Doctoral School in:
"Engineering of Civil and Mechanical Structural Systems"
26th cycle

"Dynamic substructuring of complex hybrid systems based on time-integration, model reduction and model identification techniques"

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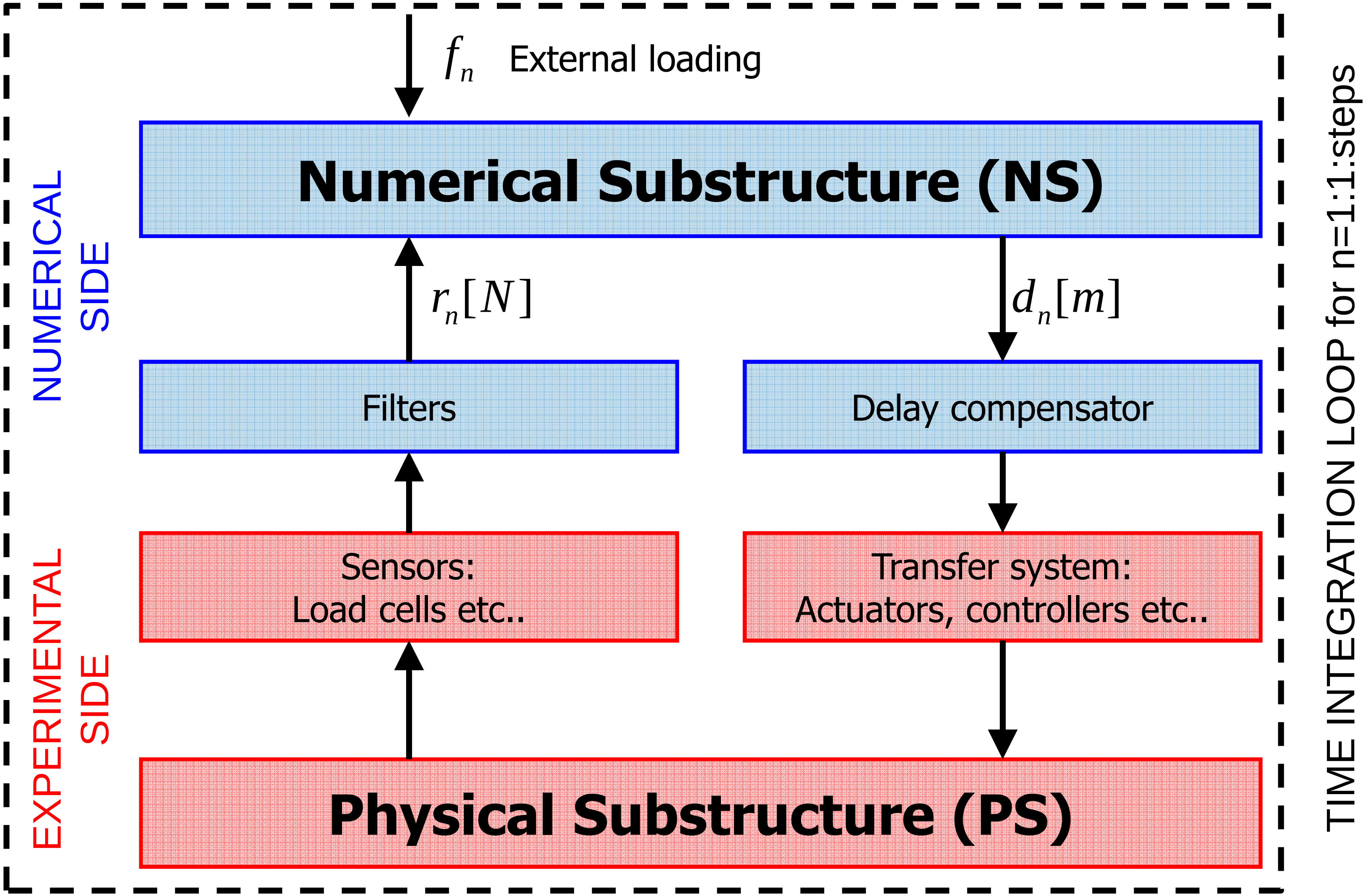
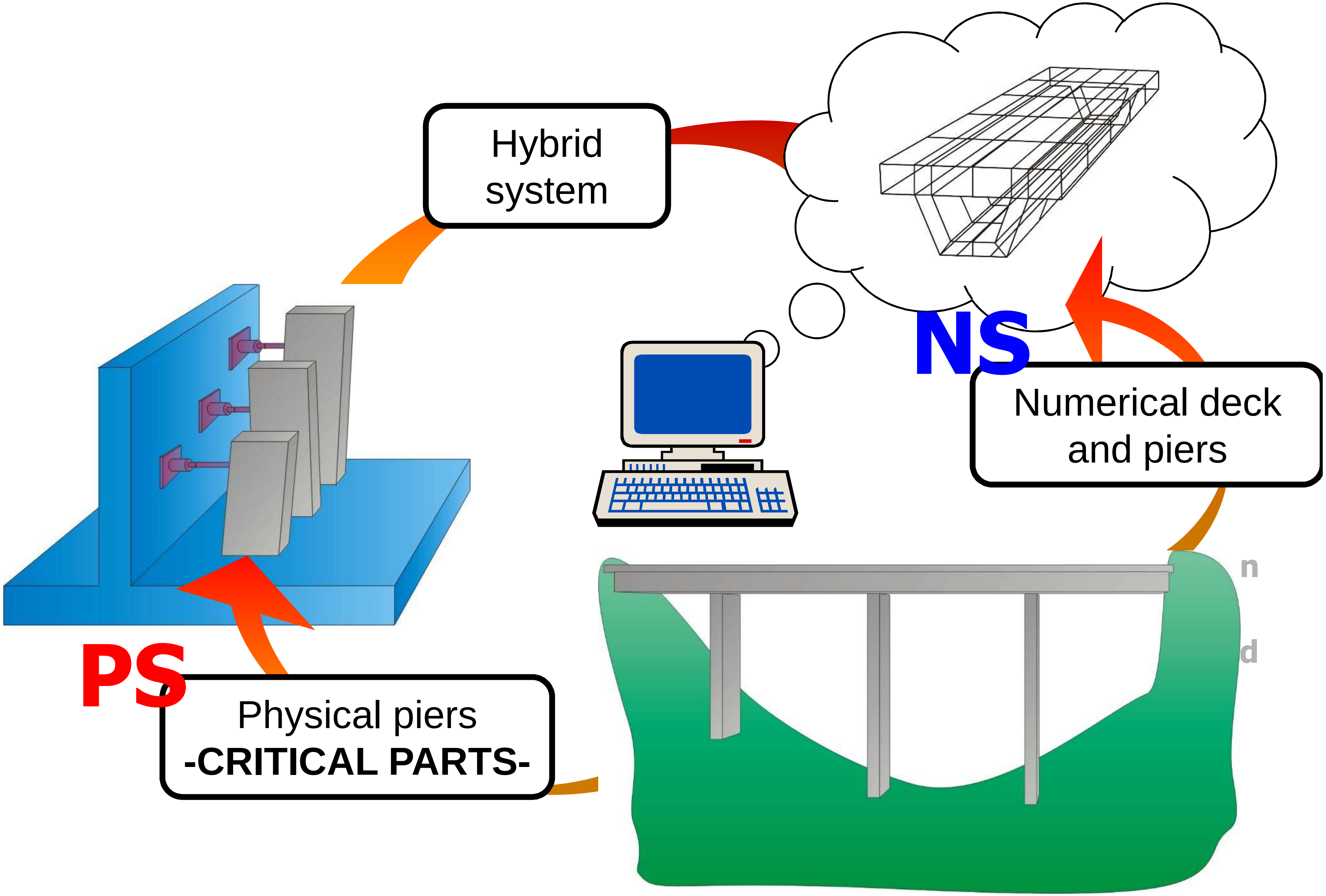
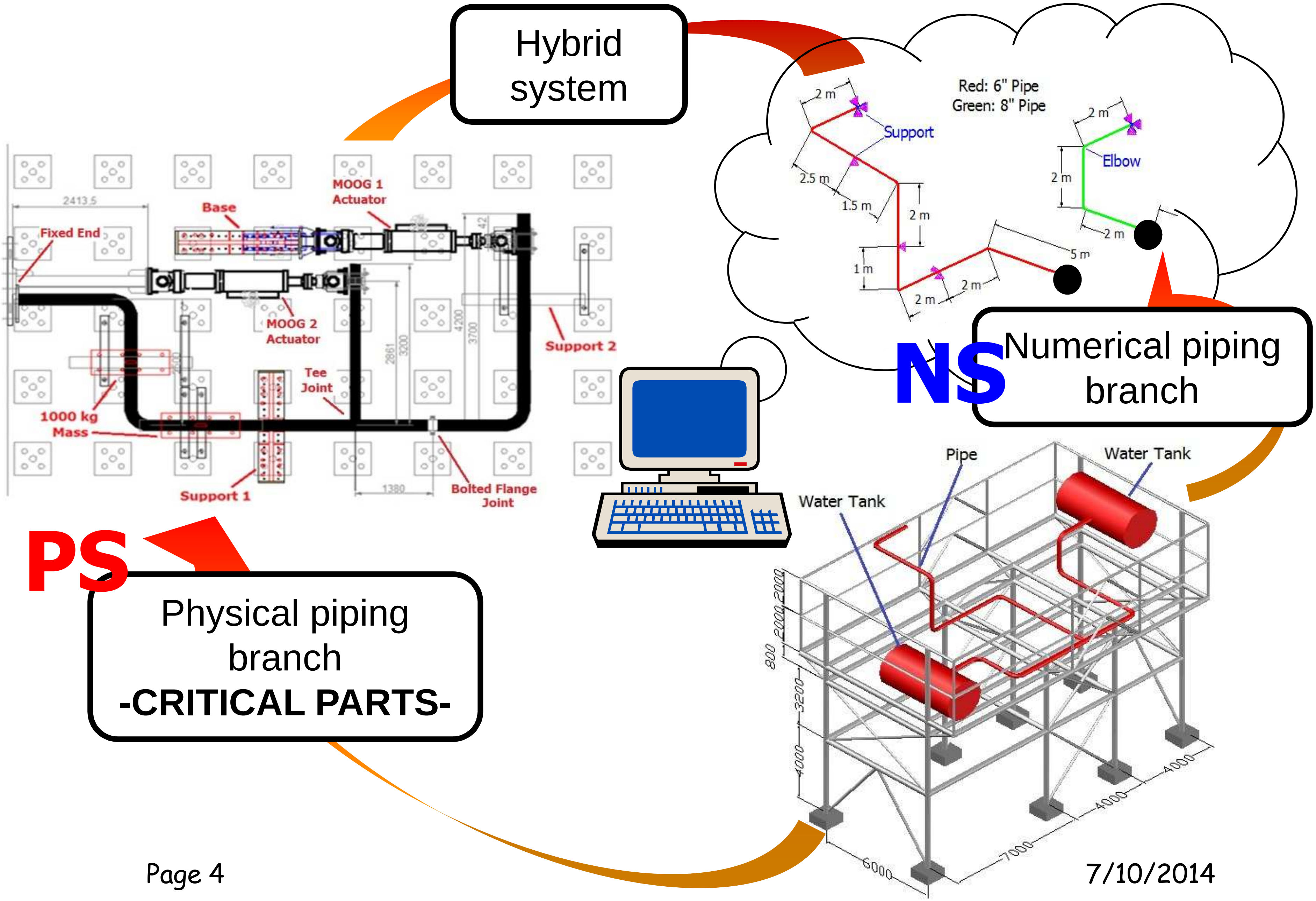
Hybrid system/Hardware-in-the-loop simulator



Civil eng. application of hybrid simul.: a RC bridge



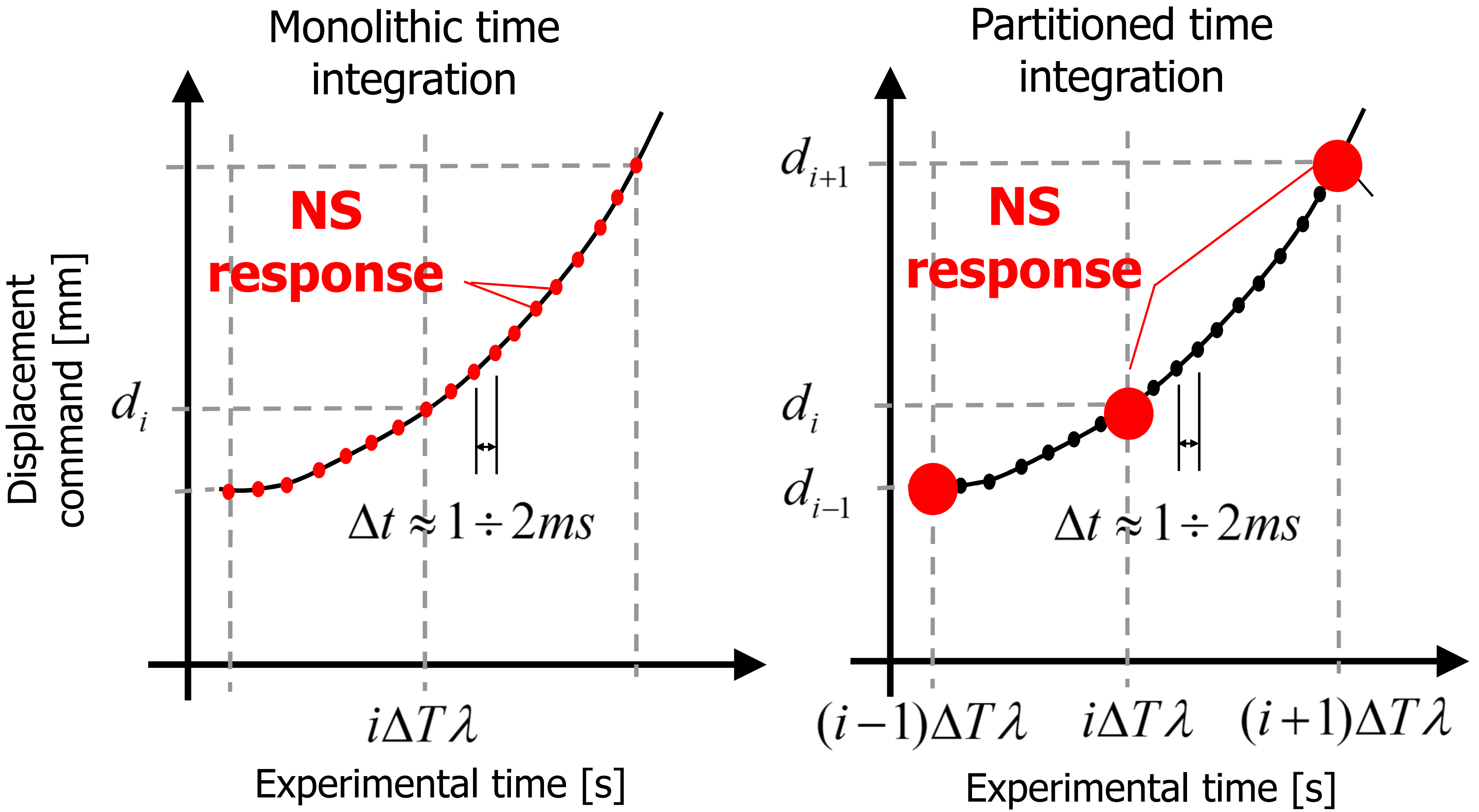
Mech. eng. application of hybrid simul.: a piping system



State of the art limitations in hybrid simulation

- PARTITIONED TIME INTEGRATION APPROACH APPLIED TO A REALISTIC CASE STUDY WITH COMPLEX **NSs**;
- MODEL UPDATING OF THE **NS** BASED ON THE RESPONSE OF A DIFFERENT **PS** SUBJECTED TO DIFFERENT LOADING;
- SIMULATION OF A HYBRID SYSTEM CHARACTERIZED BY A DISTRIBUTED PARAMETER **PSs** WITH DISTRIBUTED LOADING;

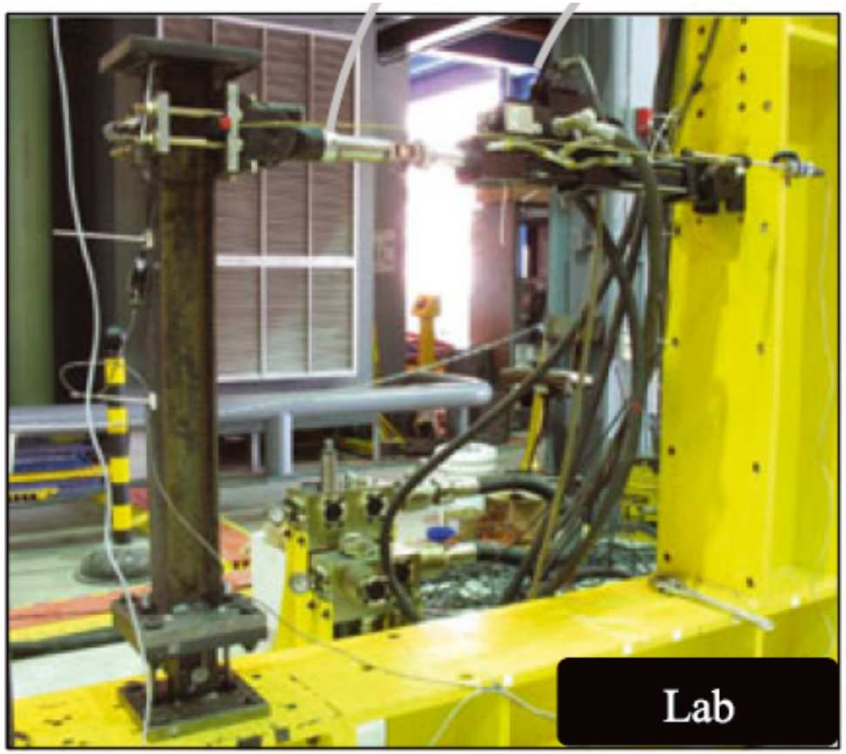
State of the art limit.: time integration

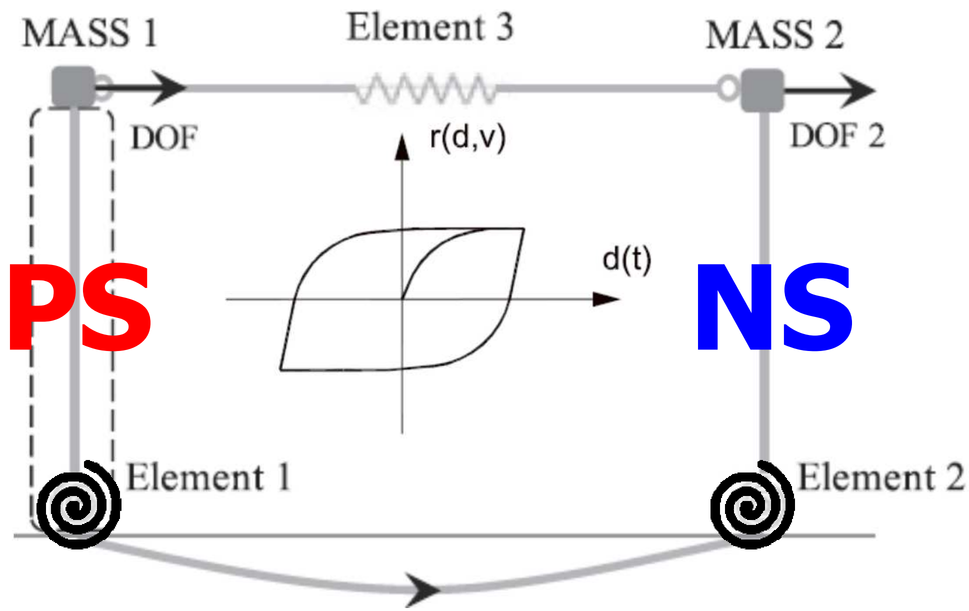


ΔT = integration time step, Δt = controller time step, λ = testing time scale

PARTITIONED TIME INTEGRATION APPROACH APPLIED TO A REALISTIC CASE STUDY WITH COMPLEX NSs

State of the art limit.: model updating of NSs

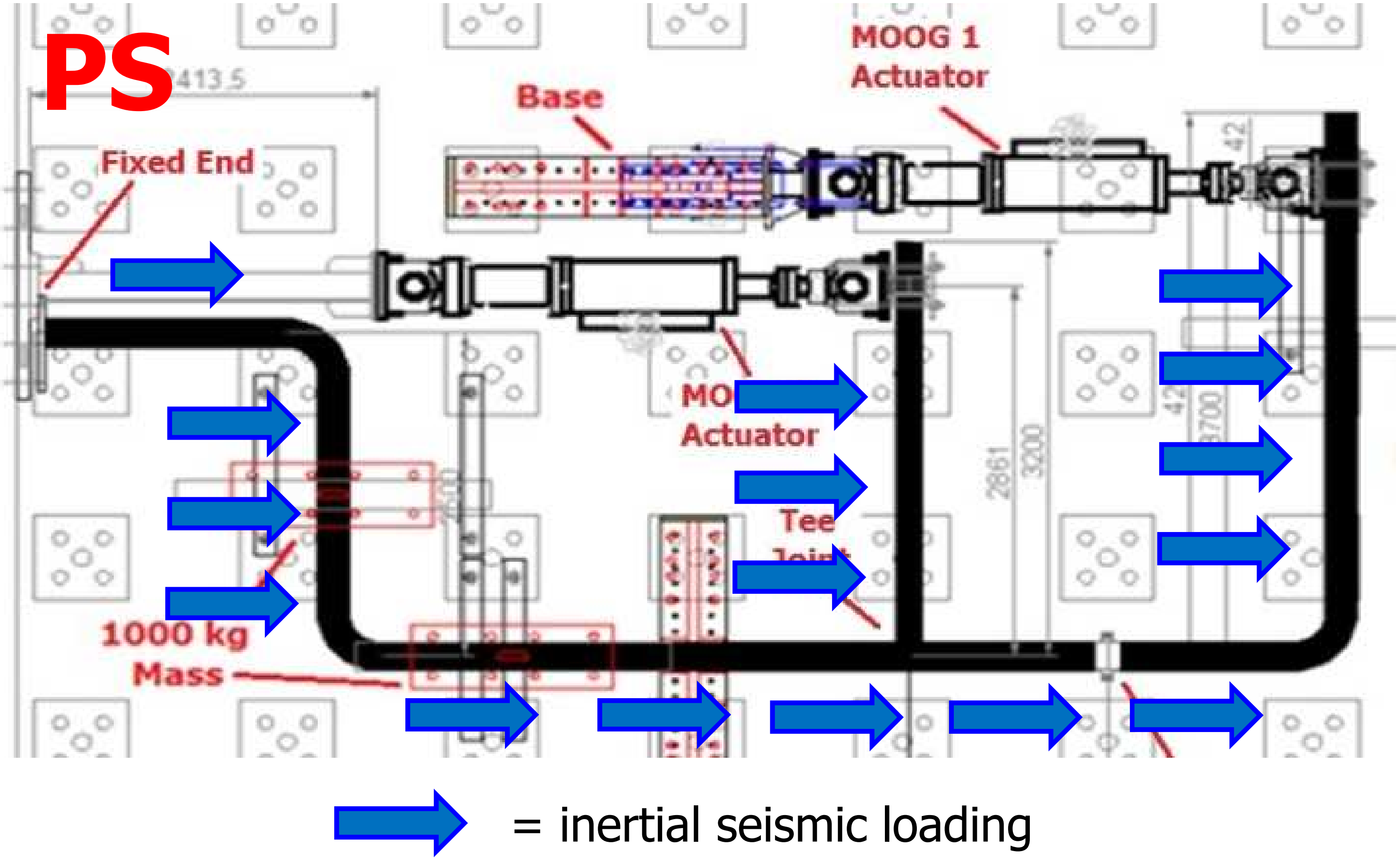




On-line model updating, Bouc-Wen model, Unscented Kalman filter

MODEL UPDATING OF THE NS BASED ON THE RESPONSE OF A DIFFERENT PS SUBJECTED TO DIFFERENT LOADING

State of the art limit.: distributed parameters PSs

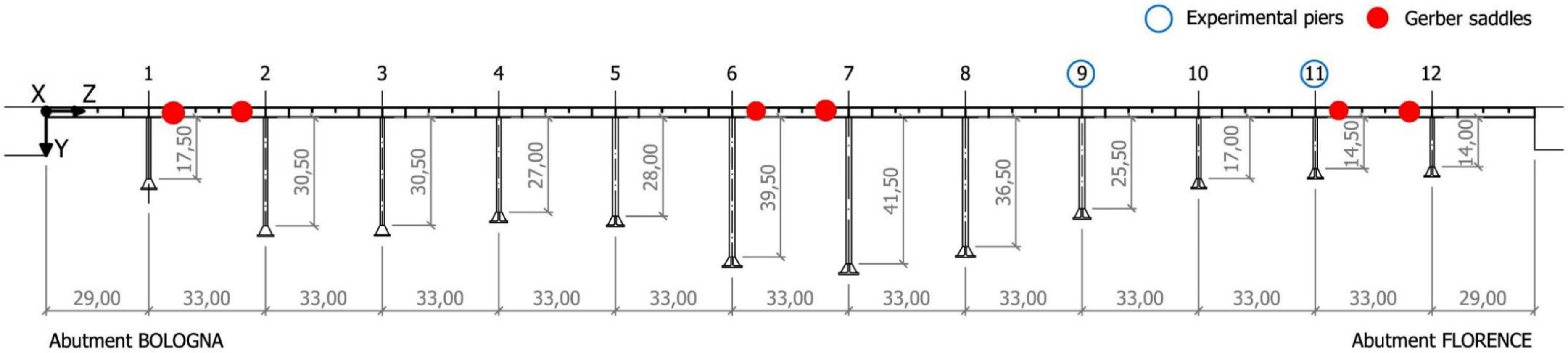


SIMULATION OF A HYBRID SYSTEM CHARACTERIZED BY A DISTRIBUTED PARAMETER PSs WITH DISTRIBUTED LOADING

Outline

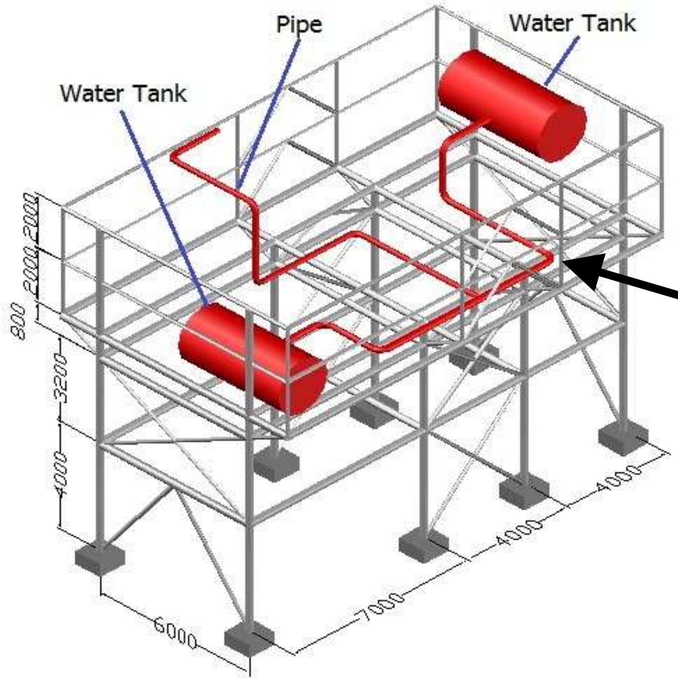
- HYBRID SIMULATION OF THE RIO TORTO BRIDGE
- HYBRID SIMULATION OF AN INDUSTRIAL PIPING SYSTEM

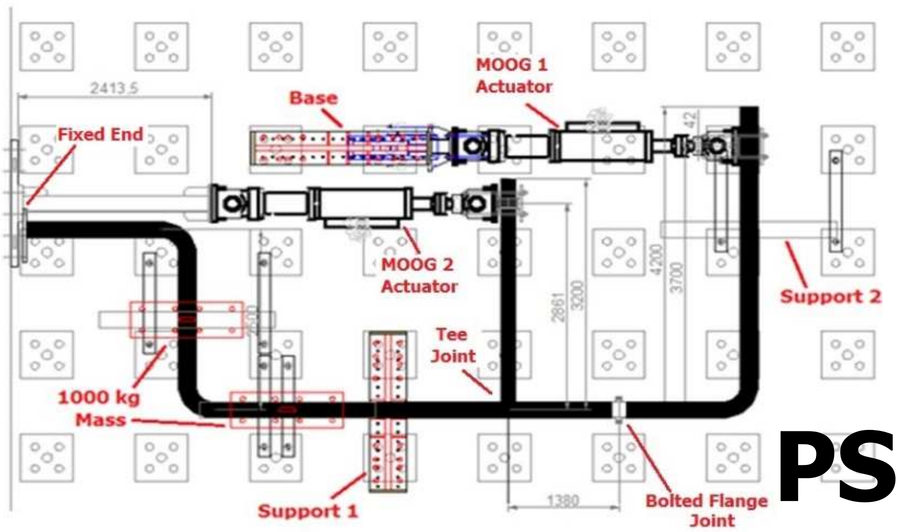
Rio Torto Bridge: innovative contributions



- Application of the partitioned time integration approach, which allowed for the simulation of nonlinear **NSs**;
- model updating of **NSs** -numerical piers- based on the response of **PSs** -physical piers-.

The piping system: innovative contributions





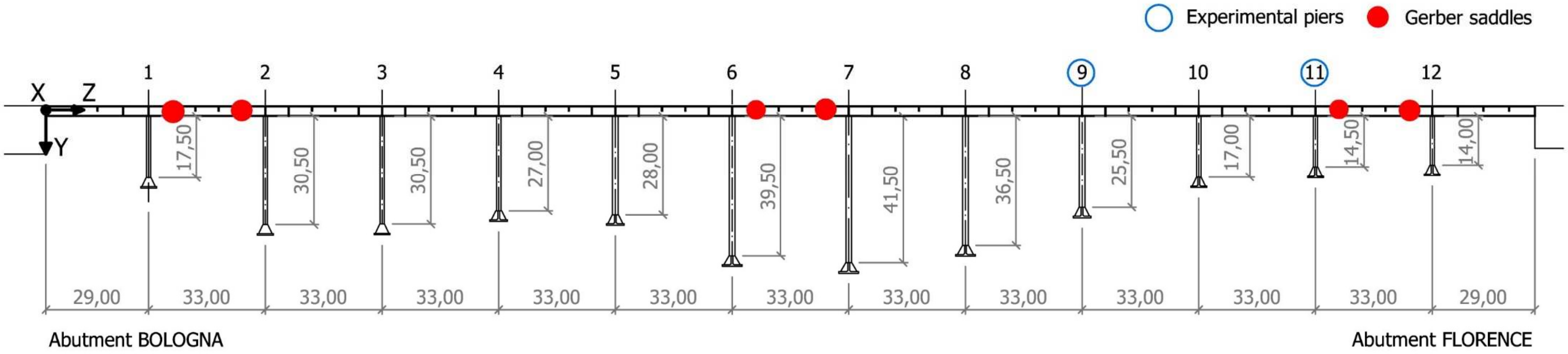
- Application of model reduction techniques to handle the **PS** and to simulate a distributed seismic loading.

HYBRID SIMULATION OF THE RIO TORTO BRIDGE

THE RIO TORTO BRIDGE CASE STUDY

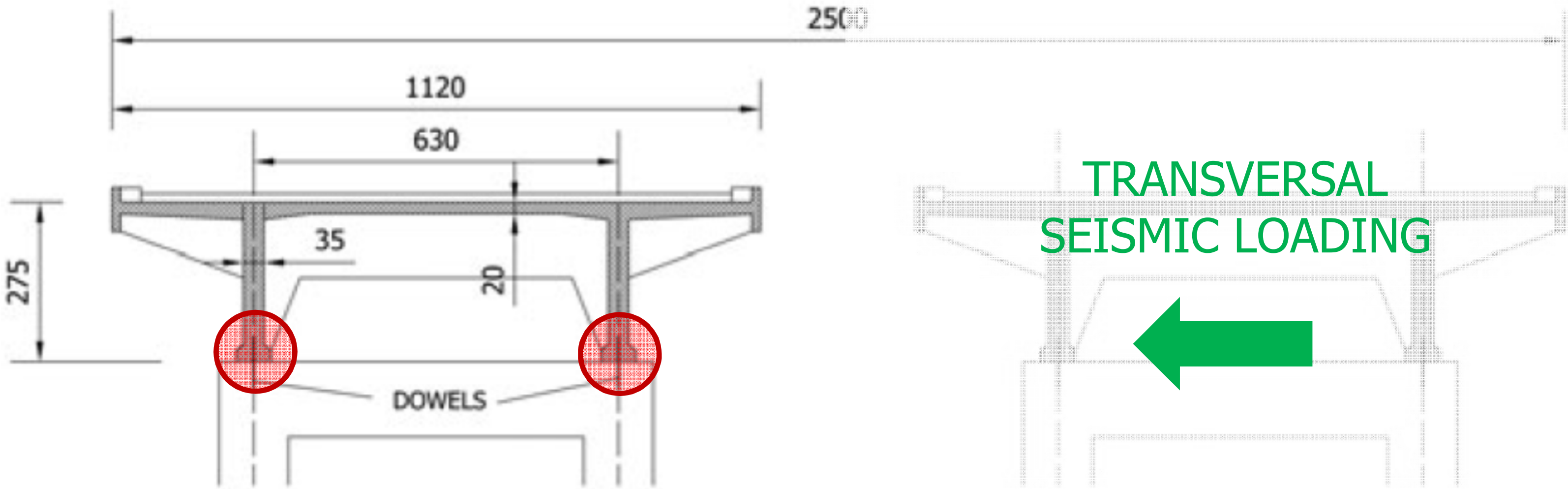
RC bridge with plain rebars, structural assessment, seismic retrofitting, hybrid simulation

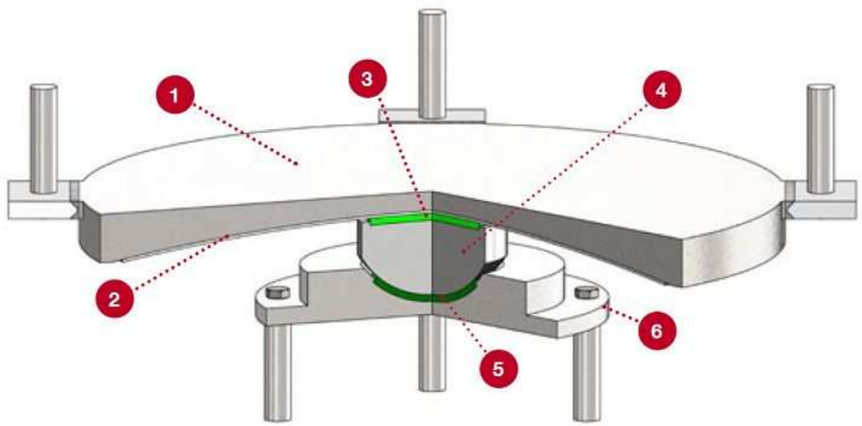
MAIN DIMENSIONS OF THE BRIDGE



- Total span = 412 m
- Single span = 33 m
- Taller pier height = 41.50 m, Pier #7
- Shorter pier height = 14.00 m, Pier #12

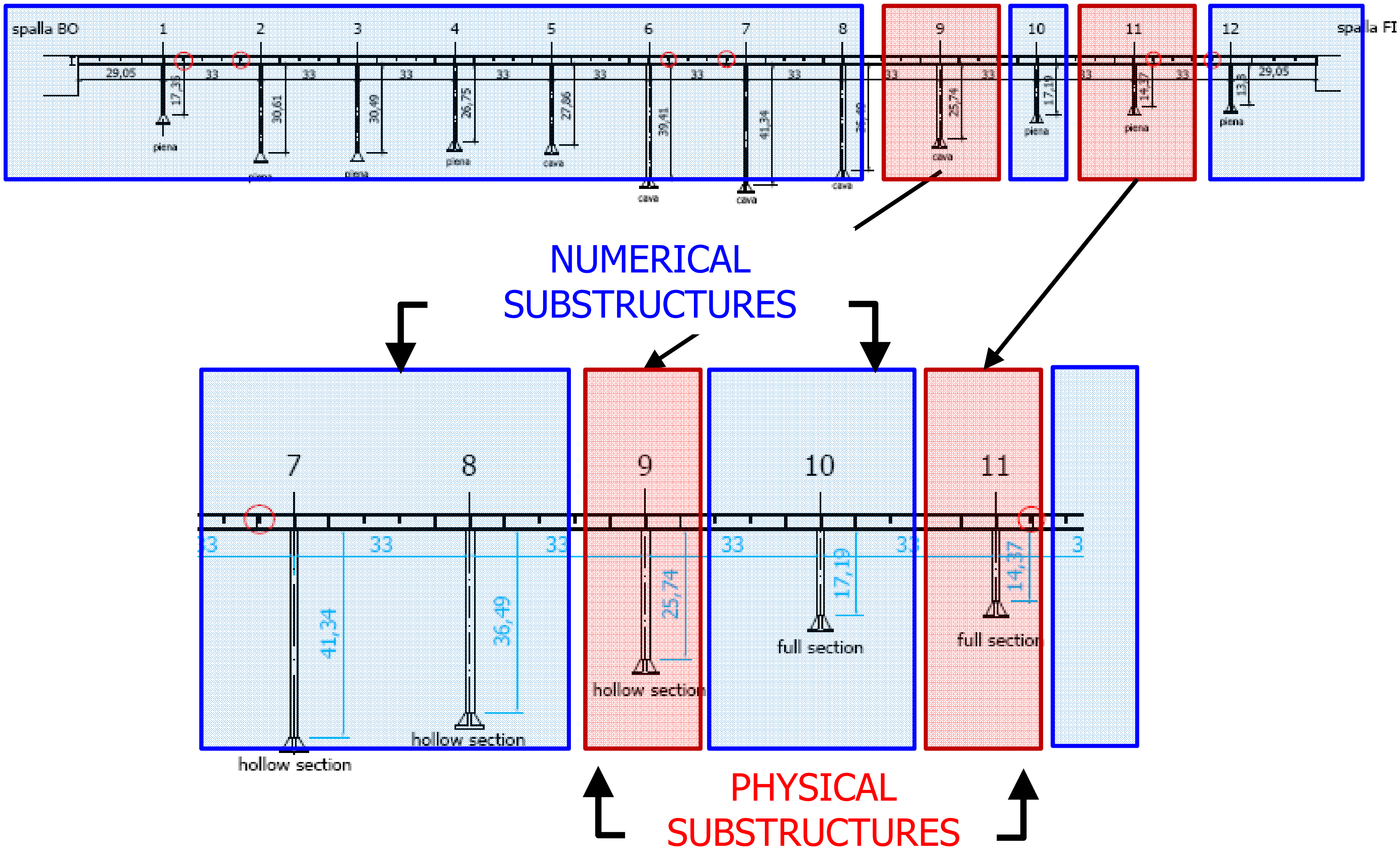
PROPOSED SEISMIC RETROFITTING SCHEME





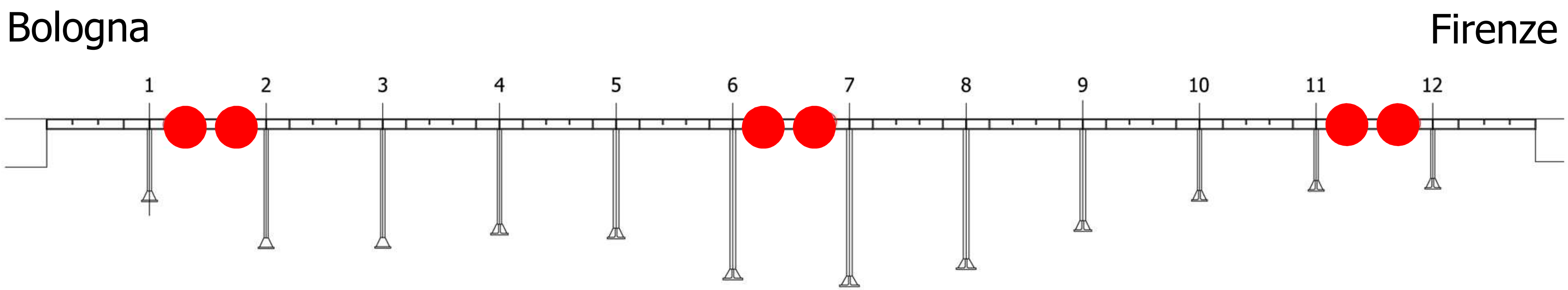
2 x 12 Friction Pendulum Bearing (FPB) isolation device

SUBSTRUCTURING SCHEME FOR TESTING PURPOSES

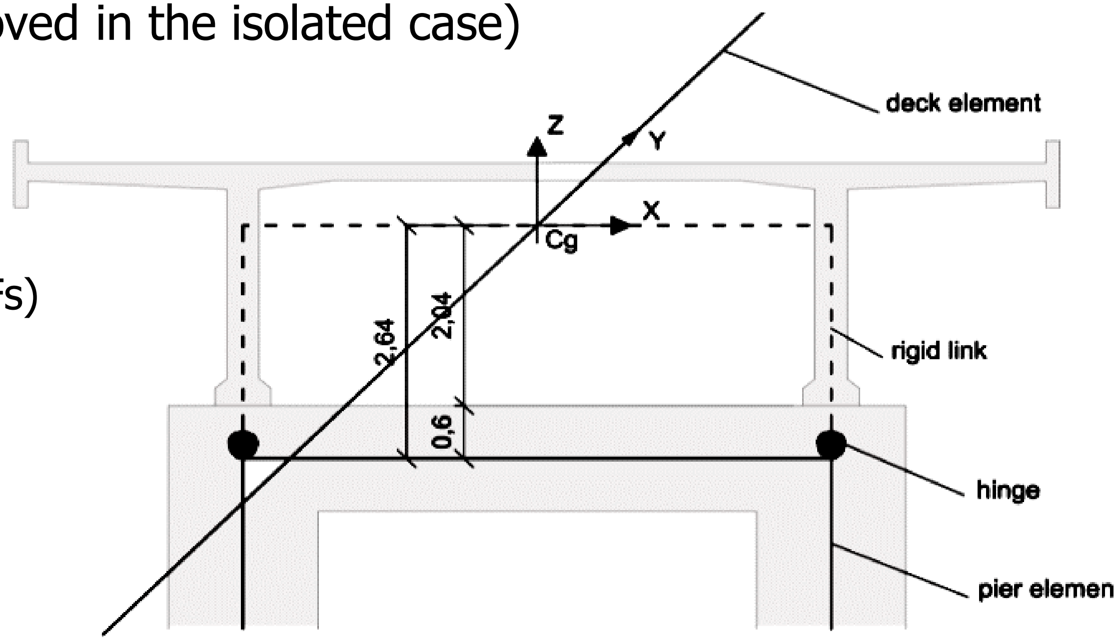


PHYSICAL SUBSTRUCTURES (2 Piers + FPB isolation devices)

THE OPENSEES REFERENCE MODEL (RM) OF THE BRIDGE



● Gerber saddles (removed in the isolated case)

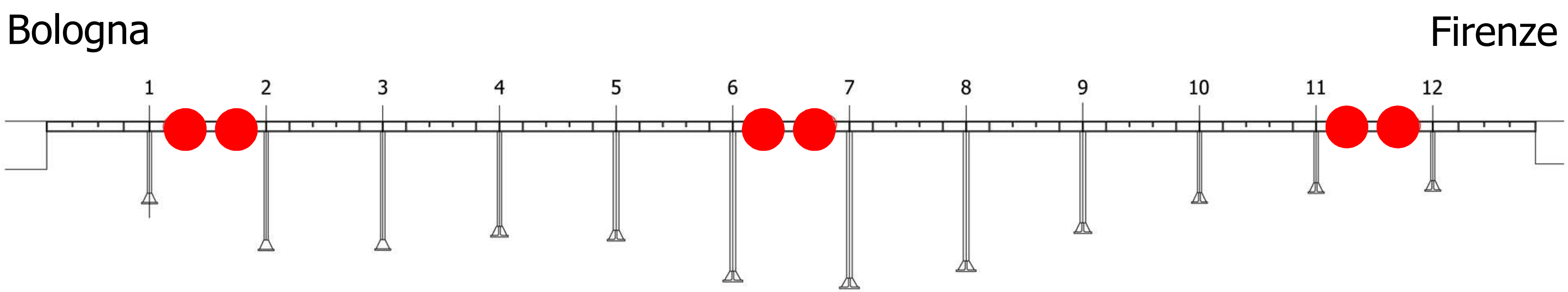


About 900 Degrees-of-Freedom (DoFs)

Element types:

- *nonlinearBeamColumn* for piers
- *elasticBeamColumn* for the deck

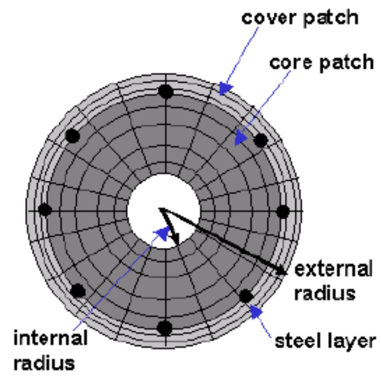
THE OPENSEES REFERENCE MODEL (RM) OF THE BRIDGE

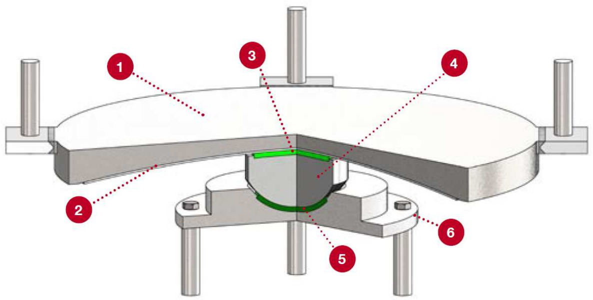


● Gerber saddles (removed in the isolated case)

Materials:

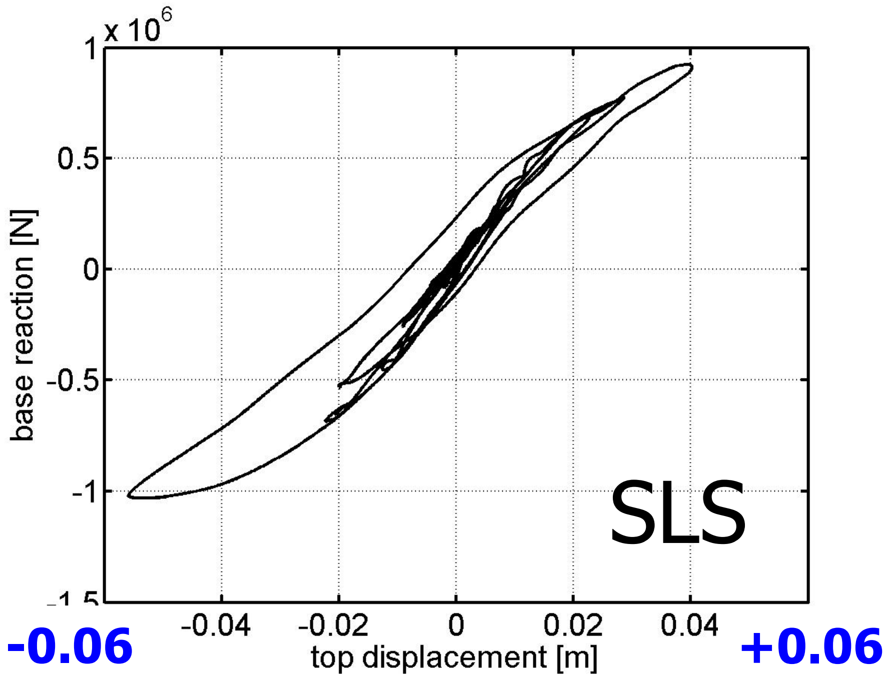
- Kent-Scott-Park model for concrete (*Concrete01*)
- Menegotto-Pinto model for rebars (*Steel02*)
- Nonlinear shear behaviour of transverse beam (*hysteretic*)

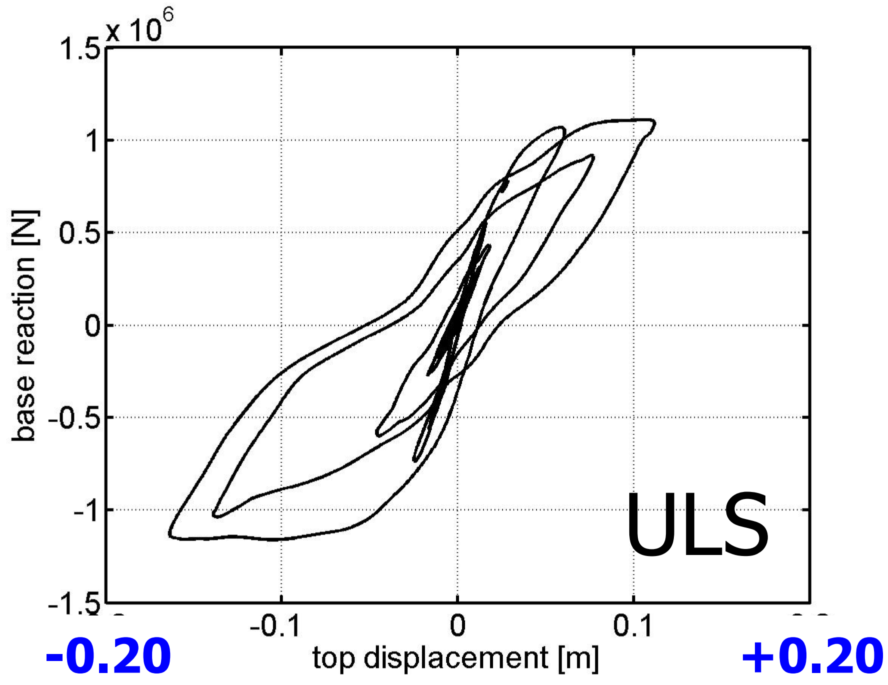




singleFPBearing elements with a *Coulomb frictionModel.*

HYSTERETIC RESPONSES OF OPENSEES PIERS

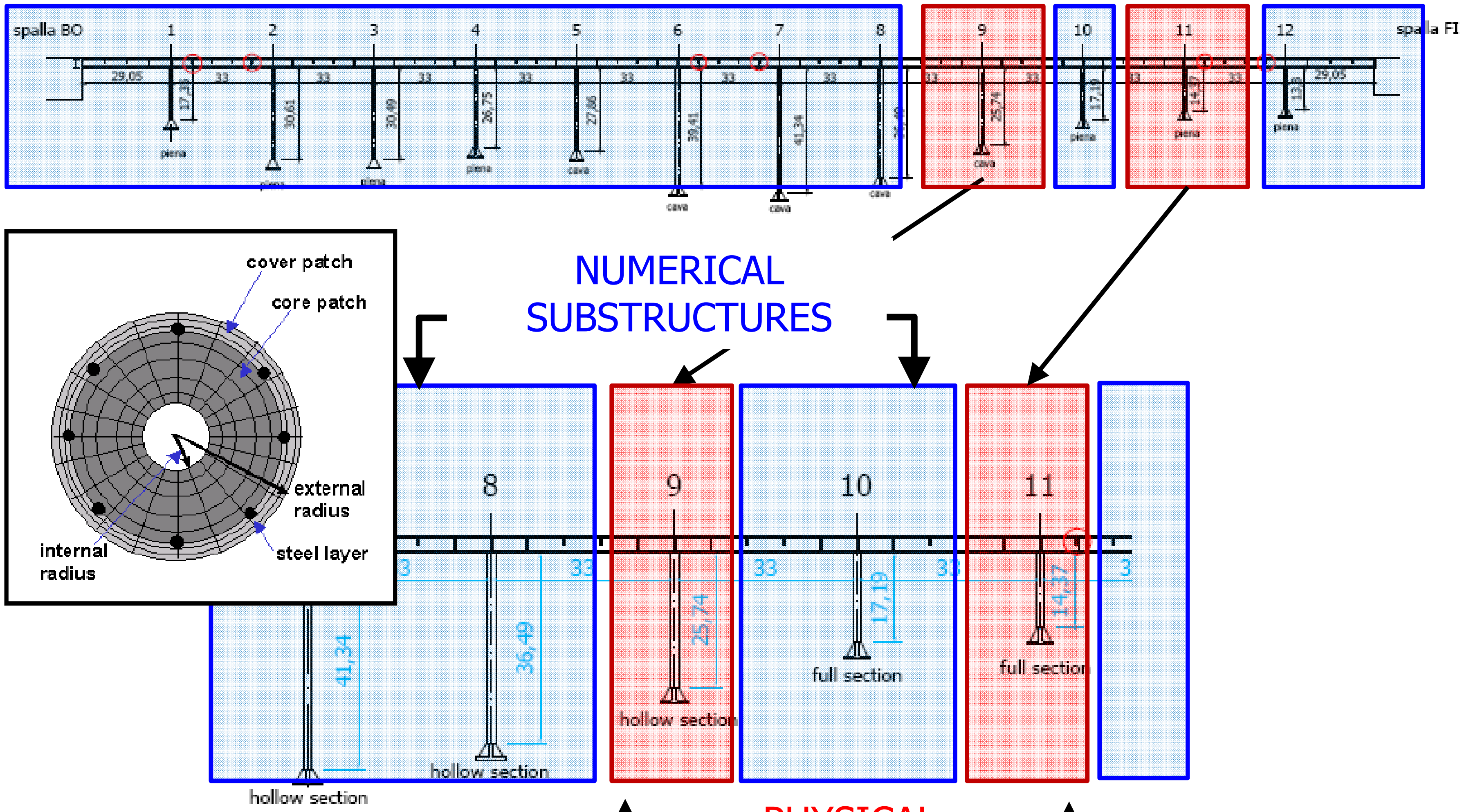




Hysteretic loops of Pier #11 in the non-isolated case

NONLINEAR NUMERICAL PIERS WERE NEEDED !!!

SUBSTRUCTURING REQUIREMENTS

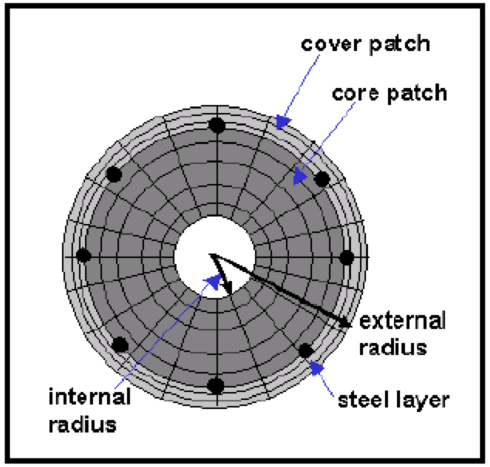


PHYSICAL SUBSTRUCTURES (2 Piers + FPB isolation devices)

SUBSTRUCTURING REQUIREMENTS

OPENSEES FIBER-BASED FE MODEL:

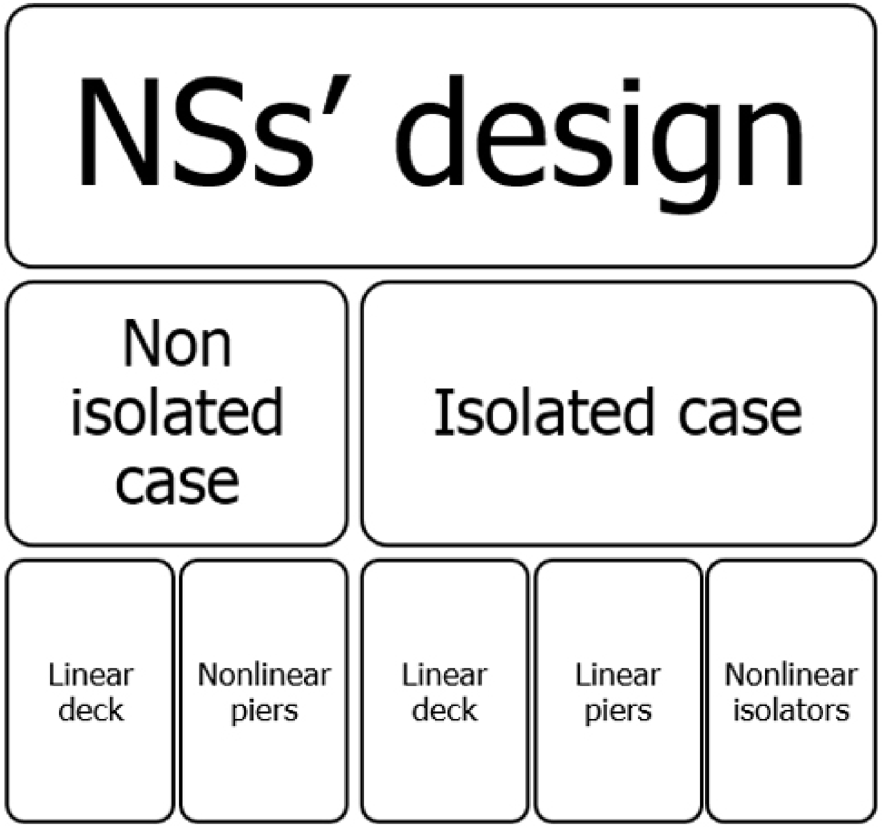
- CONVERGENCE IS NOT ENSURED;
- HIGH VARIANCE OF SINGLE STEP SOLVING TIME (NON-DETERMINISTIC).

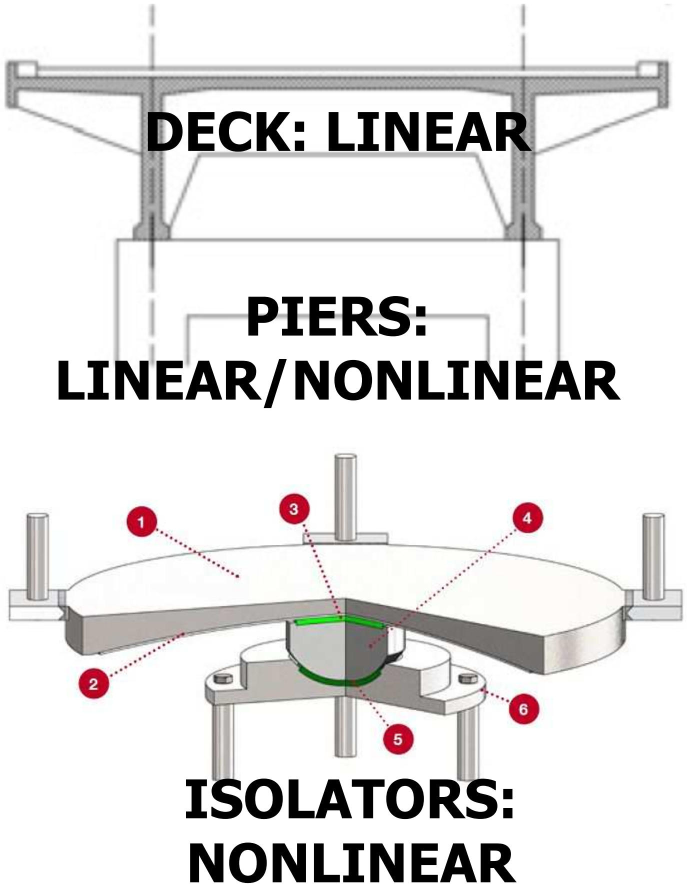


FROM THE HYBRID SIMULATION PERSPECTIVE:

- TEST CAN FAIL;
- ACTUATORS CAN STOP UNTIL THE NUMERICAL PART IS SOLVED (MATERIAL RELAXATION IN THE PS)

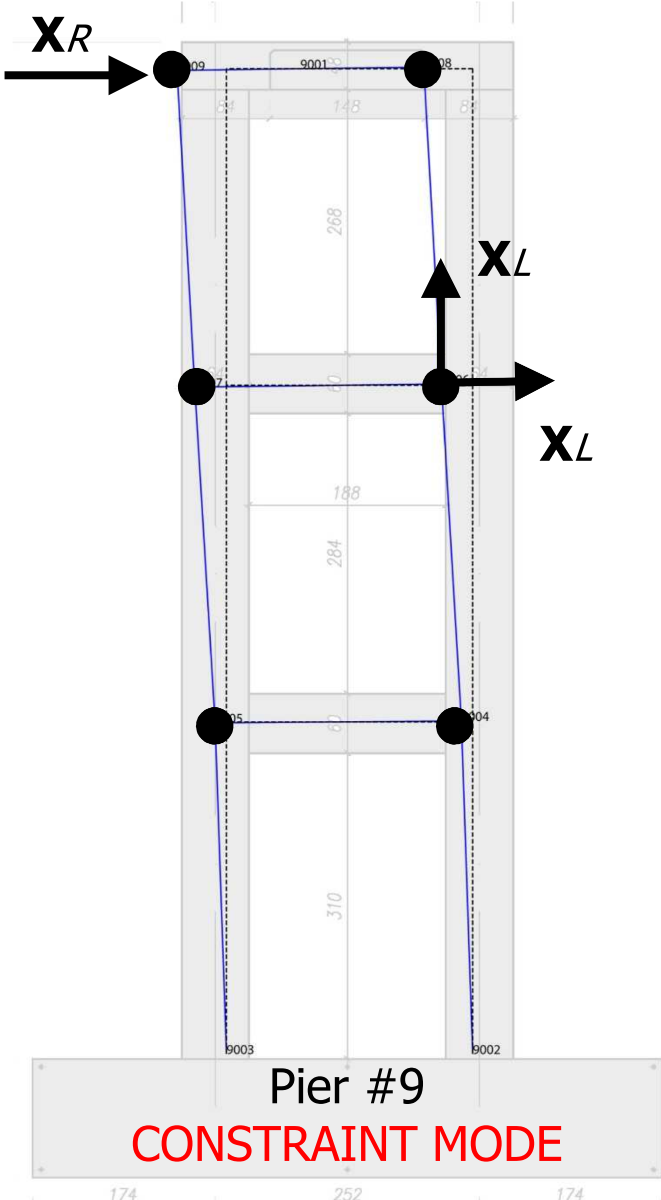
REDUCED NONLINEAR NUMERICAL PIERS WERE NEEDED !!!





Substructuring scheme and subparts

DYNAMIC SUBSTRUCTURING OF OPENSEES PIERS



Pier #9
CONSTRAINT MODE

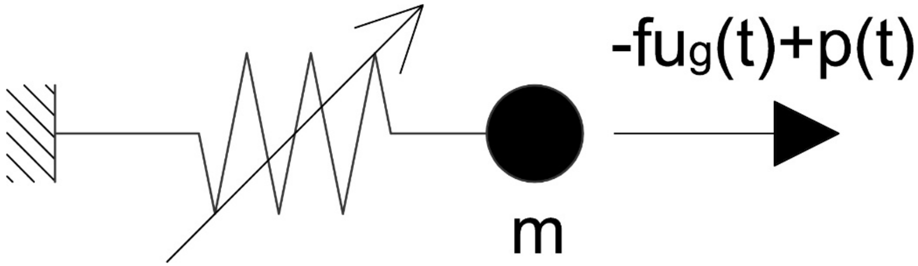
GUYAN static condensation:

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_R \\ \mathbf{x}_L \end{bmatrix} = \mathbf{T} \cdot \mathbf{x}_R$$

$$k = \mathbf{T}^T \mathbf{K} \mathbf{T}, m = \mathbf{T}^T \mathbf{M} \mathbf{T}, f = \mathbf{T}^T \mathbf{M} \mathbf{L}$$

CONSTRAINT MODES: static deformation shapes owing to unit displacements applied to boundary DoFs, one by one, whilst the others retained

PIER REDUCED TO A S-DOF NONLINEAR HYSTERETIC SYSTEM



$$\begin{cases} r + c \cdot \dot{x} + m \cdot \ddot{x} = -f \cdot \ddot{u}_g(t) + p(t) \\ \dot{r} = \left[\underline{\rho} \cdot k / \left(1 + \underline{\alpha} \cdot x^2\right) - (\underline{\beta} \cdot sgn(\dot{x} \cdot r) + \gamma) |r|^n \right] \cdot \dot{x} \end{cases}$$

$p(t)$= transversal force history from OpenSEES;

$\ddot{u}_g(t)$= input accelerogram;

k, c, m, f = linear parameters;

$\rho, \alpha, \beta, \gamma, n$ = nonlinear parameters.

PARAMETER IDENTIFICATION FOR THE S-DOF NONLINEAR REDUCED PIER

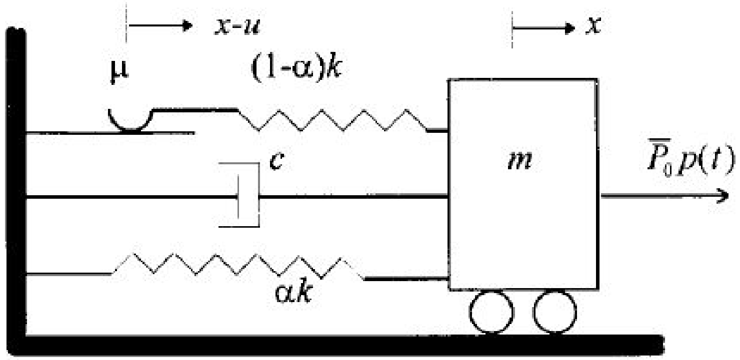
$$\begin{cases} \left\{\hat{\rho}, \hat{\alpha}, \hat{\beta}\right\} = \min_{\rho,\alpha,\beta} NRMSE\left(\mathbf{x}_{red}\left(\rho,\alpha,\beta\right), \mathbf{x}_{OS}\right) \\ \hat{n} = 1, \hat{\gamma} = 0 \end{cases}$$

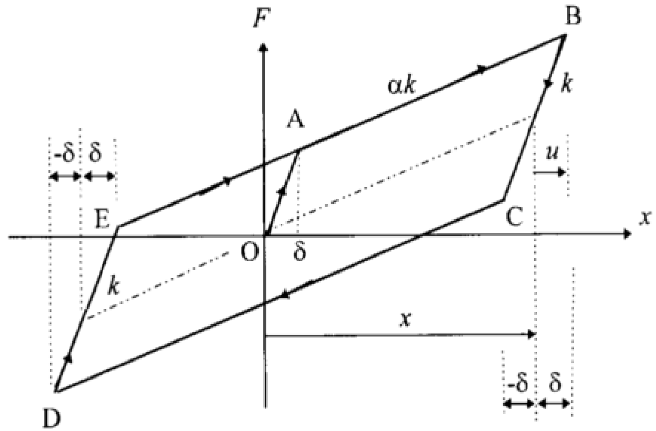
$$NRMSE\left(\mathbf{x}_{red}, \mathbf{x}_{OS}\right) = \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_{i,red} - x_{i,OS}\right)^2}}{\max\left(\mathbf{x}_{OS}\right) - \min\left(\mathbf{x}_{OS}\right)}$$

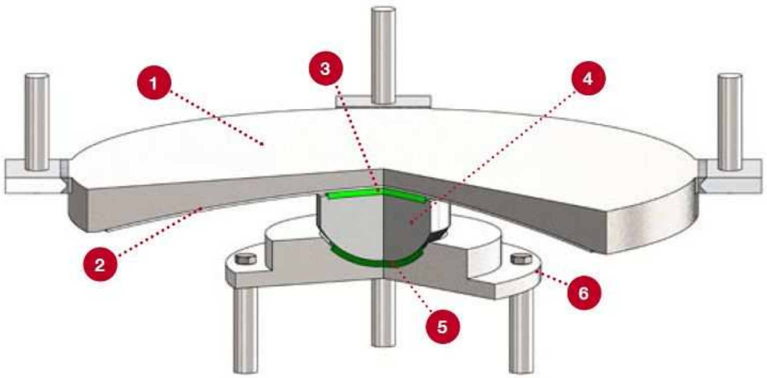
$\mathbf{x}_{OS}$ = displacement responses of the OpenSEES pier

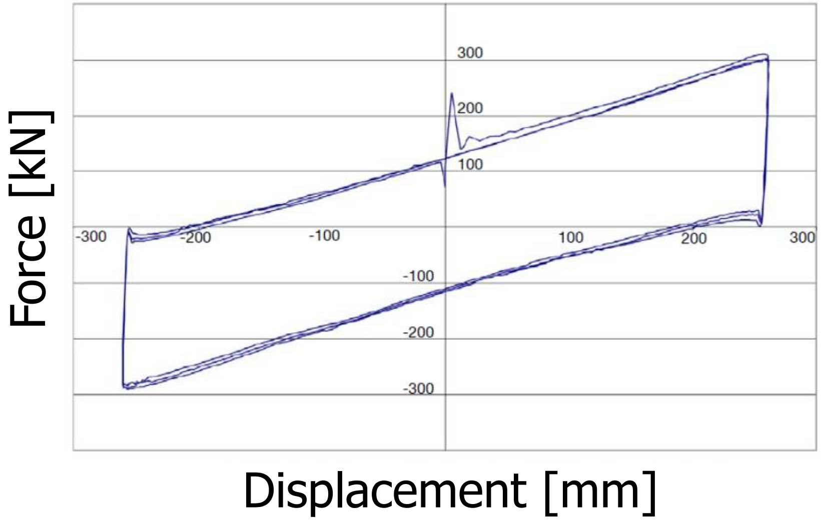
$\mathbf{x}_{red}$ = displacement responses of the S-DOF reduced pier

ISOLATOR REDUCTION TO A S-DOF NONLINEAR SYSTEM



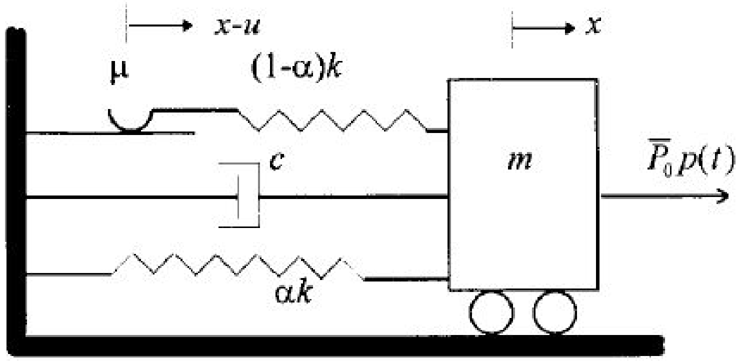


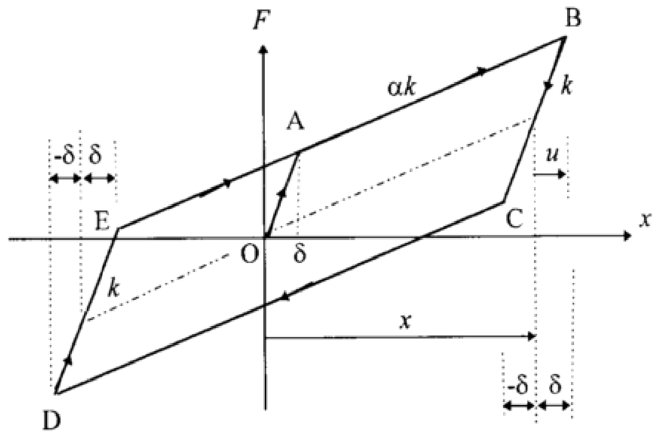




Bilinear hysteretic model

ISOLATOR REDUCTION TO A S-DOF NONLINEAR SYSTEM





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

Bilinear hysteretic model

PARAMETER IDENTIFICATION FOR THE S-DOF REDUCED ISOLATOR

$$\left\{\hat{\alpha},\hat{k},\hat{\delta}\right\} = \min_{\alpha,k,\delta} NRMSE\left(\mathbf{r}_{red}\left(\alpha,k,\delta\right),\mathbf{r}_{OS}\right)$$

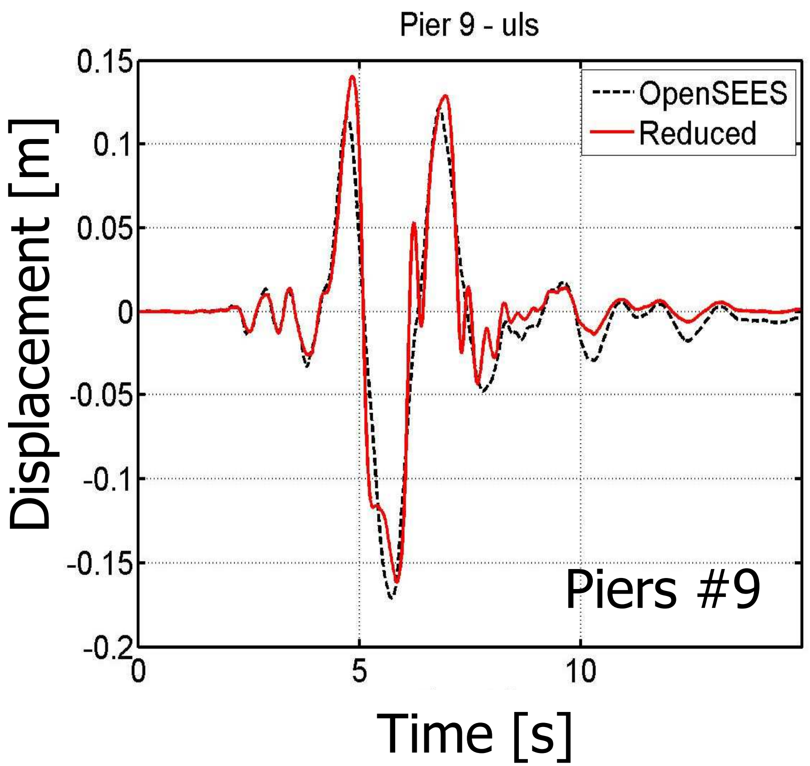
$$\begin{cases} r_{red,i} = \alpha \cdot k \cdot x_{OS,i} + \left(1-\alpha\right) \cdot k \cdot u_i \\ u_i = \sum_{j=1}^{i} \left[\bar{N}\left(\dot{x}_{OS,j}\right) \bar{M}\left(u_j - \delta\right) + M\left(\dot{x}_{OS,j}\right) N\left(u_j + \delta\right) \right] \dot{x}_{OS,j} \cdot \Delta t \end{cases}$$

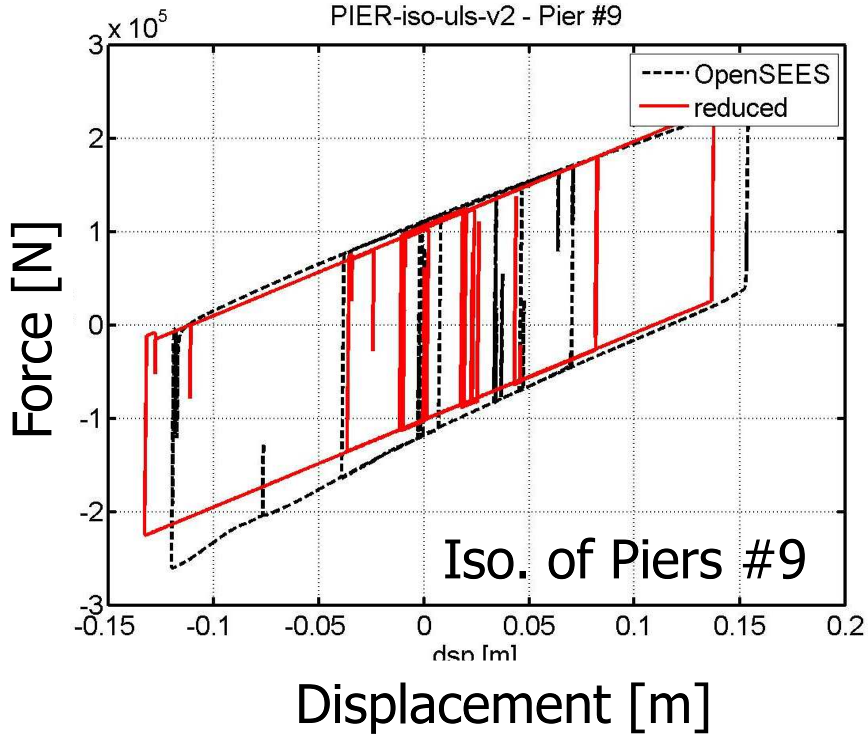
$$\alpha = 0.0046, k = 2.0278e8, \delta = 5.0000e-4$$

$\mathbf{x}_{OS}$ = displacement responses of the OpenSEES isolator

$\mathbf{x}_{red}$ = displacement responses of the S-DOF reduced isolator

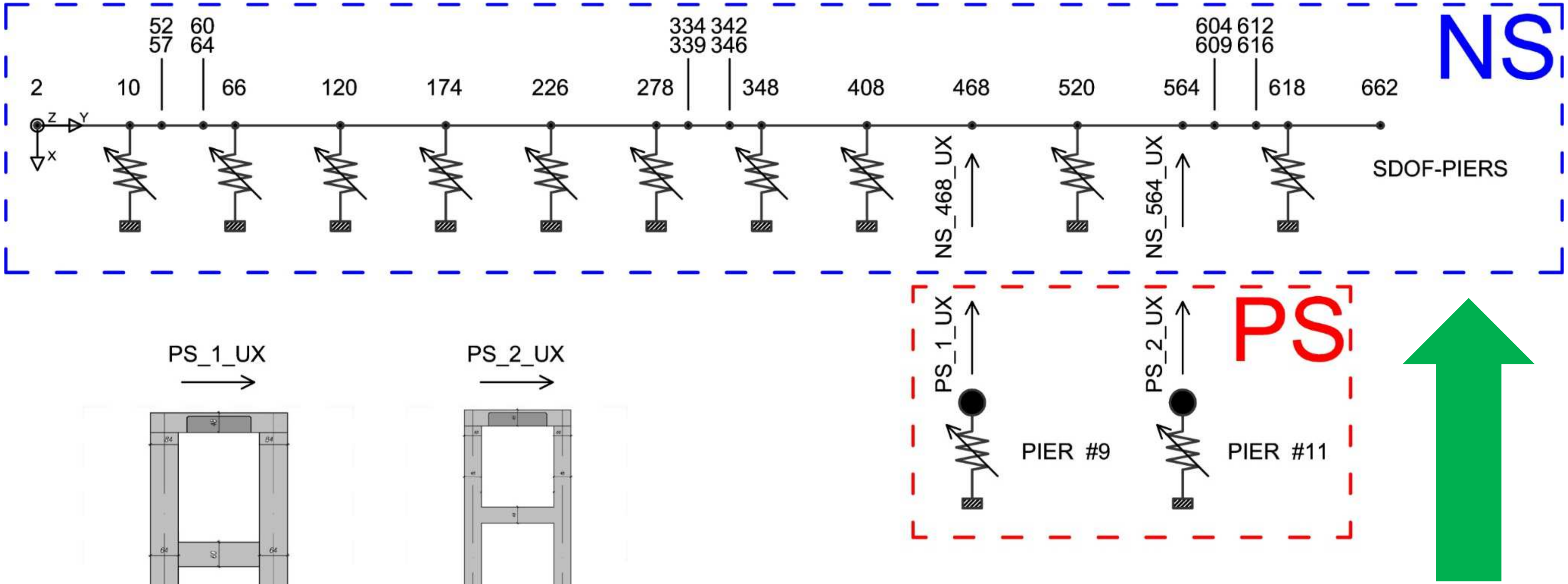
VALIDATION OF SUBSTRUCTURED NUMERICAL PARTS

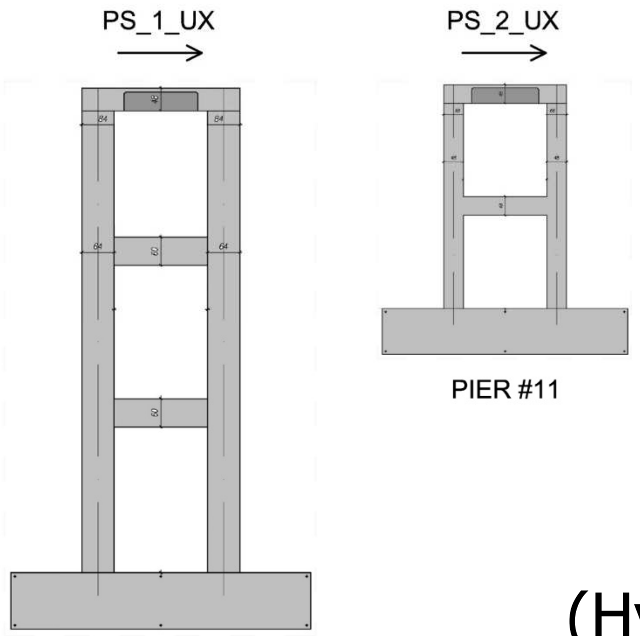




Validation of reduced NSs at ULS

HYBRID MODEL OF THE NON-ISOLATED BRIDGE



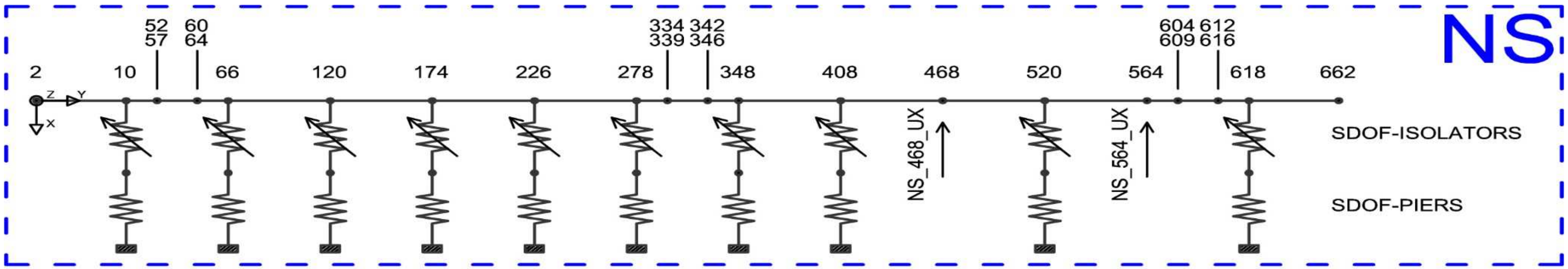


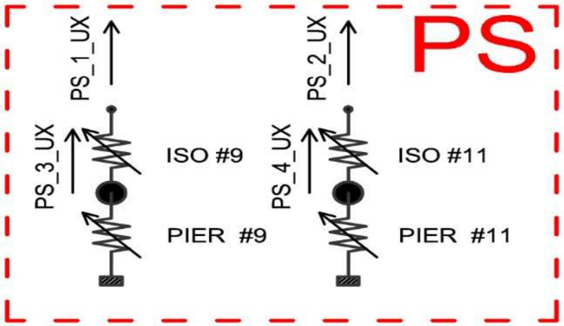
PIER #11

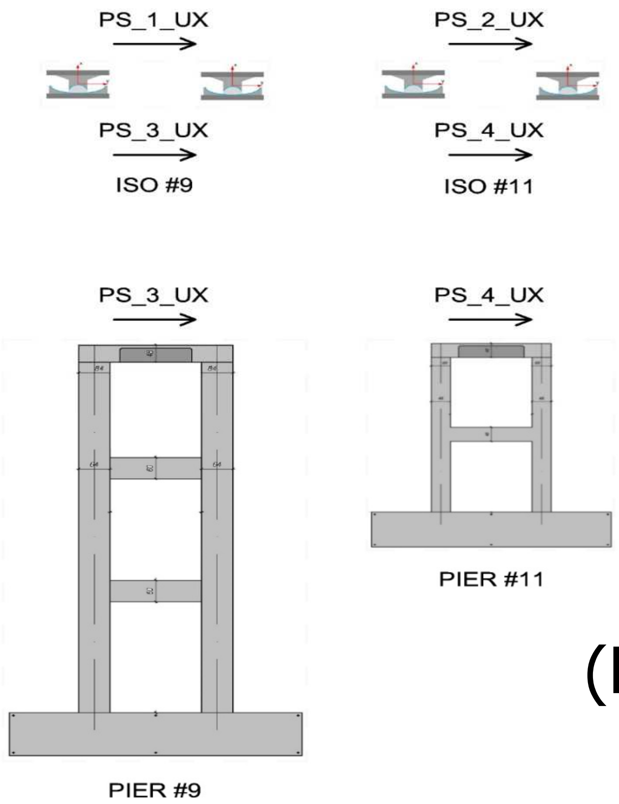
PIER #9

88-DoFs (Hybrid model) << ~900-DoFs (OpenSEES RM)

HYBRID MODEL OF THE ISOLATED BRIDGE



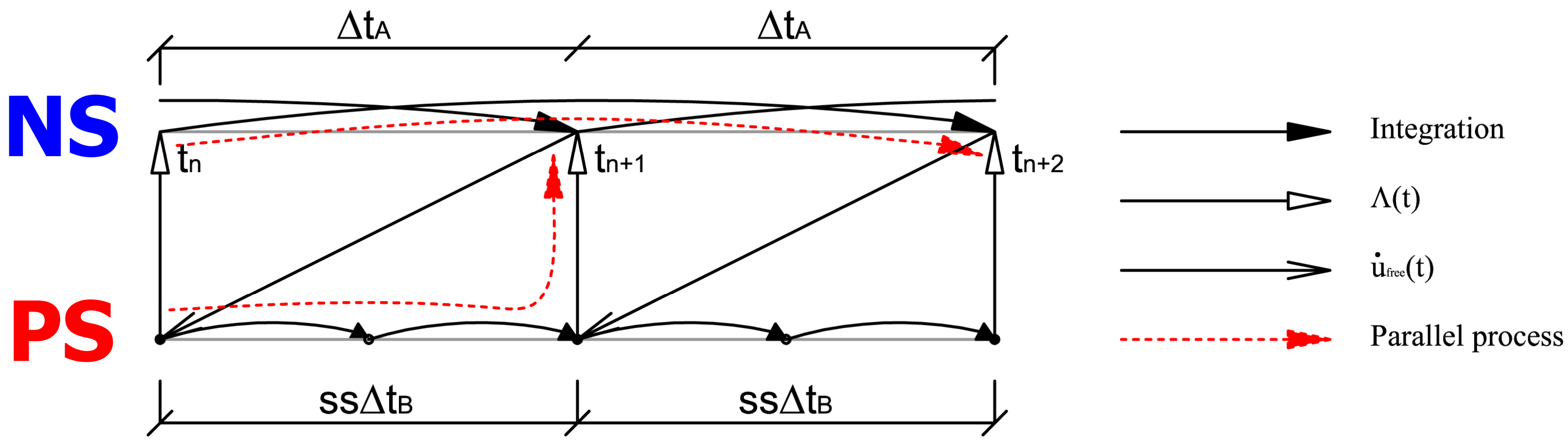




UNIFORM TRANSVERSAL SEISMIC LOADING

88-DoFs (Hybrid model) << ~900-DoFs (OpenSEES RM)

PARTITIONED TIME INTEGRATION



λ = extended testing time scale = 200

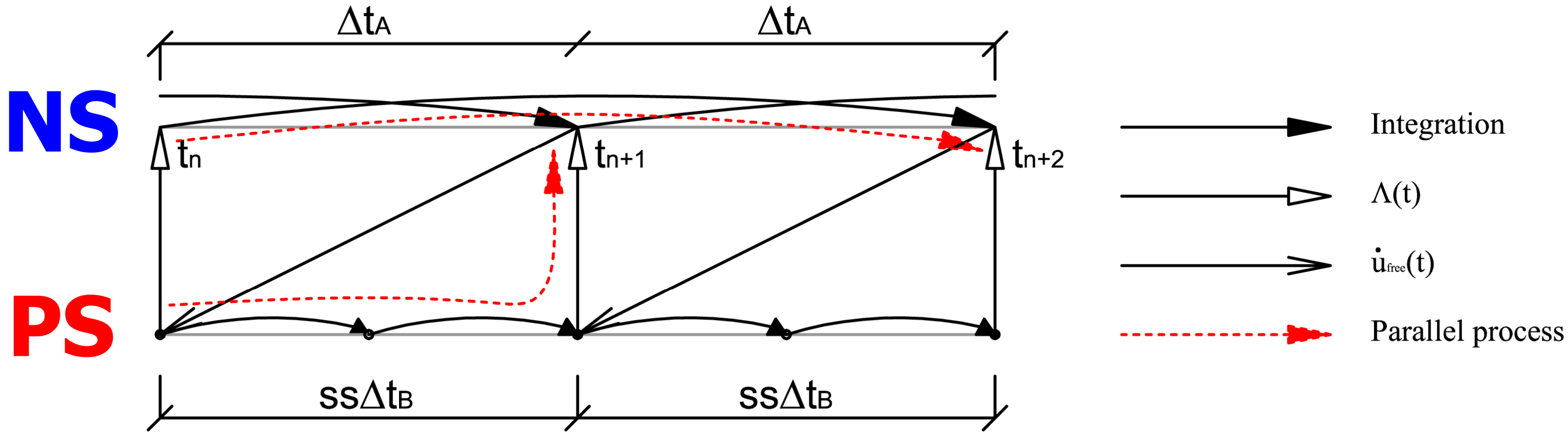
Sim. time step: $\Delta t_A = 4ms$

Exp. time step: $\lambda \cdot \Delta t_A = 200 \cdot 4 = 800ms$

Contr. time step: $\Delta t = 2ms$

Subcycling: $ss = \dfrac{\lambda \cdot \Delta t_A}{\Delta t} = \dfrac{4 \cdot 200}{2} = 400$

PARTITIONED TIME INTEGRATION



λ = extended testing time scale = 200

RESPONSE OF THE NS

Sim. time step: $\Delta t_A = 4ms$

Exp. time step: $\lambda \cdot \Delta t_A = 200 \cdot 4 = 800ms$

Contr. time step: $\Delta t = 2ms$

Subcycling: $ss = \dfrac{\lambda \cdot \Delta t_A}{\Delta t} = \dfrac{4 \cdot 200}{2} = 400$

THE GCbis-MG-α PARALLEL PARTITIONED TIME INTEGRATORS

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

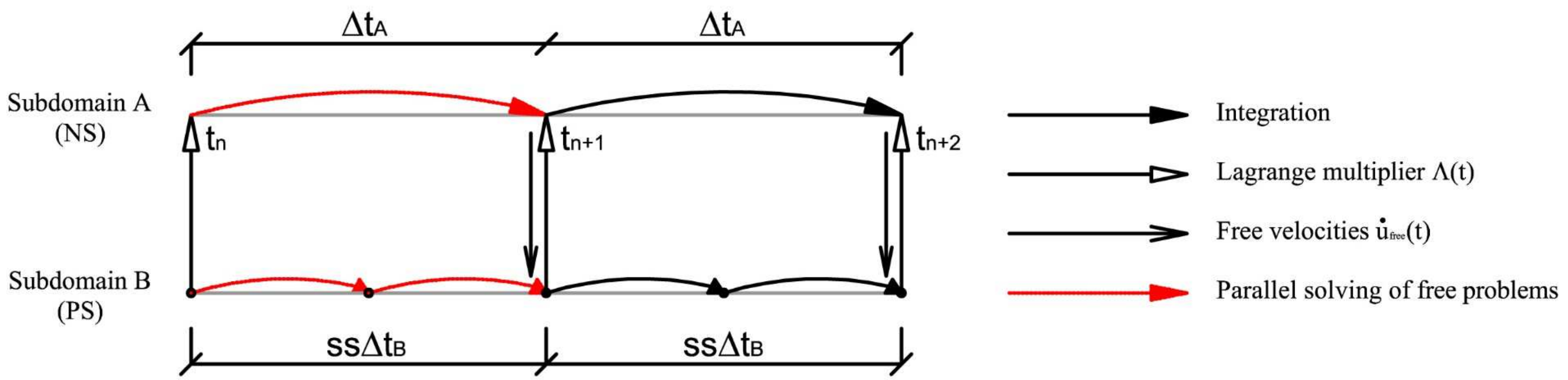
$$\Downarrow$$

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

$$\Downarrow$$

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

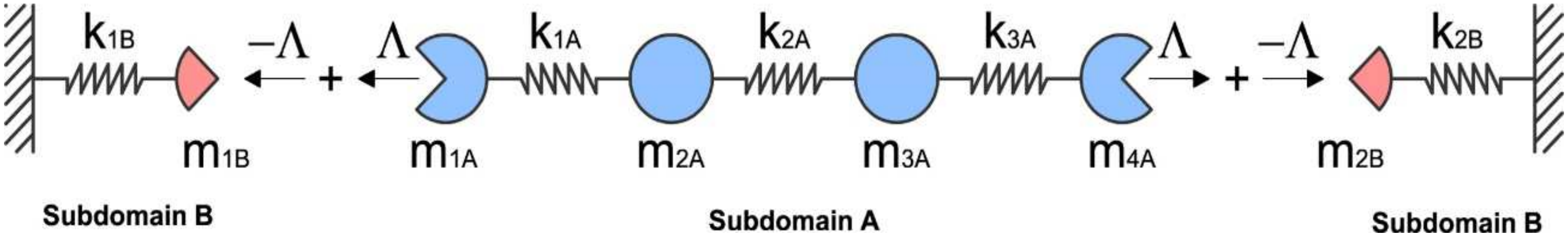
- FIRST ORDER SYSTEMS
- USER CONTROLLED ALGORITHMIC DAMPING
- SELF STARTING
- ENERGY PRESERVING

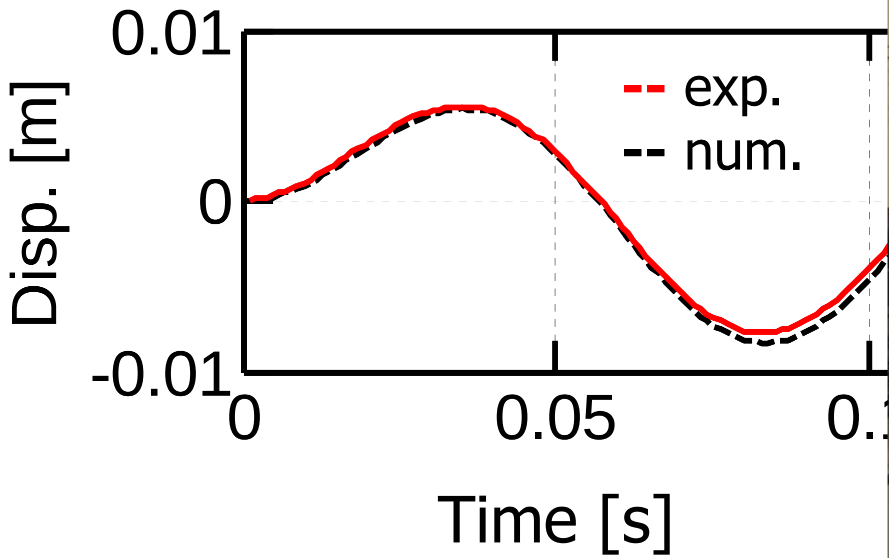


EXPERIMENTAL VALIDATION OF THE GCbis-MG-α METHOD

Free decay response to: $u_2 = 0.01$

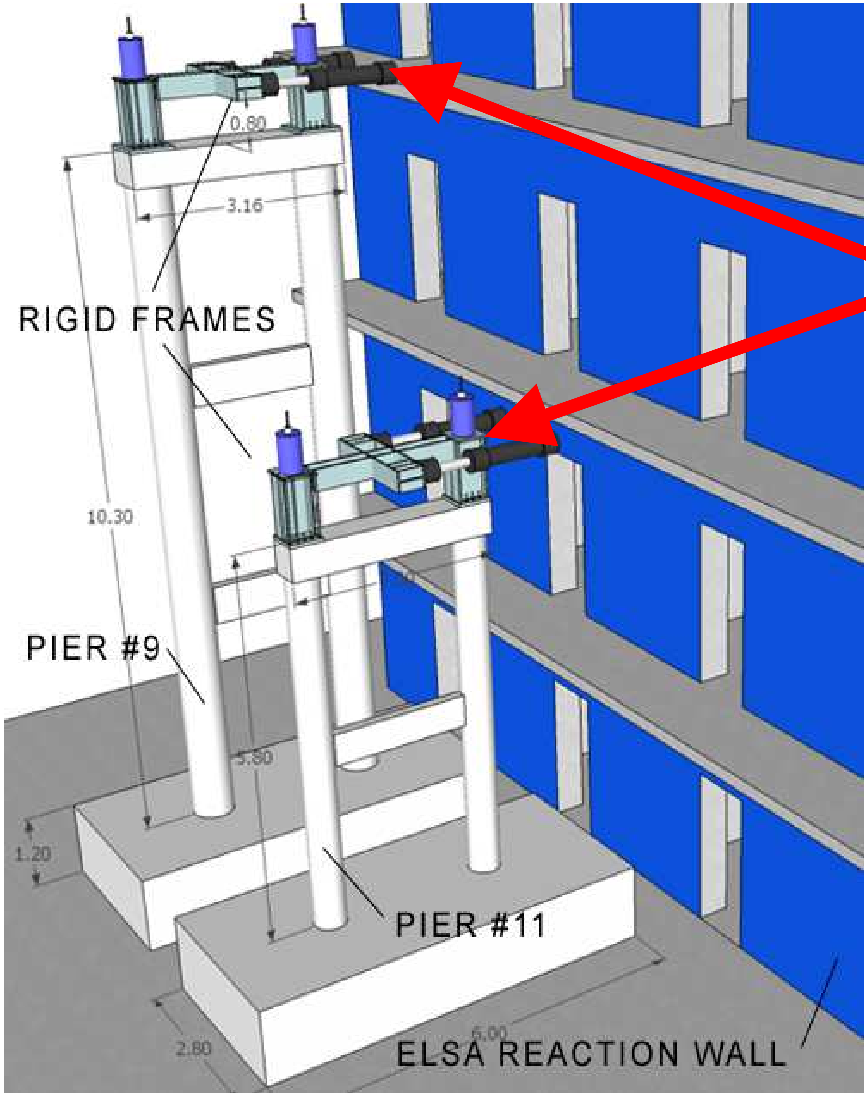
$\lambda = 128, \Delta t = 1/1024, \Delta t_A = 1/1024, ss = 128$

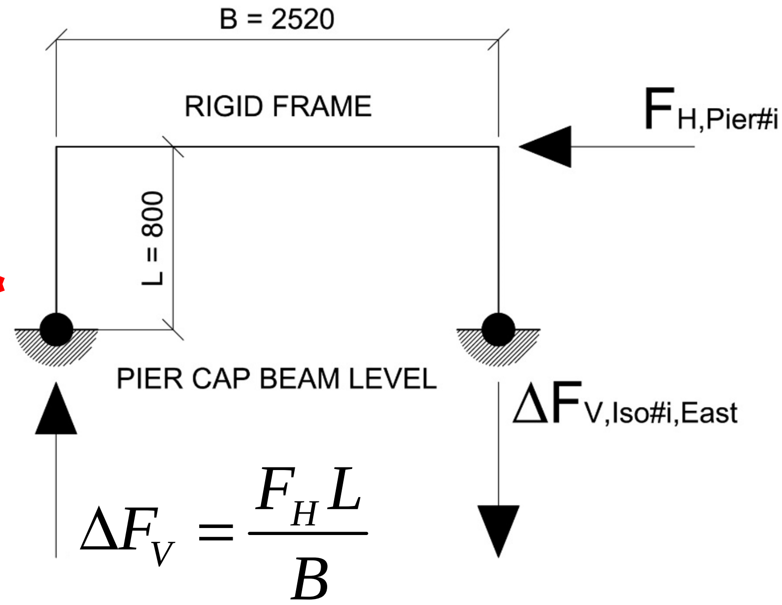




EXPERIMENTAL SET-UP AT THE ELSA LAB. OF THE JRC OF ISPRA (VA)

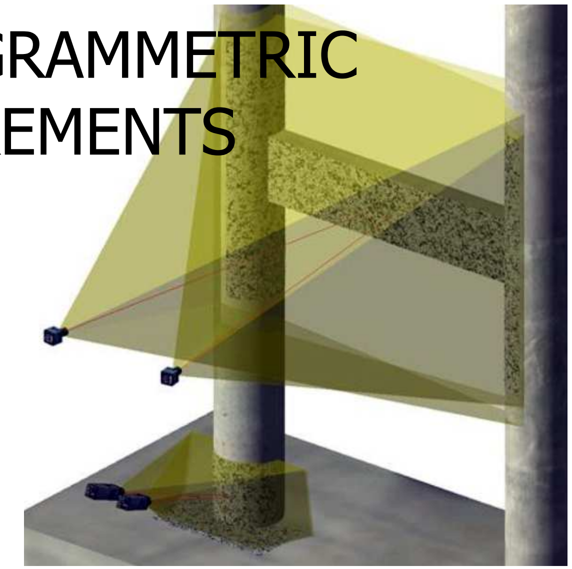
EXPERIMENTAL SET-UP OF PIERS



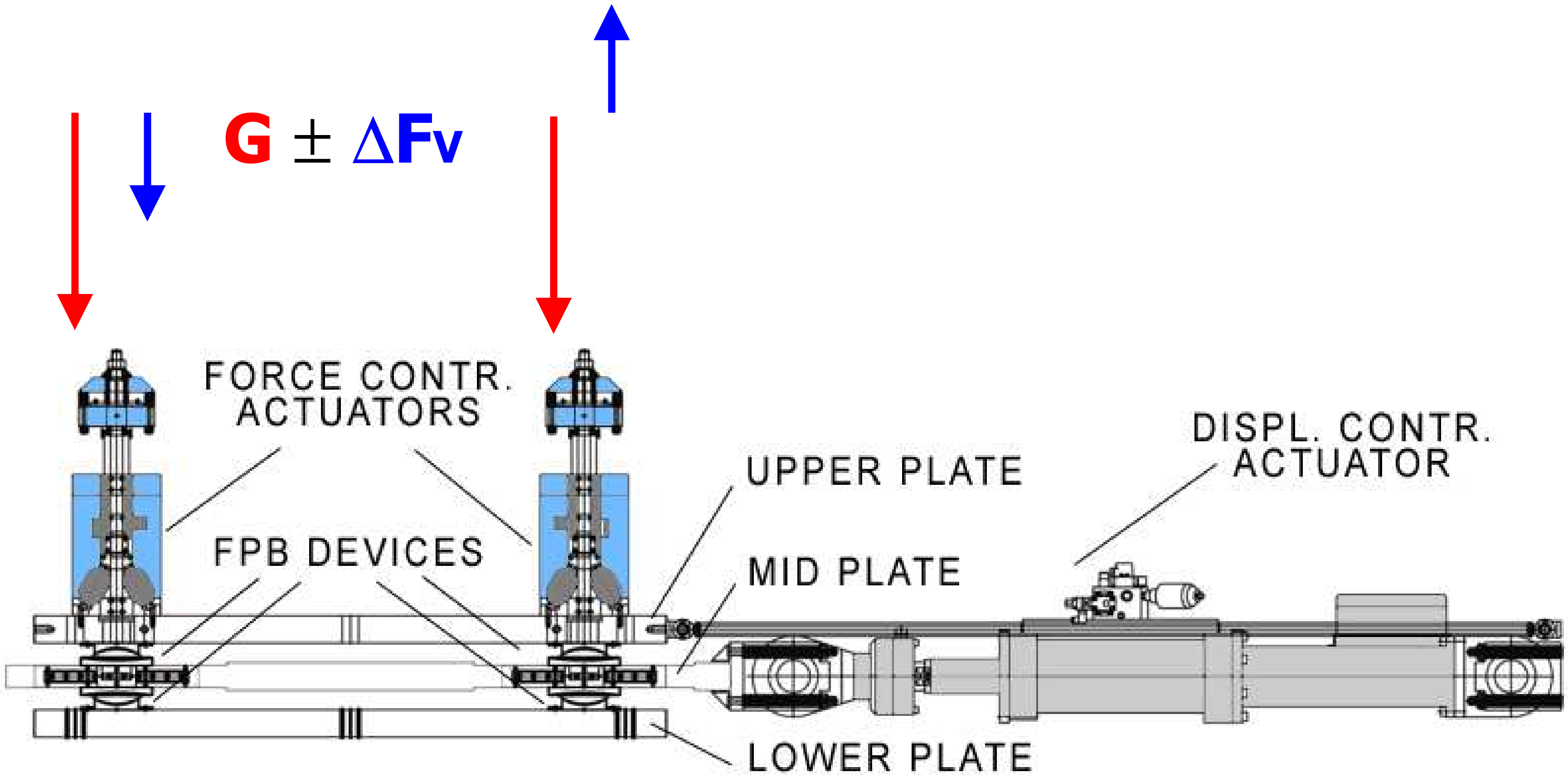


$$\Delta F_V = \frac{F_H L}{B}$$

PHOTOGRAMMETRIC MEASUREMENTS

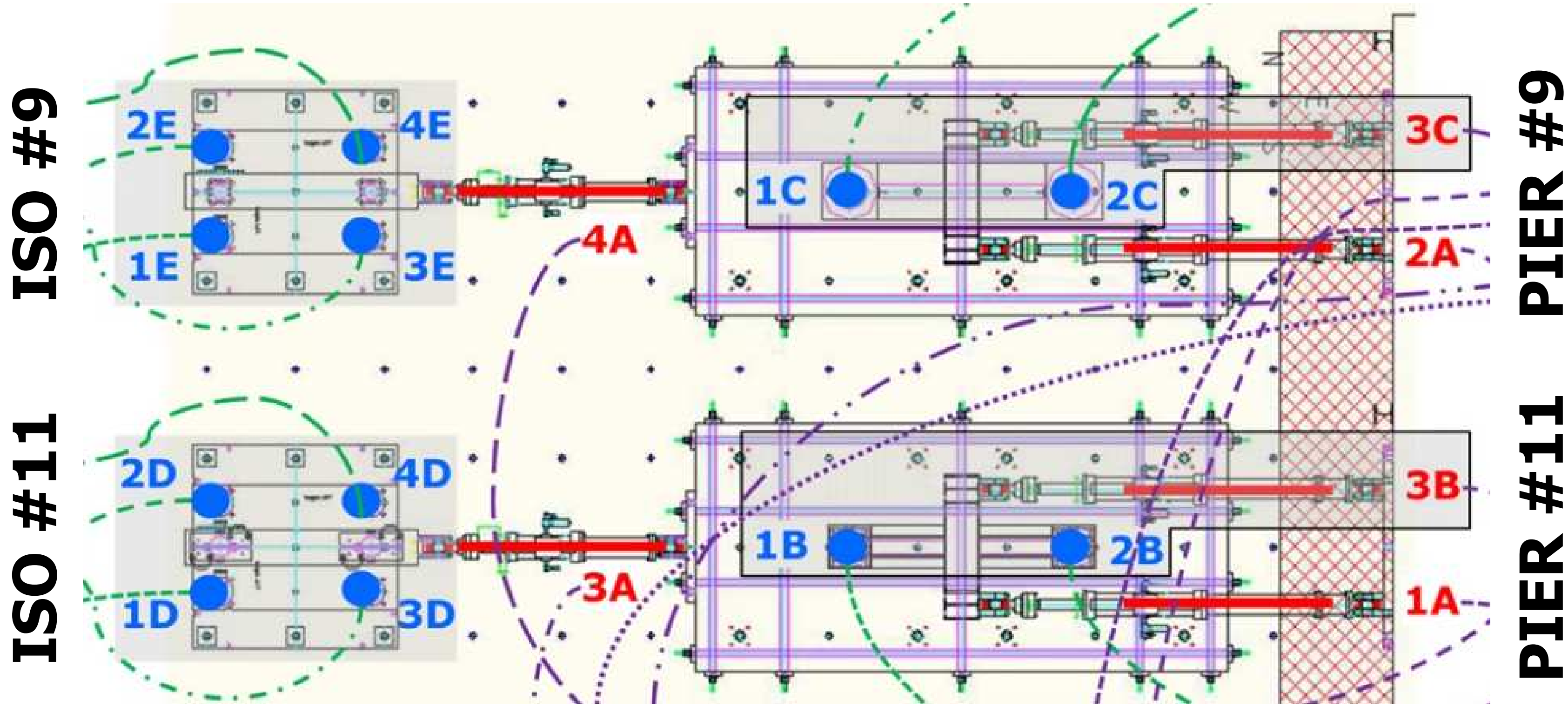


EXPERIMENTAL SET-UP OF ISOLATORS



1:2.5 SCALE MOCK-UP ISOLATORS

EXPERIMENTAL EQUIPMENT

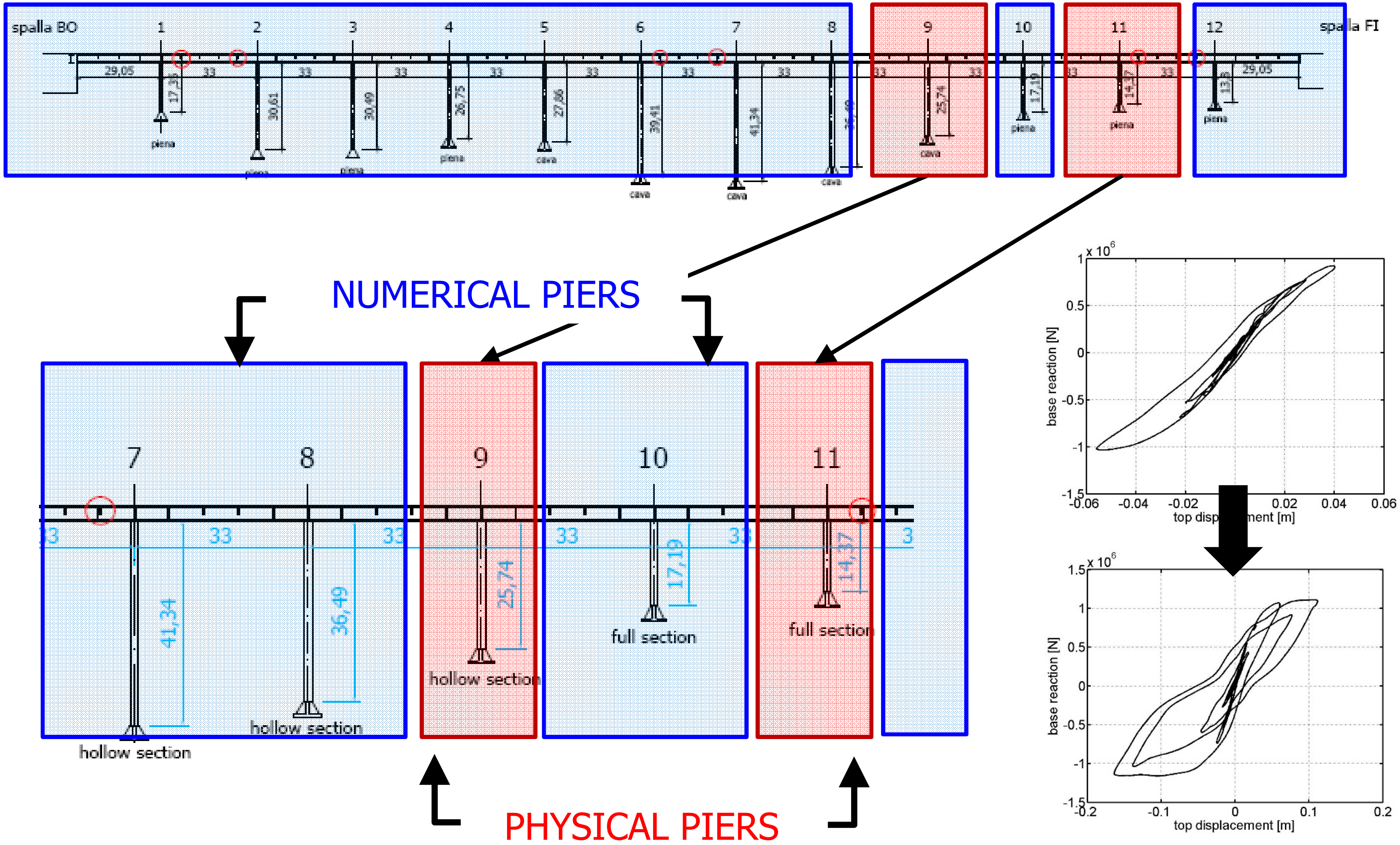


Plan view of the experimental set-up

: Vertical actuator (12x) in force control mode;

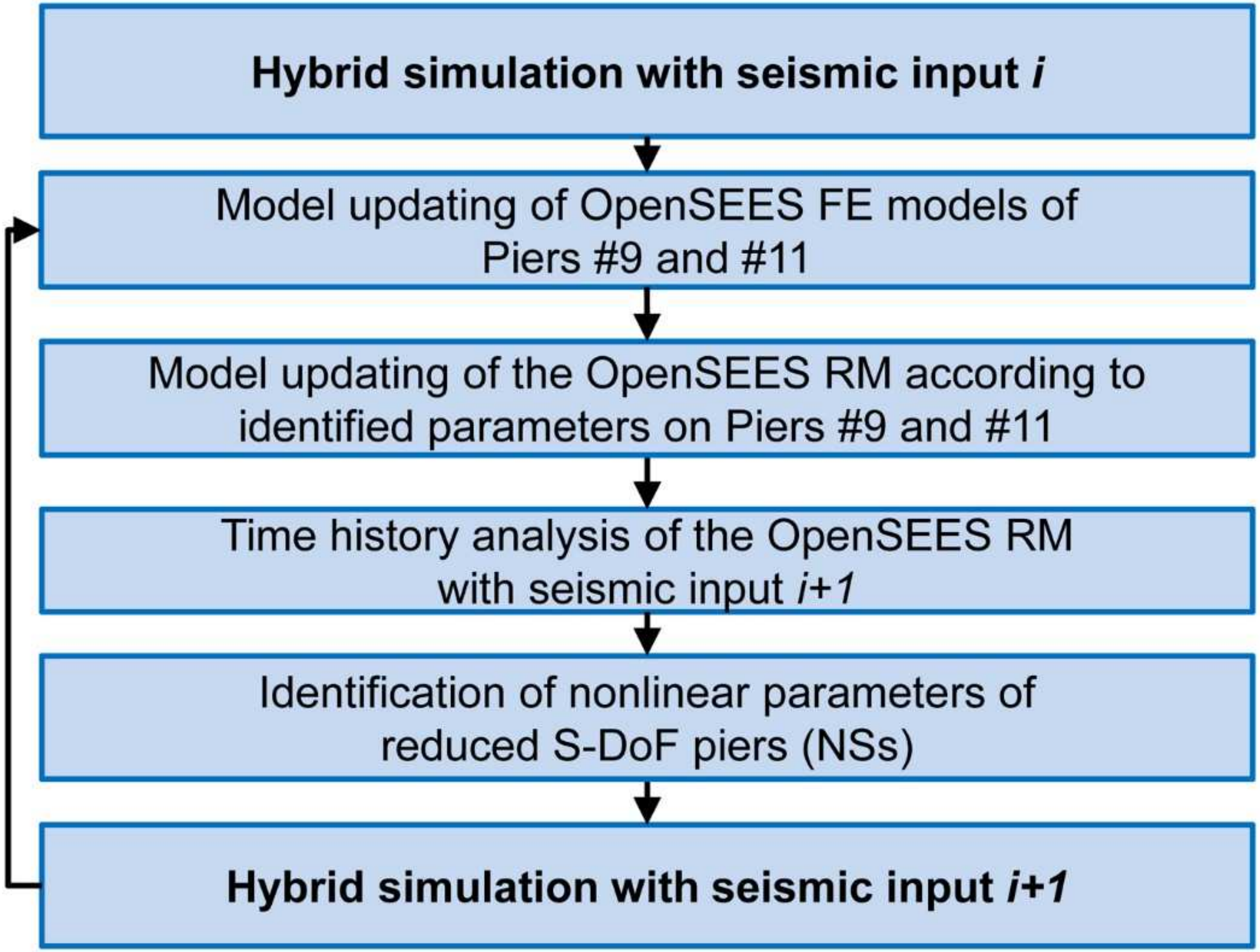
: Horizontal actuator (6x) in displacement control mode;

NEED FOR AN UPDATING STRATEGY FOR NUMERICAL PIERS

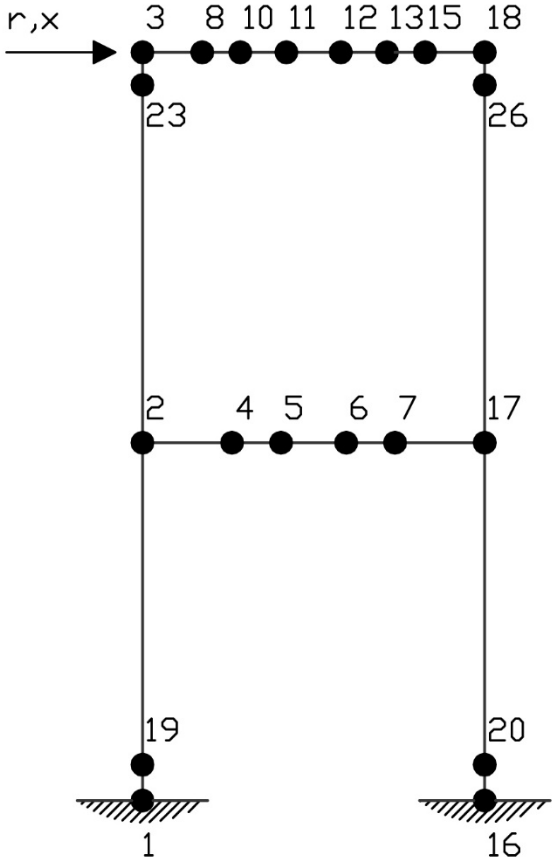


DAMAGE MUST ACCUMULATE ON BOTH PSs AND NSs TEST BY TEST

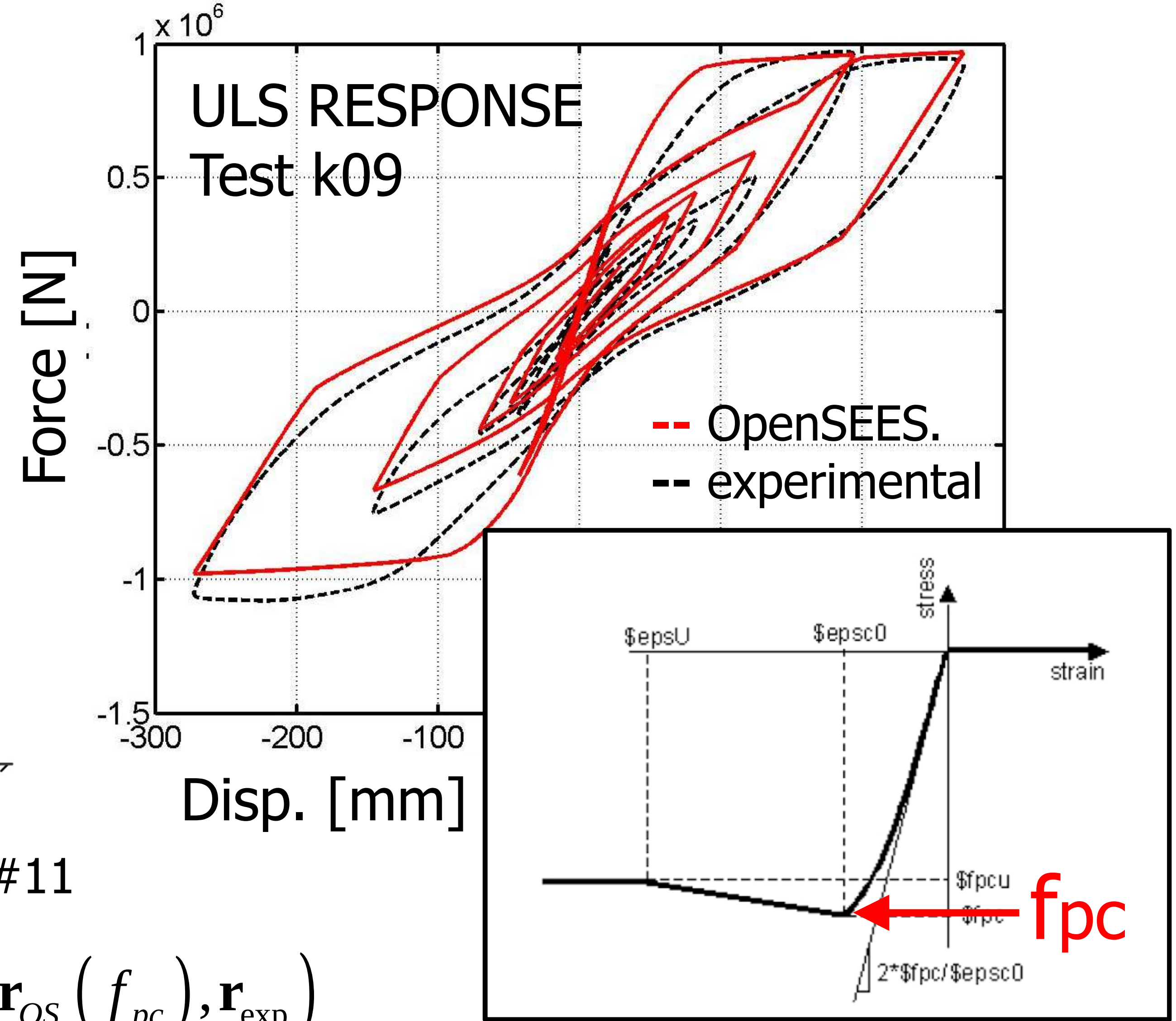
PROPOSED MODEL UPDATING TESTING PROCEDURE



MODEL UPDATING OF OPENSEES FE MODEL OF PHYSICAL PIERS



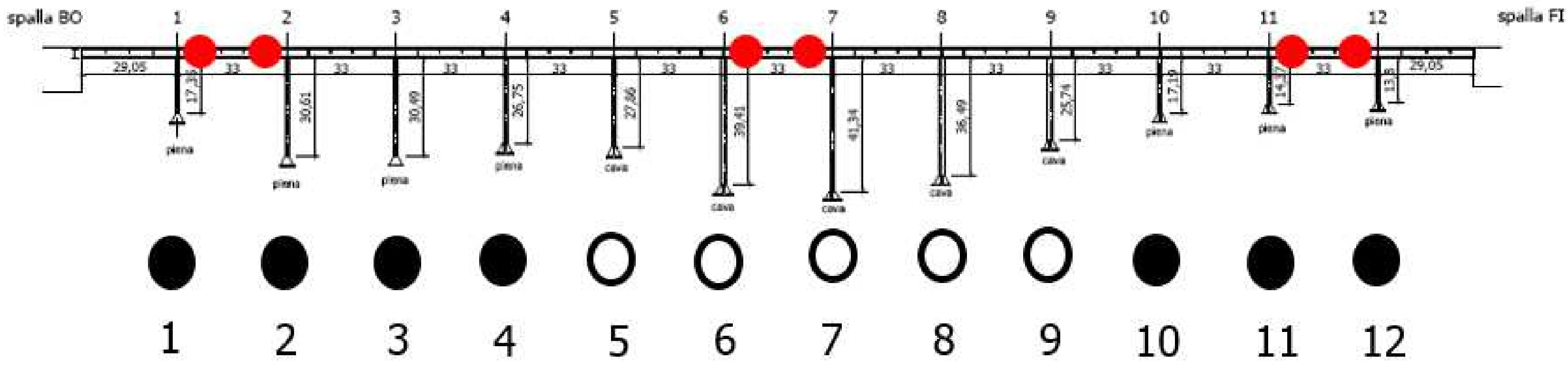
OpenSEES FEM of Pier #11



$$\left\{ \hat{f}_{pc} \right\} = \min_{f_{pc}} NRMSE\left(\mathbf{r}_{OS}\left(f_{pc} \right), \mathbf{r}_{\exp} \right)$$

 Maximum compressive strength of *concrete01*

MODEL UPDATING OF THE OPENSEES RM OF THE BRIDGE



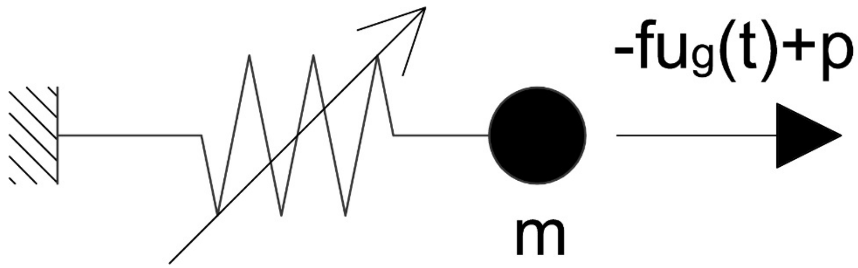
Piers with hollow cross section columns.

Piers with solid cross section columns.

Gerber saddle joint

Pier #9 → Hollow piers

Pier #11 → Solid piers



$$\begin{cases} r + c\cdot\dot{x} + m\cdot\ddot{x} = -f\cdot\ddot{u}_g(t) + p(t) \\ \dot{r} = \left[\rho\cdot k/\left(1+\alpha\cdot x^2\right) - (\beta\cdot sgn(\dot{x}\cdot r)+\gamma)\,|\,r\,|^n\right]\cdot\dot{x} \end{cases}$$

$$\begin{cases} \left\{\hat{\rho},\hat{\alpha},\hat{\beta}\right\} = \min\limits_{\rho,\alpha,\beta} NRMSE\left(\mathbf{x}_{red}\left(\rho,\alpha,\beta\right),\mathbf{x}_{OS}\right) \\ \hat{n} = 1, \hat{\gamma} = 0 \end{cases}$$

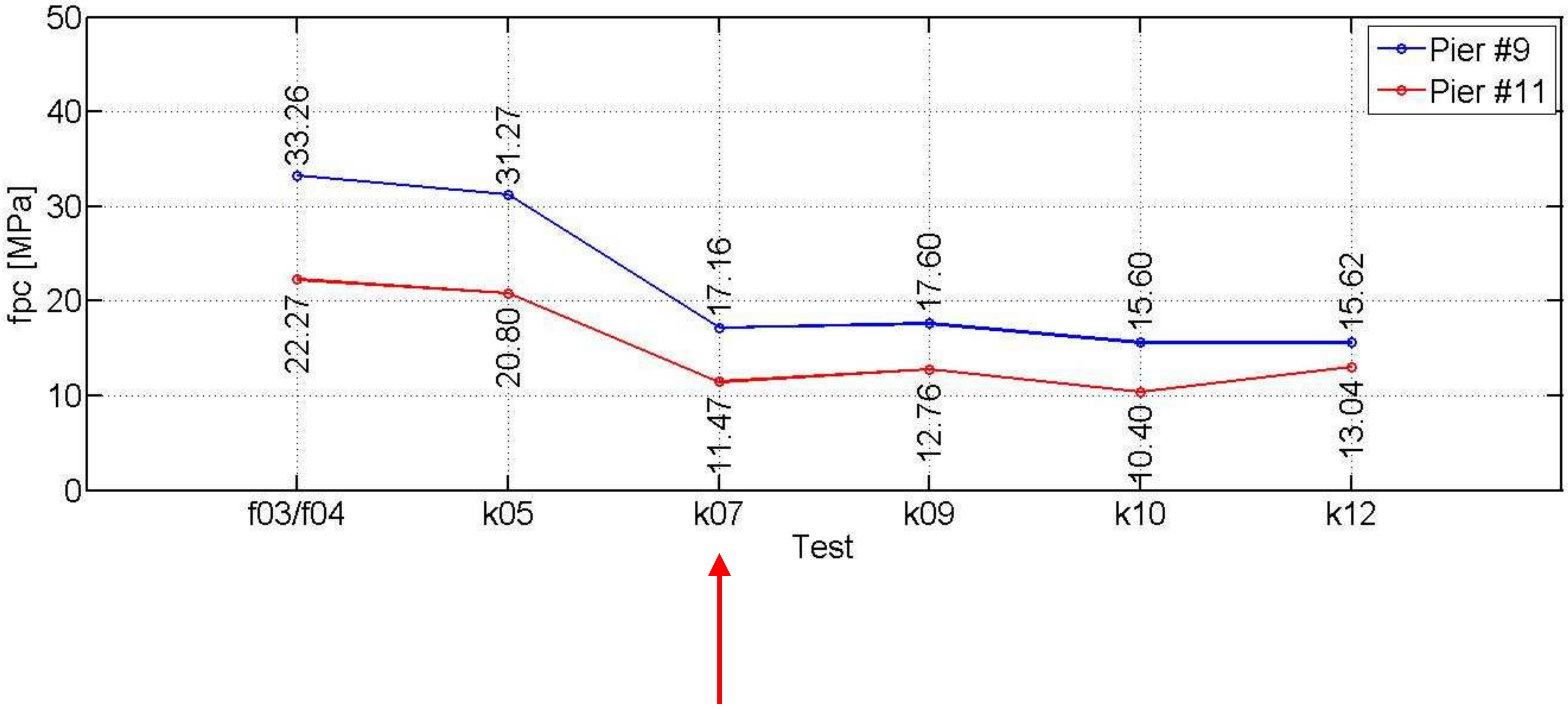
$\mathbf{x}_{OS}$ = displacement responses of the **UPDATED OpenSEES RM**

$\mathbf{x}_{red}$ = displacement responses of the reduced pier

LIST OF MAIN HYBRID SIMULATIONS

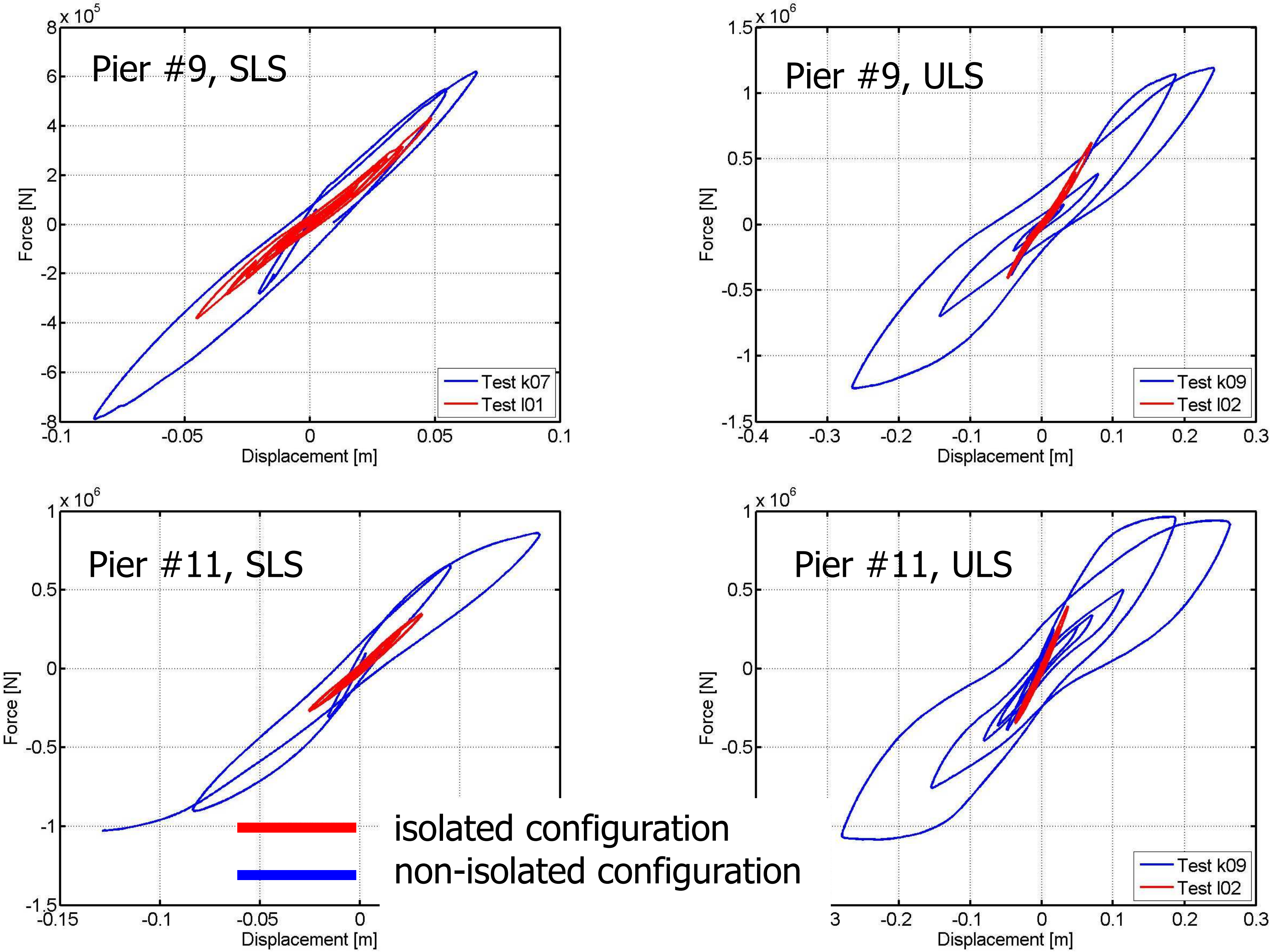
1) Test k06: non-isolated bridge at SLS (10% PGA)
2) Test k07: non-isolated bridge at SLS
3) Test l01: isolated bridge at SLS
4) Test l02: isolated bridge at ULS
5) Test k09: non-isolated bridge at ULS
6) Test k11: non-isolated bridge at ULS (after shock)
7) Test k12: non-isolated bridge at ULS (200% PGA)

EVOLUTIONS OF CONCRETE COMPRESSIVE STRENGTHS IDENTIFIED ON PHYSICAL PIERS



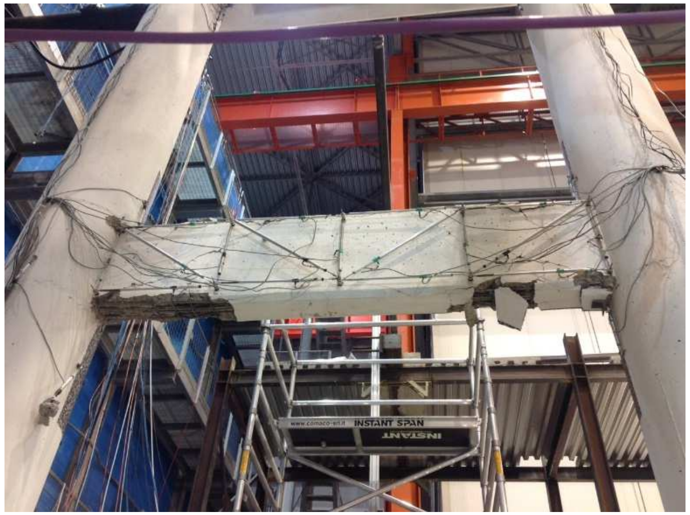
NON-ISOLATED BRIDGE AT SLS

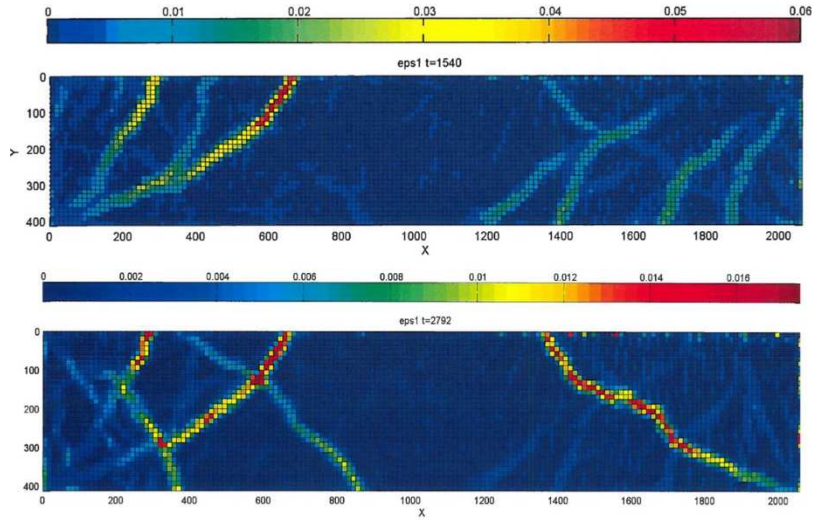
HYSTERETIC LOOPS OF PHYSICAL PIERS



DAMAGE PATTERN AFTER ULS TESTS

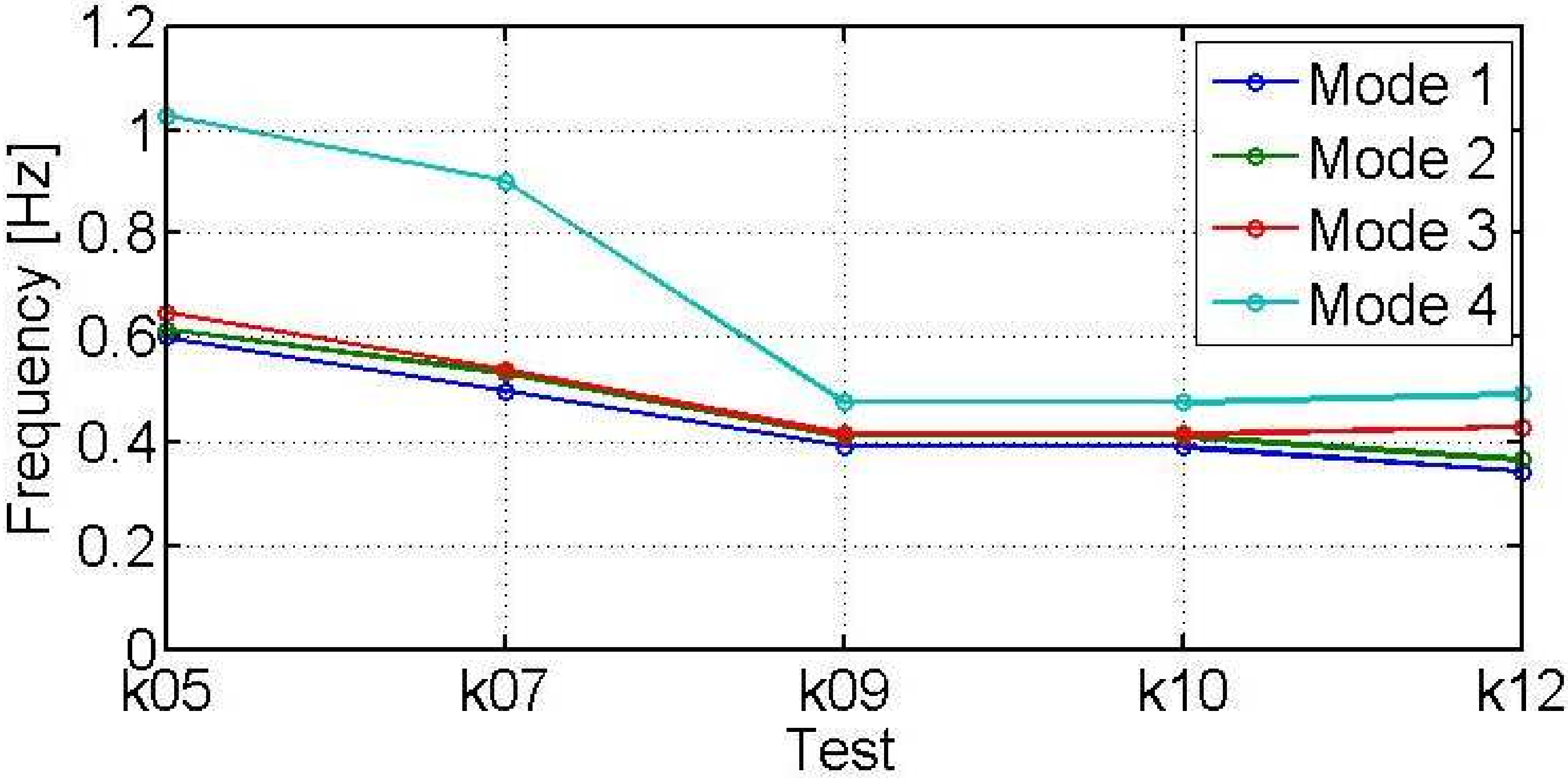
Column ends uplifting, expulsion of concrete covers





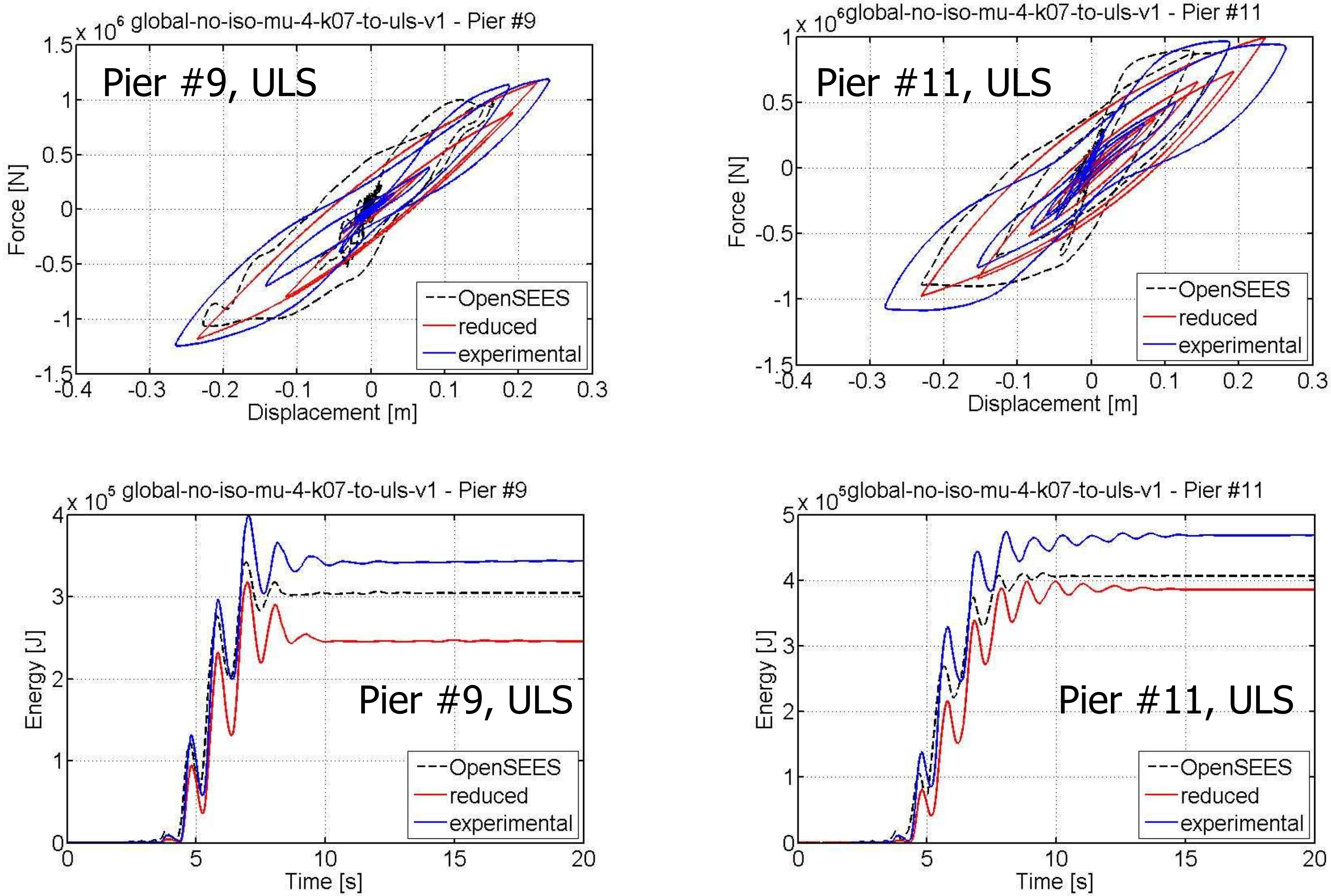
Diffuse crack patterns

EVOLUTIONS OF MAIN BRIDGE EIGENFREQUENCIES



Eigenvalues of linearized non-isolated models

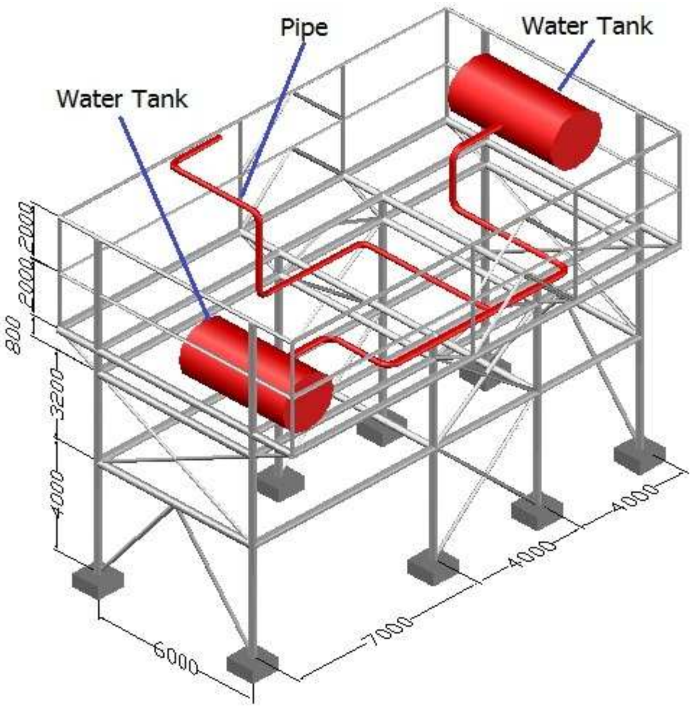
COMPARISON OF NUMERICAL RESPONSES TO PHYSICAL MEASUREMENTS



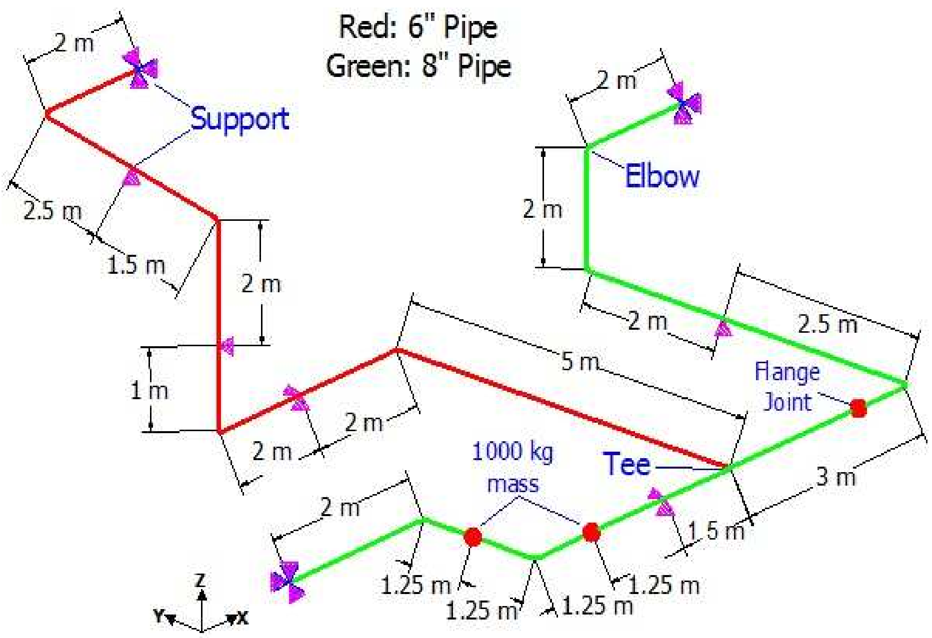
Hysteretic loops and dissipated energies of Piers #9 and #11

HYBRID SIMULATION OF AN INDUSTRIAL PIPING SYSTEM

THE INDUSTRIAL PIPING SYSTEM CASE STUDY



A 3D model of the piping+support

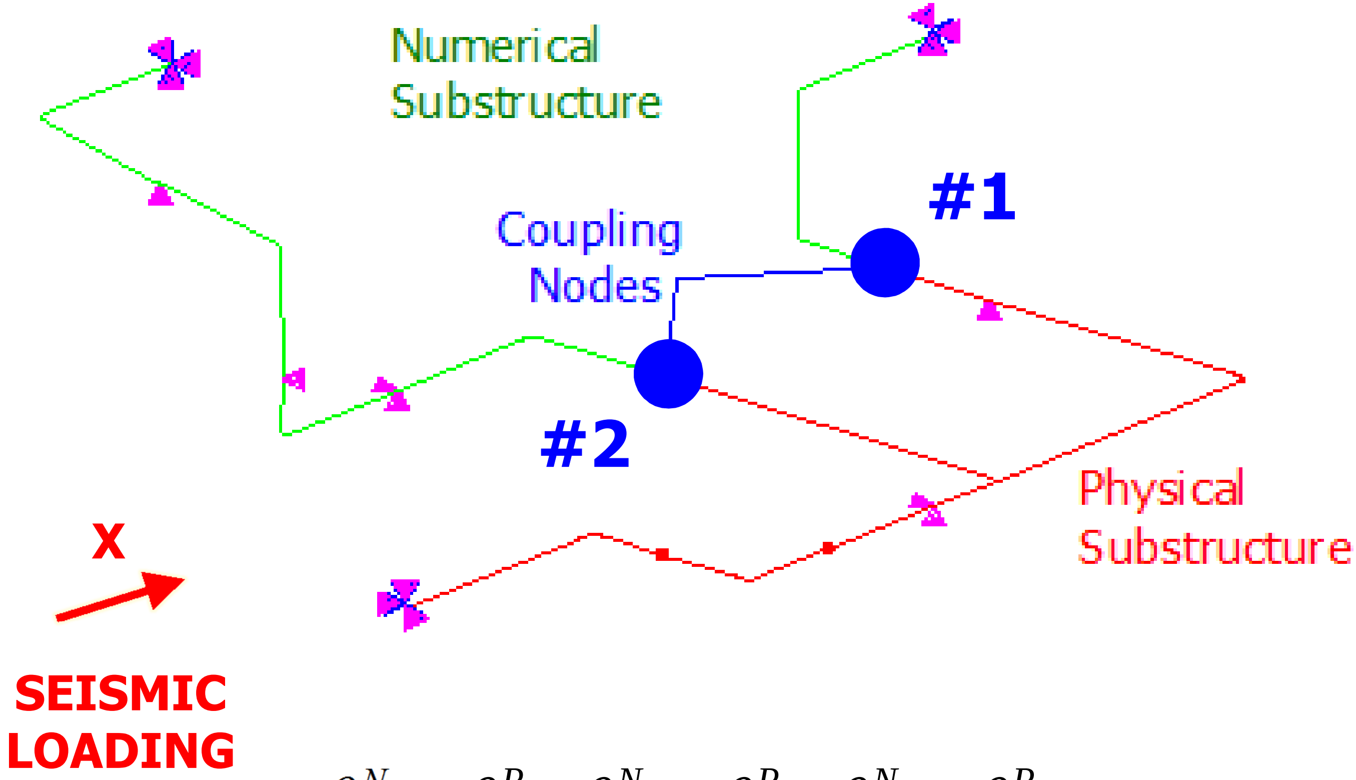


Dimensions and specifications of the piping

Table Characteristics of the piping system

Pipe Size	Material	Liquid/Internal Pressure
8″ and 6″ Schedule 40	API 5L Gr. X52 fy= 418 Mpa; fu = 554 Mpa; Elongation = 35.77%	Water/ 3.2 MPa

ANSYS REFERENCE MODEL (RM) OF THE PIPING

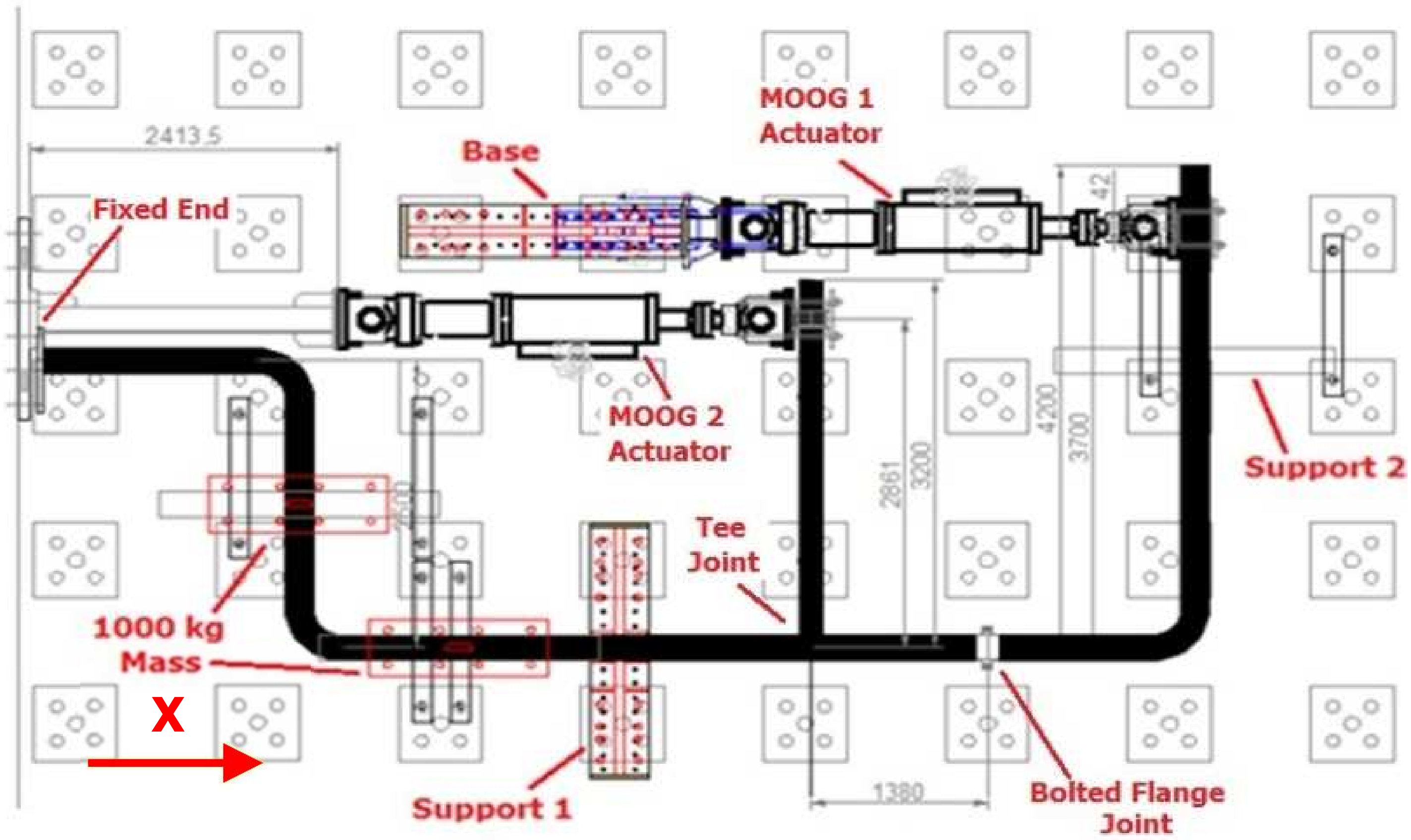


$$\theta_x^N \neq \theta_x^P,\ \theta_y^N \neq \theta_y^P,\ \theta_z^N \neq \theta_z^P$$

Positions of minimum bending moments were chosen as coupling nodes.

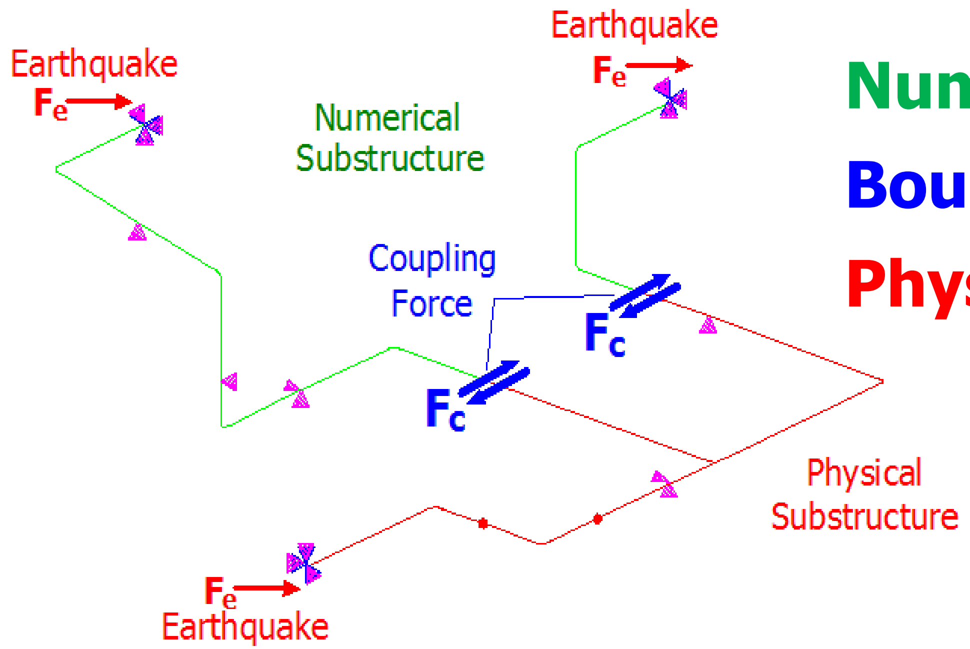
The seismic action was applied the x direction.

EXPERIMENTAL SET-UP OF THE PS



A pair of hydraulic actuators imposed displacements to coupling DoFs

DOFS PARTITIONING



Numerical-DoFs

Boundary-DoFs

Physical-DoFs

Displacement vector

Restoring force vector

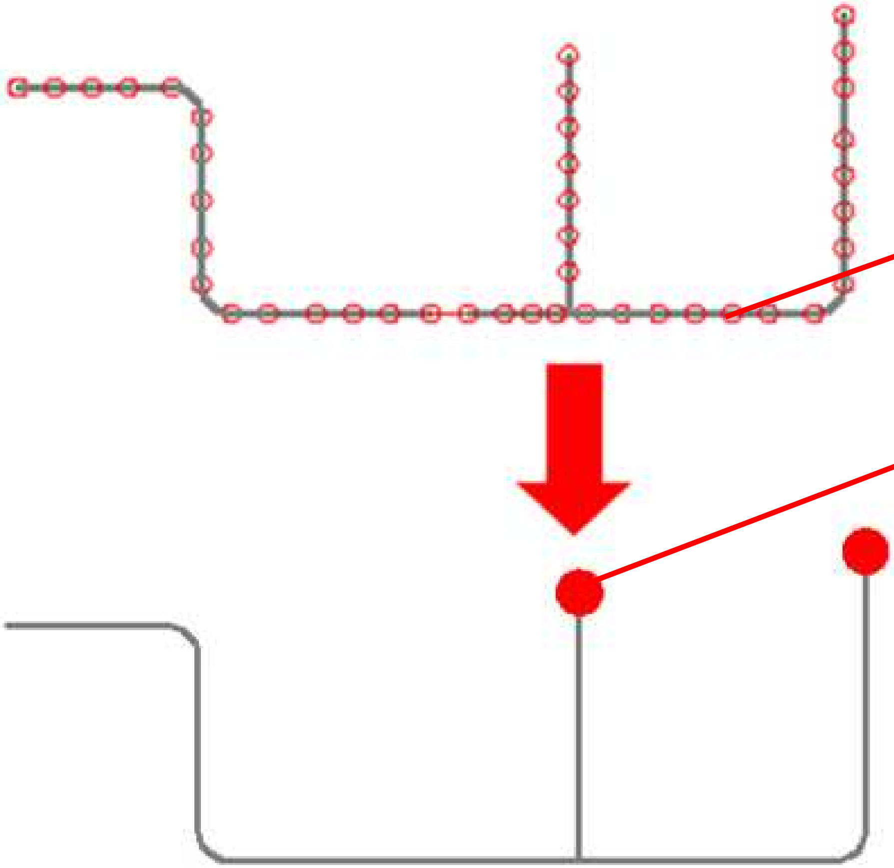
External load vector

$$\begin{cases} \mathbf{u} = \left[\mathbf{u}^{N^T} \quad \mathbf{u}^{B^T} \quad \mathbf{u}^{P^T} \right]^T \\ \mathbf{r} = \left[\mathbf{0}^T \quad \mathbf{r}^{B^T} \quad \mathbf{r}^{P^T} \right]^T \\ \mathbf{f} = \left[\mathbf{f}^{N^T} \quad \mathbf{f}^{B^T} \quad \mathbf{f}^{P^T} \right]^T = -\left(\mathbf{M}^N + \mathbf{M}^P \right) \cdot \mathbf{I} \cdot \ddot{u}_g \end{cases}$$

Challenge: to reduce P-DoFs to B-DoFs and perform tests with two actuators only

REDUCTION BASIS REQUIREMENTS

A reduction basis **T** reflects a kinematic assumption:



$$\begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \\ \mathbf{u}^P \end{bmatrix} = \mathbf{T} \cdot \begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \end{bmatrix}$$

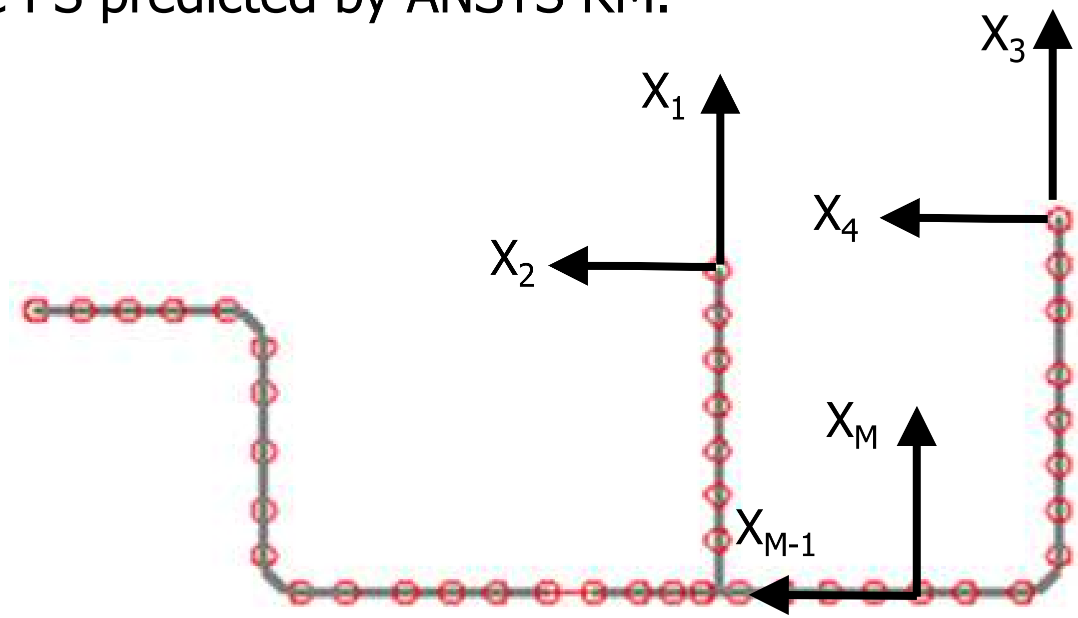
Reduced matrices of the PS:

$$\begin{cases} \tilde{\mathbf{M}}^P = \mathbf{T}^{\mathrm{T}} \mathbf{M}^P \mathbf{T} \\ \tilde{\mathbf{K}}^P = \mathbf{T}^{\mathrm{T}} \mathbf{K}^P \mathbf{T} \\ \tilde{\mathbf{f}}^P = -\mathbf{T}^{\mathrm{T}} \mathbf{M}^P \mathbf{I} \cdot \ddot{u}_g \end{cases}$$

REDUCTION BASIS REQUIREMENTS

The Principal Component Analysis (PCA) was applied to the dynamic response of the PS predicted by ANSYS RM.

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}_1 \\ \ldots \\ \mathbf{X}_M \end{bmatrix} = \mathbf{U\Sigma V}^T$$



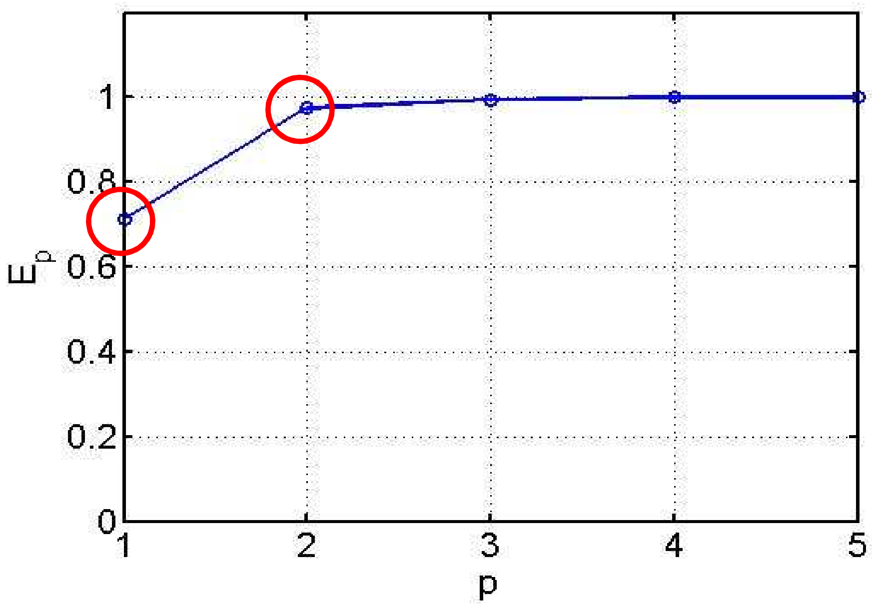
X: time history responses of the PS, i.e. B- and P-DoFs, arranged in row-wise.

U: orthonormal matrix of eigenvectors of $\mathbf{XX}^T$.

V: orthonormal matrix of eigenvectors of $\mathbf{X}^T\mathbf{X}$.

Σ: diagonal matrix of the singular values of **X**, sorted in descending order.

REDUCTION BASIS REQUIREMENTS



- rank two;
- span principal component subspace;
- entail consistent kinematic assumptions.

Σ11 > Σ22 > … > Σii: singular values of **X** in descending order

$E = \sum_{i=1}^{M} \Sigma_{ii}$: total data energy

$E_p = \sum_{i=1}^{p} \Sigma_{ii} / E$: normalized cumulative data energy

THE CRAIG-BAMPTON METHOD APPLIED TO THE PSEUDODYNAMIC CASE

$$\mathbf{T}_{CB} = \begin{bmatrix} \mathbf{I} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Phi}_S & \mathbf{\Phi}_D \end{bmatrix} \qquad \begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \\ \mathbf{u}^P \end{bmatrix} = \mathbf{T}_{CB} \cdot \begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \\ \mathbf{u}^q \end{bmatrix}$$

Additional modal coordinates ($\mathbf{u}^q$)

$$\begin{bmatrix} \mathbf{I} \\ \mathbf{\Phi}_S \end{bmatrix}$$

Constraint modes: static deformation shapes owing to unit displacements applied to B-DoFs, one by one, whilst the other retained

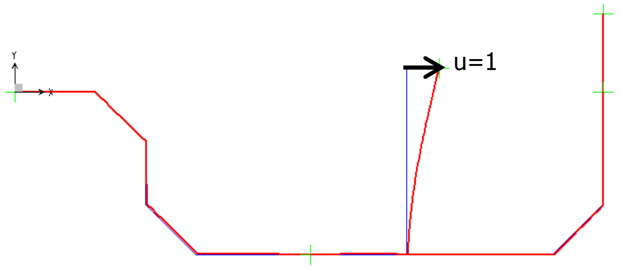
$$\begin{bmatrix} \mathbf{0} \\ \mathbf{\Phi}_D \end{bmatrix}$$

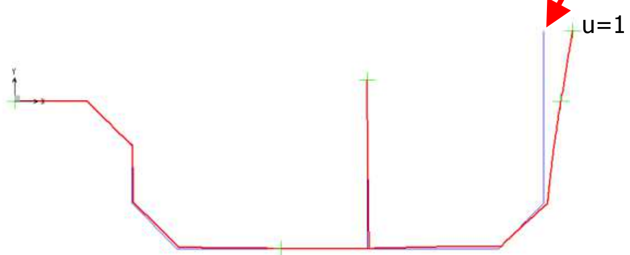
Fixed interface vibration modes: eigenmodes of the PS constrained at its B-DoFs

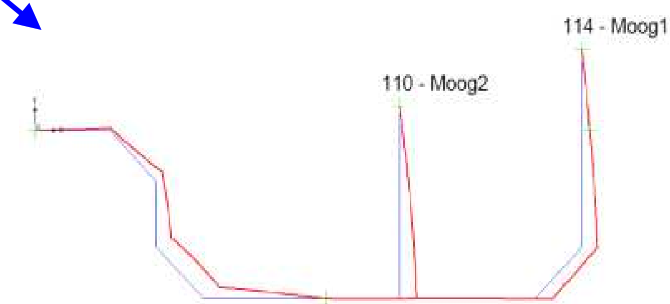
THE CRAIG-BAMPTON METHOD APPLIED TO THE PSEUDODYNAMIC CASE

STATIC AND DYNAMIC CONTRIBUTIONS ARE PLEASANTLY UN-COUPLED !!!

$$\begin{bmatrix}\mathbf{0}\\ \mathbf{r}^{B}\\ \mathbf{r}^{q}\end{bmatrix} = \begin{bmatrix}\mathbf{0}&\mathbf{0}&\mathbf{0}\\ \mathbf{0}&\mathbf{K}^{P,r}_{BB}&\mathbf{0}\\ \mathbf{0}&\mathbf{0}&\mathbf{K}^{P,r}_{qq}\end{bmatrix}\cdot\begin{bmatrix}\mathbf{u}^{N}\\ \mathbf{u}^{B}\\ \mathbf{u}^{q}\end{bmatrix} = \tilde{\mathbf{K}}^{P}\cdot\tilde{\mathbf{u}}$$







Constraint mode contribution
Experimentally measured

Fixed interface vibration mode contribution
Numerically modelled

Errors between time history responses of the

Reduced Model (NS + Reduced PS) and Reference Model

Error	Coupling DoF #1	Coupling DoF #2
NRMSE	0.003	0.001
NEE	0.006	0.001

Sensitive to frequency mismatching

$$\text{NRMSE} = \frac{\left\|\mathbf{x}_{\text{RM}} - \mathbf{x}_{\text{CM}}\right\|_2 / \sqrt{N}}{\max\left(\mathbf{x}_{\text{CM}}\right) - \min\left(\mathbf{x}_{\text{CM}}\right)}$$

Sensitive to amplitude mismatching

$$\text{NEE} = \left|\frac{\left\|\mathbf{x}_{\text{RM}}\right\|_2 - \left\|\mathbf{x}_{CM}\right\|_2}{\left\|\mathbf{x}_{\text{CM}}\right\|_2}\right|$$

X: response signal

N: length of response signal in sample

$$\mathbf{T}_{SE} = \begin{bmatrix} \mathbf{I} \\ \mathbf{\Phi}_{RP}\mathbf{\Phi}_{RB}^{-1} \end{bmatrix} \qquad \begin{bmatrix} \mathbf{u}^{N} \\ \mathbf{u}^{B} \\ \mathbf{u}^{P} \end{bmatrix} = \mathbf{T}_{SE} \cdot \begin{bmatrix} \mathbf{u}^{N} \\ \mathbf{u}^{B} \end{bmatrix}$$

$$\mathbf{\Phi} = \begin{bmatrix} \mathbf{\Phi}_{R} & \mathbf{\Phi}_{L} \end{bmatrix} = \begin{bmatrix} \mathbf{\Phi}_{RN} & \mathbf{\Phi}_{LN} \\ \mathbf{\Phi}_{RB} & \mathbf{\Phi}_{LB} \\ \mathbf{\Phi}_{RP} & \mathbf{\Phi}_{LP} \end{bmatrix}$$

where:

$\mathbf{\Phi}$: mass normalized eigenvectors of the global system (column-wise)
$\mathbf{\Phi}_R$: retained eigenmodes
$\mathbf{\Phi}_L$: truncated eigenmodes

With relevant N-DoFs, B-DoFs and P-DoFs components (row-wise)

Errors between time history responses of the

Reduced Model (NS + Reduced PS) and Reference Model

Error	Coupling DoF #1	Coupling DoF #2
NRMSE	0.015	0.0016
NEE	0.069	0.0003

Sensitive to frequency mismatching

$$\mathrm{NRMSE} = \frac{\left\| \mathbf{x}_{\mathrm{RM}} - \mathbf{x}_{\mathrm{CM}} \right\|_2 / \sqrt{N}}{\max\left(\mathbf{x}_{\mathrm{CM}}\right) - \min\left(\mathbf{x}_{\mathrm{CM}}\right)}$$

Sensitive to amplitude mismatching

$$\mathrm{NEE} = \left| \frac{\left\| \mathbf{x}_{\mathrm{RM}} \right\|_2 - \left\| \mathbf{x}_{CM} \right\|_2}{\left\| \mathbf{x}_{\mathrm{CM}} \right\|_2} \right|$$

X: response signal
N: length of response signal in sample

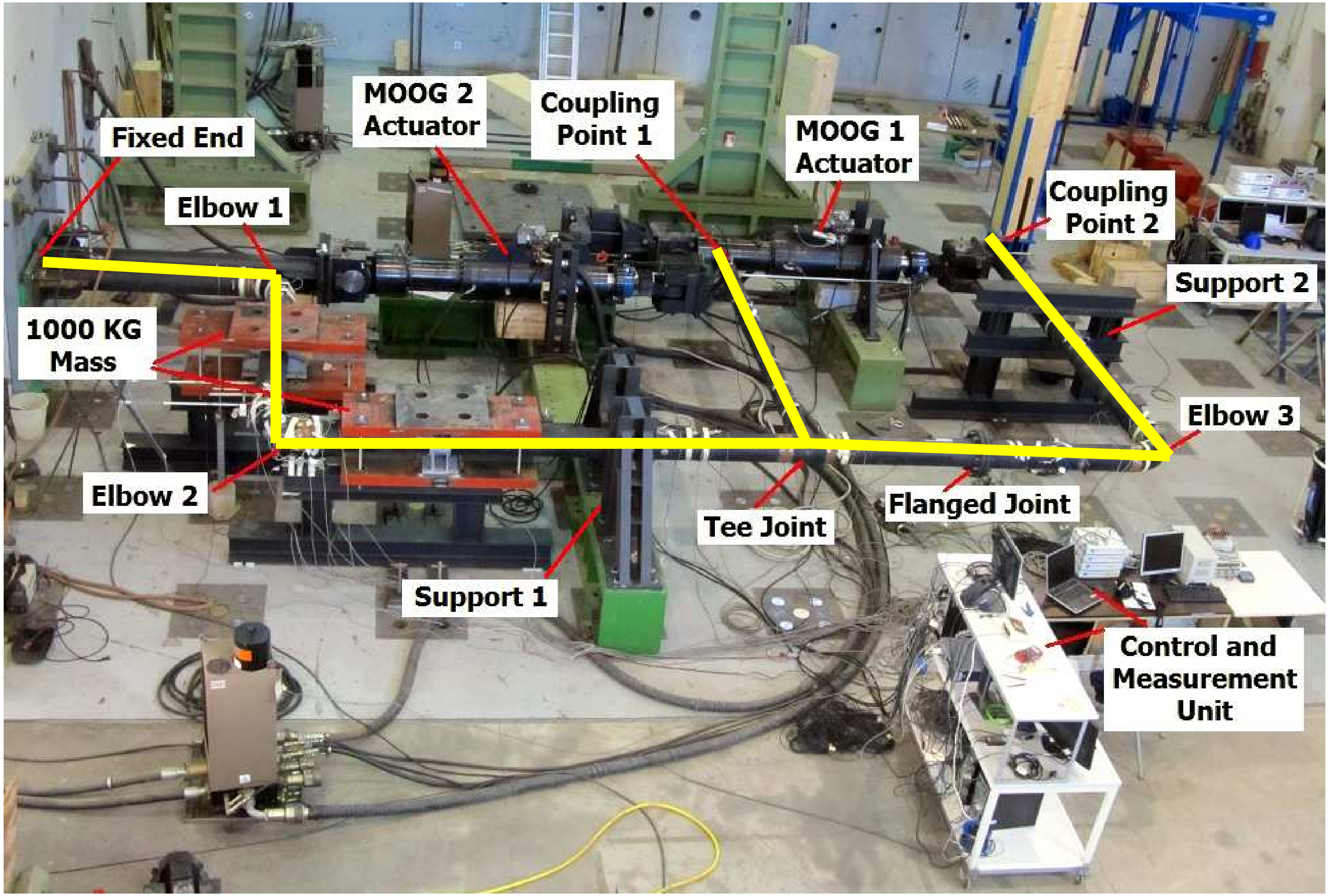
EXPERIMENTAL PROGRAM

Test Case		PGA (g)
Identification test of the PS, IDT	Hammer Test	-
Real time tests 1	RTDS	0.020
Real time tests 2	RTDS	0.020
Elastic test, ET	PDDS	0.042
Operational limit state test, SLOT	PDDS	0.079
Damage limit state test, SLDT	PDDS	0.112
Safe life limit state test, SLVT	PDDS	0.421
Collapse limit state test, SLCT	PDDS	0.599

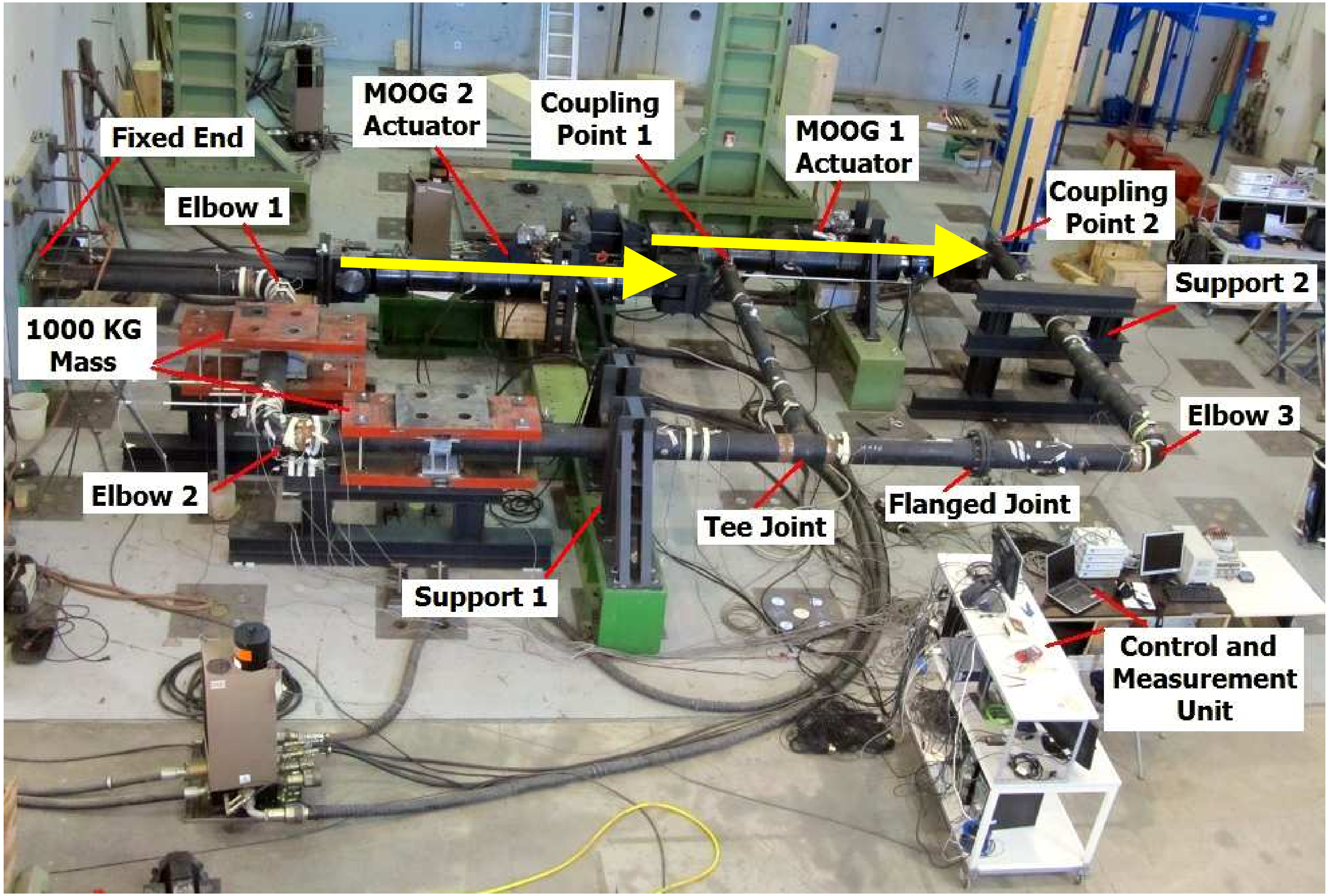
- Identified damping = 0.5%;
- Time scale factor $\lambda = 50$;
- Water pressure = 3.2MPa.

LSRT-2 time integration algorithm available on the Network for Earthquake Engineering Simulation (NEES) repository as *simlsrt2* - id #209 tool.

EXPERIMENTAL SET-UP



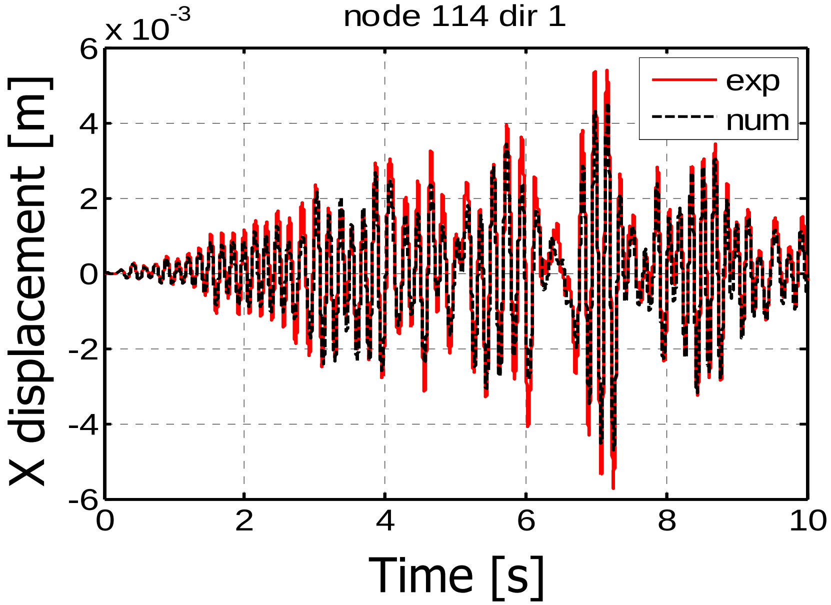
EXPERIMENTAL SET-UP

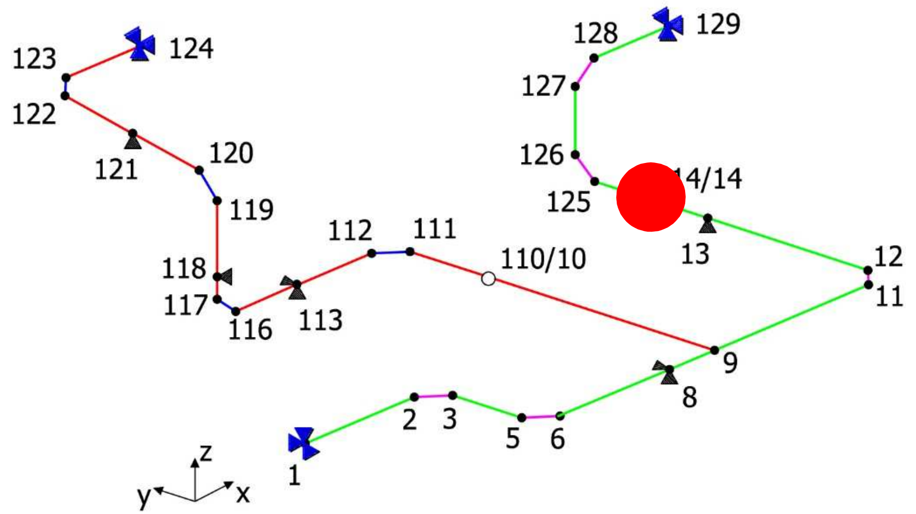


MOOG hydraulic actuator pair

EXPERIMENTAL VALIDATION OF THE CRAIG-BAMPTON-BASED APPROACH APPLIED TO THE PSEUDODYNAMIC CASE

Displacement responses at the Coupling DoF #1 and relevant errors w.r.t. numerical simulations.





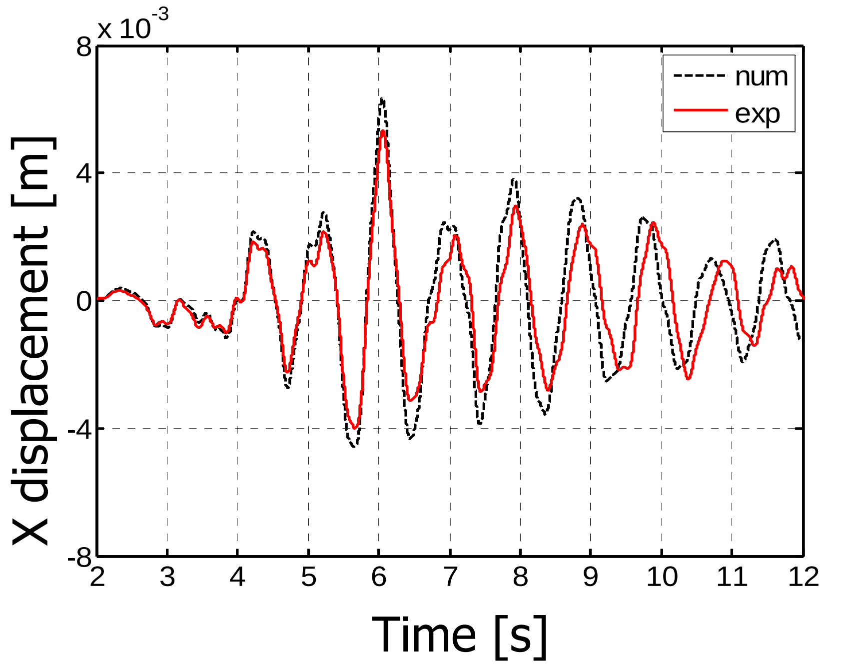
ANSYS Reference Model

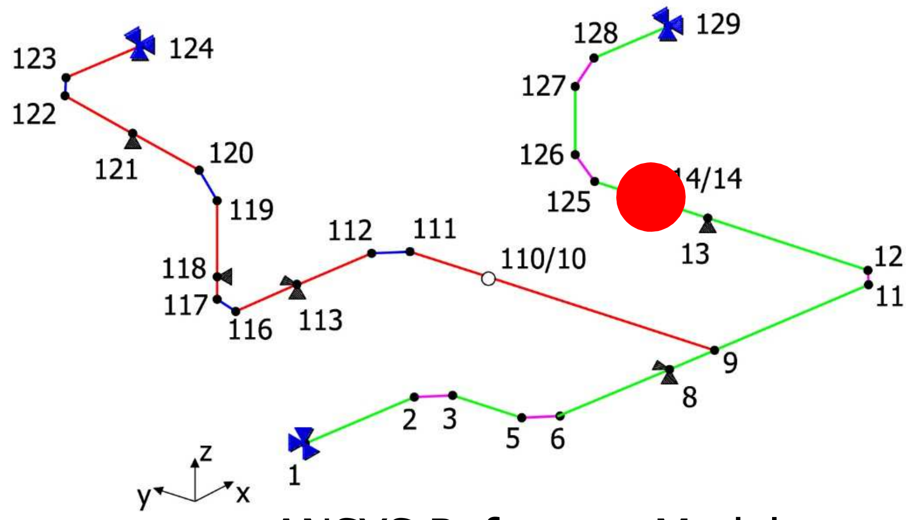
Error	Coupling DoF #1	Coupling DoF #2
NRMSE	0.038	0.066
NEE	0.112	0.396

Pseudodynamic case
SLCT, PGA = 0.599g

EXPERIMENTAL VALIDATION OF THE SEREP-BASED APPROACH APPLIED TO THE REAL-TIME CASE

Displacement responses at the Coupling DoF #1 and relevant errors w.r.t. numerical simulations.





ANSYS Reference Model

Error	Coupling DoF #1	Coupling DoF #2
NRMSE	0.083	0.239
NENERR	0.289	0.379

Real-time case
ET, PGA = 0.020g

CONCLUSIONS

- THE PARTITIONED TIME INTEGRATION APPROACH WAS APPLIED FOR THE FIRST TIME TO A COMPLEX BRIDGE PROVIDED WITH NONLINEAR **NSs** IN BOTH ISOLATED AND NON-ISOLATED CONFIGURATIONS;

- **NSs** -NUMERICAL PIERS- WERE UPDATED OFFLINE ACCORDING TO RESPONSES OF **PSs** -PHYSICAL PIERS- CHARACTERIZED BY DIFFFERENT SHAPES AND LOADING;

- HYBRID SIMULATION WAS APPLIED FOR THE FIRST TIME TO AN INDUSTRIAL PIPING SYSTEM CHARACTERIZED BY A DISTRIBUTED PARAMETER **PS**.

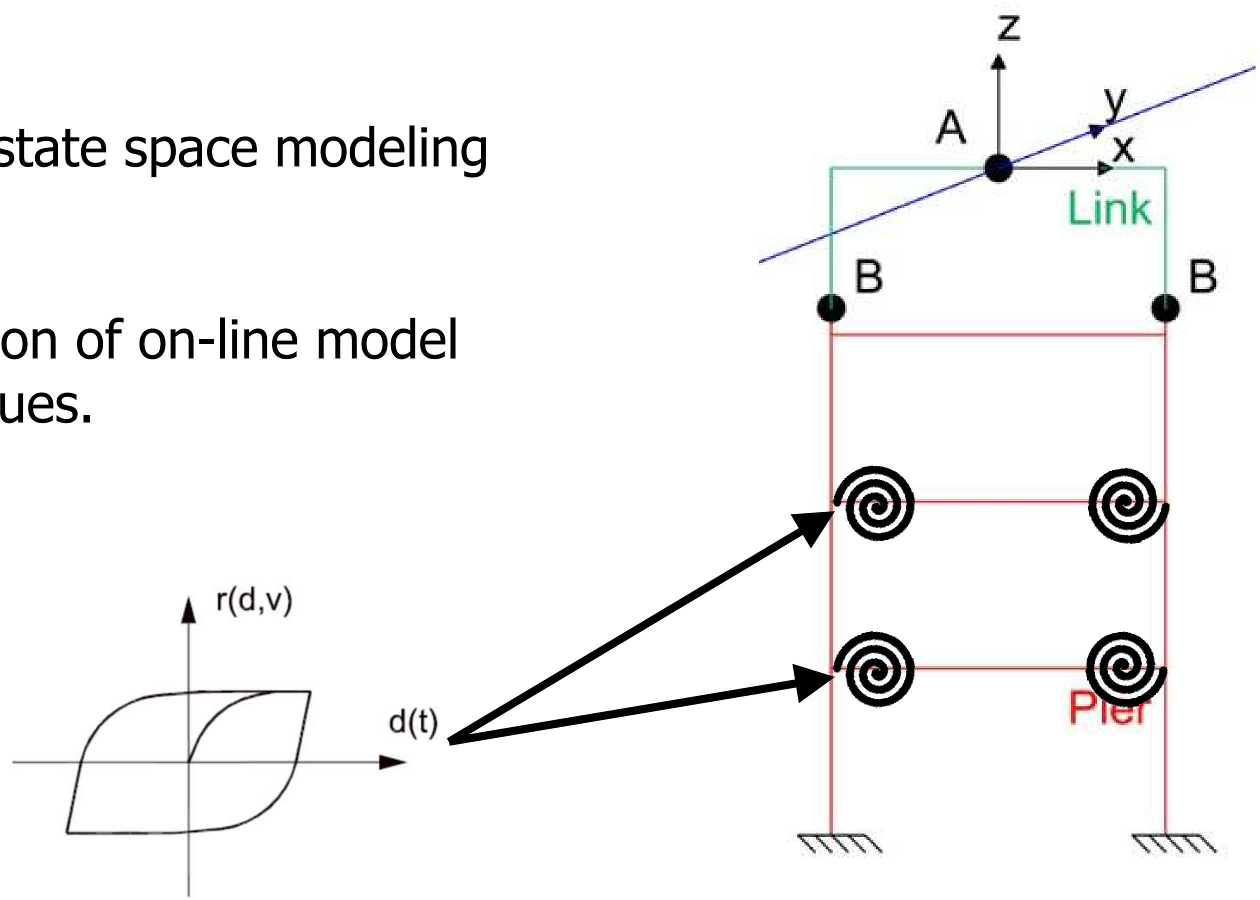
- BOTH THE CRAIG-BAMPTON AND THE SEREP METHODS WERE SUCCESSFULLY APPLIED IN THE CASE OF SEISMIC LOADING.

- STATE SPACE APPROACH FACILITATES THE INTEROPERATION OF TIME INTEGRATION, SYSTEM IDENTIFICATION AND MODEL REDUCTION TOOLS.

FUTURE PERSPECTIVES

On the NS side:

- Development of state space modeling environments.
- Possible application of on-line model updating techniques.



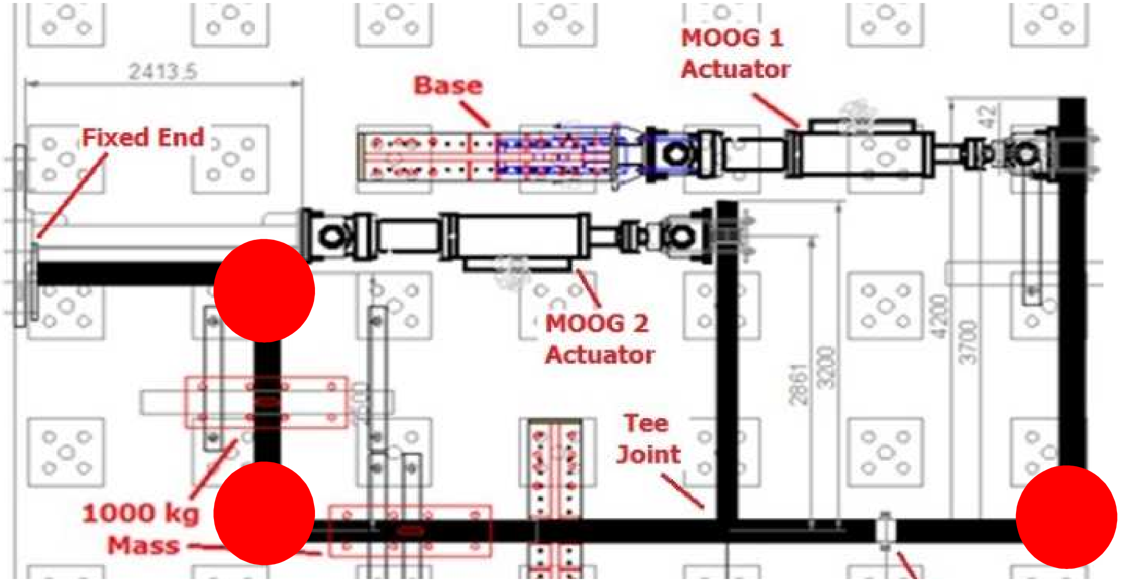
$$\dot{r} = \left[A - (\beta \cdot sgn(\dot{x} \cdot r) + \gamma) \, | \, r \, |^n \right] \cdot \dot{x}$$

FUTURE PERSPECTIVES

On the PS side:

- Experimental validation of alternative reduction bases in the linear range (balanced truncation, proper orthogonal decomposition, etc.);

- Extension of the proposed approach to nonlinear PSs.



Publications on international journals (accepted, submitted and in preparation):

1. Ceravolo R., Abbiati G., 2012. Time Domain Identification Of Structures: A Comparative Analysis Of Output-Only Methods - International Journal of Engineering Mechanics, 139(4):537-544.

2. Bursi O.S., Abbiati G., Reza Md.S., 2013. A Novel Hybrid Testing Approach for Piping Systems of Industrial Plants. Special Issue of Smart Structures and Systems on "Recent Advances in Real-time Hybrid Simulation" (RTHS) - In print.

3. Reza Md.S., Abbiati G., Bursi O.S., Paolacci F., 2013. Seismic performance evaluation of a full-scale industrial piping system at serviceability and ultimate limit states. Journal of Loss Prevention - Under review.

4. Abbiati G., Ceravolo R., Surace C., 2013. Unbiased time-dependent estimators for on-line monitoring of full-scale structures under ambient excitation. Mechanical Systems and Signal Processing - Under review.

5. Bursi O.S., Paolacci F., Di Sarno L., Abbiati G., 2014. Hybrid simulation and assessment of a multi-span RC bridge with plain bars. Earthquake Engineering & Structural Dynamics - In preparation.

Additional SCOPUS indexed publications:

1. Reza M.S, Abbiati G., Bonelli A., Bursi O.S., 2013. "Pseudo-dynamic testing of a piping system based on model reduction techniques". SERIES Concluding Workshop joint with NEES-US Earthquake Engineering Research Infrastructures. JRC Ispra, May 28-30.

2. Abbiati G., Bursi O.S., Cazzador E., Mei Z., Paolacci F., Pegon P., 2013. "Pseudo-dynamic testing with non-linear substructuring of a reinforced concrete bridge". SERIES Concluding Workshop joint with NEES-US Earthquake Engineering Research Infrastructures JRC Ispra, May 28-30.

3. Paolacci F., Di Sarno L., Pegon P., Molina F. J., Poljansek M., Bursi O.S., Abbiati G., Ceravolo R., Erdik M., Deisi R., Mohamad A, 2013. "Assessment of the seismic behaviour of a retrofitted old R.C. highway bridge through PsD testing". SERIES Concluding Workshop joint with NEES-US Earthquake Engineering Research Infrastructures JRC Ispra, May 28-30.

4. Paolacci F., Di Sarno L., De Risi R., Abbiati G., Mohamad A., Malena M., Corritore D. 2013. "Refined and simplified numerical models of an isolated old highway bridge for PsD testing". SERIES Concluding Workshop joint with NEES-US Earthquake Engineering Research Infrastructures JRC Ispra, May 28-30.

Thank you for your attention.

Any question?