The 49th Risk, Hazard and Uncertainty Workshop

Influence of Manufacturing Tolerances on the Cyclic Behavior of Steel Members

Cyrus Eshaghi, Xavier Romão, José Miguel Castro

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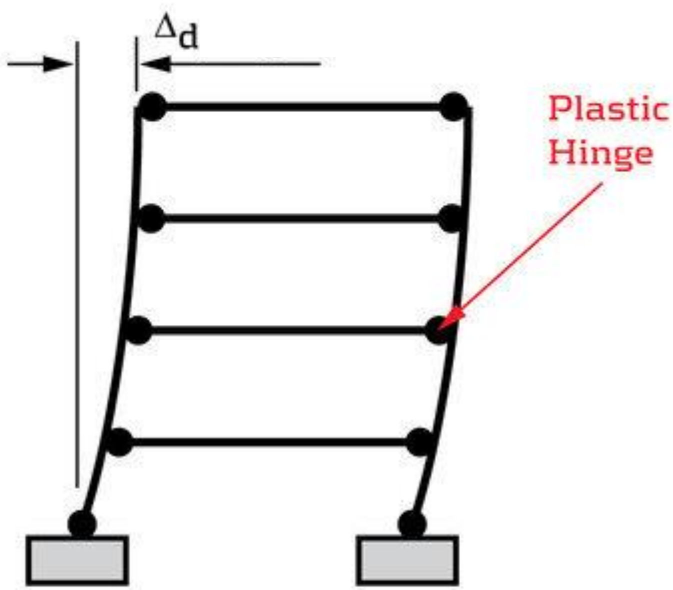
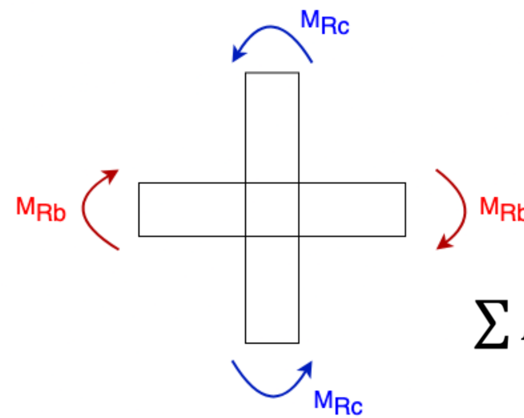
CONSTRUCT

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

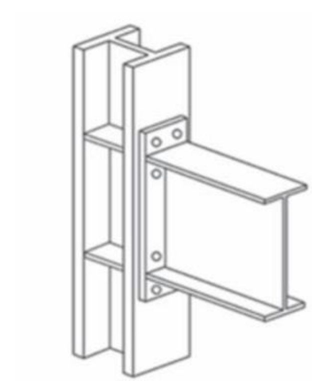
Seismic Design and Assessment of Steel Buildings

Steel moment frame buildings **dissipate energy** through hysteretic behaviour developing at **plastic hinges** located at the member ends.



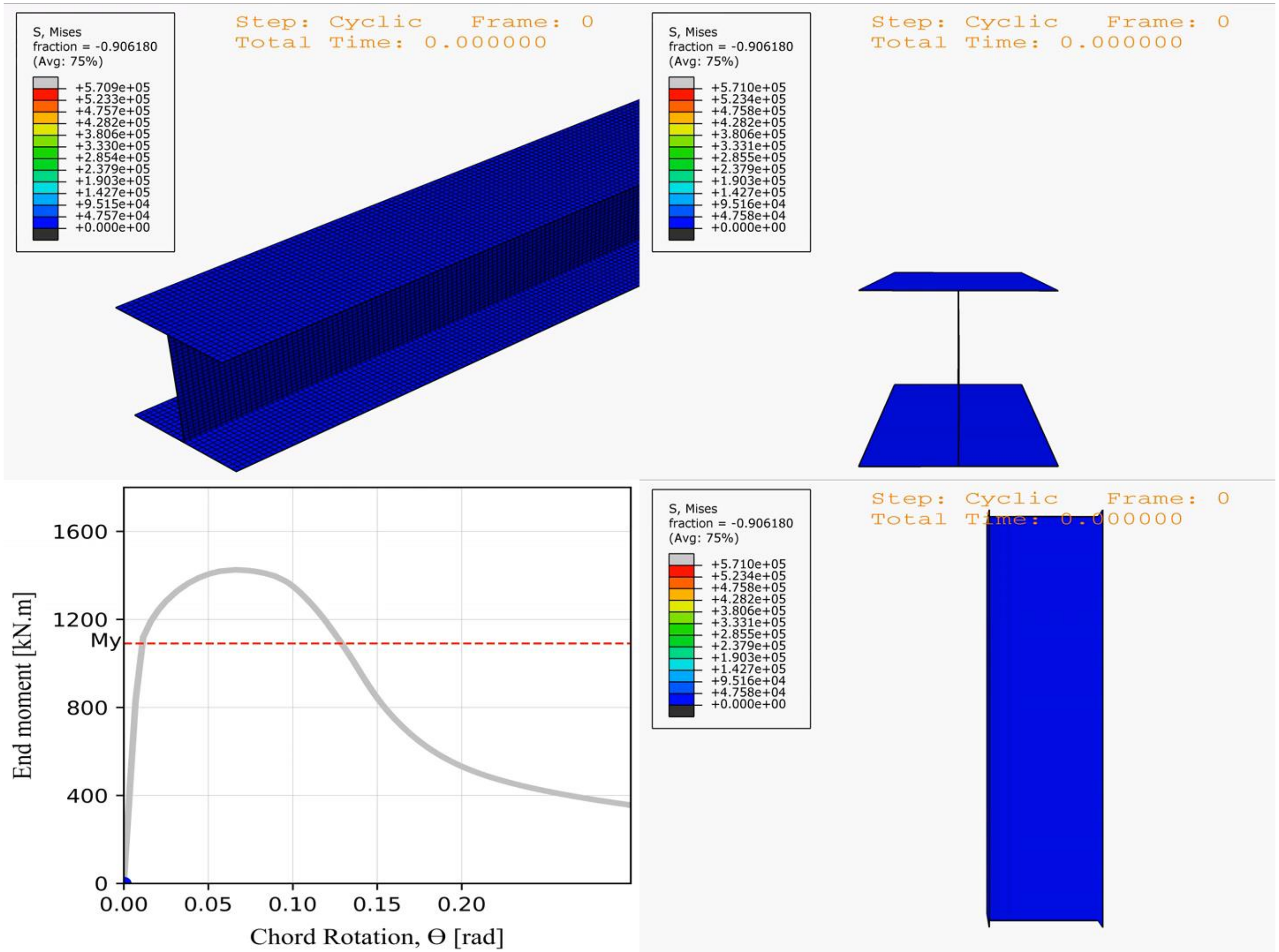


$$\sum M_{\mathrm{Rc}} \geq 1{,}3 \sum M_{\mathrm{Rb}}$$

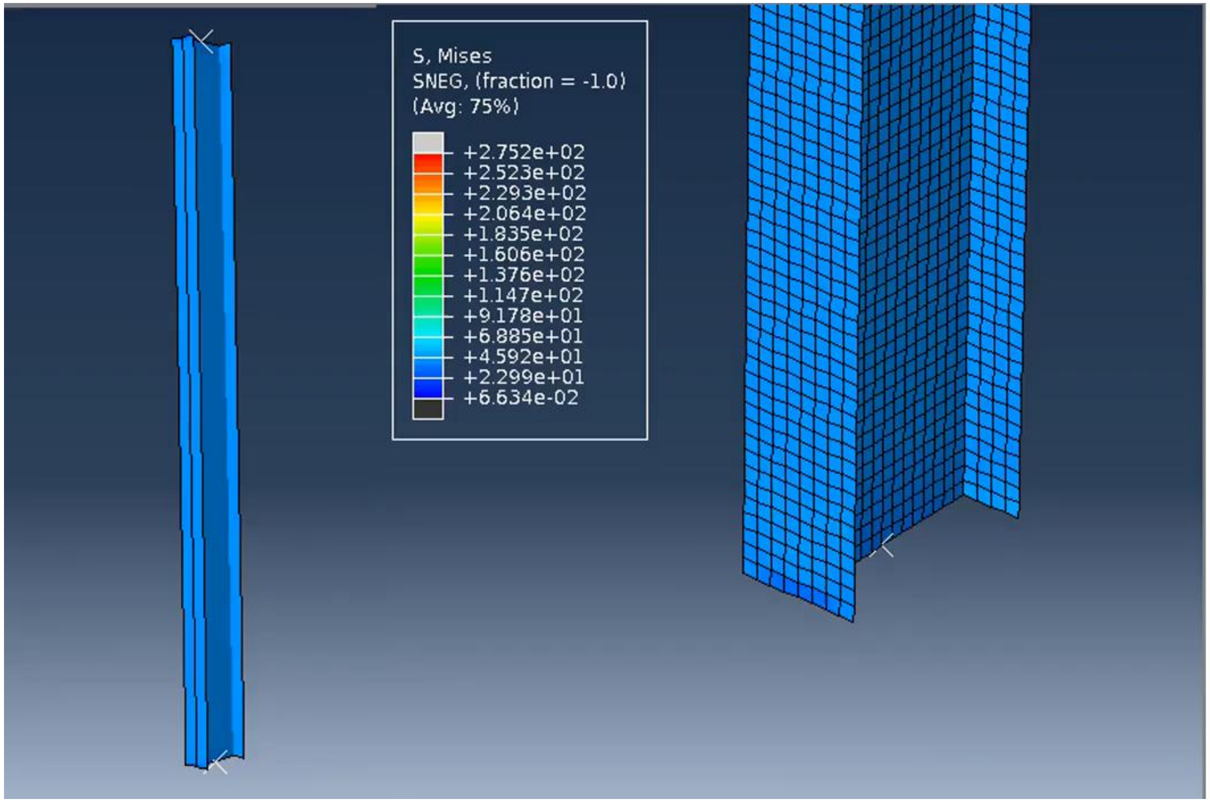


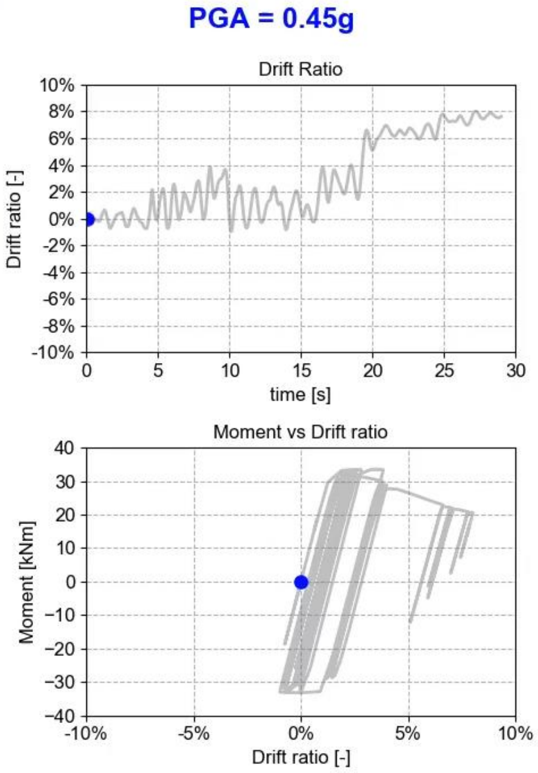
$$R_{\mathrm{d}} \geq 1{,}1\ \gamma_{\mathrm{ov}}\ R_{\mathrm{fy}}$$

Plastic Hinge Behaviour – Monotonic Loading



Plastic Hinge Behaviour – EQ Loading

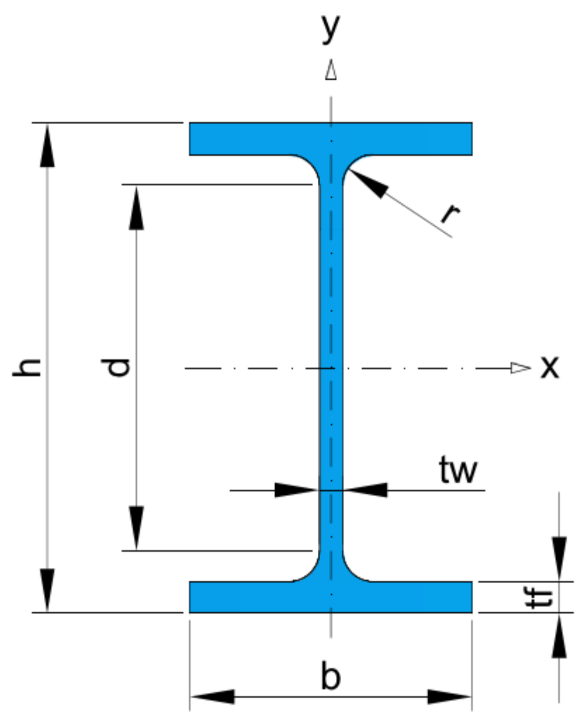




Cross-Section Slenderness

The **cross-section slenderness** of a steel member directly influences its susceptibility to **local buckling**.

Larger slenderness ratios **increase the likelihood of buckling** due to reduced stiffness and decreased ability to resist compressive stresses.

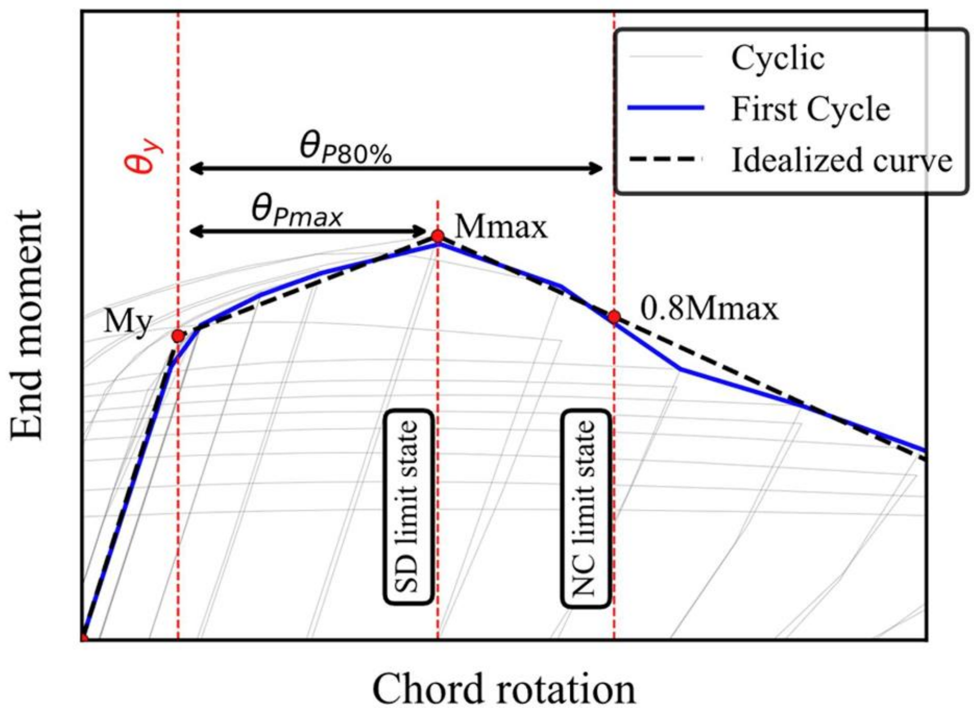


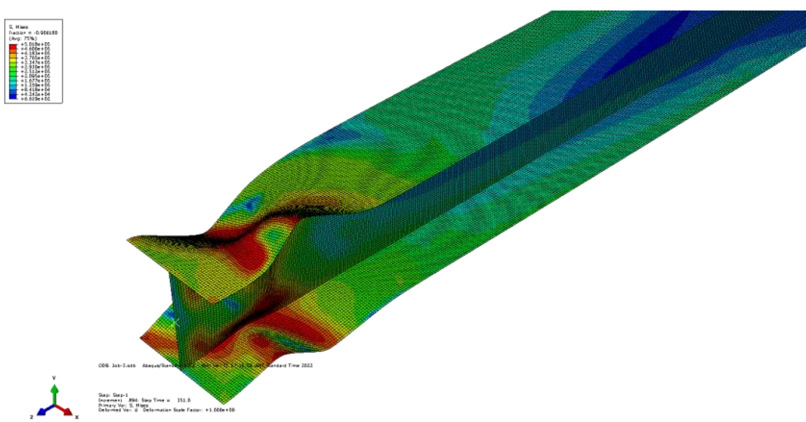
Flange slenderness: $\frac{b}{2t_f}$

Web slenderness: $\frac{d}{t_w}$

Experimental and Numerical Data

- Backbone curve **parameters** for **frame modelling**.
- **Damage criteria** for seismic performance **assessment**.





Code-Based Requirements

Limit states defined as a function of **member ductility**.

ASCE 41-16

Modeling Parameters and Acceptance Criteria for Nonlinear Procedures—Structural Steel Beams and Columns—Flexural Actions

Modeling Parameters		Acceptance Criteria		
		Plastic rotation angle (radians) Performance Level		
Plastic rotation angle a and b (radians) Residual strength ratio c		**IO**	**LS**	**CP**
Beams				
1. Where: $\frac{b_f}{2t_f} \le 0.30\sqrt{\frac{E}{F_{ye}}}$ and $\frac{h}{t_w} \le 2.45\sqrt{\frac{E}{F_{ye}}}$	$a = 9\theta_y$ $b = 11\theta_y$ $c = 0.6$	0.25[a]	[a]	[b]
2. Where: $\frac{b_f}{2t_f} \ge 0.38\sqrt{\frac{E}{F_{ye}}}$ or $\frac{h}{t_w} \ge 3.76\sqrt{\frac{E}{F_{ye}}}$	$a = 4\theta_y$ $b = 6\theta_y$ $c = 0.2$	0.25[a]	0.75[a]	[a]
3. Other: Linear interpolation between the values on lines 1 and 2 for both flange slenderness (first term) and web slenderness (second term) shall be performed, and the lower resulting value shall be used.				

EC8-3

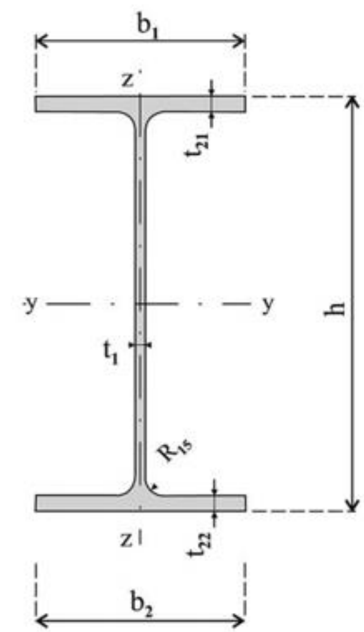
Plastic rotation capacity at the end of beams or columns with dimensionless axial load ν not greater than 0,30.

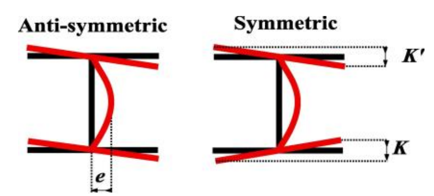
	Limit State		
Class of cross section	DL	SD	NC
1	1,0 θ_y	6,0 θ_y	8,0 θ_y
2	0,25 θ_y	2,0 θ_y	3,0 θ_y

Tolerances on Dimensions (EN 10034:1993)

Standards allow for **significant variability in thicknesses**, which can greatly affect the **slenderness ratios** and the overall performance of the members.

Dimensional tolerances for structural steel I and H sections							
Section height *h*		Flange width *b*		Web thickness *s*		Flange thickness *t*	
height mm	tolerance mm	width mm	tolerance mm	thickness mm	tolerance mm	thickness mm	tolerance mm
$h \leq 180$	+3.0 -2.0	$b \leq 110$	+4.0 -1.0	$S < 7$	± 0.7	$t < 6.5$	+1.5 -0.5
$180 < h \leq 400$	+4.0 -2.0	$110 < b \leq 210$	+4.0 -2.0	$7 \leq s < 10$	± 1.0	$6.5 \leq t < 10$	+2.0 -1.0
$400 < h \leq 700$	+5.0 -3.0	$210 < b \leq 325$	+4.0 -4.0	$10 \leq s < 20$	± 1.5	$10 \leq t < 20$	+2.5 -1.5
$h > 700$	+5.0 -5.0	$b > 325$	+6.0 -5.0	$20 \leq s < 40$	± 2.0	$20 \leq t < 30$	+2.5 -2.0
				$40 \leq s < 60$	± 2.5	$30 \leq t < 40$	+2.5 -2.5
				$s \geq 60$	± 3.0	$40 \leq t < 60$	+3.0 -3.0
						$t \geq 60$	+4.0 -4.0





Variation for geometric imperfections in **code** is based on research from the **1970s**.

Research Objectives

Evaluation of the influence of geometrical variability due to the manufacturing process on the flexural cyclic behaviour of steel members.

Focus on different parameters:

- **Flexural Overstrength (M_{max}/M_y)**
- Rotation at max moment (θ_{max})
- **Rotation at 80% of max moment ($\theta_{80\%}$)**
- **Energy dissipation**
- Axial shortening

Research Methodology

Development of a detailed 3D FE model in ABAQUS

Analyses of samples of profiles reflecting realistic variability of relevant geometrical properties

- Six variables: b_1, b_2, t_w, t_f (top), t_f (bottom), h
- Constant imperfection in shape (variable in magnitude)
- **IPE300** to **IPE600** and **HEB300** to **HEB450**
- Four **different lengths** L = 2, 2.5, 3, 3.5 m

Research Methodology

Relative statistical geometric characteristics

Quantity	Mean	Standard deviation	Skewness	Kurtosis	Min Value	Max value
h	1.001	0.00443	-0.4063	3.0150	0.989	1.013
b_1	1.012	0.01026	-0.3939	4.239	0.975	1.049
b_2	1.015	0.00961	-0.5448	3.887	0.975	1.037
t_1	1.055	0.04182	1.0545	7.4730	0.949	1.3
t_{21}	0.988	0.04357	-0.2991	2.663	0.880	1.094
t_{22}	0.998	0.04803	0.3303	2.766	0.858	1.129

Correlation matrix of geometric characteristics

Quantity	h	b_1	b_2	t_1	t_{21}	t_{22}
h	1	-0.0068	0.0534	0.0399	-0.0686	-0.0989
b_1	-0.0068	1	0.6227	-0.2142	-0.2681	-0.1456
b_2	0.0534	0.6227	1	-0.2132	-0.1596	-0.0423
t_1	0.0399	-0.2142	-0.2132	1	0.2368	0.2451
t_{21}	0.0686	-0.2681	-0.1596	0.2368	1	0.7634
t_{22}	-0.0989	-0.1456	0.0423	0.2451	0.7634	1

Melcher et al. (2005) conducted **experimental** survey on **700** steel hot rolled IPE profiles

Probabilistic distributions of each parameter defined by a distribution from the Pearson family based on survey data.

Sensitivity analysis to evaluate the influence of each individual geometrical parameter (sample of size **50** using LHS).

Global analysis involving the variability of all the considered geometrical parameters (sample of size **50** using LHS and the empirical correlation between parameters).

Numerical Model

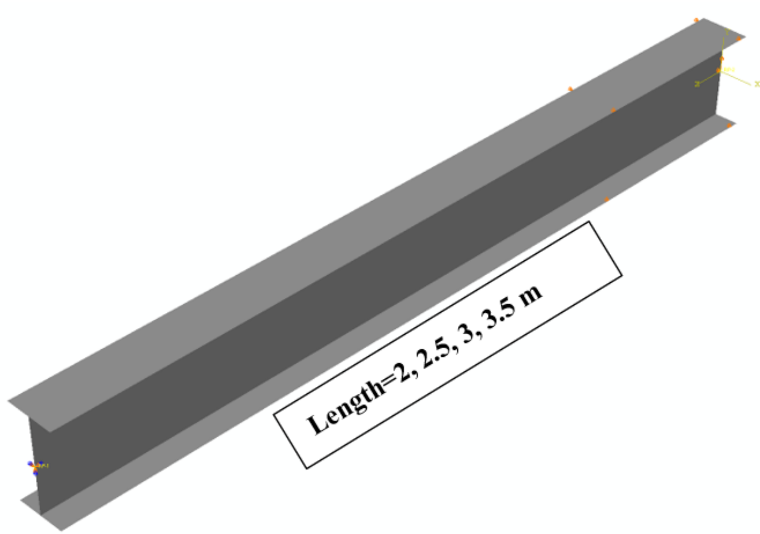
3D model in **ABAQUS** with one edge fully restrained

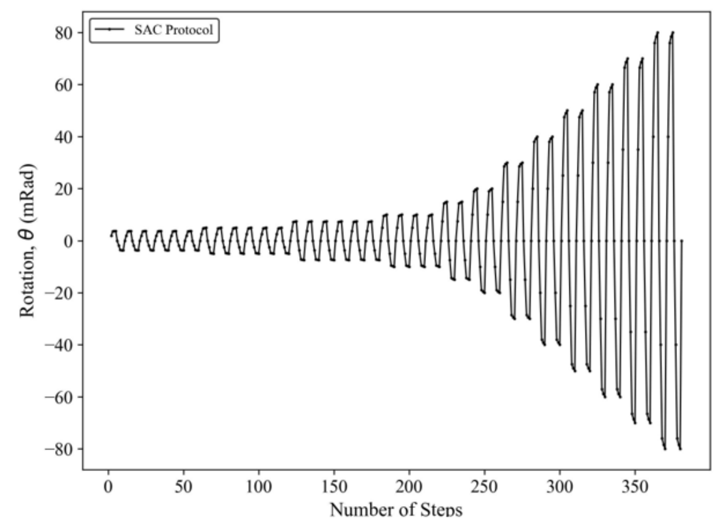
Voce-Chaboche combined isotropic and kinematic model

Cyclic loading: **SAC protocol**

Unbraced length according to AISC 341-16

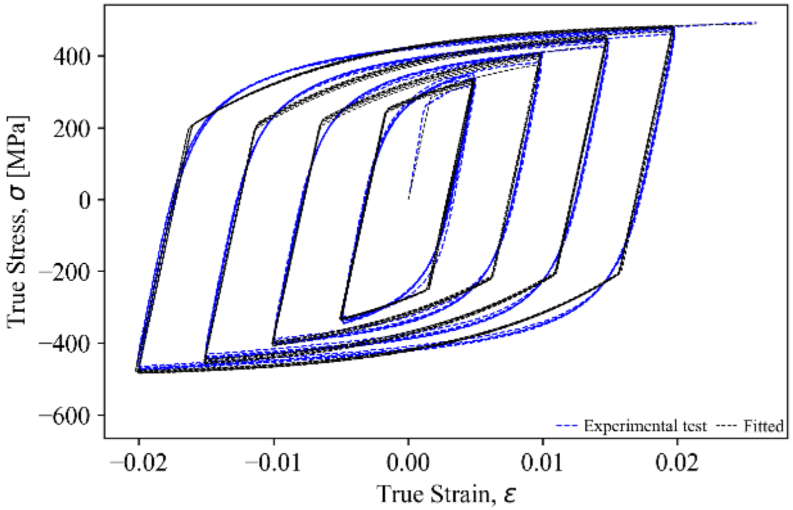
$$L_b = 0.095 i_z \frac{E}{F_y}$$



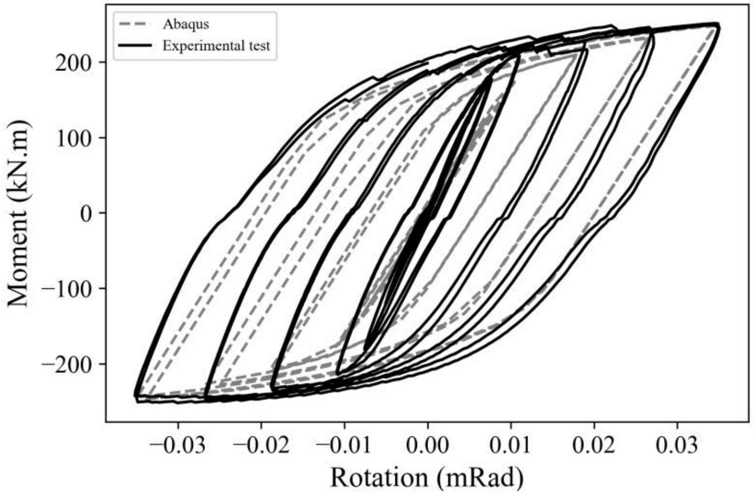


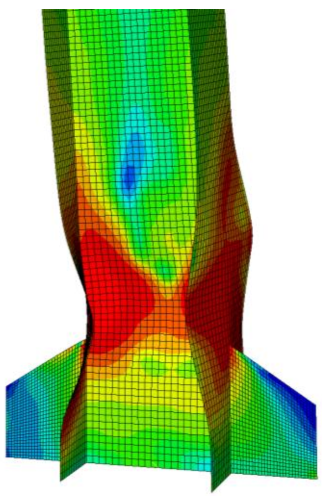
Model Validation

Experimental Coupon Test



Experimental Test on IPE 300

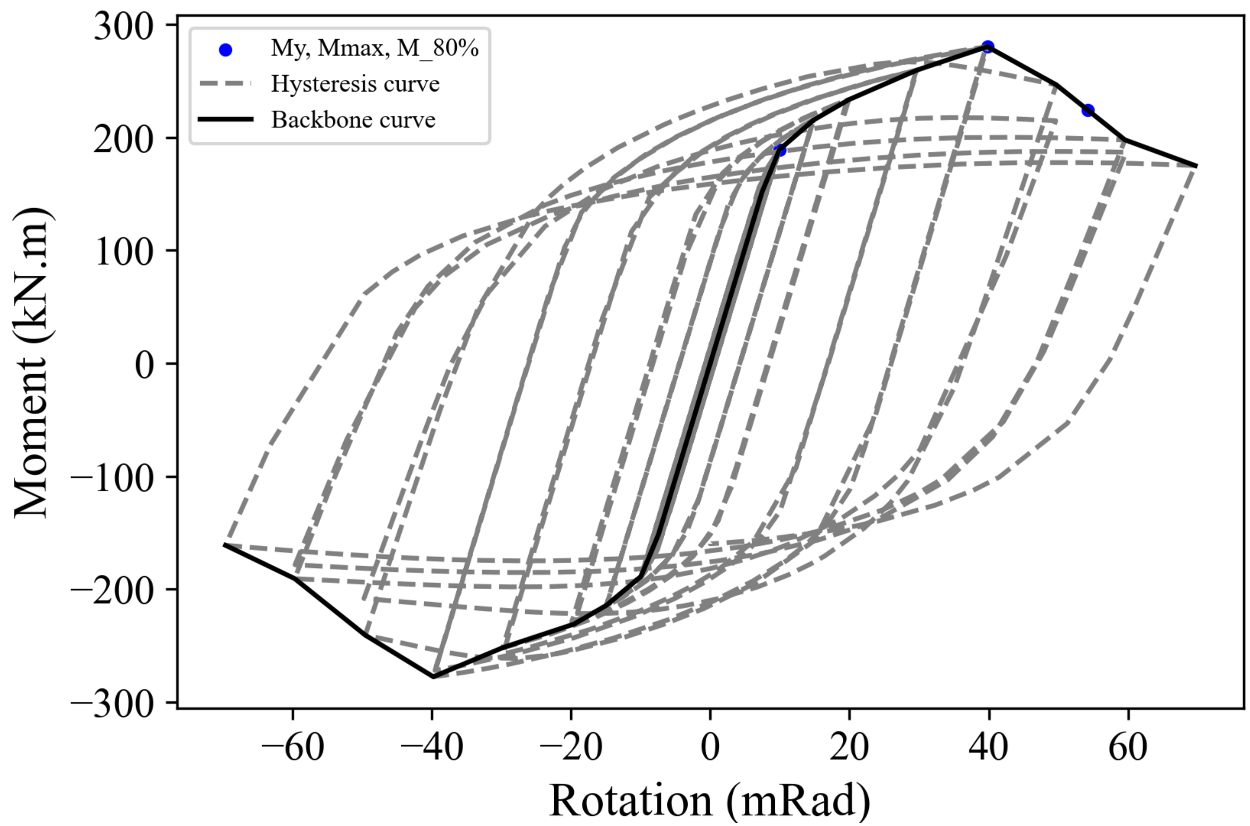




D'Aniello et al (2012)

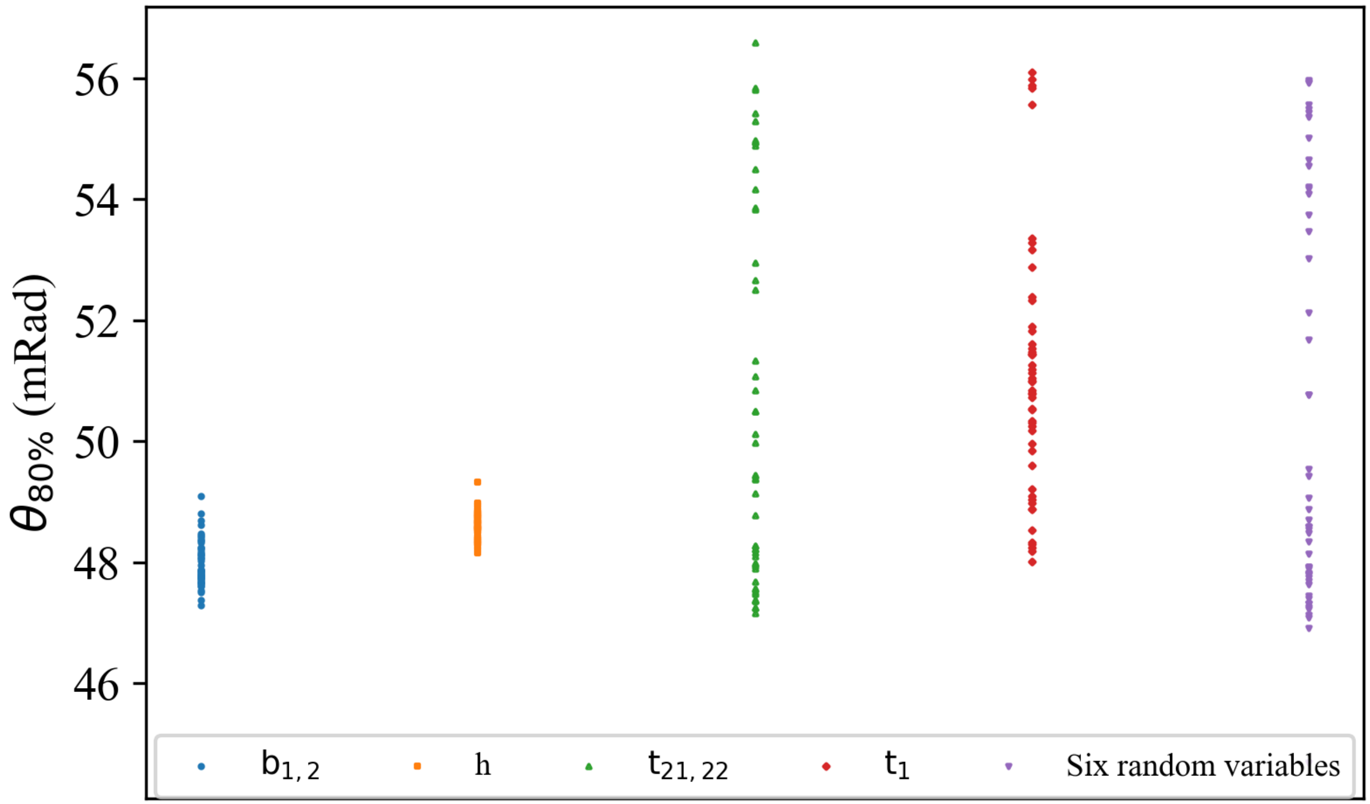
Results

Backbone Curve of an IPE300 with L=2m



Sensitivity Study

Results for an **IPE 300** with L=2m



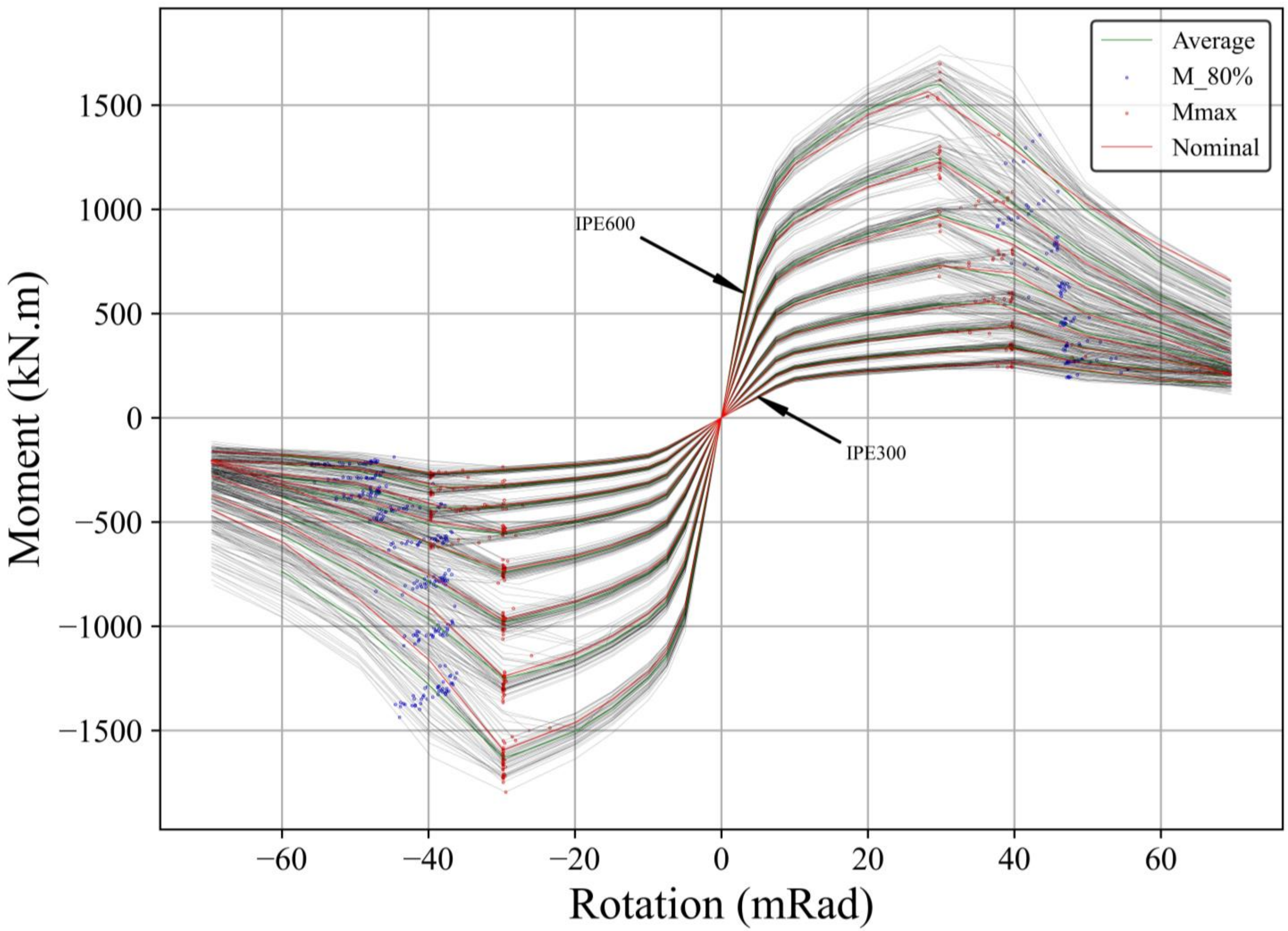
Flange and **web thickness** have the greatest influence.

Tolerance of $\mathbf{t_2}$ (flange thickness) represents a variation of **(-14%, +23%)**

Tolerance of $\mathbf{t_1}$ (web thickness) represents a variation of **(-14%, +14%)**

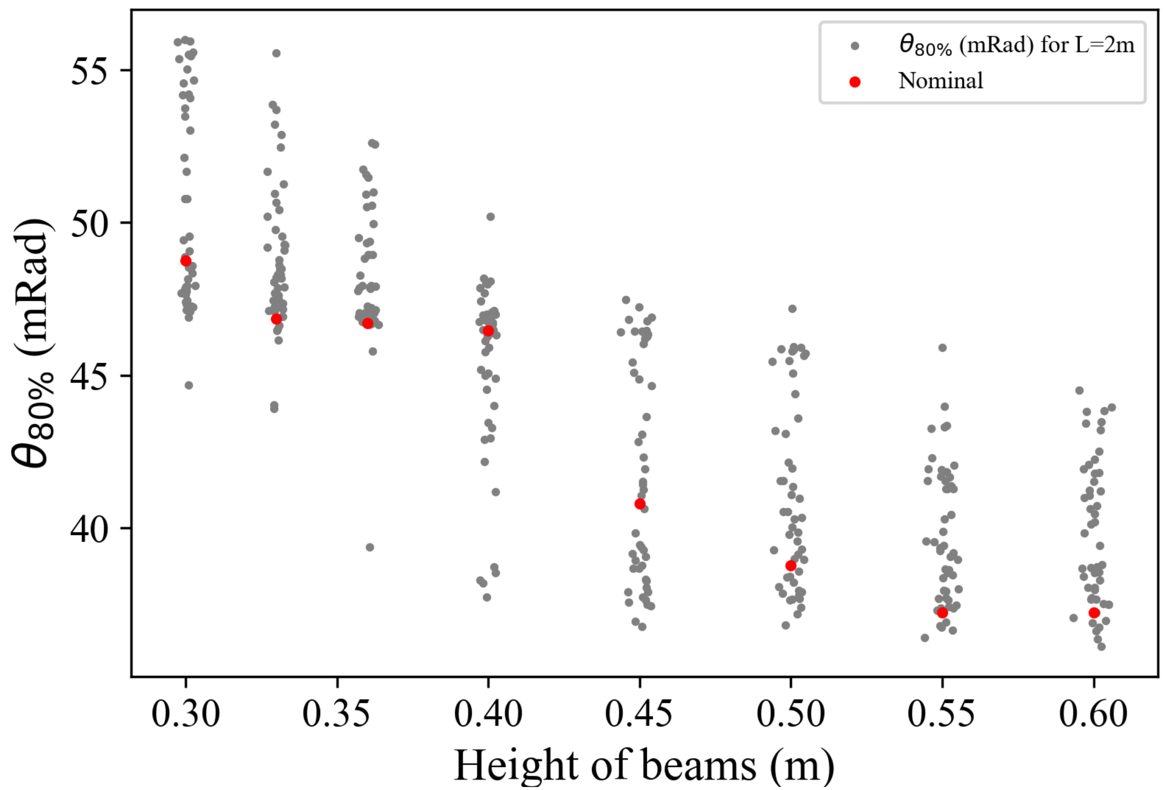
Results (IPE)

Backbone Curves of **IPE 300** to **IPE 600** (L=2m)



Results (IPE)

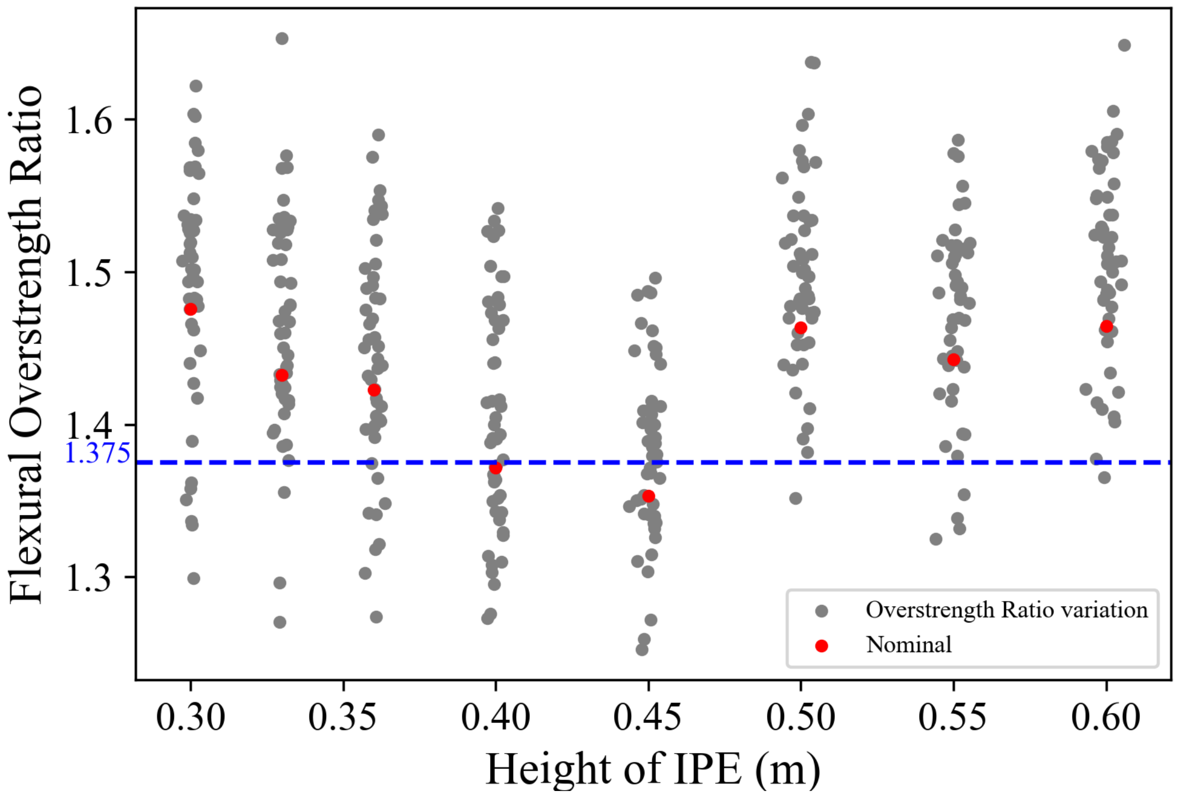
$\theta_{80\%}$ for the **IPE profiles** with L=2m



- The pattern of dispersion of the data is not constant for the range of **IPE** profiles.
- The behaviour of the **nominal profile** in relation to the sample is **variable**.

Results (IPE)

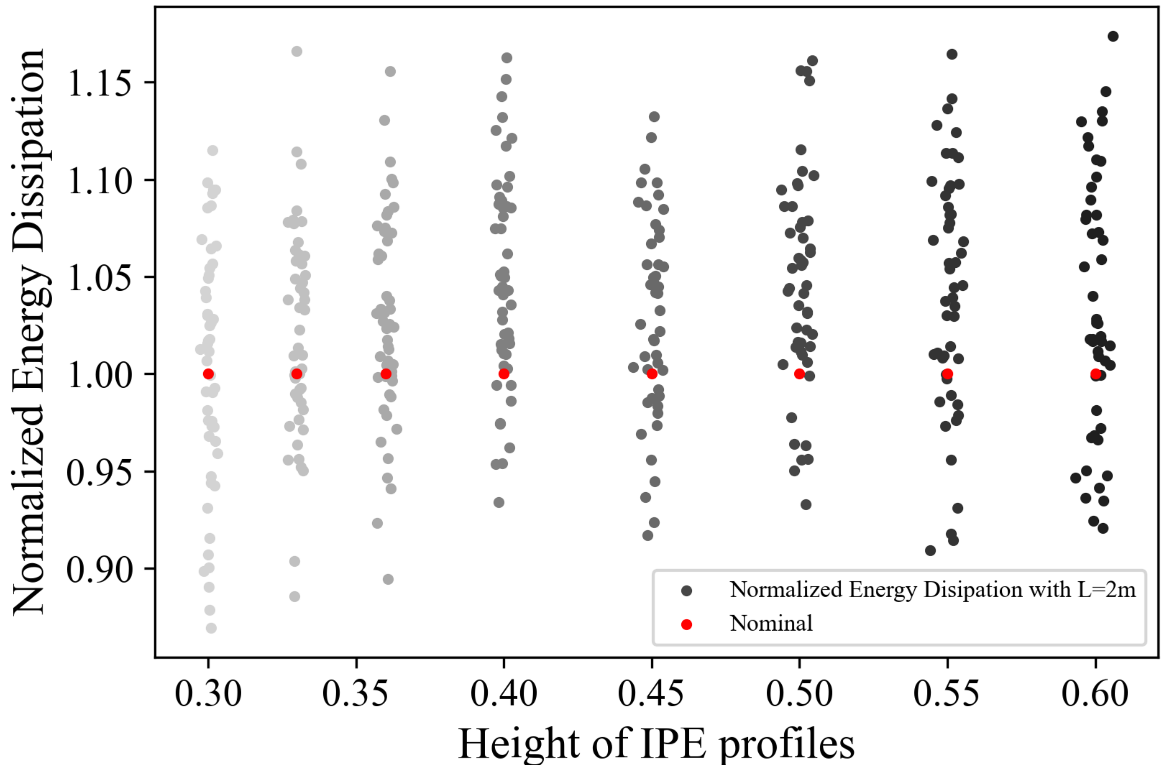
M_{max}/M_y for the **IPE profiles** with L=2m



- For most of the profiles the flexural **overstrength exceeds** that prescribed in **EC8**.
- **Capacity design** may not be as effective as one would expect.

Results (IPE)

Normalized energy dissipation for the **IPE profiles** with L=2m

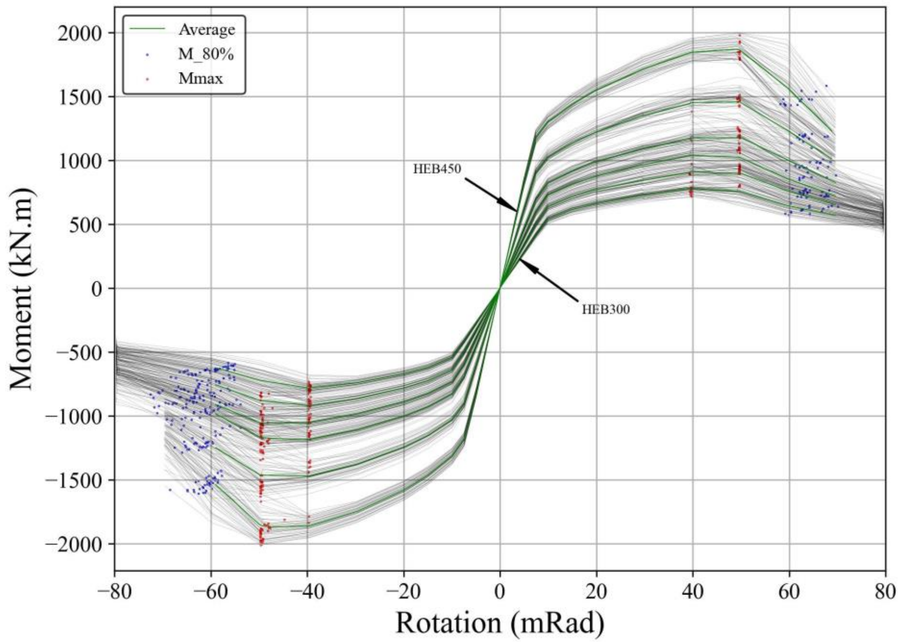


- Relatively **limited dispersion** but dependent on the **height of the profile**.

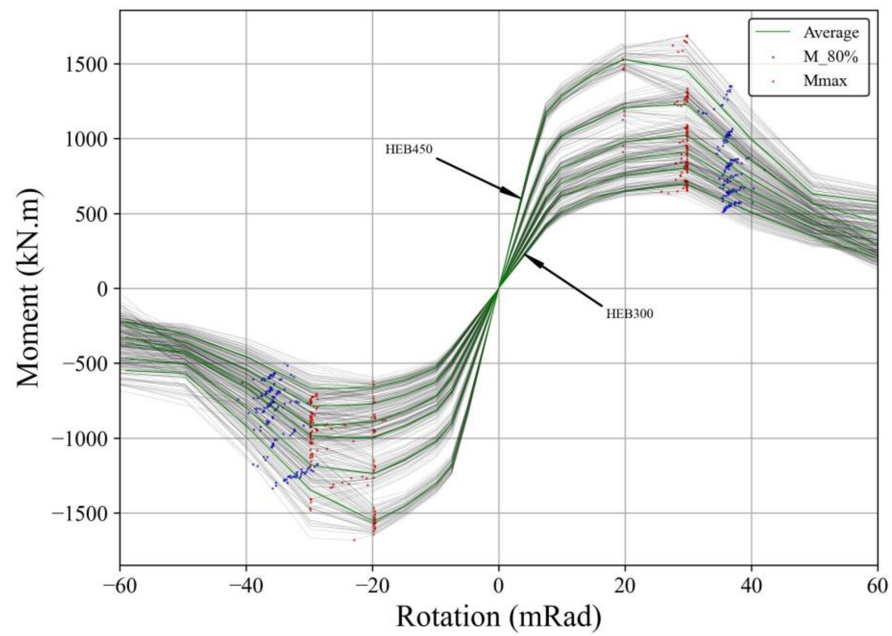
Results (HEB)

Backbone Curves of **HEB 300** to **HEB 450** (L=2m)

Normalized axial force = 0%



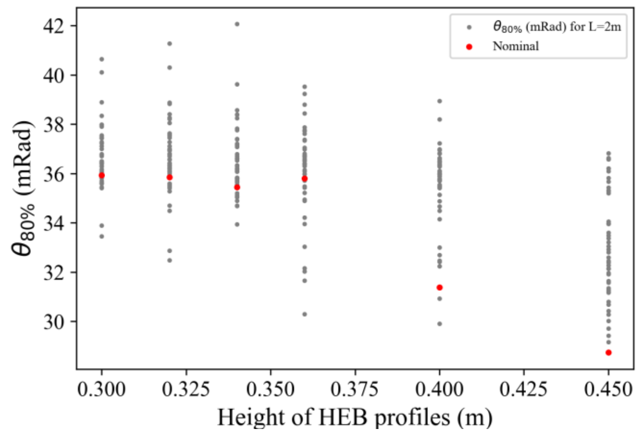
Normalized axial force = 30%

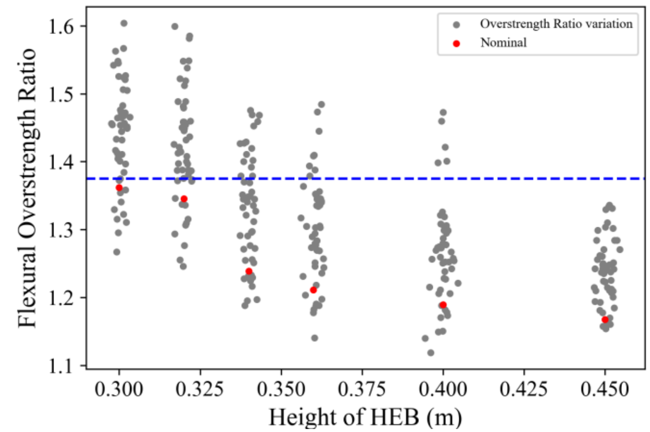


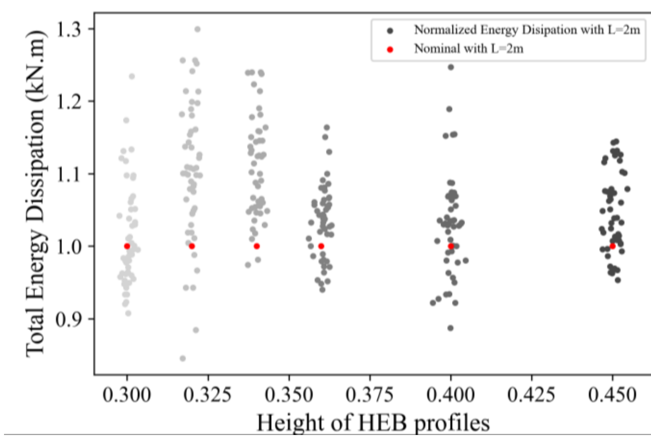
- As expected, the presence of **axial force reduces the ductility** of the members.

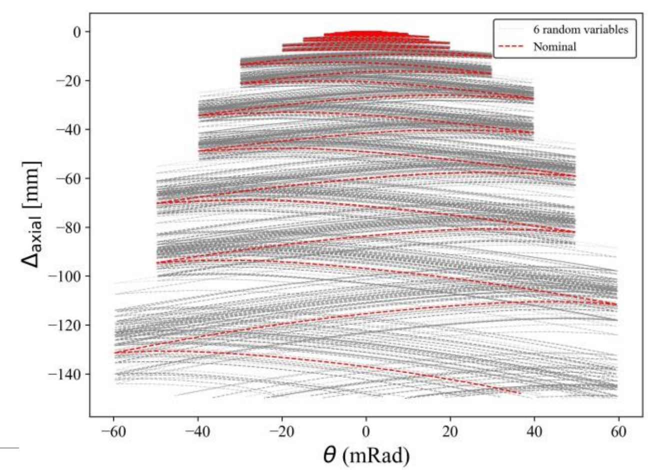
Results (HEB)

$\theta_{80\%}$, M_y/M_{max}, **Energy dissipation** and **axial shortening** for the **HEB profiles** with L=2m









- Overall, the **conclusions are similar** to those obtained for the **IPE profiles**.

Predictive Models

Nonlinear regression model

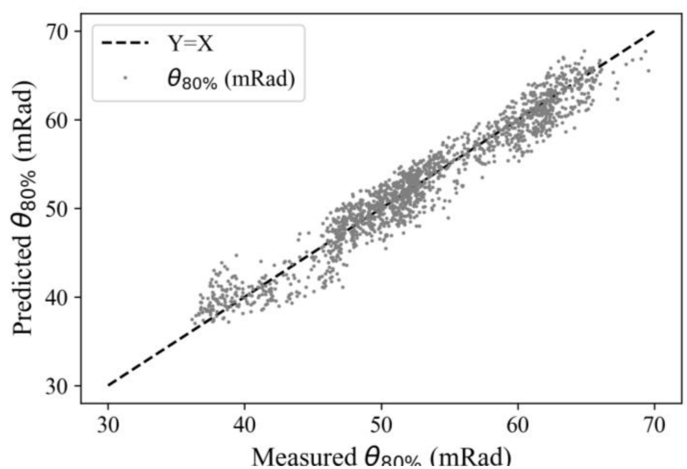
$$\theta_{80\%}(mRad) = a\left(\frac{L}{h}\right)^{b}\left(\frac{h_w}{t_w}\right)^{c}\left(\frac{b_f}{2t_f}\right)^{d}$$

Model parameters

Dataset	a	b	c	d
All IPE data	273.35	0.16	-0.45	-0.38

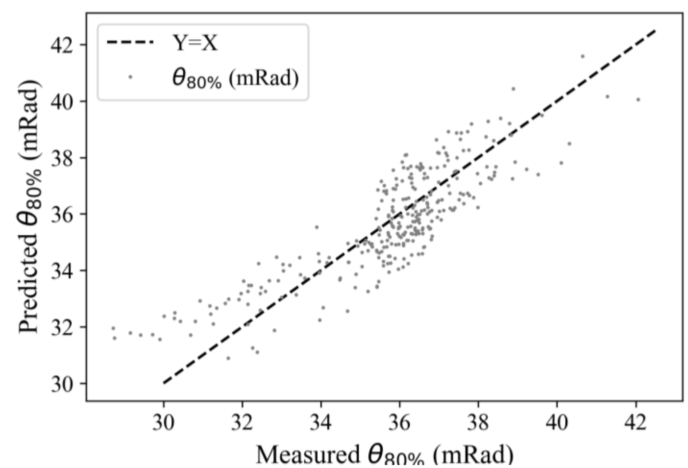
Dataset	a	b	c	d
HEB with Axial load	387	0.26	-0.61	-0.52

IPE



Prediction	RMSE	R^2
$\theta_{80\%}$	1.83	0.93

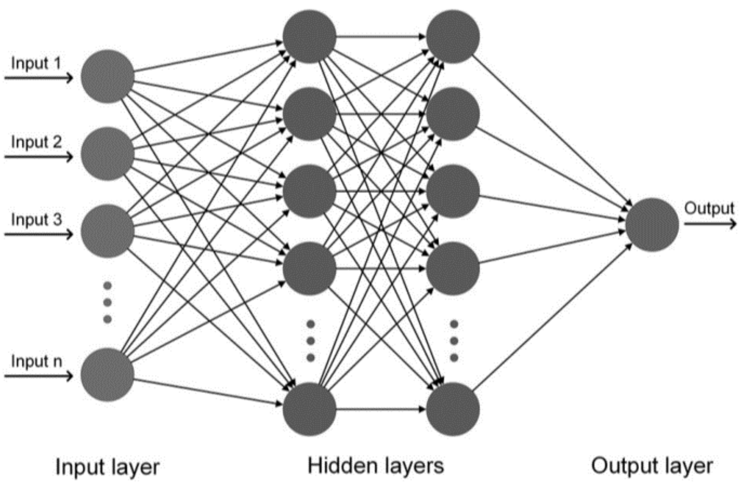
HEB



Prediction	RMSE	R^2
$\theta_{80\%}$	1.11	0.72

Predictive Models

Neural network model



Input Variables	Description
h	Height of the profile
b_1	Top flange width
b_2	Bottom flange width
t_1	Web thickness
t_{21}	Top flange thickness
t_{22}	Bottom flange thickness
L_b	Unbraced length
C	Web depth

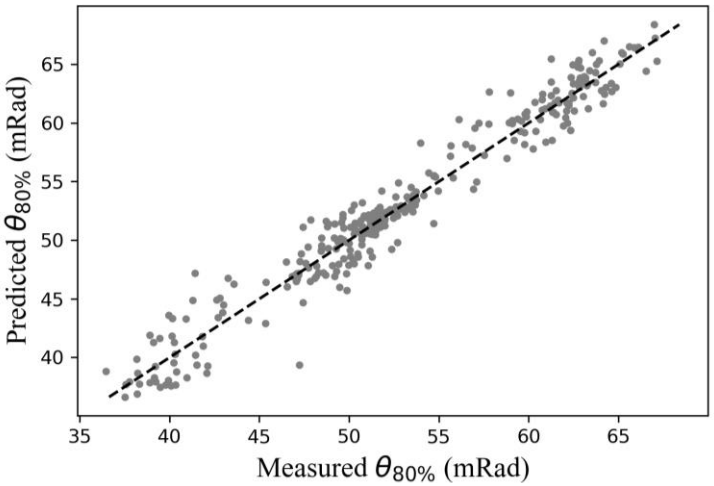
Training data set:

- **1600** results for IPE profiles
- **300** results for HEB profiles subjected to axial loading

Predictive Models

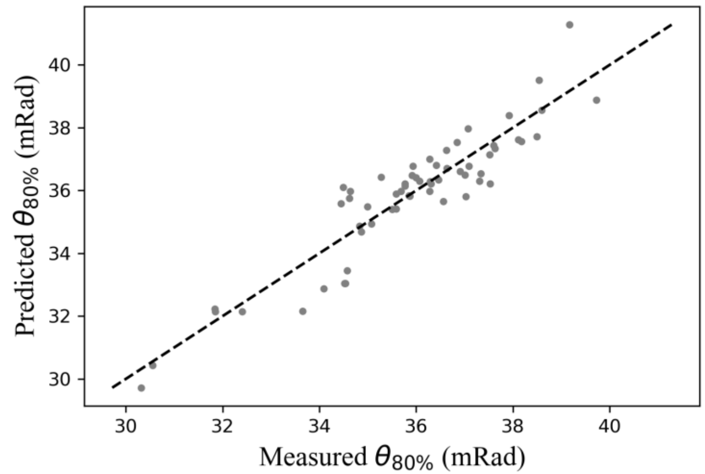
Neural network model

IPE



Prediction	RMSE	R^2
$\theta_{80\%}$	**1.23**	0.971
$\theta_{80\%}$ (NL)	1.83	0.93

HEB



Prediction	RMSE	R^2
$\theta_{80\%}$	**1.06**	0.71
$\theta_{80\%}$ (NL)	1.11	0.72

- The **neural network** model exhibits **higher accuracy**.
- But what should be the **“delivery mode”** in a seismic code?

Conclusions

- **Manufacturing tolerances** induce **geometrical variability** on steel profiles.
- The effect on **cross-section slenderness** is directly reflected on the **ductilit**y of the members.
- **Rotation** associated to the **near collapse** limit state is **highly influenced** by the geometrical variability.
- **Flexural overstrength** is also greatly influenced by the geometrical variability and can **easily exceed the EC8 prescriptions**.
- **Neural network models** can provide **accurate predictions** of different behaviour parameters.
- **Challenges** regarding the implementation of these models in a code context.

Thank You