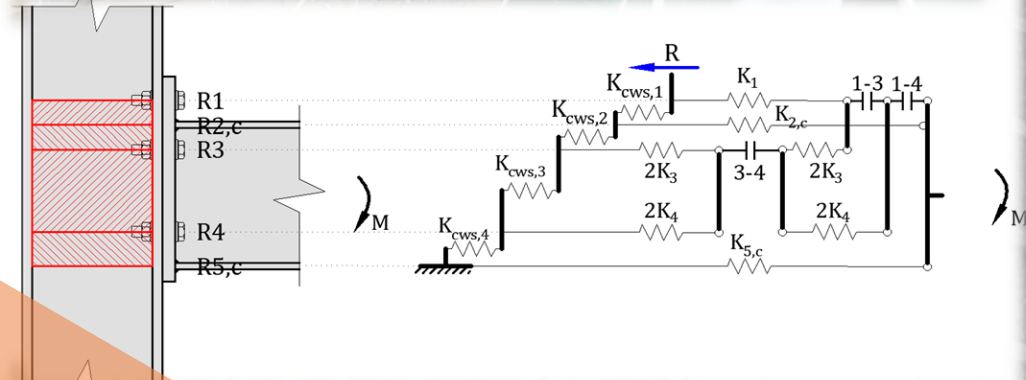




Designing Robust and Resilient Steel Structures: The Central Role of Structural Joints

Prof. Jean-François Demonceau



A multisite university in Wallonia

3 CITIES
4 CAMPUSES



- Liège town-centre
- Liège Sart Tilman
- Gembloux Agro-Bio Tech
- Arlon Campus Environment

11 Faculties

► Philosophy and letters

► Law, Political science
& Criminology

► Sciences

► Medicine
*in association with Liège
University Hospital*

► Applied sciences

► Veterinary medicine
*in association with Liège
University Veterinary Clinic*

► Psychology,
Speech and Language therapy
& Educational science

► HEC Liege,
School of management

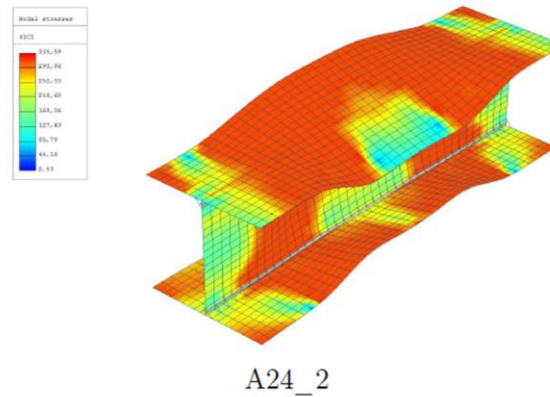
► Social Sciences

► Gembloux
Agro-Bio Tech

► Architecture

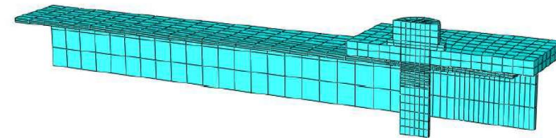
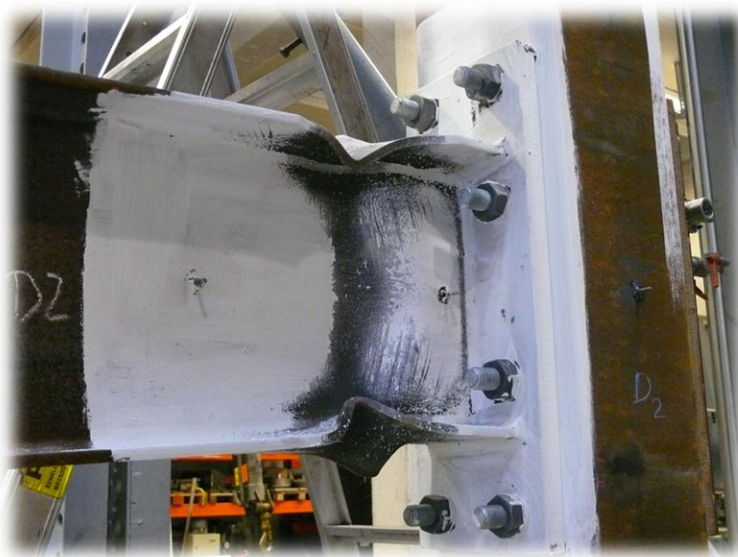
CMM research areas

- **Stability of structures and of structural members:** global stability of structures, resistance and classification of cross-sections, stability of structural members



CMM research areas

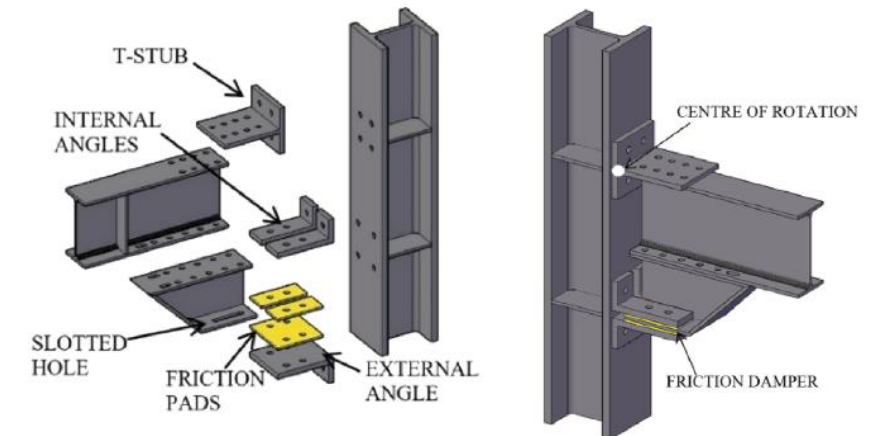
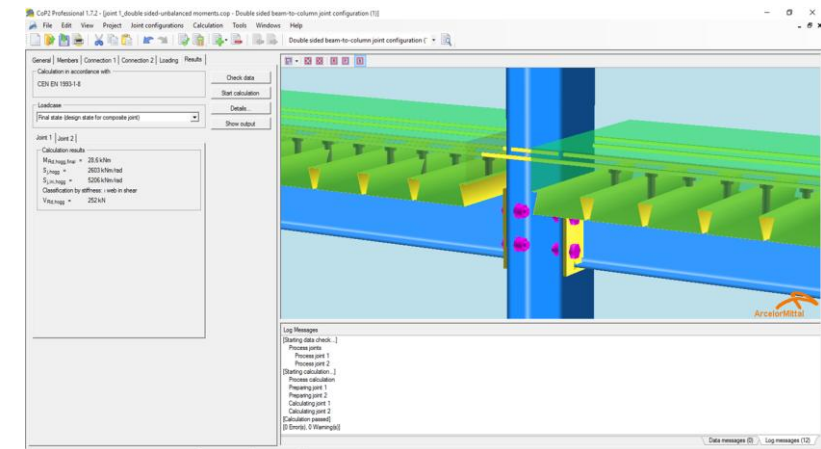
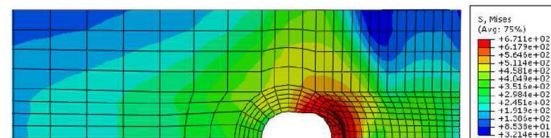
- **Behaviour of structural joints:** development of innovative joints, characterisation of joint behaviour or of new components, joints subjected to accidental/exceptional loadings



(b)

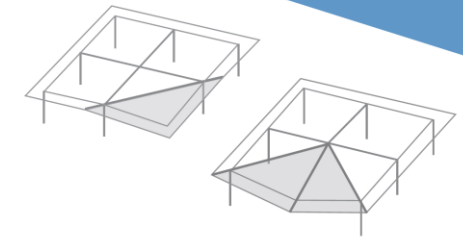
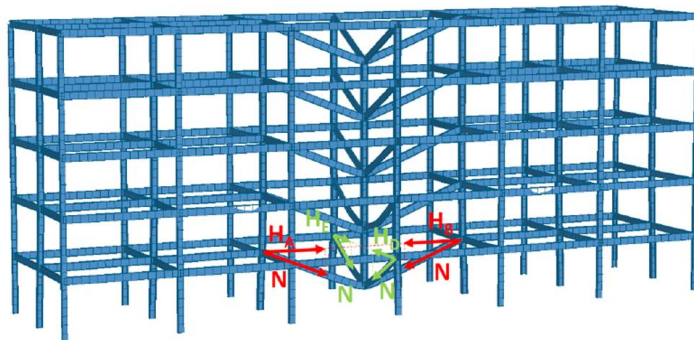
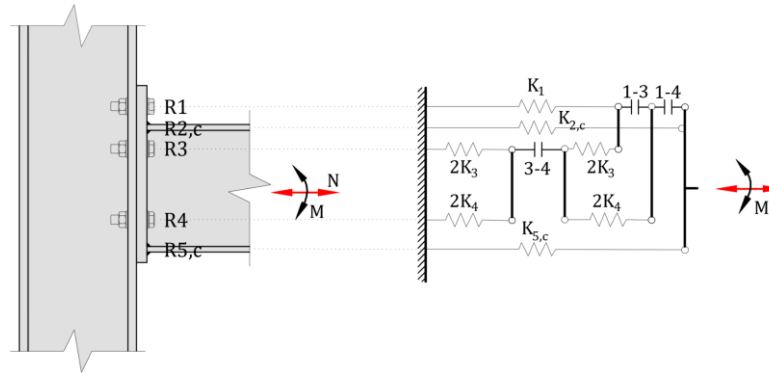


(c)



CMM research areas

- ▶ **Robustness of structures:** response of structures subjected to exceptional loadings



<https://www.steelconstruct.com/eu-projects/failnomore/>

Developed activities in the past 25 years

- ❖ Participation to national and international projects

- 22 European projects
- 7 national projects

- ❖ Development of research activities with industries

- ArcelorMittal, Astron, Peikko Group, Greisch, Elia, Drever International...



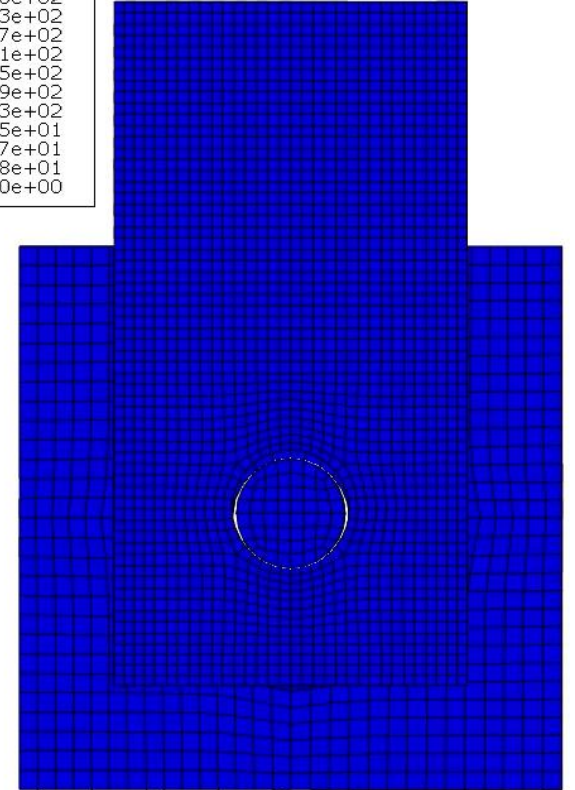
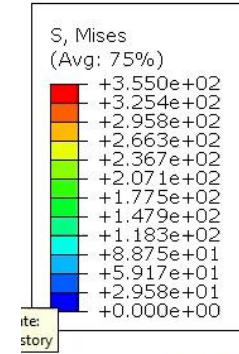
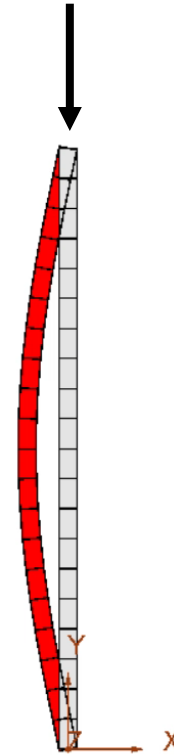
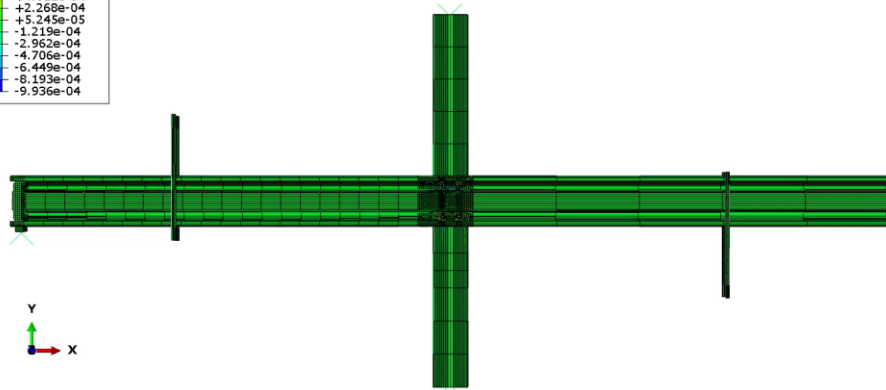
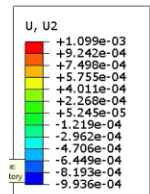
Mechanic of Materials and Structures laboratory

- ▶ 1 Lab Manager and 6 Technicians
- ▶ Laboratory divided in two parts:
 - Fixed machine lab
 - Reaction floor of 11mx21m
- ▶ Loading capacities varying from 100kN to 10.000kN
- ▶ Two furnaces to test materials at high temperatures (up to 1200°C)
- ▶ High speed DIC measurements
- ▶ Main activities in the field of civil engineering and aeronautic
- ▶ Accredited by BELAC (ISO 17025)



Numerical tools

- ▶ Abaqus®
- ▶ Homemade finite element software:
 - Finelg
 - Safir
 - Lagamine



CMM in national & international committees

▶ Participation to national and international technical and scientific committees

- European technical committees (ECCS)

- › TC 10 – Structural joints
- › TC 11 as chairman – Composite structures
- › Technical Managing Board (TMB)



- Normative committees (NBN and CEN)

- › Belgian Mirror committee E25003-04
- › CEN/TC250 SC3 (member of the reference group of WG8)
- › CEN/TC250 SC4
- › CEN/TC250 WG6 (liaison officer with SC3 and SC4)



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- ▶ Introduction
- ▶ Structural joints subjected to MN
- ▶ Actual joint behaviour in structural analysis
- ▶ Dynamic behaviour of joints
- ▶ From robustness to resilience
- ▶ Conclusions

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Introduction



Ronan Point (1968)



Introduction



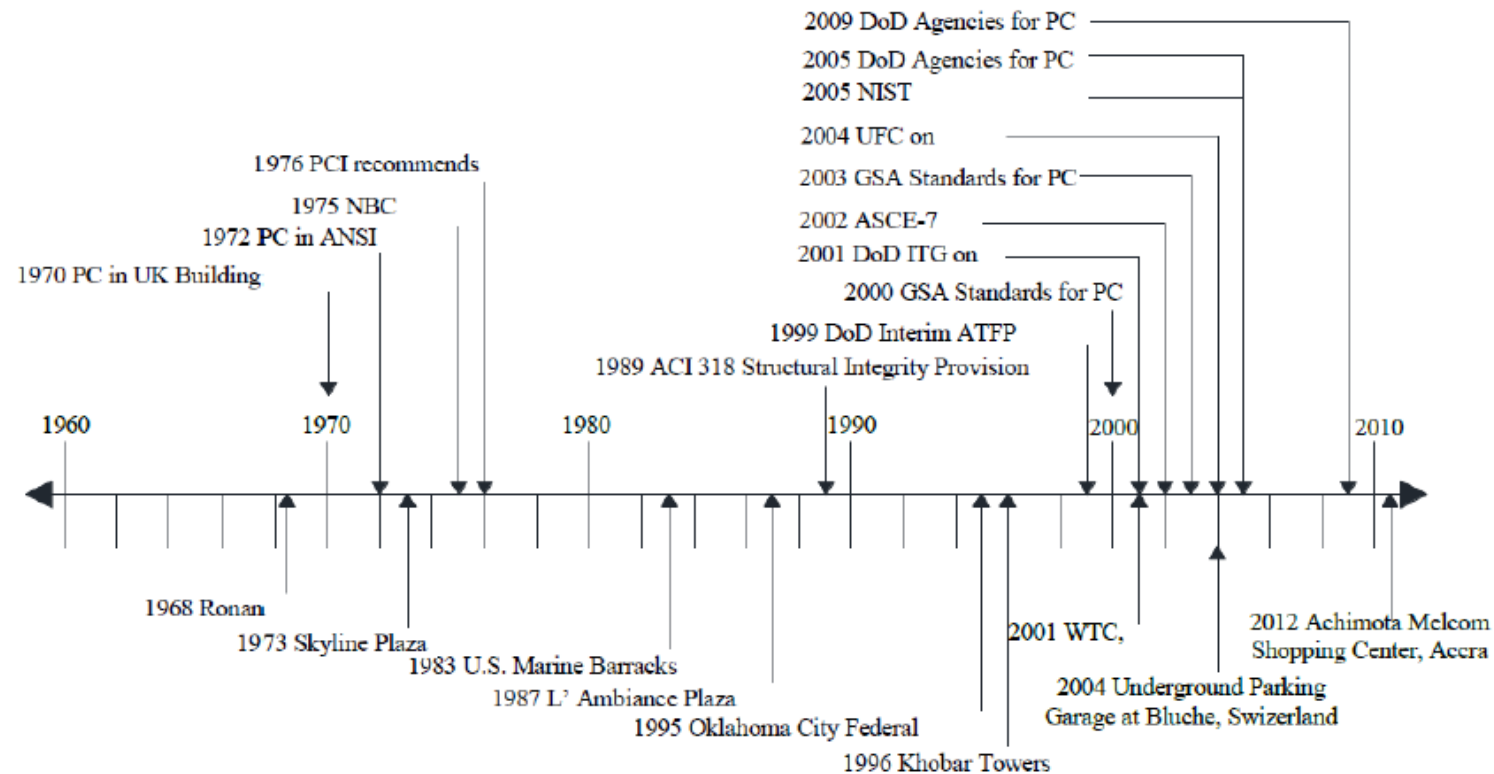
World Trade Center (2001)



Introduction

Normative context

- Since Ronan Point event in 1968, codes and standards have included recommendations to limit the risk of occurrence of progressive collapse in buildings



Qian et al., 2016

Introduction

- STRUCTURAL ROBUSTNESS can be defined as:

Ability of a structure to withstand events like fire, explosions, impact or the consequences of human error, without being damaged to an extent disproportionate to the original cause

- PROGRESSIVE/DISPROPORTIONATE COLLAPSE can be defined as:

Progressive/Disproportionate collapse of a building can be regarded as the situation where local failure of a primary structural component leads to the collapse of adjoining members and to an overall damage which is disproportionate to the initial cause

Introduction

Normative context – What about Europe?

■ EN 1990:2002

■ **EN 1990, 2.1 (4)P** sets out the basic principle related to structural robustness:

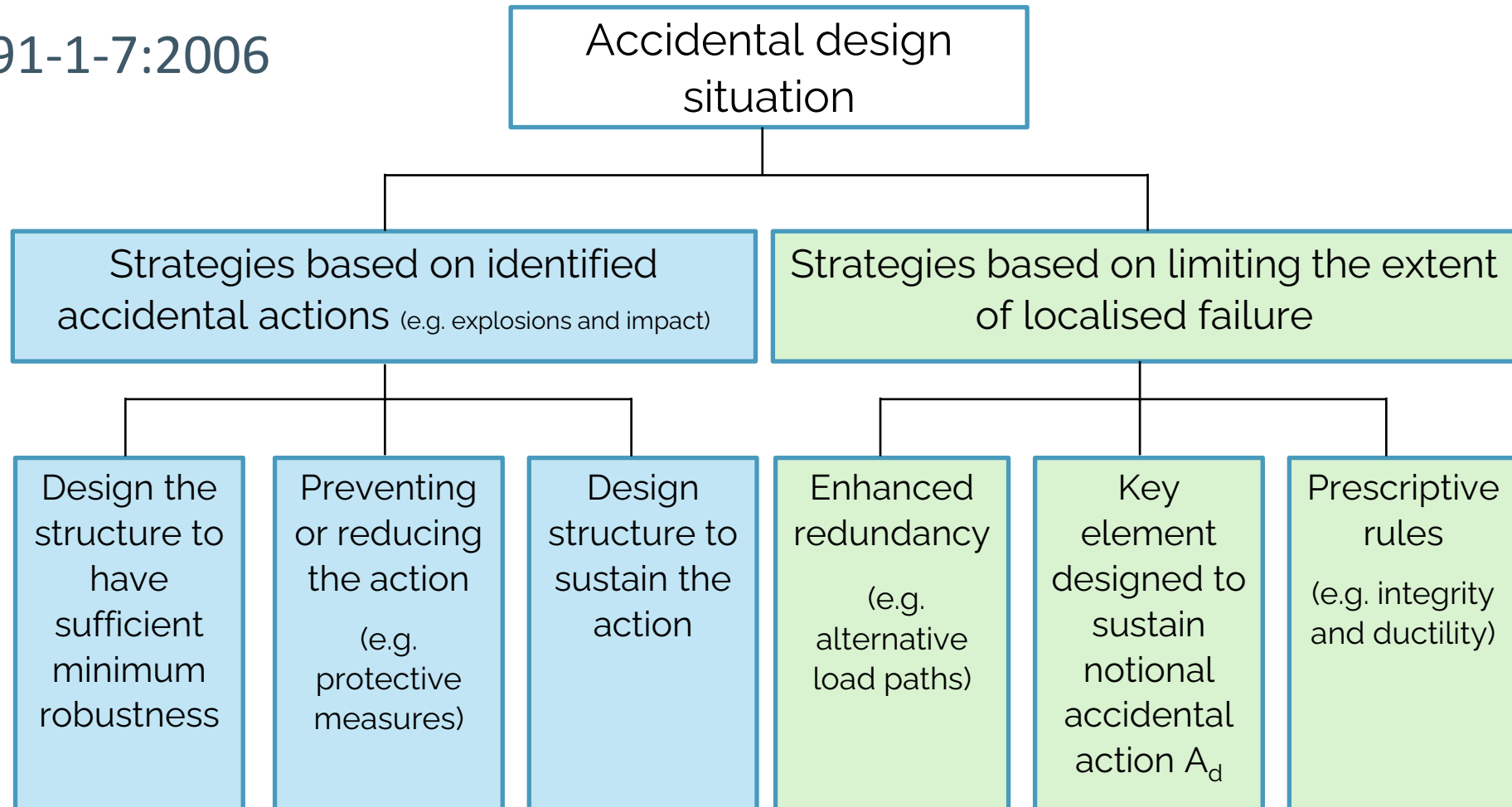
A structure shall be designed and executed in such a way that it will not be damaged by events such as: explosion, impact, and the consequences of human errors, to an extent disproportionate to the original cause

■ For more details, EN 1990 refers to **EN 1991-1-7**

Introduction

Normative context – What about Europe?

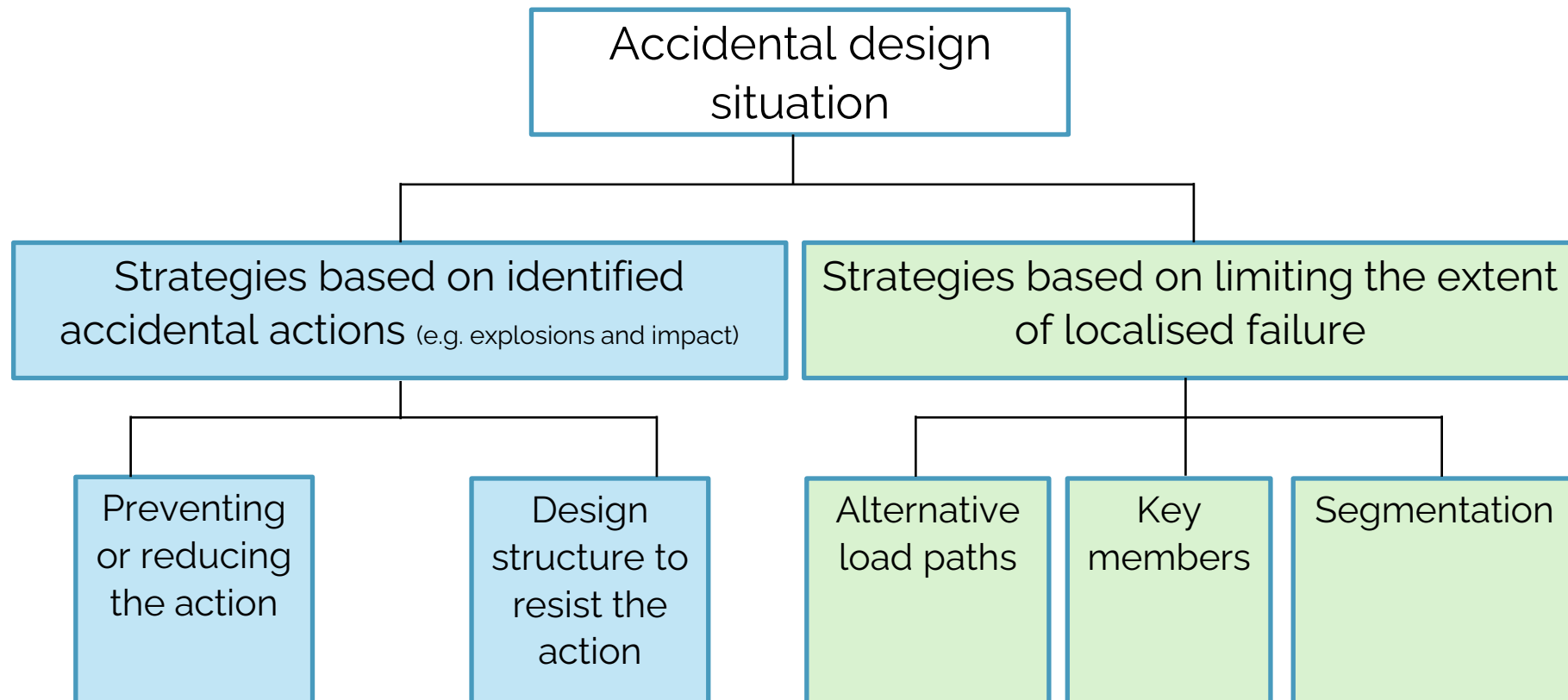
■ EN 1991-1-7:2006



Introduction

Normative context – What about Europe?

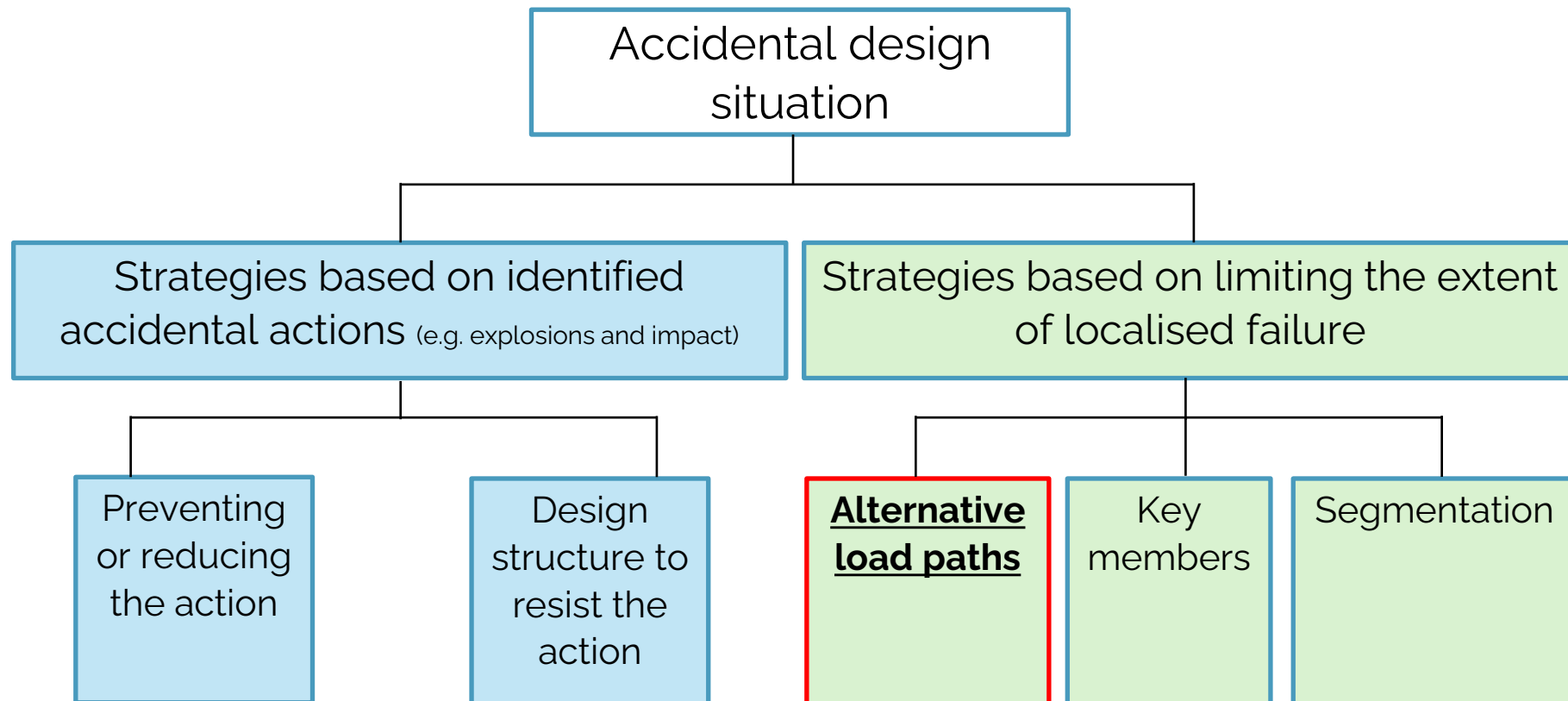
■ Next generation of EC → EN 1990:2023



Introduction

Normative context – What about Europe?

■ Next generation of EC → EN 1990:2023



Introduction

Key scenario: loss of a column

■ According to the Eurocodes, it is required to ensure the robustness of structures when subjected to identified and unidentified actions

■ How to deal with unidentified actions?

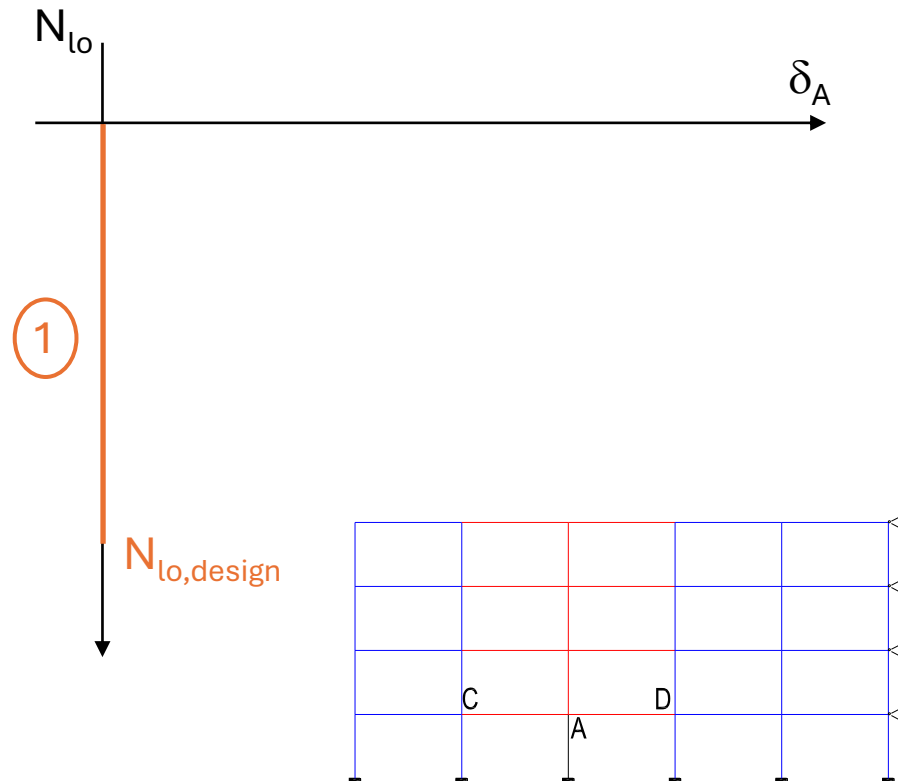
➔ Development of design strategies limiting the extend of local damages

➔ Assumed local damage in framed structures: loss of a column

Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response

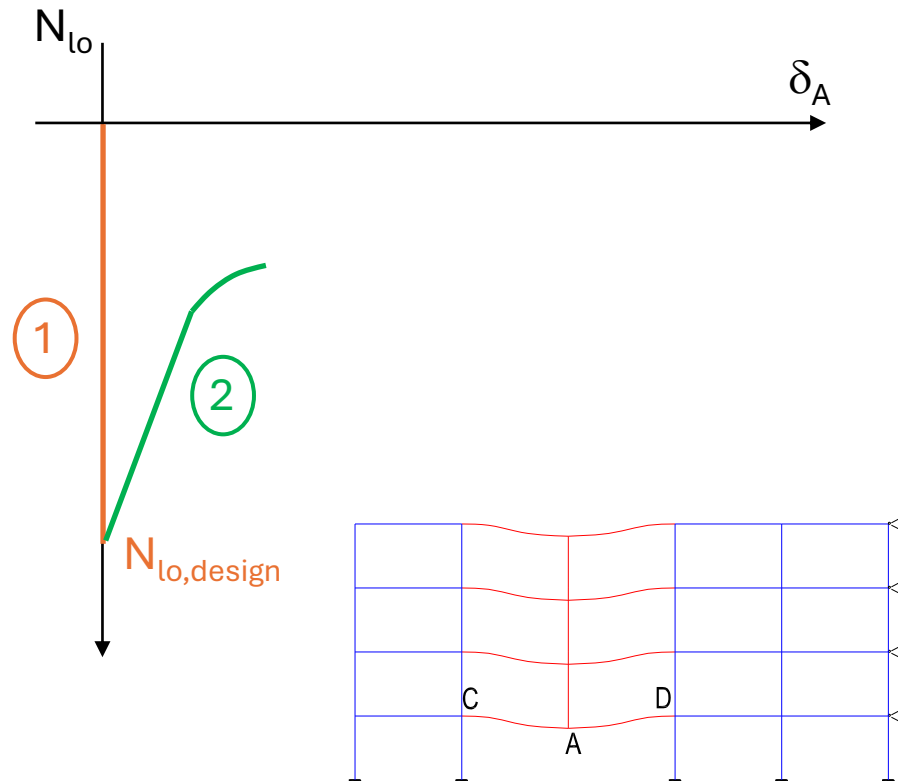


Phase 1: → Building under accidental load combination
→ Column to be lost subjected to an axial load $N_{lo,design}$

Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response

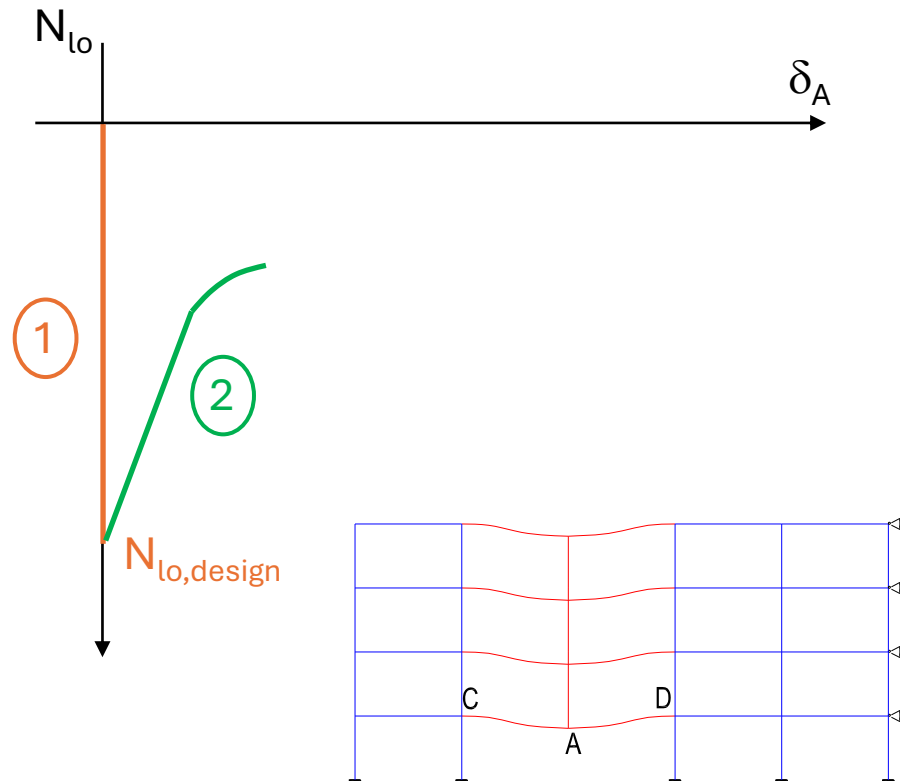


- Phase 1: → Building under accidental load combination
- Column to be lost subjected to an axial load $N_{lo,design}$
- Phase 2: → Beginning of the column loss
- First, an elastic response is observed

Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response



Phase 1: → Building under accidental load combination

→ Column to be lost subjected to an axial load $N_{lo,design}$

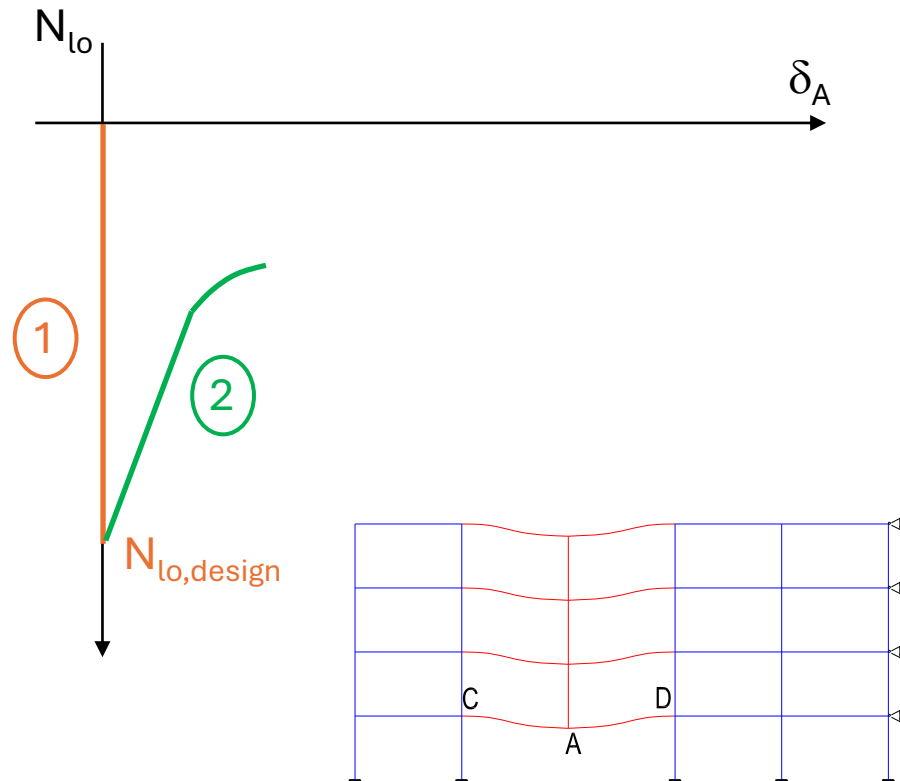
Phase 2: → Beginning of the column loss

→ First, an elastic response is observed
→ Then, a first plastic hinge forms

Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response

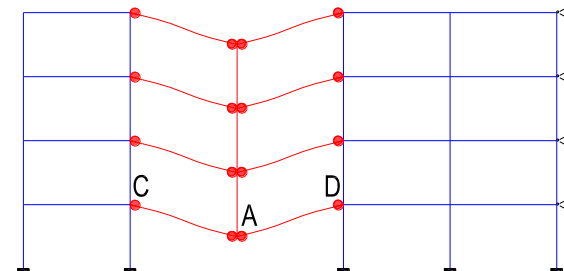


Phase 1: → Building under accidental load combination

→ Column to be lost subjected to an axial load $N_{lo,design}$

Phase 2: → Beginning of the column loss

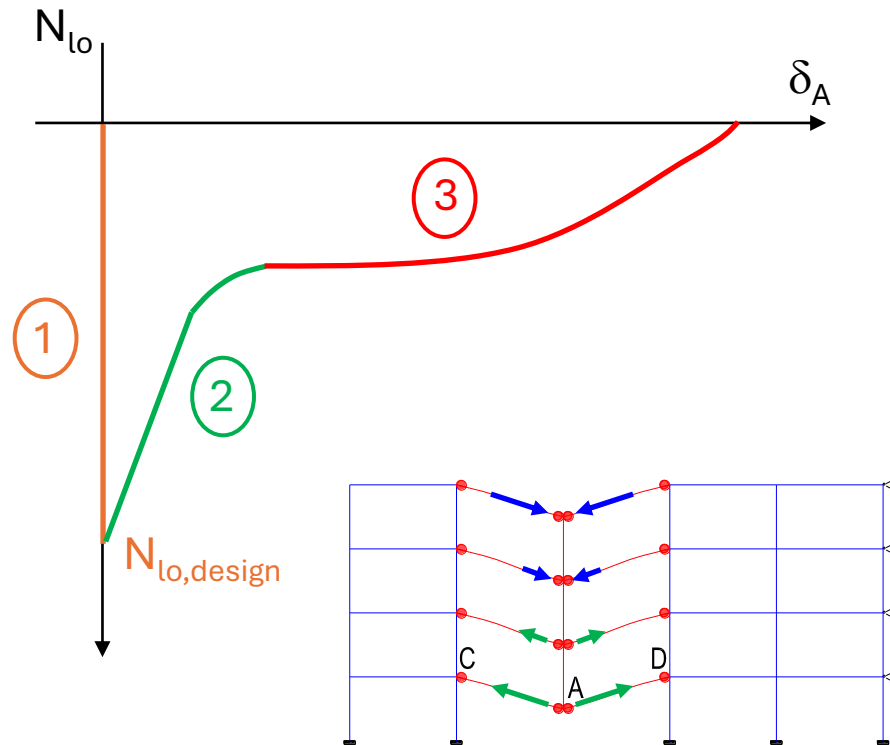
- First, an elastic response is observed
- Then, a first plastic hinge forms
- Finally, a complete plastic mechanism forms in the DAP



Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response



Phase 1: → Building under accidental load combination

→ Column to be lost subjected to an axial load $N_{lo,design}$

Phase 2: → Beginning of the column loss

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→ Finally, a complete plastic mechanism forms in the DAP

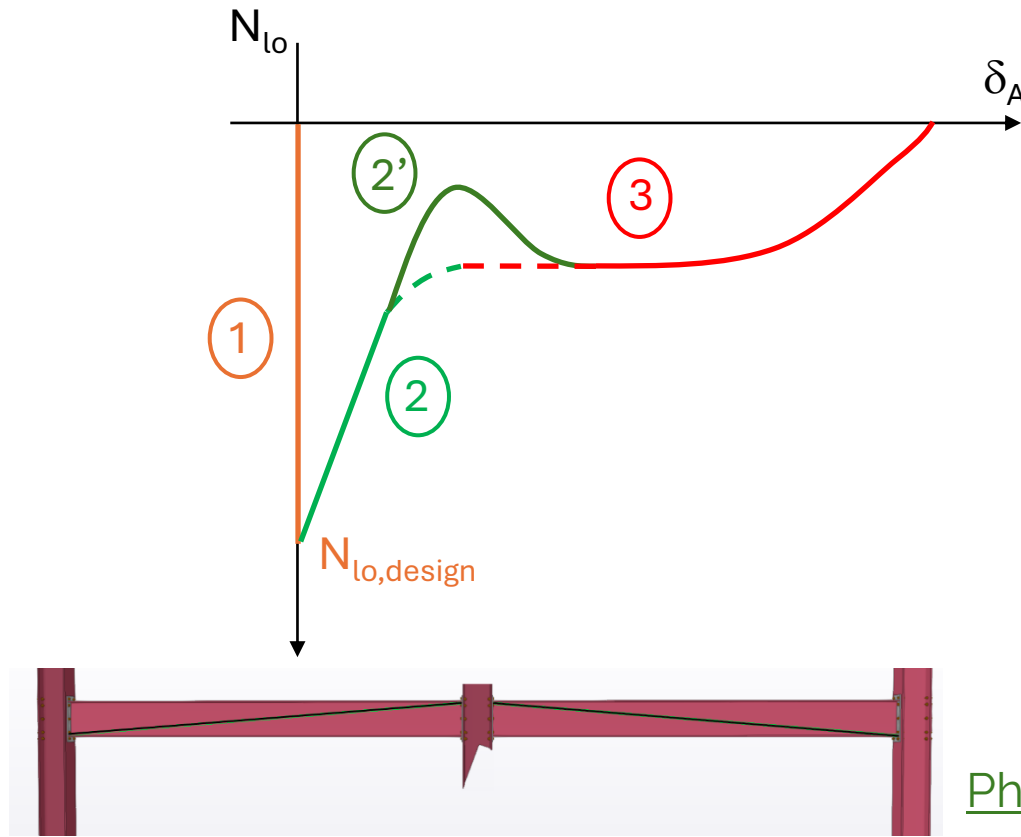
Phase 3: → Significant displacements appear

→ Development of 2nd order effects
→ Axial forces in the beams appear (membrane/catenary forces)

Introduction

Behaviour of a frame subjected to a column loss scenario

■ Visualisation of the global structural response



Phase 1: → Building under accidental load combination

→ Column to be lost subjected to an axial load $N_{lo,design}$

Phase 2: → Beginning of the column loss

→ First, an elastic response is observed
→ Then, a first plastic hinge forms
→ Finally, a complete plastic mechanism forms in the DAP

Phase 3: → Significant displacements appear

→ Development of 2nd order effects
→ Axial forces in the beams appear (membrane/catenary forces)

Phase 2': → Arching effect on the beam depth

Introduction

Key structural elements: joints at the extremities of the beams!

- The beams and the joints at their extremities are subjected to internal forces for which they have not been designed through the ULS and SLS design phases
- Accordingly, in case of partial-strength joints, the latter have to be:
 - Ductile in order to allow significant deformations/displacements to reach a new state of equilibrium in the deformed shape
 - Sufficiently resistant to support the M-N-V internal forces developing at their level through the activation of alternative load paths

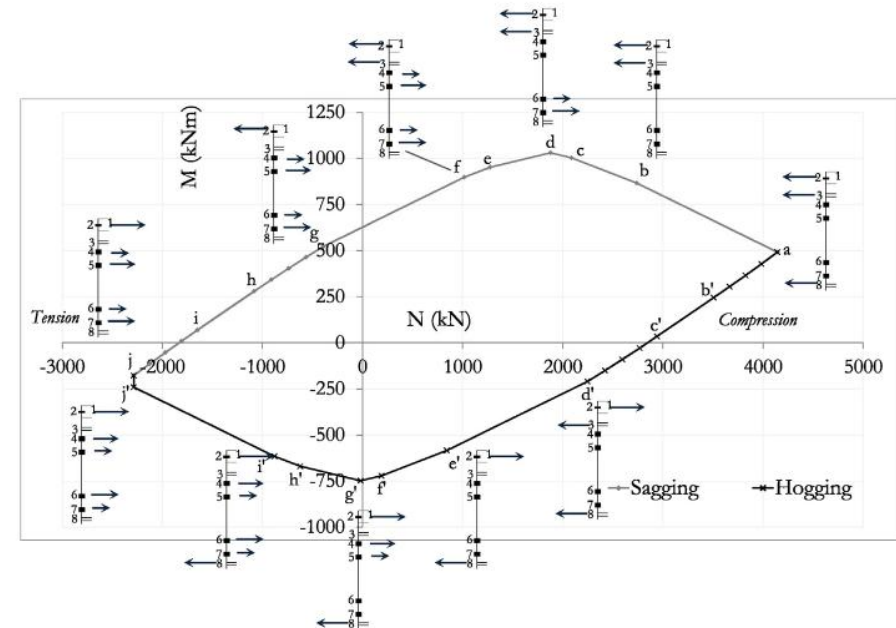
Introduction

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- ▶ Introduction
- ▶ **Structural joints subjected to MN**
- ▶ Actual joint behaviour in structural analysis
- ▶ Dynamic behaviour of joints
- ▶ From robustness to resilience
- ▶ Conclusions



Structural joints subjected to MN

EN1993-1-8:2005 design rules

- “5% rule”

Moment resistance is not influenced by an additional normal force if:

$$\left| \frac{N_{j,Ed}}{N_{c,Rd}} \right| \leq 0,05$$

Remark: - the value is fully arbitrary
- moreover it is potentially unsafe

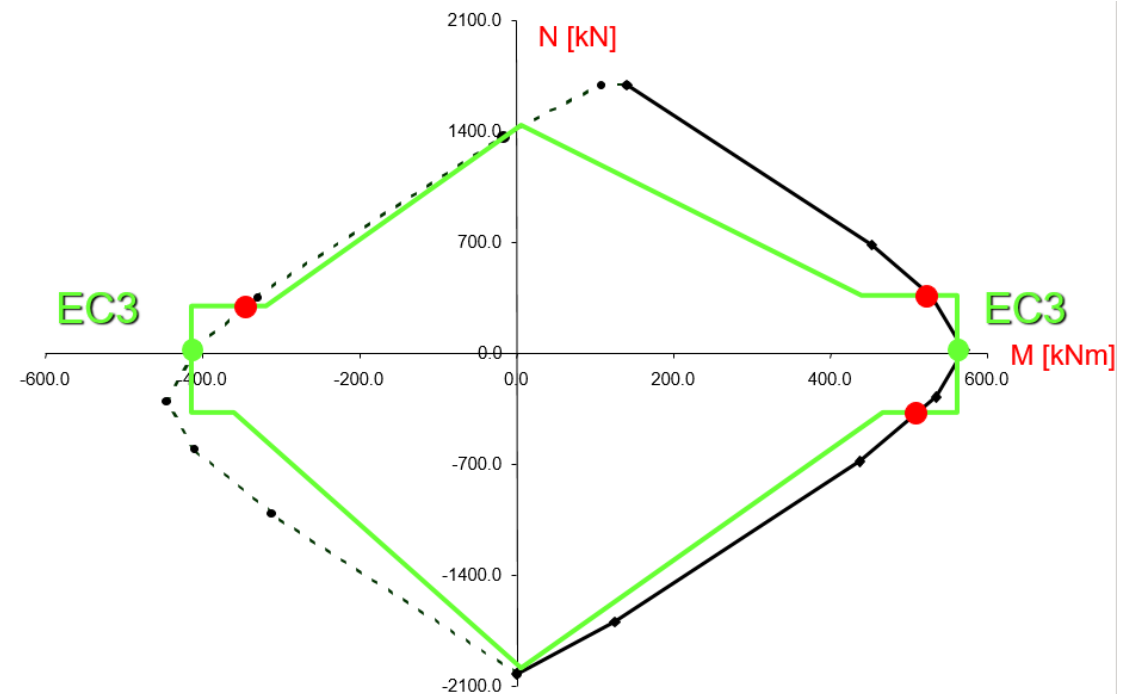
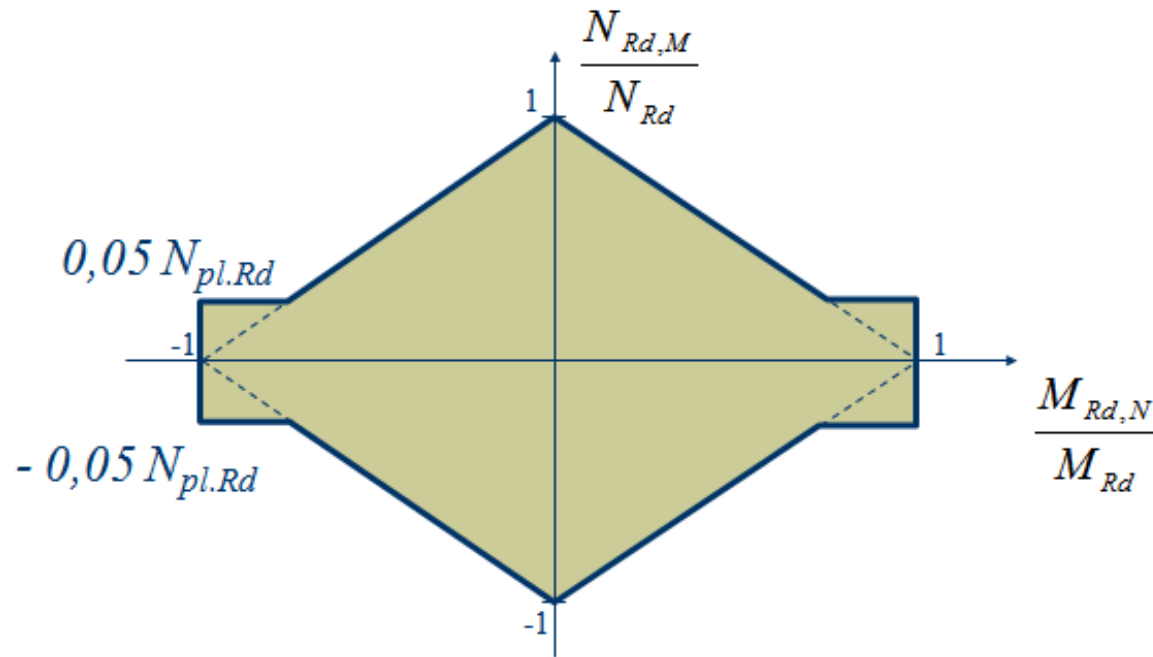
- Interaction formula as a conservative assumption if the 5% rule not satisfied:

$$\frac{M_{j,Ed}}{M_{j,Rd}} + \frac{N_{j,Ed}}{N_{j,Rd}} \leq 1,0$$

Structural joints subjected to MN

EN1993-1-8:2005 design rules

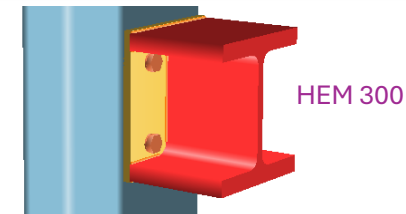
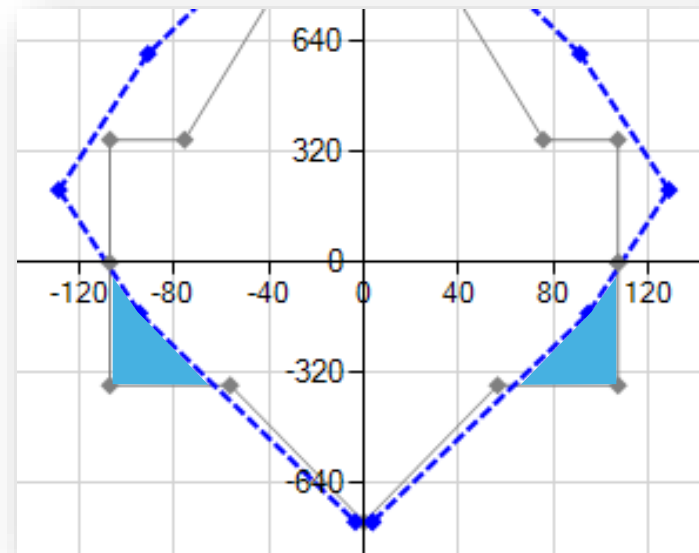
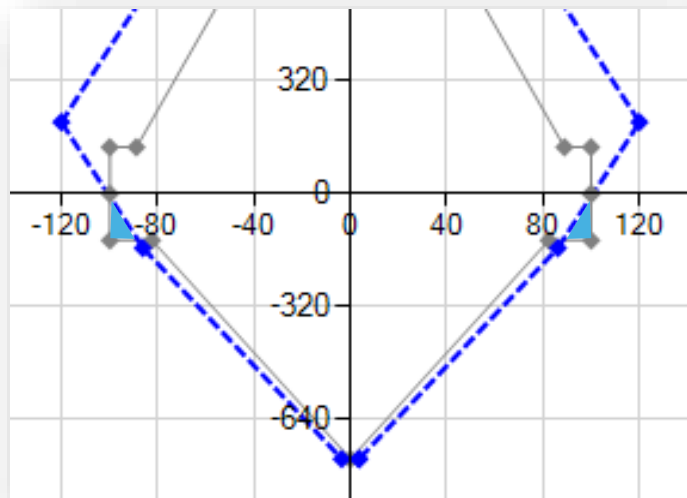
■ Inconsistency of the design rules



Structural joints subjected to MN

EN1993-1-8:2005 design rules

■ Inconsistency of the design rules



Structural joints subjected to MN

EN1993-1-8:2024 design rules

- New “5% rule”

Moment resistance is not influenced by an additional normal force if:

$$\left| \frac{N_{j,Ed}}{N_{j,Rd}} \right| \leq 0,05$$

Remark: - the value is still fully arbitrary

- moreover it is **still potentially unsafe... but less!**

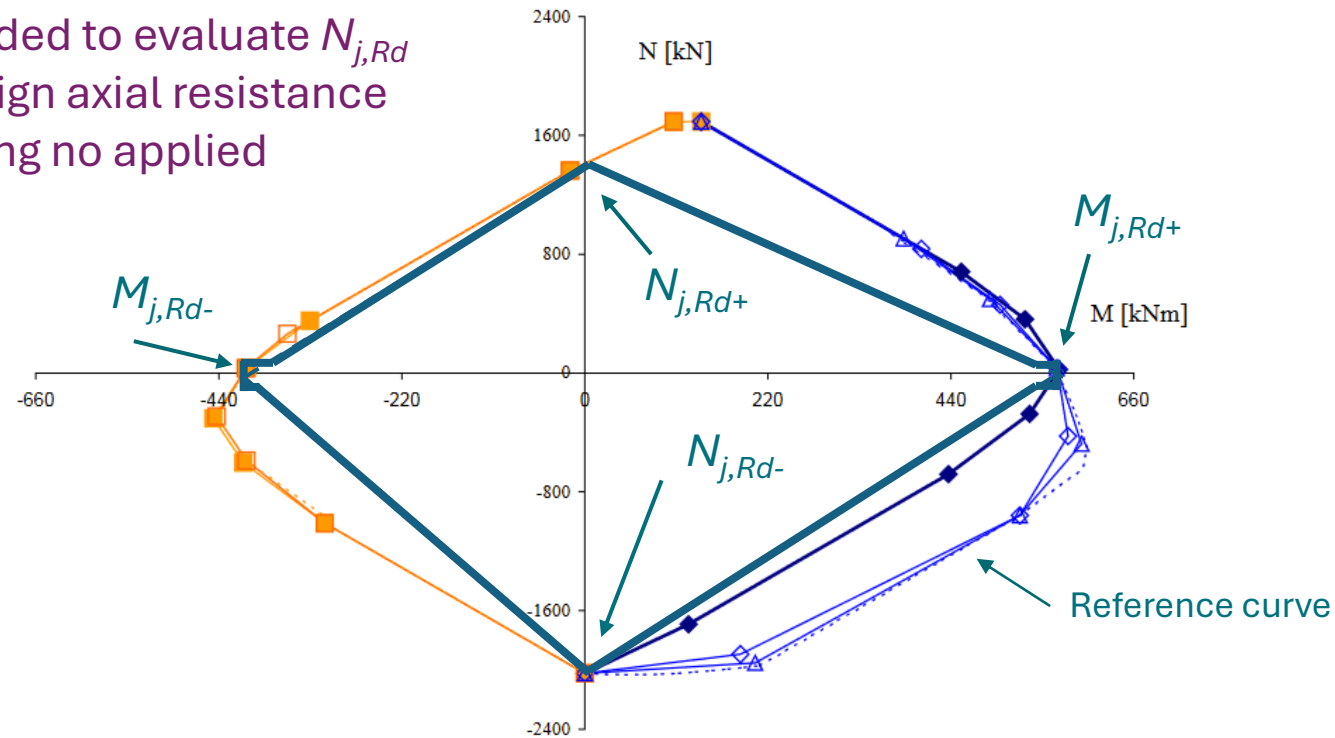
- Interaction formula as a conservative assumption if the 5% rule not satisfied:

$$\frac{M_{j,Ed}}{M_{j,Rd}} + \frac{N_{j,Ed}}{N_{j,Rd}} \leq 1,0$$

Structural joints subjected to MN

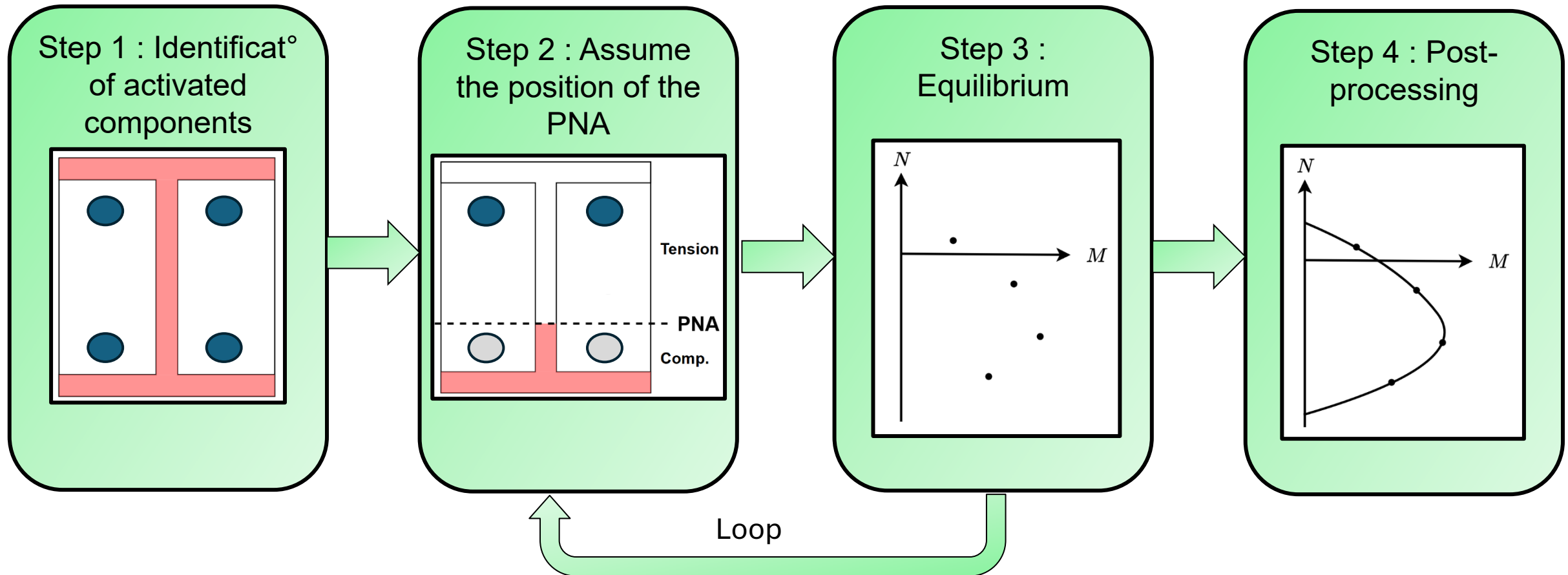
EN1993-1-8:2024 design rules

No procedure provided to evaluate $N_{j,Rd}$ defined as “the design axial resistance of the joint, assuming no applied moment”



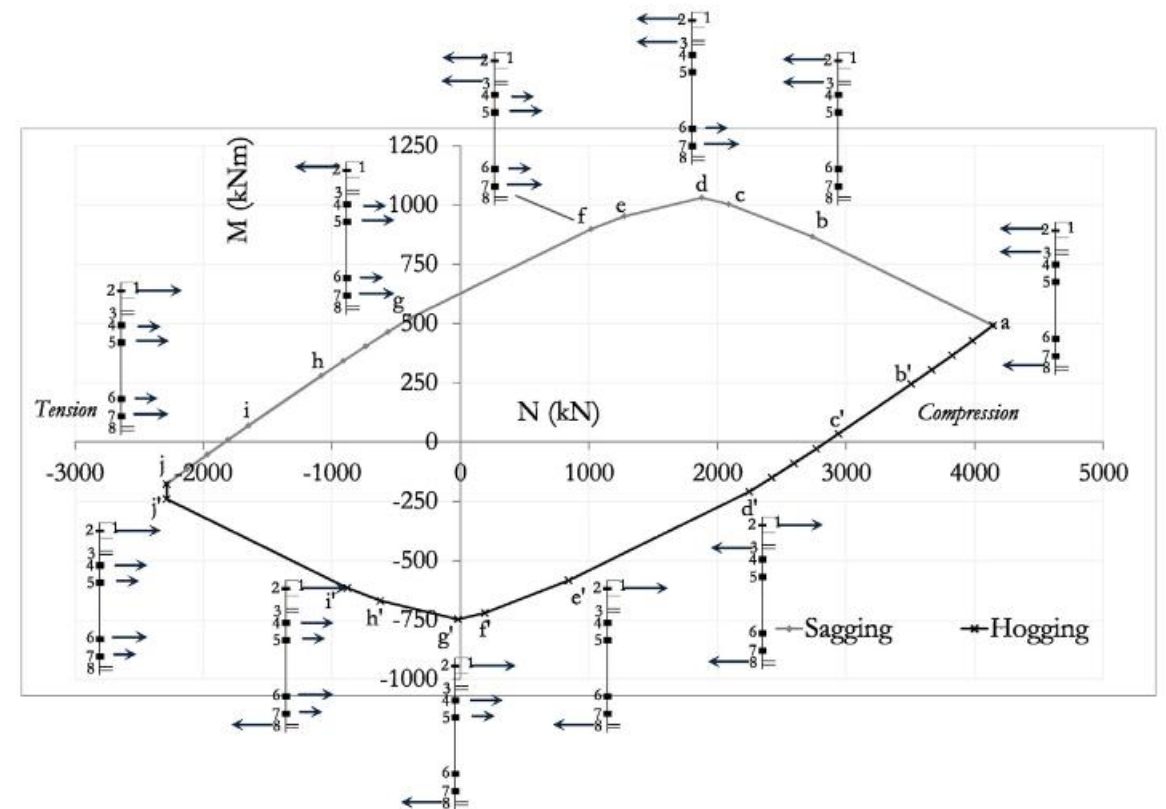
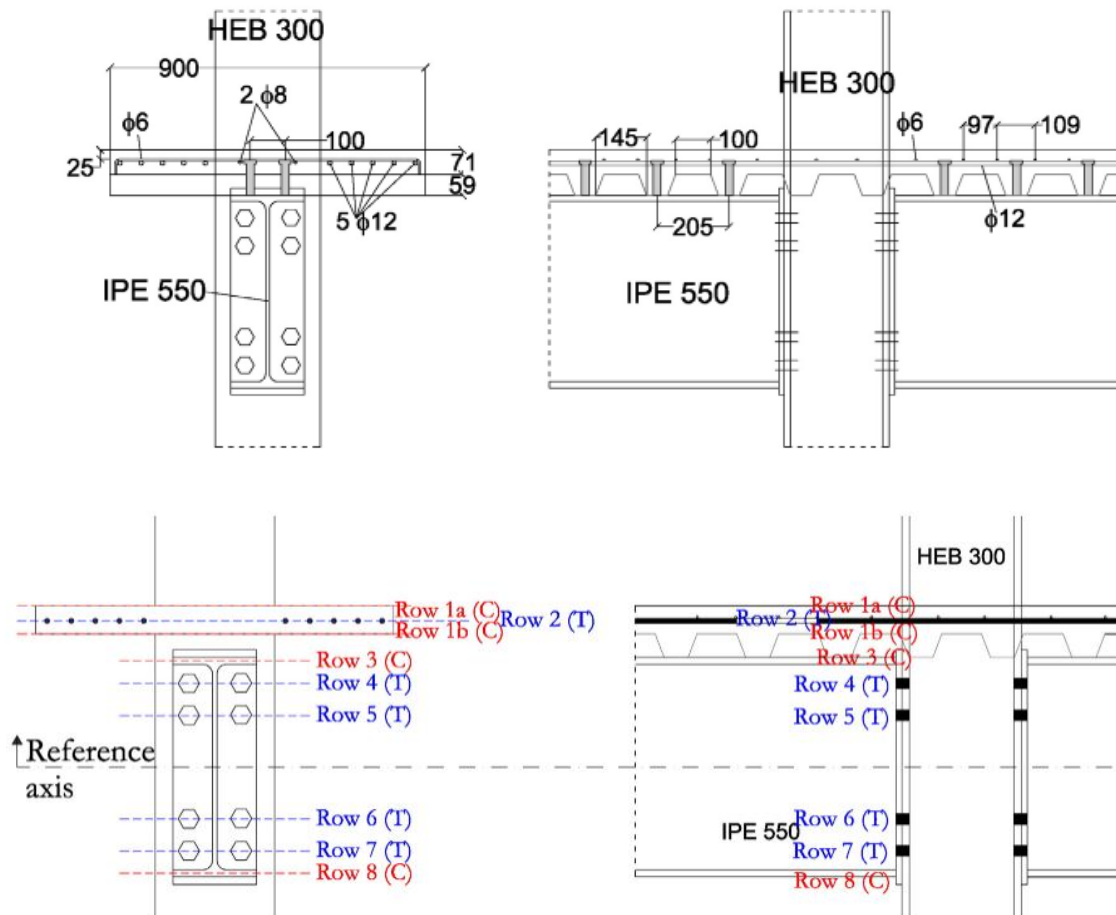
Advanced analytical model for joints under MN

Assumption : Each row has a **ductile** failure mode and an **elastic-perfectly plastic** material law



Advanced analytical model for joints under MN

Application of the model to an example



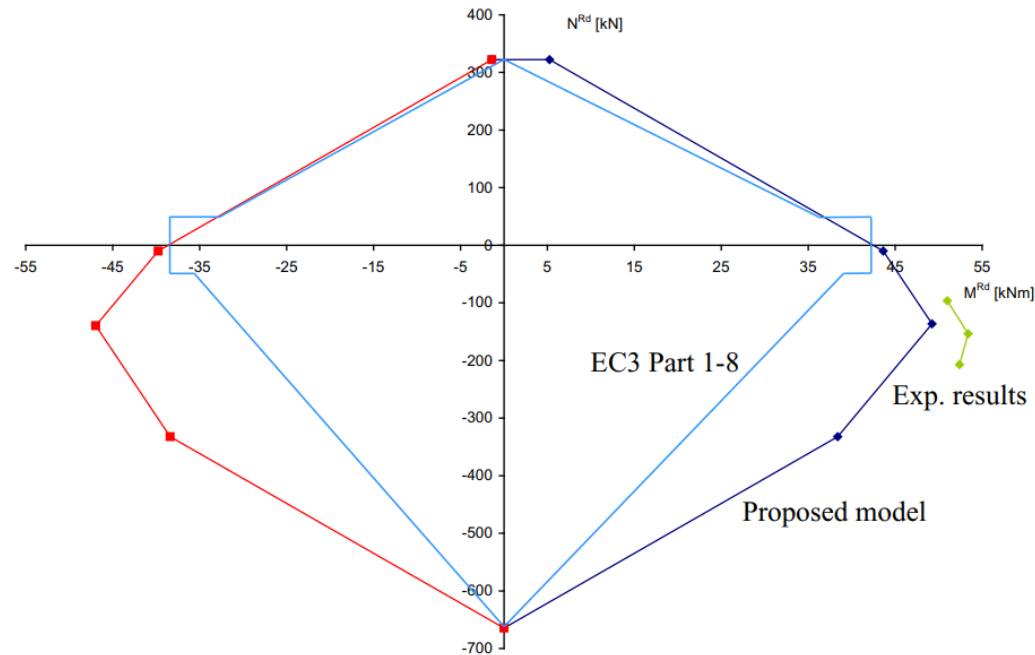
Advanced analytical model for joints under MN

Field of application and validity of the proposed model:

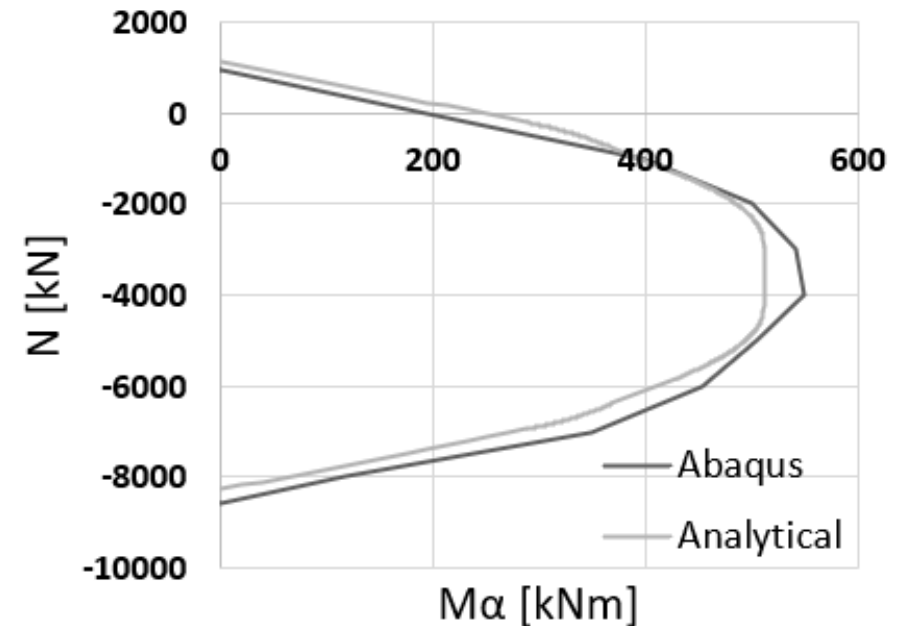
- Advanced model initially developed for steel joints by Cerfontaine
- Extended to composite joints by Demonceau
- Validated through comparisons to experimental and numerical results
- Validated to predict the response of joints at elevated temperature

Advanced analytical model for joints under MN

Validation of the advanced analytical model at room temperature



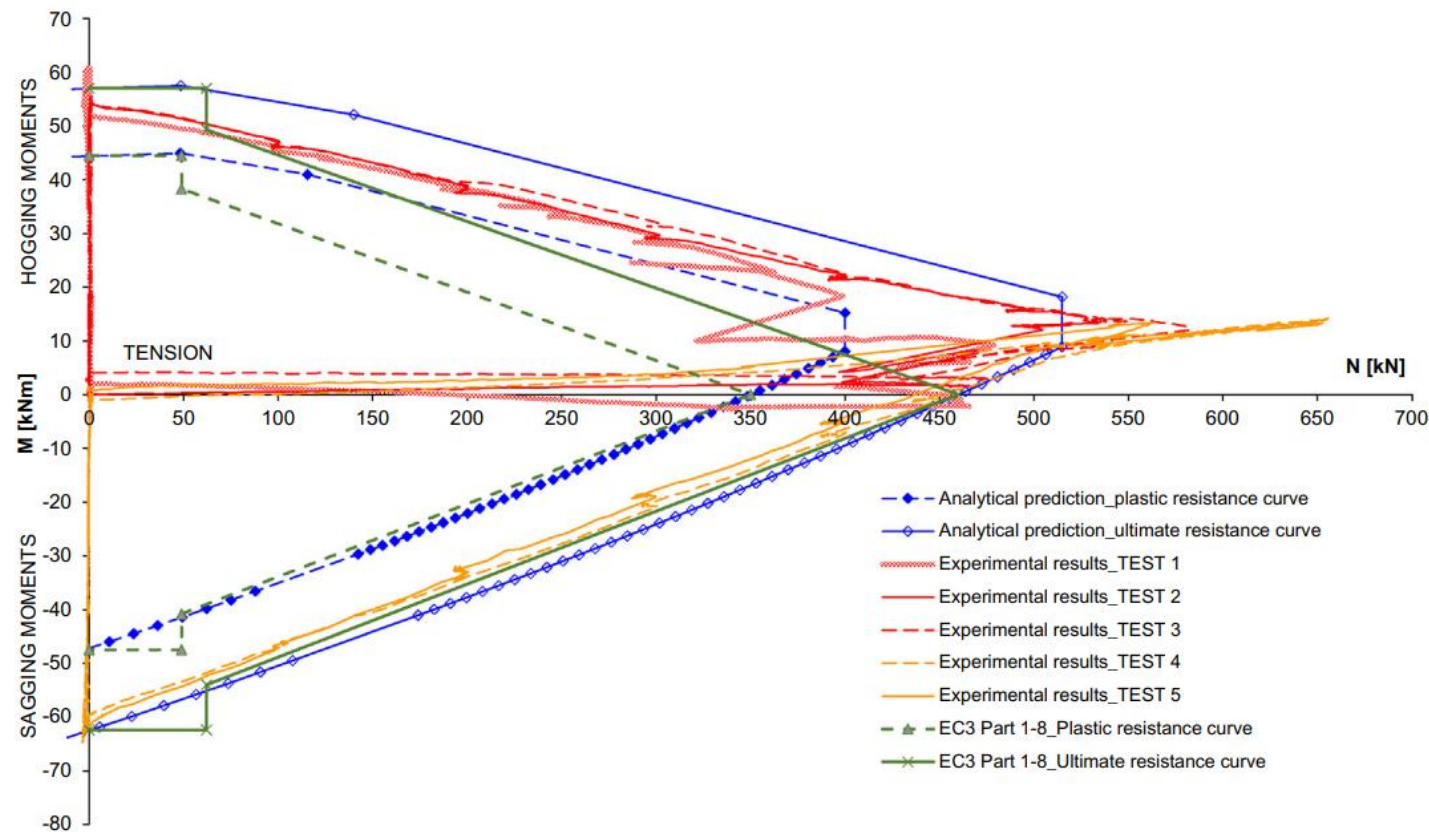
Comparison to experimental results
Limited number of tests in literature



Comparison to numerical results

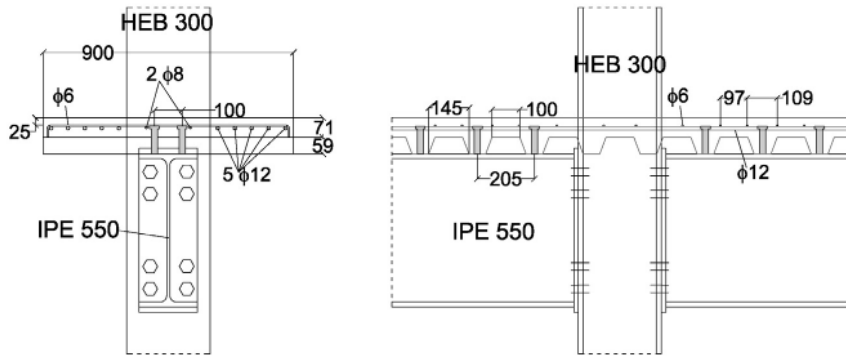
Advanced analytical model for joints under MN

Validation of the advanced analytical model at room temperature

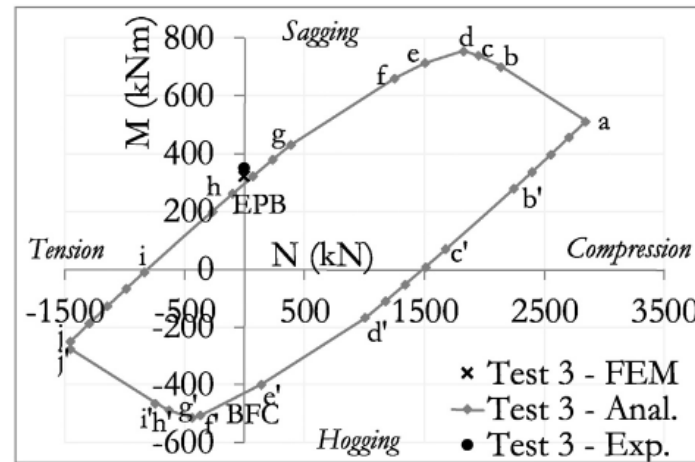


Advanced analytical model for joints under MN

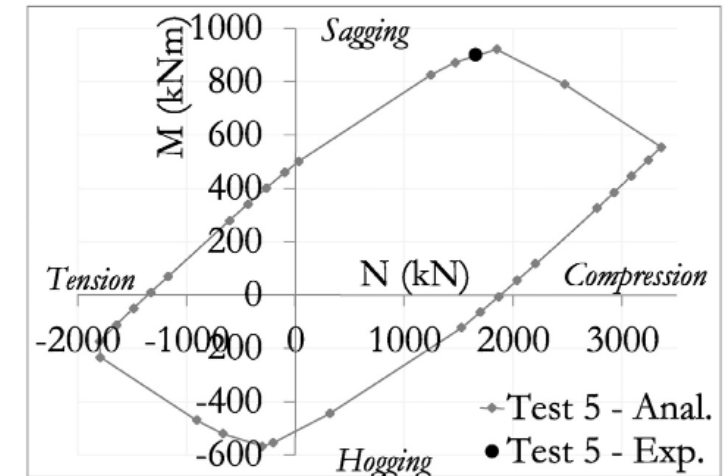
Validation of the advanced analytical model at high temperature



Fire experimental tests
performed at the University
of Coimbra



Tests at 700°C



Simplified analytical model for joints under MN

Proposal for implementation in next generation of EN 1993-1-8

Points $A^{+/-}$

$$A^+ \rightarrow \text{active} = F_{Rd}^+ < 0 : M_{A^+} = \sum F_{Rd}^+ h \text{ active} ; N_{A^+} = \sum F_{Rd}^+ \text{ active}$$

$$A^- \rightarrow \text{active} = F_{Rd}^- < 0 : M_{A^-} = \sum F_{Rd}^- h \text{ active} ; N_{A^-} = \sum F_{Rd}^- \text{ active}$$

Points $B^{+/-}$

$$B^+ \rightarrow \text{active} = F_{Rd}^+ h > 0 : M_{B^+} = \sum F_{Rd}^+ h \text{ active} ; N_{B^+} = \sum F_{Rd}^+ \text{ active}$$

$$B^- \rightarrow \text{active} = F_{Rd}^- h < 0 : M_{B^-} = \sum F_{Rd}^- h \text{ active} ; N_{B^-} = \sum F_{Rd}^- \text{ active}$$

Points $C^{+/-}$

$$C^+ \rightarrow \text{active} = F_{Rd}^+ > 0 : M_{C^+} = \sum F_{Rd}^+ h \text{ active} ; N_{C^+} = \sum F_{Rd}^+ \text{ active}$$

$$C^- \rightarrow \text{active} = F_{Rd}^- > 0 : M_{C^-} = \sum F_{Rd}^- h \text{ active} ; N_{C^-} = \sum F_{Rd}^- \text{ active}$$

Under discussion...

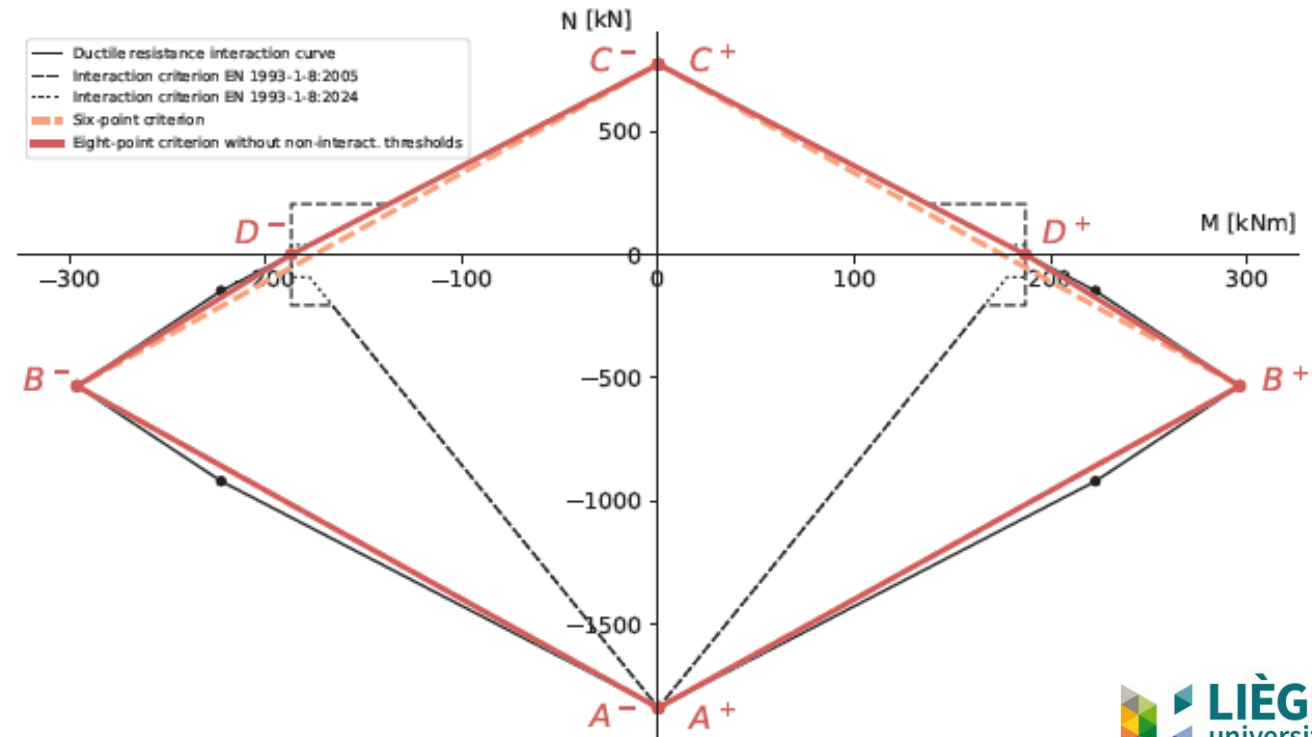
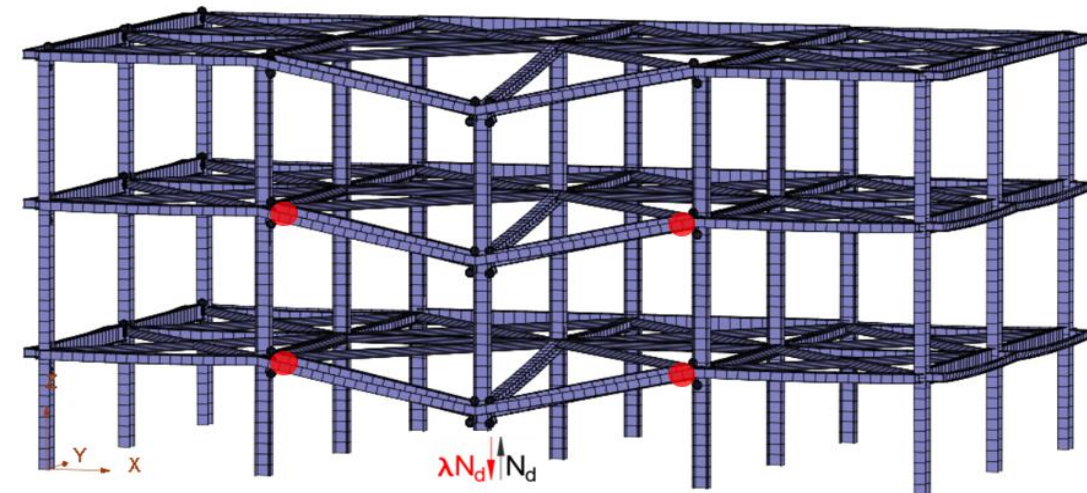


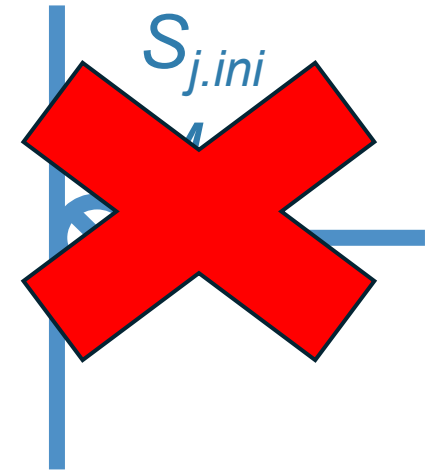
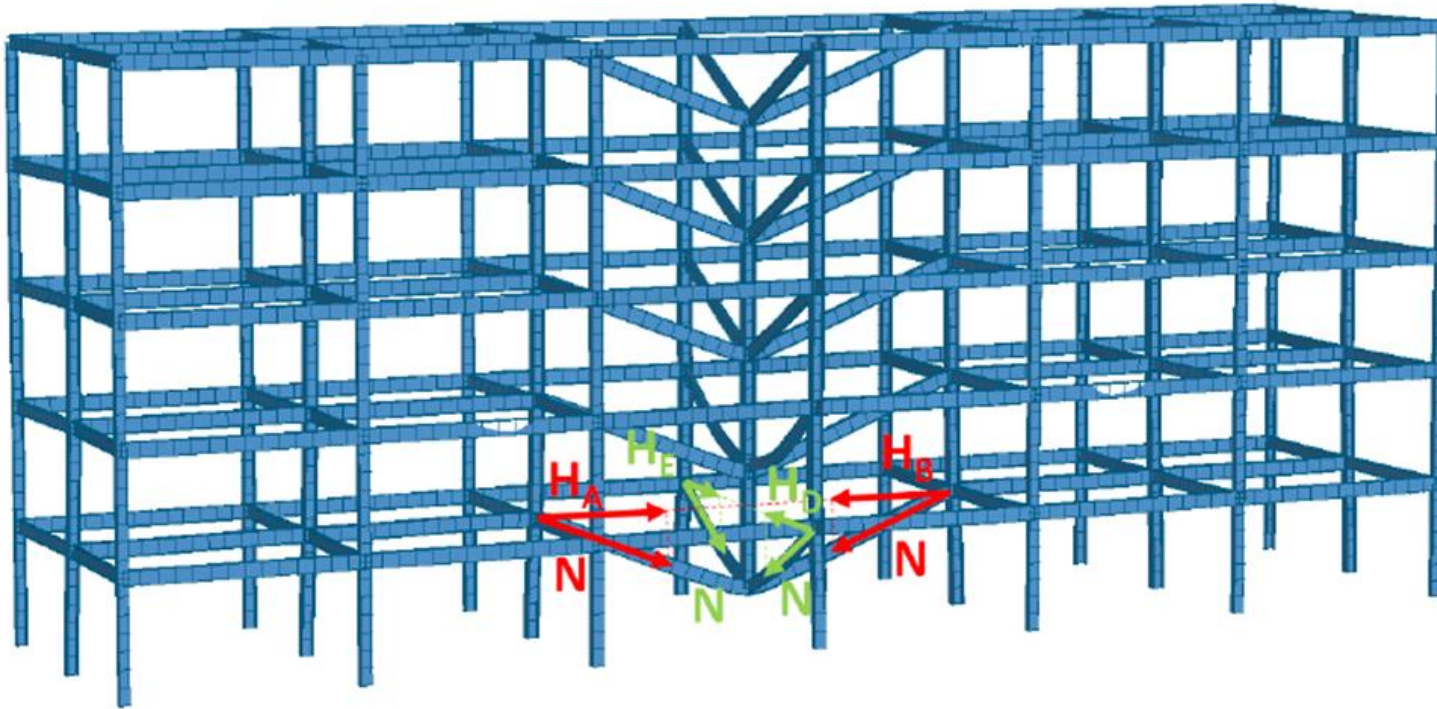
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- ▶ Dynamic behaviour of joints
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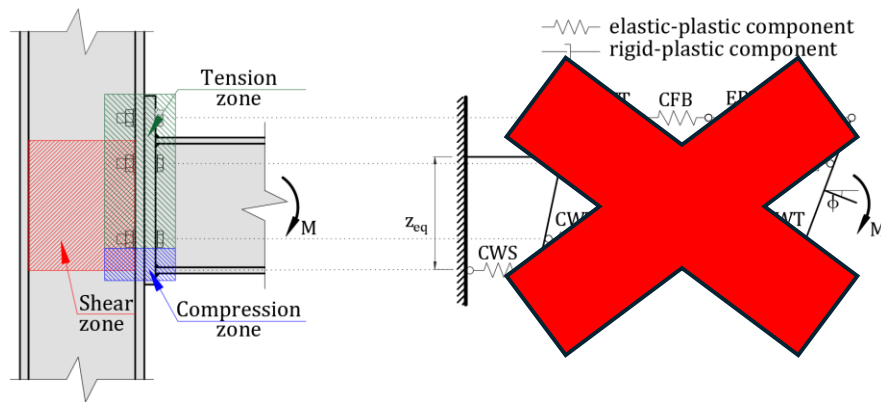
Actual joint behaviour in structural analysis

How to account for the actual joint behaviour in structural analysis?



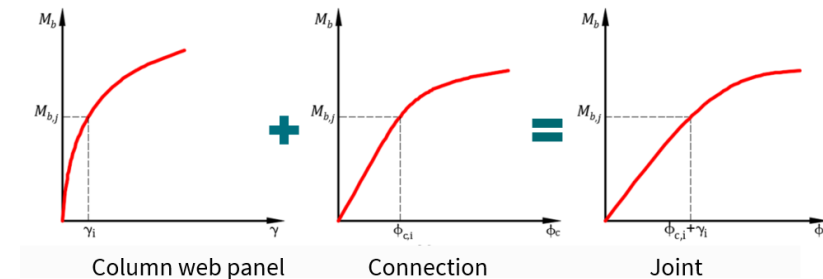
Actual joint behaviour in structural analysis

How to account for the actual joint behaviour in structural analysis?



EN 1993-1-8 (EC3) base stiffness
model

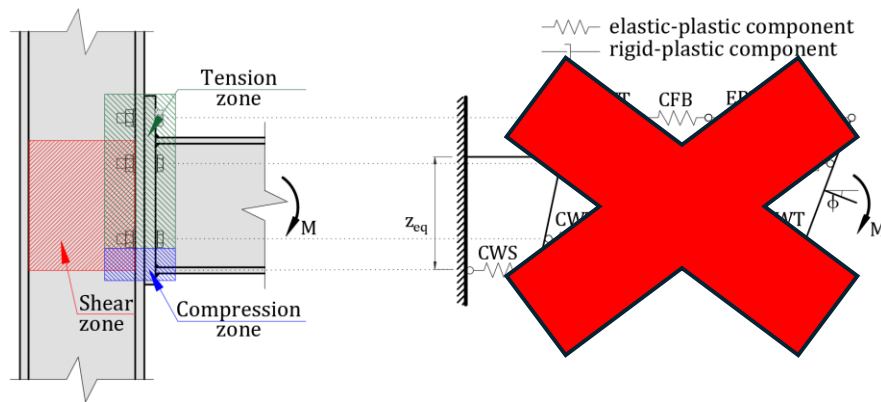
“Component Method”



- ▶ Three key phenomena disregarded by the existing mechanical models:
 - *Group effects in “plate in bending” components*
 - *Variation of shear force on the height of the panel zone*
 - *Stress interactions in some components*

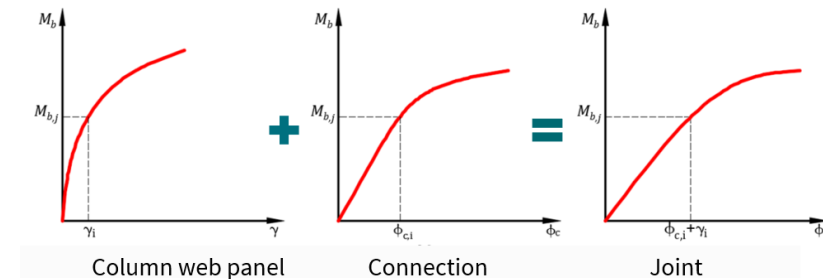
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EN 1993-1-8 (EC3) base stiffness
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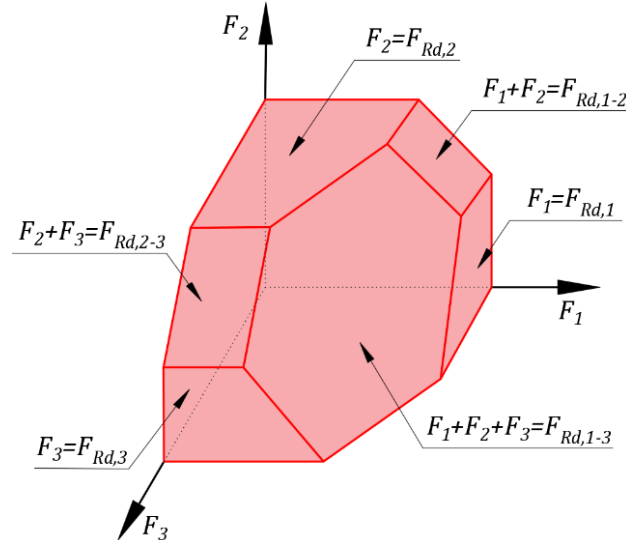
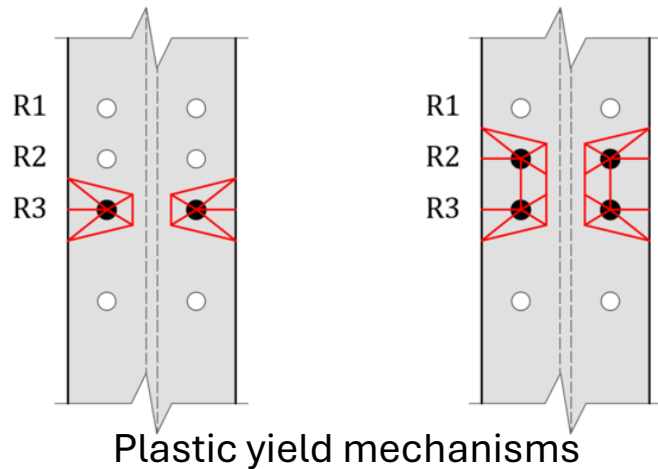


- ▶ Three key phenomena disregarded by the existing mechanical models:
 - *Group effects in “plate in bending” components*
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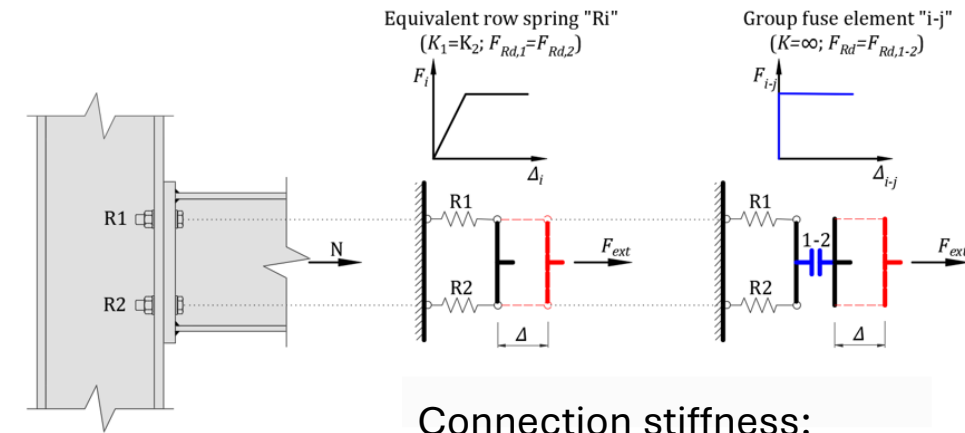
Actual joint behaviour in structural analysis

Implementation of the group effects

EC3 approach



Mechanical modelling solution

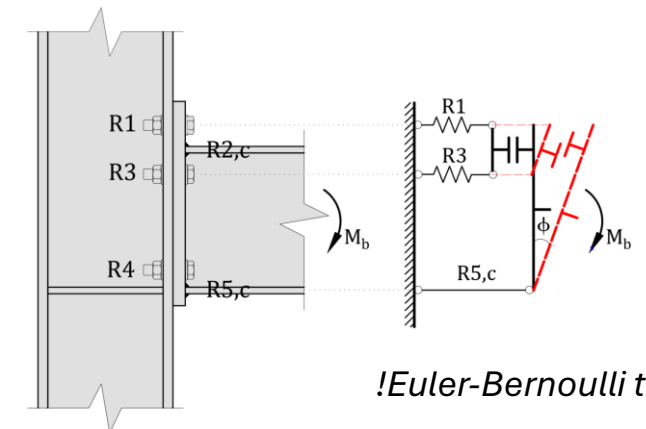


Connection stiffness:

$$K_{con} = 2K_1 \quad \checkmark$$

Resistance:

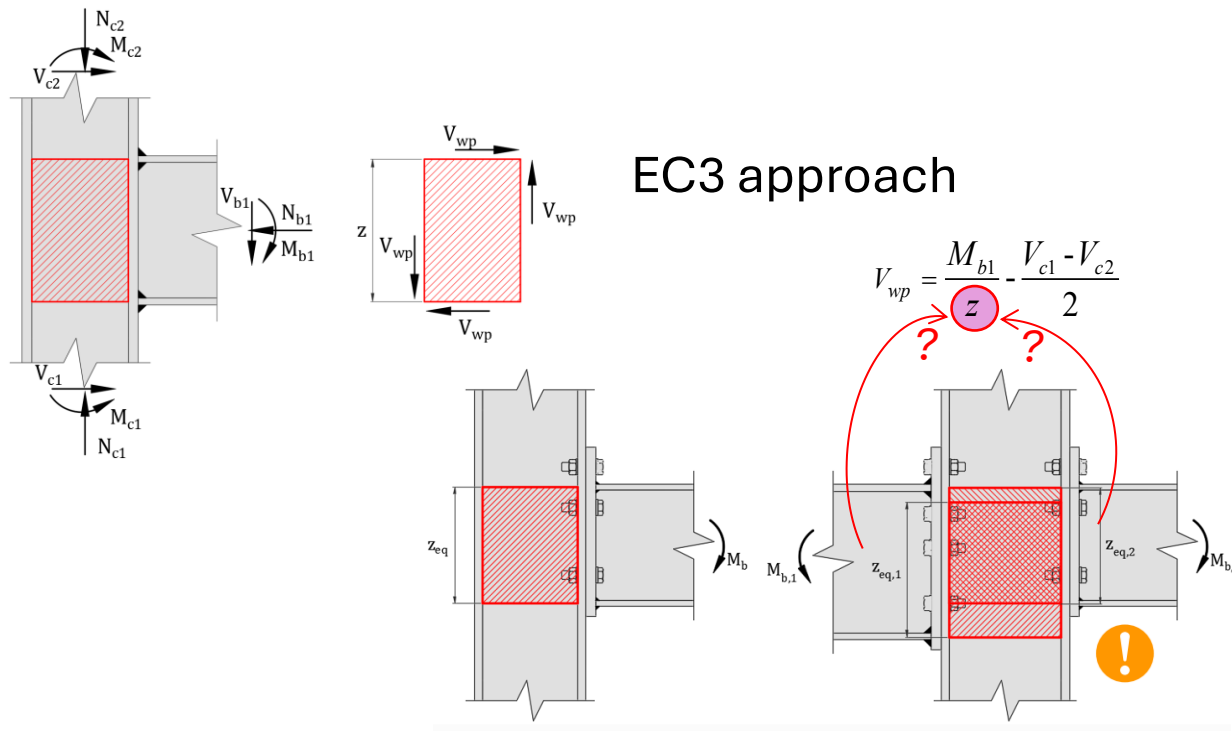
$$F_{ext,max} = F_{Rd,con} = \min(2F_{Rd,1}; F_{Rd,1-2}) \quad \checkmark$$



Actual joint behaviour in structural analysis

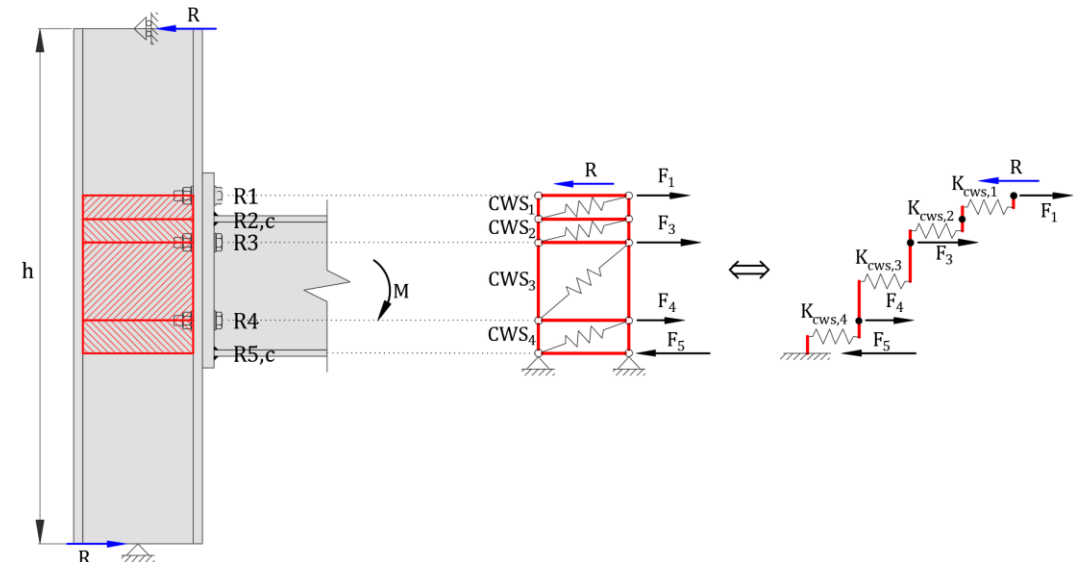
Improvement of the web panel in shear model

Shear force acting on the Column Web panel in Shear (CWS)



- z_{eq} based on a simplified stiffness calculation
- No unique value for V_{wp}

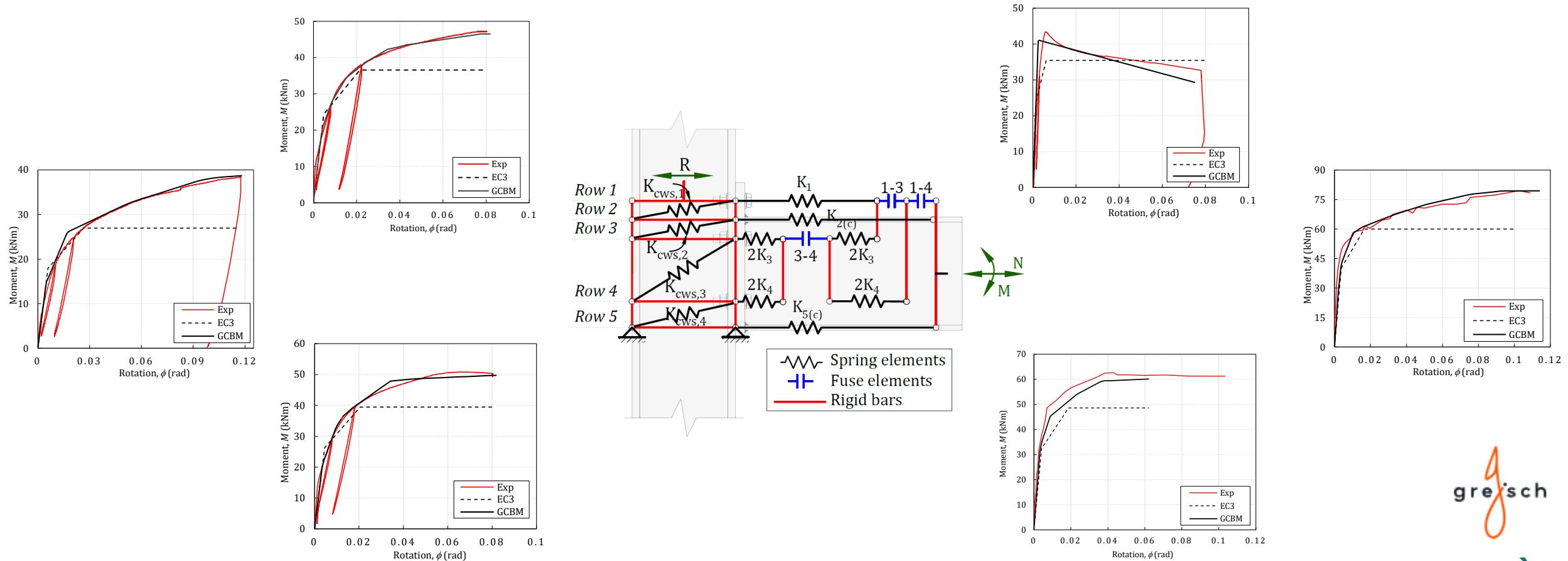
Mechanical modelling solution



Accommodation of the variation of shear force on the height of the panel zone

Actual joint behaviour in structural analysis

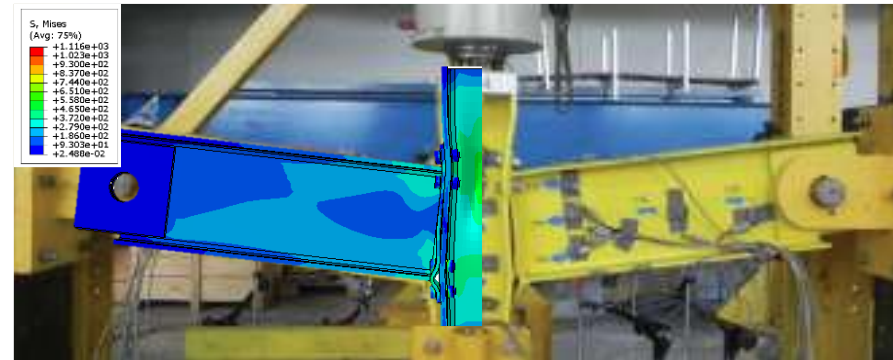
Implementation in a finite element in FineLg software



 Quality of the results strongly depends on the quality of the component behaviour law

Actual joint behaviour in structural analysis

Implementation in a finite element in FineLg software



Test performed at the University of Technology of Rzeszow in Poland

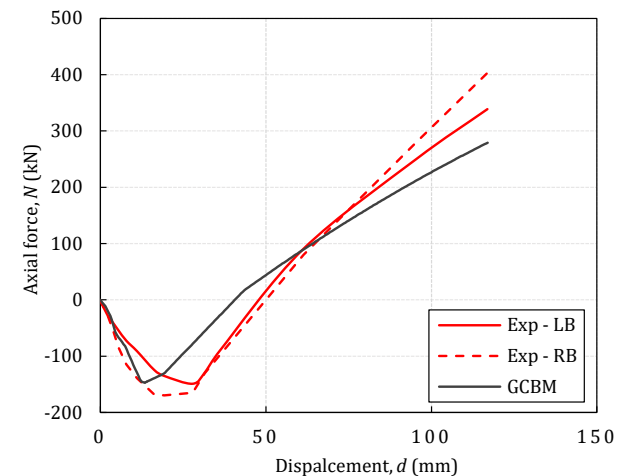
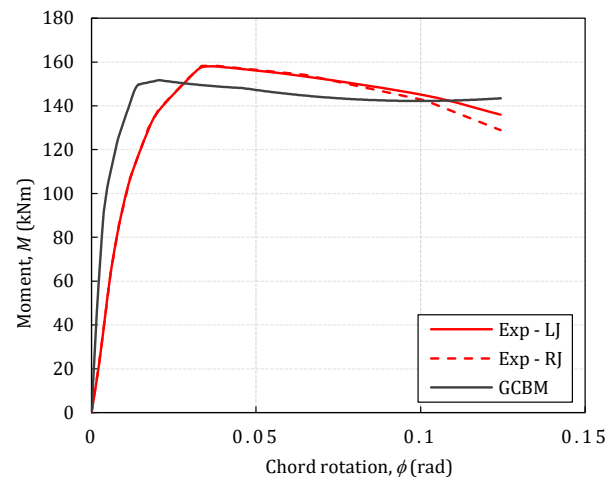
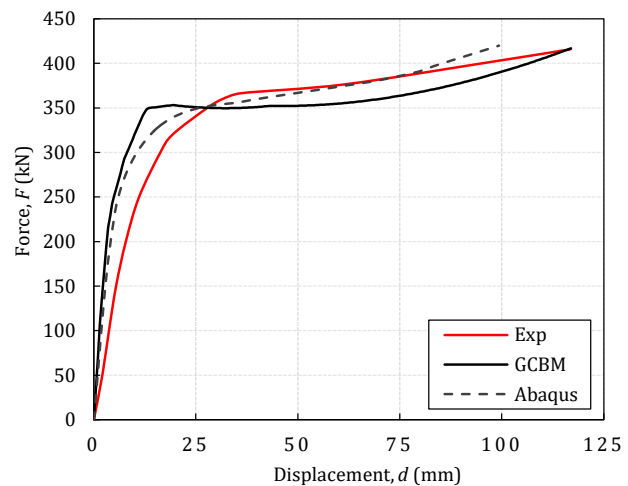


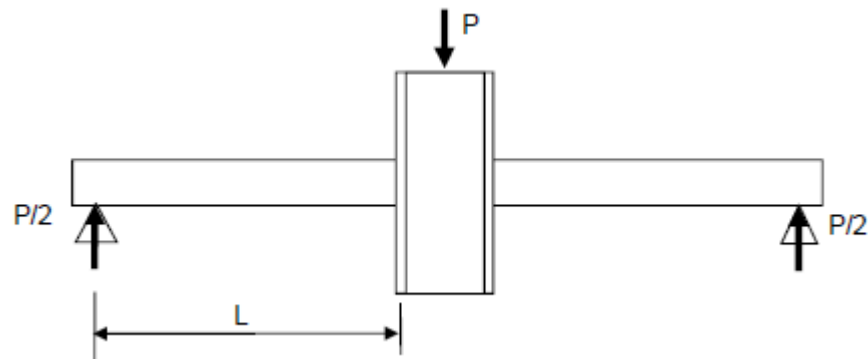
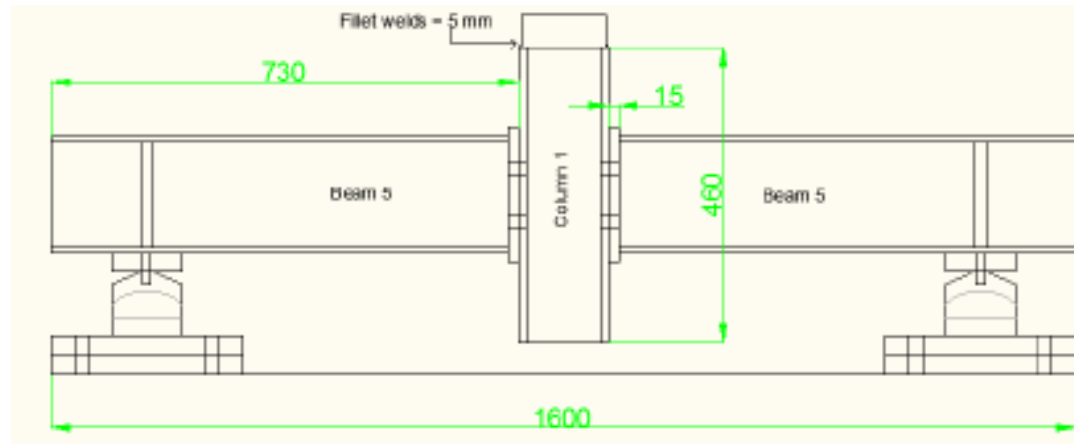
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- ▶ From robustness to resilience
- ▶ Conclusions



Dynamic behaviour of joints

Joints under impact



Dynamic behaviour of joints

Joints under impact – Test campaign

The real joint (RJ)

The end-plate in bending (EPB)

The column flange in bending (CFB)

The beam flange in compression (BFC)

The column web in compression (CWC)

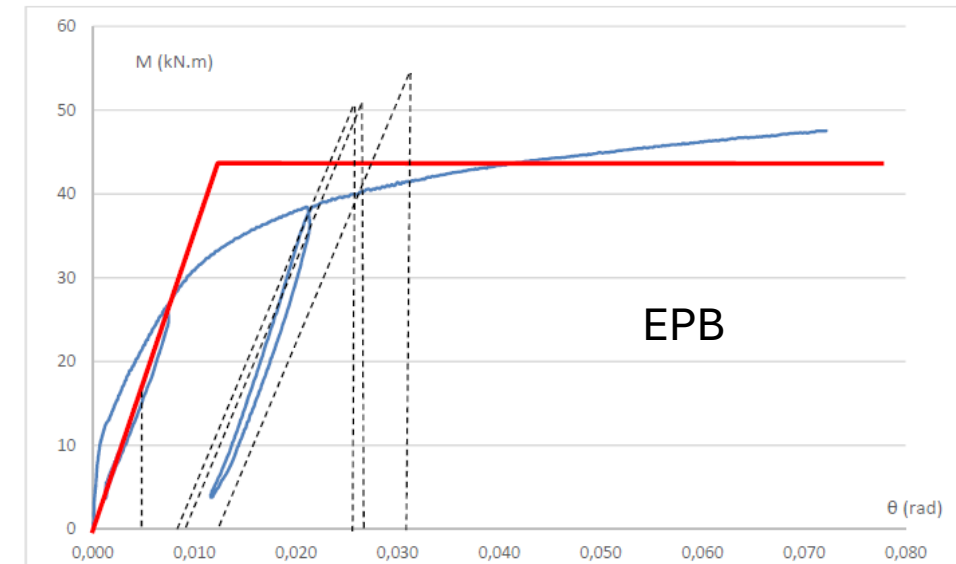
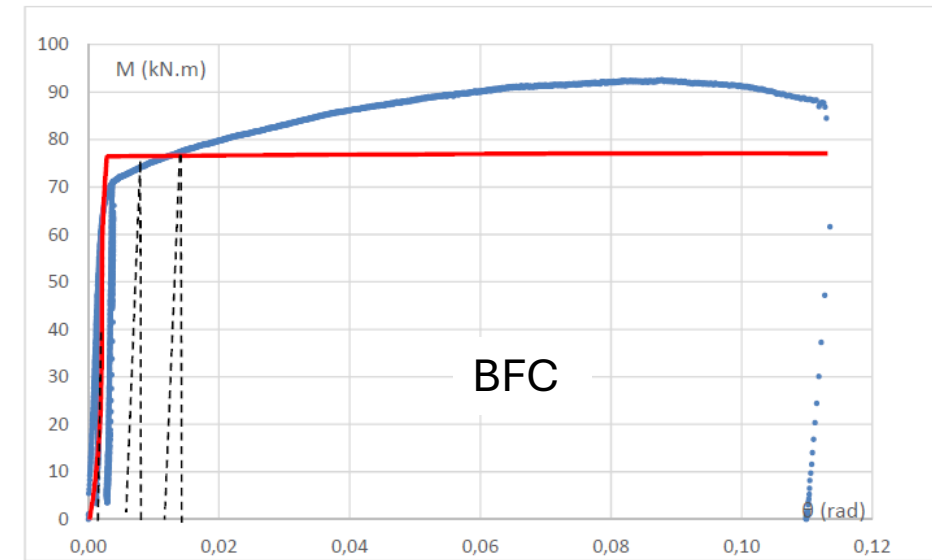
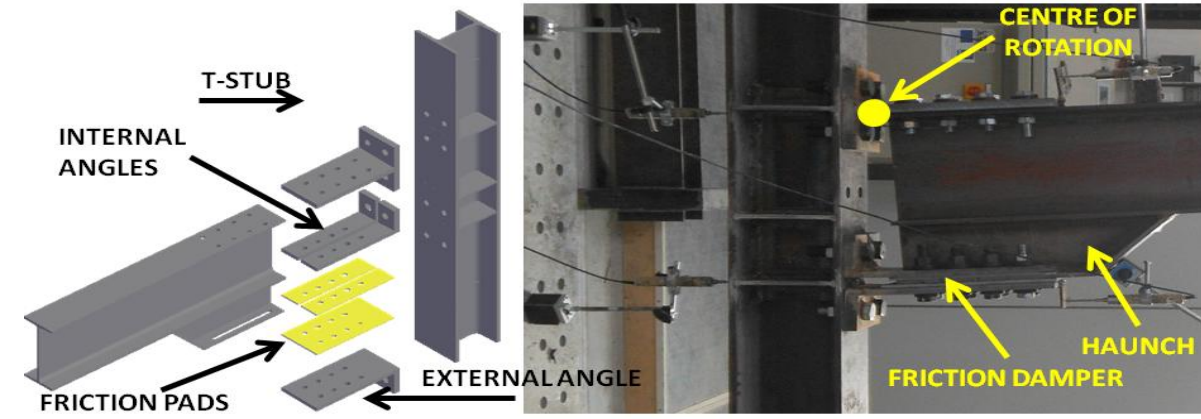
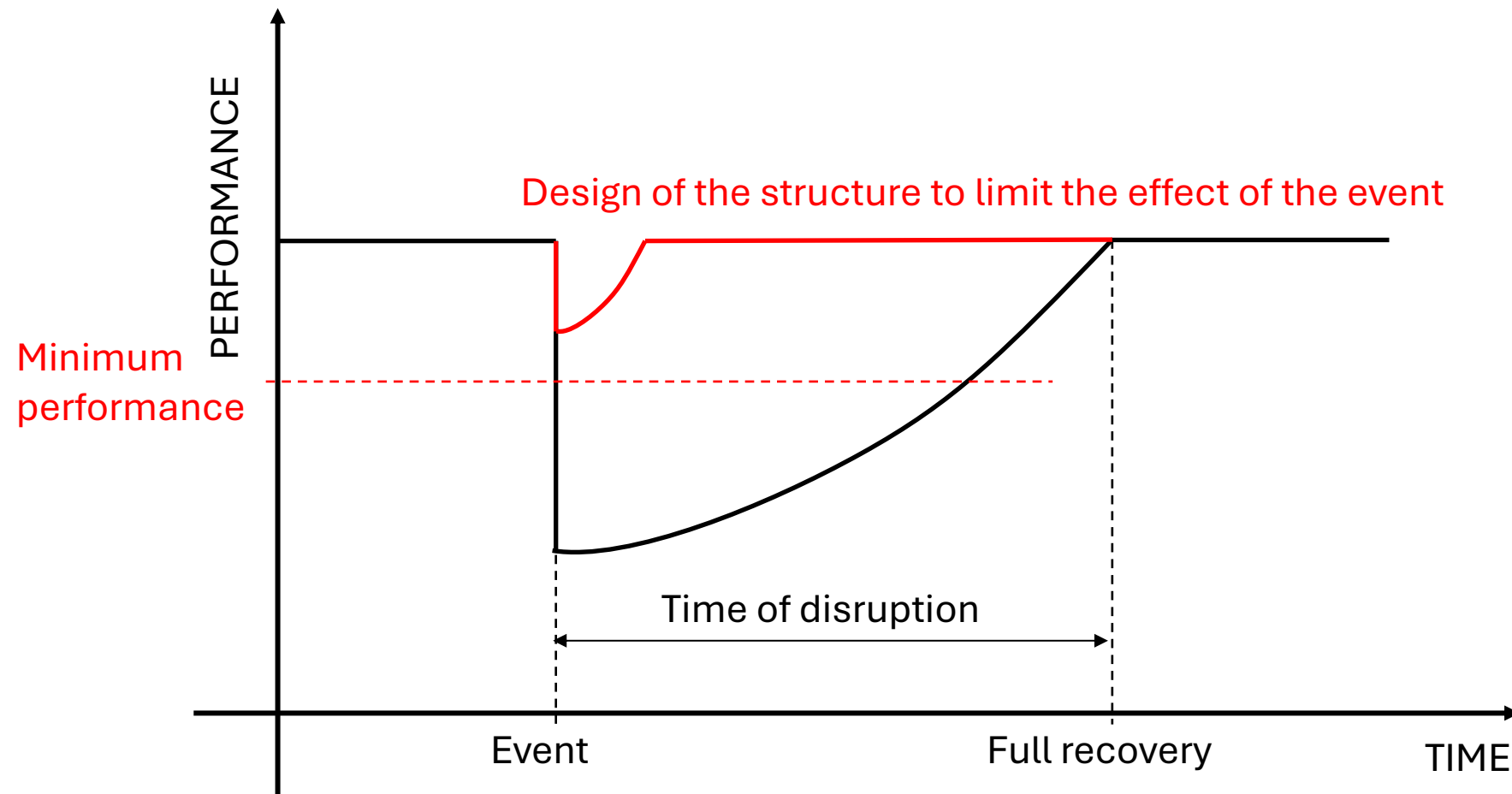


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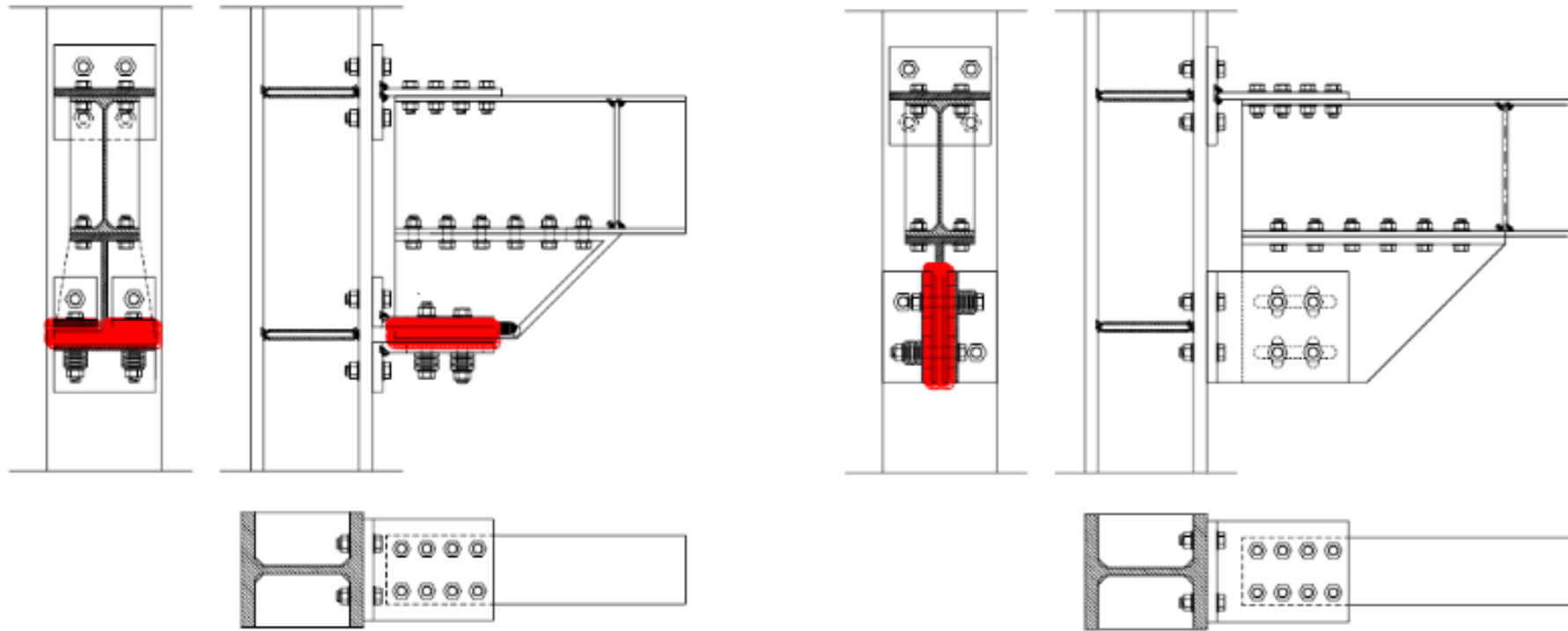


From robustness to resilience



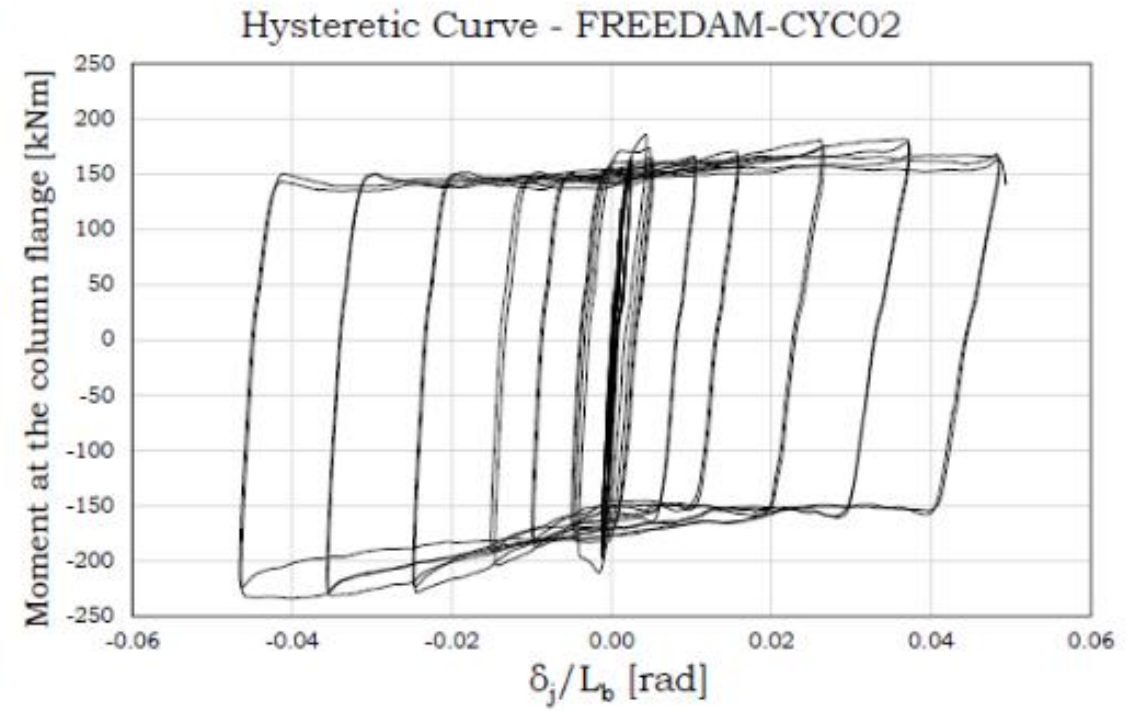
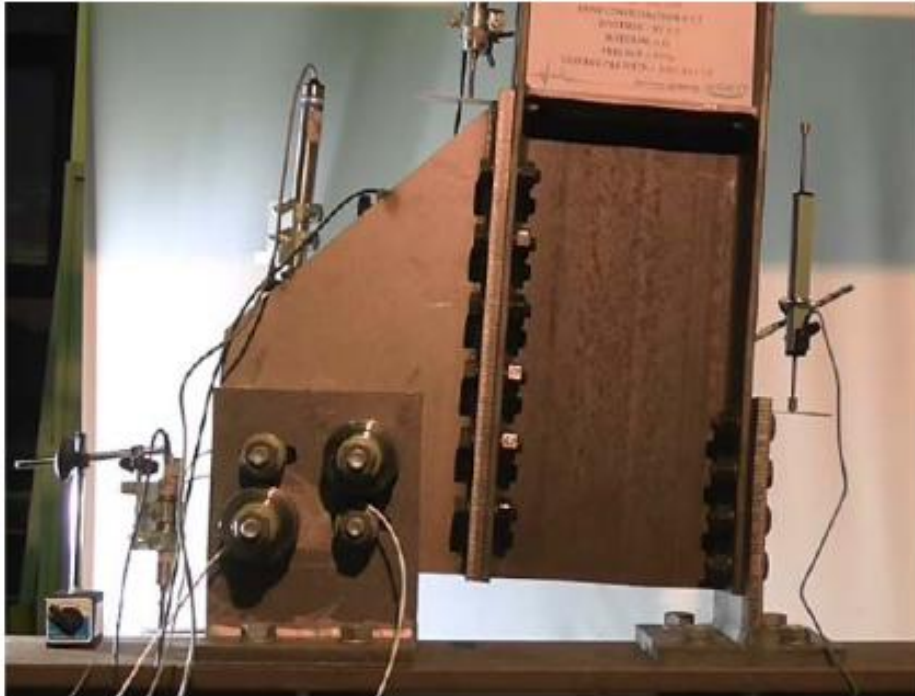
From robustness to resilience

Freedam joints (Free from Damage joint solution)



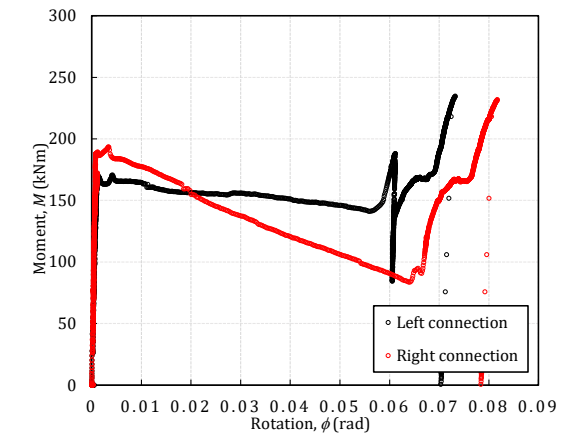
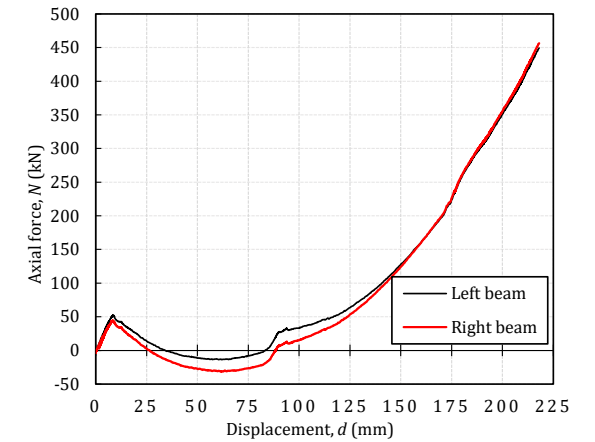
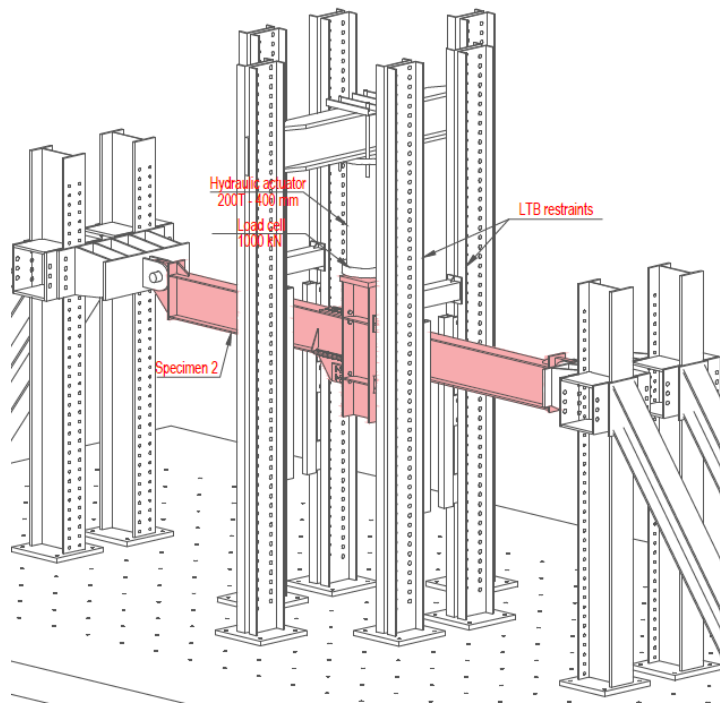
From robustness to resilience

Freedam joints – Seismic performance



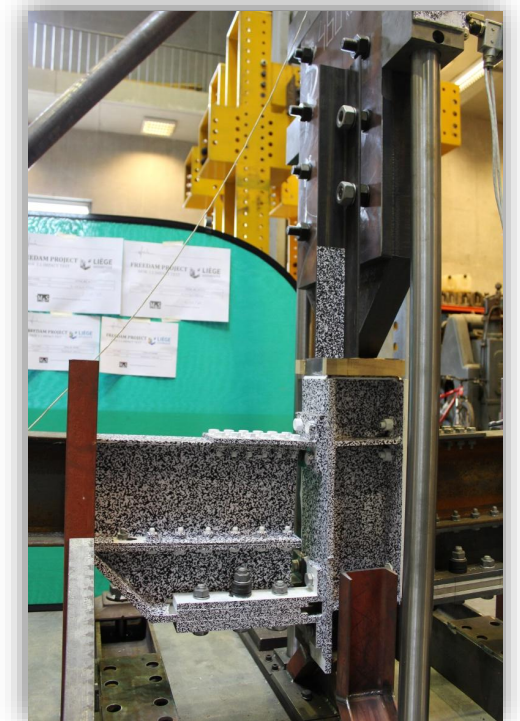
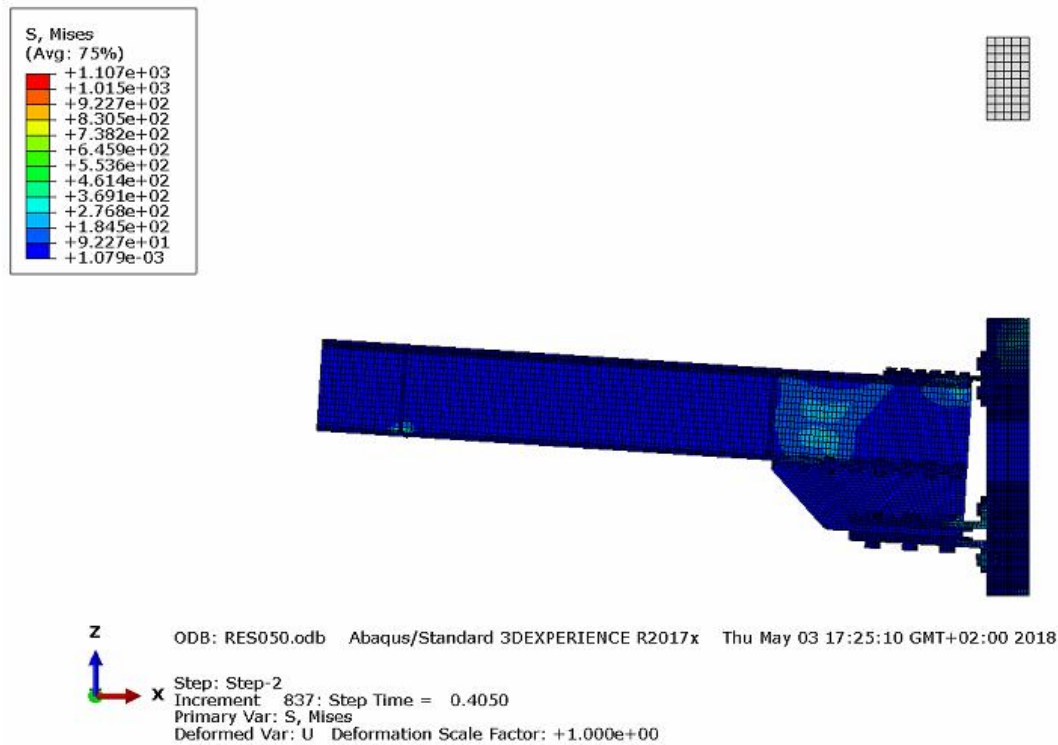
From robustness to resilience

Freedom joints – Column loss scenario



From robustness to resilience

Freedom joints – Dynamic response



From robustness to resilience

Dreamers project with Freedom joints

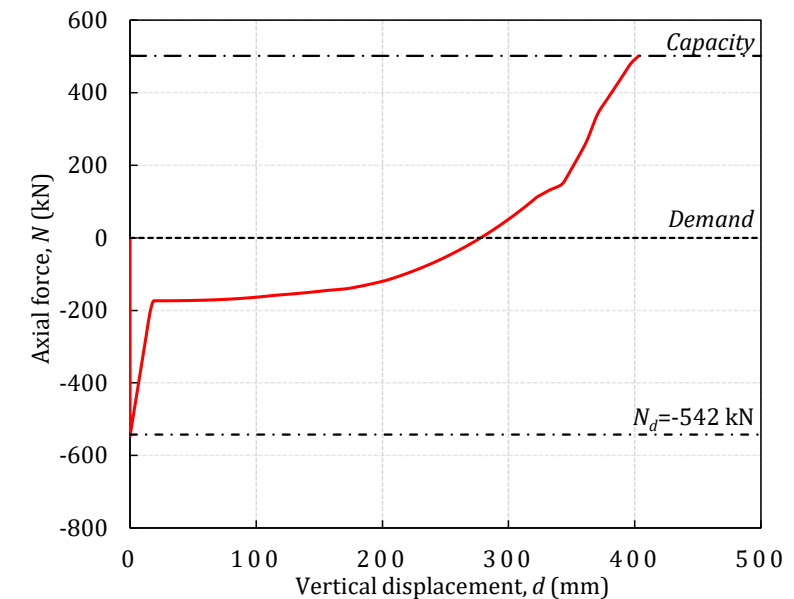
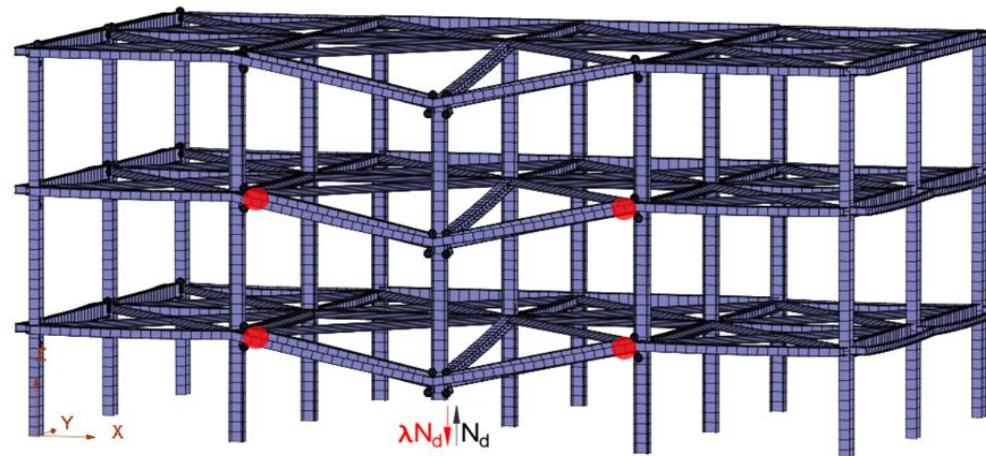
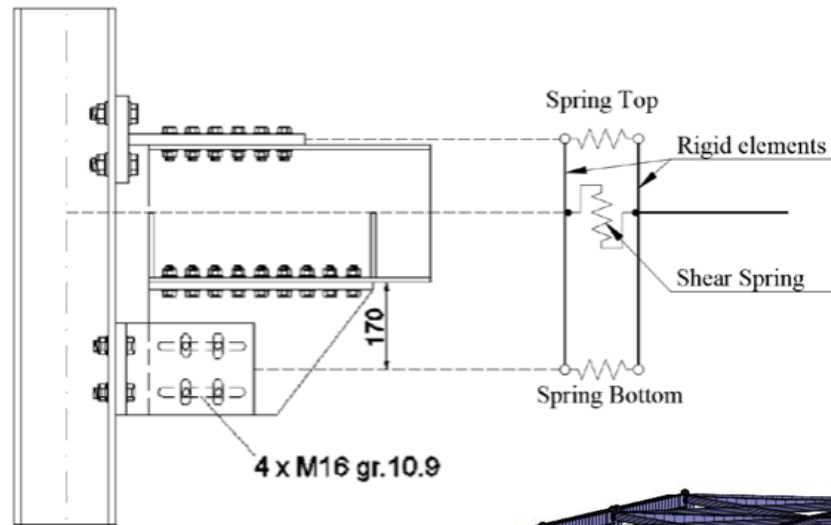
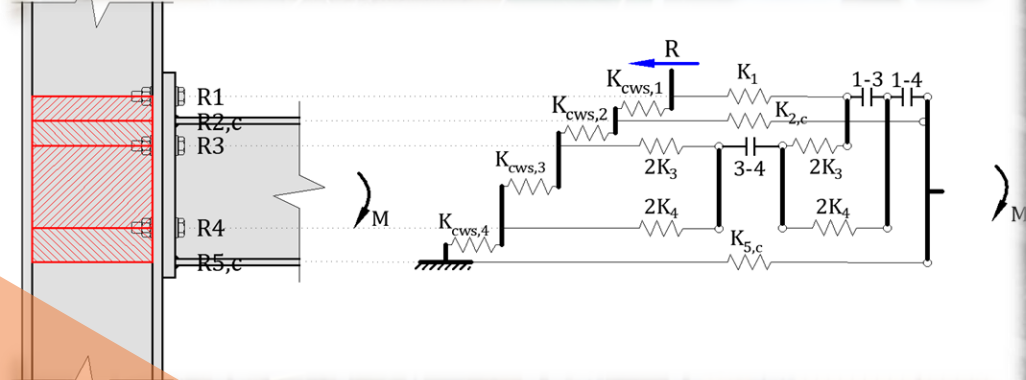


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Conclusions

- Joints identified as key structural elements in the design for robustness enhancement
- Joints subjected to other internal forces than the ones to be considered for their ultimate limit states design
- Models to predict their response when subjected to exceptional loading scenario are now available
- Development still required to predict their behaviour in case of dynamic loadings
- Development for practical tools allowing to account for the actual behaviour of joints in frame analyses still required



Thank you for your attention

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