Performance-Based Seismic Design and Evaluation of Steel MRFs with Passive Dampers

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Concept

Use of performance-based design to improve the seismic behavior of steel MRFs:

- Design structure for specified performance objectives.
- Integrate passive dampers into design to enable structure to achieve performance objectives.
- Optimize design by reducing weight of MRF while avoiding large number of dampers.
- Simplified Design Procedure (SDP) \{Lee et al. 2005 EESD; 2009 JSE ASCE\}
  - Design dampers
  - Enables various performance objectives and corresponding design criteria to be specified
Simplified Design Procedure (SDP)

- Establish desired seismic performance and design criteria.
- Design trial MRF => $K_0$: MRF story lateral stiffness.
- Select $\alpha = (K_b/K_0)$ and range of $\beta = (K_d/K_0)$.
- Use ESAP.
- Select required $\beta$ from results.
- Calculate damper area, thickness; # of dampers.

Using $\beta$ makes the design process independent of frequency sensitivity of damping material.

Elastic-Static Analysis Procedure (ESAP)

- Estimate first-mode period, damping ratio from simple analysis.
- Use design spectrum with damping reduction factor to establish seismic coefficient.
- Perform elastic-static analysis for equivalent lateral forces.
Story Drift Response from ESAP

![Graph showing story drift response with different values of beta (β).]

- **β = 0, undamped MRF**
- **Drift Limit (1%)**
- **β = 1**
- **β = 2**
- **β = 20**

Legend:
- *Story-1*
- *Story-2*
- *Story-3*
- *Story-4*
- *Story-5*
- *Story-6*
Column Response from ESAP

First Story Columns
Damped MRF

β = 1  β = 0.5

β = 20  β = 0

Column Capacity

AISC-LRFD
Column Capacity
Prototype Building
Office building in Los Angeles on stiff soil.

Plan

SMRF

12.5 ft
15 ft

4 @ 30 ft = 120 ft

MRF with dampers

12.5 ft
15 ft

4 @ 30 ft = 120 ft

6 bays @ 30 ft = 180 ft
Elastomeric-Friction Damper

Pre-compressed elastomer – Corry Rubber Company

- Robust damper: Higher deformation capacity elastomer (Butyl Blend)
- Elastomeric and frictional output at small deformation amplitudes
- Damping output dominated by friction at large deformation amplitudes
Elastomeric-Friction Dampers

Hysteretic Behaviour

Before Slip

After Slip

Mechanical Properties

Equiv. Stiffness

Loss Factor
Design of MRFs for Building

<table>
<thead>
<tr>
<th>MRF</th>
<th>Column Section</th>
<th>Beam Sections</th>
<th>Steel weight (kN)</th>
<th>$T_1$ (sec)</th>
<th>$V_s/W$</th>
<th>Story stiffness (kN/m)</th>
<th>$\theta_{\text{max}}^{(1)}$ (%)</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>W14x211</td>
<td>1st story: W24x84 2nd story: W21x50</td>
<td>200</td>
<td>1.08</td>
<td>0.27</td>
<td>1st story: 66574 2nd story: 42018</td>
<td>2.40</td>
<td>2.9</td>
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<tr>
<td>B</td>
<td>W14x120</td>
<td>1st story: W24x55 2nd story: W18x40</td>
<td>124</td>
<td>1.48</td>
<td>0.14</td>
<td>1st story: 36007 2nd story: 23894</td>
<td>3.23</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Note:  
(1) maximum story drift $\theta_{\text{max}}$ based on equal displacement principle  
(2) $\mu=\theta_{\text{max}}/\theta_y$; $\theta_y$: story drift when 1st plastic hinge forms

MRF A: Satisfies member strength criteria and 2% drift limit of IBC 2000

MRF B: Designed for design base shear $0.50V$ ($V$: design base shear of MRF A) – no IBC drift criteria, use dampers to control drift
## Design of Building with Dampers

- **Back-up frame: MRF B**

<table>
<thead>
<tr>
<th>Frame</th>
<th>Brace steel weight (kN)</th>
<th>$a$</th>
<th>$\beta$</th>
<th>$n$</th>
<th>$\xi_t$ (%)</th>
<th>$B$</th>
<th>$\mu$</th>
<th>$\theta_{\text{max}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-D1</td>
<td>8.6</td>
<td>5.0</td>
<td>0.5</td>
<td>0.75</td>
<td>12.6</td>
<td>1.28</td>
<td>2.8</td>
<td>2.03</td>
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<tr>
<td>B-D2</td>
<td>17.2</td>
<td>10.0</td>
<td>1.0</td>
<td>0.60</td>
<td>15.0</td>
<td>1.35</td>
<td>2.3</td>
<td>1.65</td>
</tr>
</tbody>
</table>

- **B-D1**: Standard performance ($\theta_{\text{max}}=2.0\%$): 44% reduction of steel weight
- **B-D2**: Higher performance ($\theta_{\text{max}}=1.65\%$): 30% reduction of steel weight
Nonlinear Dynamic Time History Analysis (Ensemble of 25 ground motions)

Time History Analysis

θ_{max} (%)

Frame A, B-D1, B-D2

- SMRF
- MRFs with dampers

Standard performance
Higher performance

median (DBE)
84\textsuperscript{th} percentile (DBE)
median (MCE)
84\textsuperscript{th} percentile (MCE)
Experimental Validation Studies

Real-Time Hybrid Simulation

- Use of NEES@Lehigh Real-time Integrated Control System for Real-Time Hybrid Simulation
- Unconditionally Stable CR Explicit Integration Algorithm
- Adapted Inverse Compensation (AIC) Actuator Control
- Ground motions:
  - Five natural ground motions.
  - Scaled to DBE and MCE levels.
- Building Design Cases:
  - MRF A (no dampers)
  - MRF B-D2 (with dampers)
Experimental Verification
Real-Time Hybrid Simulation

Analytical substructure
- MRF, Gravity Frame with P-Δ effects
- 50 DOF; Nonlinear beam-column elems

Experimental Substructure 1
- 1st Floor dampers

Experimental Substructure 2
- 2nd Floor dampers

4 @ 9.15m = 36.6m
4.57m 3.96m

• MRF, Gravity Frame with P-Δ effects
• 50 DOF; Nonlinear beam-column elems
Experimental Substructures Test Setup

Experimental Substructures

Close-up View of Damper – Experimental Substructure 1 (0.5-scale dampers)
NEES@Lehigh Servo-Hydraulic System Equipment and Power

- Equipment design based on EQ demands for real-time large-scale testing of 30+ seconds.

- 5 dynamic hydraulic actuators:
  - Each ported to receive 3 – 2082 liter/min servo valves
  - Maximum load capacity
    - 2 actuators: 2300 kN at 20.7 MPa
    - 3 actuators: 1700 kN at 20.7 MPa
  - Maximum velocity
    - 1140 mm/s for 1700 kN actuators
    - 840 mm/s for 2300 kN actuators
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

Damper hysteresis

(a) Second floor damper (DBE)

(b) Second floor damper (MCE)

(c) First floor damper (DBE)

(d) First floor damper (MCE)
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

Floor displacements

(a) Second floor (DBE)
(b) Second floor (MCE)
(c) First floor (DBE)
(d) First floor (MCE)

SMRF with dampers
- DBE: No damage, structural primarily elastic
- MCE: Yielding in beams
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

2\textsuperscript{nd} Floor response spectra

- Steel SMRF (DBE)
- Steel MRF with dampers (DBE)
- Steel SMRF (MCE)
- Steel MRF with dampers (MCE)

**Notes:**
- SMRF no dampers (MCE)
- SMRF no dampers (DBE)
- MRF with dampers (MCE)
## Median Values of Response Parameters: DBE and MCE

<table>
<thead>
<tr>
<th>Design</th>
<th>Maximum story drift (%)</th>
<th>Maximum beam plastic rotation (rad)</th>
<th>Maximum column plastic rotation (rad)</th>
<th>Peak floor velocity (m/sec)</th>
<th>Peak floor acceleration (m/sec²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DBE</td>
<td>MCE</td>
<td>DBE</td>
<td>MCE</td>
<td>DBE</td>
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<tr>
<td>100V conventional SMRF</td>
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<tr>
<td>Story 1</td>
<td>2.60</td>
<td>2.90</td>
<td>0.008</td>
<td>0.014</td>
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<td>Story 2</td>
<td>2.40</td>
<td>2.60</td>
<td>0.000</td>
<td>0.003</td>
<td>0.000</td>
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<tr>
<td>50V SMRF with dampers</td>
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<tr>
<td>Story 1</td>
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<td>2.50</td>
<td>0.002</td>
<td>0.006</td>
<td>0.002</td>
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<tr>
<td>Story 2</td>
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<td>1.80</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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Summary and Conclusions

- MRFs with passive dampers can be designed using SDP to perform better than conventional SMRFs, even when the MRF with dampers is significantly lighter in weight than the SMRF.
- Dampers become more effective for lighter steel MRFs.
- Real-time hybrid simulation successfully used to experimentally evaluate PBD procedure for steel MRFs with passive dampers.
  - Ensemble of ground motions applied resulting in various damage levels to analytical substructure
  - No need to repair test specimen (damage occurs in analytical substructure)
  - Response statistics obtained
Acknowledgements

This material is based on work supported by the National Science Foundation Award No. CMS-0402490 NEES Consortium Operation, the Pennsylvania Infrastructure Technology Alliance, and Corry Rubber Company.
Thank you