EU-US-Asia workshop on hybrid testing

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HYBRID SIMULATION OF COMPLEX ISOLATED BRIDGES ENHANCED WITH PARALLEL FETI TIME INTEGRATORS AND MODEL UPDATING

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Some issues in the hybrid simulation of non isolated\isolated bridges

1. Model order reduction strategies applied to complex Numerical Substructures (NS).

2. Model identification techniques applied to nonlinear NSs and isolators in both the Rio Torto Viaduct and EUCENTRE Case Studies.

3. Presence of isolators characterized by variable friction coefficients

4. Issues with Parallel Partitioned Time Integrators
Hybrid simulations was set within the RETRO’ TA of the SERIES European research project.

To this end, flexible reduced nonlinear models of Numerical Substructures (NSs), i.e. piers isolators and deck, were devised allowing for:

- fast time integration of the hybrid system;
- simulation of a consistent degradation of PSs and NSs based on run-by-run SI and updating of physical and numerical piers, respectively.

Substructuring scheme of the Rio Torto Viaduct and DoFs target

NS - 88 DOFS
deck, 10 piers + isol.

PS - 2÷4 DOFS
2 Piers + isol.
Model identification techniques applied to nonlinear NSs
Guyan reduction applied to pier matrices

FE pier model

Plane 3-DoFs superelement obtained via Guyan reduction based on Constraint modes*

Accommodation of isolator elements

*Constraint modes: static deformation shapes owing to unit displacements applied to boundary DoFs, one by one, whilst the others retained
Model identification techniques applied to nonlinear NSs
Nonlinear state space model for reduced piers

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

\[
\begin{bmatrix}
\dot{v}_1 \\
\dot{v}_2 \\
\dot{v}_3
\end{bmatrix} =
\begin{bmatrix}
m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}
\end{bmatrix}^{-1}
\begin{bmatrix}
f_1 \\
f_2 \\
f_3
\end{bmatrix} -
\begin{bmatrix}
0 & k_{12} & k_{13} \\
k_{21} & k_{22} & k_{23} \\
k_{31} & k_{32} & k_{33}
\end{bmatrix}
\begin{bmatrix}
u_1 \\
u_2 \\
u_3
\end{bmatrix} -
\begin{bmatrix}
r_1 \\
r_2 \\
r_3
\end{bmatrix}
\]

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

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 MIMO system by means of a robust optimization approach.
Simplified FE model of the AS BUILT bridge

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

- \(k, \rho, \alpha, \beta, \gamma, n\) = model parameters
- \(x, \dot{x}, r\) = state variables
1A, 3B, 2A, 3C: 4 DSP CONTROLLED ACTUATORS, i.e. Physical DoFs
1B, 2B, 1C, 2C, 3A, 4A, 3D, 4D, 1D, 2D, 1E, 2E, 3E, 4E: 14 FORCE CONTROLLED ACTUATORS
ISSUES ON ISOLATOR DEVICES

Estimation of the friction parameter of isolators mounted on Pier #11

Exp. Resp. of short Pier #11 isolators
Vs.
Num. resp. of OpenSEES singleFPBearing elements with Coulomb friction Model

COULOMB FRICTION MEASURED VALUE $\mu_f = 7\% > 4\%$ (DESIGN VALUE)
ISSUES ON ISOLATORS

CSB characteristics of Pier #11: a) hysteretic response; b) experimental values of $\mu_f$ vs velocity peaks at $\lambda = 1$.

$$V_{des} = \alpha \left[ \mu_{test} N_d + \frac{N_d}{R} \Delta \right]_{PS} + \beta \frac{N_d}{R} \Delta$$

Compensation via Dynamic Substructuring
Model Updating Session #1
Updating of OpenSEES fiber based 2D FE models of Piers #9 and #11

OpenSEES FE model of Pier #11

OpenSEES Concrete01 material definition

\[ f_{pc} = \text{identified} \]

\[ f_{pcu} = 0.88 \cdot f_{pc} \]

\[ E_0 = \frac{2 \cdot f_{pc}}{\varepsilon_0} \quad \varepsilon_{c0} = -0.002 \]

\[ \varepsilon_{cu} = -0.006 \]

\[ \hat{f}_{cp,i} = \min_{f_{cp,i}} \left\| r_{mes,i} - r_{num,i} \left( x_{mes,i}, f_{cp,i} \right) \right\| \]

- \( x_{mes,i} \): measured displacement history at the cap beam level at the PDT run \( i \)-th;
- \( r_{mes,i} \): measured restoring force history at the cap beam level at the PDT run \( i \)-th;
- \( r_{num,i} \): calculated restoring force history via OpenSEES nonlinear static analysis;
- \( f_{cp,i} \): max compressive strength parameter of Concrete01 OpenSEES material.

SOLVED VIA MALTAB PATTERN SEARCH ALGORITHM

10/15/2015
Offline model updating of NSs
Flow chart of the procedure

1. Preliminary cyclic tests/Hybrid test at PGA level i
2. Identification of Concrete01 parameters of OpenSEES 2D models of piers
3. Updating of the OpenSEES 3D model of the bridge
4. Time history analysis of the OpenSEES 3D model at PGA level i+1
5. Updating of reduced MatLAB/Cat3m models of piers (NSs)
6. Hybrid test at PGA level i+1
Synchronization of Num. and Phys. Substructures via monolithic algorithms

\[ \Delta t^C \cdot SS \cdot (k - 1) \quad \Delta t^C \cdot SS \cdot k \quad \Delta t^C \cdot SS \cdot (k + 1) \]

Wall clock time [s]

\[ \Delta t^C = \text{controller time step} \]
More flexibility ... via the parallel partitioned PM method

Link solutions vs. continuous testing

\[ \begin{align*}
\ddot{u}^N_{n+1} &= \ddot{u}^N_{n+1, \text{free}} + \ddot{u}^N_{n+1, \text{link}} \\
\ddot{u}^P_{n+\frac{j}{ss}} &= \ddot{u}^P_{n+\frac{j}{ss}, \text{free}} + \ddot{u}^P_{n+\frac{j}{ss}, \text{link}}
\end{align*} \]

Coupled-problem solutions
The mass fraction parameter

\[ M^N = (1 - mf) \cdot M^N \]
\[ M^P = M^P + mf \cdot M^N \]
Dispacement response of Pier #9

Total displacement
Link displacement \( m_f = 0.001 \)
Link displacement \( m_f = 0.95 \)

\[ \Delta t_N = \Delta t_P = 1 \text{ msec} \]
Starting from the GC method

A Novel Parallel Partitioned Integrator

\[
\begin{align*}
M^N \dot{Y}^N_{n+1} + G^N (Y^N_{n+1}) + L^N \Lambda_{n+1} &= F^N_{n+1} \\
M^P \dot{Y}^P_{n+j/ss} + G^P (Y^P_{n+j/ss}) + L^P \Lambda_{n+j/ss} &= F^N_{n+j/ss} \\
B^N \dot{Y}^N_{n+1} + B^P \dot{Y}^P_{n+1} &= 0
\end{align*}
\]

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

The modified-Generalized-$\alpha$ algorithm

$$M\dot{y}_{n+\alpha_m} + Ky_{n+\alpha_n} = F_{n+\alpha_n}$$

$$\Omega = \omega \cdot \Delta t$$

$\rho_\infty$: asymptotic spectral radius
Reference Test... Suitable for Hybrid Testing

Multi-span bridge with open-section deck and hollow RC piers

- Curved-surface slider for the isolated case

EXP. PIER
- re-bars slip/sudden failure
- brittle cracking
- failure mechanisms
- ...

EXP. CSB
- Wear
- Local contact pressure effects
- ...

NUM. DECK

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EUCENTRE Strong wall – Pier setup

RC Pier test setup

Vertical & horizontal load application

G. Abbiati, E. Cazzador, I. Lanese, S. Eftekhar Azam, O. S. Bursi, and A. Pavese. Recent advances on the hybrid simulation of bridges base on partitioned time integration, dynamic identification and model updating. 6th Int. Conf. on Advances in Experimental Structural Engineering. August 1-2, 2015, University of Illinois, Urbana-Champaign, USA

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CSB Friction Coefficient Compensation

Friction coefficient $\mu$ vs. Absolute Velocity peak (m/s)

- $\mu_{test} \approx 6\%$
- $\mu_{design} \approx 8\%$

Equation:

$$V_{des} = \alpha \left[ \mu_{test} N_d + \frac{N_d}{R} \Delta \right]_{PS} + \beta \frac{N_d}{R} \Delta$$

- $\alpha = \frac{\mu_{des}}{\mu_{test}} = 1.333$
- $\beta = 1 - \alpha = -0.333$

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Substructuring scheme of the EUCENTRE Bridge

**PS: 1 ÷ 2 DOFS**  
(pier + isol.)

**32 ÷ 34 NS: DOFS**  
(deck + pier + isol.)
ONLINE identification of the physical pier

\[ \begin{align*}
 r + c \cdot \dot{x} + m \cdot \ddot{x} &= p(t) \\
 \dot{r} &= \left[ A - (\beta \cdot \text{sgn}(\dot{x} \cdot r) + \gamma) \left| r \right|^n \right] \cdot \dot{x}
\end{align*} \]
Accommodation of ONLINE identification tools

Plan view of the bridge model

Gray box identification (UKF, EKF etc.)

\[
\begin{align*}
    r_j + c \cdot \dot{x}_j + m \cdot \ddot{x}_j &= \Lambda_j \\
    \dot{r}_j &= \left( A - (\beta \cdot sgn(\dot{x}_j \cdot r_j) + \gamma) | r_j |^{\nu} \right) \cdot \dot{x}_j
\end{align*}
\]
Gray box identification: a joint state and parameter estimation approach

\[
\begin{align*}
r_j + c \cdot \dot{x}_j + m \cdot \ddot{x}_j &= \Lambda_j \\
\dot{r}_j &= (A - (\beta \cdot \text{sgn}(\dot{x}_j \cdot r_j) + \gamma) \cdot |r_j|^n) \cdot \dot{x}_j
\end{align*}
\]

- **System state vector**
  \[ z_k = f^z_{k-1}(z_{k-1}, \vartheta_{k-1}) + \nu^z_{k-1} \]
- **Model parameters**
  \[ \vartheta_k = \vartheta_{k-1} + \nu^\vartheta_{k-1} \]
- **System output**
  \[ y_k = H^z z_{k-1} + w_k \]

State process noise
Parameter process noise
Measurement noise

Model Updating of NSs
Model updating online adopted during EUCENTRE PsD tests
Model Updating of NSs
Model updating online adopted during EUCENTRE PsD tests

Gray box identification: a joint state and parameter estimation approach

\[
\begin{align*}
    z_k &= f_{k-1}^z(z_{k-1}, \vartheta_{k-1}) + v_{k-1}^z \\
    \vartheta_k &= \vartheta_{k-1} + v_{k-1}^\vartheta \\
    y_k &= H^z z_{k-1} + w_k
\end{align*}
\]

\[
\begin{align*}
    z_k &= f_{k-1}^x(x_{k-1}) + v_{k-1}^x \\
    y_k &= H^x x_{k-1} + w_k
\end{align*}
\]

\[
x_k = \begin{bmatrix} z_k \\ \vartheta_k \end{bmatrix}
\]

joint representation
Numerical validation of the ONLINE model updating

Identification of the linear tangent stiffness

Time [s]

A [N/m]
Conclusions

✓ A methodological approach was proposed to handle PSs characterized by complex geometries with a reduced number of actuators. Model reduction strategies were applied to achieve this goal.

✓ Nonlinear state space models were proposed as NSs suitable for fast updating sessions aimed at reproducing the damage experienced by PSs.

✓ Partitioned time integration allows for flexibility as well as synchronization of both numerical and physical time integration processes.

✓ The magnitude of the physical link solution, which determines the smoothness of the actuator trajectory, can be easily reduced by moving mass from the NS to the PS.

✓ Lagrange multipliers can be calculated explicitly for a better SI.
Thank you for your attention!

Questions?

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