AN INVESTIGATION OF AUSTENITIC STAINLESS STEEL HOT ROLLED ANGLE SECTIONS UNDER AXIAL COMPRESSION

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Summary

- Introduction
- Background & Stainless Steel Design Standards
- Experimental Investigation
- Design Procedures Comparison
- Final Considerations

Introduction

- Vast number → stainless steel design standards → still based → carbon steel design concepts → very conservative → stainless steel
- Eurocode 3 Part 1-4 → most frequently updated → still a wide range of concepts and parameters → be confirmed & validated

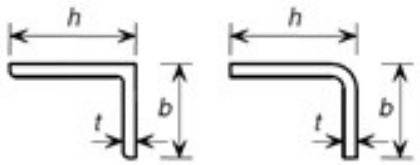
Introduction

- Additional improvements → stainless steel structural design → Continuous Strenght Method (CSM) → centred → criteria development → efficient design → stainless structural elements
- Few studies → stainless steel compressed elements → even less → hot rolled sections → motivation → investigation → angle cross section tests

Background & Stainless Steel Design Standards

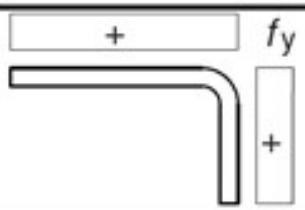
- Eurocode 3 Part 1-4
- Local buckling of angles → compression → cross-section class:

Angles

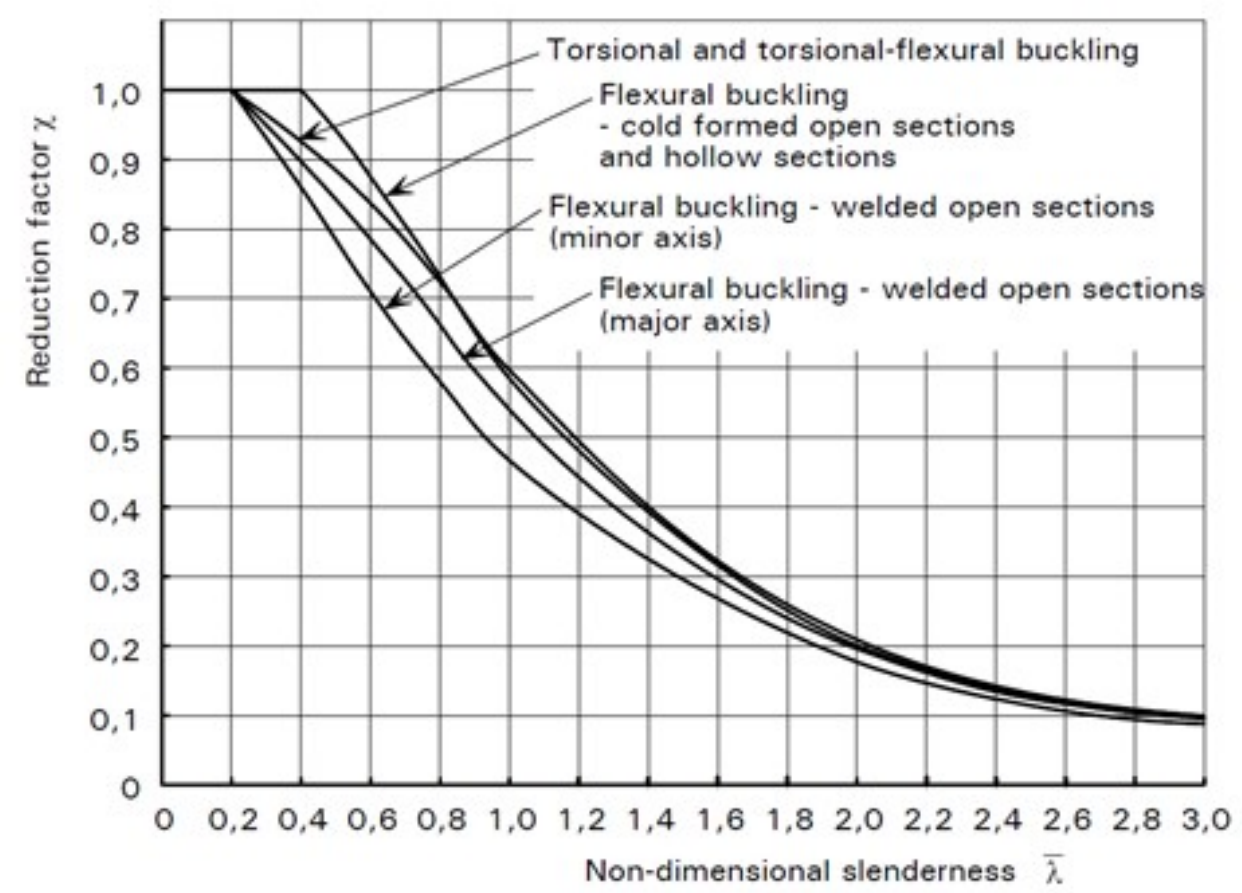


Refer also to "Outstand flanges" (see sheet 2 of 3)

Does not apply to angles in continuous contact with other components

Class	Section in compression
Stress distribution across section (compression positive)	
3	$h/t \le 15\varepsilon$: $\frac{b+h}{2t} \le 11{,}5\varepsilon$

Background & Stainless Steel Design Standards



$$\phi = 0.5\left(1 + \alpha\left(\bar{\lambda} - \bar{\lambda}_0\right) + \bar{\lambda}^2\right)$$

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

$$\bar{\lambda} = \sqrt{\frac{A_g f_y}{N_{Cr}}} \quad \text{for Class 1 to 3 sections}$$

$$\bar{\lambda} = \sqrt{\frac{A_{eff} f_y}{N_{Cr}}} \quad \text{for Class 4 sections}$$

$$N_{Cr} = \frac{\pi^2 EI}{(kL)^2} \quad \text{for flexural buckling}$$

$$N_{Cr} = \frac{1}{i_0^2}\left(GI_T + \frac{\pi^2 EI_w}{(kL)^2}\right) \quad \text{for torsional buckling}$$

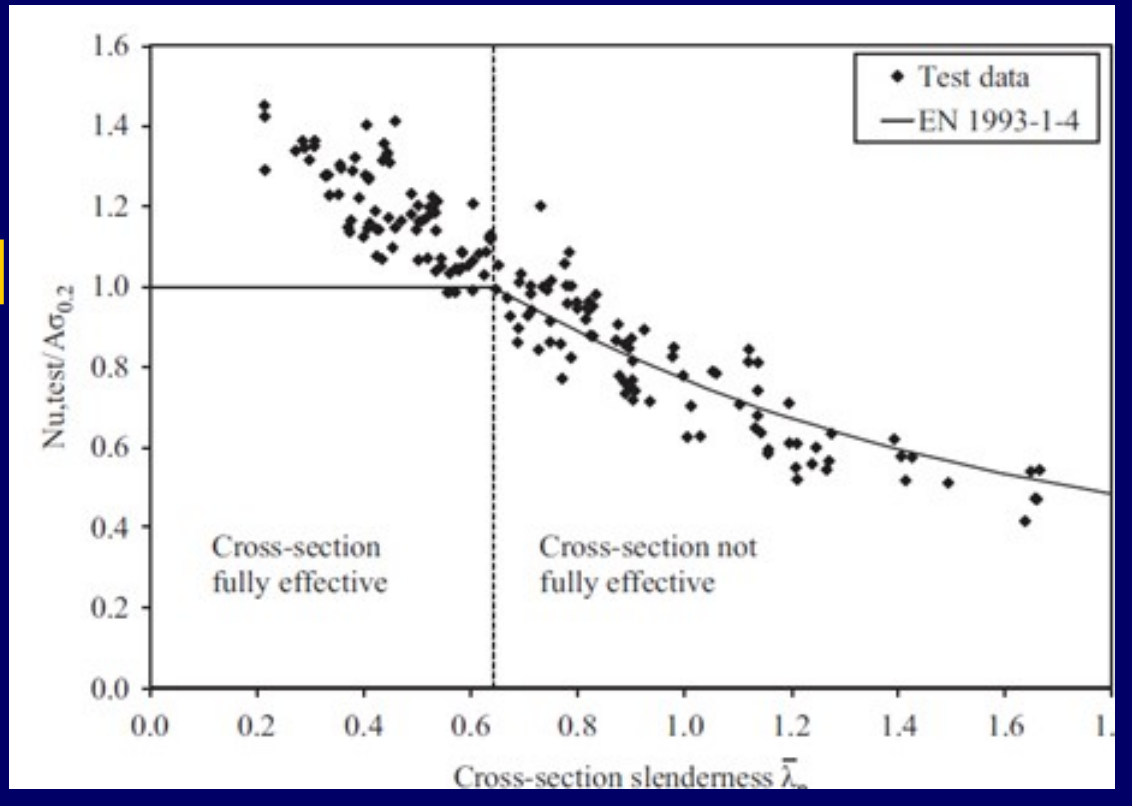
Background & Stainless Steel Design Standards

- Eurocode 3 Pt 1-4 $\rightarrow$ no criteria $\rightarrow$ stainless hot rolled profiles
- Comparisons $\rightarrow$ α = 0.49 & λ_0 = 0.40 $\rightarrow$ open cold formed sections flexural buckling
- α = 0.34 & λ_0 = 0.20 $\rightarrow$torsional & flexural-torsional buckling

Buckling mode	Type of member	α	$\overline{\lambda_0}$
Flexural	Cold formed open sections	0.49	0.40
	Hollow sections (welded and seamless)	0.49	0.40
	Welded open sections (major axis)	0.49	0.20
	Welded open sections (minor axis)	0.76	0.20
Torsional e Flexural-torsional	All members	0.34	0.20

Background & Stainless Steel Design Standards

- Continuous Strength Method - CSM
  Motivation → 81 Stub column Tests & Eurocode 3 Predictions
- Low slenderness
  → ultimate loads
  → underestimated by up to 50%



Background & Stainless Steel Design Standards

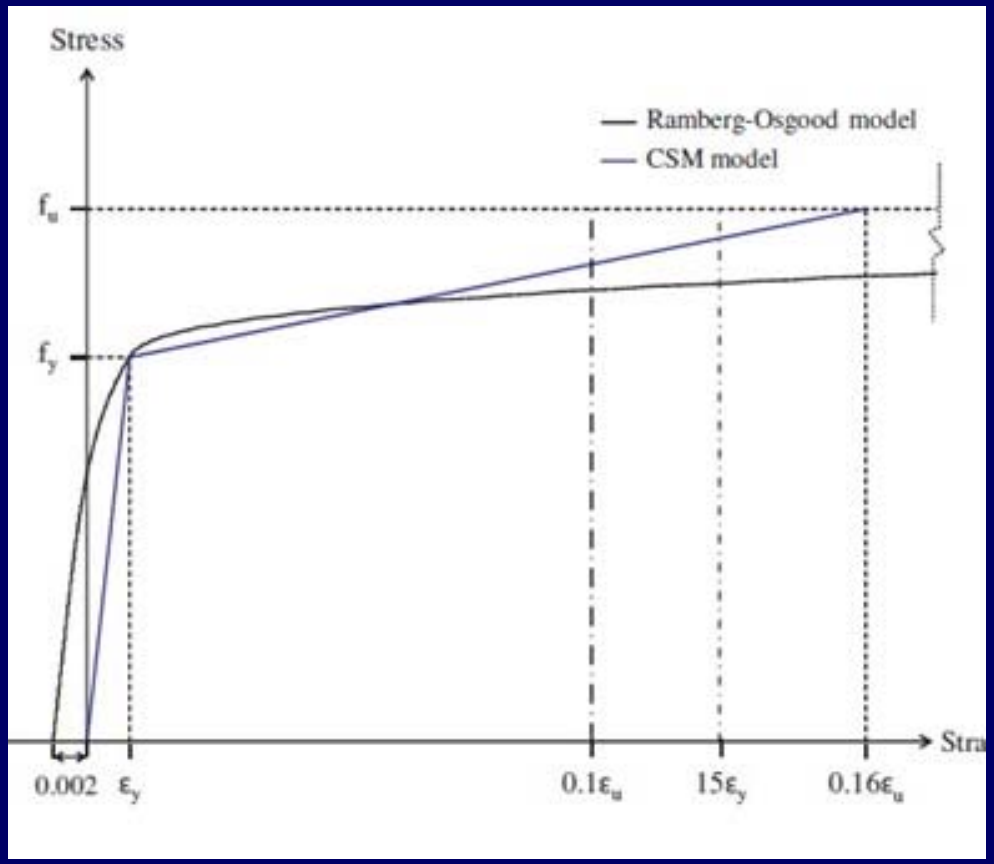
- CSM Material → simple bilinear function
- Stress strain curve → 0.2% stress →initial E
- From this point → module decreases to E_{sh} → material strain hardening until → 0.16 ε deformation limit → reaches → material ultimate tensile rupture stress

$$E_{sh} = \frac{f_u - f_y}{0.16\varepsilon_u - \varepsilon_y}$$

$$\varepsilon_u = 1 - \frac{f_y}{f_u}$$

Background & Stainless Steel Design Standards

- Comparison → CSM model & Ramberg-Osgood formulation



For compact sections → ultimate stress:

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

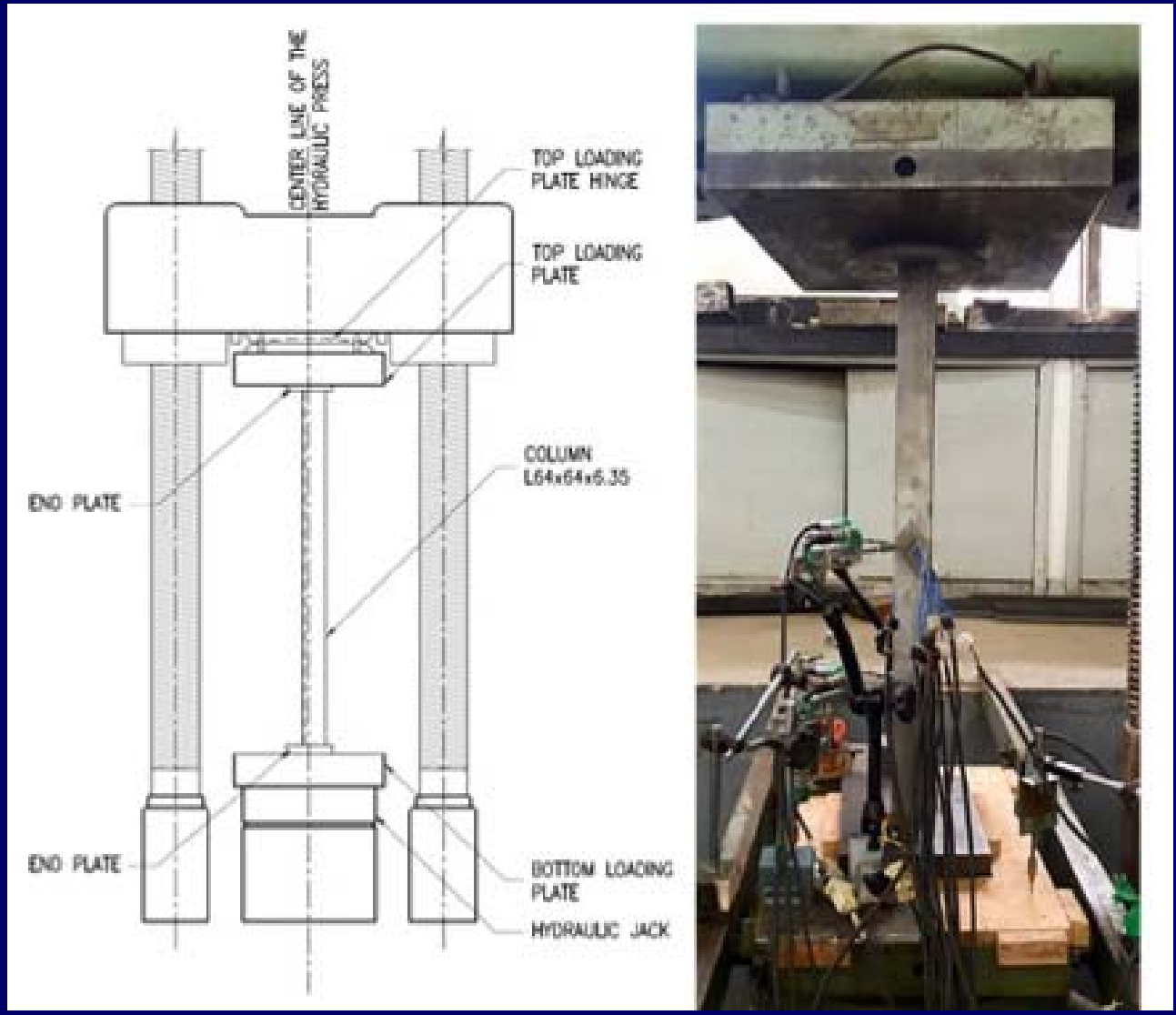
Experimental Investigation

- 11 hot rolled angle tests → L64x64x6.35 → austenitic stainless steel ASTM A276 304.
- 2 compression tests → material characterization

Test	Length (mm)	b_1 (mm)	t_1 (mm)	b_2 (mm)	t_2 (mm)
Characterization 1	250	64,00	6,50	64,00	6,54
Characterization 2	250	64,30	6,48	64,00	6,34
L64x64x6.4-AUS-500-1-23.09	488	63,63	6,40	63,56	6,48
L64x64x6.4-AUS-500-2-23.09	491	63,95	6,42	63,76	6,32
L64x64x6.4-AUS-750-1-27.09	738	63,68	6,60	63,78	6,43
L64x64x6.4-AUS-750-2-28.09	736	63,75	6,57	63,67	6,34
L64x64x6.4-AUS-1000-1-25.08	1000	63,72	6,42	63,42	6,65
L64x64x6.4-AUS-1000-2-01.09	1000*	63,60	6,55	63,73	6,35
L64x64x6.4-AUS-1000-3-19.09	1000*	63,65	6,52	63,78	6,36
L64x64x6.4-AUS-1250-1-05.10	1238	63,53	6,52	63,75	6,29
L64x64x6.4-AUS-1250-2-07.10	1241	63,55	6,47	63,78	6,34
L64x64x6.4-AUS-1500-1-13.10	1491	63,70	6,44	63,82	6,50
L64x64x6.4-AUS-1500-2-13.10	1492	63,69	6,37	63,78	6,42

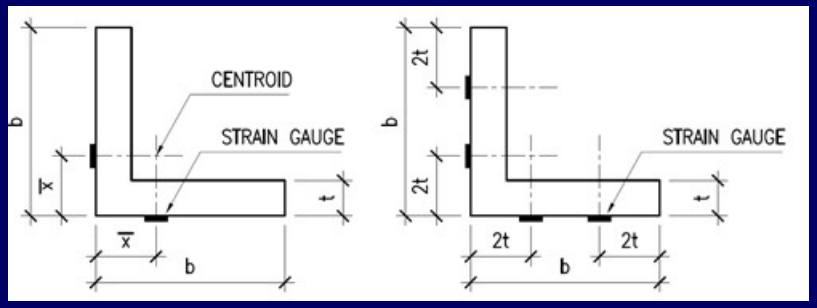
Experimental Investigation

- Test Layout



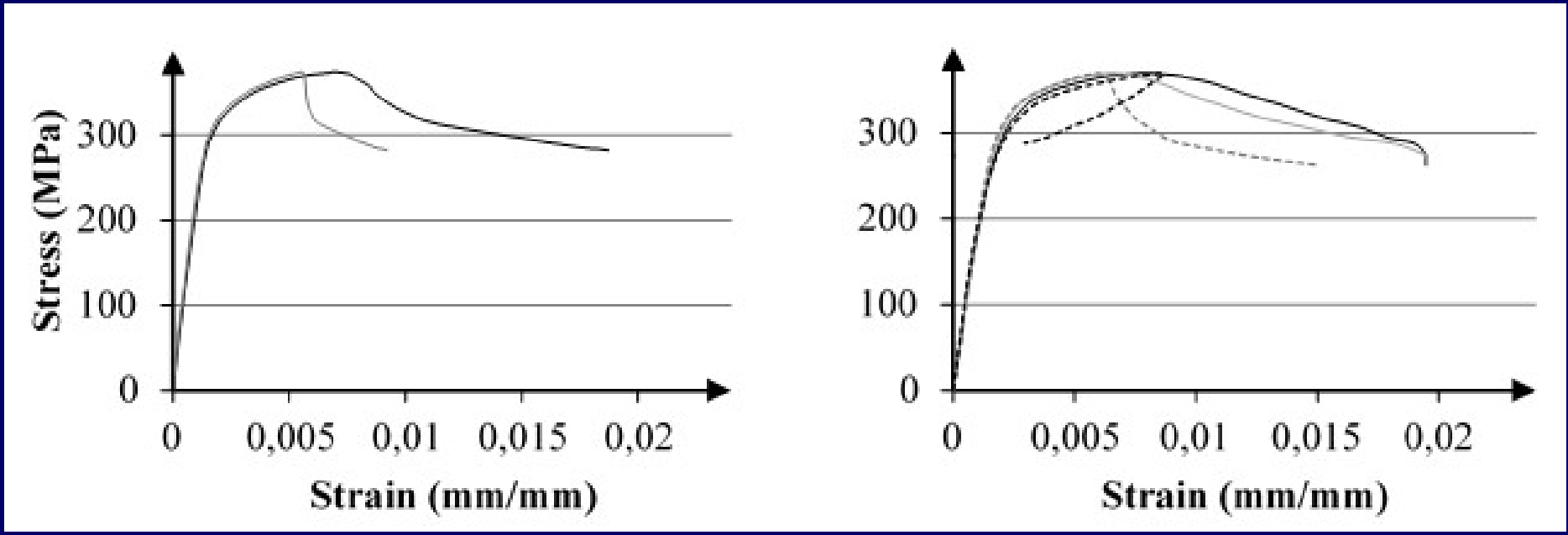
Experimental Investigation

- Material Properties
  - 2 compression 250 mm tests → material response in compression → parallel to rolling direction
  - First test → strain gauge → angle legs centroid
  - Second test → two strain gauges → each leg
  - Test layout



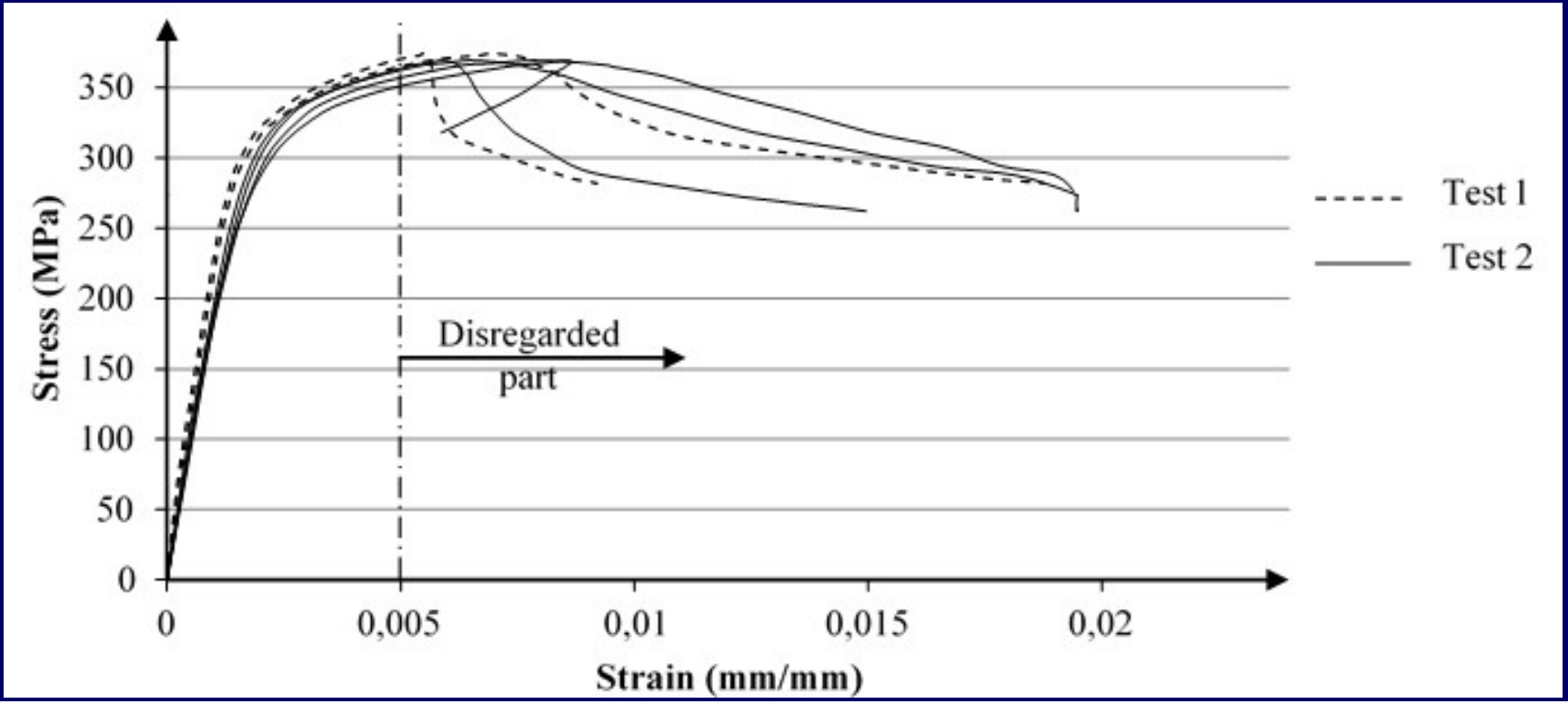
Experimental Investigation

- Stress versus strain curves



Experimental Investigation

- Material Tests → local buckling mode → less coupon tests typical tensile rupture load → strain values higher than ultimate test load → not valid (0.005 strain) → tests validity range



Experimental Investigation

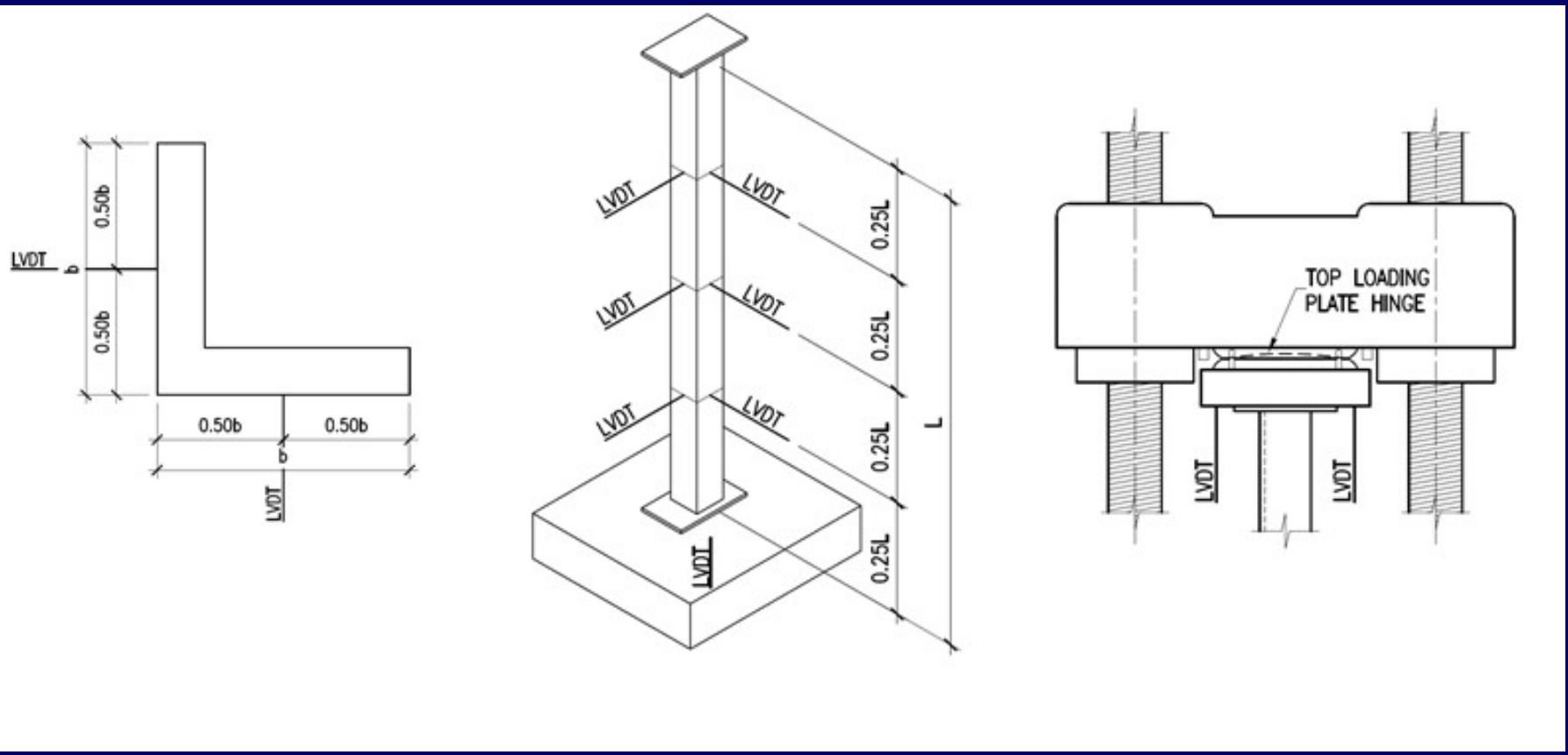
- Tests Summary

Test Specimen	E (GPa)	$s_{0.2}$ (MPa)
Test 1-S1	243.8	343
Test 1-S2	219.4	352
Test 2-S1	204.8	351
Test 2-S2	189.2	335
Test 2-S3	208.7	352
Test 2-S4	200.5	353
Average	211.0	348

- Additional analysis & CSM ultimate stress assuming
  → 713 MPa tensile rupture stress → tensile coupon
  → 45% ultimate strain

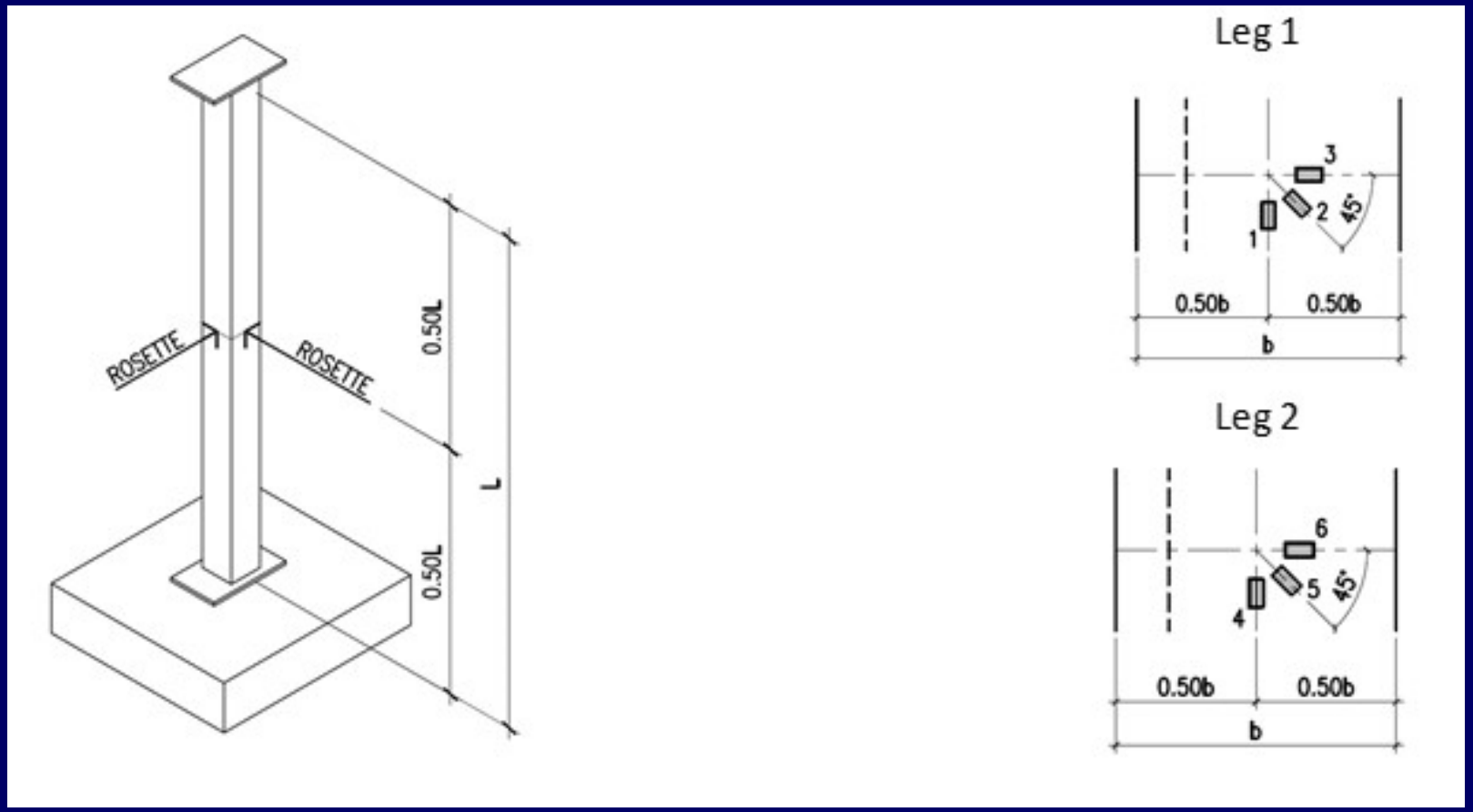
Experimental Investigation

- Main Tests Instrumentation
- LVDTs layout → varied → LVDTs layout



Experimental Investigation

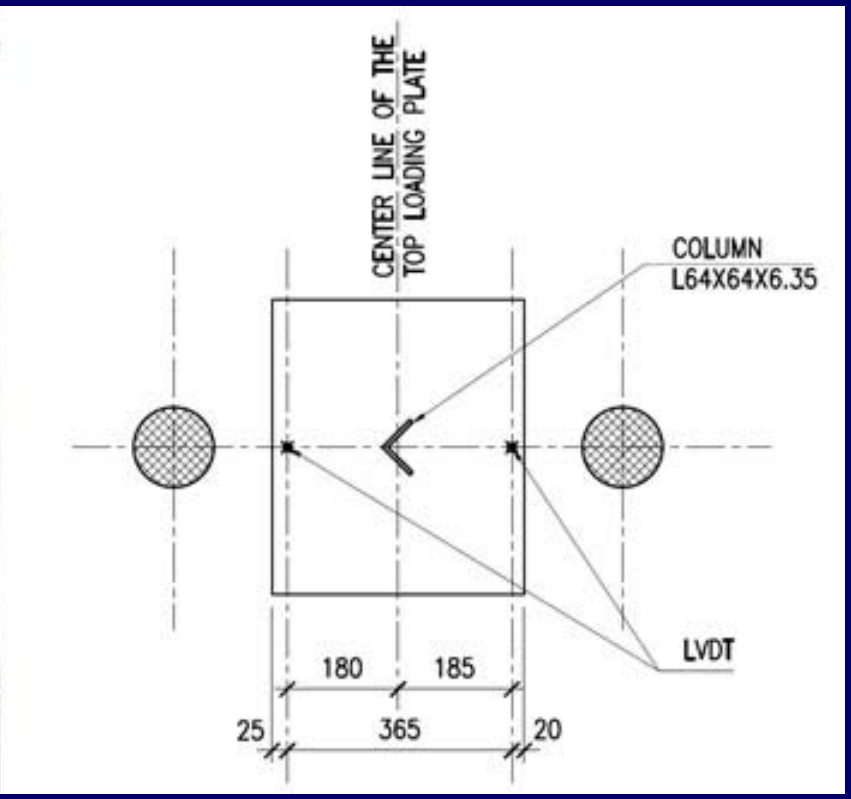
- Rosettes (Rectangular 45°) → middle → angles legs



Experimental Investigation

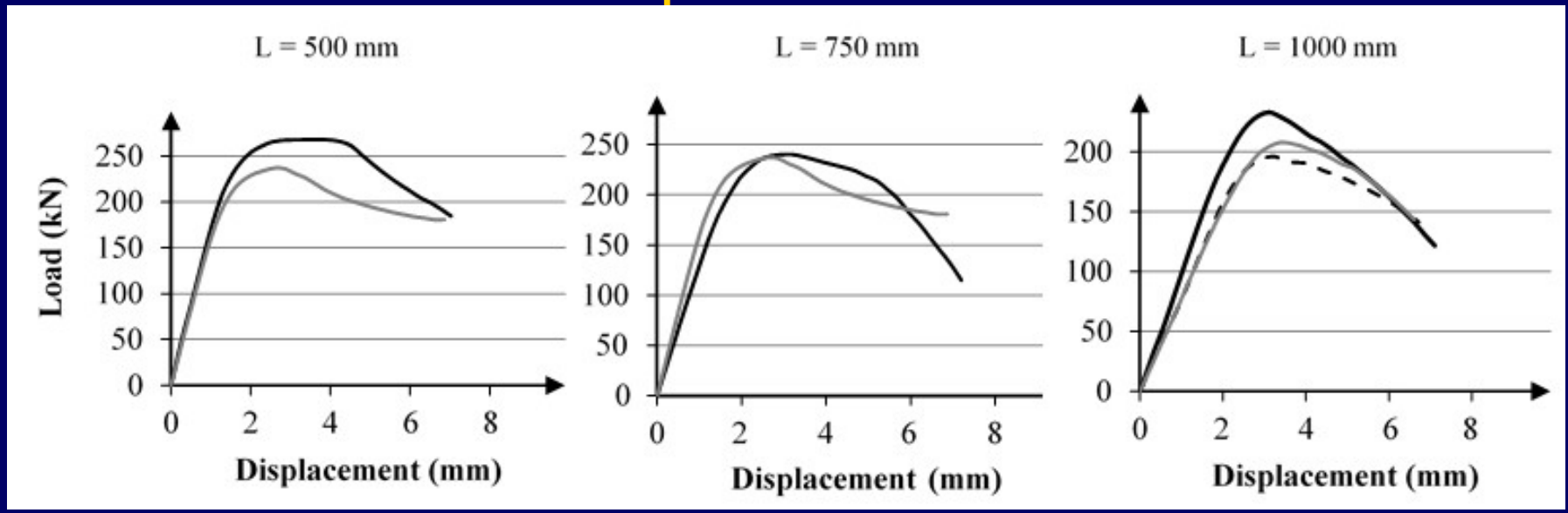
- Top loading plate rotation assessment

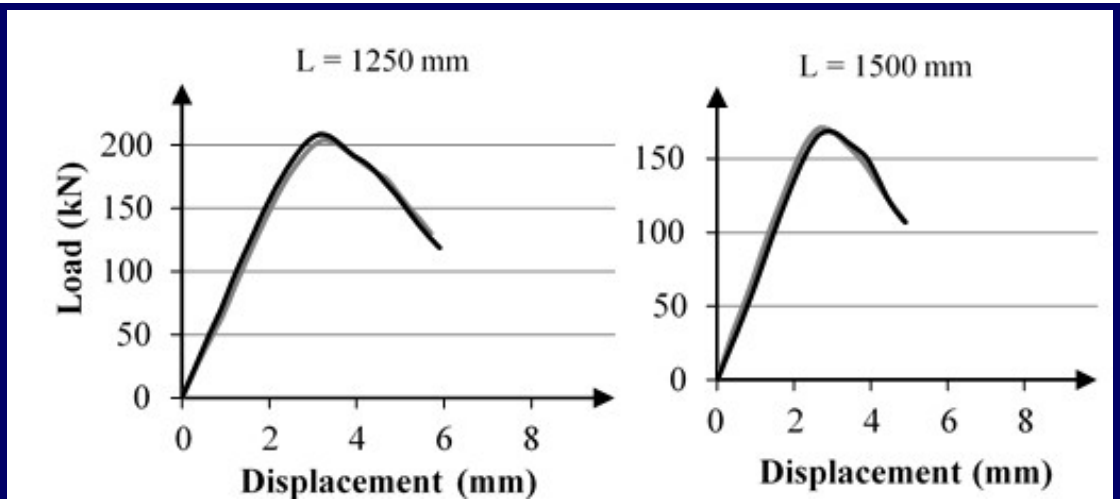
LVDT → possible → top loading plate rotation



Experimental Investigation

- Load versus axial displacement curves





Experimental Investigation

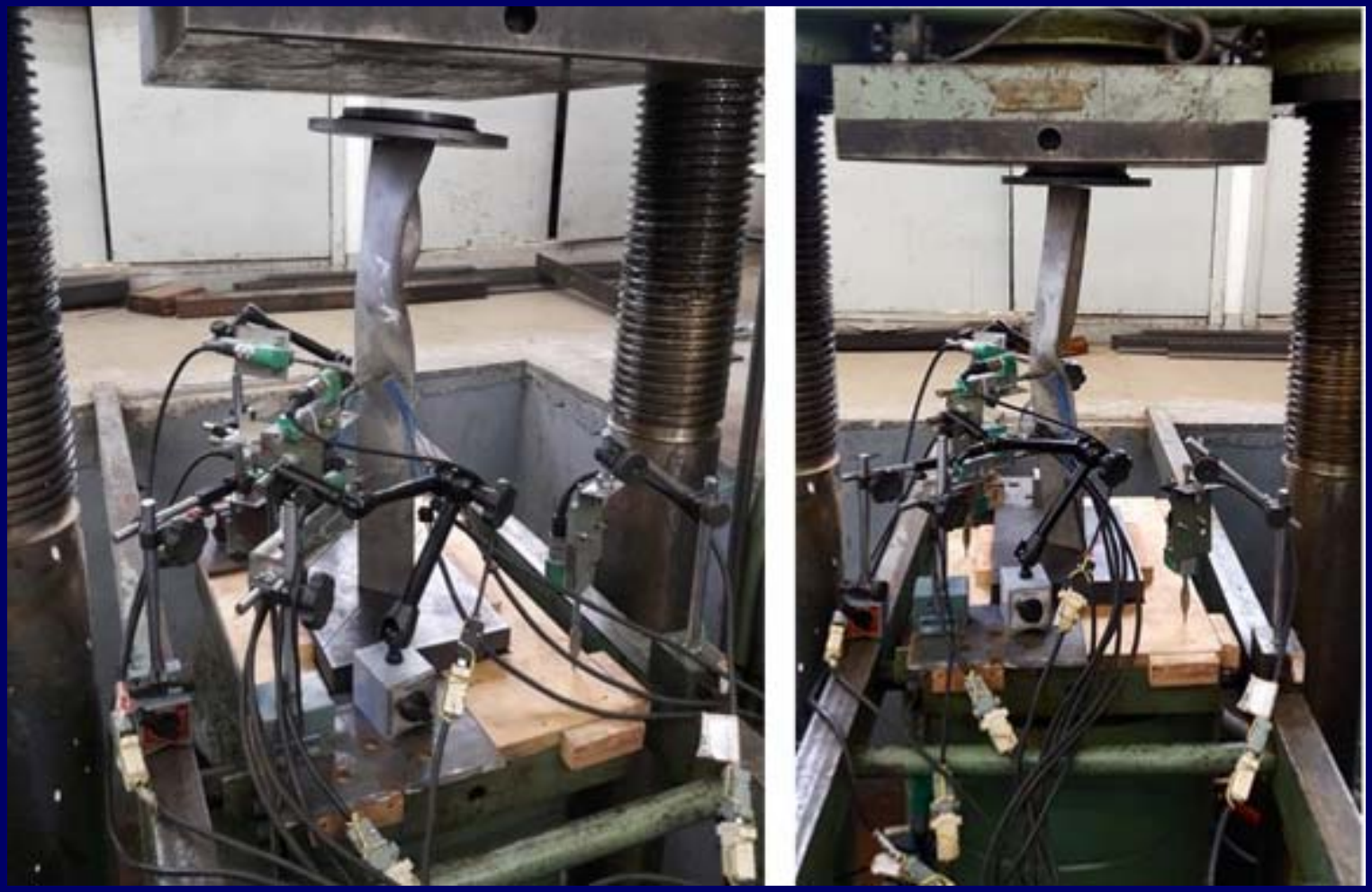
- Tests failure modes: Local buckling or flexural buckling

Tests	Ultimate Load (kN)	Buckling Mode
Characterization 1	283.6	Local
Characterization 2	287.4	Local
L64x64x6.4-AUS-500-1-23.09	239.0	Local
L64x64x6.4-AUS-500-2-23.09	272.4	Local
L64x64x6.4-AUS-750-1-27.09	248.8	Local
L64x64x6.4-AUS-750-2-28.09	241.7	Local
L64x64x6.4-AUS-1000-1-25.08	209.7	Flexural
L64x64x6.4-AUS-1000-2-01.09	197.3	Flexural
L64x64x6.4-AUS-1000-3-19.09	234.8	Flexural
L64x64x6.4-AUS-1250-1-05.10	205.4	Flexural
L64x64x6.4-AUS-1250-2-07.10	212.1	Flexural
L64x64x6.4-AUS-1500-1-13.10	172.8	Flexural
L64x64x6.4-AUS-1500-2-13.10	170.9	Flexural

- Flexural torsional buckling modes → not observed

Experimental Investigation

500mm deformed shape → typical local buckling



Experimental Investigation

1500mm deformed shape → typical flexural buckling

Experimental Investigation

- Deformed tested columns overview

Design Procedures Comparison

		L64x64x6,35					
		Length (mm)					
		250	500	750	1.000	1.250	1.500
Load (kN)	Mean tests values	**285.5**	**255.7**	**245.3**	**213.9**	**208.8**	**171.9**
	$N_{Cr,u}$	62,102.3	15,525.6	6,900.3	3,881.4	2,484.1	1,725.1
	$N_{Cr,v}$	15,911.3	3,977.8	1,767.9	994.5	636.5	442.0
	$N_{Cr,T}$	653.1	653.1	653.1	653.1	653.1	653.1
	$N_{Cr,FT}$	650.5	642.8	629.7	610.8	586.0	555.4
	$N_{Cr,LB}$	618.7					
	$N_{Rd,u}$ – EC3	319.2	308.0	297.6	287.6	277.7	267.7
	$N_{Rd,v}$ – EC3	266.6	266.6	266.6	247.7	224.7	**199.7**
	$N_{Rd,T}$ – EC3	217.8	217.8	217.8	217.8	217.8	217.8
	$N_{Rd,FT}$ – EC3	**217.7**	**217.1**	**216.2**	**214.7**	**212.7**	210.0
	$N_{Rd,u}$ – CSM	423.30	406.40	390.70	375.40	360.00	344.20
	$N_{Rd,v}$ – CSM	406.80	376.20	345.50	311.70	274.00	**234.50**
	$N_{Rd,T}$ – CSM	270.90	270.90	270.90	270.90	270.90	270.90
	$N_{Rd,FT}$ – CSM	**270.60**	**269.70**	**268.00**	**265.60**	**262.20**	257.60
	Eurocode 3 / Mean values	0.76	0.85	0.88	1.00	1.02	1.16
	CSM / Mean values	0.95	1.05	1.09	1.24	1.26	1.36

- Eurocode → conservative → length ≤750 mm → unsafe → length ≥1250 mm.
- CSM→ overestimate → ≥ 500 mm

Design Procedures Comparison

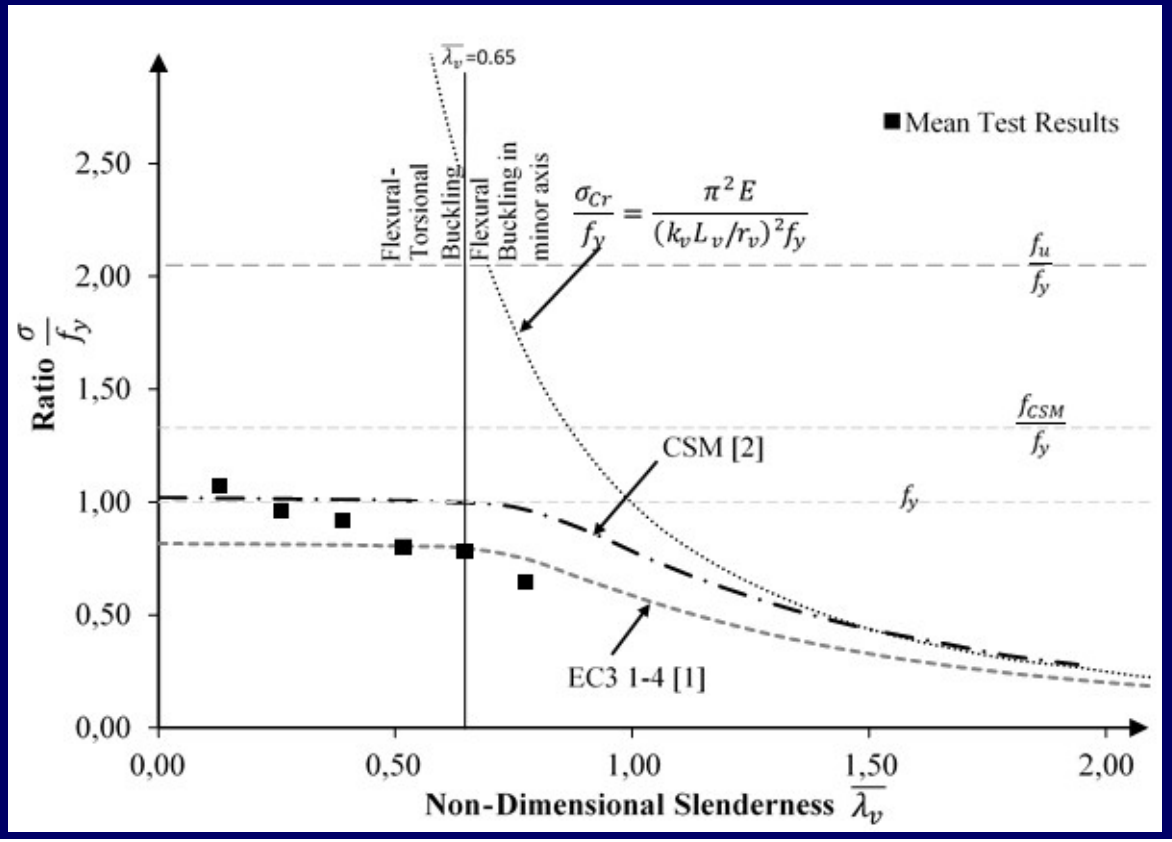
- Eurocode failure modes → not match → experimental modes → α & λ_0 → not associated → rolled angle sections → need → more accurate values

	L64x64x6.35 Length (mm)					
	250	500	750	1.000	1.250	1.500
Theoretical	Local	Local	Local	Flexural	Flexural	Flexural
Tests	Local	Local	Local	Flexural	Flexural	Flexural
Eurocode 3	Flexural Torsional	Flexural Torsional	Flexural Torsional	Flexural Torsional	Flexural Torsional	Flexural

- Theoretical buckling modes → smaller critical loads
- CSM stress → f_{csm} → 464 MPa → 1.33 fy Eurocode 3 → CSM → used without any restrictions → elements cross sections slenderness

Design Procedures Comparison

- Comparison → ultimate column stress & Austenitic yield stress → tests, Eurocode 3 & CSM
- Eurocode 3 & CSM design curves → controlling buckling phenomenon → minor axis slenderness



Final considerations

- Structural behaviour austenitic stainless steel rolled angle columns
- 11 L64x64x6.35 tests → ASTMA276 304 → heights → 250 to 1500mm
- 2 → material characterization
- Tests → compared → Eurocode 3 1-4 & Continuous Strenght Method - CSM

Final considerations

- Failure modes:
  - Local buckling → lengths ≤ 750 mm
  - Global flexural buckling → other lengths
  - Flexural torsional buckling mode → not associated → tested columns
- Top plate hinge → not interfere → results → up to tests ultimate loads → confirmed → LVTS → acquire rotations

Final considerations

- Tests → columns → normalized slenderness → less than 0.65 → Eurocode 3 → conservative designs → for more than 0.65 → overestimates → column load carrying capacity
- Eurocode 3 Failure modes → not match → the experiments

Final considerations

- Important to observe $\rightarrow \alpha$ & $\lambda_0 \rightarrow$ not associated $\rightarrow$ rolled angle sections $\rightarrow$ need $\rightarrow$ more accurate values

- CSM $\rightarrow$ overestimate $\rightarrow$column ultimate loads $\rightarrow$ length $\geq$ 500 mm

Acknowledgments

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  - CNPq
  - Capes
  - FAPERJ

Current Works

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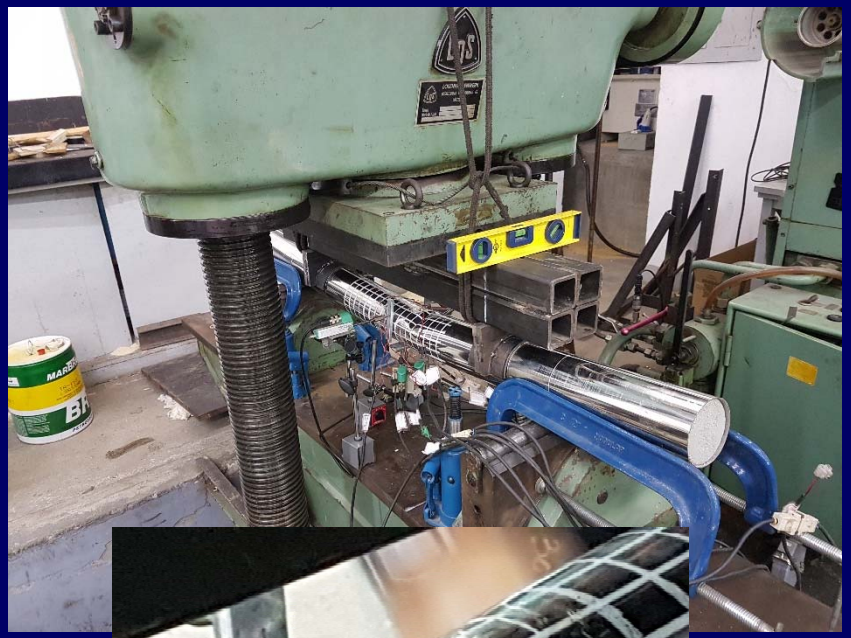

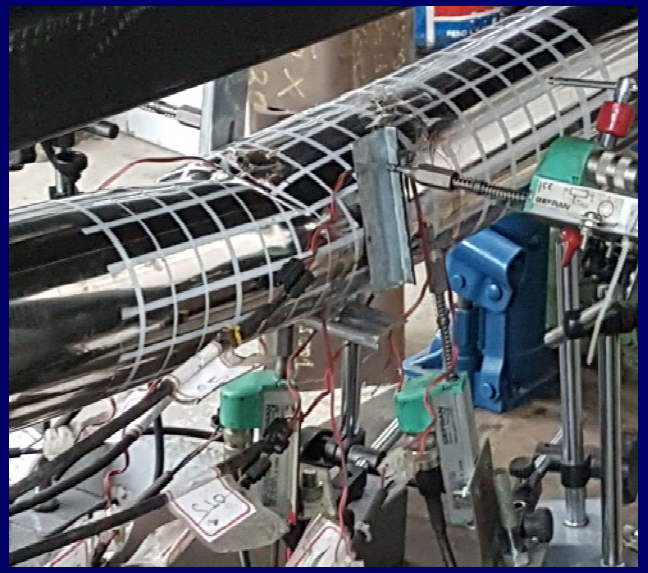

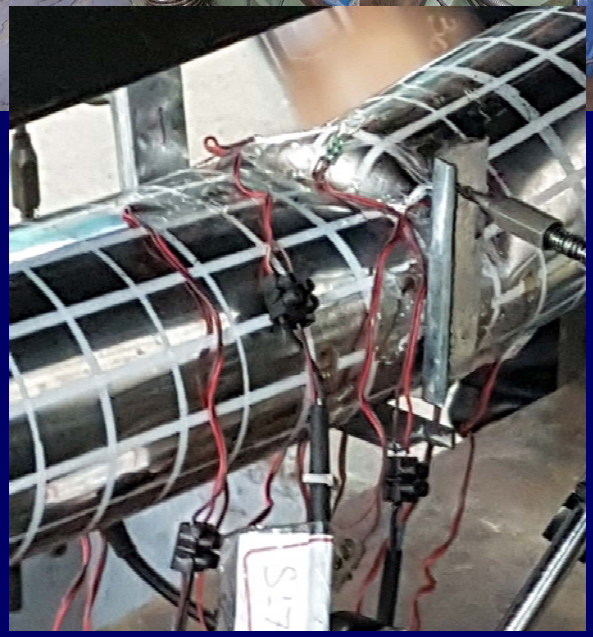

Current Works

a) EXP300

a) EXP700

a) EXP1000

a) EXP1400

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