Pseudo-dynamic Testing with Non-linear Substructuring of a Reinforced Concrete Bridge Based on System Identification and Model Updating Techniques

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Acknowledgments

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2. The author gratefully acknowledges the financial supports of the University of Trento for Lab. activities

SERIES: Seismic Engineering Research Infrastructures for European Synergies
In order to simulate the seismic response of the Rio Torto Viaduct - RETRO’TA, an experimental campaign based on hybrid simulations was set for both the non-isolated and isolated case.

To this end, our research activity focused on:

- **Flexible reduced nonlinear models of Numerical Substructures (NSs)** (piers + deck + isolators) suitable for fast integration and rapid tuning.

- A procedure capable of transferring degradation information experienced by **Physical Substructures (PSs)** to NSs, i.e. from Physical to Numerical piers, respectively.
PsD testing with Dynamic Substructuring (DS) of the Rio Torto bridge

FE models for PsD test design

Dynamic substructuring of non-linear piers

Dynamic substructuring of isolators

Validation of the reduced model of the Rio Torto Viaduct

Offline model updating of NSs

Conclusions
PsD testing with DS of Rio Torto bridge

Substructuring scheme

NUMERICAL MODEL

PHYSICAL MODEL

(2 Piers + isolation devices)
Time integration strategy
A parallel partitioned algorithm with subcycling: the PM method

The subcycling capabilities of the PM method are used to keep actuators moving on a smooth trajectories whilst the complex NS is being computed.

Lagrange multipliers enforce the velocity continuity at the interface:

\[
\begin{align*}
&M^A \dddot{u}^{A}_{n+1} + R^A(u^A_{n+1}, \dot{u}^A_{n+1}) = F^{A}_{ext,n+1} + L^{A^T} \Lambda_{n+1} \\
&M^B \dddot{u}^{B}_{n+(j-1)/n_{sub}} + R^B(u^B_{n+(j-1)/n_{sub}}, \dot{u}^B_{n+(j-1)/n_{sub}}) = F^{B}_{ext,n+(j-1)/n_{sub}} + L^{B^T} \Lambda_{n+j/n_{sub}} \\
&L^A \dddot{u}^{A}_{n+j/n_{sub}} + L^B \dddot{u}^{B}_{n+j/n_{sub}} = 0
\end{align*}
\]
Time integration strategy
Continuous time PsD testing

\[
\lambda = \frac{N_s \Delta t}{\Delta T}
\]

\[N_s = 500, \Delta t = 2ms, \Delta T = 5ms, \lambda = 200\]

Control loop:
Compute the external force: \(f_n^m\)
Measure the restoring force: \(r_n^m\)
Compute \(a_n^m\) and \(v_n^m\).
Compute the displacement: \(d_{n+1}^m\)
Impose \(d_{n+1}^m\) on the structure:

\[\ldots\] Control Algorithm:
Set control target = \(d_{n+1}^m\)
Go to Control loop
PsD testing with DS of Rio Torto bridge
Experimental set-up for the non isolated case

Mock-up 1:2.5 scale model of Pier #11 (PS #11)
Mock-up 1:2.5 scale model of Pier #9 (PS #9)

Need of simple Numerical Substructures

Numerical pier superelements (NSs)

Deck (NS)
OpenSEES fiber-based nonlinear Reference Model (RM)
Implementation details

Bologna

Gerber saddles (removed in the isolated case)

Degrees-of-Freedom (DoFs):
- 120 for the deck
- About 60 for each pier

Element types:
- `nonlinearBeamColumn` for piers
- `elasticBeamColumn` for the deck

A rigid link element connect each nonlinear pier to the linear deck
OpenSEES fiber-based nonlinear Reference Model (RM)

Implementation details

Bologna

- 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)

Each couple of nonlinear friction pendulum isolators is implemented by `singleFPBearing` elements with `Coulomb frictionModel`.
OpenSEES fiber-based nonlinear Reference Model (RM)

Preliminary time history analyses for the non isolated case

Two seismic records of the Emilia (Italy) earthquake of the 29th of May 2012 from the Mirandola station was considered:

- **East-West component for the SLS (2.56 m/s² PGA)**
- **North-South component for the ULS (2.67 m/s² PGA)**
OpenSEES fiber-based nonlinear Reference Model (RM)

Preliminary time history analyses for the isolated case

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- East-West component for the SLS (2.56 m/s² PGA)
- North-South component for the ULS (2.67 m/s² PGA)
OpenSEES fiber-based nonlinear Reference Model (RM)
Energy dissipated from piers

Clearly, isolations devices strongly reduce hysteretic energy dissipated by piers.
OpenSEES fiber-based nonlinear Reference Model (RM)
Energy dissipation localization in the isolated case

Except for Pier #2, the major part of dissipated energy is due to isolation devices.
Modelling of NSs for PdT purposes

The component-based synthesis approach aims at producing flexible state space NSs suitable for both fast time integration and rapid identification/tuning.
**ANSYS linear RM**

Description of the reference FE 3D linear model

In order to provide stiffness and mass matrices for state space reduction, an ANSYS RM was devised:

- Bernoulli Beam4 elements are used for all elements.
- DoFs number: 832

Eigenmode #1 at 0.62 Hz

- Eigenmode #2 at 0.64 Hz
In order to force an in plane response of piers, the following modifications to the original constraints of the RM was applied:

- Deck-piers relative rotations release.
- Fix constraints on vertical and longitudinal displacements of the deck.
- Fix constraints for out-of-plane displacement of piers.
Numerical simulations with original and modified constraints were conducted on ANSYS models assuming:

- SLS record normalized to 0.05g PGA
- 0.05 Rayleigh damping

The assumed constraints do not affect the dynamic response and allow for an in-plane reduction of piers!!!
Summary of modal characteristics of reference models

<table>
<thead>
<tr>
<th>Mode</th>
<th>OpenSEES RM [Hz]</th>
<th>ANSYS RM [Hz]</th>
<th>ANSYS SM [Hz]</th>
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<tr>
<td>5</td>
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<td>1.2183</td>
<td>1.2091</td>
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</table>

FE models appear to be consistent in the linear range
Dynamic substructuring of nonlinear piers
Linear substructuring of piers based on Guyan reduction

FE pier model

Accommodation of isolation elements to simulate dissipation devices

Plane 3-DoFs superelement obtained via Guyan reduction
Dynamic substructuring of nonlinear piers
Nonlinear parameters tuning of substructured piers

\[
\begin{bmatrix}
\dot{u}_1 \\
\dot{u}_2 \\
\dot{u}_3
\end{bmatrix} =
\begin{bmatrix}
v_1 \\
v_2 \\
v_3
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{v}_1 \\
\dot{v}_2 \\
\dot{v}_3
\end{bmatrix} =
\begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}^{-1}
\begin{bmatrix}
f_1 \\
f_2 \\
f_3
\end{bmatrix} -
\begin{bmatrix}
0 & k_{12} & k_{13} \\
- k_{21} & k_{22} & k_{23} \\
- k_{31} & k_{32} & k_{33}
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
u_3
\end{bmatrix} - 
\begin{bmatrix}
r_1 \\
0 \\
0
\end{bmatrix}
\]

\[
\dot{r}_1 = \left( \frac{A}{1 - \alpha \cdot u_1^2} - (\beta \cdot \text{sgn}(v_1 \cdot r_1) + \gamma) | r_1 |^n \right) \cdot v_1
\]

Loads applied to each single pier were recorded from OpenSEES TH analyses

Bouc-Wen spring with softening elastic stiffness

Each state space model was tuned with respect to OpenSEES RM for both limit states as a stand alone system by means of a robust time-frequency approach.

\[
F_{ob}(\alpha(n^*)) = \left| STFT_{x, \text{meas}}(n^*, m) - STFT_{x, \text{ALEs}}(n^*, m; \alpha(n^*)) \right|^2 = \min \quad \rightarrow \quad \alpha(n^*)
\]

An instantaneous identification at every \( t^* = n^* \Delta t \)
Dynamic substructuring of hysteretic piers
Validation of nonlinear substructured piers

Dynamic response of Pier #9 at the S.L.S.
Dynamic substructuring of isolators
Bilinear state space model of isolators (Mostaghel, 1999)

In order to simulate the bilinear behaviour of isolator OpenSEES elements, the following governing equations were implemented in state space form:

\[
\begin{cases}
m \ddot{x} + c \dot{x} + \alpha k x + (1 - \alpha) k u = \overline{P}_0 \cdot p(t) \\
\ddot{u} = \dot{x}(\overline{N}(\dot{x}) \overline{M}(u - \delta) + M(\dot{x}) N(u + \delta))
\end{cases}
\]

where:

\[
\begin{align*}
N(w) &= 0.5 \cdot (1 + \text{sgn}(w)) \cdot (1 + (1 - \text{sgn}(w))) \\
M(w) &= 1 - N(w) \\
\overline{N}(w) &= M(-w) \\
\overline{M}(w) &= N(-w)
\end{align*}
\]

Identified parameters read:
\[
\begin{align*}
\alpha &= 0.0046 \\
k &= 2.0278 \times 10^8 \\
\delta &= 5.0000e - 4
\end{align*}
\]
Dynamic substructuring of isolators
Validation of isolators reduction

The effectiveness of the proposed model is proven by the good matching in terms of restoring force and dissipated energy:

Right isolator of Pier #9: dynamic response at ULS
Validation of the reduced model of the Rio Torto Viaduct
Comparison of displacement responses* of OpenSEES RM and reduced model

Dynamic responses 43m tall Pier #7 for the non isolated case

* Measured at the cap beam level

Dynamic responses of Pier #7 for the isolated case
Validation of the reduced model of the Rio Torto Viaduct

NRMSE of transversal kinematic quantities for the non isolated case

Transversal displacements, velocities and accelerations were measured at the cap beam level of the relevant pier.

\[ NRMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_{red} - y_{ref})^2} \]

\[ y_{ref,max} - y_{ref,min} \]

<table>
<thead>
<tr>
<th>Pier</th>
<th></th>
<th>ULS</th>
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<th>SLS</th>
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Validation of the reduced model of the Rio Torto Viaduct
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Offline model updating of NSs
State of the art

Few hybrid testing procedures aimed at reducing the inconsistency of multiple identical substructures where only few of them were simulated experimentally by physical specimens, while the others were numerically simulated within a hybrid framework.

• Kwon et al (2013): they proposed an online updating of NSs based on weighted adaptive responses of multiple models of the PS.

• Yang et al (2012): they transferred online identified material properties of the PS to remainder NSs.

These procedures were just tested in a pure numerical setting.


Offline model updating of NSs

Testing procedure based on recursive identification and model updating tasks

1. Hybrid test at PGA level $i$
2. Identification of OpenSEES material parameters
3. Transfer identified parameters to the overall OpenSEES model
4. OpenSEES simulation run at PGA level $i+1$
5. Model updating of state space models of reduced piers (NSs)
6. Hybrid test at PGA level $i+1$
A sensitivity analysis on 2D OpenSEES models of Pier #9 and #11 highlighted that the **yielding strength of Steel02** and the max compressive strength of Concrete01 materials were the most sensitive parameters.

The **yielding strength of the Steel02 material** was characterized by tensile tests on rebar specimens.
Offline model updating of NSs
Tuning of OpenSEES material parameters

The maximum compressive strength $f_{pc}$ of Concrete01 material will be updated at each PsD run.

Starting values assumed:

- $\varepsilon_{pc0}$: -0.002
- $\varepsilon_{pcU}$: -0.006
- $f_{pcu}$: 23 MPa
- $f_{pc}$: 26 MPa

A model updating tool which operates across MatLAB and OpenSEES based on a patternsearch algorithm was devised.
Offline model updating of NSs
Tuning of OpenSEES material parameters

A model updating tool which operates across MATLAB and OpenSEES based on a patternsearch algorithm was devised.

The max compressive strength of Concrete01 material will be identified at the end of each PsD run.

\[ \hat{p} = \min_p \left\| r_{\exp} - r_{\text{ops}} \left( x_{\exp}, p \right) \right\| \]

\( x_{\exp} \): Measured displacement

\( r_{\exp} \): Measured restoring force

\( r_{\text{ops}} \): OpenSEES restoring force

\( p \): OpenSEES material parameters

The numerical restoring force is calculated through OpenSEES displacement control analysis.
Conclusions and future perspectives

- A complex fiber-based FE OpenSEES model of the viaduct was set to support the PsD test of the Rio Torto bridge.
- A reduced 3DoF model of nonlinear fiber-based piers was presented.
- Nonlinear springs were based on Bilinear and Bouc-Wen-Softening springs.
- The smart substructuring scheme proposed for piers lends itself to a straightforward implementation of isolation elements.
- An offline procedure aimed at transferring damage experienced by physical piers to the whole viaduct is proposed.
Thank you for your attention!

Any question?

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Ongoing developments
Pier reduction to a S-DoF system
Non parametric approach with Polynomials

Dynamic response of Pier #9 at Ultimate Limit State

\[
\begin{align*}
\dot{x} &= v \\
\dot{v} &= m^{-1}(-cv - f - g) \\
\dot{f} &= \hat{a}_0 v + \hat{a}_1 |x| v + \hat{a}_2 f + \hat{a}_3 vf
\end{align*}
\]
Since the S-DoF approach relies just on measured quantities, the identification procedure can be split in two tasks:

- Open loop id. task #1: Preliminary estimation of polynomial coefficients by means of a nonlinear regression on $f$

- Closed loop id. task #2: Tuning of the dynamic response of the resulting state space model

As far as the open loop task doesn’t need for time integration, the resulting procedure is more robust. Moreover, just few iterations are needed in the closed loop task. The global identification session is less expensive.
Validation of the reduced model of the Rio Torto Viaduct
Energy dissipation errors of piers for the non isolated case

Dissipated energies were calculated considering the top transversal displacement and the relevant base reaction force.

\[ ENER_i = \frac{ENE_{red,i} - ENE_{ref,i}}{ENE_{ref,i}} \cdot 100 \]

<table>
<thead>
<tr>
<th>Pier</th>
<th>ENER_i [%]</th>
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Dynamic substructuring of nonlinear piers
Nonlinear state space models of substructured piers

\[
\begin{bmatrix}
\dot{u}_1 \\
\dot{u}_2 \\
\dot{u}_3
\end{bmatrix} =
\begin{bmatrix}
v_1 \\
v_2 \\
v_3
\end{bmatrix}
\]

\[
\begin{bmatrix}
\dot{v}_1 \\
\dot{v}_2 \\
\dot{v}_3
\end{bmatrix} =
\begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}^{-1}
\begin{bmatrix}
f_1 \\
f_2 \\
f_3
\end{bmatrix} -
\begin{bmatrix}
0 & k_{12} & k_{13} \\
k_{21} & k_{22} & k_{23} \\
k_{31} & k_{32} & k_{33}
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
u_3
\end{bmatrix} -
\begin{bmatrix}
r_1 \\
0 \\
0
\end{bmatrix}
\]

\[
\dot{r}_1 = \left( \frac{A}{1 - \alpha \cdot u_1^2} - (\beta \cdot \text{sgn}(v_1 \cdot r_1) + \gamma) \right) r_1^n \cdot v_1
\]

Bouc-Wen spring with softening elastic stiffness

Stiffness and mass matrices of piers from the ANSYS SM were kept as bases for state space models implementations.
Dynamic substructuring of nonlinear piers
Instantaneous estimation in evolutive systems

« Instantaneous » objective function and « instantaneous » identification.

\[
F_{ob}(\alpha(n^*)) = \left| \text{STFT}_{x,\text{meas}}(n^*, m) - \text{STFT}_{x,\text{ALEs}}(n^*, m; \alpha(n^*)) \right|^2 = \min \quad \rightarrow \quad \alpha(n^*)
\]

An instantaneous identification at every \(t^* = n^* \Delta t\)