The continuous strength method for structural stainless steel design

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Outline

Outline:

- Current design basis of section design
- Continuous strength method (CSM)
- Comparisons with test results
- Reliability analysis
- Conclusions

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Current basis for section design

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Cross-section classification

Local buckling is considered through the process of cross-section classification:

- **Basis of design in current stainless steel design codes (analogous to structural steel)**
- **Cross-sections placed into discrete behavioural classes**
- **Defines cross-section resistance and ductility**
- **Based on bi-linear (elastic, perfectly-plastic) material response**

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Cross-section classification

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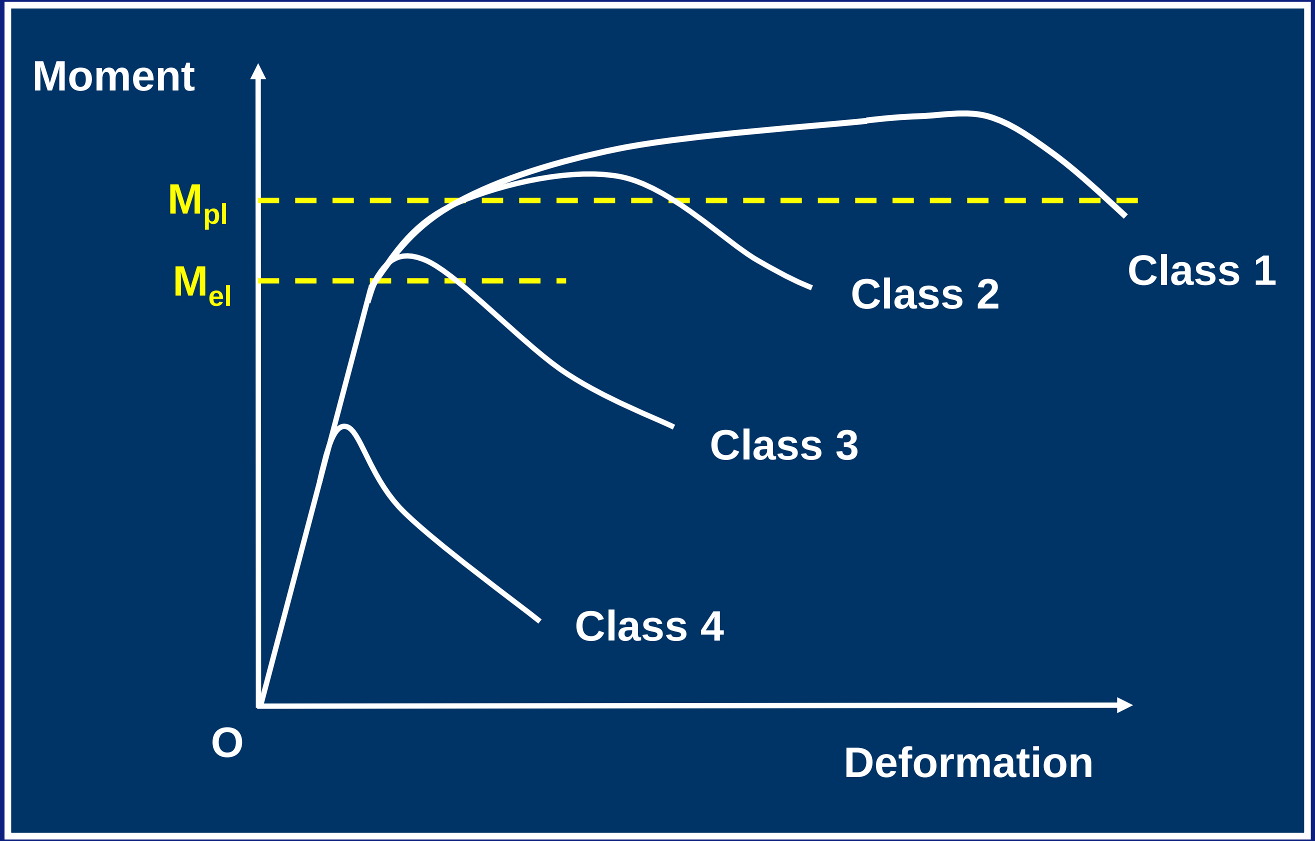
Four classes of cross-section:



Idealised bending distributions

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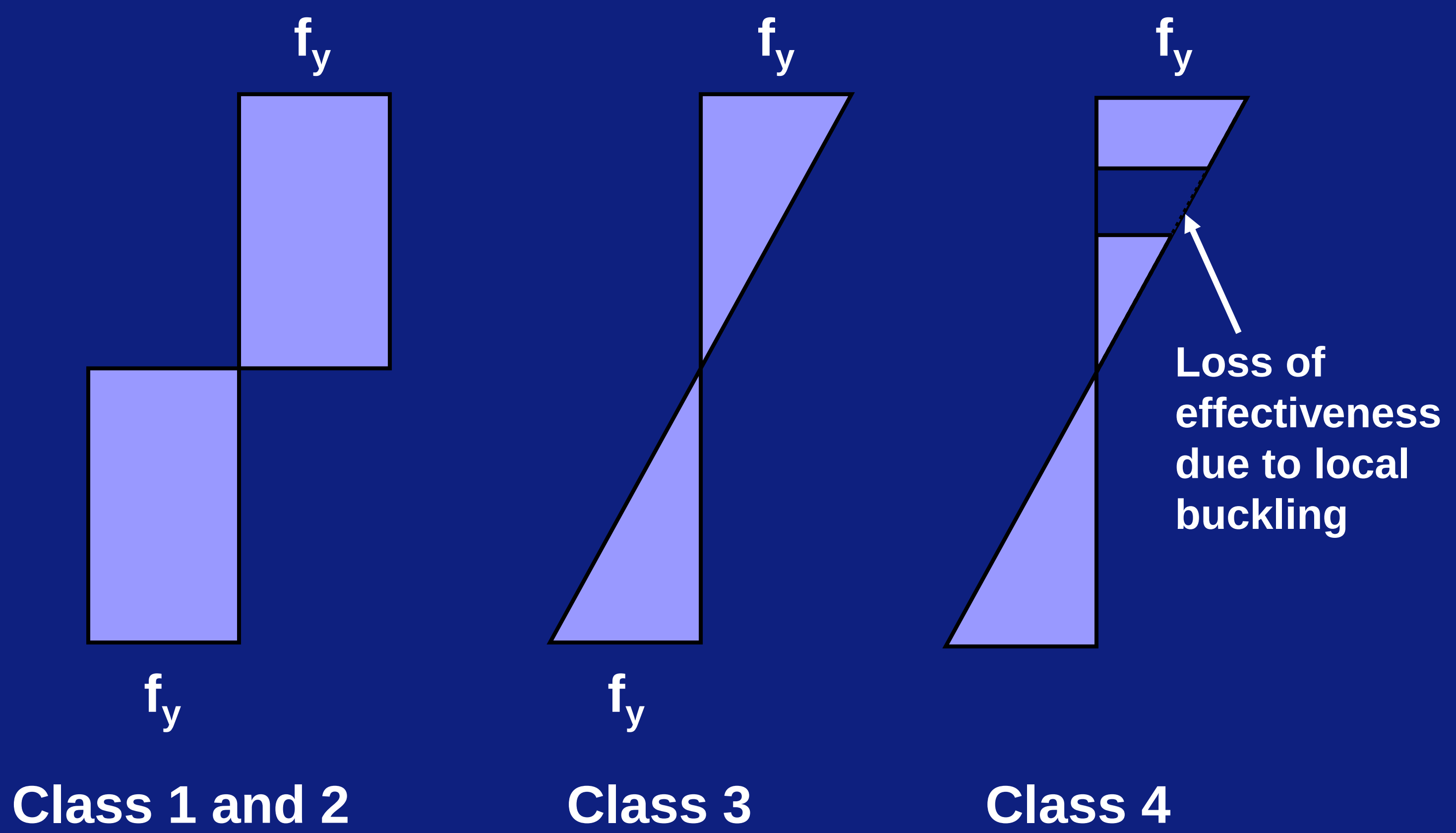
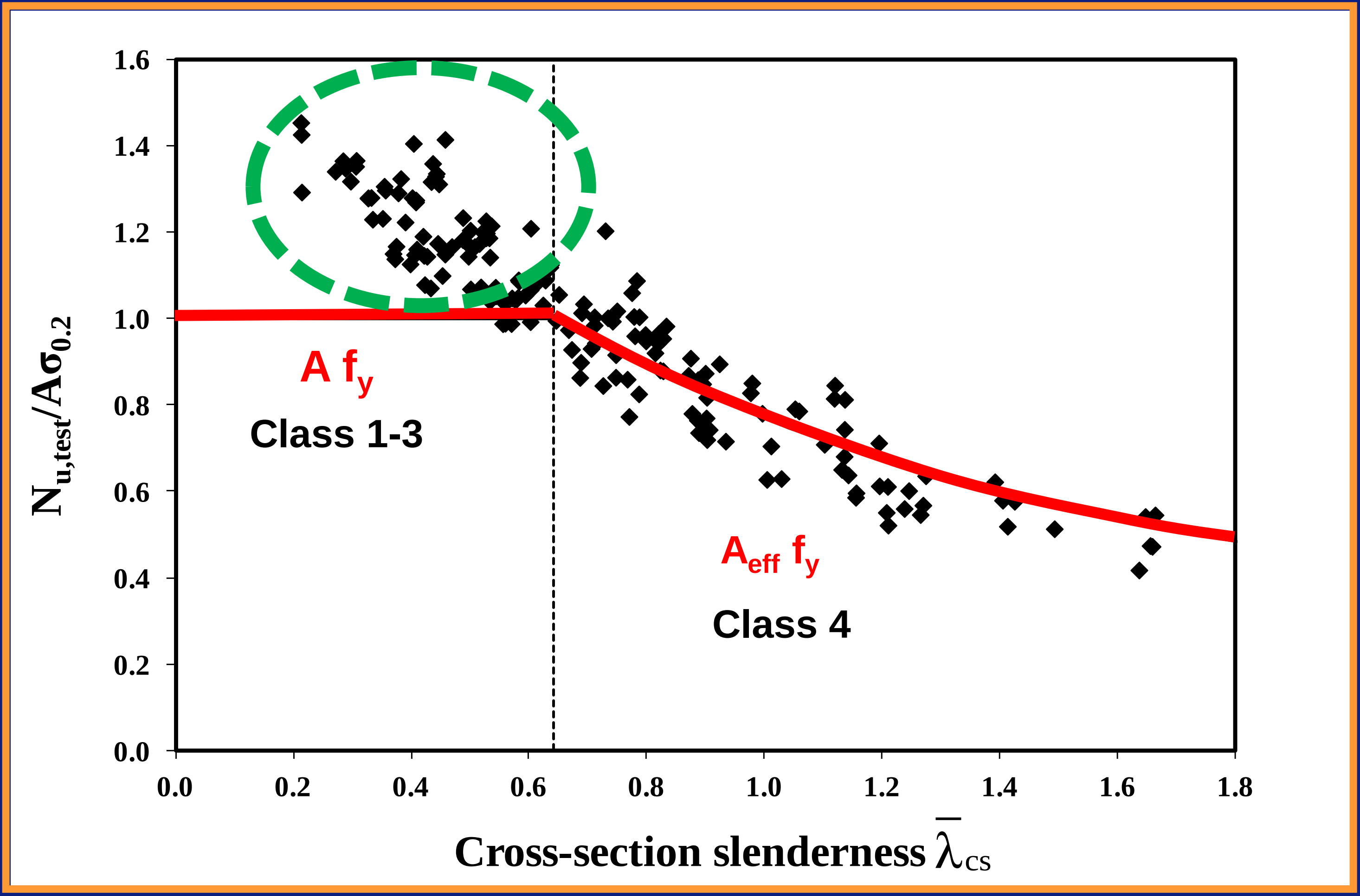
Idealised bending stress distributions:



Compression resistance



81 Compression stub column test results

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Bending resistance

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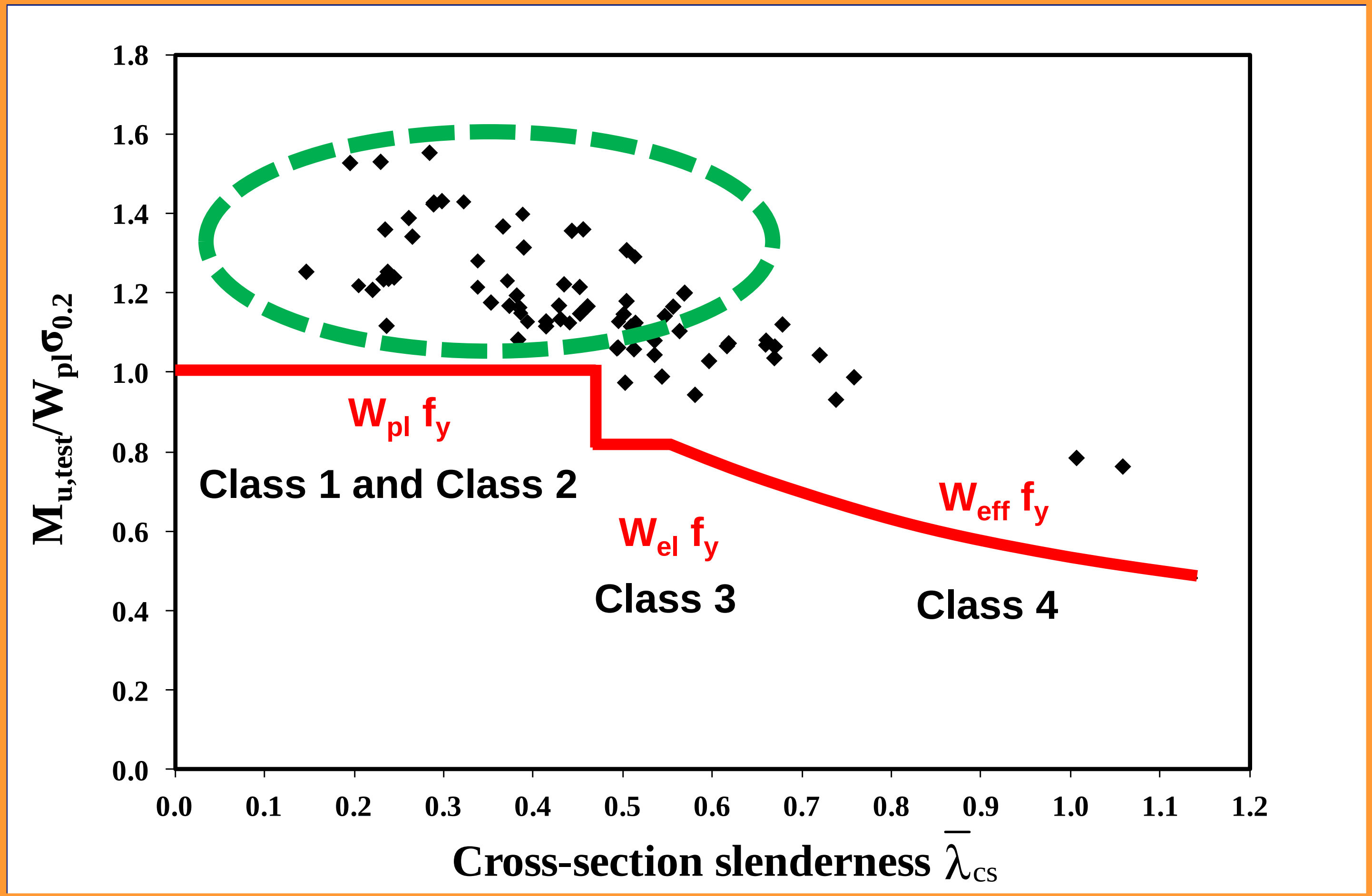

Bending test results

The continuous strength method

Continuous strength method

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Continuous strength method (CSM):

- Deformation based design approach allowing for strain hardening (and element interaction)

- Two key components to method:

1. Cross-section deformation capacity defined by the 'Design base curve'; no more section classification

2. Material nonlinearity defined through a simple elastic, linear hardening material model

- Resistance derived from basic mechanics

Continuous strength method

Aims of method:

- More efficient and rational design
- Less scatter in prediction
- Minimum increase in complexity
- Providing engineer with more information

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Design base curve

- **Continuous relationship between cross-section deformation capacity and cross-section slenderness**

Base curve development:

1. **Cross-section slenderness definition**

2. **Slender and non-slender cross-section limit**

3. **Cross-section deformation capacity**
   - **Stub column tests and**
   - **Beam tests**

Design base curve: Cross-section slenderness

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- **Cross-section slenderness definition: for cross-sections consisting of interconnected plate elements**

$$\bar{\lambda}_{cs} = \sqrt{\frac{f_y}{\sigma_{cr,cs}}}$$

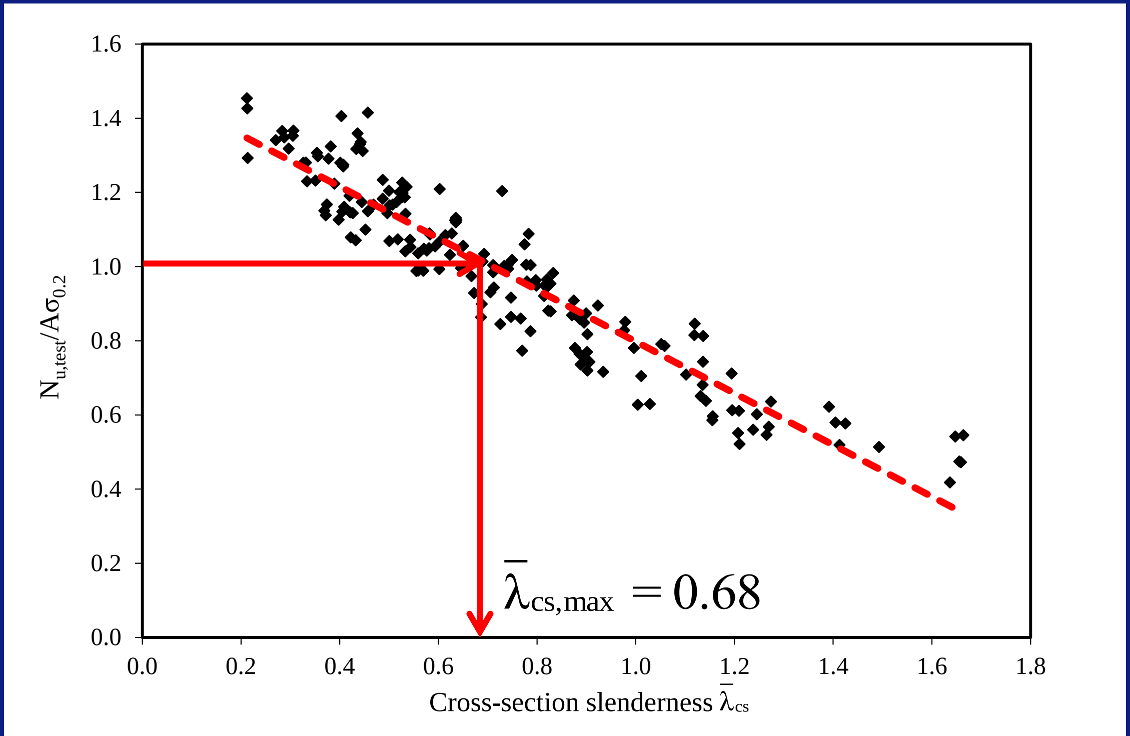
Elastic buckling stress of the full cross-section→ allowing for element interaction

OR

Elastic buckling stress of the most slender plate in the section

Design base curve: Slender and non-slender cross-section limit

- **Maximum cross-section slenderness = 0.68**
- **Limit specified based on:**
  1. **$N_{u,test}/A\sigma_{0.2}$ versus cross-section slenderness for stainless steel, carbon steel and aluminium alloys**
  2. **Current codified slenderness limits**



Cross-section deformation capacity definition

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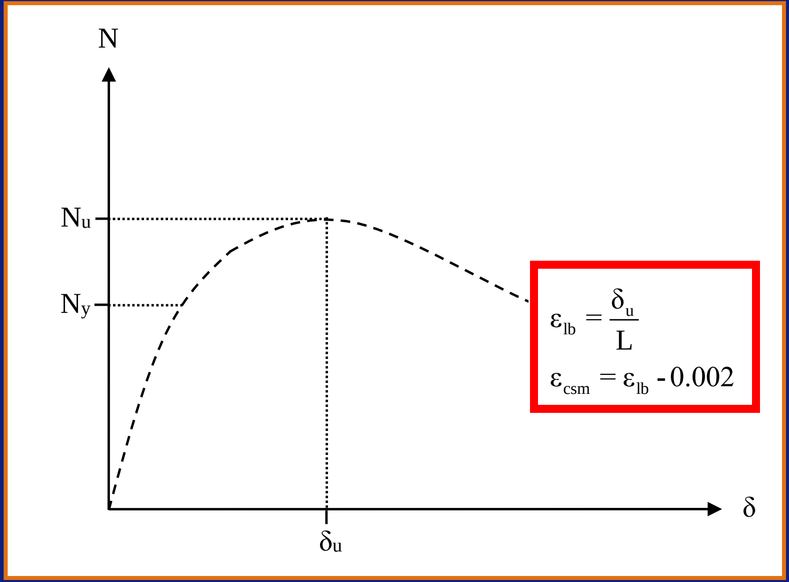
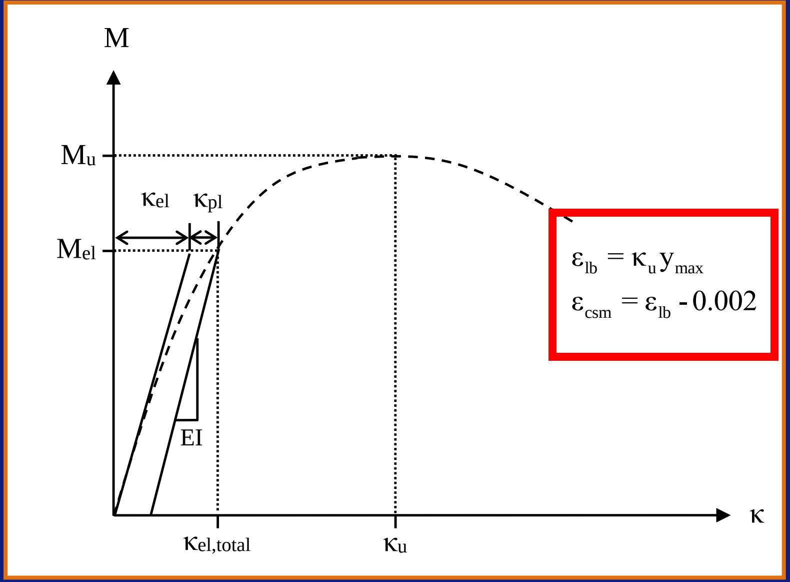
Stub column tests



Beam tests



$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{\varepsilon_{lb} - 0.002}{\varepsilon_y} = \frac{\delta_u / L - 0.002}{\varepsilon_y} \quad \text{for } N_u \geq N_y \text{ and } \bar{\lambda}_p \leq 0.68$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{\varepsilon_{lb} - 0.002}{\varepsilon_y} = \frac{\kappa_u y_{max} - 0.002}{\kappa_{el} y_{max}} \quad \text{for } M_u \geq M_{el} \text{ and } \bar{\lambda}_p \leq 0.68$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{N_u}{N_y} \quad \text{for } N_u < N_y$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{M_u}{M_{el}} \quad \text{for } M_u < M_{el}$$

'Design base curve'

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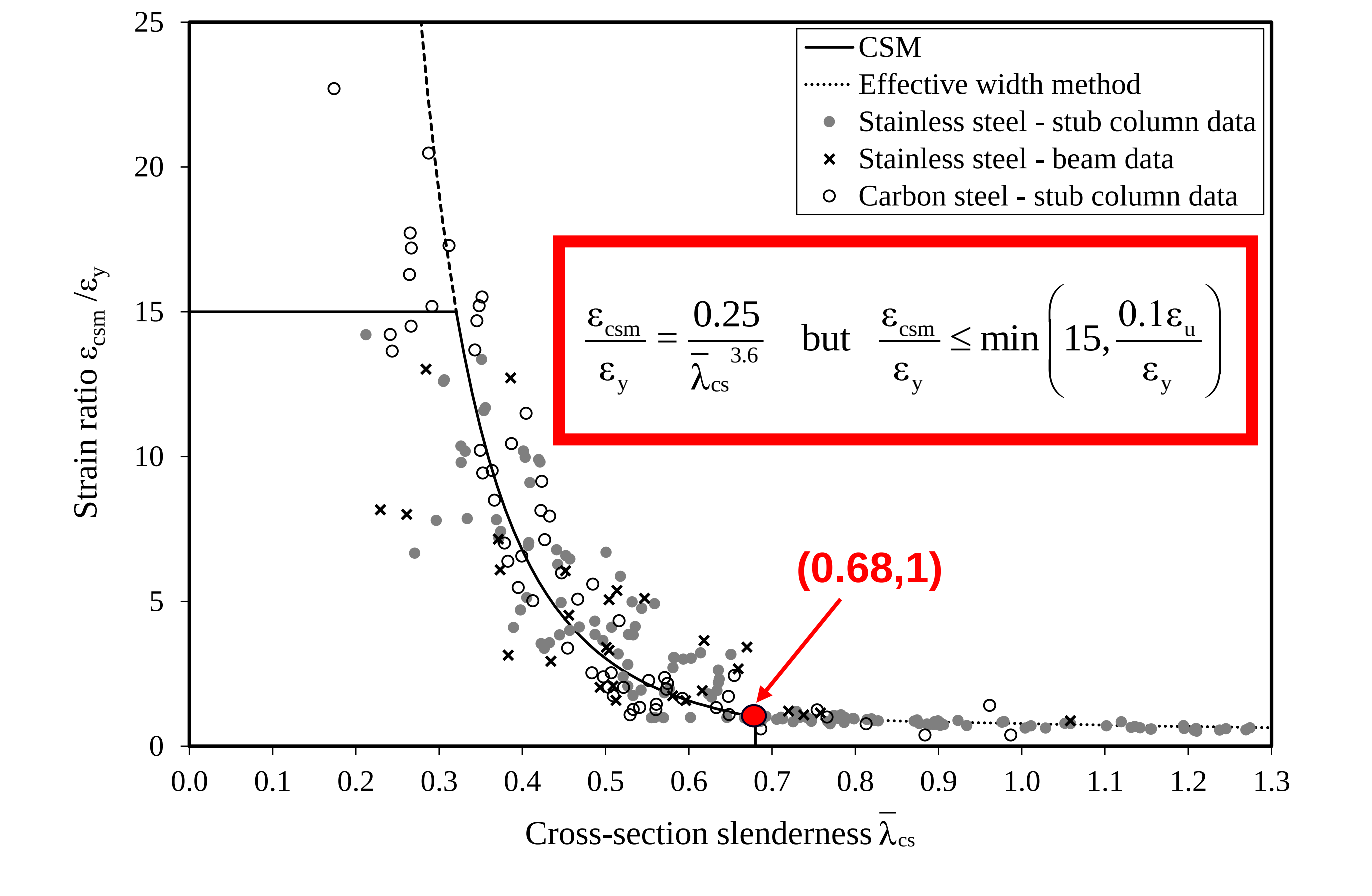
CSM 'base curve' defines deformation capacity – slenderness relationship.



Derived from stub column tests

Material modelling

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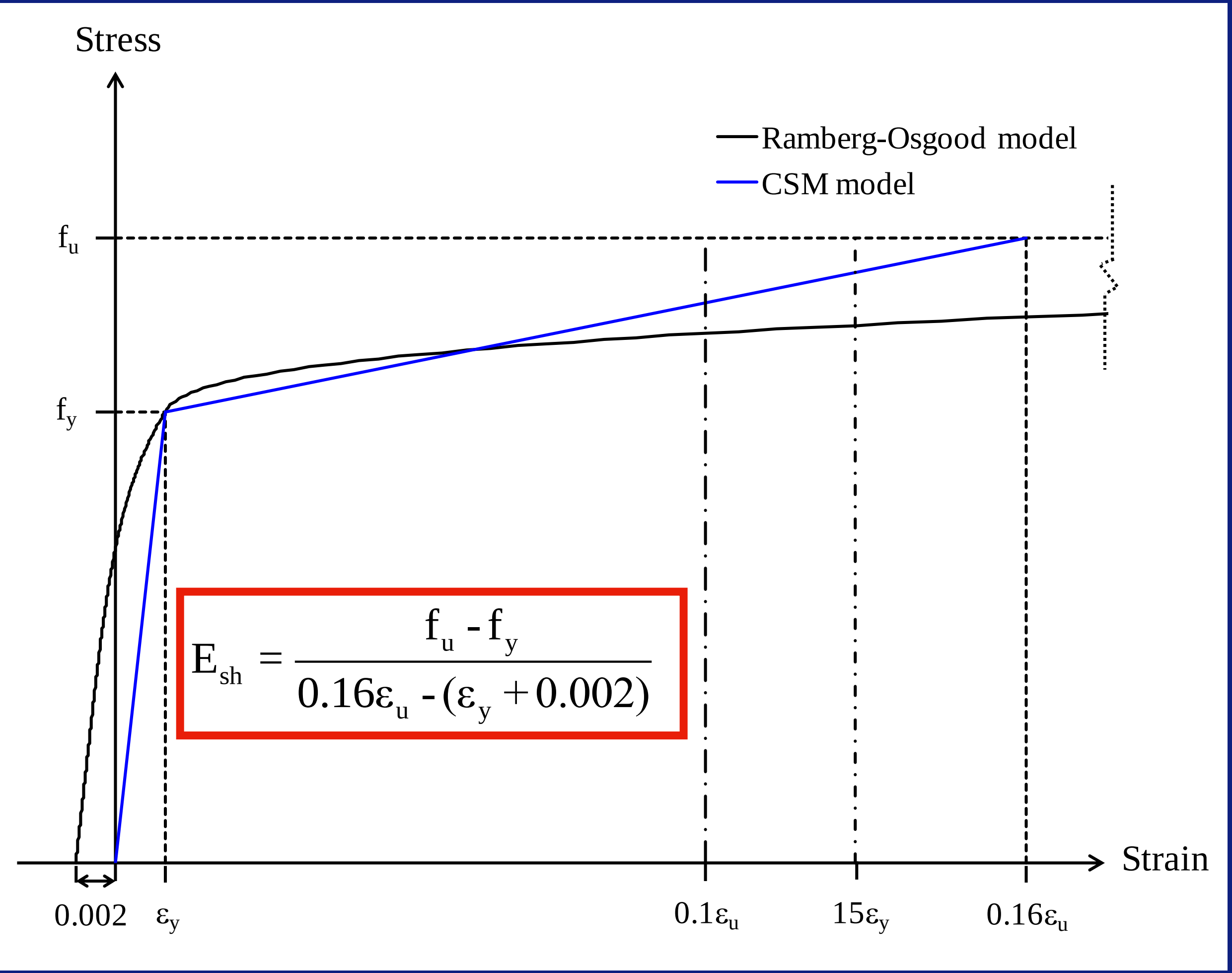
Material model chosen to reflect material stress-strain response:



Cross-section compression resistance

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1. **Determine cross-section slenderness for full section or most slender element**

$$\bar{\lambda}_{cs} = \sqrt{\frac{f_y}{\sigma_{cr,cs}}}$$

2. **Obtain corresponding deformation capacity**

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_{cs}^{3.6}}$$

$$\text{but } \frac{\varepsilon_{csm}}{\varepsilon_y} \leq \min\left(15, 0.1\frac{\varepsilon_u}{\varepsilon_y}\right)$$

3. **Determine resulting local buckling stress f_{csm} from material model**

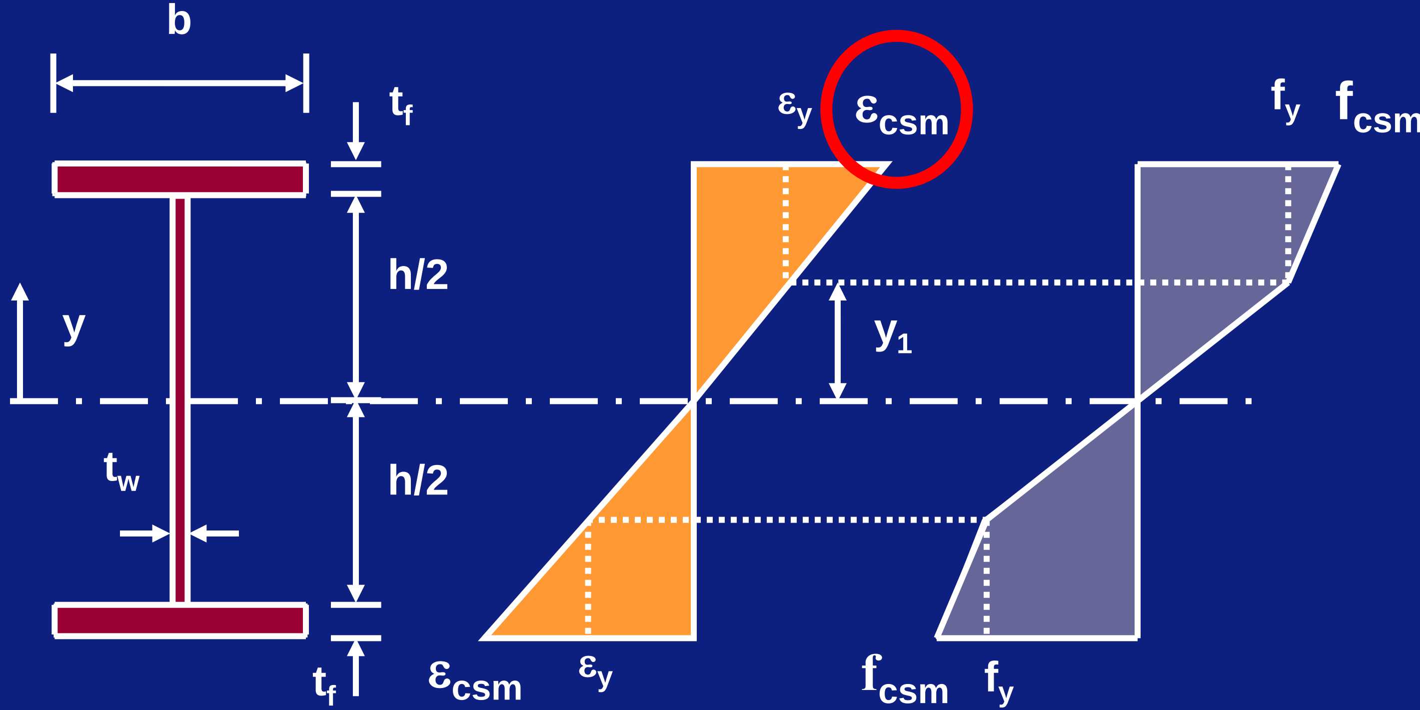
$$f_{csm} = f_y + E_{sh}\varepsilon_y\left(\varepsilon_{csm}/\varepsilon_y - 1\right)$$

4. **Section compression capacity is product of local buckling stress f_{csm} and gross cross-section area A.**

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

Cross-section bending resistance

In bending, deformation capacity ε_{csm} used to define outer fibre strain limit:



(a) Cross-section (b) Strain (c) Stress

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Bending resistance

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Bending resistance determined from basic mechanics:

$$M_{csm} = \int_A f_{csm} y \, dA$$

And may be approximated by:

Strain ratio

$$\frac{M_{csm}}{M_{pl}} = 1 + \frac{E_{sh}}{E}\frac{W_{el}}{W_{pl}}\left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1\right) - \left(1 - \frac{W_{el}}{W_{pl}}\right)\left(\frac{\varepsilon_{csm}}{\varepsilon_y}\right)^{-2}$$

Material

1/ Shape factor

Cross-section bending resistance

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1. **Determine cross-section slenderness for full section or most slender element**

$$\bar{\lambda}_{cs} = \sqrt{\frac{f_y}{\sigma_{cr,cs}}}$$

2. **Obtain corresponding deformation capacity**

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_{cs}^{3.6}}$$

$$\text{but } \frac{\varepsilon_{csm}}{\varepsilon_y} \le \min\left(15, 0.1\frac{\varepsilon_u}{\varepsilon_y}\right)$$

$$M_{y,c,Rd} = M_{y,csm,Rd} = \frac{W_{pl,y} f_y}{\gamma_{M0}}\left[1 + \frac{E_{sh}}{E}\frac{W_{el,y}}{W_{pl,y}}\left(\frac{\varepsilon_{csm}}{\varepsilon_y} - 1\right) - \left(1 - \frac{W_{el,y}}{W_{pl,y}}\right) \Big/ \left(\frac{\varepsilon_{csm}}{\varepsilon_y}\right)^2\right]$$

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Comparison with stub column tests data

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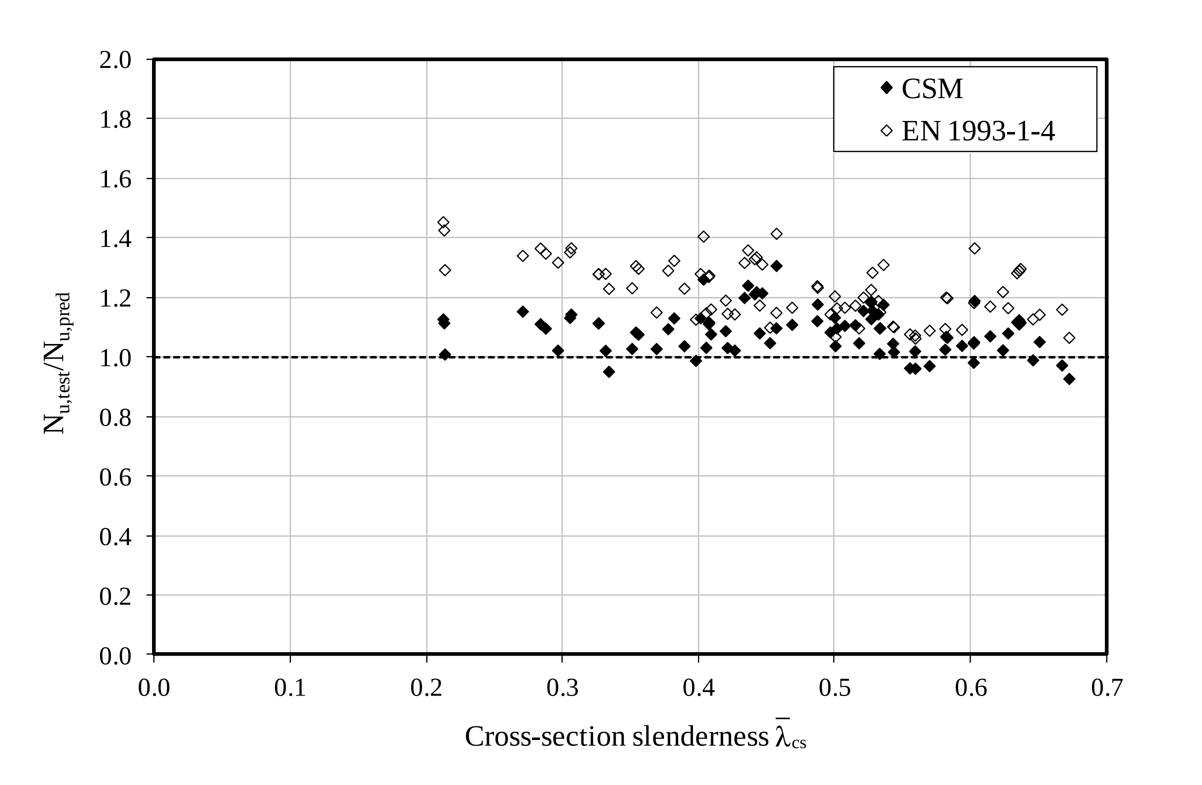
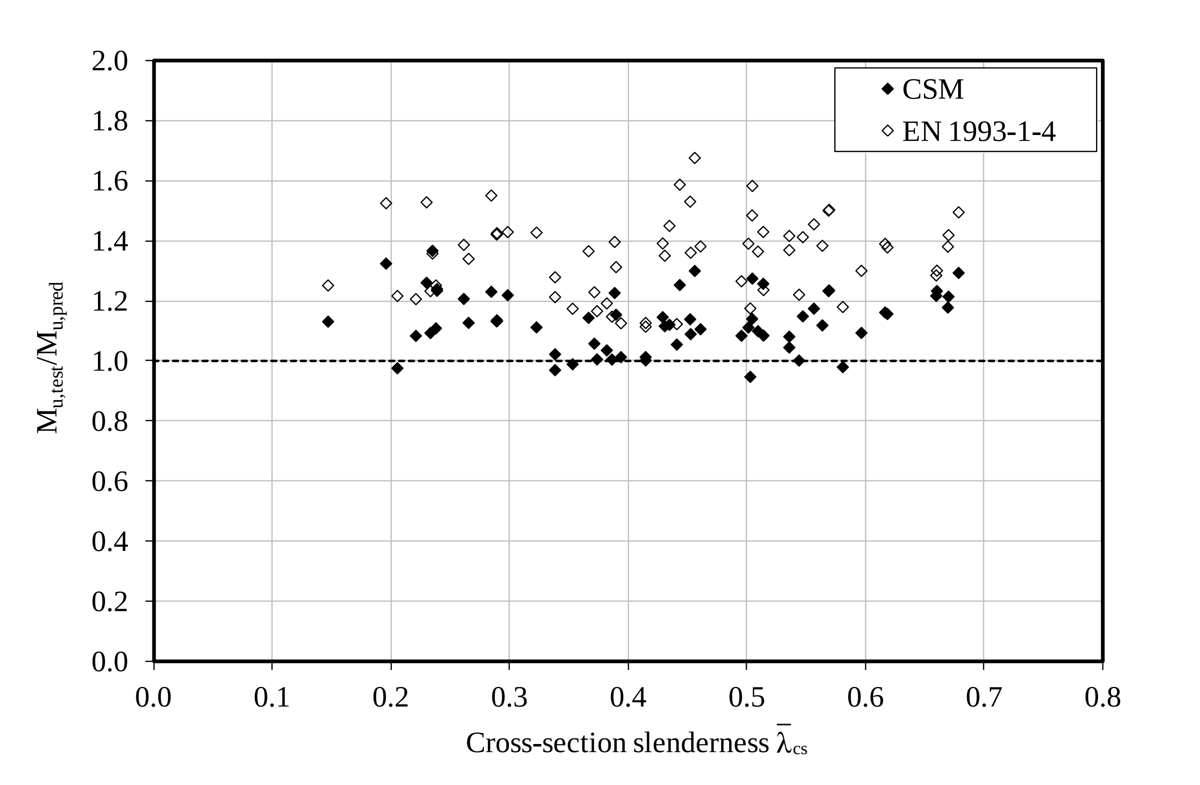


No. of tests: 81	N_{test}/N_{EC3}	N_{test}/N_{csm}	N_{csm}/N_{EC3}
Mean	1.222	1.088	1.123
COV	0.082	0.069	-

Comparison with beam tests data



No. of tests: 65	M_{test}/M_{EC3}	M_{test}/M_{csm}	M_{csm}/M_{EC3}
Mean	1.351	1.134	1.191
COV	0.098	0.085	-

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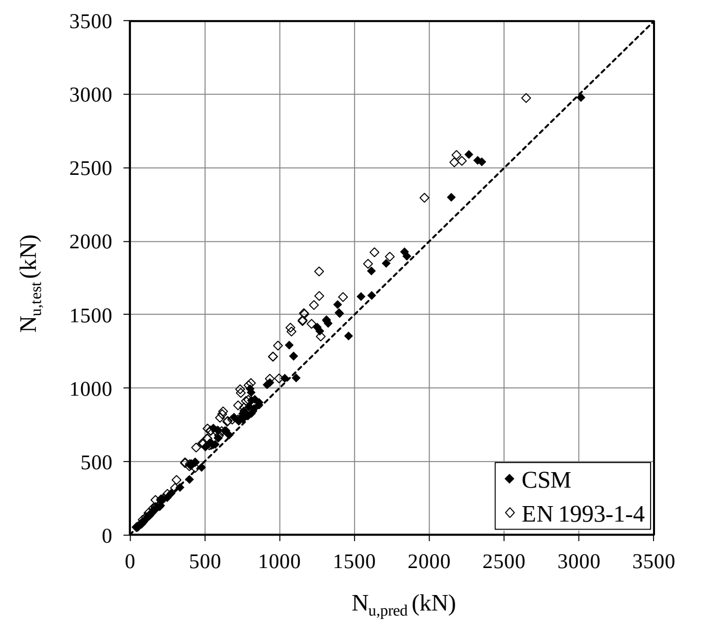
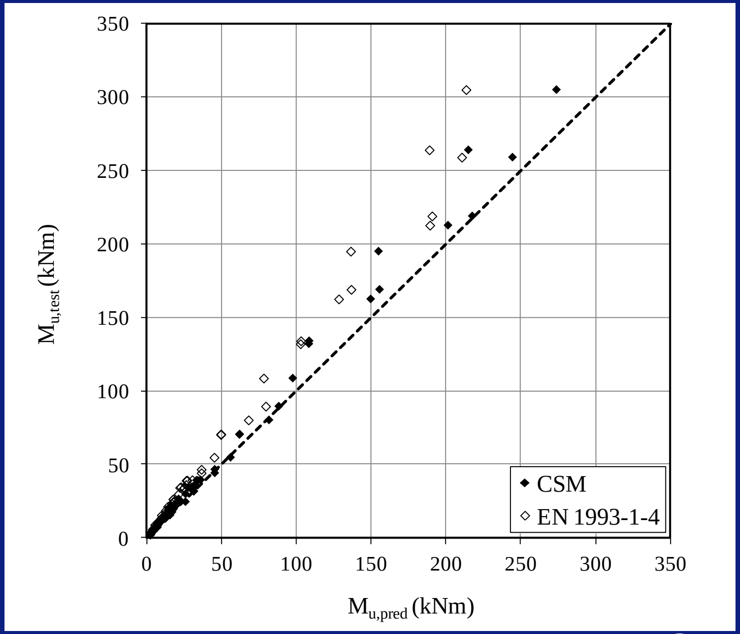
Reliability analysis

- **Standard reliability analysis in accordance with EN 1990 – Annex D**

Test data	n	$k_{d,n}$	b	V_δ	V_r	γ_{M0}
Stub columns	81	3.215	1.075	0.068	0.102	0.96
Beams	65	3.247	1.108	0.086	0.114	0.98





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Conclusions

Current approach

- Section classification underpins design of metallic structures
- Useful but artificial simplifications
  - Discrete behavioural classes; EPP σ-ε curve

CSM

- Deformation based design
- Rational exploitation of strain hardening
- Enhanced structural efficiency
- EC3 and AISC approval underway
- Finalised version now recommended for others (researchers, codes)

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