Role and application of testing and computational techniques in seismic engineering

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Contents

- Introduction (l’Aquila earthquake and PBEE)
- Taxonomy of modern testing techniques & pros and cons
- Integration of sensors and advanced numerical tools
- Applications on a steel-concrete moment-resisting composite structure
- Work in progress
Introduction

- The 5% damped acceleration response spectra for two near-fault records belonging to soil class A and B are compared with the EC8 spectral shapes scaled at 0.25 g. (Ameri et al. 2009)

- The spectrum designed for rock sites is conservative at high periods, while the observations for class B exceed both short periods (0-0.4s) and intermediate periods (0.8 – 1.5s).

Introduction (cntd)

i) Italy has a large stock of structures and infrastructures whose seismic capacity is insufficient; ii) in view of large earthquakes, it is crucial to accurately evaluate their existing seismic capacity and then to retrofit them accordingly; iii) development of construction technologies to enhance the seismic capacity, and implementation of these technologies for actual design and construction are critical.

It is crucial to identify the state of complete collapse in which the structure no longer can sustain gravity. As a result, the reserve capacity that the structure possesses for loads greater than that specified in seismic codes up to collapse, i.e. the collapse margin, needs to be identified. Actual data are scarce.
Introduction (cntd)

- Advances in numerical analysis methods, particularly those using the finite element methods, are notable, but the analyses insufficiently duplicate the behaviour of structures at collapse which involve significant material nonlinearities, strength degradation, stiffness deterioration, and topology changes such as fracture, separation and detachment.

![Two DOF system with interaction for Example 3.](image)

- Lavan et al., 2009, Progressive collapse analysis through strength degradation and fracture in the mixed Lagrangian formulation, Earthquake Engineering and Structural Dynamics, early view

- **Tests on structures and systems** that involve force redistribution owing to member yielding and plastification are possible
Performance-based seismic design is aiming at developing innovative systems by which enhance functionality, operability and safety of structures. Base-isolation and passive dampers are typical examples.

All such research and development must however, be checked for expected actual performance before being transferred with confidence to actual design and construction practices.

The need for actual data obtained by experimentation is deemed extremely urgent for the advancement of earthquake engineering, particularly for issues pertinent to collapse, rate-of-loading, realistic scale and structural systems.
Taxonomy of modern testing techniques

**Pseudo-dynamic testing**
Simulation conducted with **inertia effect** of the structural system **numerically simulated** in the computer and applied by hydraulic actuators.

**Real-time testing**
Simulation conducted with structures or substructures where **inertia effects are physically developed** onto the specimen. Dynamical load can be provided either by actuators or shake tables.

**Real-time testing with dynamic substructuring**
Simulation procedure which combines both **Physical substructures** and **Numerical substructures** to estimate/predict the structural seismic behaviour of complex specimens.

**Real-time structural behaviour monitoring**
it uses dynamic analysis and **limited sensors, e.g. fibres**, to collect **mission critical data** only from the **part of a structure that potentially experiences damage**. The **remaining part of the structure** can be **numerically modelled**.
Pseudo-Dynamic testing

*Continuous pseudo-dynamic - conceived @JRC*

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**Control loop:**

- Compute external force: \( F_i \)
- Measure the restoring force: \( R_i \)
- Compute \( a_i \) and \( v_i \)
- Compute next displacement: \( d_{i+1} \)

... Control Algorithm:

- Controller target = \( d_{i+1} \) (sampling period \( \Delta t_{st} \approx 1-2 \) ms)

Go to Control loop

---

**TIME SCALE FACTOR:**

\[ \lambda = \frac{\Delta t_{st}}{\Delta t} = \frac{n_s \Delta t_{st}}{\Delta T} \]

---

**Ground Acceleration**

- \( \Delta t \)
- \( \Delta T \)
- \( n_s \) interpolated values

**Earthquake time**

**PsD test time**

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**Structural Displacements**

- \( d_i \)
- \( d_{i+1} \)

**Step i**

**Step i+1**

\( \Delta t_{st} \)

Small time step \( \rightarrow \) explicit algorithms
Real-Time testing with Dynamic Substructuring

*High-speed on line testing - conceived @CU Boulder*

\[ d_{i+1}^{(k+1)} \]

\[ d_i \]

\[ d_i^c \]

\[ d_{i-1}^c \]

\[ (i - 1)\Delta t \quad i\Delta t \quad (i + 1)\Delta t \]

Displacement

Time

Quadratic function

Updated Displ.

Displ. Commands

\[ \delta t \]

Command signal
Pros and cons

1. *PsD testing – rate of loading*
2. *RTDS testing – Actuator compensation*

ACTUATOR DYNAMICS

- **Sensor**
- **Substructure 1**
  - Computational
- **Actuator / Transfer Device**
  - Natural Physical Feedback
- **Substructure 2**
  - Physical

**External Input** (Eg. Ground Motion)
**Substructure 1**
**Substructure 2**

**Boundary Condition**

**Work Conjugate Boundary Condition**

**Natural Physical Feedback**

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Real-Time Structure Behaviour Monitoring

*Cable-stay footbridge 160 m long @Pescara - Italy*

- Structural identification of the bridges with 24 accelerometers
- Model Updating - Behaviour monitoring on site of the dynamic properties and stress state with 8 accelerometers and 4 temp. sensors

Merging of sensors and advanced numerical tools

- PBEE is aiming at developing innovative systems by which enhance functionality, operability and safety of structures.

- By means of a better use of sensors and system identification techniques, we show how to be better interpret actual data provided by dynamic, PsD and cyclic experiments. In detail,

- Estimation of frequency, mode shapes and damping in view of local damage and global damage evaluation

- Experimental acceleration-displacement relationships.

- Hysteresis relationships -in a statically indeterminate structure-
Benchmark: Steel-concrete moment-resisting composite structure with partial strength joint

(ECOLEADER EUROPEAN PROJECT HPR-CT-1999-00059)

<table>
<thead>
<tr>
<th>Test</th>
<th>PsD test pga [g]</th>
<th>Performance objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>--</td>
<td>Identification at the undamaged state</td>
</tr>
<tr>
<td>1</td>
<td>0.10</td>
<td>Elastic behaviour</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>Serviceability Limit State (SLS)</td>
</tr>
<tr>
<td>3</td>
<td>1.40</td>
<td>Ultimate Limit State (ULS)</td>
</tr>
<tr>
<td>II</td>
<td>--</td>
<td>Identification at the Ultimate Limit State</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>Collapse Limit State</td>
</tr>
<tr>
<td>5</td>
<td>Cyclic</td>
<td>Maximum top displacement equal to 300 mm</td>
</tr>
<tr>
<td>III</td>
<td>--</td>
<td>Identification at the Collapse Limit State</td>
</tr>
</tbody>
</table>
References


Forced dynamic SHT and SST were repeated in test phases I, II and III.

In each test phase, three accelerometer configurations were set up in order to catch:

A - global behaviour
B - interior base and beam-to-column joint behaviour
C - exterior base and beam-to-column joint behaviour
Dynamic Tests: Accelerometer Location

Configuration A: 6 Accelerometers

Configuration B: 22 Accelerometers

Configuration C: 23 Accelerometers
Linear identification techniques

Domain

Frequency domain
- Welch PSD
- Ewins-Gleeson
- Dobson
- Kennedy-Pancu
- Spectral Multimatrix

Time domain
- ARMA and TARMA
- Random Decrement
- ERA
- PRTD
- Subspace

Time-frequency domain
- Time-Frequency Instantaneous Estimators (TFIE)
- Wavelet indicators etc.

In green: methods that typically support an output-only use
Assumption: 2DoF shear-type model

Mode frequencies and damping (Shock tests, ERA method by means of free decay).

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Frequency [Hz]</th>
<th>Mean Damping Ratio [%]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.38</td>
<td>0.26</td>
<td>1st longitudinal bending (x-direction)</td>
</tr>
<tr>
<td>2</td>
<td>5.10</td>
<td>0.91</td>
<td>1st longitudinal bending (y-direction)</td>
</tr>
<tr>
<td>3</td>
<td>6.87</td>
<td>2.58</td>
<td>1st torsional</td>
</tr>
<tr>
<td>4</td>
<td>11.19</td>
<td>2.2</td>
<td>2nd longitudinal bending (x-direction)</td>
</tr>
<tr>
<td>5</td>
<td>15.34</td>
<td>1.75</td>
<td>2nd longitudinal bending (y-direction)</td>
</tr>
<tr>
<td>6</td>
<td>22.31</td>
<td>2.83</td>
<td>2nd torsional</td>
</tr>
</tbody>
</table>
3D FE Model of the Test Structure

- Model updating by means of a non-linear optimization technique: the Powell’s dog leg method
Frequencies, Viscous Damping Coefficients and Damage estimates

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>3.36</td>
<td>5.09</td>
<td>6.92</td>
<td>10.94</td>
<td>16.48</td>
<td>22.52</td>
</tr>
<tr>
<td>Phase II</td>
<td>2.38</td>
<td>4.44</td>
<td>6.24</td>
<td>8.95</td>
<td>13.95</td>
<td>19.97</td>
</tr>
<tr>
<td>Phase III</td>
<td>1.95</td>
<td>4.15</td>
<td>5.70</td>
<td>8.18</td>
<td>13.72</td>
<td>19.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase I</td>
<td>0.57</td>
<td>0.66</td>
<td>0.70</td>
<td>0.69</td>
<td>0.49</td>
<td>0.76</td>
</tr>
<tr>
<td>Phase II</td>
<td>1.27</td>
<td>0.83</td>
<td>0.67</td>
<td>0.61</td>
<td>0.30</td>
<td>0.54</td>
</tr>
<tr>
<td>Phase III</td>
<td>1.44</td>
<td>0.96</td>
<td>0.68</td>
<td>0.90</td>
<td>0.59</td>
<td>0.44</td>
</tr>
</tbody>
</table>

- Modal updating: local damage indices $D_L$ of structural members and joints
- Global damage indices $D_G$ of the structure

<table>
<thead>
<tr>
<th>Element</th>
<th>$D_{L_{1,1,II}}$</th>
<th>$D_{L_{1,1,III}}$</th>
<th>$D_{L_{1,1,II}}$</th>
<th>$D_{L_{1,1,III}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$EI_{Long, HEB260}$ [N.m²]</td>
<td>0.011</td>
<td>0.032</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$EI_{Trans, HEB260}$ [N.m²]</td>
<td>0.029</td>
<td>0.086</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$GJ_{t, HEB260}$ [N.m²]</td>
<td>0.014</td>
<td>0.055</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$EI_{Long, HEB280}$ [N.m²]</td>
<td>0.010</td>
<td>0.034</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$EI_{Trans, HEB280}$ [N.m²]</td>
<td>0.029</td>
<td>0.087</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$GJ_{t, HEB280}$ [N.m²]</td>
<td>0.021</td>
<td>0.056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$EA_{braces}$ [N]</td>
<td>0.110</td>
<td>0.310</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{a_{int con}}$ [N.m/mrad]</td>
<td>0.590</td>
<td>0.690</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{a_{ext con}}$ [N.m/mrad]</td>
<td>0.660</td>
<td>0.870</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{a_{Long, b,j}}$ [N.m/mrad]</td>
<td>0.910</td>
<td>0.930</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{a_{Trans, b,j}}$ [N.m/mrad]</td>
<td>0.910</td>
<td>0.930</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>$D_{G_{1,1,II}}$</th>
<th>$D_{G_{1,1,III}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Based on 3 experimental Modes</td>
<td>0.4652</td>
<td>0.6274</td>
</tr>
<tr>
<td>Based on 6 experimental Modes</td>
<td>0.4650</td>
<td>0.6274</td>
</tr>
<tr>
<td>Based on the updated flexibility matrix</td>
<td>0.5212</td>
<td>0.6669</td>
</tr>
</tbody>
</table>
Identification of frequencies and damping ratios from measurements provided by PsD tests in the time domain

Equations on K and C:

\[
\begin{bmatrix}
    d^T(n) \\
    v^T(n) \\
    1
\end{bmatrix}
\begin{bmatrix}
    K^T \\
    C^T \\
    0^T
\end{bmatrix}
= r^T(n)
\]

\[\Rightarrow\] It is a spatial model based on DoFs and not on poles and mode

Eigenvalue problem:

\[
S \begin{bmatrix}
    C & M \\
    M & 0
\end{bmatrix} \mathbf{v} + \begin{bmatrix}
    K & 0 \\
    0 & -M
\end{bmatrix} \mathbf{v} = 0
\]

Natural frequencies and damping ratios:

\[s_i, \sigma_i = \omega_i (-\zeta_i \pm j\sqrt{1-\zeta_i^2}) \quad j^2 = -1\]
Time history of the displacement at the top storey

10% EQ:

25% EQ:

140% EQ:

180% EQ:
Evolution in time of frequency and damping ratio relevant to the first mode
Acceleration-Displacement Response Spectrum (ADRS) representation
Identification methods for evolutive systems

\[ \begin{cases} m\ddot{x} + r = u \\ \dot{r} = f(\dot{x}, r; p) \end{cases} \]

\[ m, u, \ddot{x} \text{ known (from measure or from numerical simulation with a given model)} \]

\[ p = ? \]

When \( \dot{r} = f(\dot{x}, r; p) \) is homogeneous of order 1 with respect to \( \dot{x} \)

\[ f(k\dot{x}, r; p) = k f(\dot{x}, r; p) \]

for any positive constant \( k \) then damping is rate independent and viscous effects are excluded.

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Non-linear/evolutive identification techniques

Parametric methods

Frequency domain
- Reverse path (Bendat 1992)
- Cond. reverse path (Richards & Singh 1998)

Time domain
- Direct parameter estim. (Gifford & Tomlinson 1989; Mohammad et al 1992)
- NARMA-NARMAX (Leontaritis & Billings 1985)

Non-parametric methods

Restoring force surface method

Hilbert transform
- (Feldman & Braun 1994, Spina et al 1995) and Hilbert-Huang transform

Volterra representation
- (Vinh 1986, Collis et al 1998)

Non-linear Identification through Feedback of the Outputs (NIFO) (Adams & Alleman 1999)

Time-frequency
- (Ceravolo, Demarie & Erlicher 2005, Le & Argoul 2005) etc.

Neural Networks
- (Walczak & Cerpa 1999, Pei et al 2004)
Example: shear-type frame with Bouc-Wen law

Earthquake input

(i) Identification of the time-dependent coefficients of a suitable polynomial approximating

\[
\begin{align*}
\dot{r}_{i,i-1} &= m_i \ddot{x}_i + r_{i0} - r_{21} = -m_i \ddot{x}_s \\
m_2 \ddot{x}_2 + r_{21} &= -m_2 \ddot{x}_s \\
\dot{r}_{i0} &= A_1 \dot{x}_i - \left[ \beta_1 \text{sgn}(r_{i0}, \dot{x}_i) + \gamma_1 \right] \dot{r}_{i0} |^n \dot{x}_i \\
\dot{r}_{21} &= A_2 \dot{\delta}_{21} - \left[ \beta_2 \text{sgn}(r_{21}, \dot{\delta}_{21}) + \gamma_2 \right] |^n \dot{r}_{21} \dot{\delta}_{21}
\end{align*}
\]

(ii) Identification of the parameters of the Bouc-Wen model
Example: shear-type frame with Bouc-Wen law /2

Instantaneous evaluation of the polynomial coefficients

\[
p(t^*) = \{a_1(t^*) \ a_2(t^*) \ a_3(t^*) \ a_4(t^*) \ a_5(t^*) \ a_6(t^*) \ a_7(t^*) \ a_8(t^*)\}
\]

Response vs. polynomial
Example: shear-type frame with Bouc-Wen law

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$ [kg]</td>
<td>3</td>
</tr>
<tr>
<td>$m_2$ [kg]</td>
<td>1.5</td>
</tr>
<tr>
<td>$A_1$ [N/m]</td>
<td>29.61</td>
</tr>
<tr>
<td>$A_2$ [N/m]</td>
<td>33.31</td>
</tr>
<tr>
<td>$\beta_1$ [m$^{-1}$]</td>
<td>3</td>
</tr>
<tr>
<td>$\gamma_1$ [m$^{-1}$]</td>
<td>1.5</td>
</tr>
<tr>
<td>$\beta_2$ [m$^{-1}$]</td>
<td>12</td>
</tr>
<tr>
<td>$\gamma_2$ [m$^{-1}$]</td>
<td>6</td>
</tr>
<tr>
<td>$n$</td>
<td>1</td>
</tr>
</tbody>
</table>

Linear least square at every $t^*$

$p(t^*) = \{\alpha_1(t^*) \alpha_2(t^*) \alpha_3(t^*) \alpha_4(t^*) \alpha_5(t^*) \alpha_6(t^*) \alpha_7(t^*) \alpha_8(t^*)\}$

"Identified parameters" = mean of the instantaneous estimators
Results of the non-linear identification of the benchmark structure tested at 0.1g

Hysteretic cycles: displacement vs. force

Instantaneous evaluation of the stiffness matrix
Instantaneous evaluation of Bouc-Wen parameter

Instantaneous evaluation of the $\beta$ coefficients (0.1 g)

Instantaneous evaluation of the $\beta$ coefficients (0.25 g)

Instantaneous evaluation of the $\beta$ coefficients (1.4 g)
Evolution in time of frequencies of first and second mode

Instantaneous evaluation of the 1\textsuperscript{st} mode frequency

Instantaneous evaluation of the 2\textsuperscript{nd} mode frequency
Cyclic Test: Test protocol

The cyclic test was performed by imposing a history of displacement at the top storey and fixing $r = R_1 / R_2$, the ratio of the reactions of the actuators at the first and second storeys, respectively. From the modal properties of the structure a ratio $r = 0.97$ was computed.
2D FE Model of the Test Structure
Methodology

Numerical instabilities

Transferring data series to their absolute maximum value at each half cycle

Returning all data to their original position
Results of the Model Updating

Force vs. Displacement of the bottom storey.

Force vs. Displacement of the top storey.
Results of the Model Updating

Spring no. 3

Spring no. 4

Identified shear panel, spring no. 3

Identified shear panel, spring no. 4

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Results of the Model Updating (Cntd)

Identified connection, spring no. 16

Identified connection, spring no. 17
Work in progress: Identification of evolutive systems:

At high excitation levels such as 1.4g the experimental data show an elevated influence of other effects, i.e. pinching, etc.

The Bouc-Wen model only is no more compatible with certain physical phenomena.
Identification of evolutive systems: work in progress

In order to embed the pinching effect, we are considering a pinching model, inspired to the Noori’s\(^1\) model:

The inclusion of a new model requires preliminary validation tests on numerical examples, which have just been accomplished.

After validation tests the model will be embedded into the identification procedure.

\(^1\) Noori et al. "Identification of hysteretic systems with slip using bootstrap filter"
• Increased complexity in tests, sensors and mathematical tools
• Risk of influencing actual or “real” data
• The merging of sensors and system identification techniques entails a better interpretation of “real” data
• Better information on the evolution of damage, evolution of hysteresis, also in view of PBEE.

Thank you. Any question?