HPC-aided optimization of viscous dampers for improving the seismic performance of steel buildings

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Outline

- Background
- Seismic Assessment of Existing Buildings
- Retrofit Strategies
- Optimization Study
- Concluding Remarks
PEER Tall Building Initiative

- **Phase 1**: Identify performance criteria for new tall buildings and develop guidelines for performance-based seismic design of new tall buildings.
**PEER Tall Building Initiative**

- **Phase 2**: Assessing and reducing risk in existing tall buildings and examine feasibility of retrofit strategies.
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Case Study Building

**Model building**
35-story Steel Moment Resisting Frame;
Built in 1971;
$T_1=4.70$ sec.

**Referenced guidelines**
Seismic Deficiencies

- Inadequate strength to limit inelastic deformations to levels considered acceptable by current guidelines
- Tendency to form a sidesway mechanism over a few stories in the lower one-third of the building
- Pre-Northridge beam-to-column connection details resulted in a high percentage of connection failures at BSE hazard events
Seismic Deficiencies

- The PJP column splice weld details pose a great danger to the seismic integrity of the building.
- The columns in lower stories are overloaded in compression, and they are likely to yield under combined axial and bending loads promoting weak story behavior.

As-built structure fails to meet the basic performance objectives recommended by ASCE 41.
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Retrofit Strategy: Two-Levels of Retrofit Studied

- Level-1 retrofit
  
  (a). Fix column splices
  e.g. add steel plate, upgrade flange welds

  (b). Replace exterior concrete cladding
  e.g. 80 Folsom building
  (Courtesy Olson & Co. Steel)

$T_1: 4.70 \text{ sec.} \rightarrow 4.33 \text{ sec.}$
Retrofit Strategy: Two-Levels of Retrofit Studied

- Level-2 retrofit

Supplemental energy dissipation devices

- Fluid viscous dampers
- Viscous wall dampers
- Buckling restraint braces
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Formulation of PBEE Optimization Problem

- **Design variables**
  - Eight variables

- **Initial values and selected ranges**

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>$C_x$  (\text{kip} \cdot (\text{sec/in.})^{0.35})</th>
<th>$C_y$ (\text{kip} \cdot (\text{sec/in.})^{0.35})</th>
<th>$\alpha_1$</th>
<th>$\beta_1$</th>
<th>$\alpha_2$</th>
<th>$\beta_2$</th>
<th>$C_{x_0}$ (\text{kip} \cdot (\text{sec/in.})^{0.35})</th>
<th>$C_{y_0}$ (\text{kip} \cdot (\text{sec/in.})^{0.35})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Value</strong></td>
<td>1000</td>
<td>1500</td>
<td>1.4</td>
<td>1.4</td>
<td>1.0</td>
<td>1.0</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>[1000, 3000]</td>
<td>[1500, 3000]</td>
<td>[1.4, 2.0]</td>
<td>[1.4, 2.0]</td>
<td>[1.0, 2.0]</td>
<td>[1.0, 2.0]</td>
<td>[200.0, 500.0]</td>
<td>[200.0, 500.0]</td>
</tr>
</tbody>
</table>
Formulation of PBEE Optimization Problem

- Objective function
  - Single Engineering Demand Parameter (EDP)
    - Case 1: peak story-drift ratio
    - Case 2: peak floor acceleration
  - Multiple EDPs

- Case 3: Building-specific EDP-DV function

![Diagram showing intensity measure, engineering demand parameter, damage measure, and decision variable with drift- and accel.-sensitive components for PBEE optimization problem.](image-url)
Flowchart of Computer Automated Procedure

- Start
- Initialization
  - Iteration $k=0$
  - Starting point $DV^{(0)}$ and bounds of $DV$
  - Stop criteria: $TolX$, $TolFun$, $TolCon$
  - $MaxIter$, $MaxFunEval$

  **Function Evaluation**
  - Objective Function Values
  - Constraint Function Values
  - OpenSees Model
  - Structural Analysis
  - Design point $DV^{(k)}$ & its adjacent points

  **Gradient Calculation**
  - Gradient of Objective Function
  - Gradient of Constraint Functions

- Update
- Optimization Solver
- Optimal criteria satisfied?
  - Yes
  - Stop
  - No

**A great number of analysis needed!**

**Stampede system**
**Optimal Design Patterns**

- Case 3: total building loss (normalized) as objective function

![Graphs showing distribution of story drift ratio and peak floor accelerations across iterations.](image-url)
Comparison of Various Designs

- Structural responses

![Graphs showing structural responses for different designs, with Level 1 retrofit at 1.01% and 1.48% for W/O FVDs and Manual Scheme respectively.](image-url)
Comparison of Various Designs

- Peak EDP and cost-effectiveness under BSE-2E

<table>
<thead>
<tr>
<th>Scheme</th>
<th>W/O damper</th>
<th>W/ damper</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob. of irreparable resi.</td>
<td>99.9%</td>
<td>0.24%</td>
<td>0.003%</td>
<td>0.001%</td>
<td>0.002%</td>
<td></td>
</tr>
<tr>
<td>Peak inter-story drift ratio (%)</td>
<td>5.21%</td>
<td>1.48%</td>
<td>1.04%</td>
<td>1.00%</td>
<td>1.02%</td>
<td></td>
</tr>
<tr>
<td>Peak floor acceleration (g)</td>
<td>0.628</td>
<td>0.438</td>
<td>0.500</td>
<td>0.407</td>
<td>0.438</td>
<td></td>
</tr>
<tr>
<td>Total building loss ($M) under BSE-2E</td>
<td>740.0</td>
<td>19.8</td>
<td>14.2</td>
<td>13.9</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>Damper price ($M)</td>
<td>N/A</td>
<td>6.4</td>
<td>6.3</td>
<td>7.0</td>
<td>6.8</td>
<td></td>
</tr>
</tbody>
</table>
## Comparison of Various Designs

- **Manual vs. automated**

<table>
<thead>
<tr>
<th></th>
<th>Initial scheme</th>
<th>Evaluate the efficiency of current design</th>
<th>Update design</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manual</strong></td>
<td>1 week</td>
<td>1 week (per design)</td>
<td>1 week (per design)</td>
</tr>
<tr>
<td><strong>Automated tool</strong></td>
<td>Half week</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Optimization engine</strong></td>
<td></td>
<td>$30</td>
<td></td>
</tr>
</tbody>
</table>
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Concluding Remarks

- Incorporating FVDs is a promising solution to upgrade the seismic performances of an existing steel tall building.

- The number and sizes of FVDs could be tuned manually, but not as efficiently as an automated procedure.

- With the aid of HPC and parallel processors, the design efforts could be streamlined, efficiently identify design parameters, and substantially reduce time and human effort.
In Memory of Prof. Mahin

Thanks for being a ray of sunshine to so many people around you!
thank you for your attention

Q & A time

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Future and Ongoing Work

- Expand design parameters (damper locations, driving brace stiffness etc.)
- Develop tools to speed up automated procedure (e.g., Dakota)
- Develop a more robust PBEE engine
Cost-Effectiveness of Retrofit

- Scenario BSE-2E Level Events

ASCE41-13 (BSE-2E)

Saving: > $700M
Damper price: ~$6.4M

Evaluation using FEMA P-58
Design Considerations

- Locations
  - Function and architecture
  - Efficiency of dampers
  - Impact on other members
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- Locations
  - Function and architecture
  - Efficiency of dampers
  - Impact on other members

- Design parameters
  - $\xi_{\text{eff}}$: 10%~15%
  - $\alpha$: 0.3~0.5
  - $K_b$: 2$K_f$
  - $C$: to be optimized

***Damper-frame assembly***
Formulation of PBEE Optimization Problem

- **Constraint functions**
  - Ave. peak story-drift ratio < 1.0%;
  - Ave. peak floor acceleration < 0.3g;
  - Max. damper force < 1500 kips;
  - Max. damper stroke < 5.0 in.

- **Target goal**
  - Basic performance goal under a Basic Safety Level 2 hazard event (BSE-2E)
  - 11 records selected in structural analysis