Laboratory Exercises: 3D Nonlinear Multi-hazard RTHS of a Tall Building

Safwan Al-Subaihawi
Graduate Research Assistant
Lehigh University
Presentation

• Description of prototype 40 story tall building
• Multi-natural hazard description
• Real time hybrid simulation with online model updating
• Laboratory demonstration
3D Nonlinear Multi-hazard RTHS of a Tall Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH\(^{(1)}\) for PEER Tall Building Initiative case studies – BRBFs with Outriggers

- Objectives of study
  - Improve performance using nonlinear fluid viscous dampers with outriggers
  - Assess performance of structure under multi-hazards using RTHS
  - Extend MKR-\(\alpha\) integration algorithm and ATS actuator control to wind natural hazard
  - Online model updating – explicit-based NL Maxwell model

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Multi-Hazard 3-D Nonlinear RTHS of Tall Building – EQ & Wind

• Bidirectional EQ ground motions
  ➢ 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to MCE (2500 year return period) hazard level

• Bidirectional wind loading
  ➢ Wind speed of 110 mph, 700 MRI
  ➢ Exposure B
RTHS Configuration

• Use of:
  ➢ Explicit MKR-α Integration Algorithm
  ➢ Explicit Force-based Nonlinear Fiber Element – Analytical Substructure
  ➢ Adaptive Time Series Compensator for Actuator Control
  ➢ Online Model Updating (OMU) – explicit-based NL Maxwell model

### MKR-α parameter and ATS coefficients

<table>
<thead>
<tr>
<th>Natural Hazard</th>
<th>Time Step, Δt (sec)</th>
<th>$\rho_\infty$</th>
<th>ATS Coefficients</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>$\frac{11}{1024}$</td>
<td>0.5</td>
<td>Fixed  Adaptive Fixed</td>
<td>Wind: static component with dynamic gusts - 1st mode linear response</td>
</tr>
<tr>
<td>EQ</td>
<td>$\frac{11}{1024}$</td>
<td>0.50</td>
<td>Adaptive Adaptive Adaptive</td>
<td>EQ: Multi-mode non-linear response</td>
</tr>
</tbody>
</table>
RTHS Substructures

Analytical Sub. Key features:

- 1317 Nodes
- 2974 Elements
  - 2411 Nonlinear Explicit Force-based fiber elements
  - 11 Nonlinear Explicit Maxwell Elements with real-time model updating (dampers placed in each outrigger at 20th, 30th, & 40th floors)
  - 552 Nonlinear truss elements
- Geometric nonlinearities
- Mass
- Inherent damping of building

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Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

- **Real-time Model Updating**
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via **Unscented Kalman Filter (UKF)** to numerically model the 11 dampers
    - Development of explicit, non-iterative Nonlinear Maxwell Damper Model for real-time hybrid simulation
    - Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers

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Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

Simulation Coordinator:
\[
\begin{align*}
M\ddot{X}_{i+1} + C\dot{X}_{i+1} + R_{i+1}\sum_{a}^{\alpha} + R_{i+1}^e &= F_{i+1}^a \\
\end{align*}
\]

Real-time structural response

Updated model parameters \(\bar{x}_{i+1}\):
\[
\bar{x}_{i+1} = \{Kd_{i+1}, Cd_{i+1}, a_{i+1}\}^T
\]

Dampers OMU

Analytical substructure

Real-time input EQ ground acceleration

Cmd Displ

Cmd Displ

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

Damper computational model
(Nonlinear Maxwell Model updated in real time)

Experimental substructure (damper)

S-E Damper at 40th story

(Cevis Damper Load cell Actuator)

(Modelled in lab)
### 3-D RTHS Results: Roof RMS Lateral Accelerations

**East to West 110 mph, 700 Year MRI Wind**

<table>
<thead>
<tr>
<th>RMS Roof Accelerations (mG)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>No Dampers</td>
<td>With Dampers</td>
</tr>
<tr>
<td>EW</td>
<td>NS</td>
<td>EW</td>
</tr>
<tr>
<td>40</td>
<td>7.0</td>
<td>31.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peak Roof Accelerations (mG)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>No Dampers</td>
<td>With Dampers</td>
</tr>
<tr>
<td>EW</td>
<td>NS</td>
<td>EW</td>
</tr>
<tr>
<td>40</td>
<td>28.8</td>
<td>90.3</td>
</tr>
</tbody>
</table>

Dampers added to outriggers at 20th, 30th, and 40th stories:
- RMS Acceleration: 2% reduction in EW, 49% reduction in NS
- Peak Acceleration: 10% reduction in EW, 35% reduction in NS

Note: Outrigger frames are in NS direction
### 3-D RTHS Results: BRB Maximum Ductility
#### 1989 Loma Prieta EQ Scaled to MCE

<table>
<thead>
<tr>
<th>Story</th>
<th>No Dampers</th>
<th>With Dampers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EW</td>
<td>NS</td>
</tr>
<tr>
<td>1</td>
<td>3.2</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Dampers added to outriggers at 20th, 30th, and 40th stories:
- BRB ductility demand: Minimal reduction in EW, 30% reduction in NS

Note: Outrigger frames are in NS direction
Damper Hysteretic Response – 700 MRI Wind

40th Story

30th Story

20th Story

40th Story @ SE: Experimental Substructure
All other dampers: Real-time Model Updating is UKF
Damper Hysteretic Response – EQ MCE Level

40th Story

30th Story

20th Story

40th Story @ SE: Experimental Substructure
All other dampers: Real-time Model Updating is UKF
Online Model Updating – UKF
Variation of Nonlinear Maxwell Model Parameters

Wind

EQ

Wind

EQ
Summary and Conclusions

• The application of real-time hybrid simulation to large complex non-linear systems subject to wind and earthquake natural hazards was demonstrated.

• Using dampers, building’s performance is improved (accelerations) under wind and (drift, BRB ductility) under EQ loading.
Acknowledgements

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Thank you