Experimental Validation of Performance-Based Seismic Design of Building Systems with Dampers Using Real-Time Hybrid Simulations

James Ricles¹, Richard Sause¹, Theodore Karavasilis¹, and Cheng Chen²

¹Lehigh University
²San Francisco State University
Performance-Based Design of Steel MRFs with Dampers

Improve the Seismic Behavior of Steel SMRFs:

- Design structure for specified performance objectives.
- Integrate passive dampers into design to enable structure to achieve performance objectives.
- Optimize the design by reducing weight of the MRF while avoiding need for 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 stiffness
- Select $\alpha = (K_b/K_0)$ and range of $\beta = (K_d/K_0)$.
- Use ESAP.
- Select required $\beta$ from results that satisfy performance.
- Calculate damper area and thickness, # dampers.
- Iterate on MRF design, as necessary

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, $B$, to establish seismic coefficient.
- Perform elastic-static analysis for equivalent lateral forces.
Prototype Building

- Office building in Los Angeles on stiff soil

**SMRF: UD100V**

**MRF w/ dampers: UD50V**

6 bays @ 9.15 m = 54.9 m

Perimeter Frame Designs
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

1. Bonding of elastomer onto a steel bar
2. Elastomer pre-compressed into a steel tube
3. Three tubes welded together
4. Damper attached to the structure
Elastomeric-Friction Dampers

Hysteretic Behaviour

Before Slip

After Slip

Mechanical Properties

Equiv. Stiffness

Loss Factor
## Design of MRF 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>$\theta_{\text{max}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD100V</td>
<td>W14x211</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; story: W24x84 2&lt;sup&gt;nd&lt;/sup&gt; story: W21x50</td>
<td>200</td>
<td>1.08</td>
<td>0.27</td>
<td>2.40</td>
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<tr>
<td>UD50V</td>
<td>W14x120</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; story: W24x55 2&lt;sup&gt;nd&lt;/sup&gt; story: W18x40</td>
<td>124</td>
<td>1.48</td>
<td>0.14</td>
<td>3.23</td>
</tr>
</tbody>
</table>

Note: (1) Maximum story drift $\theta_{\text{max}}$ based on equal displacement principle

- **MRF UD100V**: Satisfies member strength criteria and 2% story drift limit of IBC 2000
- **MRF UD50V**: Designed for design base shear 0.50V (V: design base shear of MRF A) – no IBC drift criteria (damper design used to control drift)
Design of Building with Dampers

- MRF UD50V: Higher performance ($\theta_{\text{max}} = 1.65\%$) and 30% reduction of steel weight compare to MRF UD100V without dampers

<table>
<thead>
<tr>
<th>MRF</th>
<th>Braces steel weight (kN)</th>
<th>$a$</th>
<th>$\beta$</th>
<th>$n$</th>
<th>$\xi_t$ (%)</th>
<th>$B$</th>
<th>$\theta_{\text{max}}$ (%)</th>
<th>Dampers</th>
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</thead>
<tbody>
<tr>
<td>UD50V</td>
<td>17.2</td>
<td>10.0</td>
<td>1.0</td>
<td>0.60</td>
<td>15.00</td>
<td>1.35</td>
<td>1.65</td>
<td>8</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

Note:  
(1) Maximum story drift $\theta_{\text{max}}$ based on equal displacement principle  
(2) $\xi_t = $ damping of system  
(3) $B = $ damping reduction factor for design base shear
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:
  - UD50V (with 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
New real-time CR integration algorithm (Chen and Ricles, ASCE JEM 2008; EESD 2009)

CR algorithm:
- Explicit
- Unconditionally stable
- Enables continuous actuator motion

\[ M\ddot{x}_{i+1} + C\dot{x}_{i+1} + R_{i+1} = P_{i+1} \]

\[ x_{i+1} = x_i + \Delta t \cdot \dot{x}_i + \alpha_2 \cdot \Delta t^2 \cdot \ddot{x}_i \]

\[ \dot{x}_{i+1} = \dot{x}_i + \alpha_1 \Delta t \cdot \ddot{x}_i \]

\( \alpha_1 \) and \( \alpha_2 \): integration parameters determined using discrete control theory to attain unconditional stability,

\[ \alpha_1 = \alpha_2 = 4 \left( 4 \cdot M + 2 \cdot \Delta t \cdot C \cdot + \Delta t^2 \cdot K \right)^{-1} M \]
Actuator Delay Compensation

- Development of Improved Actuator Delay Compensation – TI error-based adaptive compensation (Chen and Ricles, JSE 2009)

Formulation of Adaptive Inverse Compensation (AIC):

\[ G_c(z) = \frac{X^p(z)}{X^c(z)} = \frac{(\alpha_0 + \Delta\alpha) \cdot z - (\alpha_0 + \Delta\alpha - 1)}{z} \]

Adaptive Control Law:

\[ \Delta\alpha(t) = k_p \cdot TI(t) + k_I \cdot \int TI(t) dt \]

\(\alpha_0\) = estimate of act. delay, \(\Delta\alpha\) = evolutionary variable, \(k_p\) and \(k_I\) = adaptive gains, \(TI\) = tracking indicator
Real-time Actuator Error Tracking

- Development of Actuator Error Tracking Indicators - (Mercan and Ricles, ASCE JSE 2007)

Definition of Tracking Indicator (TI):

\[ TI_{i+1}^{(j)} = 0.5 \sum_{i} \sum_{j} (A_{i+1}^{(j)} - TA_{i+1}^{(j)}) \]

- Positive slope for TI corresponds to an actuator response lagging behind actuator command displacement.
- Negative slope for TI indicates a leading actuator response.

Synchronization subspace plot – command vs. measured actuator displacement

Measured disp

Command disp
Real-time Hybrid Simulation

- Simulations involved EQ motion in E-W direction

MRF w/ dampers: UD50V

6 bays @ 9.15 m = 54.9 m

dampers
dampers
dampers
dampers
Real-time Hybrid Simulation

- Modeling: NDOF=122, Concentrated plasticity element for beams and columns
- HybridFEM: Nonlinear FEM code for real-time hybrid simulation (Karavasilis et. al. 2008)
- Numerical Integration: Explicit & unconditionally stable CR algorithm (Chen & Ricles 2008a)
- Actuator control algorithm: Adaptive Inverse Control (Chen & Ricles 2008b)
Dampers in prototype structure in each story are in parallel: one damper used in each experimental substructure to model all dampers in a story.

- Story damper total restoring force = measured damper force * # dampers in story
## Experimental Validation Studies - Test Matrix

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Station/Component</th>
<th>Scale Factor</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Loma Prieta 1989</td>
<td>Hollister/HSP090</td>
<td>1.99</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>Manjil 1990</td>
<td>Abbar/Abbar-T</td>
<td>0.96</td>
<td>1.44</td>
<td></td>
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<tr>
<td>Northridge 1994</td>
<td>N Hollywood/CWC270</td>
<td>1.70</td>
<td>2.56</td>
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</tr>
<tr>
<td>Chi Chi 1999</td>
<td>TCU049/TCU049-E</td>
<td>1.92</td>
<td>3.67</td>
<td></td>
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<tr>
<td>Chi Chi 1999</td>
<td>TCU105/TCU105-E</td>
<td>2.45</td>
<td>2.89</td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
1. DBE = *Design Basis Earthquake*, approximately a 10% probability of exceedance in 50 years with a 475 year return period
2. MCE = *Maximum Considered Earthquake*, 2% probability of exceedance in 50 years with a 2475 year return period
3. SF = Scale Factor
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

Damper hysteresis

(a) Second fl oor damper (DBE)

(b) Second fl oor damper (MCE)

(c) First fl oor damper (DBE)

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

Floor displacements

MRF with dampers
- **DBE**: No damage, structural primarily elastic
- **MCE**: Yielding in beams; base of 1st story column

Conventional SMRF
- **DBE**: Damage - Yielding in beams; base of 1st story column
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

Actuator Control: Synchronization Subspace Plots

\[ RMS = \frac{\sum (d^c - d^m)^2}{\sum (d^c)^2} \]

Adaptive Inverse Compensation
- Actuator command displacement accurately achieved
Experimental Results - Real-Time Hybrid Simulation: Loma Prieta 1989 EQ

2nd Floor response spectra

![Graph showing response spectra for different scenarios: SMRF no dampers (MCE), SMRF no dampers (DBE), MRF with dampers (MCE), and MRF with dampers (DBE).]
## Median Values of Response Parameters: DBE and MCE

<table>
<thead>
<tr>
<th>Design</th>
<th>Story 1</th>
<th>Story 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD100V (Conventional SMRF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBE</td>
<td>MCE</td>
<td>DBE</td>
</tr>
<tr>
<td>2.60</td>
<td>2.90</td>
<td>0.008</td>
</tr>
<tr>
<td>2.40</td>
<td>2.60</td>
<td>0.000</td>
</tr>
<tr>
<td>UD50V (MRF w/ dampers)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBE</td>
<td>MCE</td>
<td>DBE</td>
</tr>
<tr>
<td>1.35</td>
<td>2.50</td>
<td>0.002</td>
</tr>
<tr>
<td>1.40</td>
<td>1.80</td>
<td>0.000</td>
</tr>
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</table>
Summary and Conclusions

- Real-time hybrid simulation successfully utilized to experimentally evaluate PBD procedure for steel SMRFs 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
- MRFs with passive dampers can be designed using the 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
Acknowledgements

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Thank you