Imperial College London

# Designing HSS structures: Eurocode rules and practical guidance

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**HILONG Workshop**

# Outline

Outline:

- Introduction
- Production and design guidance
- Opportunities and challenges
- Use of HSS in buildings
- Conclusions

# Introduction

Forth Rail Bridge

# Introduction

London Eye

# Introduction

Requirements for structural steels:

- Strength
- Stiffness
- Ductility
- Fracture toughness
- Weldability

# Production

Among other means, the two principal means of increasing yield strength are:

- Alloying
- Heat treatment

# Production

Alloying:

- Increases in yield strength can be achieved through the addition of alloying elements such as carbon and manganese

- However, the addition of alloying elements generally worsens the fabrication properties, particularly weldability

$$CEV = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

# Production

Heat treatment:

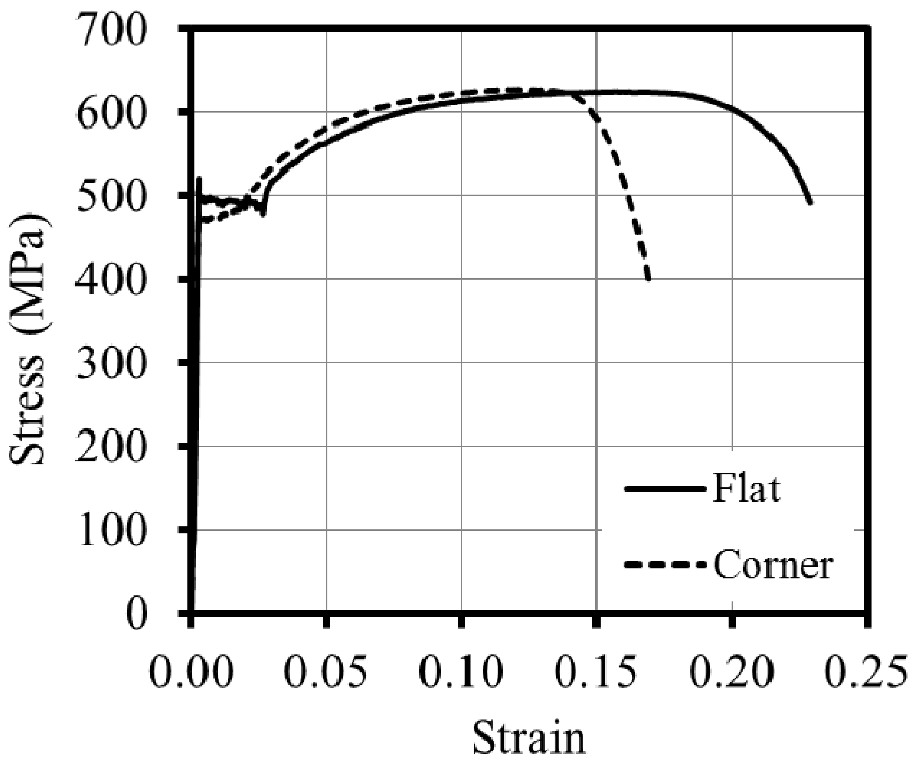
- Increases in yield strength can be achieved through heat treatment. Micro-structure and grain size are carefully controlled.
  - Normalising
  - Quenching and tempering
  - Thermo-mechanical rolling

# Material grades

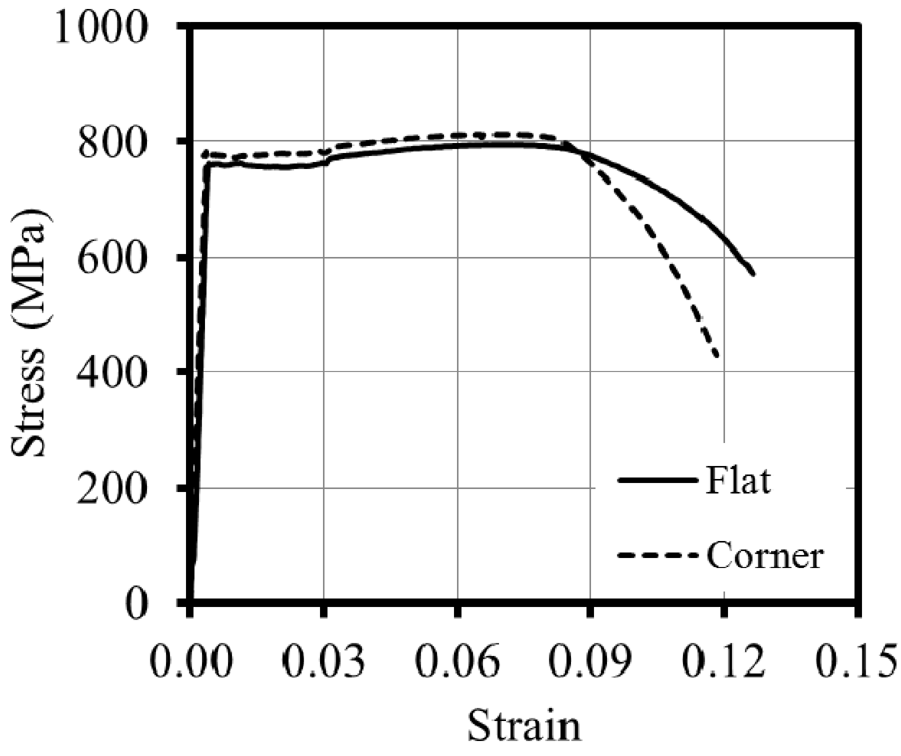
| Grade | $f_y$ (N/mm²)[a] | $f_u$ (N/mm²)[a] | Elongation at fracture (%) | |
|---|---|---|---|---|
| S235 | 235 | 360 | 28 | Normal strength |
| S275 | 275 | 430 | 22 | |
| S355 | 355 | 510 | 22 | |
| S460 | 460 | 540 | 17 | High strength |
| S500 | 500 | 590 | 17 | |
| S550 | 550 | 640 | 16 | |
| S620 | 620 | 700 | 15 | |
| S690 | 690 | 770 | 14 | |
| S890 | 890 | 940-1100 | 11 | Very high strength |
| S960 | 960 | 980-1150 | 10 | |
| S1100 | - [b] | - [b] | - [b] | |

[a] t<40 (or 50) mm, [b] Not standardised

# Material stress-strain curves




S460




S690

# European design guidance

EN 1993-1-1: Design of steel structures – General rules and rules for buildings

- Up to S460

EN 1993-1-12: Design of steel structures – Additional rules for the extension of EN 1993 up to steel grades S700

- Up to S700

# European design guidance

EN 1993-1-12: Design of steel structures – Additional rules for the extension of EN 1993 up to steel grades S700

- In general, the design rules are the same for HSS as for normal strength material
- Some modifications to the preceding eleven parts of the Eurocode are set out in Part 1-12.

# Opportunities of high strength steel

Opportunities:

- Material cost savings
- Aesthetics – more slender structures
- Environmental – less material consumption
- Lower fabrication costs
- Lower corrosion protection costs
- Lighter structures
- Smaller foundations
- Lower transportation and erection costs

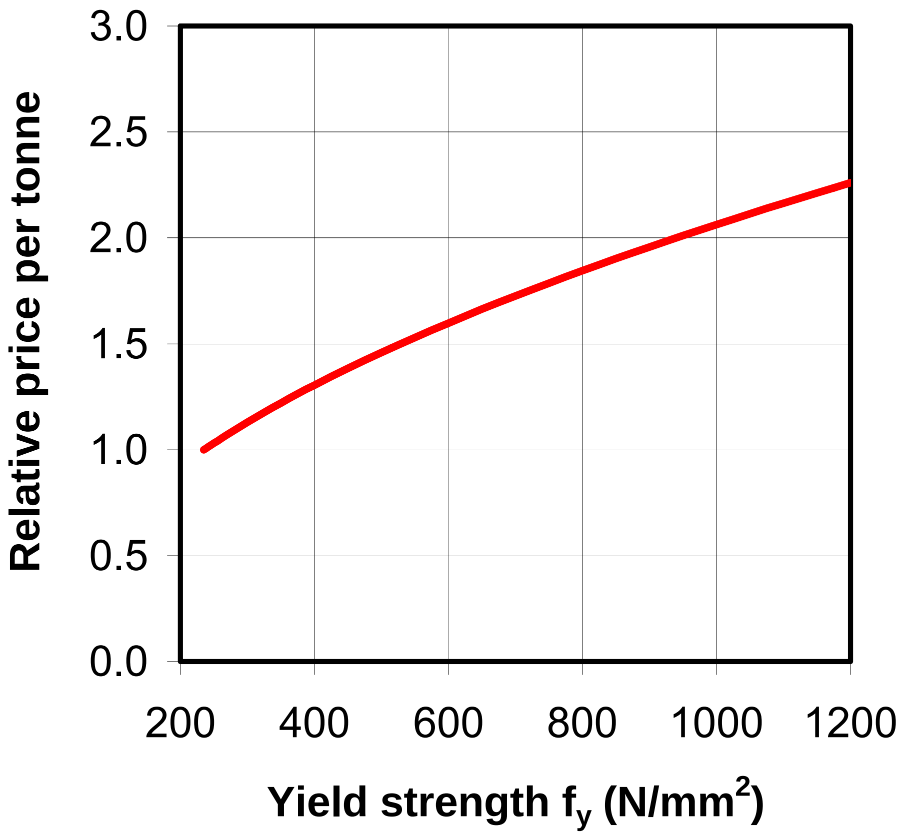
# Challenges with the use of high strength steel

Challenges:

- Instability (buckling)
- Greater deflections and vibrations
- More critical fatigue conditions
- Reduced ductility
- Higher ratio of yield to ultimate stress
- Reduced fracture toughness
- Lighter structures (if uplift critical)

# Costs

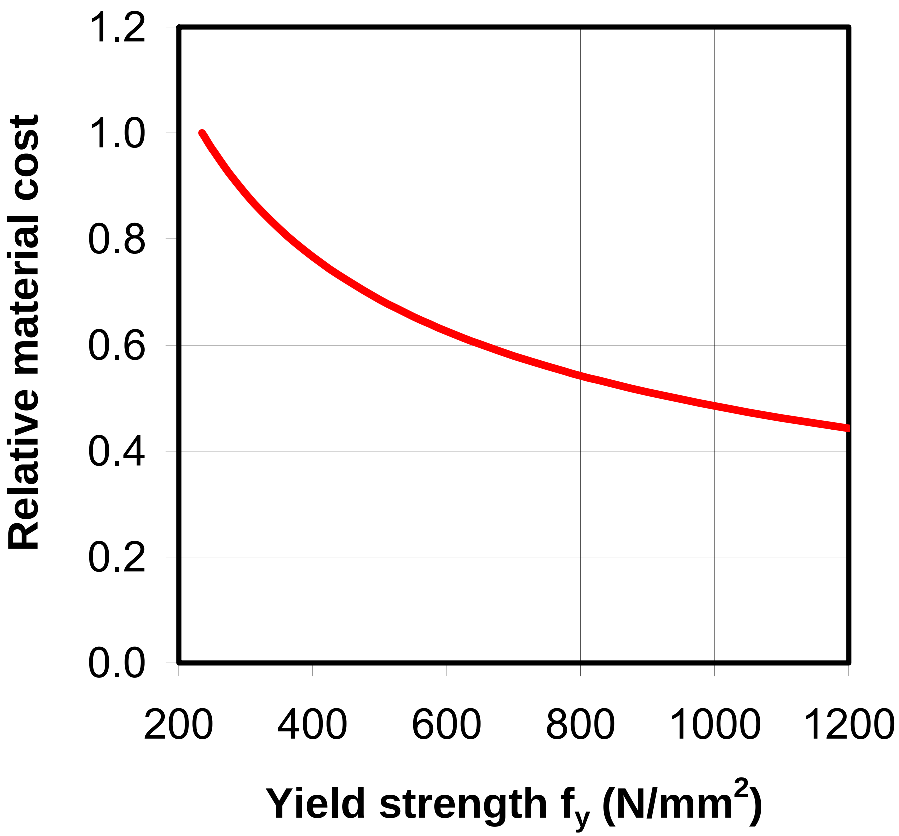
*Relative price per tonne ≈ $(f_y/235)^{1/2}$:




*IABSE (2005)

# Costs

Provided strength is fully utilised, relative material cost ≈ $(235/f_y)^{1/2}$:



# Buckling

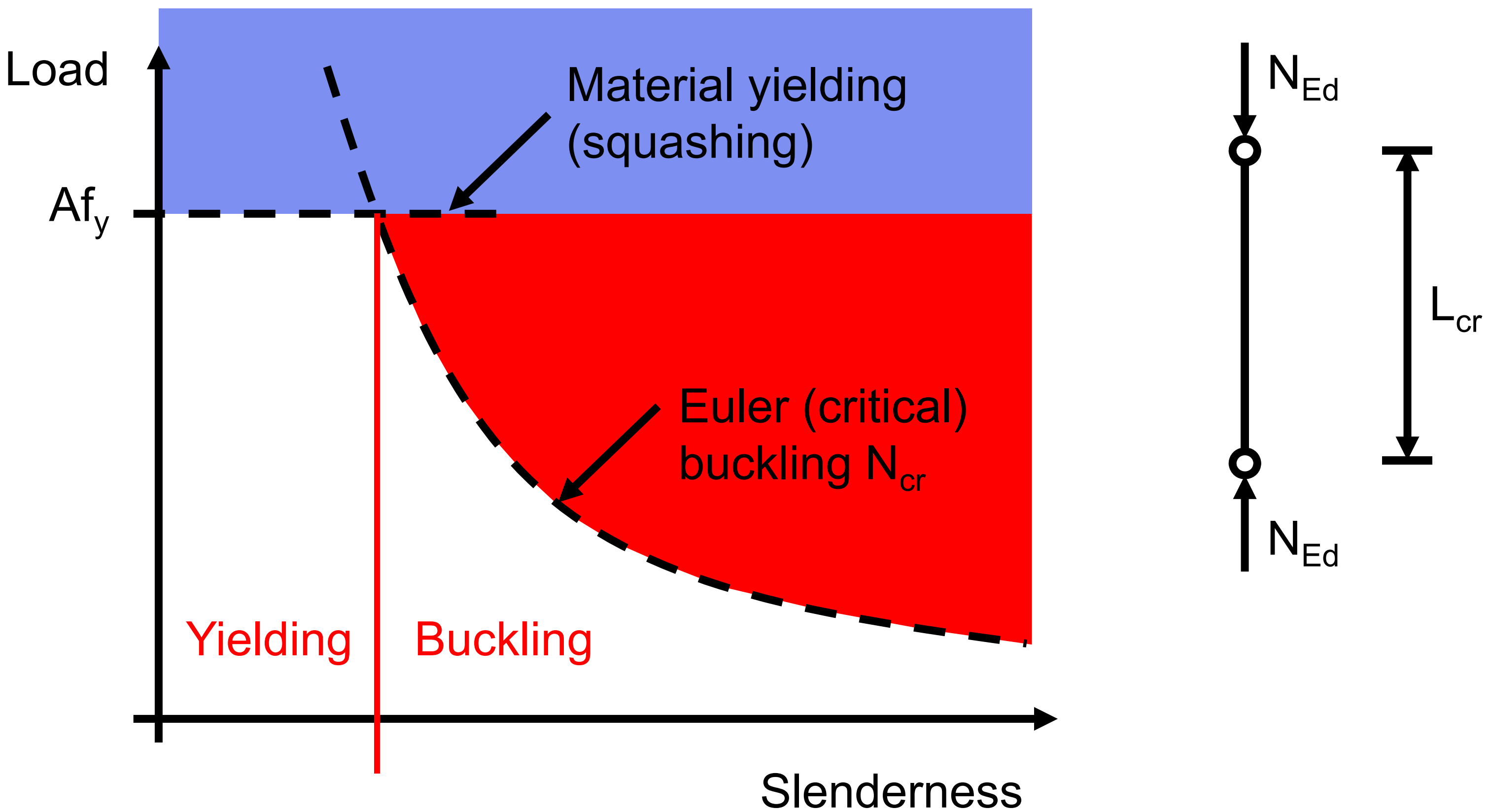
A range of buckling phenomena exist:

- Flexural buckling (columns)
- Torsional and torsional-flexural buckling (columns)
- Lateral torsional buckling (beams)
- Local buckling (plates, generally)
- Shear buckling (webs)

# Perfect column behaviour

## Two bounds: Yielding and buckling.

As yield limit increases, member buckling becomes more influential.

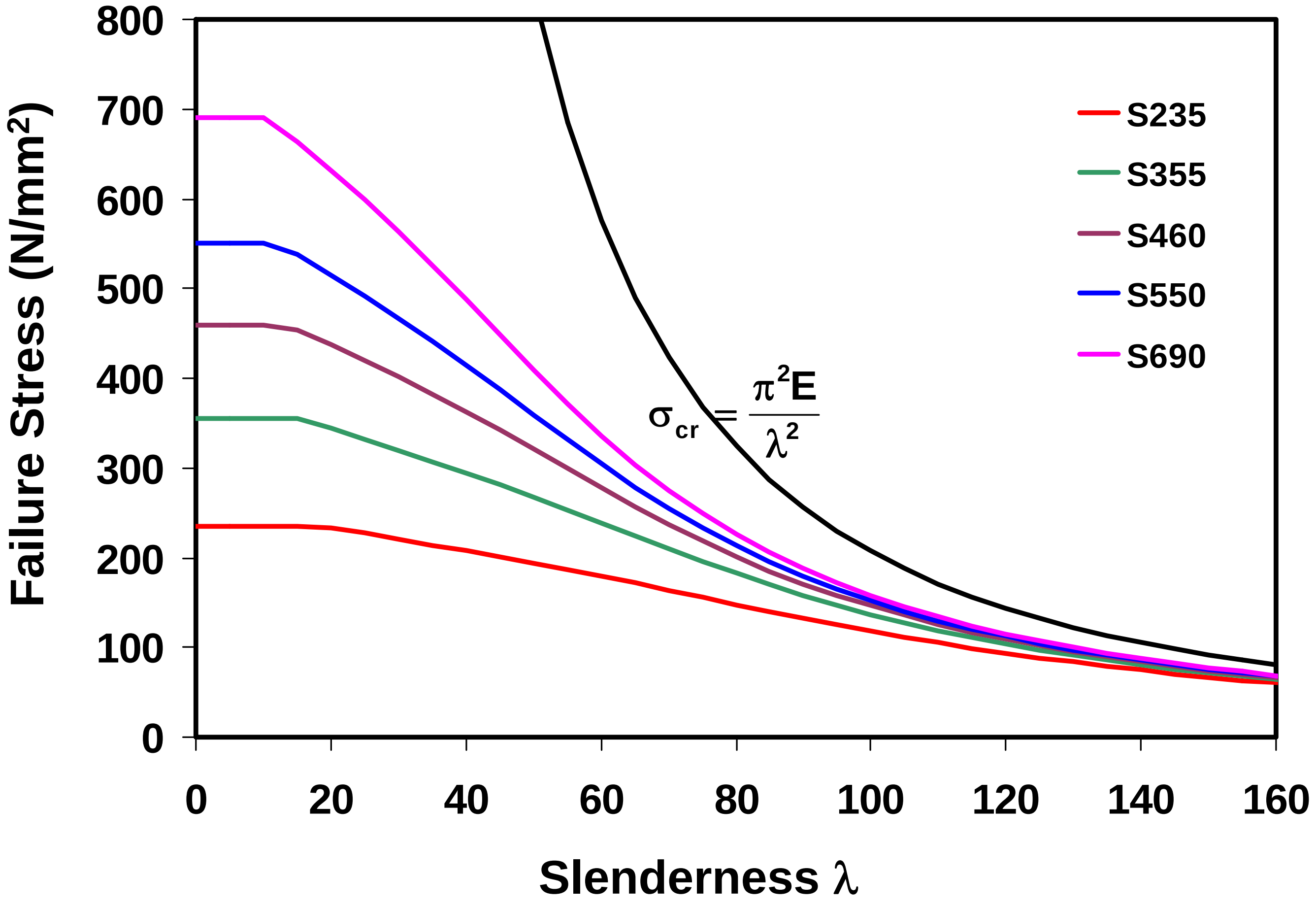


# Buckling

Resistance is controlled by two bounds – yielding and buckling (or post-buckling):

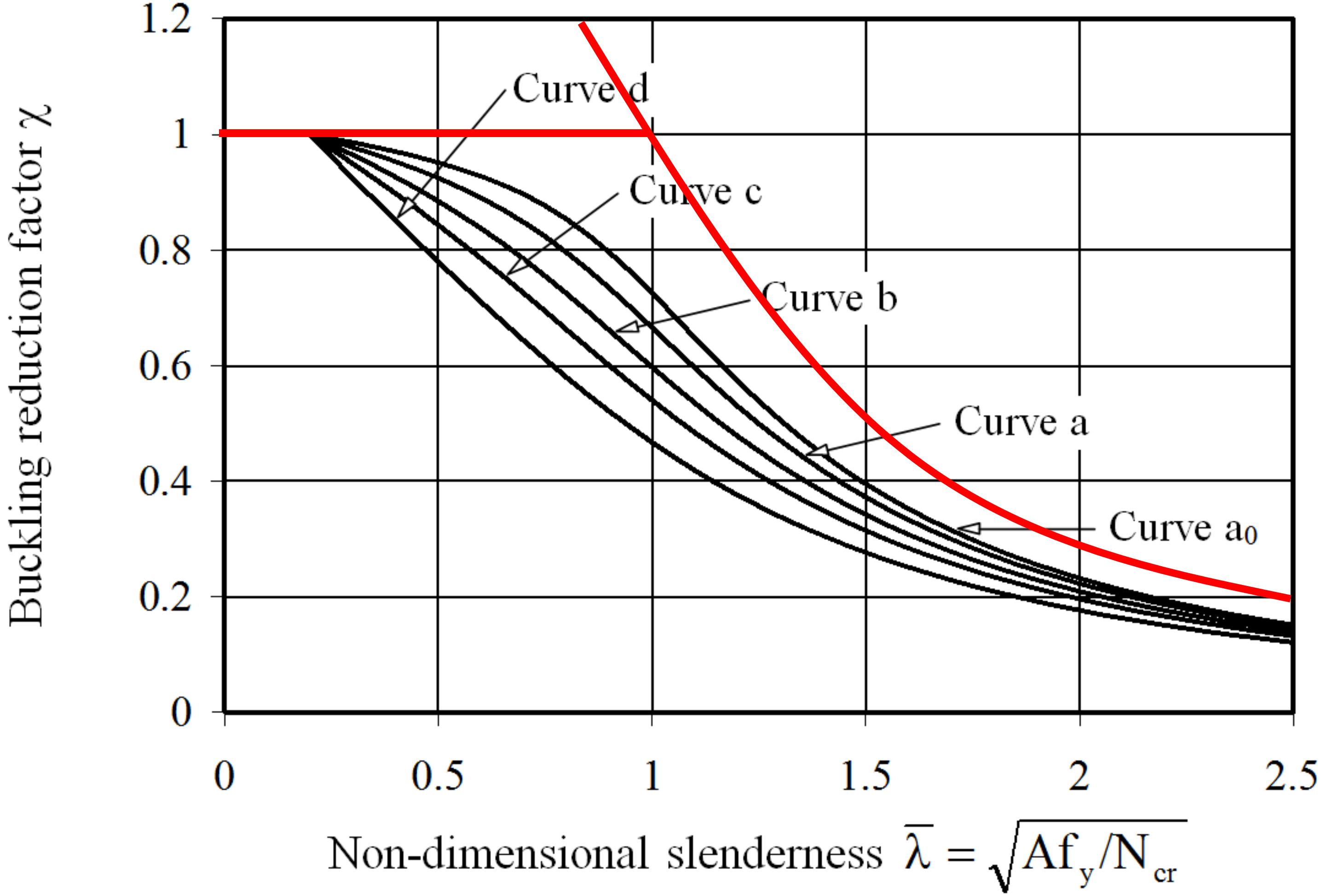
- For perfect members, there is a distinct transition from yielding to buckling behaviour
- For real (imperfect) members, yielding and buckling interact for members of all slenderness, so there is no distinct transition

# Column buckling

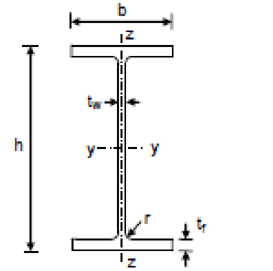
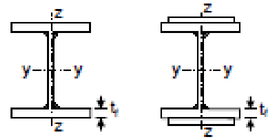
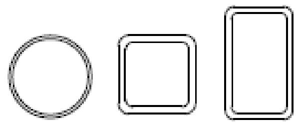
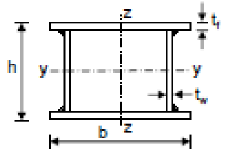
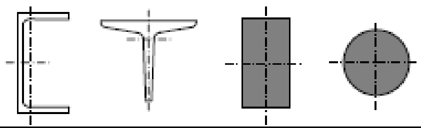
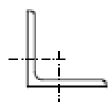


# Column buckling curves

Owing to lower sensitivity to imperfections and residual stresses being a lower proportion of $f_y$, HSS columns use higher buckling curves



# Column buckling curve selection table

| Cross-section | | Limits | | Buckling about axis | Buckling curve: S 235, S 275, S 355, S 420 | Buckling curve: S 460 |
|---|---|---|---|---|---|---|
| Rolled I-sections |  | h/b > 1.2 | $t_f \le 40$ mm | y – y<br>z – z | a<br>b | $a_0$<br>$a_0$ |
| | | | 40 mm < $t_f \le 100$ mm | y – y<br>z – z | b<br>c | a<br>a |
| | | h/b ≤ 1.2 | $t_f \le 100$ mm | y – y<br>z – z | b<br>c | a<br>a |
| | | | $t_f$ > 100 mm | y – y<br>z – z | d<br>d | c<br>c |
| Welded I-sections |  | $t_f \le 40$ mm | | y – y<br>z – z | b<br>c | b<br>c |
| | | $t_f$ > 40 mm | | y – y<br>z – z | c<br>d | c<br>d |
| Hollow sections |  | hot finished | | any | a | $a_0$ |
| | | cold formed | | any | c | c |
| Welded box sections |  | generally (except as below) | | any | b | b |
| | | thick welds: a > 0.5$t_f$<br>b/$t_f$ < 30<br>h/$t_w$ < 30 | | any | c | c |
| U-, T- and solid sections |  | | | any | c | c |
| L-sections |  | | | any | b | b |

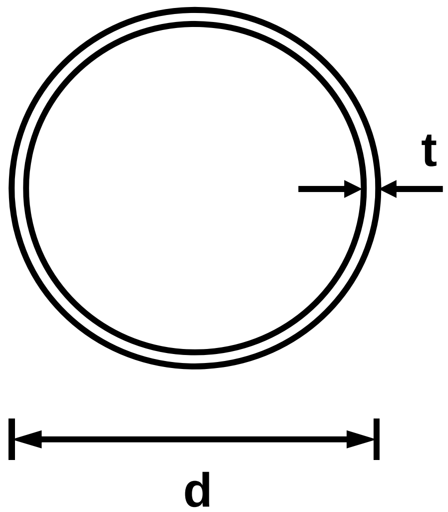
For S235 to S420

For S460 up to S690

UC buckling about minor axis

# Member buckling resistance example

Determine the compressive resistance of a 4 m long column with pinned end conditions using a hot-rolled 244.5×10 CHS in grade S355 steel and in grade S690 steel.




| | |
|---|---|
| $d$ | $= 244.5$ mm |
| $t$ | $= 10.0$ mm |
| $A$ | $= 7370$ mm$^2$ |
| $W_{el,y}$ | $= 415000$ mm$^3$ |
| $W_{pl,y}$ | $= 550000$ mm$^3$ |
| $I$ | $= 50.73\text{x}10^6$ mm$^4$ |

# Member buckling resistance example

Cross-section classification (*clause 5.5.2*):

$$\varepsilon = \sqrt{235/f_y} = \sqrt{235/355} = 0.81 \text{ for S355}$$

$$\varepsilon = \sqrt{235/f_y} = \sqrt{235/690} = 0.58 \text{ for S690}$$

d/t = 244.5/10.0 = 24.5

Limit for Class 1 section = 50 $\varepsilon^2$ = 33.1 for S355 and 17.0 for S690

Limit for Class 2 section = 70 $\varepsilon^2$ = 46.3 for S355 and 23.8 for S690

Limit for Class 3 section = 90 $\varepsilon^2$ = 59.6 for S355 and 30.7 for S690

∴ Cross-section is Class 1 in S355 steel, but Class 3 in S690 steel

# Member buckling resistance example

## Cross-section compression resistance (clause 6.2.4):

$$N_{c,Rd} = \frac{Af_y}{\gamma_{M0}} \quad \text{for Class 1, 2 or 3 cross-sections}$$

$$N_{c,Rd} = \frac{7370 \times 355}{1.00} = 2616 \times 10^3\ \text{N} = 2616\ \text{kN for S355}$$

$$N_{c,Rd} = \frac{7370 \times 690}{1.00} = 5085 \times 10^3\ \text{N} = 5085\ \text{kN for S690}$$

Provided cross-section remains non-slender (i.e. Class 1-3), full benefit of increased yield strength is seen in cross-section resistance $N_{c,Rd}$

# Member buckling resistance example

## Member buckling resistance in compression (clause 6.3.1):

$$N_{b,Rd} = \frac{\chi A f_y}{\gamma_{M1}} \quad \text{for Class 1,2 and 3 cross sections}$$

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}} \quad \text{but } \chi \leq 1.0$$

$$\text{where } \Phi = 0.5\left[1 + \alpha\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right]$$

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

# Member buckling resistance example

Elastic buckling load $N_{cr}$ is independent of material grade:

$$N_{cr} = \frac{\pi^2 EI}{L_{cr}^{\ 2}} = \frac{\pi^2 \times 210000 \times 50730000}{4000^2} = 6571\,\text{kN}$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{7370 \times 355}{6571 \times 10^3}} = 0.63 \quad \text{for S355}$$

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{cr}}} = \sqrt{\frac{7370 \times 690}{6571 \times 10^3}} = 0.88 \quad \text{for S690}$$

EC3 slenderness increases with increasing yield strength

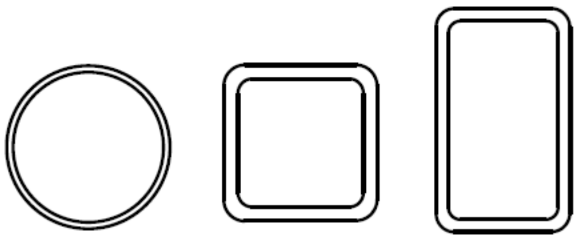
For a hot-rolled CHS, use buckling curve ‘a’ for S355 and curve ‘$a_0$’ for S690 (from Table 6.2 of EN 1993-1-1)

# Buckling curve selection

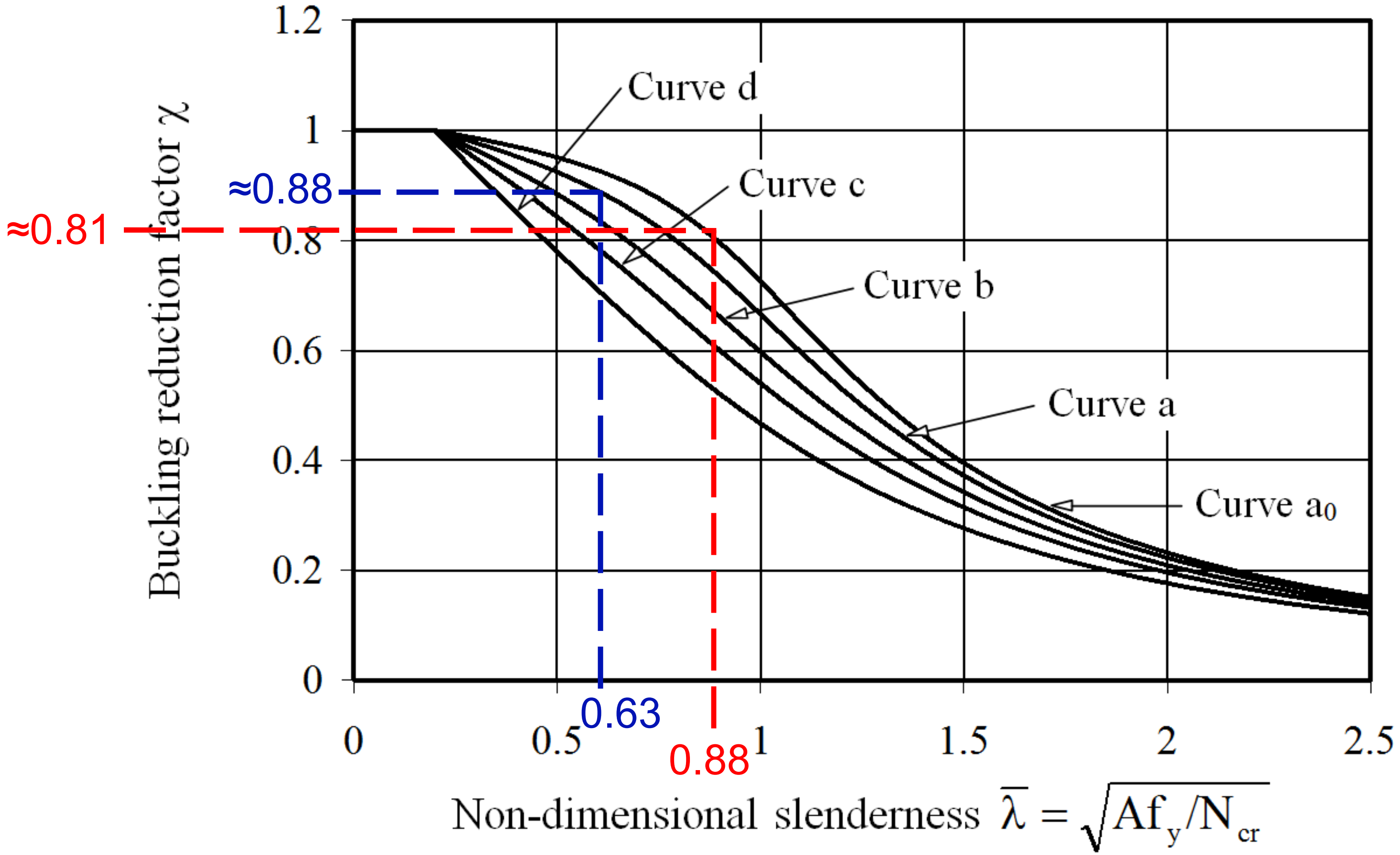
From Table 6.2 of EN 1993-1-1, for hot-finished CHS:

Use buckling curve ‘a’ for S355

Use buckling curve ‘$a_0$’ for S690

| | | | | S355 | S690 |
|---|---|---|---|---|---|
| Hollow sections |  | hot finished | any | a | $a_0$ |
| | | cold formed | any | c | c |

# Graphical approach



# Member buckling resistance example

For buckling curve 'a', $\alpha$ = 0.21; for curve '$a_0$', $\alpha$ = 0.13

$$\Phi = 0.5[1 + 0.21(0.63 - 0.2) + 0.63^2] = 0.74$$

$$\chi = \frac{1}{0.74 + \sqrt{0.74^2 - 0.63^2}} = 0.88$$

Buckling reduction factor for S355 column

$$\Phi = 0.5[1 + 0.13(0.88 - 0.2) + 0.88^2] = 0.93$$

$$\chi = \frac{1}{0.93 + \sqrt{0.93^2 - 0.88^2}} = 0.81$$

Buckling reduction factor for S690 column

$N_{b,Rd} = 2297$ kN for S355 column, and

$N_{b,Rd} = 4114$ kN for S690 column (79% increase)

# Ductility

Ductility is implicit in many aspects of structural steel design:

- Plastic design, where the full load carrying capacity of a structure may not be reached until significant plastic deformation has occurred (portal frames)
- Seismic applications, to dissipate energy
- Connections, to alleviate stress concentrations

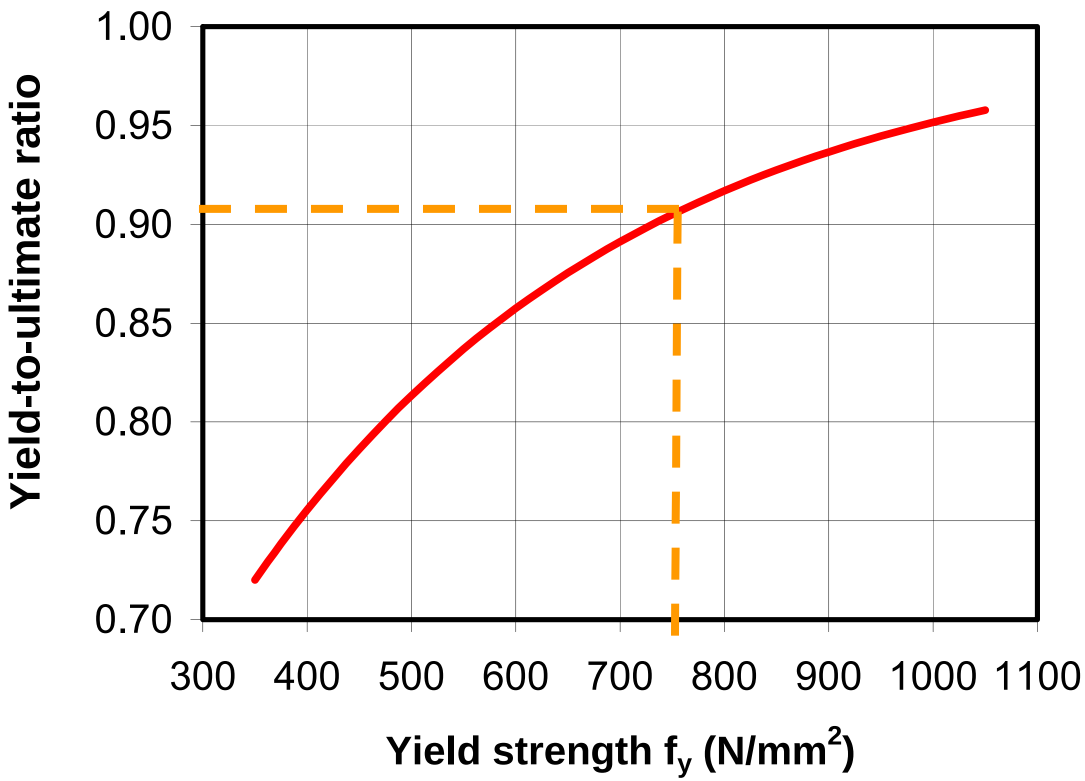
# Ductility

The explicit material requirements in EN 1993-1-1 are:

- $f_u/f_y > 1.10$
- Elongation at fracture not less than 15%
- $\varepsilon_u > 15 f_y/E$

# Ductility

Yield-to-ultimate strength ratio increases with strength




For $f_u/f_y > 1.1$ ($f_y/f_u < 0.91$), $f_y \approx 750$ N/mm$^2$)

# Ductility

For high strength steels, EN 1993-1-12 allows the material ductility requirements to be relaxed, but with certain restrictions on design applied:

- $f_u/f_y>1.05$
- Elongation at fracture not less than 10%
- $\varepsilon_u>15f_y/E$ (same as for $f_y<460$ N/mm$^2$)

Plastic analysis and semi-rigid connections should not be used.

# Deflections and vibrations

The Young's modulus of steel does not increase with strength so, in general, the use of high strength material is going to lead to more flexible structures, requiring greater emphasis on serviceability conditions, particularly deflections and vibrations.

For longer spans and taller structures, SLS is more likely to govern. Consider strategies such as pre-cambering, pre-stressing, more advanced global stability systems, active vibration control etc.

# Fatigue

Fatigue:

- In high strength steel structures
  - Design stress levels are greater
  - Ratio of variable loads to permanent loads increases, so stress ranges increase
- Fatigue resistance does not increase at the same rate as material strength
- Fatigue conditions more critical
- Careful welding procedures, detailing required

# Use of HSS in buildings

In general, the key structural engineering challenges in buildings are*:

- Minimise construction material
- Maximise number of floors for a given height
- Maximise net-to-gross area on each floor

*O' Connor (2012)

# Use of HSS in buildings

With that in mind, ideas on where HSS can be beneficial:

- As height of the structure increases, the vertical forces in the columns and foundations increase. HSS columns can resist these higher forces, while minimising footprint.

- As building height increases, the strength and stiffness demands on the lateral stability system increase. HSS can respond to the increased strength demand.

- In transfer trusses, bracing elements etc, the strength of HSS can be fully exploited in the tension members

- Beams tend to be dominated by stiffness at longer spans

# Conclusions

Conclusions:

- High strength steel can bring material and cost savings in structures
- HSS design up to S690 (with some restrictions) are covered in EN 1993-1-12
- While strength increases, other factors (buckling, fatigue etc) are likely to become more critical
- HSS applications should be chosen wisely

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