Topology Optimization of Elastic Spines in Rocking Braced Frames

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Energy Dissipation and Control Systems I

June 27, 2018
Outline

• Topology Optimization
• Motivation
• Methodology
• Results
• Conclusion
Topology Optimization

Conceptual design of high rise buildings under wind loads
Topology Optimization: Static Formulation

minimize \[ C(\rho, u) = F^T u \] (objective function)

subject to \[ \int_\Omega \rho dV - \bar{V} \leq 0 \] (constraints)

\[ 0 \leq \rho_e \leq 1, \quad \forall e \in \Omega \]

with \[ F = Ku \] (state equation)

For earthquake engineering applications, we need to consider **material nonlinearity** and **dynamic effects**
Controlled Rocking Braced Frames

1. Elastic rocking spine
2. Self-centering capabilities
3. Energy-Dissipation

- Controlled rocking braced frames (RBF) offer enhanced performance by quasi-eliminating residual drifts and allocating damage to energy dissipation elements.

- By reducing the first mode response, RBFs are susceptible to higher mode effects.
Combining the **inelastic first mode** response with elastic higher modes we can accurately predict member forces.

- The **Modified Modal Superposition (MMS)** is very accurate compared to the RHA median.
Motivation

1. **Topology optimization** can lead to **efficient and expressive structural forms** for high rise buildings under wind loads.

2. Rocking braced frames are **advantageous passive control systems**, however higher mode effects lead to costly elastic spines with large steel section.

3. **Modified modal analyses** can efficiently and accurately predict member force demands in controlled rocking frames.

**Objective:** combine surrogate dynamic analyses and topology optimization to obtain an efficient elastic spine of passive control systems such as rocking braced frames.
Proposed Formulation

\[ \text{minimize} \quad C_T(\rho, U) = \sum F_i^T U_i \quad \text{(objective function)} \]

subject to \[ \int_\Omega \rho dV - \tilde{V} \leq 0 \quad \text{(constraints)} \]

\[ 0 \leq \rho_e \leq 1, \quad \forall e \in \Omega \]

with \[ F_i = KU_i, \quad \text{for } i = 1, \ldots, m \quad \text{(state equation)} \]

\[ F_i = \Gamma_i M \phi_i S a_i / R_i \quad \text{Modal strength reduction factor} \]

\[ \{K - \omega^2 M\} \phi = 0 \]

Using modified modal analyses, we can extend the topology optimization formulation for conceptual design of buildings under earthquake loading.
Boundary & Loading Conditions

Right first mode  
Left first mode  
Second mode  
Third mode
Optimized Bracing Pattern & Stress Distribution

Model  |  Optimized Topology  |  Von Mises Stress

Optimization of Rocking Frames
Modal Results

First mode  Second Mode  Third Mode
Alternative Configurations

Configuration A

Configuration B

Aspect Ratio
Eigenvalue Analysis

\[ [K - \omega_n^2 M] \phi = 0 \]
Validation with Nonlinear Time History Analyses

RBF12-TO Model

Optimized Topology → Extruded Geometry → RBF12-TO Frame

RBF12 Model

→ RBF12 Frame
RBF12 vs RBF12-TO

20% reduction in steel weight in the frame
Conclusion

1. Using modified modal analyses, we can extend the topology optimization formulation for conceptual design of buildings under earthquake loading.

2. The proposed methodology is applied to rocking braced frames and yield important considerations for the bracing topology.

3. Validation using nonlinear time history analyses show that the optimized rocking frame is more efficient and effective at reducing higher mode effects.
Further Work

1. Extend the methodology to other self-centering and control systems with various energy dissipation elements, such as dual rocking frames and strongback systems.

2. Extend the topology optimization framework to include the performance of the system and energy dissipation element location and properties.
Thank You!

Questions?

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Acknowledgments:

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NSF

Tesla Gigafactory - Greg Luth
Bonus Slides
Topology Optimization

Ground Structure

Continuum Method
Need to consider dynamic effects and material nonlinearity
Ground Motion Selection

- 50 GMs from PEER database
- M (6.5-7.5), Rjb (0-50 km), strike-slip, Vs30 (199-599 m/s), SF <= 3
- Match periods at: 0.2T, T and 3T (0.28s, 1.4s, 4.2s)
Steel Weight

• 1.2D + 1.0E (MMS)
• 19% savings in cost

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<tr>
<th>Design</th>
<th>RBF12</th>
<th>RBF12-TO</th>
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<tbody>
<tr>
<td>Beam/brace weight (kips)</td>
<td>89</td>
<td>58</td>
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<tr>
<td>Column weight (kips)</td>
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<td>103</td>
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<tr>
<td>Total weight/frame (kips)</td>
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<td>160</td>
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<tr>
<td>Number of Frames</td>
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<tr>
<td>Total weight (ton)</td>
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<td>Cost/ton</td>
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<td>Total Steel Cost</td>
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