WORKSHOP HYSIM19
Zurich, March 13 to 15, 2019

SERA WP27/JRA5: Innovative testing methodologies for component/system resilience

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Acknowledgements

1. The author gratefully acknowledges the financial supports from the European Union through SERA, INDUSE-2-SAFETY and DISSIPABLE.

2. The author gratefully acknowledges the SERA partners and the technical work of Giuseppe Abbiati, Patrick Covi, Rocco Di Filippo and Osman Sayginer.

3. The author gratefully acknowledges the technical support of ETH-Zurich, JRC, EUCENTRE TREES Lab and LPMS of the University of Trento

Outline

1. SERA and WP27/JRA-5 objectives
2. HDS framework at the start of WP27/JRA-5
3. WP27/JRA-5 main Research Activities and achievements
4. WP27/JRA-5 main Transnational Access Activities
5. Requests for the next WP27/JRA-5

SERA

Seismology and Earthquake Engineering
Research Infrastructure Alliance for Europe

www.sera-eu.org

SERA: Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe.

(Grant No: 730900) - Planned Duration: 36 months
Consortium: 21 participants.
Coordinator: Domenico Giardini (ETH)
Total Funding: € 10,000,000 EURO

WP27/JRA-5: Innovative testing methodologies for component/system resilience

Coordinator: Oreste S. Bursi (UNITN)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

By means of hybrid (numerical/physical) dynamic substructuring simulations (HDS), SERA WP27/JRA5 will pursue the following objectives:

- ☐ reduce the computational burden of complex hybrid non-linear systems and provide additional significance to HDS both in civil engineering and mechanical engineering systems by order reduction, quantification of epistemic uncertainties and use of simple non-linear models, e.g. the Bouc-Wen model, etc.;

- ☐ compare the performances of online, i.e. the HDS method, and offline methods like the impulse-based substructuring (IBS) and the Lagrange multiplier frequency-based substructuring (LM-FBS);

- ☐ study testing equipment able to properly impose complex loading on innovative isolation/dissipation devices made of fiber-reinforced rubber, shape-memory alloys (SMAs), etc. The equipment should be also able to control temperature effects, rate effects, etc.;

- ☐ conceptualise the smart city research, with the design and development for seismic and other natural hazard actions, like tsunamis, etc. Thus, pilot and advanced development studies of the integration of dynamic substructuring/hybrid testing in smart/seismic-prone cities will be carried out.

Work package number	27		**Lead beneficiary**		UTRE				
Work package title	JRA5:Innovative testing methodologies for component/system resilience								
Participant number	1	3	5	6	7	10	12	14	33
Short name of participant	ETHZ	JRC	LNEC	UPAT	UBRI	UTRE	UPM	BOUN	UIB
Person/months per participant:	6	5	14	12	24	42	12	10	4
Start month	1			**End**	36				

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The UNITN framework based on Heterogeneous DS

The analysis procedure can be subdivided in four steps (Bridge case study)

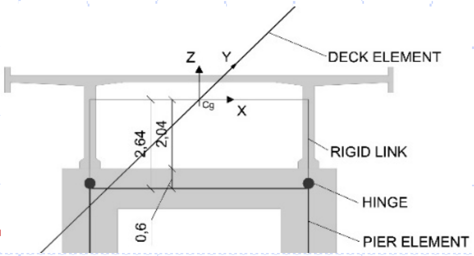
STEP I

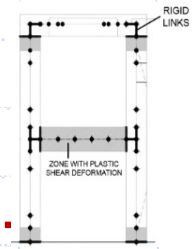
Generation of predictive FE models and selection of seismic input

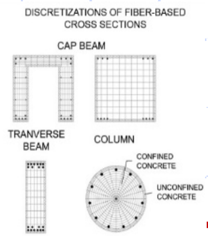
Predictive 2D/3D models have been implemented in Opensees and ABAQUS environments;

They allowed for **predicting the distribution and magnitude of nonlinearities** by the implemetation of material constitutive laws;

Seismic input was selected with different methods such as by the selection of a set of earthquakes representative of a Uniform Hazard Spectrum (UHS)





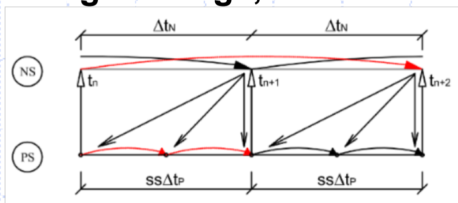


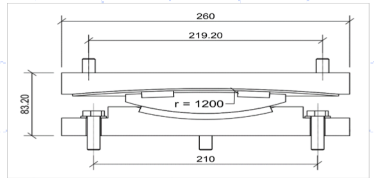
STEP II

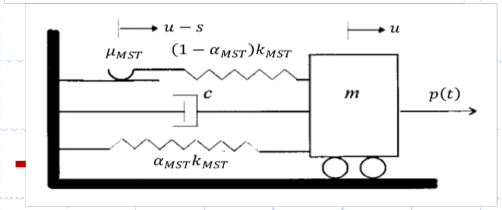
Design and development of experimental tests

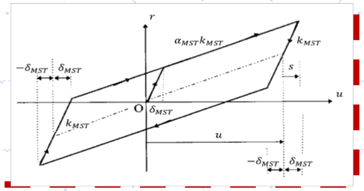
Hybrid simulation with dynamic substructuring supported by **different partitioned time integration algorithms (Pegon-Magonette integration method)** have been developed.

Bouc-Wen and Mostaghel bilinear models for modeling numerical substructures like piers, concave sliding bearings, etc.









The UNITN framework

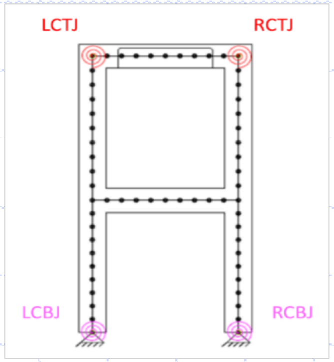
Third and fourth steps:

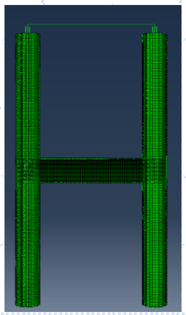
STEP III

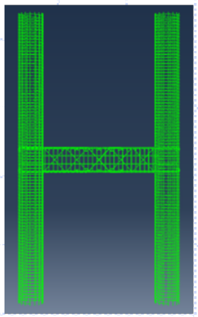
Improvement of predictive FE models by means of validation and calibration procedures (deterministic and stochastic tools)

Validation and calibration procedures were applied to quantify the global error of a pier FE model in comparison to proper benchmark functions;

The local behavior of structural joints was improved by means of discrete local springs tailored on instrumental records.





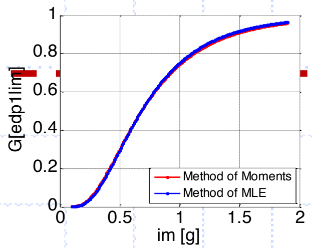


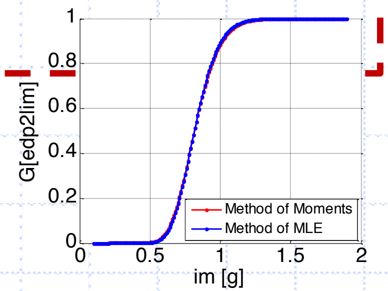
STEP IV

Development of advanced probabilistic analyses with improved FE models.

Performance-based earthquake engineering can be applied to complex bridges taking into account both structural and economic uncertainties;

$$\lambda(DV)=\int_0^\infty\int_0^\infty\int_0^\infty G(DV\,|\,DM)\,\left|dG(DM\,|\,EDP)\right|\,\left|dG(EDP\,|\,IM)\right|\,\left|d\lambda(IM)\right|$$





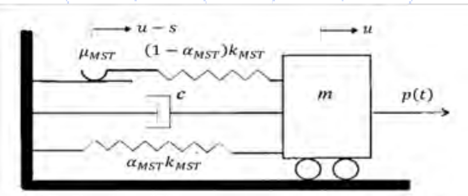
Main elements of the framework based on nonlinear heterogeneous simulation based on dynamic substructuring (HDS)

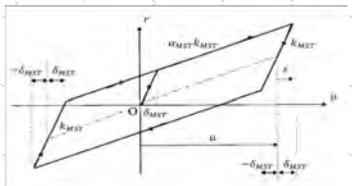
1. **Reliable predictive FE models capable of creating a Reference Model of the emulated system via validation/calibration;**

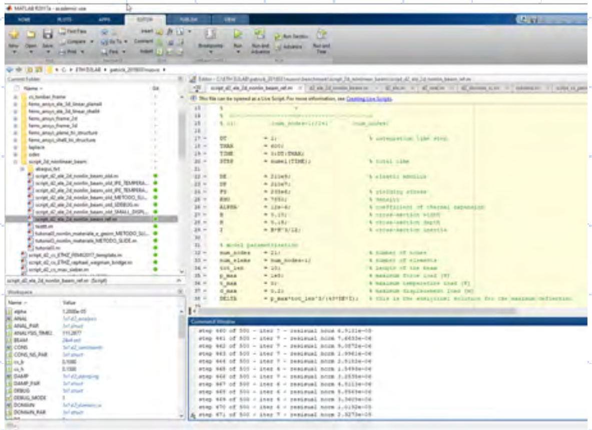
2. **A parallel time integration algorithm endowed with superior capabilities in terms of coupling/decoupling and accommodation of system ID and updating techniques**

3. **Offline/Online updating procedures for complex nonlinear Numerical Substructures**

4. **ETHZ/UNITN developed a MATLAB framework for finite element analysis with domain decomposition coded in house**







Abbiati, G., Bursi, O.S., Caperan P., Di Sarno, L., Molina, F.J., Paolacci, F. and Pegon, P., "Hybrid simulation of a multi-span RC viaduct with plain bars and sliding bearings", Earthquake Engineering & Structural Dynamics, 2015, 44,13, 2221-2240.

Bursi O.S., Abbiati G., Cazzador, E., Pegon, P. and Molina, F.J., "Nonlinear heterogeneous dynamic substructuring and partitioned FETI time integration for the development of low-discrepancy simulation models", International Journal for numerical Methods in Engineering, DOI: 10.1002/nme.5556, 2017.

WP27/JRA-5

Main Research Activities and achievements

To combine different EDS methods for simulating the response of heterogeneous systems. Experiments were conducted on a substructured petrochemical prototype plant

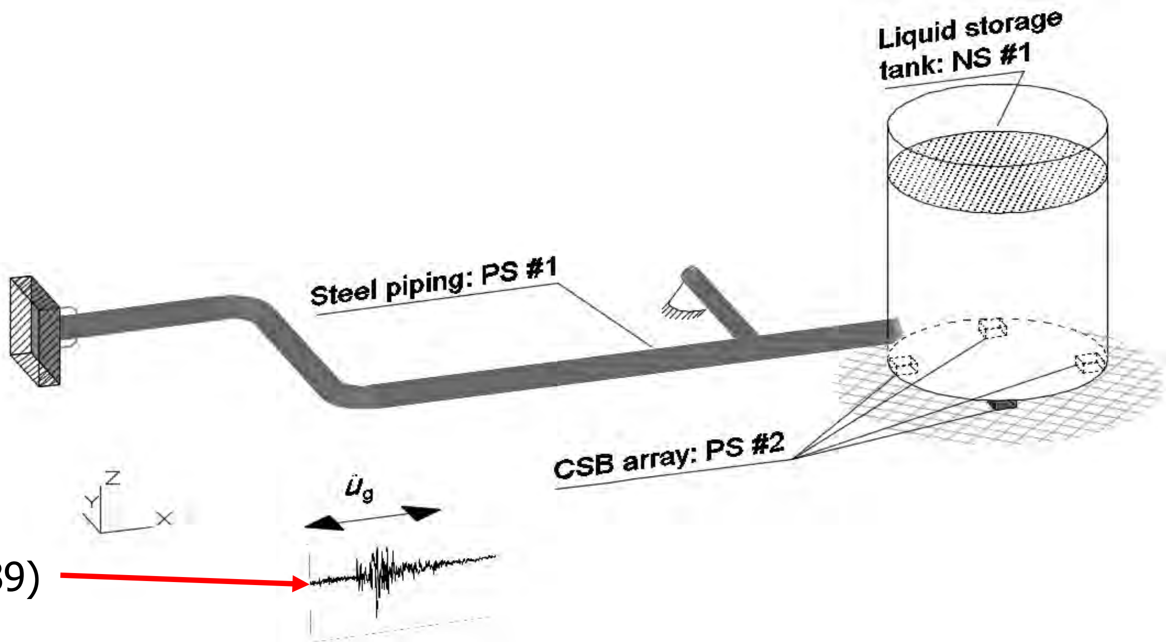
Experimental techniques	Procedure	Type of NS	Type of PS
RBS	Offline	Linear	Linear
IBS	Offline	Non-linear	Linear
Hybrid Simulation	Online	Non-linear	Non-linear

- To understand how uncertainty on input and measurements propagate through the different methods.
- To optimize their combination in the substructuring of complex structural systems.

Abbiati, G., La Salandra, V., Bursi, O.S., Caracoglia, L. "A Composite Experimental Dynamic Substructuring Method Based on Partitioned Algorithms and Localized Lagrange Multipliers", Mechanical Systems and Signal Processing, 100, 1, 2018, 85-112

Composite – EDS (C-EDS)

C-EDS framework combines different EDS methods for simulating the response of heterogeneous systems. A virtual experiment was conducted on the petrochemical prototype plant



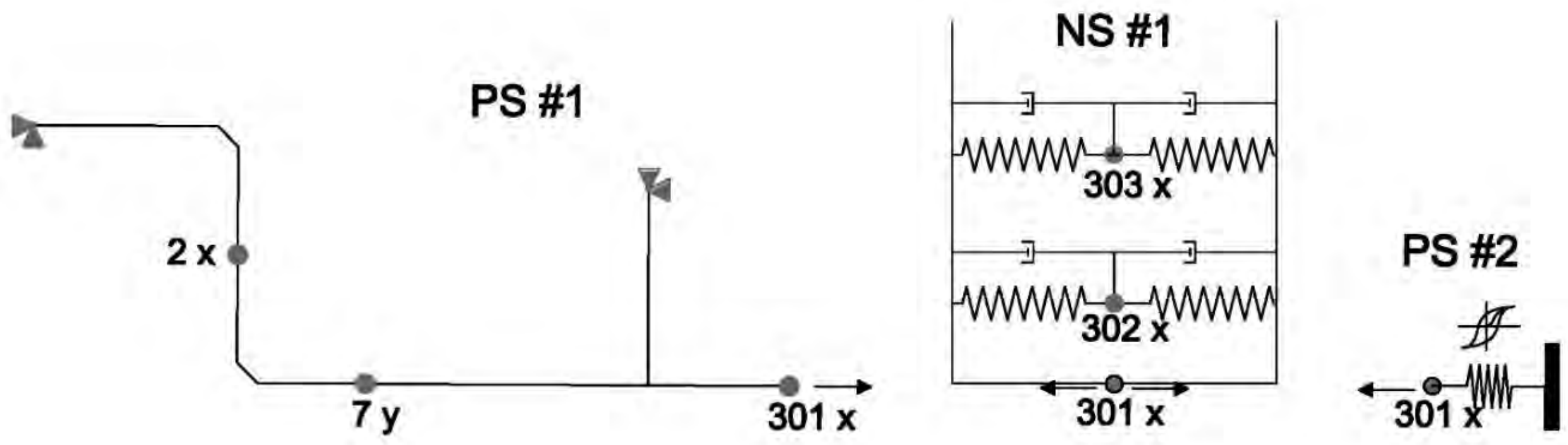
Loma Prieta earthquake (1989)

- It was assumed that the piping response remains linear but boundary conditions are highly uncertain and that such substructure is available onsite for dynamic characterization. → **IBS, RBS offline techniques**

- On the other hand, the non-linear hysteretic response of the Concave Sliding Bearings (CSB) makes very difficult the numerical modelling of sliding parts. → **HDS online technique**

C-EDS – Multiple costraints

In order to simulate the seismic response of the petrochemical prototype plant, a partitioned model of the emulated system was implemented in Matlab.



- All NS and PS models described were coupled together by using Localized Lagrangre Multipliers

- The reference "exact" solution was calculated by means of the monolithic Newmark method $(\Delta t = 0.1\,\mathrm{ms}, \gamma = 1/2, \beta = 1/4)$ considering the emulated system of the prototype plant case study.

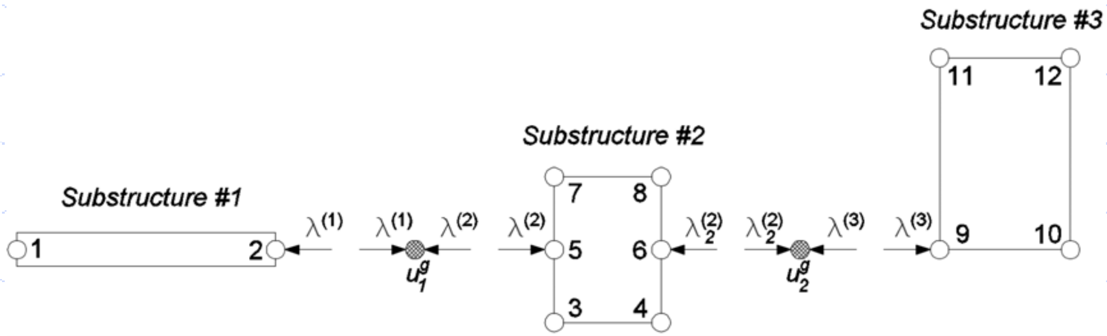
The Localized Lagrange Multiplier method

$$\begin{cases} \mathbf{M}^{(l)}\ddot{\mathbf{u}}^{(l)} + \mathbf{R}^{(l)}\left(\mathbf{u}^{(l)}, \dot{\mathbf{u}}^{(l)}\right) = \mathbf{L}^{(l)^T}\mathbf{\Lambda}^{(l)} + \mathbf{F}^{(l)}(t) \\ \mathbf{L}^{(l)}\mathbf{u}^{(l)} + \bar{\mathbf{L}}^{(l)}\mathbf{u}_g = \mathbf{0} \; or \; \mathbf{L}^{(l)}\dot{\mathbf{u}}^{(l)} + \bar{\mathbf{L}}^{(l)}\dot{\mathbf{u}}_g = \mathbf{0} \end{cases} \quad \forall\, l \in \{1, \dots, m\} \qquad (2.1a)$$

$\mathbf{u}^l$ and $\mathbf{u}^g$ are interface DoFs and generalized interface DoFs vectors

$$\sum_{l=1}^{m} \bar{\mathbf{L}}^{(l)^T}\mathbf{\Lambda}^{(l)} = \mathbf{0} \qquad (2.1b)$$

According to Eq. (2.1a), each Lagrange multiplier vector Λ^(l) enforces compatibility between the corresponding subdomain l-th and the generalized interface DoF vector u_g. Finally, Eq. (2.1b) imposes self-balance among all m interface force fields represented by Lagrange multiplier vectors.



$$\mathbf{u}^{(1)^T} = \left[u_1^{(1)}, u_2^{(1)}\right]$$

$$\mathbf{u}^{(2)^T} = \left[u_3^{(2)}, u_4^{(2)}, u_5^{(2)}, u_6^{(2)}, u_7^{(2)}, u_8^{(2)}\right]$$

$$\mathbf{u}^{(3)^T} = \left[u_9^{(3)}, u_{10}^{(3)}, u_{11}^{(3)}, u_{12}^{(3)}\right]$$

$$\mathbf{u}_g^T = \left[u_1^g, u_2^g\right]$$

$$\mathbf{L}^{(1)} = [0,1], \bar{\mathbf{L}}^{(1)} = [-1,0]$$

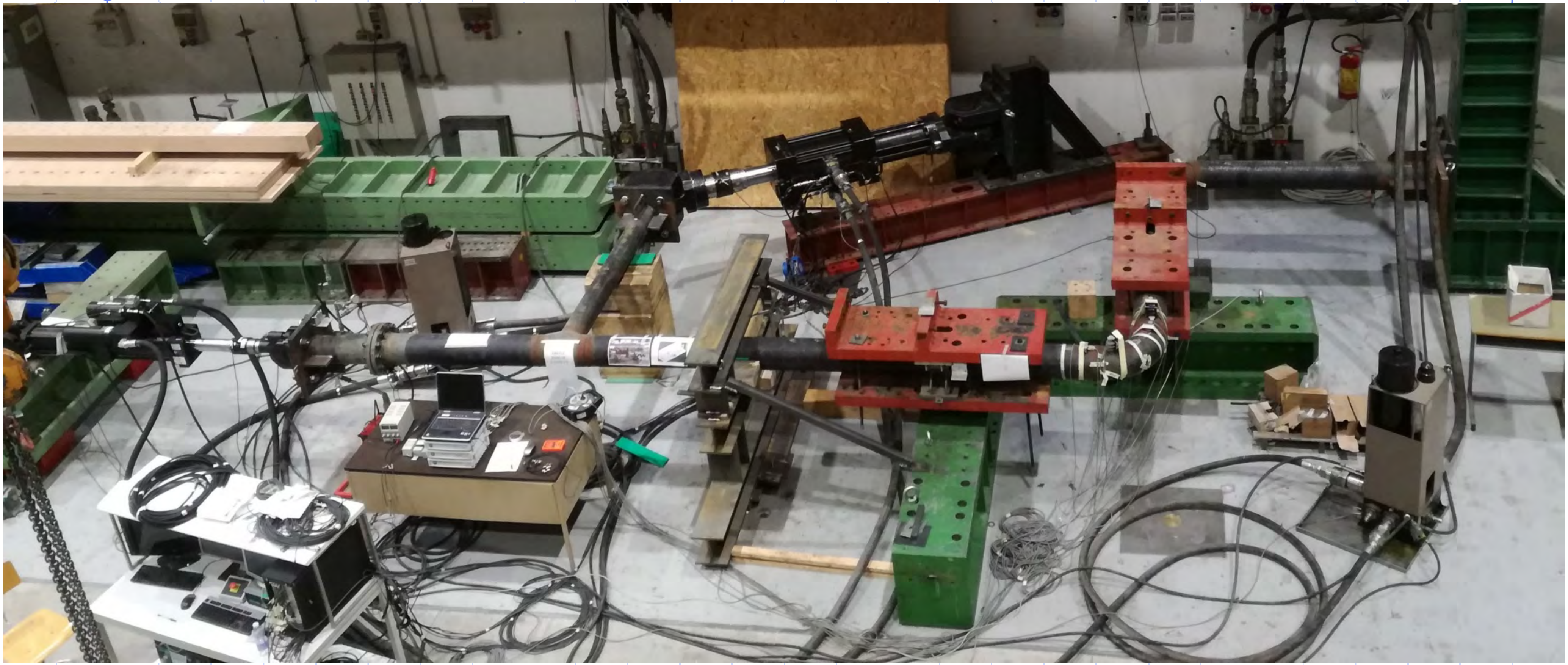
$$\mathbf{L}^{(2)} = \begin{bmatrix} 0,0,1,0,0,0 \\ 0,0,0,1,0,0 \end{bmatrix}, \bar{\mathbf{L}}^{(2)} = \begin{bmatrix} -1, & 0 \\ 0, & -1 \end{bmatrix}$$

$$\mathbf{L}^{(3)} = [1,0,0,0], \bar{\mathbf{L}}^{(3)} = [0,-1]$$

As a dual-assembly approach, the LLM introduces additional sets of Lagrange multipliers, which satisfy interface equilibrium a priori through Eq. (2.1b) and enforce kinematic compatibility a posteriori by means of Eq. (2.1a).

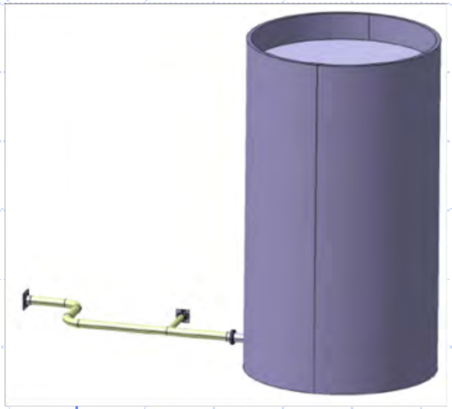
K.C. Park, C. A. Felippa, U. A. Gumaste, A localized version of the method of Lagrange multipliers and its application, Comput. Mechanics 24, 2000, 476-490.

Experimental setup @UNITN

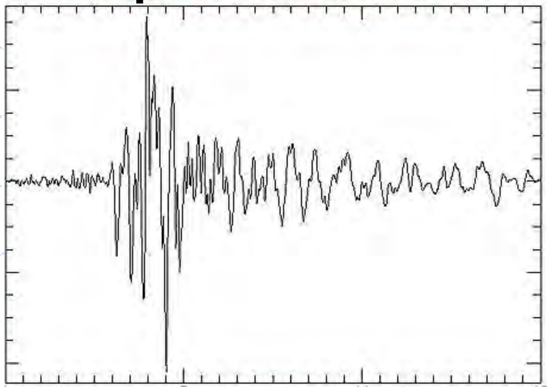


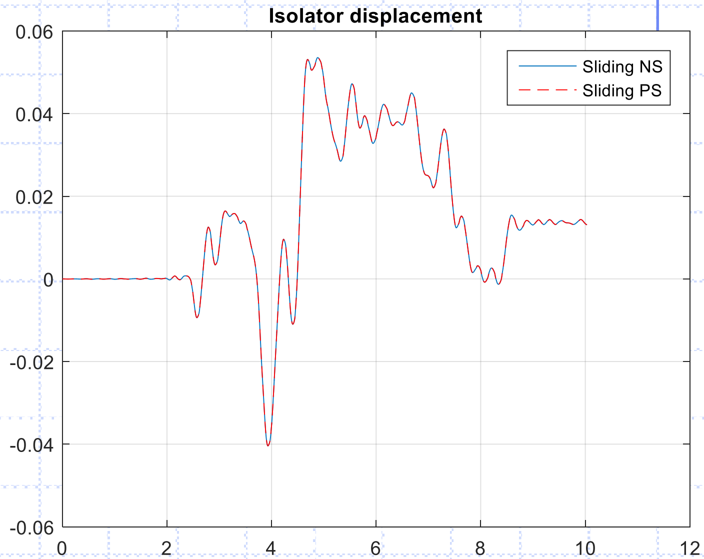
Results

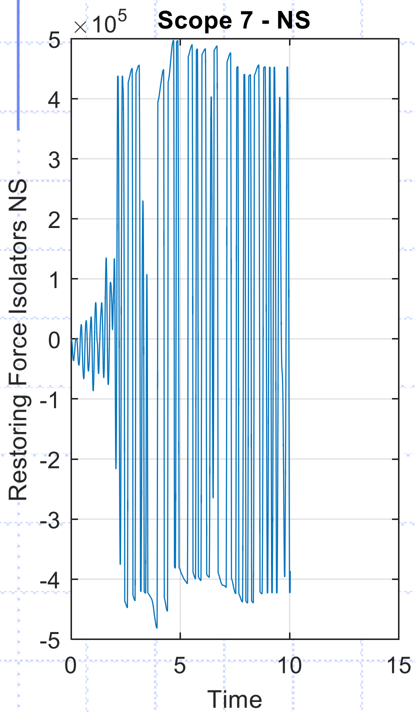
Slender tank #23

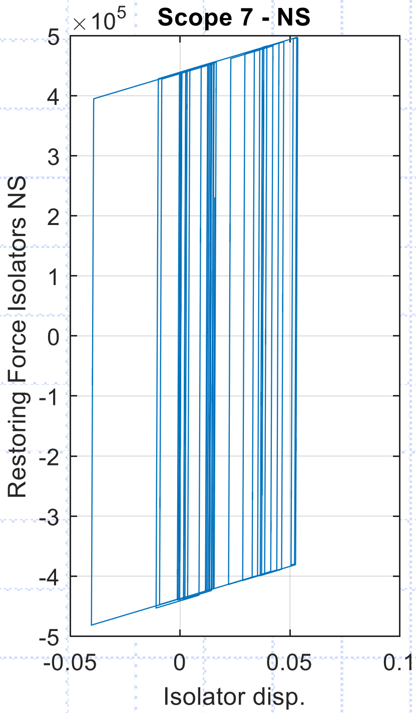


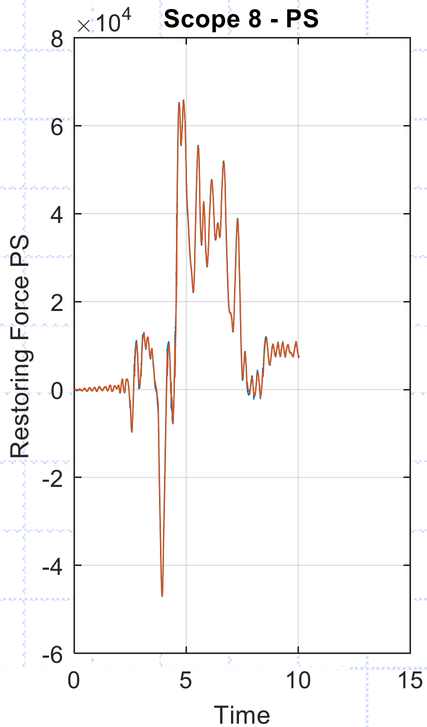
R.P. 475 years, 004673ya earthquake. T SCALE = 10

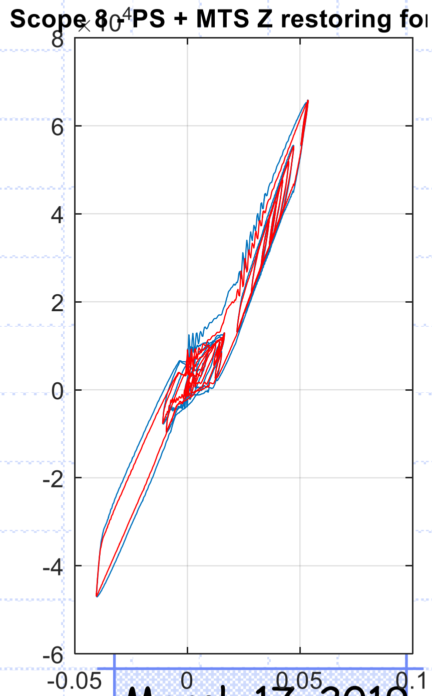












WP27/JRA-5
Main Research Activities and achievements

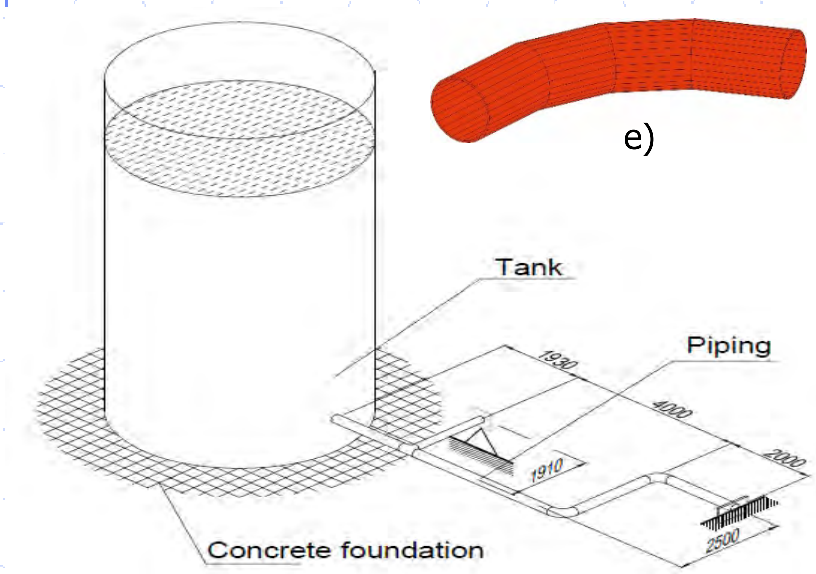
To define Seismic Fragility Assessment of a Tank-Piping System based on Hybrid Simulation and Surrogate Modelling

- Stochastic modelling of the seismic input
- Global sensitivity analysis of the structural response
- Hybrid simulation and seismic fragility assessment

Bursi, O.S., Abbiati, G. Covi, P. et al. "Enhanced HDS due to order reduction, reduced epistemic uncertainties and complementary use of offline dynamic substructuring methods", Deliverable D27.1, 2019, 1-92

Seismically Isolated Tank-Piping System

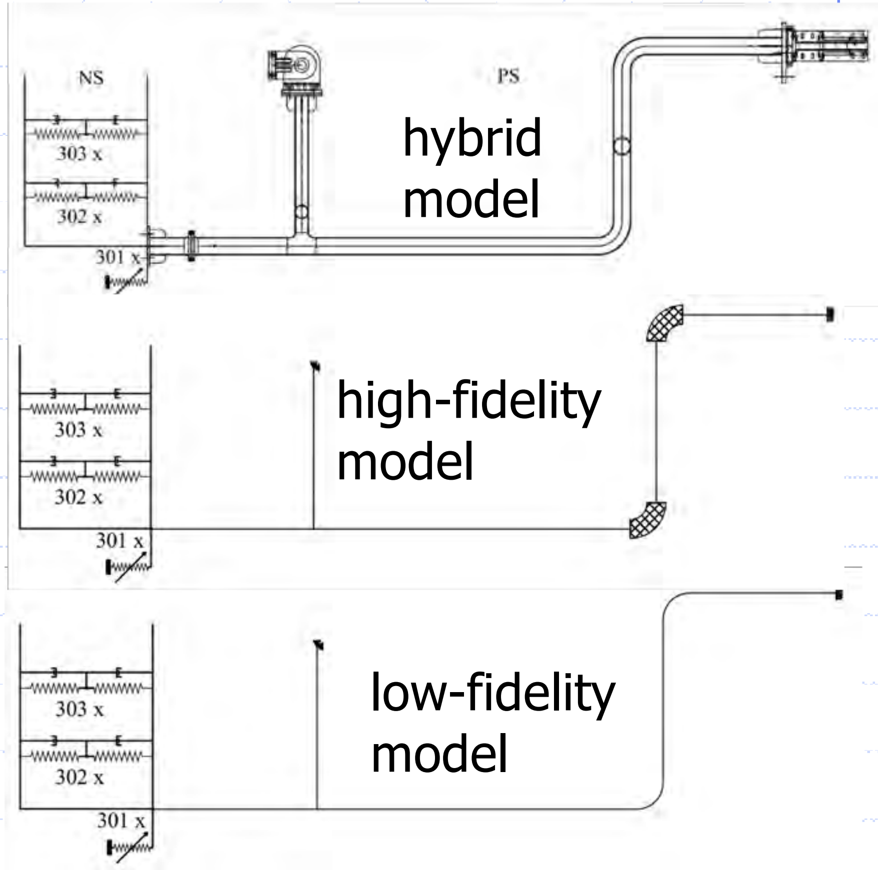
a)



b)

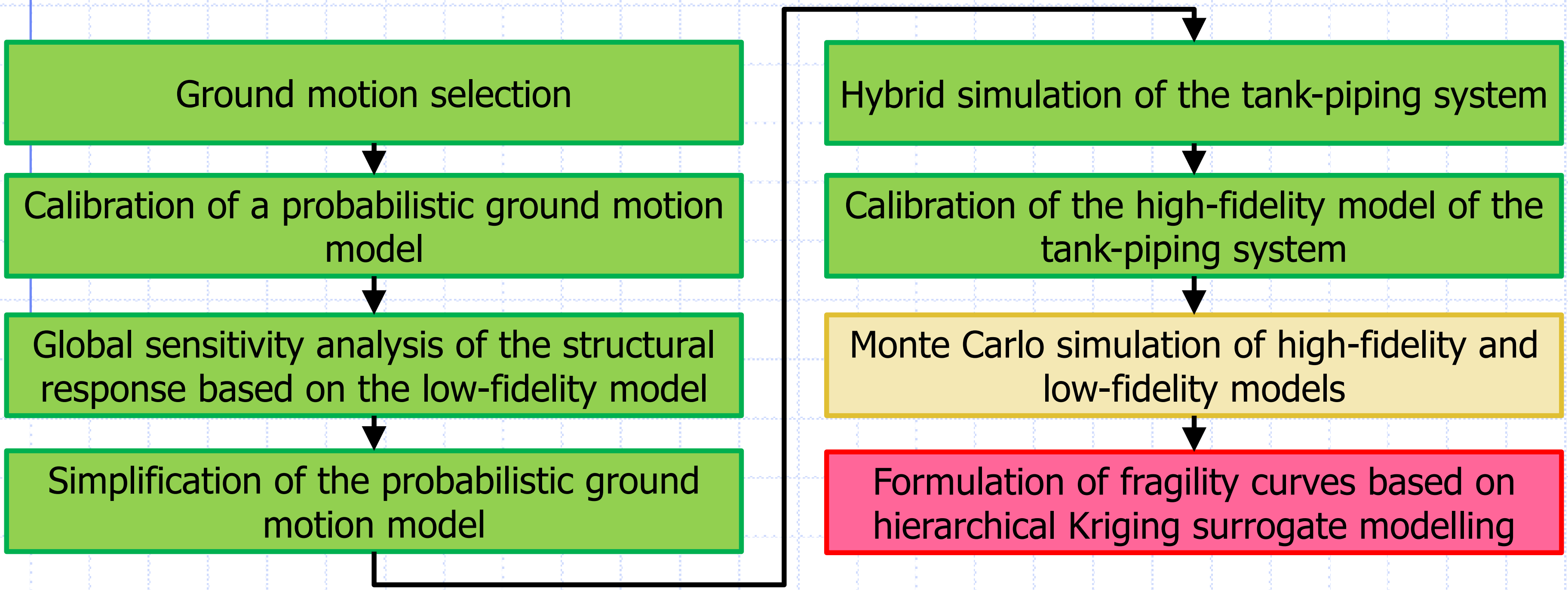
c)

d)



Tank-piping system: a) prototype structure b) hybrid model c) high-fidelity computational model d) low-fidelity computational model e) ANSYS elbow290 elements used on the high-fidelity computational simulator.

Seismic Fragility Assessment Procedure



Legend: DONE, ONGOING, PENDING

Stochastic Modelling of Seismic Input

$$a_g(t) = q(t,\boldsymbol{\alpha})\left[\frac{1}{\sigma_f(t)}\int_{-\infty}^{t} h\big(t-\tau,\boldsymbol{\lambda}(\tau)\big)\omega(\tau)d\tau\right]$$

$\omega(\tau)$: white-noise process with constant Power Spectral Density (PSD) $S_{\omega\omega}(\omega) = S$

$h\big(t-\tau,\boldsymbol{\lambda}(\tau)\big)$: Impulse Response Function (IRF) of a linear time-varying filter

$q(t,\boldsymbol{\alpha})$: time modulating function

Model Parameters

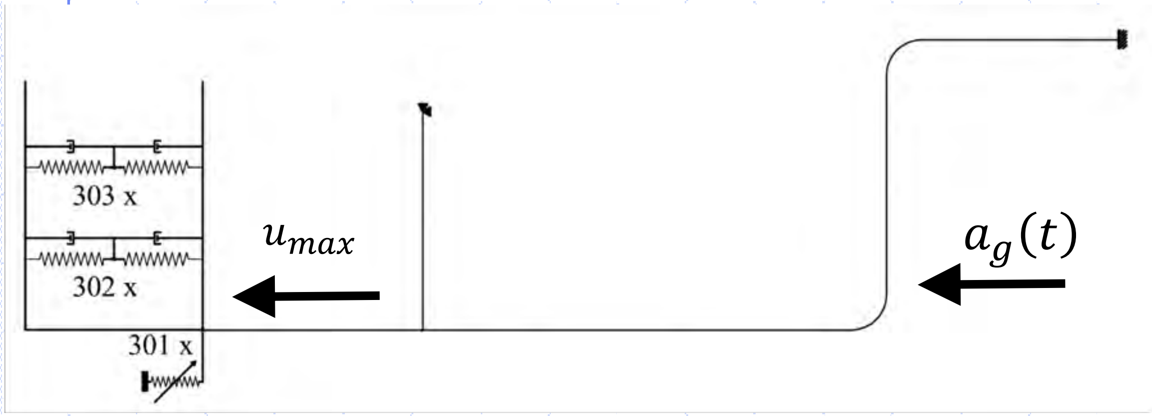
I_a	Arias intensity
D_{5-95}	Time interval of 95% of the I_a
t_{mid}	Time at which 45% of the I_a is reached
ω_{mid}	Filter frequency at t_{mid}
ζ_f,	Filter damping ratio (constant).
ω'	Rate of change of the filter frequency with time

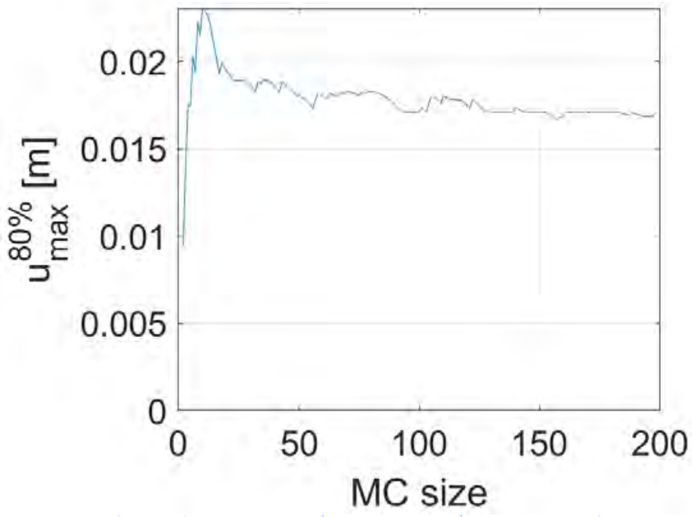
$$I_A = \frac{\pi}{2g}\cdot\int_0^t a^2\,(t)\,dt$$

Rezaeian, S., & Der Kiureghian, A. (2010). Simulation of synthetic ground motions for specified earthquake and site characteristics. Earthquake Engineering & Structural Dynamics, 39(10), 1155-1180.

Global Sensitivity Analysis of the Seismic Response

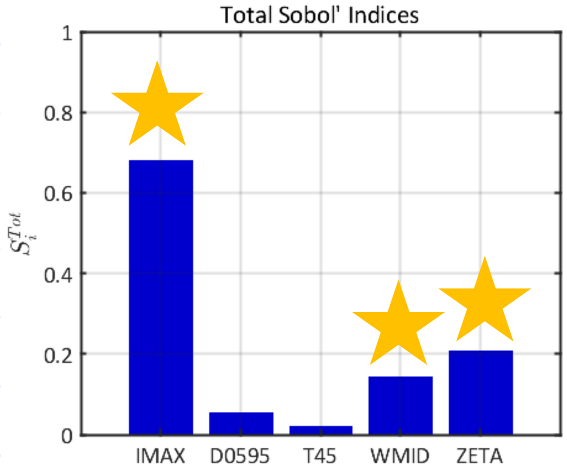
Interest in peak quantities
Input variable: $x \in X_{ED} = \{I_a, D_{5-95}, T_{45}, \omega_{mid}, \zeta\}$
Output variable: $y \in Y_{ED} = u_{max}^{80\%}$

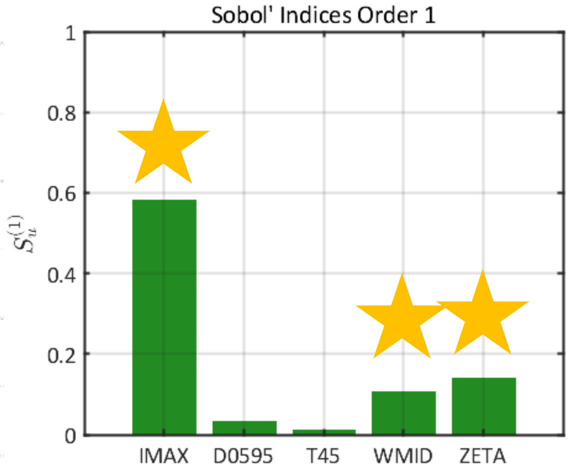




Quantile convergence

Global Sensitivity Analysis of the Seismic Response





Polynomial Chaos Expansion

$$\boldsymbol{x}) = \mathcal{M}^{PC}(\boldsymbol{x}) = \sum_{\alpha \in \mathcal{A}^{M,p}} y_{\alpha} \Psi_{\alpha}(\boldsymbol{x})$$

Model decomposition

$$\mathcal{M}^{PC}(\boldsymbol{x}) = \mathcal{M}_0^{PC} + \mathcal{M}_1^{PC}(x_1) + \cdots \mathcal{M}_2^{PC}(x_2) + \mathcal{M}_{12}^{PC}(x_1, x_2)$$

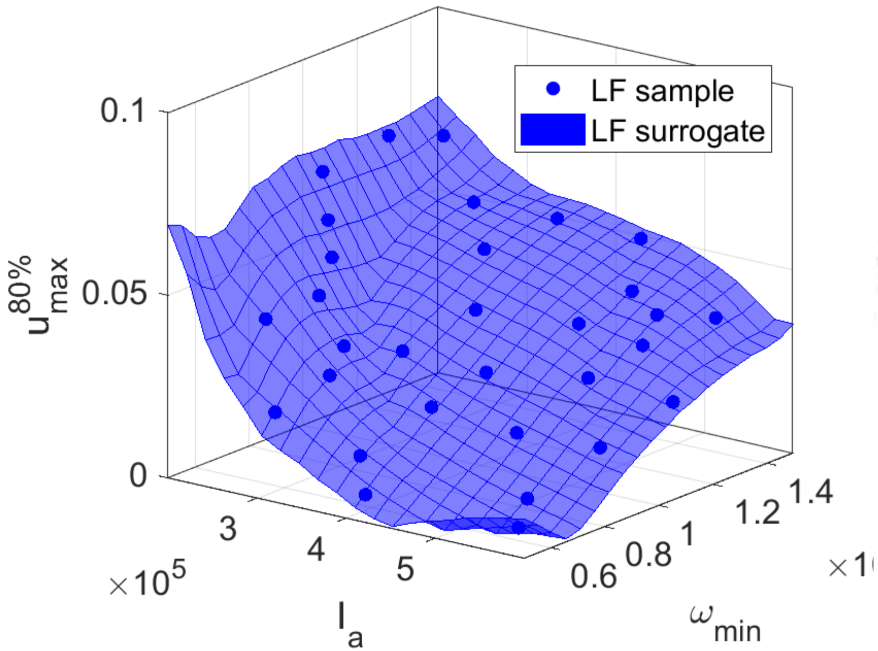
Variance decomposition

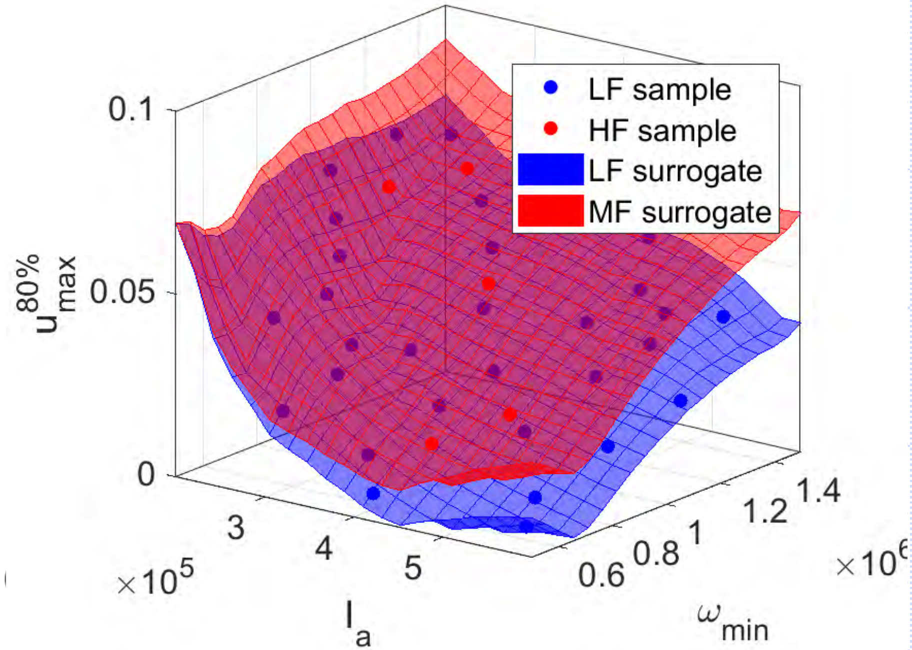
$$Var[\mathcal{M}^{PC}(\boldsymbol{x})] = Var[\mathcal{M}_0^{PC}] + Var[\mathcal{M}_1^{PC}(x_1)] \ldots + Var[\mathcal{M}_2^{PC}(x_2)] + Var[\mathcal{M}_{12}^{PC}(x_1, x_2)]$$

$$S_1^T = \frac{Var[\mathcal{M}_1^{PC}(x_1)] + Var[\mathcal{M}_{12}^{PC}(x_1, x_2)]}{Var[\mathcal{M}^{PC}(\boldsymbol{x})]} \qquad S_1 = \frac{Var[\mathcal{M}_1^{PC}(x_1)]}{Var[\mathcal{M}^{PC}(\boldsymbol{x})]}$$

2e2 parameter samples x 2e2 noise realizations = 4e4 simulation of the LF model (cost of a simulation = 30s)

Multi-Fidelity Surrogate of the Piping-Tank System Response





Multivariate Gaussian (joint) distribution:

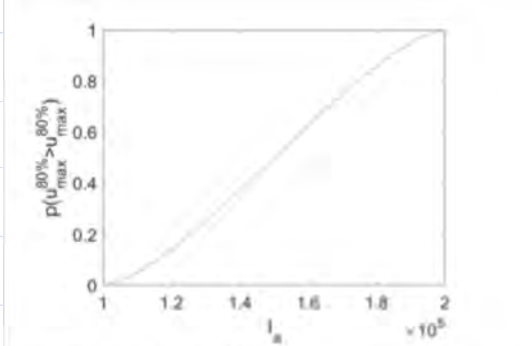
$$\begin{bmatrix} Y^* \\ \boldsymbol{Y} \end{bmatrix} \sim \mathcal{N}_{N+1}\left(\begin{bmatrix} \mu^*(X^*) \\ \boldsymbol{\mu}(\boldsymbol{X}) \end{bmatrix}, \begin{bmatrix} \Sigma^{**}(X^*,X^*) & \boldsymbol{\Sigma}^*(X^*,\boldsymbol{X}) \\ \boldsymbol{\Sigma}^*(\boldsymbol{X},X^*) & \boldsymbol{\Sigma}(\boldsymbol{X},\boldsymbol{X}) \end{bmatrix}\right)$$

Y^* = predicted response at X^*

$\boldsymbol{Y}$ = observed response at $\boldsymbol{X}$

$\boldsymbol{\mu}$ = mean vector (trend)

$\boldsymbol{\Sigma}$ = covariance matrix



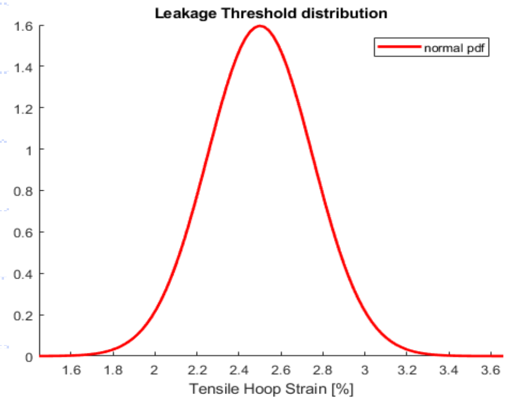
$$p(u_{max}^{80\%} > \bar{u}_{max}^{80\%}|I_a) = \int \mathbb{1}_{u_{max}^{80\%} > \bar{u}_{max}^{80\%}} f(I_a, \omega_{min}) d\omega_{min}$$

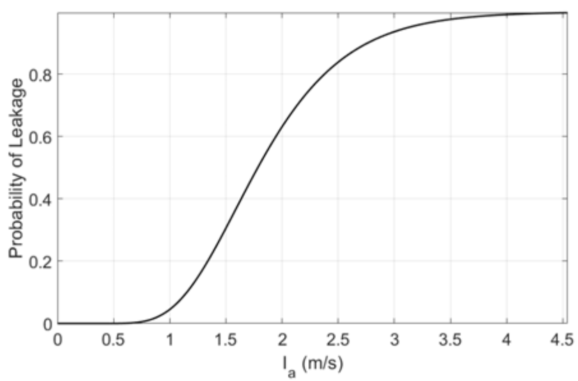
Multi-Fidelity Surrogate of the Piping-Tank System Response - Hierarchical Kriging to the Loss of Containement (LoC)

$$y = \mathcal{M}(x) \approx \beta^T f(x) + \sigma_y^2 Z(x, \omega)$$

$$elbow\ strain\ intensity = \widehat{\mathcal{M}}_{MF}(I_a, \omega_{mid}, \zeta)$$

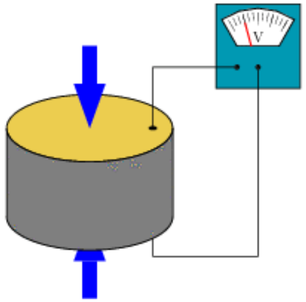
$$P(LoC) = \int_{I_a} P(D > C_{LS} | IM = I_a) |\lambda(I_a) dI_a|$$



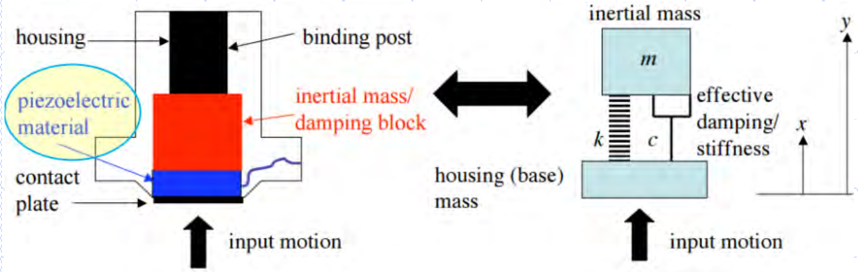


Development of Acoustic Emission Sensors

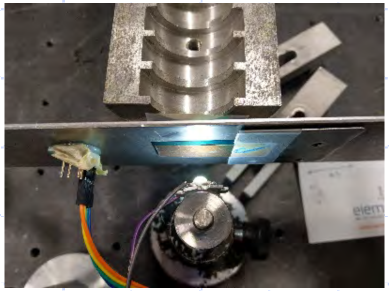
Traditional PZT Sensors

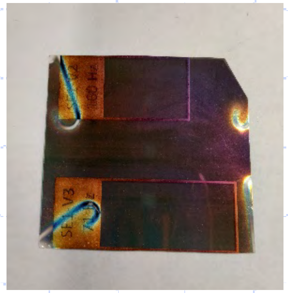


- Low cost
- Small size
- Easily fabricated
- Less sensitive to temperature variation,
- Low power consumption
- Not flexible (-)

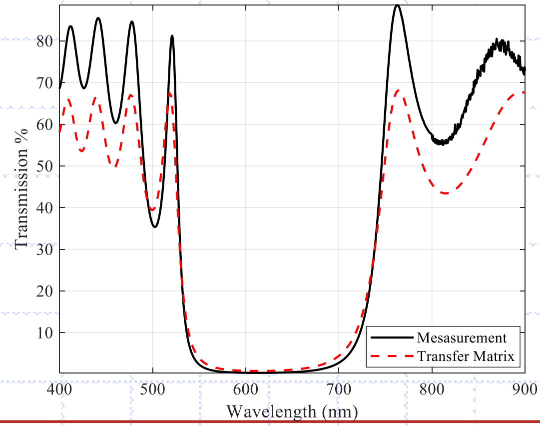


Optical Sensors (Under Development)

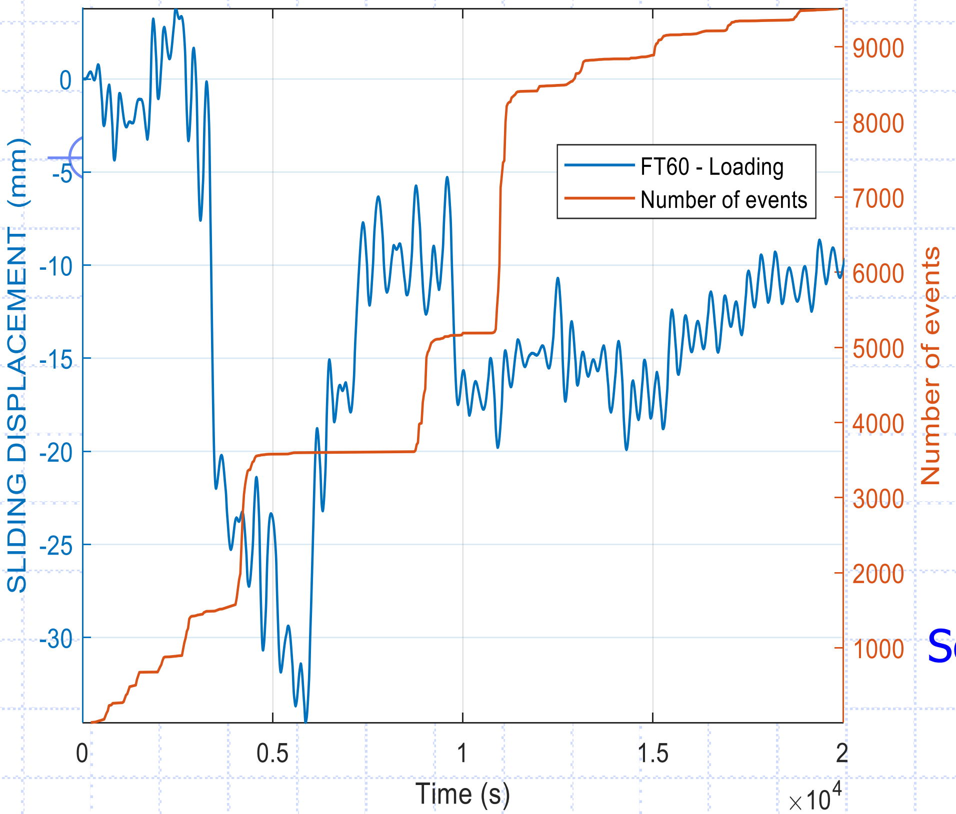


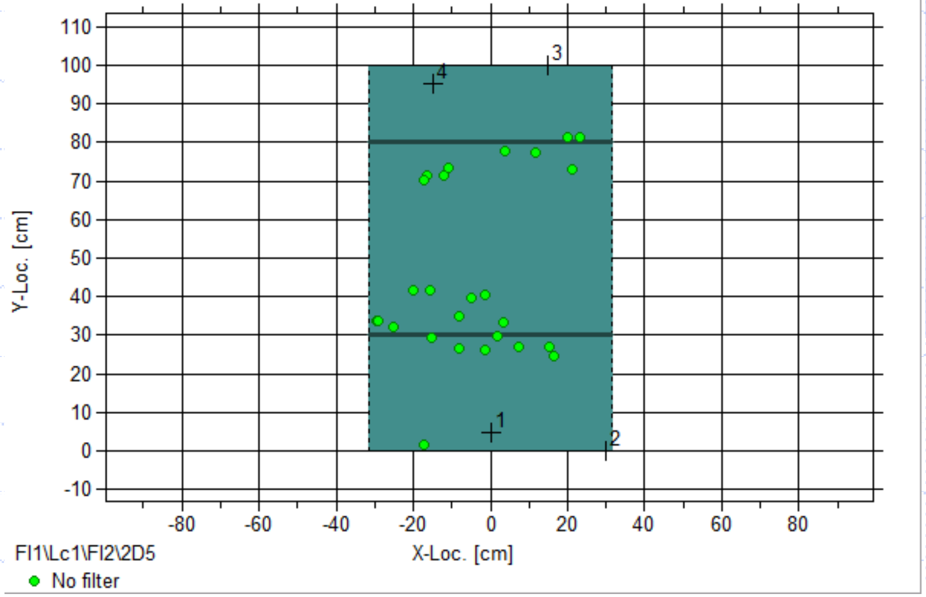


- Low cost
- Small size
- Immunity to Electromagnetic Interference
- Low power consumption

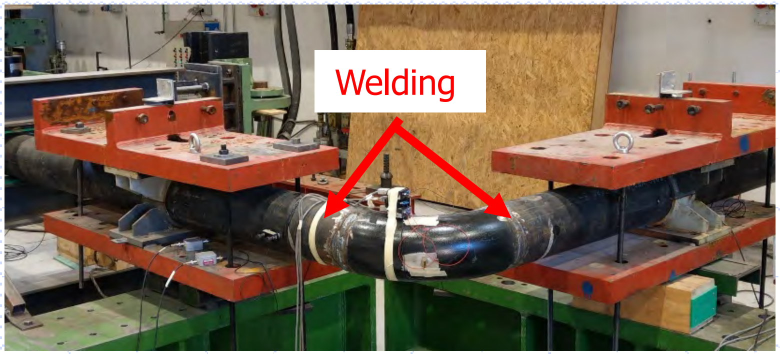


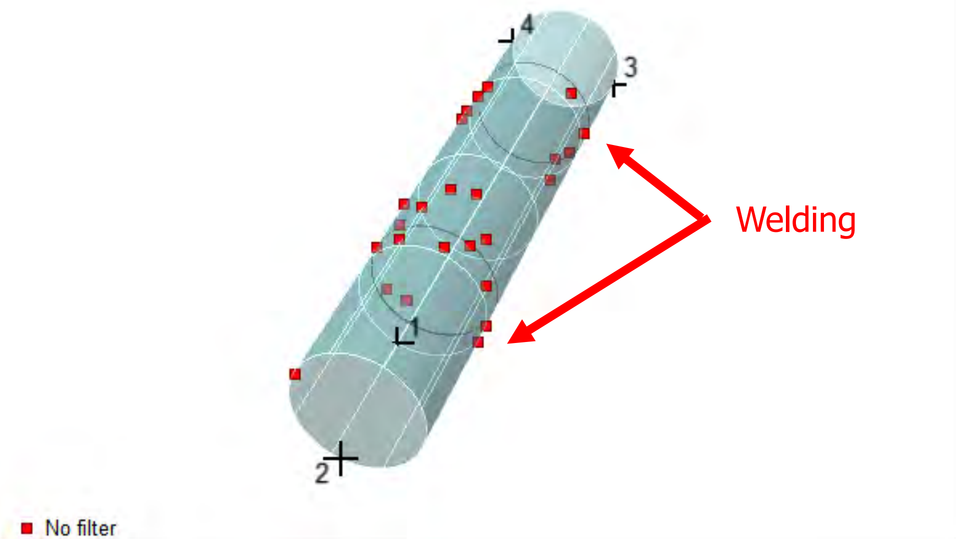
HDS at SLS



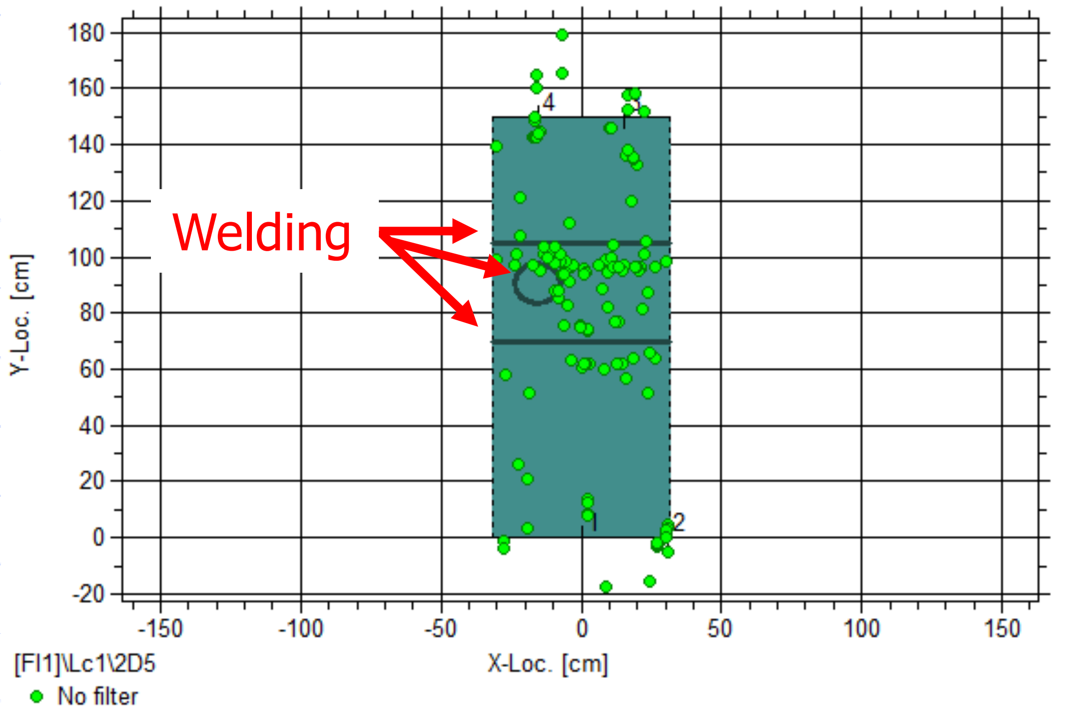


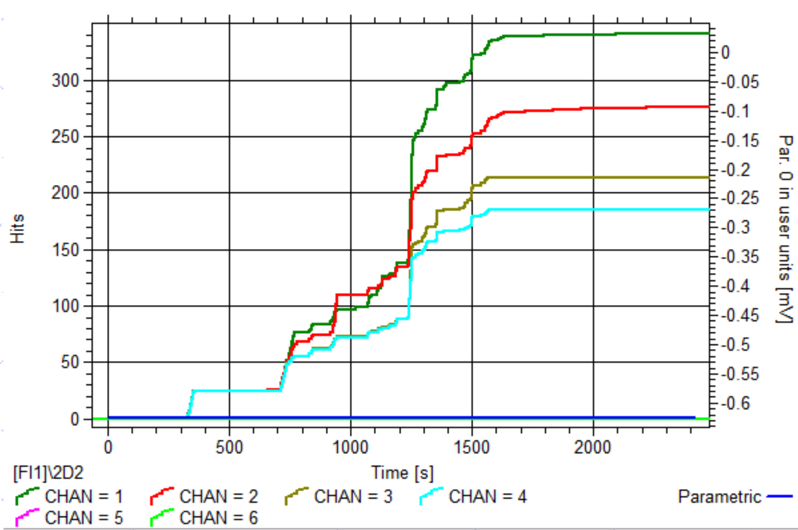
Serviceability Limit State (SLS) test ($u_{max} < 0.04m$)





HDS at SLS





Serviceability Limit State (SLS) test ($u_{max} < 0.04m$)

- Significant number of cracks are detected around the welded joints.

WP27/JRA-5 main Research Activities and achievements

Novel elements of the HS framework developed at the EUCENTRE TREES Lab

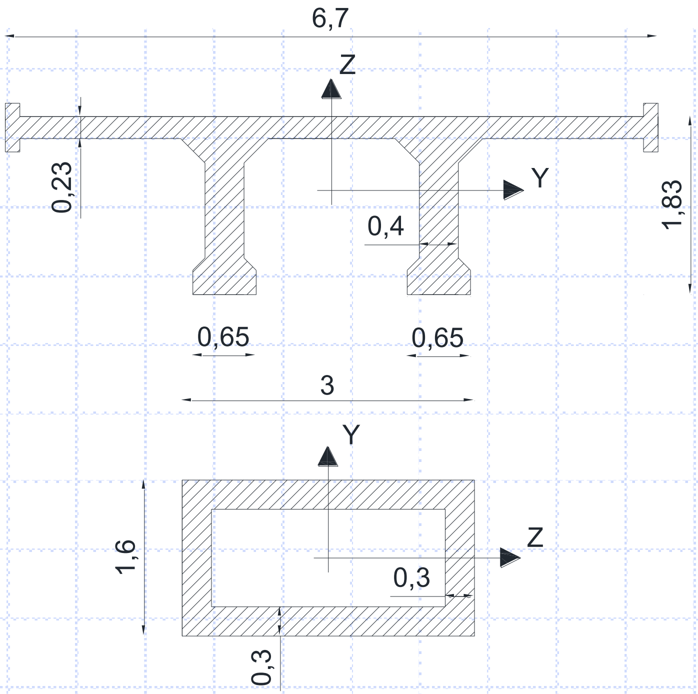
1. **Test facility – EUCENTRE TREES Lab - where different physical substructures (piers and isolators) can be decoupled and involved in real time (bearing tester)**

2. **A time integration algorithm cast in Hamiltonian form and endowed with superior capabilities in terms of coupling/decoupling and possible accommodation of System ID techniques**

3. **Online updating procedures for complex nonlinear Numerical Substructures**

4. **Modelling of different types of isolators**

G. Abbiati, I. Lanese, E. Cazzador, O. S. Bursi, and A. Pavese, A Computational Framework for Fast-Time Hybrid Simulation Based on Partitioned Time Integration and State-Space Modeling , Structural Control and Health monitoring, (in review), 2018.



Objectives of the STRIT/Reluis Project:

To prove the effectiveness of a **prototype of concave sliding bearing**;

To use an advanced **online model updating** technique based on Unscented Kalman Filter.

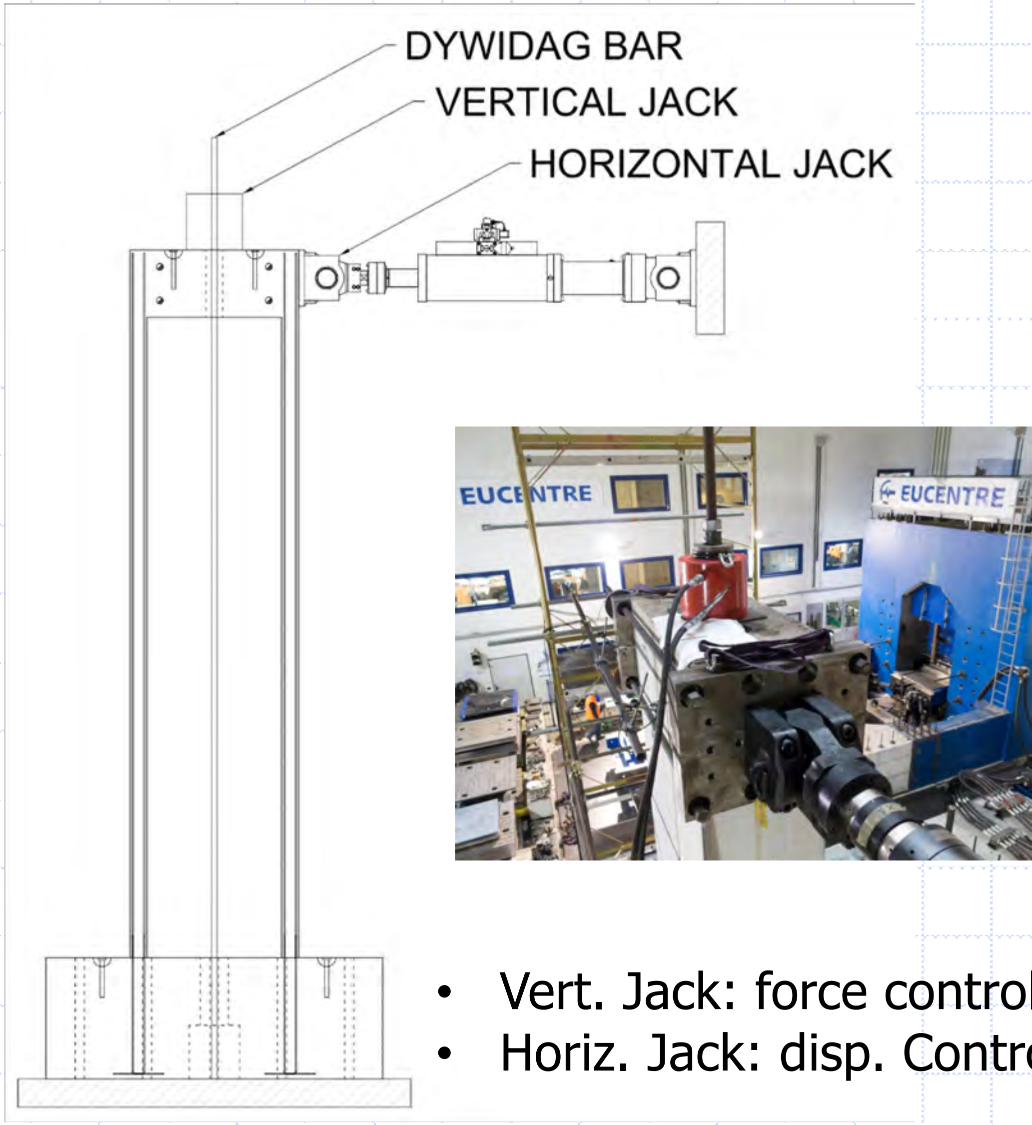
Definition and identification of the proper reduced models to simulate the numerical substructures;

Development of numerical models 2D/3D to predict and analyse the seismic response of the bridge.

Case Study

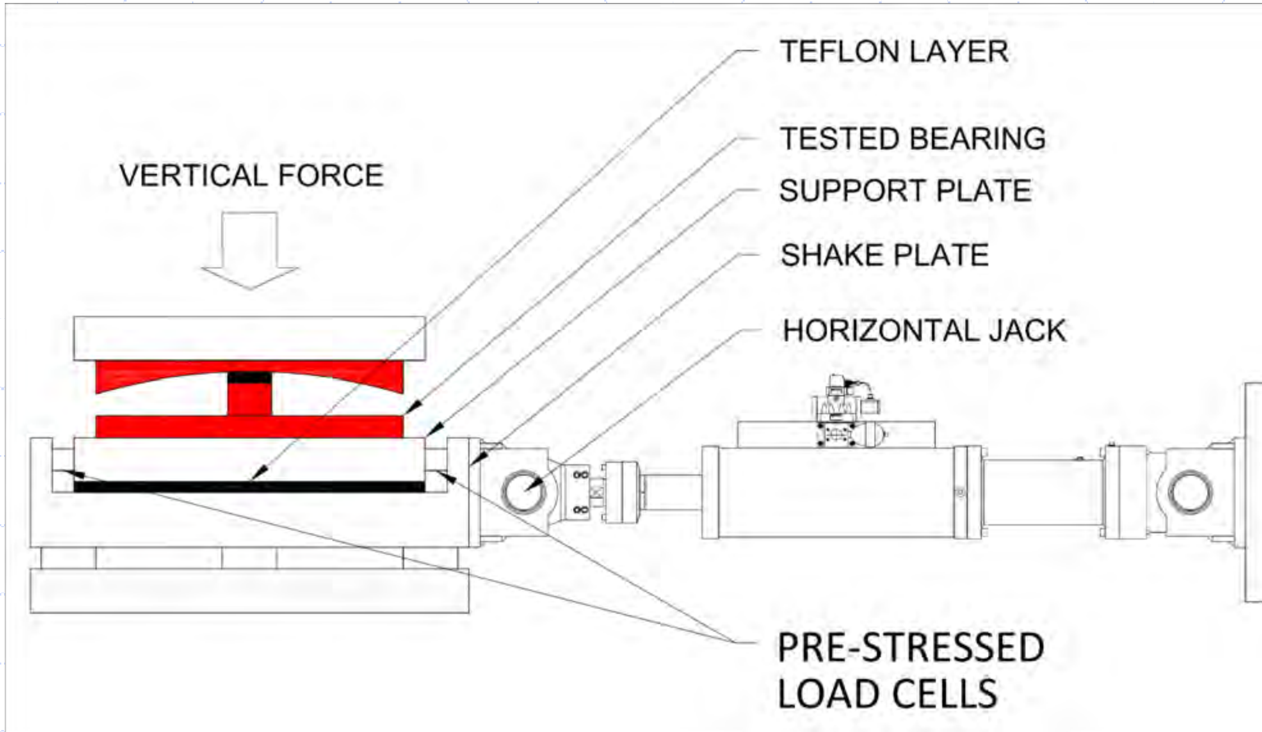
- Total length = 135 m
- Single span = 45 m
- Piers height = 12.6 m
- Cantilever box section pier
- Steel dowels between pier cap and deck
- Seismic site Naples

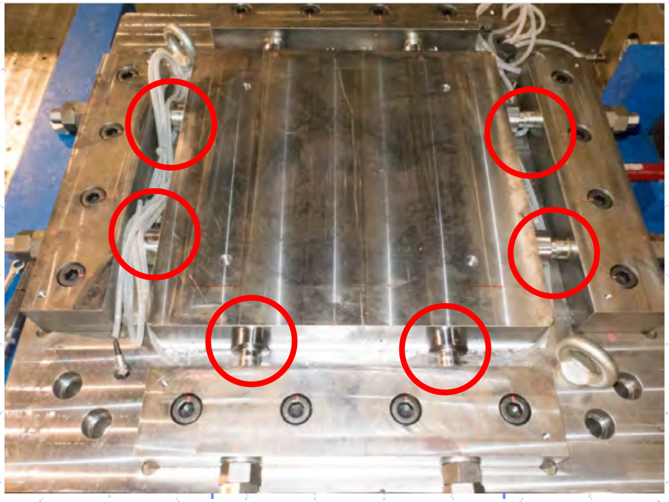
EUCENTRE TREES Lab: pier setup

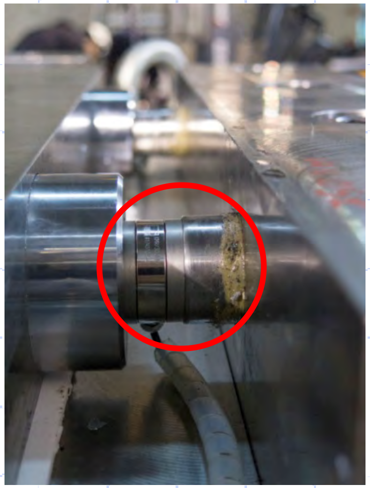


- Vert. Jack: force control
- Horiz. Jack: disp. Control

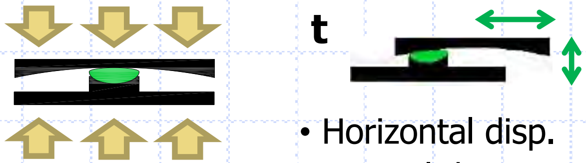
EUCENTRE TREES Lab: bearing testing system





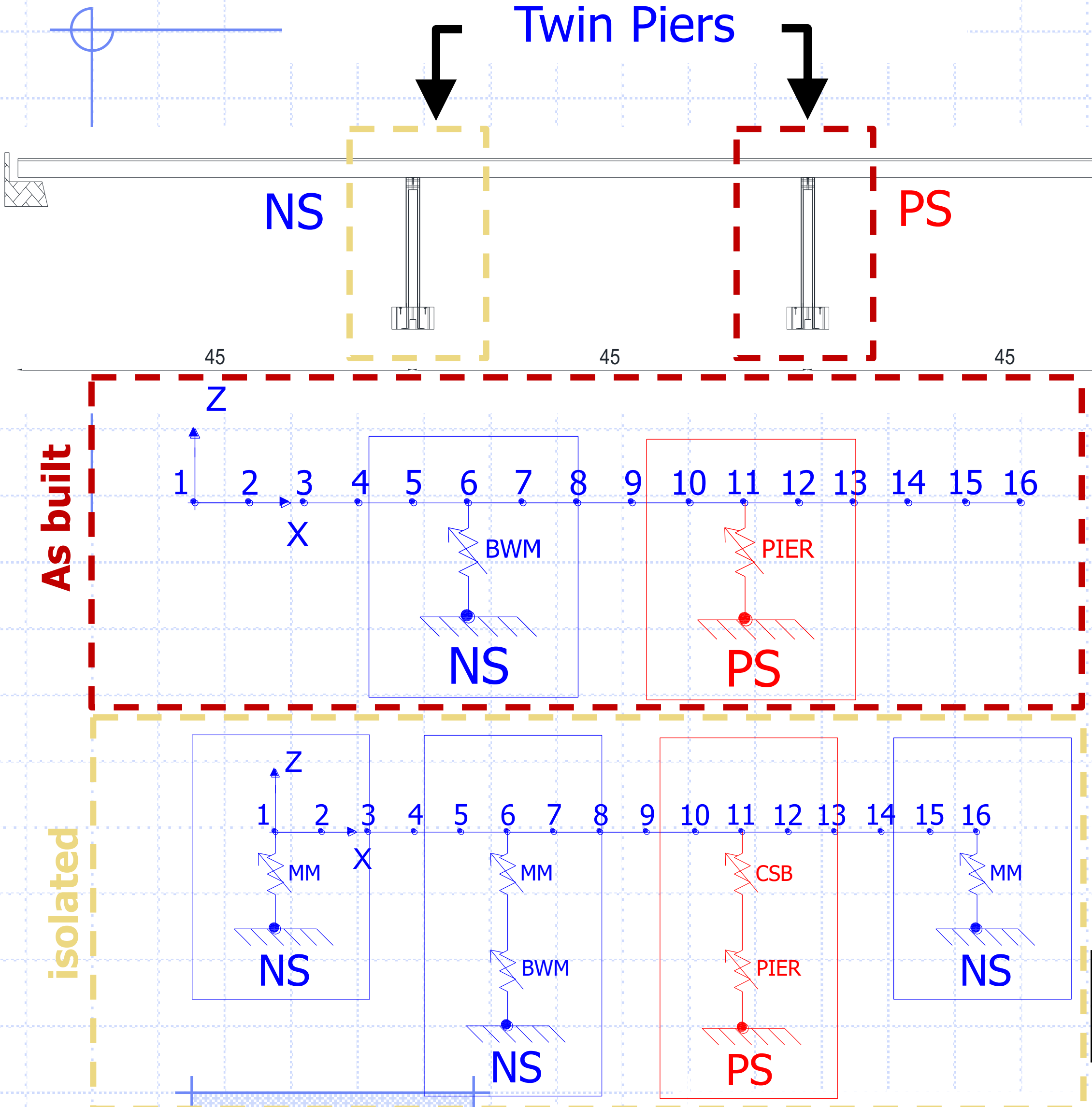


Boundary conditions



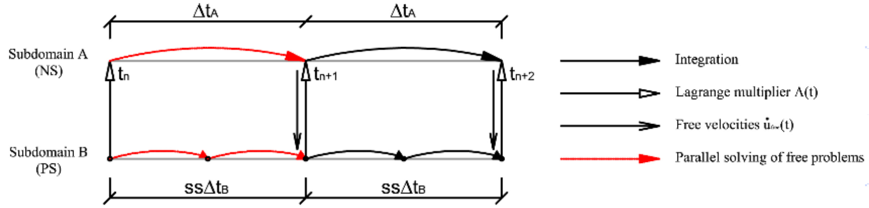
Force	Displacement
• Vertical load	• Horizontal disp. • Vertical disp. • No rotation

STEP II: DESIGN AND EXECUTION OF HS



Substructures	Scale
Pier	1:2
Prototype CSB	1:1

- Piers and CSBs were **reduced to a S-DoF springs**;
- **Model updating online** based on a Unscented Kalman Filter;
- **Partitioned time integration algorithm** Modified PH method.



λ	ss	Δt_N	Δt_P	Δt
128-256	128-256	ss·1msec	1msec	1 msec

Monolithic Generalized-α time stepping scheme used as a basis

$$\mathbf{M}\dot{\mathbf{y}}_{n+\alpha_m} + \mathbf{K}\mathbf{y}_{n+\alpha_n} = \mathbf{F}_{n+\alpha_n}$$

$$\Downarrow$$

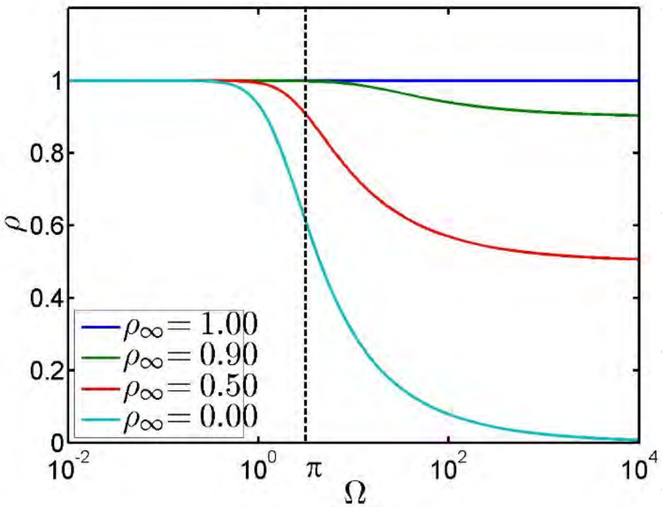
$$\mathbf{v}_n = \dot{\mathbf{y}}_n + O\left(\Delta_t^2\right)$$

$$\Downarrow$$

$$\begin{cases} \mathbf{y}_{n+1} = \mathbf{y}_n + \mathbf{v}_n \Delta t \left(1-\gamma\right) + \mathbf{v}_{n+1}\Delta t \gamma \\ \mathbf{v}_n\left(1-\alpha_m\right) + \mathbf{v}_{n+1}\left(\alpha_m\right) = \dot{\mathbf{y}}_n\left(1-\alpha_f\right) + \dot{\mathbf{y}}_{n+1}\left(\alpha_f\right) \end{cases}$$

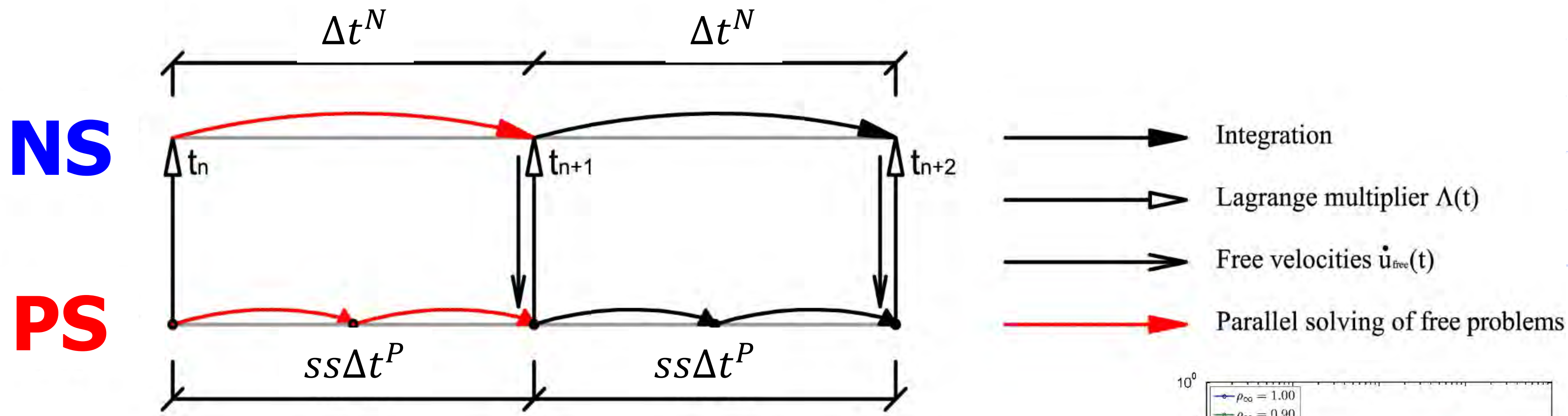
$$\Downarrow$$

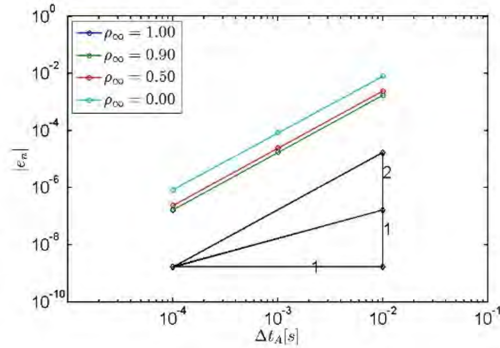
$$\mathbf{M}\dot{\mathbf{y}}_{n+1} + \mathbf{K}\mathbf{y}_{n+1} = \mathbf{F}_{n+1}$$



$$\mathbf{M} = \begin{bmatrix} \mathbf{i} & \mathbf{0} \\ \mathbf{0} & \mathbf{m} \end{bmatrix},\ \mathbf{K} = \begin{bmatrix} \mathbf{0} & -\mathbf{i} \\ \mathbf{k} & \mathbf{c} \end{bmatrix},\ \mathbf{y}_n = \begin{Bmatrix} \mathbf{u}_n \\ \dot{\mathbf{u}}_n \end{Bmatrix},\ \mathbf{F}_n = \begin{Bmatrix} \mathbf{0} \\ \mathbf{f}_n \end{Bmatrix}$$

The parallel partitioned G- α time integration scheme





With subcycling (ss = 10)

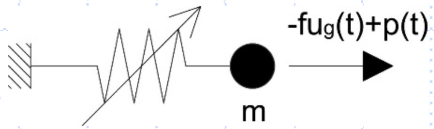
$$
\begin{cases}
\mathbf{M}^N \dot{\mathbf{Y}}^N_{n+1} + \mathbf{G}^N\left(\mathbf{Y}^N_{n+1}\right) + \mathbf{L}^N \mathbf{\Lambda}_{n+1} = \mathbf{F}^N_{n+1} \\
\mathbf{M}^P \dot{\mathbf{Y}}^P_{n+j/ss} + \mathbf{G}^P\left(\mathbf{Y}^P_{n+j/ss}\right) + \mathbf{L}^P \mathbf{\Lambda}_{n+j/ss} = \mathbf{F}^N_{n+j/ss} \\
\mathbf{B}^N \dot{\mathbf{Y}}^N_{n+1} + \mathbf{B}^P \dot{\mathbf{Y}}^P_{n+1} = \mathbf{0}
\end{cases}
$$

- $\mathbf{L}^k, \mathbf{B}^k$: Boolean matrices
- $\frac{\partial \mathbf{G}^N}{\partial \mathbf{Y}^N}, \frac{\partial \mathbf{G}^P}{\partial \mathbf{Y}^P}$: Automatic differentiation

STEP II

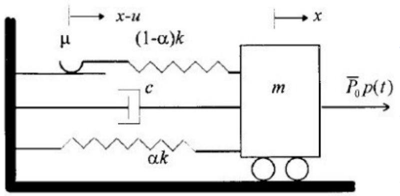
Reduced S-DoF models

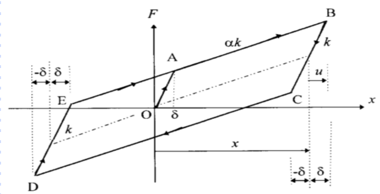
Pier S-Dof – Bouc-Wen model



$$\begin{cases} r + c\dot{x} + m\ddot{x} = -f\ddot{u}_g(t) + p(t) \\ \dot{r} = [A - (\beta \cdot sign(\dot{x}r) + \gamma)|r|^n]\dot{x} \end{cases}$$

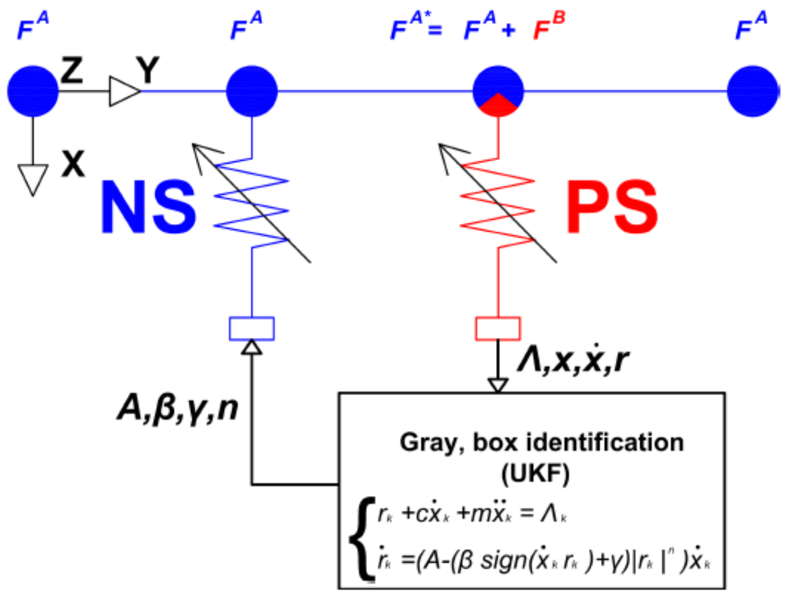
CSB S-Dof – Bilinear hysteretic model



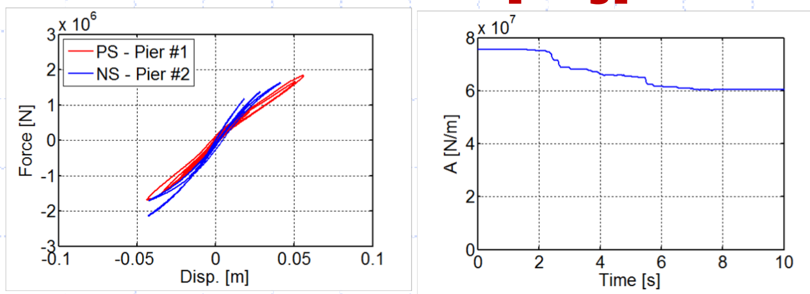


$$\begin{cases} m\ddot{x} + c\dot{x} + \alpha kx + (1-\alpha)ku = p(t) \\ \dot{u} = \dot{x}(\bar{N}(\dot{x})\bar{M}(u-\delta) + M(\dot{x})N(u+\delta)) \end{cases}$$

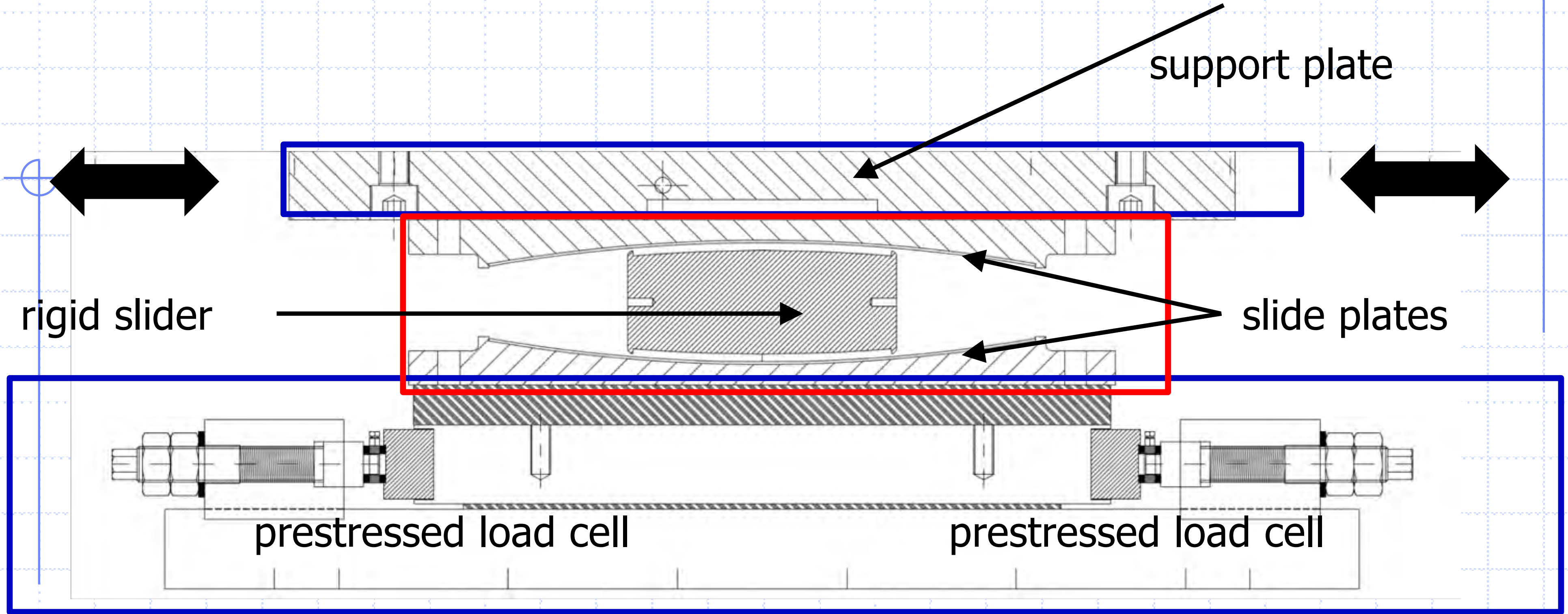
In order to take into account the degradation of piers, an online model updating method was implemented. The method was based on the Unscented Kalman Filter and the parameter updated was the stiffness A.



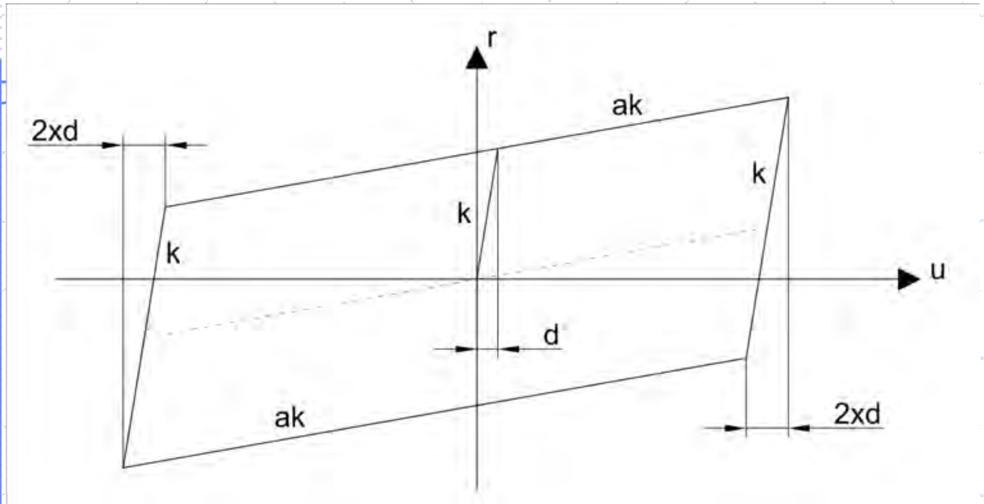
Test HE 60 [0.5g]

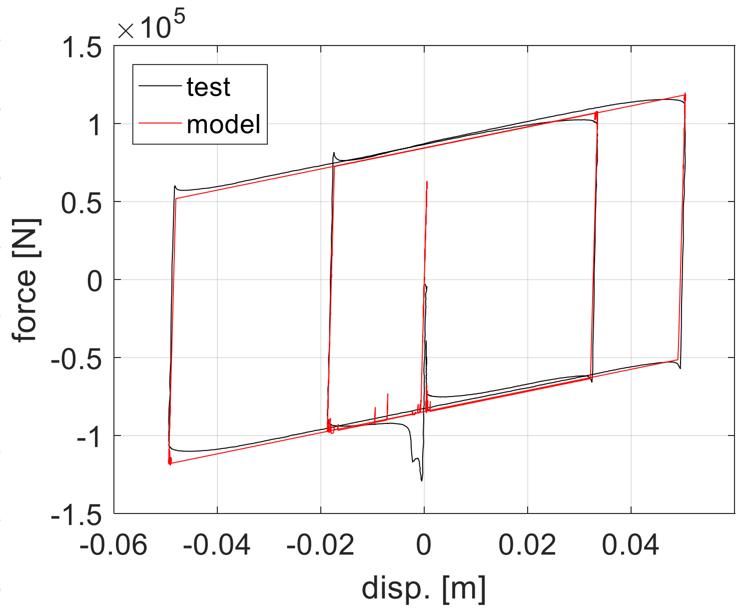


Double-surface concave sliding bearing



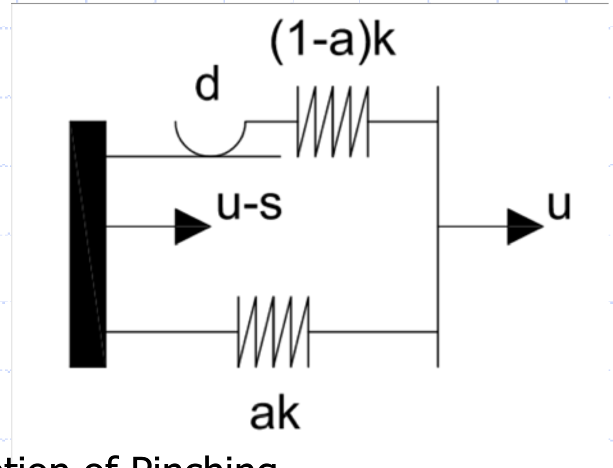
Double-surface concave sliding bearing





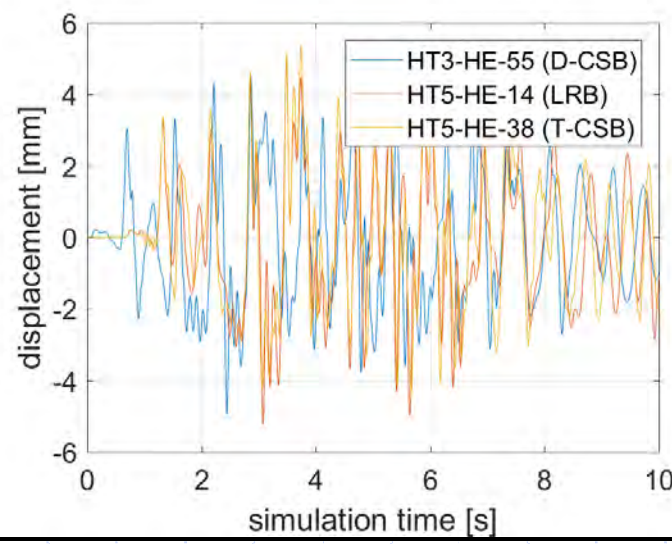
$$\begin{cases} \dot{r} = \left(\alpha k + (1-\alpha)k\left(\bar{N}(v)\bar{M}(s-\delta) + M(v)N(s+\delta)\right)\right) v \\ \dot{u} = v \end{cases}$$

$$\begin{cases} N(w) = 0.5\left(1 + sgn(w)\right)\left(1 + \left(1 - sgn(w)\right)\right) \\ M(w) = 1 - N(w) \\ \bar{N}(w) = M(-w) \\ \bar{M}(w) = N(-w) \end{cases}$$

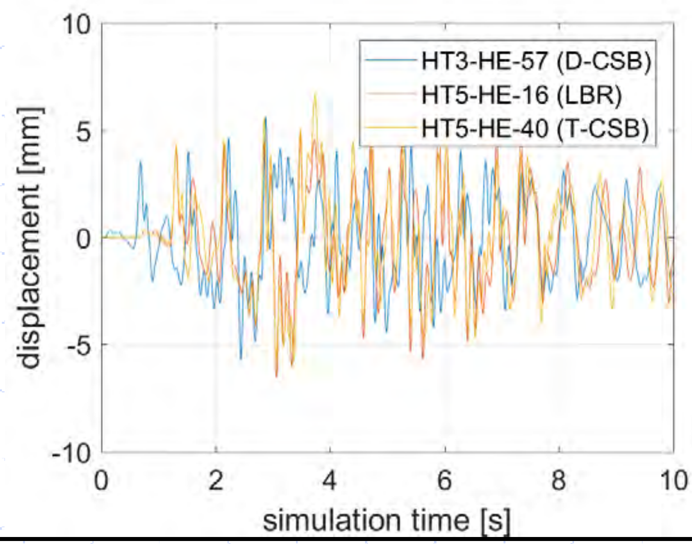


Mostaghel, N. (1999). Analytical Description of Pinching, Degrading Hysteretic Systems. Journal of Engineering Mechanics, 125(2), 216–224.

HS with isolators

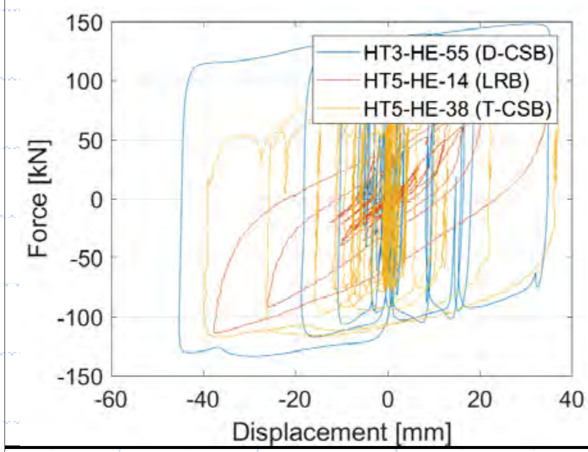


a

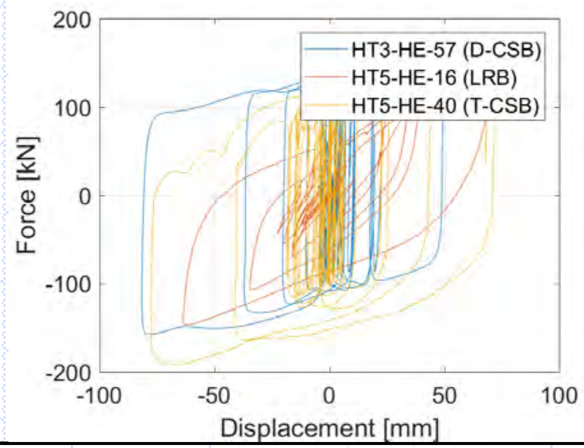


b

Displacement response history of the numerical Pier #2 in the isolated configuration: a) PGA = 0.30g; b) PGA=0.50g.



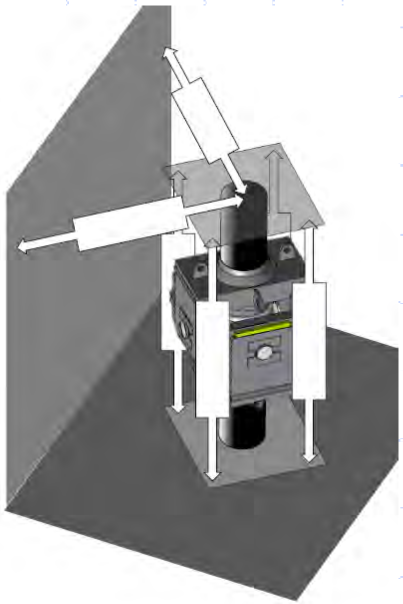
a



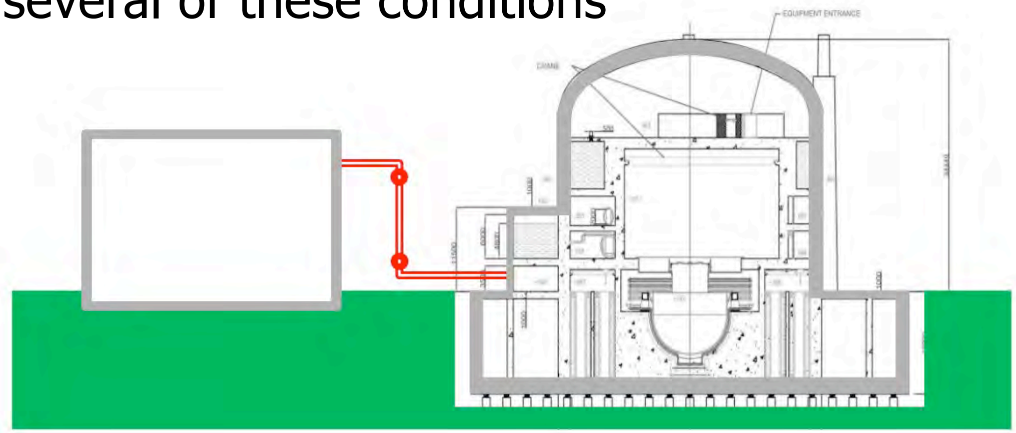
b

Hysteretic loops of isolator devices at: a) PGA = 0.35g; b) PGA=0.50g.

WP27/JRA-5 main Research Activities and achievements



Difficulties may still typically arise when testing structures at relatively high testing speed, with stiff modes, with a large number of DoFs, with a very high requested accuracy or a combination of several of these conditions

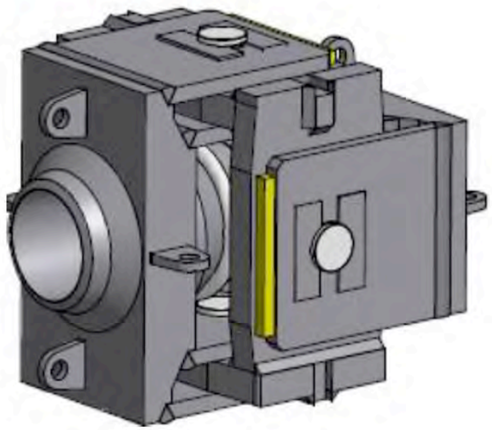


Joint design and manufacturing

Pressure: 200 bar
Temperature: 450ºC
Number of cycles: 1000

Material:
- Inconel (bellow)
- A193 B7 (Pins)
- 1.7335 steel (structure)

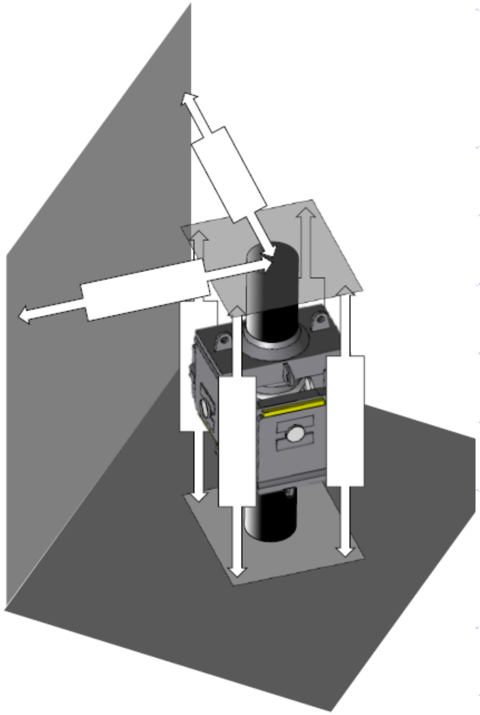
LxHxW: 1.4m x 1.1m x 1.1m
Mass: 4622 kg
Angular movement: 3º

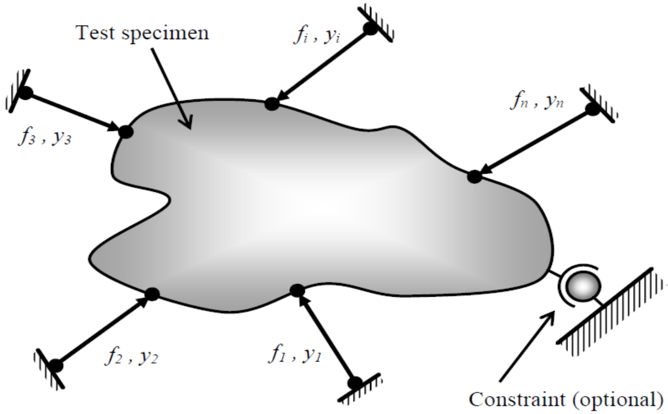


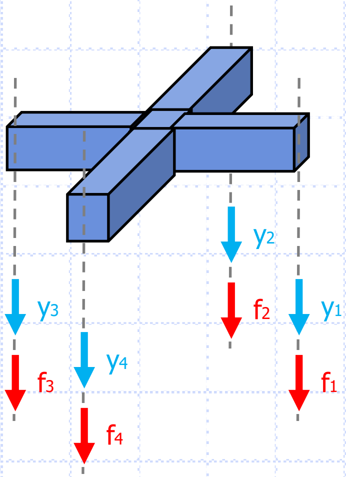
T5.2: Piping and pipe joints crossing the seismic gap

SILER Setup @JRC

Test setup at ELSA JRC

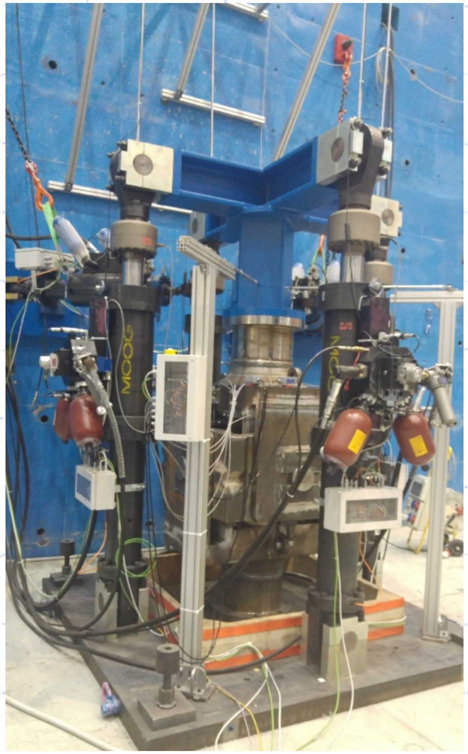


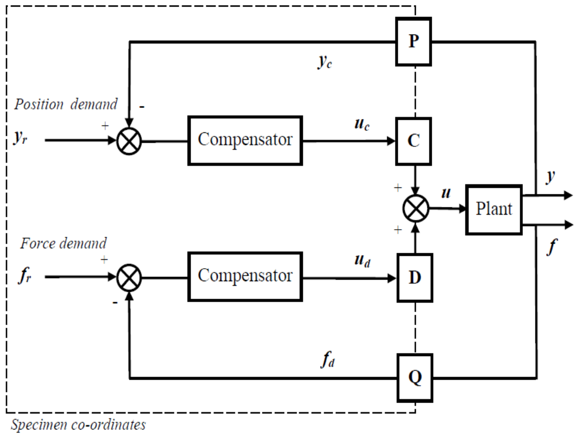




Vertical actuators

$$u = C\, u_c + D\, u_d$$





Rigid-body displacements

Actuator displacements

$y_c = Py$

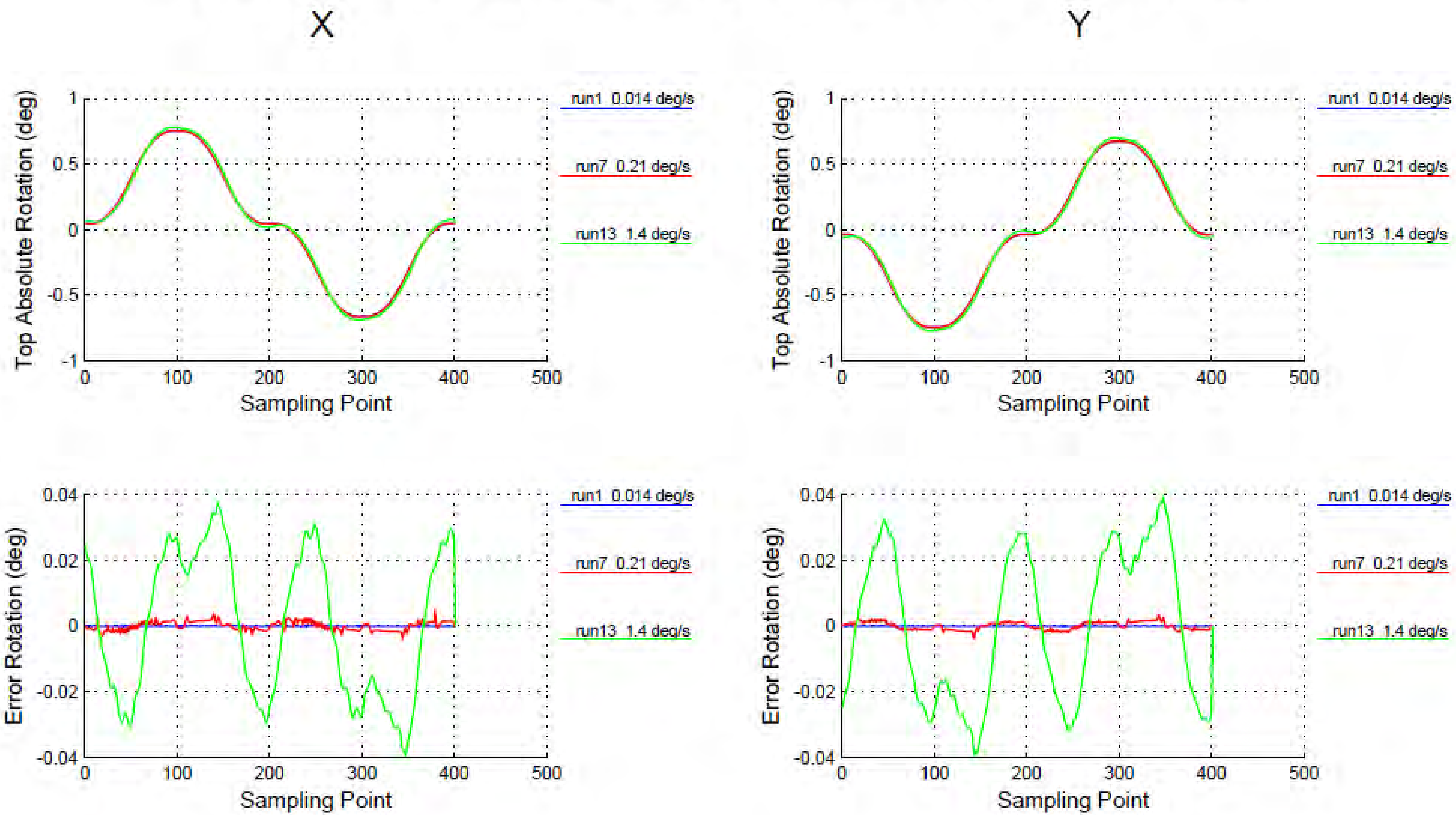
Deforming modes (in force)

Actuator forces

$f_d = Qf$

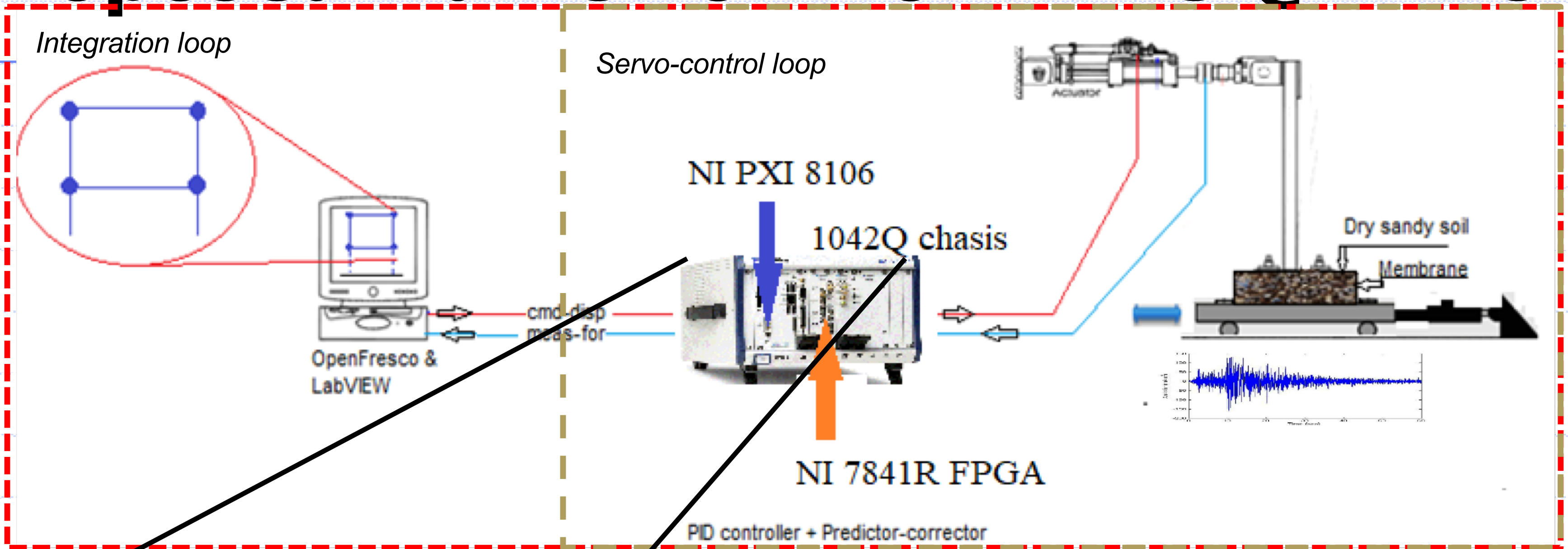
Plummer, A. R., (2010) A general co-ordinate transformation framework for multi-axis motion control with applications in the testing industry. Control Engineering Practice, 18, 598–607.

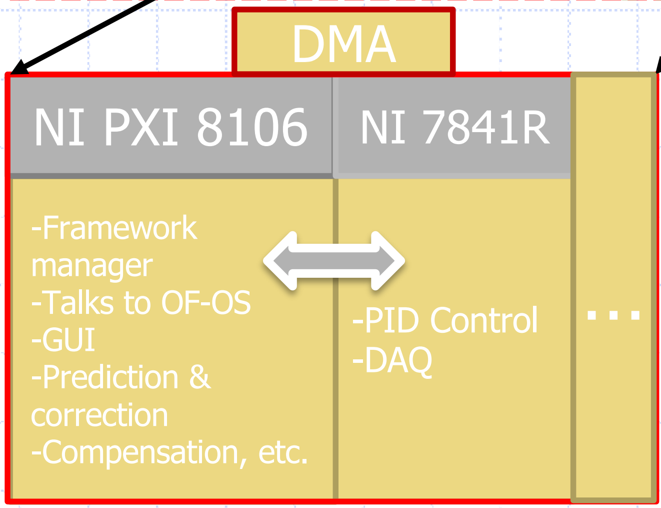
SILER ELSA [DN400 gimbal] (82: Controller Derived)
c29: X-Y Charact. Several speeds Cyclic 1 deg, 180 bar 10/12/2015



WP27/JRA-5 main Research Activities and achievements

Proposed framework for RTHS @LNEC



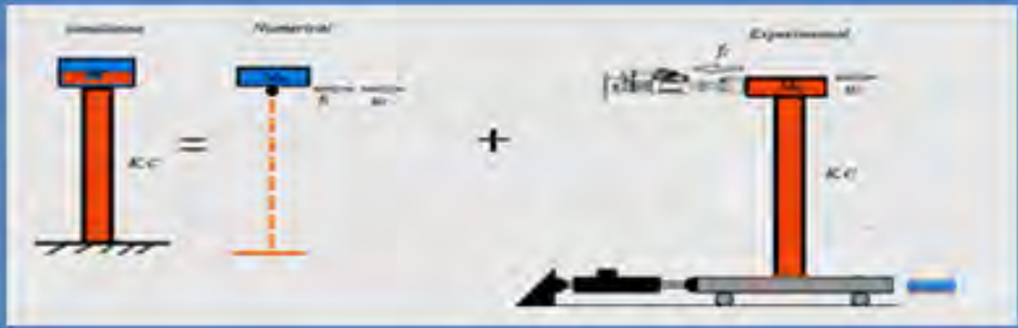


Includes:

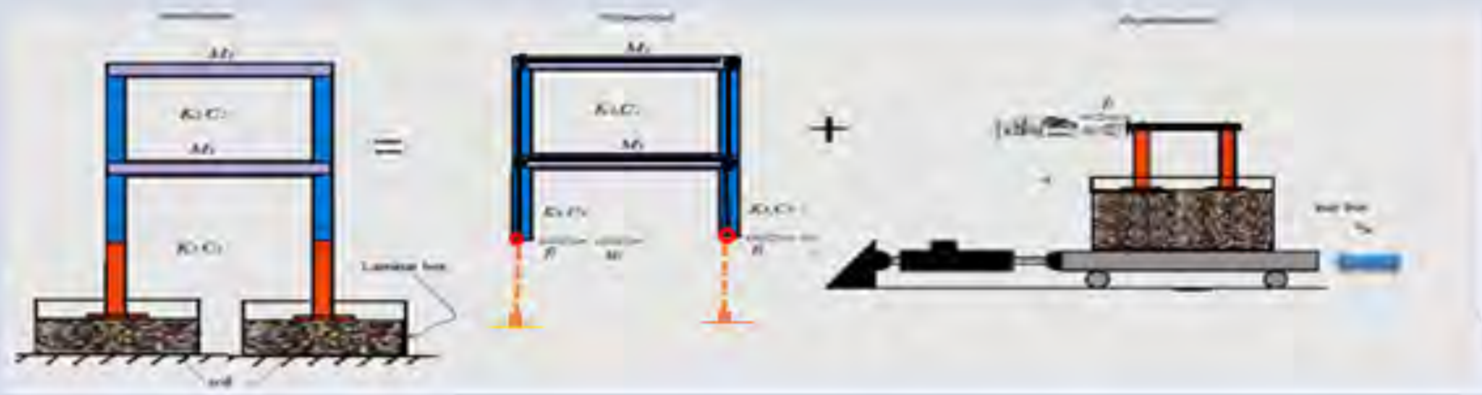
FEA software: OpenSees
Middleware: OpenFresco
Control class: ECLabVIEW
Target machine: NI RT + FPGA
Excitation: Actuator & ST1D
Control mode: Position for ST1D & position control augmented by force control for the actuator

Planned configurations of hybrid tests

5. Shake table + actuator at interface (displacement control) [λ=10-50/1-10]



6. SSI, near and/or at real-time (SSI real-time challenges and summary) [λ=1-10]



WP27/JRA-5
Main Transnational Access Activities favoured by JRA5

WP27/JRA-5
Main Transnational Access Activities

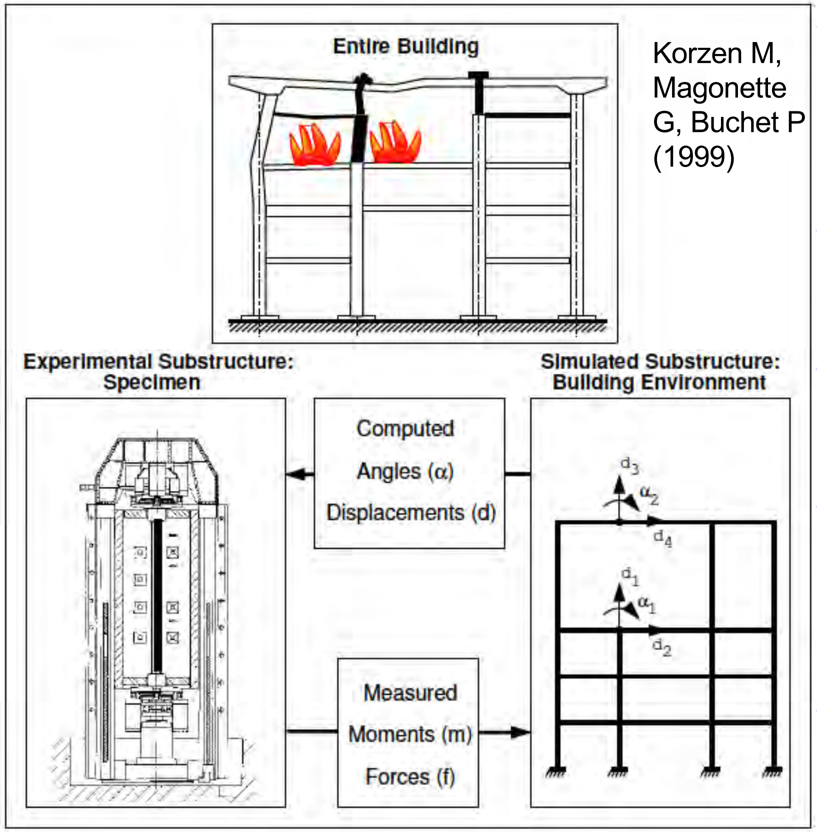
HYBRID FIRE TESTING (ACCESS TO JRC)

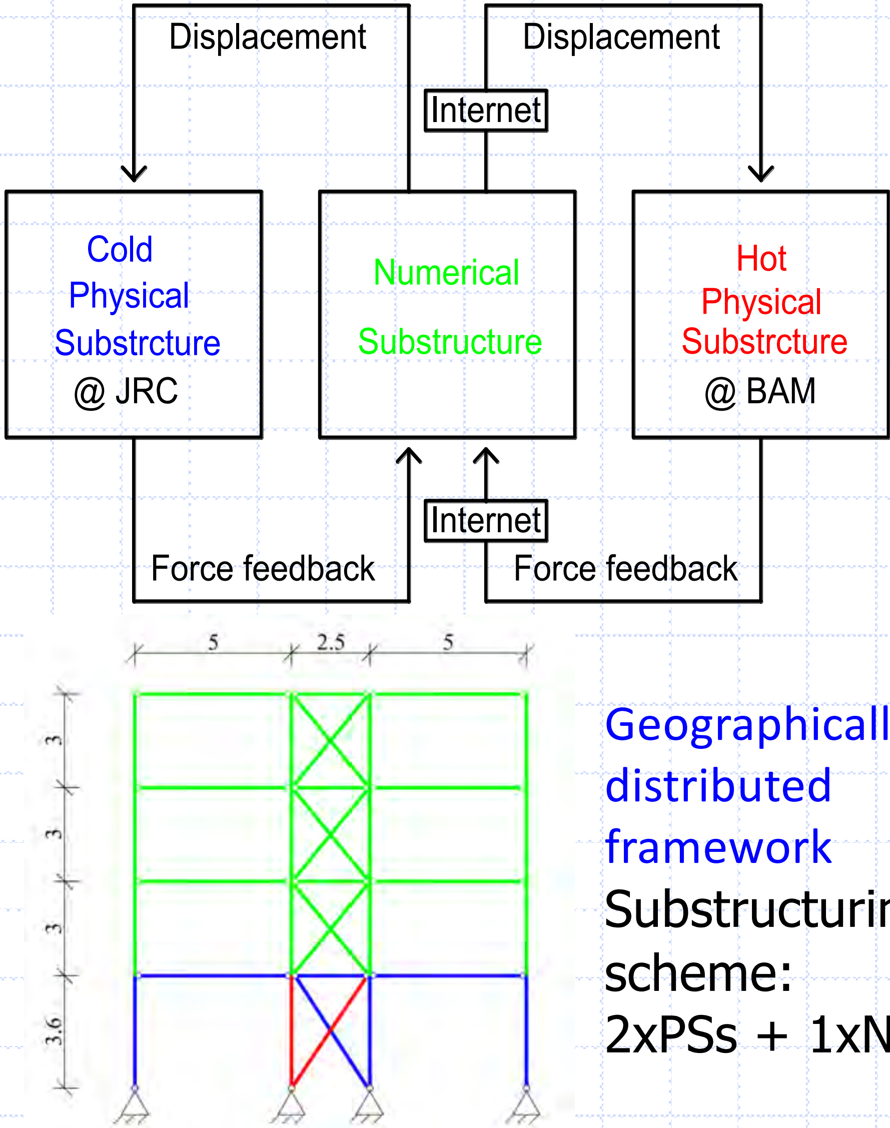
Multi-hazard performance assessment of structural and non-structural components subjected to seismic and fire following earthquake by means of geographically distributed testing (EQUFIRE)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

HYBRID FIRE TESTING (ACCESS TO JRC)

HYBRID FIRE TESTING: Fire development phase





Geographically distributed framework

Substructuring scheme: 2xPSs + 1xNS

$$\mathbf{r}_P(\mathbf{u}) + \mathbf{r}_N(\mathbf{u}) = \mathbf{f}_P + \mathbf{f}_N$$

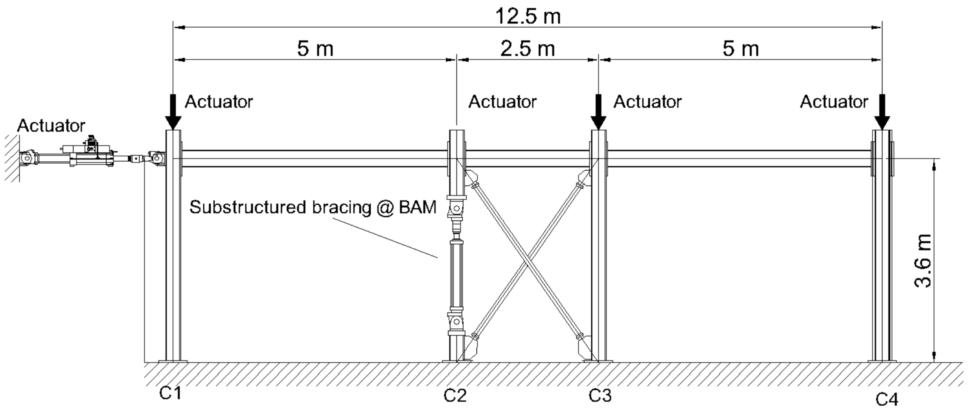
- duration of minutes/hours
- time dependent response (creep)
- static response

EXPERIMENTAL SETUP

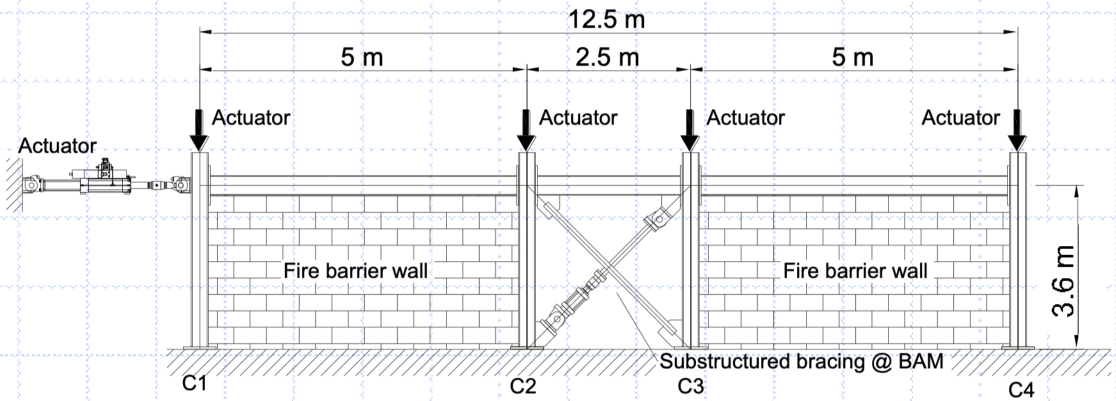
Four geographically distributed FFE hybrid tests will be carried out:

Test #1: unprotected lowly-damaged column
Test #2: fire protection system applied on a lowly-damaged column
Test #3: unprotected highly-damaged bracing component
Test #4: a fire protection system applied to a highly-damaged bracing component and fire wall

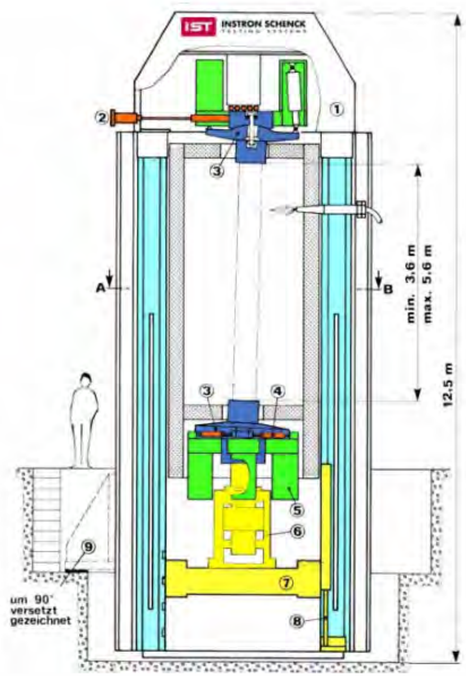
Test #1 - setup @ JRC



Test #4 - setup @ JRC

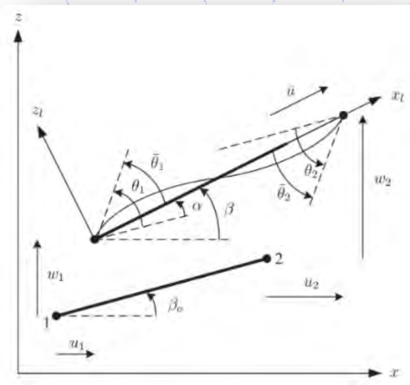


Furnace @ BAM

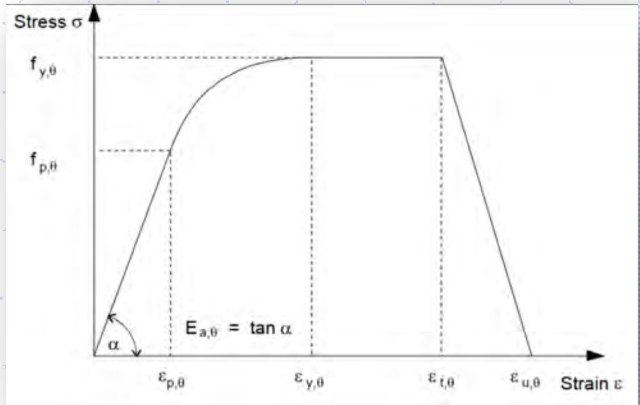


IMPLEMENTATION OF THE NONLINEAR THERMO-MECHANICAL BEAM FINITE ELEMENT

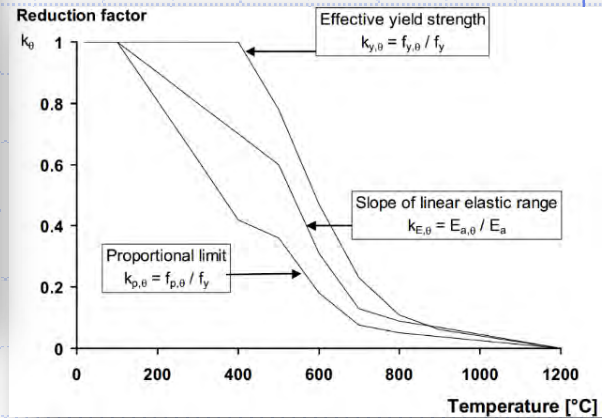
Geometric nonlinearity:
Corotational formulation



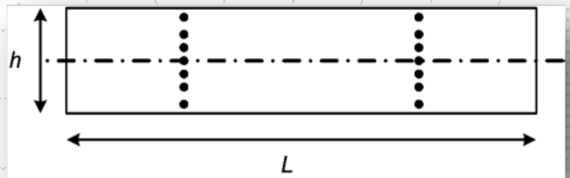
Material nonlinearity:
Stress-strain relationship for carbon steel at elevated temperatures

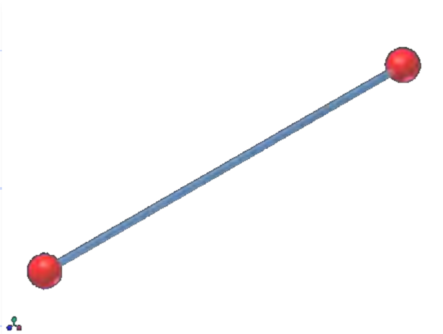


Degradation of mechanical properties at elevated temperatures



Numerical integration:
Gauss-Legendre quadrature

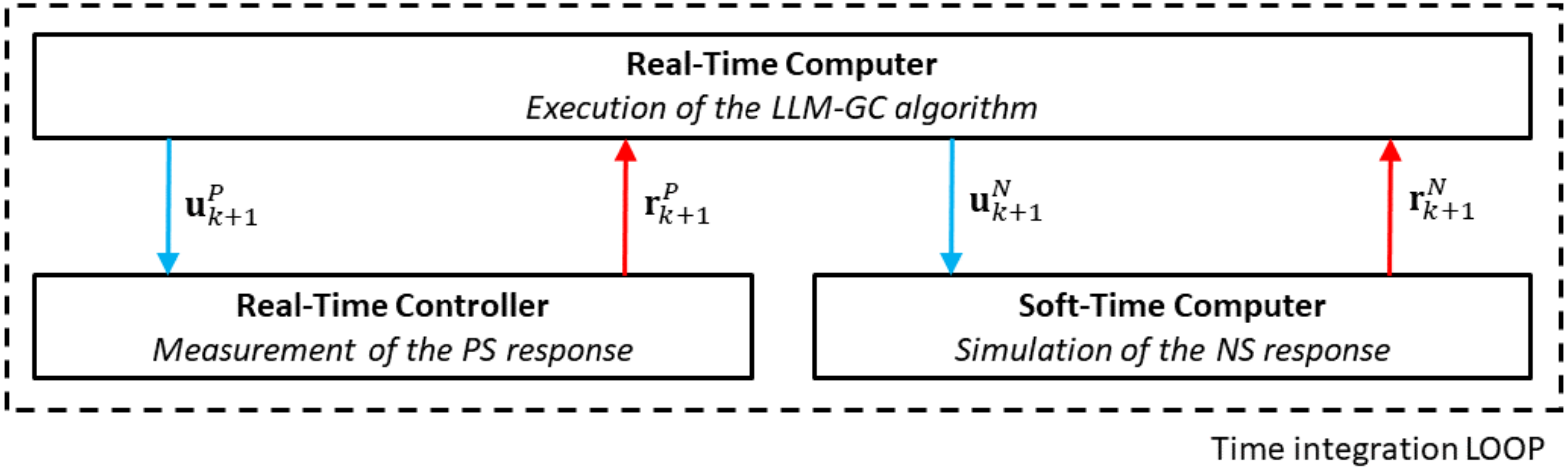




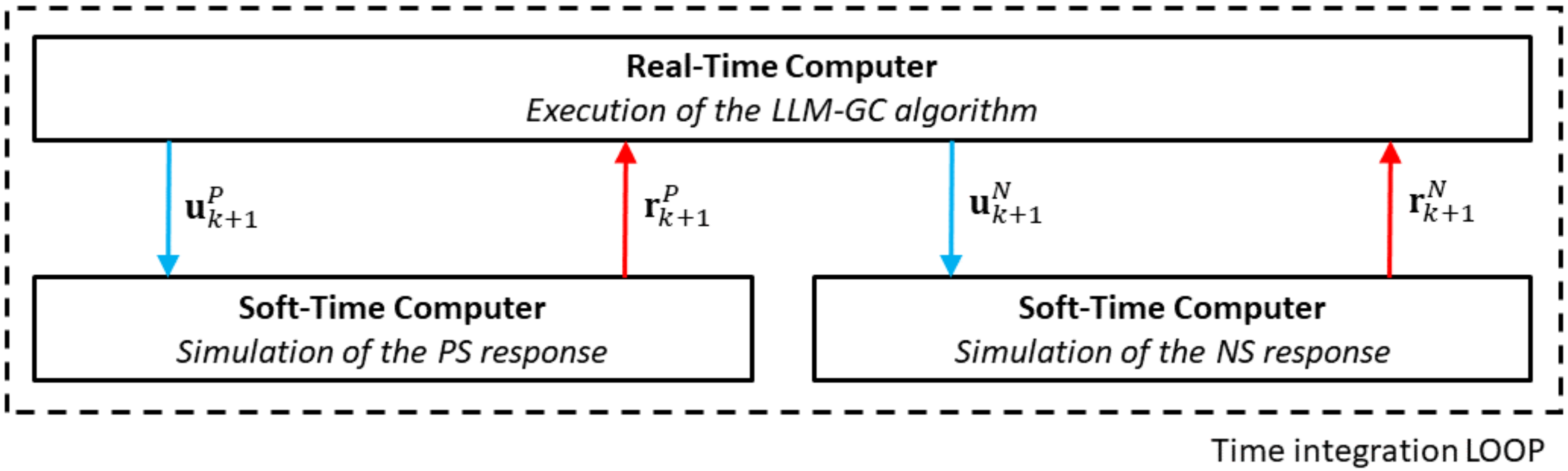
2D Nonlinear thermo-mechanical beam finite element

ARCHITECTURE OF THE HYBRID SIMULATION

Architecture of the HFT implementation of the LLM-GC algorithm

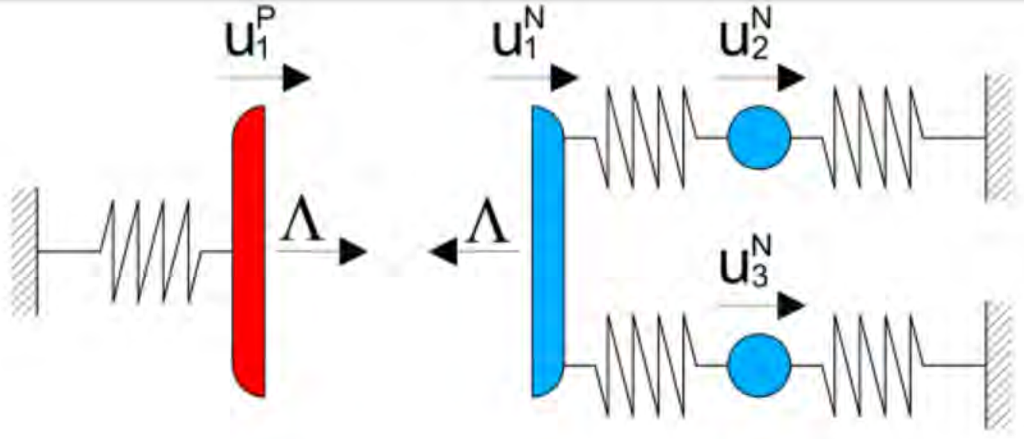


Architecture of the VIRTUAL HFT implementation of the LLM-GC algorithm



Abbiati G., Covi P., Tondini N., Bursi O.S, Stojadinović B."A Real-Time Hybrid Fire Simulation Method Based on Partitioned Time Integration, Computers & Structures (to be submitted)

Dynamics of structures during fire development



$$\begin{bmatrix}\mathbf{M}_{uu} & \mathbf{0}\\ \mathbf{0} & \mathbf{0}\end{bmatrix}\begin{bmatrix}\ddot{\mathbf{u}}\\ \ddot{\boldsymbol{\theta}}\end{bmatrix}+\begin{bmatrix}\boldsymbol{C}_{uu} & \mathbf{0}\\ \mathbf{0} & \mathbf{C}_{\theta\theta}\end{bmatrix}\begin{bmatrix}\dot{\mathbf{u}}\\ \dot{\boldsymbol{\theta}}\end{bmatrix}+\begin{bmatrix}\mathbf{K}_{uu} & \mathbf{K}_{u\theta}\\ \mathbf{0} & \mathbf{K}_{\theta\theta}\end{bmatrix}\begin{bmatrix}\mathbf{u}\\ \boldsymbol{\theta}\end{bmatrix}=\begin{bmatrix}\mathbf{f}_u(t)\\ \mathbf{f}_\theta(t)\end{bmatrix}$$

Linear thermoelastic system of EoM

$$\left(\mathbf{K}_{uu}+\omega_i^2\mathbf{M}_{uu}\right)\boldsymbol{\Phi}_i=\mathbf{0}$$

$$\mathbf{u}(t)\approx\mathbf{K}_{uu}^{-1}(\mathbf{f}_u(t)-\mathbf{K}_{u\theta}\boldsymbol{\theta}(t))$$

Quasi-static problem

$$\left(\mathbf{K}_{\theta\theta}+\lambda_j\mathbf{C}_{\theta\theta}\right)\boldsymbol{\Psi}_j=\mathbf{0}$$

$$\mathbf{r}(\mathbf{u})=\mathbf{f}(t)$$

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{C}\dot{\mathbf{u}}+\mathbf{r}(\mathbf{u})=\mathbf{f}(t)$$

Quasi-static solution obtained as a transient response of a dynamic problem

$$M_{ii}=\frac{(1.1\Delta t)^2}{4}\sum_j|K_{ij}|$$

$$C_{ii}=2\omega_0M_{ii}$$

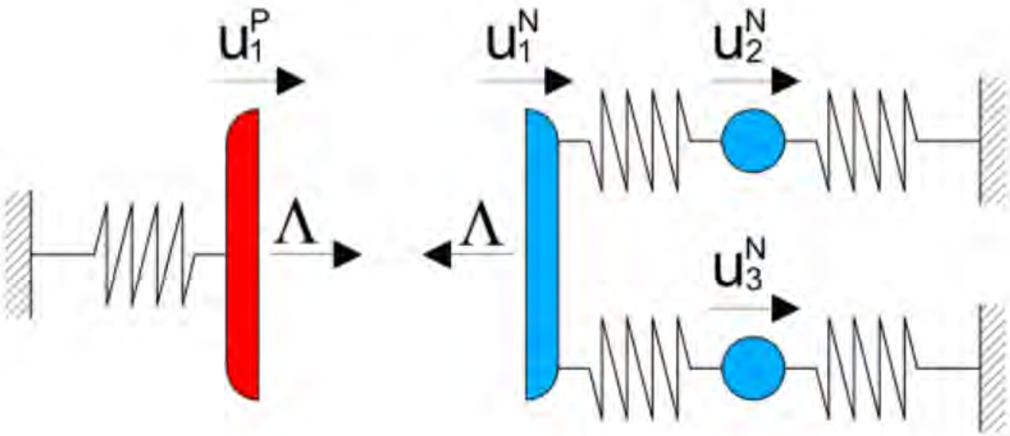
Dynamic relaxation

$$\hat{\mathbf{u}}=\boldsymbol{\Psi}\mathbf{p}$$

$$\begin{bmatrix}\hat{\mathbf{u}}_i\\ \hat{\mathbf{u}}_e\\ \hat{\mathbf{u}}_r\end{bmatrix}=\begin{bmatrix}\boldsymbol{\Phi}_{if} & \boldsymbol{\Psi}_{ie} & \boldsymbol{\Psi}_{ir}\\ \mathbf{0}_{ef} & \mathbf{I}_{ee} & \boldsymbol{\Psi}_{er}\\ \mathbf{0}_{rf} & \mathbf{0}_{re} & \mathbf{I}_{rr}\end{bmatrix}\begin{bmatrix}\mathbf{p}_f\\ \mathbf{p}_e\\ \mathbf{p}_r\end{bmatrix}$$

Component-mode synthesis via the Craig-Bampton method

The Localized-Lagrange multiplier-Gravouil Combescure algorithm



Dual assembly of PS and NS:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{r}(\mathbf{u}, \dot{\mathbf{u}}) = \mathbf{f}(t)$$

$$\downarrow$$

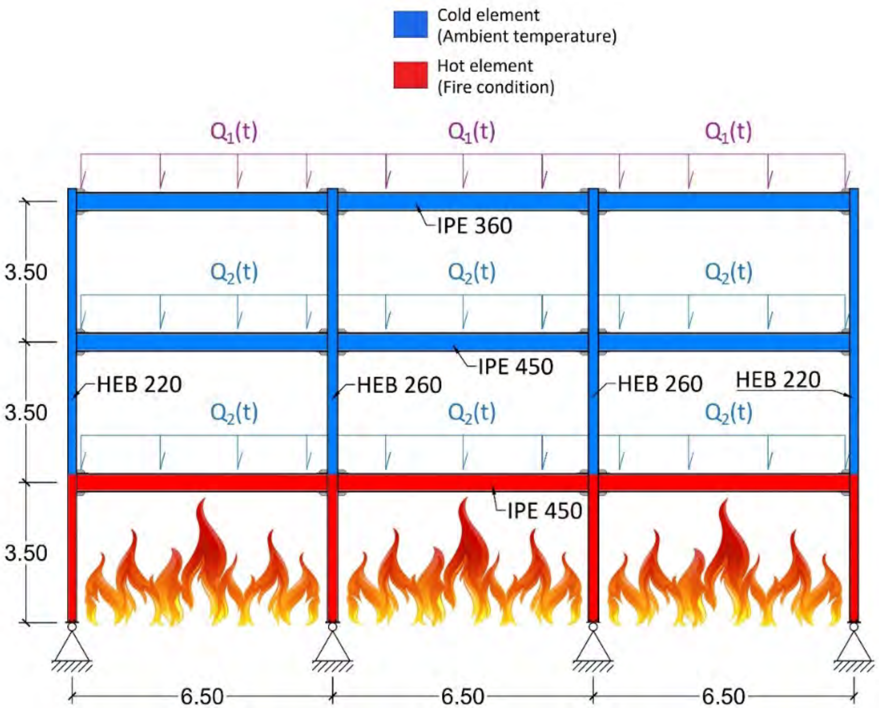
$$\begin{cases} \mathbf{M}^N\ddot{\mathbf{u}}^N + \mathbf{r}^N(\mathbf{u}^N, \dot{\mathbf{u}}^N) = \mathbf{f}^N(t) + \mathbf{L}^{N^T}\boldsymbol{\Lambda} \\ \mathbf{M}^P\ddot{\mathbf{u}}^P + \mathbf{r}^P(\mathbf{u}^P, \dot{\mathbf{u}}^P) = \mathbf{f}^P(t) + \mathbf{L}^{P^T}\boldsymbol{\Lambda} \\ \mathbf{L}^N\dot{\mathbf{u}}^N + \mathbf{L}^P\dot{\mathbf{u}}^P = \mathbf{0} \end{cases}$$

$$\mathbf{L}^P = 1, \mathbf{L}^N = [1, 0, 0]$$

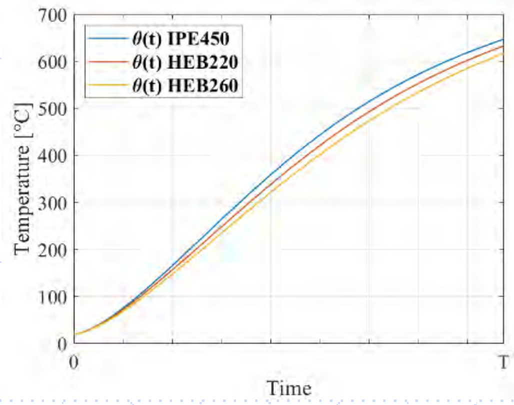
Partitioned time integrator

VIRTUAL REAL-TIME (RT) HYBRID FIRE SIMULATION (HFS) FRAMEWORK

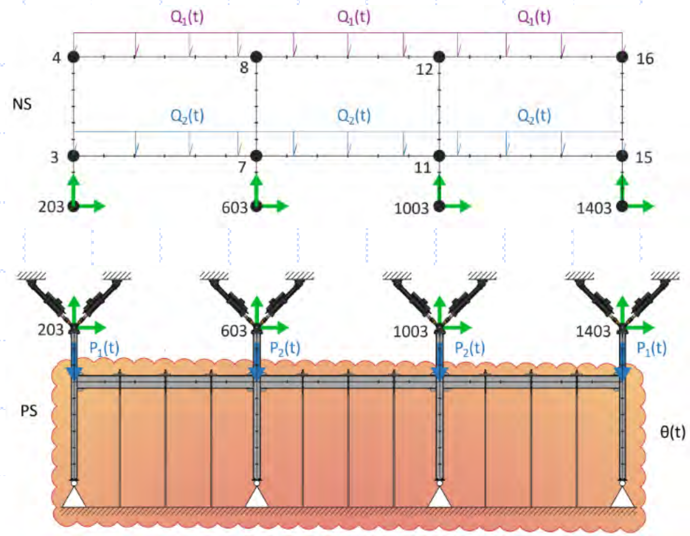
Prototype structure: emulated moment-resisting frame with a fire scenario



Time-temperature heating curves



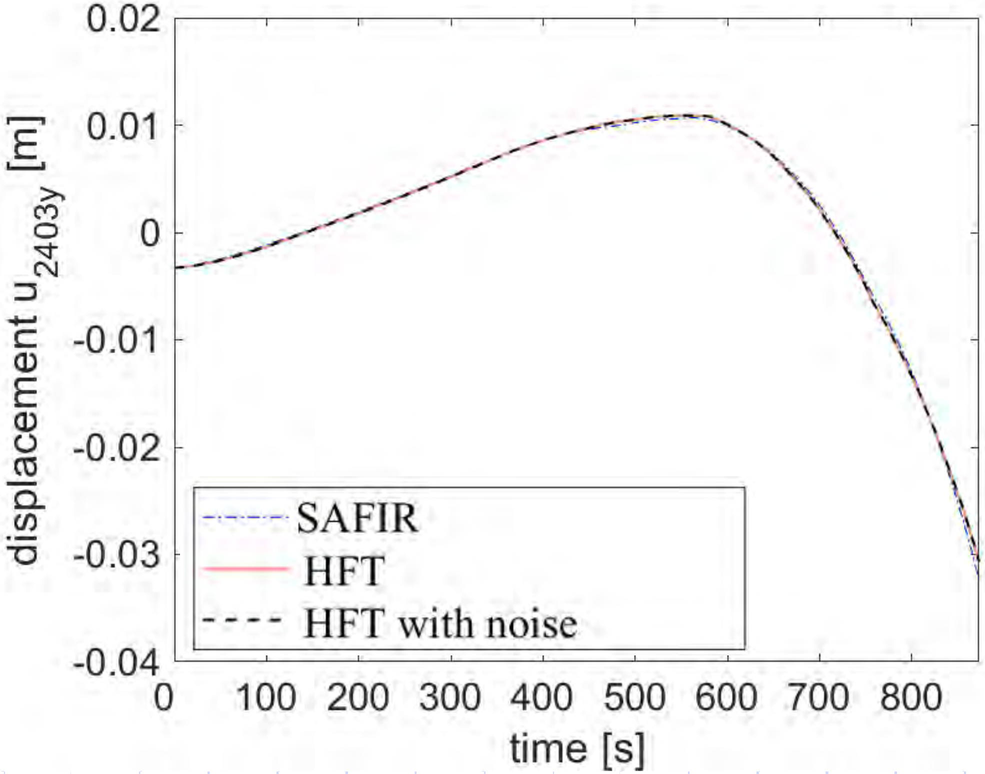
Substructuring scheme

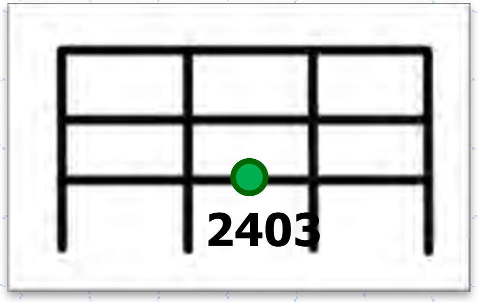


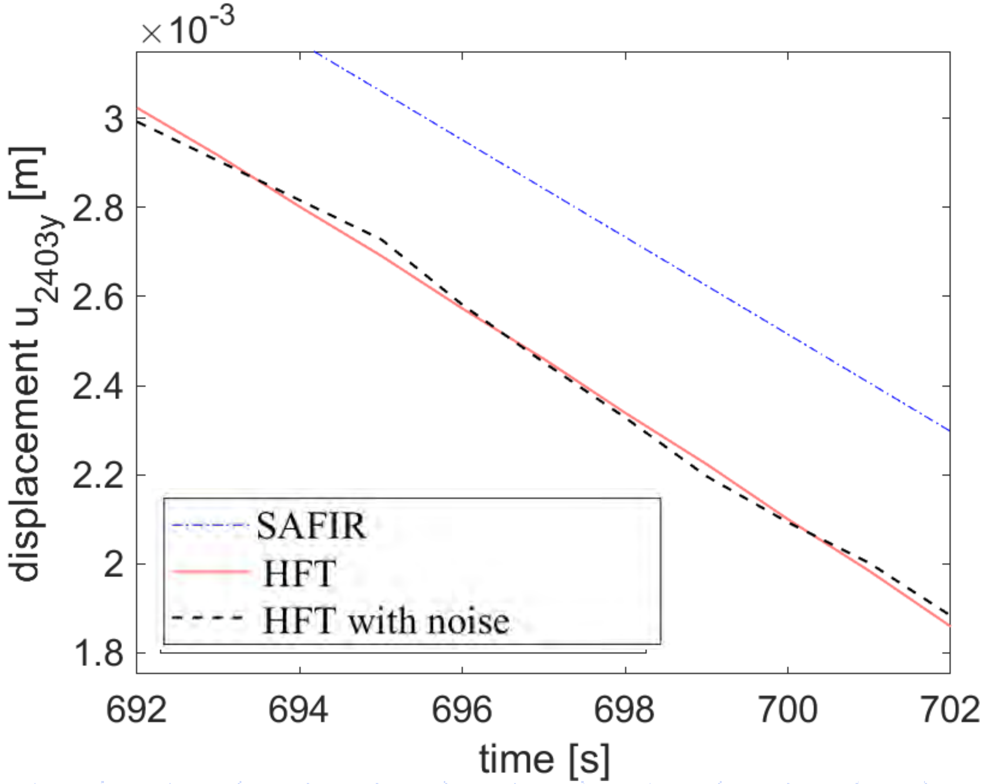
Numerical subdomain

Physical subdomain

RT HFS Framework

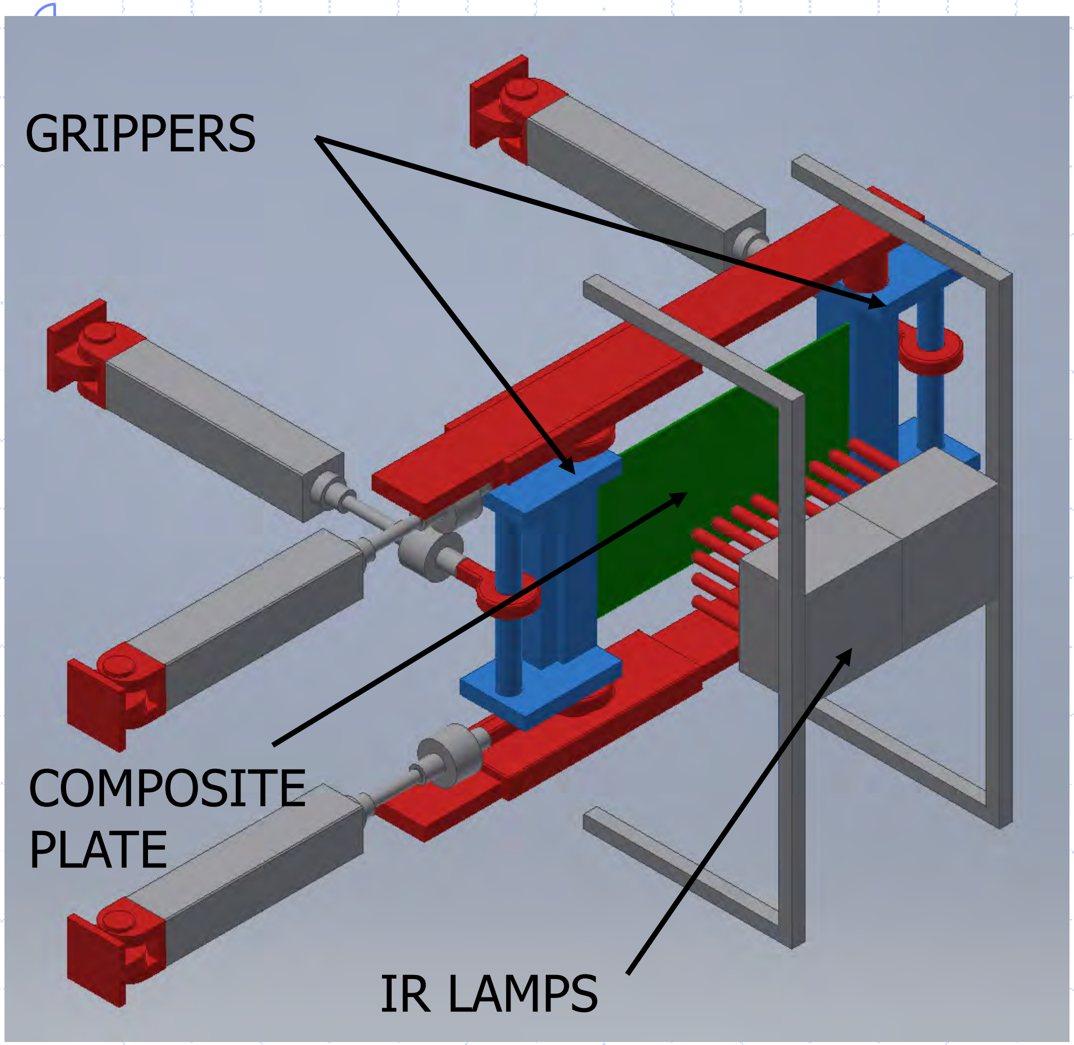






Vertical displacement node 2403 (beam)

Thermo-mechanical test rig @ETH



Infrared lamp module

Heat flux gauge

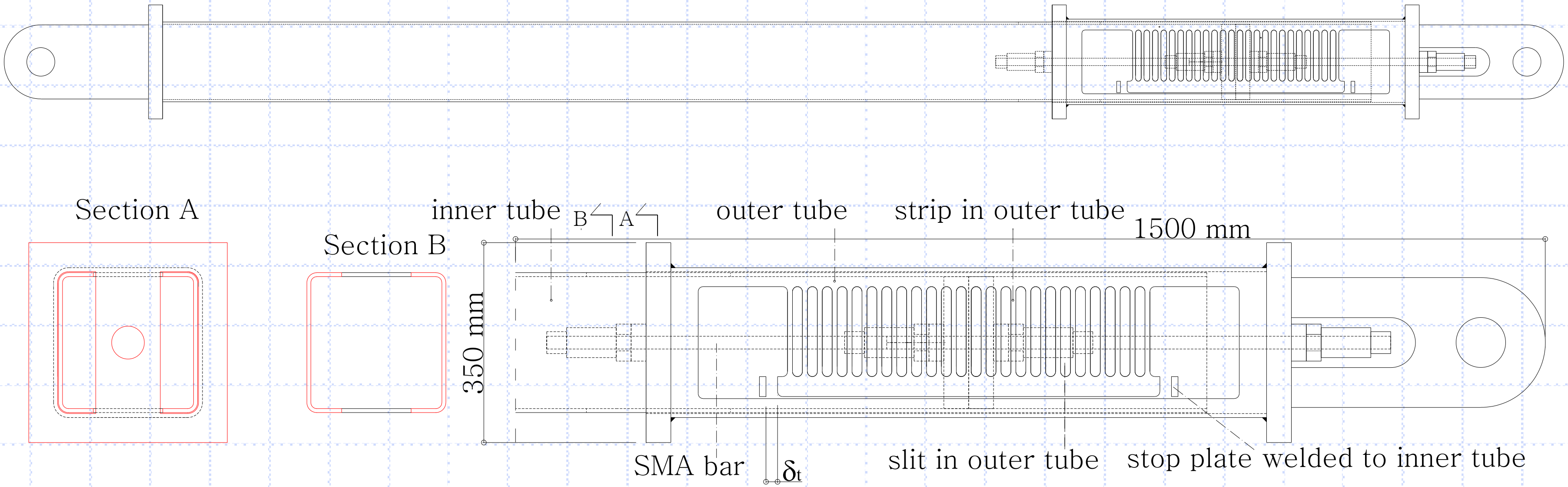
Peltier module

WP27/JRA-5

Requests for the next WP27/JRA5

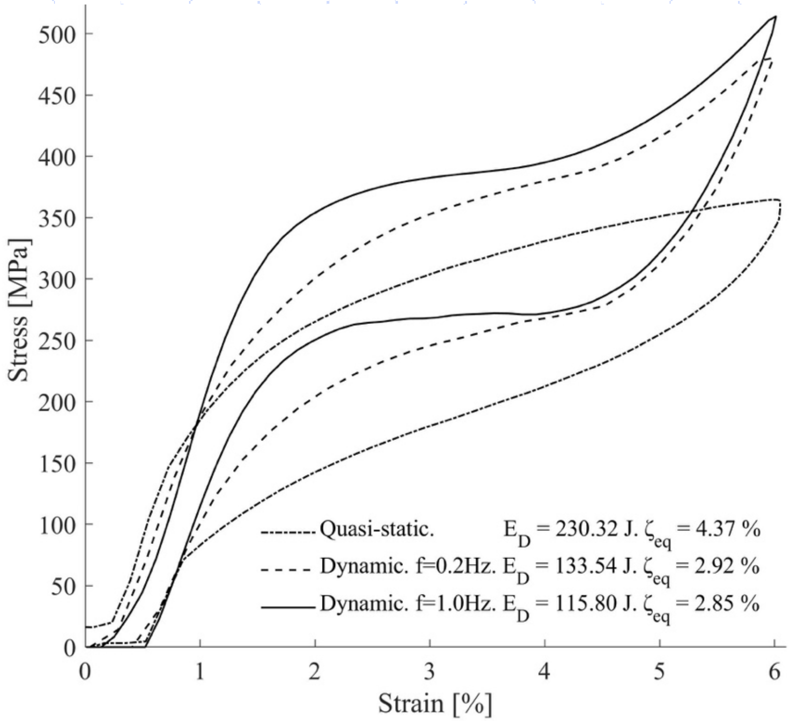
Requests for the next WP27/JRA5

- Testing of existing means to control/minimize damage and produce more resilient components/earthquake protection systems;
- That means structures with energy dissipation devices, base isolation, structures designed for unconventional seismic response, i.e. rocking, sliding systems, or with unconventional construction, i.e. masonry structures with dry, sliding joints, frames with dry-joints.

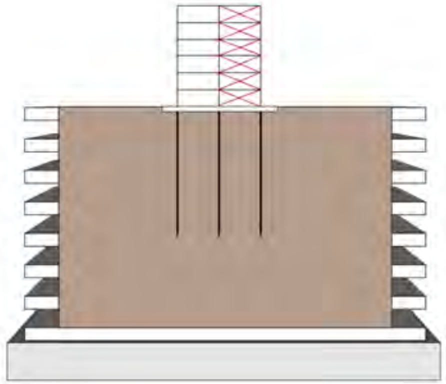


New metallic dampers with recentering capability – Amadeo Benavent – UPM Madrid.
The new damper consists of a tube-in-tube configuration of two commonly available hollow structural steel sections with a central bar made of Nickel-titanium (NiTi) Shape Memory Alloys (SMAs) that provides recentering properties and minimizes residual deformations.

From the hysteretic loops at 6% strain of the specimens subjected to quasi-static and dynamic cyclic loadings it follows that an increase in the strain rate results in: (i) greater values of loading and unloading transformation stresses; (ii) narrower hysteresis loops and (iii) earlier occurrence of the strain hardening effect.



TEST 6 : CBF FLEX



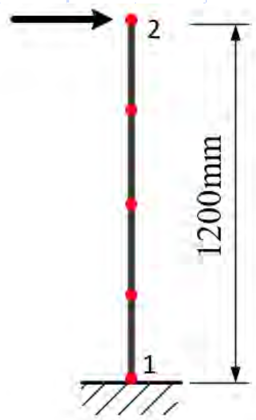
Shear stacks on shaking tables

Transnational Access @EQUALS Shacking Table at University of Bristol, United Kingdom (Panos Kloukinas)

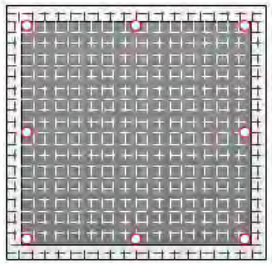
Project title: Design Rules for Steel Structures accounting for Soil-Structures Interaction

HOW TO PROPERLY SUBSTRUCTURE THE SUPERSTRUCTURE?

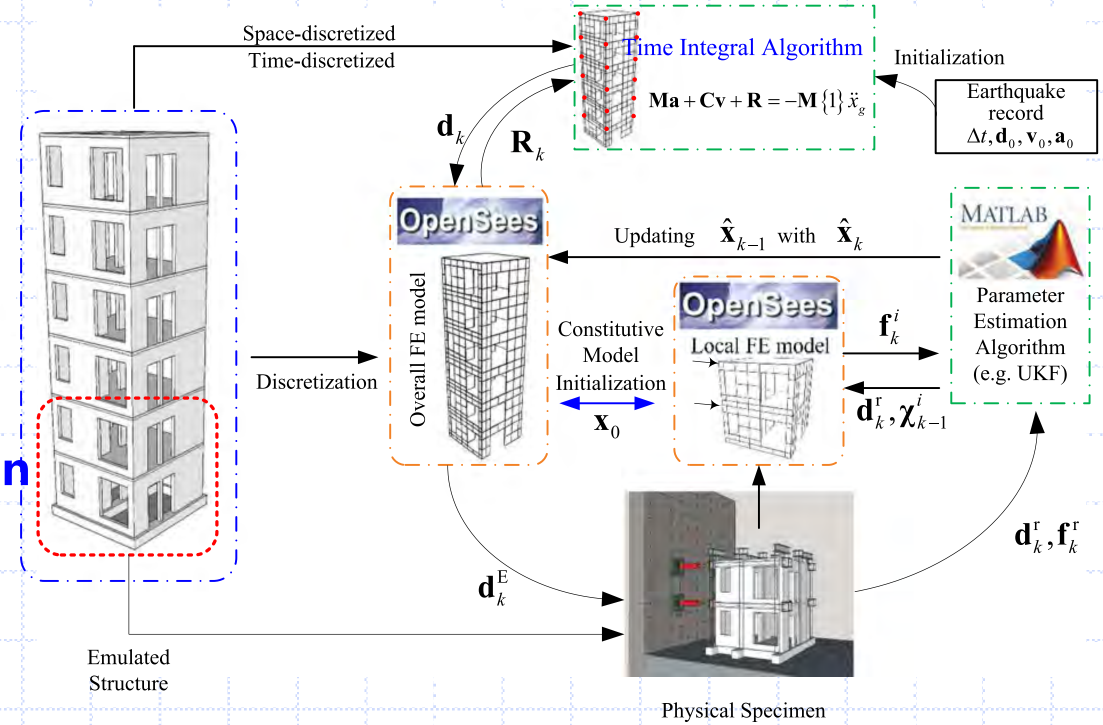
HYBRID SIMULATION WITH MODEL UPDATING OF MATERIAL CONSTITUTIVE LAWS AND FE MODELS



FE model
of an RC column



Fiber section



1) Based on restoring forces as measurements, OpenSees is modified with an embedded UKF for hybrid simulation. Thus, strong nonlinear problems are solved via parameter estimation
2) The estimation of a single-parameter is a linear time-variant system that monotonically converges.

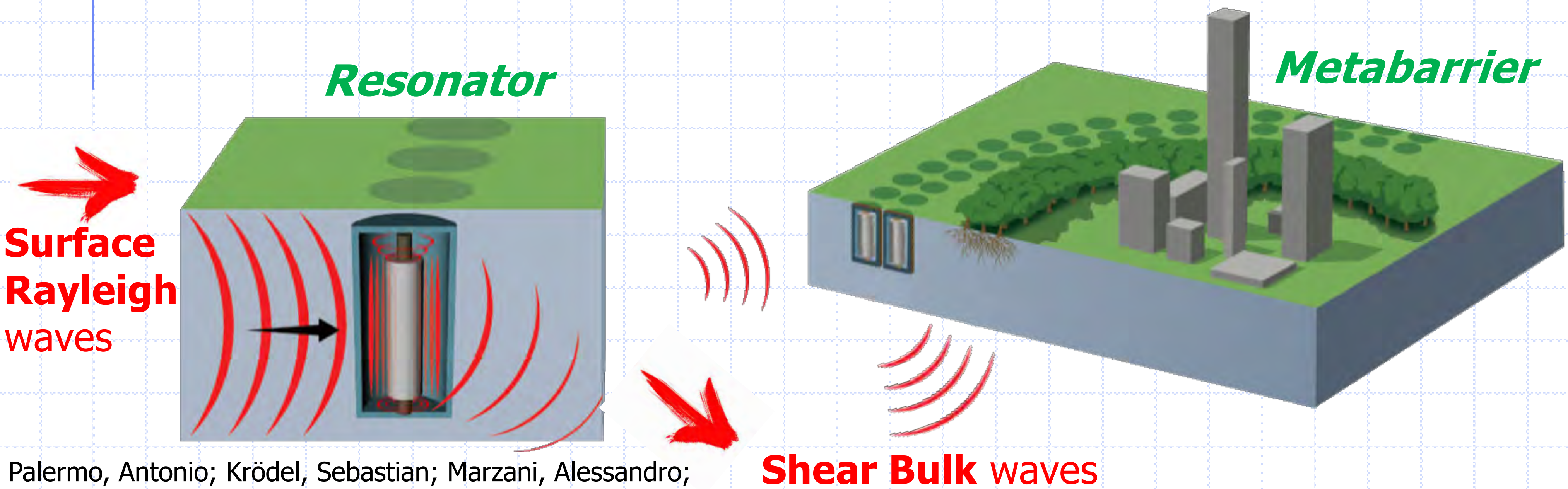
Bin Wu Xizhan Ning Guoshan Xu Zhen Wang Zhu Mei Ge Yang, Online numerical simulation: A hybrid simulation method for incomplete boundary conditions, 47, 4, 2018, 889-905
Wu B, Chen Y, Xu G, Mei Z, Pan T, Zeng C. Hybrid simulation of steel frame structures with sectional model updating. Earthq Eng Struct Dyn. 2016;45(8):1251-1269.
Mei Z, Wu B, Bursi OS, Yang G, Wang Z. Hybrid simulation of structural systems with online updating of concrete constitutive law parameters by Kalman filter. Struct Control Health Monit 2017; accepted online, doi: https://doi.org/10.1002/stc.2069.

HOW TO SUBSTRUCTURE A METABARRIER?

Prove the effectiveness of the ***Metabarrier:*** a metamaterial-inspired device designed to reduce low-frequency (<30 Hz) surface waves induced by natural and anthropic vibrations in large-scale structures and infrastructures.

REwaRd project with TA to EUROSEISTEST

The ***Metabarrier*** is constituted by an array of ***Resonators***, to be placed within the ground around the structure, or a cluster of structures, purposely designed to interact with incoming **Surface Rayleigh** waves and to convert part of their energy in **Shear Bulk** waves

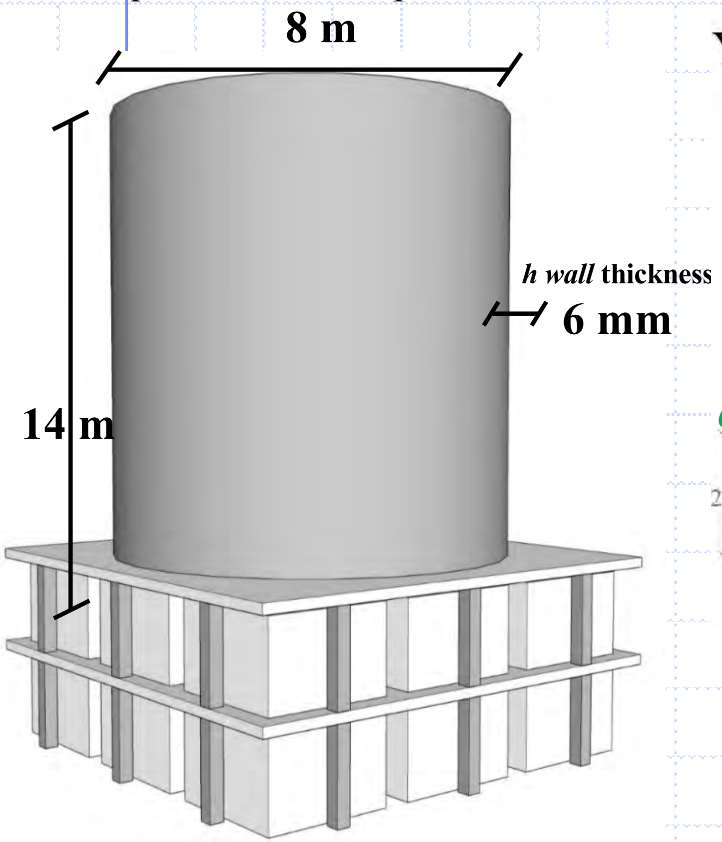


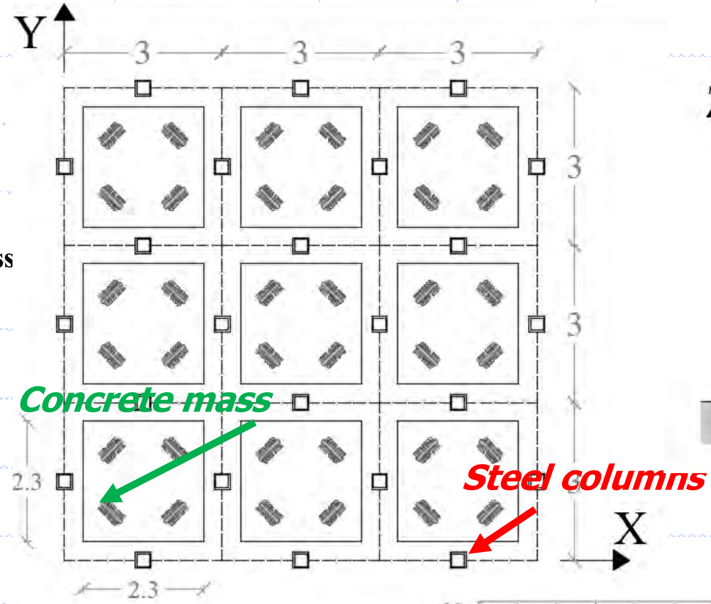
Palermo, Antonio; Krödel, Sebastian; Marzani, Alessandro; Daraio, Chiara, Engineered metabarrier as shield from seismic surface waves, SCIENTIFIC REPORTS, 2016, 6, pp. 1 - 10

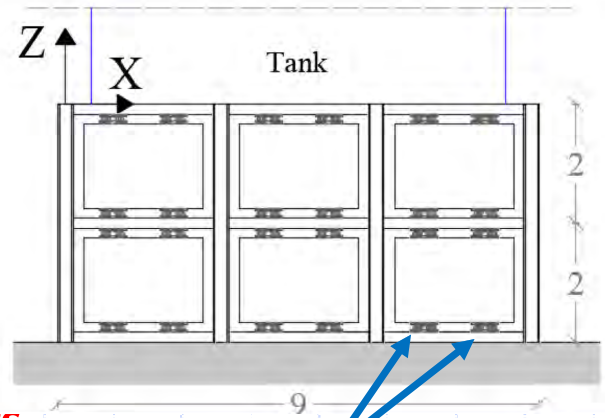
HOW TO SUBSTRUCTURE A METAFOUNDATION?

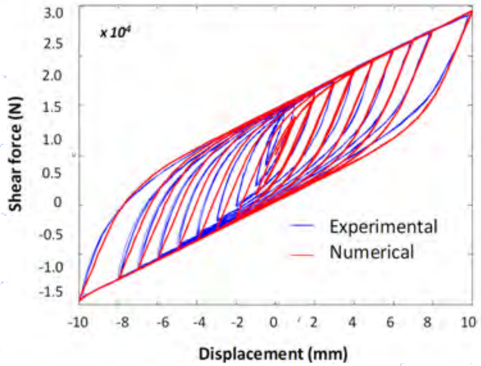
Basically, the Metafoundation is conceived to overcome the limits of previous solutions.

- feasibility of the foundation designed to be conform to current seismic standards
- effects of the coupling between foundation and superstructure
- optimization of periodic unit cells to obtain better results in term of reduction of the structural response
- performance of a periodic foundation equipped with nonlinear hysteretic dampers.









Steel wire

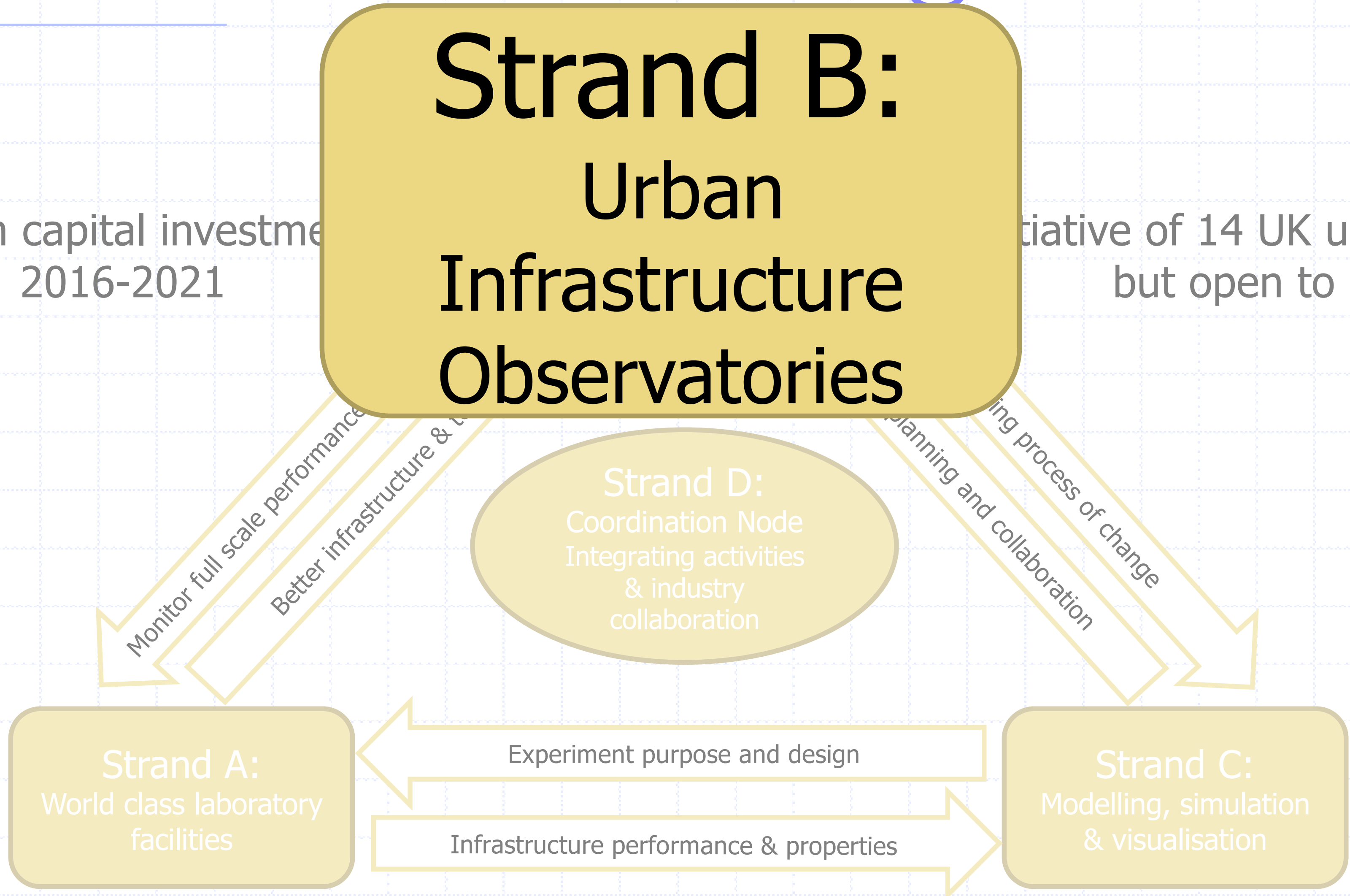
Basone, F., Wenzel, M., BURSI O.S., Fossetti, M., " Finite locally resonant metafoundations for the seismic protection of fuel storage tanks", Earthquake Engineering & Structural Dynamics, 2018, (in print).

Use of the Urban Infrastructure as a mockup

UK Collaboratorium for Research in Infrastructure and Cities @UBRISTOL

£138m capital investme
2016-2021

tiative of 14 UK universities
but open to all



UNIVERSITÀ DEGLI STUDI DI TRENTO

Thank you for your attention!
Are there questions?

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Fax: +39-0461-282521