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Lecture notes

Introduction

2 This Fourth Edition of the Design Manual has been prepared by
3 Nancy Baddoo of The Steel Construction Institute as part of the RFCS Project *Promotion of new Eurocode rules for structural stainless*
4 *steels* (PUREST).

It is a complete revision of the Third Edition; the major changes are as follows:

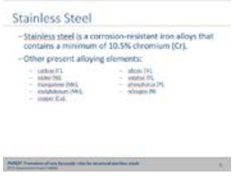
- Alignment with the 2015 amendment to EN 1993-1-4,
- Inclusion of ferritic stainless steels, based on the work of the Structural applications of ferritic stainless steels (SAFSS) project (RFSR-CT-2010-00026),
- New data on the thermal and mechanical properties of stainless steels in fire are added,
- The design data, design rules and references to current versions of European standards, including EN 10088, EN 1993 and EN 1090 are updated,
- Addition of an annex on material modelling,
- Addition of an annex which gives a method for calculating an enhanced strength arising from cold forming,
- Addition of an annex which gives less conservative design rules by exploiting the benefits of strain hardening through the use of the Continuous Strength Method.

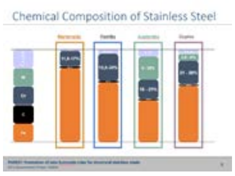
In total fifteen design examples are present which show the design approach for various cases. For students it is from great interest to recalculate the examples and evaluate the results.

The commentary presents the results of various test programs which allows designers to assess the basis of the recommendations. It also facilitates the development of revisions as and when new data becomes available.

Lastly an App is developed for PC, iOS and android which enables users to easily calculate stainless steel member resistance in accordance with EN 1993-1-4 and Design Manual. Members can be selected out of a database of standard sections or user can insert custom sections.

What is Stainless Steel?





6 Stainless steel is a steel alloy existing of chromium, nickel, iron and
7 carbon. The percentage mass of chromium content varies from 10.5 up to 30%. Stainless steel can be divided in four families:
8 martensitic, ferritic, austenitic and duplex (austenitic-ferritic). However, not all families are useful for construction purposes. The family distribution is dependent of the microstructure. The chemical composition is responsible for the chemical, physical and mechanical properties. Ferritic, martensitic, austenitic and duplex stainless steels are defined more in detail:

Ferritic: Stainless steel with chromium as main alloying element. The maximum carbon content is limited to 0,1% and the amount of chromium lies between 10,5 and 18%. Nickel is not or in very small extent present in the material and their body-centred atomic structure is the same as that of structural carbon steels. They cost less than the austenitic grades of equivalent corrosion resistance and show less price volatility. They are generally less ductile and less weldable than austenitic stainless steels.

Duplex: Is stainless steel with a mixture which consists mainly of chrome and nickel. The amount of chrome lies between 20 and 26% this is higher than the amount of nickel which is about 1-8%. Other components are present as well: molybdenum 0.05-5% and 0,05-0.3% nitrogen. Duplex stainless steels have a mixed microstructure of austenite and ferrite, and so are sometimes called austenitic-ferritic steels.

Duplex has a large strength with good corrosion resistance, but the material is harder to manipulate. But because they contain less nickel than the austenitic grades, they show less price volatility.

Austenitic: Austenitic stainless steel consists of chrome, nickel and at times molybdenum. Nickel makes it easier to deform the stainless steel. Austenitic steel contains about 17 to 18% chromium and 8% to 11% of nickel. In comparison to structural carbon steels, which have a body-centred cubic atomic (crystal) structure, austenitic stainless steels have a face-centred cubic atomic structure. As a result, austenitic stainless steels, in addition to their corrosion resistance, have high ductility, are easily cold formed, and are readily weldable.

Martensitic: Martensitic stainless steels have a similar body-centred cubic structure as ferritic stainless steel and structural carbon steels, but due to their higher carbon content, they can be strengthened by heat treatment. The use of martensitic stainless steel in construction is limited.

All of the variants have the ability to form a self-repairing protective oxide layer. This layer provides better corrosion and oxidation resistance in comparison with carbon steel. Carbon steel is usually used for steel which is not stainless, it also include alloy steels. The carbon content ranges from 0.12 up to 2.0%, much lower than carbon steel.

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9 Stainless steels have been used for building applications ever since they were invented. They have good corrosion resistance and are ideal for applications which are difficult to inspect and maintain. The corrosion resistance is possible due to the natural formation of of a passive surface film.

They are available in a range of surface finishes. Stainless steels can be manipulated and fabricated using a wide range of commonly available engineering techniques and are fully "recyclable" at the end of their useful life. They have good strength, toughness and fatigue properties.

Stainless steels are easily cleaned and so are an obvious choice for food and beverage manufacturing industries and catering equipment. There are no proven health risks from the normal use of stainless steels.

The austenitic stainless steels are essentially non-magnetic, but may become slightly magnetic when cold-worked.

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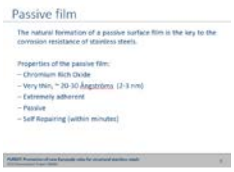
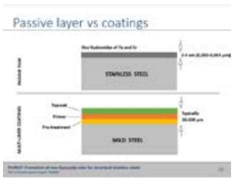
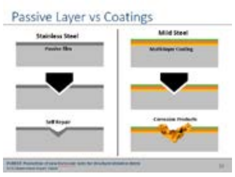
10 With a combination of the chromium content above 10,5%, a clean surface and exposure to air or any other oxidizing environment, a transparent and tightly adherent layer of chromium-rich oxide forms spontaneously on the surface of stainless steel. If scratching or cutting damages the film, it reforms immediately in the presence of oxygen. Although the film is very thin, about 5×10-6 mm, it is both stable and nonporous. As long as the stainless steel is corrosion resistant enough for the service environment, it will not react further with the atmosphere. For this reason, it is called a passive film. The stability of this passive layer depends on the composition of the stainless steel, its surface treatment and the corrosiveness of its environment. Its stability increases as the chromium content increases and is further enhanced by alloying additions of molybdenum and nitrogen.



11
12 When comparing the passive film with a multi-layer coating it can be noted that the passive film is much thinner. With a thickness of 2-3 nm (0.002-0.003 µm) compared to 20-200 µm respectively. In case the layer is damaged the passive film will self-repair itself following the damaged surface. In case of a multi-layer protection system the damage will cause corrosion in the damaged area. As seen on the illustrations on the slide.





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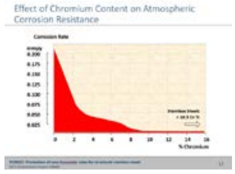
13 The corrosion rate (mmpy = millimeters per year) in the y-axis and the chromium content (%) in the x-axis. It’s clear that with a chromium content higher than 10,5% the corrosion is nearly zero.



Does Stainless Steel Ever Stain or Corrode?

Well, Yes. If the wrong grade is selected for the environment, or, if there is exposure to unexpected conditions, or, if the component is not cleaned regularly, then some grades may be susceptible to localized corrosion. However, in most natural environments stainless steel is corrosion resistant. Still, localized corrosion can occur depending on the alloy content and the service environment. Various types of corrosion are:

- **Uniform:** Does not occur in natural environments and for alloys used in structural applications.
- **Staining:** Can occur on leaner alloys in wide range of environments. Unsightly but cosmetic and of no consequence to integrity.
- **Pitting:** Risk increases with chloride deposition rate. Risk increases with decreasing alloy content. Unsightly but cosmetic and usually of no consequence to integrity.
- **Crevice:** Risk increases with chloride deposition rate. Risk increases with decreasing alloy content. Requires very fine gaps (<0.25 mm) and long periods of wetness. Potentially serious.
- **Stress Corrosion Cracking (SCC):** Combined action of tensile stress, chlorides and corrosion. Risk also related to temperature. Common lean austenitic grades most susceptible. Potentially serious resulting in collapse.
- **Bimetallic corrosion:** Usually a “problem” for the other metals: carbon steel, zinc and aluminium corrode in preference to stainless. For carbon steel it is usually painted which solves the problem.
- **Surface contamination:** Contaminants affecting the oxide surface layer protecting the stainless steel beneath.
- **Weld heat tint:** Is the thickening of the naturally occurring transparent oxide layer. Often seen in the heat affected areas of the weld. When a heat tint is formed, chromium is drawn to the surface of the stainless steel (chromium oxides form easier in comparison with iron in the steel). An area with a reduced corrosion resistance is present.

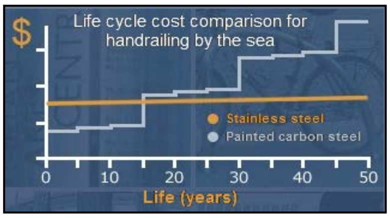
Thus, it is important to match alloy content to the service condition.

Successful Applications

15 Cost considerations

16 - Stainless steel is more expensive per tonne than carbon
17 steel.
- The price of stainless steel also tends to be more volatile, as it depends on the price of nickel.
- Whole life cost should be considered because less maintenance is required during the lifetime. Life cycle cost analyses show that stainless steel can be the cheapest

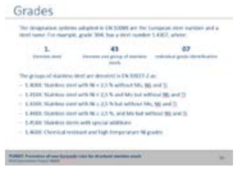
option compared to materials requiring more maintenance.



Grades and Grade Selection Procedure

19 Exercise: Try to analyze the name of following grades:

- 1.4301
- 1.4162
- 1.4016



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20 A procedure for selecting the appropriate austenitic and duplex
21 stainless steel grades for their application in certain environments, can be found in EN 1993-1-4/A1. This method is only valid for
22 Europe. The procedure does not take into account:

23 - Grade/product availability,
24 - Surface finish requirements, for example for architectural or hygiene reasons,
25 - Methods of joining/connecting.

The procedure assumes that the following criteria will be met:

- The service environment is in the near neutral pH range (pH 4 to 10),
- The structural parts are not directly exposed to, or part of, a chemical process flow stream,
- The service environment is not permanently or frequently immersed in seawater.

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

The procedure involves the following steps:

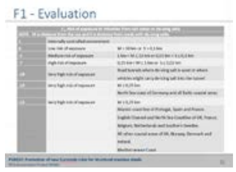
- Determination of the Corrosion Resistance Factor (CRF) for the environment (Table 3.3);
- Determination of the Corrosion Resistance Class (CRC) from the CRF (Table 3.4).

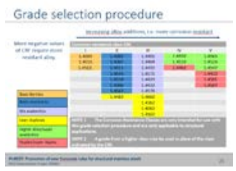
The corrosion resistance factor consists of three components and is formulated by:

$$CRF = F_1 + F_2 + F_3$$

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

See table 3.3 in the Design Manual or slide 16.

Once the CRF is obtained the corrosion resistance class should be determined using table 3.4 of the Design Manual or slide 17.

With the corrosion resistance class (CRC) you are able to select a correct stainless steel grade for your application using table 3.5 in the Design Manual (or slide 17).

For Swimming pool environments see section 3.5.3 in the Design Manual.

Procedure for grade selection for ferritic stainless steels see section 3.5.4 in the Design Manual.

Addition to slide 17.

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

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.

Properties of Stainless Steel

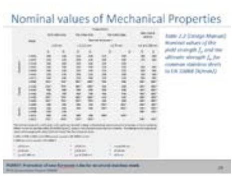
27 **Strength**

28 In design calculations, the characteristic yield strength f_y and
29 characteristic ultimate strength f_u are taken as the minimum specified values for the 0,2% proof strength ($R_{p0,2}$) and tensile strength (R_m) given in EN 10088-4 and 5 (see Table 2.2 in the design manual). These values apply to material in the annealed condition, and hence are conservative for material or sections which have undergone cold working during fabrication. Structural sections are rarely delivered in the annealed condition.

Modulus of elasticity

For structural design, it is recommended that a value of E = 200×10³ N/mm² is used for the modulus of elasticity for all stainless steels.

The value for carbon steel is E = 210×10³ N/mm².



NOTE: *EN 1993-1-4 and EN 10088-1 give a value of 200×103 N/mm2 for the modulus of elasticity for all the standard austenitic and duplex grades typically used in structural applications. For ferritic grades, a value of 220×103 N/mm2 is given. However, tests on ferritic stainless steels consistently indicate a value of 200×103 N/mm2 is more appropriate and so it is expected that the next revision of EN 1993-1-4 will recommend this value to be used for structural design for all stainless steels.*

Other parameters

A value of 0,3 can be taken for Poisson's ratio which is the same as for carbon steel. A value of $76{,}9 \times 10^3$ N/mm^2 for the shear modulus, G, is used.

Slide 28 gives an overview of the minimum specified mechanical properties of stainless steel taken from EN 10088. Properties are in the 'annealed' (softened condition).

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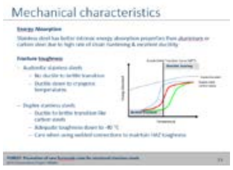
30 **Energy Absorption**



Stainless steel has better intrinsic energy absorption properties than aluminium or carbon steel due to high rate of strain hardening & excellent ductility.

Fracture toughness

- Austenitic stainless steels
  - No ductile to brittle transition
  - Ductile down to cryogenic temperatures
- Duplex stainless steels
  - Ductile to brittle transition like carbon steels
  - Adequate toughness down to -40 °C
  - Care when using welded connections to maintain HAZ toughness

Ductile = able to deform a lot under tensile stress.

Brittle = only able to deform a little under tensile stress after which it breaks.

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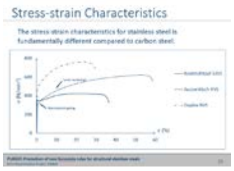
31 The key difference between carbon steel and stainless steel is in the stress-strain curve, as shown on this slide. Carbon steel (orange curve) has linear elastic behavior up-until a sharply defined yield point, after which strain can increase with no increase in stress, although there may be an small amount of strain hardening. Stainless steel on the other hand exhibits gradually yielding behavior, with high strain-hardening (green curve).



The stress-strain characteristics for stainless steel is fundamentally different compared to carbon steel:

- Nonlinear stress-strain diagram. This leads to:
  - Different member buckling behavior in compression and bending
  - Greater deflections

- Important strain hardening (also called cold-working)

In addition, stainless steel exhibit:

- Non-symmetry (tensile and compressive)
- Anisotropy (parallel and transverse to the rolling directions).

Stainless steel also exhibits:

- Non-symmetry (tensile and compressive)
- Anisotropy (parallel and transverse to the rolling directions).

Anisotropy = Properties depend on the direction, thus different properties in different directions are applicable.

However, from a structural point of view anisotropy and non-symmetry are not as important as the non-linearity.

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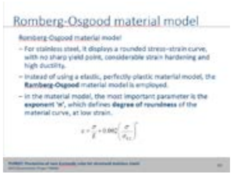
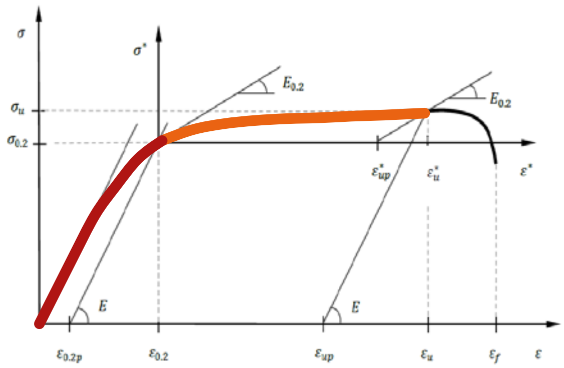
32 An approximation of the stress-strain curve is required to use it in calculations. Using an elastic, perfectly-plastic material model would ignore the beneficial effect of strain hardening. Therefore the Ramberg-Osgood material model is used for the approximation of the stress-strain curve.





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

Equations based on austenitic and duplex grades. Not always valid for ferritics. A revision is needed to represent all grades.

Careful analysis of more than 1000 coupon test results showed that:

- The model codified in Annex C of EN1993-1-4 is a valid simplification for all stainless steel grades
- No distinction between loading direction, sense of loading or cold-worked level.
- Some of the predictive equations need to be revised.

Strain hardening parameters:

Ferritics: less ductile behaviour with less strain hardening

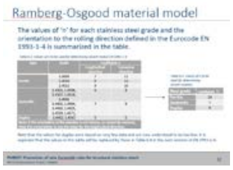
$$n = \frac{\ln 20}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \qquad m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \qquad \varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u} \qquad \frac{\sigma_{0.2}}{\sigma_u} = 0.2 + 185\frac{\sigma_{0.2}}{E}$$

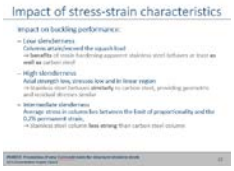
$$n = \frac{\ln 4}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.05}}\right)} \qquad m = 1 + 2.8\frac{\sigma_{0.2}}{\sigma_u} \qquad \varepsilon_u = 0.6 \cdot \left(1 - \frac{\sigma_{0.2}}{\sigma_u}\right) \qquad \frac{\sigma_{0.2}}{\sigma_u} = 0.46 + 145\frac{\sigma_{0.2}}{E}$$

NEW PROPOSALS

33 The coefficient "n" is derived from the stress at the limit of proportionality and hence is a measure of the non-linearity of the stress-strain curve. Lower values of "n" indicate a greater degree of non-linearity. The value is dependent of following factors:

34





- stainless steel group,
- processing/fabrication route,
- level of cold work
- direction of loading (tension or compression)

EN 1993-1-4 currently gives values for "n" which depend on grade and the orientation to the rolling direction (Table 6.5). Note that the values for duplex were based on very few data and are now understood to be too low. It is expected that the values in this table will be replaced by those in Table 6.4 in the next revision of EN 1993-1-4.

35 Stainless steel is a non-linear material where there is no sharply defined yield point, but instead gradually yielding behavior and significant strain hardening. In the absence of a yield strength, the proof strength is defined. The proof strength is the strength at an offset plastic strain, and it is most common to use the 0.2% proof strength.

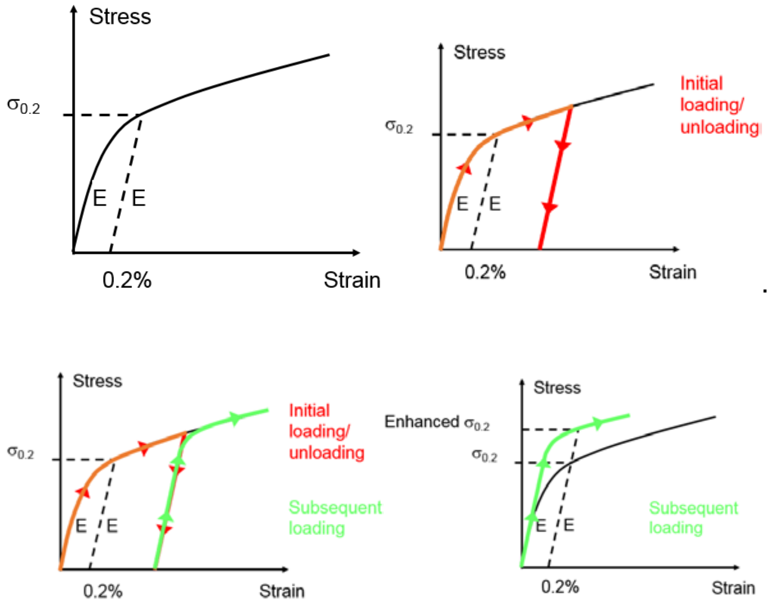
36

The effect of deformation into the plastic zone followed by unloading results in permanent plastic deformation and cold-working of the material. Cold-working may occur during:

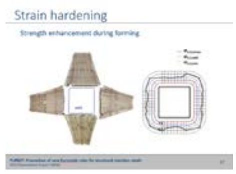
- Forming of sheet material (at the steel mill)
- Section forming (at the fabrication shop)
- Under load (in service)

Then, under subsequent loading, you see an extended elastic region and an enhanced yield strength. This is the enhanced strength. There is a loss of ductility, but the ductility of annealed stainless steel is very high, and the ductility of cold-formed elements is good.

The images below illustrate the text:

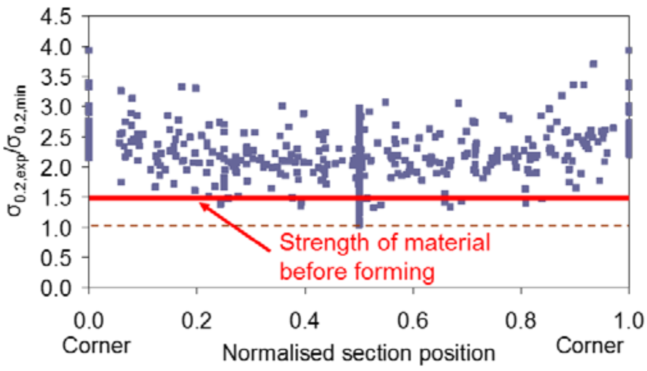


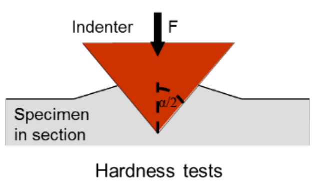
37 By slicing specimens into a series of strips and then measuring the stress-strain characteristics it is possible to build up a profile of strength around the section. With sufficient data, predictive tools can be developed – this process is underway at the moment.

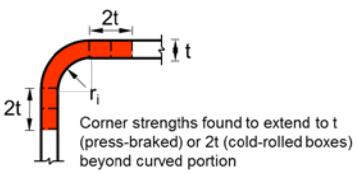


Collated results for cold-rolled box sections

- Mechanically based predictive expressions for flat faces developed and verified against collated test results
- Extent of corner regions was also identified through more refined hardness testing by means of a derived correlation with strength







Mechanically based predictive models developed and verified against collated tests; two-step process:

- Estimate plastic strain induced during section forming using simple geometric relationships (t and R)

- Determine stress corresponding to this plastic strain from material model to use as enhanced yield strength

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.

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.

Additional: Stainless steel is available in standardized cold-worked conditions. The rules in EN 1993-1-4 and the *Design Manual* can be applied to material in the following cold worked conditions:

- For CP350, characteristic f_y = 350 N/mm²
- For CP500, characteristic f_y is reduced from 500 to 460 N/mm² to account for asymmetry and anisotropy

Plastic deformation during cold-forming can introduce substantial strength enhancements. Annex B in the Design Manual allows the designer to take this strength enhancement into account.

Replace f_y with the average enhanced yield strength f_{ya}.

The additional benefit of strength enhancement due to work hardening in service may also be taken into account in design using the Continuous Strength Method, as described in Annex D.

---

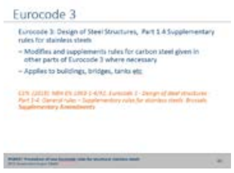
38 Strain hardening is not always useful:

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

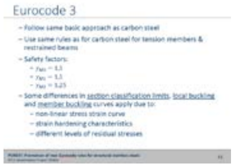
The reduction in ductility is never a problem with austenitics because they have such high ductility to start with.

Stainless Steel Design Rules

40 The main part of the Eurocode related to Stainless steel is EN 1993-1-4. This part of Eurocode 3 provides supplementary rules for stainless steel where the behavior is different. The rules are generally presented in a similar way to those presented for carbon steel, in order to aid engineers who may have more experience with carbon steel.



41 An important difference for stainless steel are the safety factors. The following factors should be used for stainless steel:



- $\gamma_{M0} = 1{,}1$
- $\gamma_{M1} = 1{,}1$
- $\gamma_{M2} = 1{,}25$

These values are different than for carbon steel.

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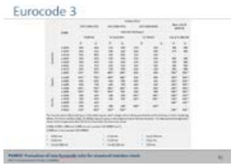
42 This slide gives the nominal values of the yield strength f_y and the ultimate strength f_u for common stainless steels to EN 10088 (N/mm2).



See table 2.2 in the Design Manual.

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43 In compression, because of small thicknesses, the behavior of plates is affected by instability phenomena called LOCAL buckling. Local buckling prevents the cross-section to attain the elastic resistance.

Therefore classification is introduced. Classification of cross-sections influence the:

- Type of analysis,
- The cross-section verification (plastic resistance? elastic?),
- Member (we also want to know whether we can profit from plasticity).

---

44 Classification is required to decide about the type of cross-section verification:

- Elastic verification,
- Plastic (or partial plastic) verification,
- Effective cross-section properties ('reduced' cross-section properties: A_{eff} and I_{eff}).

Four classes are defined:

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

Depended of the class the plastic resistance may or may not be taken into account. Having a class 1 or 2 profile can be very beneficial for most cases. Overview:

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

- Effective properties should be used:
  The effective area of the compression zone of a plate with the gross cross-sectional area A_c should be obtained from:

  $$A_{c,eff} = \rho A_c$$

  where ρ is the reduction factor for plate buckling.
  Internal compression elements (cold formed or welded) (this is a different expression from that for carbon steel)

  $$\rho = \frac{0{,}772}{\bar{\lambda}_{\mathrm{p}}} - \frac{0{,}079}{\bar{\lambda}_{\mathrm{p}}^2} \quad \text{but} \leq 1{,}0$$

  Outstand compression elements (cold formed or welded):

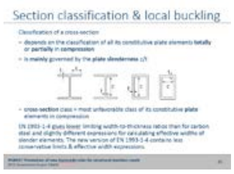
  $$\rho = \frac{1}{\bar{\lambda}_{\mathrm{p}}} - \frac{0{,}188}{\bar{\lambda}_{\mathrm{p}}^2} \quad \text{but} \leq 1{,}0$$

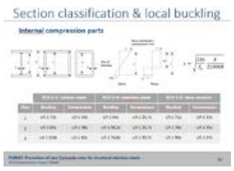
  $\bar{\lambda}_{\mathrm{p}}$ is the element slenderness:

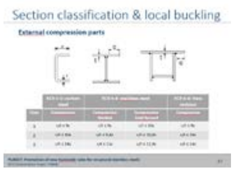
  $$\bar{\lambda}_{\mathrm{p}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}}$$

  The formulations for ρ is different for stainless steel and for carbon steel. The overall approach is the same.

45
46
47







Determination of the class is done by classification of all constitutive plate elements partially or totally in compression. The class is dependent on the plate slenderness c/t which is evaluated against limits defined for each class. The cross-section class is the most unfavorable class of its constitutive plate elements in compression.

Two important notes can be made:

- Cross-section class = most unfavorable class of its constitutive plate elements in compression. Thus fabricated girders with slender webs are usually Class 4 sections!
- Cross-section class depends on $\varepsilon = \sqrt{\frac{235}{f_y}\frac{E}{210000}}$. Thus Many sections fall in class 3 (semi-compact) and 4 when higher grades are used!

Since the design rules in the Eurocode were derived, a great deal more test data have become available for structural stainless steel and these data now justify the use of less conservative section classification limits, generally aligned to the carbon steel limits. The limits will therefore be raised in the next version of EN 1993-1-4, due to be published in 2014.

Slide 46 and 47 show the different limiting values for carbon steel, stainless steel according to EN 1993-1-4 and stainless steel according to the revision of EN 1993-1-4 in 2014.

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48 Recap of naming system with an example.

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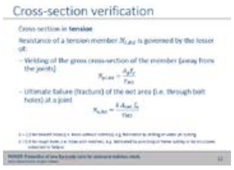
49 No extra notes.



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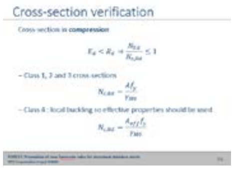
50 Depending on their member slenderness, columns display two distinct types of behavior:

- The behavior of short, stocky columns (low member slenderness) will be governed by local cross-section properties and failure will be by material yielding (squashing). The yield load $N_y = Af_y$ (area x yield strength)
- The behavior of long slender columns (high member slenderness) will be governed by global proportions and failure will be due to overall elastic member instability (buckling). The elastic buckling load is denoted N_{cr}. See later in this presentation.



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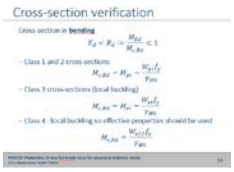
51 No extra notes.



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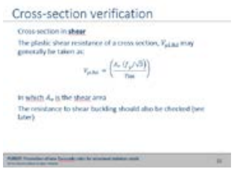
52 For more formulations for A_v see table 5.5 in the Design Manual.



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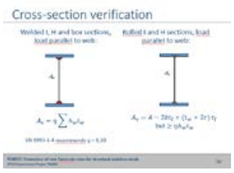

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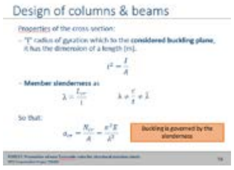
54 In compression, because of the global dimension of the column, the
55 behavior is affected by instability phenomena. Those instabilities often take the form of GLOBAL lateral buckling about the weak axis.

Buckling is governed by the slenderness:

$$\sigma_{cr} = \frac{N_{cr}}{A} = \frac{\pi^2 E}{\lambda^2}$$

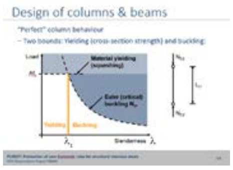


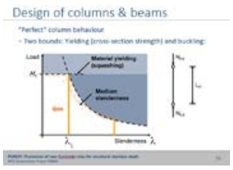
56 This graph represents the "perfect" column behavior. Two zones can
57 be specified in the load-slenderness diagram. A yielding zone, where the section fails due to yielding (cross-section strength, see section in
58 compression), and a buckling zone, where buckling occurs before the maximum cross-section strength is reached.

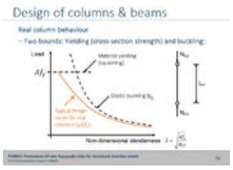
The actual strength of columns does not exactly follow the theory (i.e. Material yielding + elastic buckling) due to:

- Initial geometric out-of-straightness
- Eccentricity of loading
- Non-homogeneity of material
- Residual stresses
- …

Thus, design buckling curves lie on or below the theoretical curves.

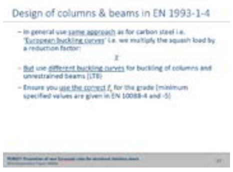






59 In general the same approach as for carbon steel i.e. 'European buckling curves' i.e. is used. Multiply the squash load by a reduction factor χ. But use different buckling curves for buckling of columns and unrestrained beams (LTB).

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



60 Compression buckling resistance $N_{b,Rd}$ is determined as follows:

61 For class 1,2 and 3 sections:

62
$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}}$$

For class 4 sections:

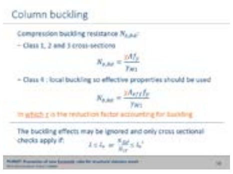
$$N_{b,Rd} = \frac{\chi A_{eff} f_y}{\gamma_{M1}}$$

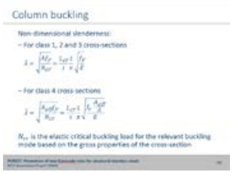
In which χ is the reduction factor accounting for buckling. The reduction factor can be calculated using:

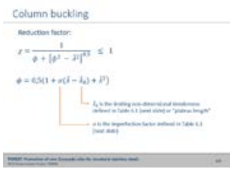
$$\chi = \frac{1}{\phi + \left[\phi^2 - \bar{\lambda}^2\right]^{0,5}} \leq 1$$

The non-dimensional slenderness $\bar{\lambda}$ can be calculated using:

For class 1,2 and 3 sections:







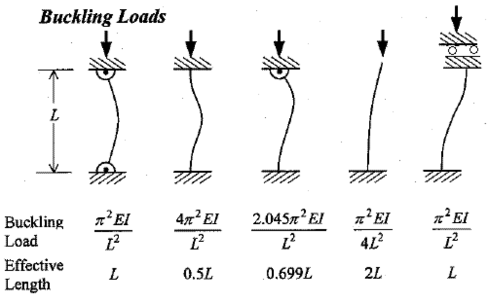
$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \frac{L_{cr}}{i}\frac{1}{\pi}\sqrt{\frac{f_y}{E}}$$

For class 4 sections:

$$\bar{\lambda} = \sqrt{\frac{A_{eff}f_y}{N_{cr}}} = \frac{L_{cr}}{i}\frac{1}{\pi}\sqrt{\frac{f_y \frac{A_{eff}}{A}}{E}}$$

N_{cr} is the elastic critical buckling load for the relevant buckling mode based on the gross properties of the cross-section. In the formulation of N_{cr}, L_{cr} represents the effective buckling length. The determination of the buckling length should be based upon structural mechanics principles, taking boundary conditions into account.

$$N_{cr} = \frac{\pi^2 EI}{{L_{cr}}^2}$$



And,

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

The buckling curves for stainless steel take the same mathematical form as those for carbon steel but the imperfection factor (α table 6.1 (slide 61)) and non-dimensional limiting slenderness ($\bar{\lambda}_0$ table 6.1 (slide 61), "plateau length") are different.

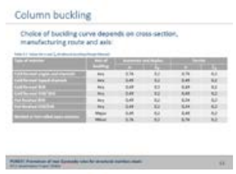
is the imperfection factor defined in Table 6.1 (slide 61).

For stainless steel sections the buckling effects may be ignored and only cross sectional checks apply if:

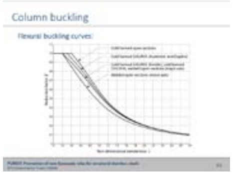
$$\bar{\lambda} \leq \bar{\lambda}_0 \quad \text{or} \quad \frac{N_{Ed}}{N_{cr}} \leq {\bar{\lambda}_0}^2$$

63 No notes.

64



65 Buckling curves for various sections is shown on this graph.



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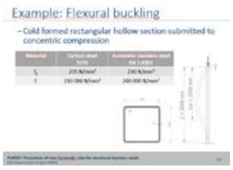
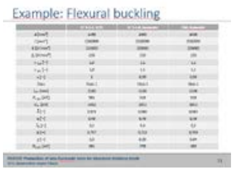
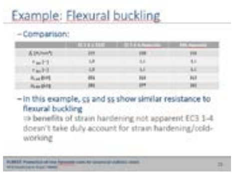
66 Two columns, one carbon steel and one stainless steel, with similar
properties are compared. The calculations for the stainless steel
67 column are calculated according to EN 1993-1-4 and Design Manual.
68 The difference between both is only related to the factor $\bar{\lambda}_0$.

In this example, cs and ss show similar resistance to flexural buckling. The benefits of strain hardening are not apparent, EN 1993-1-4 doesn't take duly account for cold-working.

Strength enhancement (annex B in Design Manual) and continuous strength method (annex D in Design Manual) should be applied.







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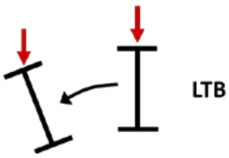
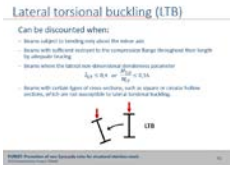
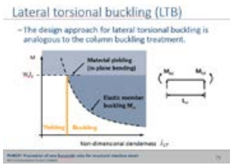
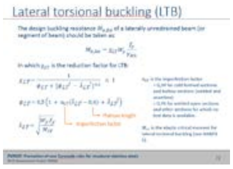
69 Beams of which the compression flange is free to rotate and displace
laterally is considered as a unrestrained beam. Unrestrained beams
70 may suffer from lateral torsional buckling (LTB). Applied loading
71 introduces a different force in the two flanges, one under
compression, one in tension causing the one on compression to rotate
of displace laterally. Lateral torsional buckling must be avoided in
construction.









In following cases LTB shouldn't be considered:

- Beams subject to bending only about the minor axis,
- Beams with sufficient restraint to the compression flange throughout their length by adequate bracing,
- Beams where the lateral non-dimensional slenderness parameter,

$$\bar{\lambda}_{\mathrm{LT}} \leq 0{,}4 \quad \text{or} \quad \frac{M_{\mathrm{Ed}}}{M_{\mathrm{cr}}} \leq 0{,}16$$

- Beams with certain types of cross-sections, such as square or circular hollow sections, which are not susceptible to lateral-torsional buckling.

For all other classes of member, the resistance to lateral torsional buckling should be checked. The design approach for LTB is analogous to the column buckling treatment. The buckling resistance can be calculated using:

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

W_y = $W_{pl,y}$ for Class 1 or 2 cross-sections

W_y = $W_{el,y}$ for Class 3 cross-sections

W_y = $W_{eff,y}$ for Class 4 cross-sections

χ_{LT} is a reduction factor accounting for lateral torsional buckling, given by:

$$\chi_{LT} = \frac{1}{\phi_{LT} + [\phi_{LT}{}^2 - \bar{\lambda}_{LT}{}^2]^{0,5}} \leq 1$$

In which:

$$\phi_{LT} = 0,5\left(1 + \alpha_{LT}(\bar{\lambda}_{LT} - 0,4) + \bar{\lambda}_{LT}{}^2\right)$$

α_{LT} is the imperfection factor. The values of α_{LT} are different for stainless steel compared to carbon steel.

> α_{LT} = 0,34 for cold formed sections and hollow sections (welded and seamless).
>
> α_{LT} = 0,76 for welded open sections and other sections for which no test data is available.

The value 0,4 in the formulae above represents the “plateau length” see on slide 71 (different for carbon steel).

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

M_{cr} is the elastic critical moment for lateral torsional buckling (see annex E of the Design Manual).

Calculation approach is identical to that for carbon steel members.

The moment distribution between the lateral restraints of members can be taken into account by the use of a modified value for χ_{LT} where:

$$\chi_{LT,mod} = \frac{\chi_{LT}}{f}$$

But, $\chi_{LT,mod} \leq 1$ and $\chi_{LT,mod} \leq \frac{1}{\bar{\lambda}_{LT}{}^2}$

The following minimum value for f is recommended:

$$f = 1 - 0,5(1 - k_c)\left[1 - 2,0\left(\bar{\lambda}_{LT} - 0,8\right)^2\right] < 1,0$$

$$k_c = \frac{1}{\sqrt{C_1}}$$

Values of C_1 can be found in annex E of the Design Manual.

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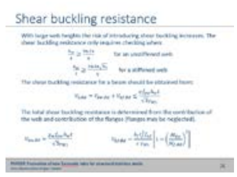
72 With large web heights the risk of introducing shear buckling increases. The shear buckling resistance only requires checking when:



$\frac{h_w}{t} \geq \frac{56,2\varepsilon}{\eta}$ for an unstiffened web

$\frac{h_w}{t} \geq \frac{24,3\varepsilon\sqrt{k_t}}{\eta}$ for a stiffened web

The shear buckling resistance for a beam should be obtained from:

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta f_{yw} h_w t}{\sqrt{3}\gamma_{M1}}$$

The total shear buckling resistance is determined from the contribution of the web and contribution of the flanges. For simplicity, the contribution from the flanges χ_f may be neglected. However, if the flange resistance is not completely utilized in withstanding the bending moment ($M_{Ed} < M_{f,Rd}$) then the contribution from the flanges may be obtained as follows:

$$V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t}{\sqrt{3}\gamma_{M1}}$$

$$V_{bf,Rd} = \frac{b_f t_f^2 f_{yf}}{c\,\gamma_{M1}}\left[1 - \left(\frac{M_{Ed}}{M_{f,Rd}}\right)^2\right]$$

For values of η, see EN 1993-1-5 (EN 1993-1-4 recommends η = 1,20.)

The UK National Annex gives η = 1,20 when the 0,2% proof strength of the steel is not higher than 460 MPa and when the temperature of the steel does not exceed 400°C. The value η = 1,0 should be used when the 0,2% proof strength exceeds 460 MPa and/or the temperature of steel exceeds 400°C.

Note: The same value of η should be used for calculating the plastic shear resistance as is used for calculating the shear buckling resistance.

For a complete design overview for shear buckling see 6.4.3 in the Design Manual.

For carbon steel the design approach is similar. However, different limiting values are given. For example shear buckling resistance for carbon steel members only requires checking when:

$\frac{h_w}{t} \geq \frac{72\varepsilon}{\eta}$ for an unstiffened web (carbon steel)

$\frac{h_w}{t} \geq \frac{31\varepsilon\sqrt{k_t}}{\eta}$ for a stiffened web (carbon steel)

Deflections

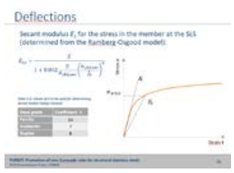
74 The determination of deflections should be conducted using the relevant serviceability limit state.

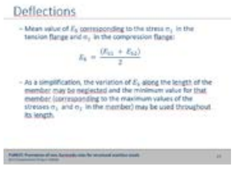
75

76 The deflection of elastic beams (i.e. those not containing a plastic hinge) may be estimated by standard structural theory, except that the secant modulus of elasticity should be used instead of the modulus of elasticity. The value of the secant modulus varies with the stress level in the beam and may be obtained as follows:

$$E_S = \frac{(E_{S1} + E_{S2})}{2}$$

E_{S1} is the secant modulus corresponding to the stress in the tension flange.
E_{S2} is the secant modulus corresponding to the stress in the compression flange.





Secant modulus E_S for the stress in the member at the SLS (determined from the Ramberg-Osgood model):

$$E_{\mathrm{S,i}} = \frac{E}{1 + 0{,}002\,\dfrac{E}{\sigma_{\mathrm{i,Ed,ser}}}\left(\dfrac{\sigma_{\mathrm{i,Ed,ser}}}{f_{\mathrm{y}}}\right)^{\mathrm{n}}}$$

$\sigma_{\mathrm{i,Ed,ser}}$ is the serviceability design stress in the tension or compression flange

n is derived from the stress at the limit of proportionality and hence is a measure of the non-linearity of the stress-strain curve, with lower values indicating a greater degree of non-linearity. Values for n depend on the stainless steel group, processing/fabrication route, level of cold work and direction of loading (tension or compression). There is a large variation in measured values. Recommended values are given in table 6.4.

Background

The non-linear stainless steel stress-strain relationship means that the modulus of elasticity varies within the cross-section and along the length of a member. Hence complex, non-linear procedures are required for the accurate determination of deflections in stainless steel beams. As a simplification, the variation of E_{S} along the length of the member may be neglected and the minimum value of E_{S} for that member (corresponding to the maximum values of the stresses σ_1 and σ_2 in the member) may be used throughout its length. Note that this method is accurate for predicting deflections when the secant modulus is based on the maximum stress in the member and this maximum stress does not exceed 65% of the 0.2% proof strength. At higher levels of stress, the method becomes very conservative and a more accurate method (e.g. one which involves integrating along the length of the member) should be used.

EN 1993-1-4

EN 1993-1-4 currently gives values for n which depend on grade and the orientation to the rolling direction (Table 6.5). Note that the values for duplex were based on very few data and are now understood to be too low. It is expected that the values in this table will be replaced by those in Table 6.4 in the next revision of EN 1993-1-4.

Strength enhancement of cold formed sections

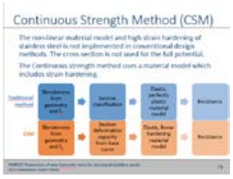
78 Strength enhancement may be applied for all types of cold formed
79 sections. The benefits of cold working during the fabrication process may be utilized in cross section and member design by replacing f_{y}
80 with the average enhanced yield strength f_{ya}.

The additional benefit of strength enhancement due to work hardening in service may also be taken into account in design using the Continuous Strength Method, as described in Annex D.

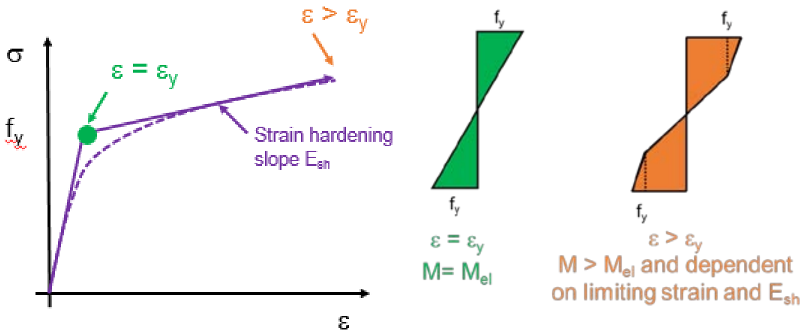
Calculation method see annex B in the Design Manual.

Continuous strength method (CSM)

82 As mentioned before the young's modulus and yield strength of
83 stainless steel is broadly similar to carbon steel. But the stress strain curve is fundamentally different:



- Carbon steel has a sharply defined yield point with a plastic yield plateau (followed later by strain hardening)
- Stainless steel exhibits gradually yielding behavior, with high strain hardening. Elastic, linear hardening material model (strain hardening):



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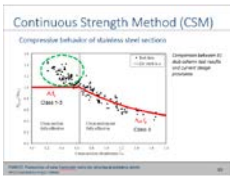
84 This graph shows the collected test data on stainless steel cross-
85 sections in compression. On the vertical axis the ultimate achieved load during testing, normalized by the yield load and on the horizontal axis the local cross-sections slenderness. The red line represents the current design approach similar to the carbon steel philosophy – i.e. elastic, perfectly plastic material behavior.



The interesting data lies on the left side of the curve. All of these specimens are deforming along the stress-strain curve and achieving capacities well in excess of the yield load due to strain hardening, but current codes are limiting their capacity to the yield load, which you can see is very conservative. Conclusion: current design provisions are overly-conservative, particularly for stocky stainless steel cross-sections. The same is observed when comparing the bending resistant.

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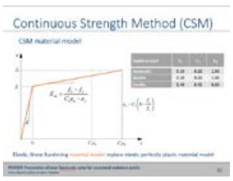
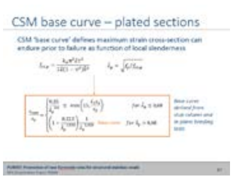
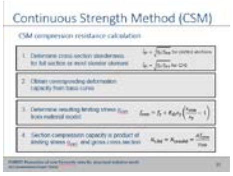
86 Elastic, linear hardening material model replace elastic perfectly
87 plastic material model.



88 The first step in CSM is the determination of the deformation capacity of the cross-section. In other words, what is the amount of strain the cross-section can resist before failure by local buckling. This is the relation between deformation capacity and local cross-section slenderness, referred to as the base curve.



Now use this limiting strain, epsilon CSM, in conjunction with the second key component of the CSM, which is the strain hardening material model, with the strain hardening slope varying with the grade of stainless steel… and different grades can show different hardening characteristics.



$\bar{\lambda}_p = \sqrt{f_y / f_{cr,p}}$ for plated sections

$\bar{\lambda}_p = \sqrt{f_y / f_{cr,c}}$ for CHS

$$f_{csm} = f_y + E_{sh}\varepsilon_y \left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1 \right)$$

For plated sections with $\bar{\lambda}_p \leq 0{,}68$ and for CHS with $\bar{\lambda}_c \leq 0{,}30$, corresponding to $\varepsilon_{csm}/\varepsilon_y \geq 1{,}0$, the cross-section compression resistance is determined as:

$$N_{c,Rd} = N_{csm,Rd} = \frac{Af_{csm}}{\gamma_{M0}}$$

For plated sections with $\bar{\lambda}_p > 0{,}68$ and for CHS with $\bar{\lambda}_c > 0{,}30$, corresponding to $\varepsilon_{csm}/\varepsilon_y < 1{,}0$, the cross-section compression resistance is determined as:

$$N_{c,Rd} = N_{csm,Rd} = \frac{\varepsilon_{csm}}{\varepsilon_y} \frac{Af_y}{\gamma_{M0}}$$

For CSM calculations for resistance in bending, see Design Manual Annex D.

Conclusion

90 Stainless steel is a remarkable material which offers significant benefits over carbon steel. Due to the lack of clear design guidance this material is yet widely used in construction. By the development of the Design Manual we hope to inspire existing and new generations to discover stainless steel as a construction material.

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