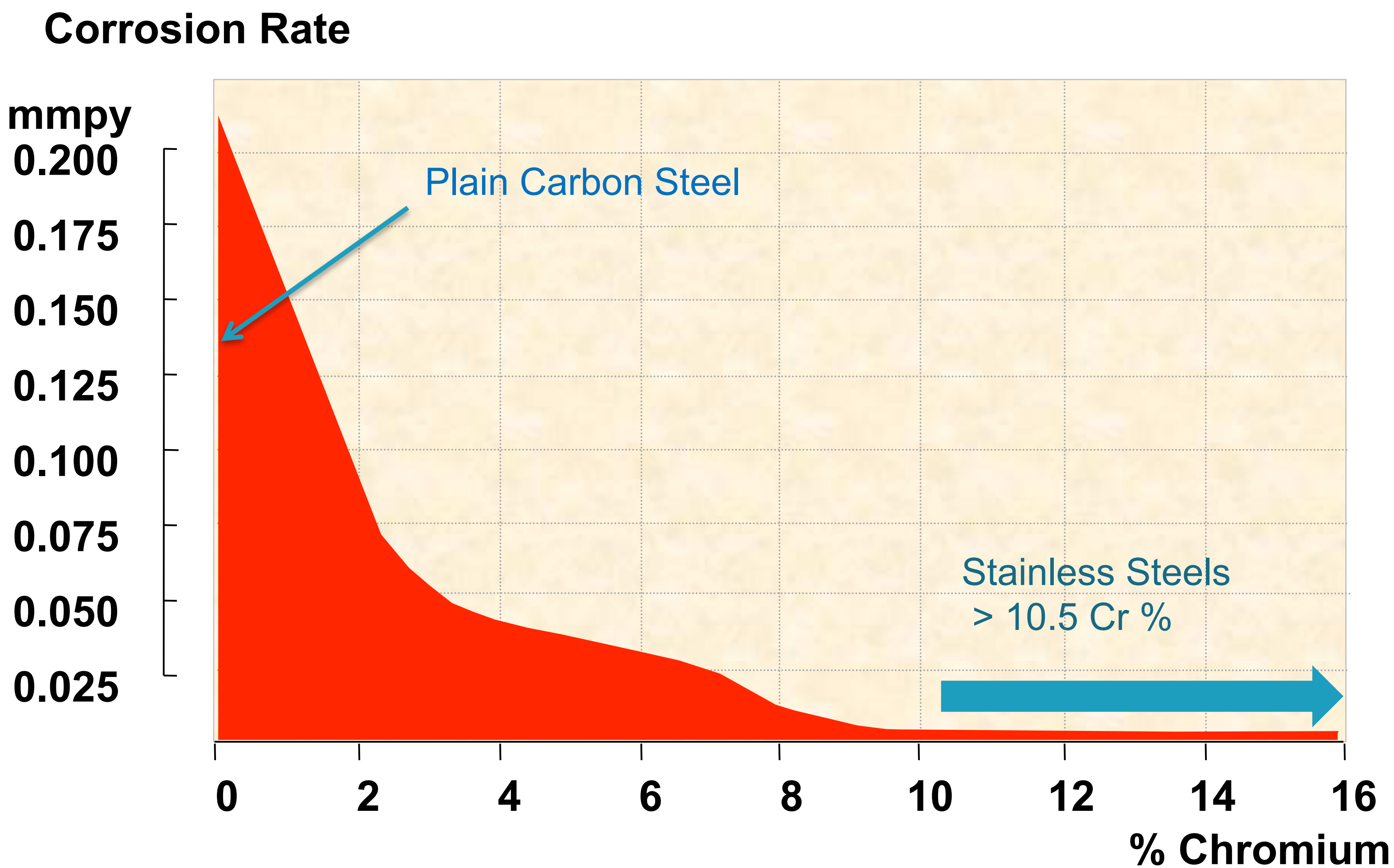
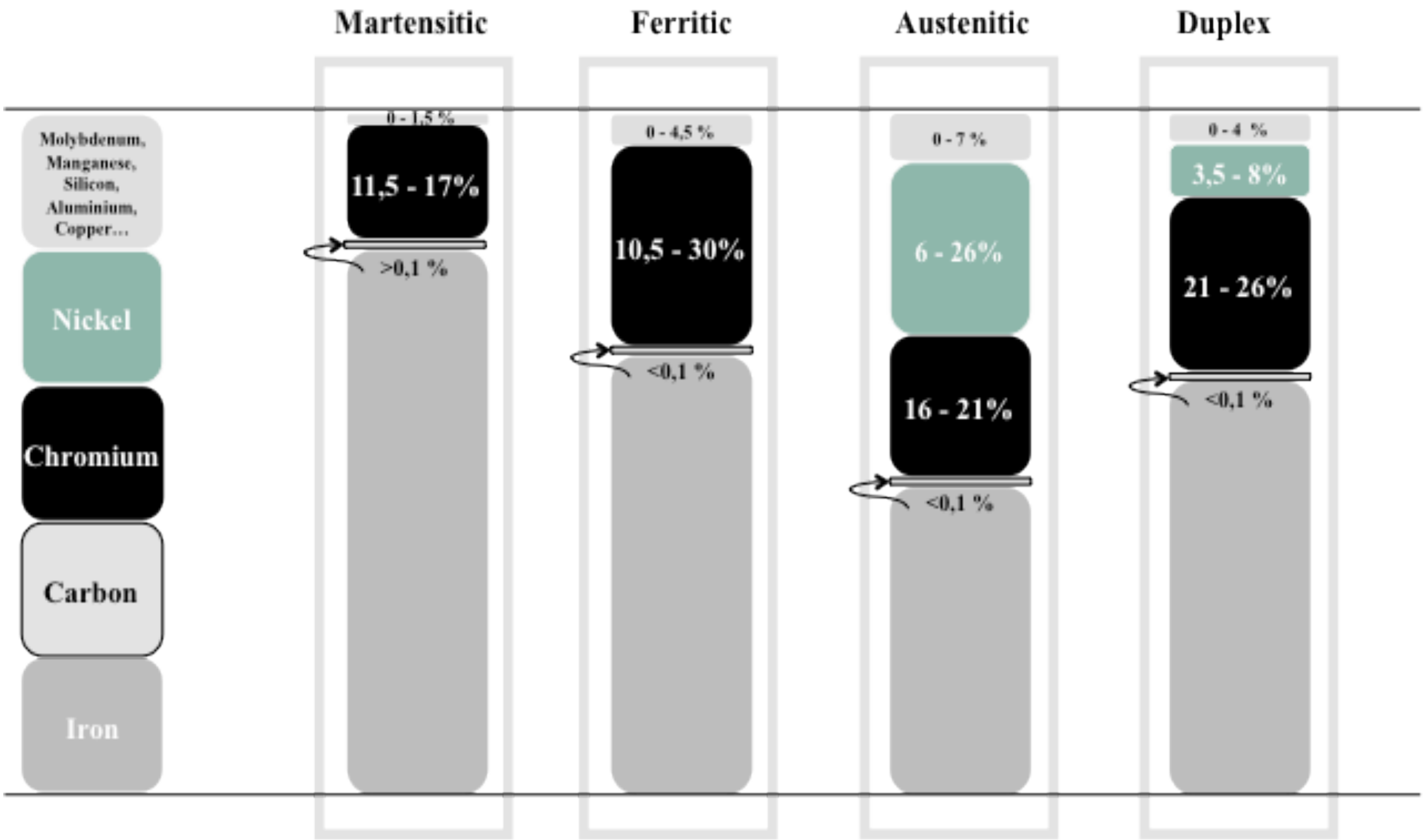
Effect of Chromium Content on Atmospheric Corrosion Resistance

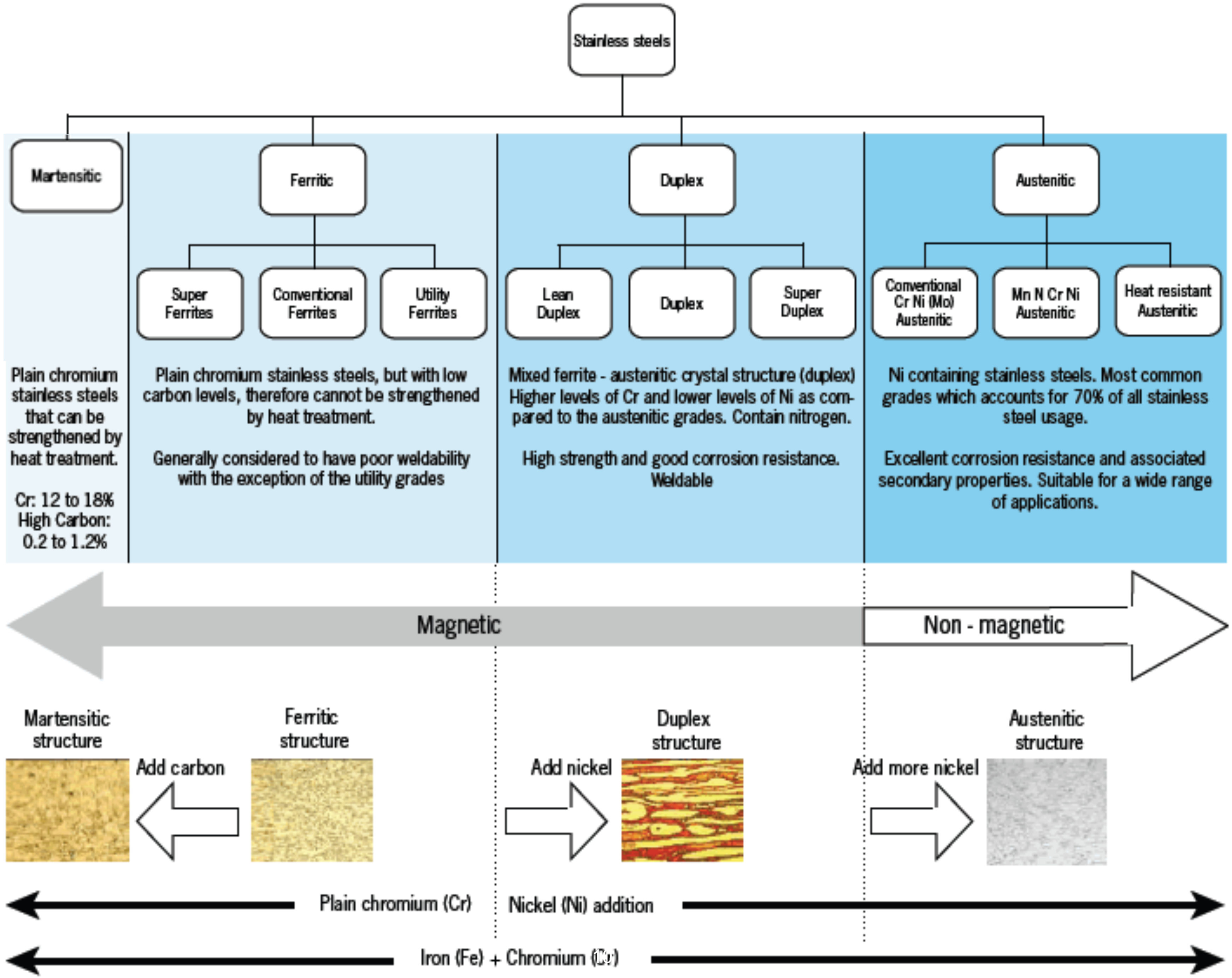


Section 2

Chemical composition

Chemical compositions for typical grades





Stainless steels
Martensitic
Ferritic
Duplex
Austenitic
Super Ferrites
Conventional Ferrites
Utility Ferrites
Lean Duplex
Duplex
Super Duplex
Conventional Cr Ni (Mo) Austenitic
Mn N Cr Ni Austenitic
Heat resistant Austenitic
Plain chromium stainless steels that can be strengthened by heat treatment.
Cr: 12 to 18% High Carbon: 0.2 to 1.2%
Plain chromium stainless steels, but with low carbon levels, therefore cannot be strengthened by heat treatment.
Generally considered to have poor weldability with the exception of the utility grades
Mixed ferrite - austenitic crystal structure (duplex) Higher levels of Cr and lower levels of Ni as compared to the austenitic grades. Contain nitrogen.
High strength and good corrosion resistance. Weldable
Ni containing stainless steels. Most common grades which accounts for 70% of all stainless steel usage.
Excellent corrosion resistance and associated secondary properties. Suitable for a wide range of applications.
Magnetic
Non - magnetic
Martensitic structure
Add carbon
Ferritic structure
Add nickel
Duplex structure
Add more nickel
Austenitic structure
Plain chromium (Cr)
Nickel (Ni) addition
Iron (Fe) + Chromium

Color code:
- Physical properties
- Corrosion resistance
- Mechanical properties
- Fabrication

Cr-Ni (Mo)Austenitics

Common Properties:
- Non Magnetic
- High expansion coefficient (compared to C-Steels)
- Low heat conductivity
- Very good corrosion resistance, increases with alloy content
- …but can be susceptible to Stress Corrosion Cracking (SCC) in hot chloride environments (e.g. swimming pools)
- High ductility and impact resistance at all (including very low) temperatures
- Strength can be increased by cold working (but not by heat treatment)
- Very good fire resistance
- Very good cold and hot forming properties (ductility, elongation)
- Easy to weld (TIG, MIG)

The best known and still the most used today

Sub-groups:
- Cr – Ni (Typically 304 /4301)
- Cr – Ni – Mo (Typically 316/4401)

Cr-Mn Austenitics

Main differences with Cr-Ni austenitics

- Fair corrosion resistance
- …but far more susceptible to SCC and to pitting, particularly at low Ni and Cr levels
- Higher strength
- Poor cold forming properties due to high work-hardening
- Poor machinability
- More difficult to weld
- Cost less

Used mostly in India and China

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Duplex

Common Properties:

- Magnetic
- Expansion coefficient (intermediate between ferritic and austenitics)
- Low heat conductivity
- Excellent corrosion resistance, increases with alloy content
- Insensitive to SCC
- High strength, Good ductility
- Strength can be increased by cold working (but not by heat treatment)
- Good cold and hot forming properties (ductility, elongation)
- Weldable (TIG, MIG)

Sub-groups:

- Cr – Ni (Typically /4362)
- Cr – Ni – Mo (Typically /4462)

Offer the best combination of corrosion resistance and mechanical properties

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Ferritics

Common Properties:

- **Magnetic**
- Low thermal expansion coefficient close to that of carbon steels
- Good Heat conductivity
- Insensitive to SCC
- Good ductility (lower than austenitic grades, though)
- Not suitable for use at very low temperatures
- Strength can be somewhat increased by cold working (but not by heat treatment)
- Very Good cold forming properties (less springback, lower tool wear but lower elongation requires a different deep drawing process compared to austenitics)
- Stabilized grades (i.e. with Nb and/or Ti) are easy to weld (TIG, MIG)

Sub-groups:

- Cr (Typically 430 /4016)
- Cr – Mo (Typically 444/4539)

Offer a an optimum performance /cost for many applications and are increasingly used

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Chemical compositions for typical grades

Grade	ASTM UNS	C Wt%	Cr Wt%	Ni Wt%	Mo Wt%	Other Wt%	Typical use [3,4]
4003	**S40977**	**0,02**	**11,5**	**0,5**	-	-	heated and unheated interiors
4016	430	0,04	16,5	-	-	-	decorative interior cladding
4509 4510	S43932 439	0,02 0,02	18 17	- -	- -	Nb Ti Ti	inland roofing and rainwater goods often Tin-coated for patina
4521	444	0,02	17,8	-	2,1	Ti	domestic plumbing market
4301 4307 4306	**304** 304L 304L	**0,04** 0,02 0,02	**18,1** 18,1 18,2	**8,1** 8,1 10,1	- - -	- - -	building interiors and exteriors in normal industrial atmospheres away from the coast
4401 4404 4571	**316** 316L 316Ti	**0,04** 0,02 0,04	**17,2** 17,2 16,8	**10,1** 10,1 10,9	**2,1** 2,1 2,1	- - Ti	permanently wet applications, locations in coastal atmosphere, polluted industrial atmospheres, near roads where deicing salts can be an issue
4529 4547	N08926 S31254	0,01 0,01	20,5 20,0	24,8 18,0	6,5 6,1	N, Cu N, Cu	road tunnels and indoor swimming pools
4362 **4462**	S32304 S322052	0.02 0.02	23.0 22.0	4.8 5.7	0.3 3.1	N, Cu N	Desalination plants, seawater system, bridges
4162/ 4062	**S32101**	**0.03**	**21.5**	**1.5**	**0.3**	**Mn, Cu**	Bridges, storage tanks

Section 3

Examples of structural applications

Station Sint Pieters, Ghent (BE)

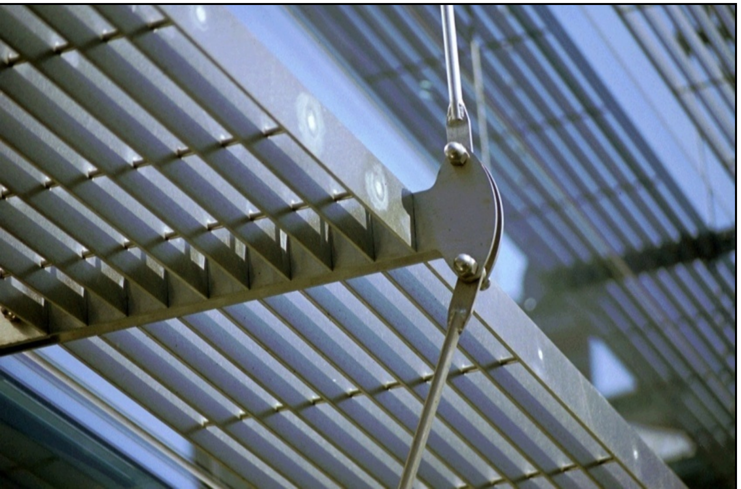
Arch. : Wefirna

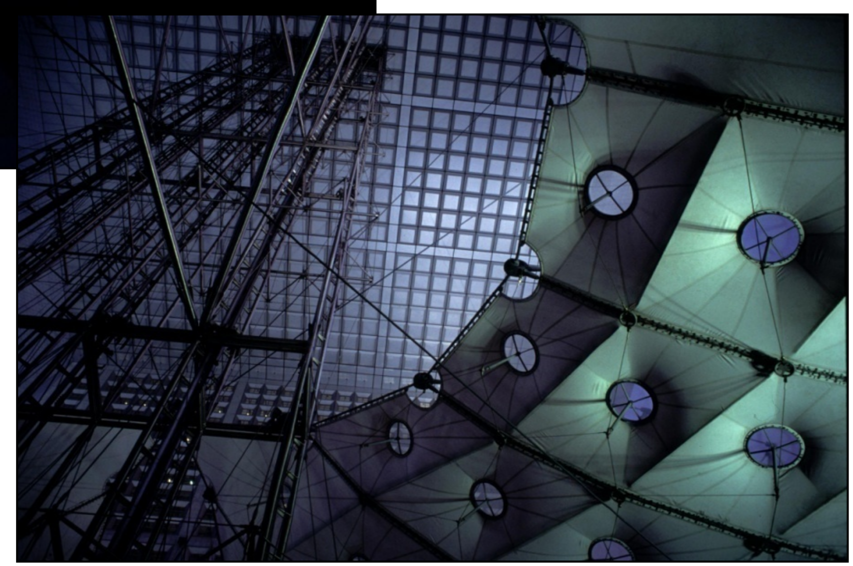
Eng. Off.: THV Van Laere-Braekel Aero

Military School in Brussels

Arch. : AR.TE

Eng. Off.: Tractebel Development





La Grande Arche, Paris

Arch. : Johan Otto von Spreckelsen

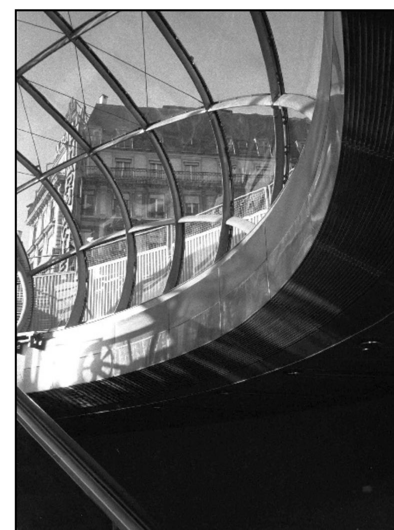
Eng. Off.: Paul Andreu

Villa Inox (FIN)

La Lentille de Saint-Lazare, Paris, (F)

Arch.: Arte Charpentiers & Associés

Eng. Off.: Mitsu Edwards



- Station in Porto (P)

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Torno Internazionale S.P.A. Headquarters
Milan, (IT), EN 1.4404

Arch. : Dante O. BENINI & Partners Architects

Photography: Toni Nicolino / Nicola Giacomin

Stainless steel frames in nuclear power plant

Photography: Stainless Structurals LLC

Stainless steel façade supports, Tampa, (USA)

Photography: TriPyramid Structures, Inc.

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Stainless steel I-shaped beams, Thames Gateway Water Treatment Works, (UK)

Photography: Interserve

Stainless steel structure,
Louis Vuitton Foundation, Paris (France)

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Duplex in bridges

- EN1.4462 grade in the Millennium footbridge in York (Whitby bird and partners)
- lean duplex EN1.4162 grade in the Siena bridge in Ruffolo (Eng. Pistoletti), in the Sölvesborg bridge in Sweden (Ljusarkitektur) and in the Sant Fruitós footbridge in Barcelona (Pedelta Structural Engineers)
- EN1.4362 grade in the Arco Ponte Malizia arch bridge in Siena (Eng. Pistoletti)

- REFERENCES:

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2. G. Gedge; *Structural uses of stainless steel –buildings and civil engineering*; Journal of Constructional Steel Research, Volume 64(11), 2008, pages 1194-1198.
3. NR. Baddoo; *Stainless steel in construction: A review of research, applications, challenges and opportunities*; Journal of Constructional Steel Research, Volume 64(11), 2008, pages 1199-1206.
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5. M. Esko*; Stainless steel in architecture*; Building Series, Volume 9, Brussels: Euro Inox, 2005.
6. International Iron & Steel Institute (IISI); Yearbook of stainless steel applications Brussels: IISI, 2006.
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Section 4

Grade selection

Grade selection procedure

- A procedure for selecting the appropriate steel grades for their application in certain environments, can be found in EN 1993-1-4/A1
- Corrosion Resistance Factor (CRF) for the environment:

$$CRF = F1 + F2 + F3$$

- in which:
  - F1 Risk of exposure to chlorides from salt water or de-icing salts
  - F2 Risk of exposure to sulphur dioxide
  - F3 Cleaning regime or exposure to washing by rain

CEN. (2015). NBN EN 1993-1-4/A1, Eurocode 3 - Design of steel structures - Part 1-4: General rules – Supplementary rules for stainless steels. Brussels.

F_1 Risk of exposure to chlorides from salt water or deicing salts		
NOTE M is distance from the sea and S is distance from roads with deicing salts.		
1	Internally controlled environment	
0	Low risk of exposure	M > 10 km or S > 0,1 km
-3	Medium risk of exposure	1 km < M ≤ 10 km or 0,01 km < S ≤ 0,1 km
-7	High risk of exposure	0,25 km < M ≤ 1 km or S ≤ 0,01 km
-10	Very high risk of exposure	Road tunnels where deicing salt is used or where vehicles might carry deicing salts into the tunnel
-10	Very high risk of exposure	M ≤ 0,25 km North Sea coast of Germany and all Baltic coastal areas
-15	Very high risk of exposure	M ≤ 0,25 km Atlantic coast line of Portugal, Spain and France. English Channel and North Sea Coastline of UK, France, Belgium, Netherlands and Southern Sweden. All other coastal areas of UK, Norway, Denmark and Ireland. Mediterranean Coast
F_2 Risk of exposure to sulfur dioxide		
For European coastal environments the sulfur dioxide concentration is usually low. For inland environments the sulfur dioxide concentration is either low or medium. The high classification is unusual and associated with particularly heavy industrial locations or specific environments such as road tunnels. Sulfur dioxide concentration may be evaluated according to the method in ISO 9225.		
0	Low risk of exposure	< 10 μg/m^3 average gas concentration
-5	Medium risk of exposure	10 - 90 μg/m^3 average gas concentration
-10	High risk of exposure	90 - 250 μg/m^3 average gas concentration
F_3 Cleaning regime or exposure to washing by rain (if $F_1+F_2 \geq 0$, then $F_3 = 0$)		
0	Fully exposed to washing by rain	
-2	Specified cleaning regime	
-7	No washing by rain or No specified cleaning	
If the component is to be regularly inspected for any signs of corrosion and cleaned, this should be made clear to the user in written form. The inspection, cleaning method and frequency should be specified. The more frequently cleaning is carried out, the greater the benefit. The frequency should not be less than every 3 months. Where cleaning is specified it should apply to all parts of the structure, and not just those easily accessible and visible.		

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Grade selection procedure

Corrosion Resistance Factor (CRF)	Corrosion Resistance Class (CRC)
CRF = 1	I
$0 \geq CRF > -7$	II
$-7 \geq CRF > -15$	III
$-15 \geq CRF \geq -20$	IV
$CRF < -20$	V

Corrosion resistance class CRC				
I	II	III	IV	V
1.4003	1.4301	1.4401	1.4439	1.4565
1.4016	1.4307	1.4404	1.4462	1.4529
1.4512	1.4311	1.4435	1.4539	1.4547
	1.4541	1.4571		1.4410
	1.4318	1.4429		1.4501
	1.4306	1.4432		1.4507
	1.4567	1.4162		
	1.4482	1.4662		
		1.4362		
		1.4062		
		1.4578		
A grade from a higher class may be used in place of the class indicated by the CRF. **NOTE:** The corrosion resistant classes are only intended for use with this grade selection procedure and are only applicable to structural applications.				

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Section 5

Material mechanical characteristics

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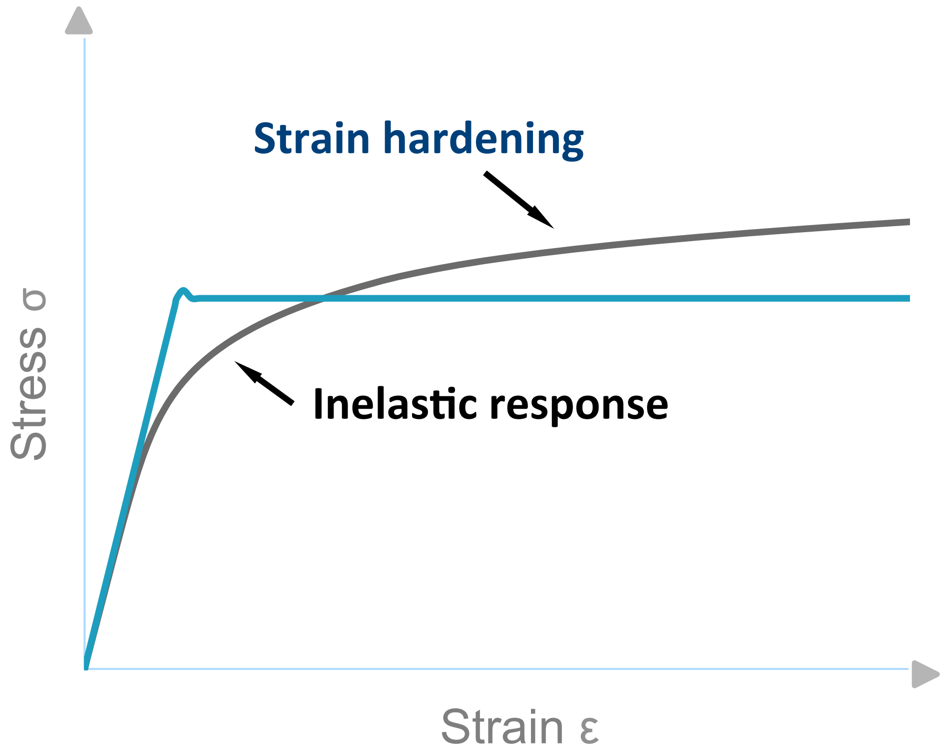
Stress-strain characteristics
Carbon steel versus stainless steel

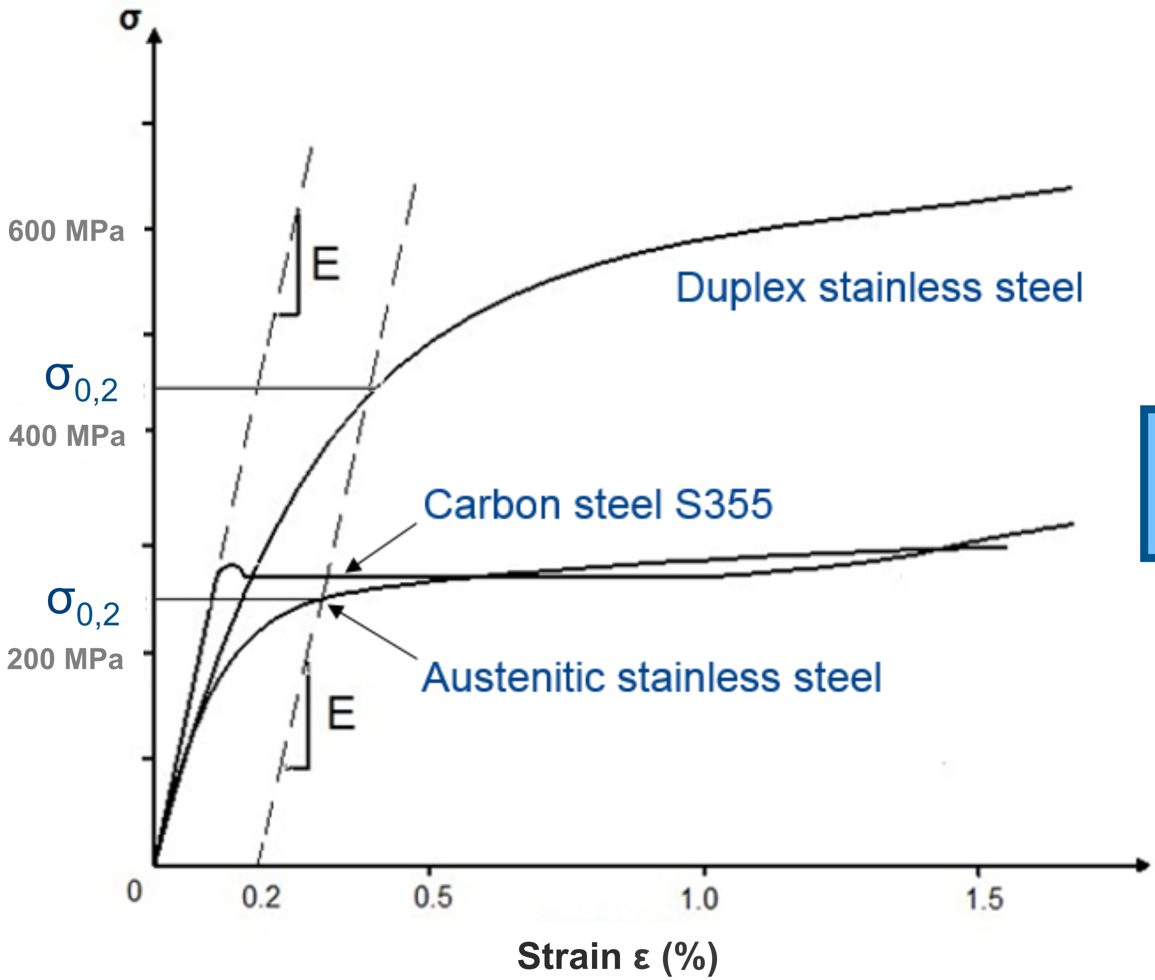
- Stainless steel exhibits fundamentally different σ-ε behaviour to carbon steel.



Carbon steel has a sharply defined yield point with a plastic yield plateau.

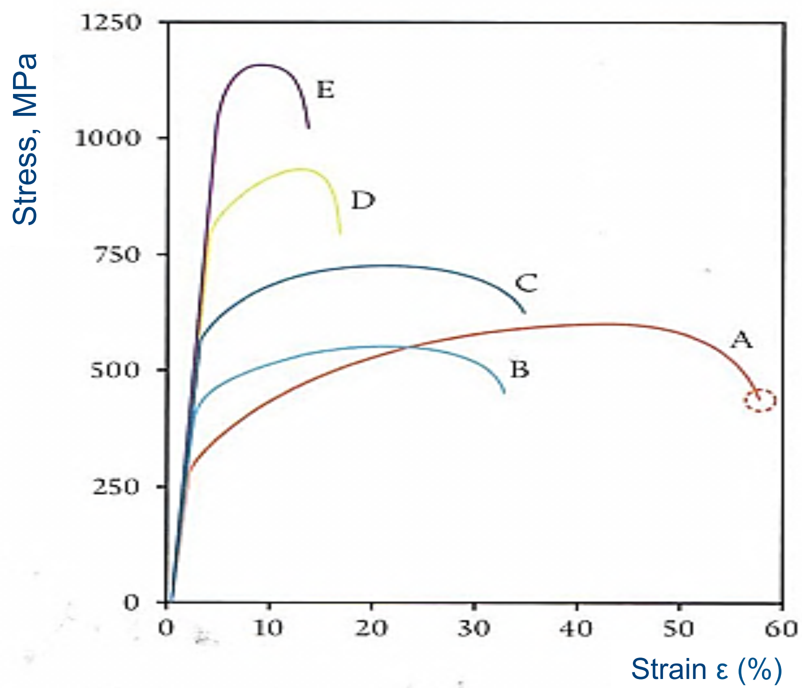
Stainless steel exhibits gradually yielding behaviour, with high strain-hardening.

Stress-strain characteristics – low strain



Stress-strain response depends on the family.

Typical tensile curves of stainless steels



Outline stress-strain test of different types of stainless steel:
A: Austenitic (e.g. 4301, 4307, 4404, etc.)
B: Ferritic (e.g. 4016, 4509, 4521)
C: Ferritic-austenitic (duplex, e.g. 4462)
D: Precipitation hardening (PH) steel (e.g. 4542)
E: Martensitic (e.g. 4057, 4109, 4034)
The dotted circle shows the rupture for curve A.

The « level of material non-linearity » or « degree of roundness » (exponent 'n'):
Ferritic > Duplex > Austenitic

Ductility:
Austenitic > Duplex > Ferritic

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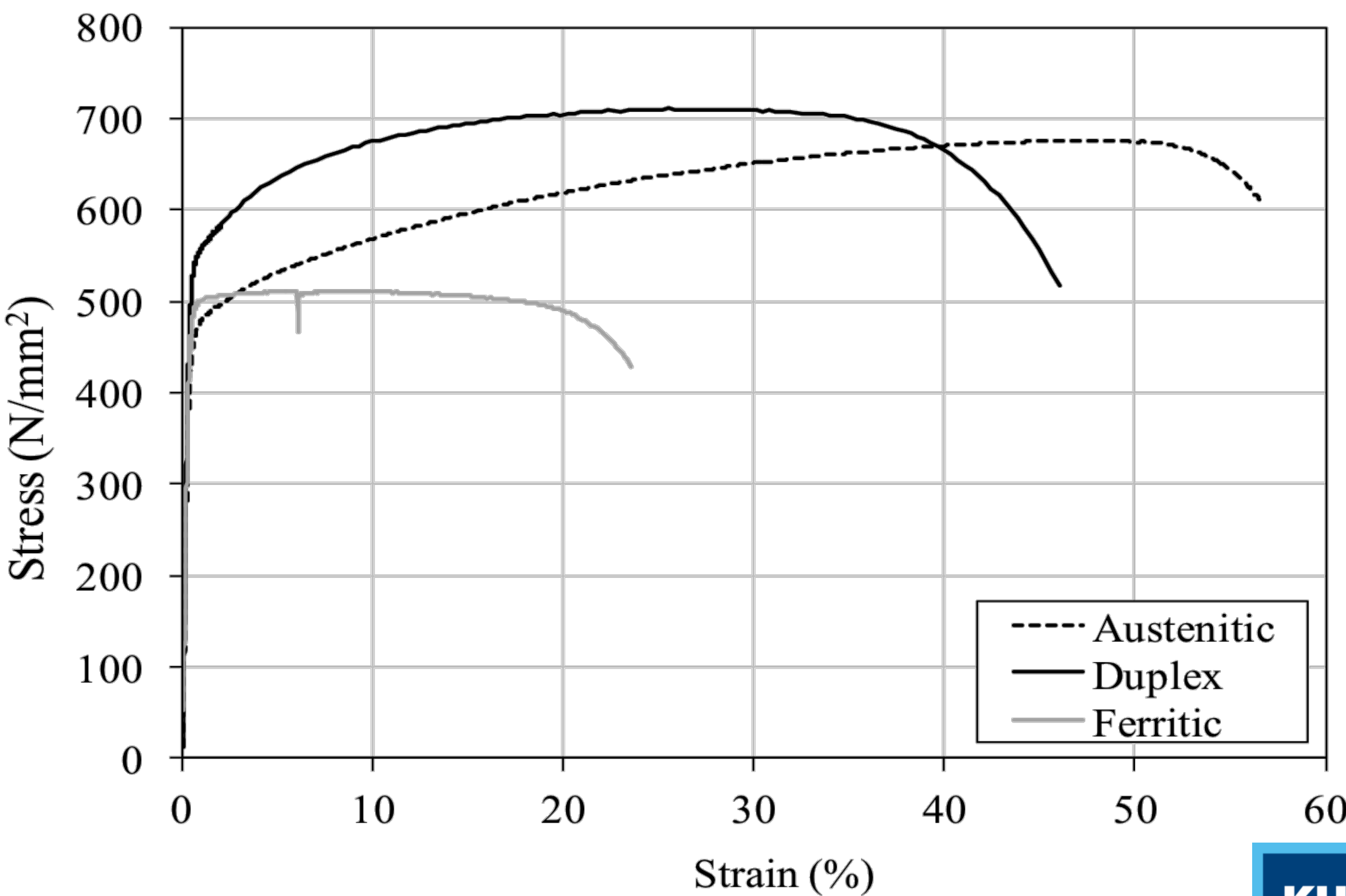
Typical tensile curves of stainless steels

- Austenitic, ferritic and duplex/Lean duplex stainless steel



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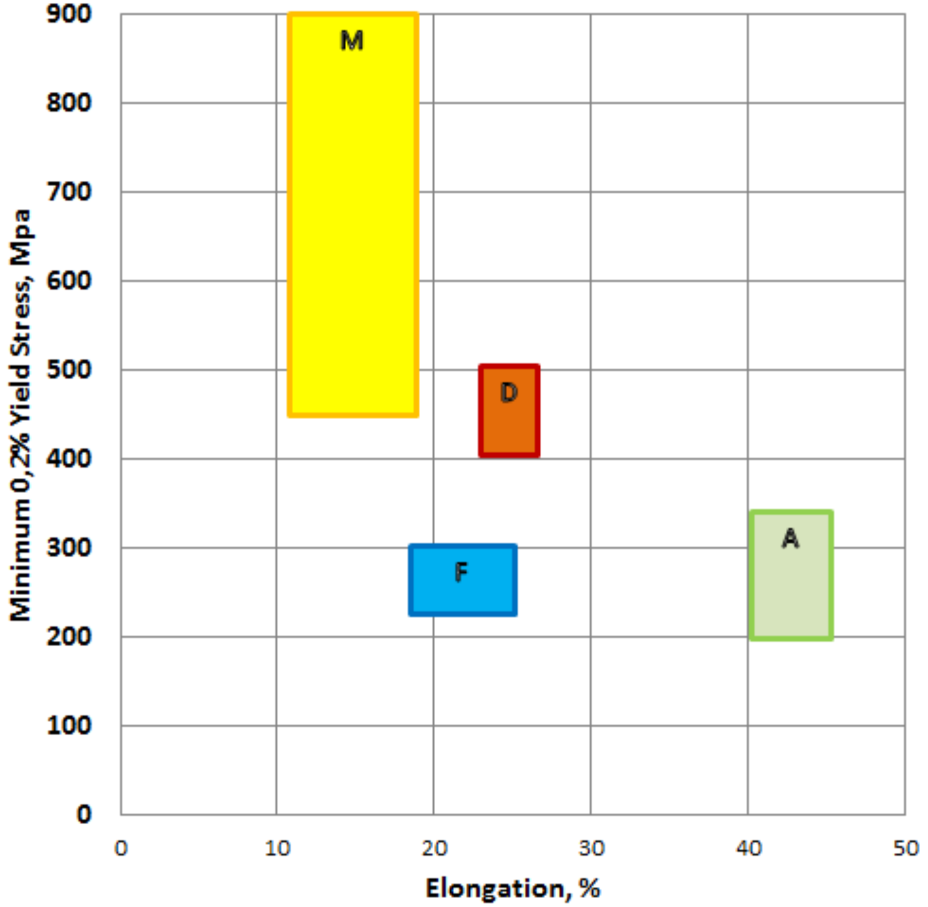
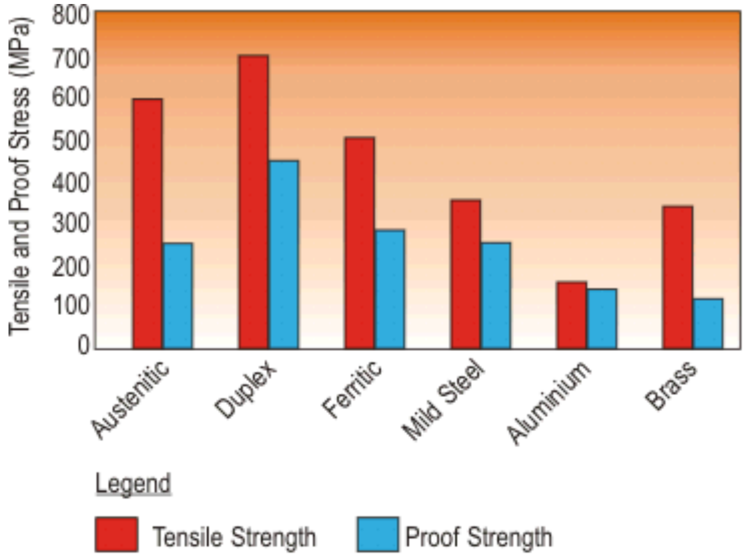
B. Rossi, S. Afshan, L. Gardner; Strength enhancements in cold-formed structural sections – Part II: Predictive models; Journal of Constructional Steel Research, Volume 83, 2013, pages 189-196.

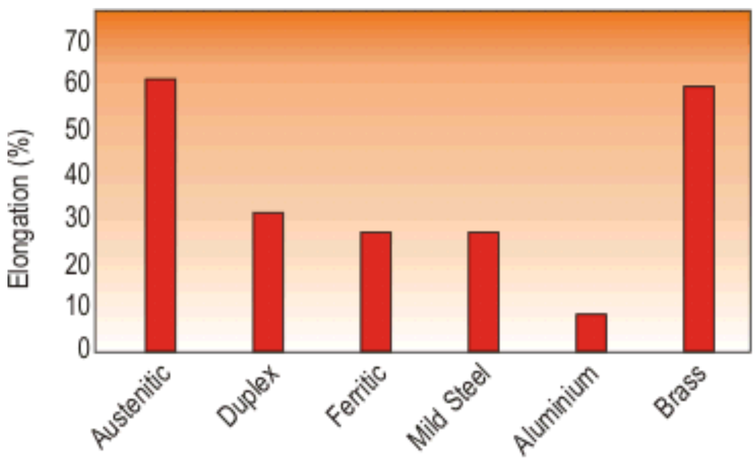
Minimum mechanical properties of stainless steels



M: Martensitics
D: Duplex
F: Ferritics
A: Austenitics

Comparison of tensile properties of various alloys



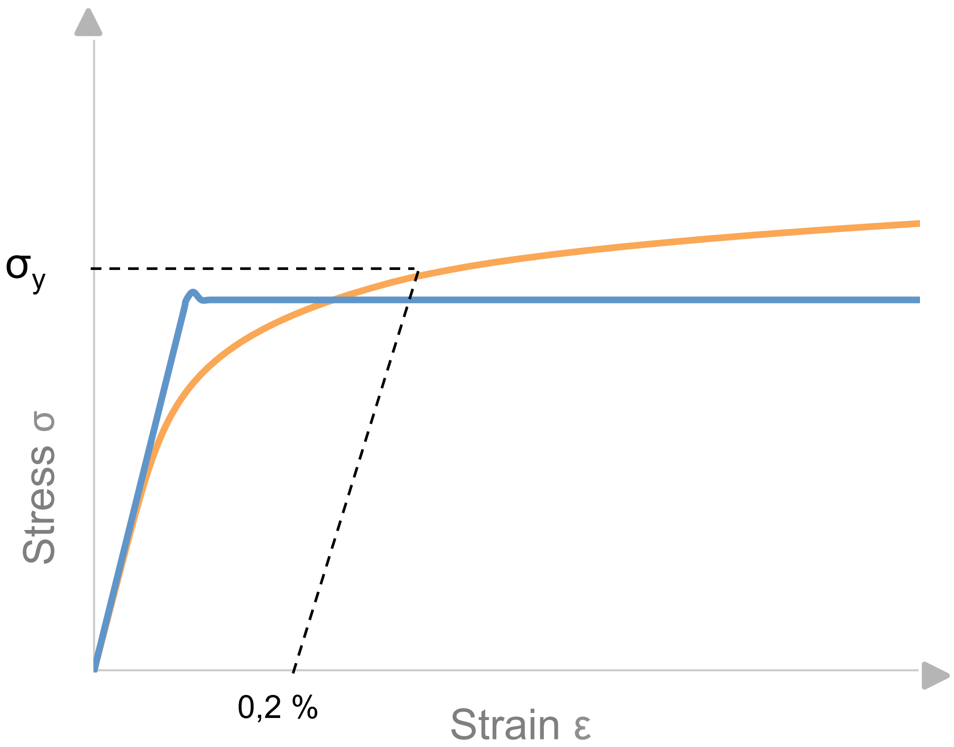


Design strength of stainless steel

Minimum specified 0.2% proof strength are given in EN 10088-4 and -5

Austenitic: f_y = 220–350 MPa
Duplex: f_y = 400–480 Mpa
Ferritic: f_y = 210–280 MPa

Young's modulus: E=200.000 to 220.000 MPa (ferritic grades)



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Design strength of stainless steel

Grade	Family	Yield strength (N/mm^2) 0.2% proof strength	Ultimate strength (N/mm^2)	Young's Modulus (N/mm^2)	Fracture strain (%)
1.4003	Ferritic	250	450	220000	25
1.4301 (304)	Austenitic	210	520	200000	45
1.4401 (316)	Austenitic	220	520	200000	40
1.4462	Duplex	460	640	200000	30
1.4062/1.4162	Duplex	450	650	200000	30

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Ramberg-Osgood material model

- For stainless steel, it displays a rounded stress–strain curve, with no sharp yield point, considerable strain hardening and high ductility.

- Instead of using a elastic, perfectly-plastic material model, the **Ramberg-Osgood** material model is employed.

- In the material model, the most important parameter is the **exponent 'n'**, which defines **degree of roundness** of the material curve, at low strain.

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n$$

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Ramberg-Osgood material model

Annex C of EN 1993-1-4

Two-stage Ramberg-Osgood model:

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n & \sigma \le \sigma_{0.2} \\ \varepsilon_{0.2} + \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u \left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m & \sigma > \sigma_{0.2} \end{cases}$$

$$n = \frac{\ln(20)}{\ln\left(\dfrac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \qquad m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \qquad E_{0.2} = \frac{E_0}{1 + 0.002n\dfrac{E_0}{\sigma_{0.2}}} \qquad \varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u}$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.2 + 185\dfrac{\sigma_{0.2}}{E_0} & \text{for austenitic and duplex} \\ \dfrac{0.2 + 185\dfrac{\sigma_{0.2}}{E_0}}{1 - 0.0375(n-5)} & \text{for all stainless steel alloys} \end{cases}$$

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Ramberg-Osgood material model

- The values of 'n' for each stainless steel grade defined in the Eurocode EN 1993-1-4 is summarised as follows:

Steel grade	Coefficient n	
	Longitudinal direction	Transverse direction
1.4003	7	11
1.4016	6	14
1.4512	9	16
1.4301 1.4306 1.4307 1.4318 1.4541	6	8
1.4401 1.4404 1.4432 1.4435 1.4539 1.4571	7	9
1.4462 1.4362	5	5

!! Wrong !!

Steel grade	Coefficient n
Austenitic	7
Ferritic	14
Duplex	8

Next revision of Annex C preliminary 'bundled' values

Next revision of Annex C …?

$$\varepsilon = \frac{\sigma-\sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\frac{\sigma-\sigma_{0.2}}{\sigma_u-\sigma_{0.2}}\right)^m + \varepsilon_{0.2} \qquad \text{for} \quad \sigma>\sigma_{0.2}$$

$$n = \frac{\ln(4)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.05}}\right)} \qquad \text{for all grades}$$

$$m = 1 + 2.8\frac{\sigma_{0.2}}{\sigma_u} \qquad \text{for all grades}$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.20 + 185\frac{\sigma_{0.2}}{E} & \text{for austenitic, duplex and lean duplex} \\ 0.46 + 145\frac{\sigma_{0.2}}{E} & \text{for ferritic grades} \end{cases}$$

$$\varepsilon_u = \begin{cases} 1-\frac{\sigma_{0.2}}{\sigma_u} & \text{for austenitic, duplex and lean duplex} \\ 0.6\left(1-\frac{\sigma_{0.2}}{\sigma_u}\right) & \text{for ferritic grades} \end{cases}$$

Description of stress–strain curves for stainless steel alloys I. Arrayago, E. Real, L. Gardner, Materials and Design, Volume 87, 15 December 2015, Pages 540–552

Impact of stress-strain characteristics

- **Nonlinearity**………..leads to
  - Different limiting width to thickness ratios for local buckling
  - Different member buckling behaviour in compression and bending
  - Greater deflections

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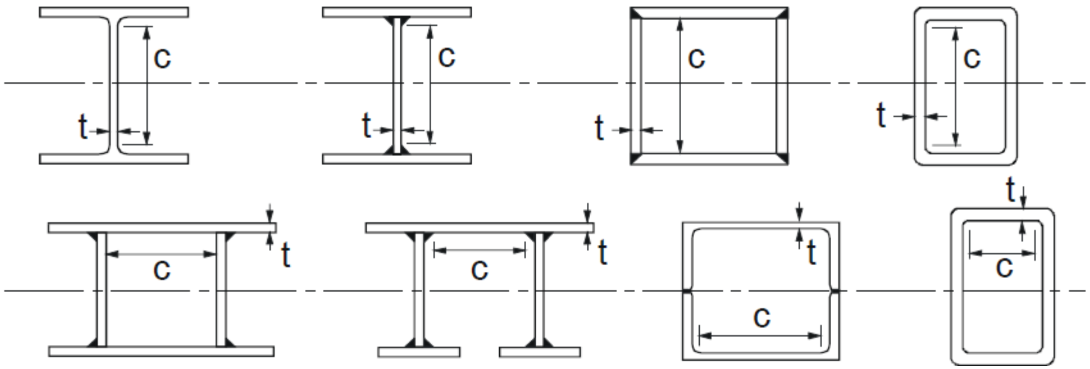
Impact on Section classification & local buckling expressions in EN 1993-1-4

- Internal compression parts



$$\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel		**EC3-1-4: stainless steel**		**EC3-1-4: New revision**	
Class	**Bending**	**Compression**	**Bending**	**Compression**	**Bending**	**Compression**
1	c/t ≤ 72ε	c/t ≤ 33ε	c/t ≤ 56ε	c/t ≤ 25,7ε	**c/t ≤ 72ε**	**c/t ≤ 33ε**
2	c/t ≤ 83ε	c/t ≤ 38ε	c/t ≤ 58,2ε	c/t ≤ 26,7ε	**c/t ≤ 76ε**	**c/t ≤ 35ε**
3	c/t ≤ 124ε	c/t ≤ 42ε	c/t ≤ 74,8ε	c/t ≤ 30,7ε	**c/t ≤ 90ε**	**c/t ≤ 37ε**

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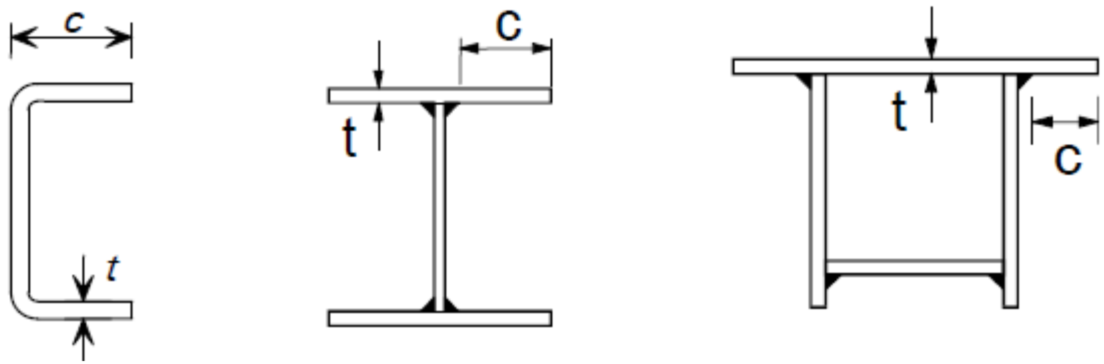
Impact on Section classification & local buckling expressions in EN 1993-1-4

- External compression parts



$$\varepsilon=\sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel	EC3-1-4: stainless steel		EC3-1-4: New revision
Class	**Compression**	**Compression Welded**	**Compression Cold-formed**	**Compression**
1	c/t ≤ 9ε	c/t ≤ 9ε	c/t ≤ 10ε	**c/t ≤ 9ε**
2	c/t ≤ 10ε	c/t ≤ 9,4ε	c/t ≤ 10,4ε	**c/t ≤ 10ε**
3	c/t ≤ 14ε	c/t ≤ 11ε	c/t ≤ 11,9ε	**c/t ≤ 14ε**

Impact on buckling performance

- **Low slenderness**
  columns attain/exceed the squash load

  ⇒ **benefits** of strain hardening apparent
  ss behaves at least **as well as** cs

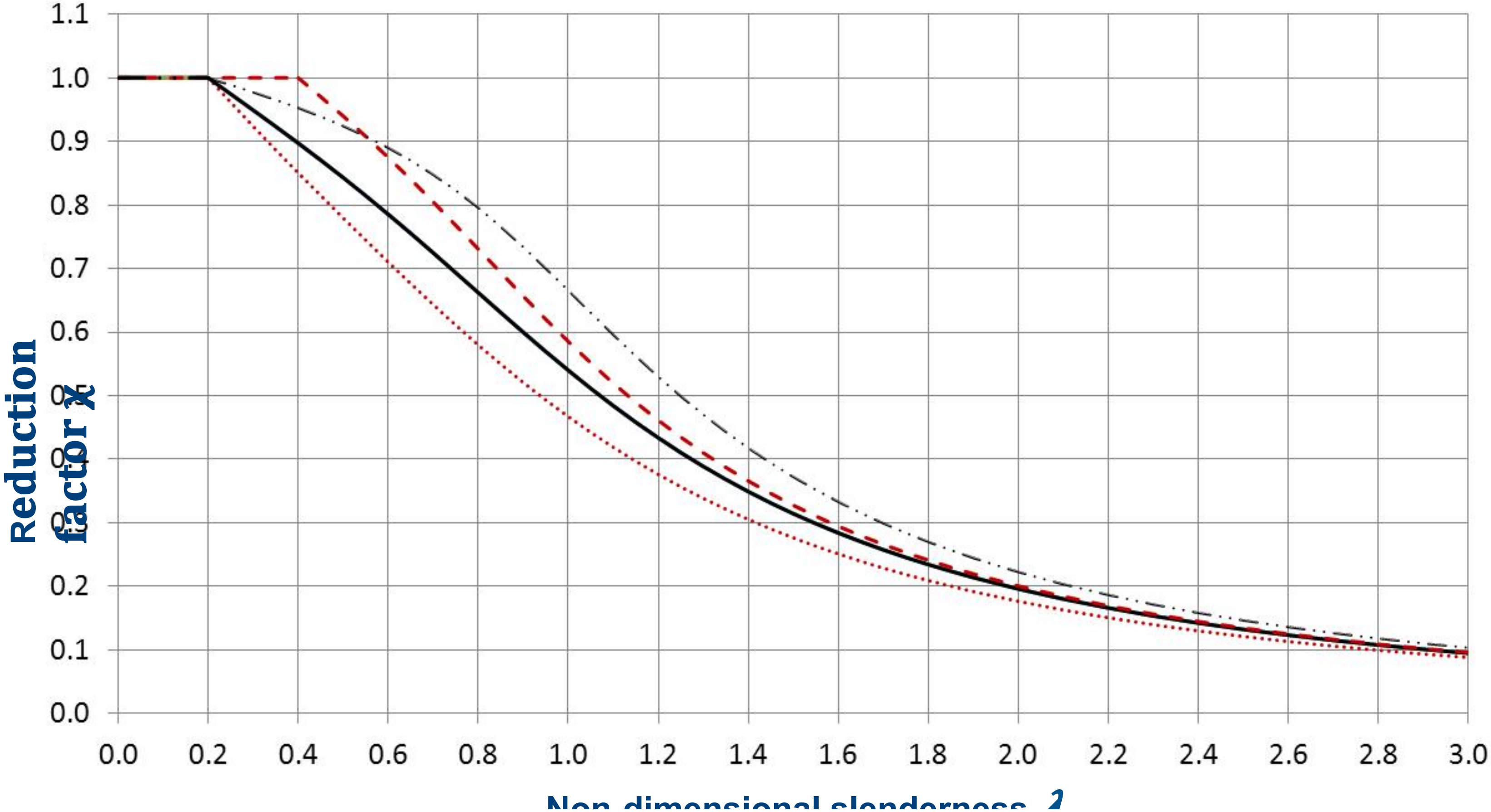
- **Intermediate slenderness**
  average stress in column lies between the limit of proportionality and the 0.2% permanent strain,

  ⇒ ss column **less strong** than cs column

- **High slenderness**
  axial strength low, stresses low and in linear region

  ⇒ ss behaves **similarly** to cs, providing geometric and residual stresses similar

Eurocode 3 Flexural buckling curves



- - Stainless steel: hollow sections (welded + seamless), cold formed channels
····· Stainless steel: welded I-sections
— Carbon steel: welded I-sections, cold formed hollow sections, cold formed channels
—··· Carbon steel: hot finished hollow sections

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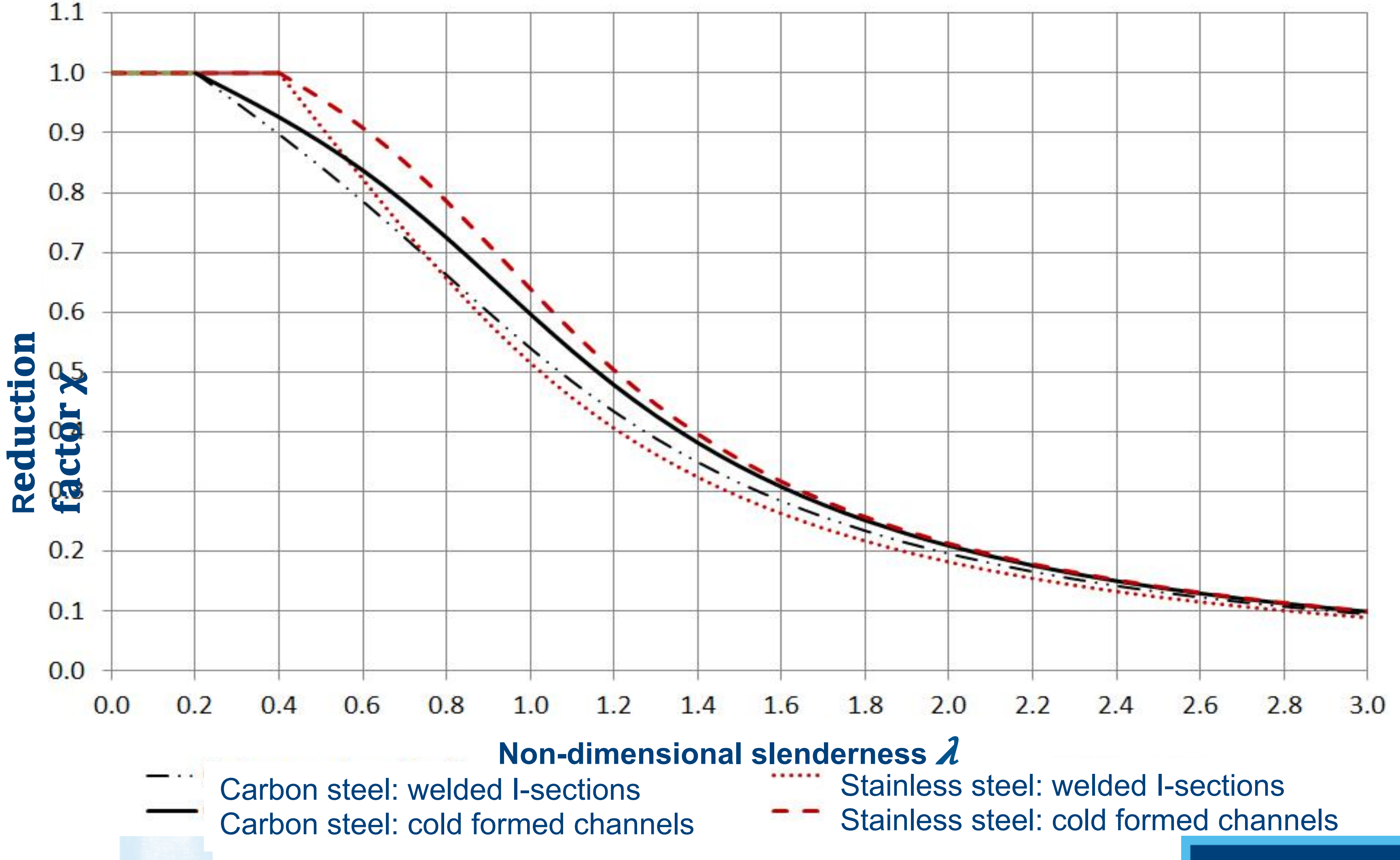
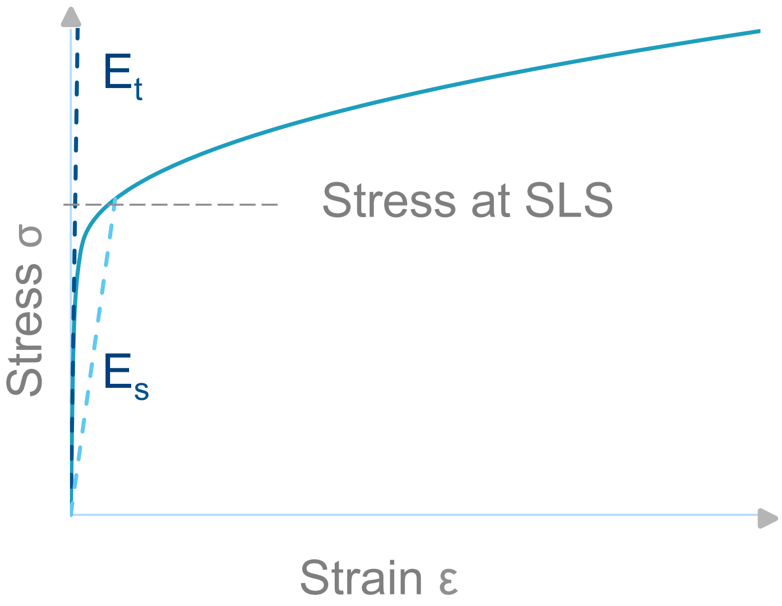
Eurocode 3 Lateral torsional buckling curves



Impact on Deflections

- Non-linear stress-strain curve means that stiffness of stainless steel decreases as stress increases
- Deflections are slightly greater in stainless steel than in carbon steel
- Use secant modulus ES at the stress in the member at the serviceability limit state (SLS)



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Impact on Deflections

- Secant modulus E_S determined from the Ramberg-Osgood model:

$$E_{SEC} = \frac{E_{S1} + E_{S2}}{2} \qquad E_{Si} = \frac{E}{1+0.002\frac{E}{\sigma_{ser,i}}\left(\frac{\sigma_{ser,i}}{f_y}\right)^n}$$

$\sigma\downarrow ser$ **stress at serviceability limit state**

n **is the non-linear material constant**

$\boldsymbol{\sigma}_1$ ***σ*** at SLS in "tension flange"

$\boldsymbol{\sigma}_2$ ***σ at SLS in "compression flange"***

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Impact on Deflections

- Deflections in an austenitic stainless steel beam

Stress ratio σ_{ser}/f_y	Secant modulus, E_S N/mm^2	% increase in deflection
0.25	200,000	0
0.5	192,000	4
0.7	158,000	27

σ_{ser} = stress at serviceability limit state

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Section 6

Design according to Eurocode 3

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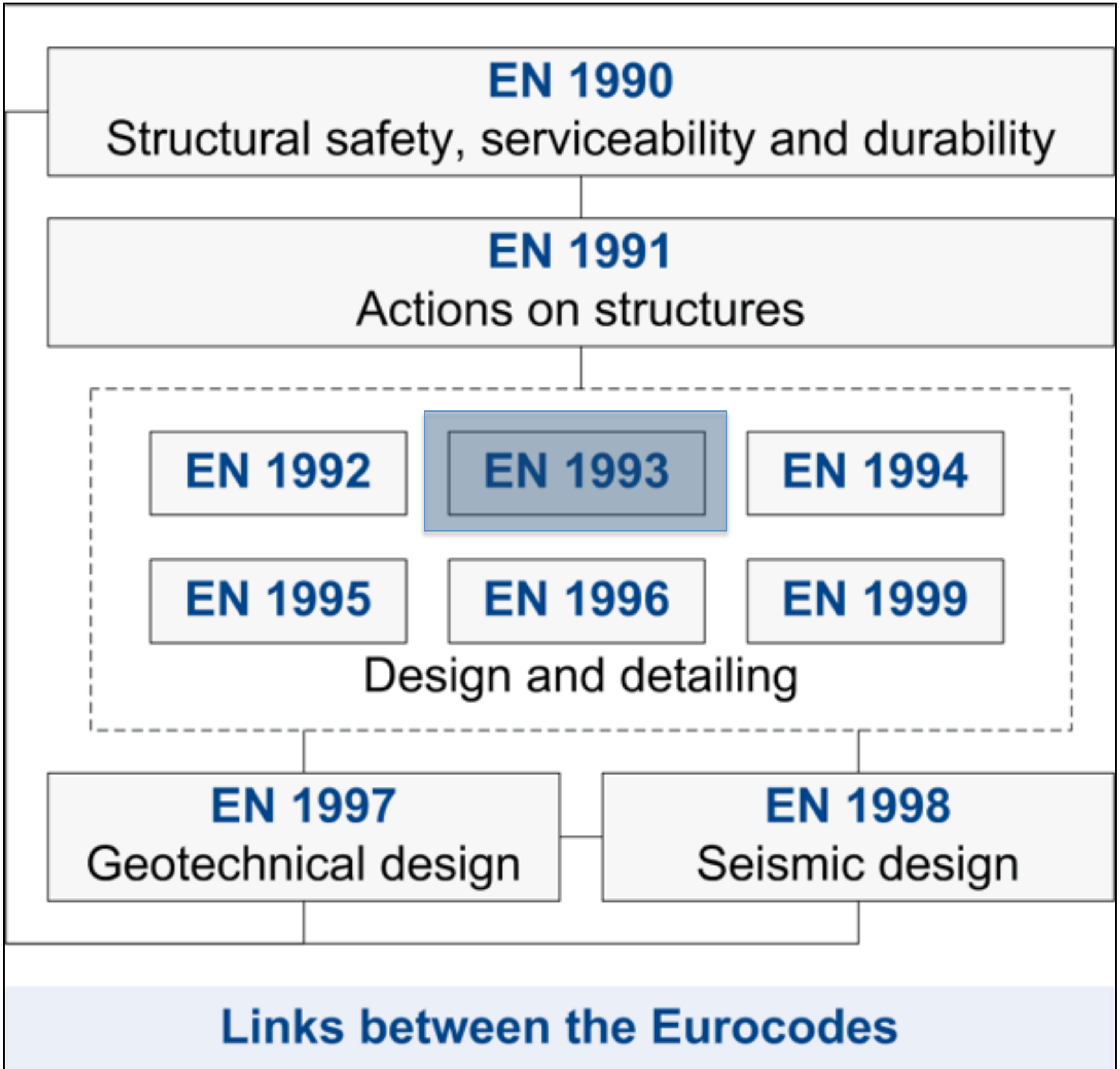
International design standards

What design standards are available for structural stainless steel?

Hamilton Island Yacht Club, Australia



Eurocodes are an integrated suite of structural design codes covering all common construction materials

Eurocode 3: Part 1 (EN 1993-1)

EN 1993-1-1 General rules and rules for buildings.

EN 1993-1-2 Structural fire design.

EN 1993-1-3 Cold-formed 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 & 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

EN 1993-1-12 Supplementary rules for high strength steels

Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

BRITISH STANDARD

BS EN 1993-1-4:2006

Eurocode 3 — Design of steel structures —

Part 1-4: General rules — Supplementary rules for stainless steels

The European Standard EN 1993-1-4:2006 has the status of a British Standard

ICS 91.040.01; 91.080.10

BSi British Standards

Design of steel structures.

Supplementary rules for stainless steels (2006):

- Modifies and supplements rules for carbon steel given in other parts of Eurocode 3 where necessary
- Applies to buildings, bridges, tanks etc

CEN. (2015). NBN EN 1993-1-4/A1, Eurocode 3 - Design of steel structures - Part 1-4: General rules – Supplementary rules for stainless steels. Brussels. ***Supplementary Amendments***

Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

- Follow same basic approach as carbon steel
- Use same rules as for carbon steel for tension members & restrained beams
- Safety factors: $\gamma_{M0} = 1.1$ $\gamma_{M1} = 1.1$ $\gamma_{M2} = 1.25$
- Some differences in section classification limits, local buckling and member buckling curves apply due to:
  - non-linear stress strain curve
  - strain hardening characteristics
  - different levels of residual stresses

Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

Types of members

- Hot rolled and welded
- Cold-formed
- Bar

Number of grades

Family	EC3-1-4	New revision
Ferritic	3	3
Austenitic	16	16
Duplex	2	**6**

Scope

- Members and connections
- Fire *(by reference to EN 1993-1-2)*
- Fatigue *(by reference to EN 1993-1-9)*

<table>
<tr><th rowspan="6">Type of stainless steel</th><th rowspan="6">Grade</th><th colspan="8">Product form</th></tr>
<tr><th colspan="2">Cold rolled strip</th><th colspan="2">Hot rolled strip</th><th colspan="2">Hot rolled plate</th><th colspan="2">Bars, rods and sections</th></tr>
<tr><th colspan="8">Nominal thickness t</th></tr>
<tr><th colspan="2">$t \leq 8$ mm</th><th colspan="2">$t \leq 13,5$ mm</th><th colspan="2">$t \leq 75$ mm</th><th colspan="2">$t \leq 250$ mm</th></tr>
<tr><th>f_y</th><th>f_u</th><th>f_y</th><th>f_u</th><th>f_y</th><th>f_u</th><th>f_y</th><th>f_u</th></tr>
<tr><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th><th>N/mm^2</th></tr>
<tr><td rowspan="3">Ferritic steels</td><td>1.4003</td><td>280</td><td>450</td><td>280</td><td>450</td><td>250 [c]</td><td>450 [c]</td><td>260 [d]</td><td>450 [d]</td></tr>
<tr><td>1.4016</td><td>260</td><td>450</td><td>240</td><td>450</td><td>240 [c]</td><td>430 [c]</td><td>240 [d]</td><td>400 [d]</td></tr>
<tr><td>1.4512</td><td>210</td><td>380</td><td>210</td><td>380</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="14">Austenitic steels</td><td>1.4306</td><td rowspan="3">220</td><td rowspan="3">520</td><td rowspan="3">200</td><td rowspan="3">520</td><td rowspan="3">200</td><td rowspan="3">500</td><td>180</td><td>460</td></tr>
<tr><td>1.4307</td><td>175</td><td>500</td></tr>
<tr><td>1.4541</td><td rowspan="2">190</td><td rowspan="2">500</td></tr>
<tr><td>1.4301</td><td>230</td><td>540</td><td>210</td><td>520</td><td>210</td><td>520</td></tr>
<tr><td>1.4401</td><td rowspan="4">240</td><td rowspan="3">530</td><td rowspan="4">220</td><td rowspan="3">530</td><td rowspan="4">220</td><td rowspan="4">520</td><td rowspan="2">200</td><td rowspan="2">500</td></tr>
<tr><td>1.4404</td></tr>
<tr><td>1.4539</td><td>230</td><td>530</td></tr>
<tr><td>1.4571</td><td>540</td><td>540</td><td rowspan="3">200</td><td rowspan="3">500</td></tr>
<tr><td>1.4432</td><td rowspan="2">240</td><td rowspan="2">550</td><td rowspan="2">220</td><td rowspan="2">550</td><td rowspan="2">220</td><td rowspan="2">520</td></tr>
<tr><td>1.4435</td></tr>
<tr><td>1.4311</td><td>290</td><td>550</td><td>270</td><td>550</td><td>270</td><td>550</td><td>270</td><td>550</td></tr>
<tr><td>1.4406</td><td>300</td><td rowspan="2">580</td><td>280</td><td rowspan="2">580</td><td>280</td><td rowspan="2">580</td><td rowspan="2">280</td><td rowspan="2">580</td></tr>
<tr><td>1.4439</td><td>290</td><td>270</td><td>270</td></tr>
<tr><td>1.4529</td><td>-</td><td>-</td><td>-</td><td>-</td><td>300</td><td>650</td><td>300 [b]</td><td>650 [b]</td></tr>
</table>

Type of stainless steel	Grade	Product form							
		Cold rolled strip		Hot rolled strip		Hot rolled plate		Bars, rods and sections	
		Nominal thickness t							
		$t \leq 8$ mm		$t \leq 13,5$ mm		$t \leq 75$ mm		$t \leq 250$ mm	
		f_y	f_u	f_y	f_u	f_y	f_u	f_y	f_u
		N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2	N/mm^2
	1.4547	320	650	300	650	300	650	300	650
	1.4318	350	650	330	650	330	630	-	-
Austenitic-ferritic steels	1.4062	530 [e]	700 [e]	480 [f]	680 [f]	450 [g]	650 [g]	380 [b]	650 [b]
	1.4162	530 [e]	700 [e]	480 [f]	680 [f]	450	650	450 [b]	650 [b]
	1.4482	500 [e]	700 [e]	480 [f]	660 [f]	450	650	400 [b]	650 [b]
	1.4662	550 [e]	750 [e]	550	750	480	680	450 [b]	650 [b]
	1.4362	450	650	400	650	400	630	400 [b]	600 [b]
	1.4462	500	700	460	700	460	640	450 [b]	650 [b]

[a] The nominal values of f_y and f_u given in this table may be used in design without taking special account of anisotropy or strain hardening effects.

[b] $t \leq 160$ mm

[c] $t \leq 25$ mm

[d] $t \leq 100$ mm

[e] $t \leq 6,4$ mm

[f] $t \leq 10$ mm

[g] $t \leq 50$ mm ($f_y = 430$ N/mm^2 and $f_u = 625$ N/mm^2 for 50 mm $< t \leq 75$ mm)

Other design standards

- **Japan** – two standards: one for cold formed and one for welded stainless members
- **South Africa, Australia, New Zealand** - standards for cold formed stainless members
- **Chinese** - standard under development
- **US** - ASCE specification for cold-formed members and AISC Design Guide for hot rolled and welded structural stainless steel

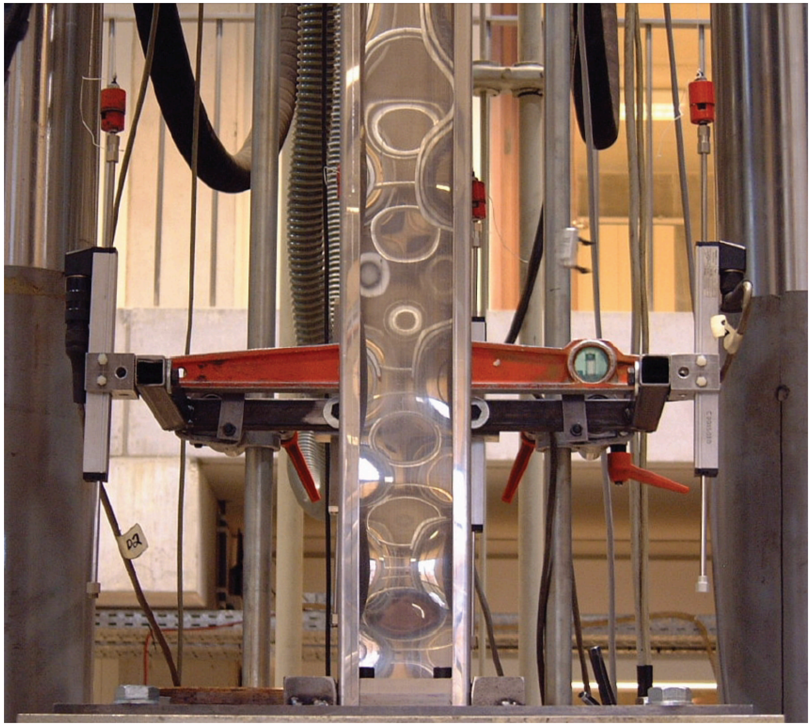
Eurocode 3: Design of Steel Structures, Part 1.4 Supplementary rules for stainless steels

What are the design rules for stainless steel given in EN 1993-1-4 and the main differences with carbon steel equivalents?

Blast resistant columns in entrance canopy,
Seven World Trade Centre, New York

Section classification & local buckling

- In compression, because of small thicknesses, the behaviour of **plates** is affected by instability phenomena called **LOCAL buckling**.



Local buckling prevents the cross-section to attain the **elastic resistance**

Section classification & local buckling

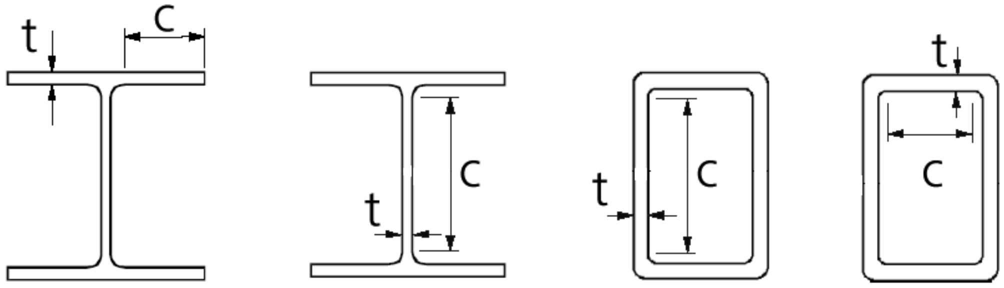
- **Classification** is required to decide about the type of cross-section verification:
  - **Elastic** verification
  - **Plastic** (or partial plastic) verification
  - **Effective** cross-section properties ('reduced' cross-section properties: A_{eff} and I_{eff})

Section classification & local buckling

- **Class 1 can form a plastic hinge**, have sufficient rotation capacity
- **Class 2** cross-sections are those which **can develop** their **plastic moment** resistance, but have limited rotation capacity because of local buckling
- **Class 3** cross-sections are those in which the stress in the extreme compression fibre of the steel member assuming an elastic distribution of stresses **can reach the yield strength**, but local buckling is liable to prevent development of the plastic moment resistance
- **Class 4** cross-sections are those in which **local buckling** will occur **before** the attainment of **yield stress** in one or more parts of the cross-section

Section classification & local buckling

- Classification of a cross-section
  - depends on the classification of all its constitutive plate elements **totally** or **partially** in **compression**
  - is **mainly** governed by the **plate slenderness** c/t



  - **cross-section** class = most unfavorable class of its constitutive **plate** elements in compression

Section classification & local buckling expressions in EN 1993-1-4

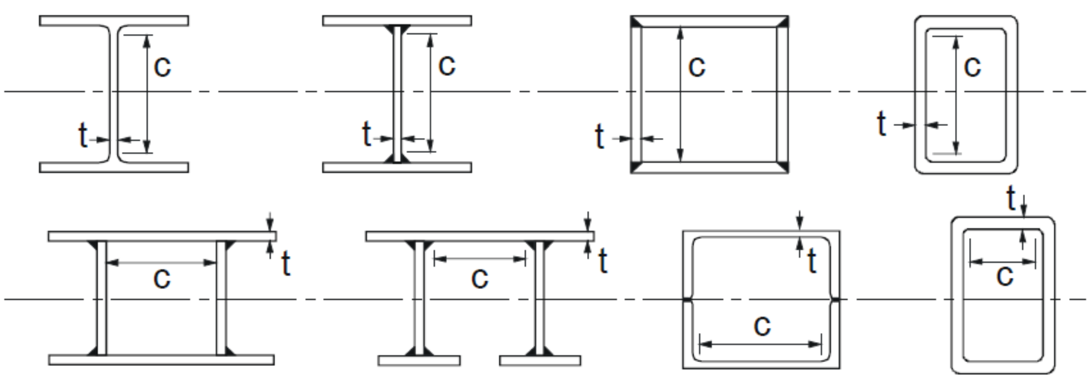
- Lower limiting width-to-thickness ratios than for carbon steel
- Slightly different expressions for calculating effective widths of slender elements

However…

The new version of EN 1993-1-4 contains <u>less conservative</u> limits & effective width expressions.

Section classification & local buckling expressions in EN 1993-1-4

- Internal compression parts

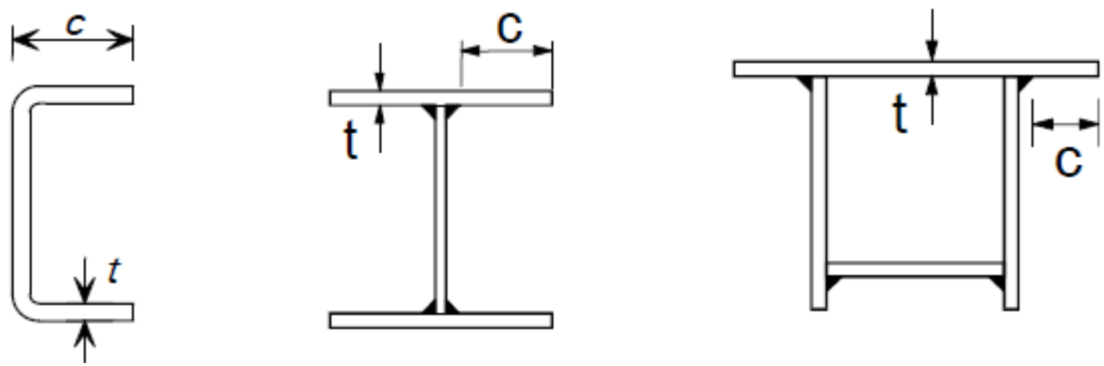


$$\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel		EC3-1-4: stainless steel		EC3-1-4: New revision	
Class	Bending	Compression	Bending	Compression	Bending	Compression
1	c/t ≤ 72ε	c/t ≤ 33ε	c/t ≤ 56ε	c/t ≤ 25,7ε	**c/t ≤ 72ε**	**c/t ≤ 33ε**
2	c/t ≤ 83ε	c/t ≤ 38ε	c/t ≤ 58,2ε	c/t ≤ 26,7ε	**c/t ≤ 76ε**	**c/t ≤ 35ε**
3	c/t ≤ 124ε	c/t ≤ 42ε	c/t ≤ 74,8ε	c/t ≤ 30,7ε	**c/t ≤ 90ε**	**c/t ≤ 37ε**

Section classification & local buckling expressions in EN 1993-1-4

- External compression parts



$$\varepsilon=\sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel	EC3-1-4: stainless steel		EC3-1-4: New revision
Class	Compression	Compression Welded	Compression Cold-formed	Compression
1	c/t ≤ 9ε	c/t ≤ 9ε	c/t ≤ 10ε	**c/t ≤ 9ε**
2	c/t ≤ 10ε	c/t ≤ 9,4ε	c/t ≤ 10,4ε	**c/t ≤ 10ε**
3	c/t ≤ 14ε	c/t ≤ 11ε	c/t ≤ 11,9ε	**c/t ≤ 14ε**

Section classification & local buckling

- PAY ATTENTION

  – Cross-section class = most unfavourable class of its constitutive plate elements in compression

    ➠ fabricated girder with slender web are usually Class 4 sections!

  – Cross-section class depends on $\varepsilon=\sqrt{\frac{235}{f_y}\frac{E}{210000}}$

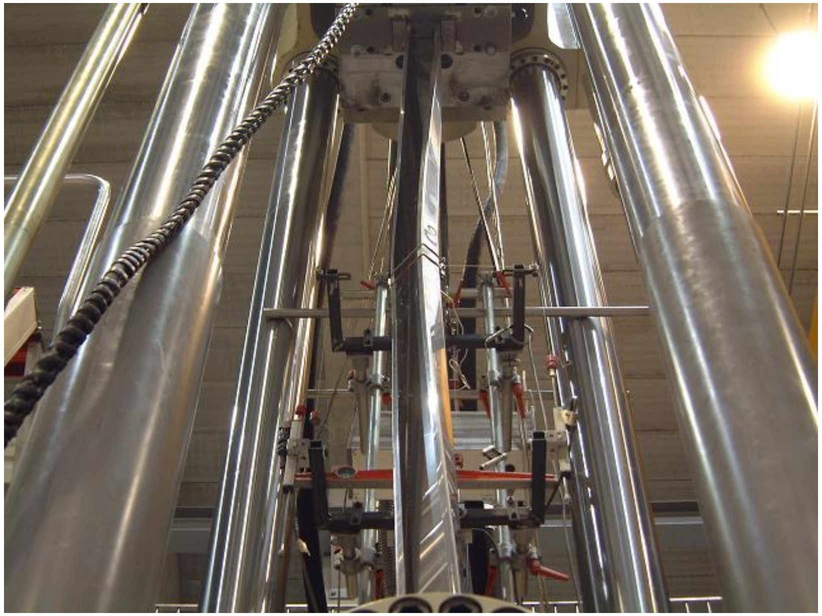
    ➠ Many sections fall in class 3 (semi-compact) and 4 when higher grades are used!

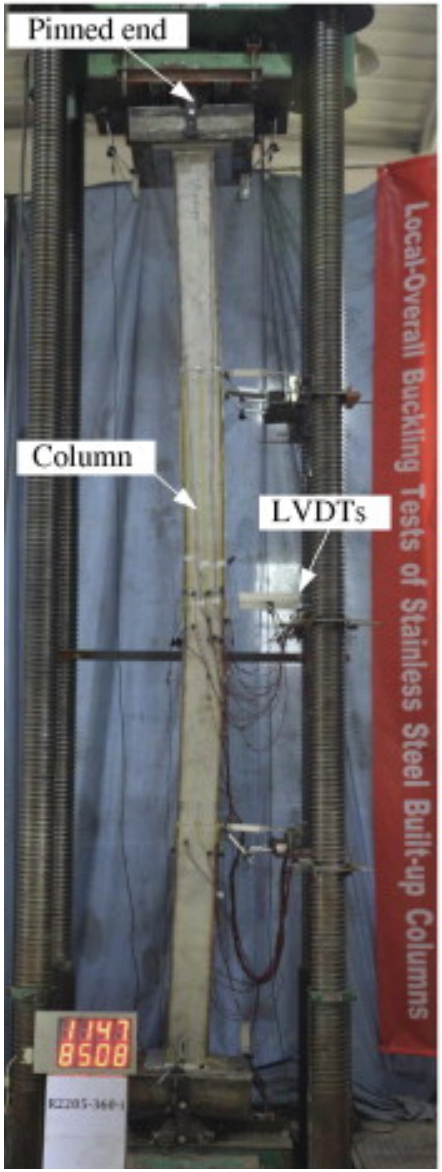
Cross-section verification

- **Class 1** and **Class 2** **plastic** resistance
- **Class 3** **elastic** resistance
- **Class 4** **effective** cross-section properties

Design of columns & beams

- In **compression**, because of the global dimension of the **column**, the behaviour is affected by instability phenomena. Those instabilities often take the form of **GLOBAL** lateral **buckling** about the weak axis.





Design of columns & beams in EN 1993-1-4

- In general use same approach as for carbon steel i.e. 'European buckling curves' i.e. we multiply the squash load by a reduction factor:

- But use different buckling curves for buckling of columns and unrestrained beams (LTB)

- Ensure you use the correct f_y for the grade (minimum specified values are given in EN 10088-4 and -5)

Column buckling

- Compression buckling resistance $N_{b,Rd}$:

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}}$$

Reduction factor

- Reduction factor:

$$\chi = \frac{1}{\phi + (\phi^2 - \bar{\lambda}^2)^{0,5}} \leq 1$$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}}$$

$$\phi = 0,5\left(1 + \alpha(\bar{\lambda} - \lambda_0) + \bar{\lambda}^2\right)$$

Imperfection factor

Plateau length

Column buckling

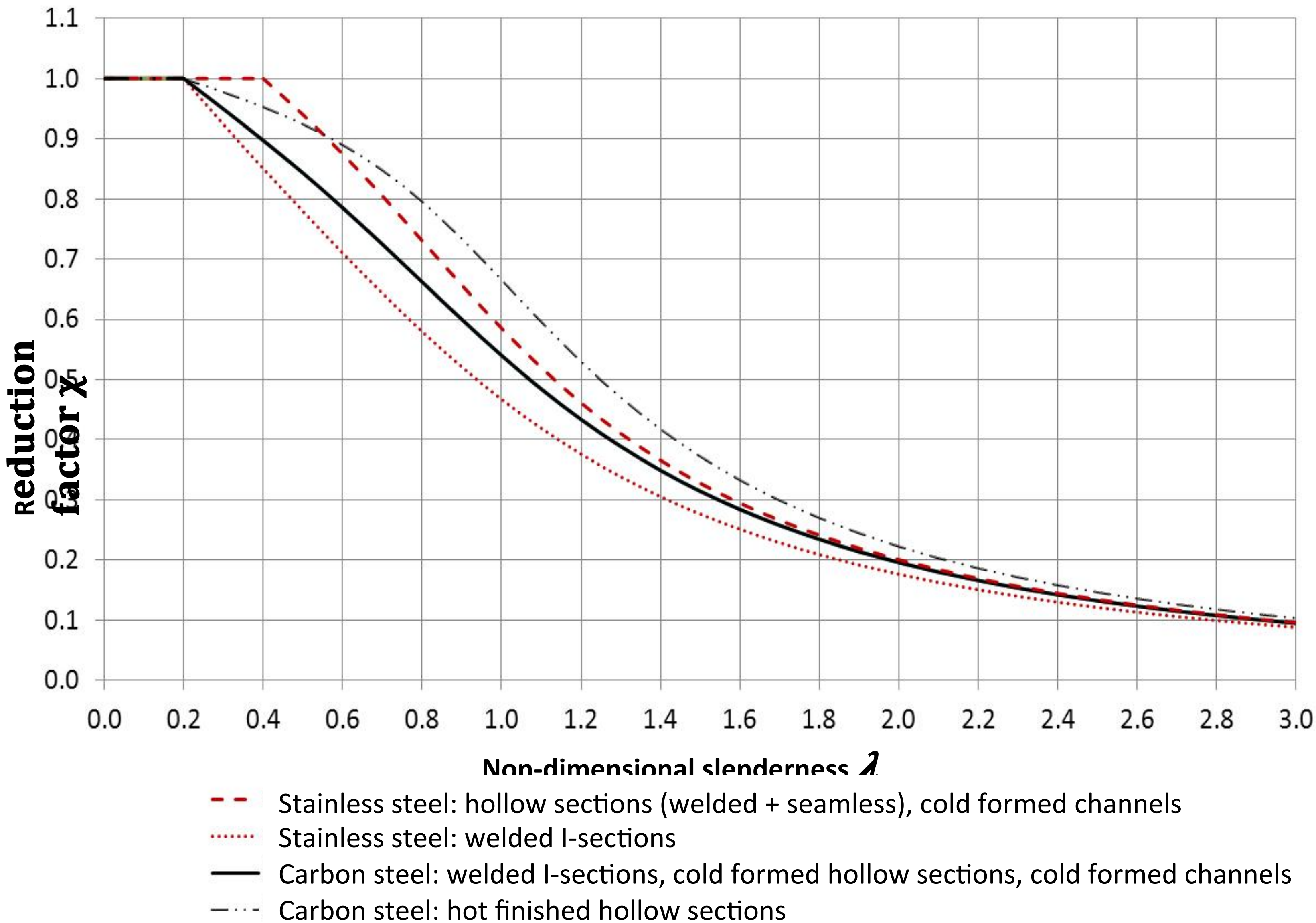
- Choice of buckling curve depends on cross-section, manufacturing route and axis:

Table 5.3: Values of α and $\bar{\lambda}_0$ for flexural, torsional and torsional-flexural buckling

Buckling mode	Type of member	α	$\bar{\lambda}_0$
Flexural	Cold formed open sections	0,49	0,40
	Hollow sections (welded and seamless)	0,49	0,40
	Welded open sections (major axis)	0,49	0,20
	Welded open sections (minor axis)	0,76	0,20
Torsional and torsional-flexural	All members	0,34	0,20

"Extract" from EN 1993-1-4

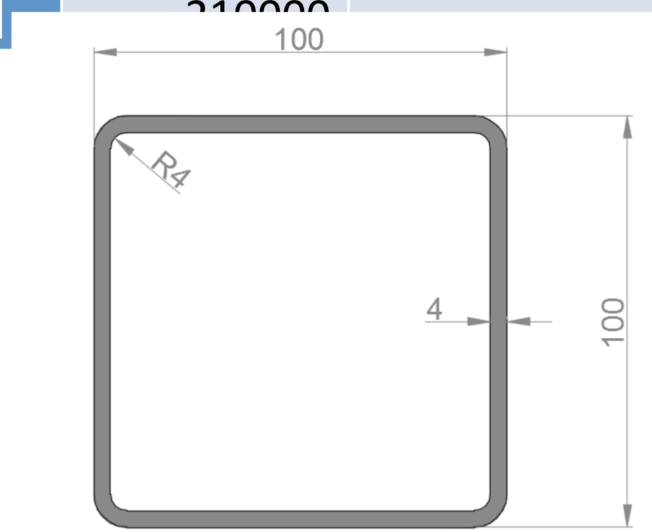
Eurocode 3 Flexural buckling curves

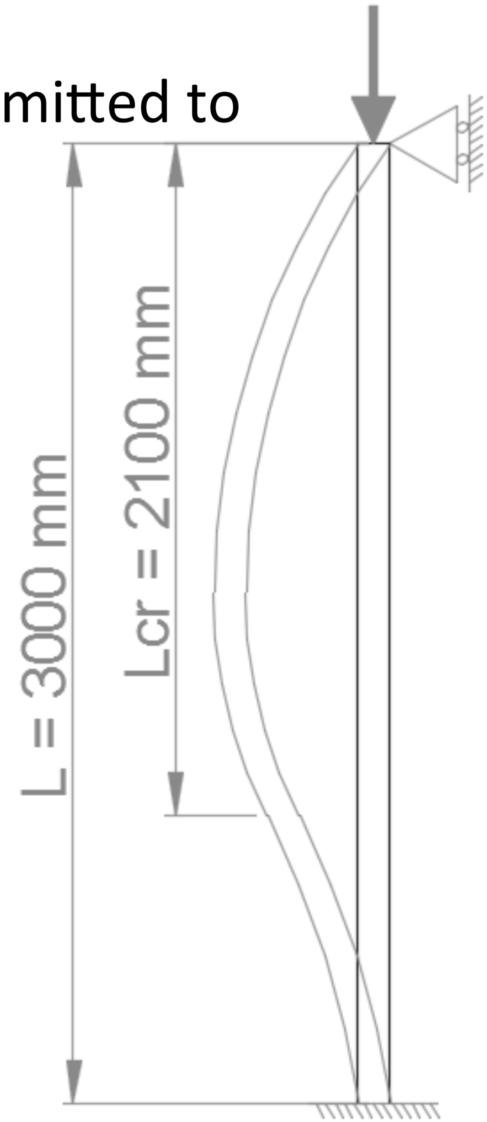


Eurocode 3 Flexural buckling example

- Cold formed rectangular hollow section submitted to concentric compression

	Carbon steel	Austenitic stainless steel
Material	S235	EN 1.4301
f_y [N/mm²]	235	230
E [N/mm²]	210000	200000





Eurocode 3 flexural buckling example

EC 3-1-1: S235

- Classification

  $\varepsilon = \sqrt{235/f_y} = 1$

  - All internal parts

    $c/t = 21 < 33 = 33\varepsilon$

    Class 1

Cross-section = class 1

EC 3-1-4: Austenitic

- Classification

  $\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}} = 0{,}99$

  - All internal parts

    $c/t = 21 < 25{,}35 = 25{,}7\varepsilon$

    Class 1

Cross-section = class 1

Eurocode 3 flexural buckling example

	EC 3-1-1: S235	EC 3-1-4: Austenitic
A [mm²]	1495	1495
f_y [N/mm²]	**235**	**230**
γ_{M0} [-]	**1**	**1,1**
$N_{c,Rd}$ [kN]	**351**	**313**
L_{cr} [mm]	2100	2100
λ_1 [-]	93,9	92,6
$\bar{\lambda}$ [-]	0,575	0,583
α [-]	0,49	0,49
$\bar{\lambda}_0$ [-]	**0,2**	**0,4**
ϕ [-]	0,76	0,71
χ [-]	0,80	0,89
γ_{M1} [-]	**1**	**1,1**
$N_{b,Rd}$ [kN]	**281**	**277**

Eurocode 3 flexural buckling example

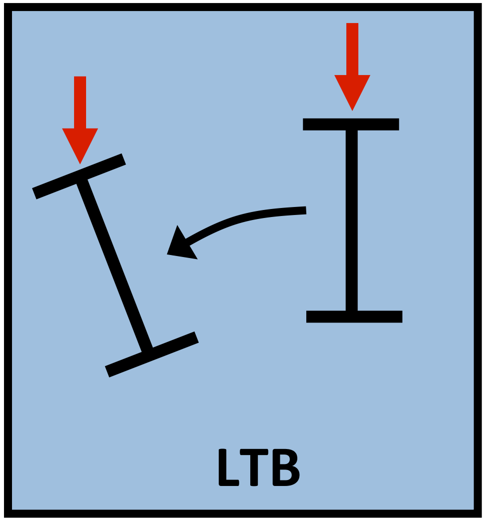
- Comparison

	EC 3-1-1: S235	EC 3-1-4: Austenitic
f_y [N/mm²]	235	230
γ_{M0} [-]	1,0	1,1
γ_{M1} [-]	1,0	1,1
Cross-section $N_{c,Rd}$ [kN]	351	313
Stability $N_{b,Rd}$ [kN]	281	277

  – In this example, cs and ss show similar resistance to flexural buckling
  ⇒ **benefits** of strain hardening not apparent
  EC3 1-4 doesn’t take duly account for strain hardening

Lateral torsional buckling

- Can be discounted when:
  - Minor axis bending
  - CHS, SHS, circular or square bar
  - Fully laterally restrained beams
  - $\bar{\lambda}_{LT} < 0.4$



Lateral torsional buckling

- The design approach for lateral torsional buckling is analogous to the column buckling treatment.

$$M_{b,Rd} = \chi_{LT} W_y \frac{f_y}{\gamma_{M1}}$$

Reduction factor for LTB

- Reduction factor:

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}} \quad \text{but } \chi_{LT} \leq 1.0$$

$$\Phi_{LT} = 0.5[1 + \alpha_{LT}(\bar{\lambda}_{LT} - 0.4) + \bar{\lambda}_{LT}^2]$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

Imperfection factor

Plateau length

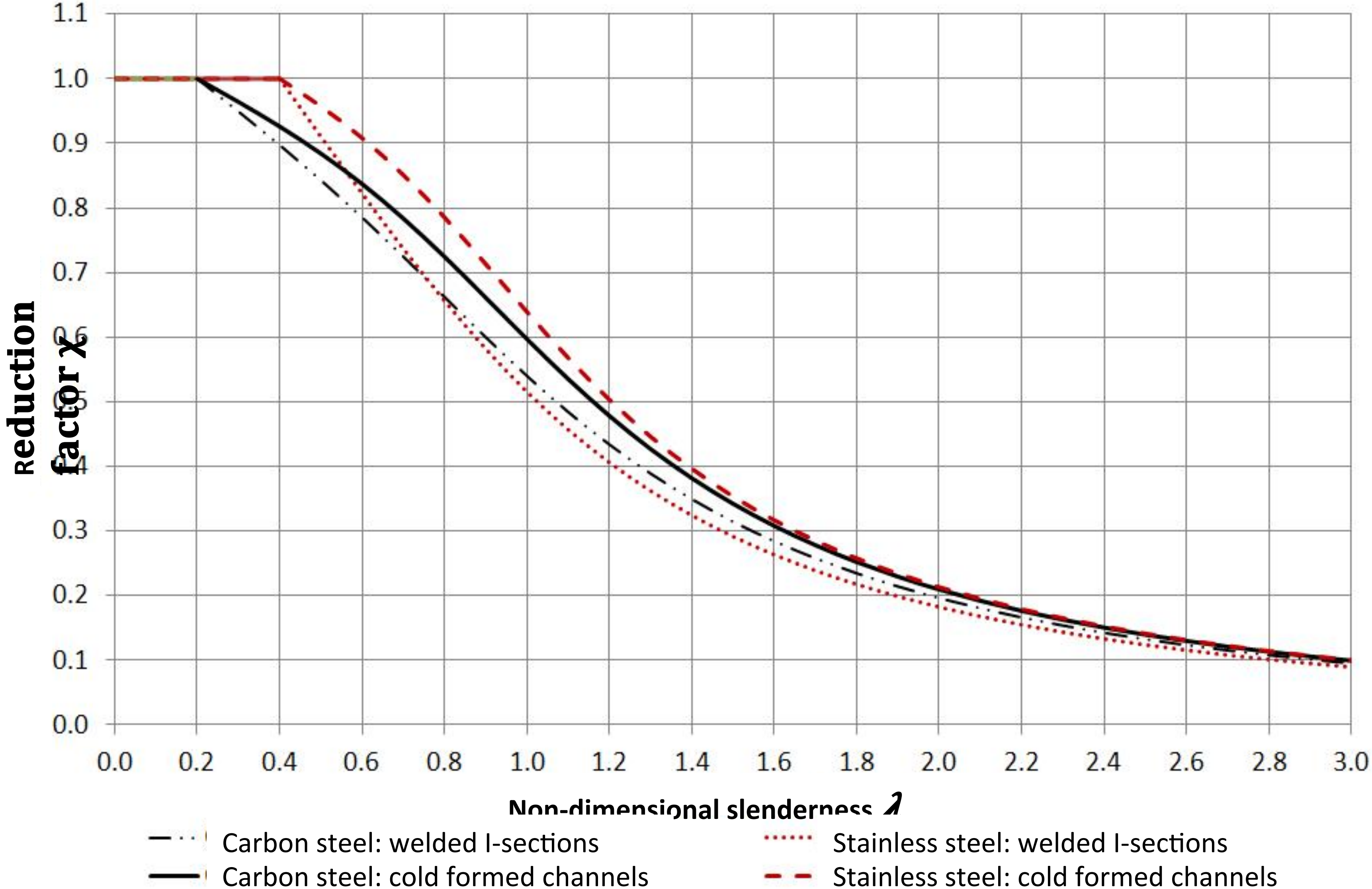
Lateral torsional buckling

- Choice of imperfection factor:

  = 0,34 for cold formed sections and hollow sections (welded and seamless)

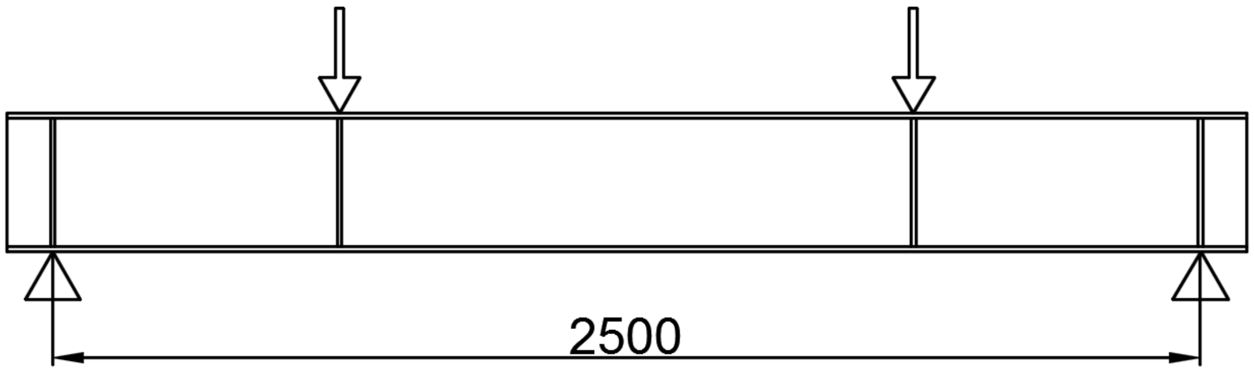
  = 0,76 for welded open sections and other sections for which no test data is available

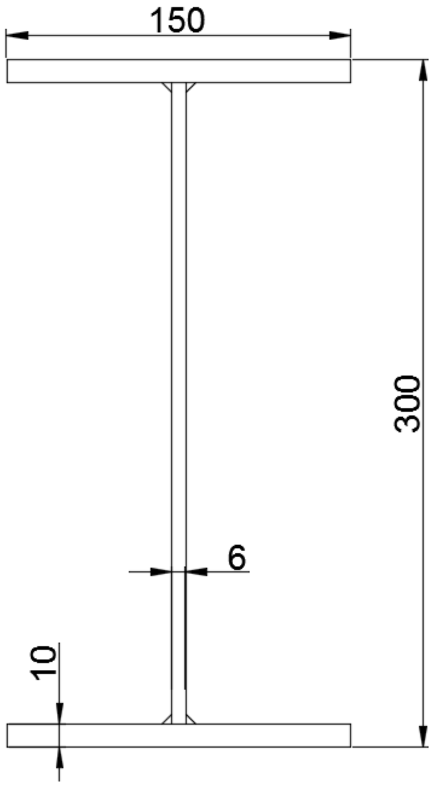
Eurocode 3 Lateral torsional buckling curves



Eurocode 3 Lateral torsional buckling example

- I-shaped beam submitted to 4-point bending





	Carbon steel	Duplex stainless steel
Material	S355	EN 1.4062
f_y [N/mm²]	355	450
E [N/mm²]	210000	200000

Eurocode 3 Lateral torsional buckling example

EC 3-1-1: S355

- Classification

  $\varepsilon = \sqrt{235/f_y} = 0{,}81$

  - Flange

    $c/t = 6{,}78 < 7{,}3 = 9\varepsilon$

    Class 1
  - Web

    $c/t = 45{,}3 < 58{,}3 = 72\varepsilon$

    Class 1

Cross-section = class 1

EC 3-1-4: Duplex

- Classification

  $\varepsilon = \sqrt{\frac{235}{f_y} \frac{E}{210000}} = 0{,}71$

  - Flange

    $c/t = 6{,}78 < 7{,}76 = 11\varepsilon$

    Class 3
  - Web

    $c/t = 45{,}3 < 58{,}3 = 72\varepsilon$

    Class 3

Cross-section = class 3

Eurocode 3 Lateral torsional buckling example

EC 3-1-1: S355

- Ultimate moment
  - *Class 1*

$M_{c,Rd} = W_{pl} \cdot f_y / \gamma_{M0}$
$= 196\ kNm$

EC 3-1-4: Duplex

- Ultimate moment
  - Class 3

$M_{c,Rd} = W_{el} \cdot f_y / \gamma_{M0}$
$= 202\ kNm$

Revision EC 3-1-4:

- Classification limits: closer to carbon steel
  - Cross-section = class 2

$M_{c,Rd} = W_{pl} \cdot f_y / \gamma_{M0} = 226\ kNm$

Eurocode 3 Lateral torsional buckling example

- Elastic critical buckling moment:

$$M_{cr} = C_1 \frac{\pi^2 E I_z}{(k_z L)^2} \left\{ \sqrt{ \left(\frac{k_z}{k_\omega}\right)^2 \frac{I_\omega}{I_z} + \frac{(k_z L)^2 G I_T}{\pi^2 E I_z} + (C_2 z_g)^2 } - C_2 z_g \right\}$$

	EC 3-1-1: S355	EC 3-1-4: duplex
C_1 [-]	1,04	1,04
C_2 [-]	0,42	0,42
k_z [-]	1	1
k_w [-]	1	1
z_g [mm]	160	160
I_z [mm^4]	$5,6.10^6$	$5,6.10^6$
I_T [mm^4]	$1,2.10^5$	$1,2.10^5$
I_w [mm^6]	$1,2.10^{11}$	$1,2.10^{11}$
E [MPa]	210000	200000
G [MPa]	81000	77000
M_{cr} [kNm]	**215**	**205**

Eurocode 3 Lateral torsional buckling example

- Lateral torsional buckling resistance

	EC 3-1-1: S355	EC 3-1-4: Duplex	EC 3-1-4: Future revision
W_y [mm^3]	**5,5.10^5**	**4,9.10^5**	**5,5.10^5**
f_y [N/mm^2]	355	450	450
M_{cr} [kNm]	215	205	205
$\bar{\lambda}_{LT}$ [-]	0,96	1,04	1,10
α_{LT} [-]	0,49	0,76	0,76
$\bar{\lambda}_{LT,0}$ [-]	0,2	0,4	0,4
ϕ_{LT} [-]	1,14	1,29	1,37
χ_{LT} [-]	0,57	0,49	0,46
γ_{M1} [-]	1,0	1,1	1,1
$M_{b,Rd}$ [kNm]	**111**	**99**	**103**

Eurocode 3 Lateral torsional buckling example

- Comparison

	EC 3-1-1: S355	EC 3-1-4: Duplex	EC 3-1-4: New revision
f_y [N/mm²]	355	450	450
γ_{M0} [-]	1,0	1,1	1,1
γ_{M1} [-]	1,0	1,1	1,1
Cross-section $M_{c,Rd}$	196	202	226
Stability $M_{b,Rd}$	111	99	103

  - In this example, cs and ss show similar resistance to LTB
  - However: Current tests and literature show that the EC3-1-4 results should be adapted to be closer to reality
    $\Rightarrow$ **too conservative**
    (This will be shown in the example on finite element methods)

Section 7

Alternative methods

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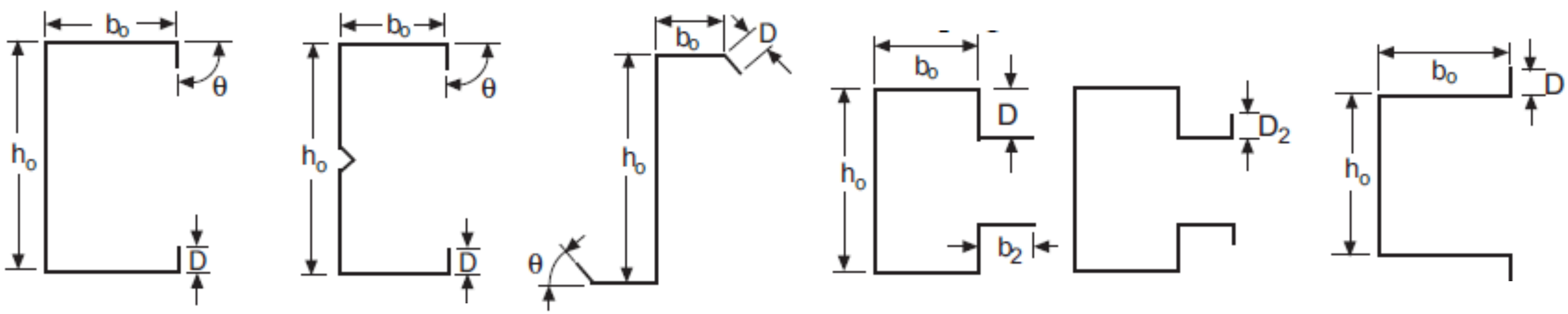
Alternative methods

- Direct strength method (DSM)
  - Part of the American code
  - For thin-walled profiles
- Continuous strength method (CSM)
  - Includes the beneficial effects of strain hardening
- Finite element methods
  - More tedious
  - Can include all the specificities of the model

Direct strength method

- Included in AISI Appendix 1
- Very simple and straightforward method
- Used for thin-walled sections:

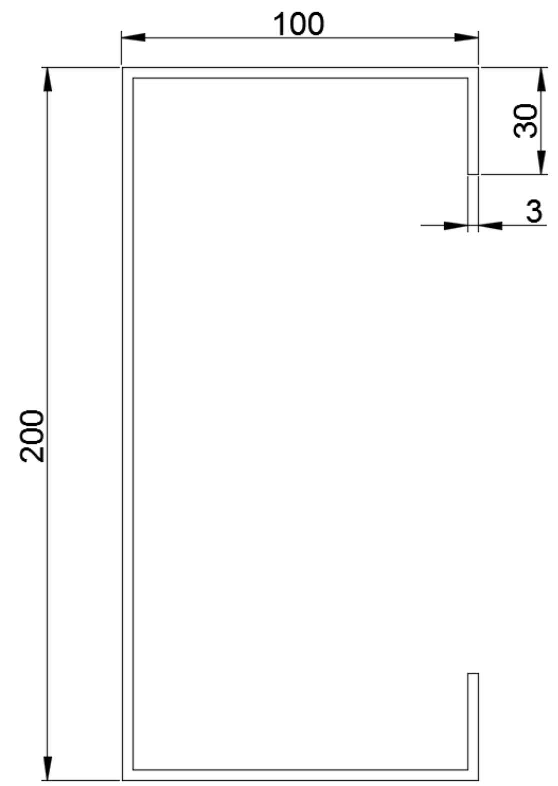


- Requires an "Elastic buckling analysis"
  - Theoretical method provided in the literature
  - Finite strip method (for example CUFSM)
- More info : http://www.ce.jhu.edu/bschafer/

Direct strength method – example

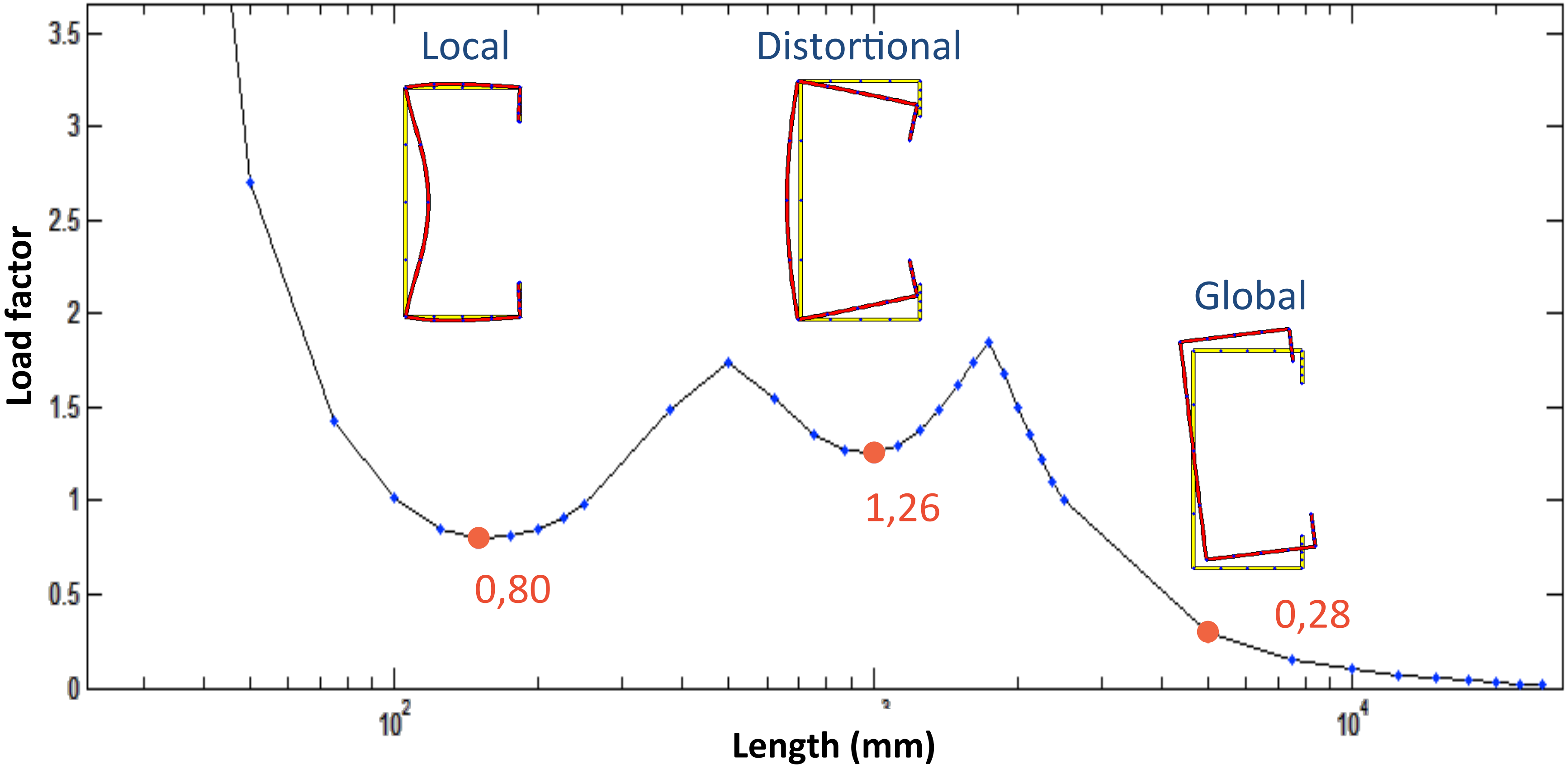
- Lipped C-channel submitted to compression
  - Simply supported column
  - Column length: 5m

	Ferritic stainless steel
Material	EN 1.4003
f_y [N/mm²]	280
f_u[N/mm²]	450
E [N/mm²]	220000



Direct strength method – example

- First step: “Elastic buckling analysis”



Direct strength method – example

- Output of the analysis = “Elastic critical buckling load”
  - In the example, the load factor from elastic buckling analysis equals:
    - For local buckling: 0,80 ➪ P_{crl} = 0.8 * 376
    - For distortional buckling: 1,26 ➪ P_{crd}
    - For global buckling: 0,28
- Second step: Calculation of the nominal strengths for
    - Local buckling ➪ one equation
    - Distortional buckling ➪ one equation
    - Global buckling ➪ one equation

Direct strength method – example

- Nominal global buckling strength P_{ne}
  - $\lambda_c = \sqrt{P_y / P_{cre}} = 1{,}88$
  - $P_y = Af_y = 376 \text{ kN}$
  - $P_{cre} = 0{,}28 * 376 = 107\ kN$

For $\lambda_c \leq 1{,}5$ $\quad$ $P_{ne} = \left(0{,}658^{\lambda_c^2}\right) P_y$

For $\lambda_c > 1{,}5$ $\quad$ $P_{ne} = \left(\frac{0{,}877}{\lambda_c^2}\right) P_y$

- $P_{ne} = 93{,}81\ kN$

Direct strength method – example

- Nominal local buckling strength P_{nl}
  - $\lambda_l = \sqrt{P_{ne}/P_{crl}} = 0{,}56$
  - $P_{crl} = 0{,}80 * 376 = 302\ kN$

For $\lambda_l \leq 0{,}776$ $\qquad P_{nl} = P_{ne}$

For $\lambda_l > 0{,}776$ $\qquad P_{nl} = \left[1 - 0{,}15\left(\frac{P_{crl}}{P_{ne}}\right)^{0{,}4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0{,}4} P_{ne}$

- $P_{nl} = 93{,}81\ kN$

Direct strength method – example

- Nominal distortional buckling strength P_{nd}
  - $\lambda_d = \sqrt{P_y / P_{crd}} = 0{,}89$
  - $P_{crd} = 1{,}26 * 376 = 473\ kN$

For $\lambda_d \leq 0{,}561$ $\quad P_{nd} = P_y$

For $\lambda_d > 0{,}561$ $\quad P_{nd} = \left[1 - 0{,}25\left(\frac{P_{crd}}{P_y}\right)^{0{,}6}\right]\left(\frac{P_{crd}}{P_y}\right)^{0{,}6} P_y$

- $P_{nd} = 344{,}56\ kN$

Direct strength method – example

- Third step : The axial resistance is “just” the minimum of the three nominal strengths

  - Local: P_{nl} = 93,81 kN
  - Distortional: P_{nd} = 344,56 kN
  - Global: P_{ne} = 93,81 kN

$$\Rightarrow P_n = 93{,}81 \text{ kN}$$

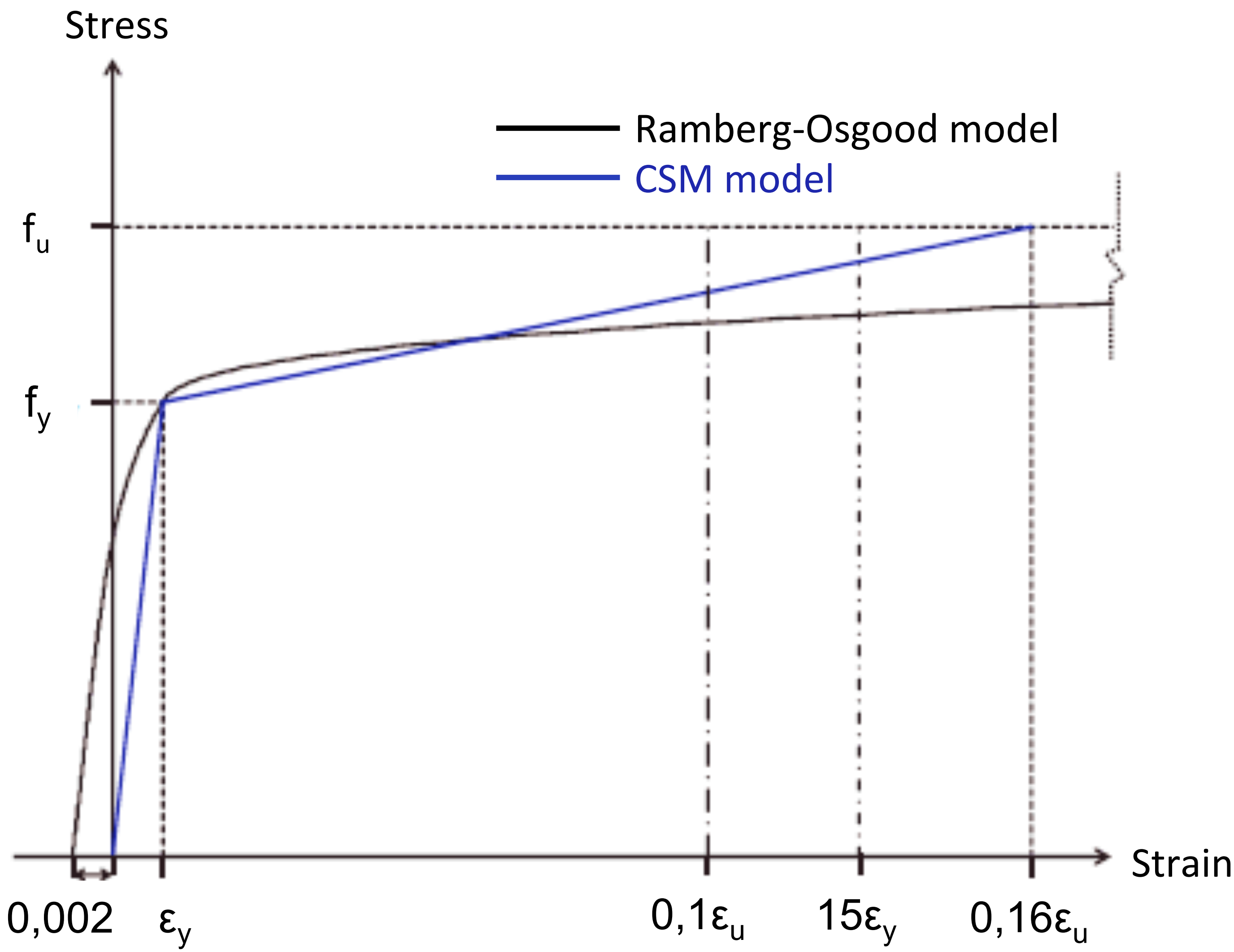
Continuous strength method

- Stainless steel material characteristics:
  - Non-linear material model
  - High strain hardening
  - Conventional design methods not able to take into account the full potential of the cross-section

The Continuous strength method uses a material model which includes strain hardening

Continuous strength method

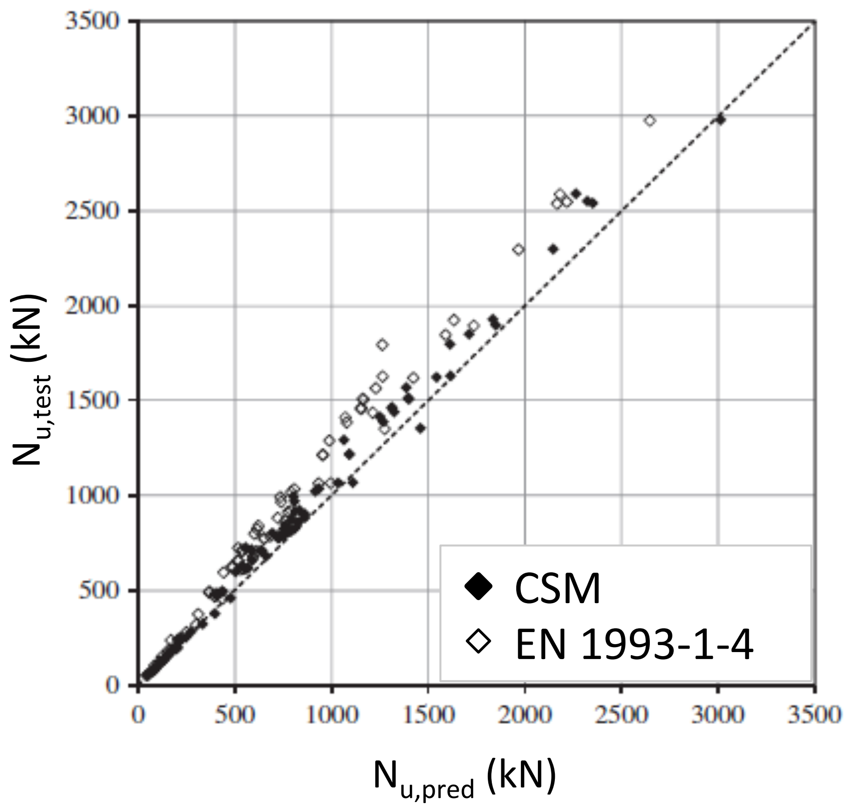
- Material model considered in the CSM:



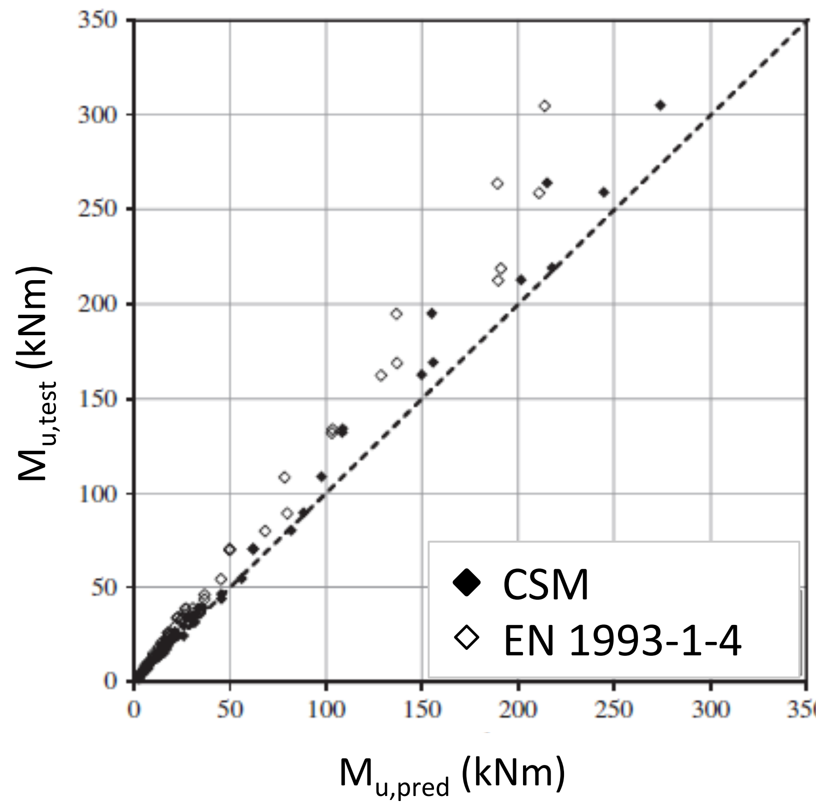
Continuous strength method

- Comparison between EC3 and CSM predictions versus tests:

In compression



In bending

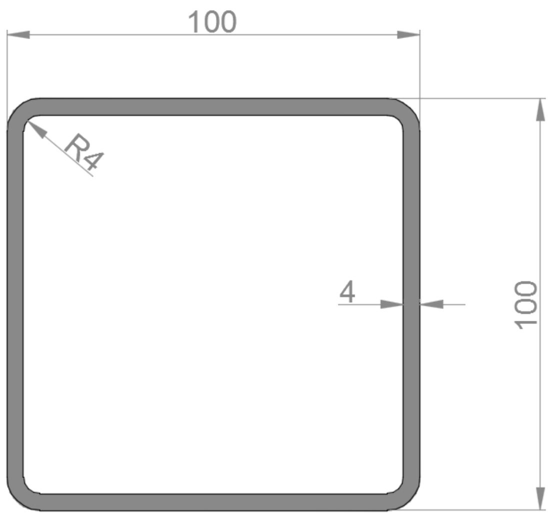


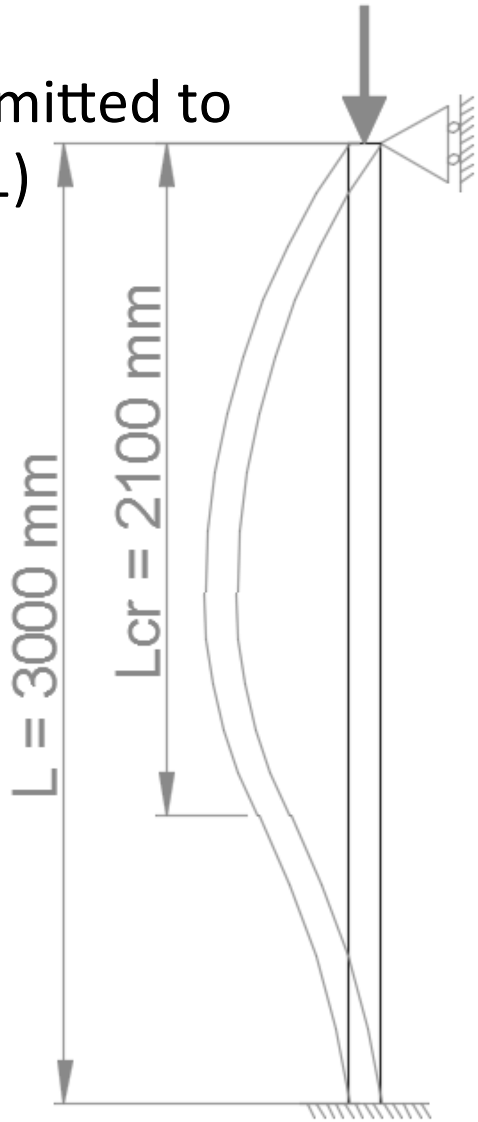
The CSM is able to accurately capture the cross-section behaviour

CSM: Flexural buckling example

- Cold formed rectangular hollow section submitted to concentric compression (example of slide 51)

	Austenitic stainless steel
Material	EN 1.4301
f_y [N/mm²]	230
E [N/mm²]	200000





CSM: flexural buckling example

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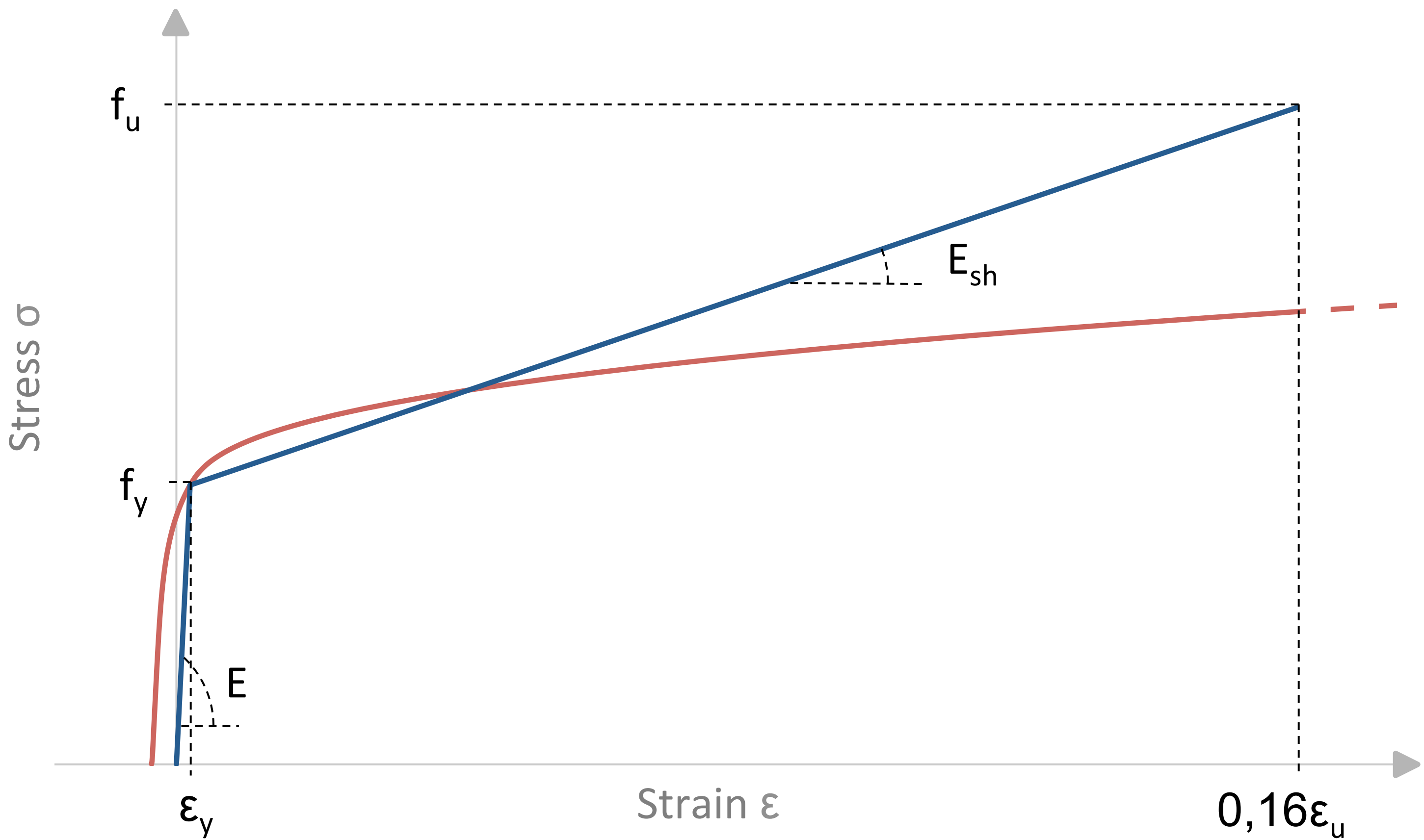
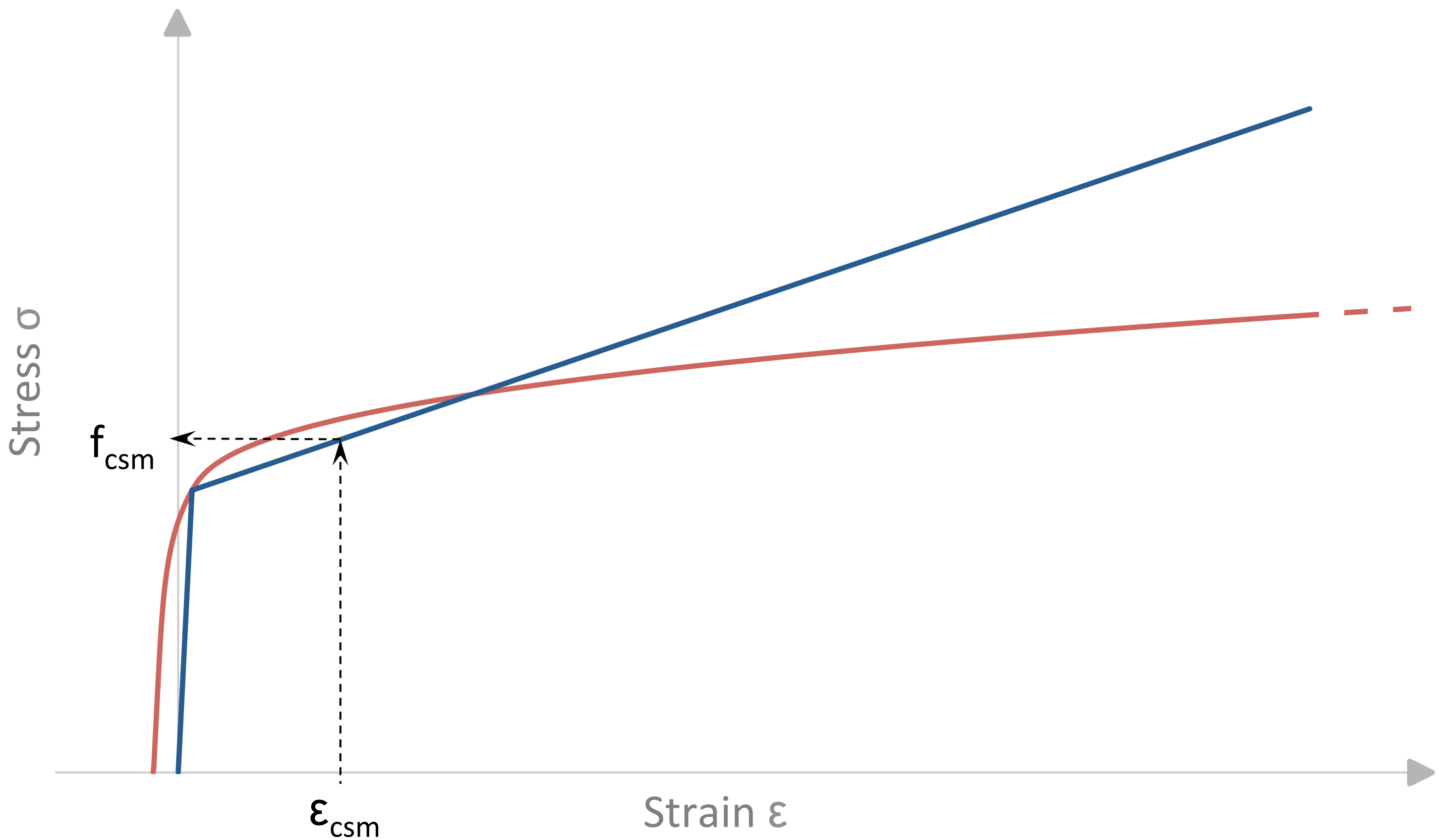


CSM: flexural buckling example

- $\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr,cs}}} = 0,60$
  - $\sigma_{cr,cs}$= elastic buckling stress of the full cross-section allowing for element interaction
- $\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0,25}{\bar{\lambda}_p^{\ 3,6}} = 5,27$
- $f_{csm} = f_y + E_{sh}\varepsilon_y\left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1\right) = 247\ {}^{N}/_{mm^2}$
- $N_{c,Rd} = \frac{Af_{csm}}{\gamma_{M0}} = 335\ kN$

CSM: flexural buckling example



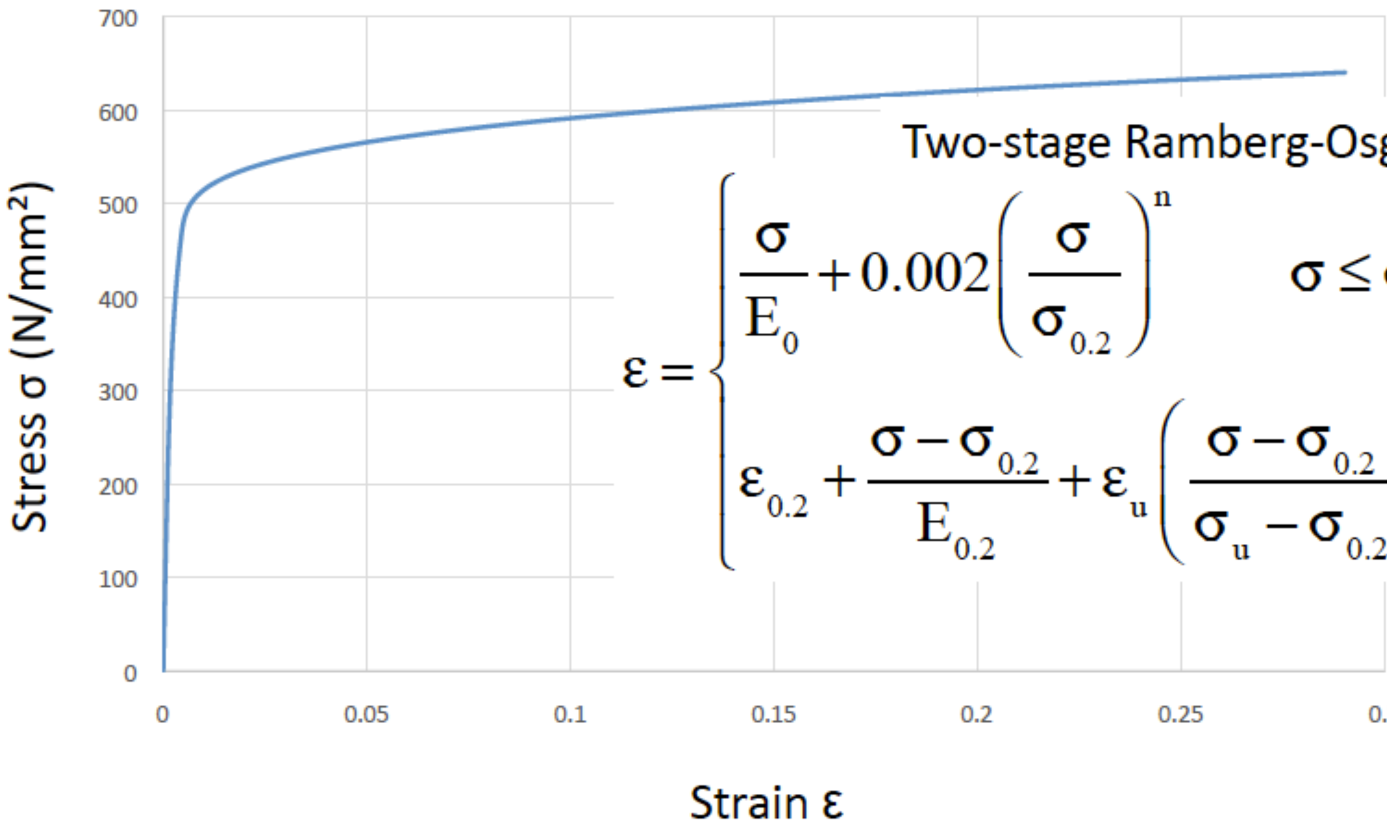
CSM: flexural buckling example

- $\bar{\lambda} = \sqrt{\frac{Af_{csm}}{N_{cr}}} = 0,60$
- $N_{b,Rd} = \chi \frac{Af_{csm}}{\gamma_{M1}} = 294\ kN$

	EC 3-1-1: S235	CSM: Austenitic	EC 3-1-4: Austenitic
f_y [N/mm²]	235	230	230
γ_{M0} [-]	1,0	1,1	1,1
γ_{M1} [-]	1,0	1,1	1,1
Cross-section $N_{c,Rd}$ [kN]	**351**	**335**	**313**
Stability $N_{b,Rd}$[kN]	**281**	**294**	**277**

Finite element model

- The material stress-strain curve can be accurately modeled (for example by using Ramberg-osgood material law or “real” measured tensile coupon tests results)



Two-stage Ramberg-Osgood model:

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^{n} & \sigma \leq \sigma_{0.2} \\ \varepsilon_{0.2} + \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^{m} & \sigma > \sigma_{0.2} \end{cases}$$

Finite element model

- The nonlinear parameters are given by the following expressions (according to Rasmussen's revision):

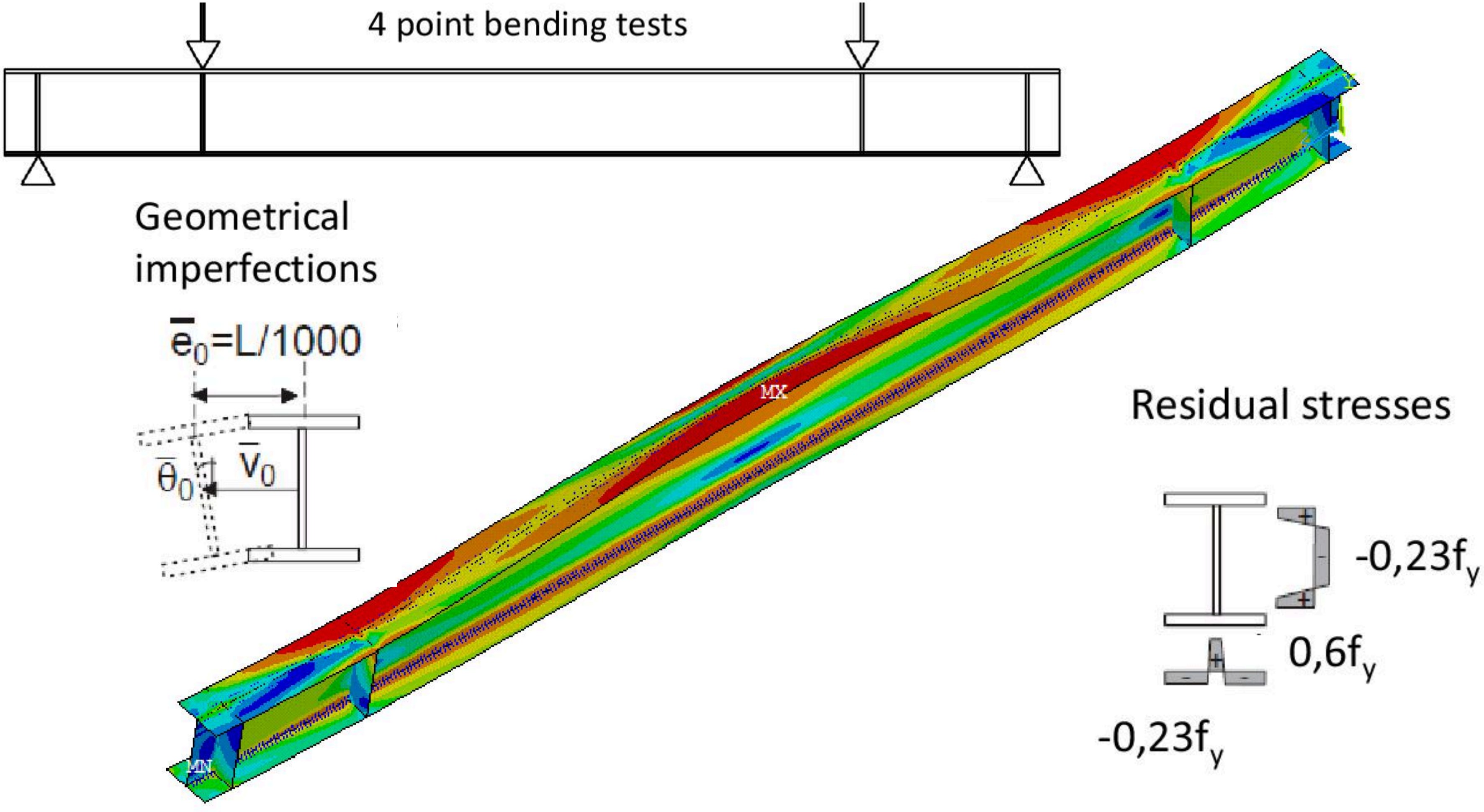
$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \qquad m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \qquad E_{0.2} = \frac{E_0}{1 + 0.002n\frac{E_0}{\sigma_{0.2}}}$$

$$\varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u}$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.2 + 185\frac{\sigma_{0.2}}{E_0} & \text{for austenitic and duplex} \\ \dfrac{0.2 + 185\frac{\sigma_{0.2}}{E_0}}{1 - 0.0375(n-5)} & \text{for all stainless steel alloys} \end{cases}$$

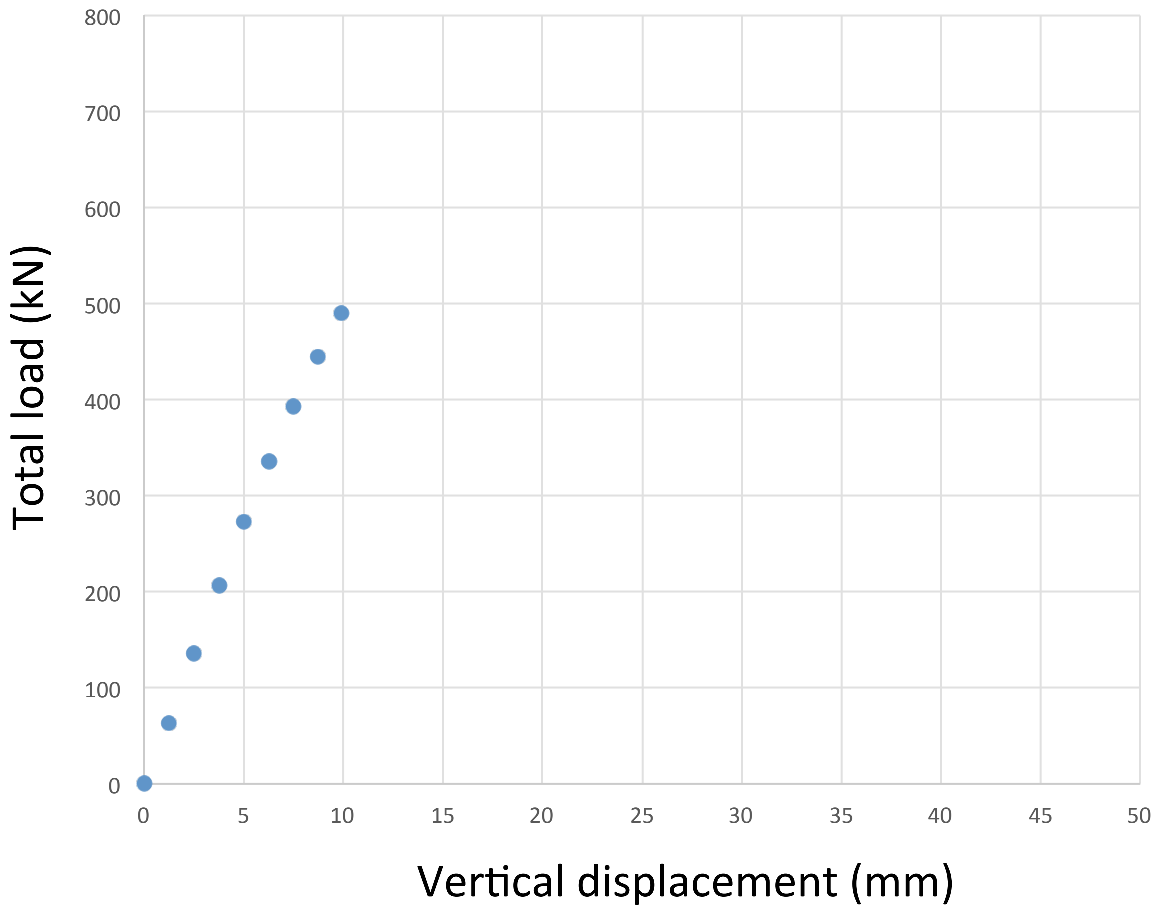
Finite element model

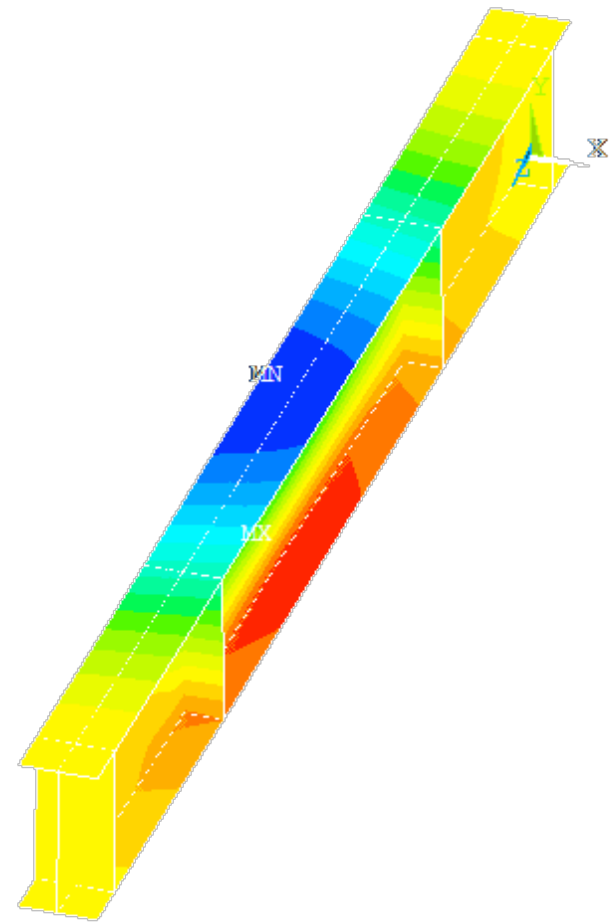
- I-shaped beam submitted to bending suffering lateral torsional buckling : all imperfections can be modelled



Finite element model

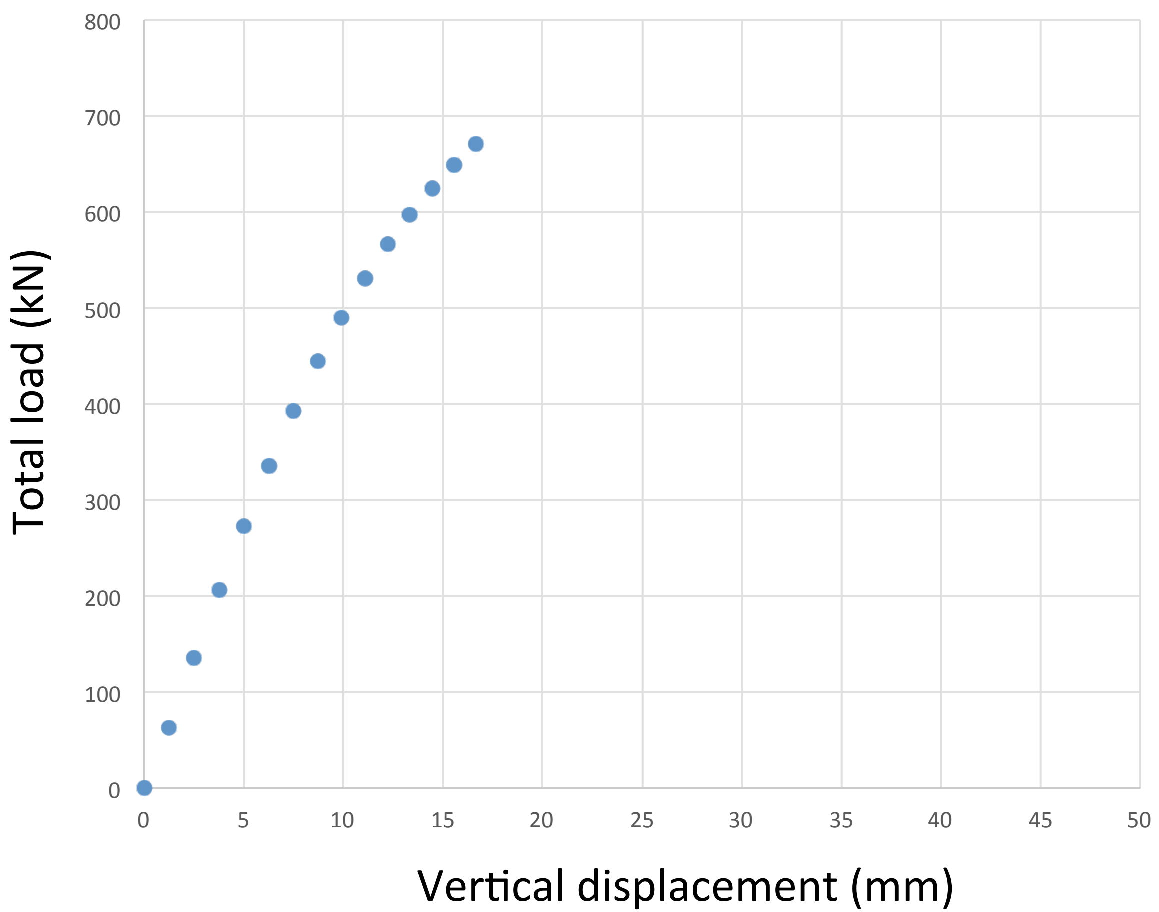
- The load-deflections curve can be calculated
  - Results: elastic behaviour and first yielding

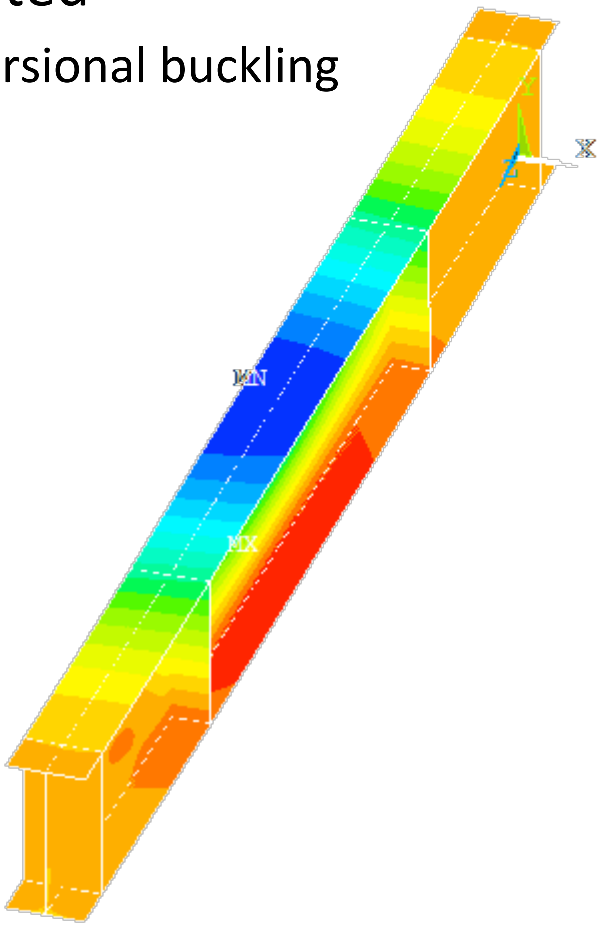




Finite element model

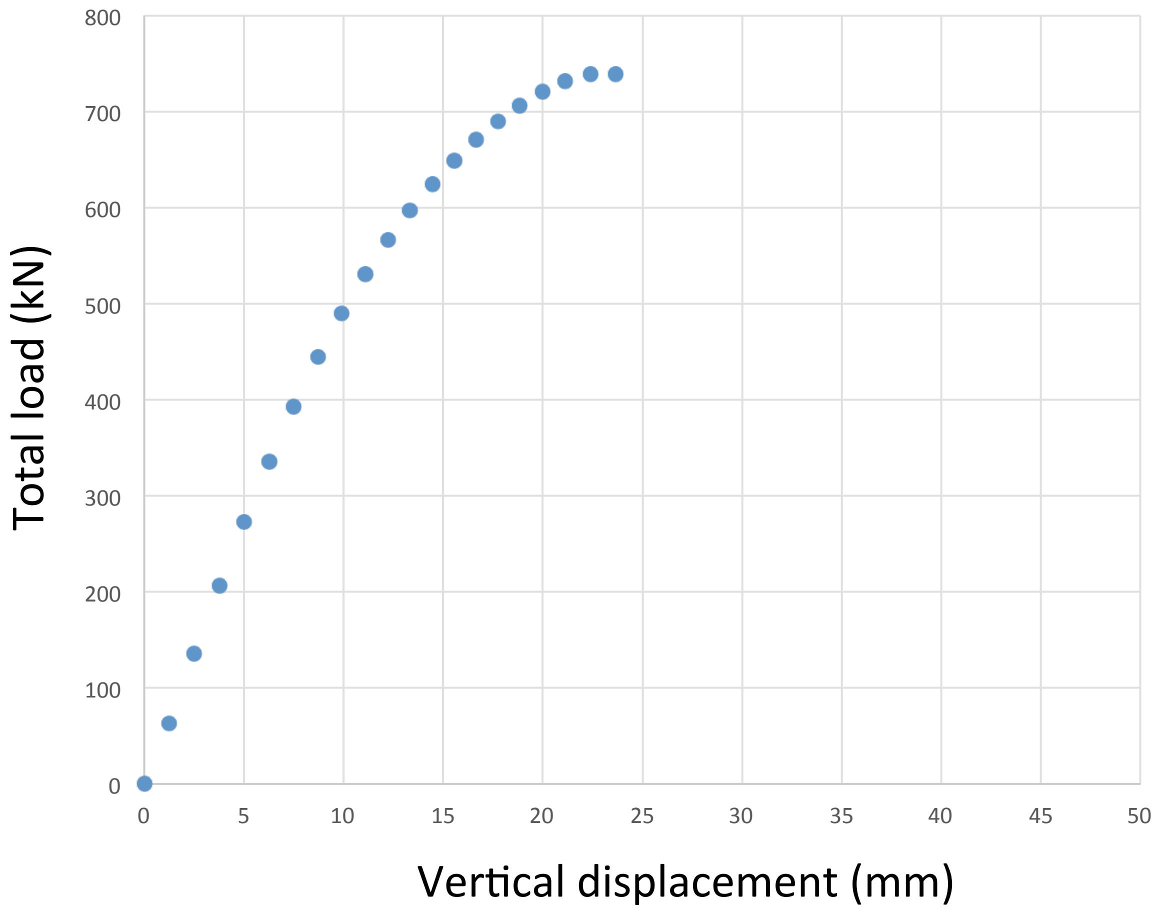
- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling

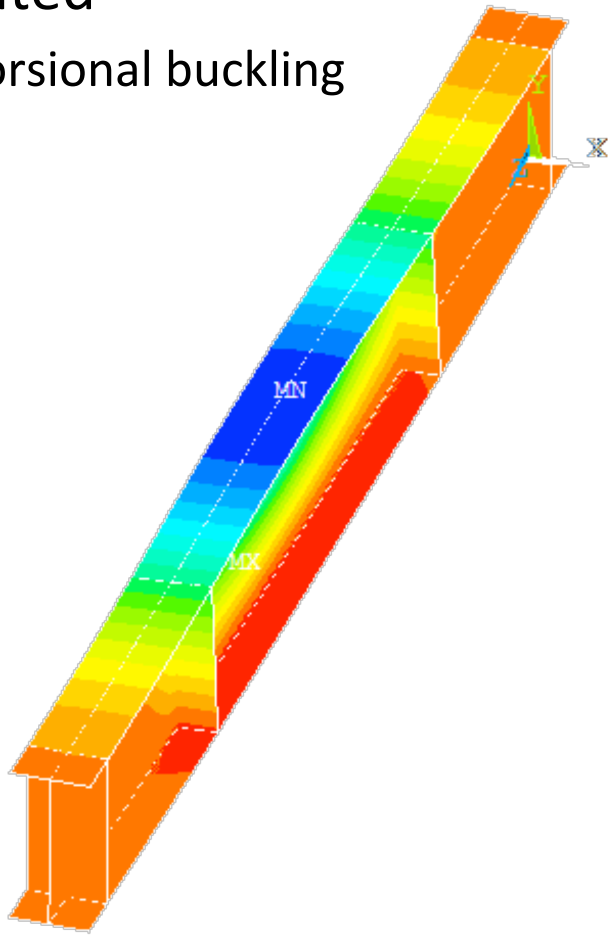




Finite element model

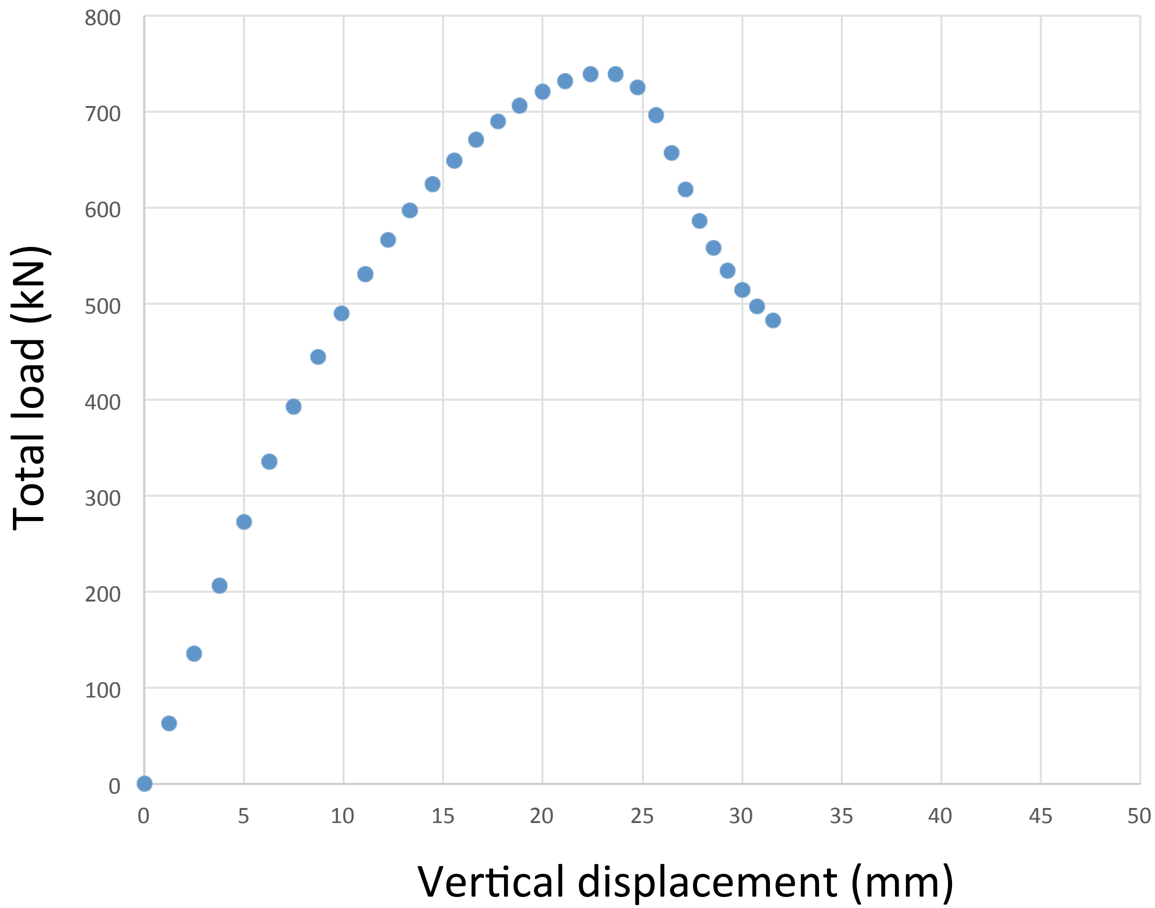
- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling

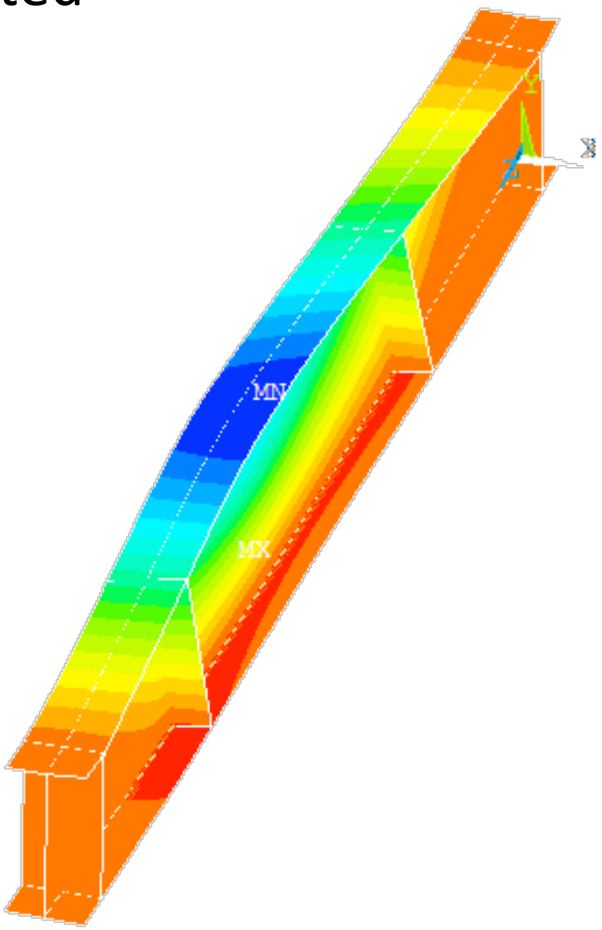




Finite element model

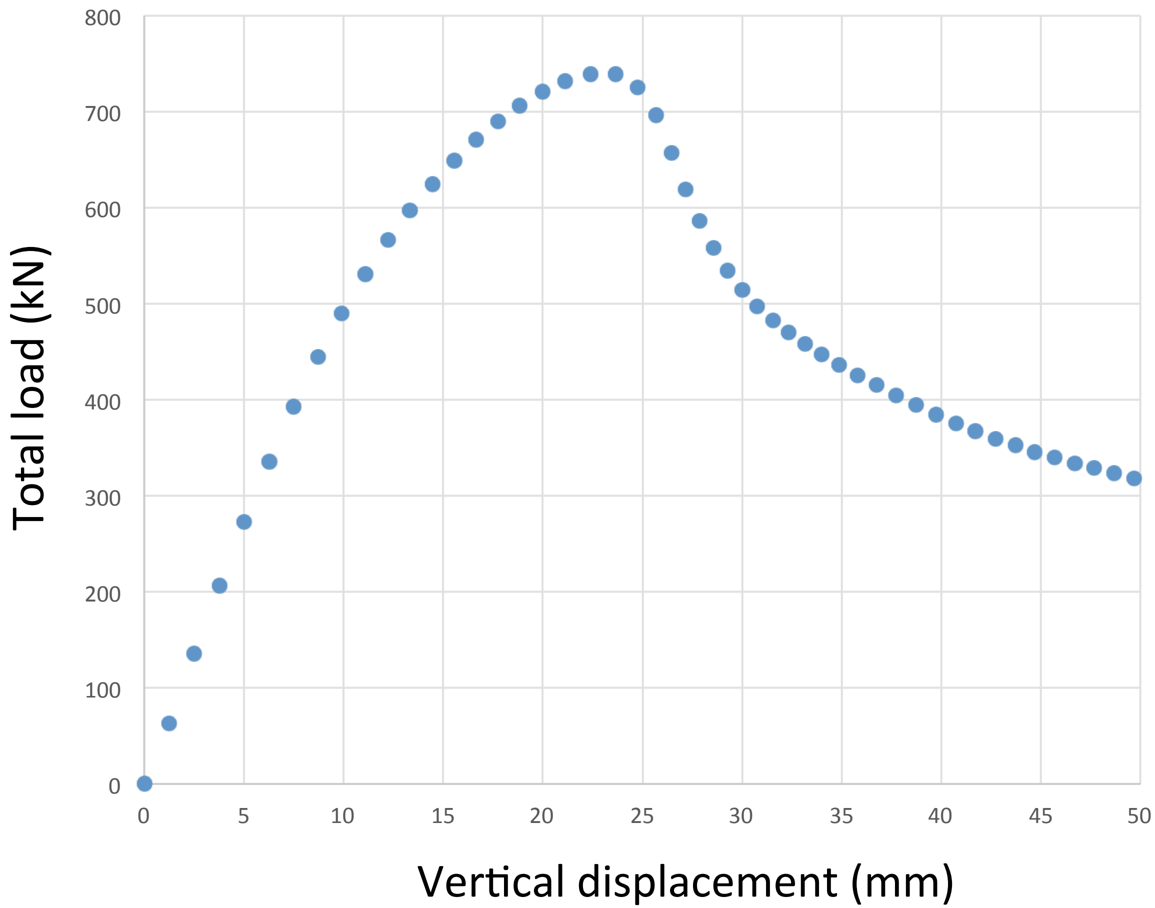
- The load-deflections curve can be calculated
  - Results: post buckling behaviour

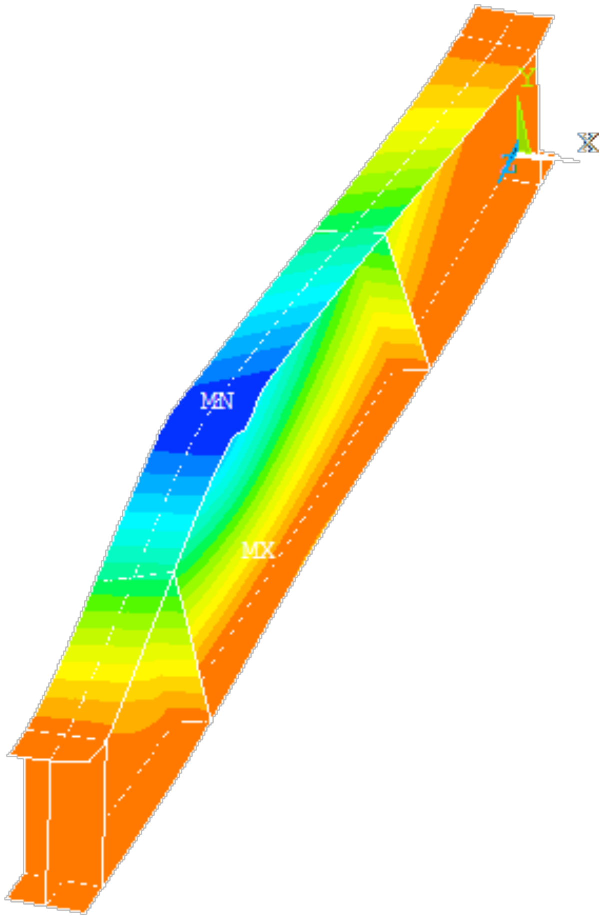




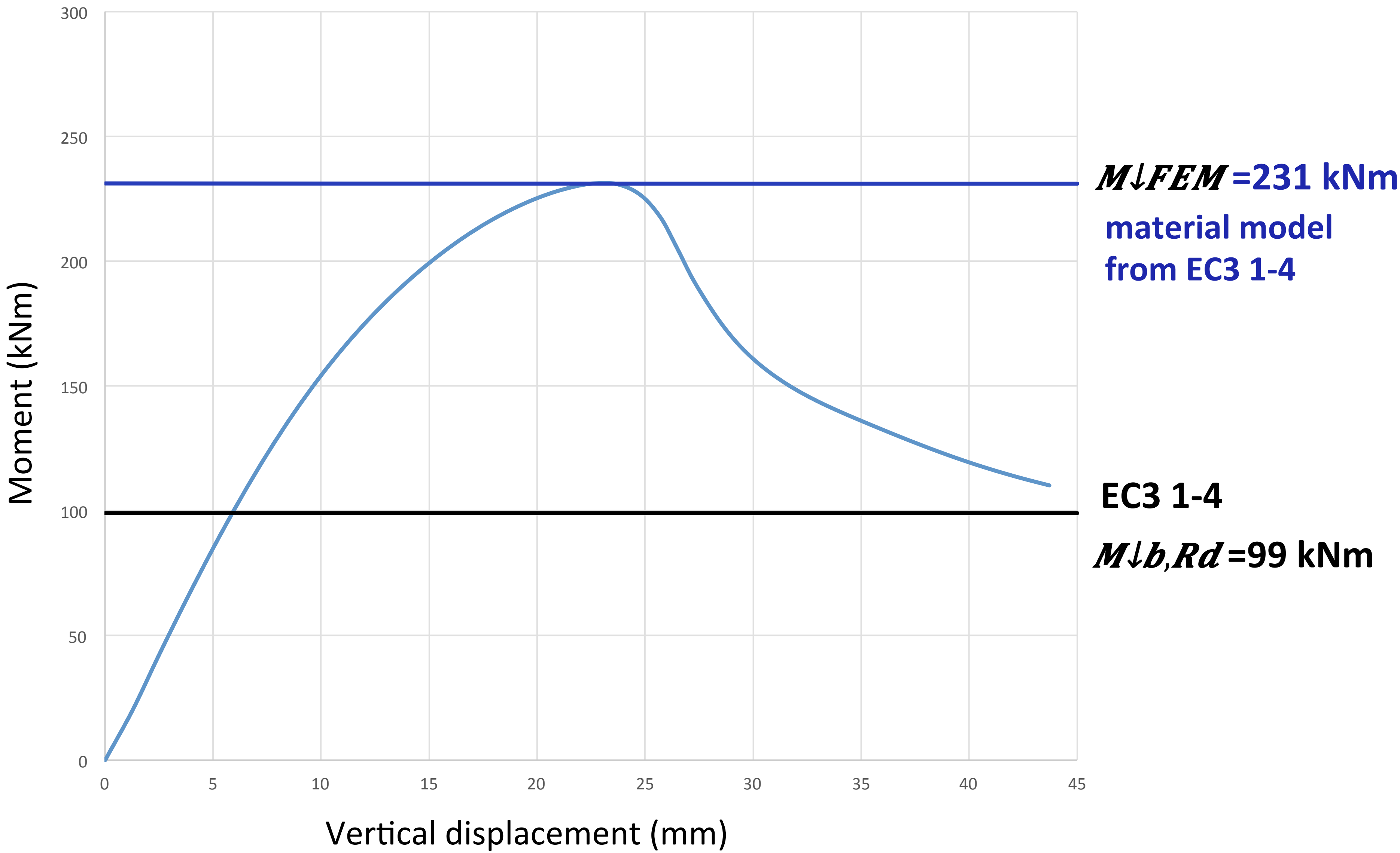
Finite element model

- The load-deflections curve can be calculated
  - Results: post buckling behaviour

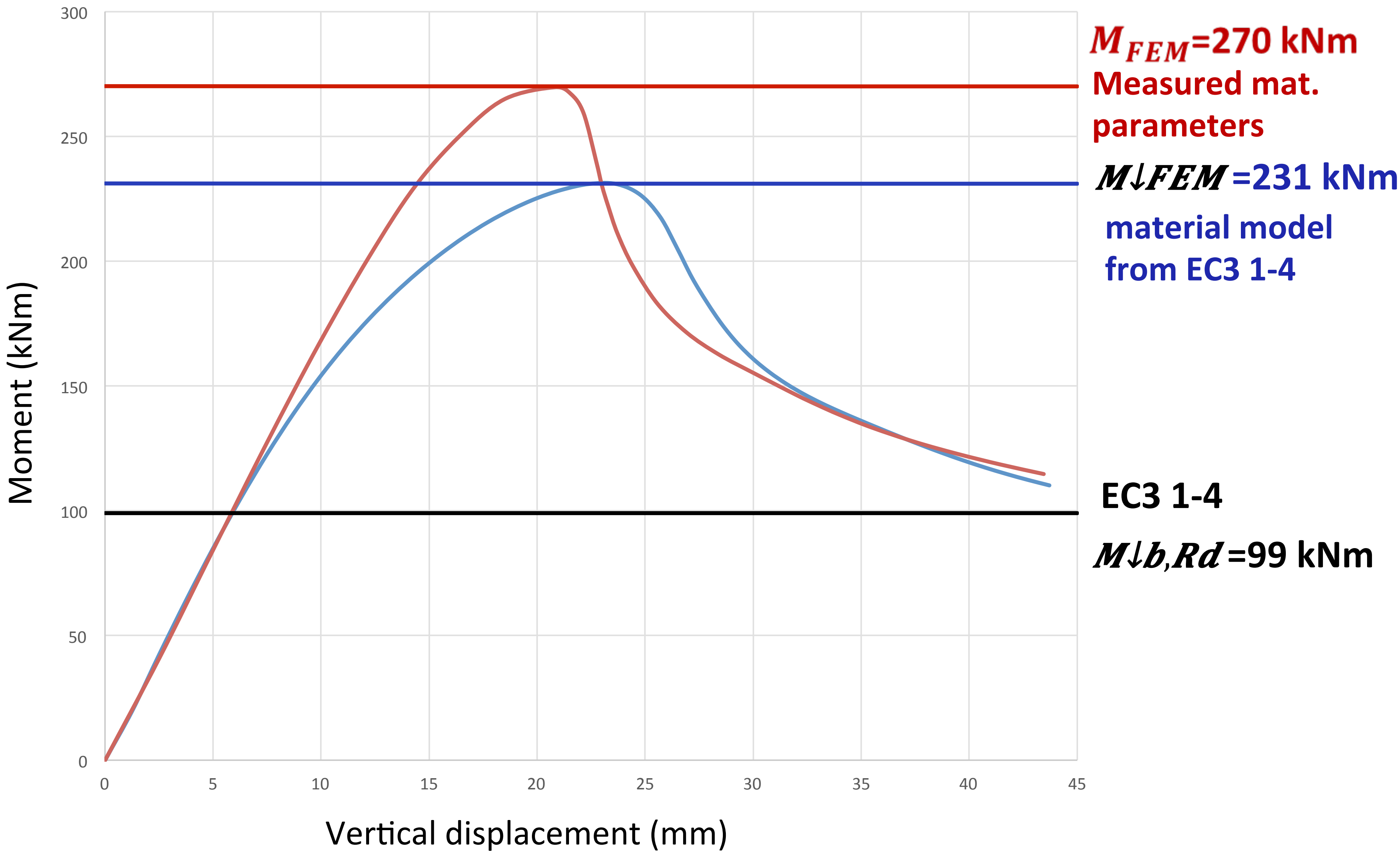




Finite element model



Finite element model



Section 8

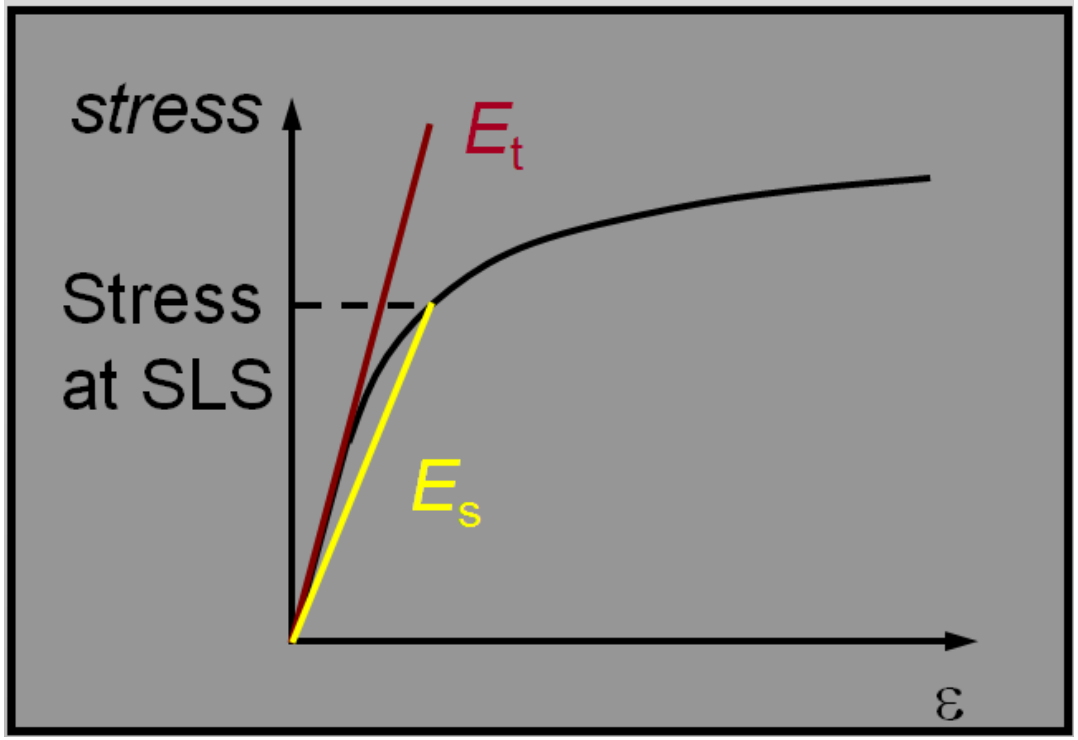
Deflections

Deflections

- Non-linear stress-strain curve means that stiffness of stainless steel decreases as stress increases
- Deflections are slightly greater in stainless steel than in carbon steel
- Use secant modulus at the stress in the member at the serviceability limit state (SLS)

Deflections

- Secant modulus E_S for the stress in the member at the SLS



Deflections

- Secant modulus E_S determined from the Ramberg-Osgood model:

$$E_{SEC} = \frac{E_{S1} + E_{S2}}{2} \qquad E_{Si} = \frac{E}{1 + 0.002 \dfrac{E}{\sigma_{ser,i}} \left(\dfrac{\sigma_{ser,i}}{f_y} \right)^n}$$

σ_{ser} **is stress at serviceability limit state**

n **is the non-linear material constant**

$\boldsymbol{\sigma}_1$ ***σ*** at SLS in “tension flange”

$\boldsymbol{\sigma}_2$ ***σ at SLS in “compression flange”***

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Deflections in an austenitic stainless steel beam

Stress ratio σ_{ser}/f_y	Secant modulus, E_S N/mm^2	% increase in deflection
0.25	200,000	0
0.5	192,000	4
0.7	158,000	27

σ_{ser} = stress at serviceability limit state

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Section 9

Additional information

Strain hardening (work hardening or cold working)

- Increased strength by plastic deformation
- Caused by cold-forming, either during steel production operations at the mill or during fabrication processes

During the fabrication of a rectangular hollow section, the 0.2% proof strength increases by about 50% in the cold-formed corners of cross sections!

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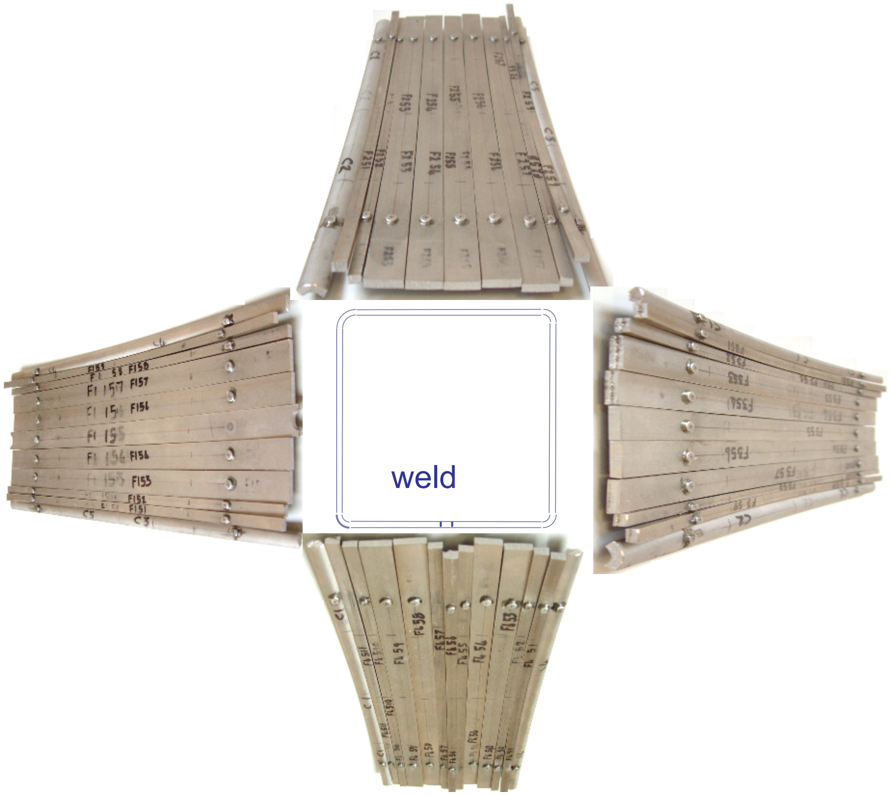
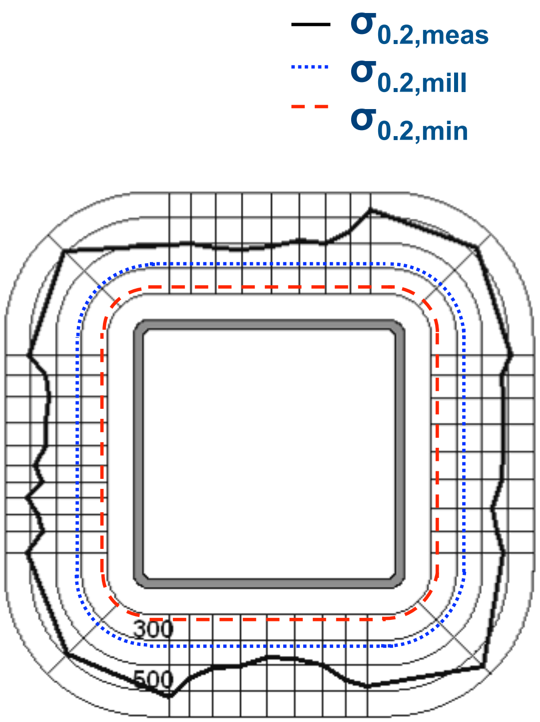
Strain hardening
(work hardening or cold working)

- Strength enhancement during forming

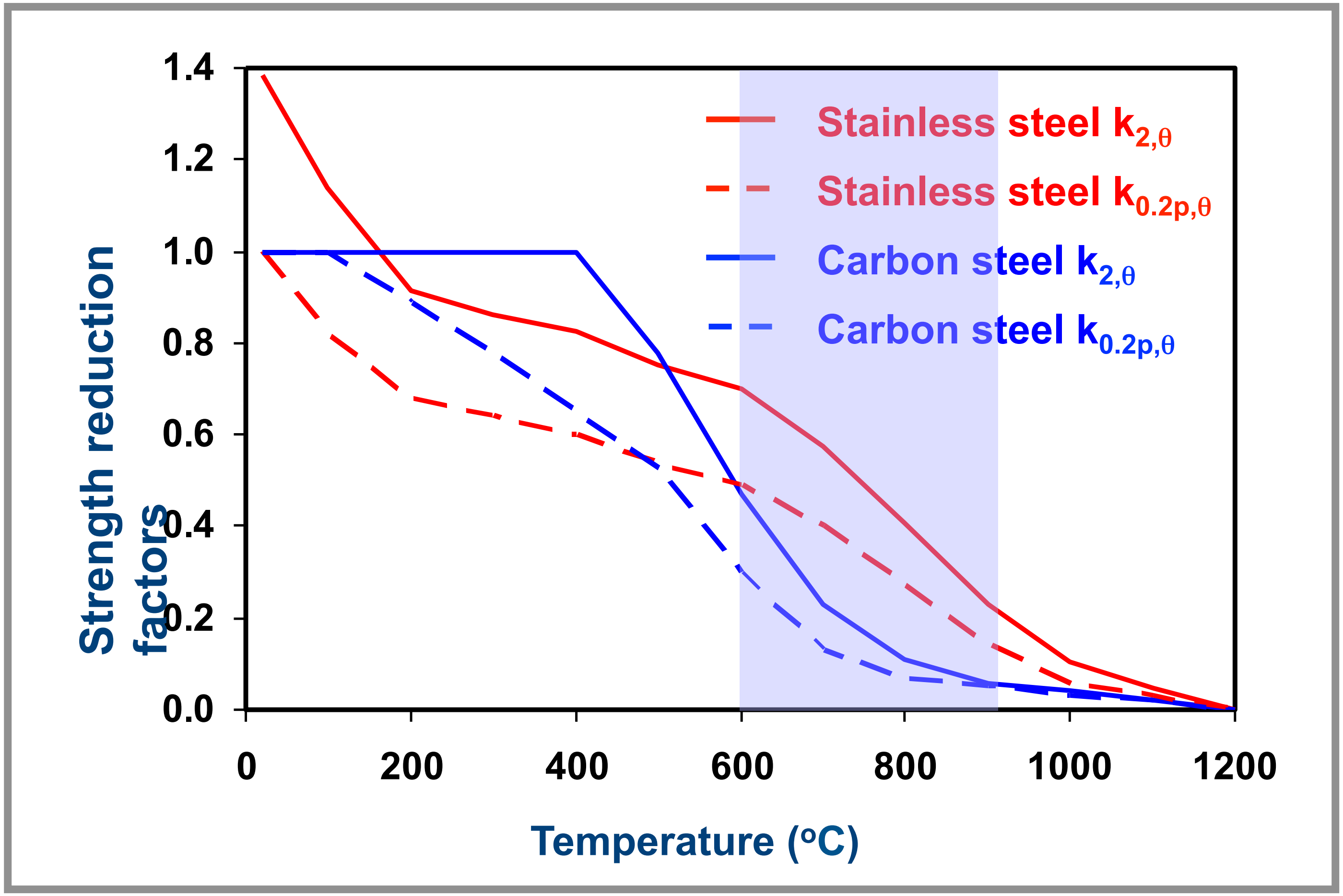




Strain hardening – not always useful

- Heavier and more powerful fabrication equipment since greater forces are required
- Reduced ductility (however, the initial ductility is high, especially for austenitic grades)
- Undesirable residual stresses may be produced

Material at elevated temperature



$k_{0.2p,q}$ = strength reduction factor at 0.2% proof strain

$k_{2,q}$ = strength reduction factor at 2% total strain

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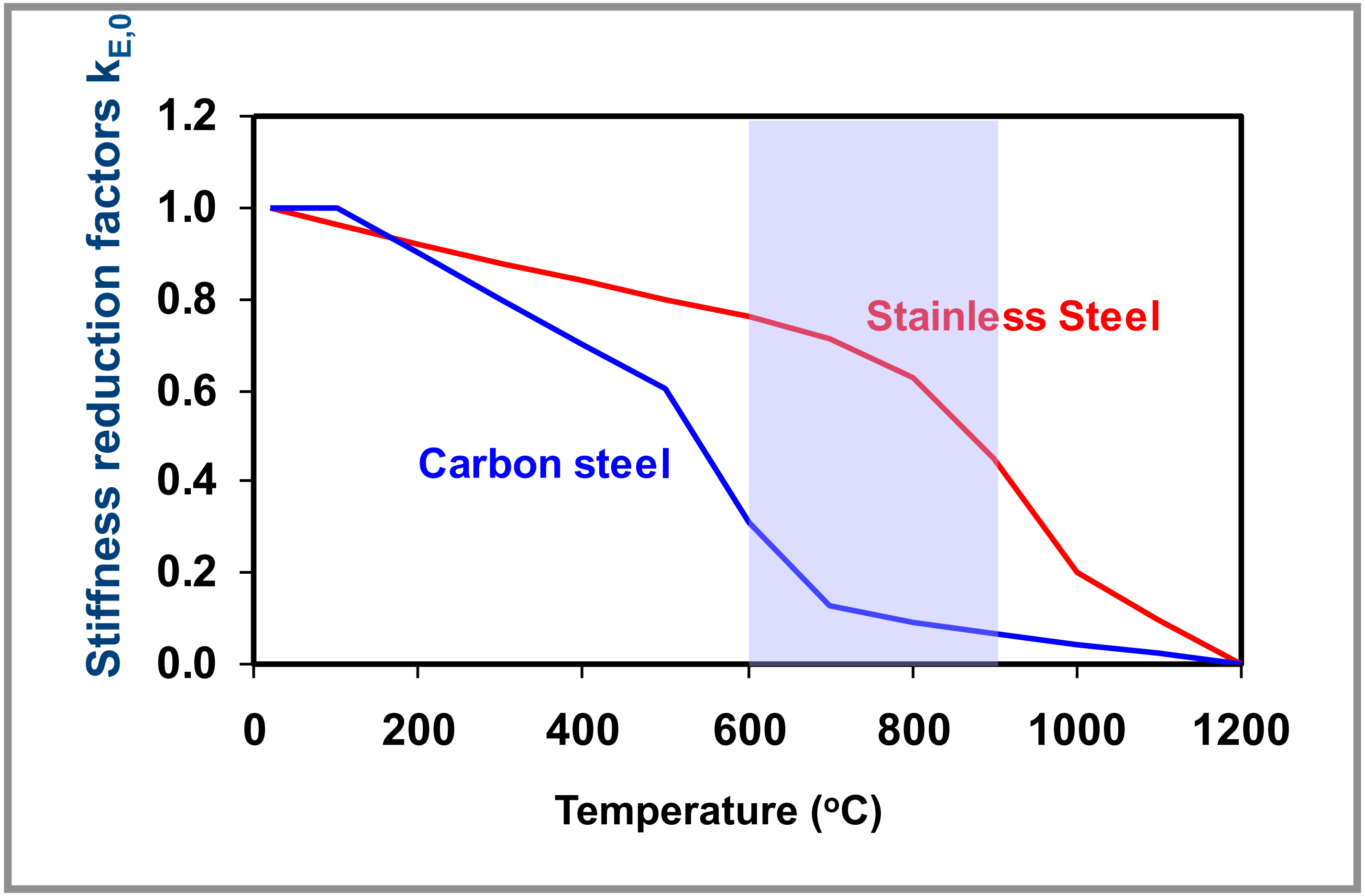
Material at elevated temperature



Stiffness reduction factor

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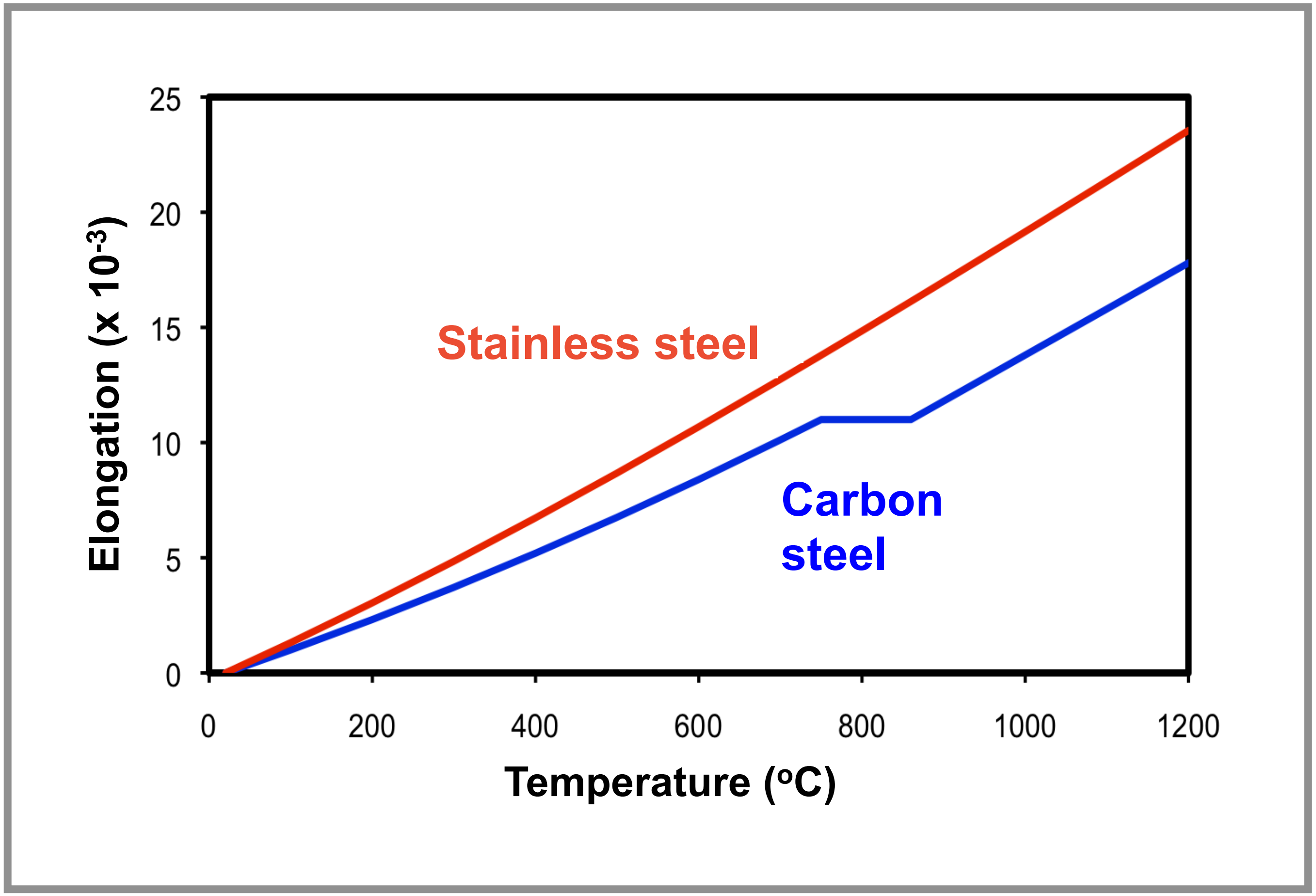
Material at elevated temperature



Thermal expansion

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Material at elevated temperature

- Stainless steel expands to a greater extent than carbon steel.
  - In fire tests, members are generally free to expand against load
  - In structural frames, restraint will exist from surrounding members. Hence additional forces are therefore likely to result

Material	Thermal expansion coefficient , 10^{-6} °K $^{-1}$	Thermal conductivity, W °m^{-1} °K^{-1}
Austenitics	18	15
Ferritics	10	25
Duplex	14	15
Martensitics	8	24
Carbon steel	12	18
Aluminum	22	230
Copper	17	380
Concrete	10	1

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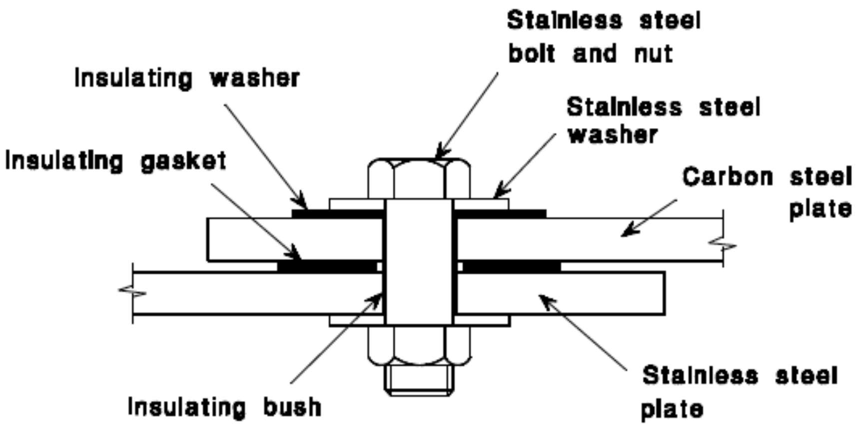
Design of bolted connections

- The strength and corrosion resistance of the bolts and parent material should be similar
- Stainless steel bolts should be used to connect stainless steel members to avoid bimetallic corrosion
- Stainless steel bolts can also be used to connect galvanized steel and aluminium members
- Stainless steel bolts can be used with carbon steel. To avoid galvanic corrosion, insulating (non-metallic) gaskets and washers are used.



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Design of bolted connections

- Rules for carbon steel bolts in clearance holes can generally be applied to stainless steel (tension, shear)

- Special rules for bearing resistance required to limit deformation due to high ductility of stainless steel

$$f_{u,red} = 0.5 f_y + 0.6 f_u < f_u$$

in $F_{b.Rd} = \frac{k_1 \alpha_b f_u d t}{\gamma_{M2}}$

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Preloaded bolts

- Useful in structures like bridges, towers, masts etc when:
  - the connection is subject to vibrating loads
  - slip between joining parts must be avoided
  - the applied load frequently changes from a positive to a negative value
- No design rules for stainless steel preloaded bolts
- Tests should still be carried out

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Fatigue strength

- Fatigue behaviour of welded joints is dominated by weld geometry
- Performance of austenitic and duplex stainless steel is at least as good as carbon steel
- Follow guidelines for carbon steel

Design of welded connections

- Carbon steel design rules can generally be applied to stainless steel
- Use the correct consumable for the grade of stainless steel (General requirements for welding consumables are given in EN 1993-1-8)
- The corrosion resistance of welds is affected by the changes in microstructure and chemical composition

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Dissimilar connection

- Stainless steel can be welded to carbon steel, provided a few ‘precautions’ (preparations) are used

> *“Duplex stainless steels can be welded to carbon and low alloy steels, but they can’t resist high temperatures or PWHT (Post Weld Heat Treatment). If there is no necessity for PWHT and the carbon steel isn’t exposed to a corrosive environment, the connection between these two steels can be welded without buffer layers. The filler metal type E 309L or duplex filler metals can be used.”*

- REFERENCES:

1. IMOA. (2014, Juli). *International Molybdenum Association. Retrieved from http://www.imoa.info/download_files/stainless-steel/IMOA_Shop_Sheet_104.pdf*
2. British Stainless Steel Association. (2015). *Welding stainless steels to other steels*. (Britisch stainless steel association) Retrieved May 06, 2016, from http://www.bssa.org.uk/topics.php?article=101
3. Course “Duurzaam ontwerp van constructies - KU Leuven” Subject 6 – dissimilar connections – 2015-2016

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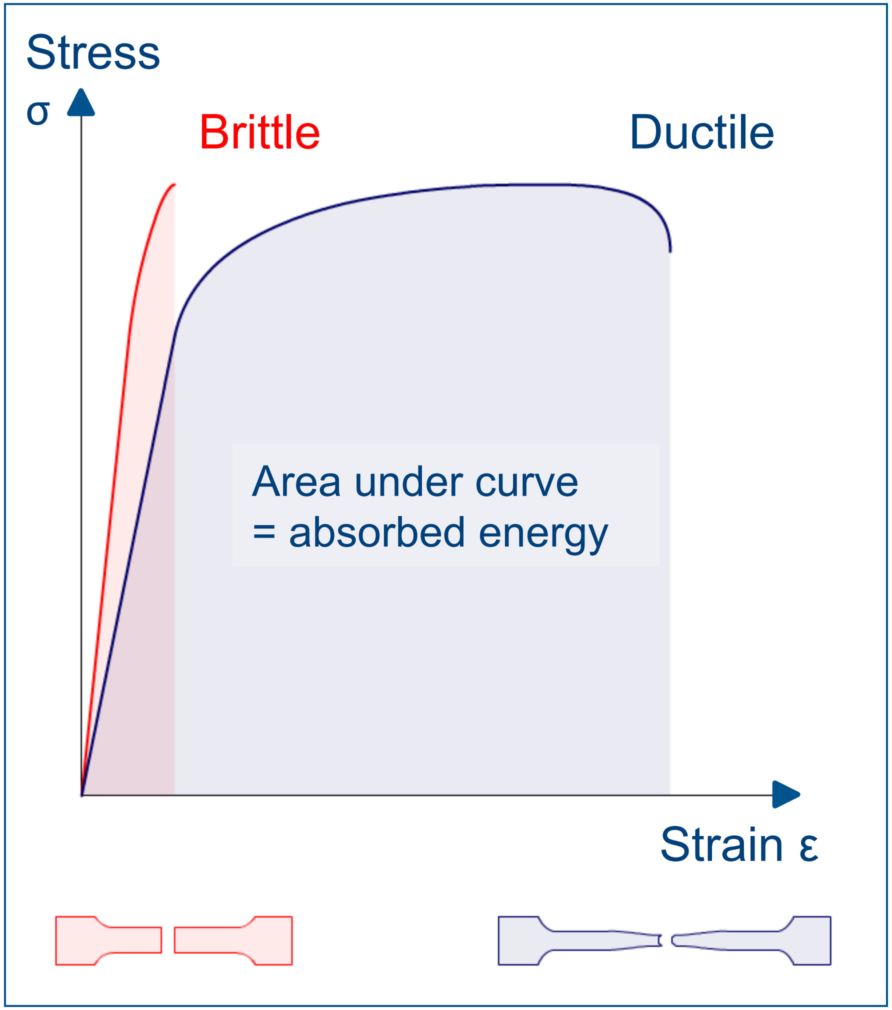
Ductility and toughness



- **Ductility** - ability to be stretched without breaking
- **Toughness -** ability to absorb energy & plastically deform without fracturing

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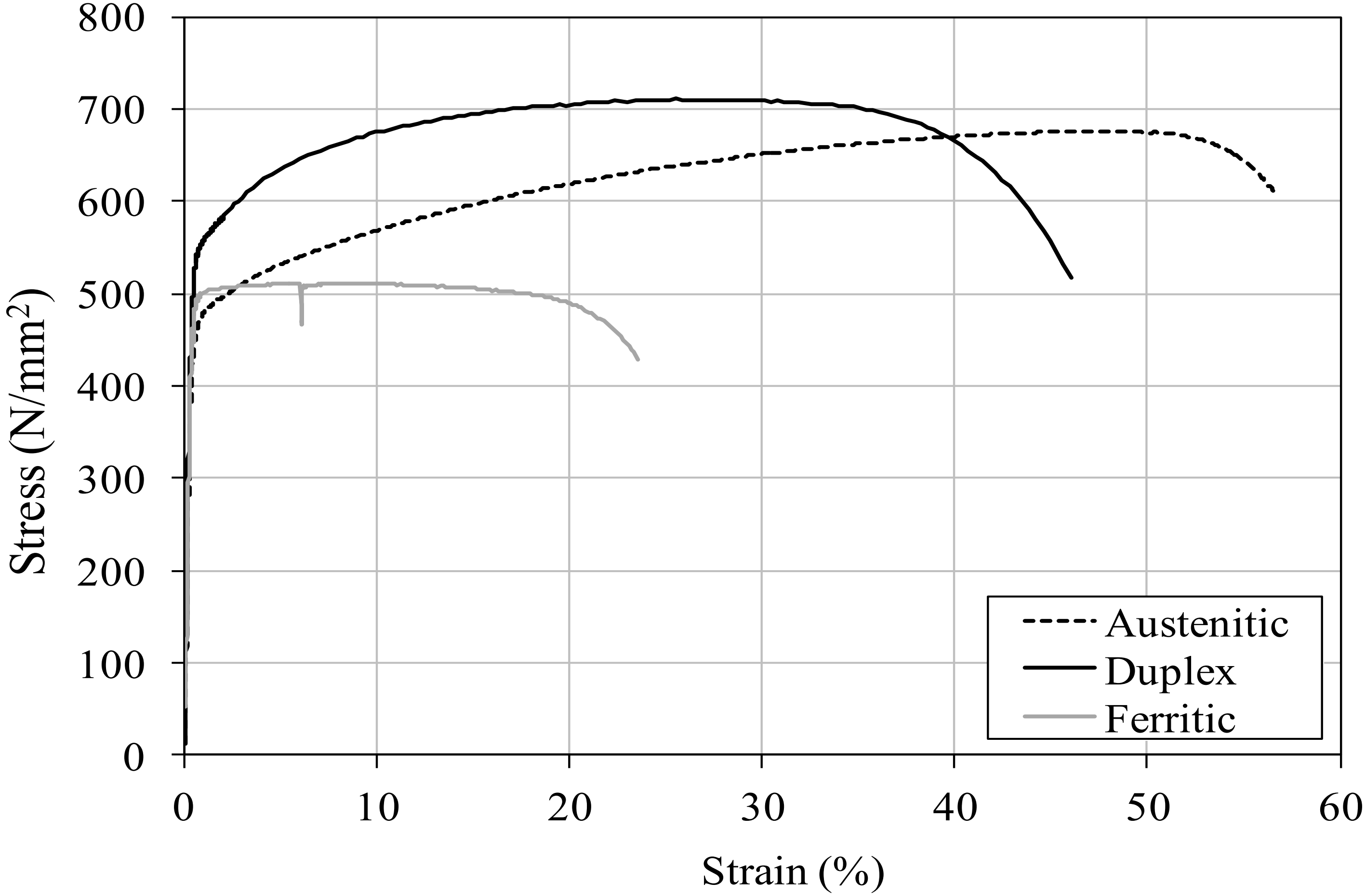
Stress-Strain Characteristics – high strain

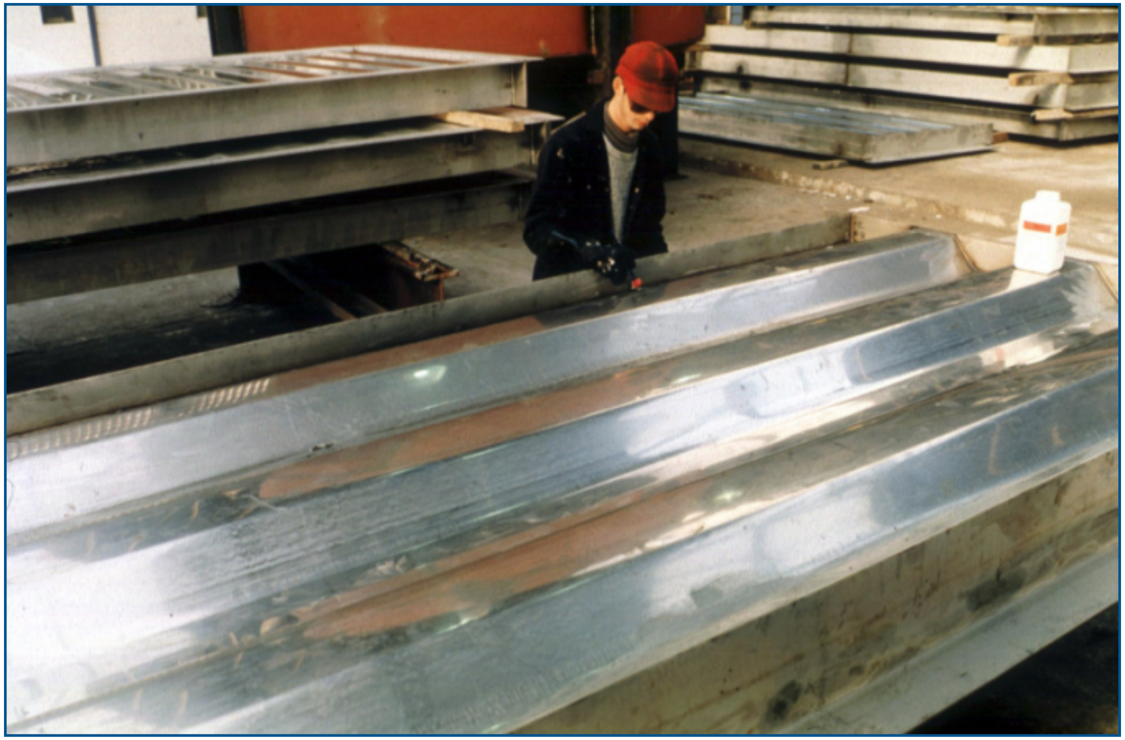
- Austenitic, ferritic and duplex/Lean duplex stainless steel



B. Rossi, S. Afshan, L. Gardner; Strength enhancements in cold-formed structural sections – Part II: Predictive models; Journal of Constructional Steel Research, Volume 83, 2013, pages 189-196.

Blast/impact resistant structures

Security bollard



A trapezoidal blast resistant wall being fabricated for the topsides of an offshore platform

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Response to seismic loading

- Higher ductility (austenitic ss) + sustains more load cycles
  ⇒ greater hysteretic energy dissipation under cyclic loading

- Higher work hardening
  ⇒ enhances development of large & deformable plastic zones

- Stronger strain rate dependency
  ⇒ higher strength at fast strain rates

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Section 10

Resources for engineers

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Resources for engineers

- Online Information Centre
- Case studies
- Design guides
- Design examples
- Software

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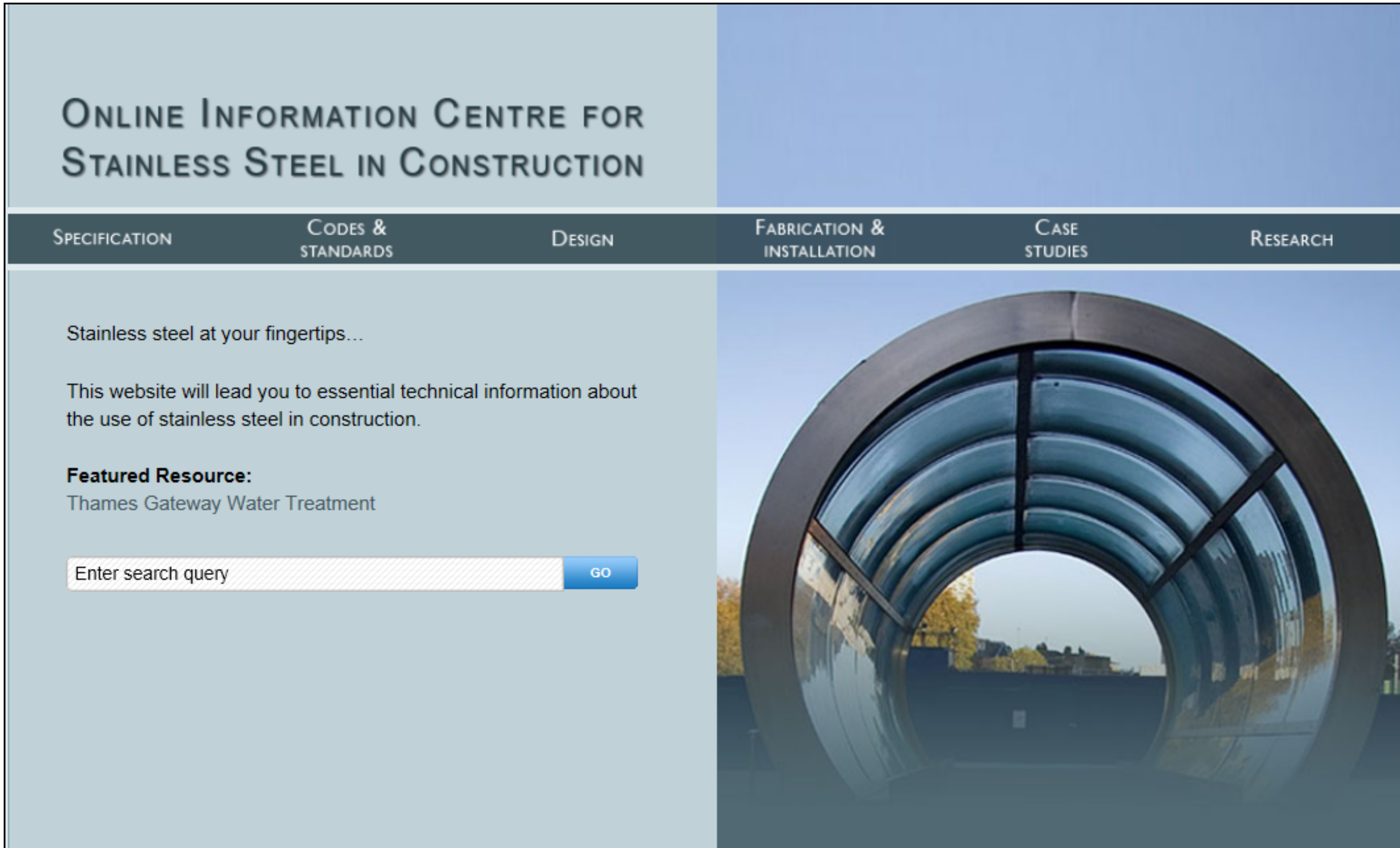


12 Structural Case Studies

www.steel-stainless.org/CaseStudies


SCI Steel Knowledge

Structural Stainless Steel Case Study 01

Stonecutters Bridge Towers

Stonecutters Bridge, Hong Kong, is a cable stayed structure with a total length of 1596 m and a main span of 1018 m. The bridge crosses the Rambler Channel and is the main entrance to the busy Kwai Chung Container Port. It is visible from many parts of Hong Kong Island and Kowloon. The most striking features of the bridge are the twin tapered mono towers at each end supporting the 50 m wide deck. These tapered towers rise to 295 m above sea level; the lower sections are reinforced concrete while the upper 115 m are composite sections with an outer stainless steel skin and a reinforced concrete core.

Material Selection

Figure 1: General view of Stonecutters Bridge

The design life of the bridge is 120 years. A highly durable material was required for the upper sections of the bridge towers because of the harsh marine and polluted environment. Additionally, post-construction maintenance on the towers will be extremely difficult, due to the live traffic beneath. Stainless steel was chosen for the skin of the composite section of the upper tower because of its durability and also its attractive appearance. Carbon steel would have required protective coatings that would have needed replacing after an estimated 25-30 years.

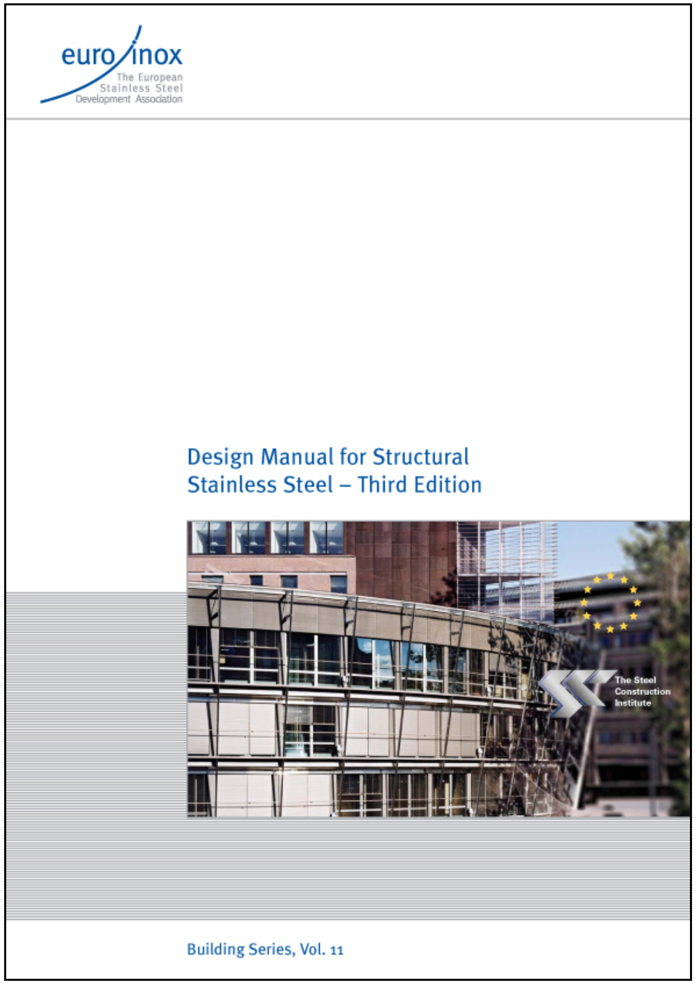
Standard molybdenum-alloyed austenitic steel grades were initially considered but discounted because of their relatively low design strength (220 N/mm^2) and uncertainty regarding corrosion performance, given the roughness of the desired surface finish. Higher alloyed austenitics with better corrosion resistance, e.g. 1.4539 (N08904) and 1.4439 (S31726), were not considered in detail as they would not have met the requirements for cost, availability and strength. Duplex steel 1.4462 (S32205) was chosen as it has high strength (460N/mm^2) with good corrosion resistance and tolerance on surface finish.

Figure 2: Mono tower and stay cables

A polished 1K finish (as defined in EN 10088 Part 2 [1]) was specified for all exposed surfaces, with an average surface roughness R_a of 0.5 µm. A slightly textured, non-directional, low reflective appearance was then created by shot peening the surface with a mixture of aluminium oxide and glass beads.

Structural Stainless Steel Case Study 01 Page 1

Design Guidance to Eurocodes



www.steel-stainless.org/designmanual

- Guidance
- Commentary
- Design examples

Online design software:

www.steel-stainless.org/software

www.steel-stainless.org/software

Thank You

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Based on *Supporting presentation for lecturers of Architecture/Civil Engineering - Chapter 9B - Structural Applications of Stainless Steel Flat Products*

Inspired by previous version prepared in collaboration with Nancy Baddoo, Steel Construction Institute, Ascot, UK

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Some more references…

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