Pseudo-dynamic testing of a piping system based on model reduction techniques

Reza MS, Abbiati G, Bonelli A, Bursi OS

Department of Civil, Environment and Mechanical Engineering, University of Trento, Via Mesiano 77, 38123, Trento, Italy.

Oreste S. Bursi, Ph.D., P.E., MASCE
Prof. of Structural Dynamics and Control
email: oreste.bursi@ing.unitn.it
Acknowledgement

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2. The authors gratefully acknowledge the financial supports of the University of Trento for Lab. activities

*INDUSE*: Structural safety of industrial steel tanks, pressure vessels and piping systems under seismic loading
Piping Systems and Components

Piping Systems:
- one of the major parts in many industries;
- carry fluids from a location to another;
- most preferred means of transferring oil and gas worldwide;

A single failure can cause serious accidents.
Seismic risks in Piping Systems and Components

Piping Systems and Components suffered severe damages under earthquakes.

**Consequences:**
- loss of life;
- loss of asset;
- environmental pollution...

Refinery Conflagration
Kocaeli Earthquake
Turkey, 1999

Pipeline failure
Kobe Earthquake
Japan, 1995

Bolted flange joint failure
Kobe Earthquake
Japan, 1995
Several seismic design Codes and Standards exist for piping systems:

<table>
<thead>
<tr>
<th>American</th>
<th>European</th>
</tr>
</thead>
<tbody>
<tr>
<td>- ASME SecIII Div1 (2002)</td>
<td></td>
</tr>
<tr>
<td>- FEMA 450 (2003)</td>
<td></td>
</tr>
</tbody>
</table>

- Current design Standards have been found over-conservative (Touboul et al., 2006; Otani et al., 2011).

- Modifications have been proposed to relax this conservatism.

- Some components, e.g., Bolted Flange Joints, do not have seismic design rules.


Previous experimental tests

- Several shaking table tests have been performed under seismic loading.
- Failure at very high level of earthquake loading (~3g PGA)
- Failure in the critical components, e.g., elbows, Tee-joints.
- Pseudo-dynamic tests on a piping system by Melo et al. (2001).

Objectives and Scope of the work

European Project, INDUSE
Structural Safety of Industrial Steel Tanks, Pressure Vessels
and Piping Systems under Seismic Loading (INDUSE)
(Grant No. RFSR-CT-2009-00022).

Activities carried out by the University of Trento (UNITN)
Experimental testing on a piping system:
- Pseudo-dynamic and Real Time tests under earthquake loading

Challenges:
- Hybrid tests are considered inadequate for distributed mass systems,
  e.g., piping systems.
- Earthquake forces are distributed on the piping system.
Objectives and Scope of the work

**Objectives**
Seismic performance evaluation of a piping systems and its critical components, i.e., Pipe elbow, Tee joint, Bolted flange joints.

Fig. Some critical components of a piping system

Figure: Deformed three-dimensional and cross-sectional shapes of an elbow (D/t=55) under in-plane closing bending moments for zero pressure.
Objectives and Scope of the work

- We wanted to use actuators instead of a shaking table.

Experiments on elbow by TUDelft

Experimental results of TUDelft were utilised for modelling elbow elements.

Negative displ. Implies closing; $e_y = -57.8$ mm; Positive displ. Implies opening; $e_y = +43.7$ mm;

Fig. Shaking table tests by DeGrassi et al. (2008)
The piping system under investigation

Fig. A 3D model of the piping system
We designed the support

Fig. General dimensions and specifications of the piping system after DeGrassi et al. (2008)

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”</td>
<td>API 5L Gr. X52</td>
<td>Water/3.2 MPa</td>
</tr>
<tr>
<td>Schedule 40</td>
<td>fy= 418 Mpa; fu = 554 Mpa;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elongation = 35.77%</td>
<td></td>
</tr>
</tbody>
</table>
FE modelling of the piping system

- Finite element models were developed in ANSYS and SAP2000.
- Flexibilities of straight elbow elements were adjusted according to an ABAQUS-based FE analysis on corresponding curved elbows from UThessaly.
Modal analysis

Table First 20 eigenfrequencies and participation masses of the piping system model

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency Hz</th>
<th>Excited Mass in x, %</th>
<th>Mode</th>
<th>Frequency Hz</th>
<th>Excited Mass in x, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.18</td>
<td>36.00</td>
<td>11</td>
<td>16.19</td>
<td>0.79</td>
</tr>
<tr>
<td>2</td>
<td>6.32</td>
<td>12.00</td>
<td>12</td>
<td>17.59</td>
<td>9.56</td>
</tr>
<tr>
<td>3</td>
<td>6.69</td>
<td>0.29</td>
<td>13</td>
<td>18.52</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>7.44</td>
<td>0.97</td>
<td>14</td>
<td>23.50</td>
<td>1.11</td>
</tr>
<tr>
<td>5</td>
<td>7.87</td>
<td>2.44</td>
<td>15</td>
<td>27.22</td>
<td>1.64</td>
</tr>
<tr>
<td>6</td>
<td>9.22</td>
<td>8.33</td>
<td>16</td>
<td>28.23</td>
<td>0.43</td>
</tr>
<tr>
<td>7</td>
<td>10.84</td>
<td>1.44</td>
<td>17</td>
<td>28.78</td>
<td>1.01</td>
</tr>
<tr>
<td>8</td>
<td>11.35</td>
<td>8.13</td>
<td>18</td>
<td>29.46</td>
<td>0.14</td>
</tr>
<tr>
<td>9</td>
<td>11.98</td>
<td>0.64</td>
<td>19</td>
<td>33.75</td>
<td>1.59</td>
</tr>
<tr>
<td>10</td>
<td>14.33</td>
<td>0.26</td>
<td>20</td>
<td>37.19</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Total</strong></td>
<td><strong>87.00</strong></td>
</tr>
</tbody>
</table>

- About 87% of the total mass is excited by first 20 modes.
- Mode #1 and Mode #2 excites most masses in the x direction.
Selection of input earthquakes

- Filtered accelerograms were generated on different floors applying El Centro earthquake with a 0.29g PGA.
- PGA of the reference earthquake was modified according to Serviceability and Ultimate limit states based on performance based earthquake engineering Standards.

<table>
<thead>
<tr>
<th>Limit States</th>
<th>PGA (g)</th>
<th>PGA (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Serviceability</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLO</td>
<td>0.08</td>
<td>0.77</td>
</tr>
<tr>
<td>SLD</td>
<td>0.11</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Ultimate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLV</td>
<td>0.42</td>
<td>4.13</td>
</tr>
<tr>
<td>SLC</td>
<td>0.60</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Figure: Accelerograms relevant to point (1) of the support structure.
Substructuring

- Two coupling DoF were chosen to be compatible with an MTS controller configured for two actuators.
- Position of minimum bending moments were chosen as coupling nodes.
Substructuring

Hinges were placed in xy plane; movements of the two coupling nodes were allowed in x.

Favourable agreement between time history responses of the Reference and Continuous Models

Average $e_{RMS} = 0.22$

$e_{RMS}$: Root mean square error between time history responses of RM and CM.

$$e_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_{CM}^2)_i - \frac{1}{N} \sum_{i=1}^{N} (x_{RM}^2)_i}$$
The system of equations of motion without damping:

\[ M \ddot{u} + Ku = -M I \ddot{u}_g \]

where M and K are mass and stiffness matrix; u is the displacement vector; \( u_g \) is the ground displacement from an earthquake; I is an identity matrix.

Splitting the components into the PS and NS,

\[ M^N \ddot{u}^N + K^N u^N + M^N I \ddot{u}_g = -M^P I \ddot{u}_g - M^P \dddot{u}^P - K^P u^P \]

Where, subscript N and P correspond to the NS and PS, respectively.

**Challenges:**

- Applications of \( -M^P I \ddot{u}_g \) required one actuator per DoF — NOT FEASIBLE

Hence, mass matrix was reduced to 2 by 2 size.

**Mode Synthesis/Model Reduction techniques were adopted.**
System of equations of motion

- The PS was reduced to a 2 by 2 system in the two coupling DoFs.
- The earthquake force vector of the PS was reduced to a 2 element vector.
Mode Synthesis / Model Reduction

DoFs of a large model is reduced to a smaller number that are capable of reproducing original system behaviour of interest.

\[
\{X_n\} = \begin{bmatrix} X_a \\ X_d \end{bmatrix} = [T] \{X_a\}
\]

\(T\) is a Transformation matrix

The Reduced mass and stiffness matrices

\[
[M_a] = [T]^T [M_n] [T]
\]

\[
[K_a] = [T]^T [K_n] [T]
\]
Model Reductions
SEREP (System Equivalent Reduction-Expansion Process)

- Dynamic Reduction- modal properties of the GLOBAL SYSTEM are retained.
- Accounts for both mass and stiffness

Write the equations in modal co-ordinates, \( x = \phi r \) and pre-multiply by \( \phi^T \) (\( \phi \) is the eigenvector)

\[
\phi^T M_n \phi \ddot{r}_n + \phi^T K_n \phi r_n = \phi^T F_n
\]

where, \( I = \begin{bmatrix} I_a & 0 \\ 0 & I_d \end{bmatrix} \) is an Identity matrix and \( \lambda = \begin{bmatrix} \lambda_a & 0 \\ 0 & \lambda_d \end{bmatrix} \) contains the natural frequencies of the system;

\[
x_n = \begin{bmatrix} x_a \\ x_d \end{bmatrix} = \phi r = \begin{bmatrix} \phi_{na} \\ \phi_{nd} \end{bmatrix} \begin{bmatrix} r_a \\ r_d \end{bmatrix} = \begin{bmatrix} \phi_{aa} & \phi_{ad} \\ \phi_{da} & \phi_{dd} \end{bmatrix} \begin{bmatrix} r_a \\ r_d \end{bmatrix} \]

Now, Truncate the modal vector \( r_n = [r_a \ r_d]^T \) by assuming \( r_d = 0 \):

\[
I \ddot{r}_a + \lambda_a r_a = \phi_{na}^T F_a (1)
\]

Use the value of \( r_a \) to solve (1) for \( x_a \).

\[
\phi_{aa}^{-1} \phi_{na}^T M \phi_{na} \phi_{aa}^{-1} \ddot{x}_r + \phi_{aa}^{-1} \phi_{na}^T K \phi_{na} \phi_{aa}^{-1} x_r = \phi_{aa}^{-1} \phi_{na}^T F
\]

The reduced system:

\[
\overline{M} = T^T M; \quad \overline{K} = T^T K; \quad \overline{F} = T^T F
\]

Transformation Matrix: \( T = \phi_{na} \phi_{aa}^{-1} \)
Model Reductions
SEREP

\[ \begin{bmatrix} x_n \\ x_d \end{bmatrix} = \phi r = \begin{bmatrix} \phi_{na} & \phi_{nd} \\ \phi_{da} & \phi_{dd} \end{bmatrix} \begin{bmatrix} r_a \\ r_d \end{bmatrix} = \begin{bmatrix} \phi_{aa} & \phi_{ad} \\ \phi_{da} & \phi_{dd} \end{bmatrix} \begin{bmatrix} r_a \\ r_d \end{bmatrix} \]

Transformation Matrix: \( T = \begin{bmatrix} \phi_{na} & \phi_{aa}^{-1} \end{bmatrix} \)

Modes of the overall system are retained in order to better approximate the emulated system’s behaviour.

Suitable for Real Time tests
Only Earthquake forces have to be condensed.

Model Reduction
Craig-Bampton (CB) method

- Combines motion of boundary points with modes of the structure assuming the boundary points are held fixed.
- Accounts for both mass and stiffness.
- Contributions of internal DoFs are measured by rigid movements of the coupling DoFs and modal responses of the other DoFs.

\[ x_n = \begin{cases} x_C \\ x_L \end{cases} = \begin{bmatrix} I & 0 \\ \phi_R & \phi_L \end{bmatrix} \begin{bcases} x_C \\ q \end{bcases} \]

\[ = \begin{bmatrix} I & 0 \\ \phi_R & \phi_L \end{bmatrix} = \phi_{CB} = \text{CB Transformation} \]

\( \phi_R \) = rigid body vector
\( \phi_L \) = fixed based mode shape
\( q \) = modal DoFs
\( x_C \) = Coupling DoFs
\( x_L \) = internal DoFs

CB reduction is suitable for Pseudo-dynamic tests

Overall Contribution: Experimental measurements of static restoring force + Numerical modelling of modal responses of the PS.

\[
x_n = \begin{bmatrix} x_C \\ x_L \end{bmatrix} = \begin{bmatrix} I & 0 \\ \phi_R & \phi_L \end{bmatrix} \begin{bmatrix} x_C \\ q \end{bmatrix}
\]

Response of internal DoFs

\[
x_L = \phi_R x_C + \phi_L q
\]

Rigid movements of coupling nodes

Experimentally measured

Modal response

Numerically modelled
Effectiveness of model reductions

Table $e_{\text{RMS}}$ between time history responses of the Reduced Model (NS + Reduced PS) and Reference Model

<table>
<thead>
<tr>
<th>Reduction</th>
<th>$e_{\text{RMS}}$ Coupling Node #1</th>
<th>$e_{\text{RMS}}$ Coupling Node #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td>SEREP</td>
<td>0.31</td>
<td>0.17</td>
</tr>
</tbody>
</table>

CB and SEREP2 methods were found to be the most effective reductions.

Assumptions
- The piping system was assumed to remain in the linear range during experiments
- Modes ($\phi$) were not updated during tests
Transfer Function of MOOG actuators

- Sensitivity analysis of the actuator transfer function with increasing mass
- Signals up to 15 Hz with displacement range of +/- 1 mm (Real-Time feasible)

![MOOG Actuator with masses](Image)

**Figure: Two masses (2500 kg each) attached to a MOOG actuator**

<table>
<thead>
<tr>
<th></th>
<th>P</th>
<th>I</th>
<th>D</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOOG 1</td>
<td>15</td>
<td>1</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>MOOG 2</td>
<td>15</td>
<td>1</td>
<td>0</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Figure: Bode diagram of the actuator with the masses**

**Figure: A step response**
Modification of the NS for RTDS

Displacement lags showed by actuators for higher displacements

- Not possible to run RTDS with high frequency and high PGA.
- Eigenfrequency was reduced by adding masses to the NS.
- RTDS was carried out with low PGA.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td>1.10</td>
</tr>
<tr>
<td>3</td>
<td>1.11</td>
</tr>
<tr>
<td>4</td>
<td>1.39</td>
</tr>
<tr>
<td>5</td>
<td>1.60</td>
</tr>
<tr>
<td>6</td>
<td>1.79</td>
</tr>
<tr>
<td>7</td>
<td>2.60</td>
</tr>
<tr>
<td>8</td>
<td>3.41</td>
</tr>
<tr>
<td>9</td>
<td>5.00</td>
</tr>
<tr>
<td>10</td>
<td>6.58</td>
</tr>
</tbody>
</table>
Integration Scheme

LSRT2 algorithm

The Linearly Stable Real Time 2 stages LSRT2 method developed by Bursi et al. (2008) is suitable for real-time applications:

\[ y_{n+1} = y_n + b_1 k_1 + b_2 k_2 \]

\[ k_1 = (I - \gamma \Delta t J)^{-1} f(t_n, y_n) \Delta t \]

\[ k_2 = (I - \gamma \Delta t J)^{-1} (f(t_n + \Delta t / 2, y_n + k_1 / 2) - \gamma k_1 J) \Delta t \]

In order to ensure L-Stability,

\[ b_1 = 0 \text{ and } b_2 = 1, \quad \gamma = 1 \pm \sqrt{2} / 2 \]

• The actual delay $\tau$ is bounded between $\tau_{c,i}$ and $\tau_{c,s}$.
• By the upper limit $\tau_{c,s}$ the displacement command is overcompensated in order to let the desired displacement $X_d$ at time $t_n$ to be achieved earlier than it should be.
• The corresponding reaction force $f_d$ is then interpolated and fed back to the NS.

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Delay (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOOG 1</td>
<td>11</td>
</tr>
<tr>
<td>MOOG 2</td>
<td>11</td>
</tr>
</tbody>
</table>

$\tau_{c,s} = 22$ ms

Hardware-software architecture

Fig. Hardware-software configuration for hybrid tests

Fig. Hardware for hybrid tests
## Experimental program

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Hammer Test</th>
<th>PGA (g)</th>
<th>PGA (m/s²)</th>
<th>Internal Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Identification tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identification test of the PS, IDT</td>
<td>Hammer Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Real time tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RT1</td>
<td>RTDS</td>
<td>0.020</td>
<td>0.196</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td>RT2</td>
<td>RTDS</td>
<td>0.020</td>
<td>0.196</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td><strong>Elastic tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic test, ET</td>
<td>PDDS</td>
<td>0.042</td>
<td>0.413</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td><strong>Serviceability limit state tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operational limit state test, SLOT</td>
<td>PDDS</td>
<td>0.079</td>
<td>0.772</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td>Damage limit state test, SLDT</td>
<td>PDDS</td>
<td>0.112</td>
<td>1.098</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td><strong>Ultimate limit state tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safe life limit state test, SLVT</td>
<td>PDDS</td>
<td>0.421</td>
<td>4.128</td>
<td>3.2 MPa</td>
</tr>
<tr>
<td>Collapse limit state test, SLCT</td>
<td>PDDS</td>
<td>0.599</td>
<td>5.878</td>
<td>3.2 MPa</td>
</tr>
</tbody>
</table>

- PDDS were carried out with a **time scale factor**, \( \lambda = 50 \).

\[
\lambda = N_s \Delta t_s / \Delta T
\]

where,
\( \Delta t_s = \) sampling time of the controller (1/1024 sec);
\( \Delta T = \) earthquake time step;
\( N_s = \) integer no of division of \( \Delta T \).
Experimental set-up

Support #1
Support #2
1000 kg mass

An Elbow
Tee-joint
Bolted flange joint

Elbow 1
Elbow 2
Elbow 3
1000 kg Mass
MOOG 1 Actuator
MOOG 2 Actuator
Support 1
Support 2
Flanged Joint
Control and Measurement Unit

Fixed End
Coupling Point 1
Coupling Point 2
8" pipe
2.861 m
1.2 m
2.5 m
2 m
1.62 m
1.25 m
1.25 m
1.38 m
1.75 m
1.75 m
6" pipe
2.5 m
MOOG 1 Actuator
MOOG 2 Actuator
Support 1
Tee Joint
Support 2
Bolted Flange Joint

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Identification Tests (IDTs)

**Identification tests**

<table>
<thead>
<tr>
<th>IDT</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDT 1</td>
<td>Without water</td>
</tr>
<tr>
<td>IDT 2</td>
<td>With water and low pressure (0.1 MPa)</td>
</tr>
<tr>
<td>IDT 3</td>
<td>With water and pressure (3.2 MPa)</td>
</tr>
<tr>
<td>IDT 4</td>
<td>Long signal with water and low pressure (0.1 MPa)</td>
</tr>
</tbody>
</table>

**Results of Identification tests**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency, Hz</th>
<th>Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDT1</td>
<td>IDT2</td>
</tr>
<tr>
<td>1</td>
<td>4.00</td>
<td>3.41</td>
</tr>
<tr>
<td>2</td>
<td>7.01</td>
<td>5.55</td>
</tr>
<tr>
<td>3</td>
<td>7.98</td>
<td>7.17</td>
</tr>
<tr>
<td>4</td>
<td>8.74</td>
<td>8.94</td>
</tr>
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<td>5</td>
<td>9.28</td>
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</tr>
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<td>14.15</td>
<td>16.68</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>17.32</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>18.19</td>
</tr>
</tbody>
</table>

- Modes of the PS were confirmed.
- Addition of water stiffened the structure.
- No considerable effect of pressure on the stiffness
- A 0.5% damping of the PS was confirmed.
Experimental Results - PDDS

- The piping system and all components remained below their yield limit even at Collapse Limit State.
- Significant amplifications of input PGAs were found in the piping system.
- Lower modes dominated system’s responses.

Fig. Acceleration at Coupling Node #1 at SLCT (PGA: 0.599g)

Fig. Displacements of Coupling Node #1 at SLCT (PGA: 0.599g)
Experimental Results - RTDS

- Both RT1 (with SEREP) and RT2 (with CB) were successfully executed.
- Input PGA was amplified in the piping system.
- Lower modes governed responses of the system.

Fig. Acceleration histories and relevant Fourier spectra of Coupling Node #1 at: (a) RT1; (b) RT2. (PGA: 0.02g)
Comparison
Numerical and Experimental Results

A good agreement was found between numerical and experimental responses.

Experimental results showed stiffer response than the numerical model due to support frictions.

The Piping system remained elastic
- initial assumption was justified
- effectiveness of CB and SEREP reduction was justified

Fig. Displacement histories and relevant Fourier spectra of Coupling Node #2 at: (a) SLVT; (b) SLCT.

\[ e_{RMS} = \text{About 2\% at SLVT (PsD) and 11\% at SLCT (PsD)} \]

Fig. Displacement histories and relevant Fourier spectra of Coupling Node #2 at: (a) RT1 (with SEREP); (b) RT2 (with CB)

\[ e_{RMS} = \text{About 30\%} \]

June 7, 2013
Concluding Remarks

• Several PDDS and RTDS were performed under Serviceability and Ultimate limit state earthquake loading.
• Mode Synthesis techniques were applied to conduct hybrid tests.
• The piping system and its components under all limit state earthquake events remained below their yield limit without leakage.
• Effectiveness of CB and SEREP reduction was experimentally justified.
  - Suitable eigenmodes could be updated through identification tests between two successive experiments.
  - Control-based reduction techniques, e.g., gramian-based approach (Hahn et al., 2002), could be employed for reduction purposes.
Thank you for your attention!

Questions?

Oreste S. Bursi, Ph.D., P.E., MASCE
Prof. of Structural Dynamics and Control
email: oreste.bursi@ing.unitn.it
Future Perspectives

• A non-linear analysis could be performed by updating the linear reduced model of the PS.
  - Suitable eigenmodes could be updated through identification tests between two successive experiments.

• Control-based reduction techniques, e.g., gramian-based approach (Hahn et al., 2002), could be employed for reduction purposes.
  - A better control of desired output, e.g., elbow rotations, with input forces can be achieved.

The parameterized stiffness matrix is built by putting on the main diagonal values estimated by numerical simulations in ABAQUS, and then deriving terms out the diagonal whereas a weight factor $\omega$ that linearly combines the contributions made by shear and bending moments.

$$
\begin{pmatrix}
  k_{11} & 0 & 0 & k_{14} & 0 & 0 \\
  0 & k_{22} & k_{23} & 0 & k_{25} & k_{26} \\
  0 & k_{32} & k_{33} & 0 & k_{35} & k_{36} \\
  k_{41} & 0 & 0 & k_{44} & 0 & 0 \\
  0 & k_{52} & k_{53} & 0 & k_{55} & k_{56} \\
  0 & k_{62} & k_{63} & 0 & k_{65} & k_{66}
\end{pmatrix}
\begin{pmatrix}
  u_1 \\
  v_1 \\
  \phi_1 \\
  u_4 \\
  v_4 \\
  \phi_4
\end{pmatrix}
= 
\begin{pmatrix}
  H_1 \\
  F_1 \\
  M_1 \\
  H_4 \\
  F_4 \\
  M_4
\end{pmatrix}
$$

$$
k_{36} = k_{63} = (1 - \omega) \frac{1}{6} K_{sh} l^2 + \omega \frac{1}{2} K_{bg}
$$

$$
-k_{23} = -k_{32} = -k_{26} = k_{35} = k_{53} = -k_{62}
$$

$$
k_{56} = k_{65} = (1 - \omega) \frac{1}{2} K_{sh} l + \omega \frac{3}{2} \frac{K_{bg}}{l}
$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Theory</th>
<th>EB bg ($\omega=1$)</th>
<th>EB sh ($\omega=0$)</th>
<th>TI bg ($\omega=1$)</th>
<th>TI sh ($\omega=1$)</th>
<th>EB par (0&lt;$\omega$&lt;1)</th>
<th>TI par (0&lt;$\omega$&lt;1)</th>
<th>TI par (0&lt;$\omega$&lt;1, $\chi=2$)</th>
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<tbody>
<tr>
<td>kB</td>
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<td>-</td>
<td>0,89</td>
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<tr>
<td>$\omega$</td>
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<td>-</td>
<td>-</td>
<td>-</td>
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<td>0,87</td>
<td>0,74</td>
</tr>
<tr>
<td>Global error</td>
<td>-</td>
<td>4,13 %</td>
<td>170,58 %</td>
<td>3,97 %</td>
<td>97,03 %</td>
<td>3,83 %</td>
<td>3,43 %</td>
<td>5,23 %</td>
</tr>
</tbody>
</table>

bg: contribution from bending; sh: contribution from shear; par: different weight from bending and shear contributions.