What is Stainless Steel?

PUREST

http://www.steel-stainless.org/media/1533/dmsss4-french-complete.pdf

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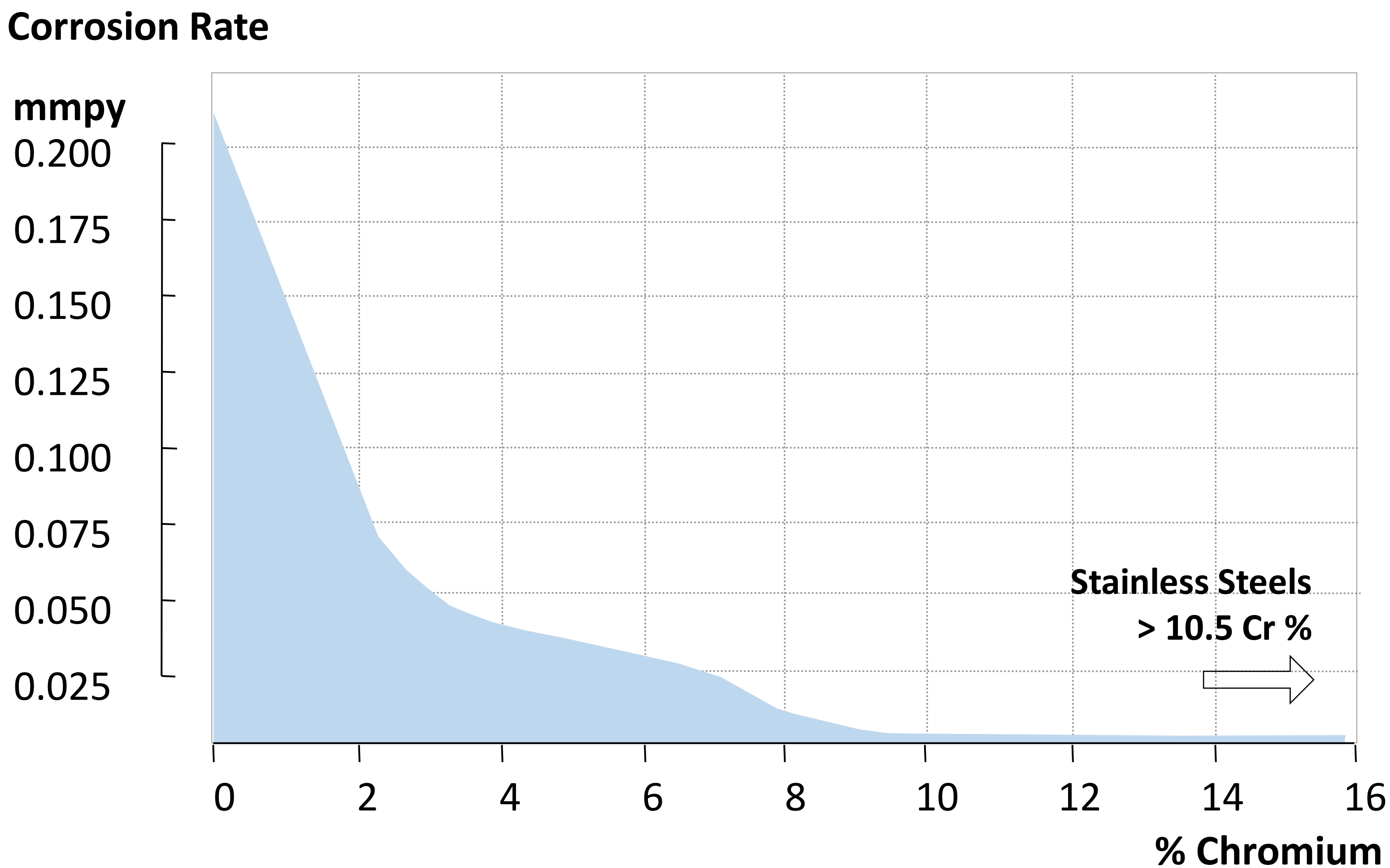
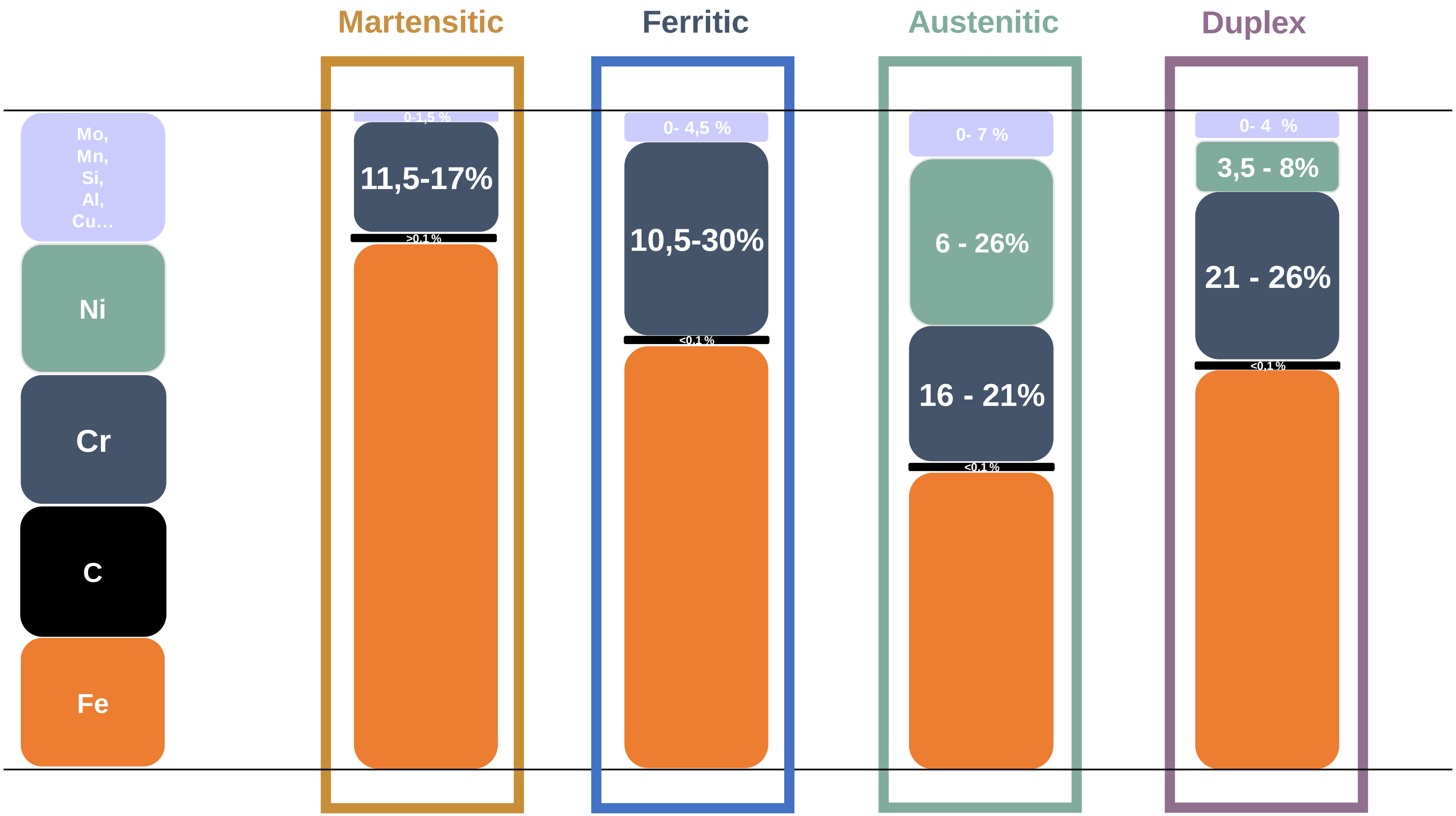
What is stainless steel?

- Stainless steel is a corrosion-resistant iron alloys that contains 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),
  - Nitrogen (N).

Effect of Chromium Content on Atmospheric Corrosion Resistance



Chemical composition of stainless steel



Passive film

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

Properties of the passive film:

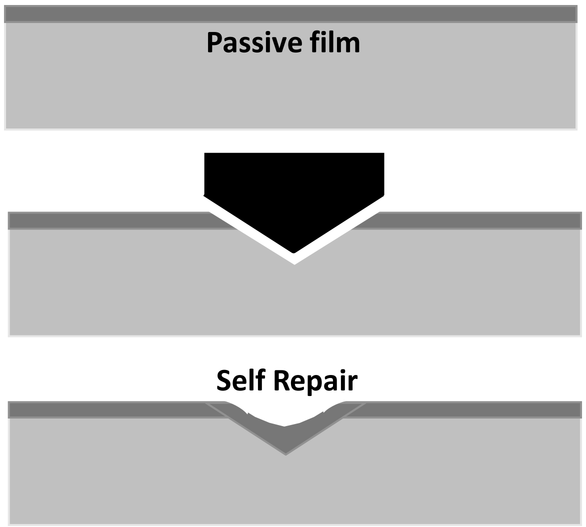
– Chromium Rich Oxide

– Very thin, ~ 20-30 Ångströms (2-3 nm)

– Extremely adherent

– Passive

– Self Repairing (within minutes)



Why use stainless steel in structures?

- Where you need corrosion resistance and long life combined with strength
- Where maintenance and/or inspection is difficult
- Where you need attractive metallic surface

- Good toughness at very low temperatures
- Hygienic properties
- Non-magnetic properties

The **austenitic** and **duplex** stainless steels are
most widely used in construction

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Duplex compared to austenitic steels

Duplex stainless steels have:

– a mixed microstructure of ferrite & austenite

– equivalent corrosion resistance to austenitics

– higher strength

– improved cost, by reduction in Ni (and Mo) content (lean grades)

Group	Strength	Ductility	Magnetic	Weldable	Corrosion	Formability
Austenitic	●●	●●●	✗	✓	●●	●●●
Duplex	●●●	●●	✓	✓	●●●	●●

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Duplex compared to austenitic steels

	Cr – Ni (Typically 304 /4301) Cr – Ni – Mo (Typically 316/4401)	Cr – Ni (Typically /4362) Cr – Ni – Mo (Typically /4462)
	Best known and most used today	**Best combination of corrosion resistance and mechanical properties**
Physical prop.	– Non Magnetic – Higher expansion coefficient (compared to C-Steels) – Low heat conductivity	– Magnetic – Expansion coefficient (intermediate between ferritic and austenitic) – Low heat conductivity
Corrosion	– Very good corrosion resistance, increases with alloy content – …but can be susceptible to SCC in hot chloride environments (e.g. swimming pools)	– Excellent corrosion resistance, increases with alloy content – Insensitive to SCC
Mech. prop.	– Very 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	– High strength, high ductility – Strength can be increased by cold working (but not by heat treatment)
Fabri.	– Very good cold and hot forming properties (ductility, elongation) – Easy to weld (TIG, MIG)	– Good cold and hot forming properties (ductility, elongation) – Weldable (TIG, MIG)

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Designation - Grades

The designation systems adopted in EN 10088 are the European steel number and a steel name. For example, grade 304L has a steel number 1.4307, where:

1.	43	07
Denotes steel	Denotes one group of stainless steels	Individual grade identification

The groups of stainless steel are denoted in EN 10027-2 as:

- 1.40XX: Stainless steel with Ni < 2,5 % without Mo, Nb and Ti
- 1.41XX: Stainless steel with Ni < 2,5 % and Mo but without Nb and Ti
- 1.43XX: Stainless steel with Ni ≥ 2,5 % but without Mo, Nb and Ti
- 1.44XX: Stainless steel with Ni ≥ 2,5 %, and Mo but without Nb and Ti
- 1.45XX: Stainless steels with special additions
- 1.46XX: Chemical resistant and high temperature Ni grades

Grade selection procedure

- New procedure introduced in Annex A of EN 1993-1-4:A1 2015 (and included in section 3.5 of Design Manual)
- Avoid confusion with huge choice of grades
- Pan-European (wide range of environments)
- Conservative, robust, unambiguous
- Based on many years experience with similar procedures in German National Approval Z-30.3-6 and tools developed by IMOA and Arup
- Calibrated against existing structures

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Grade selection procedure

Corrosion Resistance Factor (CRF)

For the environment

↓

Corrosion Resistance Class (CRC)

Designer does **not** need to choose the specific alloy

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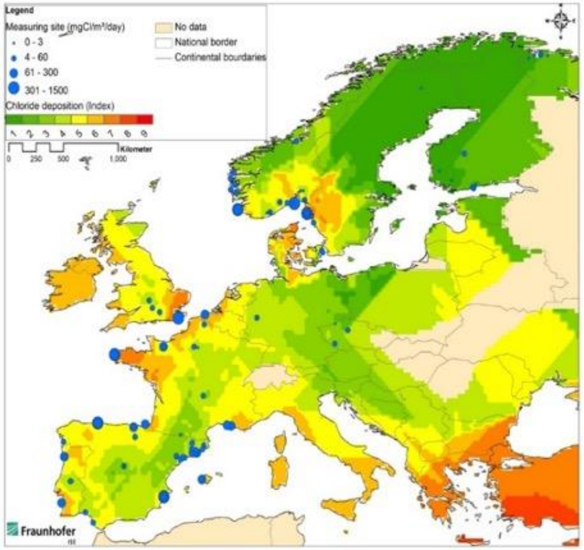
Grade selection procedure

– 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



Based on:
- practical experience with existing structures
- exposure trials
- research on corrosion mapping

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F1

F_1 Risk of exposure to chlorides from salt water or de-icing salts		
NOTE M is distance from the sea and S is distance from roads with de-icing 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 de-icing salt is used or where vehicles might carry de-icing salt 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

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F2

F_2 Risk of exposure to sulphur dioxide		
NOTE For European coastal environments the sulphur dioxide concentration is usually low. For inland environments the sulphur 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. Sulphur dioxide concentration may be evaluated according to the method in ISO 9225.		
0	Low risk of exposure	<10 μg/m³ average gas concentration
-5	Medium risk of exposure	10 - 90 μg/m³ average gas concentration
-10	High risk of exposure	90 - 250 μg/m³ average gas concentration

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F3

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

NOTE 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) for the environment:

$$CRF = F1 + F2 + F3$$

More negative values of CRF require more resistant alloy.

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

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Grade selection procedure

Increasing alloy additions, i.e. more corrosion resistant →

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	1.4539	1.4529
1.4512	1.4311	1.4435	1.4462	1.4547
	1.4541	1.4571		1.4410
	1.4318	1.4429		1.4501
	1.4306	1.4432		1.4507
	1.4567	1.4578		
	1.4482	1.4662		
		1.4362		
		1.4062		
		1.4162		

NOTE 1 The Corrosion Resistance Classes are only intended for use with this grade selection procedure and are only applicable to structural applications.

NOTE 2 A grade from a higher class may be used in place of the class indicated by the CRF.

Basic ferritics
Basic austenitics
Mo austenitics
Lean duplexes
Higher alloy/super austenitics
Duplex/super duplex

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Grade selection procedure

Relates to the selection of materials **for structural applications** and does not take account of:

- grade/product availability
- surface finish requirements
- methods of joining/connecting

Not intended for architectural applications such as facades

Procedure assumes the service environment:

- near neutral pH range (pH 4 to 10)
- not part of a chemical plant/ process
- not permanently/intermittently immersed in seawater

If these conditions are not met, specialist advice should be sought

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Grade selection procedure – Special cases: swimming pools

- Highly corrosive environments
- Immersion in pool water is **not** a problem
- Do not use standard austenitics for load-bearing members which cannot be cleaned regularly - they may fail by **stress corrosion cracking** (SCC)

Load-bearing parts in swimming pool atmospheres	Corrosion resistance class CRC
Load-bearing members which are regularly cleaned 1	CRC III or CRC IV (excluding 1.4162, 1.4662, 1.4362, 1.4062)
Load-bearing members which are not regularly cleaned	CRC V (excluding 1.4410, 1.4501 and 1.4507)
All fixings, fasteners and threaded parts	CRC V (excluding 1.4410, 1.4501 and 1.4507)
Note: 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 week. 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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Overview of Structural Applications of stainless steel

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Structural members

“The Gap”
Western Australia
© David Iles

Stainless steel columns, entrance canopy at Seven World Trade Center, New York
© Catherine Houska

Structural members – subway entrances

New York
© Catherine Houska

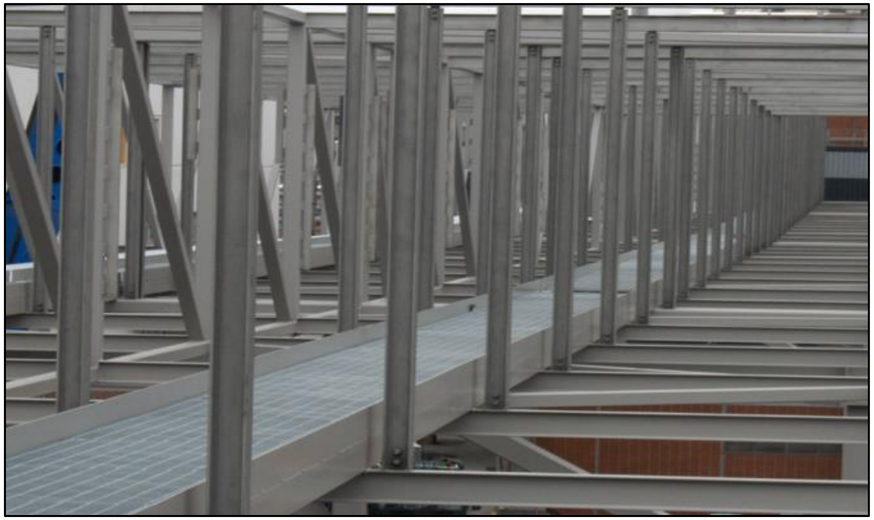
Washington DC
© Graham Gedge

Bilbao
© Bassam Burgan

Industrial structures

Access walkways and ladders

Skid for offshore regasification plant



Walkway in pulp and paper plant

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Bridges

Cala Galdana Bridge, Menorca

Helix Bridge, Singapore

Masonry support and fixings

Wall ties

Masonry support

Shear connectors

Wind posts

Photos © Ancon Building Products

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Tunnels…

… require highly durable materials due to corrosive environment, high maintenance costs & severe consequences of a structural failure or fire

Stainless framework supports a stainless steel lining in Glasgow’s Clyde Tunnel due to good retention of mech. prop. in a fire

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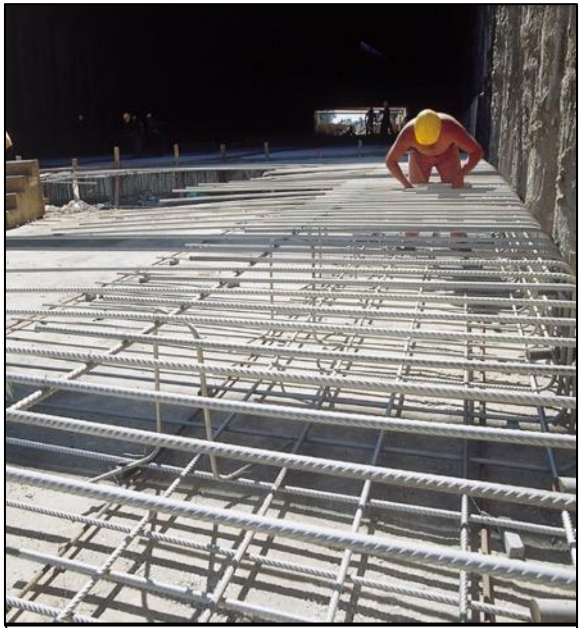
Stainless steel reinforcing bar

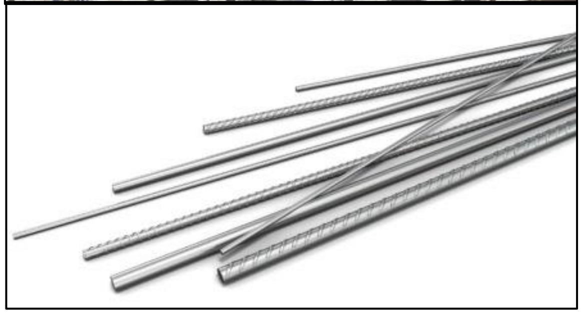
Benefits

- Longer design life of structure (>100 years)
- Reduced concrete cover
  - Reduced deck weight
  - Reduced substructure

Applications

- Highway bridges, overpasses, tunnels, car parks, wharfs, piers, coastal buildings, historical building restorations, buildings with sensitive electronic equipment





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Design rules for stainless steel

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Eurocode 3: Part 1 (EN 1993-1)

Huge amount of research carried out over the last 25 years

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 + A1:2015 + A2:2020

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

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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

EN 1993

EN 1993

EN 1993

EN 1993

EN 1993

EN 1993

EN 1993

Eurocode 3 Part 1.4: 2006 + A1:2015 + A2:2020

Design of steel structures. Supplementary rules for stainless steels

- Follow same basic approach as carbon steel
- Use same rules as for carbon steel for tension members & restrained beams
- Modifies and supplements rules for carbon steel where necessary

- Applicable to:
  - Welded, hot rolled & cold formed members
  - Austenitic, duplex (and ferritic) grades
  - Applies to buildings, bridges, etc

EN 1993-1-11 Design of structures with tension components

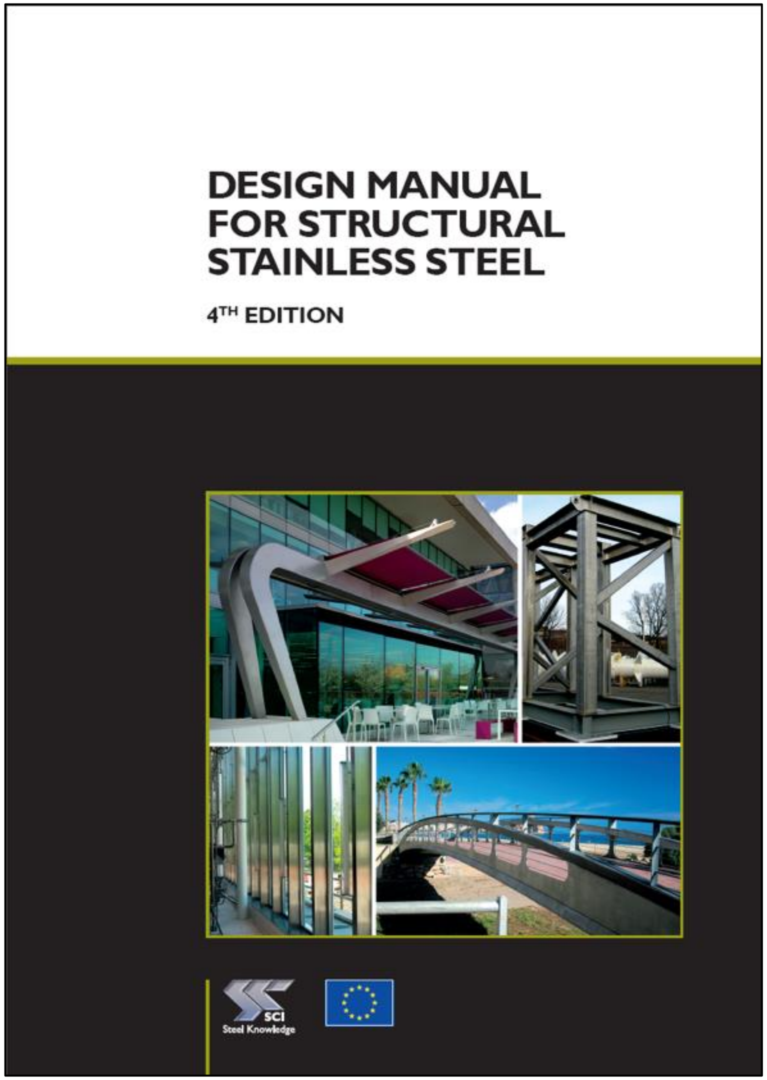
EN 1993-1-12 Supplementary rules for high strength steels

Design Manual

- Guidance
- Design Examples
- Commentary
- Software and apps

History:

- 1st Edition: 1993
- 2nd Edition: 2002
- 3rd Edition: 2006
- 4th Edition: 2017



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Safety factor

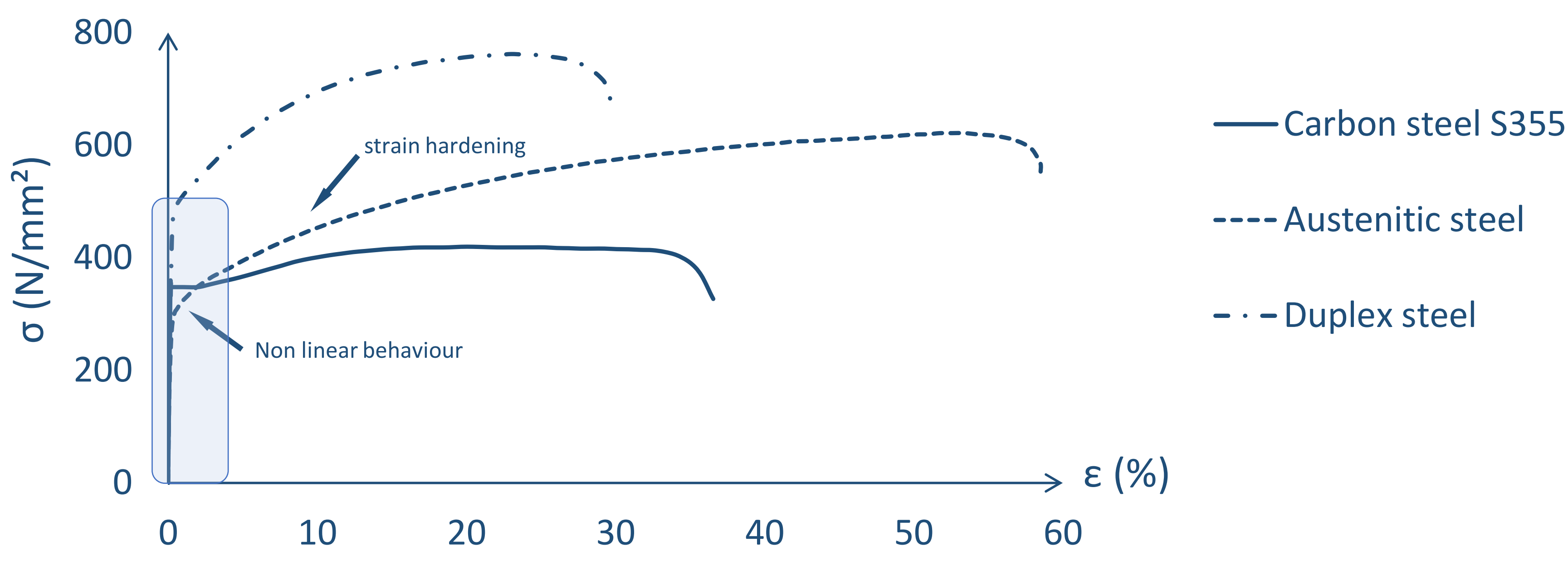
- Safety factors:
  - $\gamma_{M0} = 1{,}1$ instead of 1,0
  - $\gamma_{M1} = 1{,}1$ instead of 1,0
  - $\gamma_{M2} = 1{,}25$

mainly due to **variability** of material properties within families

Stress-strain curve

Carbon steel:
Linear elastic behaviour up to yield
Clear yield plateau
Less strain hardening

Stainless steel:
Rounded curve
No well defined yield strength
Greater strain hardening



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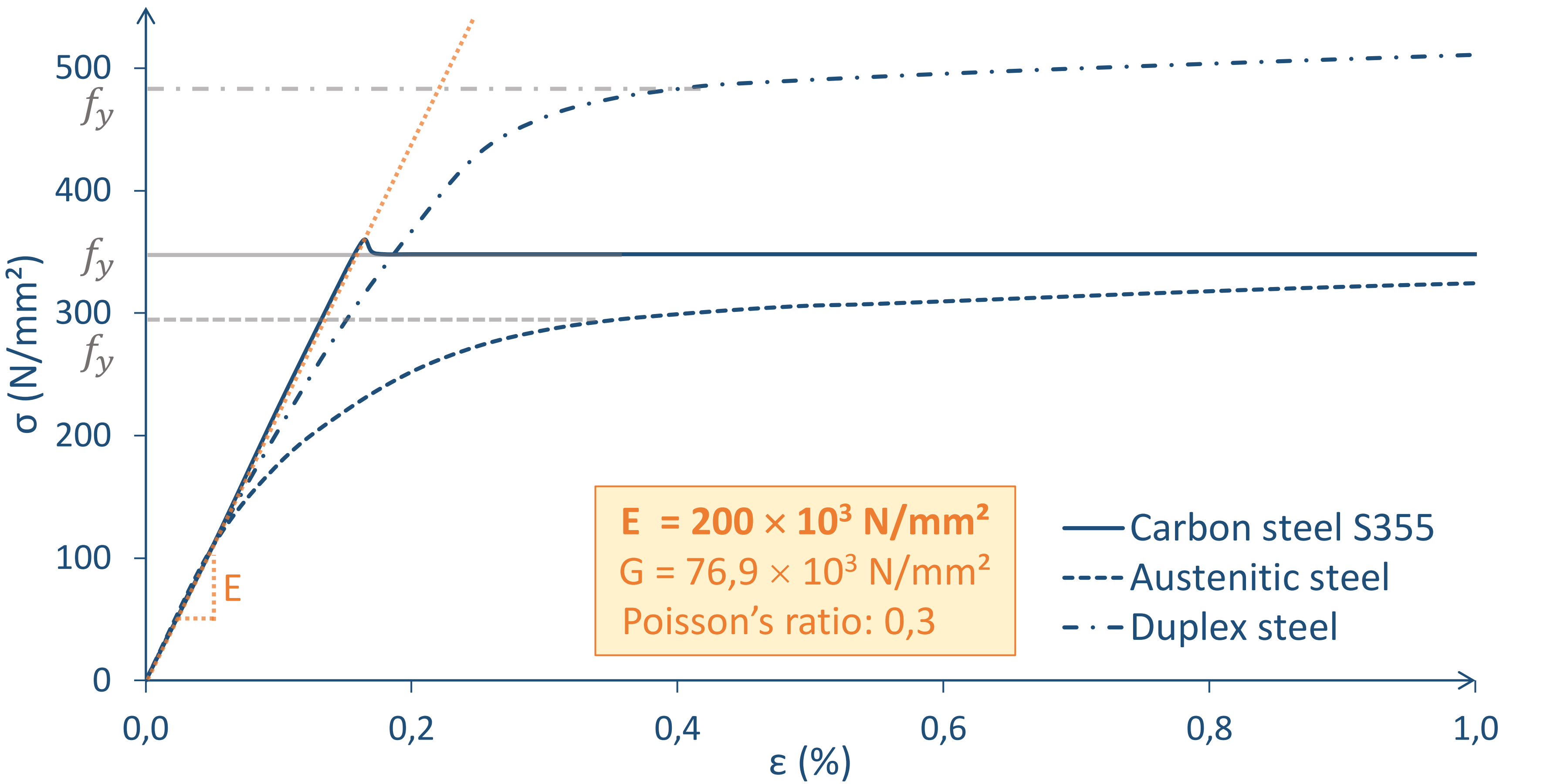
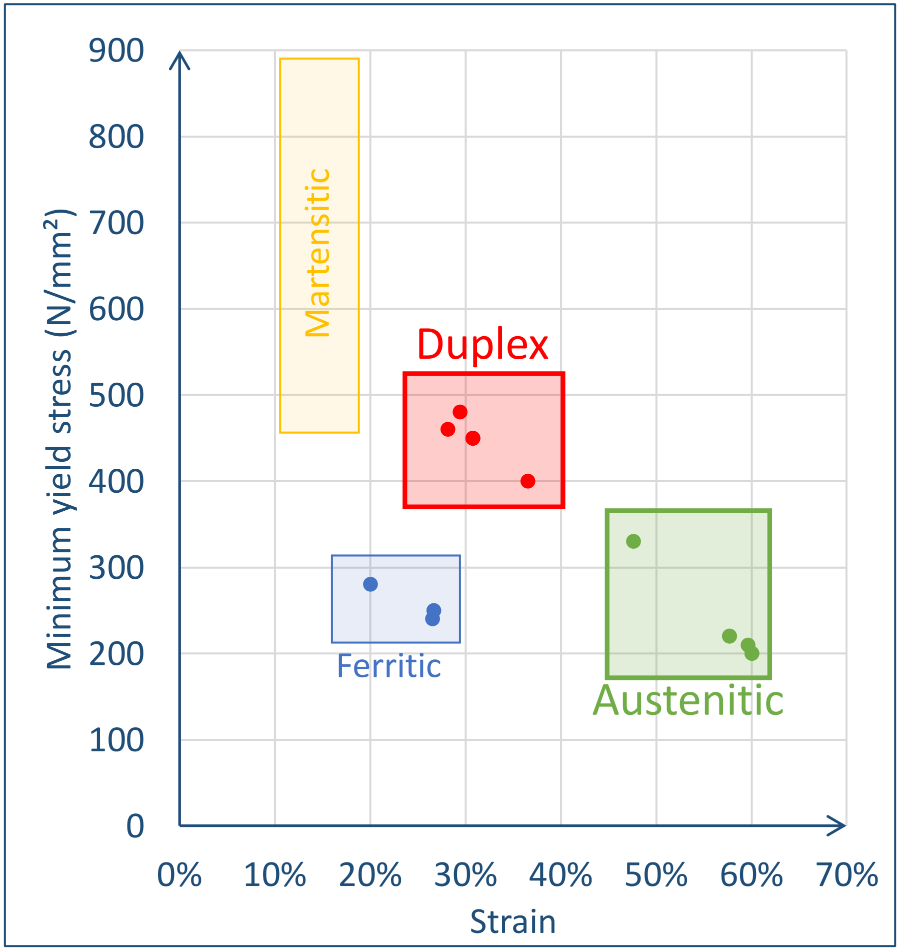
Stress-strain curve

– Yield strength f_y: 0,2% proof strength



Mechanical characteristics

– Yield & ultimate strength



	Grade	Cold rolled strip		Hot rolled strip		Hot rolled plate		Bars, rods & sections	
		Product form							
		Nominal thickness t							
		t ≤ 8 mm		t ≤ 13,5 mm		t ≤ 75 mm		t or ϕ ≤ 250 mm	
		f_y	f_u	f_y	f_u	f_y	f_u	f_y	f_u
Austenitic	1.4301	230	540	210	520	210	520	190	500
	1.4307	220	520	200	520	200	500	175	500
	1.4318	350	650	330	650	330	630	-	-
	1.4401	240	530	220	530	220	520	200	500
	1.4404	240	530	220	530	220	520	200	500
	1.4541	220	520	200	520	200	500	190	500
	1.4571	240	540	220	540	220	520	200	500
Duplex	1.4062	530 [1]	700 [1]	480 [2]	680 [2]	450	650	380 [3]	650 [3]
	1.4162	530 [1]	700 [1]	480 [2]	680 [2]	450	650	450 [3]	650 [3]
	1.4362	450	650	400	650	400	630	400 [3]	600 [3]
	1.4462	500	700	460	700	460	640	450 [3]	650 [3]
	1.4482	500 [1]	700 [1]	480 [2]	660 [2]	450	650	400 [3]	650 [3]
	1.4662	550 [1]	750 [1]	550 [4]	750 [4]	480	680	450 [3]	650 [3]
Ferritic	1.4003	280	450	280	450	250 [5]	450 [5]	260 [6]	450 [6]
	1.4016	260	450	240	450	240 [5]	430 [5]	240 [6]	400 [6]
	1.4509	230	430	-	-	-	-	200 [7]	420 [3]
	1.4521	300	420	280	400	280 [8]	420 [8]	-	-
	1.4621	230 [5]	400 [9]	230 [8]	400 [8]	-	-	240 [7]	420 [7]

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. For ferritic stainless steels, EN 10088-4 gives f_y values in the longitudinal and transvers direction. This table gives the longitudinal values which are generally about 20 N/mm^2 lower than the transverse values.

1.4621, 1.4482, 1.4062 and 1.4662 are only covered in EN 10088-2 and 3.

1.4509 bar is only covered in EN 10088-3.

[1] t ≤ 6,4 mm
[2] t ≤ 10 mm
[3] t or ϕ ≤ 160 mm
[4] t ≤ 13 mm
[5] t ≤ 25 mm
[6] t or ϕ ≤ 100 mm
[7] t or ϕ ≤ 50 mm
[8] t ≤ 12 mm
[9] t ≤ 6 mm

Tabel 2.2: Nominal values of the yield strength f_y and the ultimate strength f_u for common stainless steels to EN 10088 (N/mm^2)

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Material model

Carbon steel:

Linear elastic behaviour up to yield

Clear yield plateau

Less strain hardening

Stainless steel:

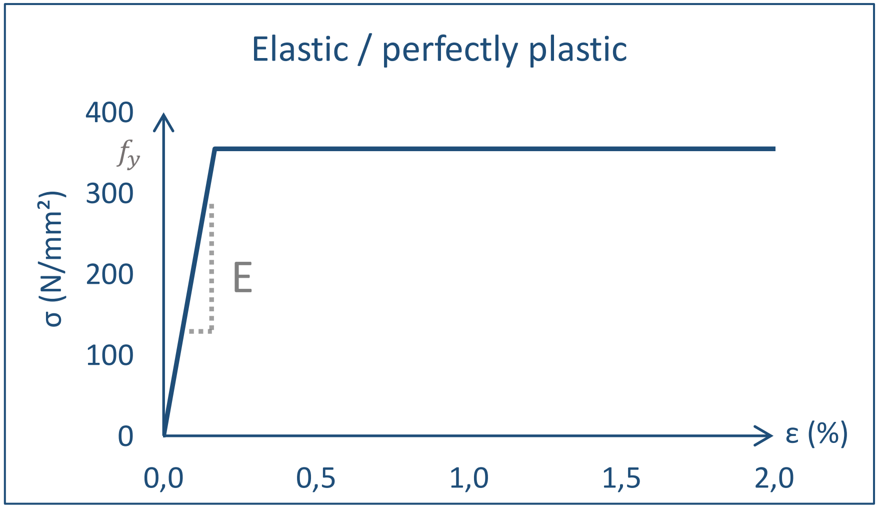
Rounded curve

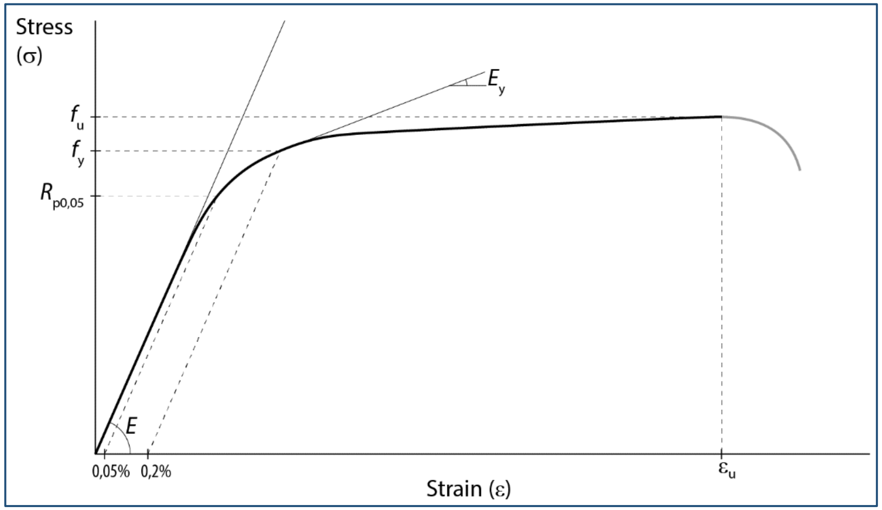
No well defined yield strength

Greater strain hardening

Elastic / perfectly plastic

Non-linear





Ramberg-Osgood material model

$$\varepsilon = \begin{cases} \frac{\sigma}{E} + 0{,}002\left(\frac{\sigma}{f_y}\right)^n \; for\; \sigma \le f_y \\ 0.002 + \frac{f_y}{E} + \frac{\sigma - f_y}{E_y} + \varepsilon_u \left(\frac{\sigma - f_y}{f_u - f_y}\right)^m \; for\; f_y < \sigma \le f_u \end{cases}$$

Parameter	EN 1993-1-4, old version	Design Manual And in EN 1993-1-14
E_y	$\frac{E}{1 + 0{,}002n\frac{E}{f_y}}$	$\frac{E}{1 + 0.002n\frac{E}{f_y}}$
ε_u	$1 - \frac{f_y}{f_u}$	$\begin{cases} 1 - \frac{f_y}{f_u} \text{ for austenitic and duplex} \\ 0{,}6\left(1 - \frac{f_y}{f_u}\right) \text{ for ferritic} \end{cases}$
m	$1 + 3{,}5\frac{f_y}{f_u}$	$1 + 2{,}8\frac{f_y}{f_u}$
n	Table 6.5	Austenitic: 7; Ferritic: 14; Duplex: 8

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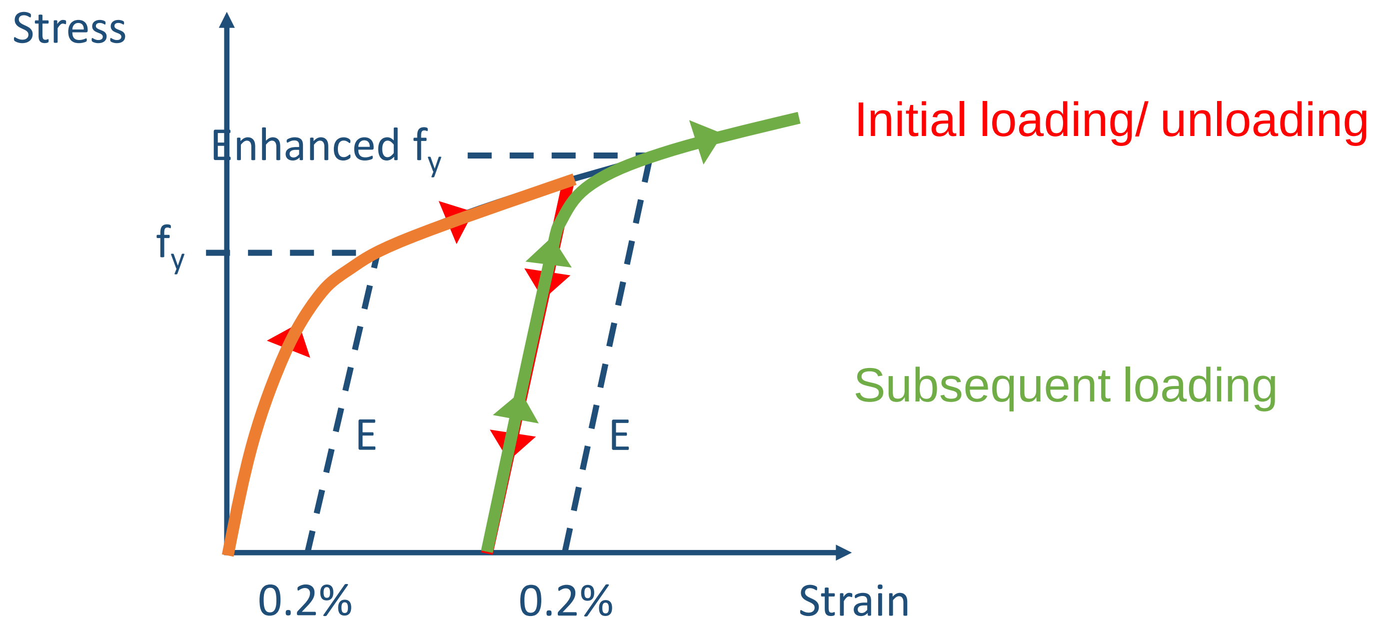
Strength enhancement

Cold working / forming occurs during:

- Forming of sheet material (at the steel mill)
- Section forming (at the fabrication shop)
- Under load (in service)



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Strength enhancement – forming of sheet material

Stainless steel is available in standardised cold-worked conditions (EN 1993-1-4 and Design Manual applicable):

- CP350 (The characteristic yield strength is f_y = 350 N/mm².)
- CP500 (The characteristic yield strength f_y is reduced from 500 to 460 N/mm² to take into account asymmetry of the cold worked material.)

	Cold worked condition			
	CP350		CP500	
	$f_y\ (N/mm^2)$	$f_u (N/mm^2)^1$	$f_y (N/mm^2)$	$f_u (N/mm^2)^1$
1.4301	350	600	460	650
1.4318	[2]	[2]	460	650
1.4541	350	600	460	650
1.4401	350	600	460	650
1.4571	350	600	460	650

[1] According to EN 10088, the CP classification defines only the required 0,2 % proof strength, f_y. The steels used should have declared properties that meet the conservative tabulated values for ultimate strength, f_u, unless type testing is used to demonstrate the acceptability of lower values.

[2] Grade 1.4318 develops a 0,2 % proof strength of 350 N/mm² in the annealed condition; see Table 2.2.

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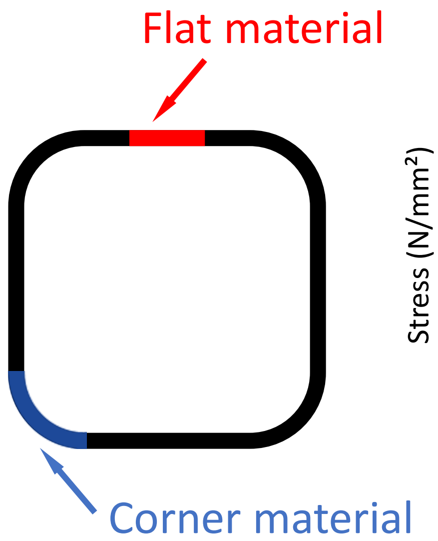
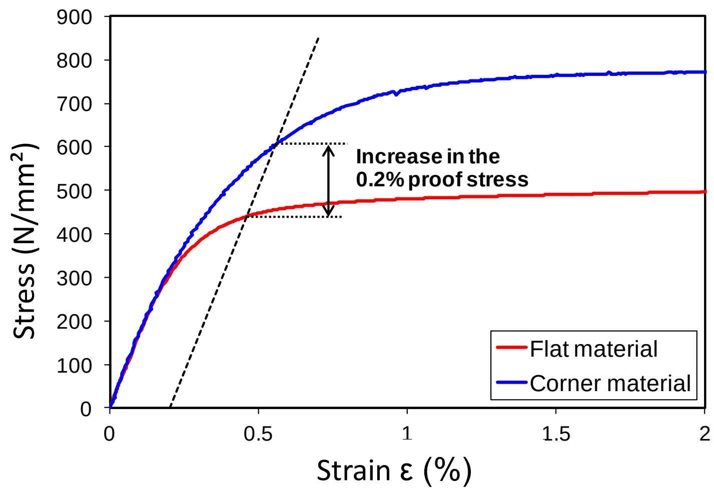
Strength enhancement – section forming

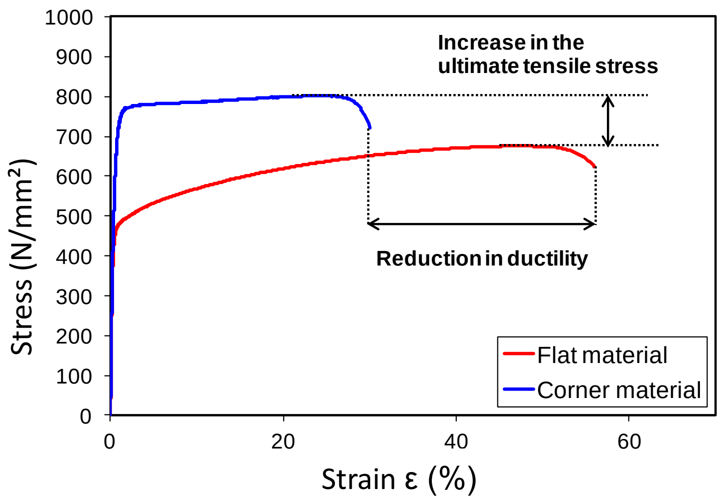
Test data on flat and corner material from the same section show :

- an increase of f_y and f_u and;
- a reduction of ductility.





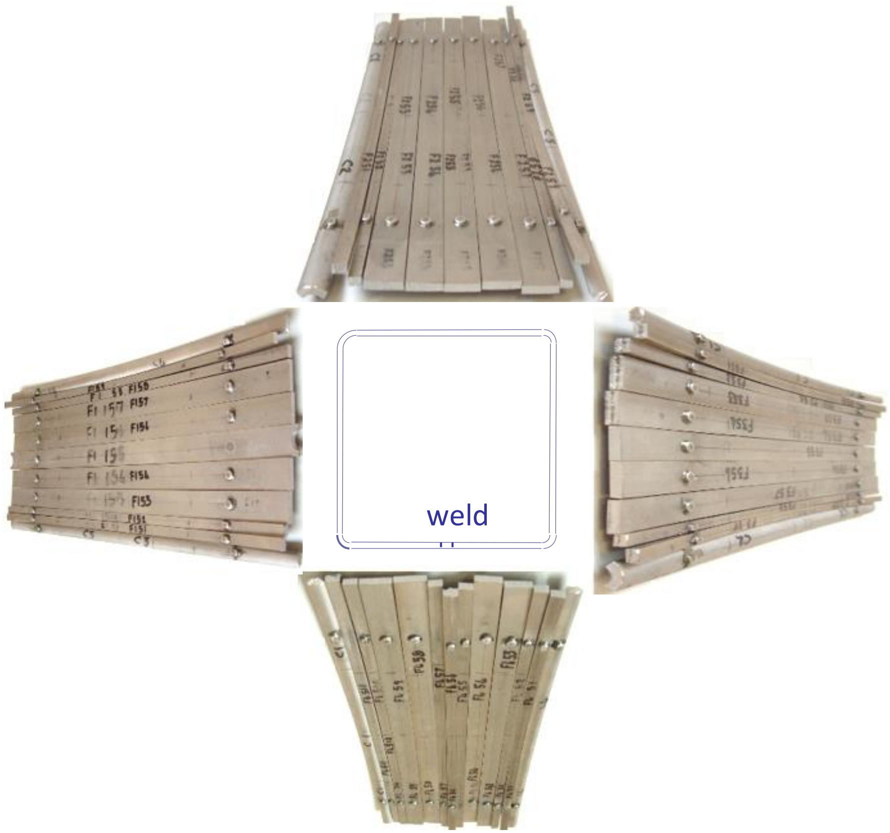
Early stage of σ-ε curve

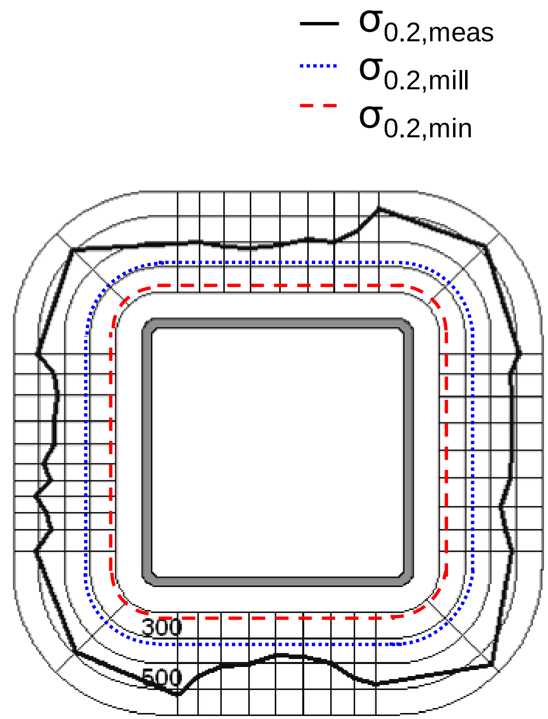


Full σ-ε curve

Strength enhancement – section forming

Strength enhancement during forming





Cruise, R. B. and Gardner, L. (2008). Strength enhancements induced during cold forming of stainless steel sections. Journal of Constructional Steel Research. **64(11)**, 1310-1316.

Strength enhancement – section forming

- The benefit of strength enhancement can be introduced in calculations by replacing f_y by the enhanced average yield strength f_{ya}.
- For box sections, typical enhancements in strength of 30% in flat regions and 50% in corners can be harnessed.

Afshan, S., Rossi, B. and Gardner, L. (2013). Strength enhancements in cold-formed structural sections – Part I: Material testing. Journal of Constructional Steel Research. 83, 177-188.

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

Strength enhancement – section forming

f_{ya} can be determined by:

- For stainless steel sections formed by press braking:

$$f_{\mathrm{ya}} = \frac{f_{\mathrm{yc}}\, A_{\mathrm{c,pb}} + f_{\mathrm{y}}\,(A - A_{\mathrm{c,pb}})}{A}$$

- For stainless steel cold rolled box sections (RHS):

$$f_{\mathrm{ya}} = \frac{f_{\mathrm{yc}}\, \mathrm{A}_{\mathrm{c,rolled}} + f_{\mathrm{yf}}(A - A_{\mathrm{c,rolled}})}{A}$$

- For stainless steel cold rolled circular hollow sections (CHS):

$$f_{\mathrm{ya}} = f_{\mathrm{yCHS}}$$

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Strength enhancement – section forming

Formulas for f_{yc}, f_{yf} and f_{yCHS}:

$$f_{\mathrm{yc}} = 0{,}85K\left(\varepsilon_{\mathrm{c}} + \varepsilon_{\mathrm{p0,2}}\right)^{n_{\mathrm{p}}}$$ and $$f_{\mathrm{y}} \leq f_{\mathrm{yc}} \leq f_{\mathrm{u}}$$

$$f_{\mathrm{yf}} = 0{,}85K\left(\varepsilon_{f} + \varepsilon_{\mathrm{p0,2}}\right)^{n_{\mathrm{p}}}$$ and $$f_{\mathrm{y}} \leq f_{\mathrm{yf}} \leq f_{\mathrm{u}}$$

$$f_{\mathrm{yCHS}} = 0{,}85K\left(\varepsilon_{\mathrm{CHS}} + \varepsilon_{\mathrm{p0,2}}\right)^{n_{\mathrm{p}}}$$ and $$f_{\mathrm{y}} \leq f_{\mathrm{yCHS}} \leq f_{\mathrm{u}}$$

In which:

$$\varepsilon_c = \frac{t}{2(2r_i + t)} \qquad \varepsilon_{CHS} = \frac{t}{2(d - t)} \qquad K = \frac{f_y}{\varepsilon_{p0,2}^{n_p}}$$

$$\varepsilon_f = \left[\frac{t}{900}\right] + \left[\frac{\pi t}{2(b + h - 2t)}\right] \qquad \varepsilon_{p0,2} = 0{,}002 + \frac{f_y}{E} \qquad n_p = \frac{ln(f_y/f_u)}{ln(\varepsilon_{p0,2}/\varepsilon_u)}$$

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Strength enhancement – section forming

Determination of total corner cross-sectional area $A_{c,pb}$ and $A_{c,rolled}$ can be conducted using:

$$A_{\mathrm{c,pb}} = \left(n_c\,\pi\frac{t}{4}\right)(2r_i + t)$$

$$A_{\mathrm{c,rolled}} = \left(n_c\,\pi\frac{t}{4}\right)(2r_i + t) + 4n_c t^2$$

In which n_c represents the amount of 90° corners.

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Strength enhancement – section forming

The enhancement arising during the fabrication of cold formed structural sections may be utilised in cross section and member design using annex B in Design Manual.

Example: Cold formed SHS (austenitic EN1.4301)

$$f_y = 230\ N/mm^2$$

+ 42%

$$f_{ya} = \frac{f_{yc}\ A_{c,rolled} + f_{yf}(A - A_{c,rolled})}{A}$$

$$= \frac{369 \times 373 + 304 \times (1099 - 373)}{1099}$$

$$= 326\ N/mm^2$$

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Impact of stress-strain characteristics

Fatigue

- The fatigue strength of stainless steel is similar to that of carbon steels.

Seismic performance

- High ductility domain ⇨ greater hysteretic energy dissipation
- High work hardening domain ⇨ development of large & deformable plastic zones
- Stronger strain rate dependency ⇨ strain rate ↑ leads to strength↑

But the nonlinear behaviour leads to:

- Different cross-section classification
- Different member buckling behaviour in compression and bending
- Greater deflections

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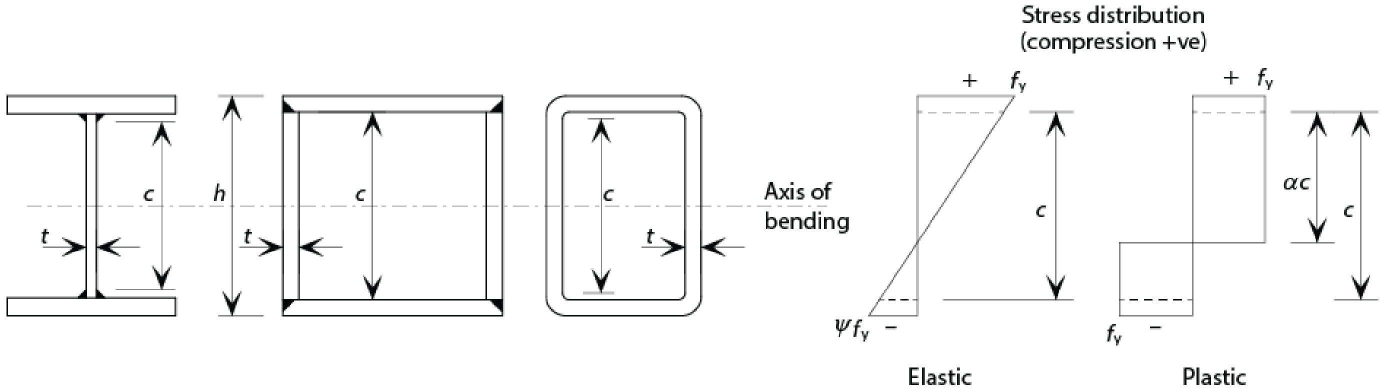
Section classification & local buckling

- EN 1993-1-4 gave lower limiting width-to-thickness ratios than for carbon steel and slightly different expressions for calculating effective widths of slender elements.

- The **first** amendment of EN 1993-1-4, that was published in 2015, contains less conservative limits & effective width expressions.

Section classification & local buckling

Internal compression parts

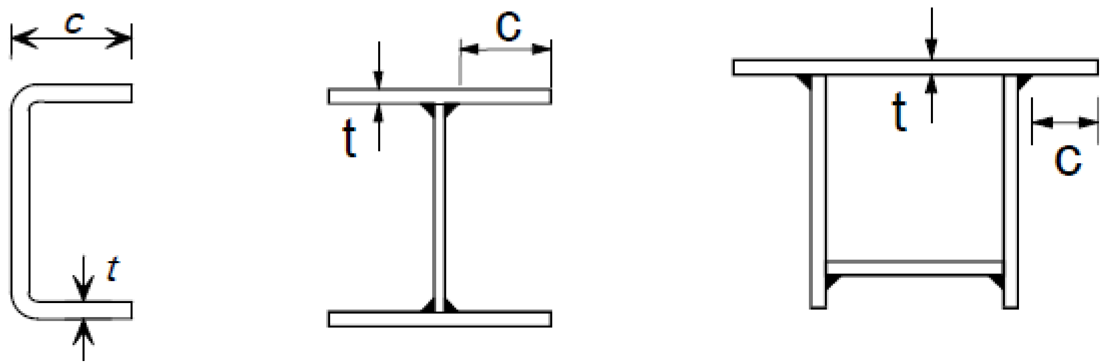


$$\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel		EC3-1-4, old version: stainless steel		EC3-1-4/A1:2015: stainless steel	
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

External compression parts



	EC3-1-1: carbon steel	EC3-1-4, old version: stainless steel		EC3-1-4/A1:2015: stainless steel
Class	Compression	Compression Welded	Compression Cold-formed	Compression Cold-formed and welded
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

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Design of columns 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 χ to get the global resistance of the column.
- **But different buckling curves** are used 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)

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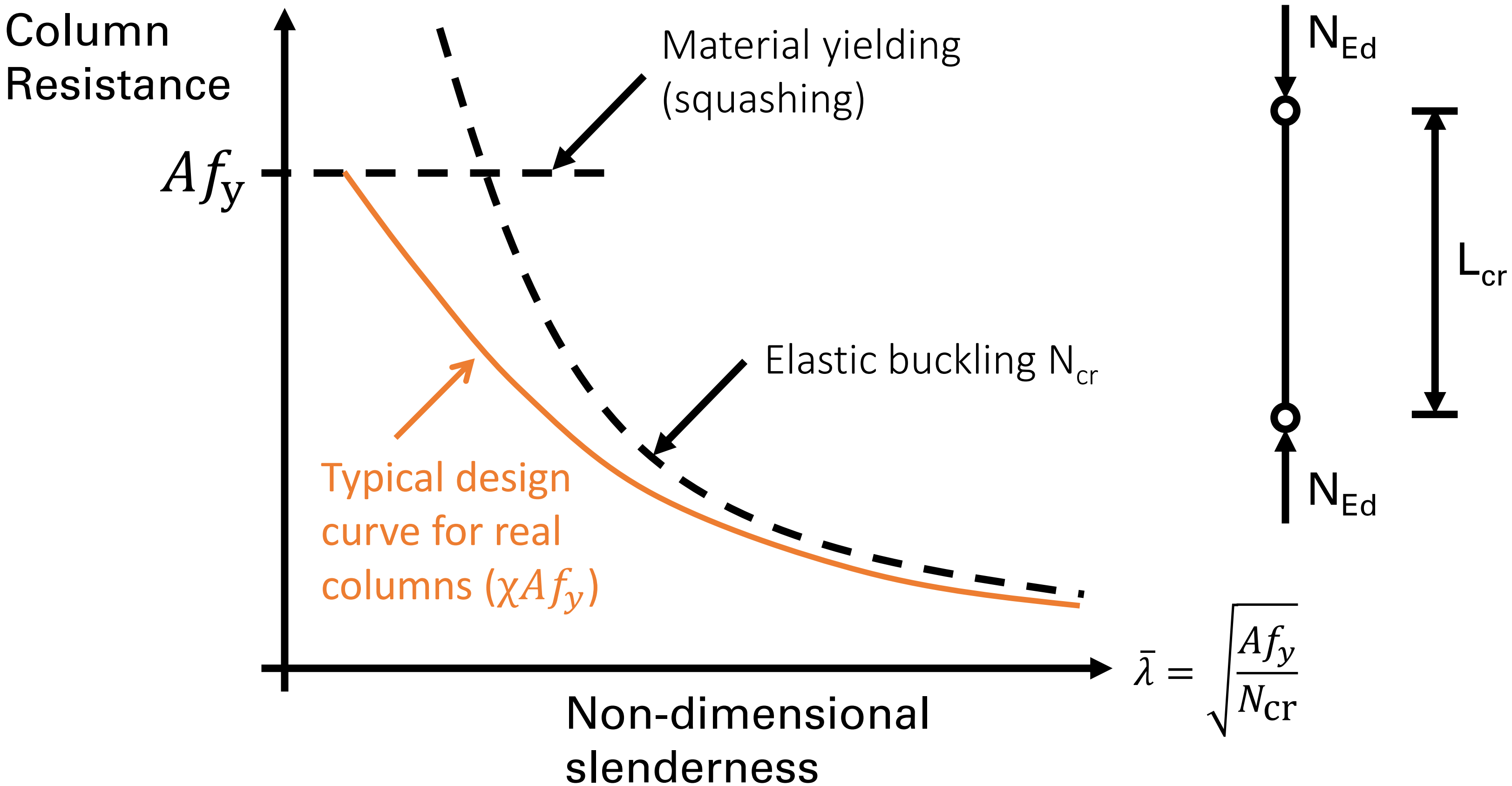
Design of columns in EN 1993-1-4

Real column behaviour

– Two bounds: Yielding (cross-section strength) and buckling:



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Column buckling

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

– Class 1, 2 and 3 cross-sections

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

– Class 4 : local buckling so effective properties should be used

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

In which χ is the reduction factor accounting for buckling

The buckling effects may be ignored and only cross sectional checks apply if: $\bar{\lambda} \leq \bar{\lambda}_0$ or $\frac{N_{Ed}}{N_{cr}} \leq \bar{\lambda}_0{}^2$

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Column buckling

Reduction factor:

$$\chi = \frac{1}{\phi + \left[\phi^2 - \bar{\lambda}^2\right]^{0,5}} \leq 1$$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}}$$ or $\bar{\lambda} = \sqrt{\frac{A_{eff} f_y}{N_{cr}}}$ if class 4

$$\phi = 0,5\left(1 + \alpha(\bar{\lambda} - \bar{\lambda}_0) + \bar{\lambda}^2\right)$$

$\bar{\lambda}_0$ is the limiting non-dimensional slenderness defined in Table 6.1 (next slide) or "plateau length"

α is the imperfection factor defined in Table 6.1 (next slide)

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Column buckling

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

Table 6.1: Values for α and $\bar{\lambda}_0$ for flexural buckling (Design Manual and A2:2020)

Buckling mode	Type of member	Axis of buckling	Austenitic & austenitic-ferritic		Ferritic	
			α	$\bar{\lambda}_0$	α	$\bar{\lambda}_0$
Flexural	Cold formed angles and channels	Any	0,76	0,2	0,76	0,2
	Cold formed lipped channels	Any	0,49	0,2	0,49	0,2
	Cold formed rectangular hollow sections	Any	0,49	0,3	0,49	0,2
	Cold formed circular hollow sections	Any	0,49	0,2	0,49	0,2
	Hot finished rectangular hollow sections	Any	0,49	0,2	0,34	0,2
	Hot finished circular hollow sections	Any	0,49	0,2	0,34	0,2
	Hot rolled sections & welded open or box sections	Major	0,49	0,2	0,49	0,2
		Minor	0,76	0,2	0,76	0,2
Torsional and torsional-flexural	All members	The values of α and $\bar{\lambda}_0$ for minor axis flexural buckling apply.				

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Design example

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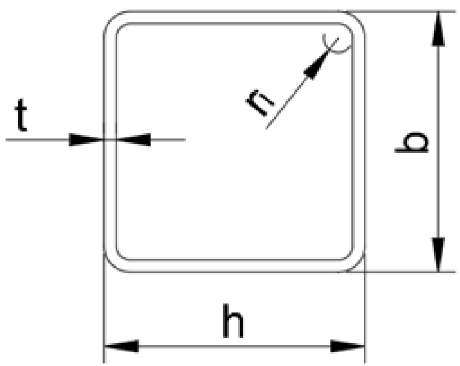
Design example #1



Cold formed square hollow section
80×80×4 Austenitic stainless steel grade 1.4301

$h = 79{,}9\ mm$
$b = 79{,}9\ mm$
$t = 3{,}75\ mm$
$L = 2\ m$
$r_i = 4{,}4\ mm$

$A = 10{,}99\ cm^2$
$W_{el} = 26{,}0\ cm^3$
$W_{pl} = 30{,}9\ cm^3$
$f_y = 230\ N/mm^2$
$E = 200\ 000\ N/mm^2$

Step 1 - Cross section properties and material properties

$A_{c,rolled} = \left(n_C\,\pi \frac{t}{4}\right)(2r_i + t) + 4n_C t^2 = \left(4\times\pi\times\frac{3{,}75}{4}\right) \times (2\times4{,}40 + 3{,}75) + 4\times4\times3{,}75^2 = 373\ mm^2$

$\varepsilon_{p0,2} = 0{,}002 + f_y/E = 0{,}00315$

$\varepsilon_u = 1 - f_y/f_u = 0{,}57$

Design example #1

Step 2 - Induced strain

$$\varepsilon_c = \frac{t}{2(2r_i + t)} = \frac{3{,}75}{2 \times (2 \times 4{,}40 + 3{,}75)} = 0{,}149$$

$$\varepsilon_f = \left[\frac{t}{900}\right] + \left[\frac{\pi t}{2(b + h - 2t)}\right] = \left[\frac{3{,}75}{900}\right] + \left[\frac{\pi \times 3{,}75}{2 \times (79{,}6 + 79{,}9 - 2 \times 3{,}75)}\right] = 0{,}043$$

Step 3 - Parameters material model

$$n_p = \frac{ln(f_y/f_u)}{ln(\varepsilon_{p0,2}/\varepsilon_u)} = \frac{ln(230/540)}{ln(0{,}00315/0{,}57)} = 0{,}164$$

$$K = \frac{f_y}{\varepsilon_{p0,2}^{\,n_p}} = \frac{230}{(0{,}00315)^{0{,}164}} = 591{,}6\ N/mm^2$$

Step 4 - Strength enhancement for flat and corner regions

$$f_{yc} = 0{,}85K\left(\varepsilon_c + \varepsilon_{p0,2}\right)^{n_p} = 0{,}85 \times 591{,}6 \times (0{,}149 + 0{,}00315)^{0{,}164} = 369\ N/mm^2 \quad and \quad f_y \leq f_{yc} \leq f_u$$

$$f_{yf} = 0{,}85K\left(\varepsilon_f + \varepsilon_{p0,2}\right)^{n_p} = 0{,}85 \times 591{,}6 \times (0{,}043 + 0{,}00315)^{0{,}164} = 304\ N/mm^2 \quad and \quad f_y \leq f_{yf} \leq f_u$$

Step 5 - Strength enhancement of cold formed sections

$$f_{ya} = \frac{f_{yc}\,A_{c,rolled} + f_{yf}(A - A_{c,rolled})}{A} = \frac{369 \times 373 + 304 \times (1099 - 373)}{1099} = \mathbf{326}\ N/mm^2$$

Design example #1

Step 6 - Cross section classification

Based on f_y:

$$\varepsilon = \left[\frac{235}{f_y}\frac{E}{210\ 000}\right]^{0,5} = \left[\frac{235}{230}\times\frac{200000}{210\,000}\right]^{0,5} = 0,986$$

$$\frac{c}{t} = \frac{(79,9 - 3\times 3,75)}{3,75} = 18,3 < 32,5 = 33\varepsilon \Rightarrow \boldsymbol{Class\ 1}$$

Based on f_{ya}:

$$\varepsilon = \left[\frac{235}{f_y}\frac{E}{210\ 000}\right]^{0,5} = \left[\frac{235}{326}\times\frac{200000}{210\,000}\right]^{0,5} = 0,829$$

$$\frac{c}{t} = \frac{(79,9 - 3\times 3,75)}{3,75} = 18,3 < 27,4 = 33\varepsilon \Rightarrow \boldsymbol{Class\ 1}$$

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Design example #1

Cross-sectional resisting moment

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

Based on f_y:

$$M_{c,Rd} = \frac{30860 \times 230}{1,1} = 6,45\ kNm$$

Based on f_{ya}:

$$M_{c,Rd} = \frac{30860 \times 326}{1,1} = 9,15\ kNm$$

Conclusion: When the strength enhancement due to cold forming of the cross section is included in calculations an improvement of 42% can be found for the moment resistance.

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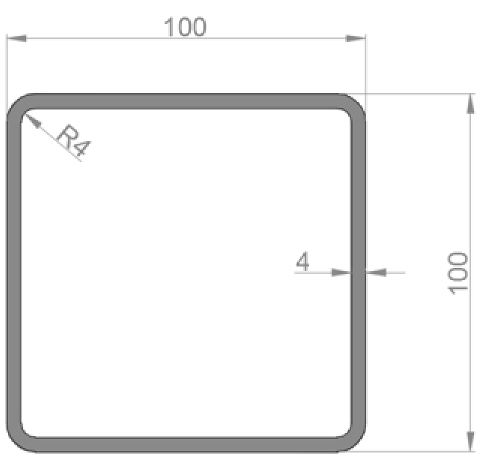
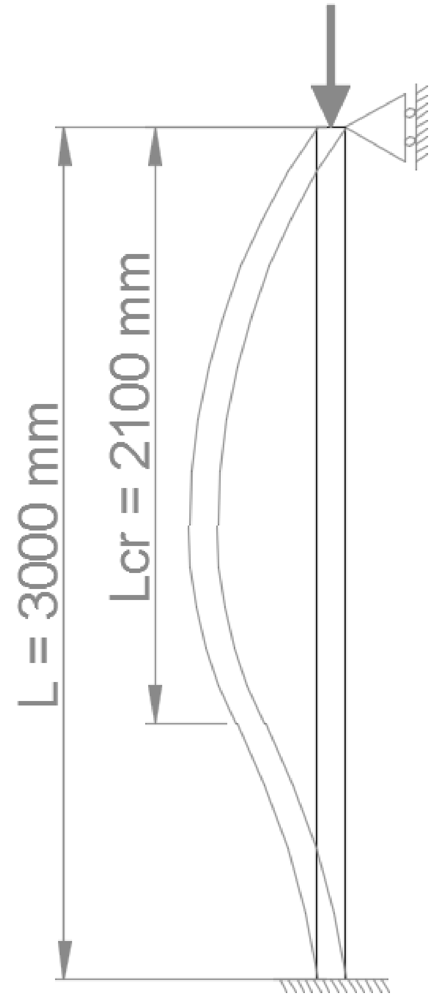
Design example #2

– Column buckling - Comparison with carbon steel:

Material	Carbon steel S235	Austenitic stainless steel EN 1.4301
f_y	235 N/mm²	230 N/mm²
E	210 000 N/mm²	200 000 N/mm²





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Design example #2

	EC 3-1-1: S235	EC3-1-4, old version: stainless steel	DM and EC3-1-4, with amendments
$A\ [mm^2]$	1495	1495	1495
$I\ [mm^4]$	2260000	2260000	2260000
$E\ [N/mm^2]$	210000	200000	200000
$f_y\ [N/mm^2]$	**235**	**230**	**230**
$f_{ya}\ [N/mm^2]$	**235**	**323**	**318**
$\gamma_{M0}\ [-]$	**1,0**	**1,1**	**1,1**
$\gamma_{M1}\ [-]$	**1,0**	**1,1**	**1,1**
$\varepsilon\ [-]$	**1**	**0,99**	**0,99**
Class	Class 1	Class 1	Class 1
$N_{c,Rd}\ [kN]$	351	439	432
$L_{cr}\ [mm]$	2100	2100	2100
$N_{cr}\ [kN]$	1062	1012	1012
$\bar{\lambda}\ [-]$	0,575	0,691	0,685
$\alpha\ [-]$	0,49	0,49	0,49
$\bar{\lambda}_0\ [-]$	**0,2**	**0,4**	**0,3**
$\phi\ [-]$	0,757	0,810	0,829
$\chi\ [-]$	0,80	0,81	0,77
$N_{b,Rd}\ [kN]$	281	356 >	334

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Design example #2

– Comparison:

	EC 3-1-1: S235	DM and EC3-1-4, with amendments
$f_y\ [N/mm^2]$	235	230
$f_{ya}\ [N/mm^2]$	**235**	**318**
$\gamma_{M0}\ [-]$	1,0	1,1
$\gamma_{M1}\ [-]$	1,0	1,1
$N_{c,Rd}\ [kN]$	351	432
$N_{b,Rd}\ [kN]$	281	334

– In this example, stainless steel shows a higher resistance to flexural buckling and compression. ⇒ **benefits** of strain hardening due to the cold worked section.

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Life-Cycle Cost Assessment (LCCA) of bridges

PUREST

Rossi B., Marquart S., Rossi G. (2017). Comparative life cycle cost assessment of painted and hot-dip galvanized bridges. *Journal of Environmental Management*, 197, 41-49.

Stainless steel…

- Has proven longevity
  - Numerous projects with >80 years of service
  - Appropriate specification & maintenance can give >100’s years of service
- Is indefinitely recyclable
  - 92% recaptured at the end of life and made into new metal
  - Can also be restored & reused during renovation
- Has high scrap content
  - 60% international average
  - 75 to 90% - European and US producers


Gateway Arch, St Louis, 1965: the first large stainless structural application
© Catherine Houska

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Cost considerations

– Initial cost of stainless steel is high
– And dependent on the cost of alloying elements

But life cycle cost analyses show that stainless steel can be the cheapest option compared to materials requiring more maintenance

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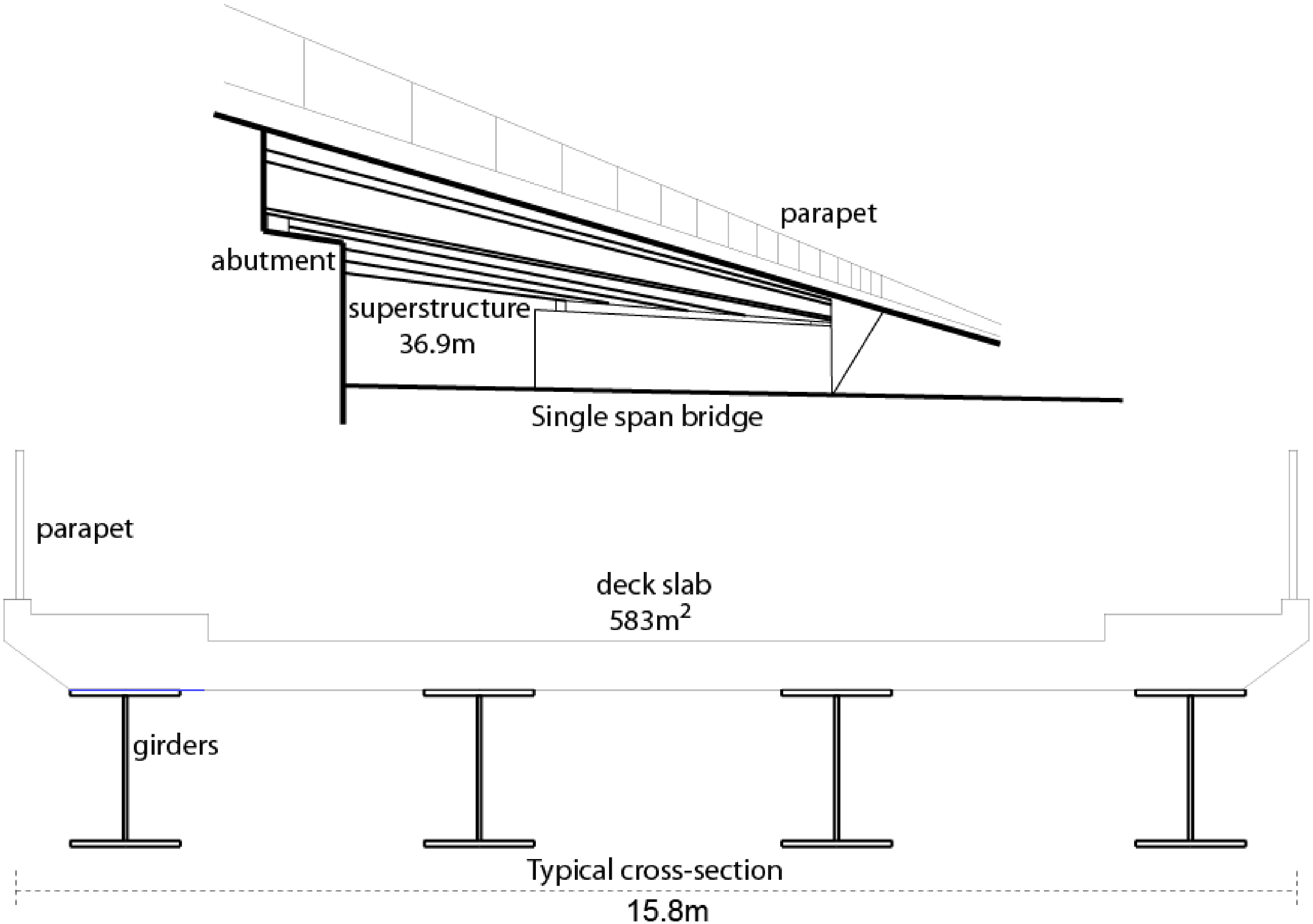
Studied bridge



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Studied bridge

– Size, weight and surface chosen according to Bridge Inventory data:

Bridge Overall Dimensions			Data steel				
Length (m)	Width (m)	Area (m^2)	Specific Weight (t/m^2)	Steel Weight (t)	Specific Surface (m^2/t)	Steel Surface (m^2)	Steelwork Data)
36.9	15.8	583	0.18	104.94	14.25	1495	1346

– Material option:
  – Option 1: Carbon steel with initial coating including regular maintenance and variable maintenance scenario
  – Option 2: Stainless steel

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The boundary of the LCCA

- Following the principles described in EN 15643-4:2012 for buildings, the system boundary includes costs related to:
  - **Module A** i.e. the Cost of **products supplied at factory gate** ready for construction, all other costs (i.e. purchase of land, professional fees, taxes…) being disregarded ;
  - **Module B2** i.e. the Cost of **repairs and replacement** of minor components/small areas and the cost of Replacement or refurbishment of major systems and components.
  - No Economic impacts and aspects at the End of Life (**Modules C1-C4**) are presently taken into account
  - Traffic congestion costs are not included in this analysis (as in the sense of EN 15643-4:2012)

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Coated steel bridges – Painting system

- **Step 0 : Initial coating**
  - Surface preparation (solvent cleaning, hand & tool cleaning, abrasive blast cleaning, water jetting)
  - Application of coating, commonly:
    - A zinc-rich primer onto the prepared surface (in shop) ⇨ adhesion and corrosion protection
    - Followed by one or more undercoat(s) (in shop) ⇨ barrier function
    - Followed by the finish coat (on site) ⇨ UV-radiation protection and aesthetic

- E.g. typical high performance layer composition (supposed to be used in corrosive environment)

Layer	Binder / Pigment	Thickness (µm)	Total thickness (µm)
Topcoat (Finish)	Aliphatic polyurethane	1 x 50	275 measured (mean): 268
Intermediate Coat	Epoxy polyamide	1 x 150	
Primer	Ethyl silicate / Zinc powder	1 x 75	

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Coated steel bridges – Maintenance activities

- **Step 1: 'Patch-up'** (or 'touch-up') i.e. Preparation on localized areas + application of a compatible new coat
- **Step 2: Overcoating** i.e. removal of small deteriorated areas or of a whole layer of coating + preparation + new coating of the whole surface
- **Step 3: Remove & Replace** i.e. All rusted areas and existing coatings are removed + new coating of the whole surface

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Painting system – Cost data

– Cost data **($/m²)** based on Literature review & Interview with experts:

Reference	**Cost range for different painting operations ($/m²)**											
	Initial Coating			Patch Up			Overcoating			Remove & Replace		
(Mark Yunovich)	17.12	-	53.70	17.12	-	53.70	11.00	-	86.00	43.00	-	215.25
(Jayson L. Helsel, 2008)	11.05	-	44.67	23.96	-	220.34	13.25	-	116.93	27.94	-	258.83
(bauforumstahl, et al., 2013)	17.70	-	36.97	n.a.	-	n.a.	35.79	-	74.97	n.a.	-	n.a.
(Raed El Sarraf)	37.50	-	57.45	82.70	-	122.95	n.a.	-	n.a.	50.50	-	n.a.
(Kwang-Min Lee, 2006)	n.a.	-	n.a.	n.a.	-	n.a.	n.a.	-	n.a.	n.a.	-	236.00
(American Iron and Steel Institute, 2007)	n.a.	-	n.a.	n.a.	-	n.a.	43.06	-	64.58	129.20	-	150.69
Experts (3)	n.a.	-	n.a.	56.95	-	68.34	n.a.	-	n.a.	113.90	-	170.85
Average	**20.8**	**-**	**48.2**	**45.1**	**-**	**116.3**	**25.7**	**-**	**85.6**	**72.9**	**-**	**206.3**
StdDev.	**11.5**		**9.2**	**30.5**		**75.5**	**16.1**		**22.5**	**45.5**		**44.9**

Painting system – Service life data

– **Service life (year)** data based on Literature review & Interview with experts:

Painting system	Maintenance Event	System age in environment C4 (years)				Average Service Life Extension (years)
		Literature	Experts	Average	StdDev.	
	'Touch Up'	15.2	10.5	**12.8**	**3.0**	5.7
	'Overcoating'	17.1	19.3	**18.5**	**2.2**	12.5
	'Remove & Replace'	31.6	30	**31.0**	**8.6**	12.8

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Case study 1 – Hypotheses and results

- **E0: Initial coating**
- **E1: 'Patch-up'**
- **E2: Overcoating**
- **E3: Remove & Replace**

- **SCENARIO** painted steel: E1/E2/E3-E1/E2/E3

- Touch Up: 5% of the surface

- Overcoating: Preparation of 10% and coating of 100% (already included in the previous costs)

- Material cost: $C_{\text{stainless steel}} / C_{\text{carbon steel}} = 3$

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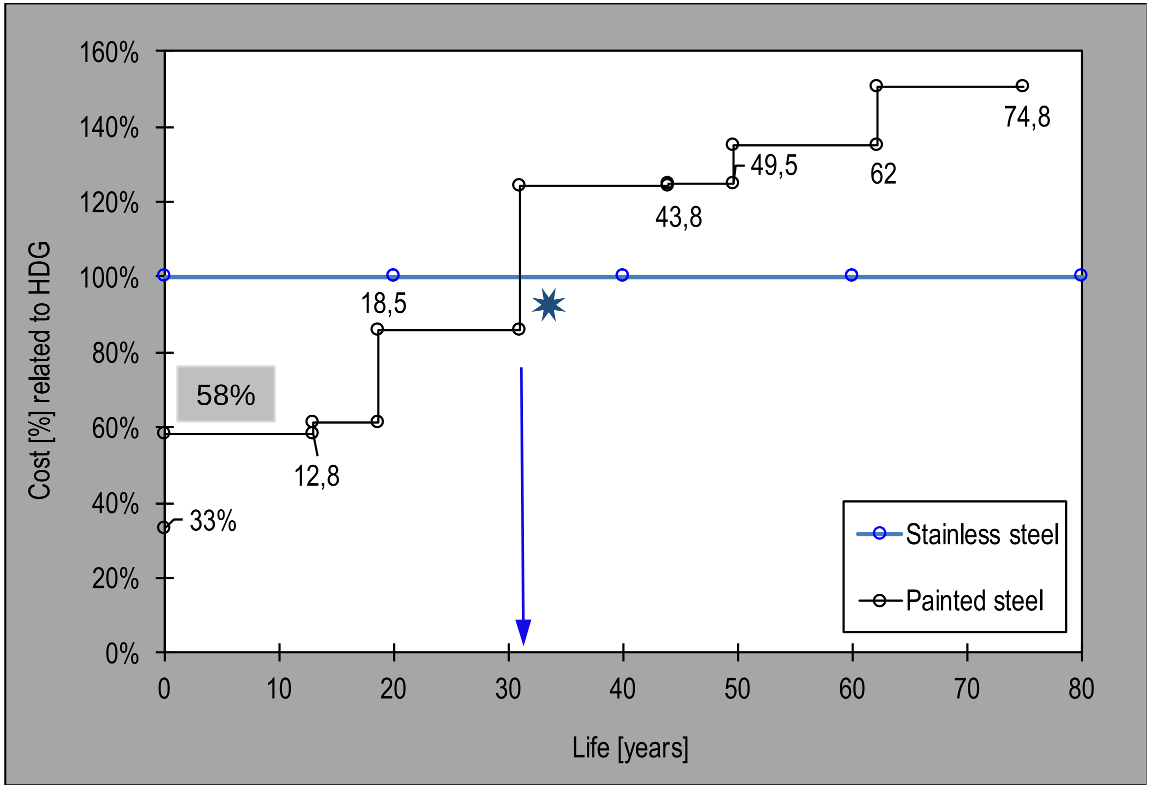
Case study 1 – Hypotheses and results



The ratio $C_{stainless\ steel}$ / $C_{carbon\ steel}$ is the most important parameter to ↙ the return on investment time:

- If $C_{stainless\ steel}$ / $C_{carbon\ steel}$ = 3 about 30 for return on investment
- If $C_{stainless\ steel}$ / $C_{carbon\ steel}$ = 2 about 20 years !

Case study 2 – Influence of the scenario

- Maintenance Scenario:
  - E0: Initial coating
  - E1: 'Patch-up'
  - E2: Overcoating
  - E3: Remove & Replace

- Permutation of « independent events » over the life of the bridge e.g.

  - E0: Initial coating
  - E1: 'Patch-up'
  - E1: 'Patch-up'
  - E2: Overcoating
  - E3: Remove & Replace…

- With probability of occurrence P

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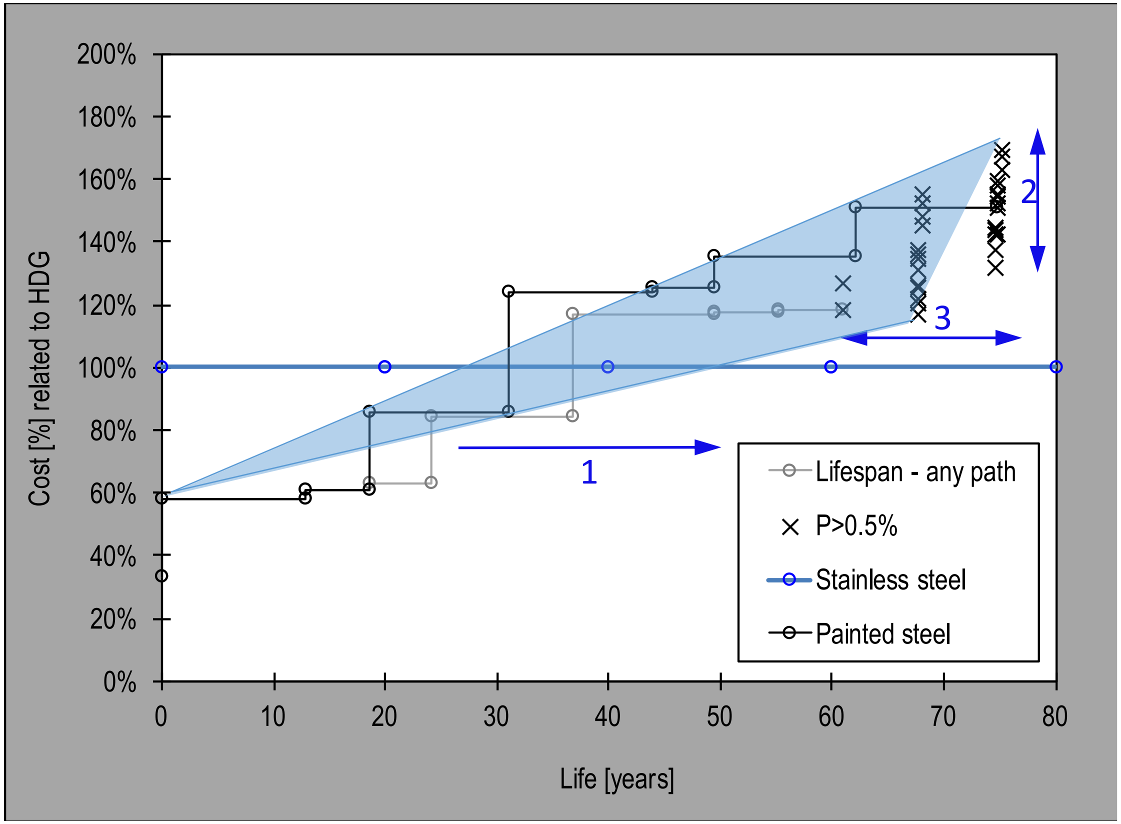
Case study 2 – Influence of the scenario



Only for the « most probable » cases (P>0.5%)

1 Investment return: depending on the chosen scenario, investment return happens early or very late
but for small lifespan !

2 and 3 Range of LC cost of painted steel bridge:
from ~100% for ~60 year's life
up to ~170% for ~90 year's life!

http://www.steel-stainless.org/media/1533/dmsss4-french-complete.pdf

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