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Plastic design of stainless steel continuous beams

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Presentation outline

- Introduction
- Methodology
- Experimental studies
- Numerical modelling
- Discussion of results
- Conclusions & future research

Stainless steel structures

Chrysler building, New York

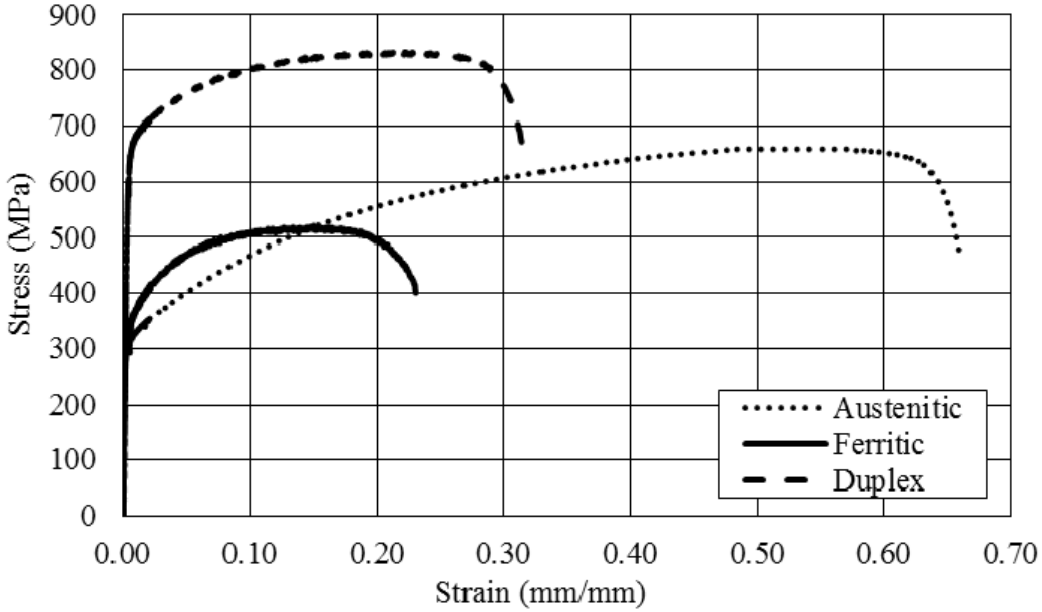
(source: https://vi.wikipedia.org/wiki/Art_Deco)

Cloud Gate in Chicago, USA

(source: https://en.wikipedia.org/wiki/Cloud_Gate)

Stainless steel - Benefits

- High strength, stiffness and ductility
- Weldability
- Better retention of strength and stiffness at elevated temperatures
- Excellent corrosion resistance
- High residual value-recyclability-sustainability
- High quality surface finish-aesthetic appeal



Arrayago, I., Real, E., Gardner, L. (2015). Description of stress–strain curves for stainless steel alloys. Materials & Design, 87, 540-552.

Knowledge Gap

Current Status (focus on plastic design):

- Due to lack of available experimental data, **plastic design** of stainless steel (SS) indeterminate structures is currently not permitted by Eurocode 3: Part 1.4.

- The **high initial material cost** warrants the development of novel design procedures, which fully utilise its merits.

Research aim: Investigate the structural performance of **SS continuous beams** and provide design recommendations.

Methodology

Experimental study

- tensile coupon tests
- tests on simply supported beams
- tests on continuous beams

→

Modelling & Validation of the FE models

- applied element type
- material model
- mesh size
- boundary conditions

→

Parametric studies

- cross-sectional slendernesses
- cross section aspect ratios
- loading arrangements.

→

Analysis of the results and design recommendations

- assessment of design methods

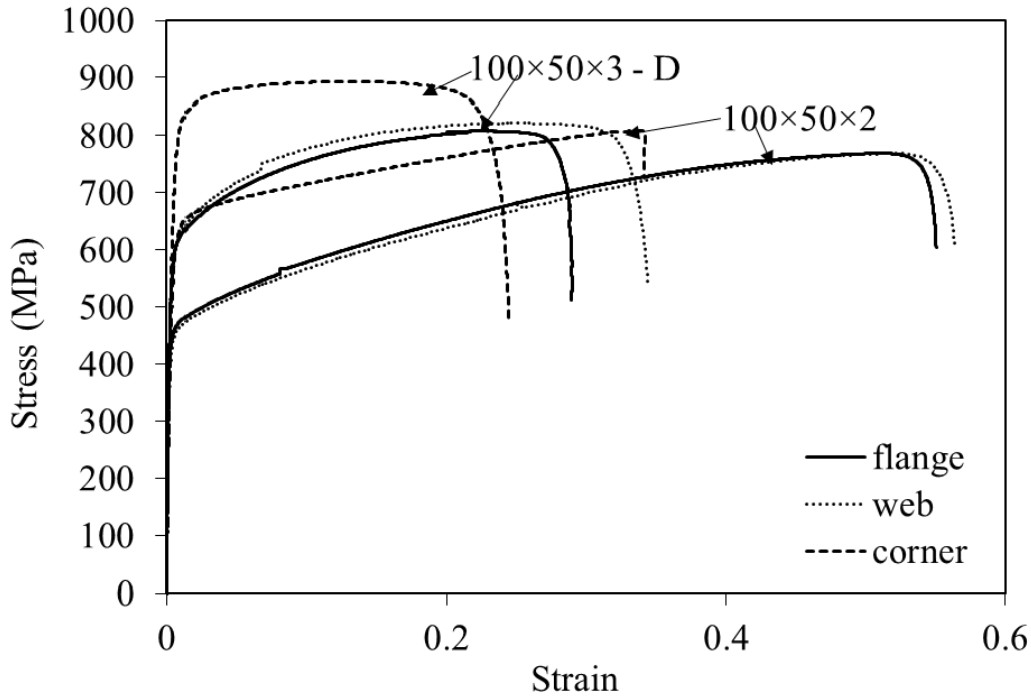
Tensile coupon tests

Flat coupon

Corner coupon

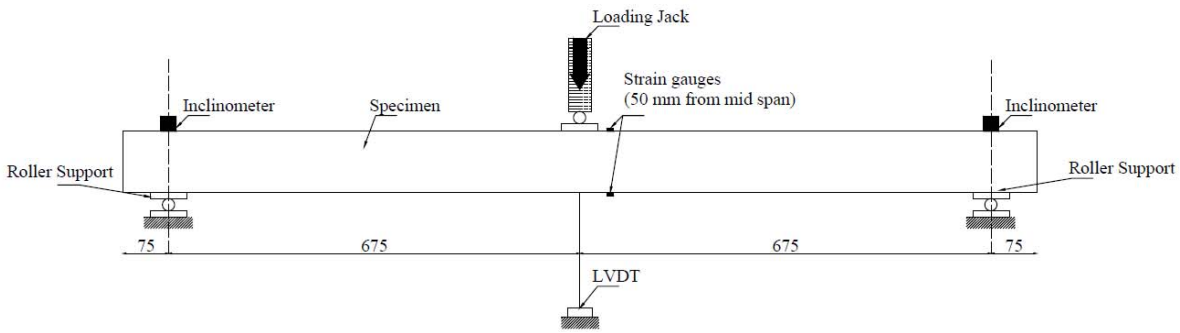
100×50×3 web | 100×50×5 flange | 100×50×5 corner

Tensile coupon tests

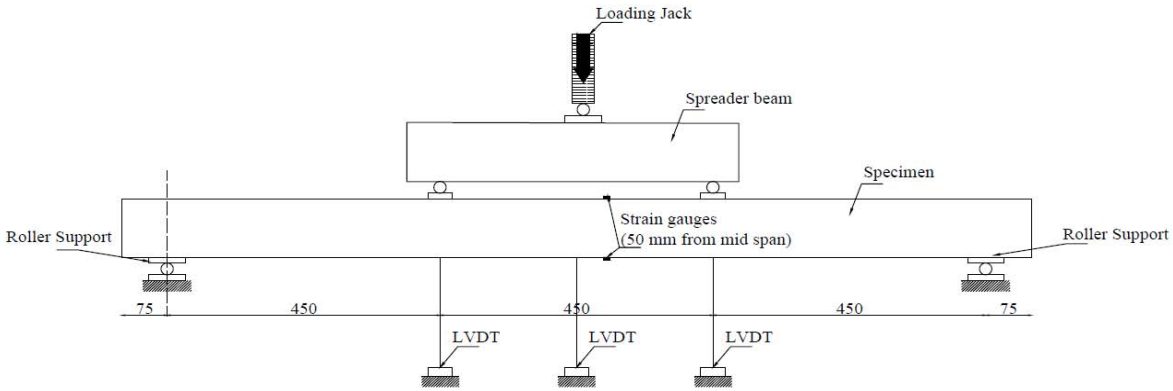


Coupon test results

Simply supported tests



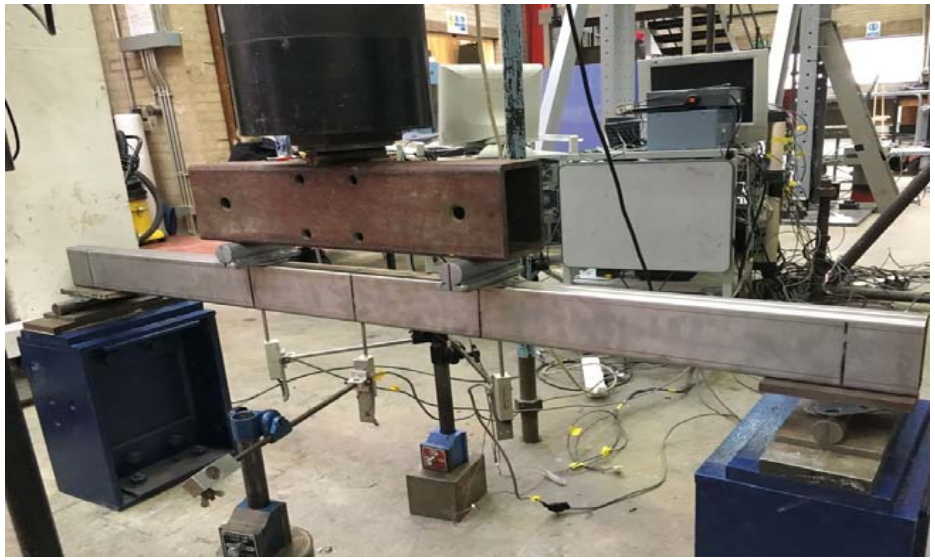
3-P bending tests



4-P bending tests

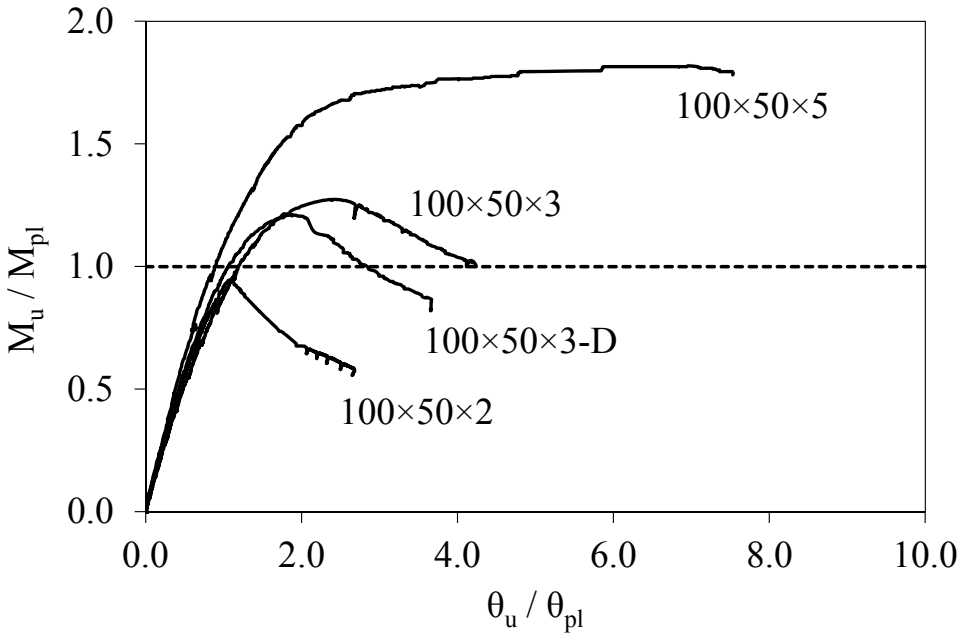
Simply supported tests

3-P bending tests

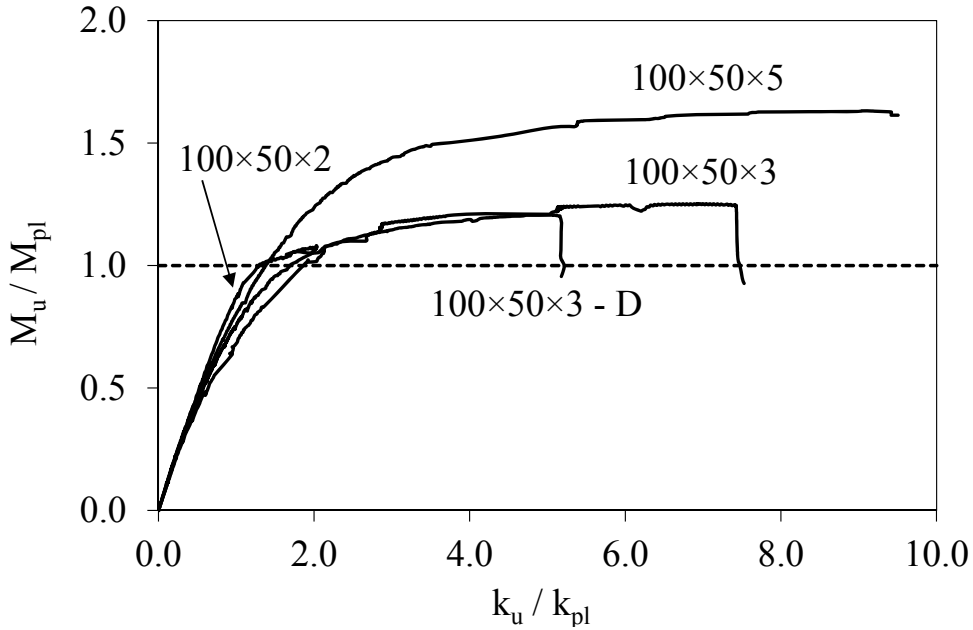


4-P bending tests

Simply supported test results

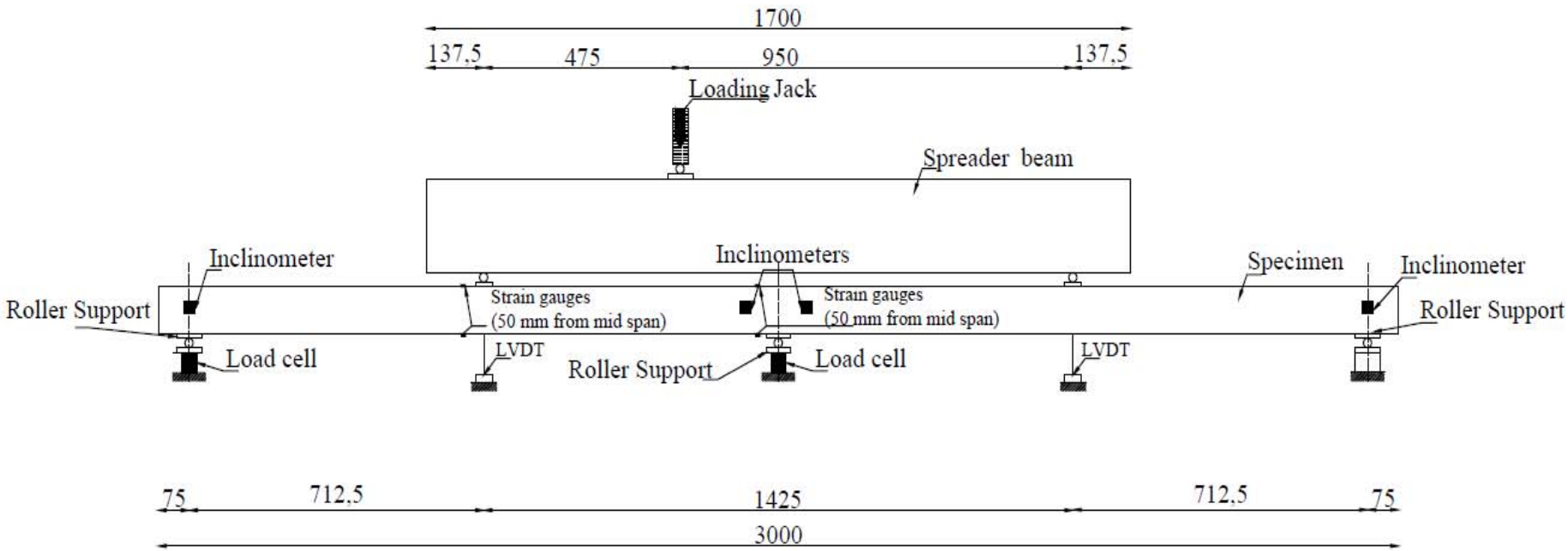


3-P bending results

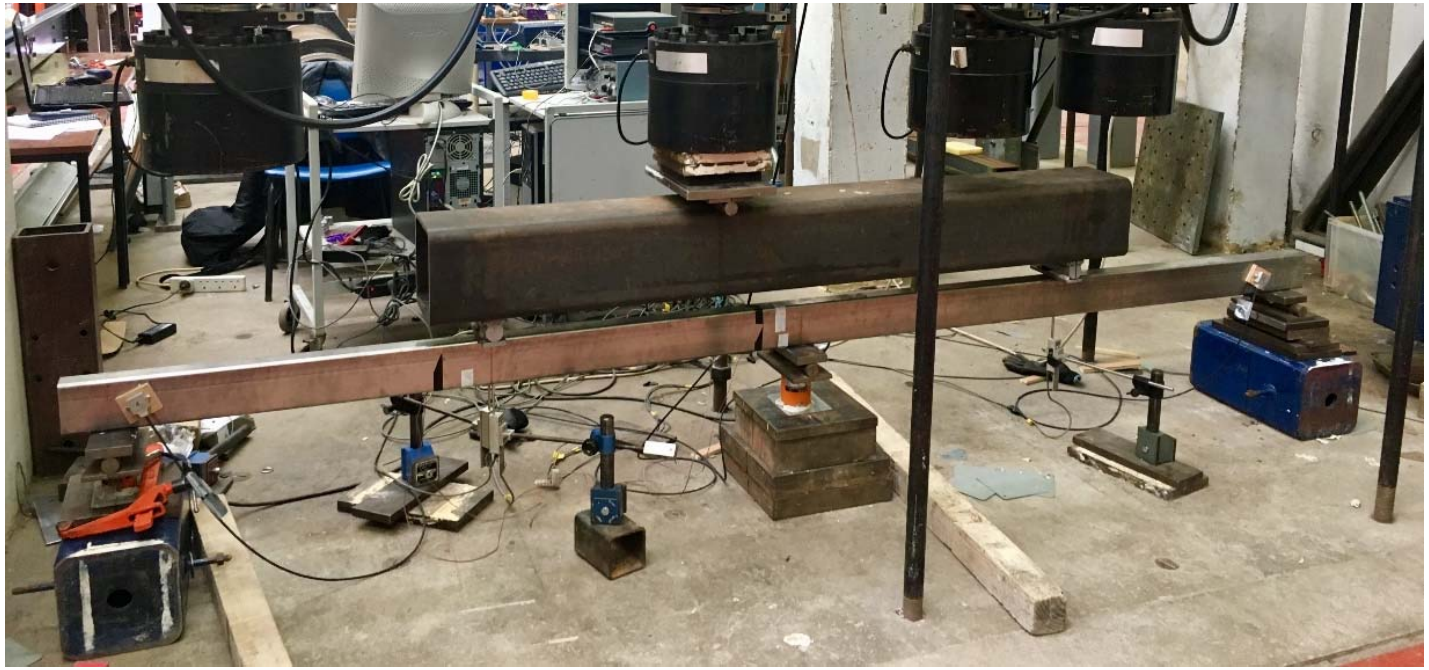


4-P bending results

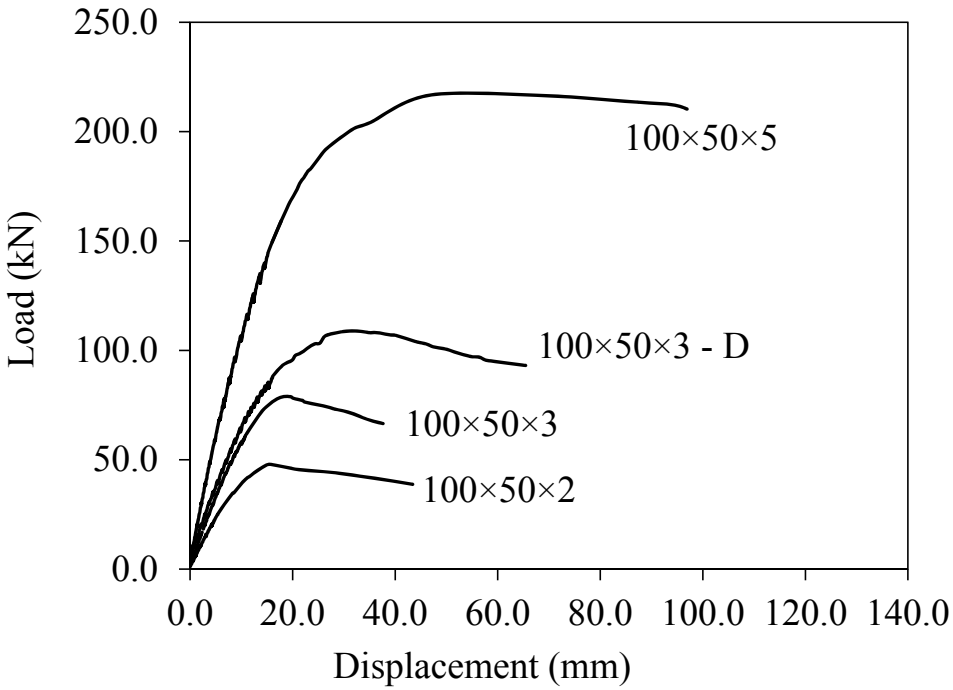
Continuous beam tests

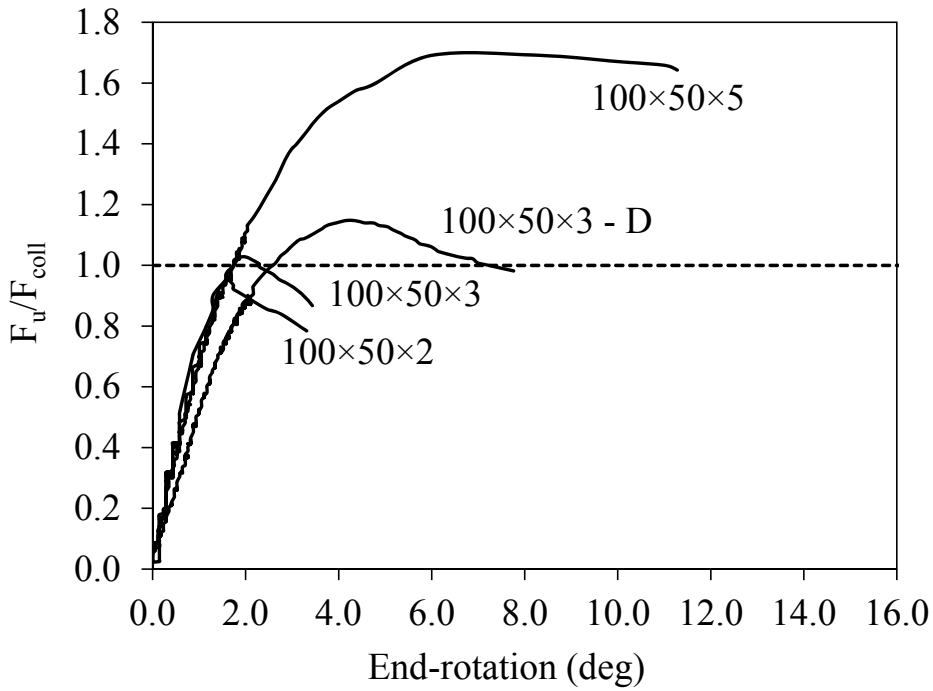


Continuous beam tests



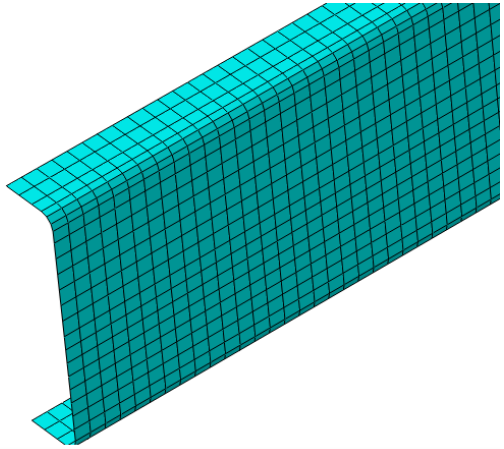
Continuous beam results



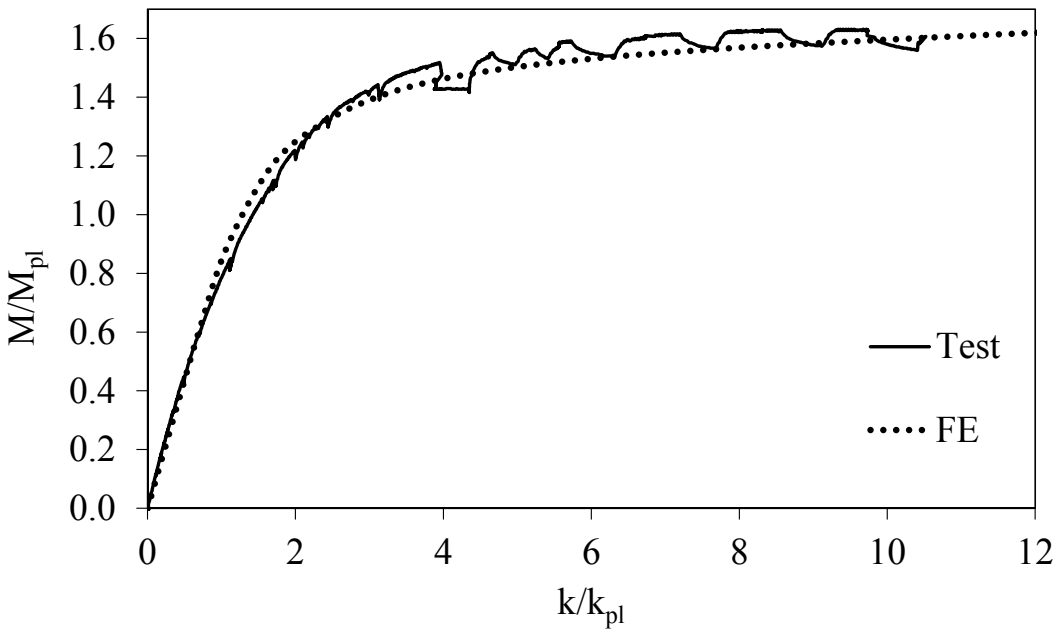


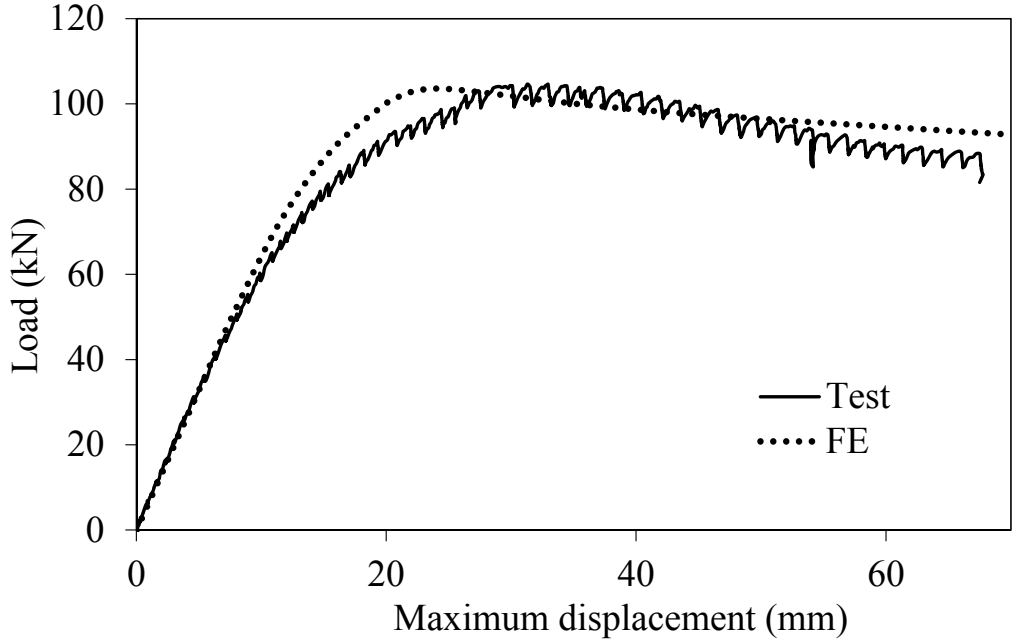
FE Modelling

- Finite element models were developed using the **reduced integration 4-noded shell** elements
- **Precise geometric dimensions** were incorporated on the FE model
- To increase computational efficiency, the **symmetry** in boundary conditions, loading and failure mode was exploited only in half of the cross-section
- The **material properties** conducted by the tensile coupon test were utilized in the FE models
- The **corner properties** are extended to a distance equal twice the thickness of the section beyond the curved corner regions
- **Distributing coupling** was used at the loading points and at the mid support
- The amplitude of **local imperfection** was considered as a fixed fraction of the component thickness **t.**

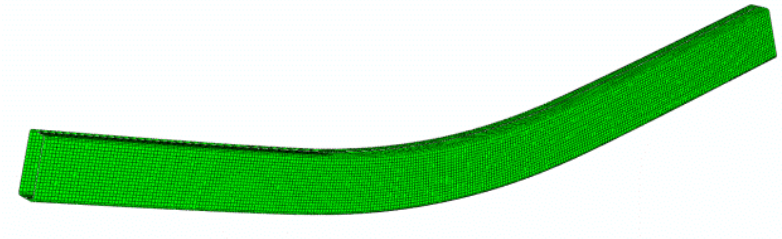


Validation

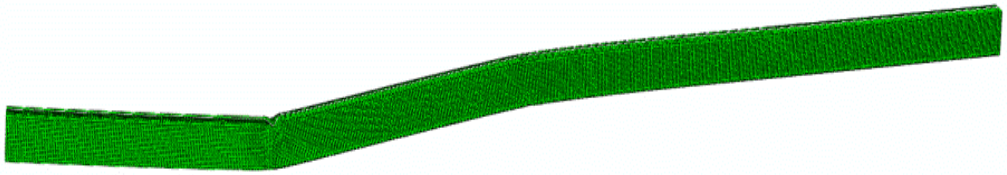

1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
M/M_pl
0
2
4
6
8
10
12
k/k_pl
Test
FE


120
100
80
60
40
20
0
Load (kN)
0
20
40
60
Maximum displacement (mm)
Test
FE

Typical experimental and numerical failure modes



Simply supported beams
(RHS 100 × 50 × 5 – 4-point bending)

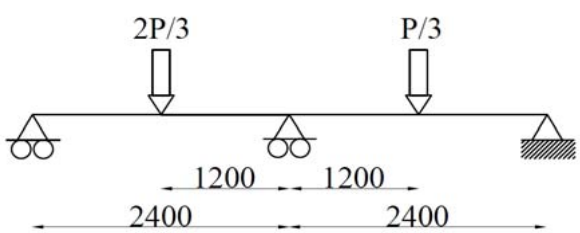


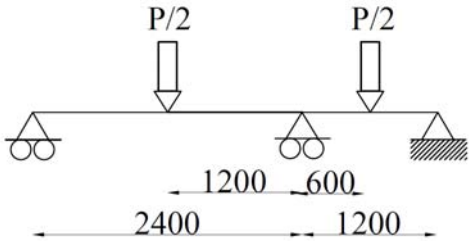
Continuous beams (RHS 100 × 50 × 3-D)

Parametric Studies

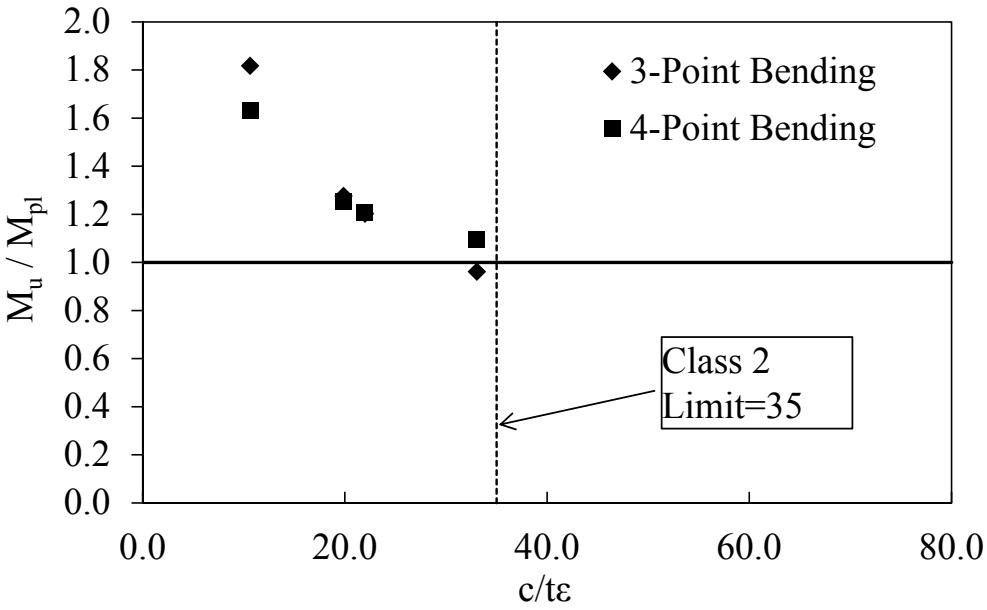
- Two **materials**: stainless steel and duplex
- Four **thicknesses:** 2 mm, 3 mm, 4 mm and 5 mm
- Three cross-section **aspect ratios** (h/b): 1.00, 2.00, 2.44
- **Span length**: 2400 mm
- Two **loading cases** (LC1 & LC2)

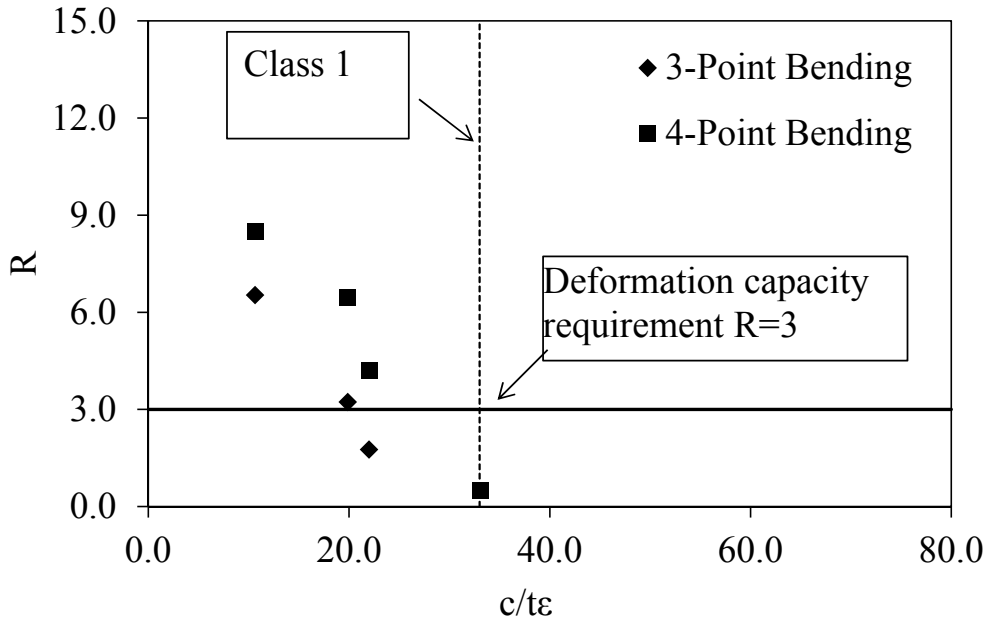
48 analyses in total





Assessment of cross-section slenderness limits





Design methods for continuous beams

1. EC3 without moment redistribution:

- The **bending moment of the most heavily stressed** cross-section to reach its respective moment resistance (M_{pl} for Class 1 and 2 sections, M_{el} for Class 3 sections and, M_{eff} for Class 4 sections)
- The current provisions account **neither** for **strain-hardening nor** for **moment redistribution.**

2. EC3 with moment redistribution:

- Plastically designed, assuming **rigid-plastic material response**

Design methods for continuous beams

3. CSM without moment redistribution:

- treatment of **local buckling** of stainless steel cross-sections, rationally accounting for the significant **strain-hardening** exhibited by stocky sections
- based on a base curve, which relates the **non-dimensional slenderness** $\bar{\lambda}_{cs}$ of a cross section to its **deformation capacity** ε_{csm}.

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

*Afshan S., Gardner L., The continuous strength method for structural stainless steel design, Thin-Walled Structures, Vol. 68, pp. 42-49, 2013

Design methods for continuous beams

4. CSM with moment redistribution:

1. Location of the i plastic hinges; hinge rotations ϑ_i

→ 2. Maximum strain (ε_{csm})

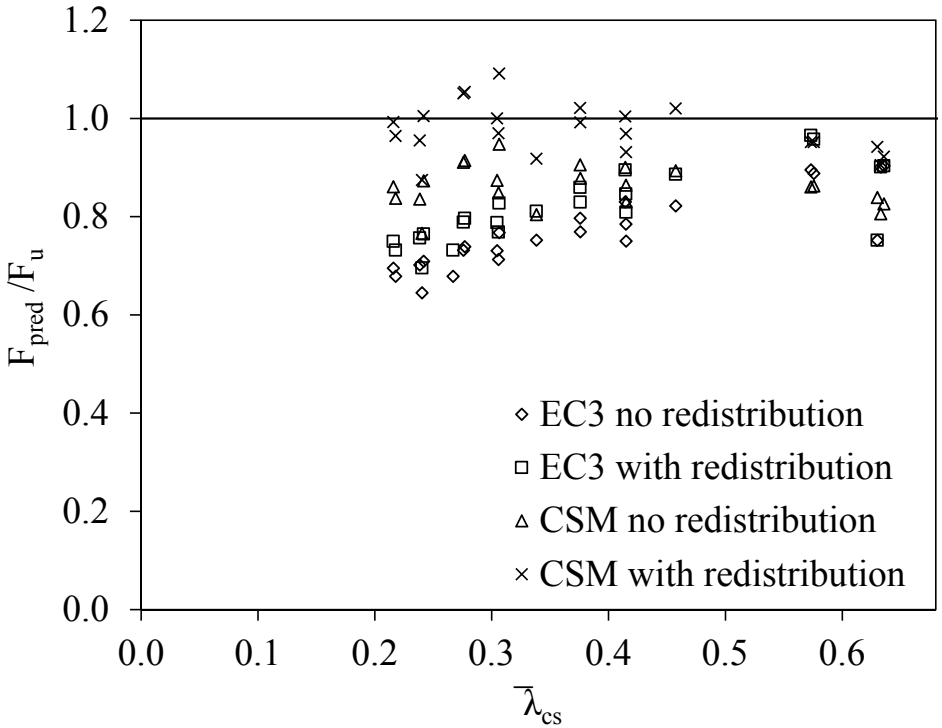
→ 3. Rotation demand α_i

→ 4. Deformation demands assigned relative to that of the critical hinge.

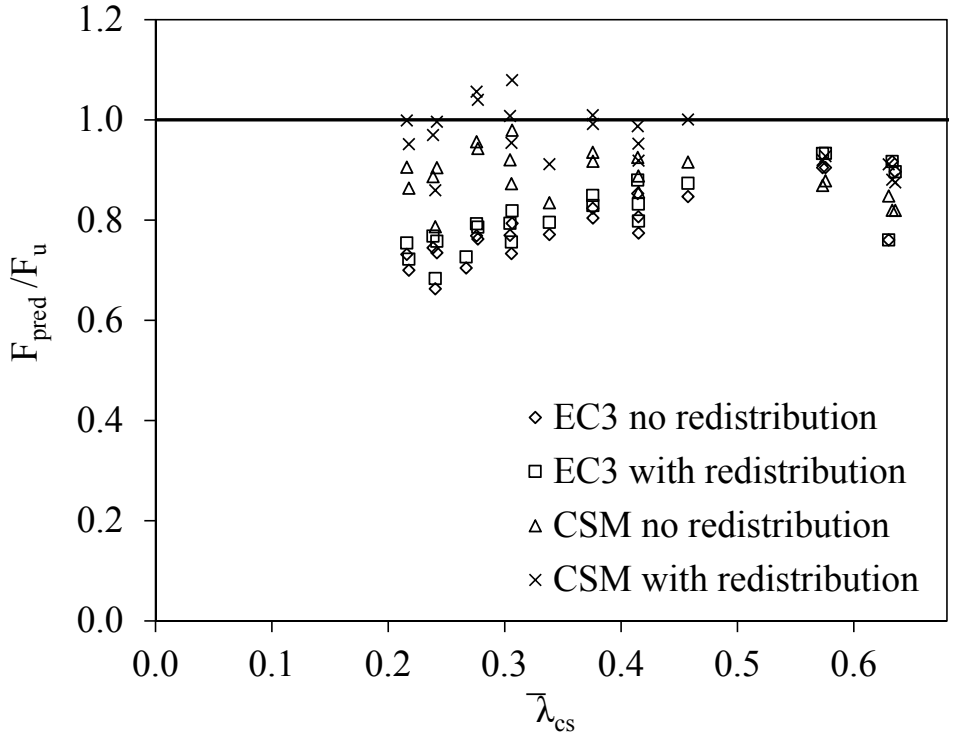
→ 5. M_i at each plastic hinge on the corresponding strain ratio $(\varepsilon_{csm}/\varepsilon_y)_i$

→ 6. Collapse load by equating external and internal work

Results of parametric studies



Load case 1



Load case 2

Results of parametric studies

	Specimen	Grade	Class	EC3 no redistribution	EC3 with redistribution	CSM no redistribution	CSM with redistribution
				F_{pred}/F_u			
LC1	100 × 50 × 2	1.4301/1.4307	1	0.90	0.97	0.86	0.95
	100 × 50 × 3	1.4301/1.4307	1	0.80	0.86	0.91	1.02
	100 × 50 × 4	1.4301/1.4307	1	0.74	0.80	0.91	1.05
	100 × 50 × 5	1.4301/1.4307	1	0.68	0.73	0.84	0.96
	100 × 50 × 2	1.4462	2	0.90	0.90	0.81	0.91
	100 × 50 × 3	1.4462	1	0.78	0.85	0.86	0.97
	100 × 50 × 4	1.4462	1	0.71	0.77	0.85	0.97
	100 × 50 × 5	1.4462	1	0.65	0.70	0.77	0.87
	50 × 50 × 2	1.4301/1.4307	1	0.89	0.96	0.86	0.95
	50 × 50 × 3	1.4301/1.4307	1	0.77	0.83	0.88	0.99
	50 × 50 × 4	1.4301/1.4307	1	0.73	0.79	0.91	1.05
	50 × 50 × 5	1.4301/1.4307	1	0.70	0.75	0.86	0.99
	50 × 50 × 2	1.4462	2	0.90	0.90	0.83	0.92
	50 × 50 × 3	1.4462	1	0.75	0.81	0.83	0.93
	50 × 50 × 4	1.4462	1	0.73	0.79	0.87	1.00
	50 × 50 × 5	1.4462	1	0.70	0.76	0.84	0.96
	122 × 50 × 2	1.4301/1.4307	3	0.75	0.75	0.84	0.94
	122 × 50 × 3	1.4301/1.4307	1	0.83	0.89	0.90	1.00
	122 × 50 × 4	1.4301/1.4307	1	0.77	0.83	0.95	1.09
	122 × 50 × 5	1.4301/1.4307	1	0.71	0.76	0.87	1.01
	122 × 50 × 2	1.4462	4	0.73	0.73	N/A	N/A
	122 × 50 × 3	1.4462	1	0.82	0.89	0.87	0.96
	122 × 50 × 4	1.4462	1	0.75	0.81	0.89	1.02
	122 × 50 × 5	1.4462	1	0.68	0.73	0.80	0.92
	Mean	All		0.77	0.81	0.86	0.98
	COV			0.10	0.09	0.05	0.05

	Specimen	Grade	Class	EC3 no redistribution	EC3 with redistribution	CSM no redistribution	CSM with redistribution
				F_{pred}/F_u			
LC2	100 × 50 × 2	1.4301/1.4307	1	0.90	0.93	0.87	0.92
	100 × 50 × 3	1.4301/1.4307	1	0.82	0.85	0.94	1.01
	100 × 50 × 4	1.4301/1.4307	1	0.76	0.79	0.94	1.04
	100 × 50 × 5	1.4301/1.4307	1	0.70	0.72	0.86	0.95
	100 × 50 × 2	1.4462	2	0.92	0.92	0.82	0.88
	100 × 50 × 3	1.4462	1	0.81	0.83	0.89	0.95
	100 × 50 × 4	1.4462	1	0.73	0.76	0.87	0.95
	100 × 50 × 5	1.4462	1	0.66	0.68	0.79	0.86
	50 × 50 × 2	1.4301/1.4307	1	0.91	0.93	0.88	0.93
	50 × 50 × 3	1.4301/1.4307	1	0.80	0.83	0.92	0.99
	50 × 50 × 4	1.4301/1.4307	1	0.77	0.79	0.96	1.06
	50 × 50 × 5	1.4301/1.4307	1	0.73	0.75	0.91	1.00
	50 × 50 × 2	1.4462	2	0.90	0.90	0.82	0.88
	50 × 50 × 3	1.4462	1	0.77	0.80	0.86	0.92
	50 × 50 × 4	1.4462	1	0.77	0.79	0.92	1.01
	50 × 50 × 5	1.4462	1	0.75	0.77	0.89	0.97
	122 × 50 × 2	1.4301/1.4307	3	0.76	0.76	0.85	0.91
	122 × 50 × 3	1.4301/1.4307	1	0.85	0.88	0.93	0.99
	122 × 50 × 4	1.4301/1.4307	1	0.79	0.82	0.98	1.08
	122 × 50 × 5	1.4301/1.4307	1	0.74	0.76	0.90	1.00
	122 × 50 × 2	1.4462	4	0.77	0.77	N/A	N/A
	122 × 50 × 3	1.4462	1	0.85	0.87	0.89	0.95
	122 × 50 × 4	1.4462	1	0.77	0.80	0.92	1.00
	122 × 50 × 5	1.4462	1	0.70	0.73	0.84	0.91
	Mean	All		0.79	0.81	0.89	0.96
	COV			0.09	0.08	0.05	0.06

Conclusions

1. EC3 without moment redistribution:

The most conservative design predictions for both LC1 and LC2

2. EC3 with moment redistribution:

Improved design predictions both in terms of accuracy and consistency

3. CSM without moment redistribution:

The effect of strain-hardening is considered; improved design predictions

4. CSM with moment redistribution:

Both the effect of strain-hardening and moment redistribution have to be taken into account; accurate predictions of the observed response

Summary - Future work

- The **CSM with moment redistribution** has been found to results in more accurate design estimations.

- Further research is underway to extend the method to the design of pinned based and fixed based **stainless steel portal frames.**

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Acknowledgements

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Thank you for your kind attention!