Design methods for HSS cross-sections

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Overview

1. Experimental programme on HSS hollow sections

   - Material tests
   - Stub column tests
   - Beam tests
   - Combined axial load and bending tests

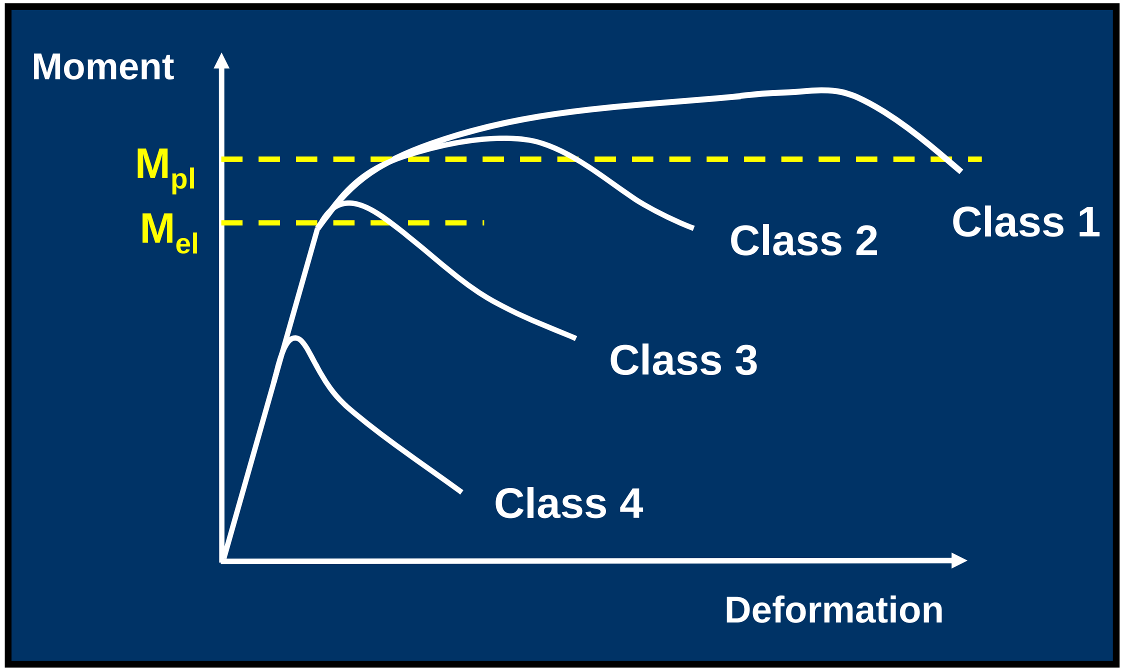
2. Cross-section design of HSS hollow sections

   - Slenderness limits for internal elements in compression
   - Slenderness limits for internal elements in bending
   - Interaction curve for combined axial load and bending

3. Concluding remarks

Cross-section design: Eurocode 3 approach

- Local buckling is considered through the process of cross-section classification:
- Four Classes of behavior based on:
  - Moment capacity;
  - Rotation capacity and
  - Compression capacity of the cross-section

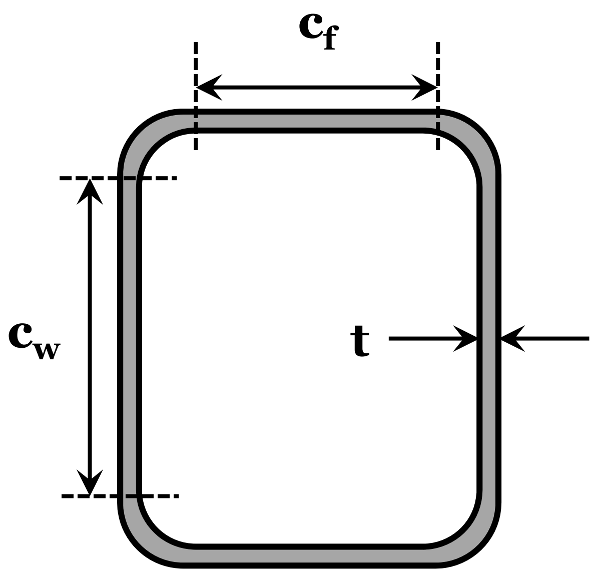


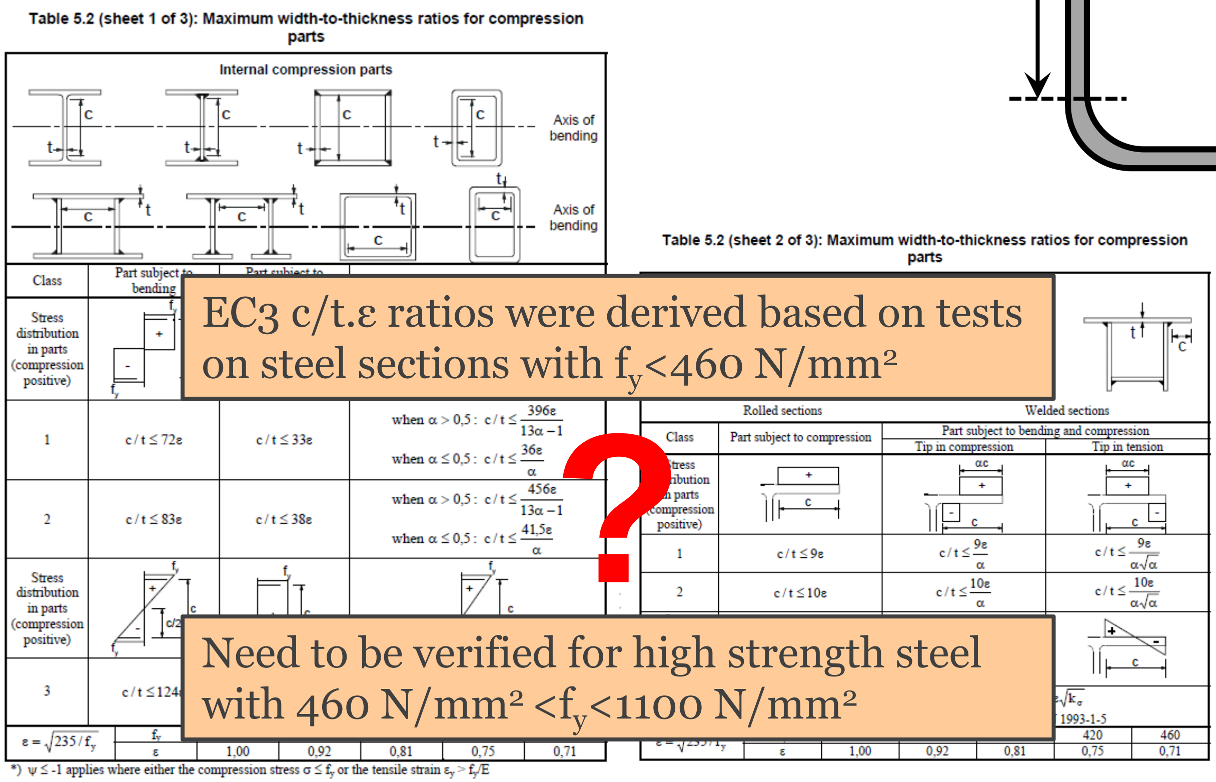
Cross-section design: Eurocode 3 design approach

Which cross-section classification does a section fall into?

- Geometric properties of the section
- Material properties (f_y) of the section

Single slenderness parameter **c/t.ε** ratio $\left(\varepsilon = \sqrt{235/f_y}\right)$





EC3 c/t.ε ratios were derived based on tests on steel sections with f_y<460 N/mm²

Need to be verified for high strength steel with 460 N/mm² <f_y<1100 N/mm²

Experimental programme

Investigated cross-sections

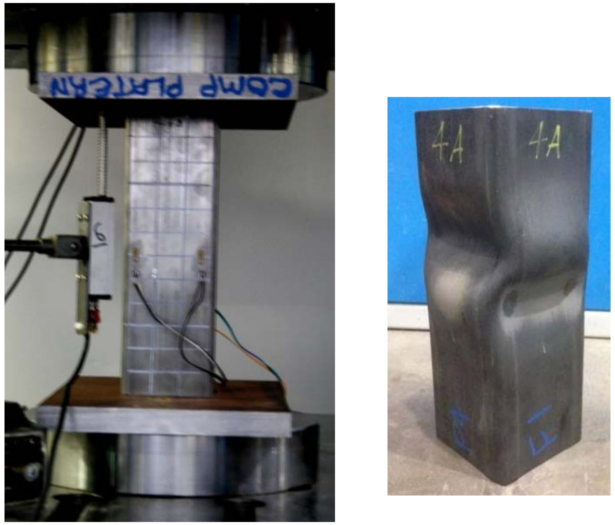
- Tubular SHS and RHS
- Grades S460 and S690
- S460 hot-rolled and normalised
- S690 hot-rolled and quenched and tempered
- Specimens were provided by Vallourec

Grade	Cross-section
S460	SHS 50×50×5
	SHS 50×50×4
	SHS 100×100×5
	SHS 90×90×3.6
	RHS 100×50×6.3
	RHS 100×50×4.5
S690	SHS 50×50×5
	SHS 100×100×5.6
	SHS 90×90×5.6
	RHS 100×50×6.3
	RHS 100×50×5.6

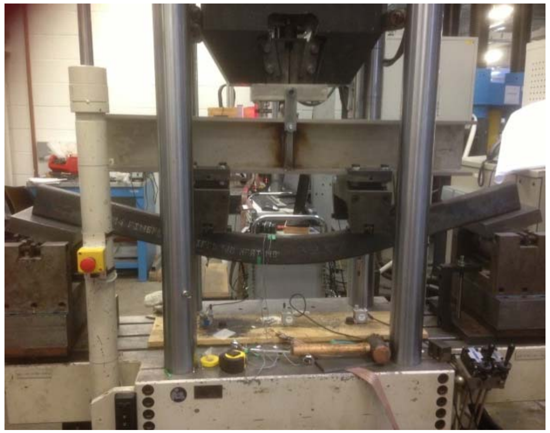
Experimental programme

Summary of cross-section tests:

- 11 concentrically loaded stub column tests
- In-plane bending tests (11 3-PB and 11 4-PB configurations)
- 12 eccentrically loaded stub column tests
- Tensile coupon (29 flats and 11 corners) and compressive coupon (11 flats) tests



Stub column test



Bending test

Combined loading tests

Cross-section design

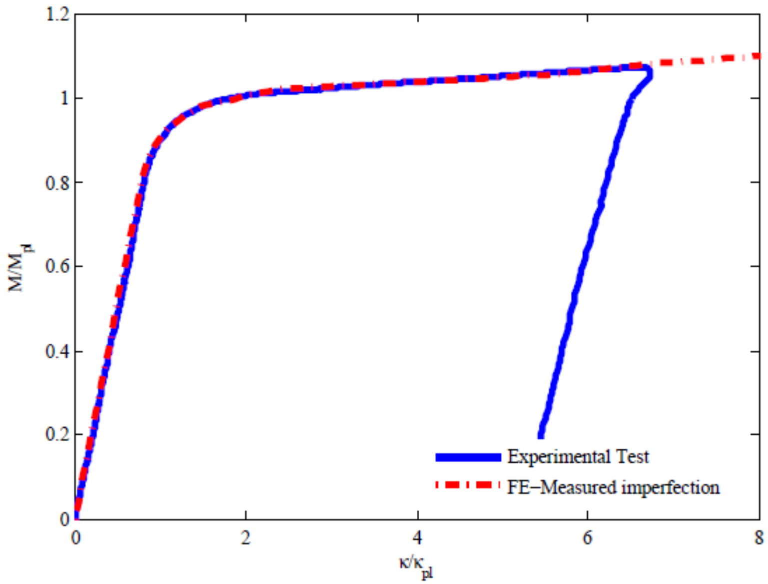
Finite Element Modelling

- FE models of stub columns and beams were developed in ABAQUS
- Models were validated against the test results
  - Full loading history and failure modes well predicted
- Parametric studies were conducted, varying:
  - Material grade;
  - Moment gradient and
  - Cross-section aspect ratio (h/b)

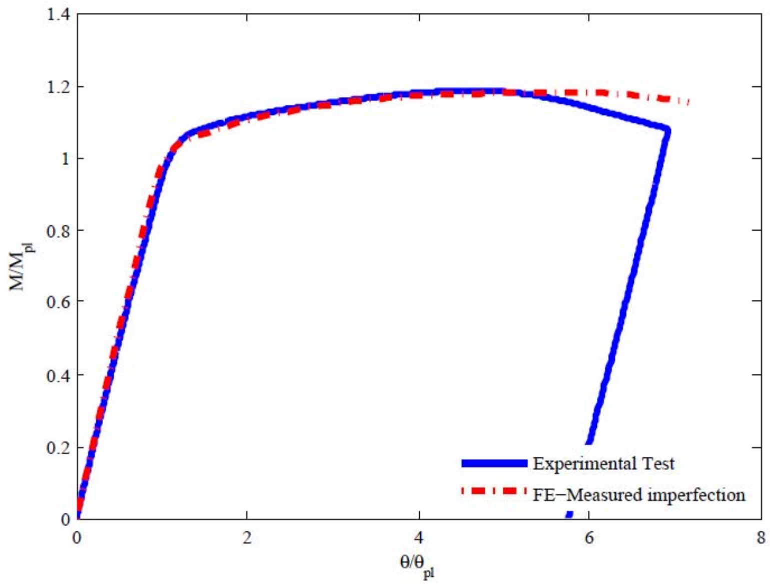
Cross-section design

Finite Element Modelling - validation

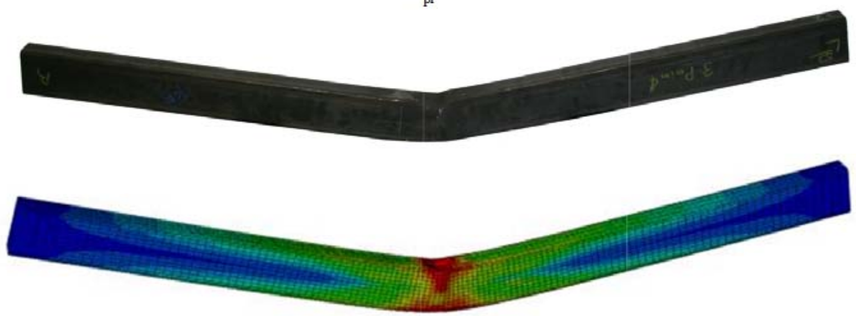
4PB: Moment-curvature response



3PB: Moment-rotation response



Four-point bending

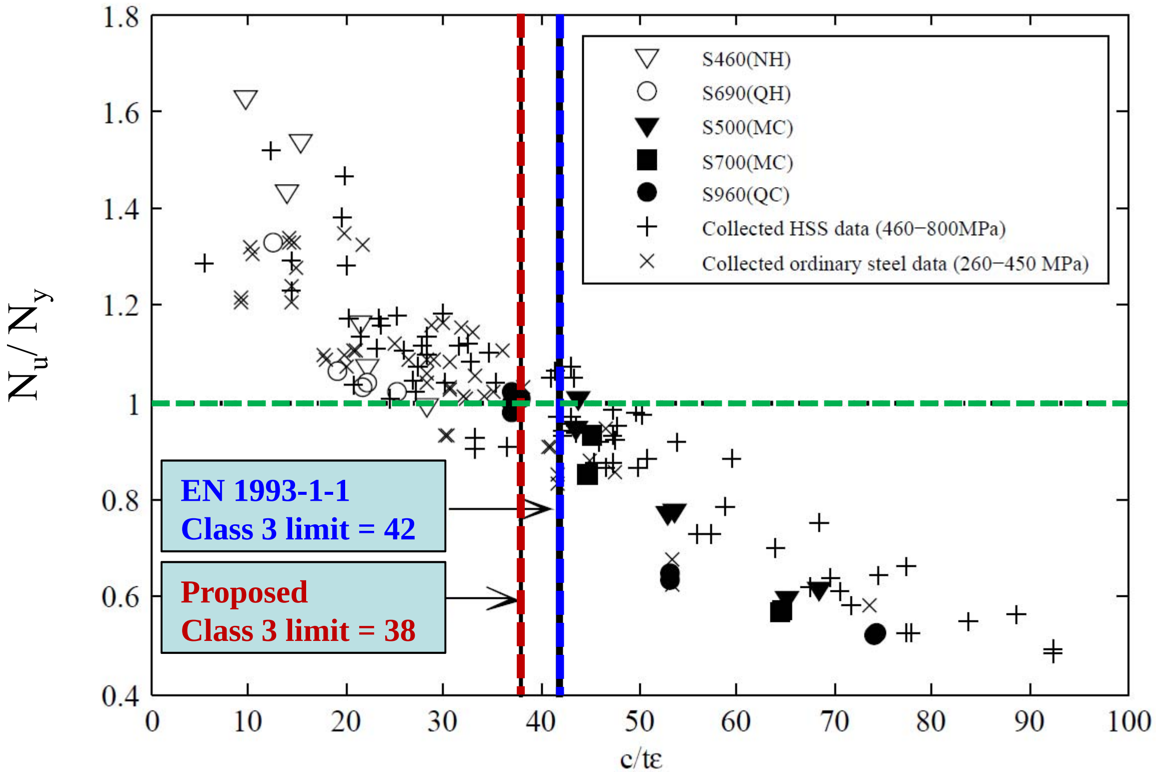


Three-point bending

Cross-section design

Class 3 (c/t.ε) limit for internal elements in compression:

Max load N_u normalised by yield load N_y

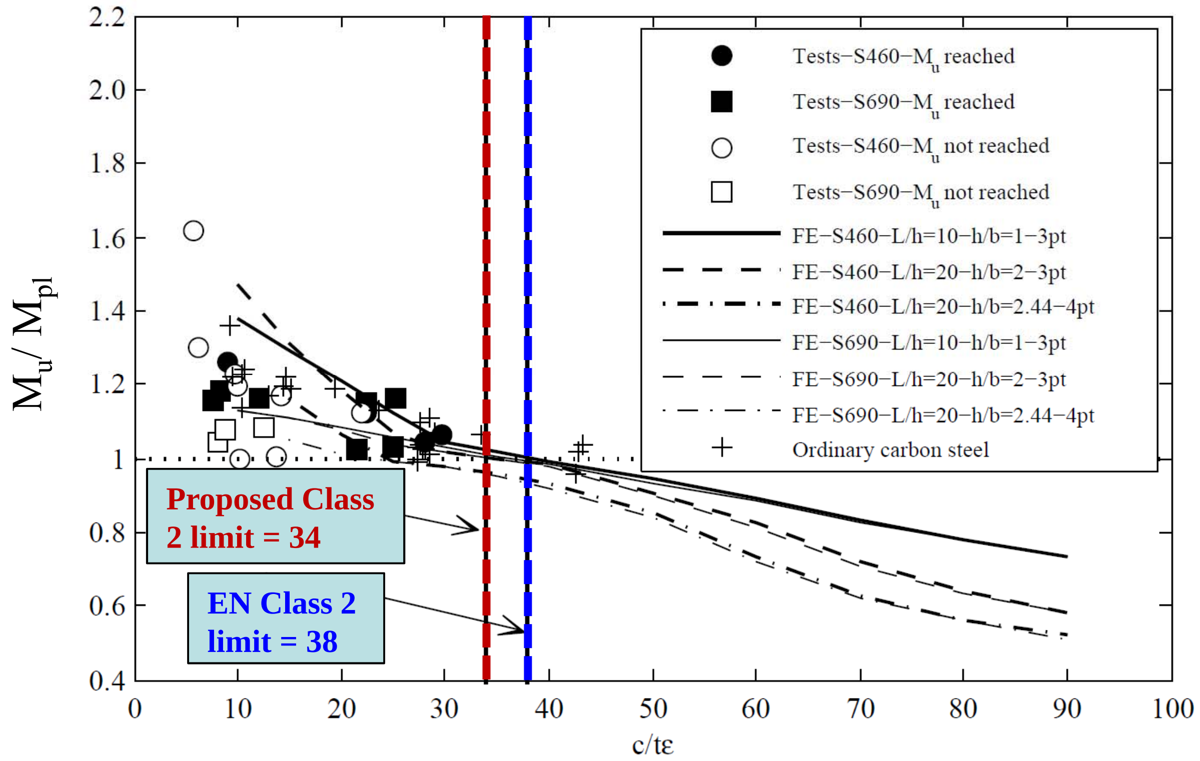


- EN 1993-1-1→ 42 unsafe
- SC3 Evolution group for ordinary carbon steel → 38 more appropriate

Cross-section design

Class 2 (c/t.ε) limit for internal elements in compression:

Max moment M_u normalised by plastic moment capacity M_{pl}

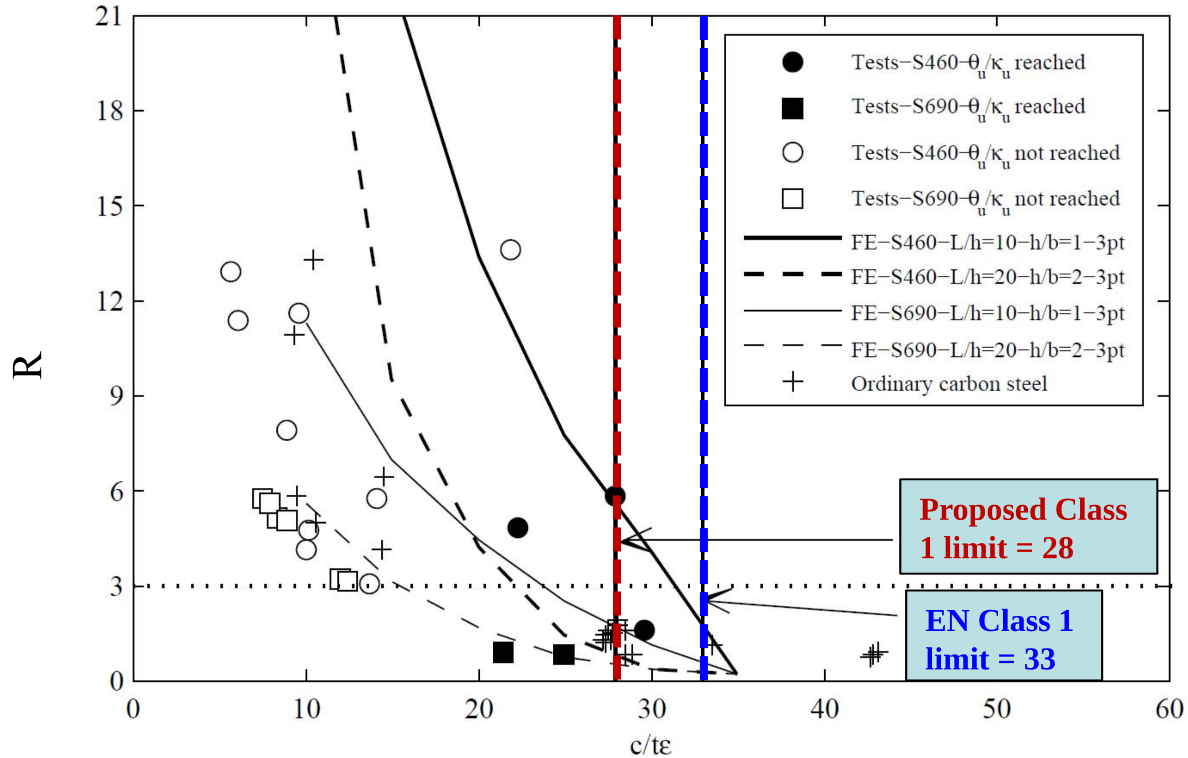


- EN 1993-1-1→ 38 too optimistic
- SC3 Evolution group for ordinary carbon steel → 34 more appropriate

Cross-section design

Class 1 (c/t.ε) limit for internal elements in compression:

Max rotation capacity R



- EN 1993-1-1→ 33 too optimistic
- SC3 Evolution group for ordinary carbon steel → 28 more appropriate

Cross-section design

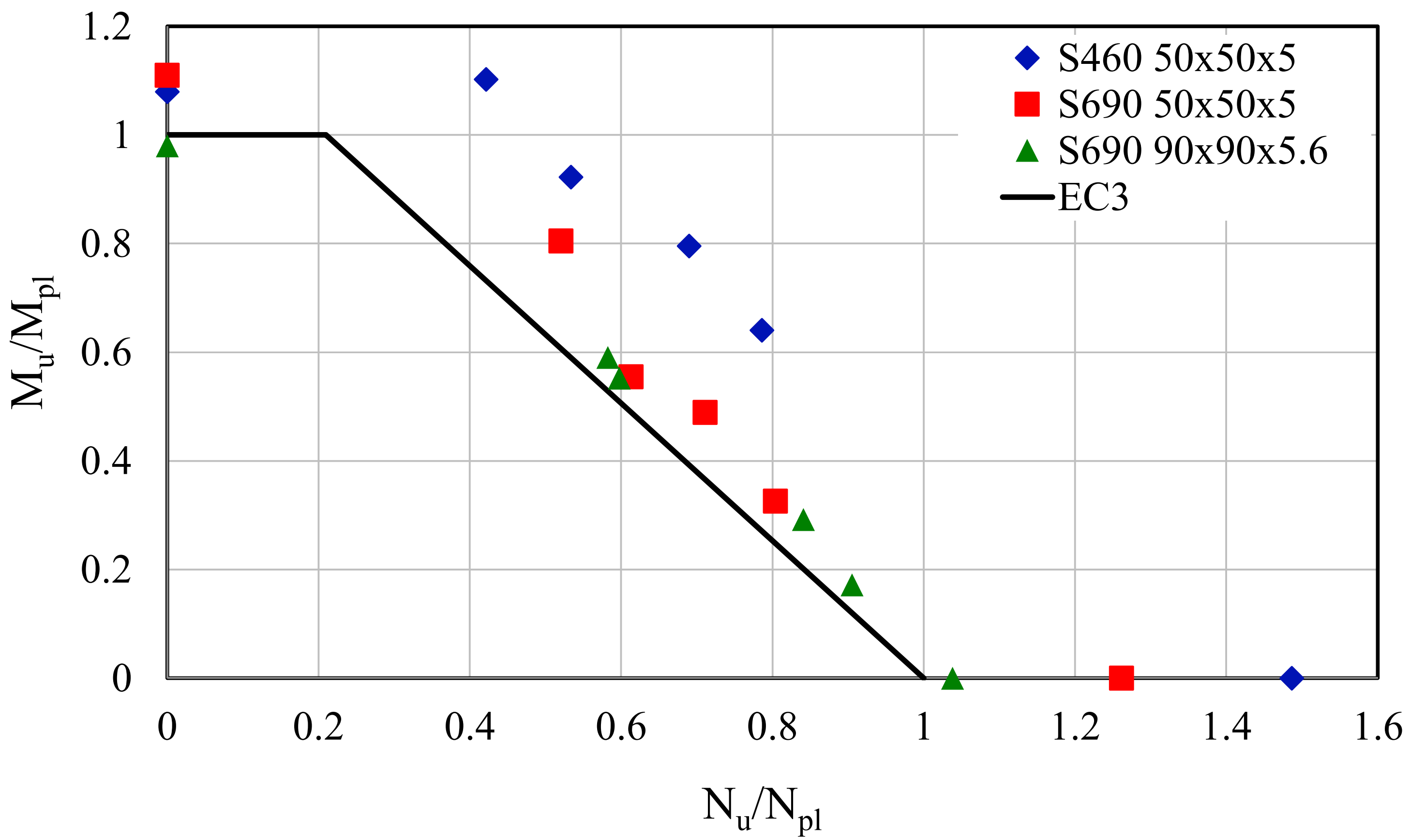
Summary of (c/t.ε) slenderness limits for:

- Internal elements in compressions
- Internal elements in bending

Element Type	Class 1	Class 2	Class 3
Internal element in compression	28	34	38
Internal element in bending	72	83	121

Cross-section design

Moment axial load interaction curve based on test results



- Current EC3 interaction curve is also suitable for high strength steel hollow sections

Concluding remarks

- Experimental programme on HSS hollow sections

- Cross-section classification limits for hollow sections
  - Internal elements in compression
  - Internal elements in bending

- Interaction curve for cross-sections under combined axial load and bending

Design methods for HSS cross-sections

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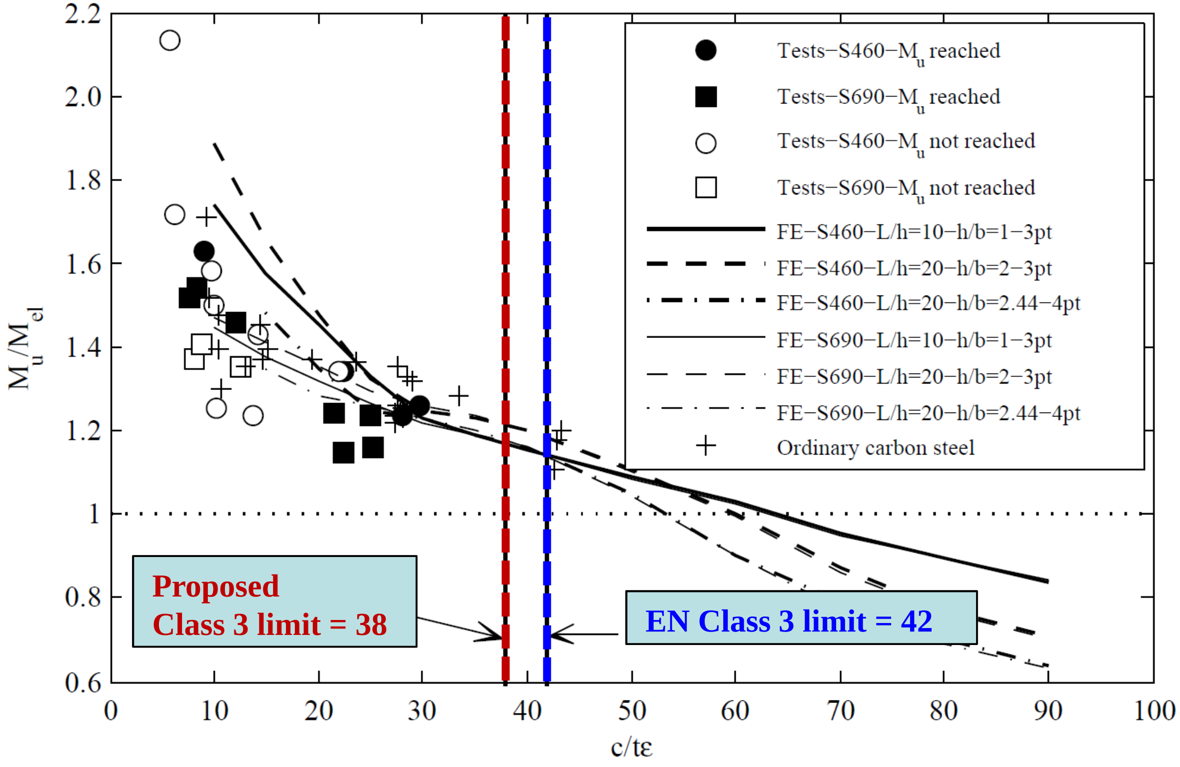
Cross-section design

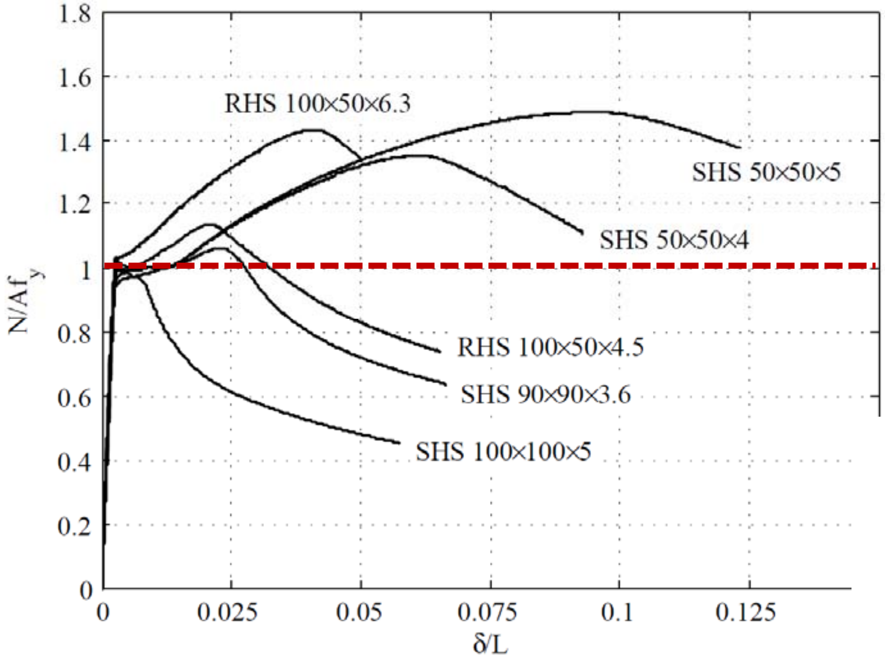
Class 3 (c/t.ε) limit based on bending test results:

Max moment M_u normalised by elastic moment capacity M_{el}

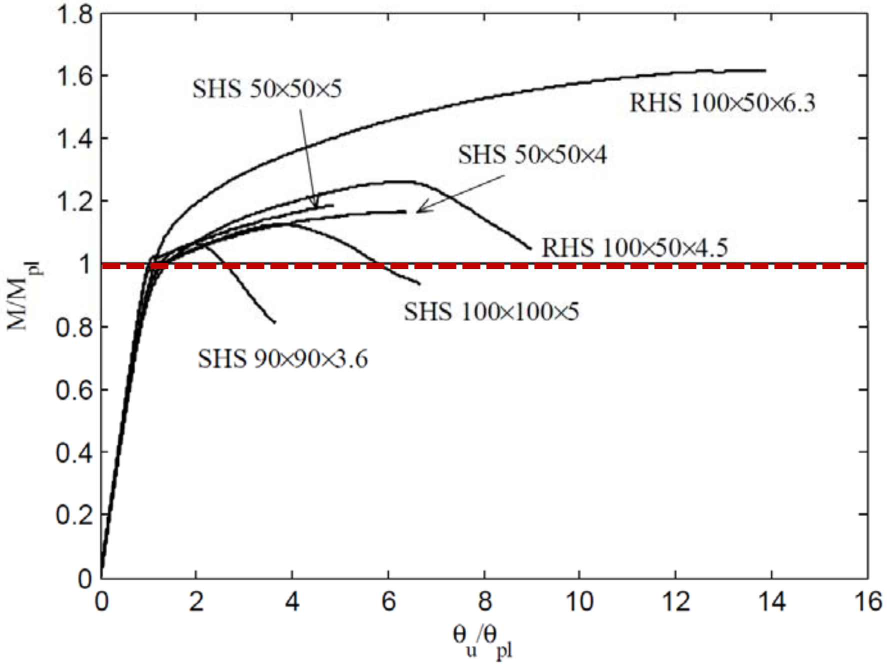


The Continuous Strength Method (CSM)

HSS sections capable of reaching $N_u > N_y$



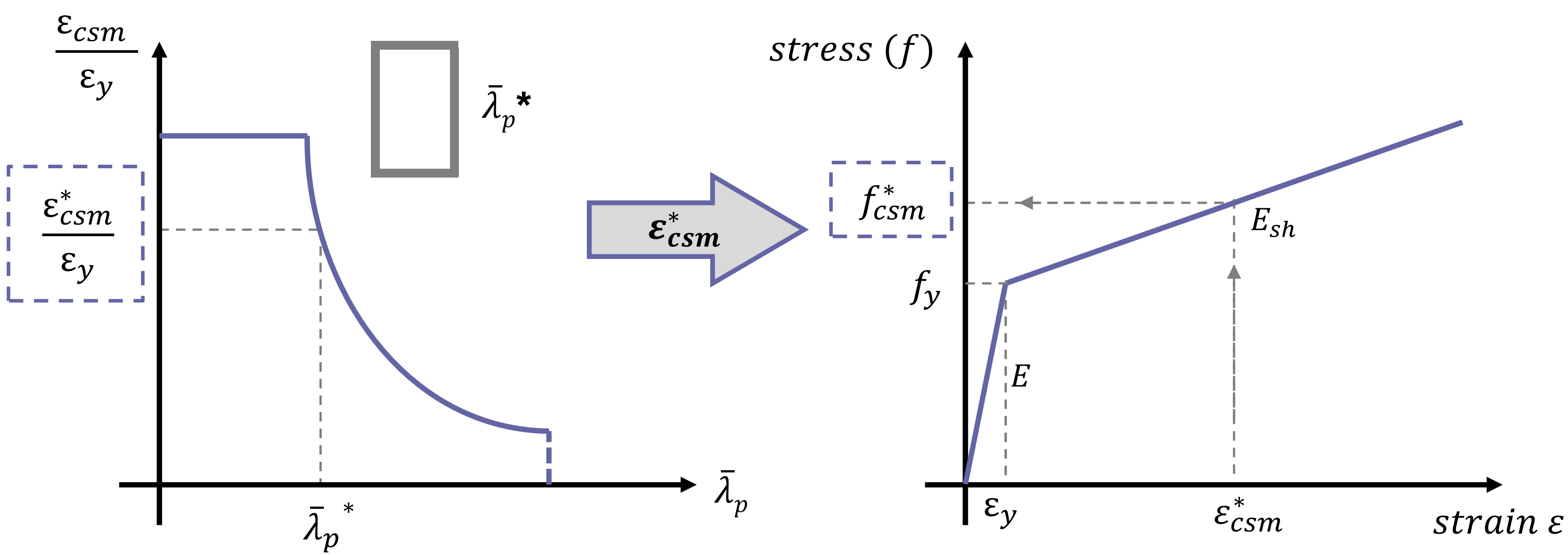
HSS sections capable of reaching $M_u > M_{pl}$



The Continuous Strength Method (CSM)

Base curve

Material model



Cross-section compression resistance

Cross-section bending resistance

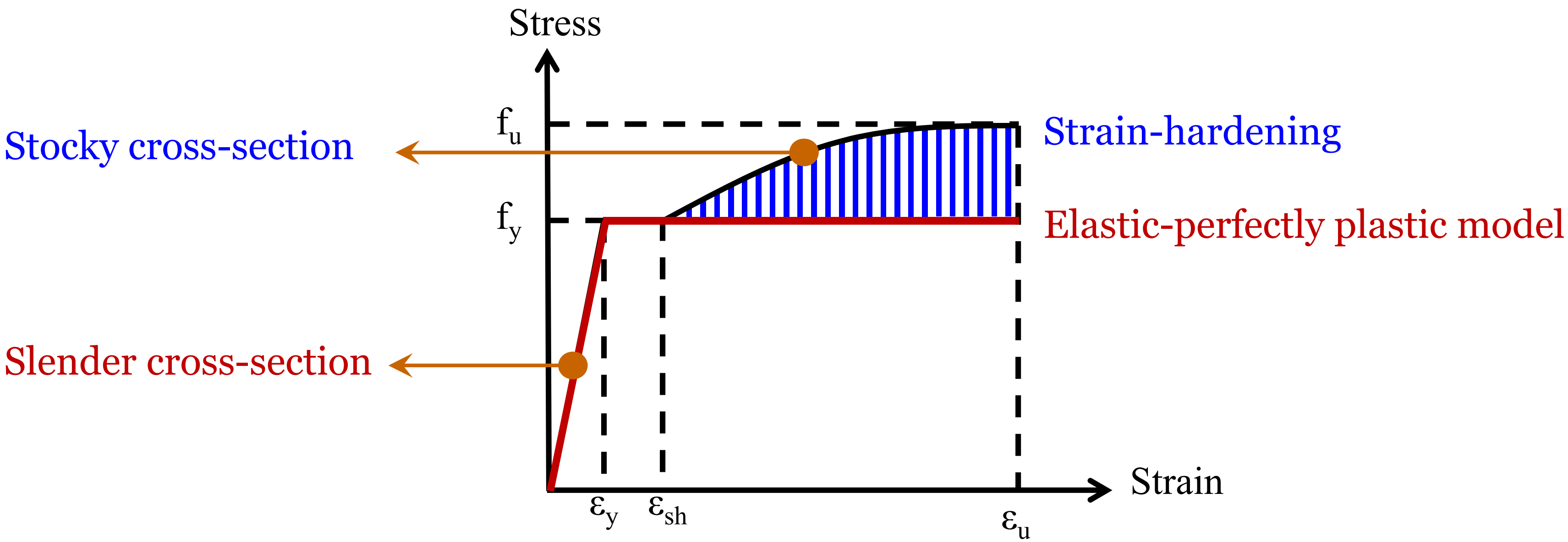
$$N_{csm} = Af_{csm} = A\left[f_y + \left(\varepsilon_{csm} - \varepsilon_y\right)E_{sh}\right]$$

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

The Continuous Strength Method (CSM)

Background:

- Drawbacks of current EC3 classification system:
  - Limits the compression resistance to yield load N_y (Af_y)
  - Limits the cross-section bending resistance to plastic moment M_{pl} ($W_{pl}f_y$)

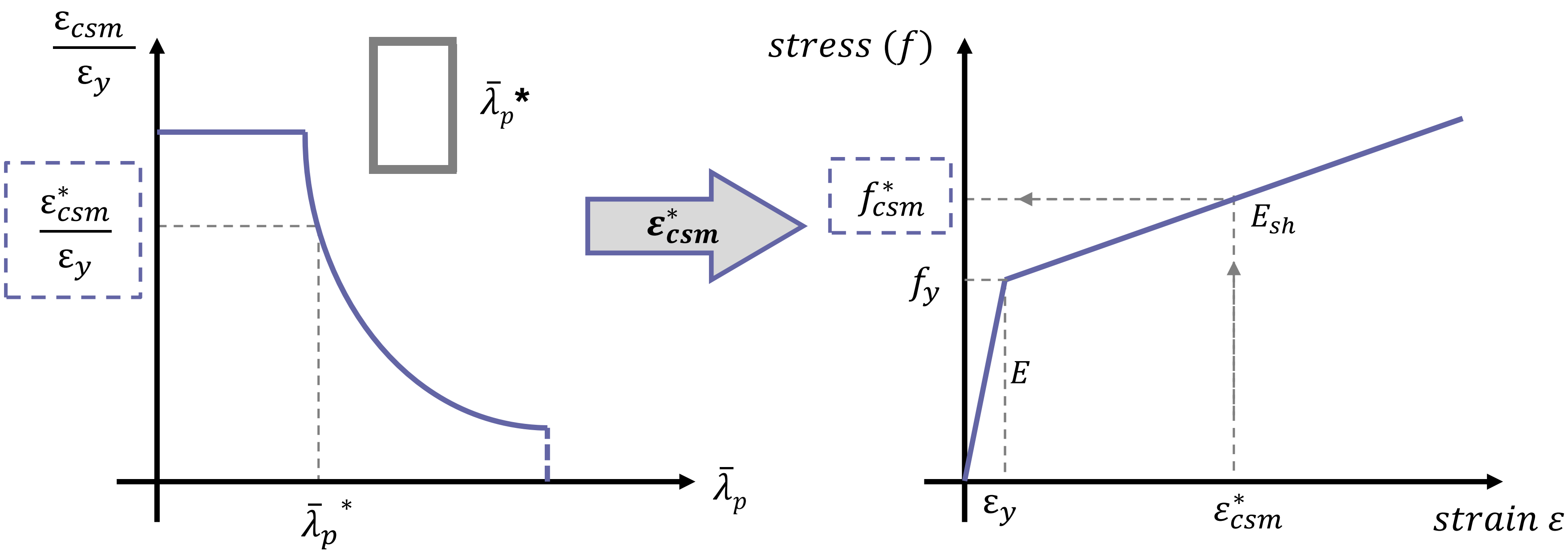


- Continuous Strength Method developed for the design of:
  - Stocky cross-sections (low c/t.ε ratio) which are capable of reaching $N_u > N_y$
  - Stocky cross-sections (low c/t.ε ratio) which are capable of reaching $M_u > M_{pl}$

The Continuous Strength Method (CSM)

Base curve

Material model



Cross-section compression resistance

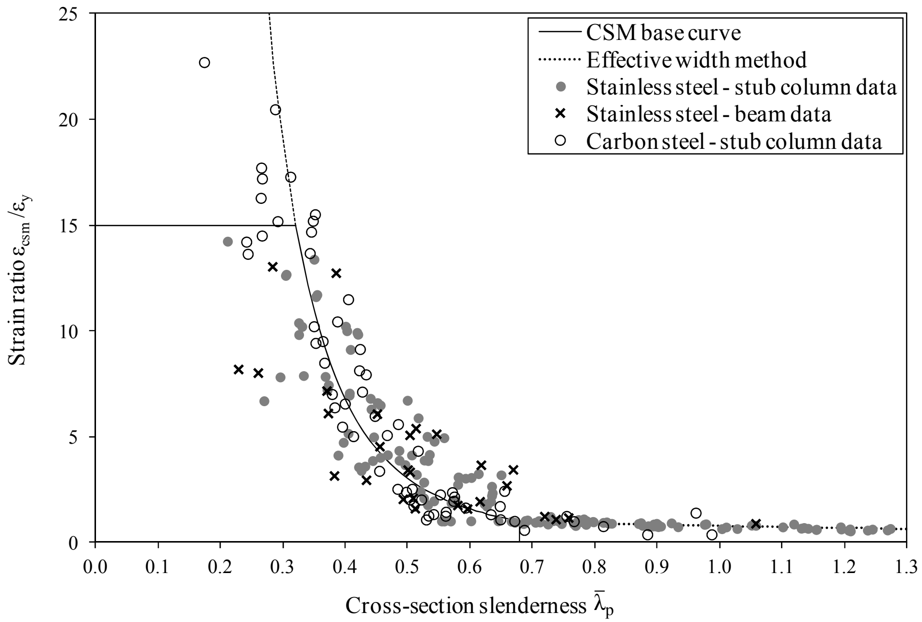
Cross-section bending resistance

$$N_{csm} = A f_{csm} = A[f_y + (\varepsilon_{csm} - \varepsilon_y)E_{sh}]$$

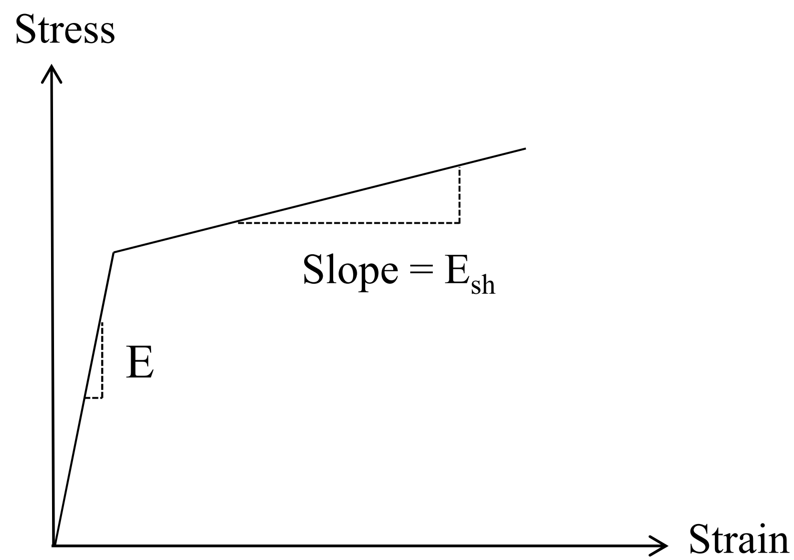
$$\frac{M_{csm}}{M_{pl}} = 1 + \frac{E_{sh}}{E}\frac{W_{el}}{W_{pl}}\left(\frac{\varepsilon_{csm}}{\varepsilon_y}-1\right) - \left(1-\frac{W_{el}}{W_{pl}}\right)\left(\frac{\varepsilon_{csm}}{\varepsilon_y}\right)^{-2}$$

The Continuous Strength Method (CSM)

Base curve



Material model



$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{0.25}{\bar{\lambda}_p^{3.6}} \quad but \quad \frac{\varepsilon_{csm}}{\varepsilon_y} < min\left(15, 0.45\frac{\varepsilon_u}{\varepsilon_y}\right)$$

$$E_{sh} = \frac{f_u - f_y}{0.5\varepsilon_u - \varepsilon_{sh}} \; if \frac{\varepsilon_{sh}}{\varepsilon_u} < 0.5 \; else, E_{sh} = 0$$

Initial analysis of the results has shown that:

- CSM provides more accurate estimation of cross-section capacity
- Especially for HSS grades with higher f_u/f_y ratio