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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Advisor: Prof. Oreste S. Bursi

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Hybrid system/Hardware-in-the-loop simulator

\[ f_n \] External loading

**Numerical Substructure (NS)**

- **Filters**
  - \( r_n[N] \)

- **Delay compensator**
  - \( d_n[m] \)

**Physical Substructure (PS)**

- **Sensors:** Load cells etc.
- **Transfer system:** Actuators, controllers etc.

**TIME INTEGRATION LOOP for n=1:steps**

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

Hybrid system

Physical piers -CRITICAL PARTS-

Numerical deck and piers
Mech. eng. application of hybrid simul.: a piping system

Hybrid system

Numerical piping branch

Physical piping branch -CRITICAL PARTS-
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

Experimental time [s]

Monolithic time integration

\[ \Delta t \approx 1 \div 2\,\text{ms} \]

 Partitioned time integration

\[ \Delta t \approx 1 \div 2\,\text{ms} \]

\[ d_i \]

\[ d_{i+1} \]

\[ d_i \]

\[ d_{i-1} \]

Displacement command [mm]

Experimental time [s]

\[ (i-1)\Delta T \lambda \]

\[ i\Delta T \lambda \]

\[ (i+1)\Delta T \lambda \]

\( \Delta T \) = integration time step, \( \Delta t \) = controller time step, \( \lambda \) = 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

PS

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

= inertial seismic 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)

NUMERICAL SUBSTRUCTURES

PHYSICAL SUBSTRUCTURES (2 Piers + FPB isolation devices)
Gerber saddles (removed in the isolated case)

About 900 Degrees-of-Freedom (DoFs)

Element types:

- *nonlinearBeamColumn* for piers
- *elasticBeamColumn* for the deck
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 !!!
PHYSICAL SUBSTRUCTURES (2 Piers + FPB isolation devices)

NUMERICAL SUBSTRUCTURES

SUBSTRUCTURING REQUIREMENTS
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 !!!
**NSs’ design**

<table>
<thead>
<tr>
<th>Non isolated case</th>
<th>Isolated case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear deck</td>
<td>Linear deck</td>
</tr>
<tr>
<td>Nonlinear piers</td>
<td>Linear piers</td>
</tr>
<tr>
<td>Linear deck</td>
<td>Nonlinear isolators</td>
</tr>
</tbody>
</table>

Substructuring scheme and subparts

- **DECK:** LINEAR
- **PIERS:** LINEAR/NONLINEAR
- **ISOLATORS:** NONLINEAR
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

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

\( p(t) = \) transversal force history from OpenSEES;
\( \dddot{u}_g(t) = \) input accelerogram;
\( k, c, m, f = \) linear parameters;
\( \rho, \alpha, \beta, \gamma, n = \) nonlinear parameters.
PARAMETER IDENTIFICATION FOR THE S-DOF NONLINEAR REDUCED PIER

\[
\begin{align*}
\{\hat{\rho}, \hat{\alpha}, \hat{\beta}\} &= \min_{\rho, \alpha, \beta} \text{NRMSE}(x_{\text{red}}(\rho, \alpha, \beta), x_{\text{OS}}) \\
\hat{n} &= 1, \hat{\gamma} = 0
\end{align*}
\]

\[
\text{NRMSE}(x_{\text{red}}, x_{\text{OS}}) = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (x_{i,\text{red}} - x_{i,\text{OS}})^2}
\]

\[
\frac{\max(x_{\text{OS}}) - \min(x_{\text{OS}})}{m}
\]

\(x_{\text{OS}}\) = displacement responses of the OpenSEES pier

\(x_{\text{red}}\) = 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

\[ \begin{aligned} m \ddot{x} + c \dot{x} + \alpha k x + (1 - \alpha) k u &= p(t) \\ \dot{u} &= \dot{x} \left( \overline{N}(\dot{x}) \overline{M}(u - \delta) + M(\dot{x}) \overline{N}(u + \delta) \right) \end{aligned} \]

Bilinear hysteretic model
PARAMETER IDENTIFICATION FOR THE S-DOF REDUCED ISOLATOR

\[
\min_{\alpha, k, \delta} \text{NRMSE}(r_{\text{red}}(\alpha, k, \delta), r_{\text{OS}})
\]

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

\[
\alpha = 0.0046, \quad k = 2.0278e8, \quad \delta = 5.0000e - 4
\]

\(X_{\text{OS}} = \) displacement responses of the OpenSEES isolator

\(X_{\text{red}} = \) displacement responses of the S-DOF reduced isolator
Validation of reduced NSs at ULS
HYBRID MODEL OF THE NON-ISOLATED BRIDGE

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

UNIFORM TRANSVERSAL SEISMIC LOADING
HYBRID MODEL OF THE ISOLATED BRIDGE

UNIFORM TRANSVERSAL SEISMIC LOADING

88-DoFs
(Hybrid model)

~900-DoFs
(OpenSEES RM)
\( \lambda = \text{extended testing time scale} = 200 \)

Sim. time step: \( \Delta t_A = 4\, \text{ms} \)

Exp. time step: \( \lambda \cdot \Delta t_A = 200 \cdot 4 = 800\, \text{ms} \)

Contr. time step: \( \Delta t = 2\, \text{ms} \)

Subcycling: \( ss = \frac{\lambda \cdot \Delta t_A}{\Delta t} = \frac{4 \cdot 200}{2} = 400 \)
PARTITIONED TIME INTEGRATION

\[ \lambda = \text{extended testing time scale} = 200 \]

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: \[ ss = \frac{\lambda \cdot \Delta t_A}{\Delta t} = \frac{4 \cdot 200}{2} = 400 \]

RESPONSE OF THE NS
\[
\ddot{\textbf{M}} y_{n+\alpha_m} + \ddot{\textbf{K}} y_{n+\alpha_n} = \ddot{\textbf{f}}_{n+\alpha_n}
\]
\[
\downarrow
\]
\[
\begin{cases}
y_{n+1} = y_n + v_n \Delta t (1 - \gamma) + v_{n+1} \Delta t \gamma \\
v_n (1 - \alpha_m) + v_{n+1} (\alpha_m) = \dot{y}_n (1 - \alpha_f) + \dot{y}_{n+1} (\alpha_f)
\end{cases}
\]
\[
\downarrow
\]
\[
\ddot{\textbf{M}} y_{n+1} + \ddot{\textbf{K}} y_{n+1} = \ddot{\textbf{f}}_{n+1}
\]

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

**THE GCbis-MG-\(\alpha\) PARALLEL PARTITIONED TIME INTEGRATORS**
EXPERIMENTAL VALIDATION OF THE GCbis-MG-α METHOD

Free decay response to: \( u_2 = 0.01 \)

\[ \lambda = 128, \Delta t = 1/1024, \Delta t_A = 1/1024, \text{ss} = 128 \]
EXPERIMENTAL SET-UP AT THE ELSA LAB. OF THE JRC OF ISPRA (VA)
EXPERIMENTAL SET-UP OF PIERS

\[ \Delta F_v = \frac{F_H L}{B} \]

PHOTOGRAHMETRIC 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;

PID-based control architecture
NEED FOR AN UPDATING STRATEGY FOR NUMERICAL PIERS

DAMAGE MUST ACCUMULATE ON BOTH PSs AND NSs TEST BY TEST
PROPOSED MODEL UPDATING TESTING PROCEDURE

1. Hybrid simulation with seismic input $i$
2. Model updating of OpenSEES FE models of Piers #9 and #11
3. Model updating of the OpenSEES RM according to identified parameters on Piers #9 and #11
4. Time history analysis of the OpenSEES RM with seismic input $i+1$
5. Identification of nonlinear parameters of reduced S-DoF piers (NSs)
6. Hybrid simulation with seismic input $i+1$
MODEL UPDATING OF OPENSEES FE MODEL OF PHYSICAL PIERS

\[
\{ \hat{f}_{pc} \} = \min_{f_{pc}} NRMSE\left( r_{OS} \left( f_{pc} \right), r_{exp} \right)
\]

OpenSEES FEM of Pier #11

ULS RESPONSE
Test k09

<table>
<thead>
<tr>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.5</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>-0.5</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
</tr>
</tbody>
</table>

Disp. [mm]

\[ f_{pc} \]

Maximum compressive strength of \textit{concrete01} 7/10/2014
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
DYNAMIC IDENTIFICATION OF NONLINEAR REDUCED PIERS

\[
\begin{align*}
\dot{\mathbf{x}} &= \left[ \rho \cdot k \left(1 + \alpha \cdot x^2\right) - (\beta \cdot \text{sgn}(\dot{x} \cdot r) + \gamma) \left| r \right|^n \right] \cdot \dot{x} \\
\end{align*}
\]

\[
\begin{align*}
\left\{ \hat{\rho}, \hat{\alpha}, \hat{\beta} \right\} = \min_{\rho, \alpha, \beta} \text{NRMSE} \left( \mathbf{x}_{\text{red}}(\rho, \alpha, \beta), \mathbf{x}_{\text{OS}} \right) \\
\hat{n} = 1, \hat{\gamma} = 0 \\
\end{align*}
\]

\( \mathbf{X}_{\text{OS}} = \) displacement responses of the \text{UPDATED OpenSEES RM} \( \mathbf{X}_{\text{red}} = \) 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)
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

<table>
<thead>
<tr>
<th>Pipe Size</th>
<th>Material</th>
<th>Liquid/Internal Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>8” and 6” Schedule 40</td>
<td>API 5L Gr. X52 fy = 418 Mpa; fu = 554 Mpa; Elongation = 35.77%</td>
<td>Water/3.2 MPa</td>
</tr>
</tbody>
</table>

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Positions of minimum bending moments were chosen as coupling nodes.

The seismic action was applied the x direction.
A pair of hydraulic actuators imposed displacements to coupling DoFs
DOFS PARTITIONING

Displacement vector
\[ u = \begin{bmatrix} u^N & u^B & u^P \end{bmatrix}^T \]

Restoring force vector
\[ r = \begin{bmatrix} 0^T & r^B & r^P \end{bmatrix}^T \]

External load vector
\[ f = \begin{bmatrix} f^N & f^B & f^P \end{bmatrix}^T = - \left( M^N + M^P \right) \cdot I \cdot \ddot{u}_g \]

Challenge: to reduce P-DoFs to B-DoFs and perform tests with two actuators only
A reduction basis $\mathbf{T}$ 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:

$$
\begin{aligned}
\mathbf{\tilde{M}}^P &= \mathbf{T}^T \mathbf{M}^P \mathbf{T} \\
\mathbf{\tilde{K}}^P &= \mathbf{T}^T \mathbf{K}^P \mathbf{T} \\
\mathbf{\tilde{f}}^P &= -\mathbf{T}^T \mathbf{M}^P \mathbf{I} \cdot \ddot{\mathbf{u}}_g
\end{aligned}
$$
The Principal Component Analysis (PCA) was applied to the dynamic response of the PS predicted by ANSYS RM.

\[ X = \begin{bmatrix} X_1 \\ \vdots \\ X_M \end{bmatrix} = U \Sigma V^T \]

- **X**: time history responses of the PS, i.e. B- and P-DoFs, arranged in row-wise.
- **U**: orthonormal matrix of eigenvectors of \( XX^T \).
- **V**: orthonormal matrix of eigenvectors of \( X^TX \).
- **\Sigma**: diagonal matrix of the singular values of **X**, sorted in descending order.
REDUCTION BASIS REQUIREMENTS

\[ \Sigma_{11} > \Sigma_{22} > ... > \Sigma_{ii} \] singular values of \( \mathbf{X} \) in descending order

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

\[ E_p = \frac{\sum_{i=1}^{p} \Sigma_{ii}}{E} : \text{normalized cumulative data energy} \]

- rank two;
- span principal component subspace;
- entail consistent kinematic assumptions.
### THE CRAIG-BAMPTON METHOD APPLIED TO THE PSEUDODYNAMIC CASE

The diagram shows a mathematical relationship involving matrices and vectors. Specifically, it illustrates the transformation between different coordinate systems.

\[
T_{CB} = \begin{bmatrix}
I & 0 & 0 \\
0 & I & 0 \\
0 & \Phi_S & \Phi_D
\end{bmatrix}
\begin{bmatrix}
\mathbf{u}^N \\
\mathbf{u}^B \\
\mathbf{u}^P
\end{bmatrix} = T_{CB} \cdot \begin{bmatrix}
\mathbf{u}^N \\
\mathbf{u}^B \\
\mathbf{u}^q
\end{bmatrix}
\]

**Additional modal coordinates**

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

- **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 !!!

\[
\begin{bmatrix}
0 \\
r^B \\
r^q
\end{bmatrix}
= 
\begin{bmatrix}
0 & 0 & 0 \\
0 & K_{BB}^{P,r} & 0 \\
0 & 0 & K_{qq}^{P,r}
\end{bmatrix}
\begin{bmatrix}
u^N \\
u^B \\
u^q
\end{bmatrix}
= \tilde{K}^P \cdot \tilde{u}
\]

Constraint mode contribution
Experimentally measured

Fixed interface vibration mode contribution
Numerically modelled
THE CRAIG-BAMPTON METHOD APPLIED TO THE PSEUDODYNAMIC CASE

Errors between time history responses of the Reduced Model (NS + Reduced PS) and Reference Model

<table>
<thead>
<tr>
<th>Error</th>
<th>Coupling DoF #1</th>
<th>Coupling DoF #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSE</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>NEE</td>
<td>0.006</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Sensitive to frequency mismatching

\[
\text{NRMSE} = \frac{\| x_{RM} - x_{CM} \|_2}{\sqrt{N}} \frac{1}{\max(x_{CM}) - \min(x_{CM})}
\]

Sensitive to amplitude mismatching

\[
\text{NEE} = \left| \frac{\| x_{RM} \|_2 - \| x_{CM} \|_2}{\| x_{CM} \|_2} \right|
\]

\( X \): response signal

\( N \): length of response signal in sample
\[ T_{SE} = \begin{bmatrix} I & \Phi_{RP} \Phi_{RB}^{-1} \end{bmatrix} \]

\[ \begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \\ \mathbf{u}^P \end{bmatrix} = T_{SE} \cdot \begin{bmatrix} \mathbf{u}^N \\ \mathbf{u}^B \end{bmatrix} \]

\[ \Phi = \begin{bmatrix} \Phi_R \\ \Phi_L \end{bmatrix} = \begin{bmatrix} \Phi_{RN} & \Phi_{LN} \\ \Phi_{RB} & \Phi_{LB} \\ \Phi_{RP} & \Phi_{LP} \end{bmatrix} \]

where:

\( \Phi \): mass normalized eigenvectors of the global system (column-wise)
\( \Phi_R \): retained eigenmodes
\( \Phi_L \): 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

<table>
<thead>
<tr>
<th>Error</th>
<th>Coupling DoF #1</th>
<th>Coupling DoF #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSE</td>
<td>0.015</td>
<td>0.0016</td>
</tr>
<tr>
<td>NEE</td>
<td>0.069</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Sensitive to frequency mismatching

\[
NRMSE = \frac{\|x_{RM} - x_{CM}\|_2}{\sqrt{N}} \frac{1}{\max(x_{CM}) - \min(x_{CM})}
\]

Sensitive to amplitude mismatching

\[
NEE = \left| \frac{x_{RM} - x_{CM}}{\|x_{CM}\|_2} \right|
\]

\textbf{X}: response signal
\textbf{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

- MOOG hydraulic actuator pair
- Fixed End
- Elbow 1
- MOOG 1 Actuator
- MOOG 2 Actuator
- Coupling Point 1
- Coupling Point 2
- Support 2
- Elbow 3
- Support 1
- 1000 KG Mass
- Elbow 2
- Tee Joint
- Flanged Joint
- Control and Measurement Unit
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.

<table>
<thead>
<tr>
<th>Error</th>
<th>Coupling DoF #1</th>
<th>Coupling DoF #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSE</td>
<td>0.038</td>
<td>0.066</td>
</tr>
<tr>
<td>NEE</td>
<td>0.112</td>
<td>0.396</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Error</th>
<th>Coupling DoF #1</th>
<th>Coupling DoF #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSE</td>
<td>0.083</td>
<td>0.239</td>
</tr>
<tr>
<td>NENERR</td>
<td>0.289</td>
<td>0.379</td>
</tr>
</tbody>
</table>

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 DIFFERENT 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.

\[
\dot{r} = \left[ A - (\beta \cdot \text{sgn}(\dot{x} \cdot r) + \gamma) \right] \cdot \dot{x}
\]
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):


Additional SCOPUS indexed publications:


Thank you for your attention.

Any question?