Seismic Risk Mitigation in Steel Moment-frame Construction

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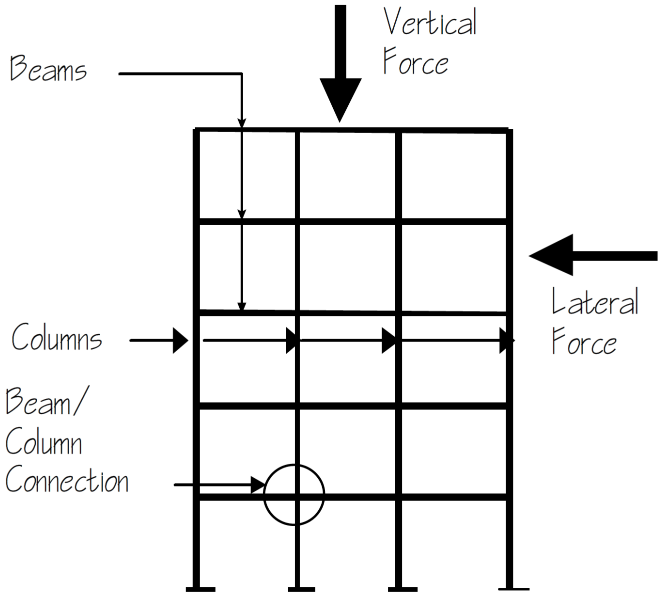
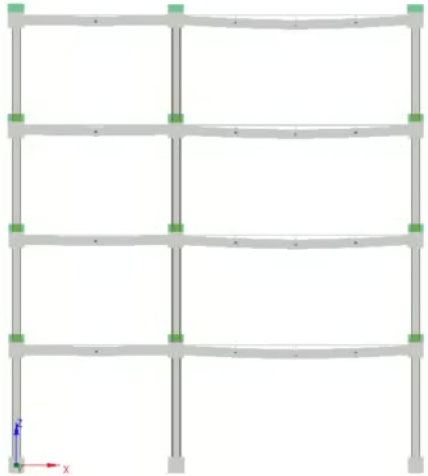
InfraRisk PhD Summer Workhop 2021
September 17

Foreword

- **Steel Moment-Frame Construction**

Photo: AISC / Michael Engelhardt





Foreword

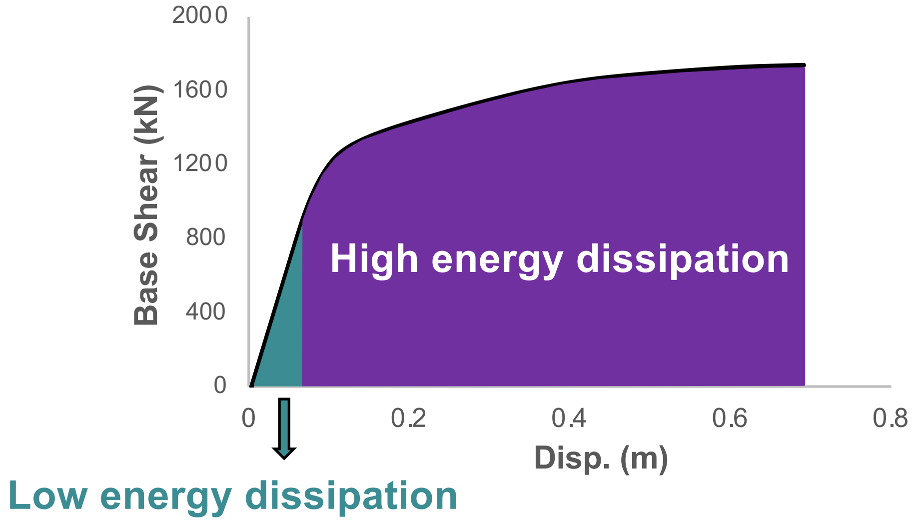
- Steel Moment-Frame Construction

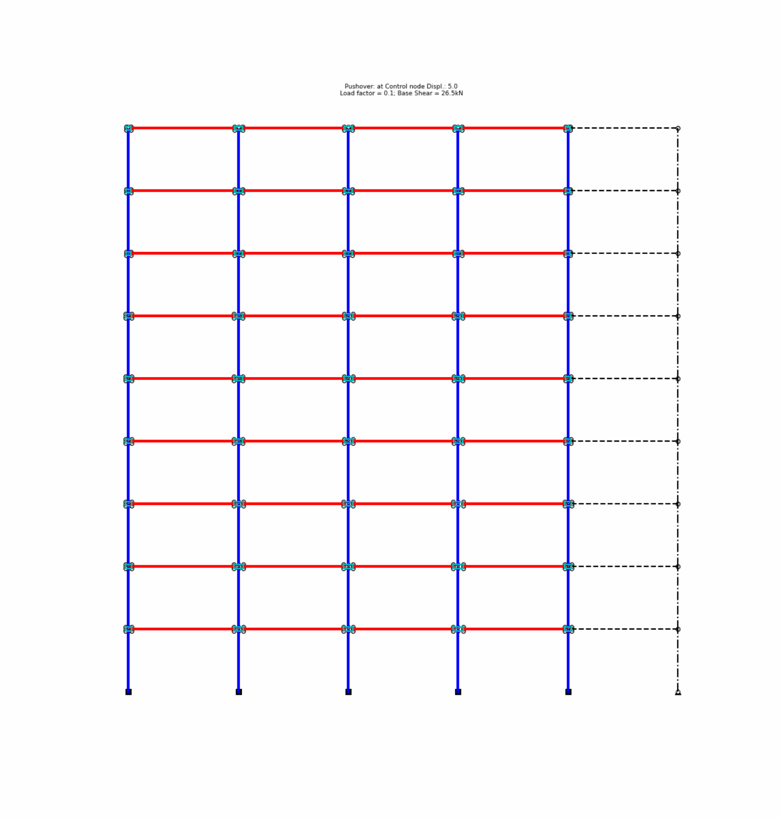
Photo: AISC / Michael Engelhardt

- Architectural versatility
- High ductility
- Low lateral stifness

Foreword

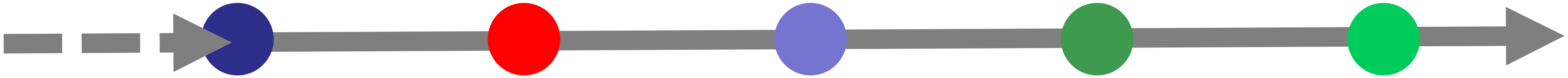
- when a earthquake occurs these structural systems will behave:
  - Elastically
  - With plastic deformation





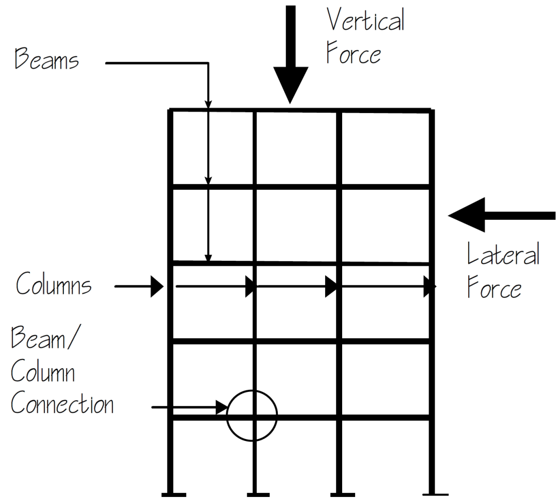
Foreword

Northridge earthquake
Kobe earthquake.
1994, 1995



In steel buildings built before 1960s, the **connections between the beams and columns were either bolted or riveted**.

While these older buildings also may be vulnerable to earthquake damage, **they did not experience the type of connection fractures discovered following the Northridge earthquake**.

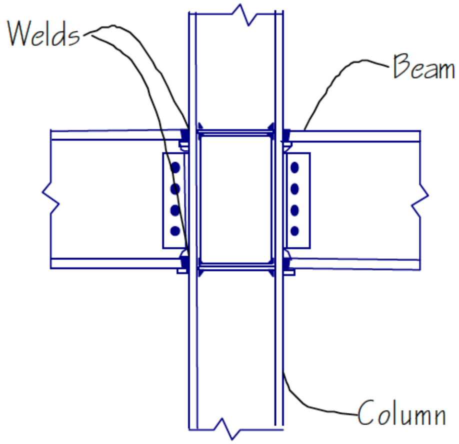


Foreword

Northridge earthquake
Kobe earthquake.

1994, 1995

The steel moment-frame buildings damaged in the 1994 Northridge earthquake are welded steel moment-frames, where the beams and columns are connected with welded joints.



In 1995, the Kobe earthquake resulted in damage to several hundred steel buildings, and the collapse of 50 older steel buildings. Japanese researchers have confirmed **problems similar to those experienced in the Northridge earthquake**

Foreword

A Policy Guide to Steel Moment-frame Construction
Structural Engineers Association of California (SEAOC)
FEMA 354/November 2000.

2000

After the Northridge earthquake, US FEMA and SAC joint venture developed a six-years research project to **prequalify a set of selected joint types** to be used in moment resisting frames. The results were directed to feed into a specific standard (ANSI/AISC 358-05)

Seismic prequalification activity was also successfully accomplished in Japan.

Foreword

Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

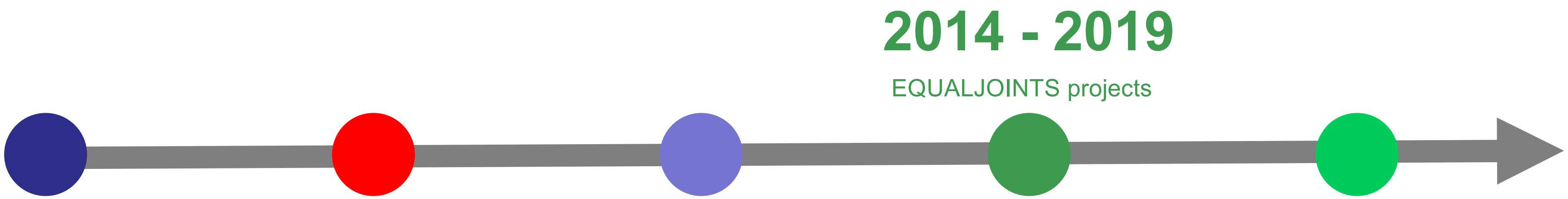
2004

Both non-dissipative and dissipative joints are allowed by EN1998-1:2004.

Specific requirements and design rules for seismic applications are missing.

The Code prescribes design assisted by tests for dissipative joints, incompatible with real-life projects.

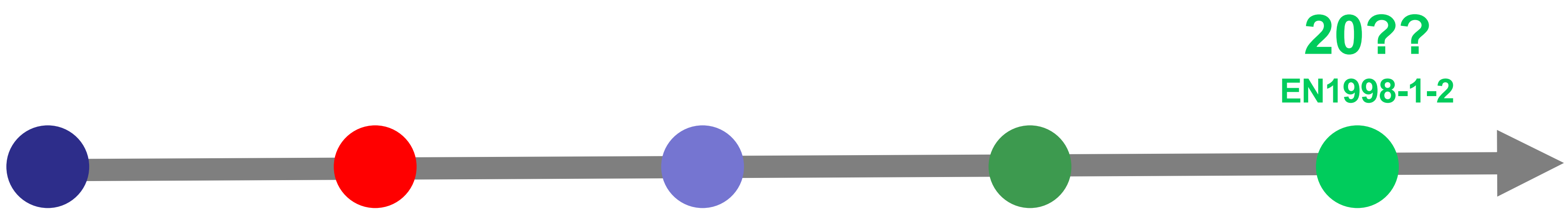
Foreword



https://publications.europa.eu/s/j7q0

- Design recommendation per type of qualified joint have been developed.
- Design guidelines including step-by-step design procedure per joint type.
- The limits of application of the current EC3 requirements for dissipative and non-dissipative joints have been examined
- Technical criteria have been developed to clearly highlight which beam-to-column joints for seismic application should be used.

Foreword



Experimental validation for partial and full-strength connections may be omitted if prequalified connections are used

Seismic Risk Mitigation in Steel Moment-frame Construction

OUTLOOK

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OUTLOOK

1. The role of the joints in analysis of Steel Moment-Frames (SMF)
2. Cyclic behaviour of steel joints – assessment strategies
3. The Cyclic Component Model (CCM) – Computational implementation
4. Research projects – seismic pre-qualification of steel connections
5. Final Remarks

Seismic Risk Mitigation in Steel Moment-frame Construction

The role of the joints in Steel Moment-Frames (SMF)

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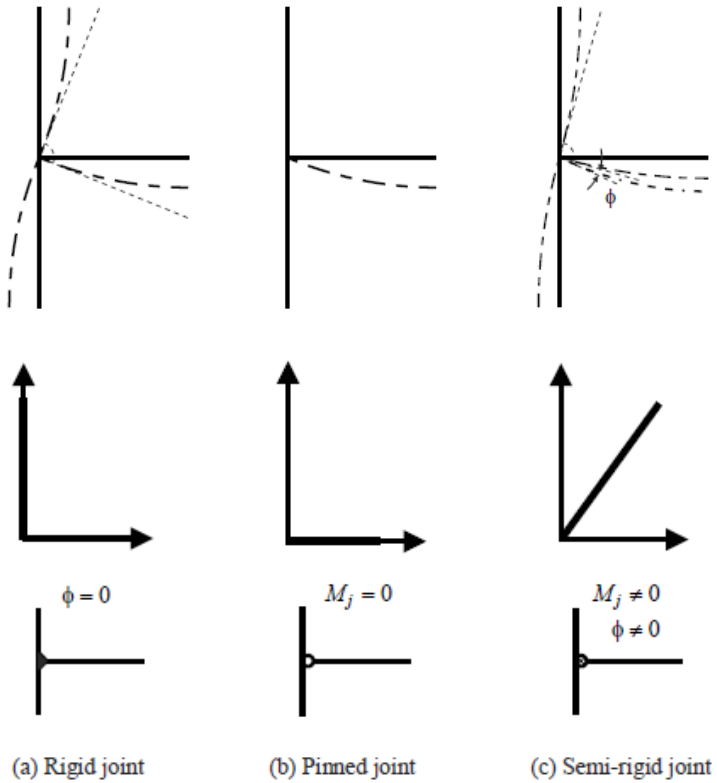
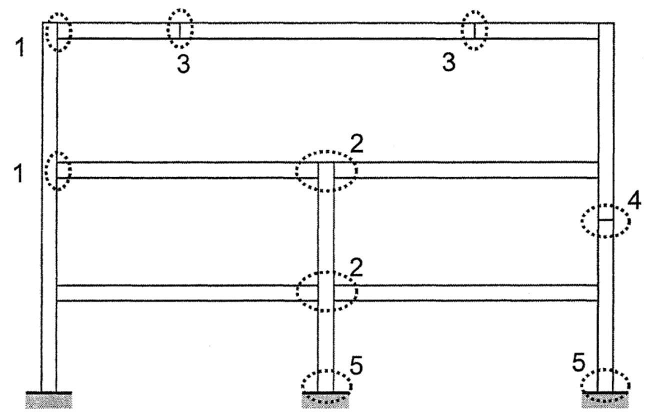
The role of the joints in SMF

- Why are joints important?



- Joints represent 50% of the cost of a steel structure.
- Needed to allow for pre-fabrication.
- Adjacent or included in critical regions for seismic performance.



The role of the joints in SMF

- According to Eurocode 8 (EN 1998-1:2004):

  - 6.5.2 (Design criteria for dissipative structures)

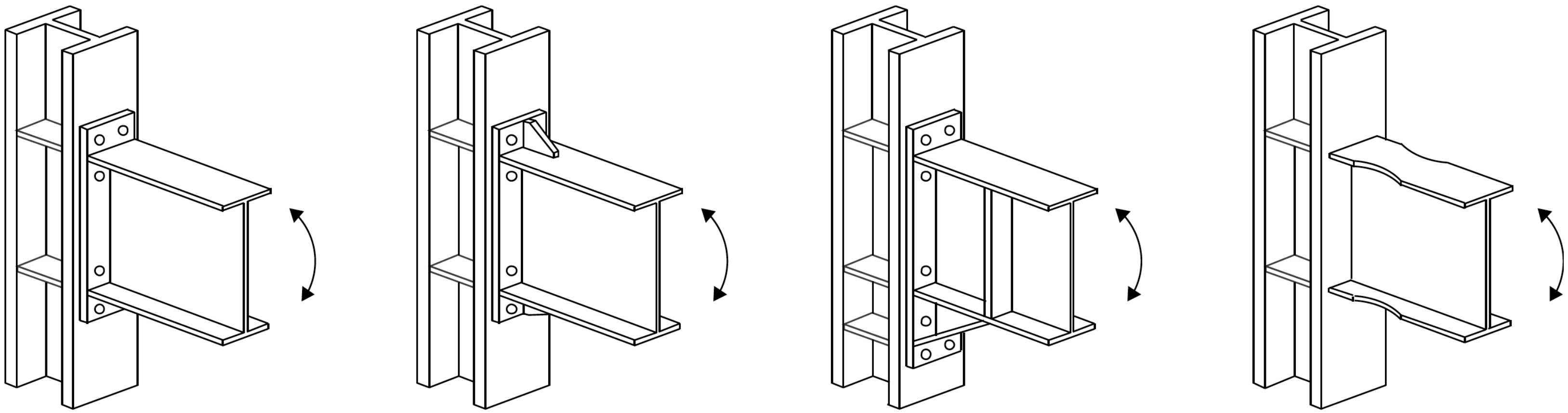
    (3) Dissipative zones may be located in the structural members or in the connections.

  - 6.6.4(3c) (Beam to column connections)

    c) the effect of connection deformation on global drift is taken into account using non-linear static (pushover) global analysis or non-linear time history analysis.

The role of the joints in SMF

- ❑ **What are joints in SMF? - Definitions**



Bolted extended endplate Joints

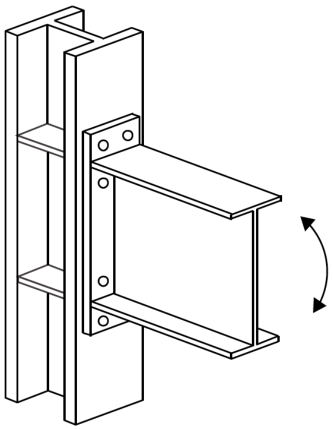
unstiffened **stiffened**

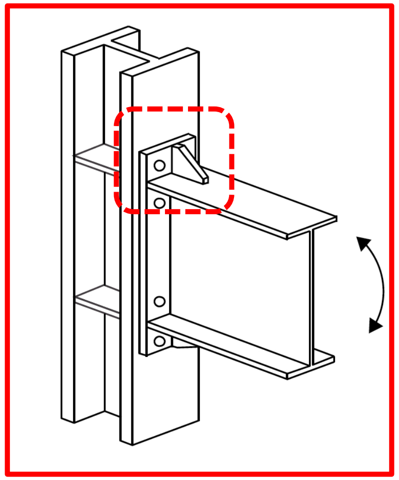
Bolted haunched joints

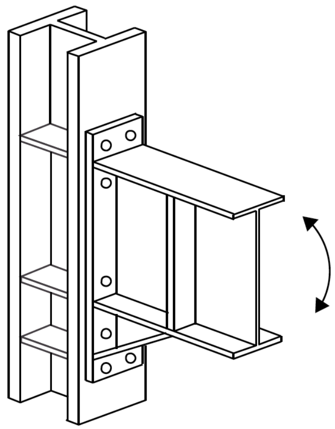
Welded dog-bone joints

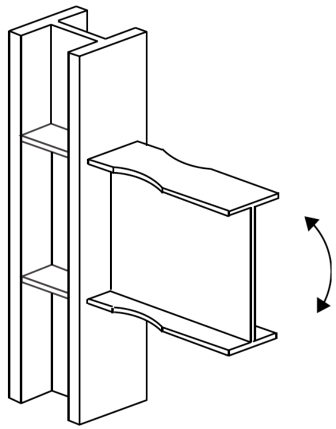
The role of the joints in SMF

- ❑ **What are joints in SMF? - Definitions**









Bolted extended endplate Joints

unstiffened **stiffened**

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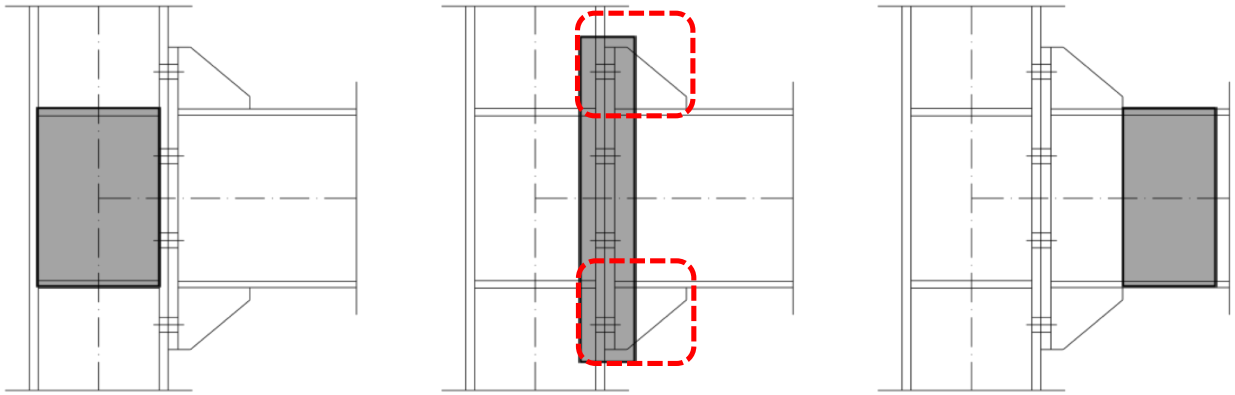
The role of the joints in SMF

- What are joints in SMF? - Definitions

regions adopted for performance design objectives



Column web panel **Connection** **Beam**

The role of the joints in SMF

- What are joints in SMF? - Definitions

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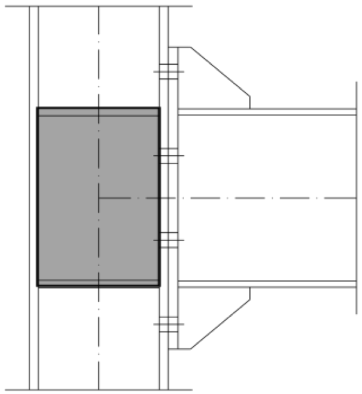


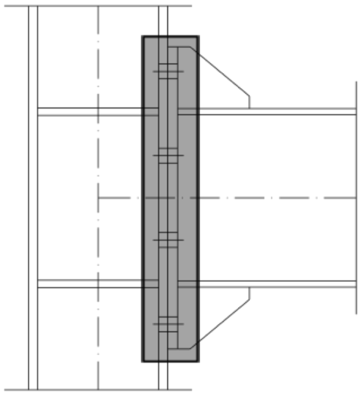
Column web panel

- **Full strength column web panel** is designed to be stronger than other macrocomponents (beam or connection).
- **Equal strength column web panel** is designed to have a strength close to the one of the beam/connection/both.
- **Partial strength column web panel** is designed to develop plastic deformations exclusively with itself.

The role of the joints in SMF

- What are joints in SMF? - Definitions

regions adopted for performance design objectives



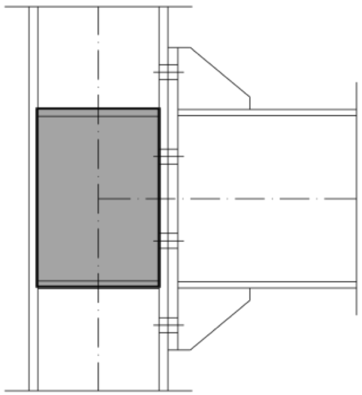
Connection

- **Full strength connection** is designed to be stronger than other macro-components (beam or CWP)
- **Equal strength connection** is designed to have a strength close to the one of the beam or CWP or both.
- **Partial strength connection** is designed to develop plastic deformations within its components

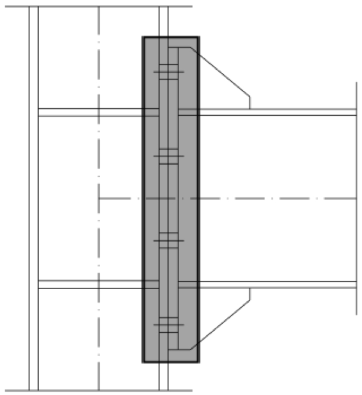
The role of the joints in SMF

- **What are joints in SMF? - Definitions**

regions adopted for performance design objectives



Column web panel



Connection

ES-B-E (**E**xtended-**S**tiffened end-plate joint with a **B**alanced panel zone and **E**qual strength connections**)**

ES-S-F (**E**xtended-**S**tiffened end-plate joint with a **S**trong panel zone and **F**ull strength connections**)**

The role of the joints in SMF

❑ Research question:

- what is the **impact of semi-rigid joint** on the analysis and design of SMF?

  According to Eurocode 8 (EN 1998-1:2004):
- 6.6.4(3c) (Beam to column connections)

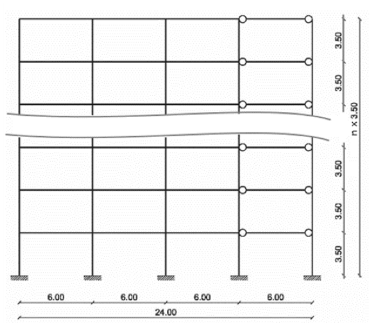
  c) the effect of connection deformation on global drift is taken into account using non-linear static (pushover) global analysis or non-linear time history analysis.

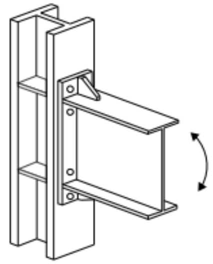
❑ Numerical assessment made on a large number of study cases

- Different joint modelling strategies
- Variation of number of stories, beam span, steel grade, ductility classes
- Non-linear static and dynamic analyses

The role of the joints in SMF

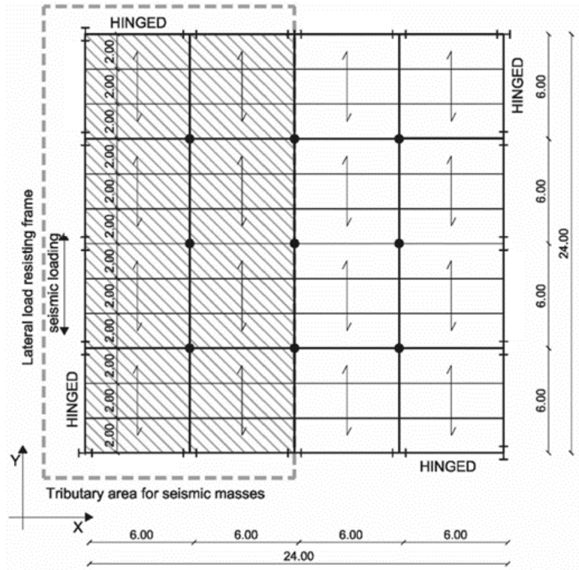
- **Seismic Analysis & Design w/out Joint Behaviour**





Case Study Buildings:

- 3, 6 and 9 storey office building, 3.50m storey height 6m span, seismic resistance of the building provided by the perimeter frames.
- **Connections:** Extended Stiffened (ES) endplate
  - with Balanced panel zone and Equal strength **(BE)**
  - with Strong panel zone and Equal strength **(SE)**
  - with Strong panel zone and Full strength **(SF)**



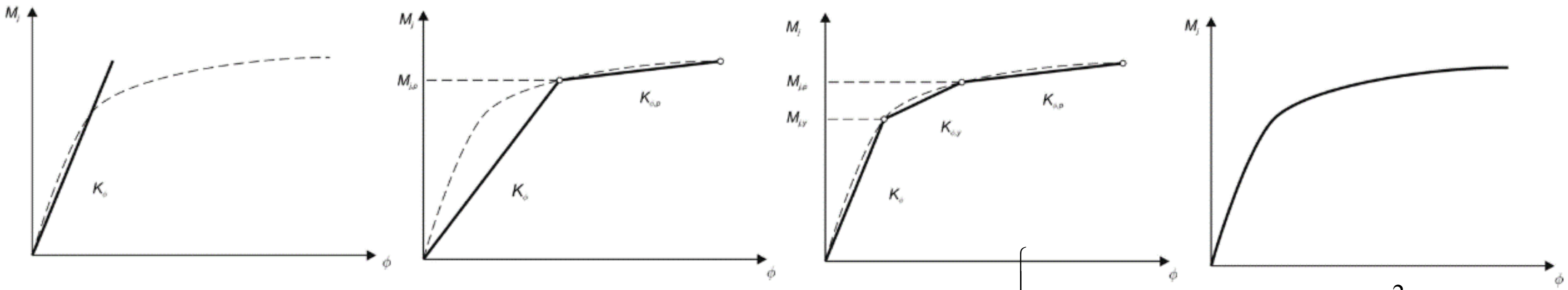
- *Seismic performance of dual concentrically braced steel frames accounting for joint behavior (RPEE, novembro 2019)*
- *Seismic Design and Performance Assessment of Steel Frames Considering Joints' Behaviour (EUROSTEEL2020)*

The role of the joints in SMF

❑ Moment-rotation Behaviour

- A mathematical model of the moment–rotation curve is required

- *Different degrees of accuracy* via; linear, bilinear, multilinear and nonlinear representations.



$$M_j = \begin{cases} S_{j,ini} \cdot \phi & \text{for } M_{j,Ed} \le \frac{2}{3} M_{j,Rd} \ \text{; Or} \\ \frac{S_{j,ini}}{\eta} \cdot \phi & \text{for all } M_{j,Ed} \le M_{j,Rd} \end{cases}$$

$$M_j = \begin{cases} \frac{S_{j,ini}}{\eta} \cdot \phi & \text{for } M_{j,Ed} \le M_{j,Rd} \\ M_{j,Rd} & \text{for } \left(M_{j,Ed} > M_{j,Rd} \text{; and } \phi \le \phi_{Cd} \right) \end{cases}$$

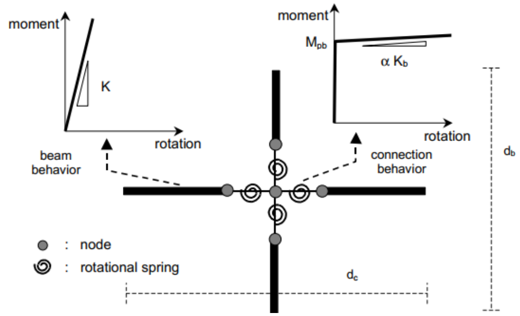
$$M_j = \begin{cases} S_{j,ini} \cdot \phi & \text{for: } M_{j,Ed} \le \frac{2}{3} M_{j,Rd} \\ \frac{S_{j,ini}}{\left(1.5 \cdot \frac{M_j}{M_{j,Rd}} \right)^{\xi}} \cdot \phi & \text{for: } \frac{2}{3} M_{j,Rd} < M_j < M_{j,Rd} \\ M_{j,Rd} & \text{for: } \left(M_{j,Ed} > M_{j,Rd} \text{; and } \phi \le \phi_{Cd} \right) \end{cases}$$

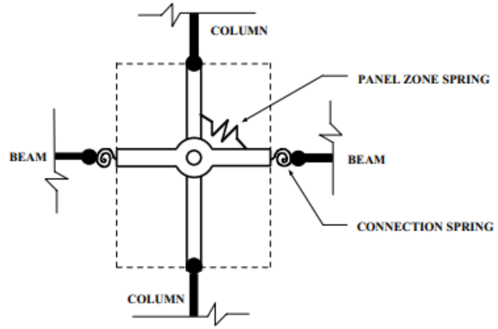
The role of the joints in SMF

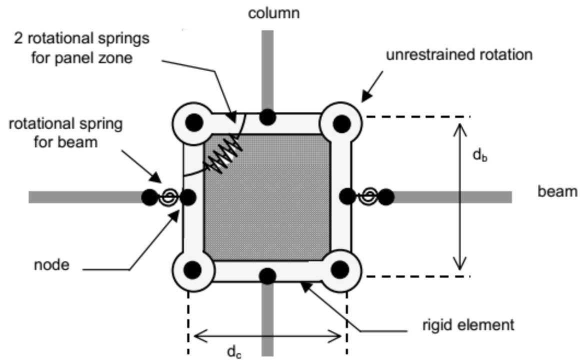
❑ Structural Modelling of Steel Frames

- **<u>Centerline models</u>** are commonly practiced. [*Linear/Non-linear*]

- Models with **Column Panel Zone**
  - **<u>Scissors model</u>:** a simplified centreline model where the panel zone is modelled with a scissors type arrangement. Can be linear or non-linear depending on the spring property.
  - **<u>Krawinkler model:</u>** introduces the full dimension of the panel zone in the modelling.





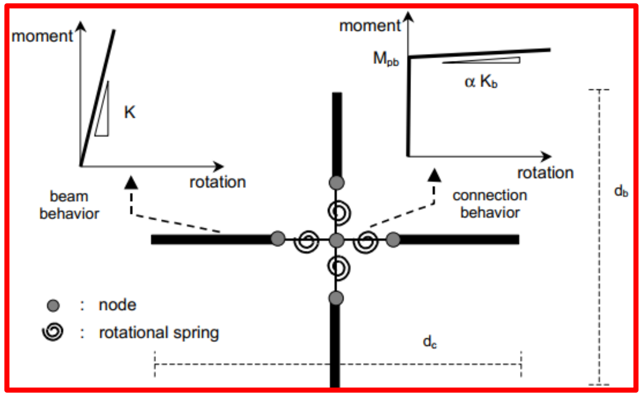


The role of the joints in SMF

❑ Modelling Strategies

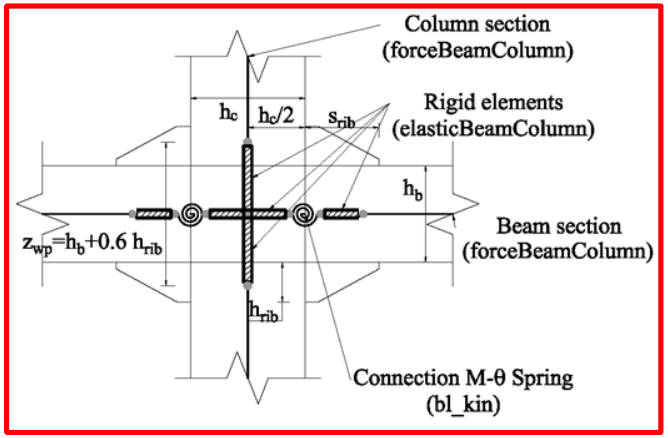
SIMPLIFIED MODELS DISREGARDING THE JOINT DIMENSIONS

- The structural elements are modelled from **centreline-to-centreline** of each intersecting element. These models disregard the size of the panel zone.
- the connection modelled by a bilinear moment rotation spring.



REFINED MODEL 1: CONSIDERING THE JOINT DIMENSIONS

- The panel zones of extended stiffened joints with **strong web panels** (**ES-S-E and ES-S-F)** are modelled using rigid elements. Stiffening ribs are also modelled with rigid elements.
- The connections are modelled by a bilinear moment rotation spring.

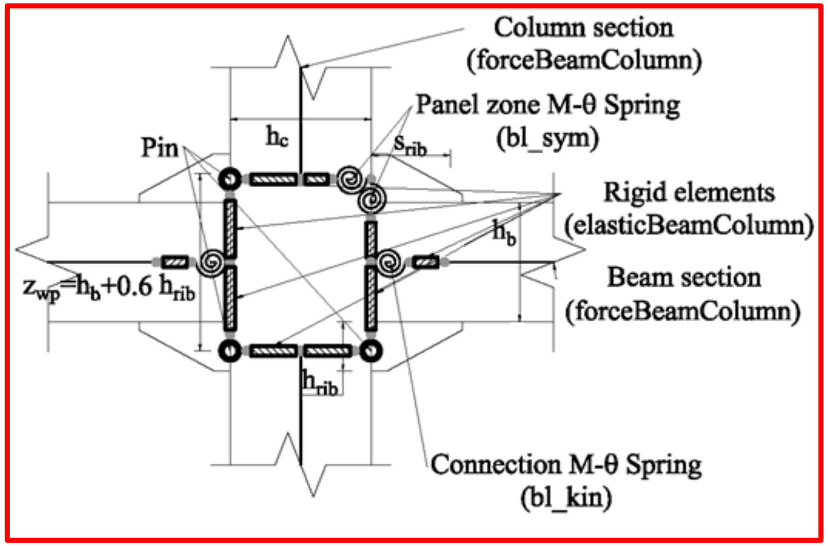


The role of the joints in SMF

❑ Modelling Strategies

REFINED MODEL 2: CONSIDERING THE JOINT DIMENSIONS

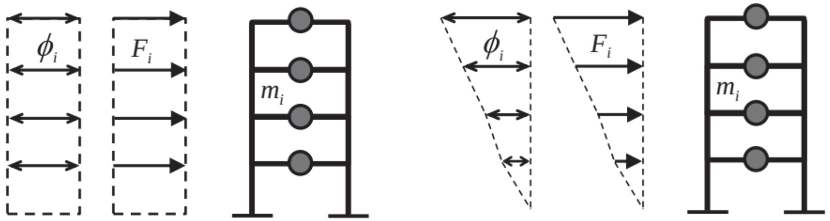
- For joints with **balanced web panel zone (BE)**, the Krawinkler-Gupta model is applied which accounts for the web panel dimensions and properties.
- The stretches of the beams that are stiffened by the stiffening ribs are also modelled with rigid elements.
- The connections are modelled by a bilinear moment rotation spring. Tri-linear behaviour of the web panel modelled by two bi-linear springs acting in parallel.

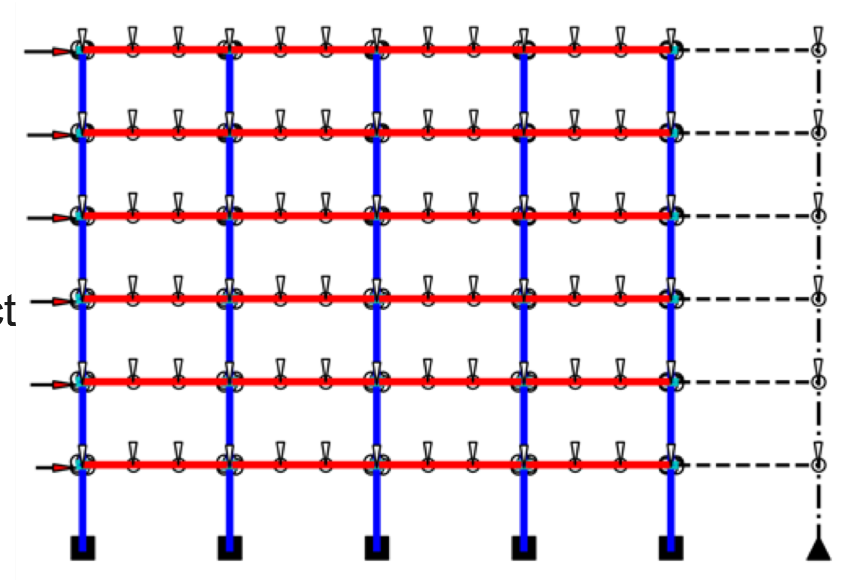


The role of the joints in SMF

❑ Non-Linear Static Analysis (Pushover)

- Two loading forms were used: Uniform pattern and Modal pattern





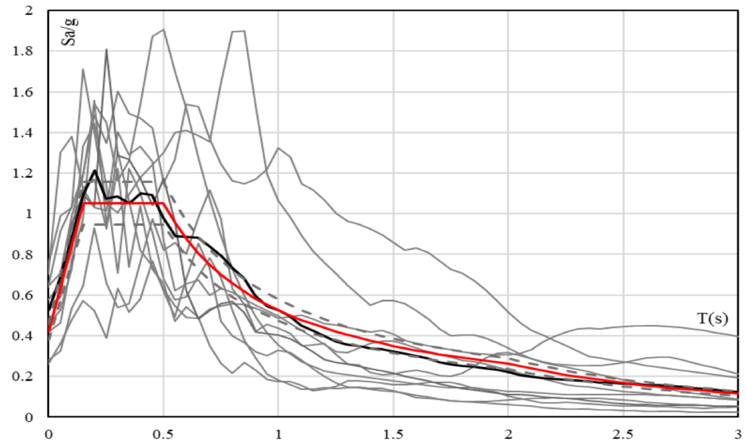
- Leaning columns were used to capture the P-Δ effect
- Parameters in the pushover capacity curves
  - The ratio V_u/V_1 is a measure of redundancy.
  - the μ factor given by δ_{max}/δ_1 reflects on ductility.

The role of the joints in SMF

❑ Non-Linear Incremental Dynamic Analysis (IDA)

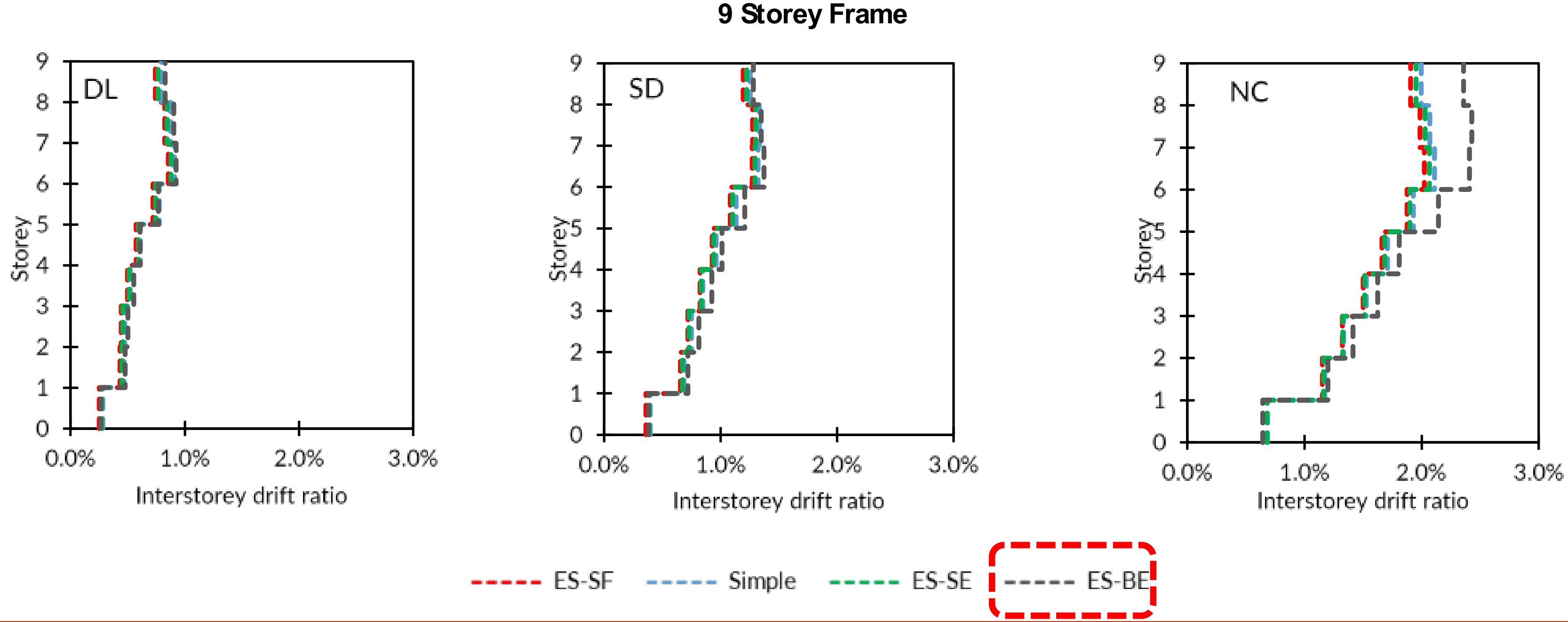
- **10 accelerograms** (real ground motion records)
- The accelerograms **match the linear elastic response spectrum of EN 1998-1 for soil type B and PGA of 0.35g**.
- Performance levels: **0.59 for Damage limitation (DL)**, **1.0 for Severe Damage (SD)** and **1.73 for Near Collapse (NC)**.

	Recorded accelerogram	Accelerogram multipliers
R1	Accumuli bevagna N-S	55.43
R2	ACHAIA Transversal	12.75
R3	AMATRICE E-W	9.81
R4	Brienza N-S	39.24
R5	Castelluccio Norcia N-S	15.21
R6	Castelsantangelosulnera E-W	5.89
R7	GEMONA L-T	11.97
R8	STURNO L-T	12.26
R9	TOLMEZZO Transversal	15.70
R10	Mirandola N-S	15.70



The role of the joints in SMF

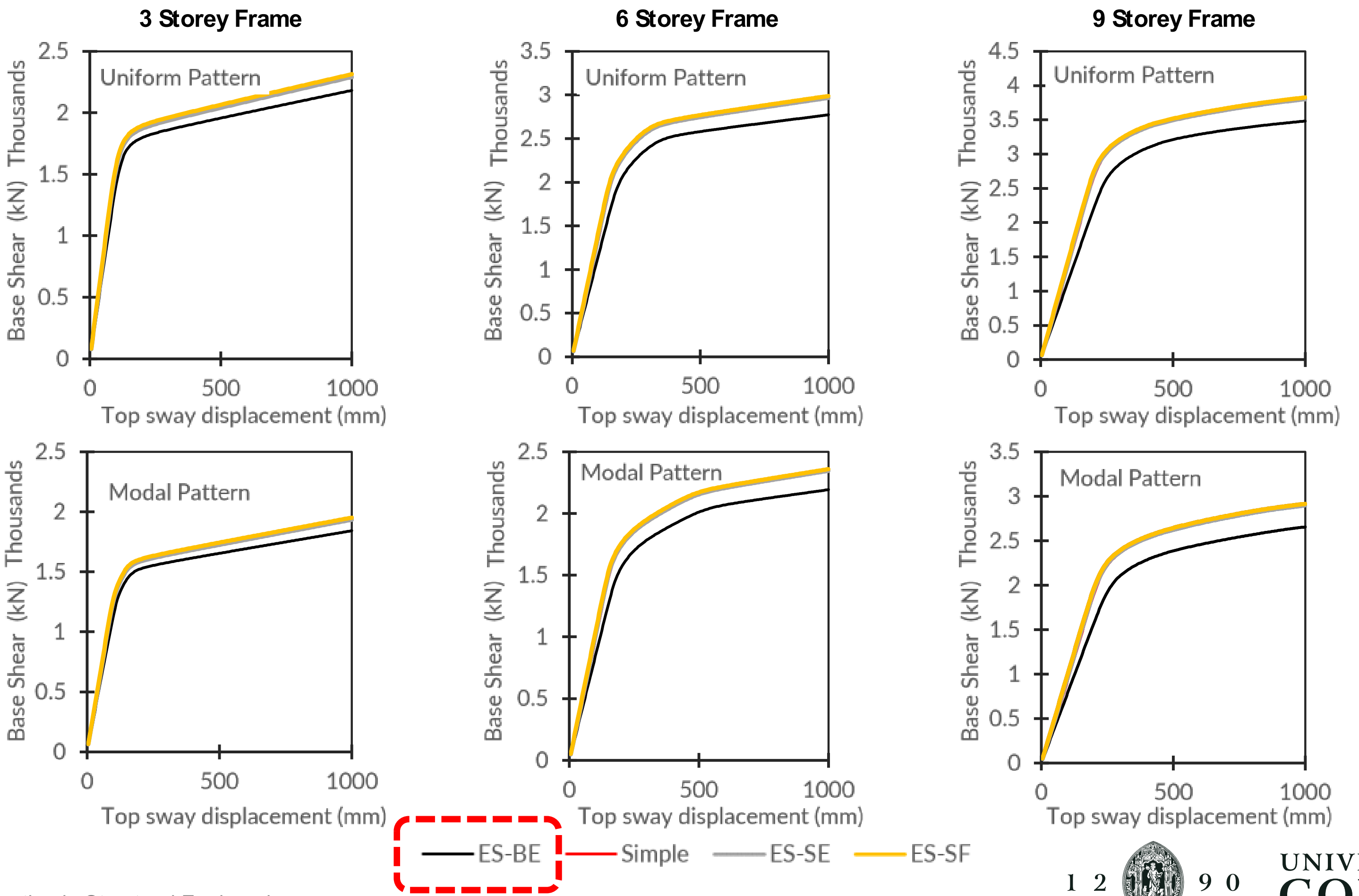
- **<u>Refined Models</u>' Results (Considering The Joint Dimensions)**



Comparatively higher interstorey drifts (12% average increase) with B-E type joints compared to the other two (strong web panels)

The role of the joints in SMF

Pushover Analysis Results

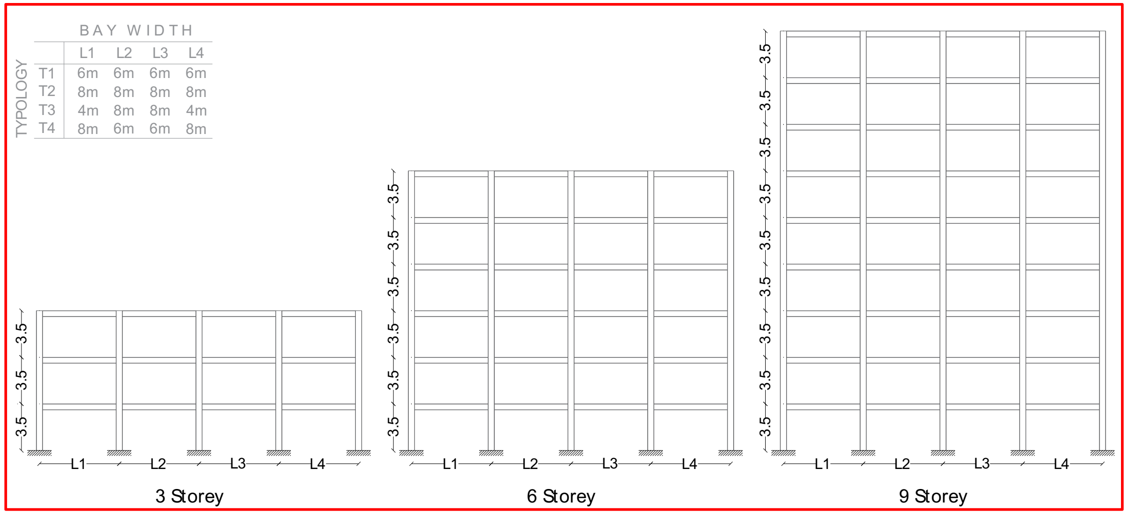


The role of the joints in SMF

- Additional parametric study

96 study cases
En1998-1:2004 vs. prEN1998-1-2:2021

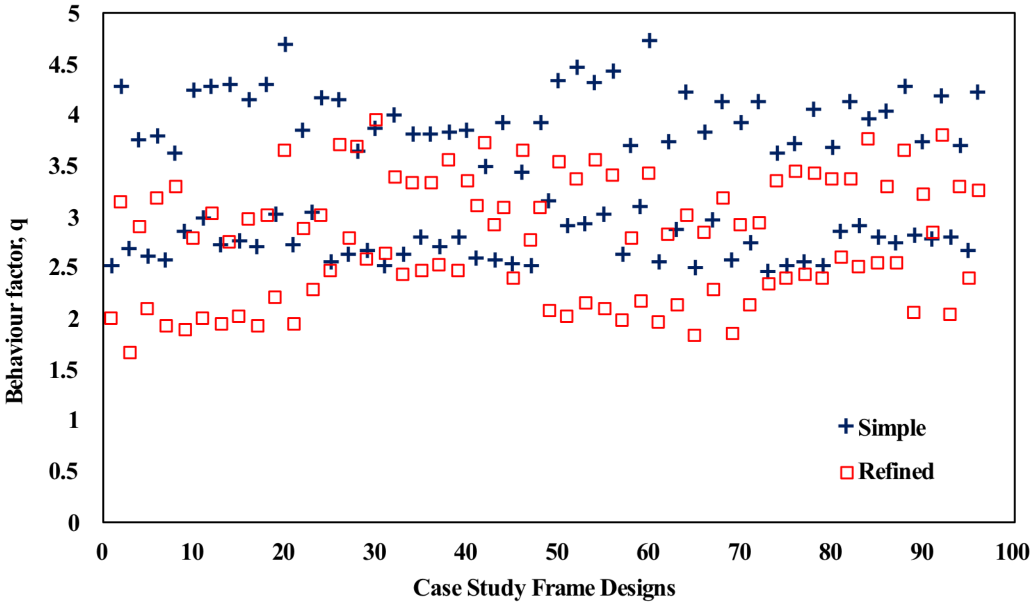
Current Code [1]		Revised Code [45]					
DCM	DCH	DC2			DC3		
$\boldsymbol{q}$	$\boldsymbol{q}$	q_D	q_R	$\boldsymbol{q}$	q_D	q_R	$\boldsymbol{q}$
4	$5 \cdot \alpha_u/\alpha_1$	1.8	1.3	3.5	3.3	1.3	6.5



Parameter Variations		Design					Assessment
Type	Spans (m)	Nº Floors	Location	DC - Q	Code	Grade	Joint
1	6;6;6;6	3	0.35g	DCM	Current	S235	Center-line
2	8;8;8;8	6	Type 1				
3	4;8;8;4	9	Soil type B	DCH	Revised	S355	ES-B-E
4	8;6;6;8						

The role of the joints in SMF

- Behaviour factors



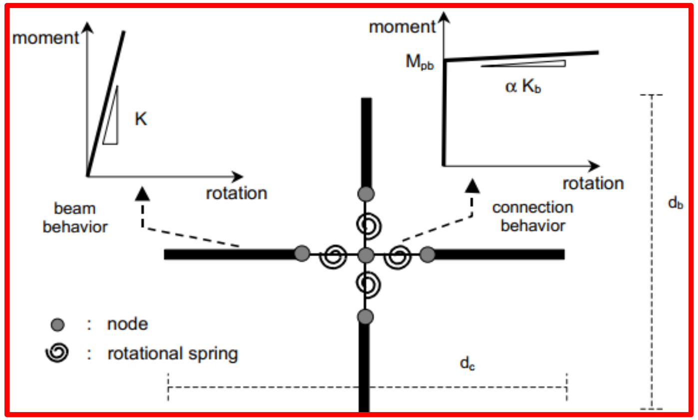
Behaviour factors computed with **Refined Models are lower**

The behaviour factors assumed in the design of the frames are much higher than the actual behaviour factors estimated from the analyses.

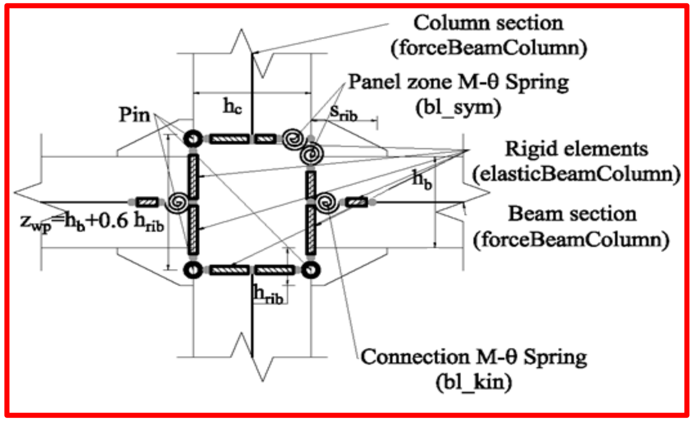
	q_Ω		q_μ		q	
	Simple	Refined	Simple	Refined	Simple	Refined
Minimum	1.21	1.03	1.85	1.58	2.45	1.67
Maximum	1.52	1.55	3.44	3.08	4.74	3.96
Average	1.35	1.24	2.50	2.24	3.37	2.78
Median	1.36	1.21	2.40	2.26	3.29	2.81
Stan. Dev.	0.07	0.10	0.48	0.41	0.68	0.59

The role of the joints in SMF

- The **simplified modelling** technique could be considered sufficient for cases with **strong web panel**.



- The **refined modelling techniques** are recommended for frames with **balanced web panel** zone.



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Cyclic behaviour of steel joints

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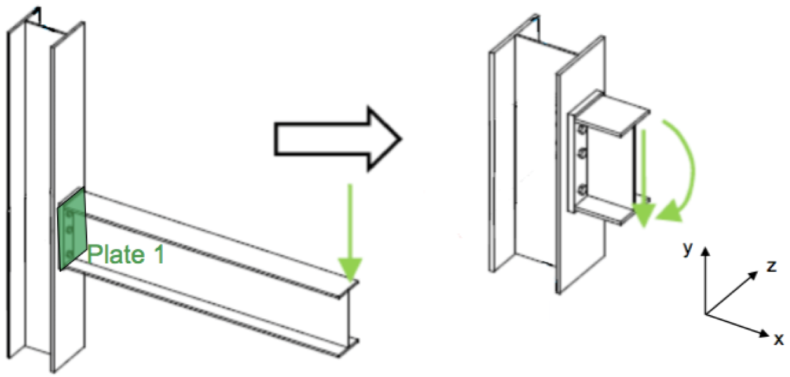
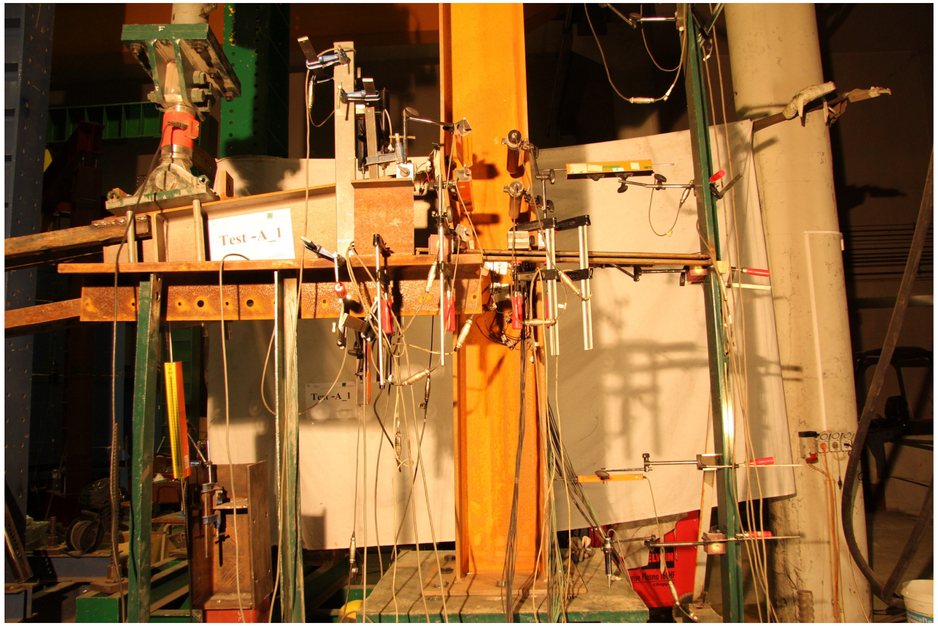
Cyclic behaviour of steel joints

❑ Behaviour Assessment Strategies

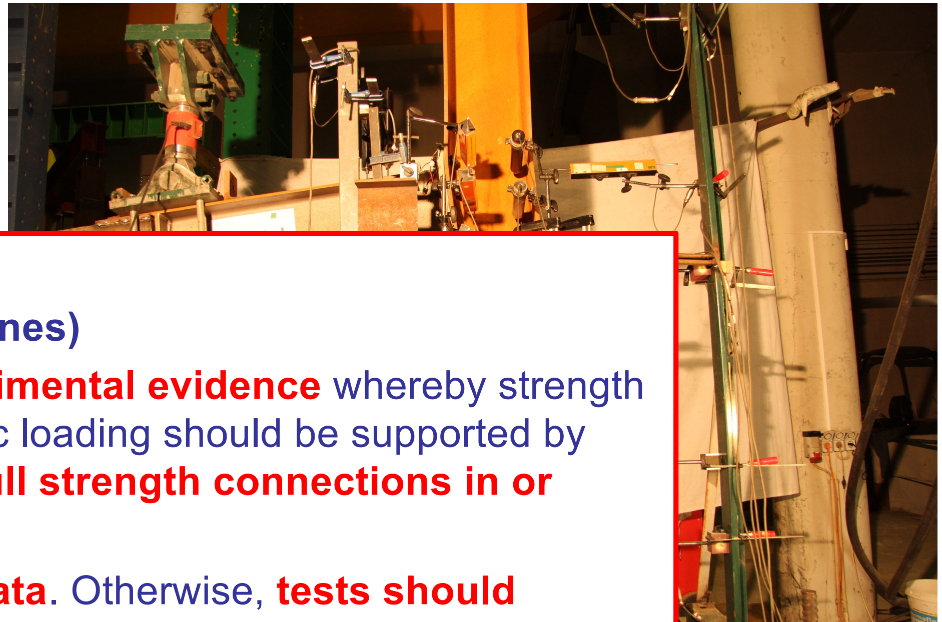
- **Experimental Tests**
  - The most accurate procedure
  - Requires specialized technicians and equipment
  - High consumption of time and resources





Cyclic behaviour of steel joints

- Behaviour Assessment Strategies
  - **Experimental Tests**
    - The most accurate procedure
    - Requires specialized technicians and equipment
    - High consumption of time and resources



EN 1998-1 (2004)

- **6.5.5 (Design rules for connections in dissipative zones)**

(6) The adequacy of design should be supported by **experimental evidence** whereby strength and ductility of members and their connections under cyclic loading should be supported by experimental evidence (…). **This applies to partial and full strength connections in or adjacent to dissipative zones**.

(7) **Experimental evidence may be based on existing data**. Otherwise, **tests should be performed**.

Cyclic behaviour of steel joints

❑ Behaviour Assessment Strategies

- **Experimental Tests**
  - The most accurate procedure
  - Requires specialized technicians and equipment
  - High consumption of time and resources

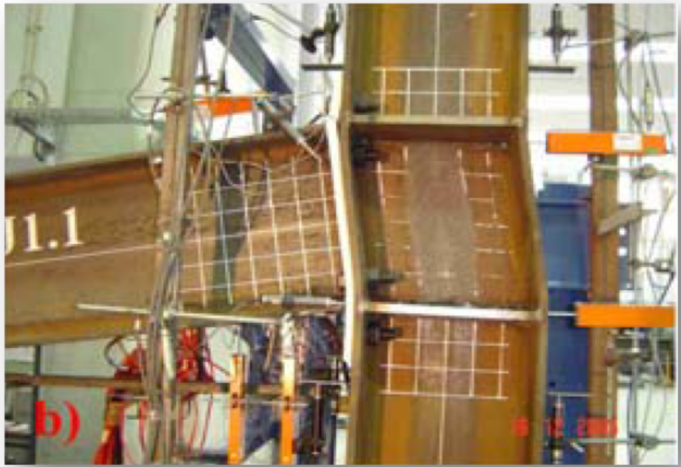
However:

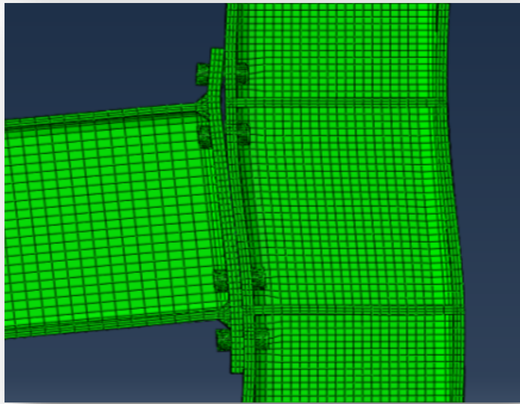
- Limited number of available publications reporting cyclic tests for European standards
- Difficulty of generalization of results
  - Diversity of testing procedures (e.g. cyclic loading protocol) >> RFCS project ‘EQUALJOINTS‘
  - Lack of data bases with detailed information >> RFCS project ‘HSS-serf’
  - …

Cyclic behaviour of steel joints

❑ Behaviour Assessment Strategies

- **Experimental Tests**
- **Finite Element models**
  - The most accurate and versatile of the analytical procedures
  - Requires model calibration
  - Allows for parametric studies
  - Serve as benchmark for simplified design methodologies: Component Model





Cyclic behaviour of steel joints

❑ Behaviour Assessment Strategies

- **Experimental Tests**
- **Finite Element models**
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  - Allows for parametric studies
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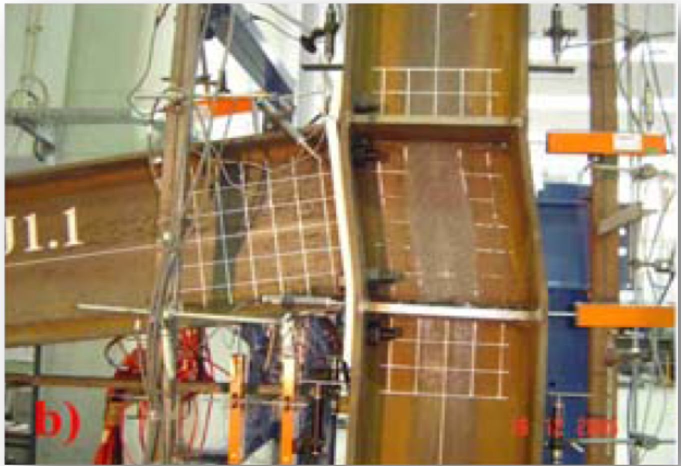
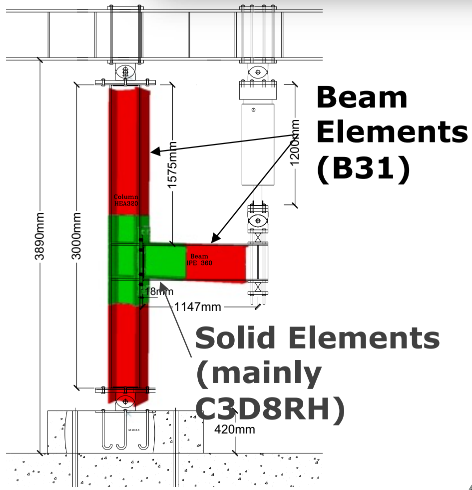
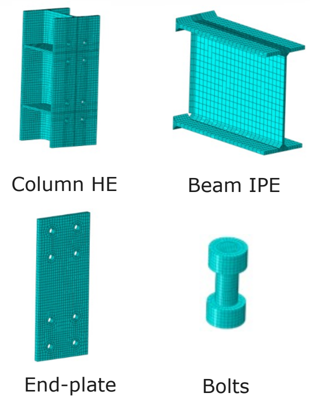
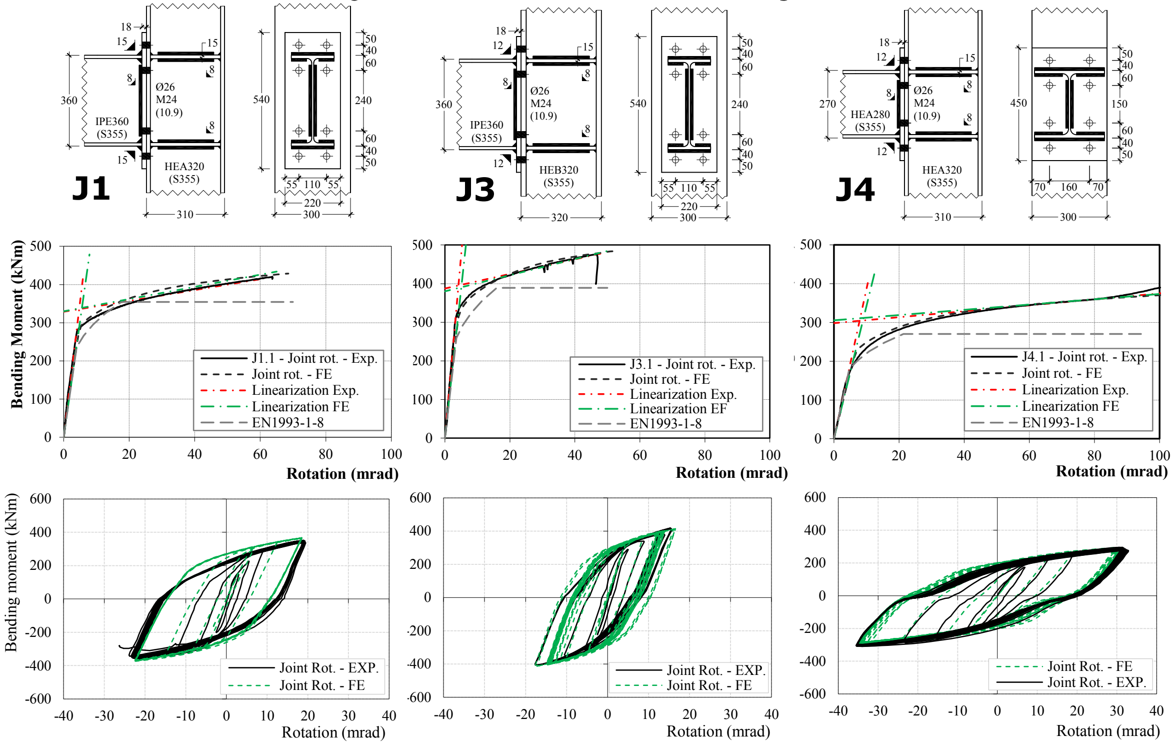






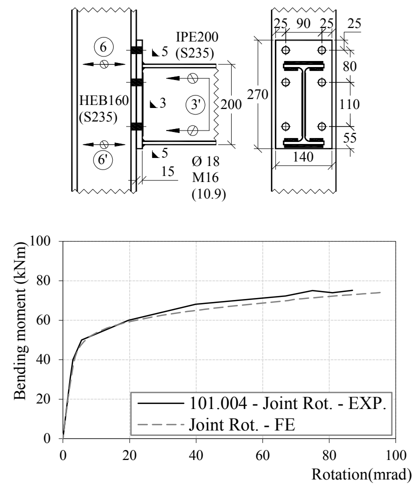
Cyclic behaviour of steel joints

- Development and Validation of the FEM with benchmarks (experimental tests) – static and cyclic behaviour of joints



Nogueiro (2009)

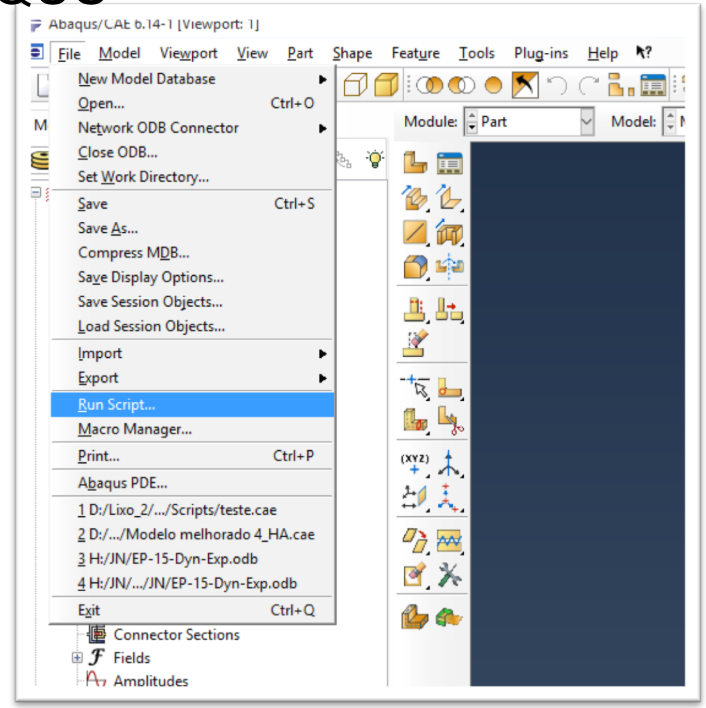
101.004

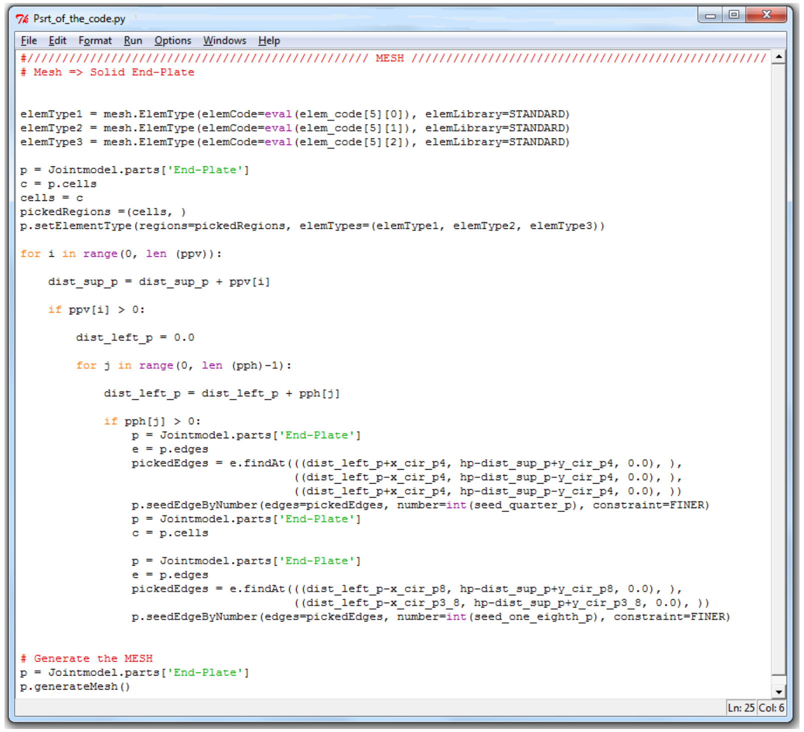


Jaspart and Maquoi (1990)

Cyclic behaviour of steel joints

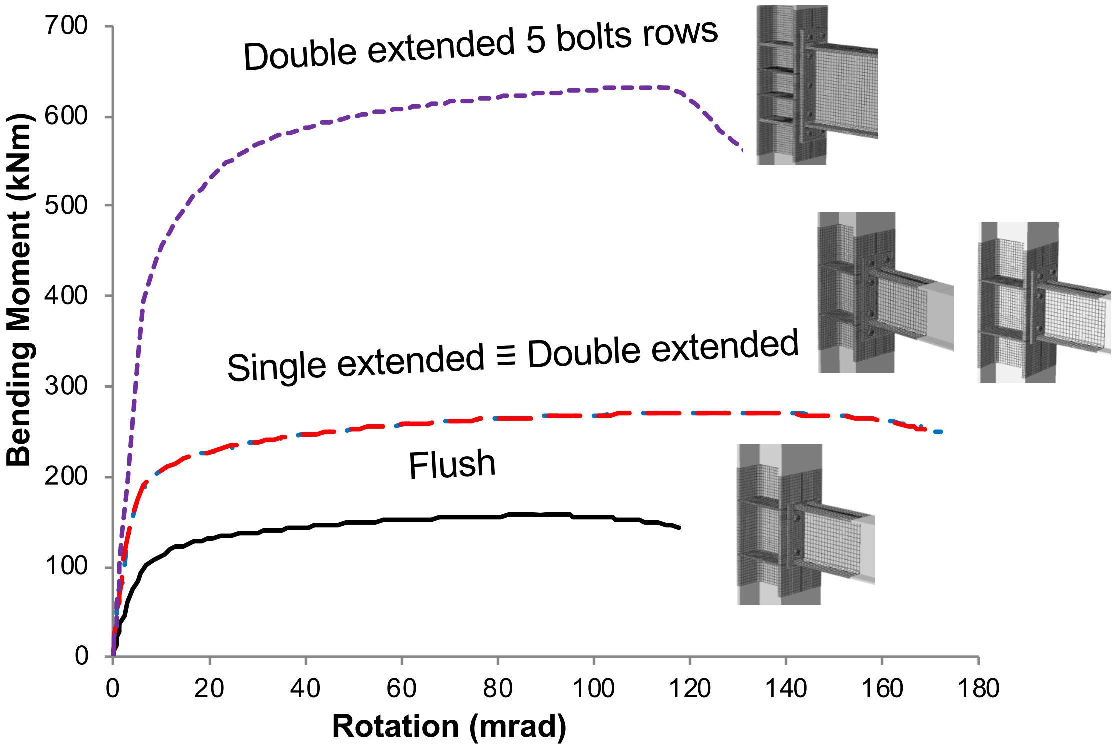
- ❑ Models may be generated automatically by Python scripts and compiled by ABAQUS

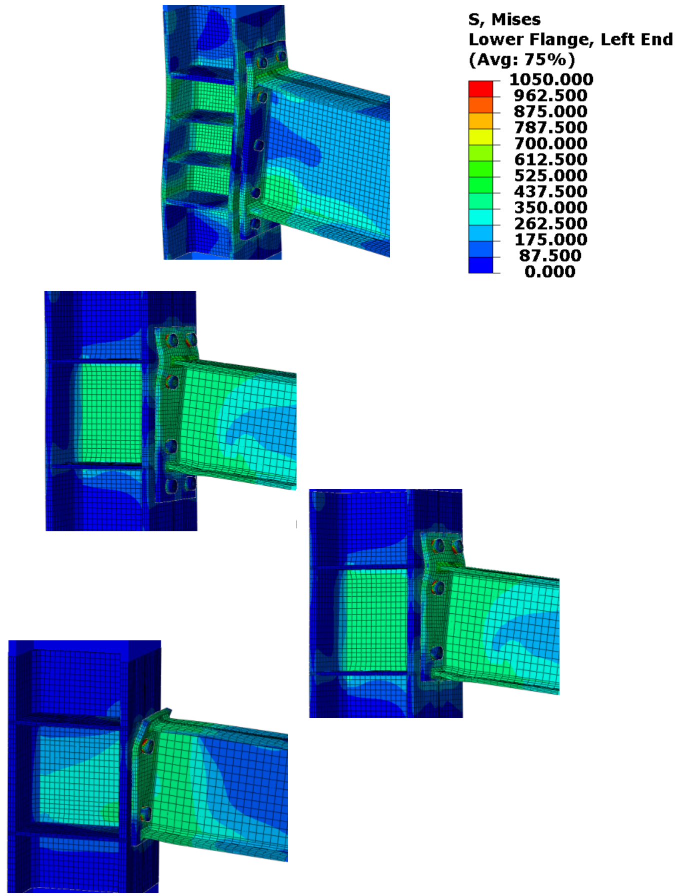




Cyclic behaviour of steel joints

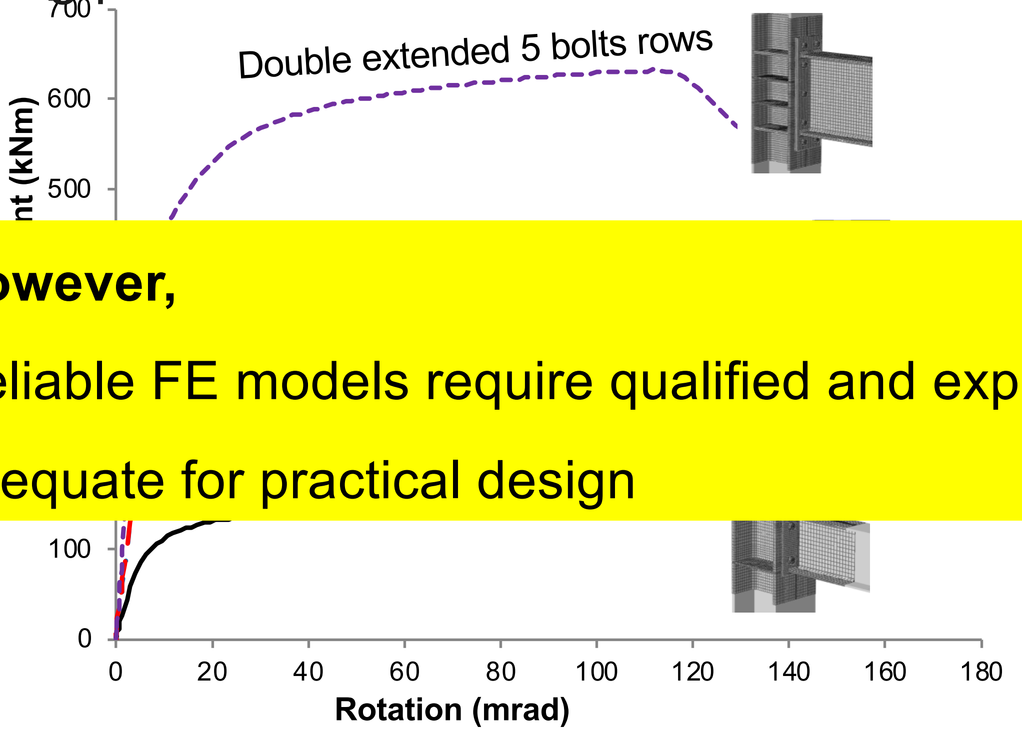
- Allowing parametric studies





Cyclic behaviour of steel joints

- ❑ Allowing parametric studies

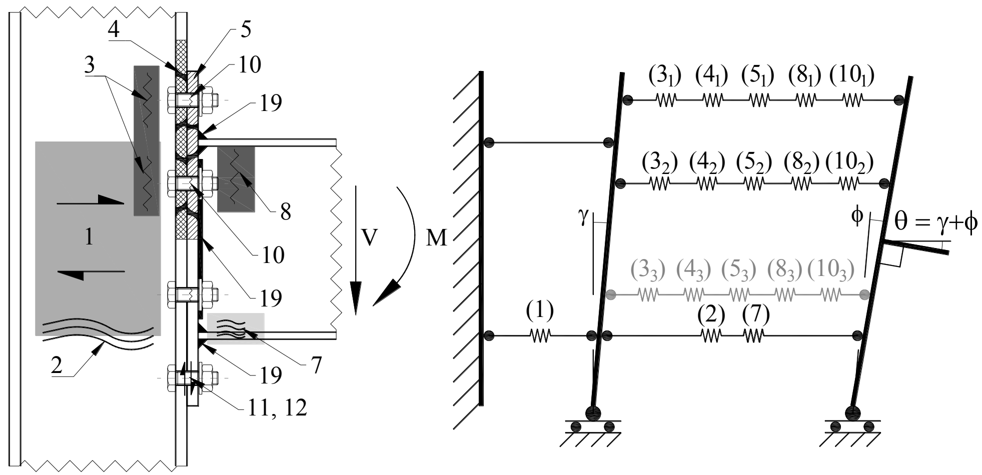


However,

Reliable FE models require qualified and experienced users and is not adequate for practical design

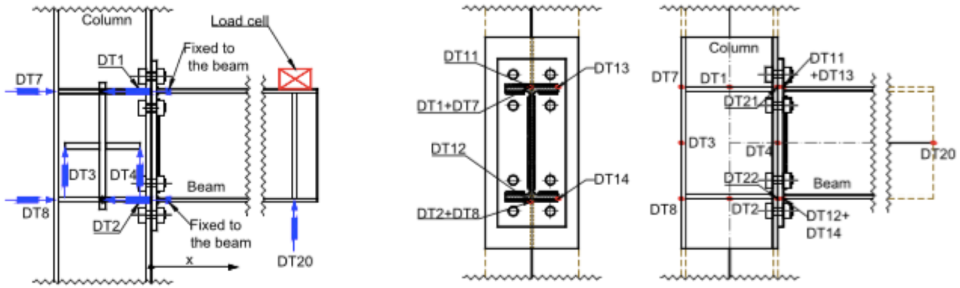
Cyclic behaviour of steel joints

- Behaviour Assessment Strategies
  - **Experimental Tests**
  - **Finite Element models**
  - **Mechanical Models (Components Model)**
    - Accurate for the application field
    - Requires calibration of the components behaviour (EXP or FE)
    - Can be incorporated in design codes (standard in EN1993 for monotonic static loading)



Cyclic behaviour of steel joints

- FE Model development and validation: **interpretation of FE results at component level**



(a) (b)

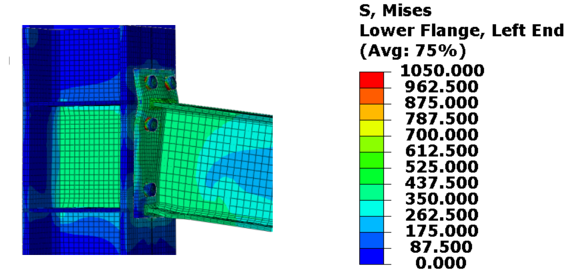


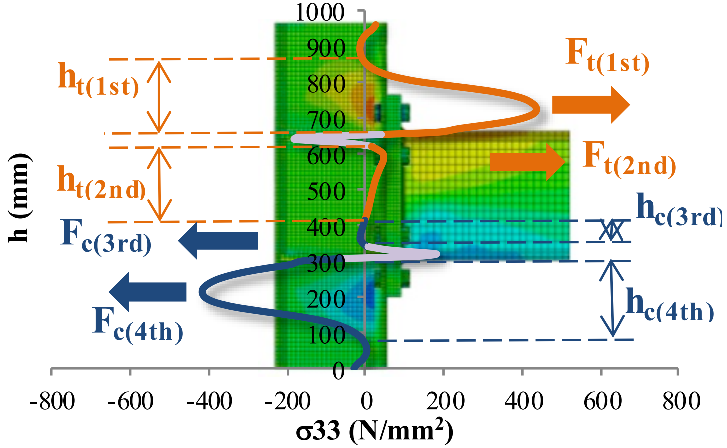
Table B.2
Equations for the extraction of the F–Δ curves from the numerical results.

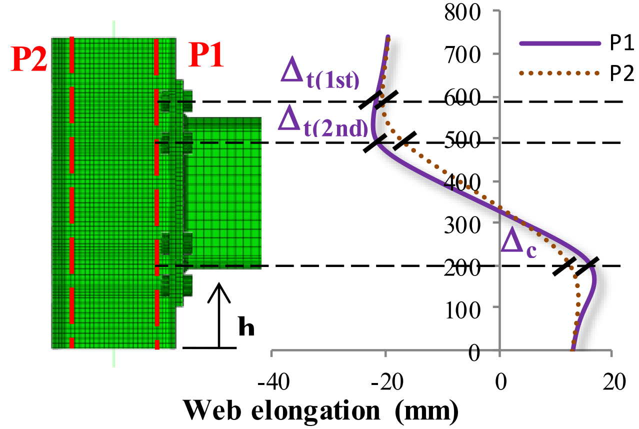
Component	Resistance (F)		Deformation (Δ)	
Column web panel in shear	$V_n = \left(\int^{(2t_{fc}/3+r)_{back}} \tau 23dz\right)\cdot t_1 + \left(\int^{h_{wc}} \tau 23dz\right)\cdot t_{wc} + \left(\int^{(2t_{fc}/3+r)_{front}} \tau 23dz\right)\cdot t_1$	(B.16)	$\gamma = \arctan\left(\frac{DT1-DT2}{h_b}\right) + \arctan\left(\frac{DT3-DT4}{h_c}\right)$	(B.17)
Column web panel in shear with stiffeners	$M_{fc} = \int^{t_{fc}} z(\sigma_{22}dA)$	(B.18)		
	$V_c = \frac{M_{fc(P4)}+M_{fc(P5)}+M_{fc(P6)}+M_{fc(P7)}}{d_b}$	(B.19)		
	$V = V_n + V_c$	(B.20)		
Column web In transverse compression	$F_c = \left(\int^{h_c} \sigma_{33}dy\right)\cdot t_{wc}$	(B.21)	$\Delta_c = (\Delta P1 - \Delta P2)_{compressed\_beam\_flange}$	(B.22)
Column web in transverse tension	$F_{t,i} = \left(\int^{h_{t,i}} \sigma_{33}dy\right)\cdot t_{wc}$	(B.23)	$\Delta_{t,i} = (\Delta_{P1} - \Delta_{P2})_{row\_i}$	(B.24)

Characterisation of steel joints behaviour

❑ Components cyclic behaviour

- Practical procedures were proposed to extract the force-displacement relationships from the individual components of the joint.
- The procedures are based on the integration of the stress and displacement fields in the FE model
- Results revealed good accuracy when compared to the Eurocode 3 procedure (static monotonic) and with experiments (cyclic).



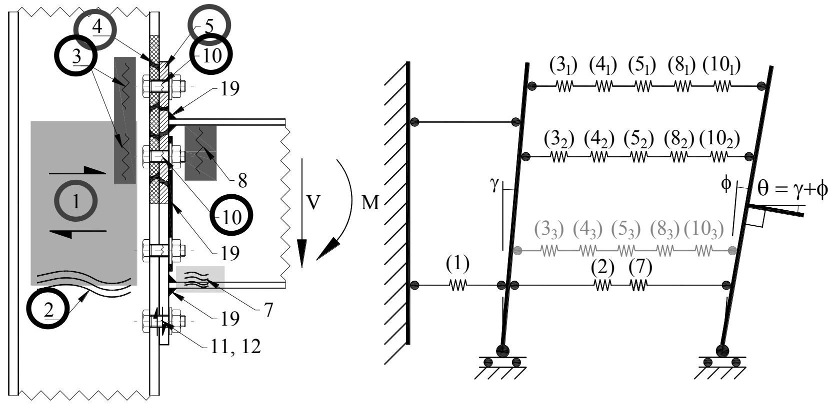


CHARACTERIZATION OF THE BEHAVIOUR OF PARTIAL-STRENGTH JOINTS UNDER CYCLIC AND SEISMIC LOADING CONDITIONS

PhD UC (2017)

Cyclic behaviour of steel joints

- **Basic components identification and idealized mechanical model of the joint**

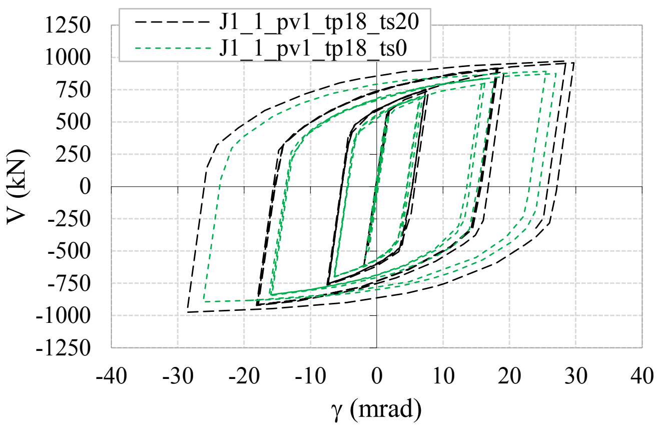


Type	Ref.	Component description	Ductility
Tension	3	Column web in transverse tension	Limited
	4	Column flange in bending	High
	5	End-plate in bending	High
	8	Beam web in tension	High
	10	Bolts in tension	Brittle
	19	Welds in tension	Brittle
Horizontal shear	1	Column web panel in shear	High
Compres.	2	Column web in transverse compression	Limited
	7	Beam flange and web in compression	Limited

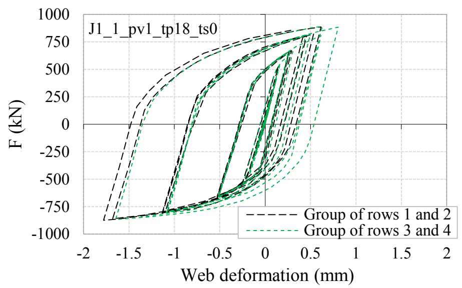
Cyclic behaviour of steel joints

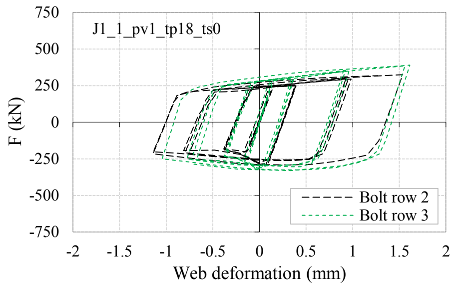
❑ *Experimental Characterization of the Joints Components*

Component: 1

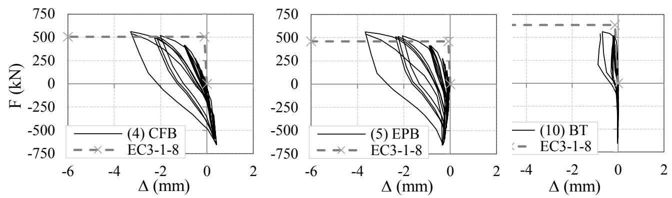


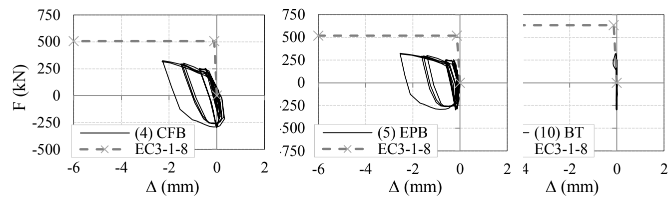
Components 2 & 3





Components 4, 5 & 10





Seismic Risk Mitigation in Steel Moment-frame Construction

The Cyclic Component Model (CCM) – Computational implementation

isise

1 2 9 0

UNIVERSIDADE D
COIMBRA

InfraRisk PhD Summer Workhop 2021
September 17

The Cyclic Component Model (CCM) – Computational implementation

- **Cyclic Component Method (CCM)**
  - Provides an adequate basis for the design of joints by allowing a simple assessment of the influence of key geometrical properties of the joint on their cyclic response
  - Basis for the development of the CCM are defined
    - procedures for the extraction of the cyclic behaviour of components from experimental tests and/or refined FEM models
    - analytical models for the cyclic behaviour of components (e.g. the Modified Richard-Abbot model) and the calibrations of their parameters
    - stable numerical procedures for the cyclic analysis of the joint mechanical model

Component-based method for quasi-static cyclic behaviour of steel joints
Journal of Constructional Steel Research 181 (2021)

The Cyclic Component Model (CCM) – Computational implementation

SCOPE

- **Prediction of the behaviour of beam-to-column joints**
  - Monotonic loading ⇒ Component method (EC3-1-8)
  - Cyclic loading ⇒ The usual approach is to develop multi-parameter mathematical expressions which need to be experimentally calibrated
  - EQUALJOINTS project ⇒ Development of a cyclic component method

OBJECTIVES

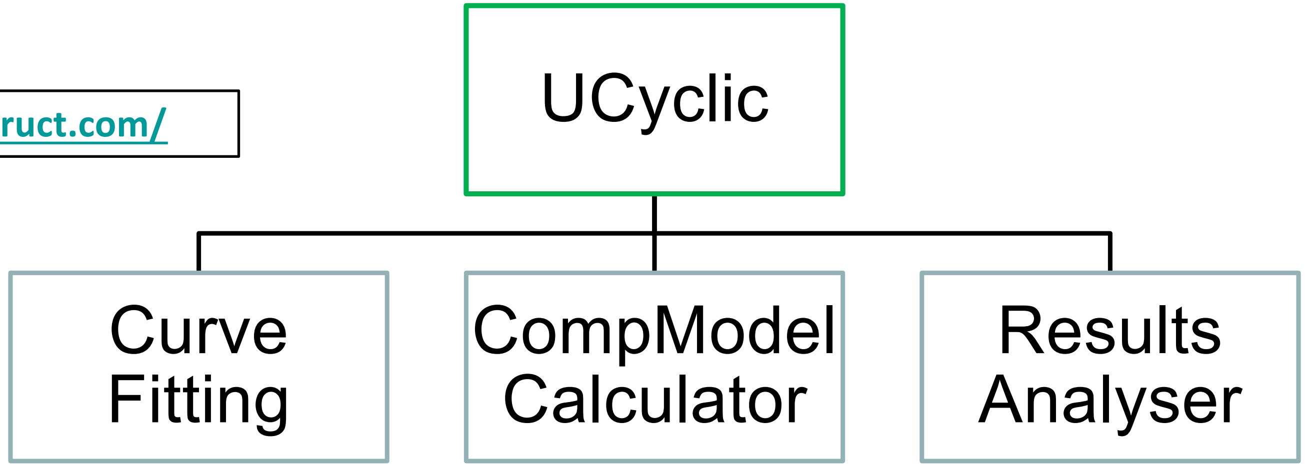
- **Cyclic component method**
  - Extension of the component method for simulating joints subjected to cyclic loading
  - Develop a numerical tool to compute the global behaviour of beam-to-column joints through the characterization of its components

⇓

UCyclic

The Cyclic Component Model (CCM) – Computational implementation

https://www.steelconstruct.com/



- Assessment of the cyclic response of steel joints making use of the cyclic component model (CCM)
- Program developed in MATLAB
- The program is organized in three interconnected modules

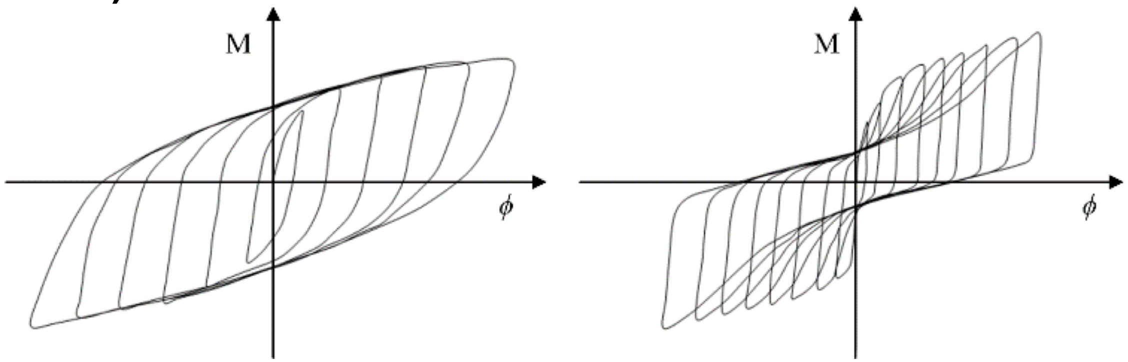
MATLAB

Excel

The Cyclic Component Model (CCM) – Computational implementation

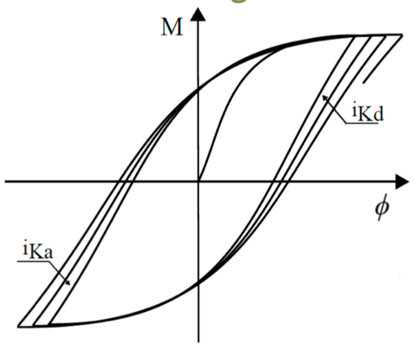
❑ Typification of Cyclic joint (component) behaviour

- stable and unstable with pinching

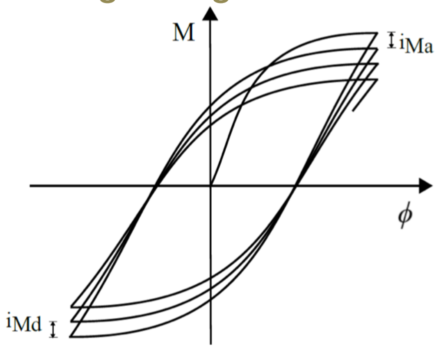


- Hysteresis loop types

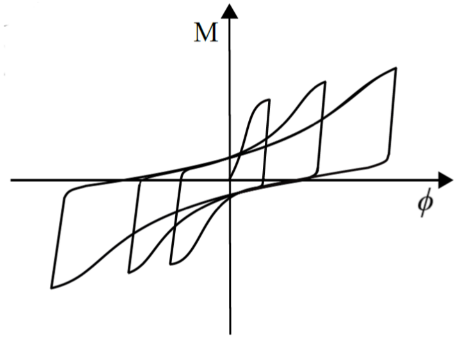
stiffness degradation



strength degradation



pinching effect



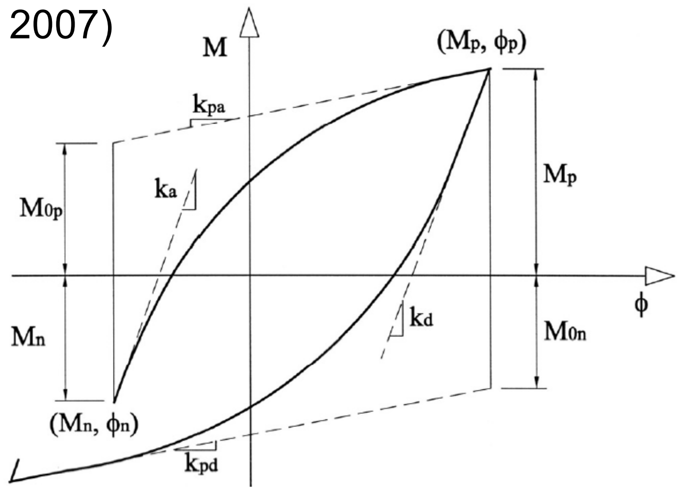
The Cyclic Component Model (CCM) – Computational implementation

❑ Multi-parameter mathematical models

- Cyclic moment-rotation response
  - Richard-Abbott: (Richard e Abbot, 1975)
  - Modified Richard-Abbott: (Della Corte *et al*., 2000) and (Nogueiro, 2007)

$$M = M_{\mathrm{start}} - \frac{\left(K_{0,\mathrm{red}} - K_{\mathrm{p}}\right)\left(\phi_{\mathrm{start}} - \phi\right)}{\left(1 + \left|\frac{\left(K_{0,\mathrm{red}} - K_{\mathrm{p}}\right)\left(\phi_{\mathrm{start}} - \phi\right)}{\left|M_{\mathrm{start}}\right| + M_{0,\mathrm{red}}}\right|^{n}\right)^{\frac{1}{n}}} - K_{\mathrm{p}} \cdot \left(\phi_{\mathrm{start}} - \phi\right)$$

Generic loading and unloading branches



Strength and stiffness degradation

$$M_{0,\mathrm{red}} = M_0 \cdot \left(1 - i_{\mathrm{M}} \cdot \frac{E_{\mathrm{h}}}{M_y \cdot \phi_{\mathrm{u},0}}\right) \qquad K_{0,\mathrm{red}} = K_0 \cdot \left(1 - i_{\mathrm{K}} \cdot \frac{E_{\mathrm{h}}}{K_0 \cdot \phi_{\mathrm{u},0}}\right)$$

The Cyclic Component Model (CCM) – Computational implementation

❑ Multi-parameter mathematical models

30 parameters

- ➢ Modified Richard-Abbot parameters

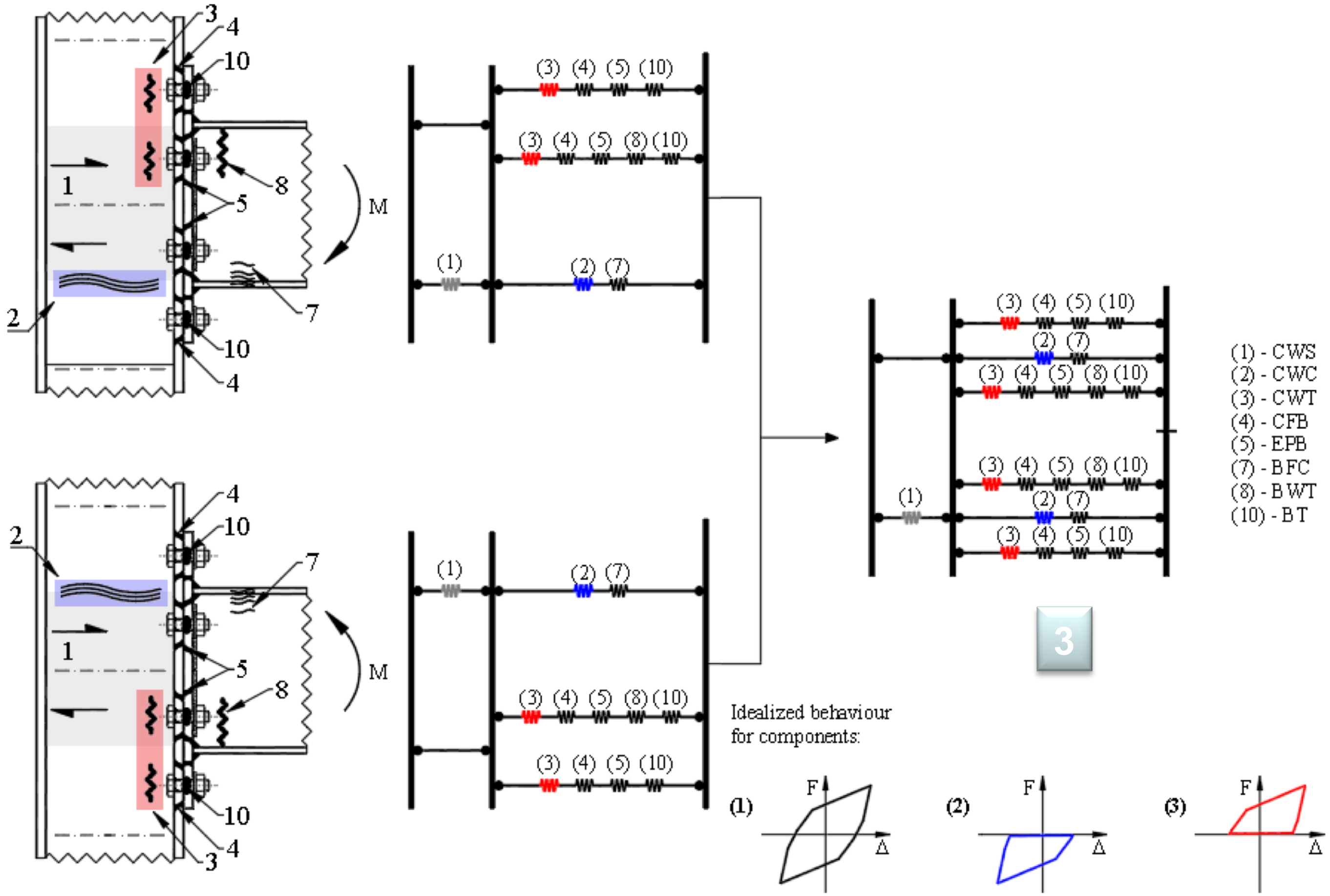
$\mathbf{K_a}$ (and $\mathbf{K_d}$) is the initial stiffness
$\mathbf{M_a}$ (and $\mathbf{M_d}$) is the moment resistance
$\mathbf{K_{pa}}$ (and $\mathbf{K_{pd}}$) is the post limit stiffness
$\mathbf{n_a}$ (and $\mathbf{n_d}$) is the shape parameter
$\mathbf{K_{ap}}$ (and $\mathbf{K_{dp}}$) is the initial stiffness
$\mathbf{M_{ap}}$ (and $\mathbf{M_{dp}}$) is the strength
$\mathbf{K_{pap}}$ (and $\mathbf{K_{pdp}}$) is the post limit stiffness
$\mathbf{n_{ap}}$ (and $\mathbf{n_{dp}}$) is the shape parameter
$\mathbf{t_{1a}}$ and $\mathbf{t_{2a}}$ (and $\mathbf{t_{1d}}$ and $\mathbf{t_{2d}}$) are the two parameters related to the pinching
$\mathbf{C_a}$ (and $\mathbf{C_d}$) is the calibration parameter related to the pinching, normally equal to 1
$\mathbf{i_{Ka}}$ (and $\mathbf{i_{Kd}}$) is the calibration coefficient related to the stiffness damage rate
$\mathbf{i_{Ma}}$ (and $\mathbf{i_{Md}}$) is the calibration coefficient related to the strength damage rate
$\mathbf{H_a}$ (and $\mathbf{H_d}$) is the calibration coefficient that defines the level of isotropic hardening
$\mathbf{E_{maxa}}$ (and $\mathbf{E_{maxd}}$) is the maximum value of deformation

a – ascending
d – descending

The Cyclic Component Model (CCM) – Computational implementation

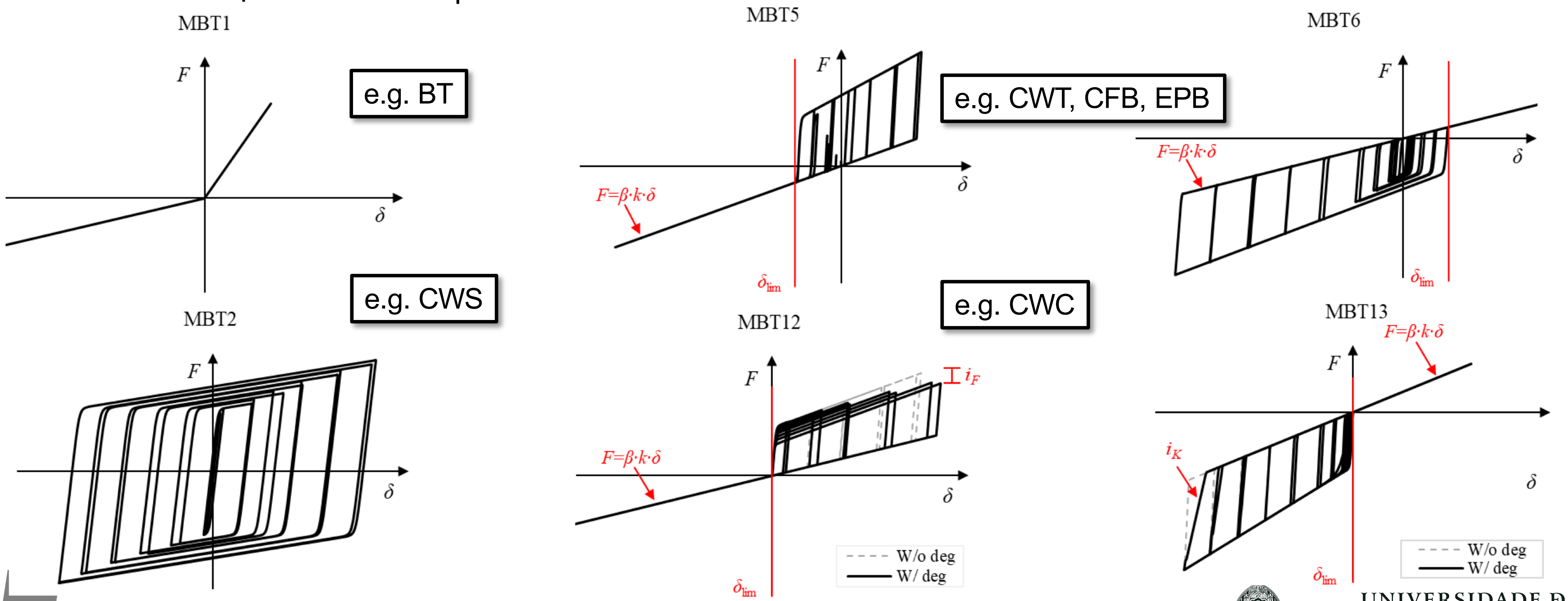
Sagging 1

Hogging 2



The Cyclic Component Model (CCM) – Computational implementation

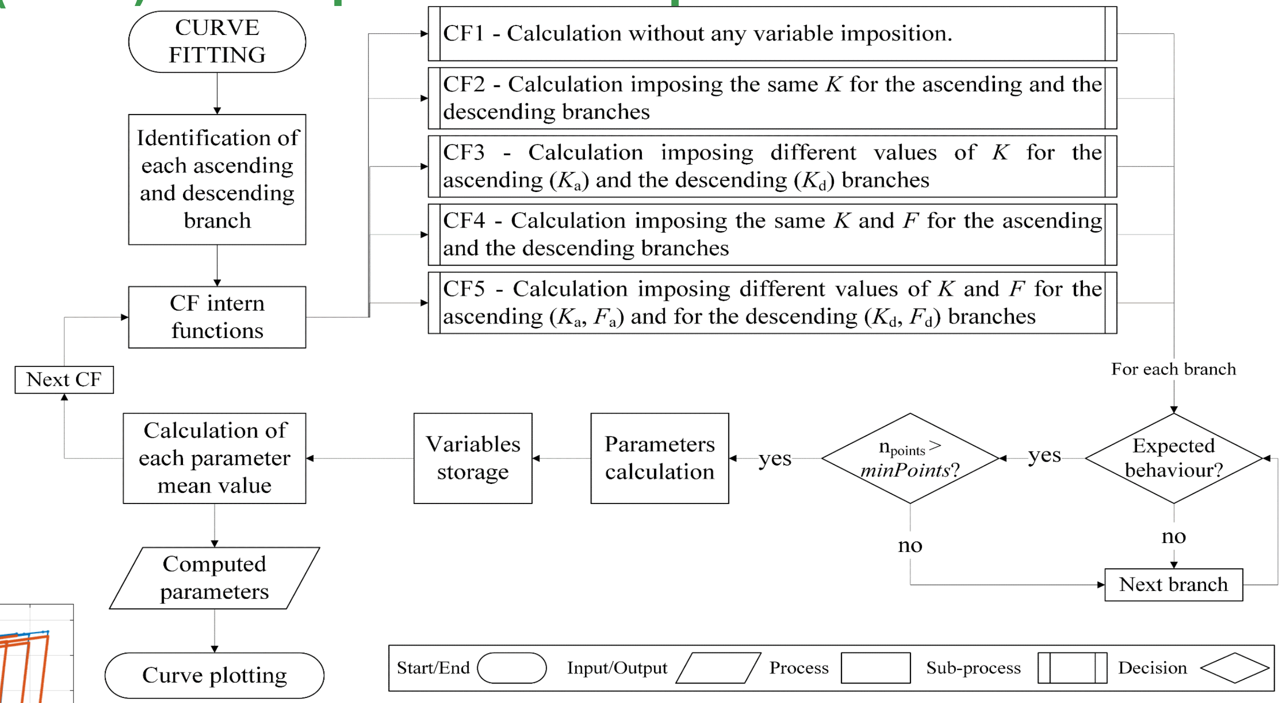
- **Mechanical characterization of the cyclic behaviour of the components**
  - Non-dissipative and dissipative components

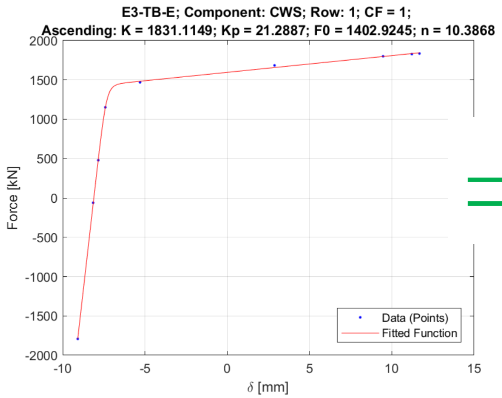


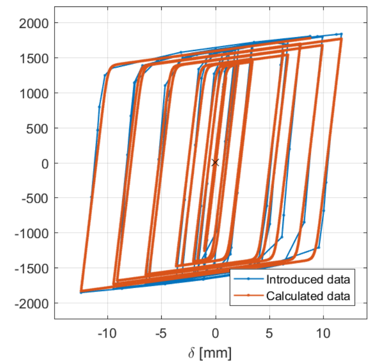
The Cyclic Component Model (CCM) – Computational implementation

❑ CurveFitting

- Computes the **best fit for the parameters** for each branch of the force-deformation curve extracted from tests or Finite Element models (ABAQUS)
- Gives RA parameters



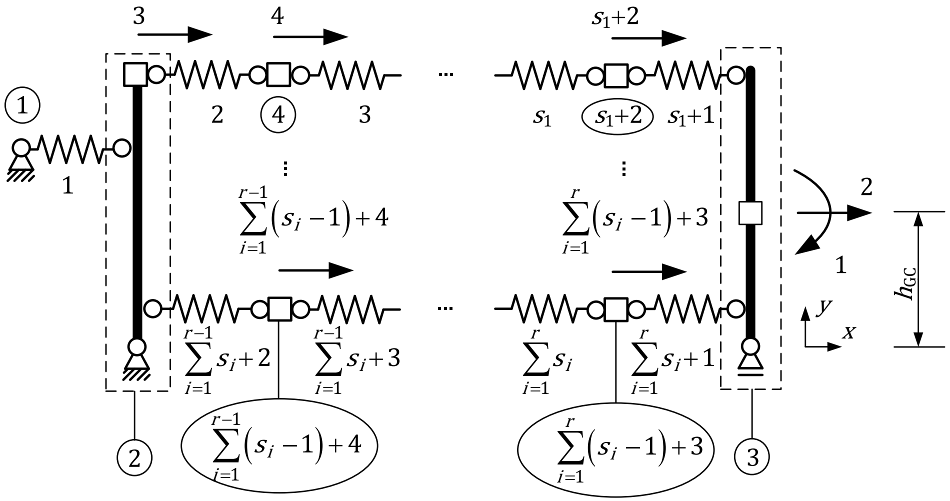




The Cyclic Component Model (CCM) – Computational implementation

❑ CompModel Calculator

- Computes the quasi-static and cyclic nonlinear behaviour of beam-to-column joints
- The user is free to define components and their behaviour based on the joint's typology
- There are available various possibilities for the force-deformation laws of the dissipative components
- May be used to predict the behaviour of beam-to-column joints with arbitrary dimensions falling within the limits of application of EC3-1-8

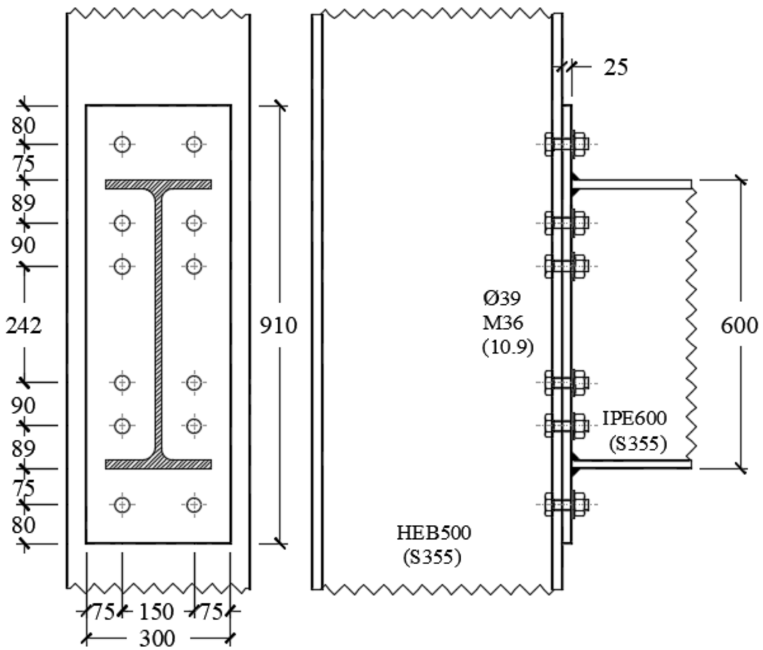


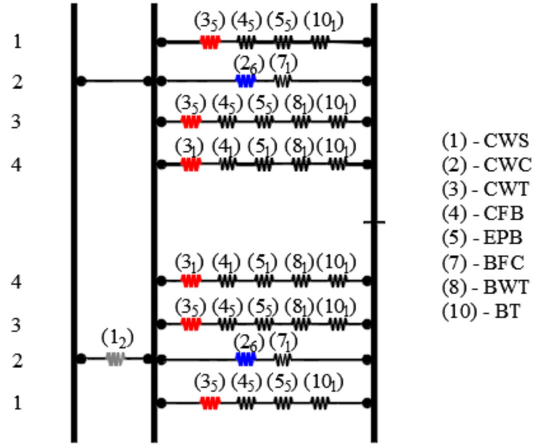
The Cyclic Component Model (CCM) – Computational implementation

❑ Double extended end-plate joint

- Joint E3-TB-E_ts0 – EQUALJOINTS project

Beam: IPE 600
Column: HEB 500
Steel grade: S355
Bolts: M36 (10.9)
End-plate: 25 mm



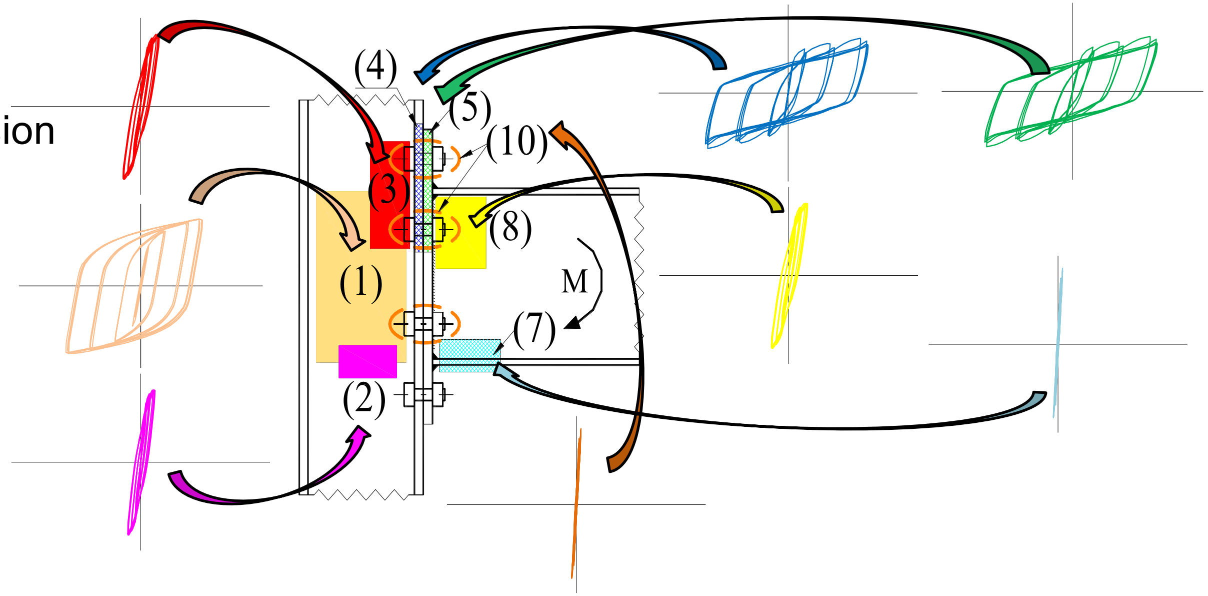


The Cyclic Component Model (CCM) – Computational implementation

- **1st step** – identification and classification of components
- **2nd step** – computation of the strength F and the stiffness K_0 of each component according to EC3
- **3rd step** – characterization of joint components using FEM models

Dissipative components
- (1) CWS – column web panel in shear
- (2) CWC – column web in transverse compression
- (3) CWT – column web in transverse tension
- (4) CFB – column flange in bending
- (5) EPB – end-plate in bending

Non-dissipative components
- (7) BFC – beam flange in compression
- (8) BWT – beam web in tension
- (10) BT – bolts in tension

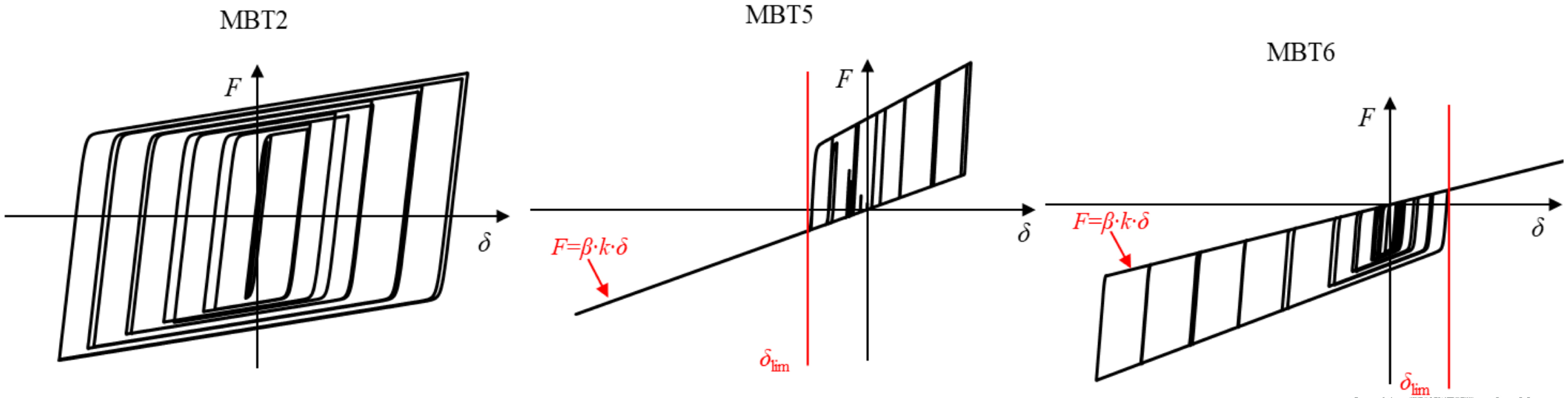


The Cyclic Component Model (CCM) – Computational implementation

- **4th step** – computation of the RA model parameters using CurveFitting
- **5th step** – computation of the cyclic behaviour of the joint using CompModel Calculator
  - Assign a mechanical behavior to each component

CWS – column web panel in shear	⇒ MBT2
CWC – column web in transverse compression	⇒ MBT6
CWT – column web in transverse tension	⇒ MBT5
CFB – column flange in bending	⇒ MBT5
EPB – end-plate in bending	⇒ MBT5

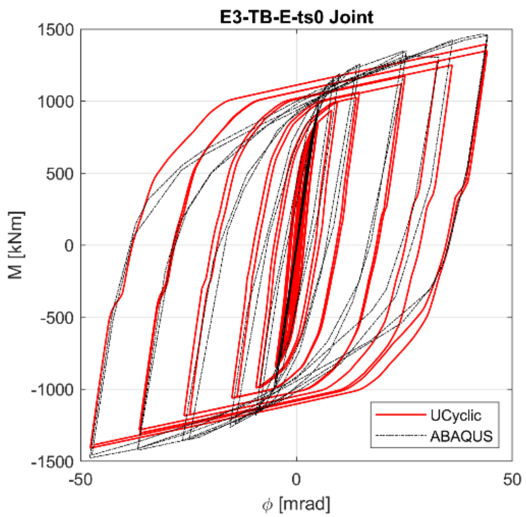
$\delta_{lim}=0$
$\beta=2\%$



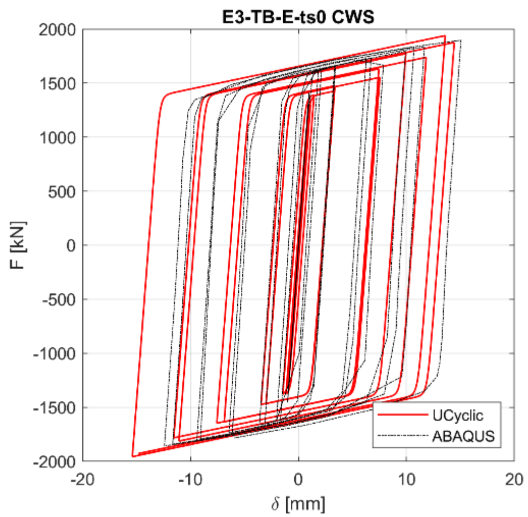
The Cyclic Component Model (CCM) – Computational implementation

- **5th step** – computation of the cyclic behaviour of the joint using CompModel Calculator
  - Global results

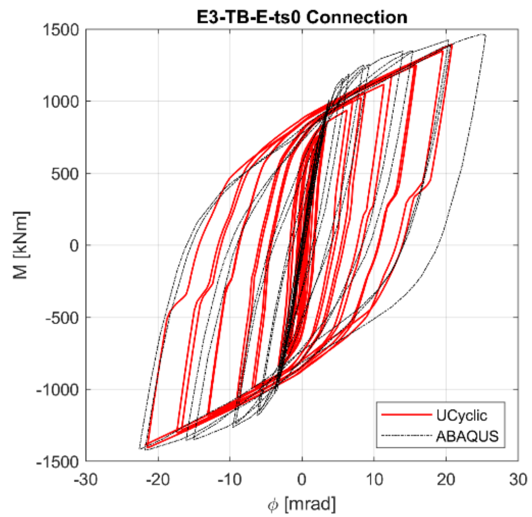
Joint: *M-ϕ* curve



Column Web panel: *F-d* curve



Connection: *M-ϕ* curve



Seismic Risk Mitigation in Steel Moment-frame Construction

Research projects – seismic pre-qualification of steel connections

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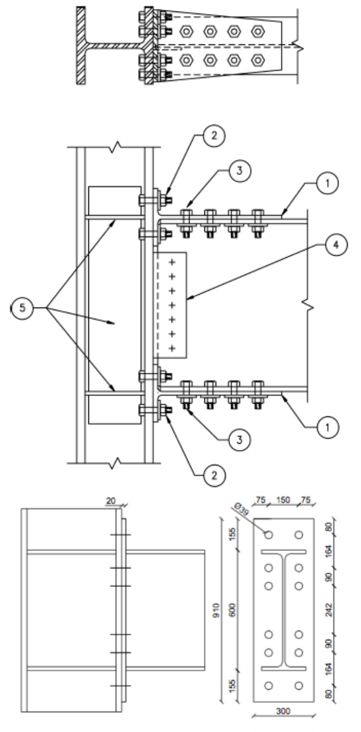
Research projects – seismic pre-qualification of steel connections

NORTH AMERICAN PRE-QUALIFICATION

- **European materials, section shapes, and welding processes** used in beam-to-column joints **differ** from the US and Japan (maximum column depth W14 ≈ HE 340);
- The type of **European seismic input**, which obviously affects the ductility demand, **differs** from the Pacific earthquakes;
- Only **1** pre-qualified **SEMI-RIGID, FULL STRENGTH** bolted joint;
- **No** pre-qualified **PARTIAL STRENGTH** joints.

EUROPEAN PRE-QUALIFICATION

- **EQUALJOINTS RFCS Project** (European pre-qualified steel joints) + **EQUALJOINTSplus RFCS Project**



RFCS Project

EQUALJOINTS

EUROPEAN PRE-QUALIFIED STEEL JOINTS

Imperial College London

Université de Liège

CORDIOLI&C COSTRUZIONI METALLICHE - STEEL CONSTRUCTION

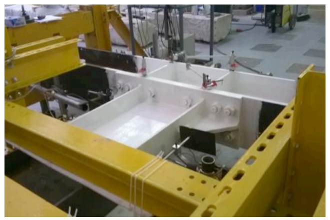
ArcelorMittal

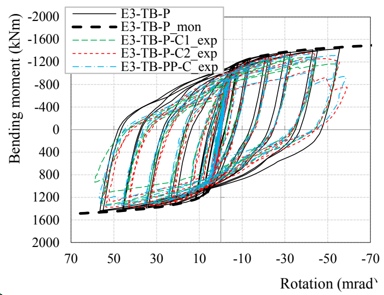
Funding: 1.64 M€ July 2013 – July 2016

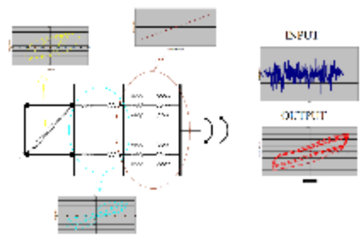
- Development of a prequalification procedure for typical joints used in the EU practice, on the basis of experimental, numerical and analytical investigations;
- Development of analytical and numerical models predicting the behaviour of beam-to-column joints under cyclic loading.
- Define technological requirements for fabrication of the codified joints and to evaluate the economical benefits related to the costs and construction time of different solutions.

(a)

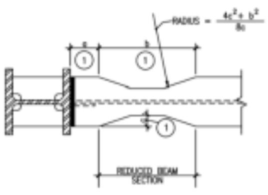
(b)



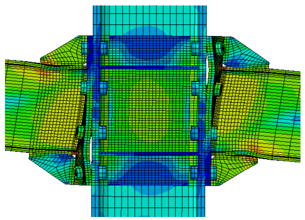


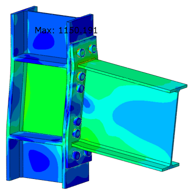


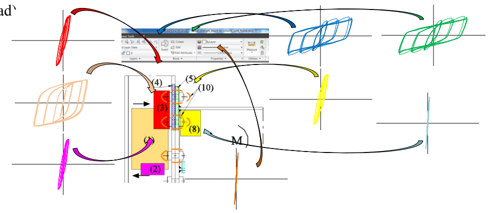
(c)



(d)







RFCS Project

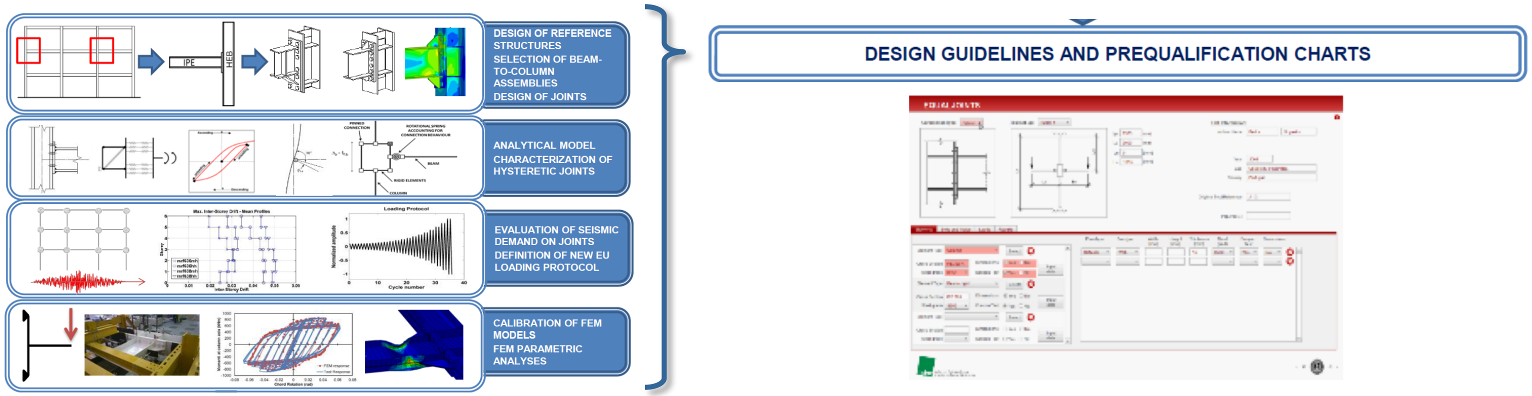
EQUALJOINTS-PLUS

VALORISATION OF KNOWLEDGE FOR EUROPEAN PRE-QUALIFIED STEEL JOINTS

Funding: 1.22 M€ July 2017 – July 2019

ASBL

- Valorisation, dissemination and extension of the developed prequalification criteria for practical applications to a wide audience, within the previous RFCS project EQUALJOINTS (RFSR-CT-2013-00021) ;
- Development of pre-normative design recommendations of seismically qualified joints on the basis of results from EQUALJOINTS project. .
- Development of design guidelines and software in order to design steel structures accounting for the type of joints and their relevant nonlinear response.



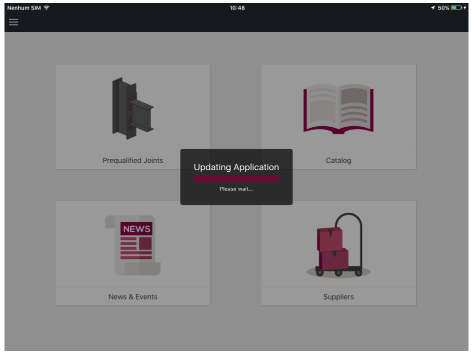
Research projects – seismic pre-qualification of steel connections

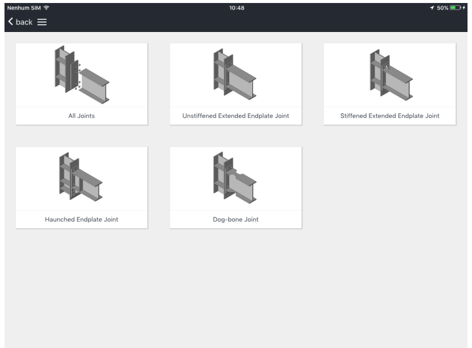
EQUALJOINTS APP

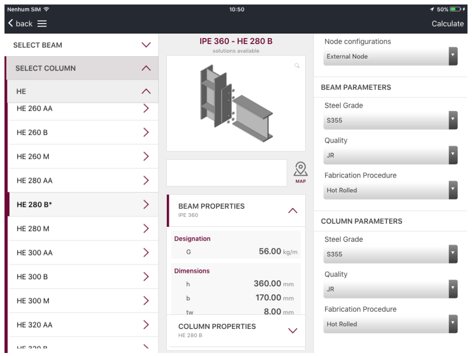
- iOS (AppStore)
- Android (Google Play)

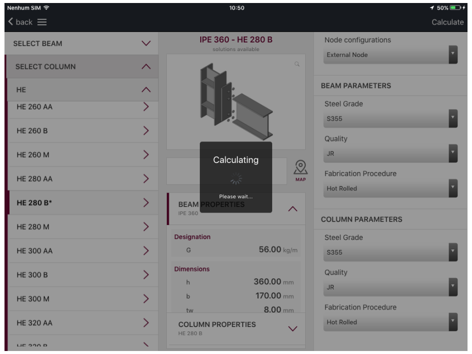
(search for EqualJoints)

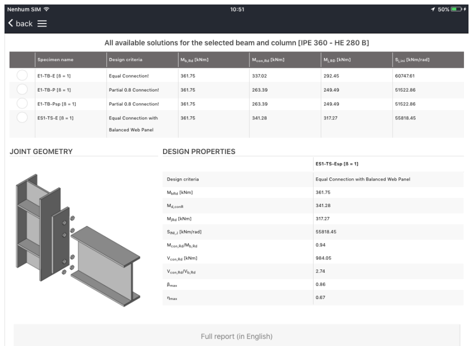
Pre-qualification of steel connections - Research projects

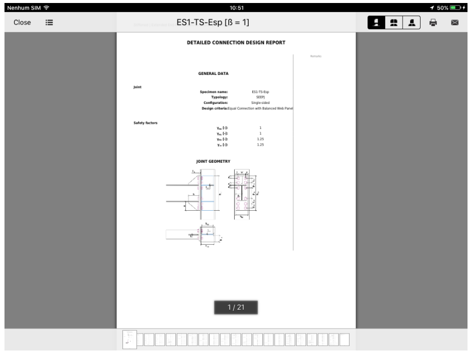












Seismic Risk Mitigation in Steel Moment-frame Construction

Final Remarks

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Final Remarks

Contributions to normative seismic prequalification of connection commonly used in Europe

❑ **Eurocode prEN1998-1-2 (202X)**

- **11.8.6. Design rules for connections in dissipative zones**
  - (7)The resistance and ductility of members and their connections under cyclic loading should be demonstrated by tests.
- NOTE **CEN doc. XXE gives a loading protocol and acceptance criteria for such tests**.
  - (8) Past test results from the literature and refined numerical simulations may be used to demonstrate the effectiveness of the designed partial and full-strength connections in or adjacent to dissipative zones of DC2 and DC3 structures.
  - **(9) Experimental validation for partial and full-strength connections may be omitted if prequalified connections are used.**
    - Annex E gives complementary rules on seismic prequalification of beam-to-column joints and design rules for gusset connections of braced structures.
- **ANNEX E - (normative) SEISMIC DESIGN OF CONNECTIONS FOR STEEL BUILDINGS**

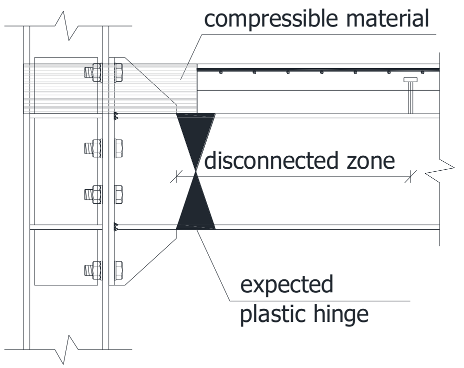
 Carlos Rebelo | crebelo@dec.uc.pt

Final Remarks

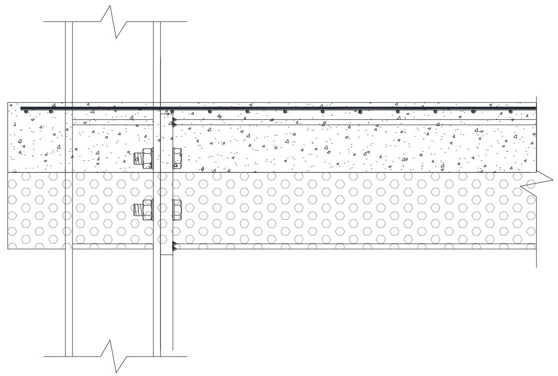
❑ **Future developments include:**

- **Further development and validation of Cyclic Component Model and computational tool**
- **Extension of the CCM to other type of steel connections**
- **Experimental testing and extension of the method to composite connections**

Extended Stiffened End-Plate:
Full Strength Connection



Composite slim floor joint



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Carlos Rebelo

Thank you for your Attention

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