6th NATIONAL CONFERENCE ON EARTHQUAKE ENGINEERING
&
2nd NATIONAL CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY

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Design assisted by testing of seismic resistant steel structures

by

Acad. Dan Dubina

Politehnica University of Timisoara

Introduction

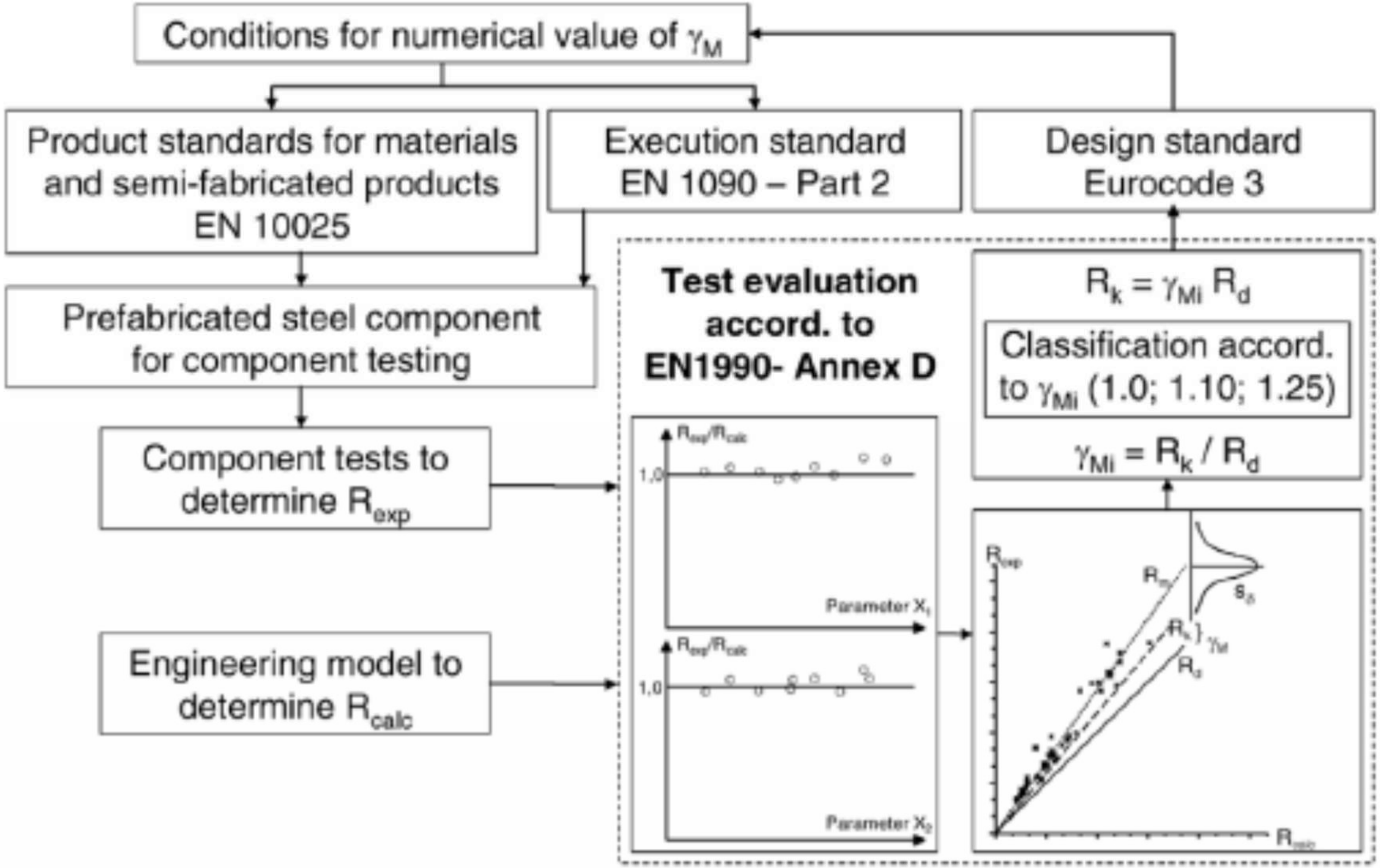
- Design assisted by testing is a powerful tool for evaluating the performance characteristics of materials, members or components. Sometimes, structures are too complicate to be designed using simple code formulas or theoretical methods i.e.
  - **Experimental prequalification of some design parameters, for which no code analytical procedures are available**
  - **Complex structural configurations, loading conditions, material properties**
  - **Difficult to model and characterize structural response under complex loading conditions**
  - **Difficult to model and characterize essential parameters (capacity, stiffness, ductility)**
  - **Difficult to estimate safety margins**

EU Codification Base for Design & Research assisted by Testing

EN 1990 , Annex D ⟹ testing migth be used when:

- the properties of materials are unknown
- no adequate analytical procedures for designing the component by calculation alone are available
- realistic data for design cannot otherwise be obtained
- check the performance of an existing structure or structural component;
- replicate a number of similar structures or components on the basis of a prototype
- confirmation the consistency of production is required
- determine the effects of interaction with other structural components;
- prove the validity and adequacy of an analytical procedure
- provide resistance tables based on tests, or on a combination of testing and analysis
- take into account practical factors that might alter the performance of a structure, but are not addressed by the relevant analysis method for design by calculation
- **Calibrate and Validate numerical models**
- **Validate new technical solutions**

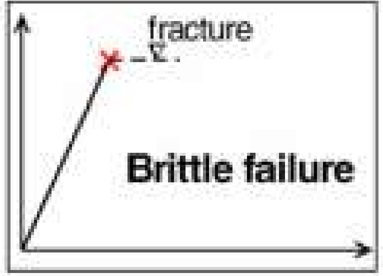
EN 1993: Determination of characteristic values R_k and γ_M values from tests

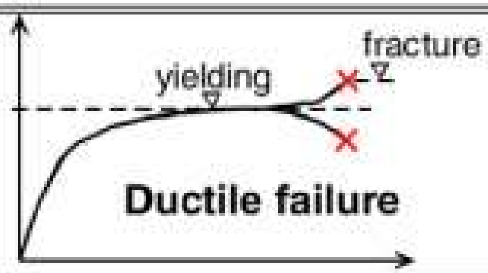


(Sedlacek & Müller, 2006)

Definition of γ_M associated with failure mode

Failure modes





excluded by appropriate choice of material	**1. Mode 0** excessive deformation by yielding e.g. tension bar $R_d = \frac{R_k(f_y)}{\gamma_{M0}}$	**Mode 1** member failure by instability e.g. column buckling $R_d = \frac{R_k(f_y, \bar{\lambda})}{\gamma_{M1}}$	**Mode 2** fracture after yielding e.g. bolt $R_d = \frac{R_k(f_u)}{\gamma_{M2}}$
	2. Test evaluation $R_d = m_R \exp(0{,}8\,\beta\,\sigma_R - 0{,}5\,\sigma_R^2)$; $\beta = 3{,}80$		
	3. Recommended values		
	$\gamma_{M0} = 1{,}00$	$\gamma_{M1} = 1{,}10$	$\gamma_{M2} = 1{,}25$
	4. Characteristic value $R_k = \gamma_M R_d$		

(Sedlacek & Müller, 2006)

Testing of Seismic Components and devices: normative framework

- **EN 15129: 2009 : Anti-seismic devices**

Covers the design of devices that are provided in structures, with the aim of modifying their response to the seismic action. It specifies functional requirements and general design rules for the seismic situation, material characteristics, manufacturing and testing requirements, as well as evaluation of conformity, installation and maintenance requirements

  - Rigid connection devices
  - Displacement depended devices
  - Velocity Depended Devices
  - Seismic isolators

- **EN 1998-1 (and P100-1/2013)**
  - Requests for experimental qualification of Beam-to-Column Joins in terms of plastic rotation capacity

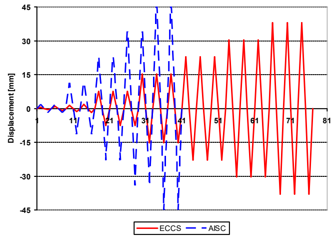
- **EN 1990 :** Basis of structural design
  - Section 5: Structural analysis and design assisted by testing
  - Annex D : Design assisted by testing

Testing Seismic Resistant Components Subassemblies and Structures

- There are three main types of experimental testing that can be realized in the laboratory
  - quasi-static monotonic and cyclic testing
  - pseudo-dynamic testing
  - dynamic testing

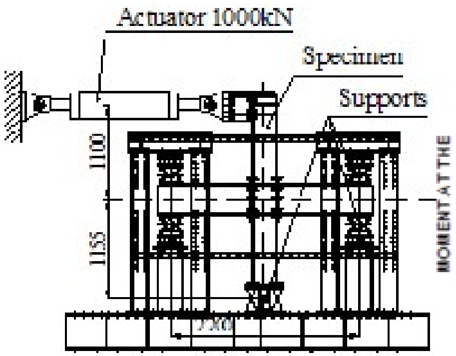
Quasi-static monotonic and cyclic testing

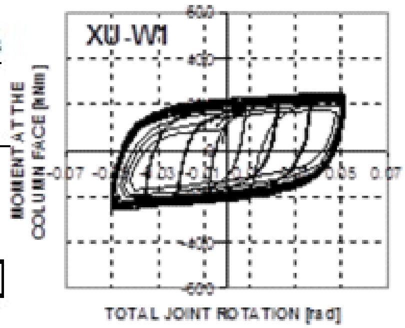
Tests on joints and members (ex. BRB)

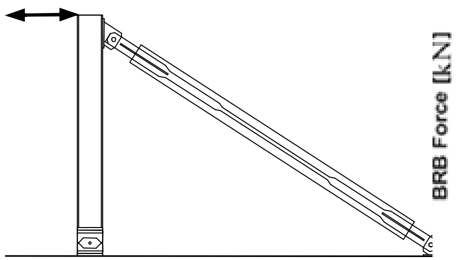


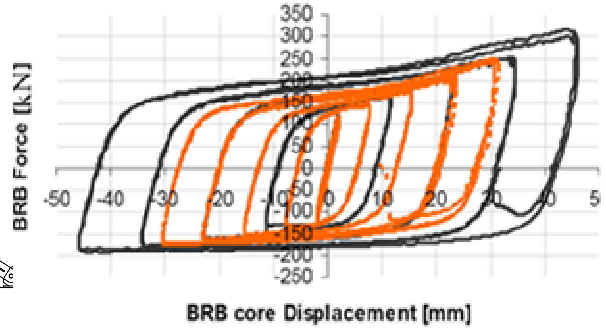
AISC protocol

ECCS protocol

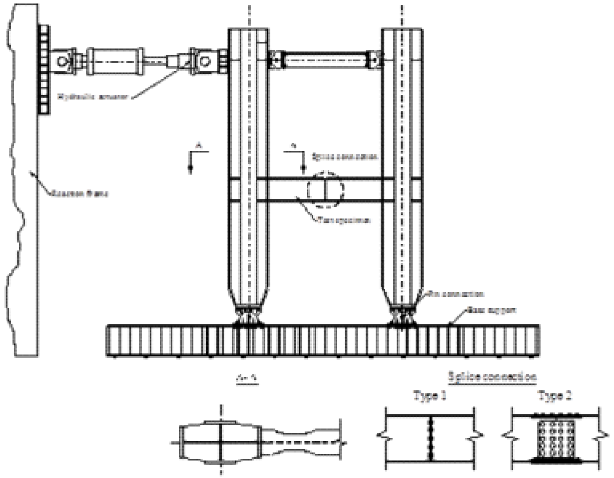


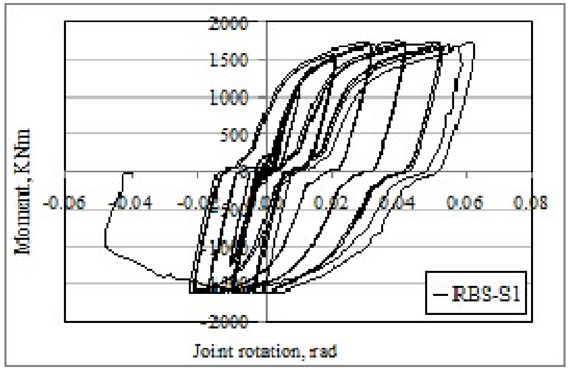




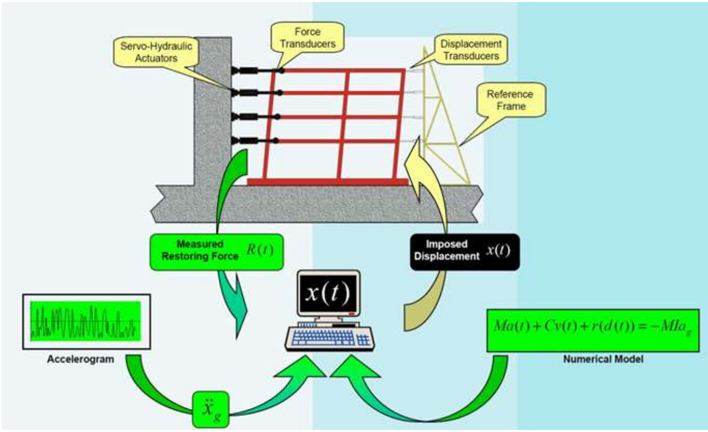


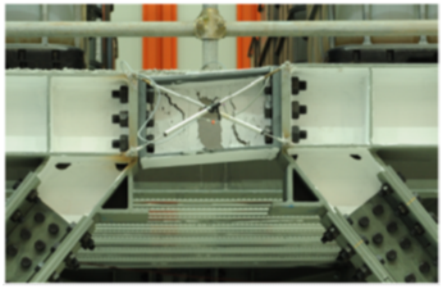
Tests on subassemblies





Pseudo-dynamic tests





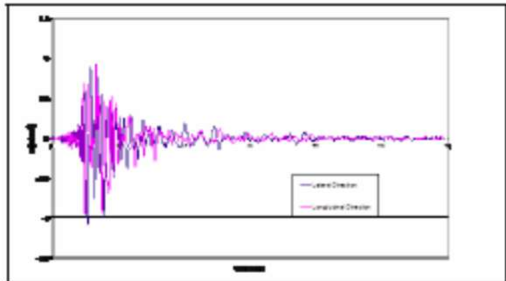
"DUAREM" FP7 SERIES Project (ELSA/ISPRA JRC)

http://publications.jrc.ec.europa.eu/repository/handle/JRC93136

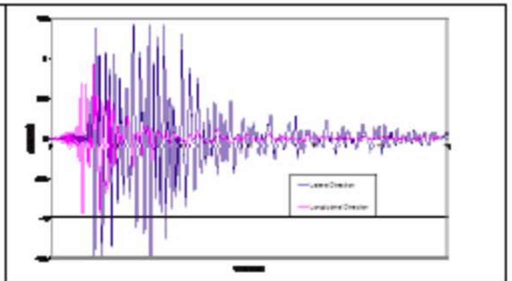
Dynamic tests (Shaking table)

Three freestanding columns in a row

Three columns in a row with architraves



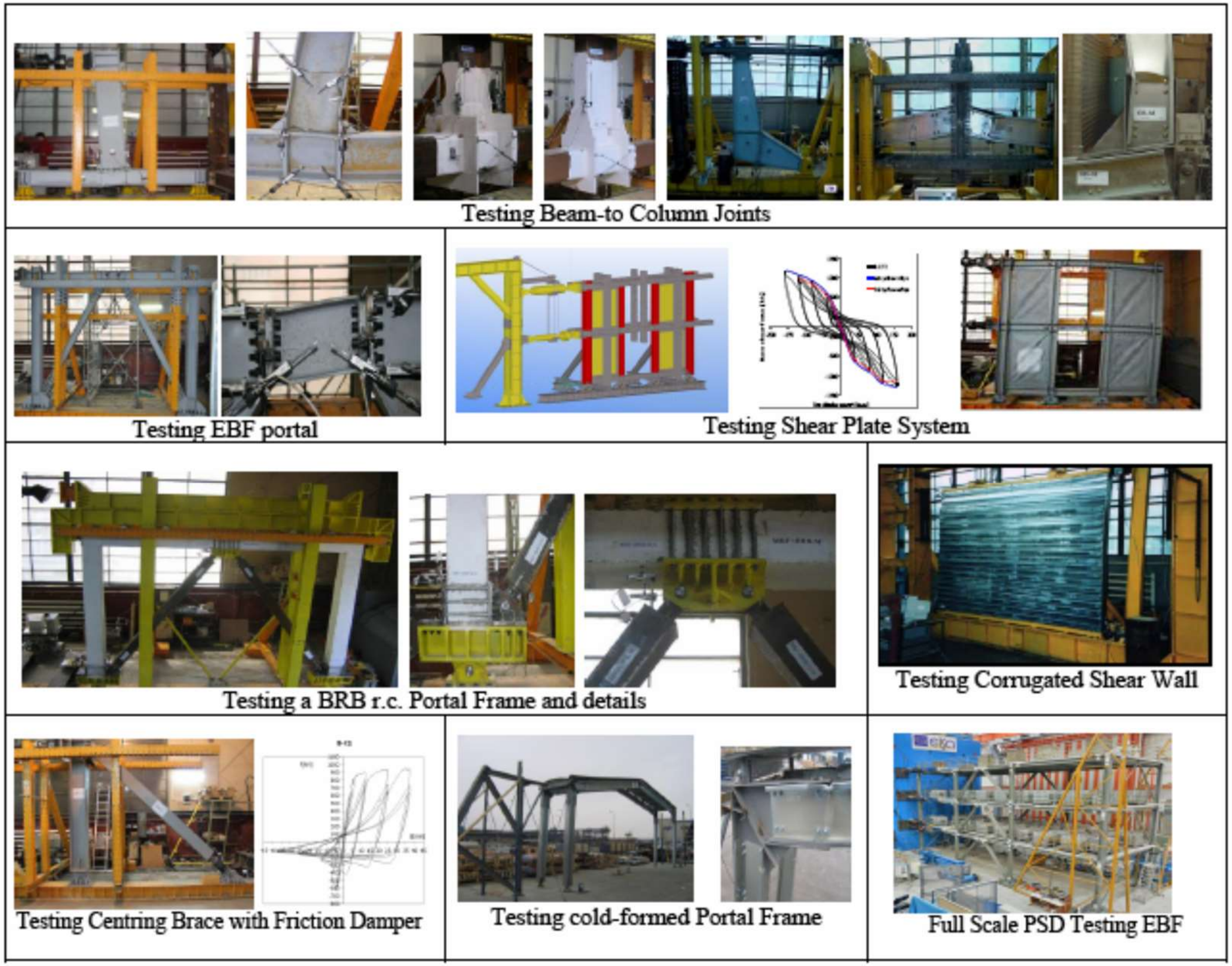
40% of Kalamata Earthquake



40% of Lefkada Earthquake

"PROHITECH" FP 6 Project : NTUA- Shacking table tests on Greek Temple subassemblies

Examples of some tests for characterisation of seismic performance and/or validation of technical solutions



Testing Beam-to Column Joints

Testing EBF portal

Testing Shear Plate System

Testing a BRB r.c. Portal Frame and details

Testing Corrugated Shear Wall

Testing Centring Brace with Friction Damper

Testing cold-formed Portal Frame

Full Scale PSD Testing EBF

Seismic Design assisted by testing

- Two Examples of Prequalification's tests
  - **Prequalification of Beam-to-Column Joints**
  - **Prequalification of replaceable bolted links for EBF**
- Two Case Studies for validation solution's tests and numerical model test based calibration of real designed problems for multistory building frames
  - **Tubular brace with true-pin connections**
  - **Dissipative reduced section coupling beam**

Prequalification of bolted beam-to- column Joints (RFCS EQUALJOINTS Project)

Research Fund for Coal and Steel "European pre-QUALified steel JOINTS" (EQUALJOINTS)
Grant Agreement No RFSR-CT-2013-00021

PARTNERS

- **Università degli Studi di Napoli Federico II - CO1 -Italy**
- **Arcelormittal Belval & Differdange SA- BEN2 - Luxembourg**
- **Universite de Liege- BEN3 – Belgium**
- **Universitatea Politehnica din Timisoara BEN4 – Romania**
- **Imperial College of Science, Technology and Medicine- BEN5 –**
- **Universidade de Coimbra- BEN6 - Portugal**
- **European Convention for Constructional Steelwork Vereniging-BEN7 - Belgium**

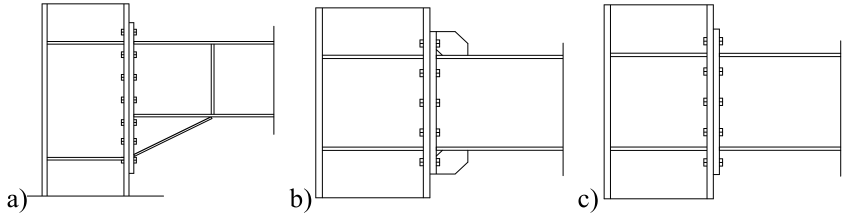
EN 1998 -1 revised version oriented research

(and revised P 100 -1)

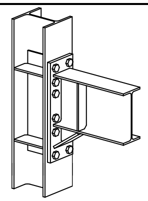
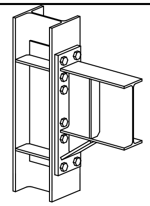
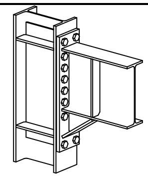
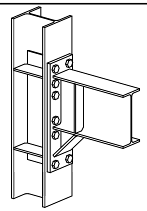
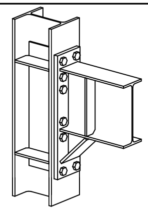
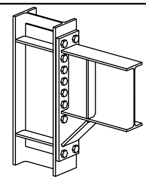
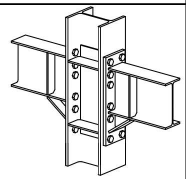
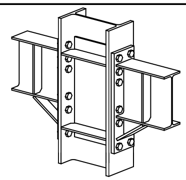
Prequalification of bolted beam-to- column Joints (RFCS EQUALJOINTS Project)

Joint's typologies selected for prequalification of Plastic Rotation Capacity

(a- Timisoara; b- Liege; c- Naples)

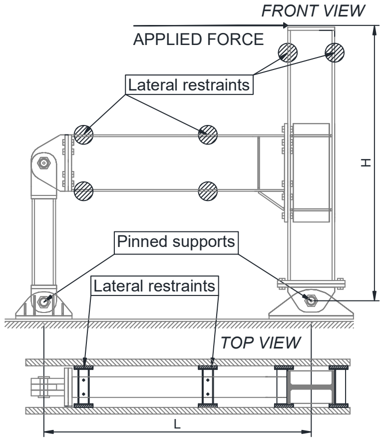


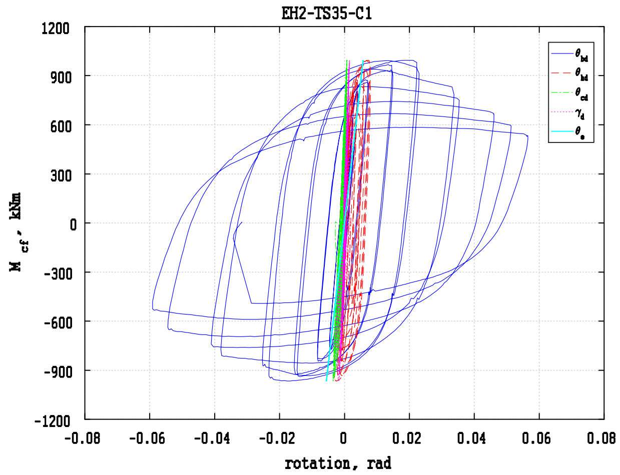
UPTimisoara Experimental program : 24 specimens + material tests

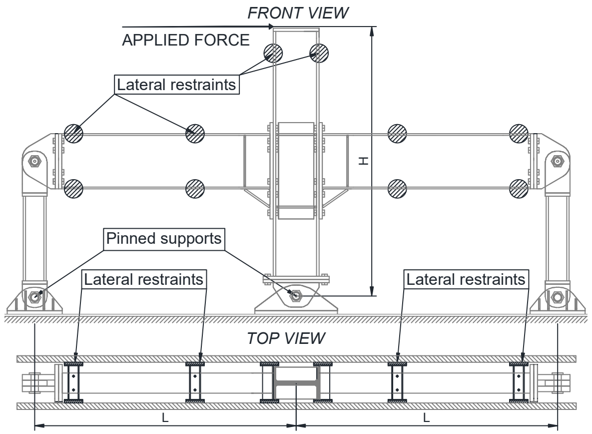
Group A: single- sided joint, 35° haunch, strong web panel		EH1-TS35 Beam: IPE360 Column: HEB280 End-plate: 25mm Bolts: M27 gr.10.9		EH2-TS35 Beam: IPE450 Column: HEB340 End-plate: 30mm Bolts: M30 gr.10.9		EH3-TS35 Beam: IPE600 Column: HEB500 End-plate: 35mm Bolts: M36 gr.10.9
Group B: single- sided joint, 45° haunch, strong web panel		EH1-TS45 Beam: IPE360 Column: HEB280 End-plate: 25mm Bolts: M27 gr.10.9		EH2-TS45 Beam: IPE450 Column: HEB340 End-plate: 30mm Bolts: M30 gr.10.9		EH3-TS45 Beam: IPE600 Column: HEB500 End-plate: 35mm Bolts: M36 gr.10.9
Group C: double- sided joint, 35° haunch, balanced web panel		EH1-XB35 Beam: IPE360 Column: HEB340 End-plate: 25mm Bolts: M27 gr.10.9		EH2-XB35 Beam: IPE450 Column: HEB500 End-plate: 30mm Bolts: M30 gr.10.9		

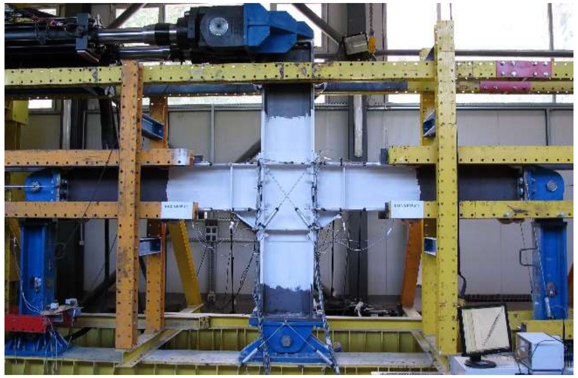
Prequalification of bolted beam-to- column Joints (RFCS EQUALJOINTS Project)

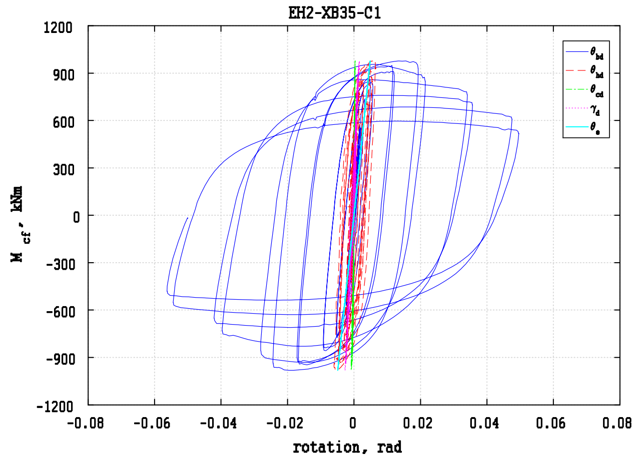
UP Timisoara tests : to confirm a plastic rotation of min. 35 mRad





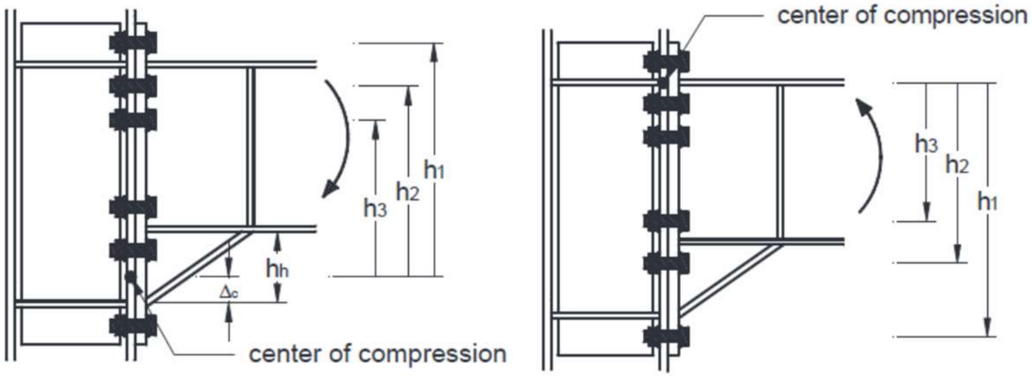






Prequalification of bolted beam-to- column Joints (RFCS EQUALJOINTS Project)

Design Tools



5.1.4.2 Global procedure

Step 1: Initial choice of the connection geometries and materials

- Bolt grade, bolt size and number of bolt rows
- Thickness and dimension of the end-plate
- Thickness and dimensions of haunch
- Thickness and dimensions of transverse stiffeners
- Thickness and dimensions of the supplementary web plates (if necessary)
- The weld specification

Step 2: Component characterisation

- Component resistances (joint under bending)
- Component stiffness (joint under bending)
- Component resistances (joint under shear)

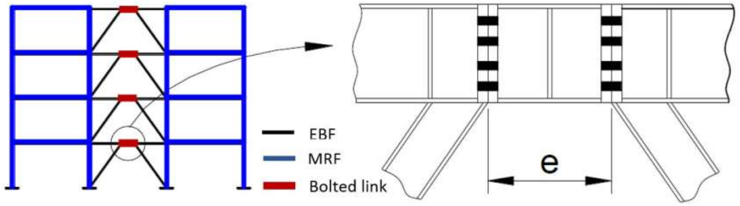
Step 3: Connection characterisation (component assembling)

- Connection resistance in bending
- Connection resistance in shear
- Column web panel resistance
- Joint stiffness in bending

Step 4: Connection classification and check

Prequalification of replaceable bolted links for EBF

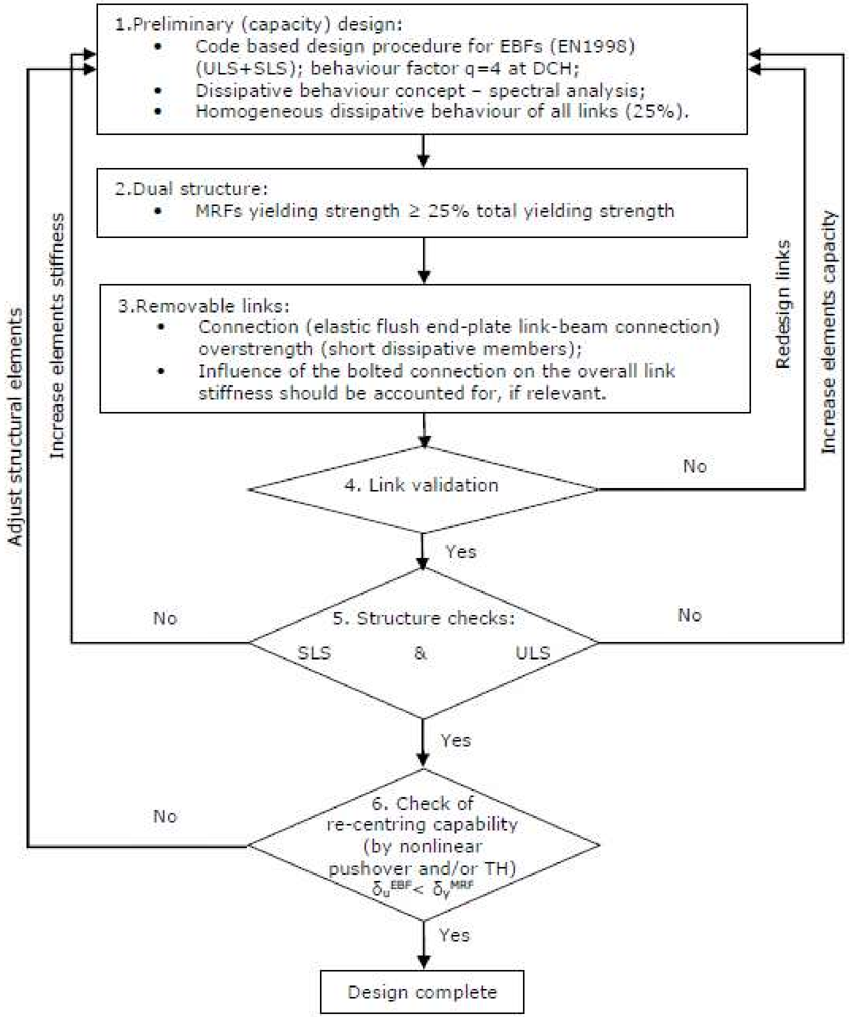
(FP 7 Series “DUAREM Project)

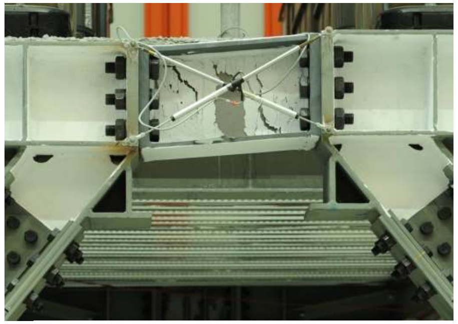


Objectives

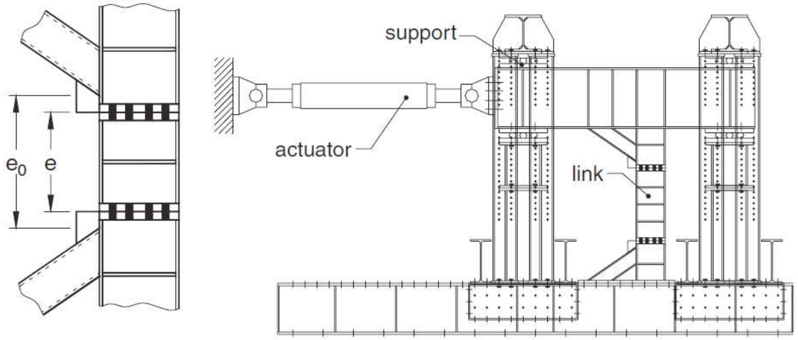
- Confirm the feasibility of technical solution
- Confirm the capability of after remove of links
- Confirm the feasibility of replacement of new links
- Basis for design provisions
- Benchmark for validation of numerical models

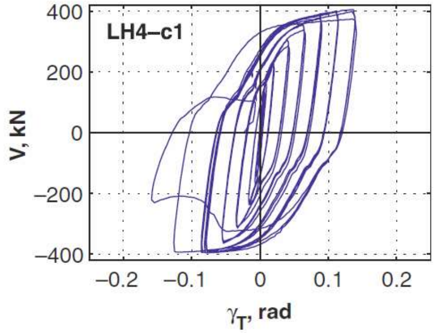
Prequalification of bolted beam-to- column Joints (RFCS EQUALJOINTS Project)





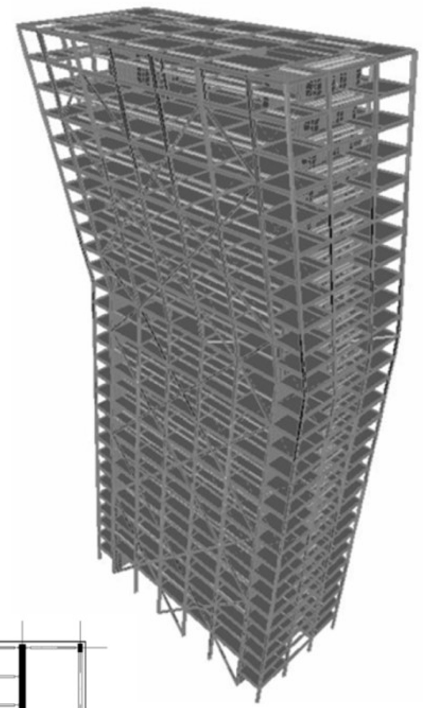
Experimental validation of Link : **confirm plastic rotation capacity**



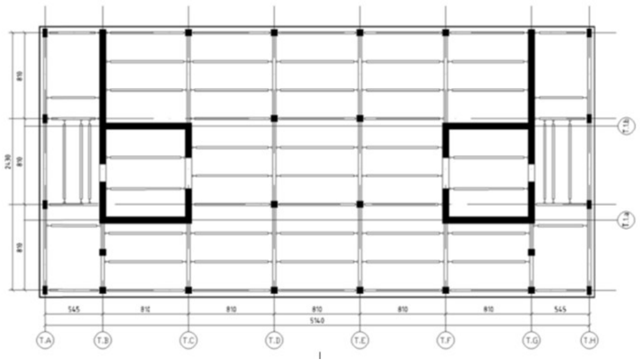


Case Study 1: Tubular brace with true-pin connections

- **Design structure in Bucharest** (PGA=0.24 g):
  - Typical floor dimensions: 52.0x25.6 m
  - Two basements and 29 levels above ground: height of 117.6 m
  - Structural system:
    - Steel frame
    - Reinforced concrete cores
    - Concentrically braced steel frame in the longitudinal direction

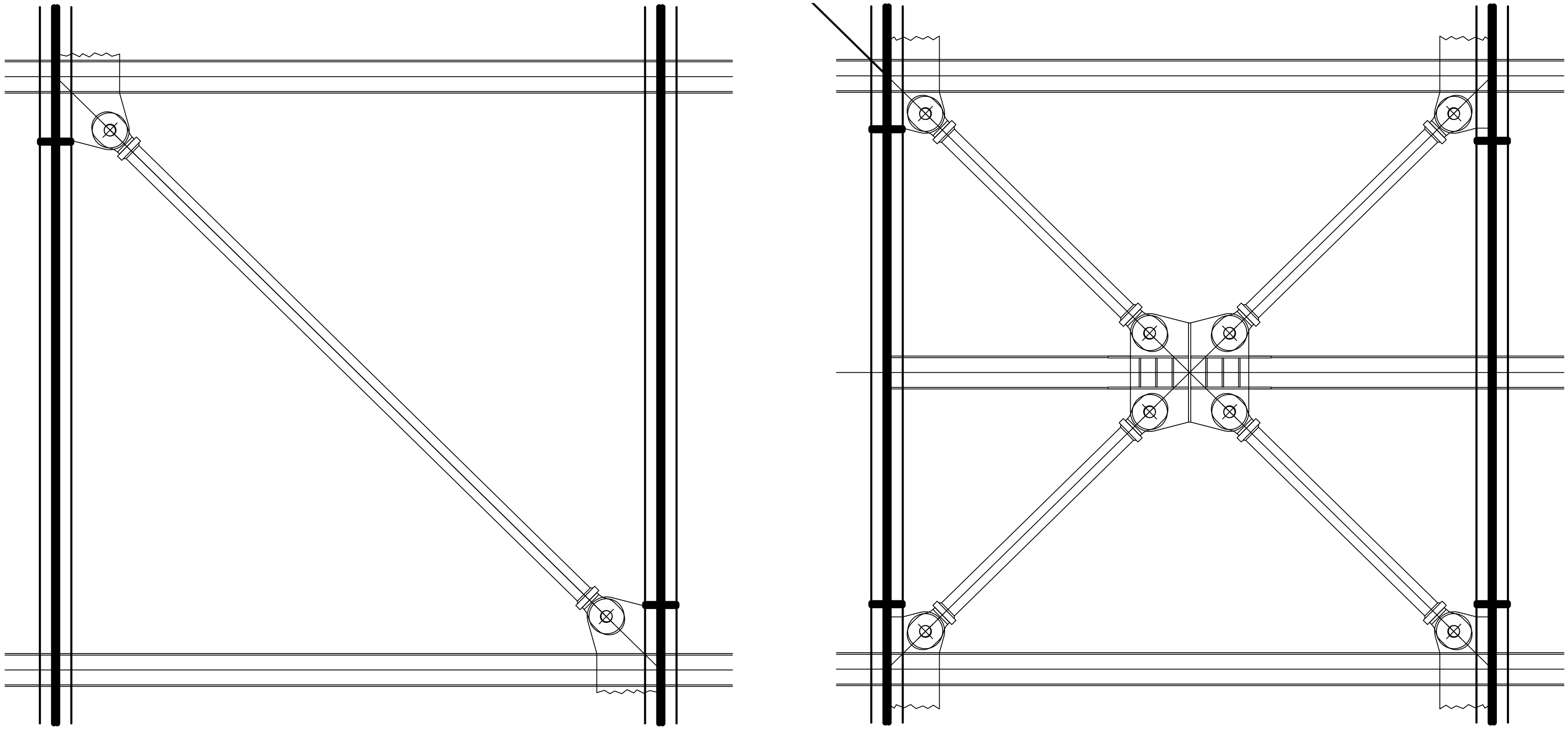


- **Research objectives:**
  - Qualify cyclic performance of a brace with true pin connections
  - Validate performance of the pinned connection
  - Check the control by design of buckling plane



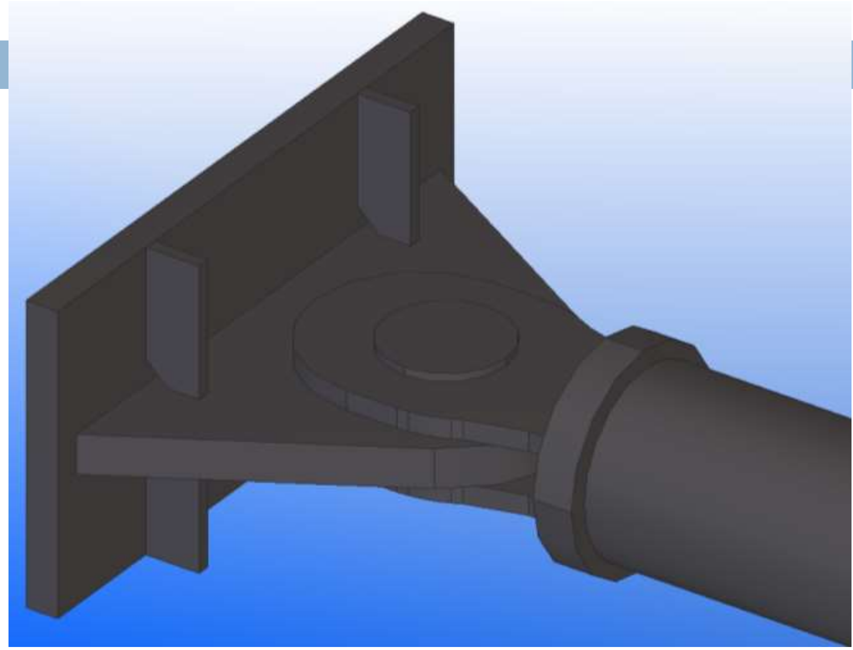
Brace configurations

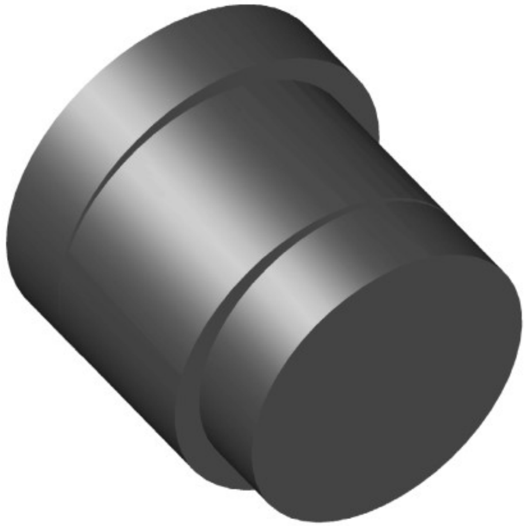
- 9300 mm Pin to pin distance 4200 mm
- 1.53-1.69 $\bar{\lambda}$ 0.69-0.76



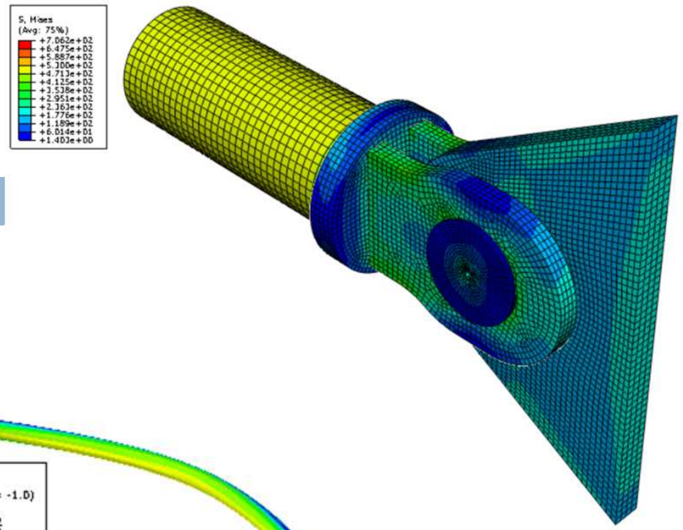
Brace connections

- Brace cross-sections:
  - D244.5x25
  - D244.5x20
  - D219.1x20
  - D219.1x16
  - D219.1x10
- Pinned connection with eccentric pin:
  - Accommodate erection tolerances
  - Reduce the effect of gravity loading (braces installed to be activated after casting of r.c. slabs)

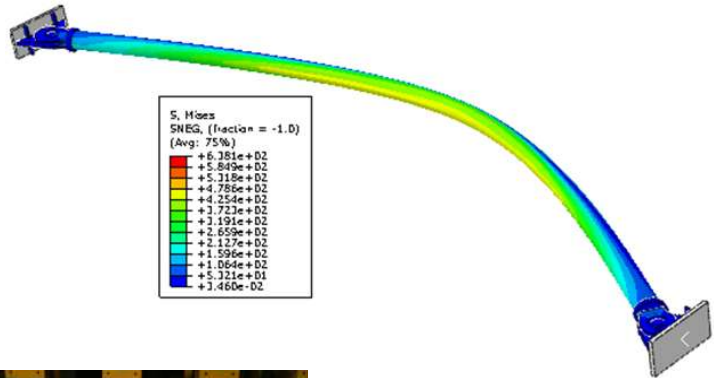




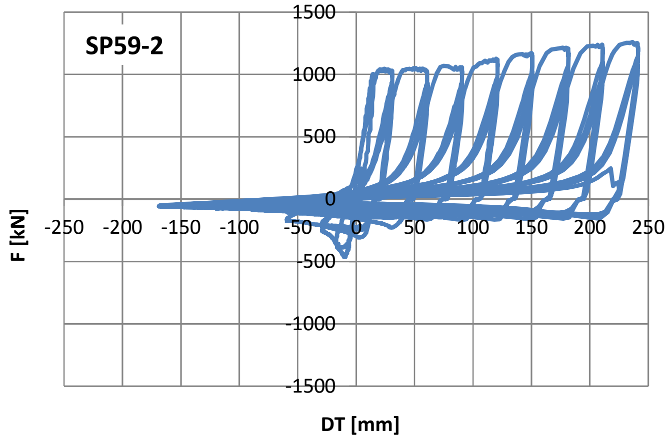
Research outline



- Connection FEM analysis



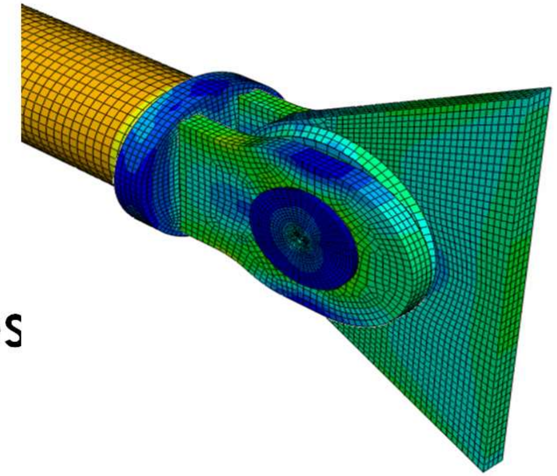
- Brace FEM analysis

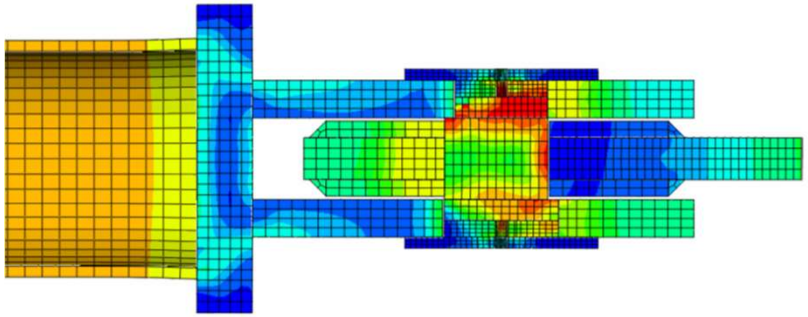


- Monotonic/Cyclic tests

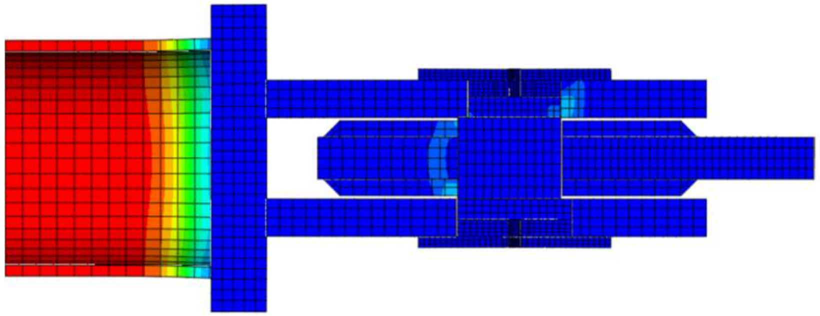
FEM simulations: connection

- Brace: S355 (f_y=355x1,25)
- Gusset plates and pin: S460 and S690
- End plate: S460 (nominal properties





Von Mises stress



Equivalent plastic strain

Experimental models

- Scaled to fit the
  - Actuator capacity
  - Size of the testing platform
- Braces used in design:

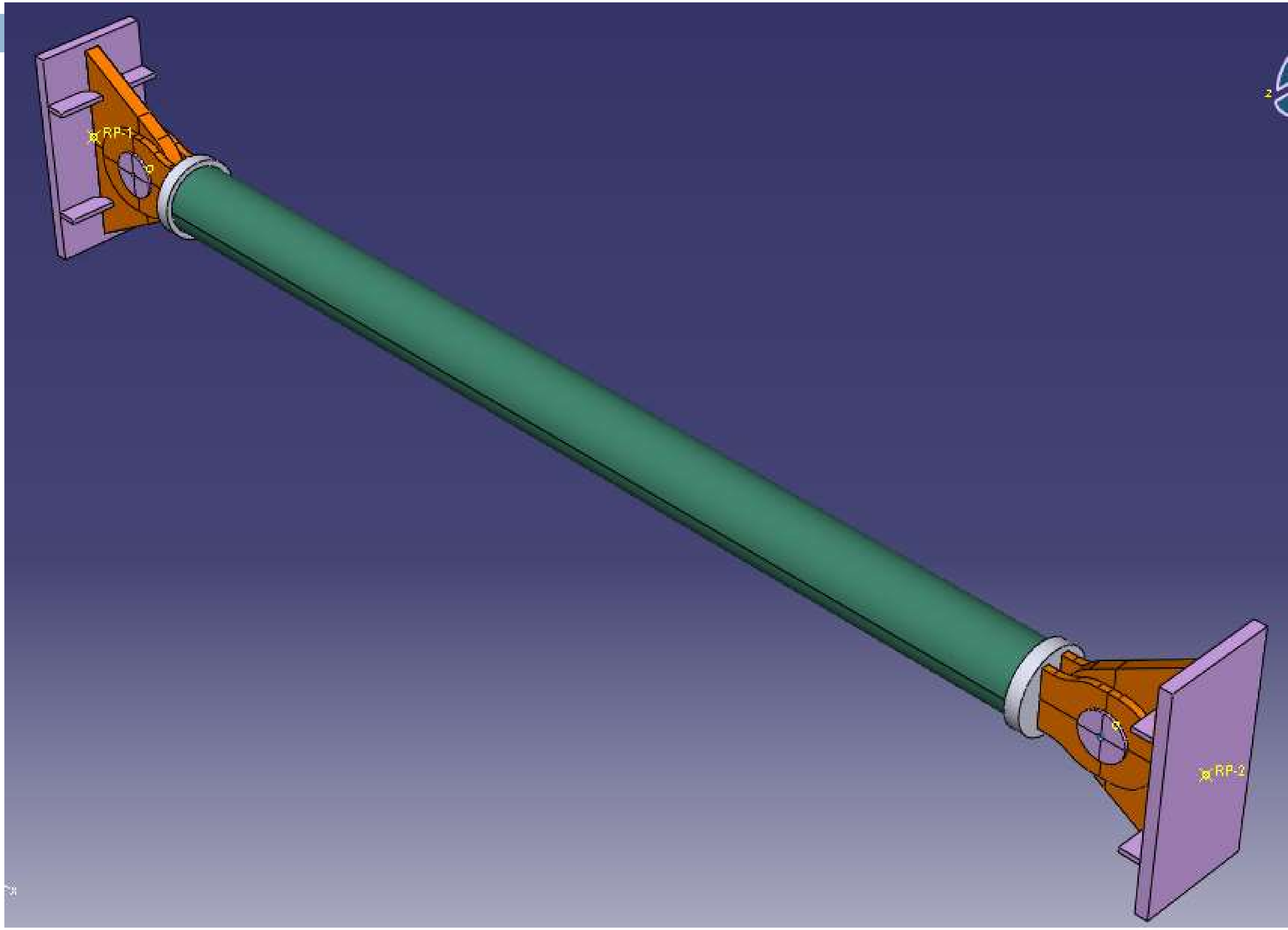
D244.5x25 D244.5x20 D219.1x20 D219.1x16 D219.1x10

L = 9300 mm L = 4200 mm

1.53-1.72 $\bar{\lambda}$ 0.69-0.78

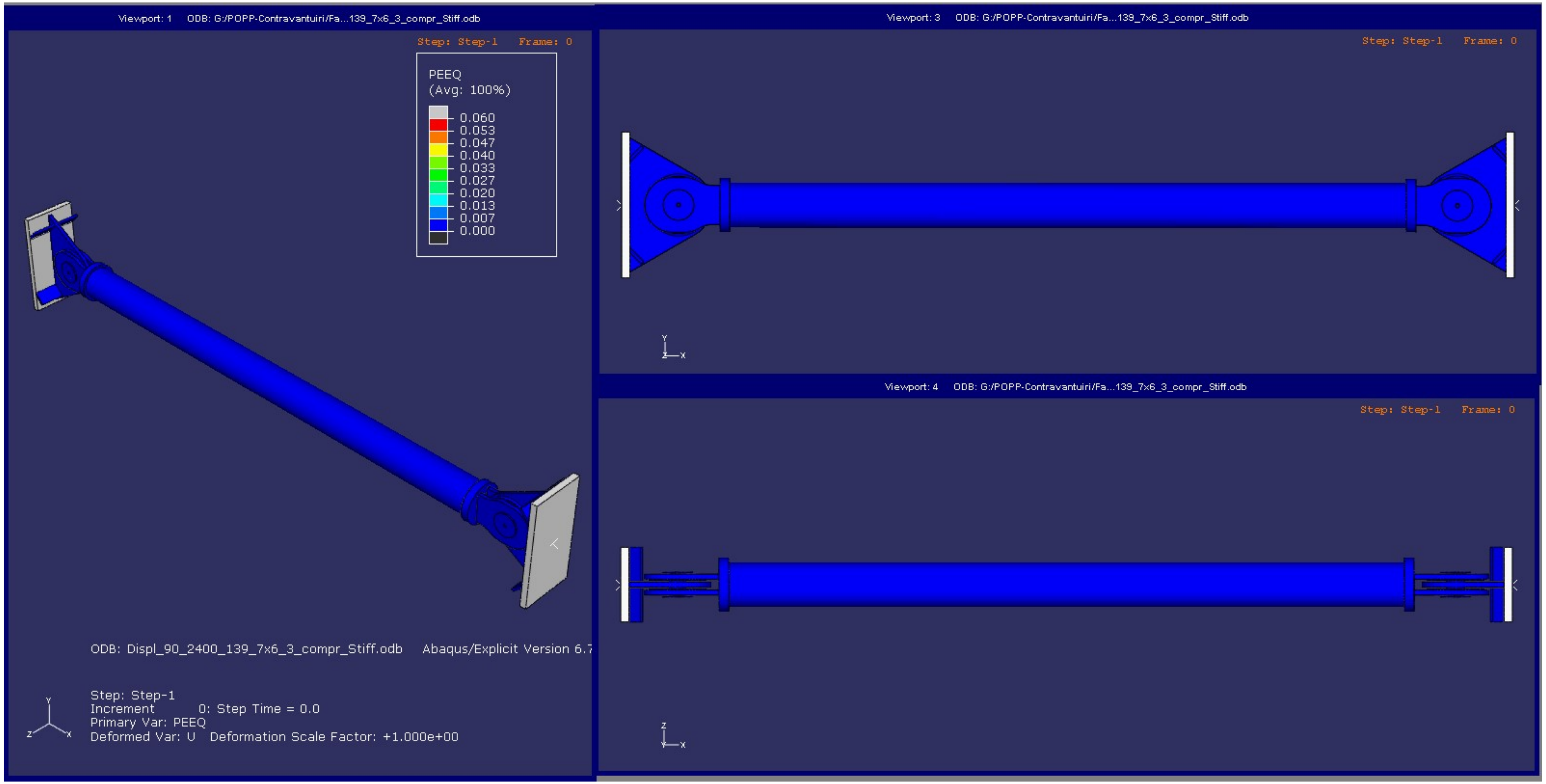
Class 1 cross sections

FEM simulations: brace assembly



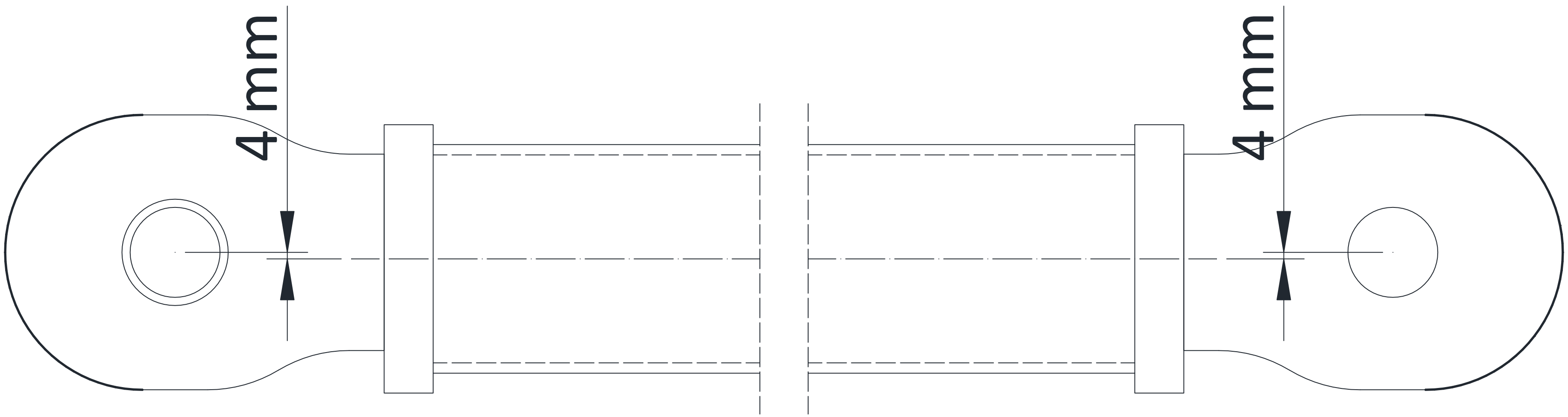
FEM simulations: brace assembly

- **Problem – in-plane or out-of-plane buckling ?**



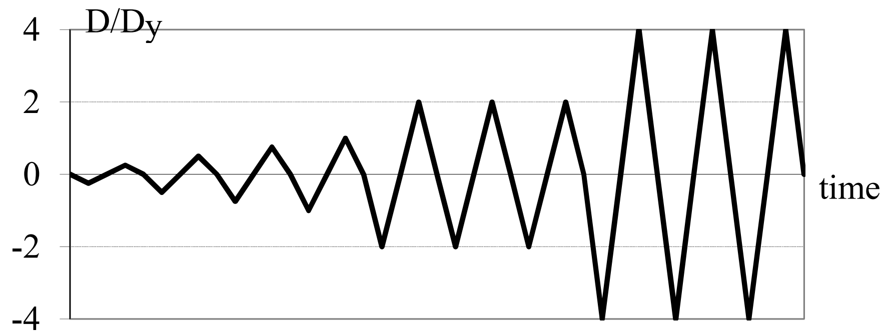
FEM simulations: brace assembly

- Eccentricity to force in-plane buckling



Experimental program

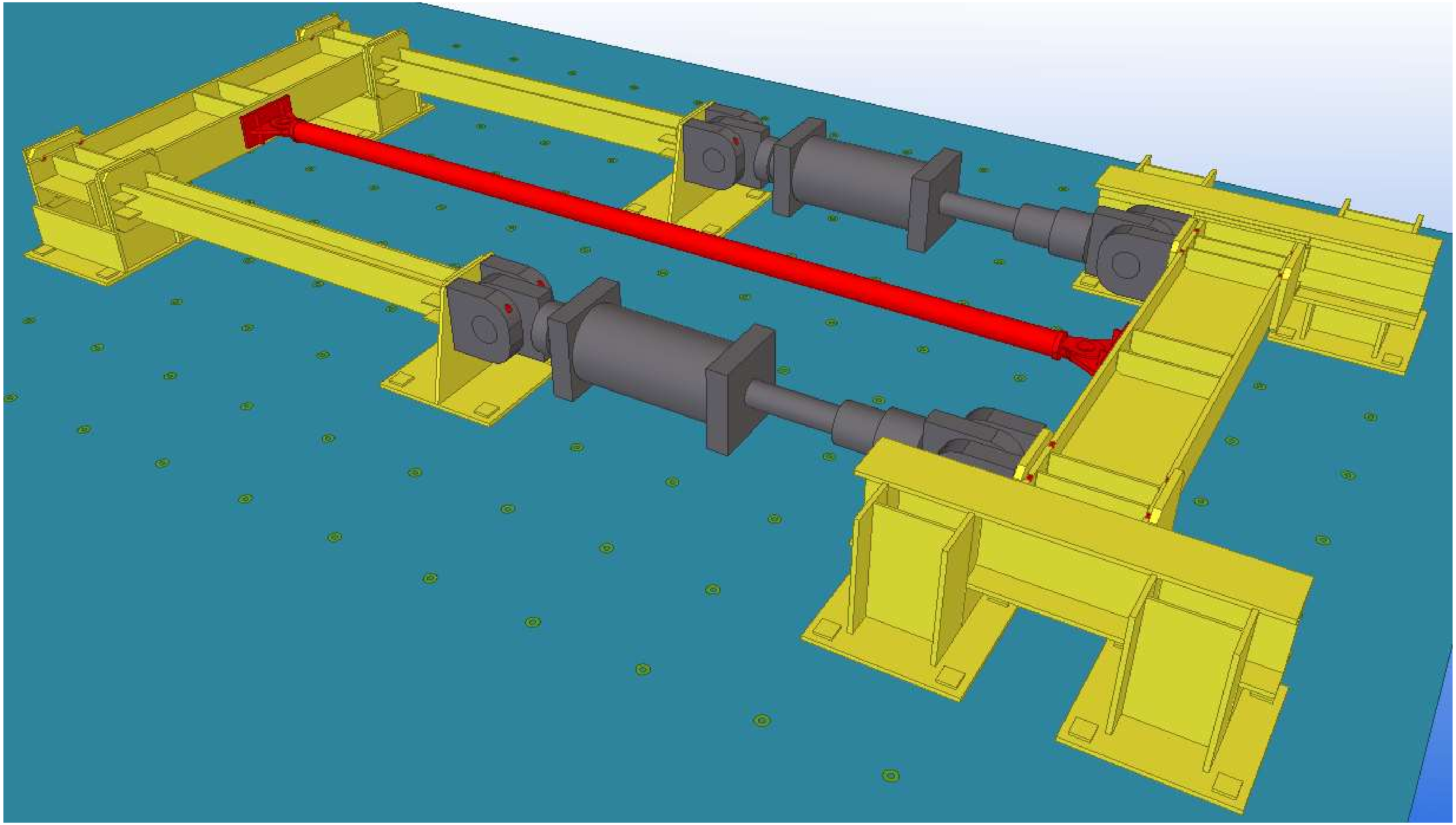
- Four specimens
- Cyclic loading
- ECCS loading procedure



- D_y from numerical simulations using measured material

Specimen	Pin to pin length [mm]	Cross-section	Cross section class	Non dimensional slenderness	Loading protocol
SP27-1	2700	D139.7x6.3	1	0.75	Cyclic, first cycle in tension
SP27-2	2700	D139.7x6.3	1	0.80	Cyclic, first cycle in compression
SP59-1	5900	D139.7x6.3	1	1.64	Cyclic, first cycle in tension
SP59-2	5900	D139.7x6.3	1	1.64	Cyclic, first cycle in compression

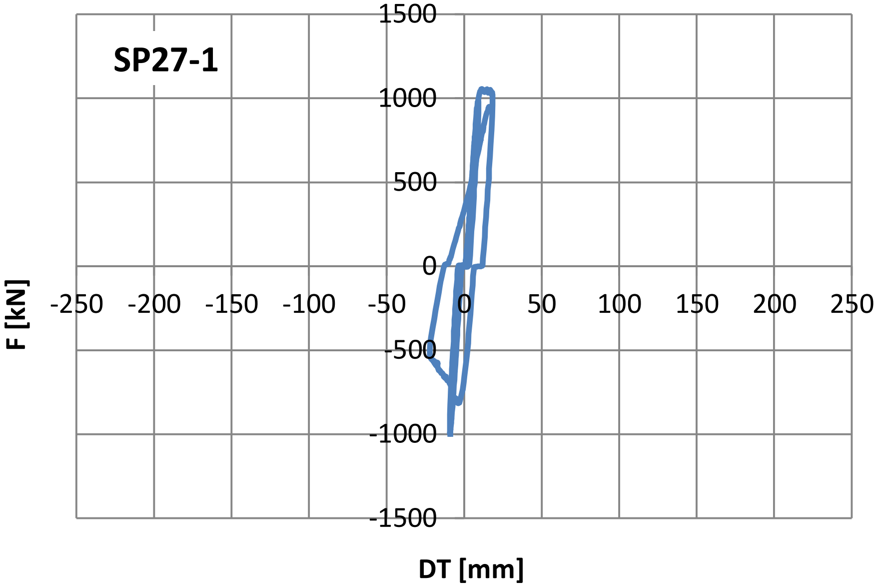
Test setup



SP27-1 specimen

SP27-1 specimen

- Out of plane buckling in the first cycle of 2Dy
- Fracture of screws connecting the washers to the pins



FEM simulations: brace assembly

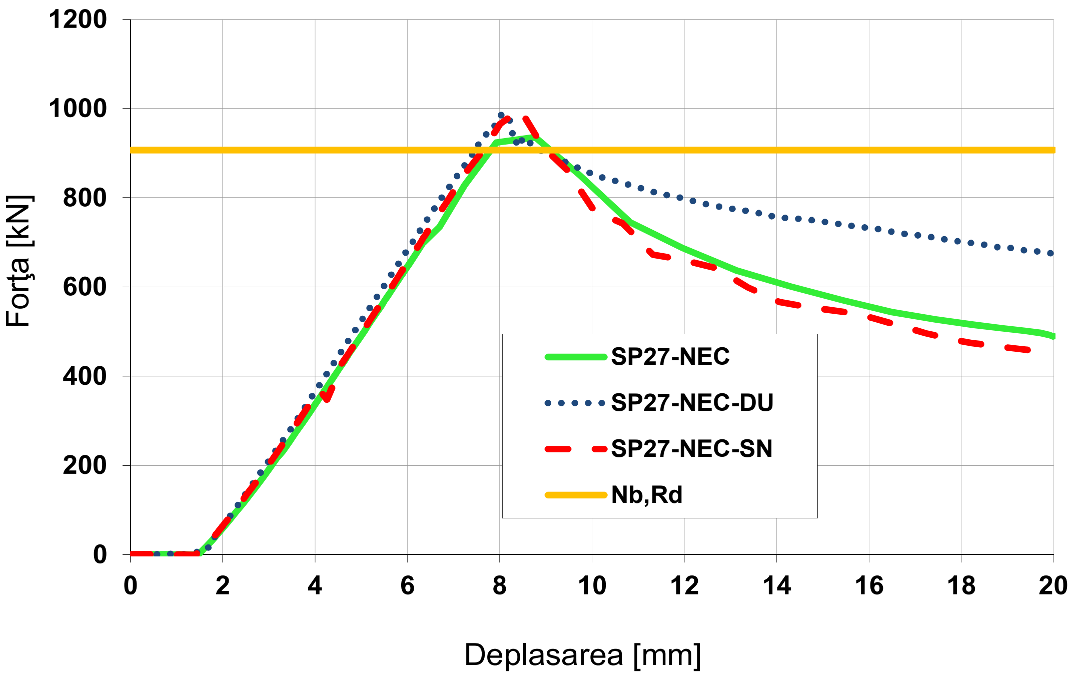
Model	N_{cr} [kN]		$N_{cr,2}$ / $N_{cr,1}$
	Mode 1	Mode 2	
SP27	1623 (in-plane)	2376 (out-of-plane)	1.46
SP59	342 (in-plane)	685 (out-of-plane)	2.00

Model	$N_{b,Rd}$ [kN]		$N_{b,Rd,2}$ / $N_{b,Rd,1}$
	in-plane	out-of-plane	
SP27	897.6	992.0	1.11
SP59	301.0	545.9	1.81

SP27-1 specimen: FEM simulations

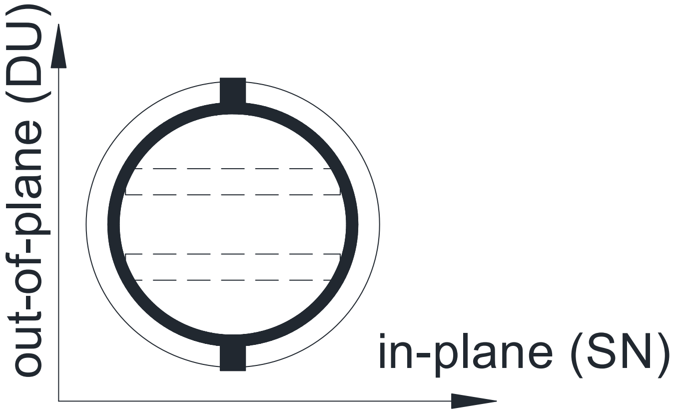
- Nominal material characteristics
- Out of plane member imperfection L/500 (5.4 mm)
- Connection eccentricity 4 mm
- Compression resistance:
  - FEM model
  - Model with blocked in plane displacements
  - Model with blocked out of plane displacements

Model	N_b, kN
SP27-NEC	936.0
SP27-NEC-DU	990.0
SP27-NEC-SN	998.1

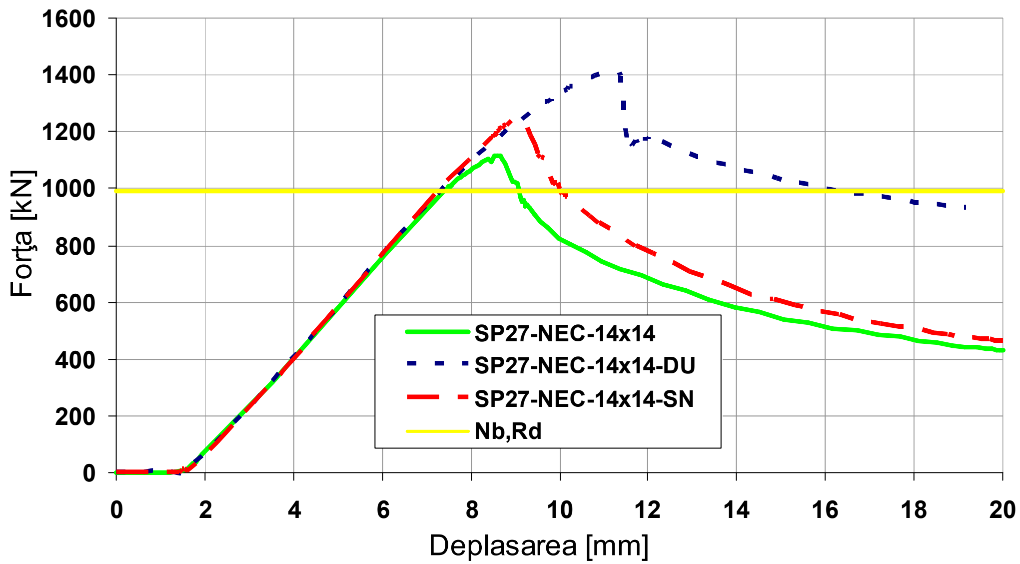


SP27-2 specimen: FEM simulations

- Two square 14x14 bars welded along the tube
- Strong washers

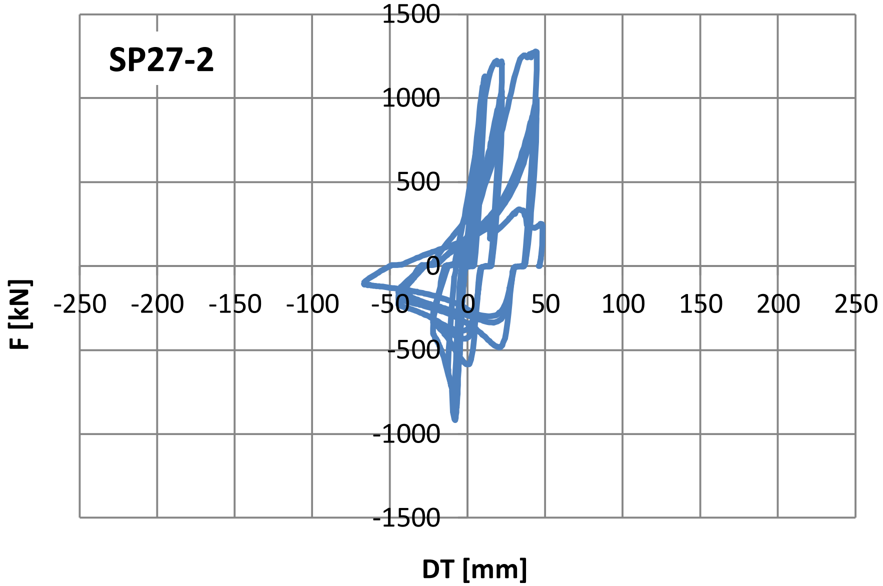


Model	N_b, kN
SP27-NEC-14x14	1115.4
SP27-NEC-14x14-DU	1411.9
SP27-NEC-14x14-SN	1245.9



SP27-2 specimen

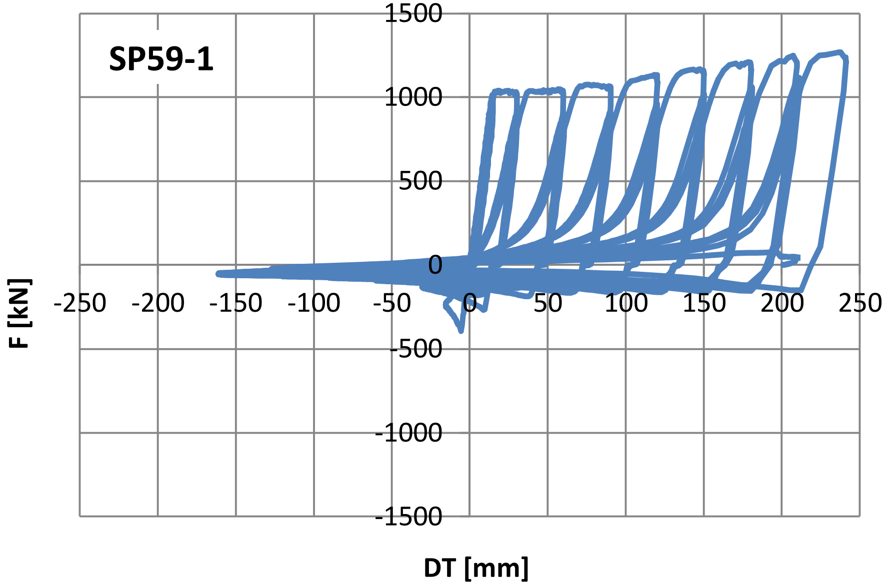
- In-plane buckling
- Failure during the first tension cycle of 6Dy due to fracture of the cross section



SP59-1 specimen

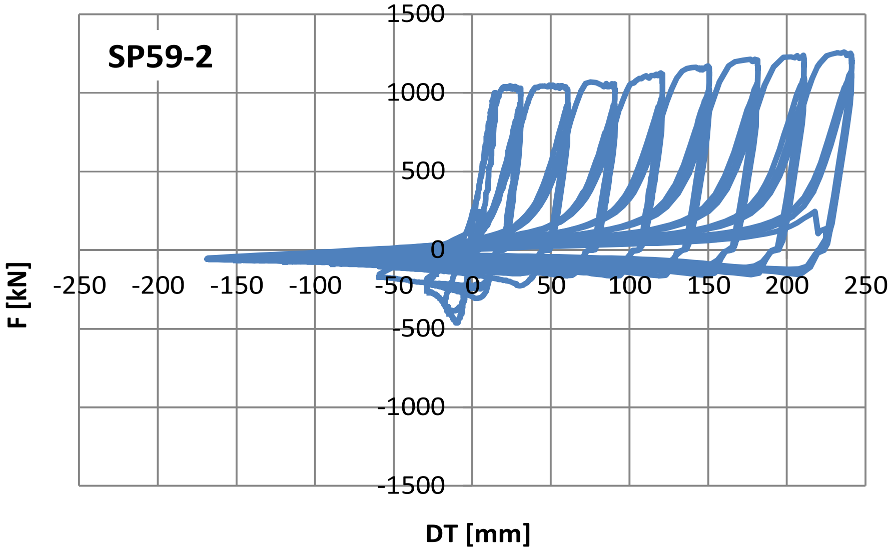
SP59-1 specimen

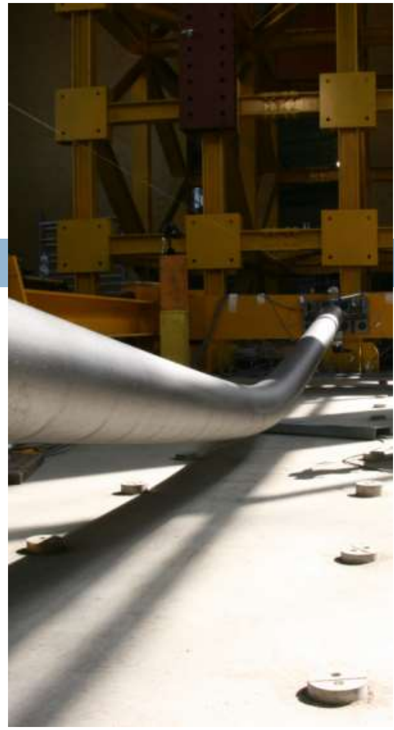
- In-plane buckling
- Failure during the 16Dy cycles due to fracture of the cross section



SP59-2 specimen

- In of plane buckling
- Progressive in-plane deformations starting with 4Dy
- Failure during the 16Dy





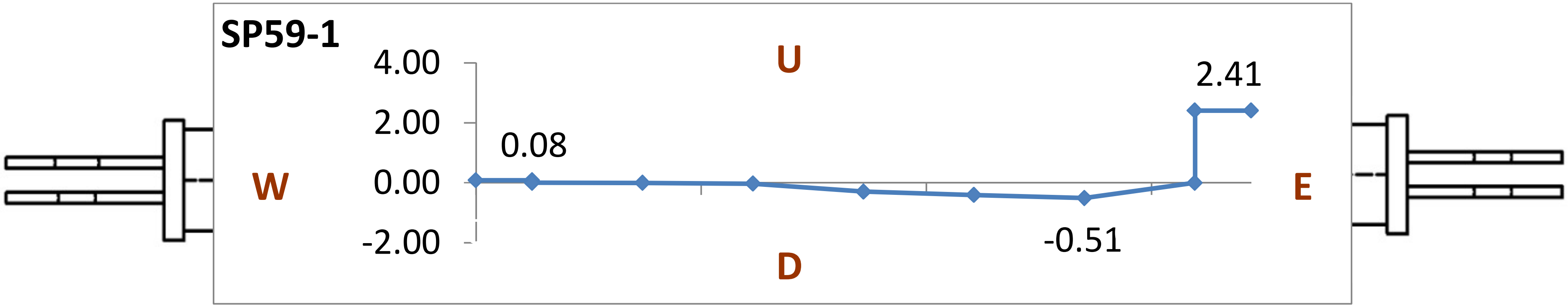
Remarks

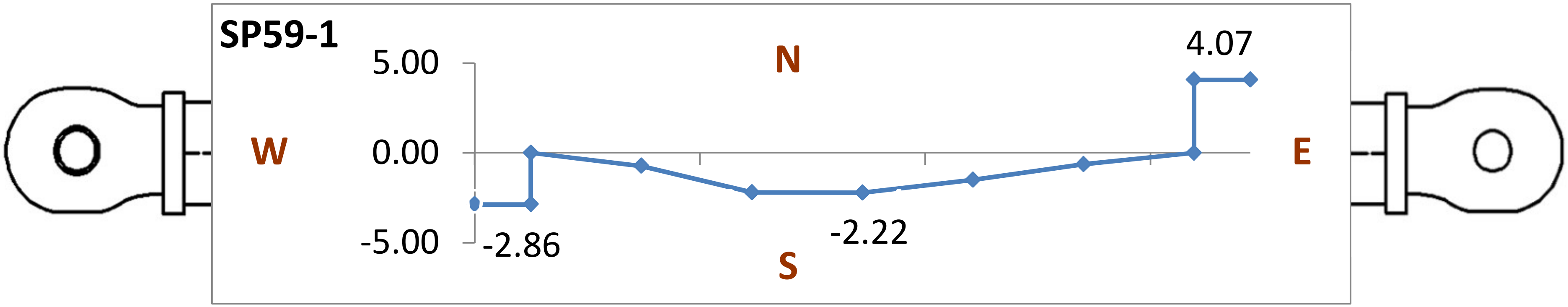
- Welded connections performed adequately
- Ductility larger for slender braces
- Pins rotated during tests (except for SP27-1)
- Pinching due to slip in both pins and rotation of the eccentric pin
- Connection deformations / total deformations:

Specimen	D_y [mm]	N_y [kN]	N_{max} [kN]	N_b [kN]	μ_F
SP27-1	9.3	1053.6	1056.2	995.8	4.3
SP27-2	11.5	1218.0	1278.3	917.9	9.6
SP59-1	15.1	1037.1	1267.9	393.4	26.6
SP59-2	14.5	1039.6	1259.0	464.3	28.3

Member and connection imperfections

- Member imperfections: small (around L/2500)
- Connection imperfections:
  - Large in magnitude and even change of sign
  - Disagreement with design eccentricity

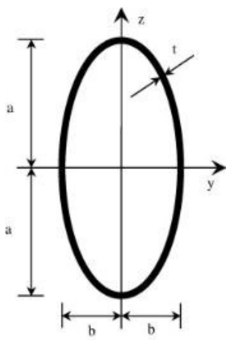


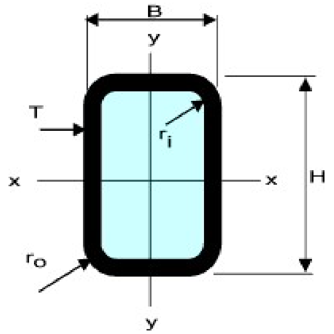


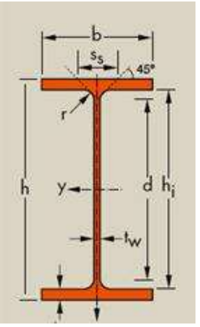
Case study concluding remarks

- Slender braces are more ductile
- Large fabrication tolerances were observed for position of gusset plates with respect to the brace
- Braces with CHS cross section and true pin connections are sensible to out of plane buckling
  - Stocky braces are more prone to out of plane buckling than slender ones
  - Connection detailing should take account of possibility of out of plane buckling (strong washers securing the pin)
- Avoid out-of-plane buckling: cross-sections with different moments of inertia about the two principal axes

  (elliptical, RHS, wide flange)

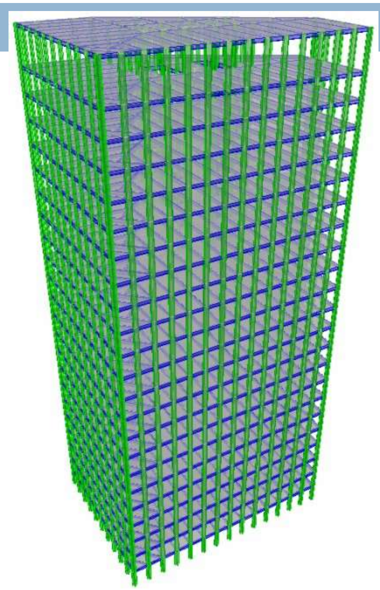




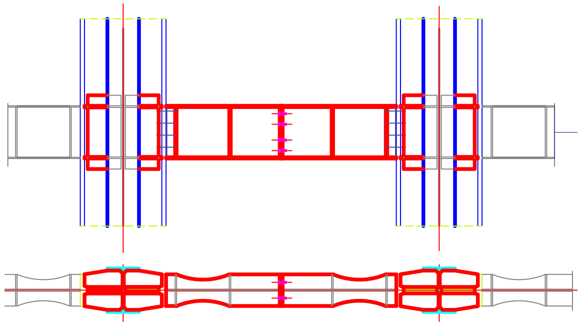


Case Study 2 : Validation of a dissipative system for Multistory Steel Frame Building

- 18 story office building
- Bucharest, Romania
- H =94 m ; L=43,3m; B = 31,3m
- Lateral force-resisting system:
  - Exterior steel framing with closely spaced columns and short beams
  - Central core of steel framing with closely spaced columns and short beams
- The length of the beams L/h vary from 3.2 to 7.4. Some beams are therefore below the general accepted inferior limit (L/h=4)
- Cyclic tests are necessary to confirm the plastic deformation capacity (e.g. the Bending Moment plastic hinge model)

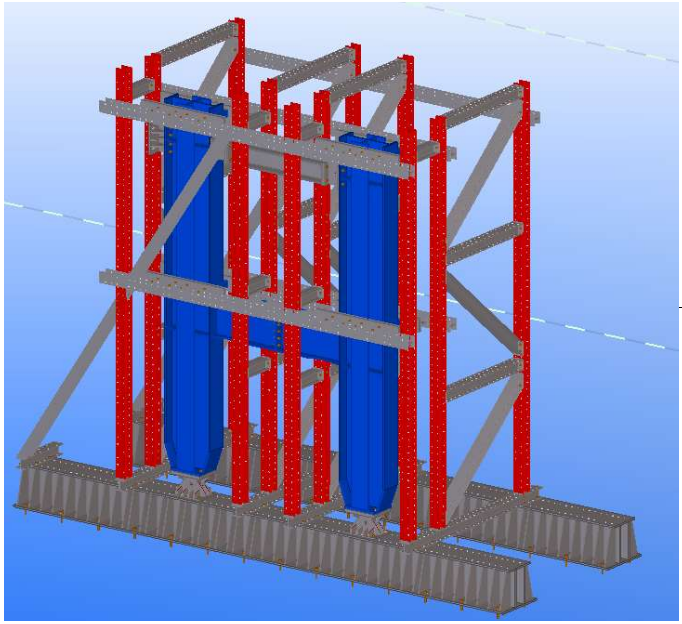


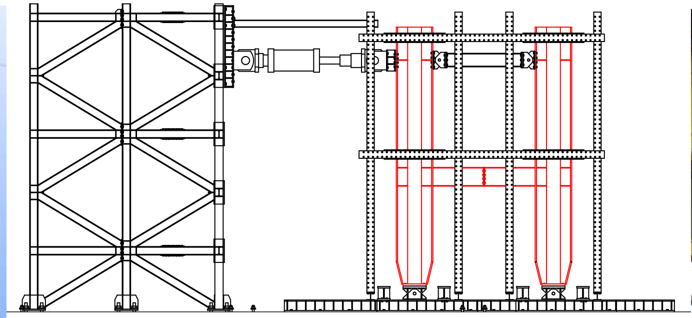
Typical frame configuration

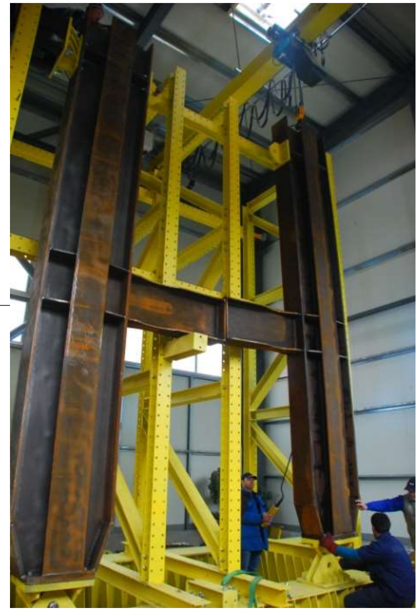


Tip	h	L	W	Av	fy	Mp	Vp	Mp/Vp	L/h	L/[Mp/Vp]
	[mm]	[mm]	[mm^3]*10^3	[mm^2]*10^2	[N/mm^2]	[KNm]	[KN]			
A	450	1450	1806	90	355	641	1845	0.35	3.2	4.17
A	450	1650	1806	90	355	641	1845	0.35	3.7	4.75
A	450	2210	1806	90	355	641	1845	0.35	4.9	6.36
B	400	2210	1264	64	355	449	1312	0.34	5.5	6.46
C	300	2210	785	42	355	279	861	0.32	7.4	6.83
D	500	2210	2481	125	355	881	2562	0.34	4.4	6.43
D	500	3600	2481	125	355	881	2562	0.34	7.2	10.47

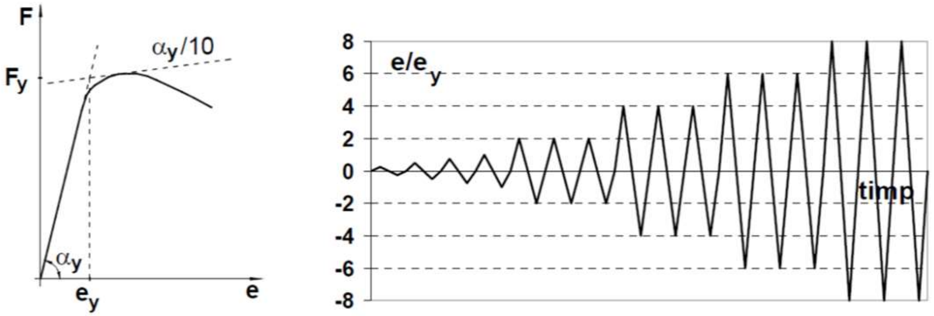
Experimental test





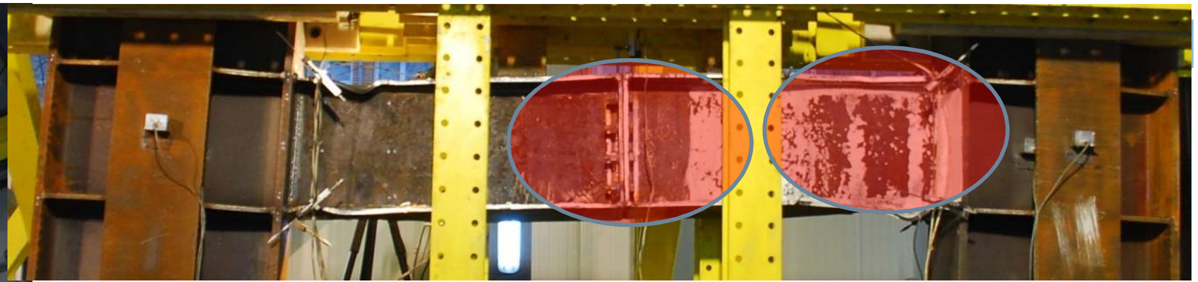


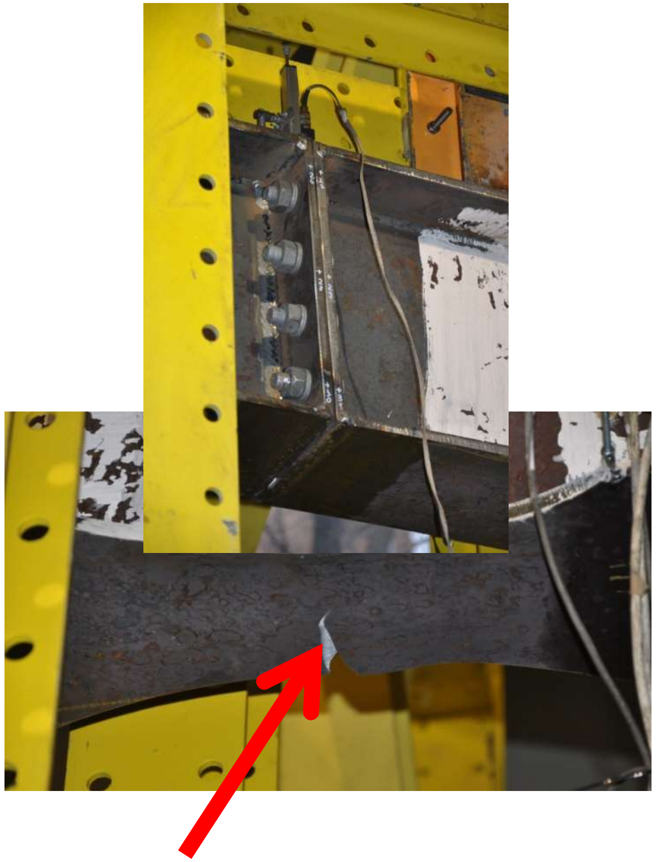
- **Beams with clear length 1450 mm (RBS-S)**
    - Two specimens
    - Cyclic tests
- **Beams with clear length 2210 mm (RBS-L)**
    - Two specimens
    - Cyclic tests



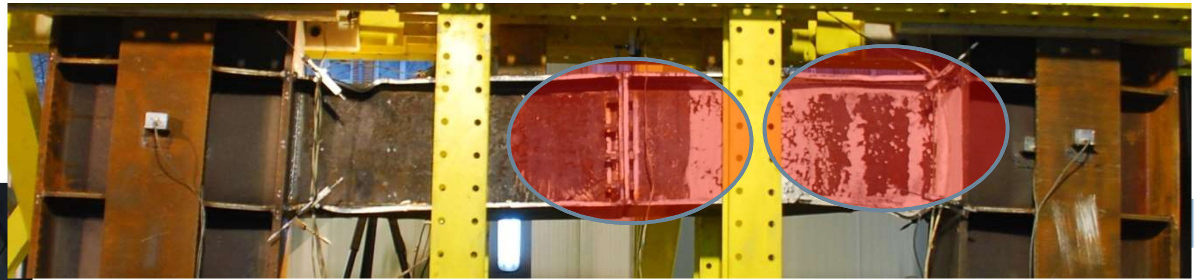
(a) (b)

Specimens RBS-L1

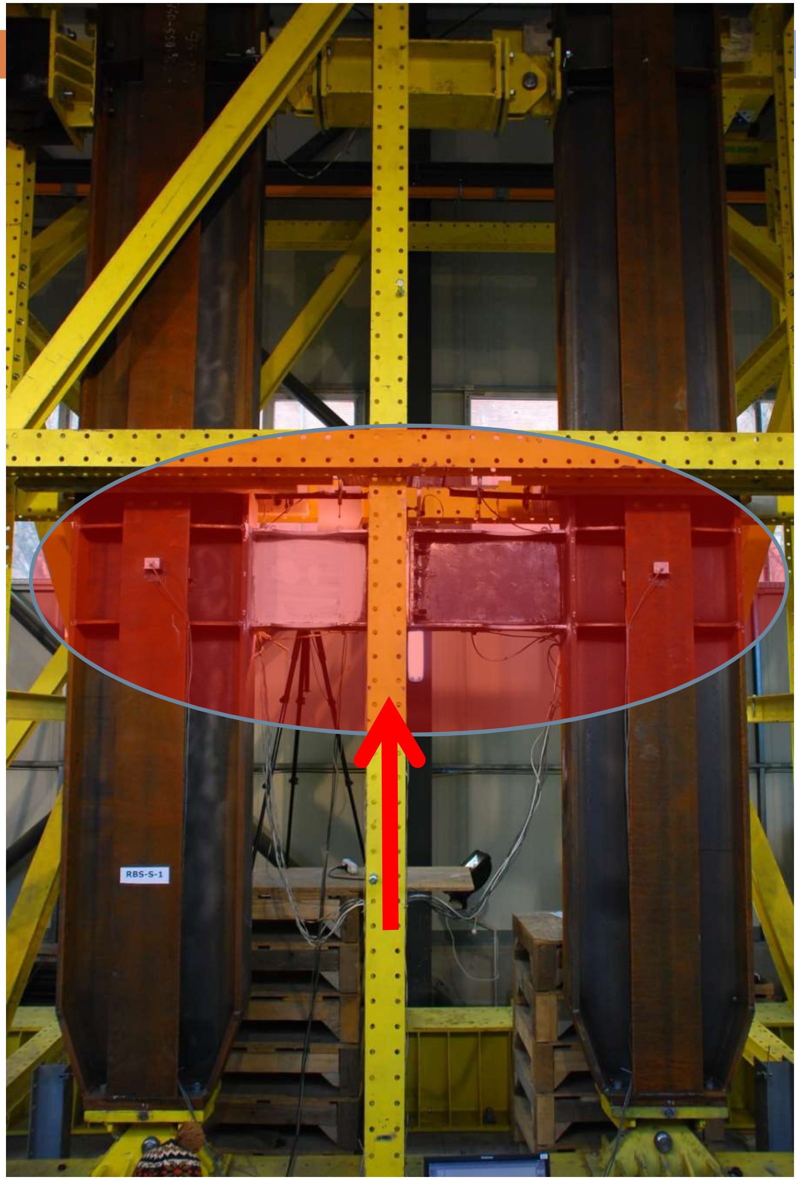


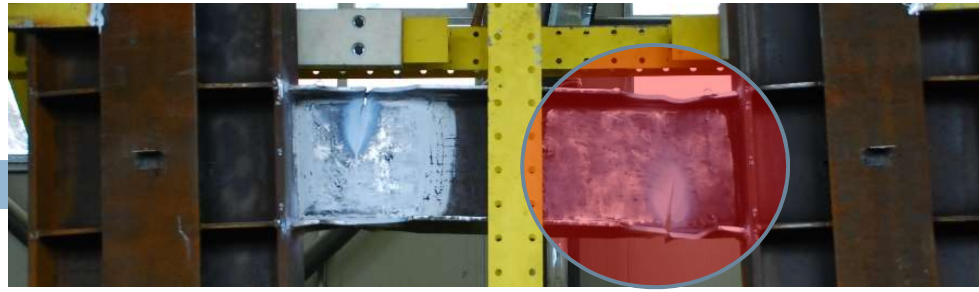


RBS-L2

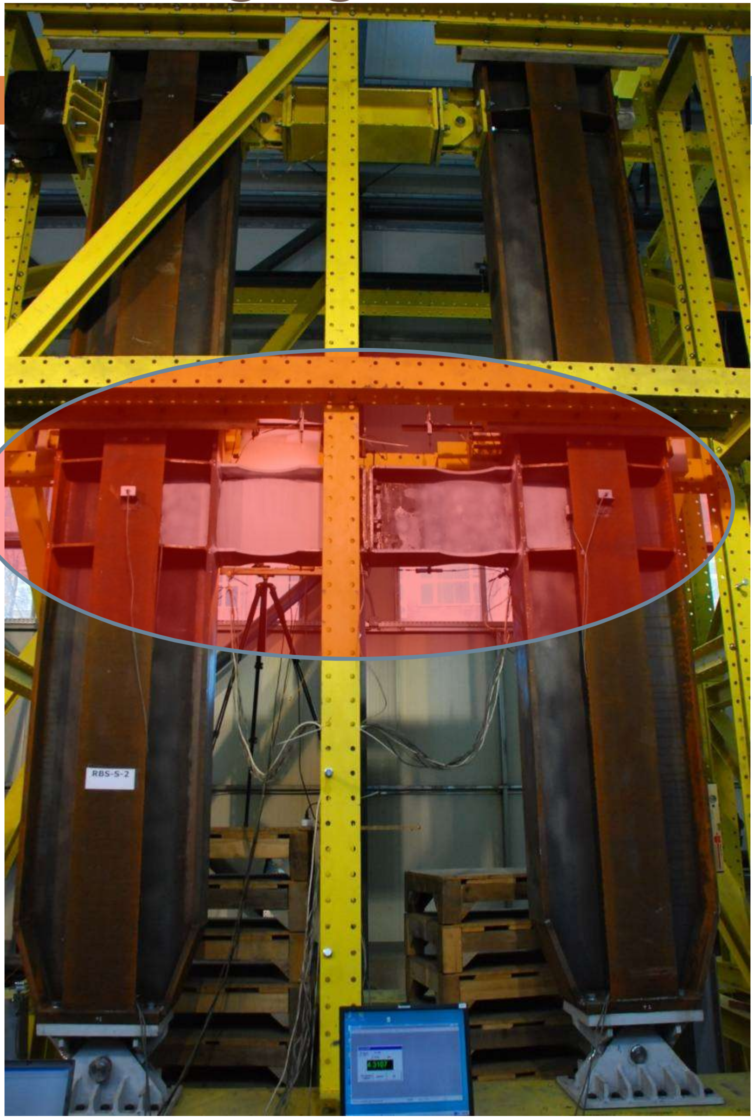


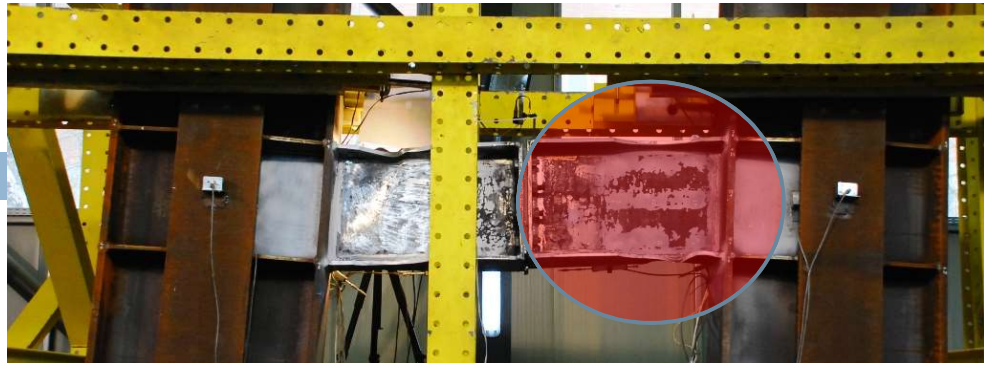
Specimen RBS-S1



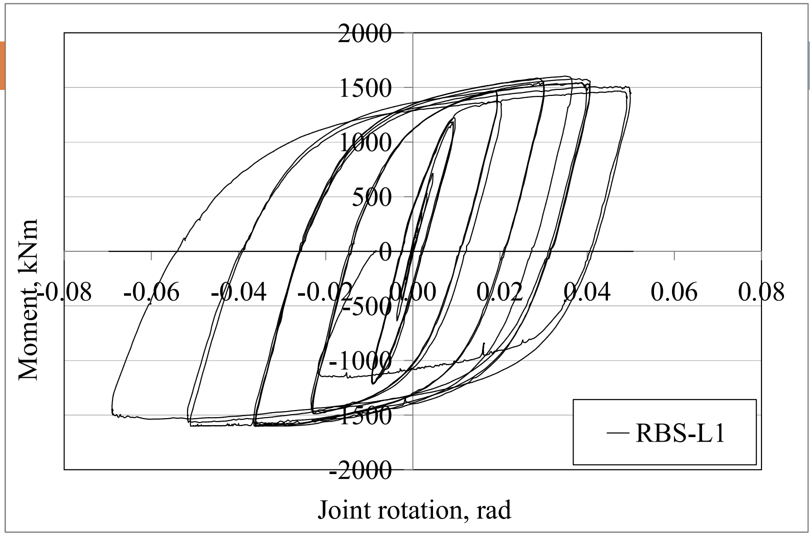


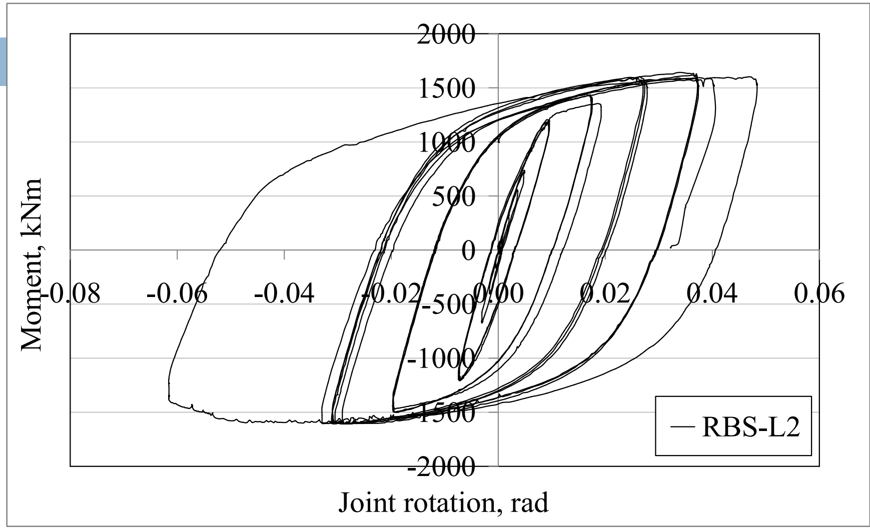
RBS-S2

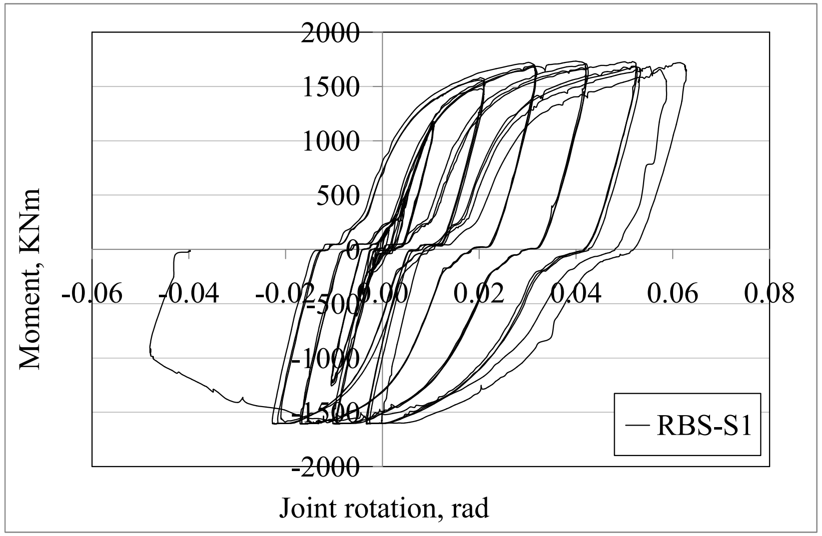


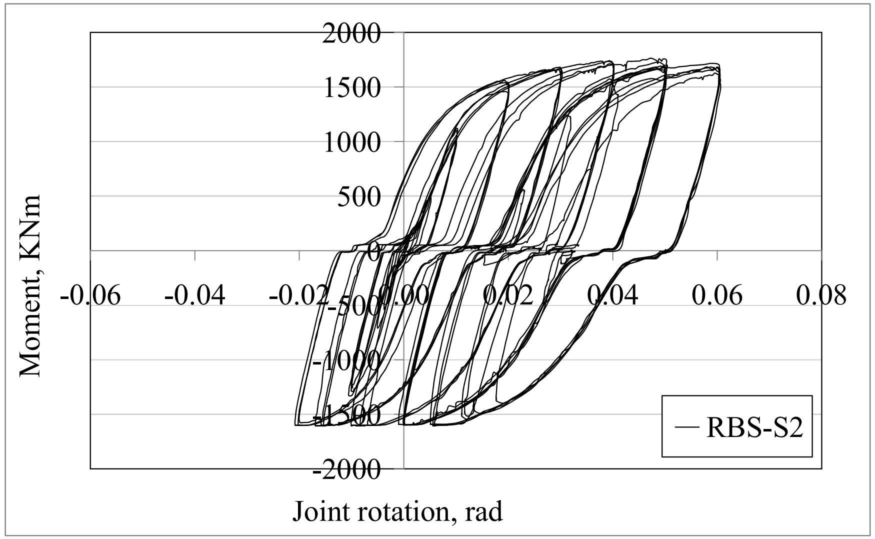


Global behavior

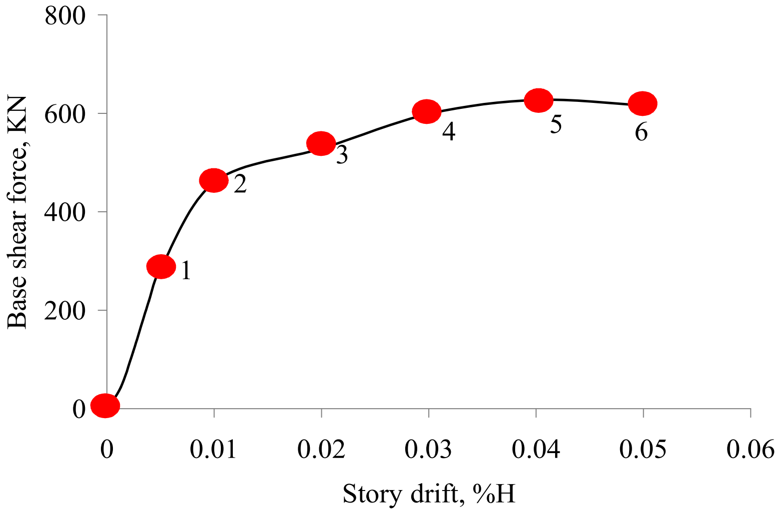


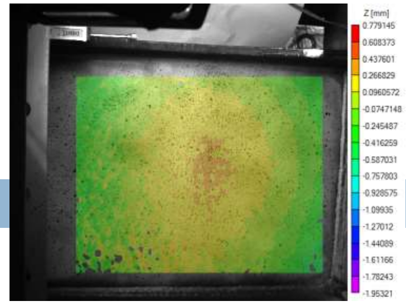


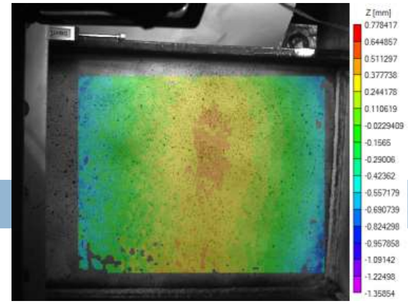


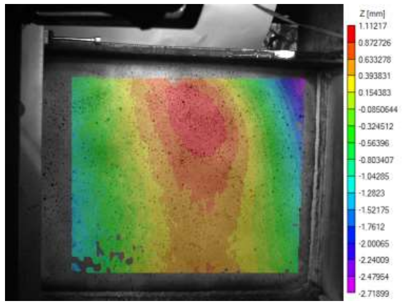


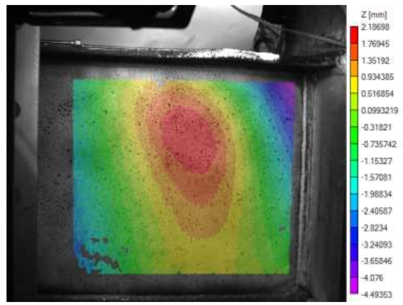
Long specimens

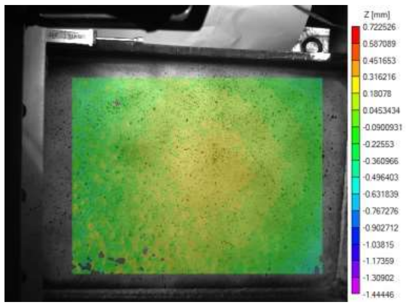


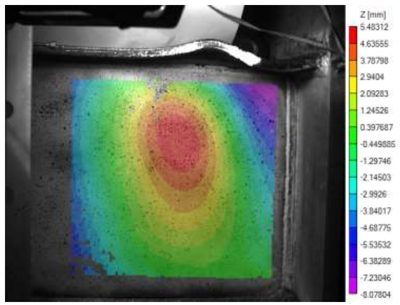

Ποιντ 1

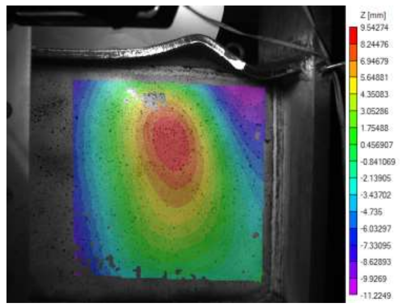

Ποιντ 2


Ποιντ 3

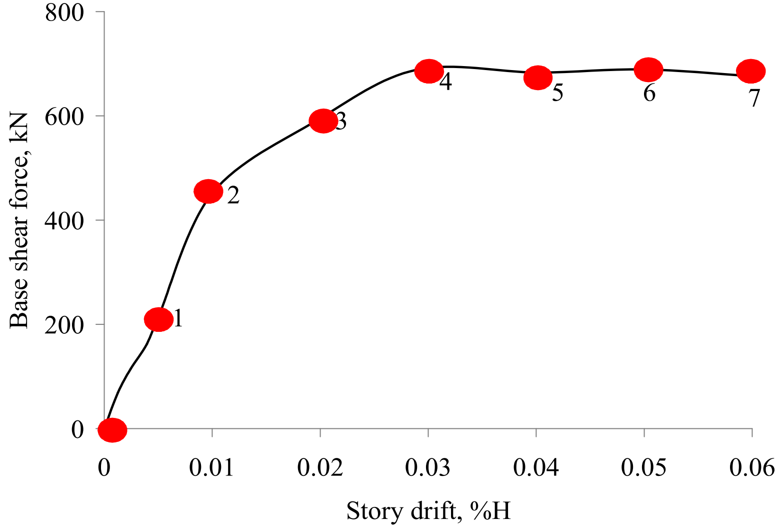

Ποιντ 4

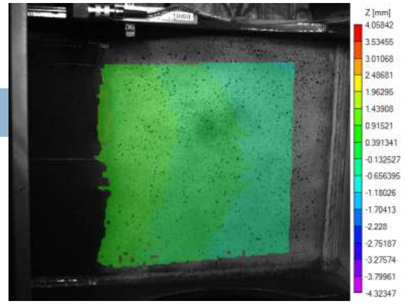

Ινιτια
λ


Ποιντ 5


Ποιντ 6

Short specimens





Ινιτια
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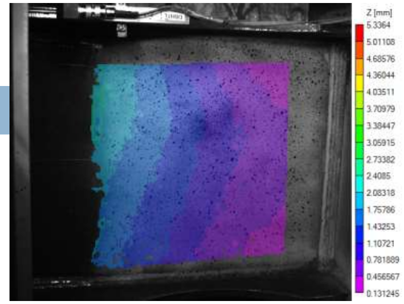
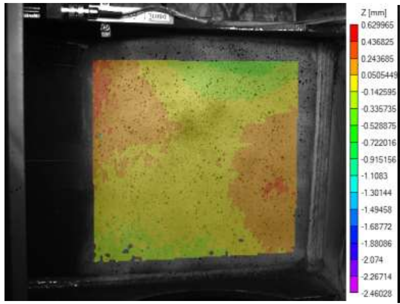
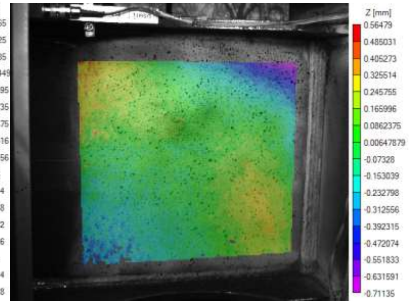


Ποιντ 1



Ποιντ 2



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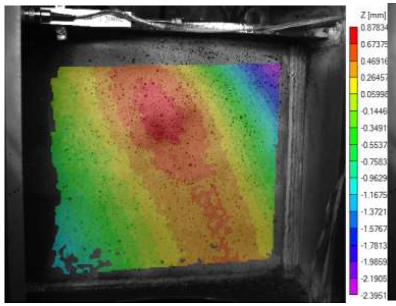
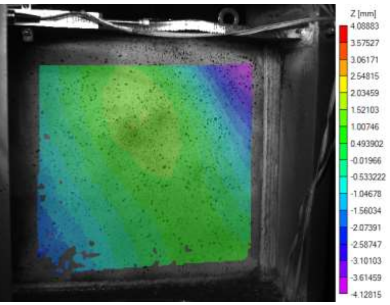


Ποιντ 4



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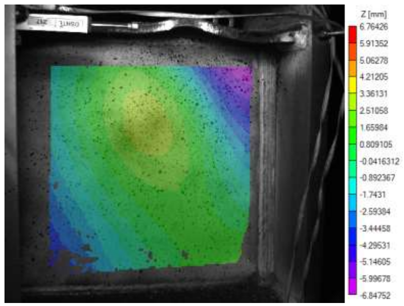
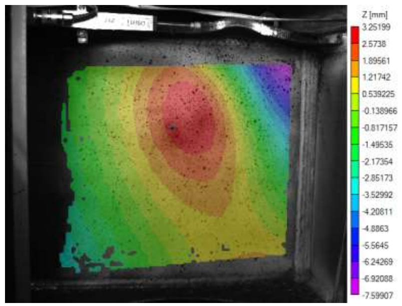


Ποιντ 6



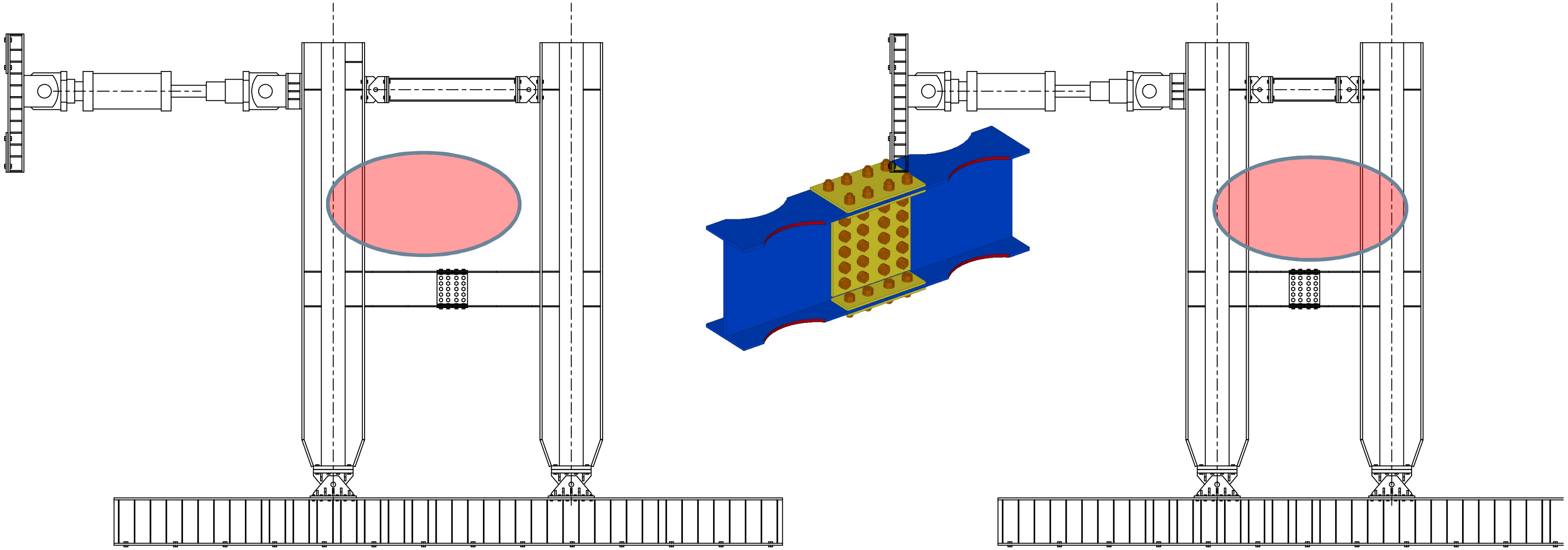
Ποιντ 7

Preliminary conclusions and recommendations

- A good example of a design assisted by testing
- RBS detailing concentrates the plastic deformations in the reduced zone
- Flush end plate beam splice connection – influences the behavior, can cause brittle failure due to bolt fracture, especially for shorter beams - **improved connection detail proposed and tested**
- Beam flanges and web to column flange weld – quality is critical in assuring the failure does not initiate from face of column – strictly controlled welding operation
- Flange cutouts can cause premature failure – NDT (eg. magnetic particle testing) to verify that reduced flange sections are free of notches and cracks
- Significant contribution from web panel distortion to total plastic rotation
- New connection detail (extended end plate bolted connection) will be investigated experimentally and numerically

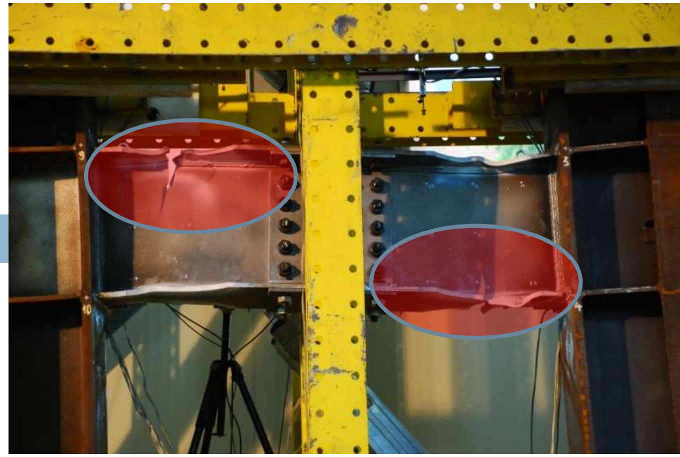
2nd series of tests – new connection detail

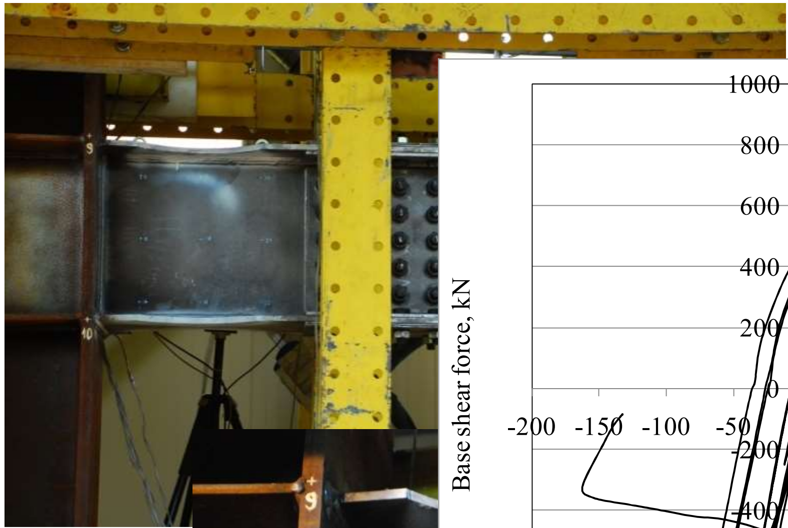
- The flush-end plate bolted connection has been replaced by a shear slip resistant splice connection
- Two more specimens, one with short beam (RBS-S3) and one with long beam (RBS-L3)

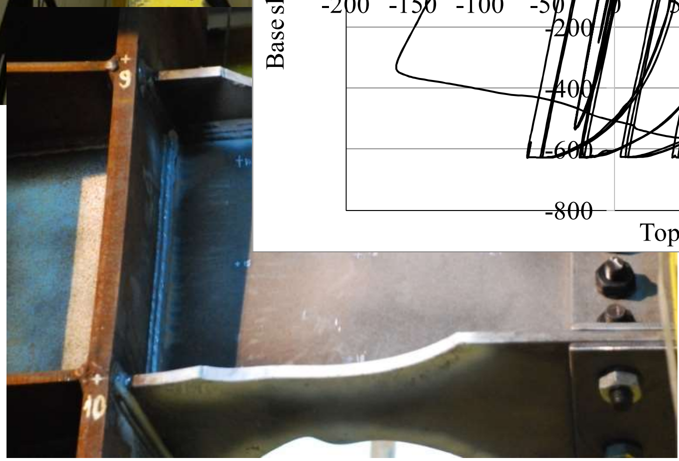


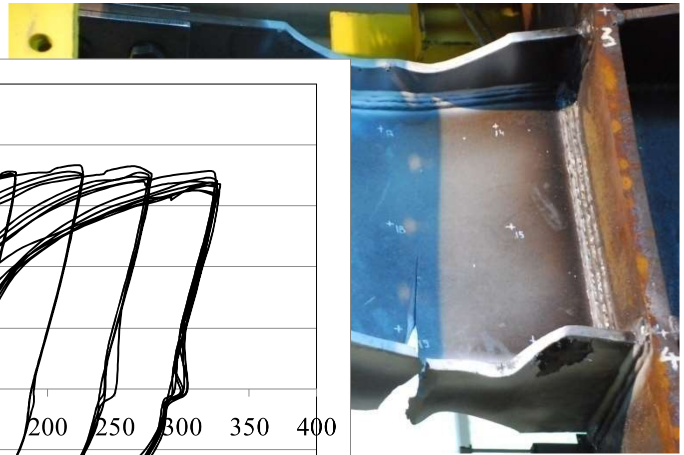
Experimental results

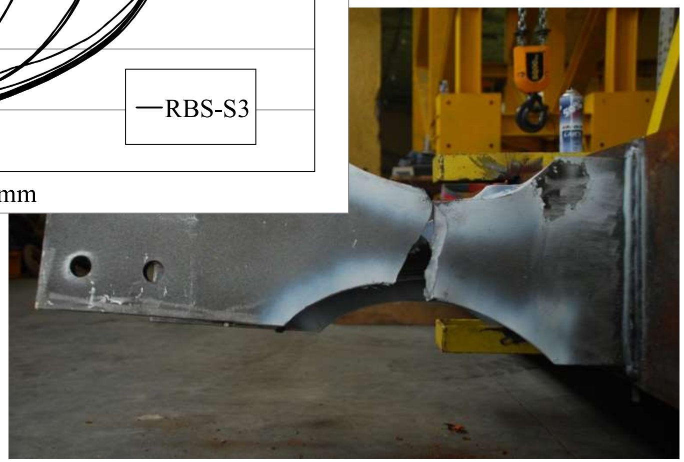
- RBS-S3

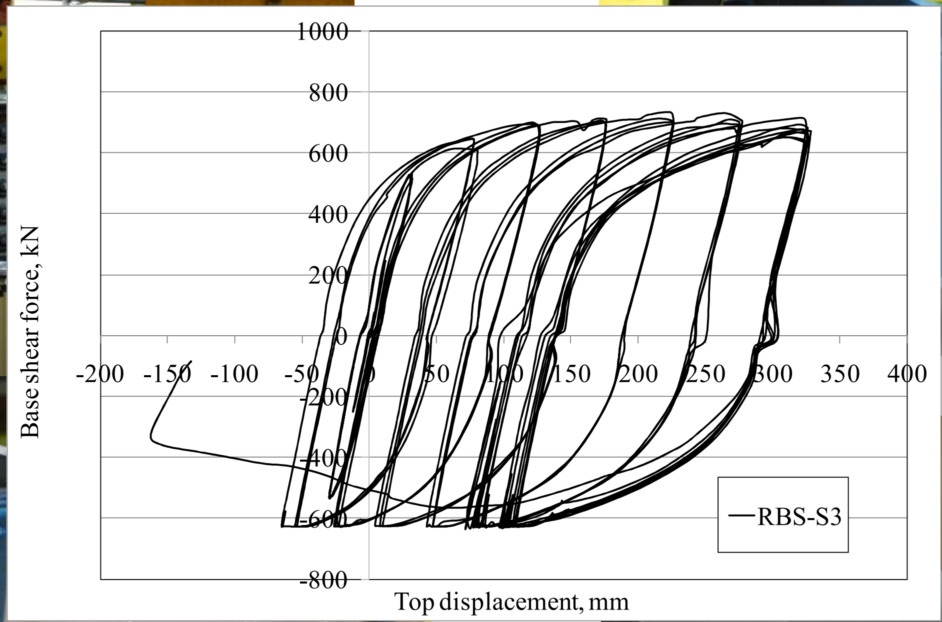






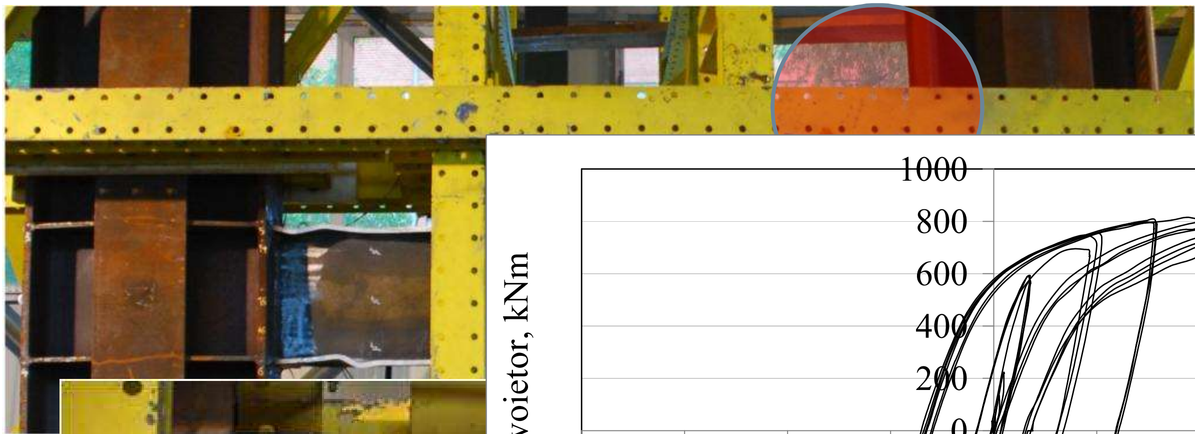


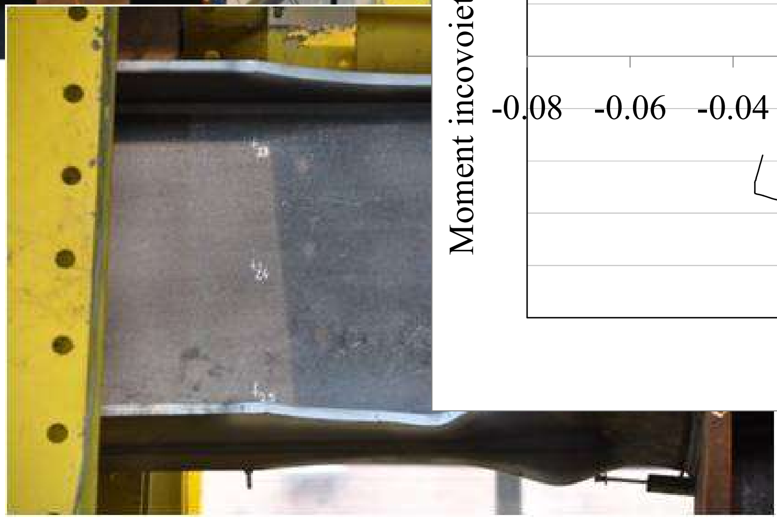


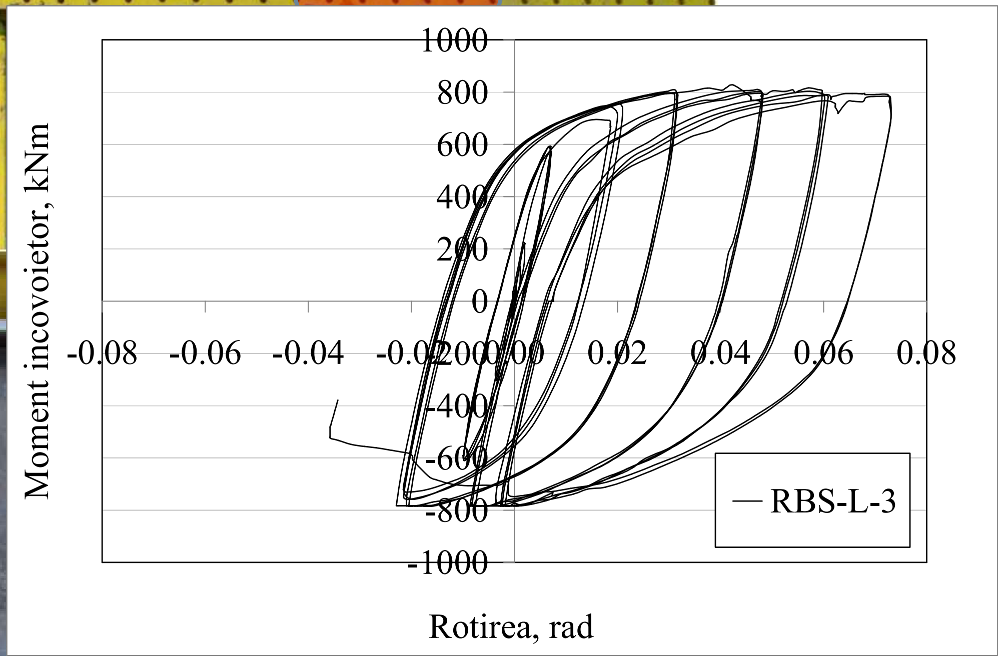


Experimental results

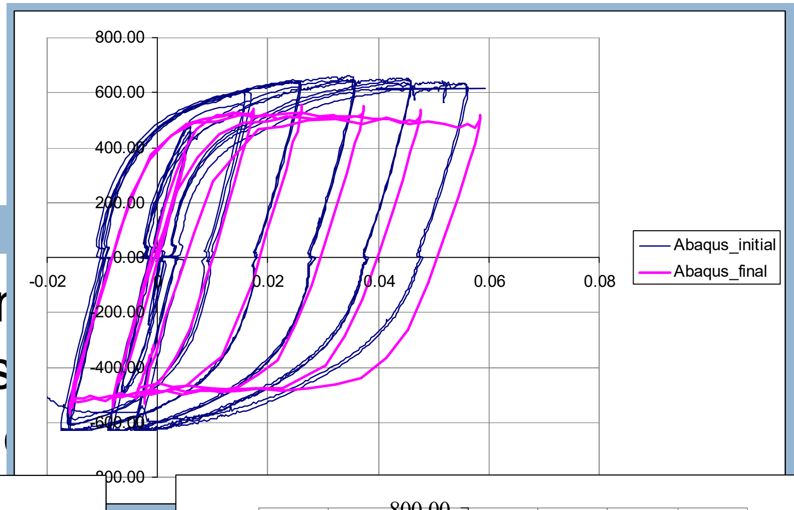
❑ RBS-L3





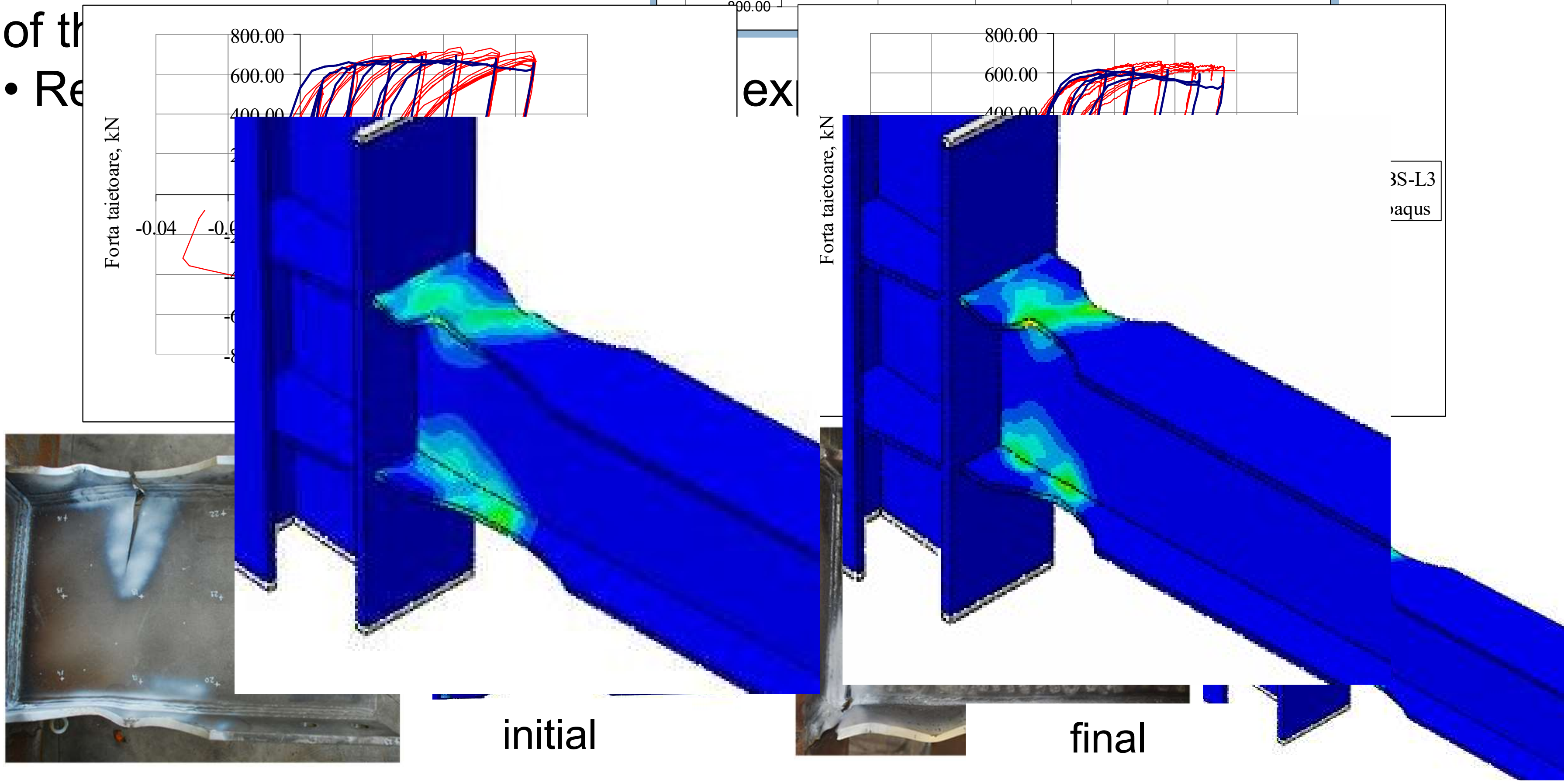


Numerical pro



- Numerical models have been
experimental results – Abaqus
- Aims: improve the behavior,
of th
- Re

ex



initial

final

Case-study concluding remarks

- New dissipative frame of RBS coupling beams evaluated
- Short and Long Beams systems tested
- Dog-bone geometry optimized
- Influence of bolted end-plate splice evaluated
- Lateral-flexural buckling risk evaluated
- Numerical model calibrated experimentally for coupled beams to enable global analysis of structure.

Final Remarks

- Laboratory tests – full or reduced scale – enable to better understand the real behavior of a **structure/component/detail** and offer a realistic base to validate a technical solution or develop engineering calculation models
- Numerical models, if properly calibrated by tests, can extend the experimental data base
- **Without experimental calibration and validation, numerical models, only, cannot replace tests !**