Laboratory Exercises: RTHS of a Tall Building Subject to Multi-Natural Hazards

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Outline

• Description of prototype 40-story tall building
• Real-time hybrid simulation studies
• Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
• Laboratory demonstration
Outline

• Description of prototype 40-story tall building
• Real-time hybrid simulation studies
• Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
• Laboratory demonstration
Prototype Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH for PEER Tall Building Initiative case studies
- Mean roof height = 544.5 ft. (166 m)
- Original design omitted dampers
- Lehigh added Non-linear viscous dampers to outriggers to enhance wind and earthquake performance of building

Ref.: Moehle et al., *Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Means - Task 12 Report for the Tall Buildings Initiative*
PEER Rpt 2011/05
Prototype Building Design Criteria

Design criteria without supplemental dampers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Wind Speed, 3 sec. gust (V)</td>
<td>85 mph</td>
</tr>
<tr>
<td>Basic Wind Speed, 3 sec. gust (V), for serviceability wind demands</td>
<td>67 mph</td>
</tr>
<tr>
<td>based on a 10 year mean recurrence interval</td>
<td></td>
</tr>
<tr>
<td>Exposure</td>
<td>B</td>
</tr>
<tr>
<td>Occupancy Category</td>
<td>II</td>
</tr>
<tr>
<td>Importance Factor ($I_w$)</td>
<td>1.0</td>
</tr>
<tr>
<td>Topographic Factor ($K_d$)</td>
<td>1.0</td>
</tr>
<tr>
<td>Exposure Classification</td>
<td>Enclosed</td>
</tr>
</tbody>
</table>

Table 7 – Seismic Performance Objectives

<table>
<thead>
<tr>
<th>Level of Earthquake</th>
<th>Earthquake Performance Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent/Service : 43 year return period, 2.5% damping (SLE43)</td>
<td>Serviceability: Drift limited to 0.5%. Demand capacity ratio for buckling restrained braces not to exceed 1.5.</td>
</tr>
<tr>
<td>Maximum Considered Earthquake (MCE): As defined by ASCE 7-05, Section 21.2, 2.5% damping.</td>
<td>Collapse Prevention: Extensive structural damage, repairs are required and may not be economically feasible. Drift limited to 3%.</td>
</tr>
</tbody>
</table>

3-D view of the building. Image courtesy of Dutta and Hamburger (2010)

(after Moehle et al. 2011)
Prototype Building Seismicity

Location of Building in Southern California

PSHA deaggregation, 2475-year return period at 5 sec. (Moehle et al. 2011)

For long periods, hazard dominated by two types of events:
- A relatively large magnitude small distance event (e.g., $M = 6.6$, $R = 5$ km, $\varepsilon = 1.5$), or
- An extremely large magnitude long distance event (e.g., $M = 8$, $R = 60$ km, and $\varepsilon = 2.5$).

Table 2.1

<table>
<thead>
<tr>
<th>Set Number</th>
<th>Seismic Zone</th>
<th>$M_r$</th>
<th>Station</th>
<th>$R$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Denali</td>
<td>7.90</td>
<td>Bakersfield</td>
<td>93.4</td>
</tr>
<tr>
<td>5</td>
<td>Northridge</td>
<td>7.90</td>
<td>CH103</td>
<td>104.9</td>
</tr>
<tr>
<td>6</td>
<td>Chi-Chi</td>
<td>7.02</td>
<td>Pump Station #9</td>
<td>54.75</td>
</tr>
<tr>
<td>7</td>
<td>Landers</td>
<td>7.28</td>
<td>Yermo</td>
<td>23.62</td>
</tr>
</tbody>
</table>

PSHA

Note: Target Spectrum = USGS UHS SLE43 – Serviceability EQ (43 year return period), DBE – Design EQ (475 year return period), MCE – Max. Considered EQ (2475 year return period).

(after Moehle et al. 2011)
Design Detailing

Building (3C) designed used a single central bay of bracing (BRBs) augmented with outrigger trusses spanning three bays at the 20th, 30th, and 40th stories.

Gravity framing:
- Steel columns and beams with composite metal decking and lightweight concrete fill.

BRB bays:
- Beams - WF sections.
- Buckling Restained Braces (BRBs) columns, fabricated from steel plates (38 mm to 76 mm), high strength concrete ($f'_c=69$ MPa).
- Design modified with NL Viscous dampers at 20th and 30th floors (wind)

Composite Columns

Note:
1 Kip = 4.448 kN
1 inch = 25.4 mm
Nonlinear Viscous Dampers

Characterization testing

600 kN dampers manufactured by Taylor Devices, Inc.

Damper testbed

Loading Protocol

Damper force - deformation

Damper force - velocity
Outline

• Description of prototype tall building
• Real-time hybrid simulation studies
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• Laboratory demonstration
Real-time Hybrid Simulation Study of Tall Building Subjected to Multi-Natural Hazards

- Natural Hazards
  - Earthquake Loading
  - Wind Loading
- Nonlinear Viscous Dampers at 20th and 30th floors
# Building Modal Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>T (sec)</th>
<th>f (Hz)</th>
<th>$\zeta_{eq}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.38</td>
<td>0.16</td>
<td>8.3</td>
</tr>
<tr>
<td>2</td>
<td>1.71</td>
<td>0.59</td>
<td>10.0</td>
</tr>
<tr>
<td>3</td>
<td>0.84</td>
<td>1.19</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.55</td>
<td>1.81</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.41</td>
<td>2.46</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.32</td>
<td>3.12</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.27</td>
<td>3.77</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.22</td>
<td>4.46</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.19</td>
<td>5.15</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.17</td>
<td>5.88</td>
<td></td>
</tr>
</tbody>
</table>

$\zeta_{eq}$: System total damping, half-power bandwidth method
RTHS Configuration

Building Floor Plan

Test Structure Elevation

Wind load:
- Tokyo Polytechnic University Wind Tunnel Test database
- Normalized pressure coefficient time histories are converted to full scale forces corresponding to Exposure B and wind speed of 110 mph, 700 year MRI

EQ load:
- 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to SLE, DBE, and MCE (43, 475, 2475 year return periods, respectively) hazard level
RTHS Substructures

Analytical Substructure

- BRB: nonlinear truss element with isotropic hardening
- Beams and columns: beam-column fiber element
- Nonlinear fluid viscous dampers: Modeled physically
  - Mass
  - Inherent damping of building
  - Wind: $\rho_\infty = 0.866$
  - EQ: 0.50
- Time step for RTHS, $\Delta t = 0.006$ sec.
- 780 Nodes
- 996 Elements
- 1590 DOFs

Experimental Substructures

- Damper
- Load cell
- Loading beam
- South Side Damper at 30th Floor
- South Side Damper at 20th Floor
Response of Building under Wind Loading

• Building subjected to 700 year mean recurrence interval (MRI) wind storm
• Response quantities of interest:
  ➢ Dampers
  ➢ Floor displacements and accelerations
  ➢ Members
Wind RTHS: Exposure B, 110 mph Wind Speed

110 mph = 177 km/hr

Real-time Hybrid Simulation of a Wind Excited Tall Building

Wind Speed = 110 mph (MRI 700 years)
Illustration of Effects of Member Stiffness in Damper Force Load Path

To develop damper velocity (and therefore make dampers efficient):

- Members in damper load path must have adequate stiffness
- Equivalent damper stiffness cannot be too large relative to members in load path.

Two springs in series analogy

- $k_1 > k_2$ (more deformation in Spring 2)
- $k_1 < k_2$ (more deformation in Spring 1)
Outrigger truss members’ and columns’ axial stiffness increased using stiffness multiplier in analytical substructure

A larger member’s stiffness results in an increase in the deformations being concentrated in the dampers

Inefficient to increase stiffness multiplier beyond value of 3.0
Effect of Number of Supplemental Dampers - 700 Year MRI Wind

- Increasing the number of dampers beyond a certain number in the outrigger reduces further the velocity in the dampers, making them less effective.
- Not efficient to use more than four – 600 kN dampers.
RTHS Results: Floor RMS Lateral Accelerations – 700 Year MRI Wind

<table>
<thead>
<tr>
<th>Floor</th>
<th>RMS Acceleration (mG)</th>
<th>Peak Acceleration (mG)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Dampers</td>
<td>With Dampers</td>
</tr>
<tr>
<td>20</td>
<td>4.2</td>
<td>2.5</td>
</tr>
<tr>
<td>30</td>
<td>6.9</td>
<td>3.9</td>
</tr>
<tr>
<td>40</td>
<td>9.9</td>
<td>5.6</td>
</tr>
</tbody>
</table>

6 dampers added to outriggers at 20th and 30th floors:
- RMS Acceleration: 43% to 48% reduction
- Peak Acceleration: 29% to 37% reduction
Response of Building under Earthquake Loading

- Building subjected to different hazard levels
  - Serviceability earthquake – 43 year return period (SLE43)
  - Design basis earthquake - 475 year return period (DBE)
  - Maximum considered earthquake – 2475 year return period (MCE)
- Effects of ground motion record-to-record variability considered
  - Ensemble of ground motions selected and appropriately scaled to hazard level
  - Statistics of Response determined
- Response quantities of interest:
  - Members
  - Story Drift
  - Floor Accelerations
  - Dampers
RTHS: 1989 Loma Prieta EQ Scaled to MCE

MCE: 2475 return period EQ

Analytical Substructure

South Side Damper at 30th Story Outrigger

Experimental Substructures

South Side Damper at 20th Story Outrigger

Real-time Hybrid Simulation of a Seismically Excited Tall Building
1989 Loma Prieta EQ Scaled to MCE Level
RTHS Results: Damper Force-Displacement, Loma Prieta EQ

- Dampers developed appreciable dynamic response
  - Dampers performed as nonlinear dampers, where force is capped
Member Stiffness in Damper Force Load Path - Loma Prieta EQ scaled to MCE

- Outrigger truss members’ and columns’ axial stiffness increased using stiffness multiplier in analytical substructure
- A larger stiffness of members results in an increase in the deformations being concentrated in the dampers
- Inefficient to increase stiffness multiplier beyond value of 3.0
RTHS Results: Maximum Story and Residual Story Drift - Loma Prieta EQ

Maximum Story Drift

SLE34

Without dampers

With dampers

DBE

Without dampers

With dampers

MCE

Without dampers

With dampers

Design limit

Maximum Residual Story Drift

SLE34

Without dampers

With dampers

DBE

Without dampers

With dampers

MCE

Without dampers

With dampers

Stiffness multiplier = 3

Number dampers at 20 and 30th floors = 6
RTHS Results: Maximum Normalized BRB Deformation - Loma Prieta EQ

Stiffness multiplier = 3
Number dampers at 20 and 30th floors = 6
<table>
<thead>
<tr>
<th>EQ Hazard</th>
<th>Maximum Story Drift (rad)</th>
<th>Maximum Residual Story Drift (rad)</th>
<th>BRB Maximum Ductility $\Delta_{\text{max}}^{\text{b}}/\Delta_{\text{y}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Dampers</td>
<td>With Dampers</td>
<td>Design Obj</td>
</tr>
<tr>
<td>SLE43</td>
<td>0.005</td>
<td>0.004</td>
<td>$\leq 0.005$</td>
</tr>
<tr>
<td>DBE</td>
<td>0.012</td>
<td>0.007</td>
<td>-</td>
</tr>
<tr>
<td>MCE</td>
<td>0.017</td>
<td>0.011</td>
<td>$\leq 0.03$</td>
</tr>
</tbody>
</table>

- All configurations meet design objectives
- Dampers improved performance under DBE and MCE by reducing inelastic demand in structure (BRBs)

Stiffness multiplier = 3
Number dampers at 20 and 30th floors = 6
RTHS Summary and Conclusions

• The application of real-time hybrid simulation to large complex systems subject to wind and earthquake natural hazards was illustrated, demonstrating these new advancements.

• Using dampers, building’s performance was demonstrated to be improved (accelerations) under wind and (drift, BRB ductility) under EQ loading.

• The methodologies presented herein will enable real-time large-scale simulations of complex systems to be successfully achieved, leading to new knowledge for hazard mitigation solutions and innovative, resilient hazard-resistant structural concepts.
Outline

• Description of prototype tall building
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• Laboratory demonstration
RTHS OMU Background

Dynamic testing using real-time hybrid simulation

• Complex substructures may be difficult to model numerically
• If multiple experimental substructures are needed, all must be present in the lab

Dynamic testing using real-time hybrid simulation with online model updating

• Reduce the number of experimental substructures required for a hybrid simulation by including some of them as computational model components of the analytical substructure
• Update the component computational model of analytical substructure using information obtained from the experimental substructure of a similar component during the hybrid simulation
Real-time Hybrid Simulation

Real-time input EQ ground acceleration

Real-time structural response

Integrates Eqns of Motion

Restoring Force

Cmd Displ

Simulation Coordinator

Mx_{i+1} + CX_{i+1} + R^a_{i+1} + R^e_{i+1} = F^a_{i+1}

Cmd Displ

Analytical substructure

Experimental substructure (dampers)

(Modeled in lab)

Wind Tunnel Data

Restoring Force

Experimental substructure

(30th floor)

(20th floor)

Cmd Displ

Cmd Displ

Cmd Displ

Cmd Displ
Real-time Hybrid Simulation with Online Model Updating

Real-time input EQ ground acceleration

\[ \dot{x}_{i+1} = \{Kd_{i+1}, Cd_{i+1}, a_{i+1}\}^T \]

Updated model parameters \( \bar{x}_{i+1} \)

\[ M\ddot{X}_{i+1} + CX_{i+1} + R^a_{i+1} + R^e_{i+1} = F^a_{i+1} \]

Integrates Eqns of Motion

Real-time structural response

Simulation Coordinator

Dampers added to 40th floor

Analytical substructure

Cmd Displ

\( X^a_{i+1} \)

\( R^a_{i+1} \)

Cmd Displ

\( X^e_{i+1} \)

\( R^e_{i+1} \)

Real-time system identification using Unscented Kalman Filter (UKF)

Real-time Hybrid Simulation with Online Model Updating

Experimental substructure (dampers)

Southside damper at 30th floor

Cmd\ Displ

Damper computational model (updated in real time)

Southside damper at 20th floor

Real-time Hybrid Simulation with Online Model Updating

Dampers added to 40th floor

Analytical substructure

Cmd Displ

\( X^a_{i+1} \)

\( R^a_{i+1} \)

Cmd Displ

\( X^e_{i+1} \)

\( R^e_{i+1} \)

Real-time system identification using Unscented Kalman Filter (UKF)

Dampers added to 40th floor

Analytical substructure

Cmd Displ

\( X^a_{i+1} \)

\( R^a_{i+1} \)

Cmd Displ

\( X^e_{i+1} \)

\( R^e_{i+1} \)

Real-time system identification using Unscented Kalman Filter (UKF)
• Development of explicit, non-iterative damper model for real-time hybrid simulation

• Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers
RTHS OMU: 40-story building with dampers at 20\textsuperscript{th}, 30\textsuperscript{th}, and 40\textsuperscript{th} floors

Restoring force of the 40\textsuperscript{th} floor damper

\[ R_{i+1}^a \]

Explicit damper model

\[ \dot{x}_{i+1} \]

UKF

\[ \ddot{x}_{i+1} = \{ Kd_{i+1} \ C_{d_{i+1}} \ \alpha_{i+1} \}^T \]

Real-time input EQ ground acceleration
RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors
Response under the MCE Loma Prieta EQ

Physical
Numerical (OMU)

Damper force-deformation hysteretic response

Real-time input EQ ground acceleration
RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors

Response under the MCE Loma Prieta EQ

<table>
<thead>
<tr>
<th>Case</th>
<th>Stiffness multiplier</th>
<th>20th Flr</th>
<th>30th Flr</th>
<th>40th Flr</th>
<th>Roof peak disp (m)</th>
<th>Disp reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base – no dampers</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.82</td>
<td>-</td>
</tr>
<tr>
<td>Dampers at two floors</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>0.68</td>
<td>17</td>
</tr>
<tr>
<td>Dampers at three floors</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>0.60</td>
<td>27</td>
</tr>
</tbody>
</table>

The graph shows the displacement over time for different cases: Base Case – no dampers (numerical simulation), Dampers at two locations (hybrid simulation), and Dampers at three locations (hybrid simulation). The Y-axis represents displacement (m) ranging from -0.8 to 0, and the X-axis represents time (sec) ranging from 0 to 50.
RTHS OMU: 40-story building with dampers at 20\(^{th}\), 30\(^{th}\), and 40\(^{th}\) floors

Response under the MCE Loma Prieta EQ

- Displacement history of the damper at the 40\(^{th}\) story is applied to the physical damper at the 30\(^{th}\) story after the hybrid simulation is completed.

- Forces predicted based on the OMU compared to the experimentally measured results.

- Good agreement achieved.

![40\(^{th}\) floor damper](chart.png)
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• Laboratory demonstration
# Laboratory Demonstration

<table>
<thead>
<tr>
<th>Test</th>
<th>Hazard</th>
<th>Model</th>
<th>Dampers at 20th story</th>
<th>Dampers at 30th story</th>
<th>Dampers at the 40th story</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MCE EQ</td>
<td>40 story building</td>
<td>Physical</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>MCE EQ</td>
<td>40 story building</td>
<td>Physical</td>
<td>OMU</td>
<td>OMU</td>
</tr>
<tr>
<td>3</td>
<td>110 mph wind</td>
<td>40 story building</td>
<td>Physical</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>4</td>
<td>110 mph wind</td>
<td>40 story building</td>
<td>Physical</td>
<td>OMU</td>
<td>OMU</td>
</tr>
</tbody>
</table>
## RTHS Configuration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Motion (scaled to MCE)</td>
<td></td>
</tr>
<tr>
<td>• Near Field</td>
<td>1989 Loma Prieta Earthquake, component SN802_LOMAP_STG000</td>
</tr>
<tr>
<td>• Integration Algorithm</td>
<td>MKR-(\alpha) method</td>
</tr>
<tr>
<td>• Integration Time step</td>
<td>7/1024 sec</td>
</tr>
<tr>
<td>• Numerical damping, (\rho_{\infty})</td>
<td>0</td>
</tr>
<tr>
<td>• UKF tuning parameters</td>
<td>Measurement noise = 8 KN</td>
</tr>
<tr>
<td></td>
<td>State variables uncertainty = 0.001</td>
</tr>
<tr>
<td>Storm (110 mph wind speed)</td>
<td></td>
</tr>
<tr>
<td>• Integration Algorithm</td>
<td>MKR-(\alpha) method</td>
</tr>
<tr>
<td>• Integration Time step</td>
<td>7/1024 sec</td>
</tr>
<tr>
<td>• Numerical damping, (\rho_{\infty})</td>
<td>0</td>
</tr>
<tr>
<td>• UKF tuning parameters</td>
<td>Measurement noise = 8 KN</td>
</tr>
<tr>
<td></td>
<td>State variables uncertainty = 0.0001</td>
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</tbody>
</table>
Acknowledgements

• Research reported in this presentation was performed at the NHERI Lehigh Large-Scale Multi-Directional Hybrid Simulation Experimental Facility

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