Supporting presentation for lecturers of Architecture/Civil Engineering

Part A:

Structural Applications of Stainless Steel Reinforcing Bar

See also: stainlesssteelrebar.org

Wrong choice of materials can lead to big problems


19
13
14

A textbook case: Corrosion of the Turcot highway interchange in Montreal [1,2]

- A key interchange between Decarie (North-South) and Ville Marie (East-West) highways, built in 1966.
- Over 300,000 vehicles per day
- Made of reinforced concrete, badly corroded today by deicing salts

It had to be replaced

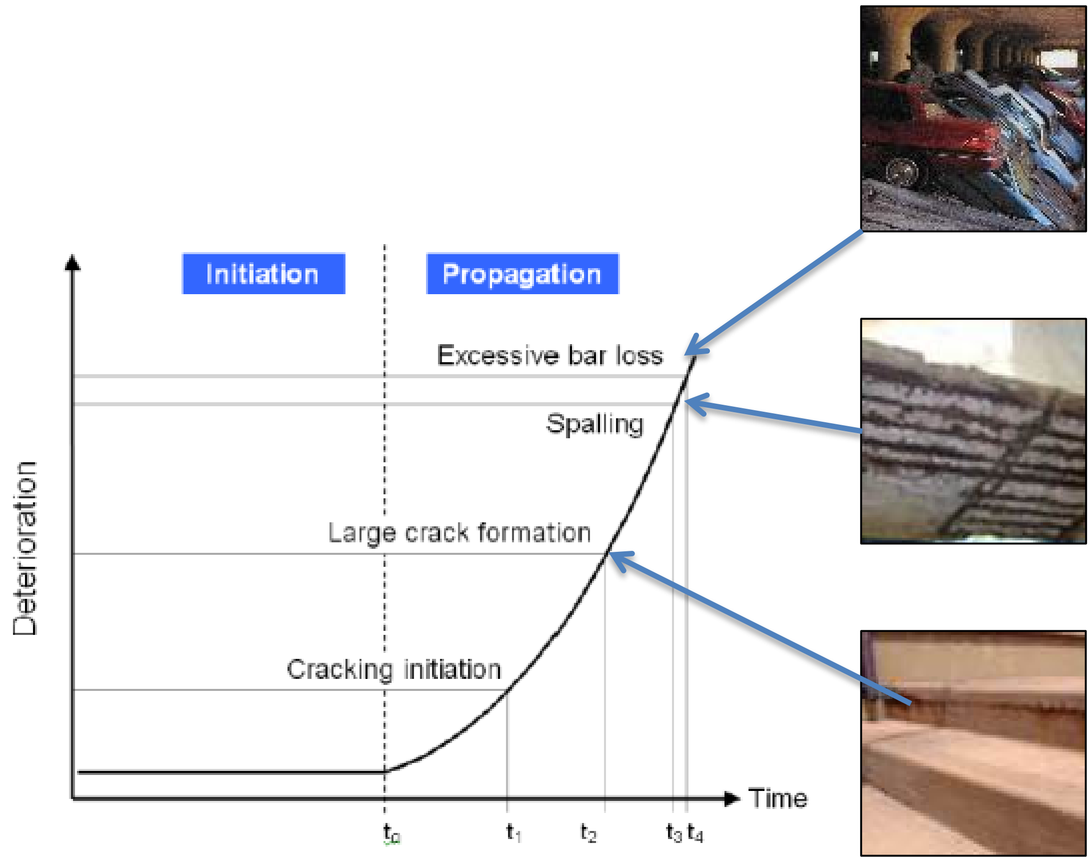
- In spite of constant supervision and repairs, it had to be replaced,
  - Cost CAD 3000M.
  - Moreover, CAD 254M had to be spent to ensure safety until its replacement in 2018
- Lifespan of the structure was only 50 years!

How reinforced concrete can be damaged by corrosion

Diffusion of corrosive ions (usually chlorides) into concrete:

Steps[3]:

1. Once corrosive ions reach the carbon steel rebar (t0), corrosion begins
2. Corrosion products, which occupy a greater volume than steel, exert an outwards pressure
3. Concrete cracking occurs (t1), opening easy access to chlorides
4. Concrete cover cracks (spalling) (t3), exposing the rebar
5. If unattended, corrosion continues until the rebar cannot bear the applied tensile stresses and the structure collapses (t4)



Corrosion of rebar in concrete [21]

- In the high pH of concrete, in the absence of chlorides, carbon steel rebar is in a passive state (i.e. does not corrode)
- A low chloride content is sufficient to activate corrosion of carbon steel
- Stainless steel properly specified never corrodes.
- Galvanic coupling between stainless steel rebar (anode) and carbon steel rebar (cathode) contributes only to ~1% of the overall corrosion rate*. It is therefore negligible.
- Type of concrete, temperature, exposure conditions, distance between carbon steel rebar and surface, etc… have a strong influence on the corrosion rate of the carbon steel rebar

* Specific references are provided at the end of the presentation

Cracks in concrete accelerate corrosion [4]

Concrete often exhibits cracks, though which corrosive ions reach quickly the steel.

Here are some causes of crack formation.

Please note that cracks do not take place immediately, and will also occur in concealed areas, where they cannot be repaired.

Type of cracking	Form of crack	Primary Cause	Time of Appearance
Plastic settlement	Above and aligned with steel reinforcement	Subsidence around rebar; excessive water in the mix	10 minutes to three hours
Plastic shrinkage	Diagonal or random	Excessive early evaporation	30 minutes to six hours
Thermal expansion and contraction	Transverse (example: across the pavement)	Excessive heat generation or temperature gradients	One day to two or three weeks
Drying shrinkage	Transverse or pattern	Excessive water in the mix; poor joint placement; joints over-spaced	Weeks to months
Freezing and thawing	Parallel to the concrete surface	Inadequate air entrainment; non-durable coarse aggregate	After one or more winters
Corrosion of reinforcement	Above reinforcement	Inadequate concrete cover; ingress of moisture or chloride	More than two years
Alkali-aggregate reaction	Pattern cracks; cracks parallel to joints or edges	Reactive aggregate plus moisture	Typically, over five years, but may be much sooner with highly reactive aggregate
Sulfate attack	Pattern cracks	External or internal sulfates promoting the formation of ettringite	One to five years

Major civil engineering structures must last over 100 years now

Haynes Inlet Slough Bridge, Oregon, USA 2004[7,8]

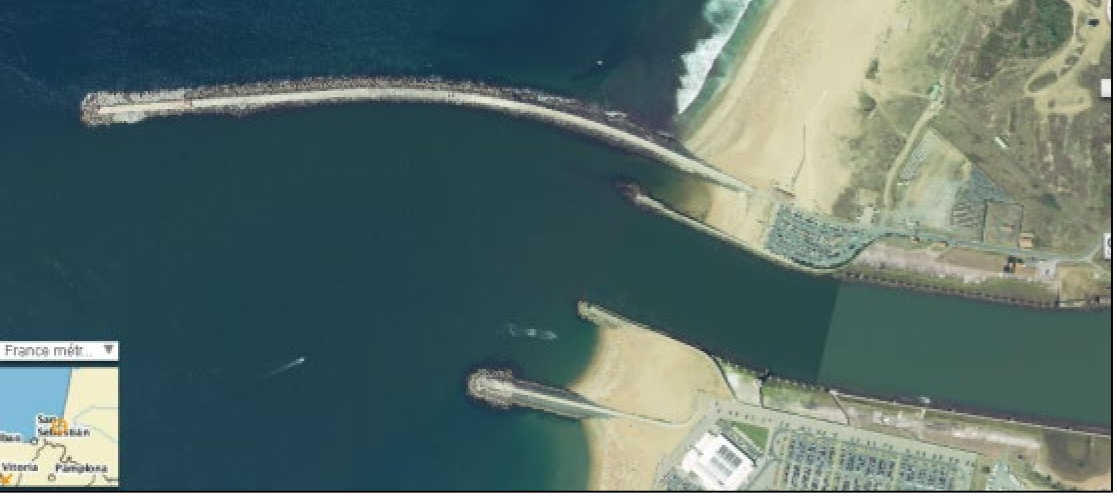
An unusual arch-hinged bridge with 400 tons of stainless steel reinforcing bar in its deck.

The 230m-long link over Haynes Inlet Slough is expected to last 120 maintenance-free years.

Although stainless steel costs a lot more than average steel, the bridge life-cycle cost will be greatly reduced.

Broadmeadow Bridge, Dublin, Ireland (2003)[10]

A new construction built over the estuary using 105MT of stainless steel reinforcement in the columns and parapets.



Aerial view

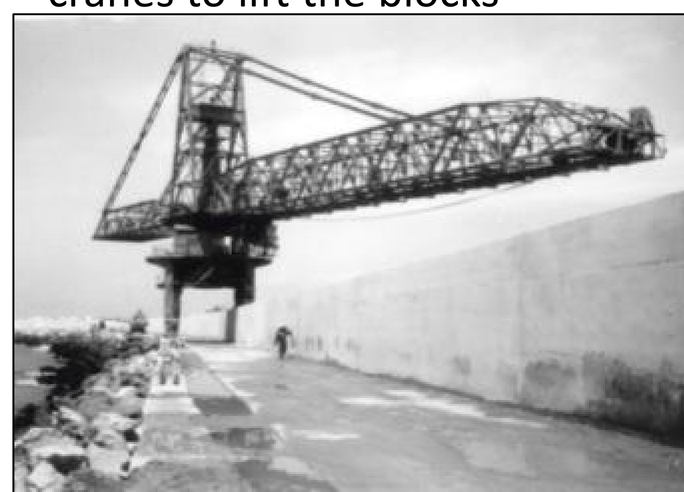
Cracks on the deck and wall required repairs

Dam repair [11] Bayonne, France

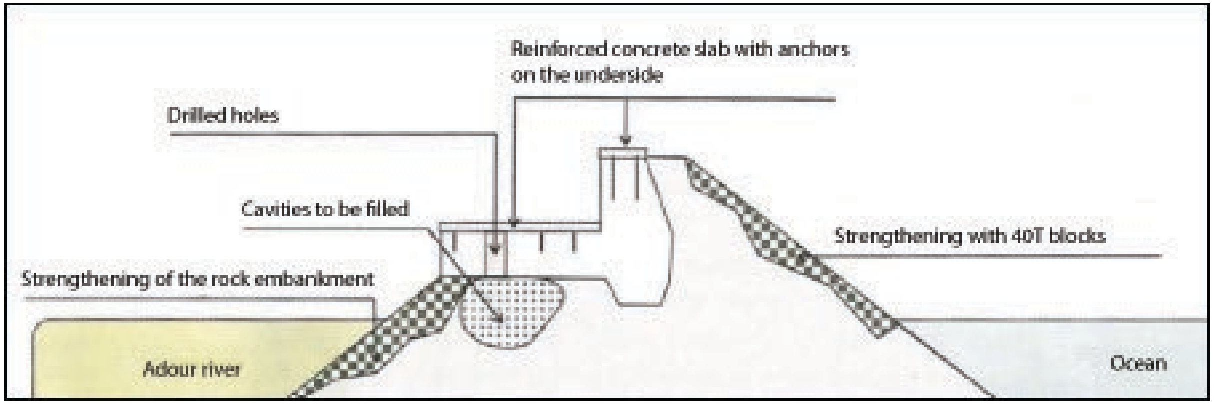
Dam built in the 1960s to protect the entrance to the harbour

The ocean side is higher and protected by 40T blocks which must be replaced as the storms wear them

On the river side a 7m wide platform allows the heavy-duty cranes to lift the blocks



Section through the sea wall



Sea wall repair Bayonne, France

Platform and sea wall have been reinforced with lean duplex stainless steel (EN 1.4362)[11]

Sea wall repair under way

Early 2014 gale over the dam

Belt Parkway Bridge, Brooklyn, USA (2004)[14]

To assure long-term (100 years) durability and resistance to the corrosive attack of the area's marine environment and road salt, the bridge units and parapet barriers were reinforced with stainless steel grade 2205 rebar.

When should stainless steel rebar be considered [15-20]?

- In corrosive environments:
- Sea water and even more in hot climates
  - Bridges
  - Piers
  - Docks
  - Anchors for lampposts, railings,….
  - Sea walls
  - …..
- Deicing salts
  - Bridges
  - Traffic overpasses and interchanges
  - Parking garages
- Waste water treatment tanks
- Desalination plants
- In structures with a very long life
  - Repairs of historic structures
  - Nuclear waste storage
- In unknown environments in which
  - inspection is impossible,
  - Repairs are almost impossible or very expensive

Comparison of stainless rebar with alternative solutions[15-20]

	Advantages	Drawbacks
Epoxy coating	Lower initial costs	▪ cannot be bent without cracking ▪ Requires careful handling to avoid damaging it during installation
Galvanizing	Lower initial costs	▪ cannot be bent without cracking ▪ No longer effective when the zinc coating has been corroded
Fiber-reinforced Polymers	Lower initial costs	▪ Cannot be bent without cracking ▪ No heat resistance and poor impact resistance in harsh winters ▪ Lower stiffness than that of steel ▪ Cannot be recycled
STAINLESS STEEL	Low Life Cycle cost: • Design similar to C-steels • Mixed C-steel/stainless reinforcements work well • Easy installation, insensitive to poor workmanship • No maintenance • No life limit • Allows a thinner concrete cover • Better fire resistance • 100% Recycled to premium stainless	▪ Higher initial cost, but no more than a few % when ✓ Stainless is selected for the critical areas ✓ Lean duplex grades are selected

Comparison of stainless rebar with alternative solutions[15-20]

	Advantages	Drawbacks
Cathodic protection	Lower initial costs ? Often used for repairs	▪ Requires careful design for overall protection ▪ Requires careful installation to maintain proper electrical contacts ▪ Requires a permanent source of current (which must be monirored and maintained) or sacrificial anodes that require monitoring & replacement
Membranes/ sealants	Lower initial costs?	▪ Require careful installation (bubbles) ▪ Cannot be installed in any weather ▪ Performance over time debatable ▪ Limited to horizontal surfaces

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NEW !

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Thank you

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6

Supporting presentation for lecturers of Architecture/Civil Engineering

Part B

Structural Applications of Stainless Steel Plates, Sheets, Bars, ….

Structural Stainless Steel
Designing with stainless steel

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Based on a previous version prepared by Nancy Baddoo
Steel Construction Institute, Ascot, UK

Outline

- Examples of structural applications
- Material mechanical characteristics
- Design according to Eurocode 3
- Alternative methods
- Deflections
- Additional information
- Resources for engineers

Section 1

Examples of structural applications

Station Sint Pieters, Ghent (BE)

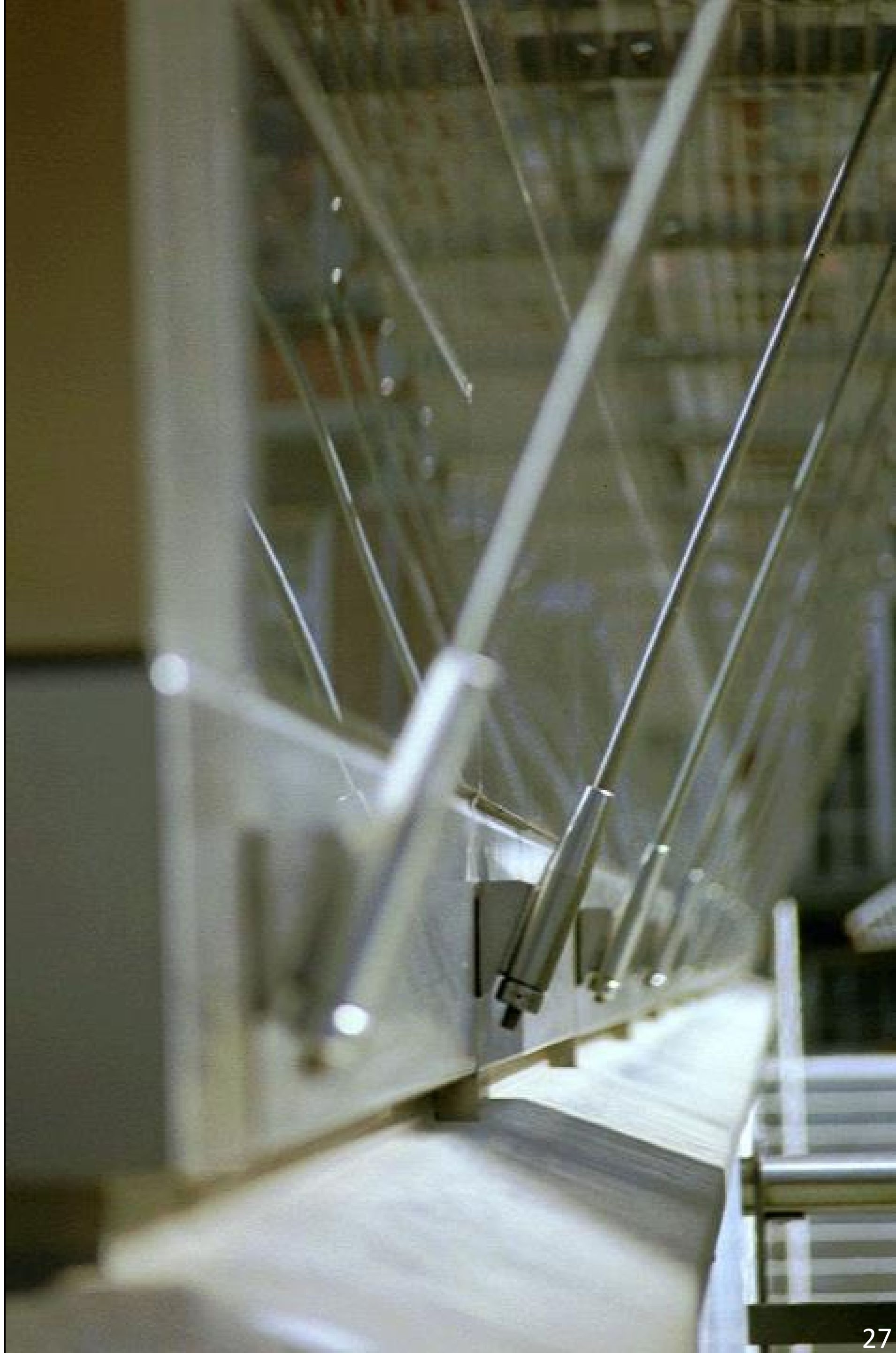
Arch : Wefirna

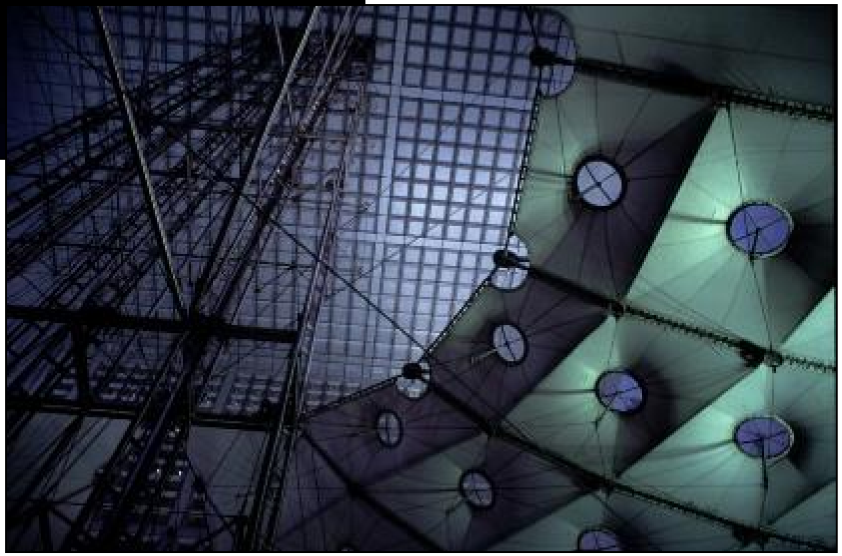
Eng. Off.: THV Van Laere-Braekel Aero

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, (France)

Arch: Arte Charpentiers & Associés

Eng. Off.: Mitsu Edwards

Station in Porto (Portugal)

Torno Internazionale S.P.A. Headquarters Milan, (IT), Stainless steel grade: EN 1.4404 (AISI 316L)

Architect : 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.

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

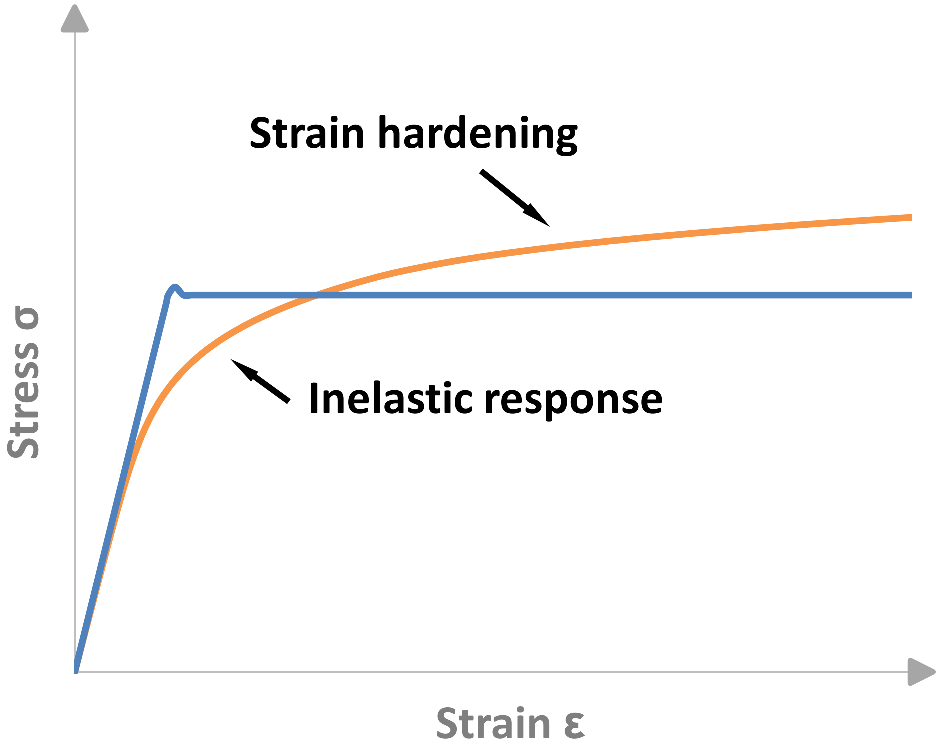
Photography: Interserve

Section 2

Material mechanical characteristics

Stress-Strain characteristics: Carbon steel vs stainless steel

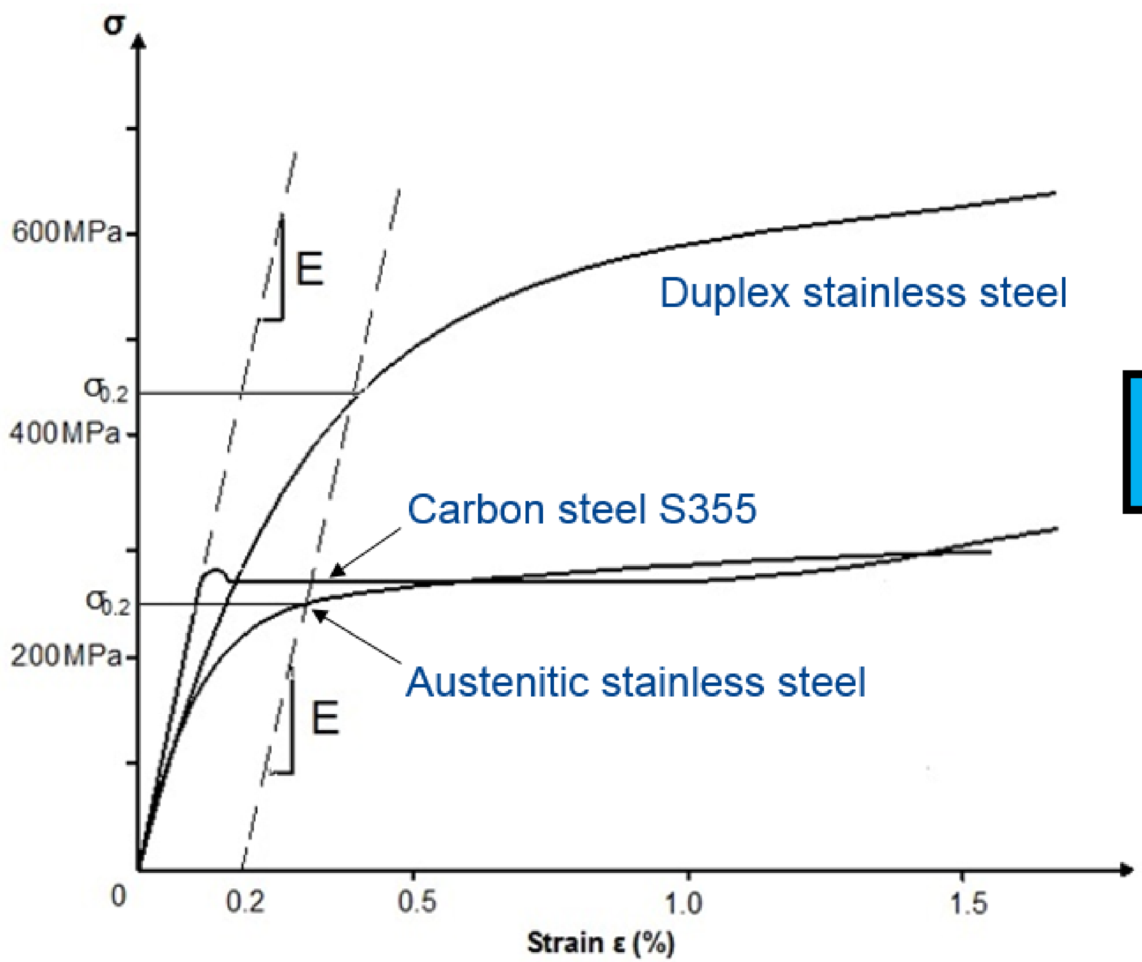
Stainless steel exhibits fundamentally different σ-ε behaviour to carbon steel.



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



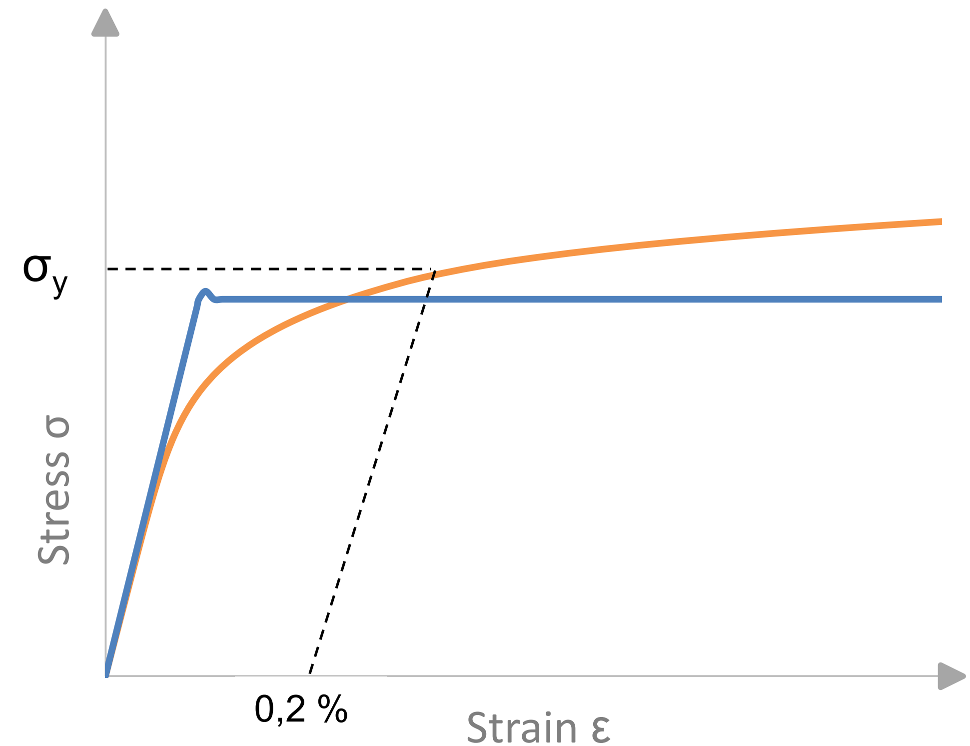
Stress-strain response depends on the family.

Design strength of stainless steel

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

Austenitics: f_y = 220-350 MPa
Duplexes: f_y = 400-480 Mpa
Ferritics: f_y = 210-280 MPa

Young's modulus: E=200,000 to 220,000 MPa



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 (%)
1.4301 (304)	Austenitic	210	520	200000	45
1.4401 (316)	Austenitic	220	520	200000	40
1.4062	Duplex	450	650	200000	
1.4462	Duplex	460	640	200000	
1.4003	Ferritic	250	450	220000	

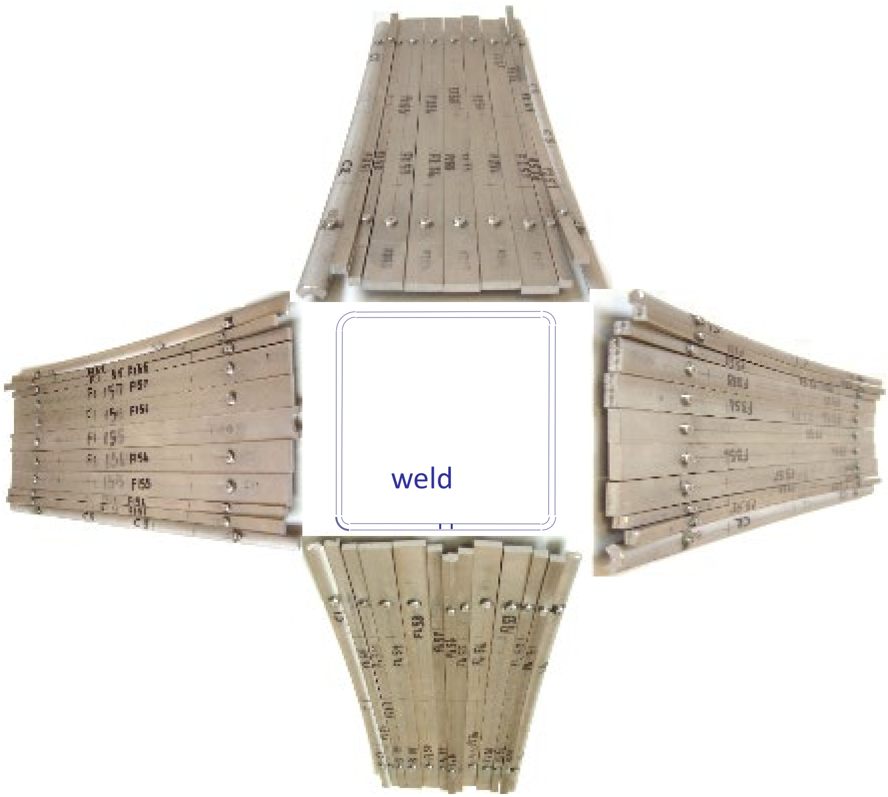
Strain hardening (work hardening or cold working)

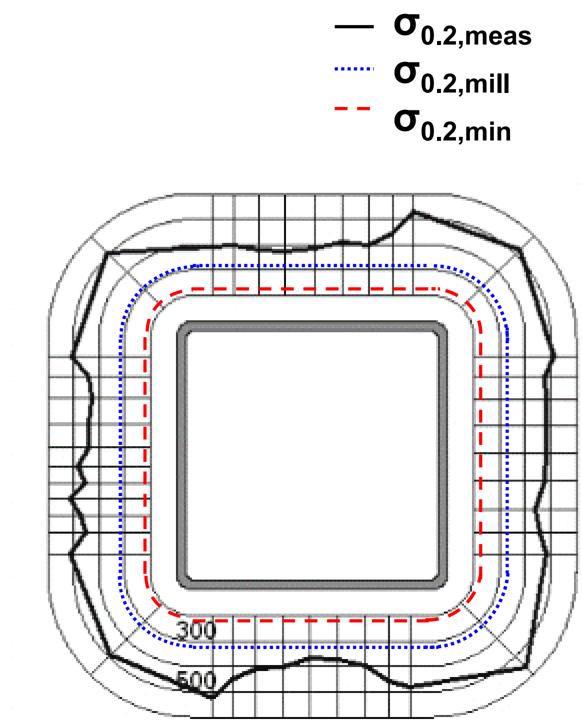
- Increased strength by plastic deformation
- Caused by cold-forming, either during steel production operations at the mill or during fabrication processes

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!

Strain hardening (work hardening or cold working)

- **Strength enhancement during forming**

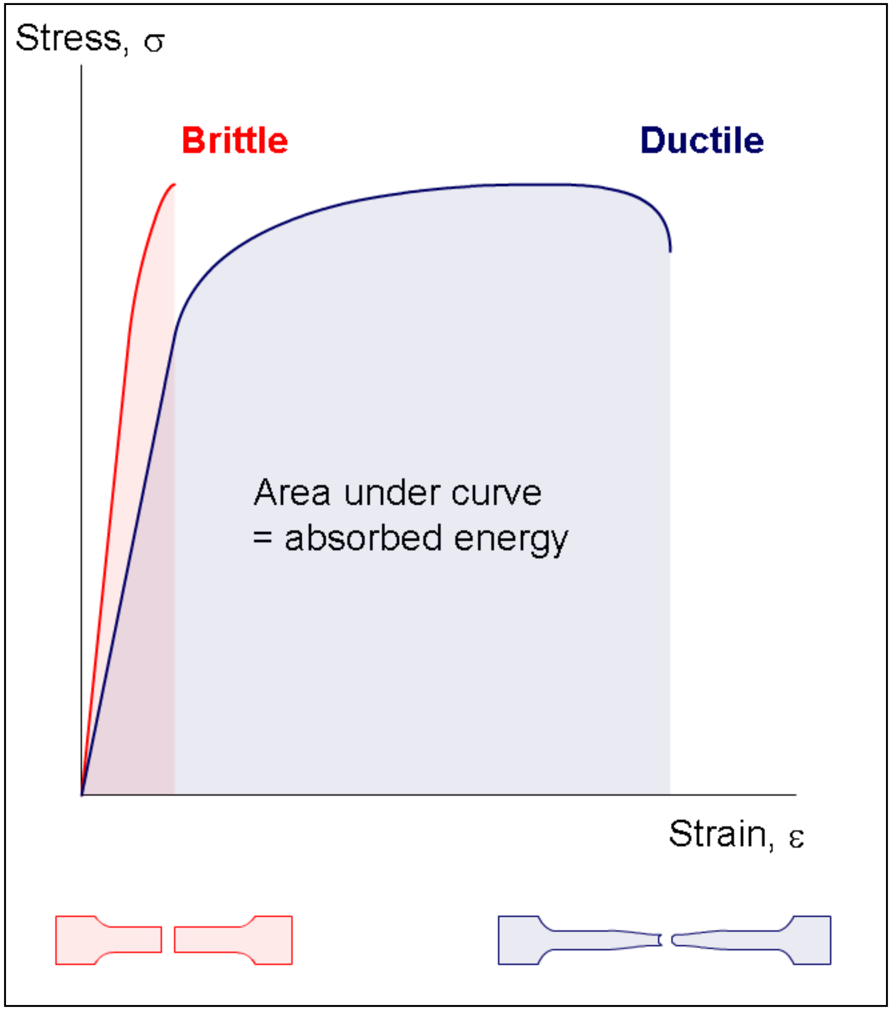




Strain hardening – not always useful

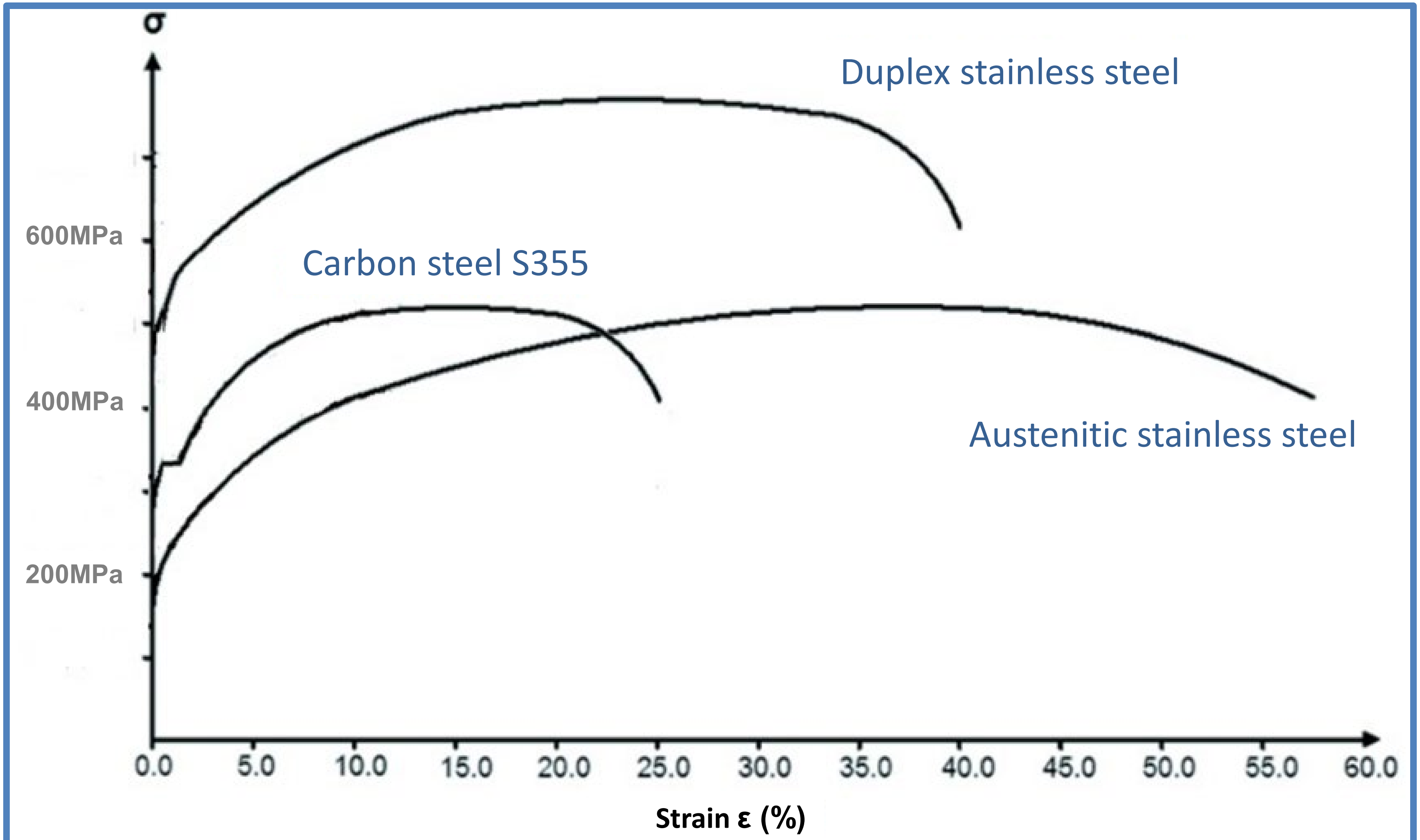
- Heavier and more powerful fabrication equipment
- Greater forces are required
- Reduced ductility (however, the initial ductility is high, especially for austenitics)
- Undesirable residual stresses may be produced

Ductility and toughness



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

Stress-Strain Characteristics – high strain



Blast/impact resistant structures

Security bollard

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

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

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

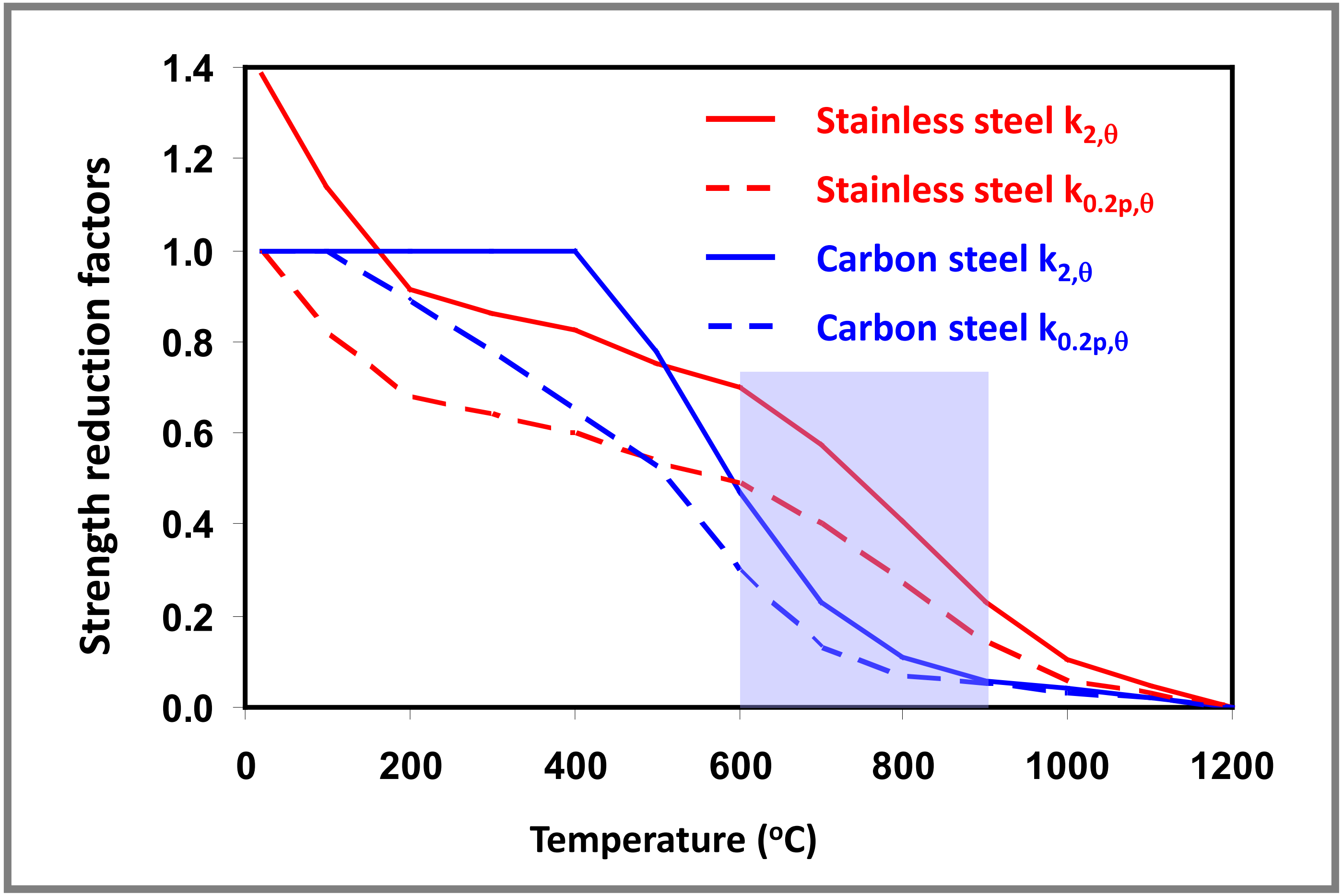
- **High slenderness**
  axial strength low, stresses low and in linear region

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

Impact on buckling performance

- **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

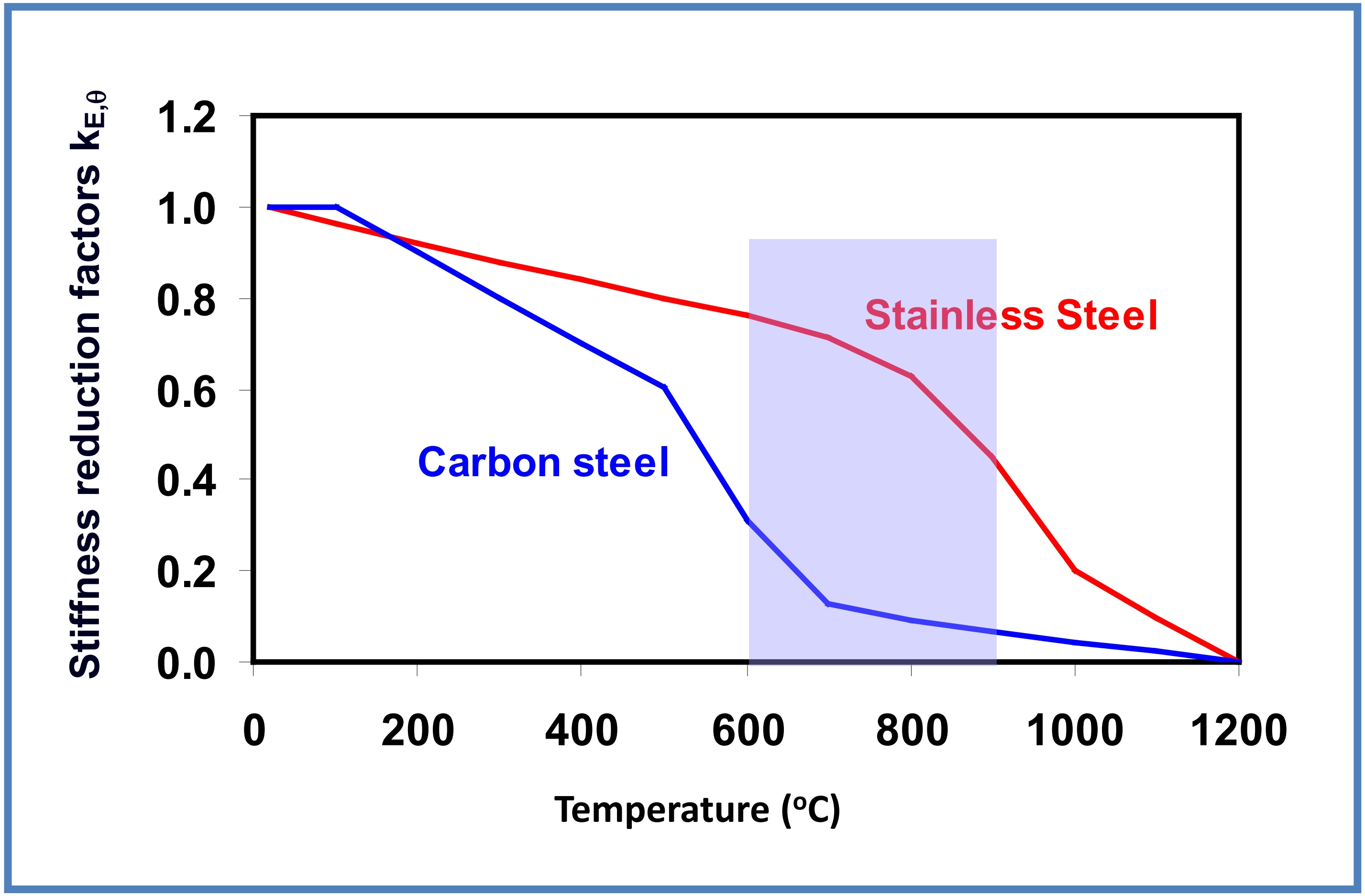
Material at elevated temperature



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

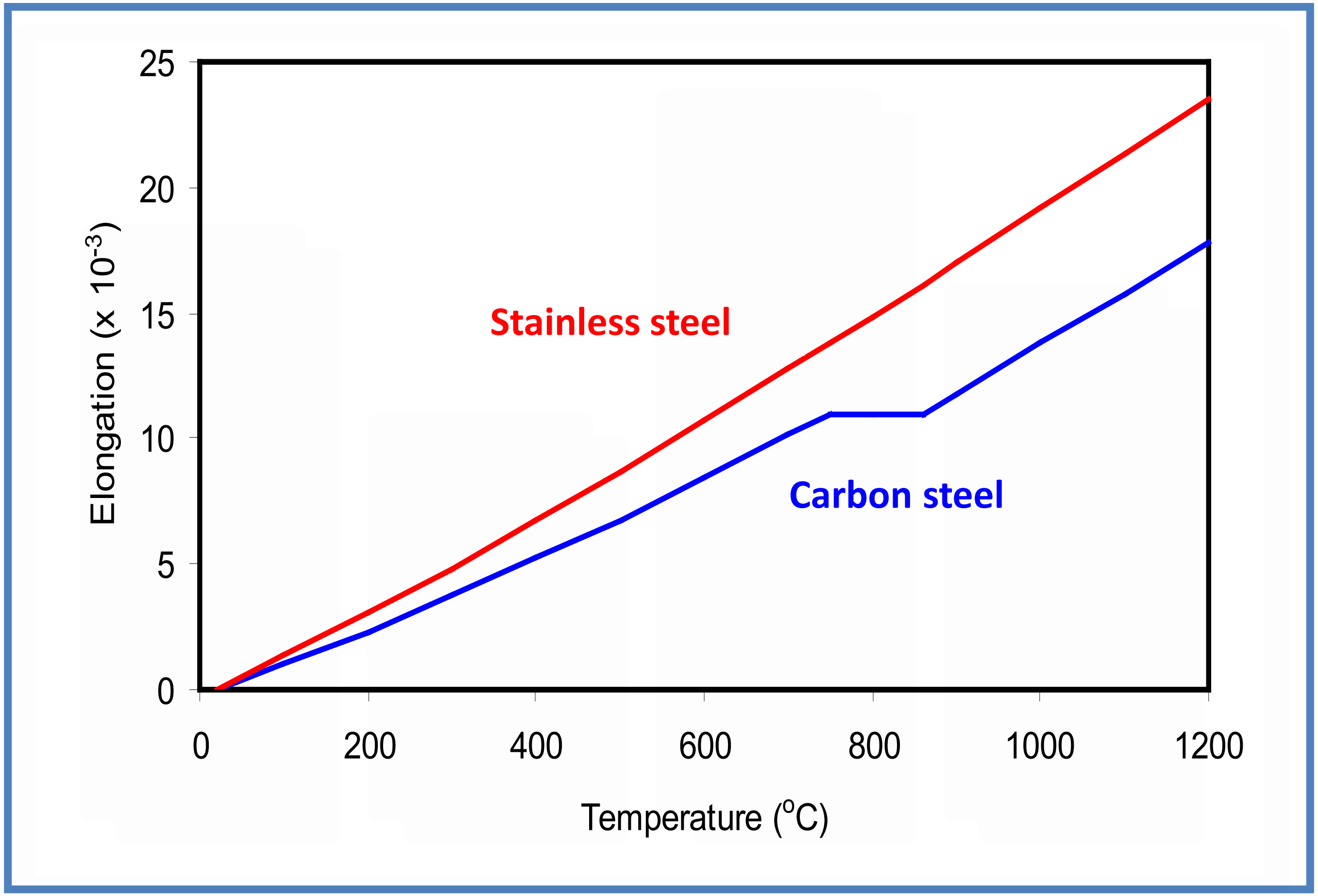
$k_{2,q}$ = strength reduction factor at 2% total strain

Material at elevated temperature



Stiffness reduction factor

Material at elevated temperature



Thermal expansion

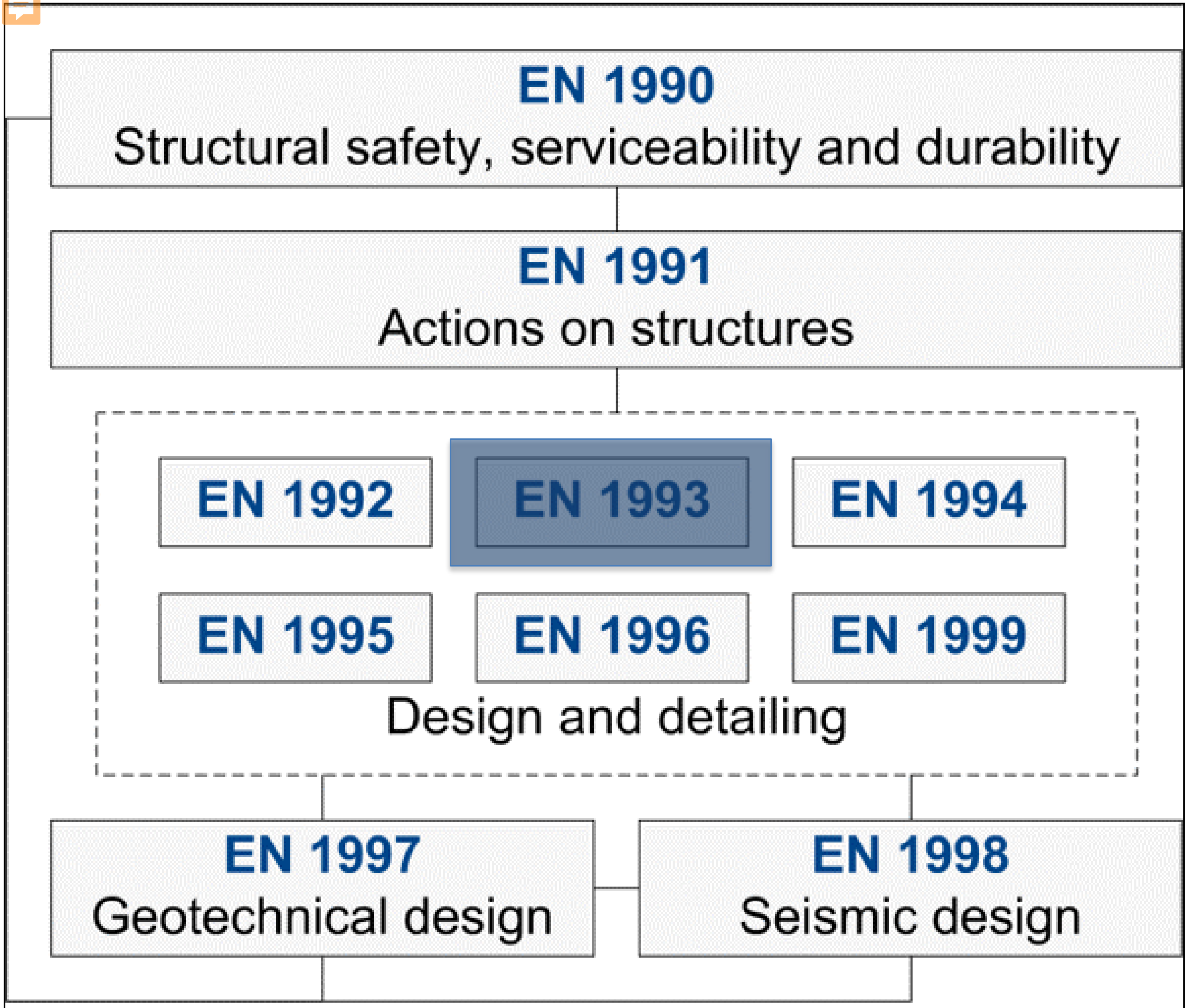
Section 4

Design according to Eurocode 3

International design standards

What design standards are available for structural stainless steel?

Hamilton Island Yacht Club, Australia



Links between the Eurocodes

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

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
- 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	Future 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)*

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 expressions in EN 1993-1-4

- Lower limiting width-to-thickness ratios than for carbon steel

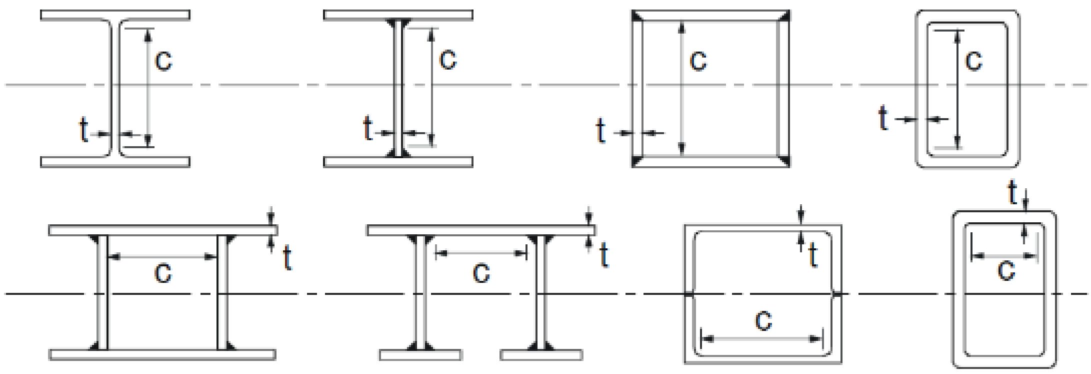
- Slightly different expressions for calculating effective widths of slender elements

However…

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

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

- Internal compression parts

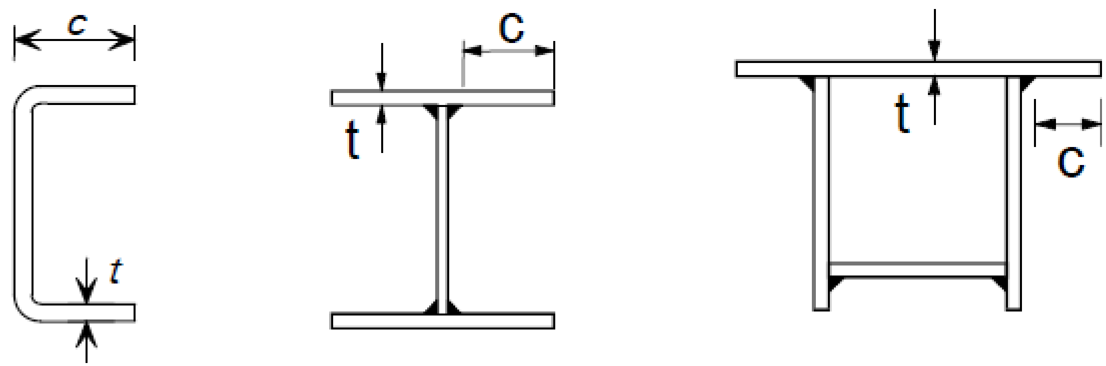


$$\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}}$$

	EC3-1-1: carbon steel		EC3-1-4: stainless steel		EC3-1-4: Future 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



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

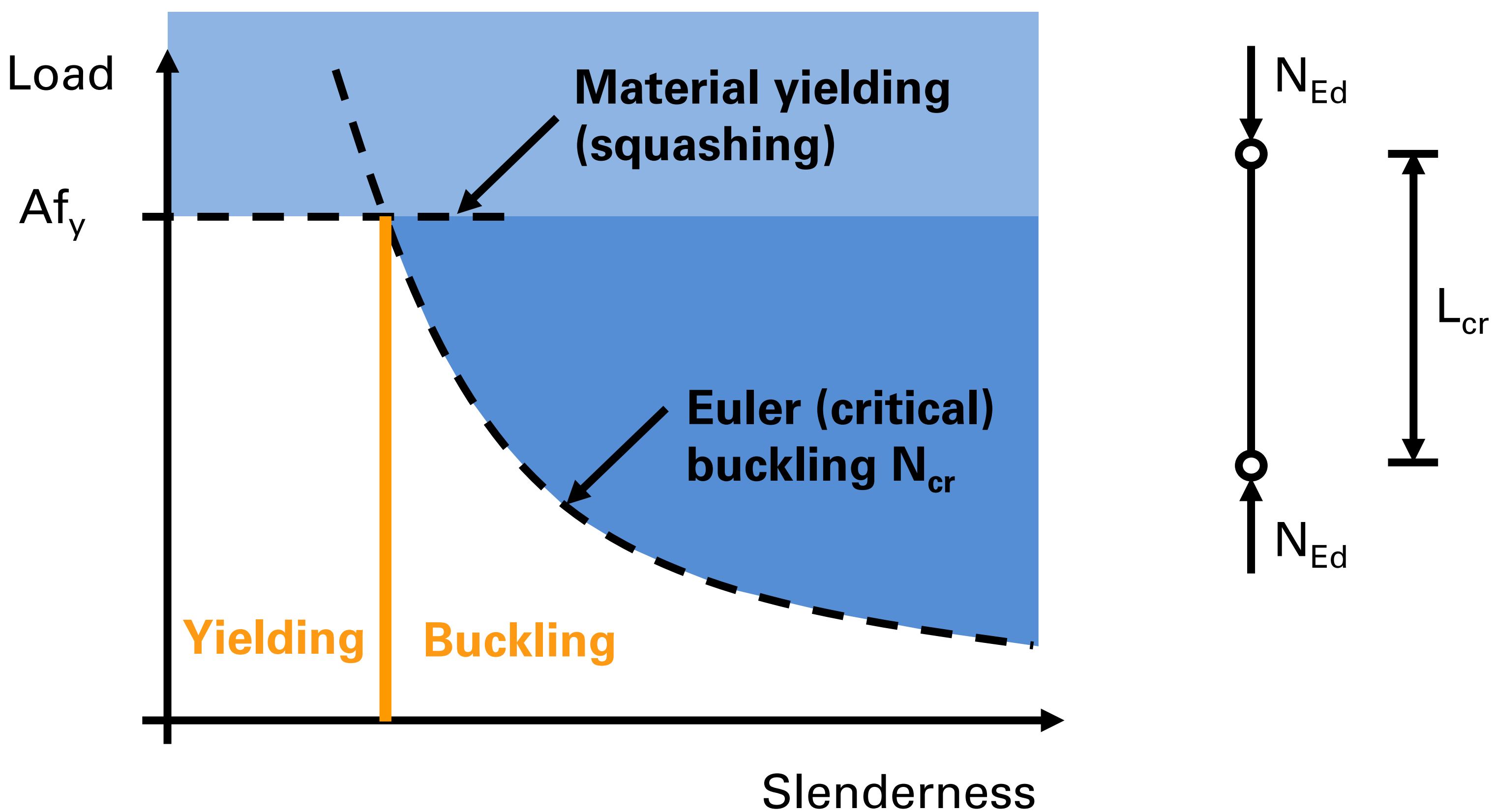
	EC3-1-1: carbon steel	EC3-1-4: stainless steel		EC3-1-4: future revision
Class	Compression	Compression Welded	Compression Cold-formed	Compression
1	c/t ≤ 9ε	c/t ≤ 9ε	c/t ≤ 10ε	c/t ≤ 9ε
2	c/t ≤ 10ε	c/t ≤ 9,4ε	c/t ≤ 10,4ε	c/t ≤ 10ε
3	c/t ≤ 14ε	c/t ≤ 11ε	c/t ≤ 11,9ε	c/t ≤ 14ε

Design of columns & beams

- In general use same approach as for carbon steel
- 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)

"Perfect" column behaviour

Two bounds: Yielding and buckling:



Column buckling

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

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

for Class 1, 2 and 3

Reduction factor

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

for (symmetric) Class 4

Column buckling

Non-dimensional slenderness: $\bar{\lambda}$

$$\bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}}$$ for Class 1, 2 and 3 cross-sections

$\bar{\lambda}$

$$= \sqrt{\frac{A_{eff} f_y}{N_{cr}}}$$ for Class 4 cross-sections

N_{cr} is the elastic critical buckling load for the relevant buckling mode based on the gross properties of the cross-section

Column buckling

Reduction factor: χ

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

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

Imperfection factor (α)

Plateau length (λ_0)

Column buckling

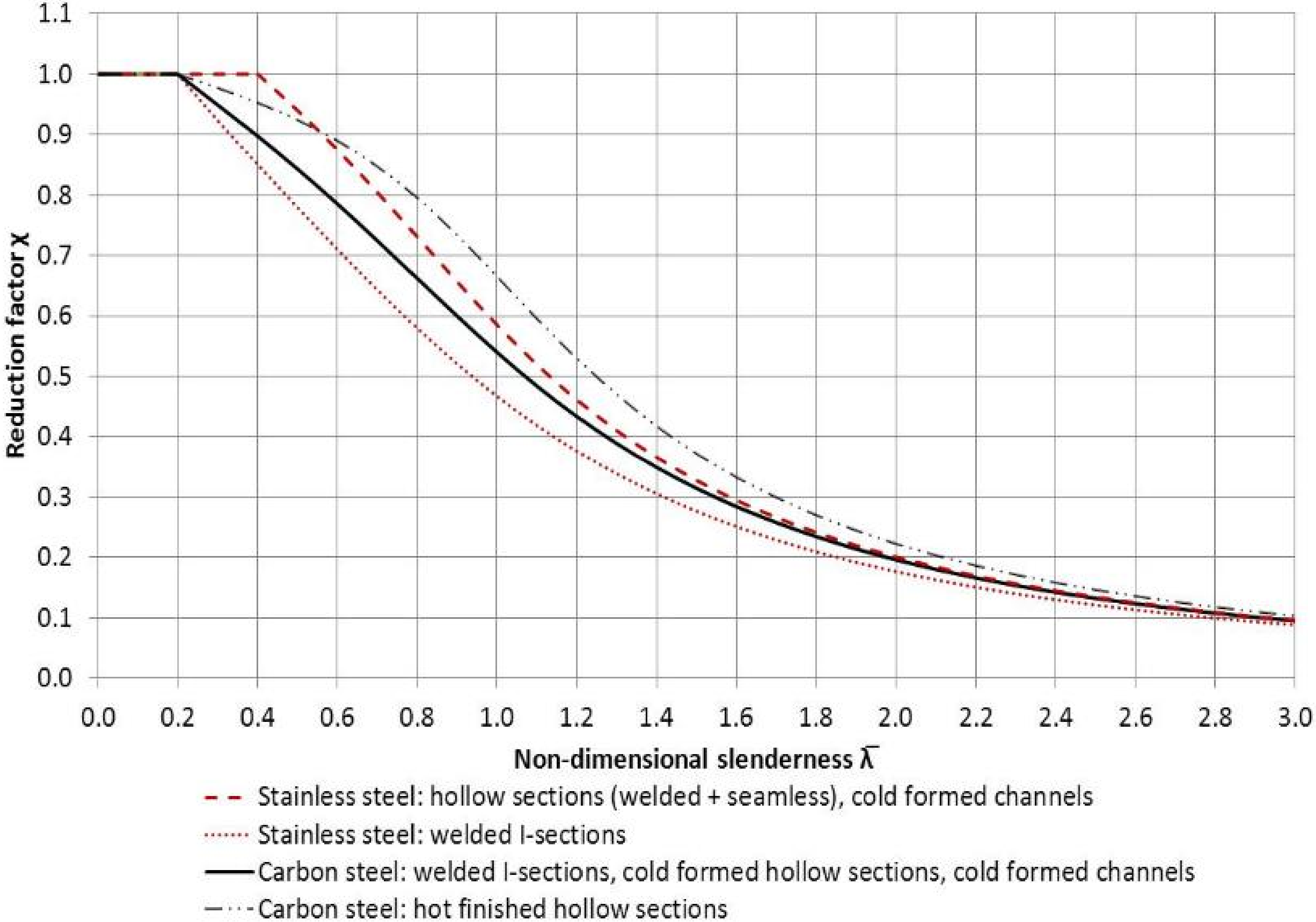
- Choice of buckling curve depends on cross-section, manufacturing route and axis

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

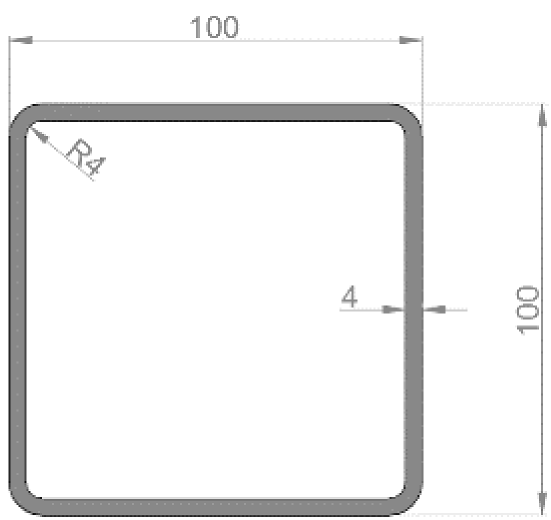
Eurocode 3 Flexural buckling curves

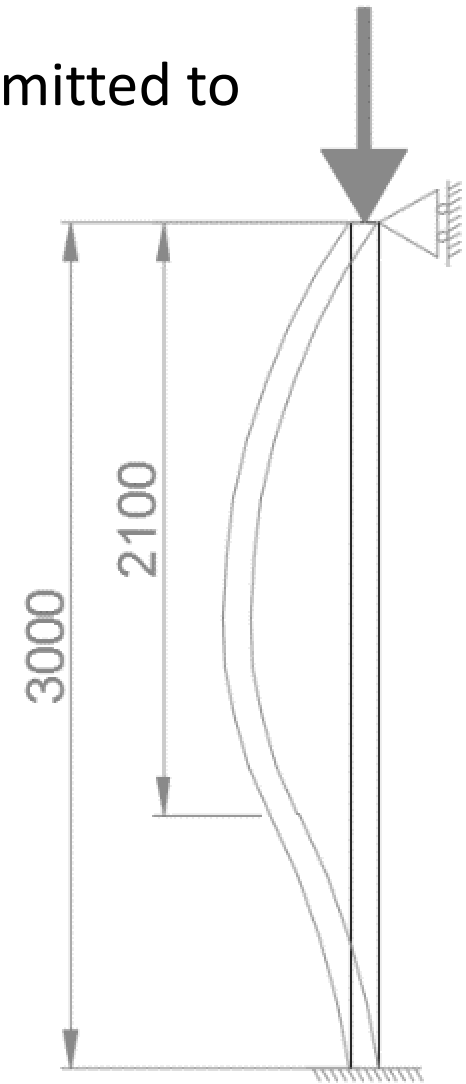


Eurocode 3 Flexural buckling example

- 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

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

  - 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: S355	EC 3-1-4: Duplex
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

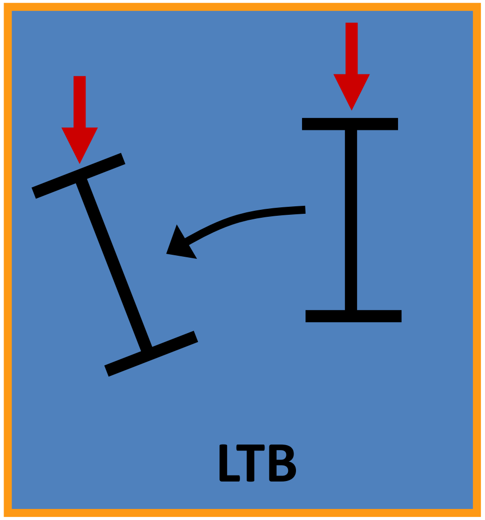
- Comparison

	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

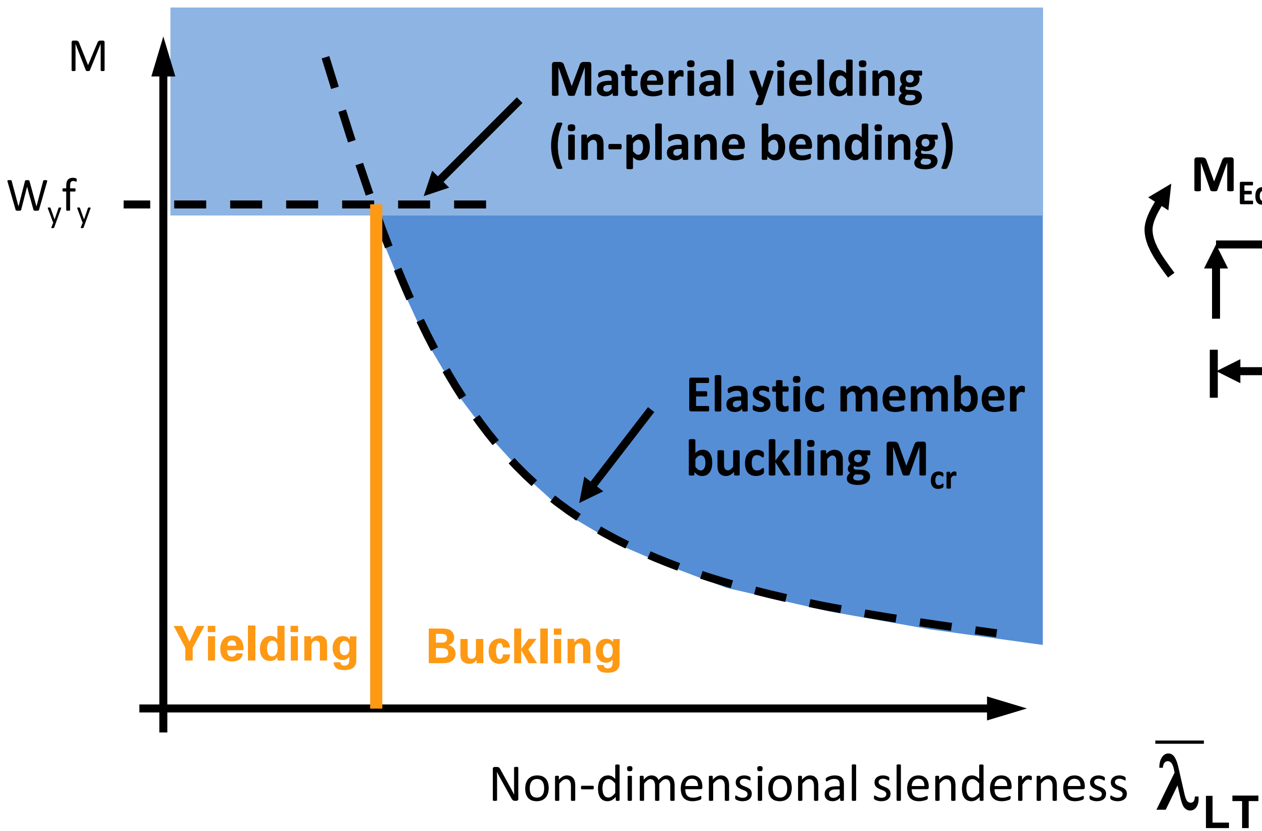
Lateral torsional buckling

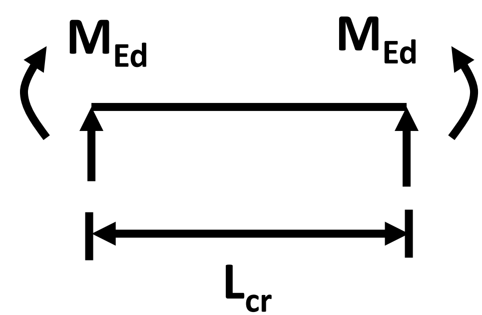
- Can be discounted when:
  - Minor axis bending
  - CHS, SHS, circular or square bar
  - Fully laterally restrained beams
  - $\overline{\lambda}_{LT} < 0.4$



Lateral torsional buckling

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





Lateral torsional buckling

- The design buckling resistance $M_{b,Rd}$ of a laterally unrestrained beam (or segment of beam) should be taken as:

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

Reduction factor for LTB

Lateral torsional buckling

- Lateral torsional buckling curves are given below:

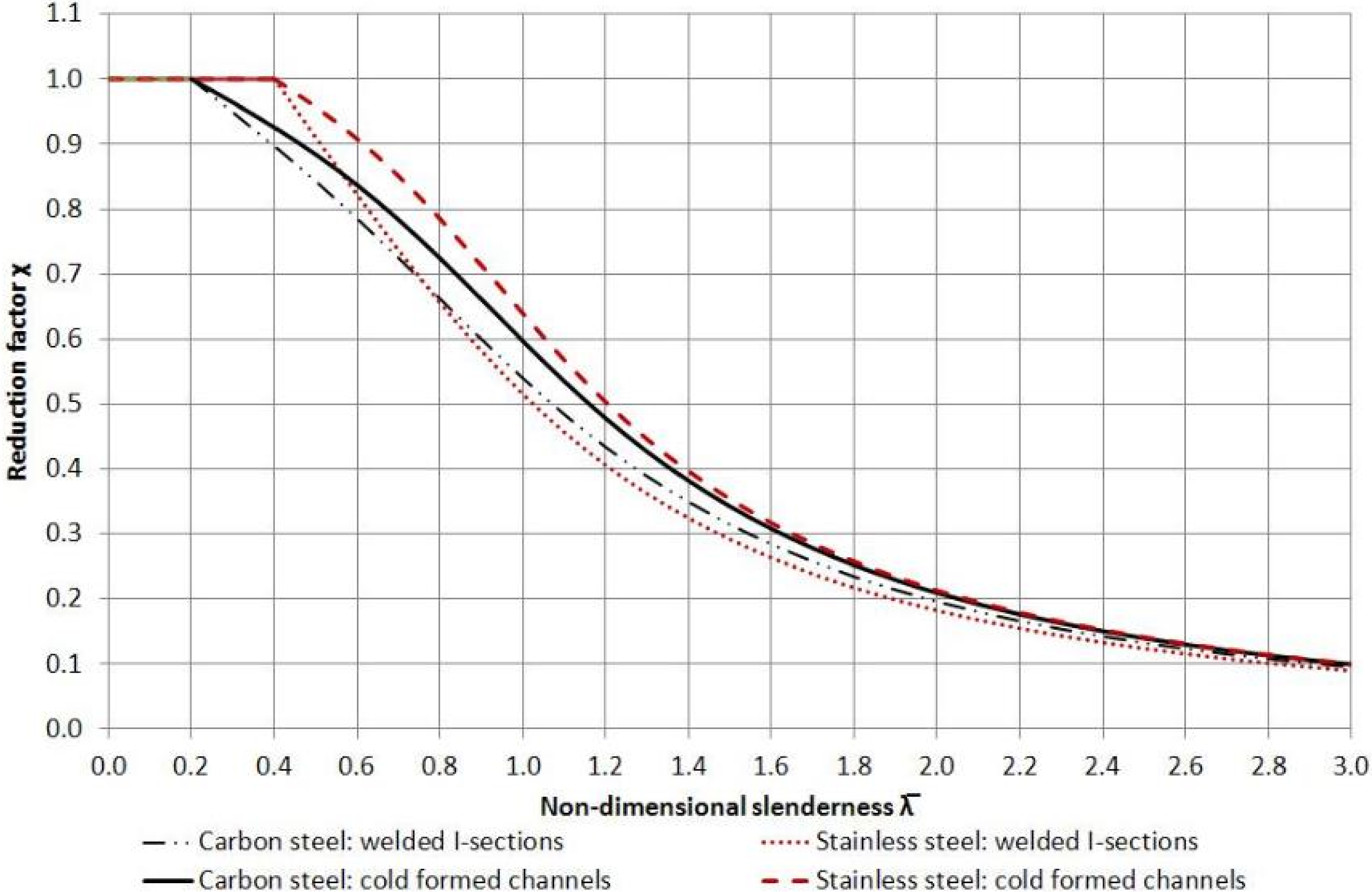
$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{LT}^2}} \quad \text{but } \chi_{LT} \leq 1.0$$

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

Plateau length

Imperfection factor

Eurocode 3 Lateral torsional buckling curves



Non-dimensional slenderness

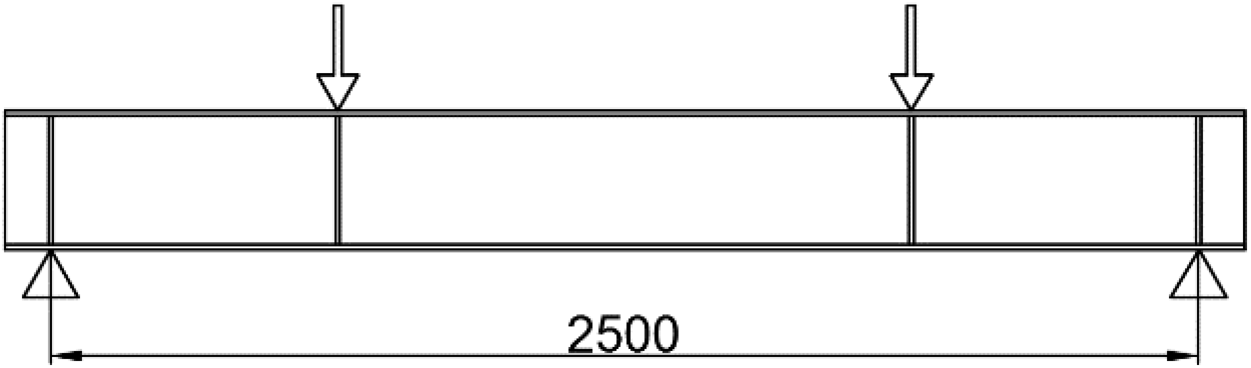
- Lateral torsional buckling slenderness:

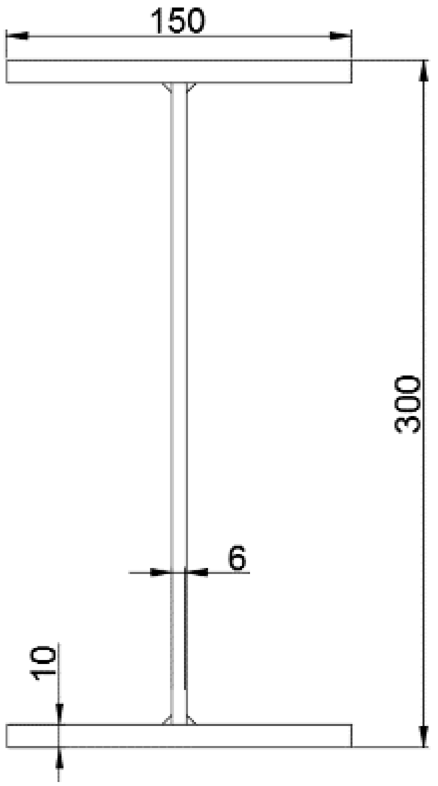
$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

  - Buckling curves as for compression (except curve a_0)
  - W_y depends on section classification
  - M_{cr} is the elastic critical LTB moment

Eurocode 3 Lateral torsional buckling example

- I-shaped beam submitted to bending





	Carbon steel	Duplex stainless steel
Material	S355	EN 1.4162
f_y [N/mm²]	355	450
E [N/mm²]	210000	200000

Eurocode 3 Lateral torsional buckling example

EC 3-1-1: S355

- Classification

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

  - 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*

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

EC 3-1-4: Duplex

- Ultimate moment
  - Class 3

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

Revision EC 3-1-4:

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

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

Eurocode 3 Lateral torsional buckling example

Elastic critical buckling moment:

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

	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: Future 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
    ⇒ **too conservative**
    (This will be shown in the example on finite element methods)

Section 4

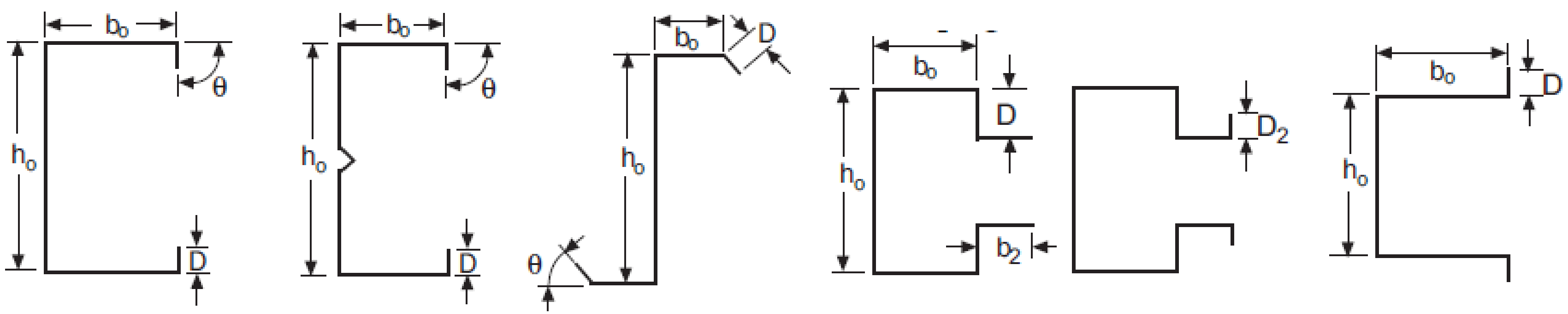
Alternative methods

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

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

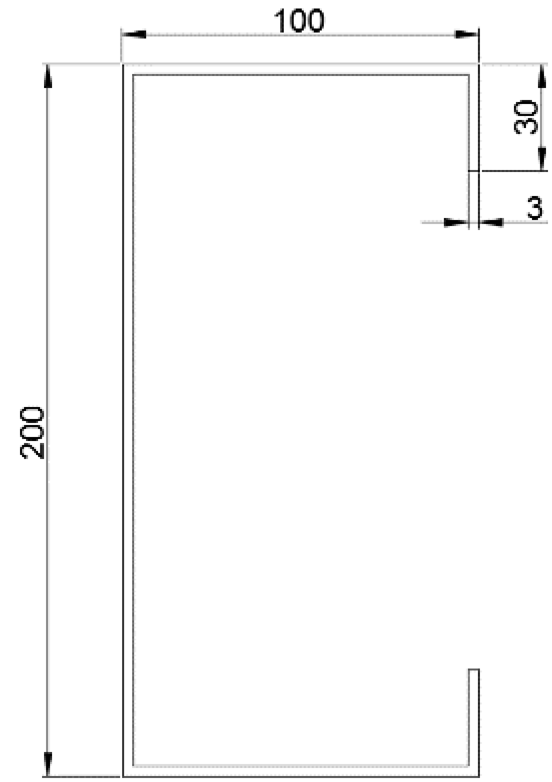


- But requires an "Elastic buckling analysis"
  - Theoretical method provided in the literature
  - Finite strip method (for example CUFSM)
- More info : http://www.ce.jhu.edu/bschafer/

Direct strength method – example

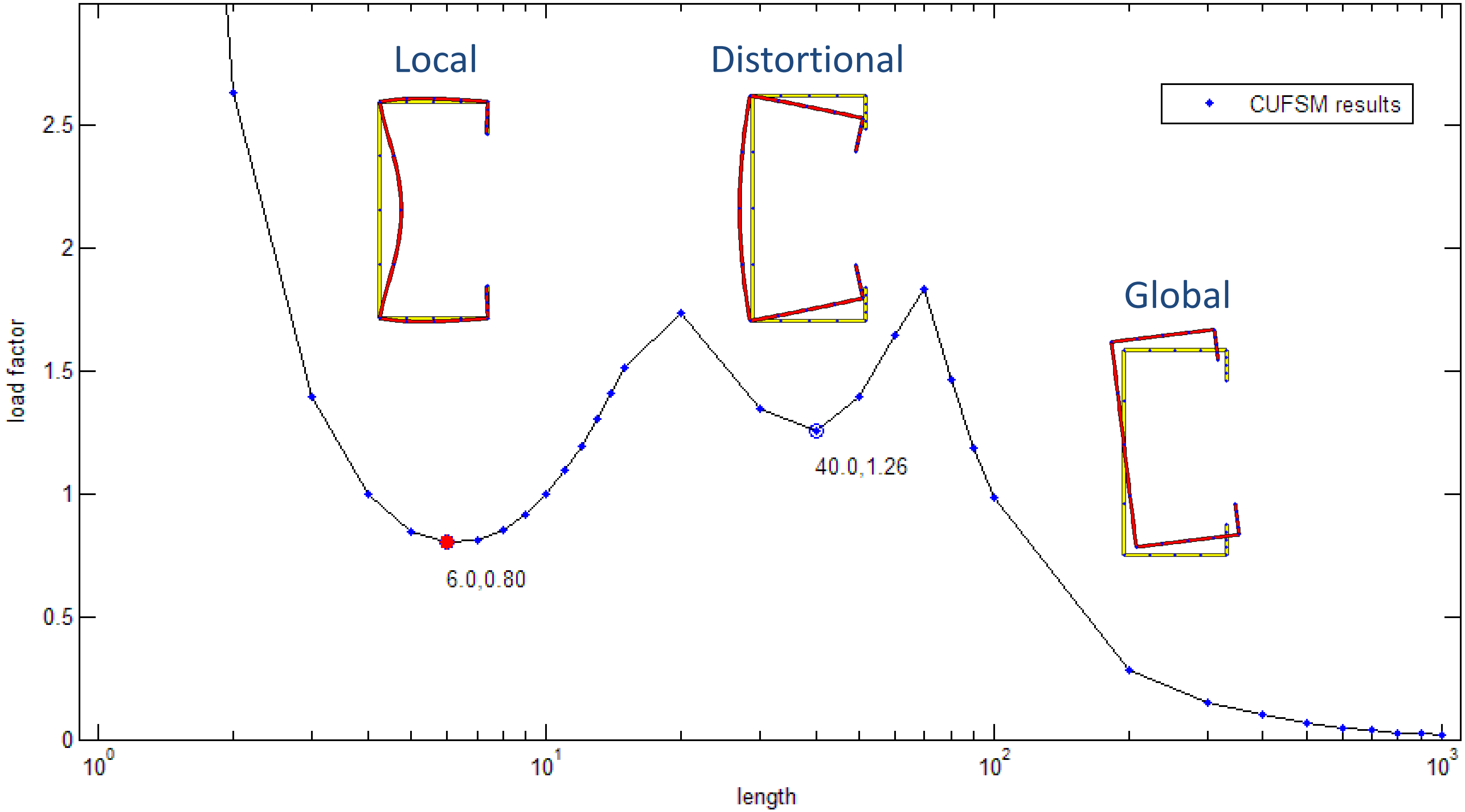
- Lipped C-channel submitted to compression
  - Simply supported column
  - Column length: 5m

	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
    - For distortional buckling: 1,26
    - 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}
  - $\lambda_c = \sqrt{P_y / P_{cre}} = 1{,}88$
  - $P_y = A f_y = 376 \text{ kN}$
  - $P_{cre} = 0{,}28 * 376 = 107\ kN$

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

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

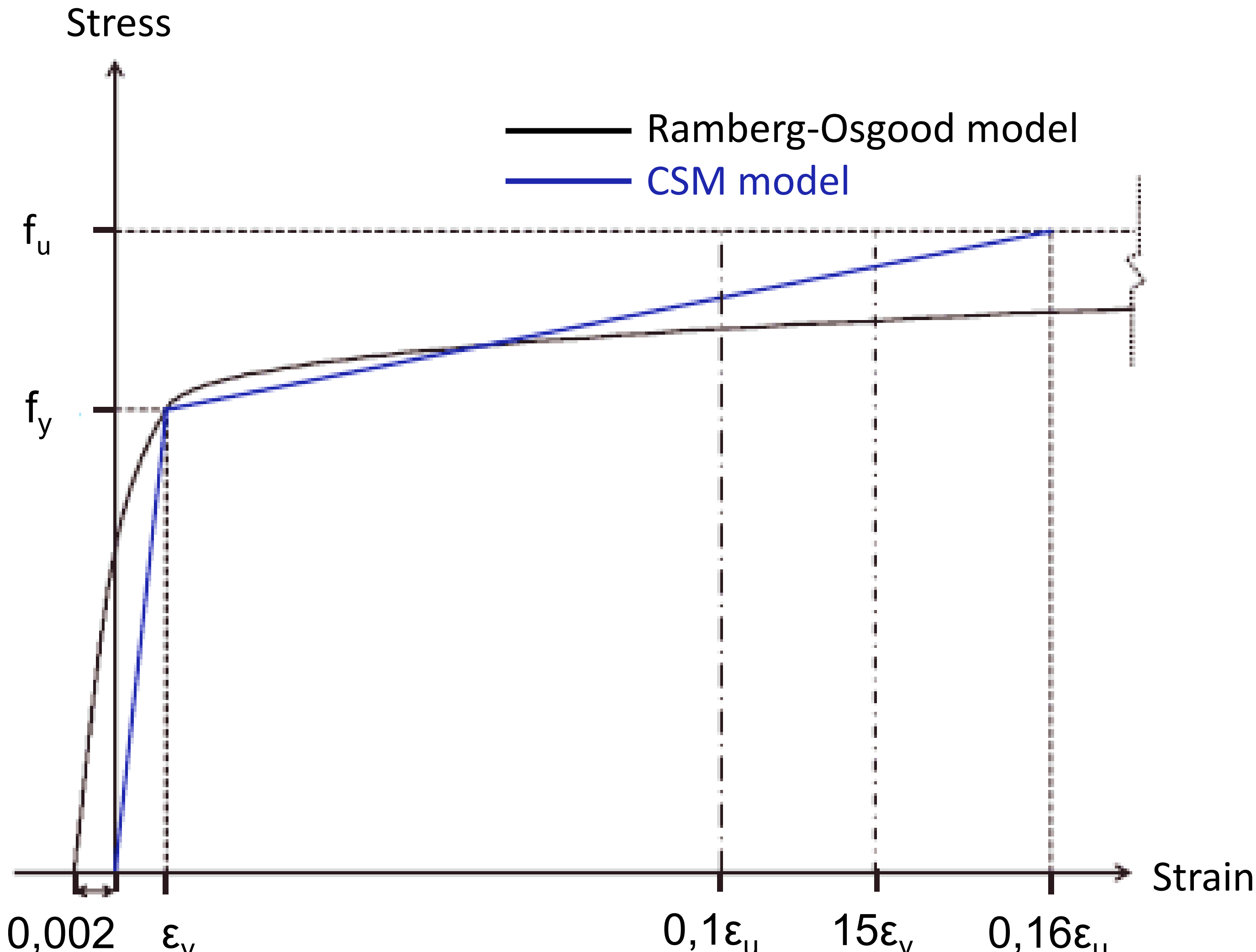
Continuous strength method

- Stainless steel material characteristics:
  - Non-linear material model
  - High train 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

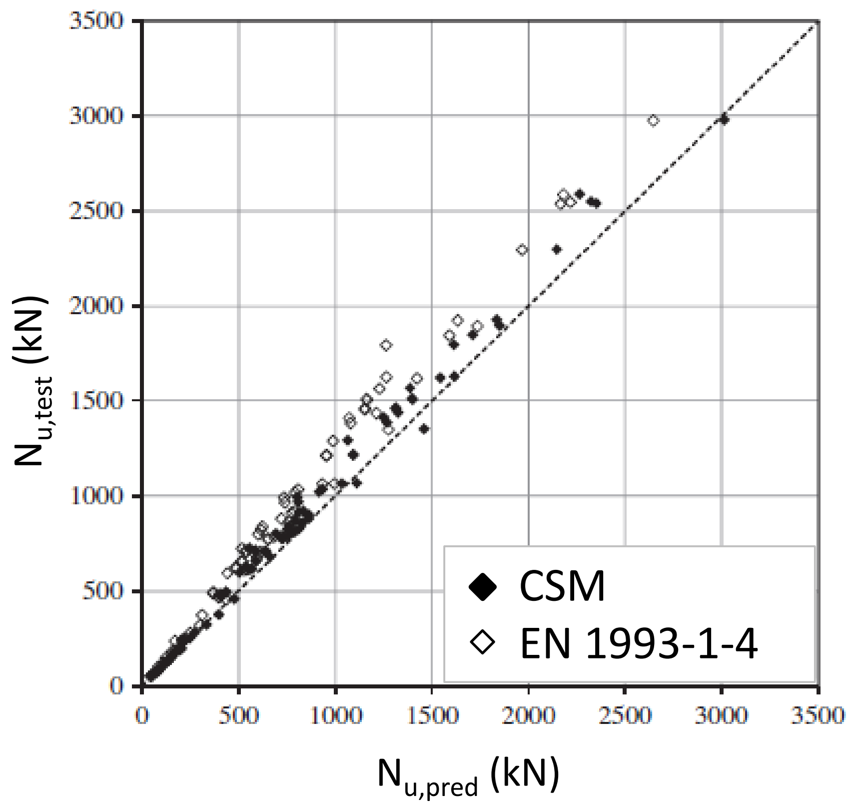
- Material model considered in the CSM:



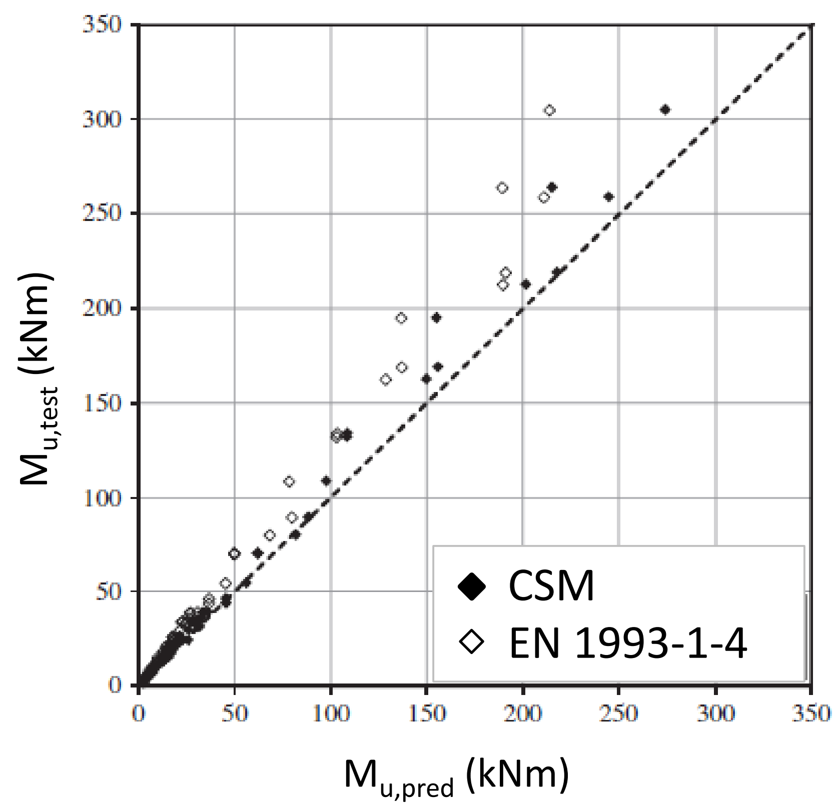
Continuous strength method

- Comparison between EC3 and CSM predictions versus tests:

In compression



In bending

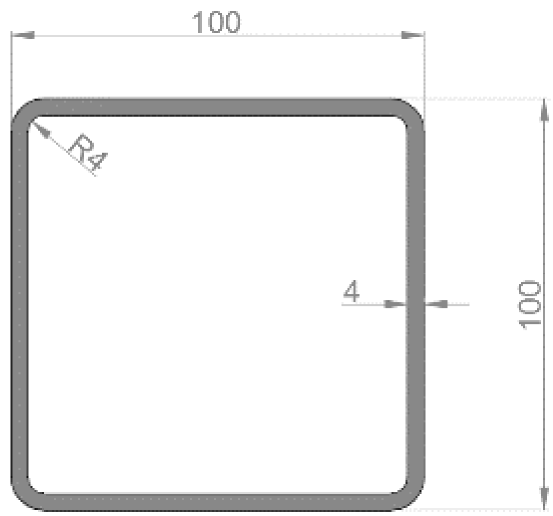


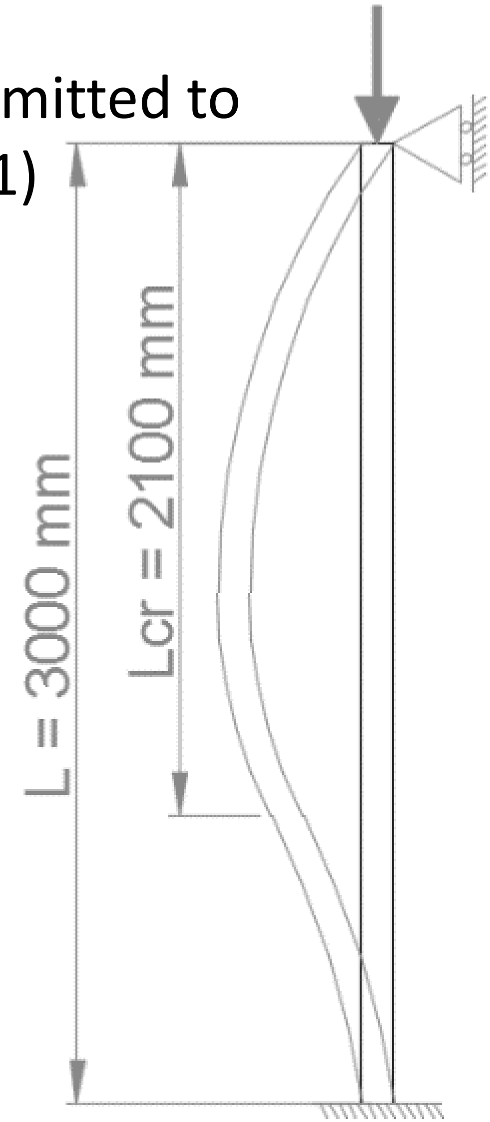
The CSM is able to accurately capture the cross-section behaviour

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

$f_y = 230\ {}^{N}/_{mm^2}$

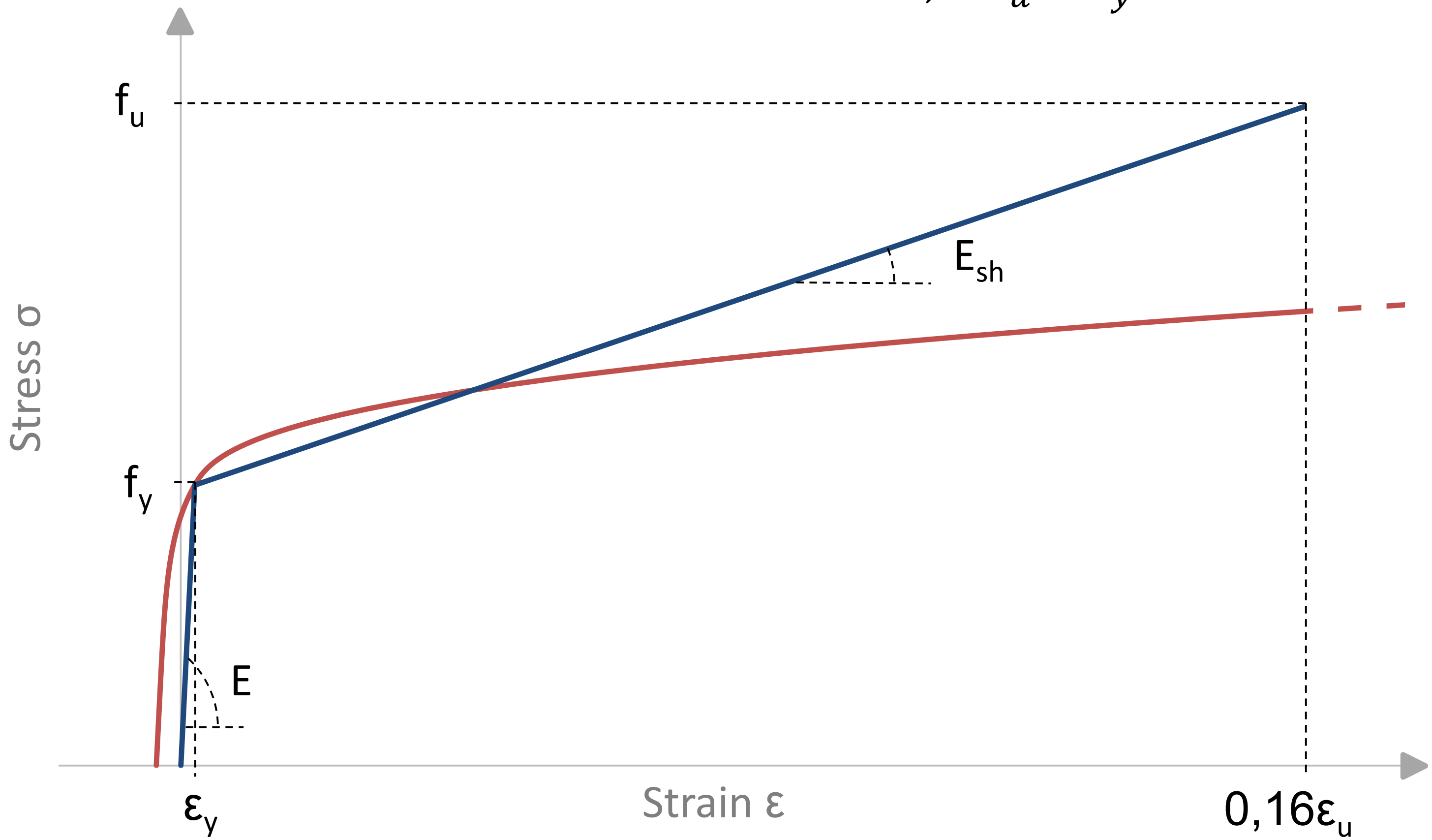
$f_u = 540\ {}^{N}/_{mm^2}$

$E = 200000\ {}^{N}/_{mm^2}$

$0{,}16\varepsilon_u = 0{,}16(1 - {}^{f_y}/_{f_u}) = 0{,}0919$

$\varepsilon_y = {}^{f_y}/_{E} = 0{,}0012$

$$E_{sh} = \frac{f_u - f_y}{0{,}16\varepsilon_u - \varepsilon_y} = 3418\ {}^{N}/_{mm^2}$$



CSM: flexural buckling example

$f_y = 230 \,{}^{N}\!/_{mm^2}$

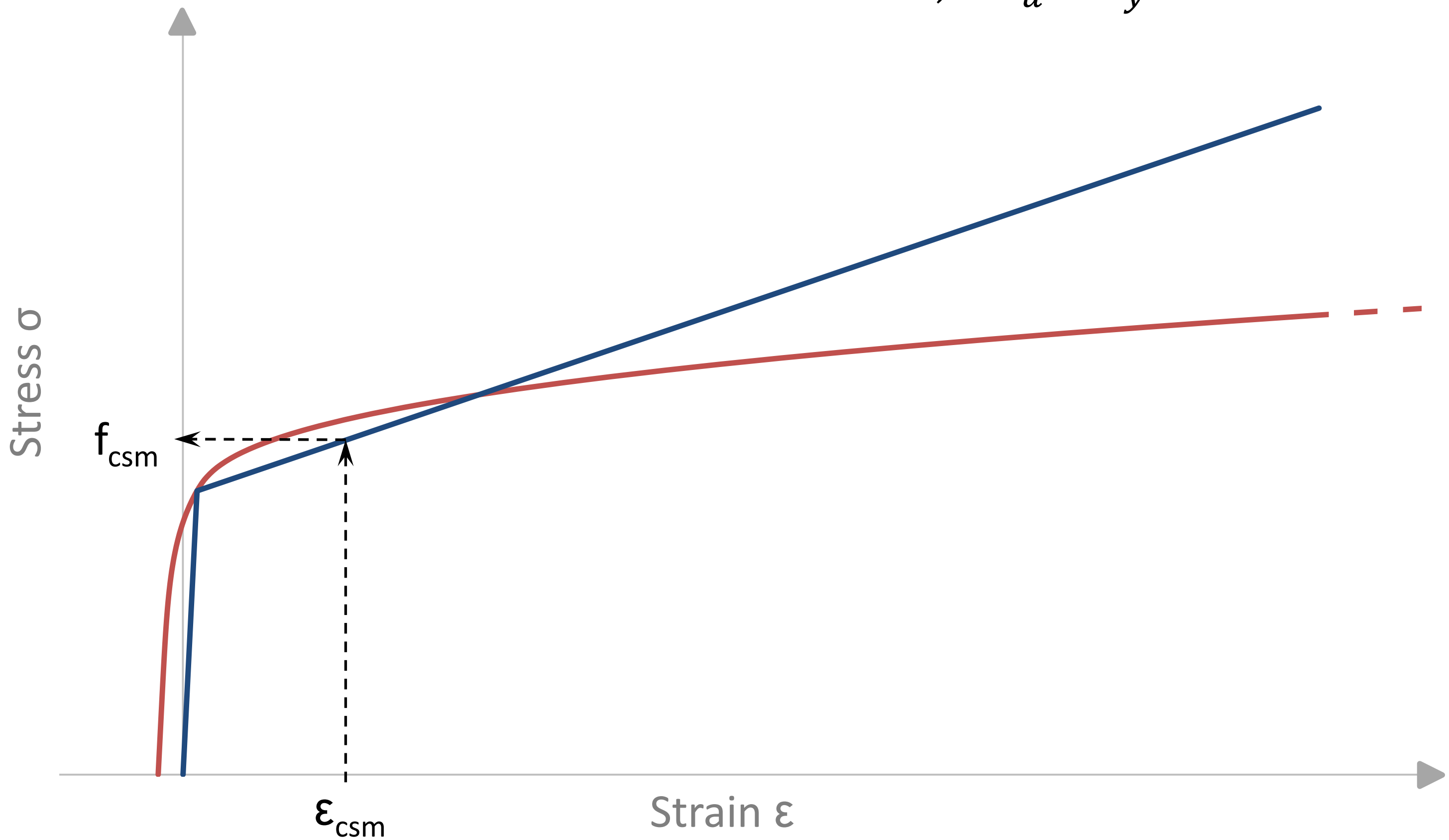
$E = 200000 \,{}^{N}\!/_{mm^2}$

$\varepsilon_y = {}^{f_y}\!/_{E} = 0{,}0012$

$f_u = 540 \,{}^{N}\!/_{mm^2}$

$0{,}16\varepsilon_u = 0{,}16(1 - {}^{f_y}\!/_{f_u}) = 0{,}0919$

$E_{sh} = \dfrac{f_u - f_y}{0{,}16\varepsilon_u - \varepsilon_y} = 3418 \,{}^{N}\!/_{mm^2}$



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
- $\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0,25}{\bar{\lambda}_p^{\;3,6}} = 5,27$
- $f_{csm} = f_y + E_{sh}\varepsilon_y\left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1\right) = 247\ {}^{N}/_{mm^2}$
- $N_{c,Rd} = \frac{Af_{csm}}{\gamma_{M0}} = 335\ kN$

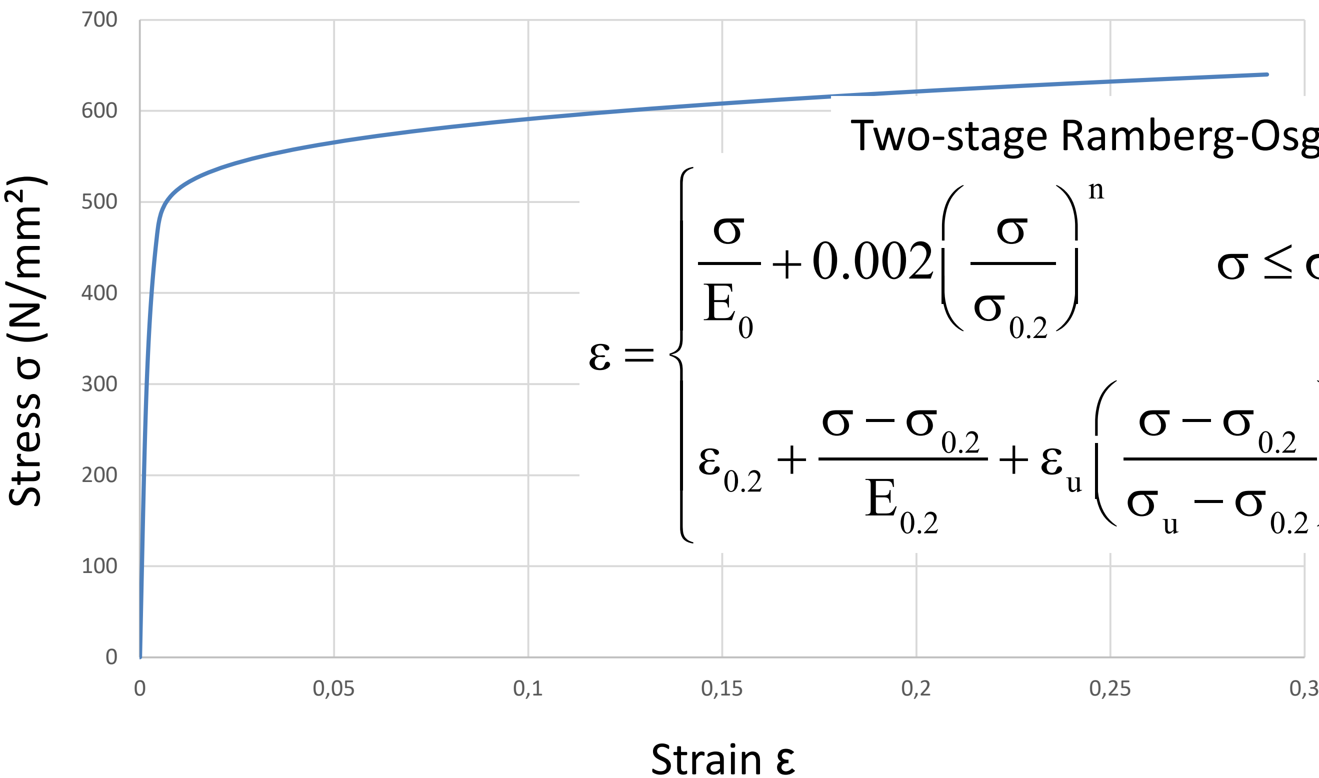
CSM: flexural buckling example

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

	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:

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

Finite element model

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

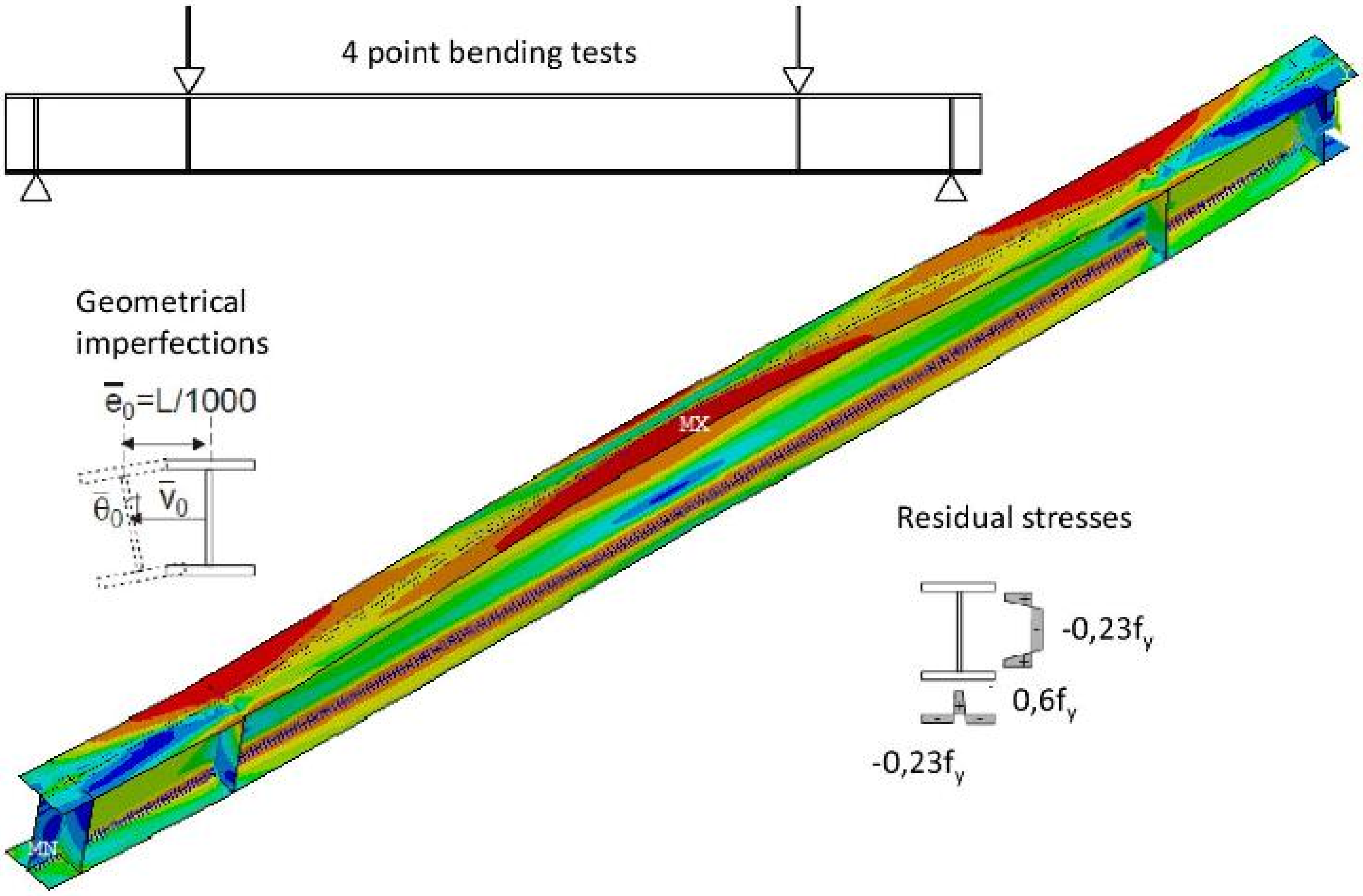
$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \qquad m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \qquad E_{0.2} = \frac{E_0}{1 + 0.002n\frac{E_0}{\sigma_{0.2}}}$$

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

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

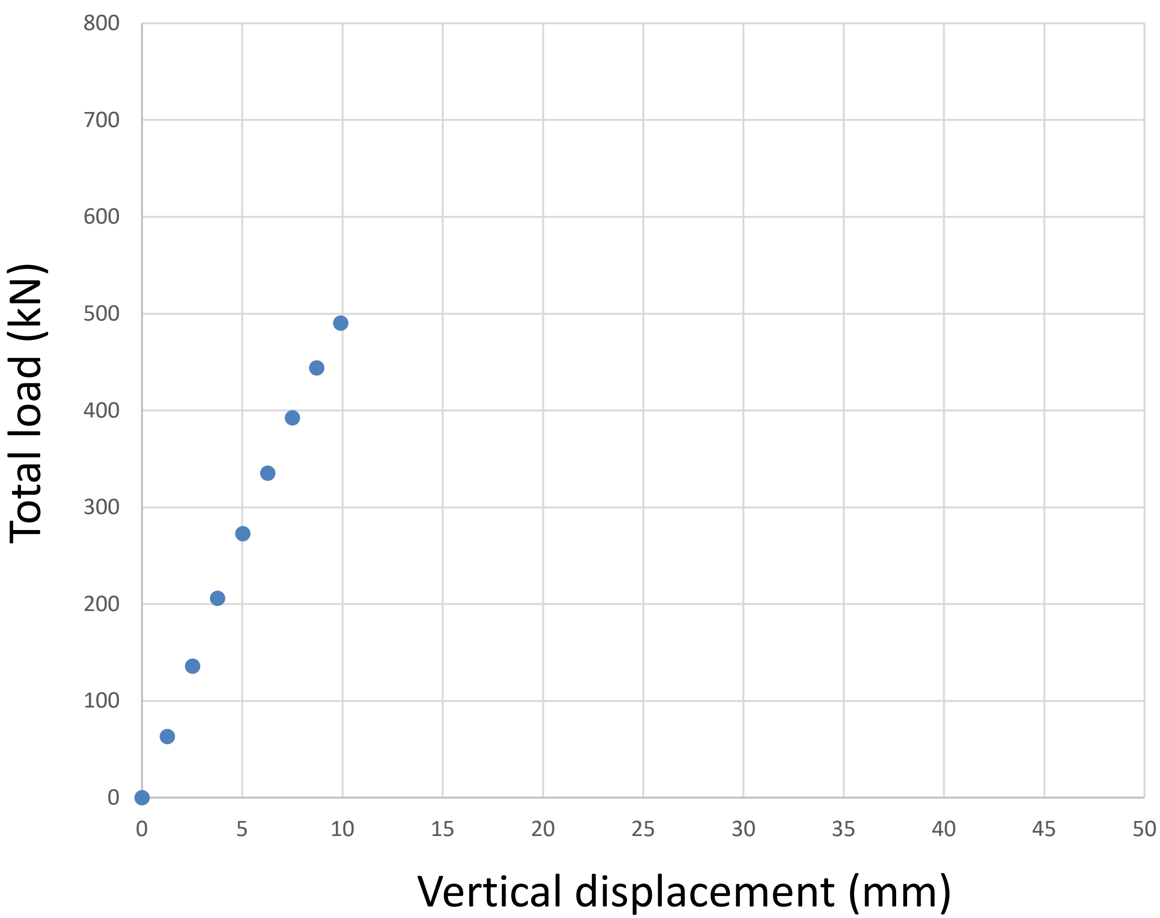
Finite element model

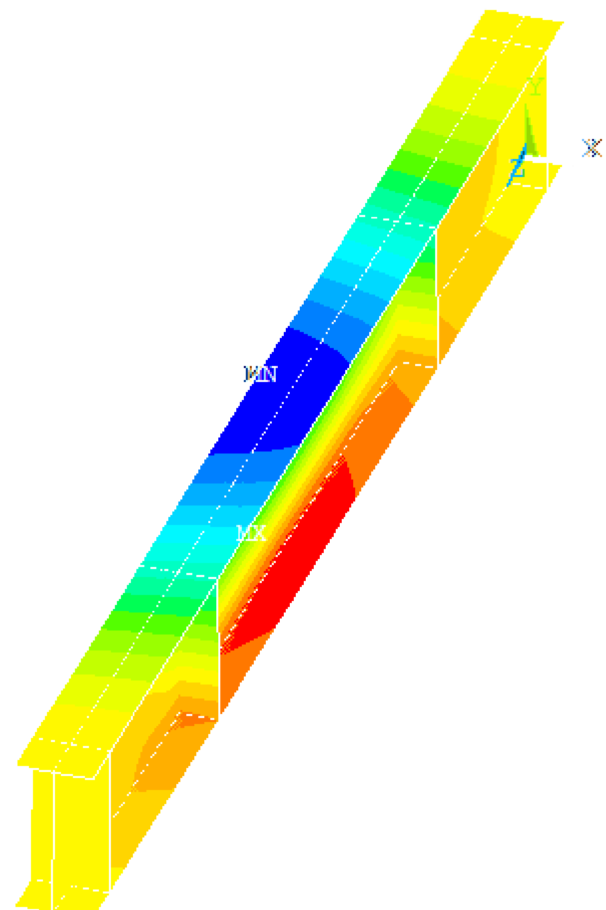
- I-shaped beam submitted to bending suffering lateral torsional buckling : all imperfections can be modelled



Finite element model

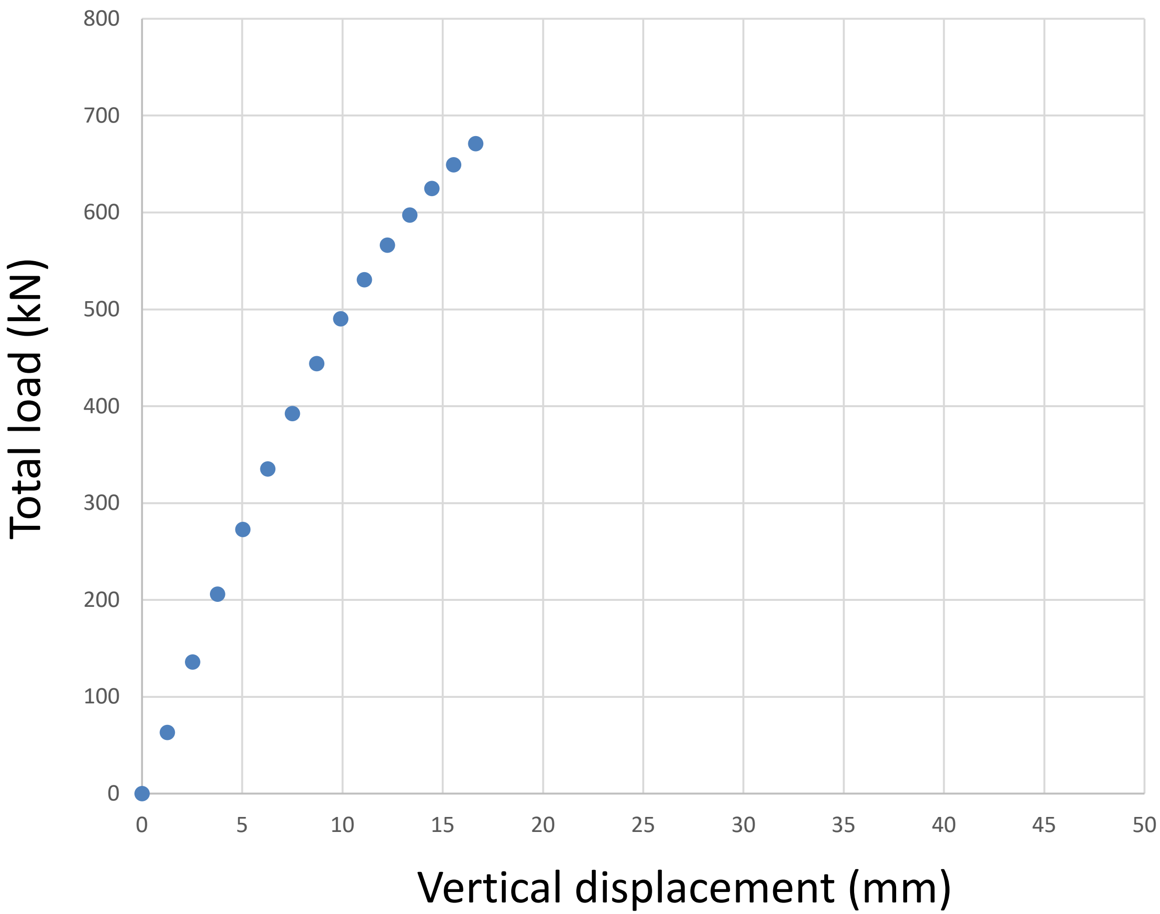
- The load-deflections curve can be calculated
  - Results: elastic behaviour and first yielding

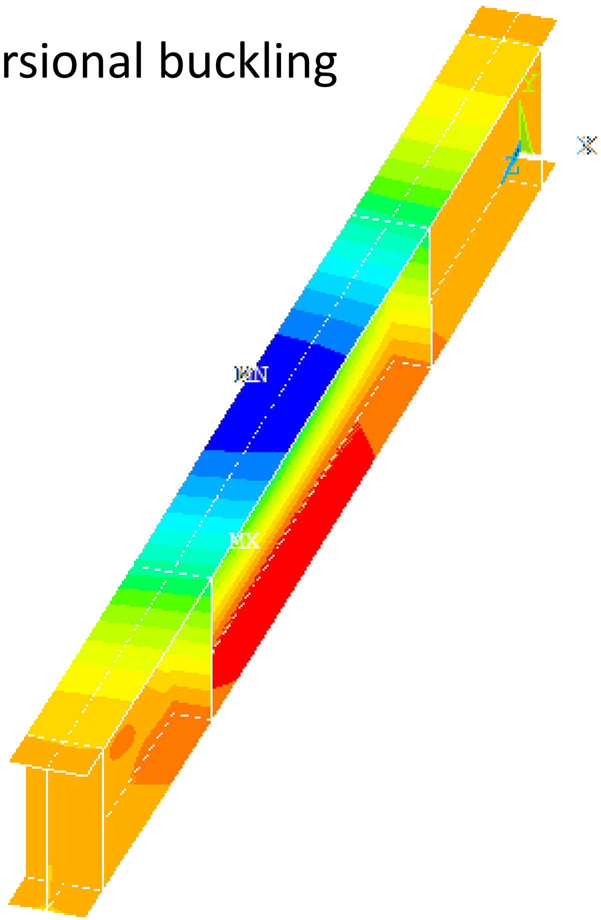




Finite element model

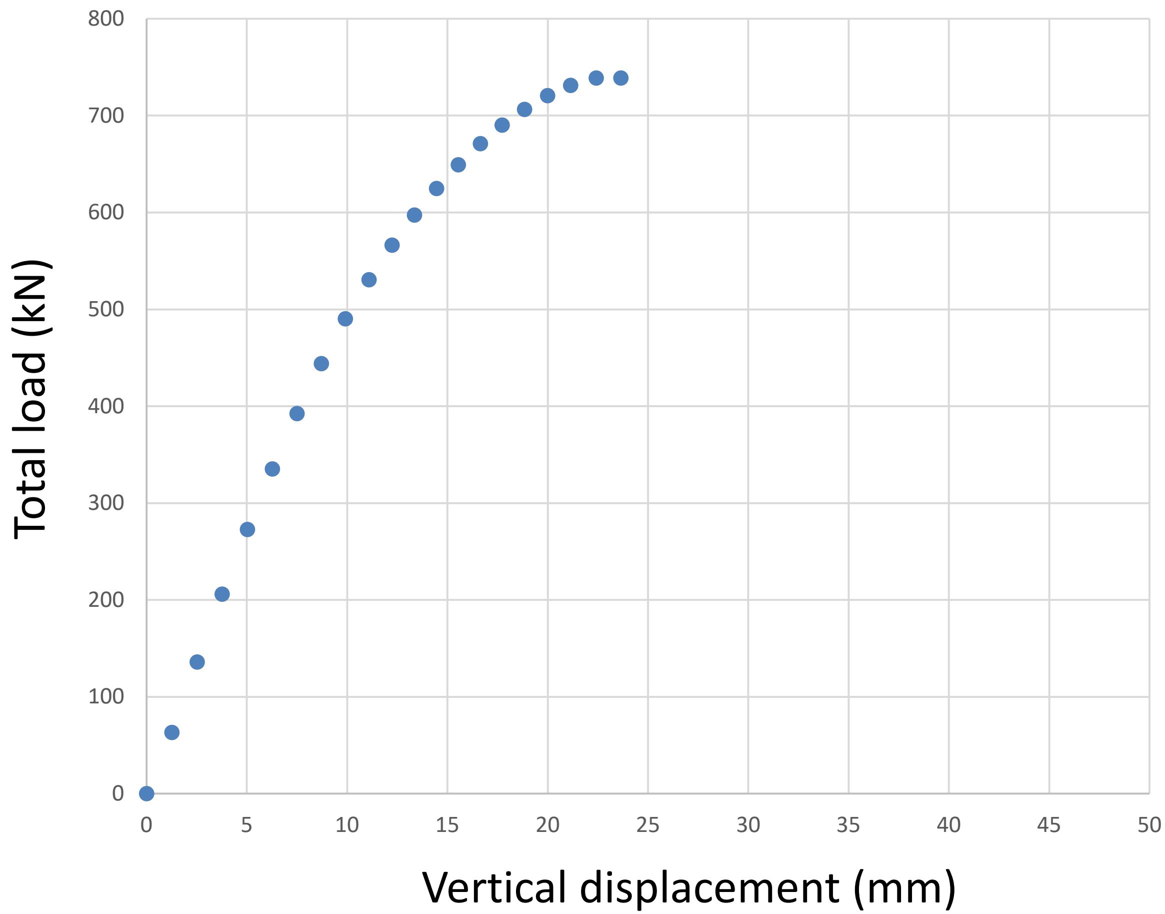
- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling

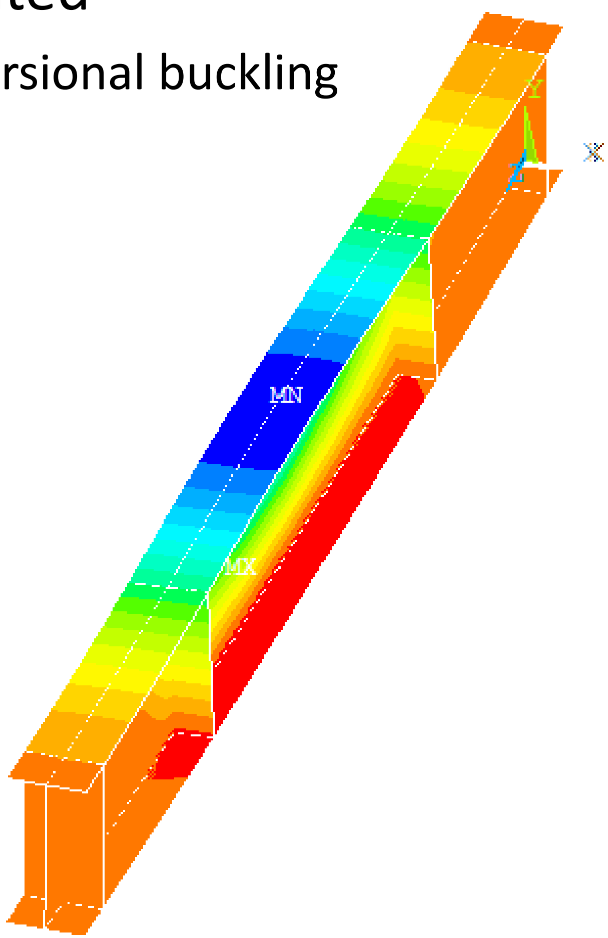




Finite element model

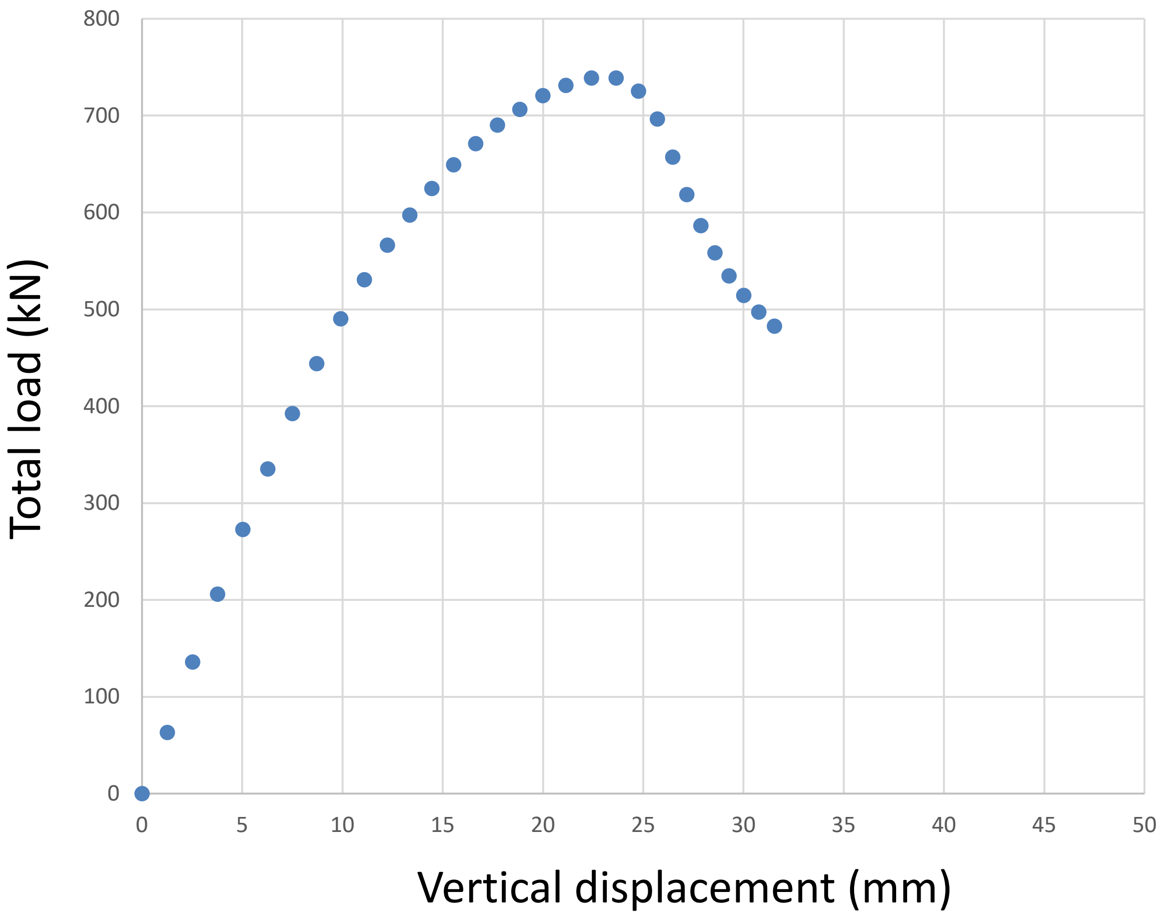
- The load-deflections curve can be calculated
  - Results: instability phenomenon => Lateral torsional buckling

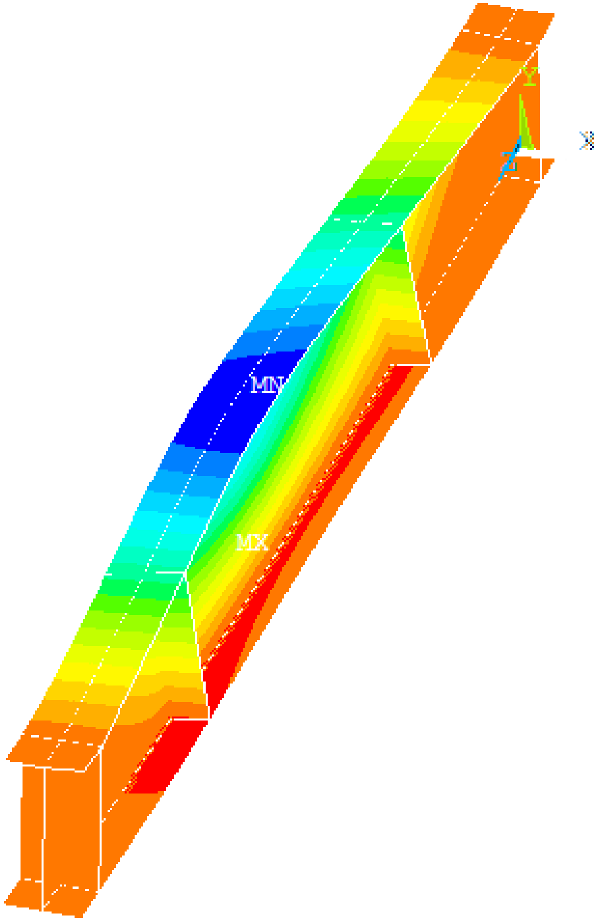




Finite element model

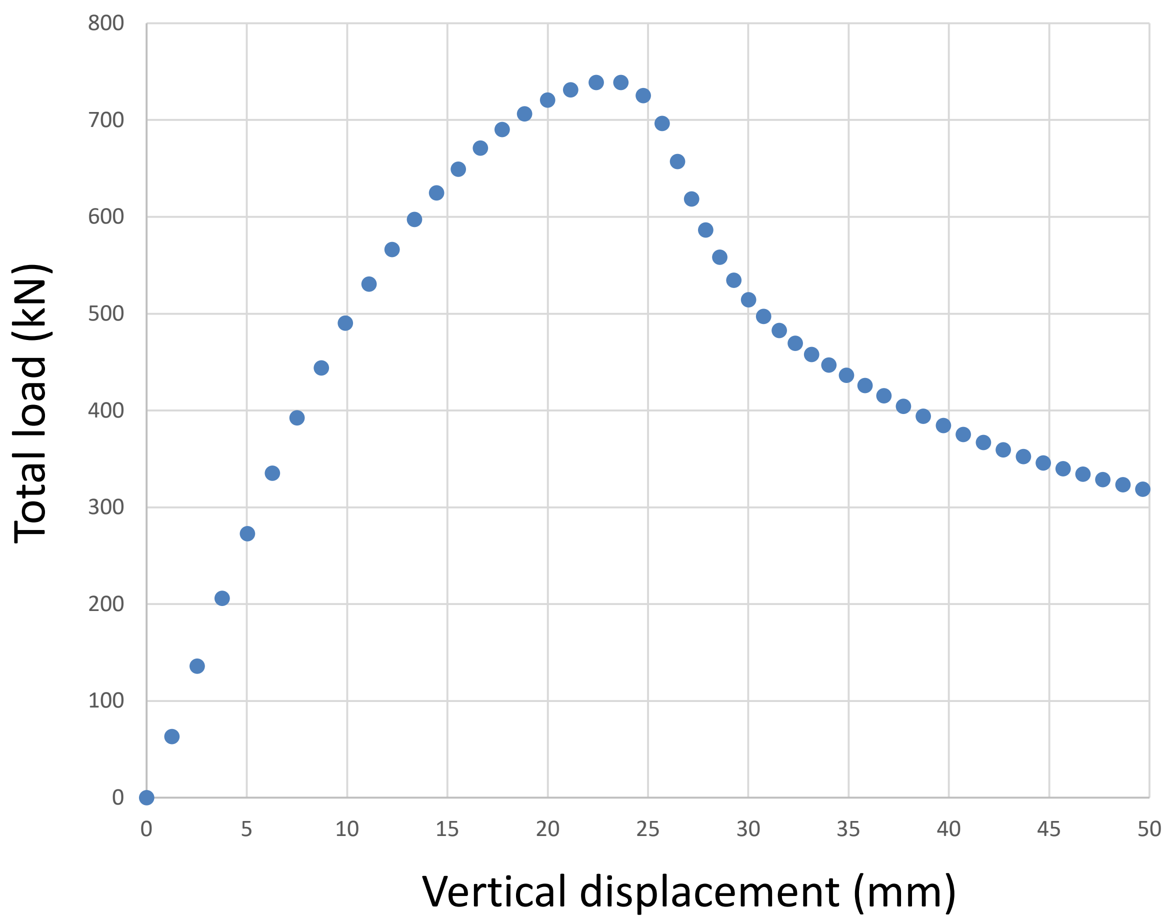
- The load-deflections curve can be calculated
  - Results: post buckling behaviour

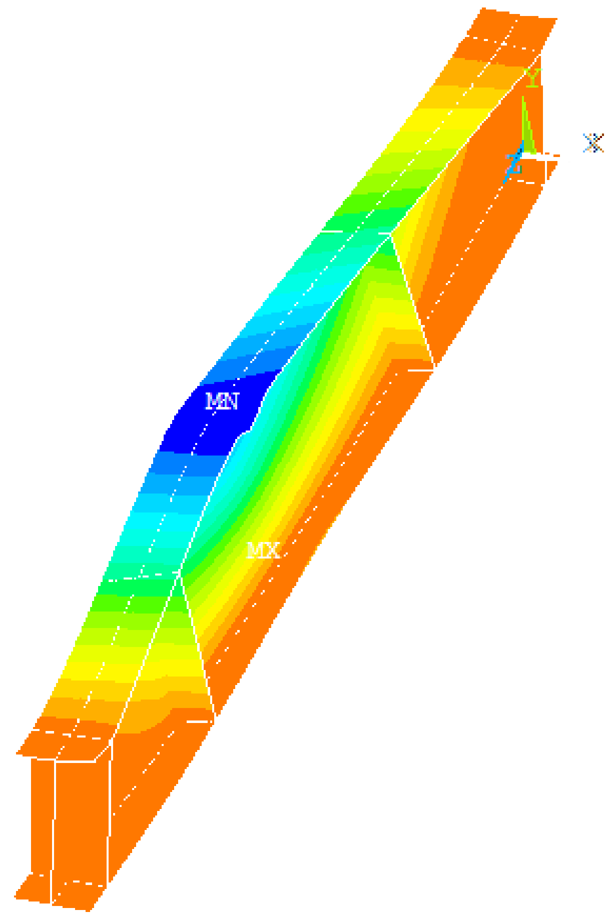




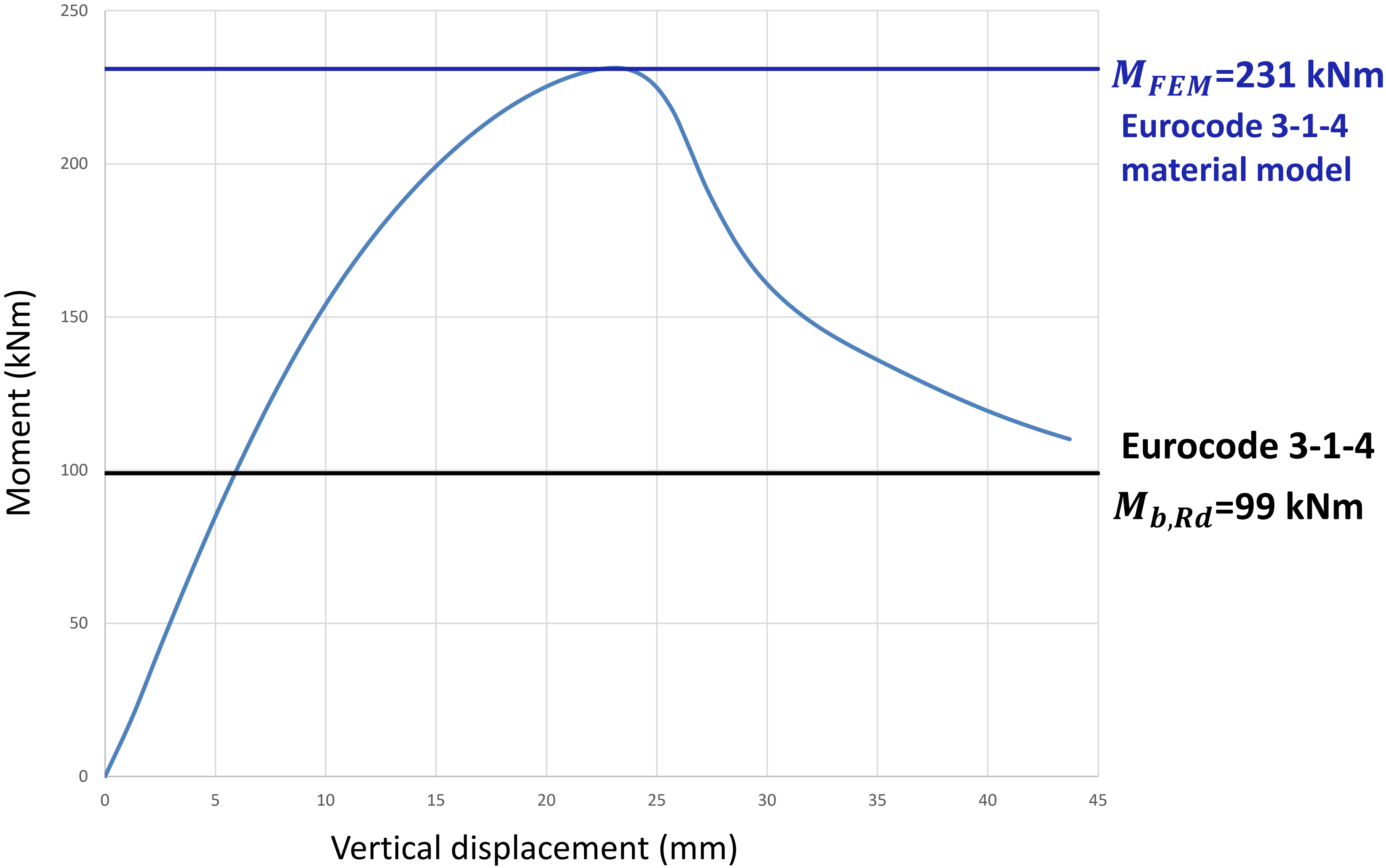
Finite element model

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

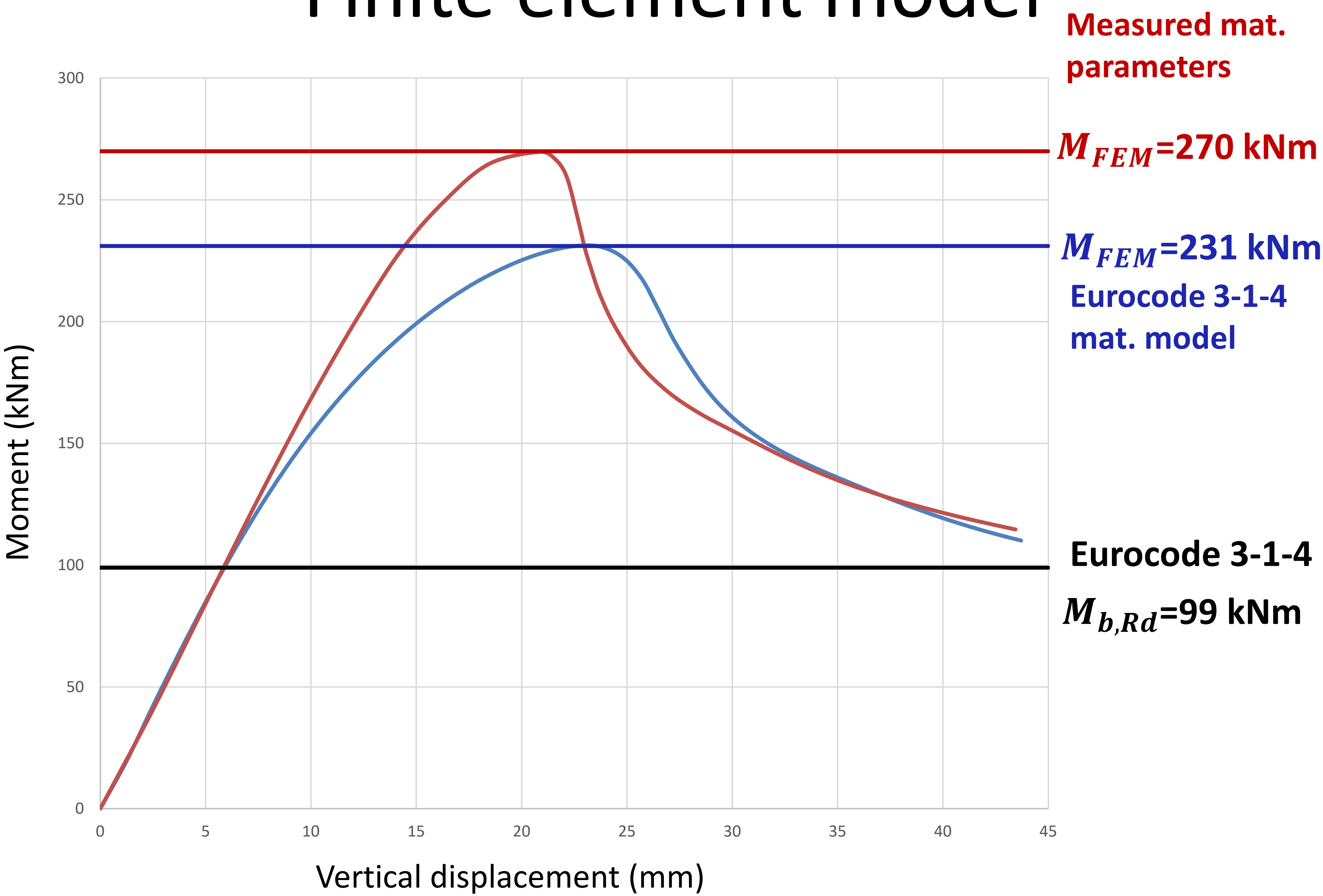




Finite element model



Finite element model



Section 5

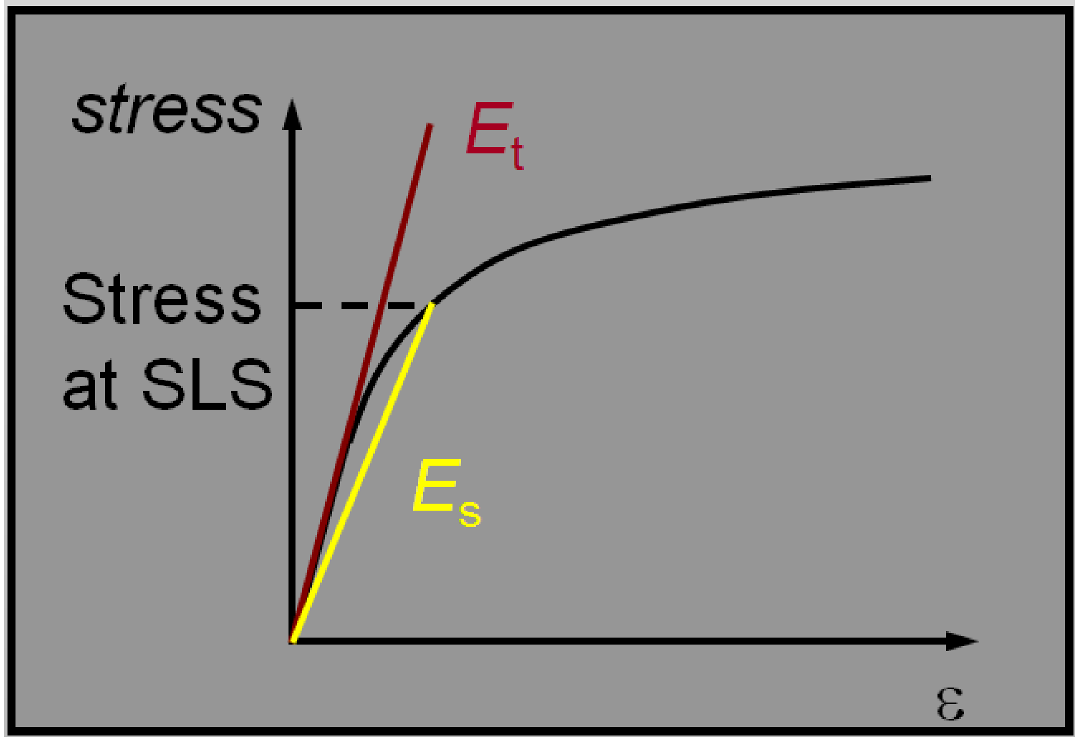
Deflections

Deflections

- Non-linear stress-strain curve means that stiffness of stainless steel ↓ as stress ↑
- 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 ES determined from the Ramberg-Osgood model:

$$E_S = \frac{E}{1 + 0.002\frac{E}{f}\left(\frac{f}{f_y}\right)^n}$$

f is stress at serviceability limit state

n is a material constant

Deflections in an austenitic stainless steel beam

Stress ratio f/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

f = stress at serviceability limit state

Section 6

Additional information

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

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

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

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

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 always be carried out

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
- Stainless steel can be welded to carbon steel, but special preparation is needed

Fatigue strength

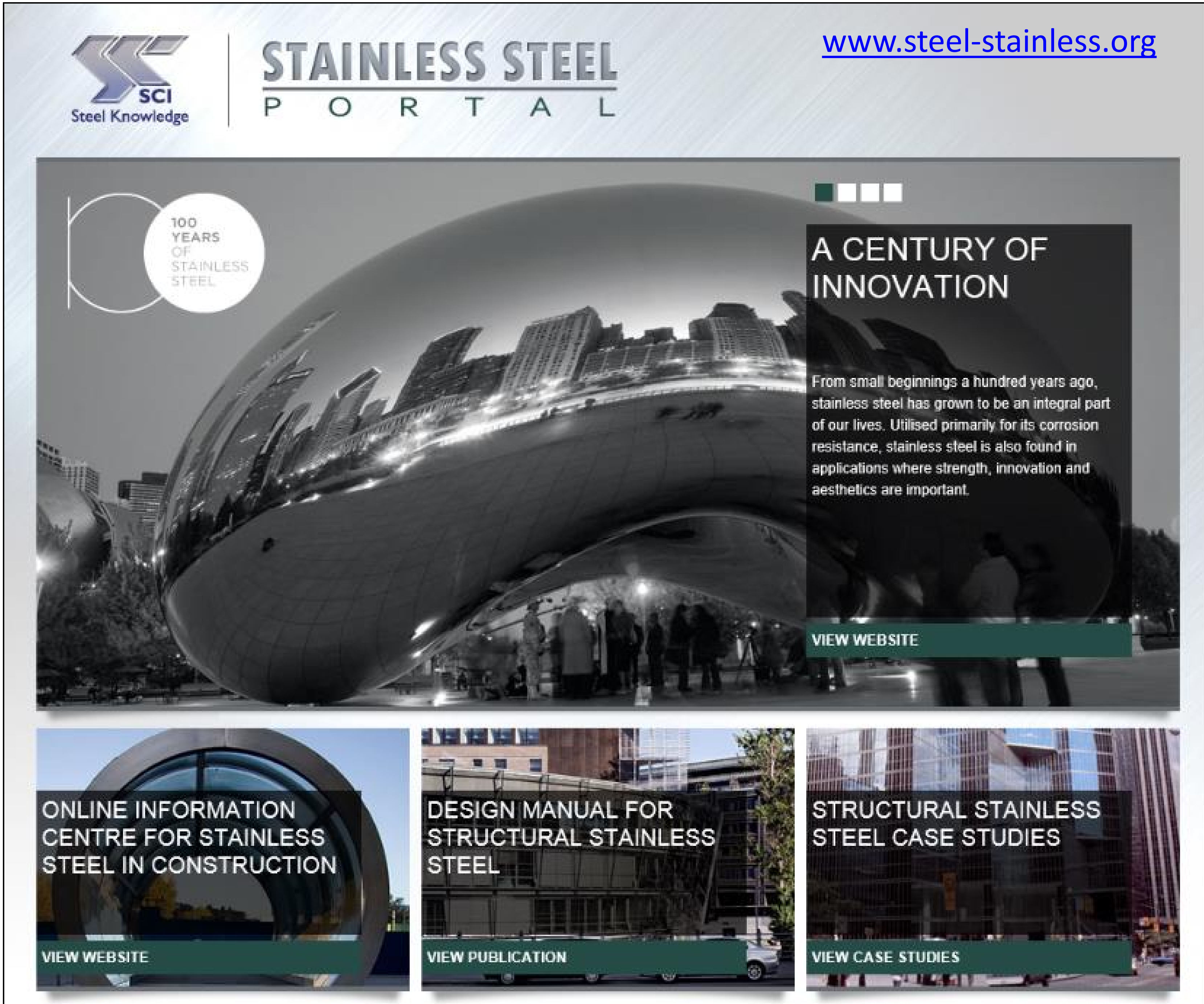
- Fatigue behaviour of welded joints is dominated by weld geometry
- Performance of austenitic and duplex stainless steel is at least as good as carbon steel
- Follow guidelines for carbon steel

Section 7

Resources for engineers

Resources for engineers

- Online Information Centre
- Case studies
- Design guides
- Design examples
- Software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PORTAL
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A CENTURY OF INNOVATION
From small beginnings a hundred years ago, stainless steel has grown to be an integral part of our lives. Utilised primarily for its corrosion resistance, stainless steel is also found in applications where strength, innovation and aesthetics are important.
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ONLINE INFORMATION CENTRE FOR STAINLESS STEEL IN CONSTRUCTION
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DESIGN MANUAL FOR STRUCTURAL STAINLESS STEEL
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VIEW CASE STUDIES

Stainless in Construction Information Centre

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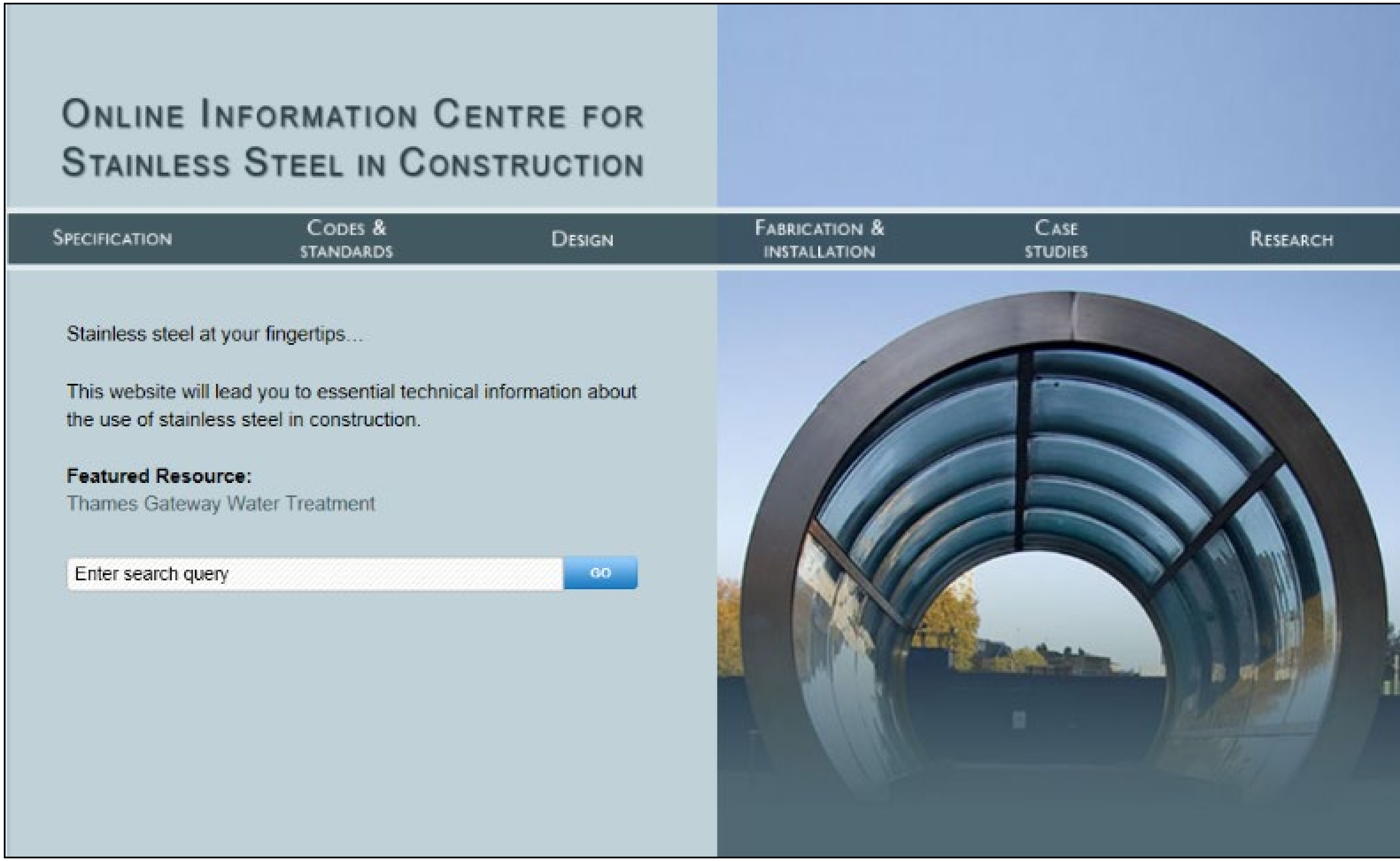
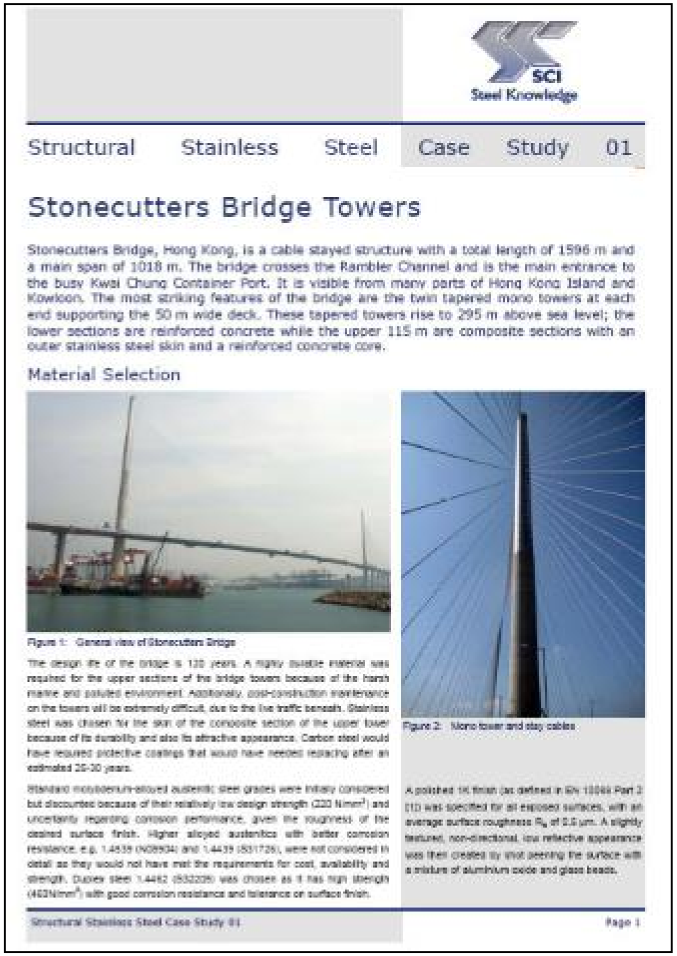


12 Structural Case Studies

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

Figure 2: Mono tower and stay cables

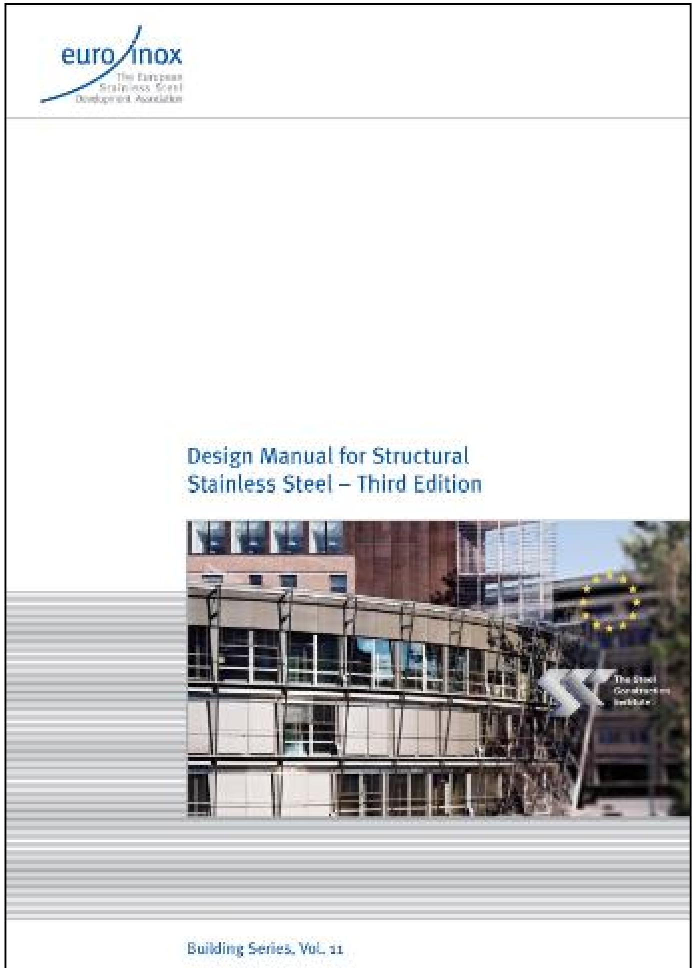
The design life of the bridge is 120 years. A highly durable material was required for the upper sections of the bridge towers because of the harsh marine and polluted environment. Additionally, post-construction maintenance on the towers will be extremely difficult, due to the live traffic beneath. 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 (460 N/mm^2) with good corrosion resistance and tolerance on surface finish.

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

Summary

- Structural performance:
  similar to carbon steel but some modifications needed due to non-linear stress-strain curve
- Design rules have been developed
- Resources (design guides, case studies, worked examples, software) are freely available!

References

- EN 1993-1-1. Eurocode 3: Design of steel structures – Part1-1: General rules and rules for buildings. 2005
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- B.W. Schafer. Review: The Direct Strength Method of cold-formed steel member design. Journal of Constructional Steel Research 64 (2008) 766-778
- S.Afshan, L. Gardner. The continuous strength method for structural stainless steel design. Thin-Walled Structures 68 (2013) 42-49

Thank You

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Maarten Fortan – maarten.fortan@kuleuven.be

Test your knowledge of stainless steel here:

https://www.surveymonkey.com/r/3BVK2X6