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Strength of Materials and Structural Engineering Department
School of Engineering in Barcelona

Compression tests on uprights: Checks for the effects of distortional buckling

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Purpose of the research:

- To find the adequate experimental conditions of the tests for the determination of the distortional buckling strength of single uprights.

- To relate the buckling strength of single uprights to the behaviour of upright frames

Investigation of the test method for distortional buckling

To find the adequate experimental conditions of the tests for the determination of the distortional buckling strength of single uprights.

Test setup

Specimen length

Which is the length of the specimen to be tested?

7.1 Column Length - The length requirements of the column test specimen, L, are that it be (1) sufficiently short to minimize overall column buckling effects, and (2) sufficiently long to minimize the end effects during loading. The required column length is defined by Section 7.1.1.

AISI Committee on Specifications For the Design of Cold-Formed Steel Structural Members Subcommittee 6, Test Procedures

Date: August 9, 2005

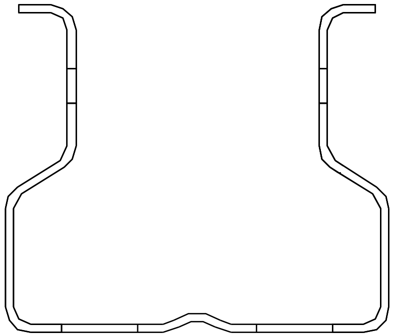
Test length expressed in terms of the distortional critical length

7.1.1 The length L is to be determined analytically or experimentally. If ~~A~~analytical determination of the test specimen length is used, the length is to be based on the minimum distortional buckling wave as determined by a finite strip or other appropriate finite element analysis. The specimen length with consideration of distortional buckling shall be at least four half wavelengths and should be tested between flat ends. If the distortional buckling mode is not observed experimentally, the specimen length shall be adjusted to achieve the ~~desired~~ distortional buckling mode. If experimental determination of the test specimen length is used the test specimen length is to be based on an array of tests of differing specimen lengths until the ~~desired~~ distortional buckling mode is observed or it is shown that distortional buckling is not a controlling limit state.

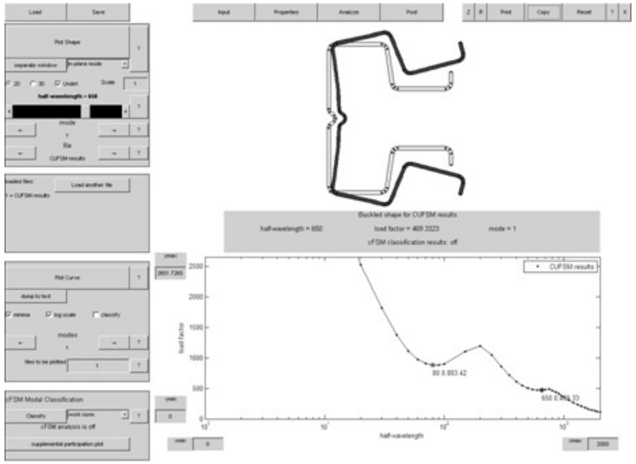
AISI Committee on Specifications For the Design of Cold-Formed Steel Structural Members
Subcommittee 6, Test Procedures
Date: August 9, 2005

K ? ⟵ $L_{test} = K \cdot L_{cr,D}$ ⟶ $L_{cr,D}$

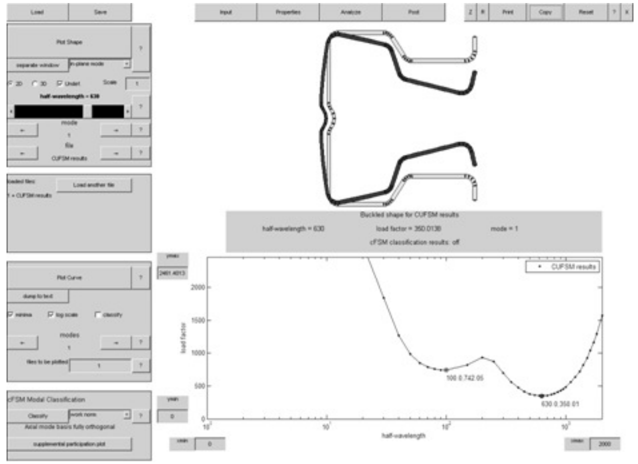
Distortional critical length



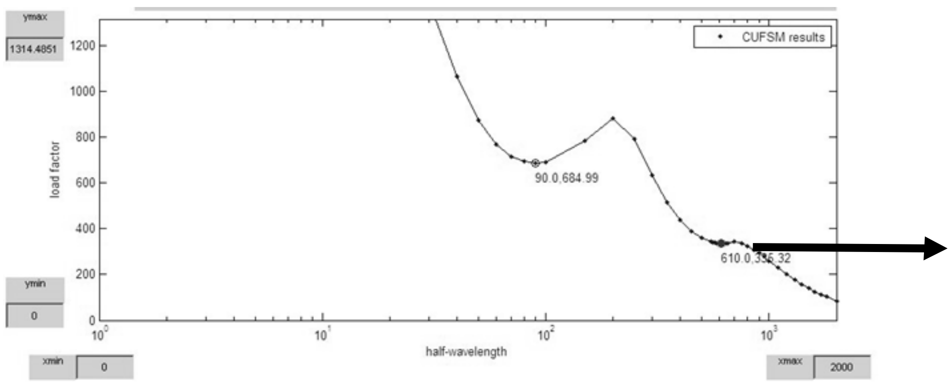
S4



CUFSM



CUFSM



$L_{cr,D}$=630 mm

$$t_{r,w} = \left[\frac{L_p}{L_{bp}} \cdot \frac{b_{wnp1} + 2 \cdot b_{wnp2}}{b_w} + \left(1 - \frac{L_p}{L_{bp}} \right) \right] \cdot t$$

- 1. Introduction
- 2. Resume of results presented in Trento
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- 6. Results obtained
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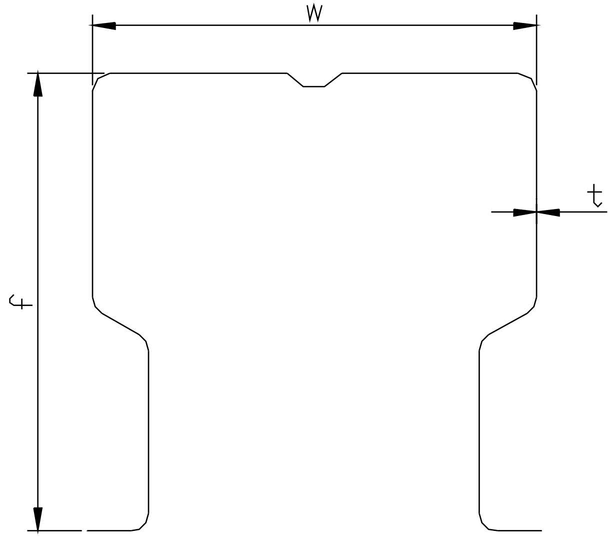
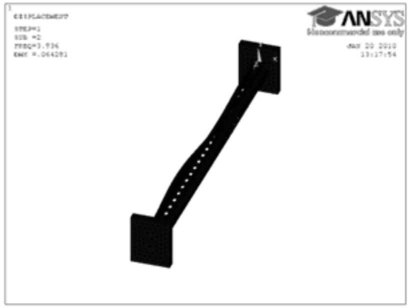
- The sections analyzed are 5 different types of uprights, with thickness between 1.0 and 2,0 mm.



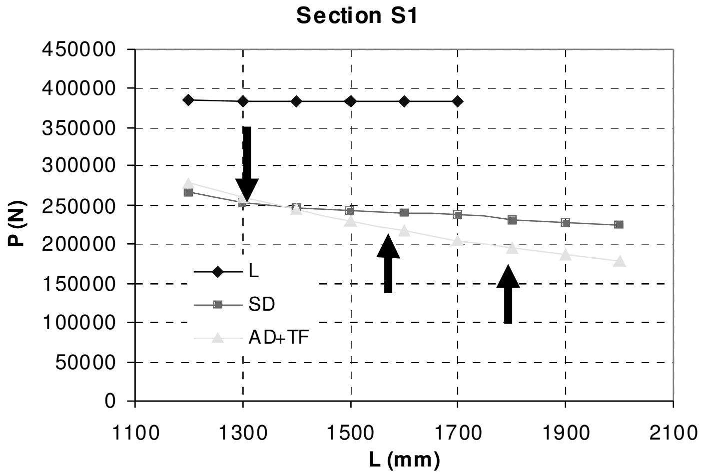
Section	w (mm)	f (mm)	t (mm)	t_t (mm)	f_y (N/mm^2)	$f_{y,t}$ (N/mm^2)
S1	74.4	61.4	1.8	1.83	355	440
S2	47.25	52.15	2	2.01	355	356
S3	29	49.5	1	1.01	205	268
S4	78.8	67.2	1.8	*	355	*
S5	76.7	61.2	1.8	1.88	355	395

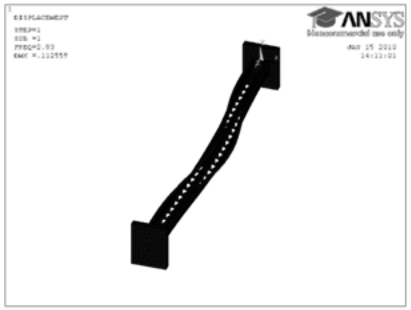
Length of the tested specimens

Failure mode preciction from FEM linear buckling analyses and DSM

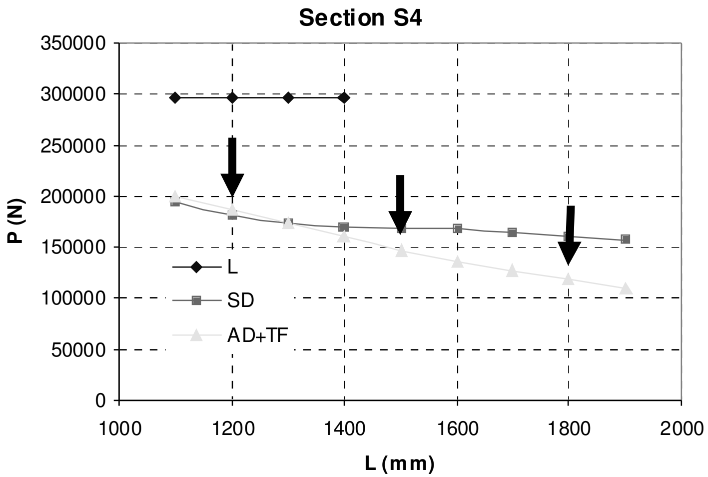


S1-1300 mm



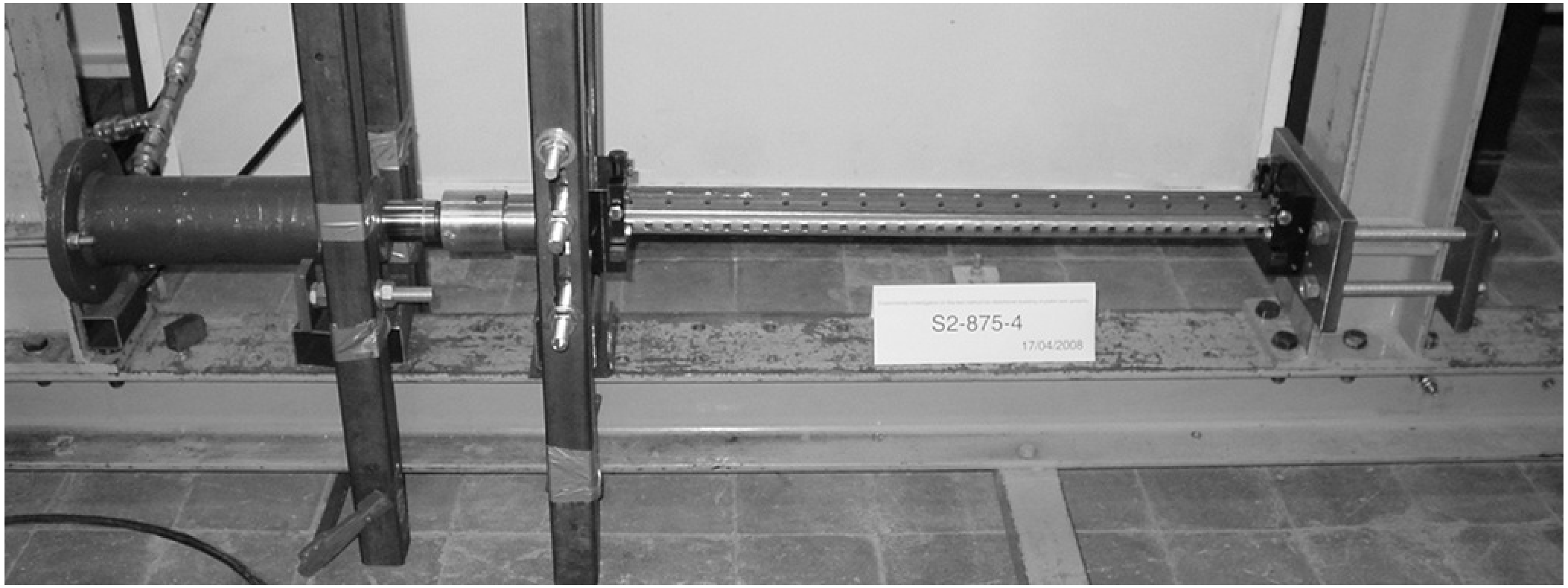


S4-1500 mm



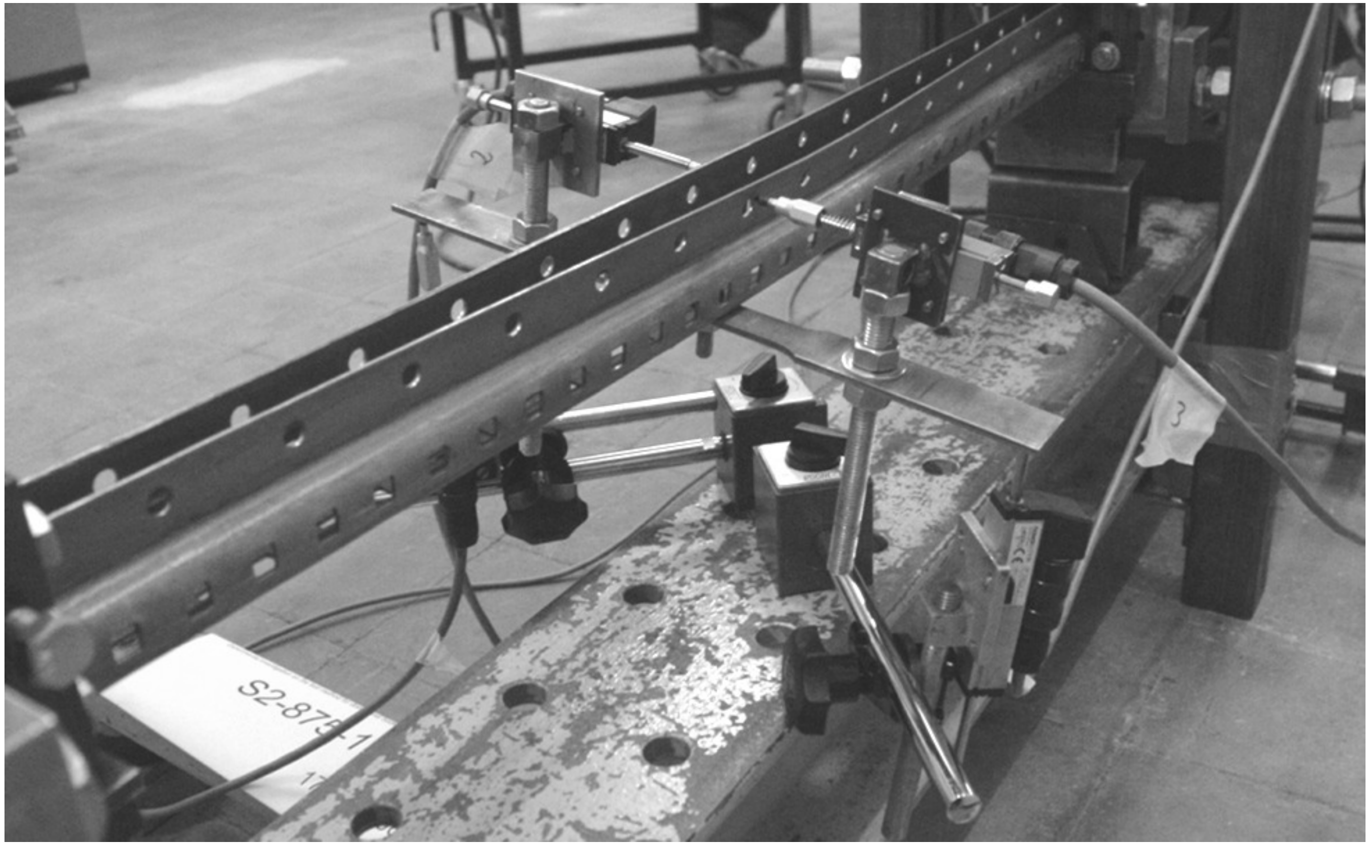
Section	L_{test} (mm)	$L_{test}/L_{cr,D}$	DSM prediction
S1	250	-	L (D*)
	1300	2.06	D
	1650	2.61	L+TF
	1950	3.09	L+TF
S2	250	-	L (D*)
	750	2.77	D
	875	3.24	L+TF
	1000	3.70	L+TF
S3	150	-	L (D*)
	700	2	D
	875	2.5	L+TF
	1050	3	L+TF
S4	250	-	L (D*)
	1200	1.96	D
	1500	2.45	D
	1800	2.95	L+TF
S5	250	-	L (D*)
	900	2	D
	1100	2.45	D

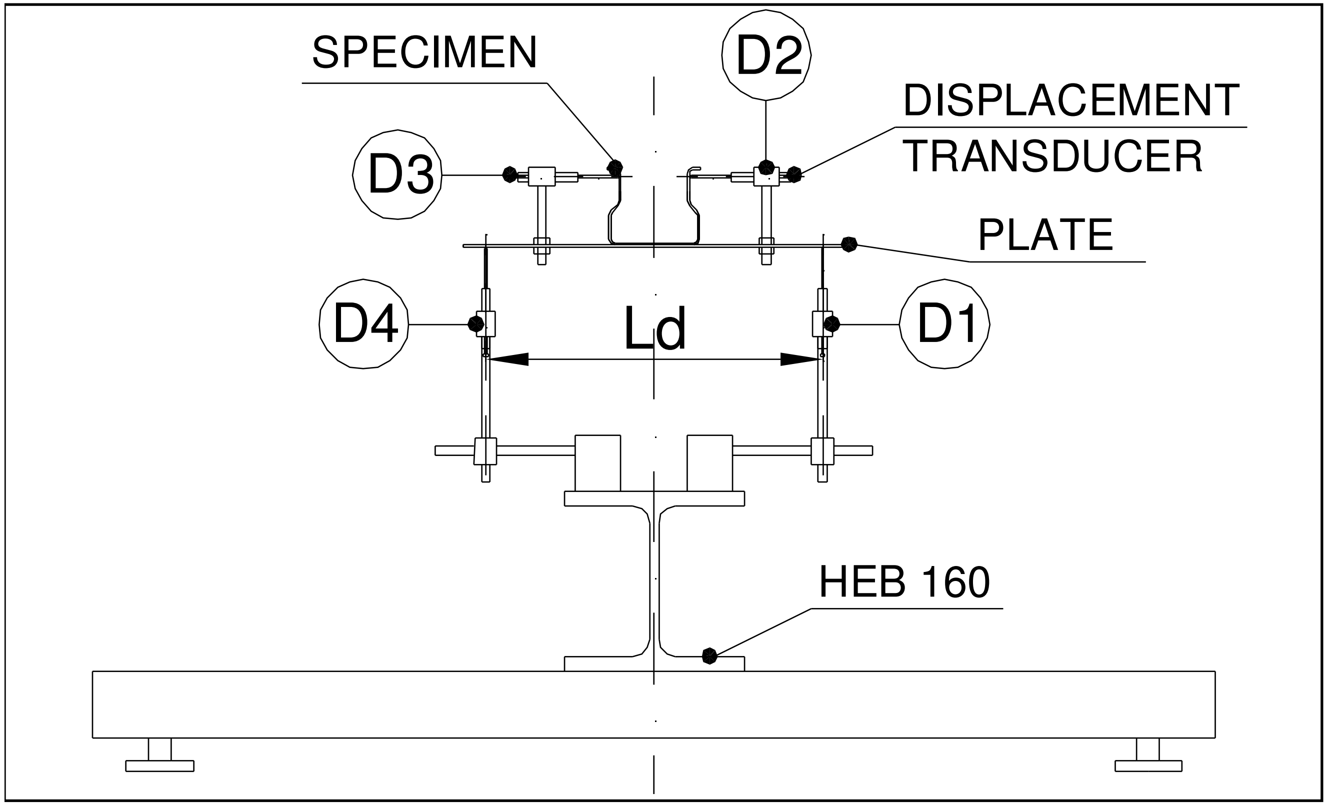
- The test setup:



- The ends of the specimen are fixed with grips, that have all the degrees of freedom restricted (except the axial displacement on the grip fixed to the hydraulic jack).

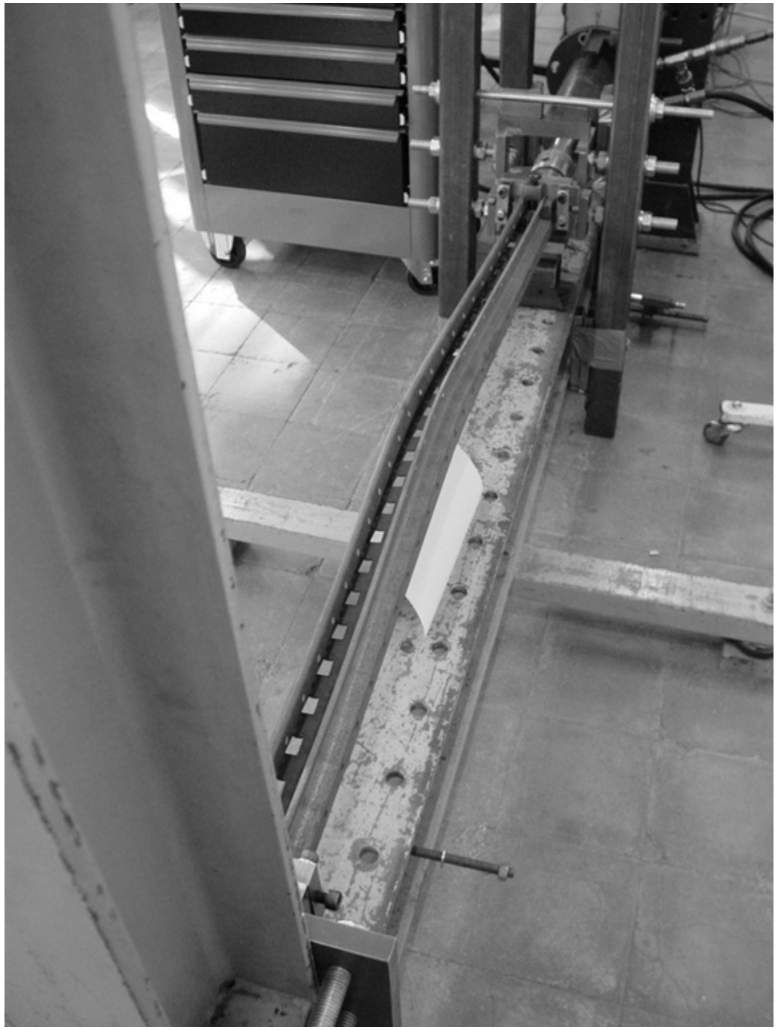
- The central cross section rotations are measured by means of displacement transducers.



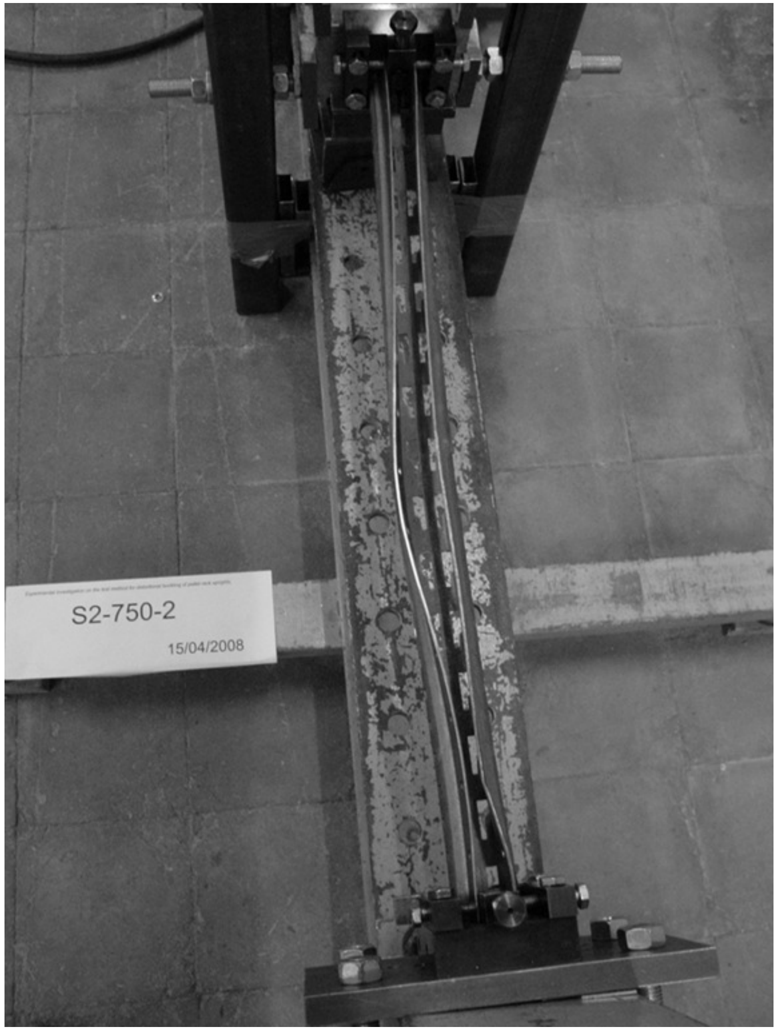


- With this displacement transducers setup it can be obtained:
  - the absolute rotation of the web
  - the absolute vertical displacement of the web
  - the rotation of each flange relative to the web

Results of the 2008 experimental tests



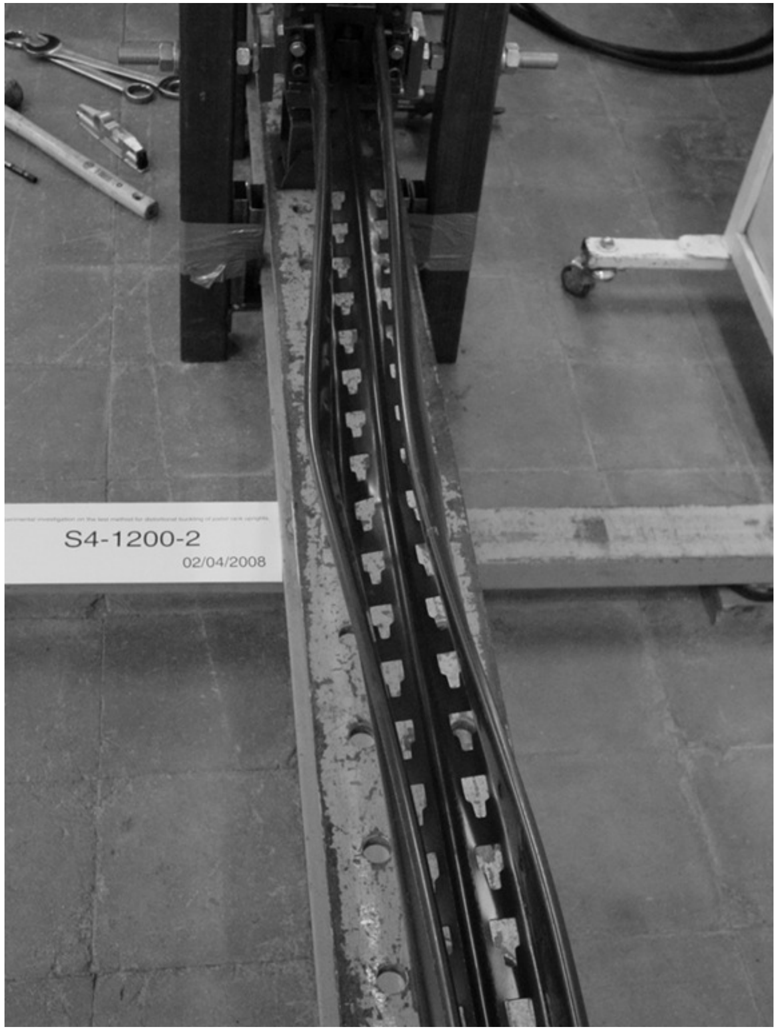
S1-1300-1 L/L_{crD}=2.06



S2-750-2 L/L_{crD}=2.77

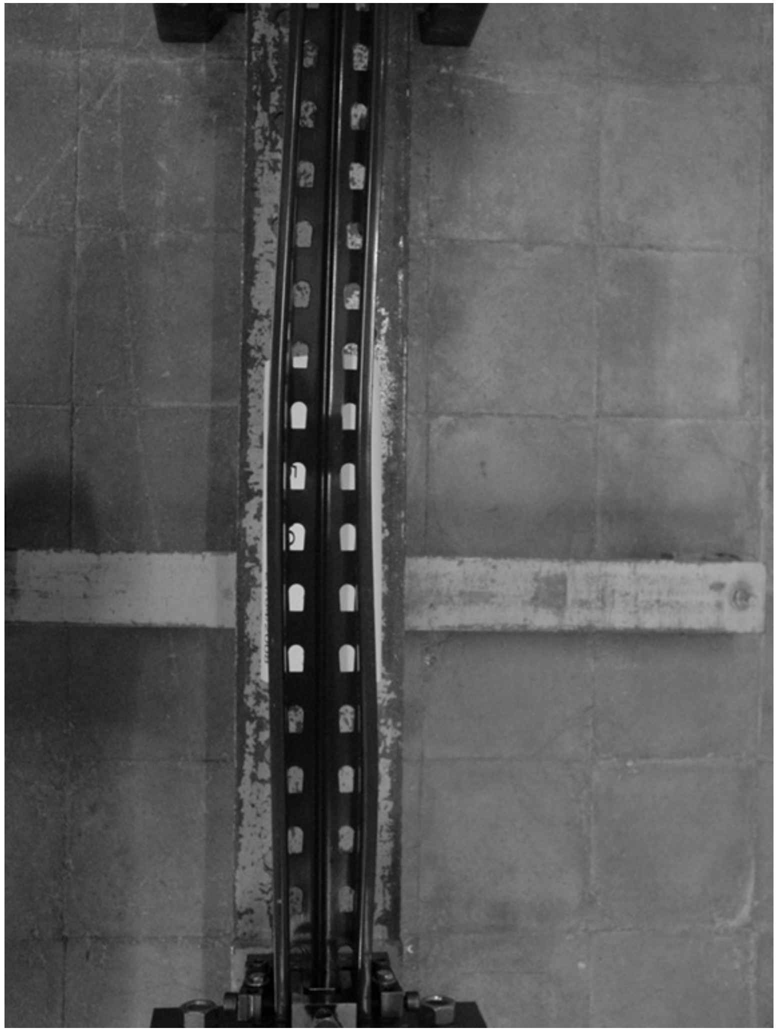
Results of the 2008 experimental tests

S3-700-1 L/L_{crD}=2.00



S4-1200-2 L/L_{crD}=1.96

Results of the 2008 experimental tests



S5-900-2 $L/L_{crD}=2$

Section	L_{test} (mm)	L_{test}/L_{crd}	1st specimen Mode of failure	2nd specimen Mode of failure	3rd specimen Mode of failure
S1	250	-	L(+SD)	L+SD	L+SD
	1300	2.06	AD+TF	AD+TF	SD-->TF
	1650	2.61	TF	TF	TF
	1950	3.09	TF	TF	TF
S2	250	-	(L) +SD	(L) +SD	(L) +SD
	750	2.77	SD+TF	SD+TF	AD+TF
	875	3.24	(AD+) TF	AD +TF	AD+TF
	1000	3.70	(AD+) TF	TF	TF
S3	150	-	L	L	L
	700	2	L+AD+TF	L+AD+TF	L+SD (+TF)
	875	2.5	L+AD+TF	L+AD+TF	L+AD+TF
	1050	3	L+AD+TF	L+AD+TF	L+AD+TF
S4	250	-	L+SD	L+SD	L+AD
	1200	1.96	(AD+) TF	AD+TF	AD (+TF)
	1500	2.45	(AD+) TF	TF	(AD+) TF
	1800	2.95	TF	TF	TF
S5	250	-	L+SD	L+SD	L+SD
	900	2	AD (+TF)	AD (+TF)	SD (+TF)
	1100	2.45	(AD+) TF	(AD+) TF	AD+TF

Visual inspection at the end of the test

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Conclusions of the 2008 research

- In the specimens with lengths of 2 ÷ 2,5 · L_{crd} , distortional (SD, AD) and global (TF) buckling appear combined.

- According to these experimental results it seems that best length of the specimens for the determination of the distortional buckling compression strength of the uprights should be 2 · L_{crd} or lower.

- Further research work is needed before proposing any changes in the test method or the design method.

Aspects analyzed

1. The compression tests have been done with both ends of the specimen fixed. In the FEM Recommendations and in the EN 15512 Standard the compressions tests are prescribed with pinned ends.

- ➢ *The influence of the end conditions has to be analyzed with more detail, before proposing a change in the standards.*

2. In the specimens with lengths of $2 \div 2{,}5 \cdot L_{crd}$, distortional (SD, AD) and global (TF) buckling appear combined.

- ➢ *The experimental method to measure and separate distortional and global buckling should be improved, before deciding the optimum length of the specimens.*

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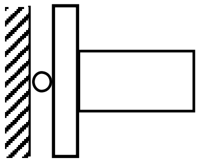
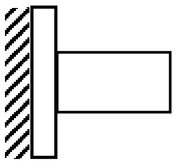
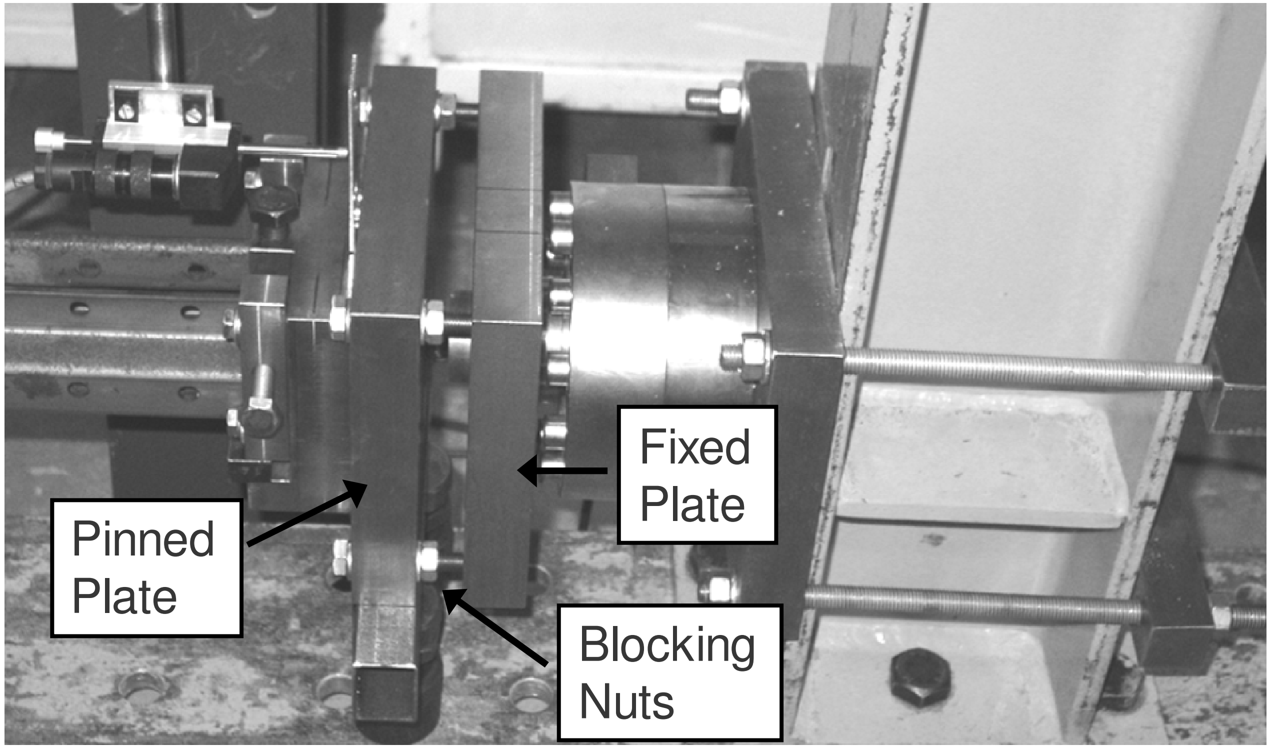
Two types of end conditions considered until now:

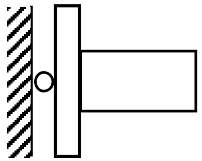
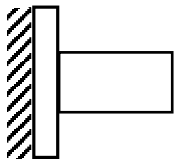
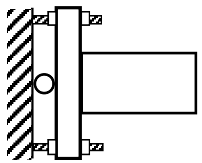
Type	Symbol	Standard	Advantages	Disadvantages
Pinned		FEM EN	- Useful for finding G_{eff} - Force line defined - Precise machining of end surface not neces.	- End condition has zero stiffness, while the actual stiffness is different than zero.
Fixed		AISI (AS)	- End condition includes stiffness, but higher than the actual.	- No way to find G_{eff} - Force line not defined - Precise machining of end surface is neces.

We have tested, a new type of end condition: **Fixed adjustable**

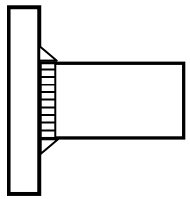
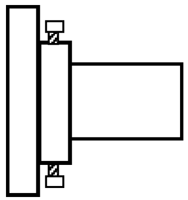


1. Nuts free, the ends are pinned, apply pre-compression to allow for self adjustment.
2. Maintaining the pre-compression, block the nuts, and discharge.
3. The ends are fixed, and perfectly adapted to the end surfaces; start the compression test.

Comparison of the three types of end conditions:

Type	Symbol	Standard	Advantages	Disadvantages
Pinned		FEM EN	- Useful for finding G_{eff} - Force line defined - Precise machining of end surface not neces.	- End condition has zero stiffness, while the actual stiffness is different than zero.
Fixed		AISI	- End condition includes stiffness, but higher than the actual.	- No way to find G_{eff} - Force line not defined - Precise machining of end surface is neces.
Fixed, adjustable		New Proposal	- Useful for finding G_{eff} - Force line defined - Precise machining of end surface not neces. - End condition more similar to real condition in frame	

Two types of end plates considered until now:

Type	Symbol	Advantages	Disadvantages
Welded		- End surface constraints clearly defined as fixed	- Two end plates have to be machined for each specimen - Precise positioning and drilling necessary for each specimen.
Grip		- Only two grips have to be machined for all the set of specimens. -The specimens can be cut by saw, and no machining is necessary.	- End surface constraints need to be verified

So, in the compression tests that we have done, we have used and compared the behaviour of:

- 2 types of end conditions:
  - Pinned
  - Fixed adjustable

- 2 types of end plates:
  - Welded
  - Grip

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- With the displacement transducers setup used before it can be obtained:
  - the absolute rotation of the web
  - the absolute vertical displacement of the web
  - the rotation of each flange relative to the web

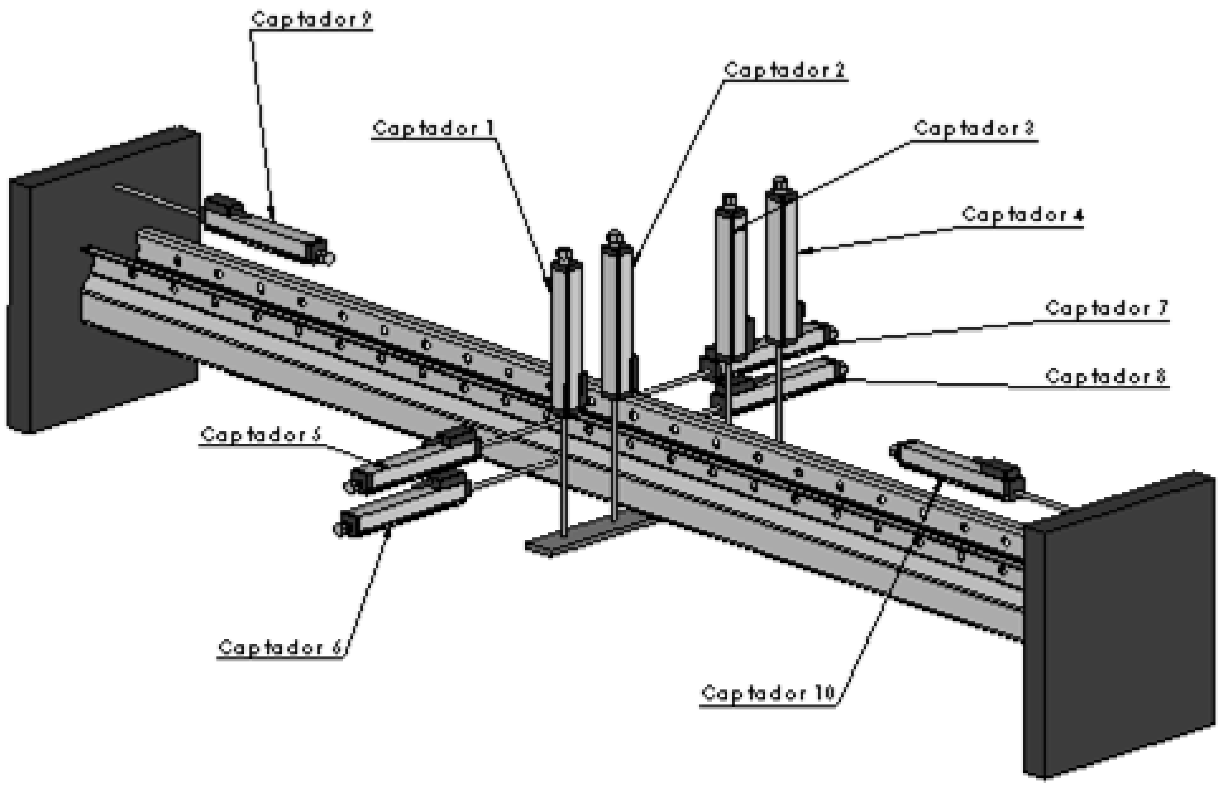
  But the transversal displacement of the section is not measured, and so the global flexural buckling is not controlled.

- It has been observed that the distortional buckling takes place in a section close to the central section, but not in the central section, where the displacement transducers are installed.

  There is a suspect that the support of the transducers may stiffen the central section and change its behaviour.

➢ A new support and a new setup for the displacement transducers has been designed and implemented.

- New setup:


Captador 9
Captador 2
Captador 1
Captador 3
Captador 4
Captador 7
Captador 8
Captador 5
Captador 6
Captador 10

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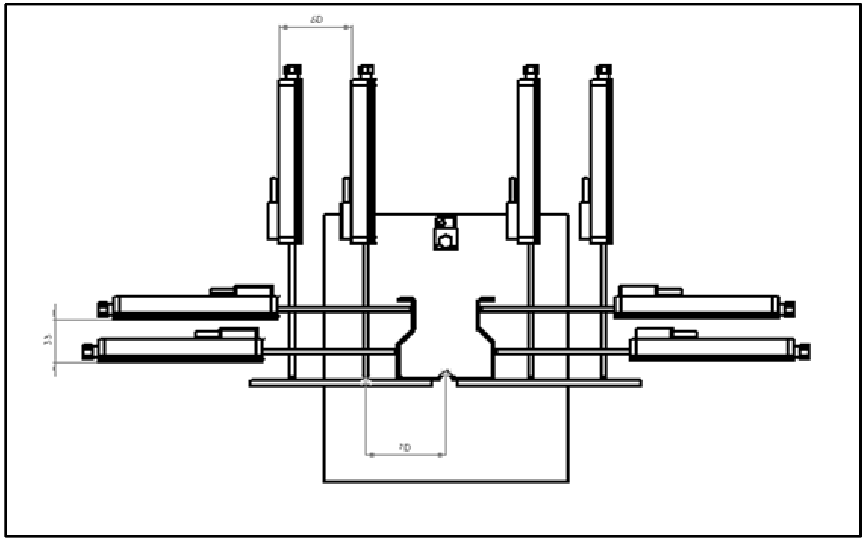
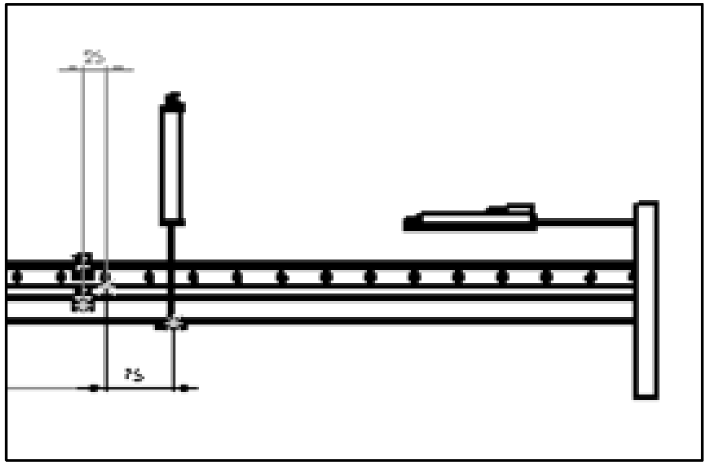
- New setup:





- With this new displacement transducers setup it can be obtained:
  - absolute vertical displacement of the section
  - absolute horizontal displacement of the section
  - absolute rotation of the web
  - absolute rotation of each flange
  - rotation of the ends

- With this new displacement transducers setup there is no stiffening effect on the section.

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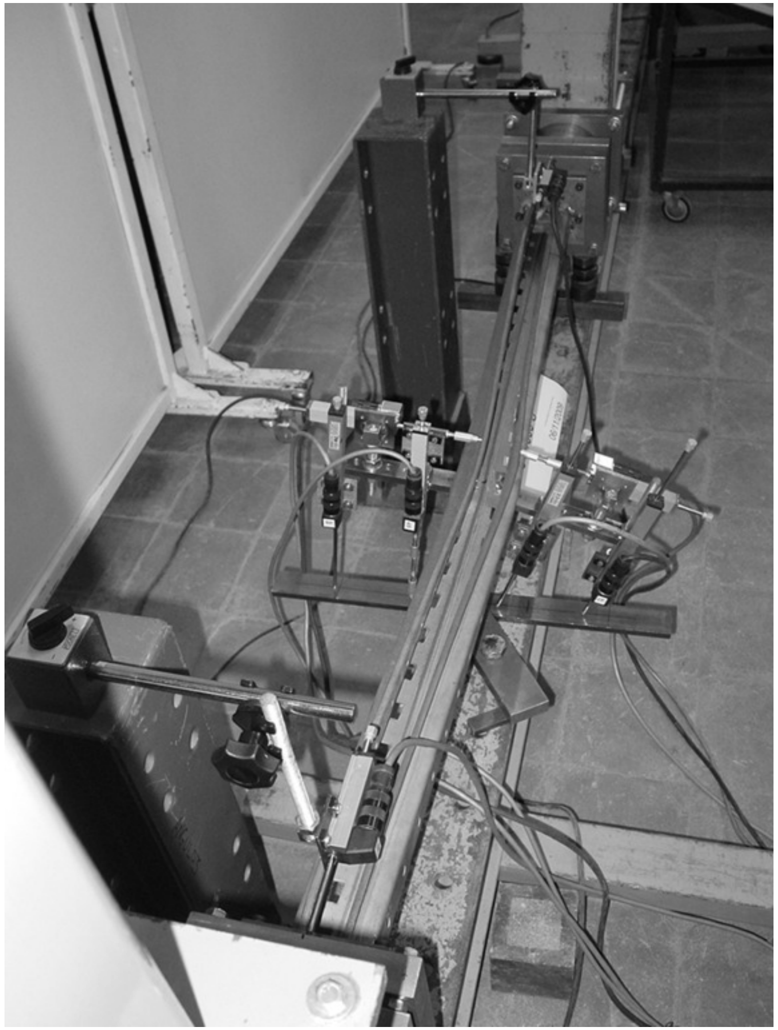
Results of the 2009 experimental tests. Fixed end specimens



S1-1300W-3 L/L_{crD}=2.06

S4-1200W-1 L/L_{crD}=1.96

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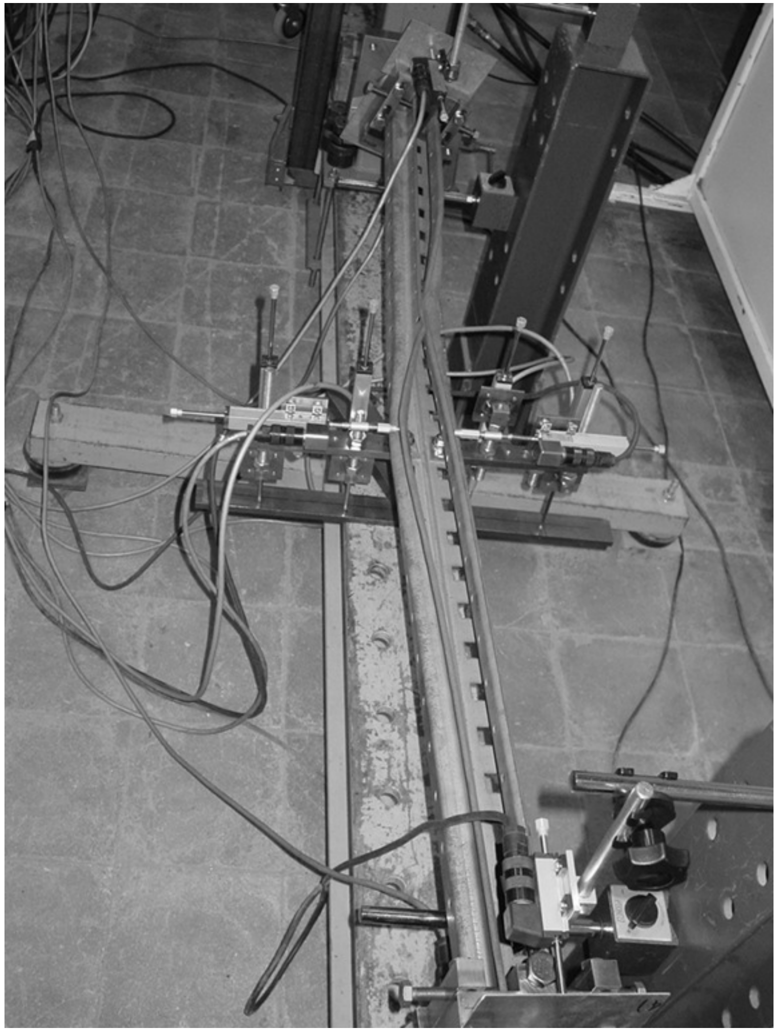
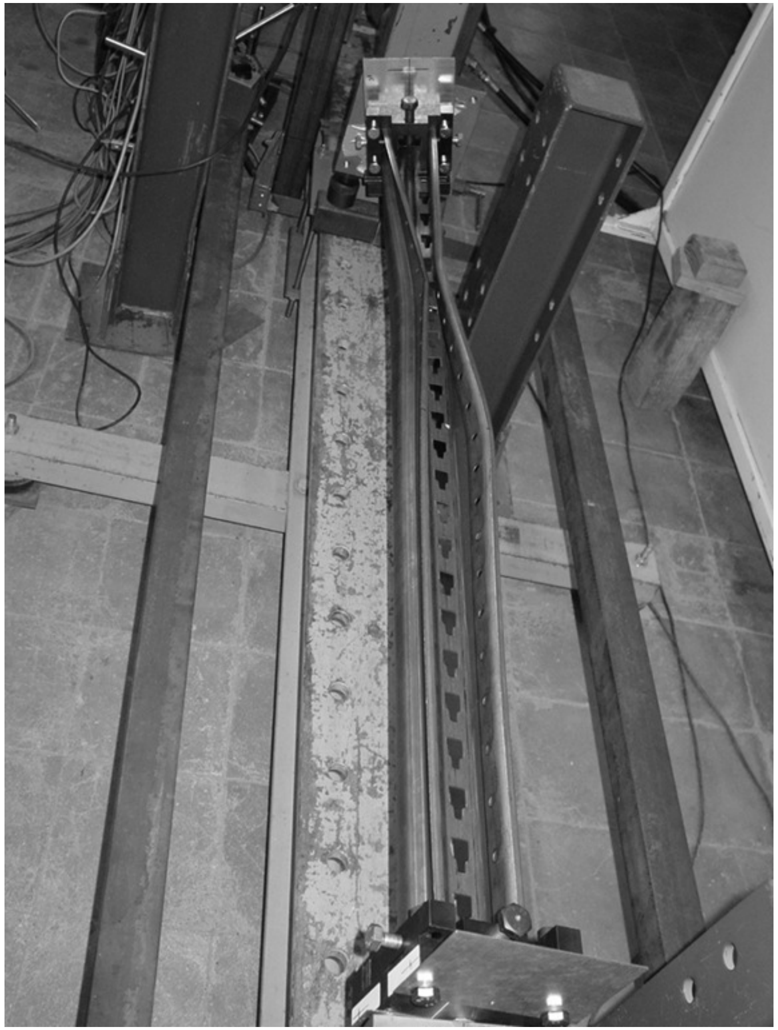
Results of the 2009 experimental tests. Pinned end specimens



S1-1300P-3 L/L_{crD}=2.06



S4-1200P-1 L/L_{crD}=1.96

Results of the 2009 experimental tests–First conclusions

Section	L_{test} (mm)	L_{test}/L_{crD}	1st specimen	2nd specimen	3rd specimen	1st specimen	2nd specimen	3rd specimen
			Mode of failure	Mode of failure	Mode of failure	Fu (N)	Fu (N)	Fu (N)
S1Pinned	1300	2.06	SD + TF	SD	SD + TF*	124673	122165	110454
	1650	2.53	SD + FX	-	-	(86269)	-	-
S1 Grip	1300	2.06	TF	(AD+) TF	(AD+) TF*	139490	135578	131618
S1 Welded	1300	2.06	TF	(AD+) TF	AD + TF	131595	133930	134607
	1650	2.53	TF	TF	TF	123598	112055	117895
S4 Pinned	1200	1.96	SD + TF	AD	AD	119912	114243	116811
	1500	2.45	AD + TF	AD + TF	-	92272	92871	-
S4 Grip	1200	1.96	(AD+) TF	AD + TF	AD + TF	110912	114243	116811
S4 Welded	1200	1.96	AD (+TF)	AD (+TF)*	SD	108219	108046	114606
	1500	2.45	AD + TF	AD + TF	-	98977	102887	-

Visual inspection at the end of the test

1- Fixed members: Ultimate load GRIPS = Ultimate load of WELDED members.

2- Ultimate load of PINNED members is lower than the ultimate load than FIXED members (most of the times about 10% lower).

3- The torsional-flexural buckling mode (TF) is observed in almost all the tests.

4- It seems that the torsional-flexural mode (TF) is always combined with other distortional modes, mainly the anti-symmetric distortional.

5- However, It is difficult to know how the behaviour during loading, and to guess which is the dominant buckling mode just from the observation of the tests.

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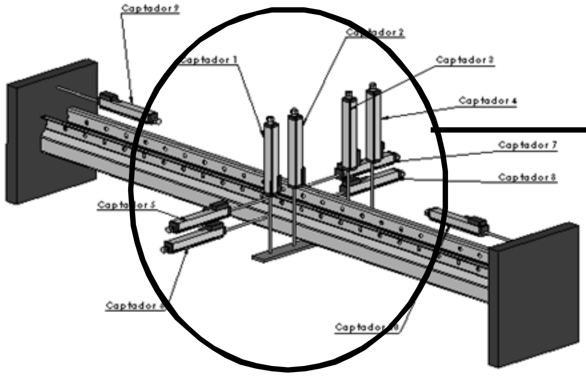
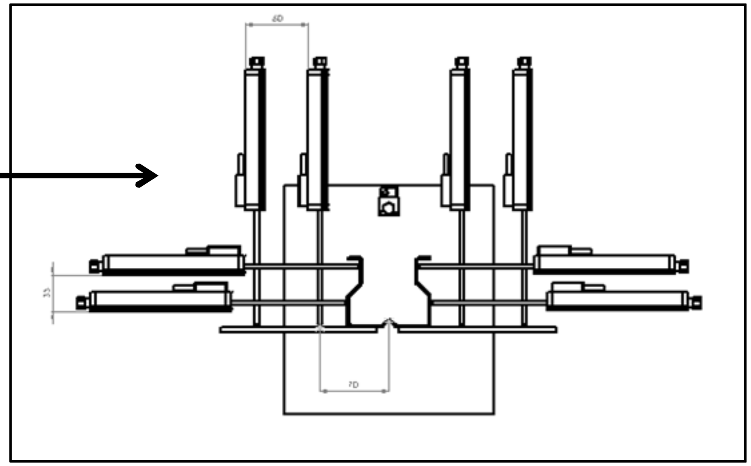
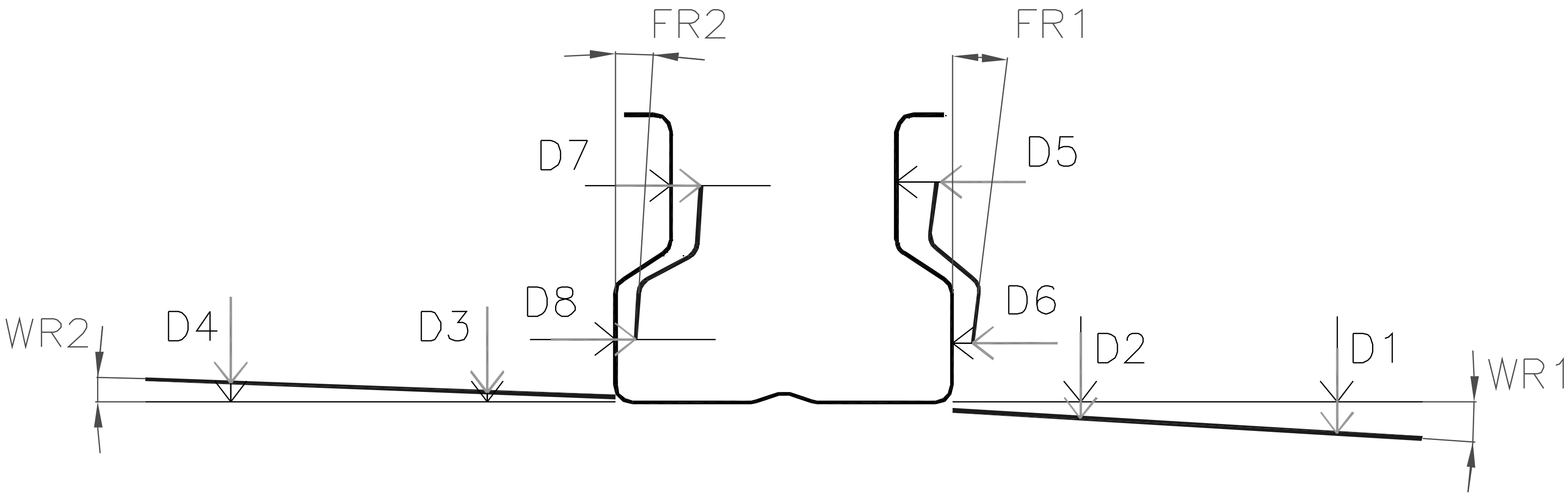
Cross-section rotations







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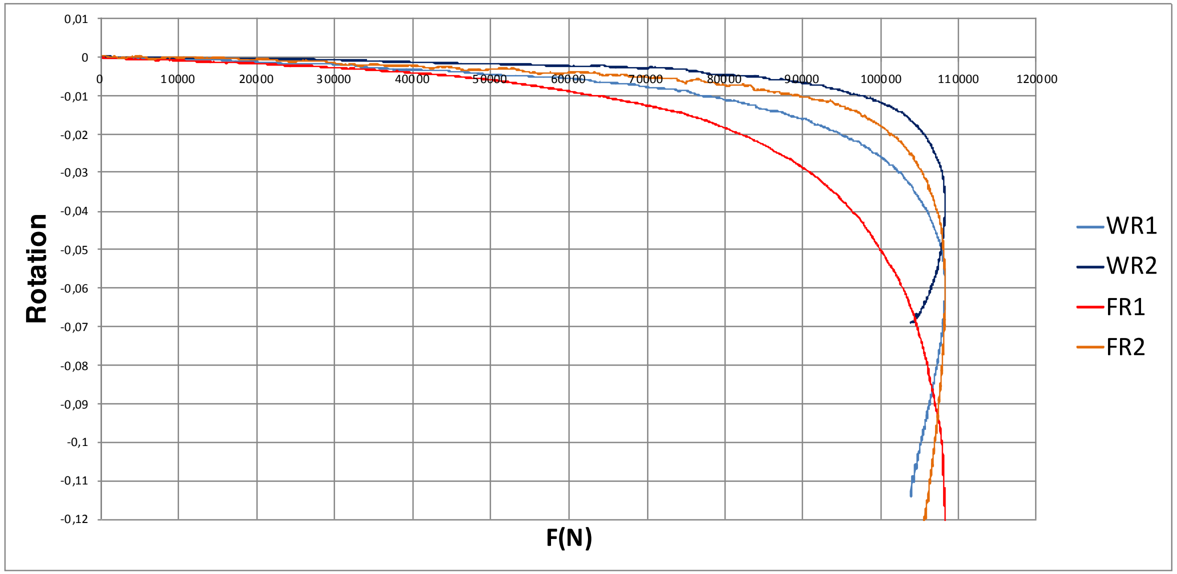
Measured rotations of members with fixed ends

Most common pattern of measured rotations

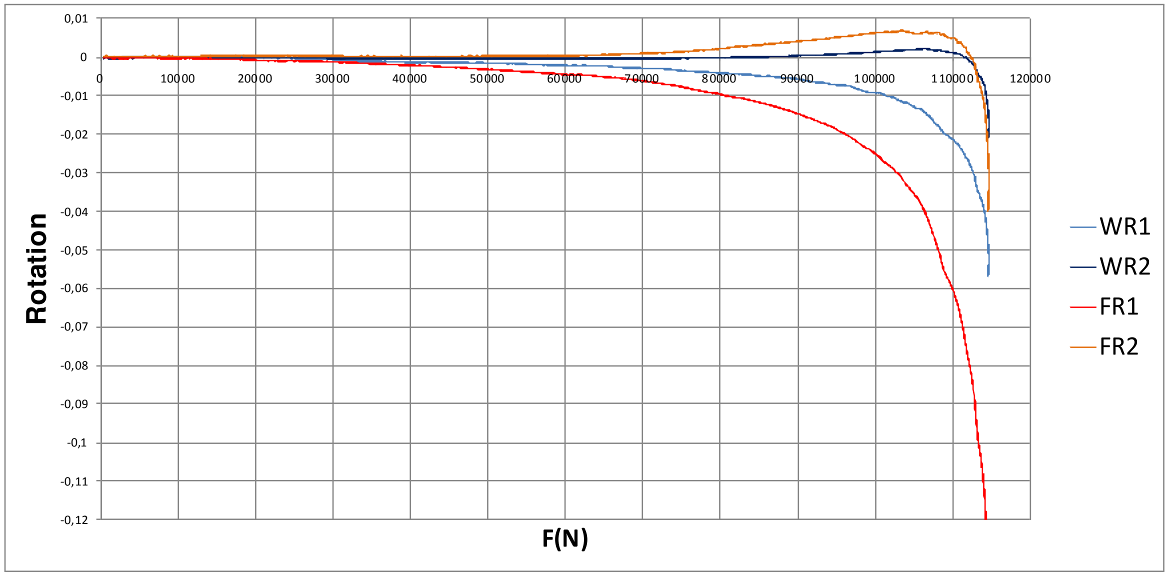
S4-1200W-1

$L/L_{crD}=1.96$



S4-1200W-3

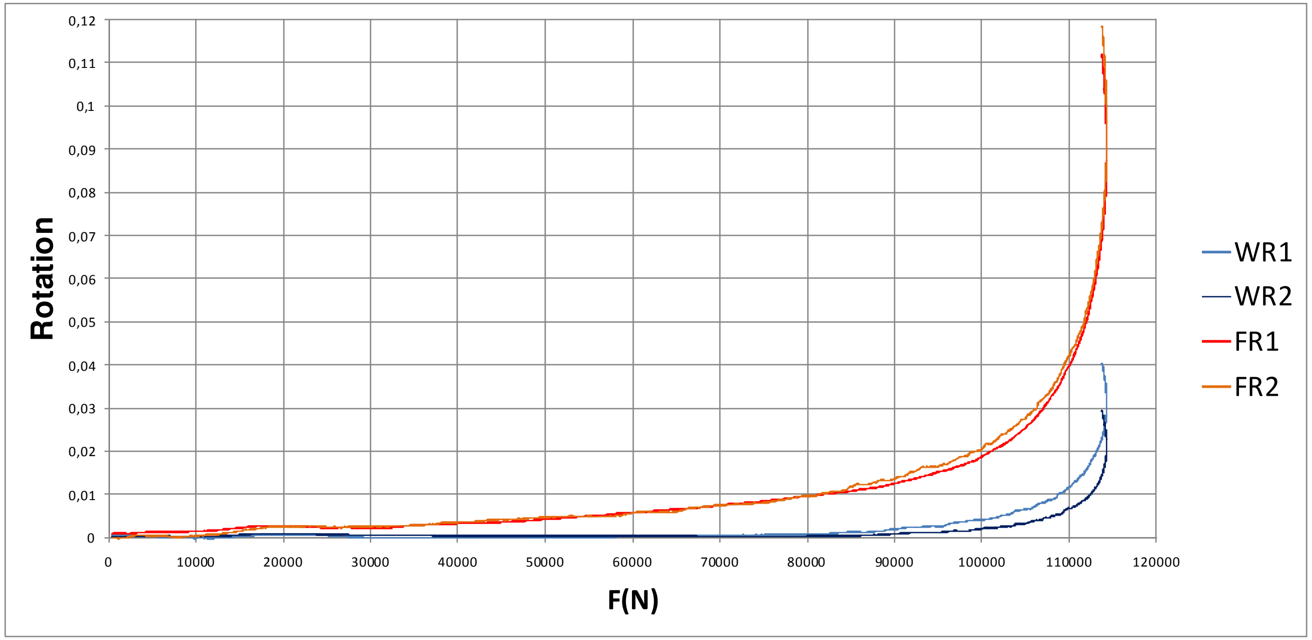
$L/L_{crD}=1.96$



Measured rotations of members with fixed ends

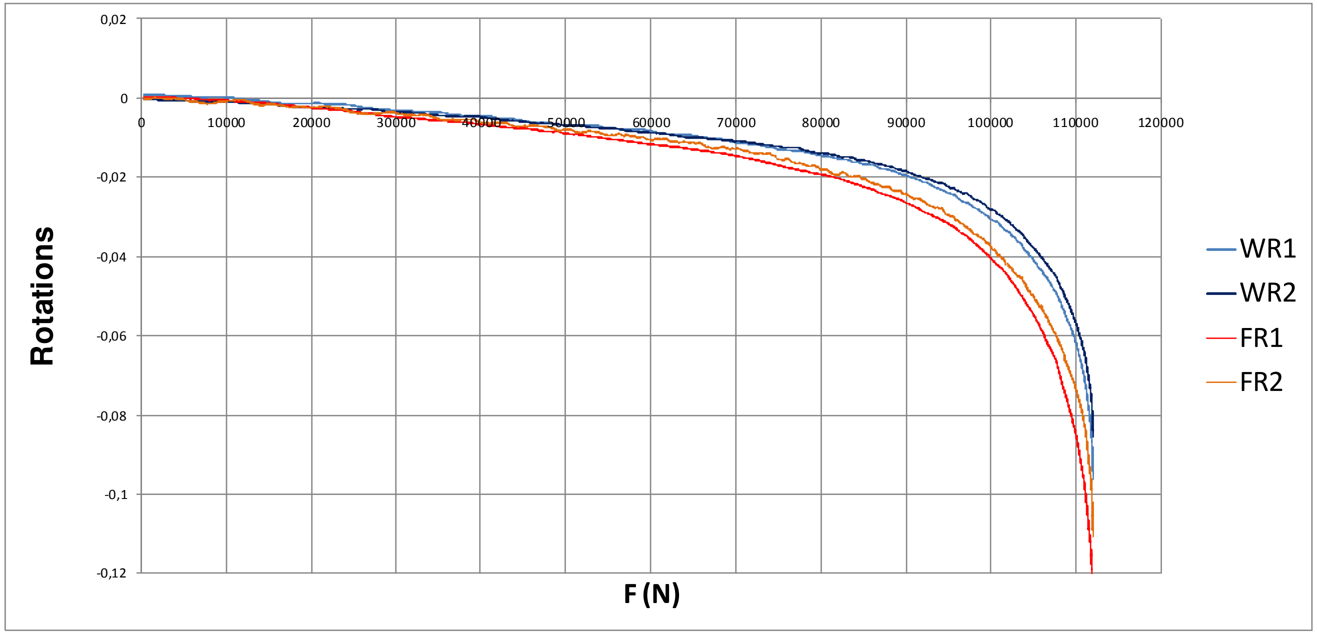
S4-1200G-2

$L/L_{crD}=1.96$



S1-1650W-2

$L/L_{crD}=2.61$



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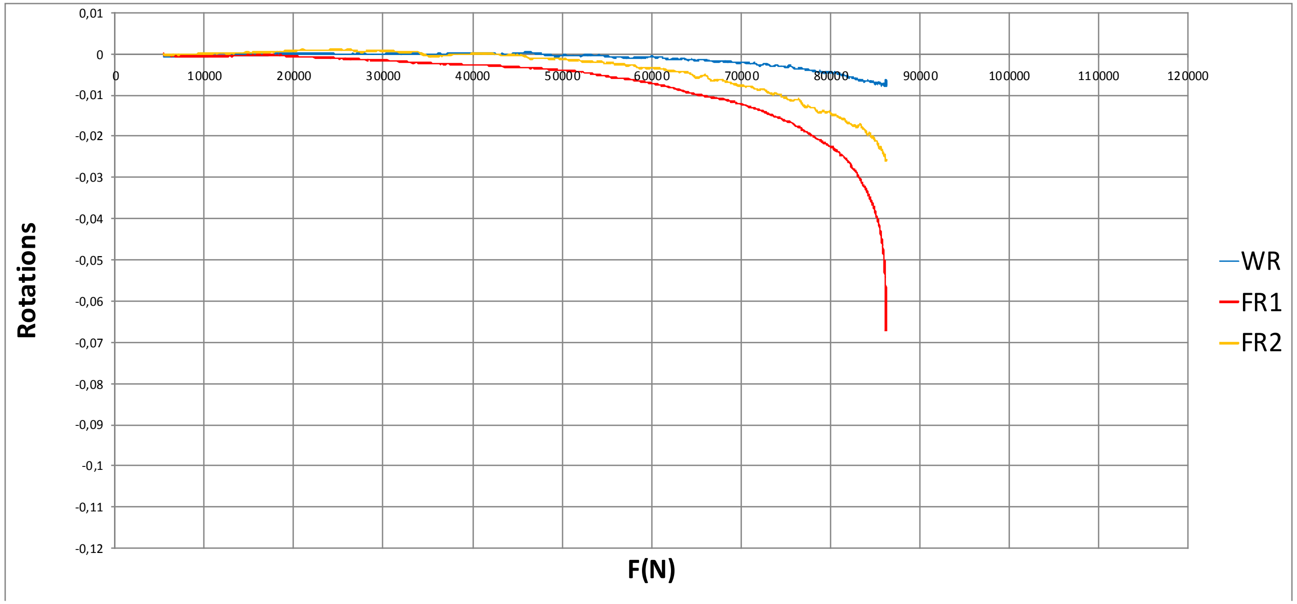
Measured rotations of members with pinned ends

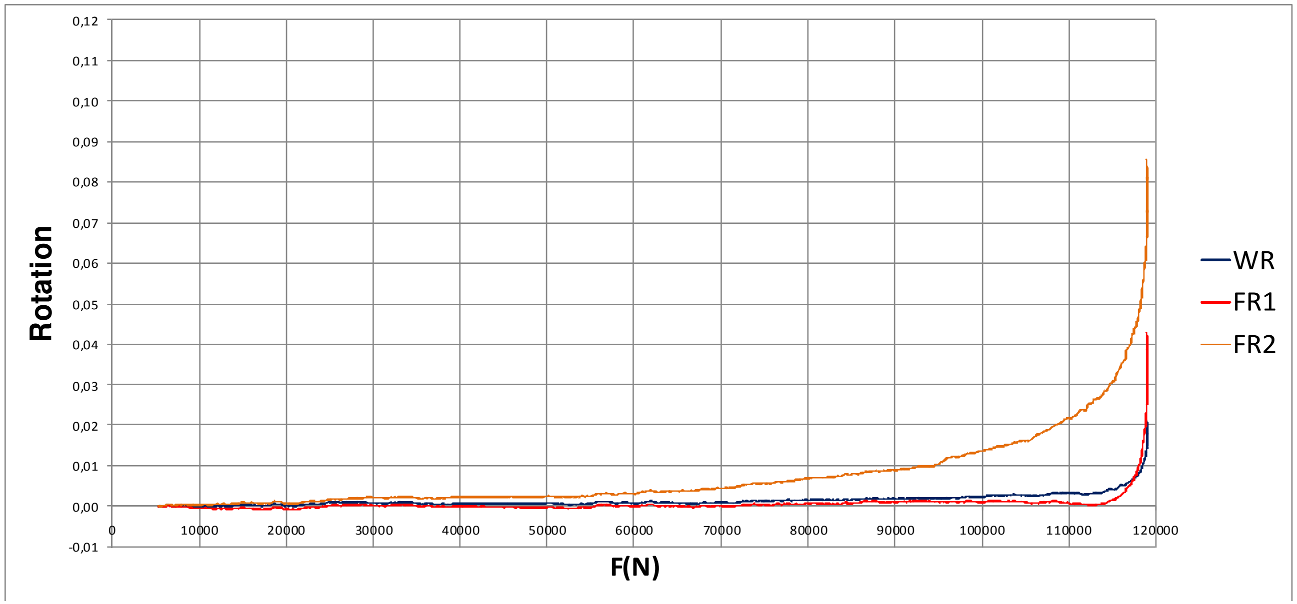
S1-1650P-1

$L/L_{crD}=2.61$



S4-1200P-1

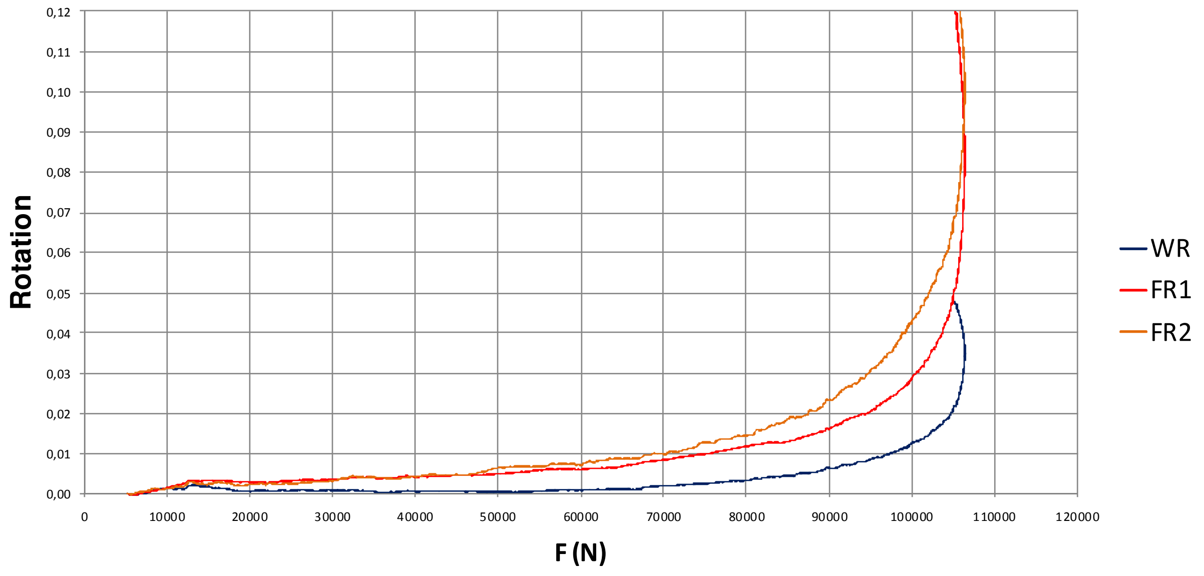
$L/L_{crD}=1.96$



Measured rotations of members with pinned ends

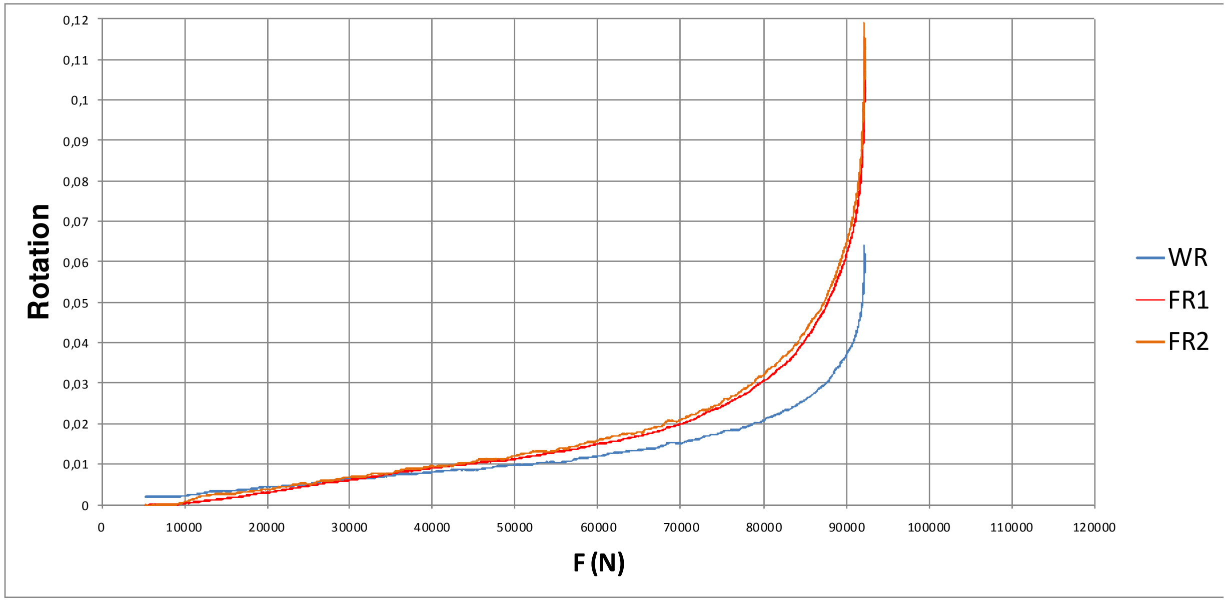
S4-1200P-2

$L/L_{crD}=1.96$



S4-1500P-1

$L/L_{crD}=2.45$



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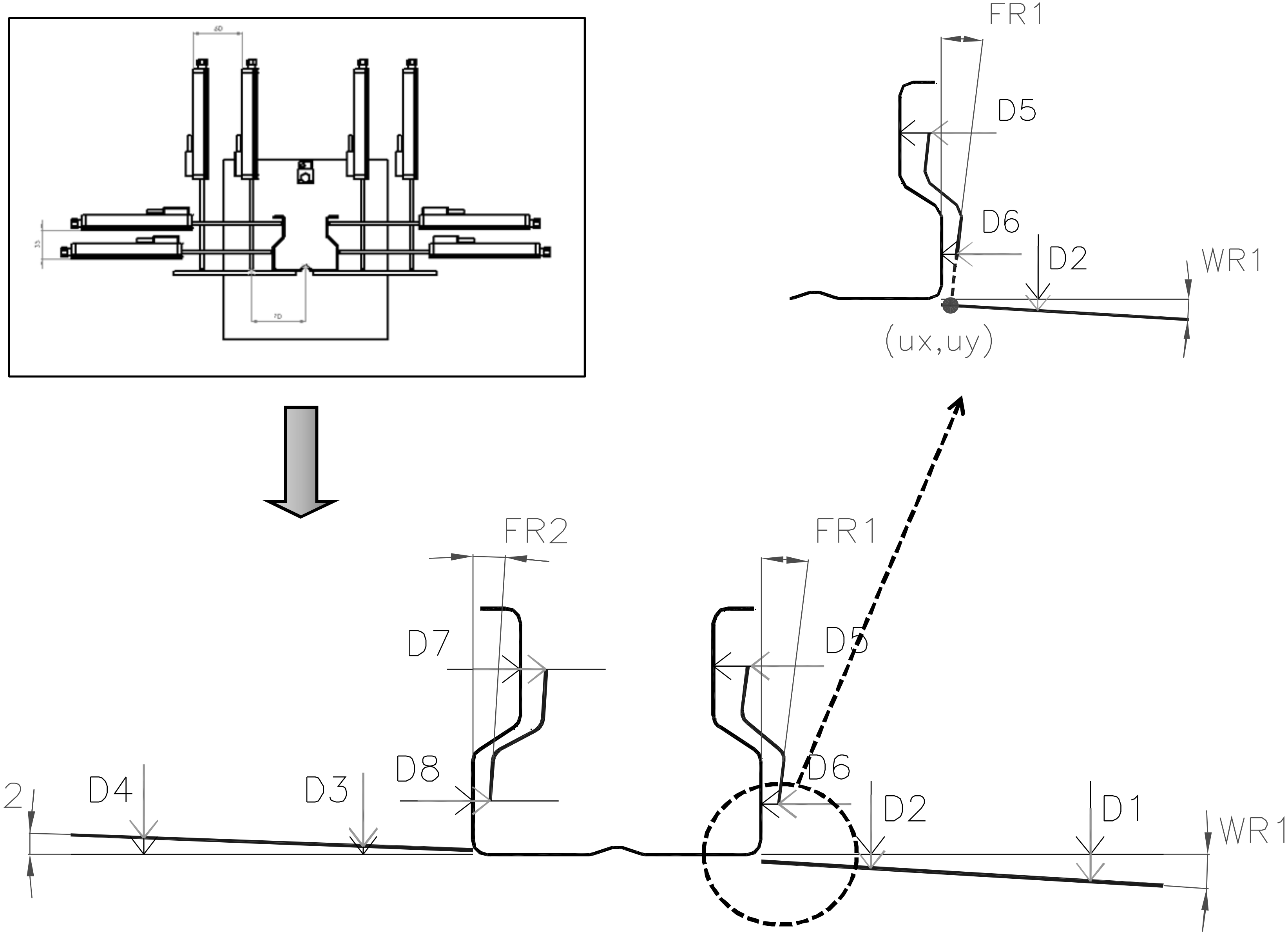
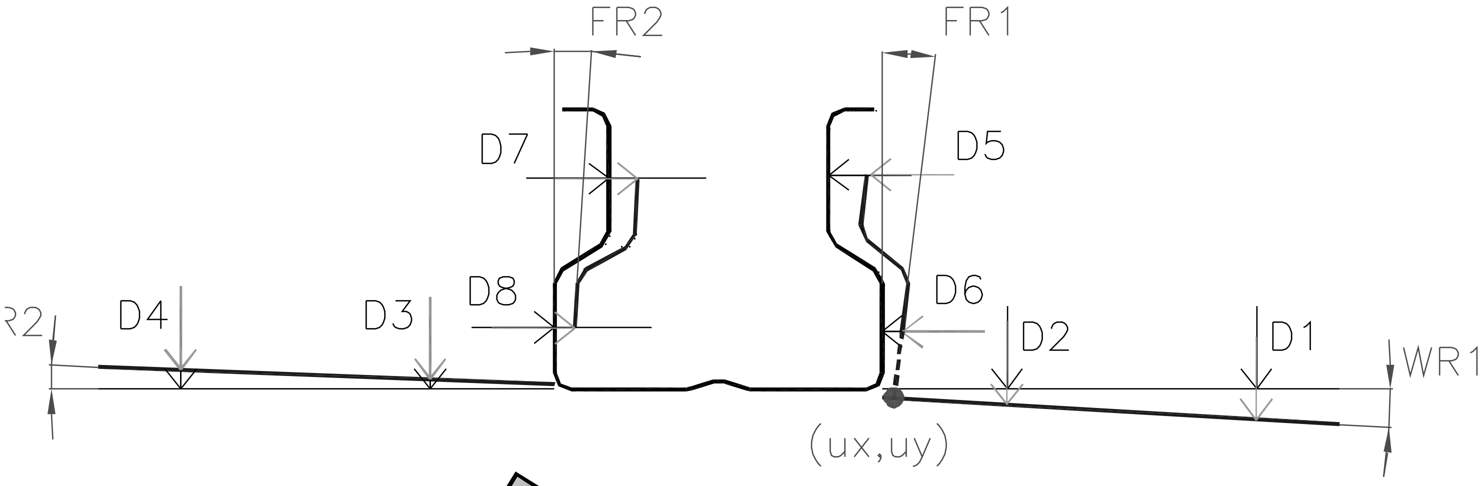
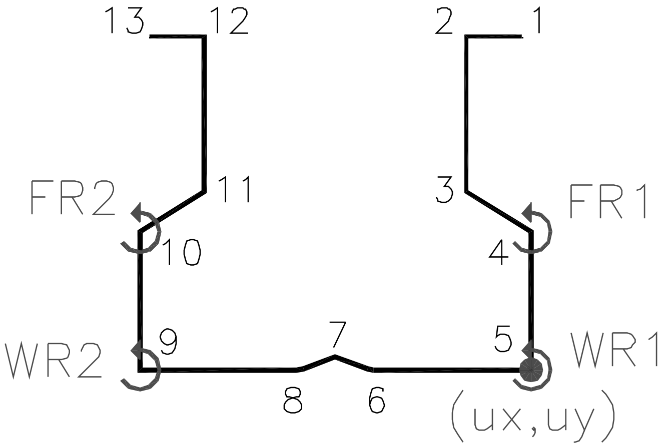
Modal participation from measured cross-section rotations

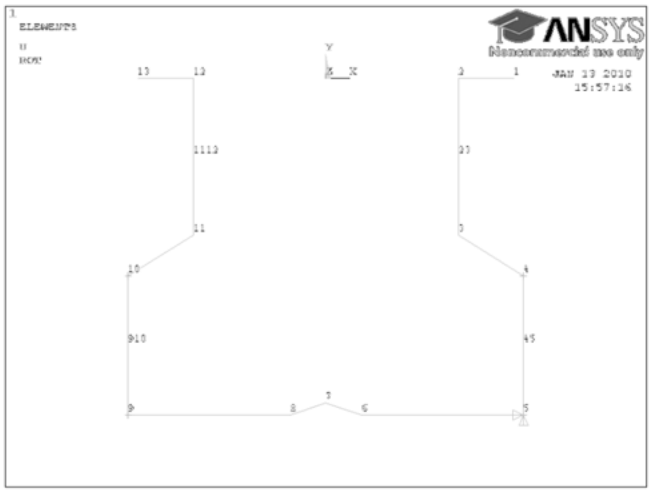


Finite Element Model of the cross-section

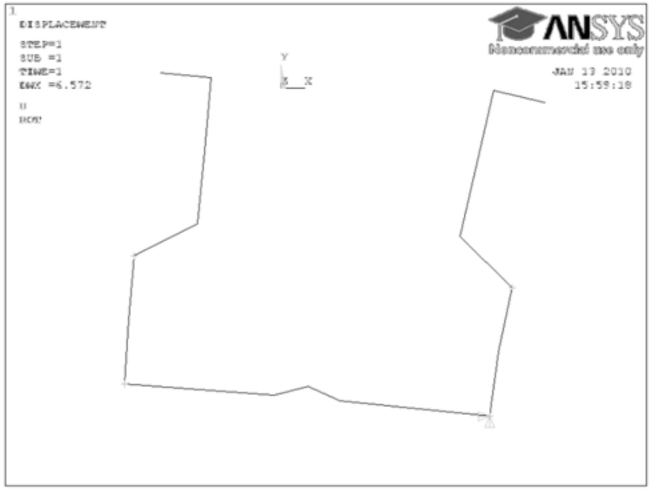




Beam finite element model



Nodal displacements of the cross-section



S4-1200W-1

NODE	UX	UY	ROTZ
1	6.4949	-1.0013	-0.76570E-01
2	6.4949	-0.15463	-0.76570E-01
3	4.0932	-0.15463	-0.76570E-01
4	3.4733	-1.1466	-0.76570E-01
5	1.8739	-1.1466	-0.38747E-01
6	1.8739	-0.17391E-01	-0.31148E-01
7	1.9480	0.19770	-0.29381E-01
8	1.8782	0.40023	-0.27613E-01
9	1.8782	1.1697	-0.20014E-01
10	2.5871	1.1697	-0.31096E-01
11	2.8388	0.76683	-0.31096E-01
12	3.8142	0.76683	-0.31096E-01
13	3.8142	1.11	-0.31096E-01

$$\bar{u}_{x,test} = \begin{Bmatrix} 6.49 \\ 6.49 \\ 4.09 \\ 3.47 \\ 1.87 \\ 1.87 \\ 1.94 \\ 1.87 \\ 1.87 \\ 2.58 \\ 2.83 \\ 3.81 \\ 3.81 \end{Bmatrix} \quad \bar{u}_{y,test} = \begin{Bmatrix} -1.00 \\ -0.15 \\ -0.15 \\ -1.14 \\ -1.14 \\ -0.01 \\ 0.19 \\ 0.40 \\ 1.16 \\ 1.16 \\ 0.76 \\ 0.76 \\ 1.11 \end{Bmatrix} \quad \overline{rot}_{z,test} = \begin{Bmatrix} -0.076 \\ -0.076 \\ -0.076 \\ -0.076 \\ -0.038 \\ -0.011 \\ -0.029 \\ -0.027 \\ -0.020 \\ -0.031 \\ -0.031 \\ -0.031 \\ -0.031 \end{Bmatrix}$$

GBT Modal identification

Modes considered:

SD – AD – FY – T - Oth

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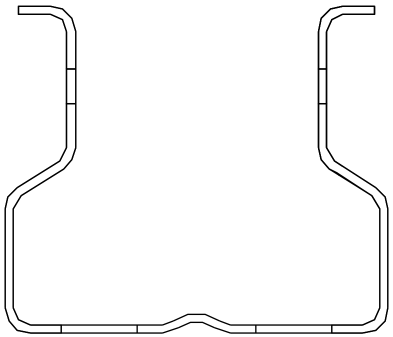
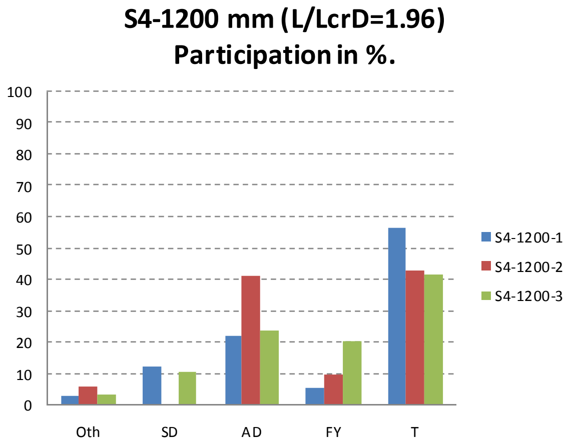
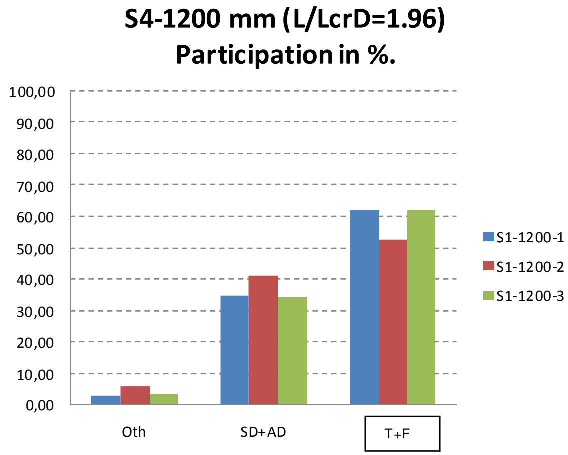
Participation factors at ultimate load. Grip specimens

Section	Oth (%)	SD (%)	AD (%)	FY (%)	T (%)	SD+AD (%)	T+F (%)
S4-1200-1	2.96	12.44	22.37	5.45	56.76	34.81	62.21
S4-1200-2	5.71	0	41.55	9.80	42.90	41.55	52.70
S4-1200-3	3.58	10.38	23.85	20.44	41.70	34.23	62.14



S4-L/LcrD=1.96





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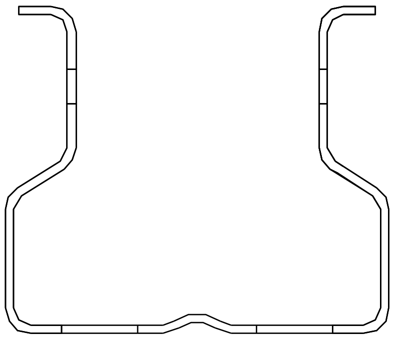
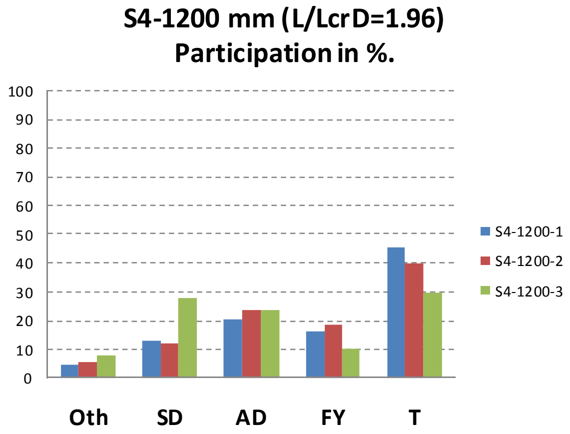
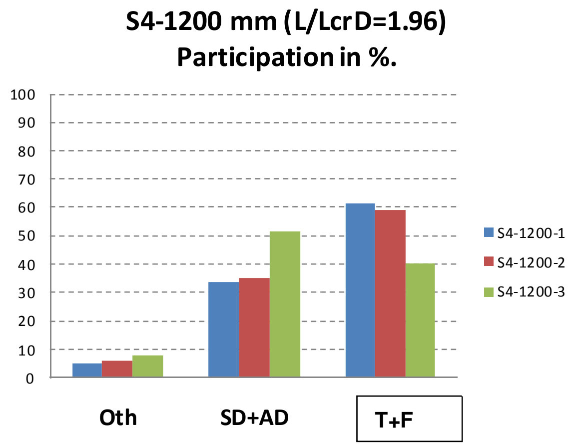
Participation factors at ultimate load. Welded specimens

Section	Oth (%)	SD (%)	AD (%)	FY (%)	T (%)	SD+AD (%)	T+F (%)
S1-1650-1	0,93	6,66	9,46	26,45	56,48	16,12	82,93
S1-1650-2	2,34	2,74	8,65	33,18	53,07	11,39	86,25
S1-1650-3	4,64	4,14	12,7	29,69	48,7	16,84	78,39
S4-1200-1	4,79	13,28	20,29	16	45,61	33,57	61,61
S4-1200-2	5,71	11,82	23,44	18,94	40,06	35,26	59
S4-1200-3	8,06	27,65	24,08	10,24	29,94	51,73	40,18
S4-1500-1	4,47	12,83	17,19	15,73	49,75	30,02	65,48
S4-1500-2	3,19	5,84	7,68	2,69	80,56	13,52	83,25

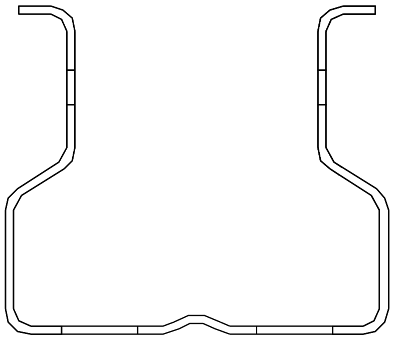


S4-L/LcrD=1.96

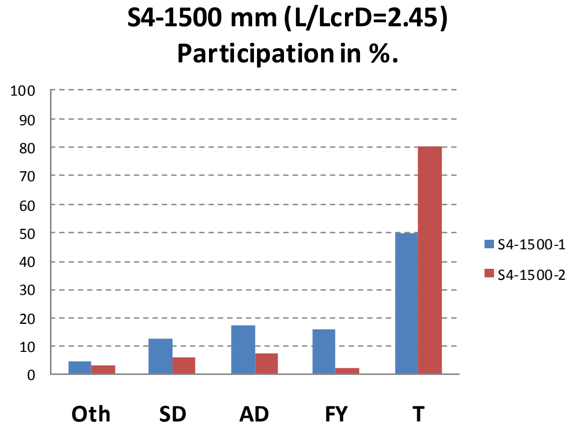


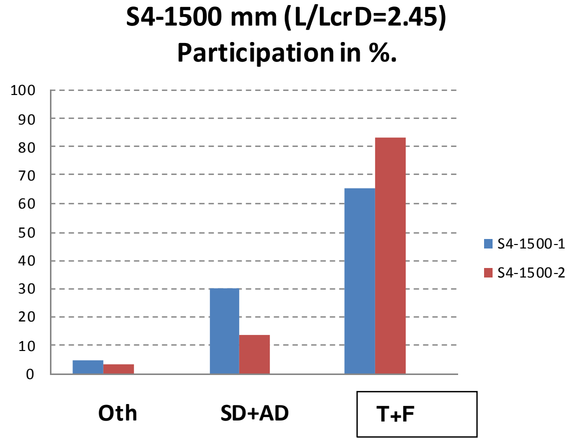


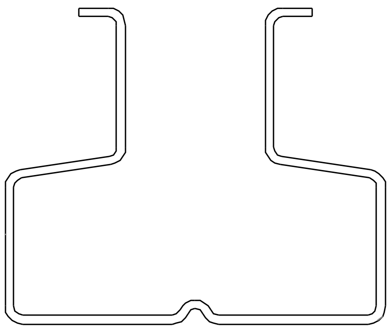
Participation factors at ultimate load. Welded specimens



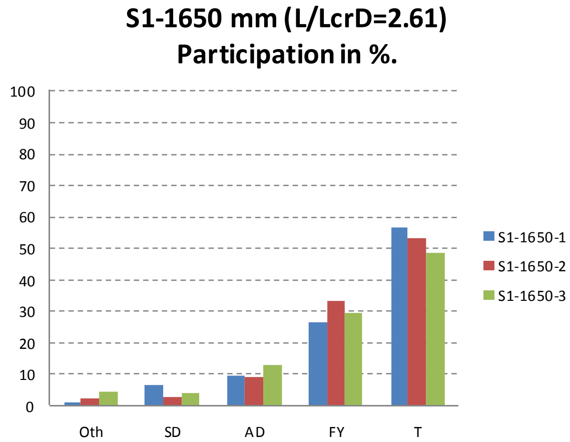
S4-L/LcrD=2.45

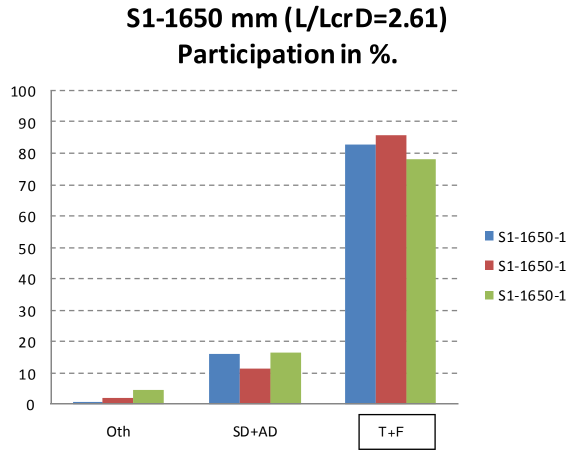






S1-L/LcrD=2.61





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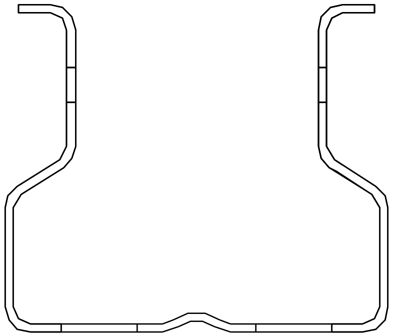
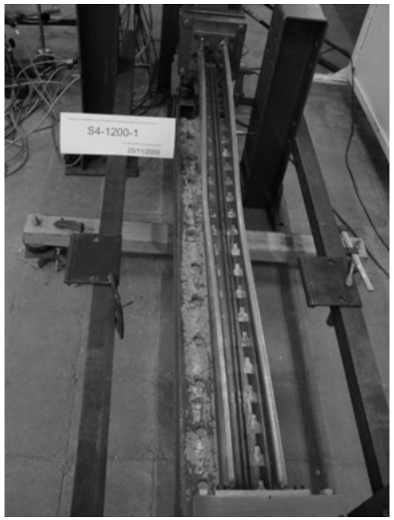
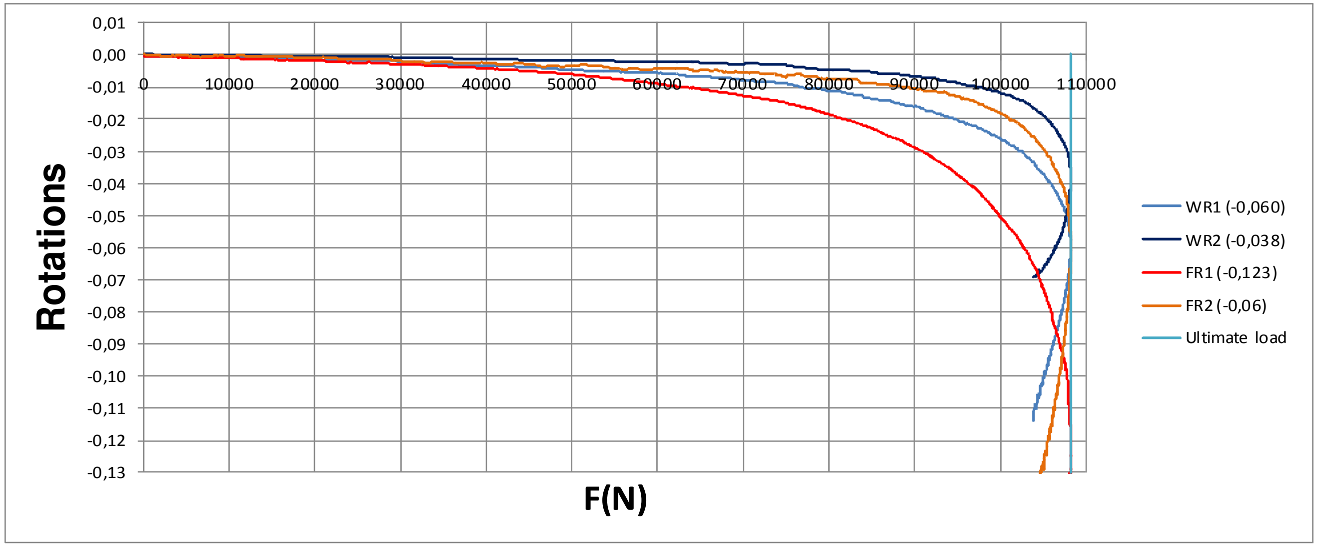
Participation factors during the loading process

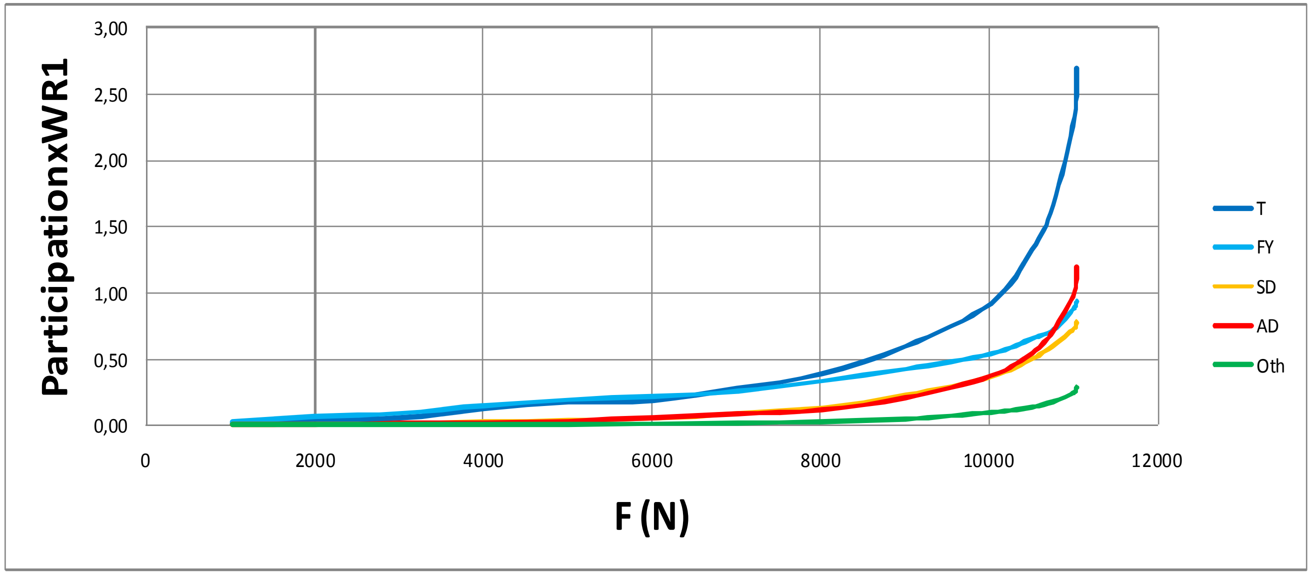
S4-1200W-1

L/LcrD=1.96





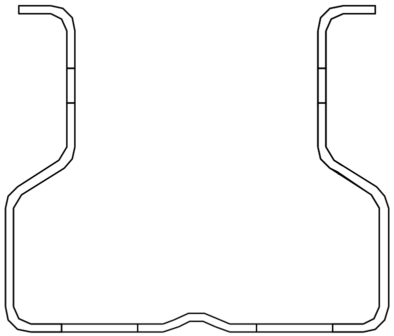


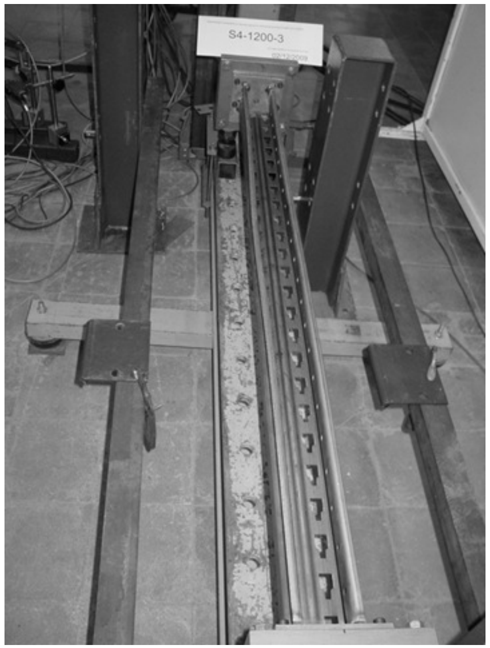


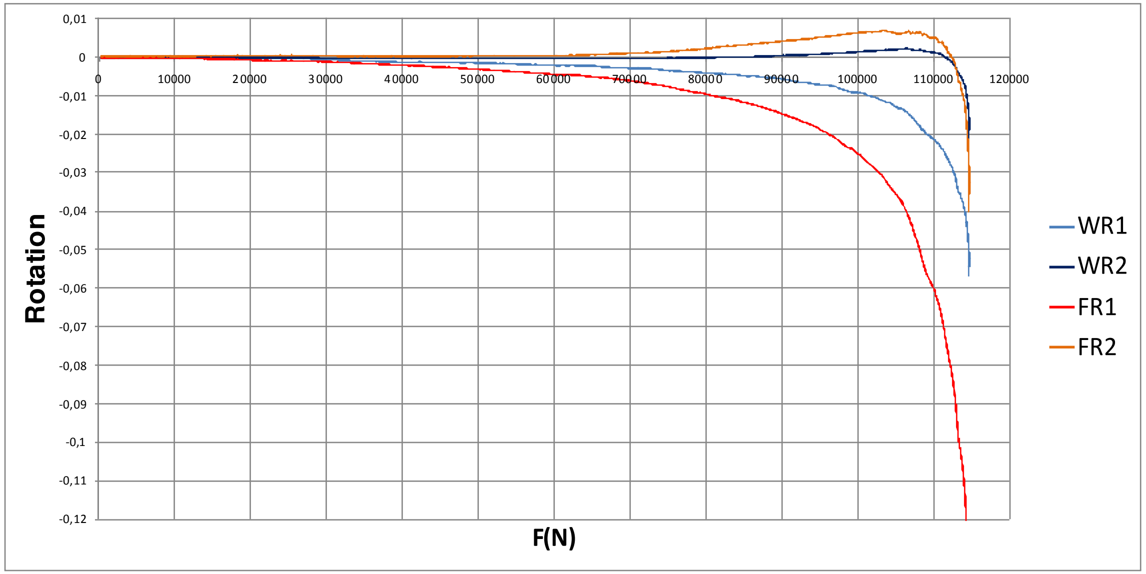
Participation factors during the loading process

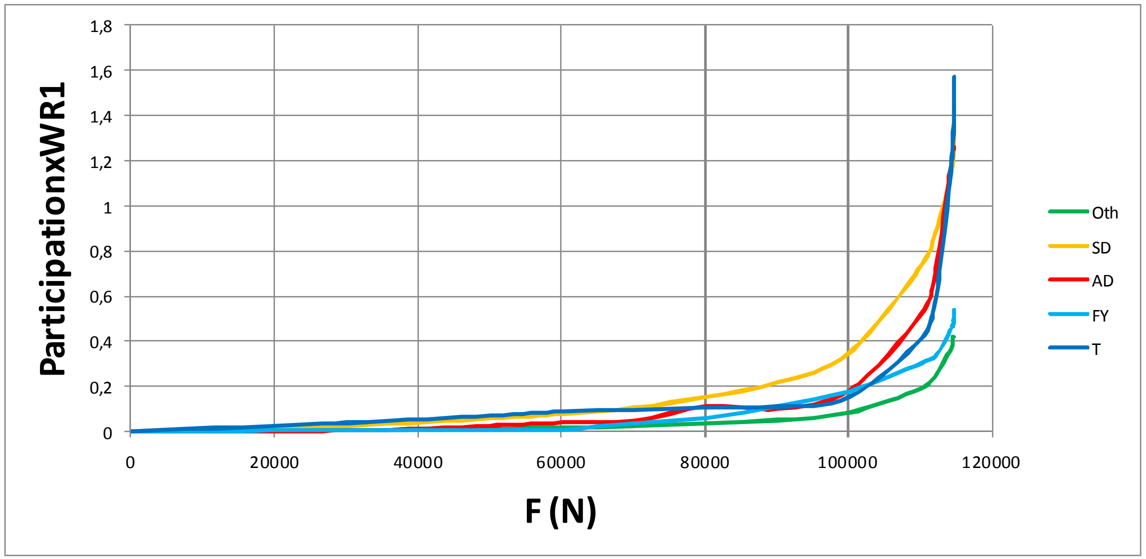
S4-1200W-3

L/LcrD=1.96









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- 1. Introduction
- 2. Resume of results presented in Trento
- 3. New aspects analyzed
- 4. End conditions
- 5. Displacement and rotation measurements
- 6. Results obtained
- 7. Discussion of results
- 8. Conclusions and future work

Conclusions

1- Members with GRIPS and members with WELDED ends show the same behaviour and ultimate load.

2-PINNED members show lower ultimate loads than FIXED members, but their behaviour seems to be similar (distortional and global modes are combined for the tested lengths).

3- According to these experimental results it seems that the best length of the specimens for the determination of the distortional buckling compression strength of the uprights should be $2 \cdot L_{crd}$ or lower.

4- If a dominant distortional failure is wanted, it seems that the test length should be reduced (to about $1.5 \cdot L_{crd}$). Further tests are needed to verify this.

Future work

1- Shorter members will be tested to look for distortional dominant failure modes.

2- The investigation on pinned members will be completed.

3-