Validating Performance of Self-Centering Steel Frame Systems Using Hybrid Simulation

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Introduction – Current Seismic Design Practice

• Design for “Life Safety” for the “Design Basis Earthquake”.

• No specific focus on damage or collapse; expect (hope?) current practice will also provide:
  – “Immediate Occupancy” for “Frequently Occurring Earthquake”.
  – “Collapse Prevention” for the “Maximum Considered Earthquake”.

• These earthquake intensities are defined (U.S.) as follows:
  – Frequently Occurring Earthquake (FOE) – 50% in 50 years.
  – Design Basis Earthquake (DBE) – approx. 10% in 50 years.
  – Maximum Considered Earthquake (MCE) – 2% in 50 years.
Introduction – Current Design Practice
What does it provide?

• “Life Safety” for “DBE”.
  – Expect serious structural damage for ground motion with a return period of 400 to 500 years.

• “Immediate Occupancy” for “FOE”.
  – Expect that buildings may be damaged and unusable after ground motion with a return period more than 75 years.

At the same time…

• Recent research (Miranda) shows that significant economic loss is due to damaged buildings that must be demolished during post-earthquake recovery because of structural damage (e.g., residual drift).
Introduction: Expected Damage for Conventional Steel Frames

Reduced beam section (RBS) beam-column specimen with slab:
(a) at 3% drift, (b) at 4% drift.
Introduction – Two Current Research Themes for Earthquake-Resistant Structures

• Innovations to reduce damage and residual drift:
  – Goal: reduce economic losses and social disruption from future earthquakes.
  – Protective systems (base isolation, passive dampers, semi-active control, etc.).
  – Self-centering structural systems.

• Rational approaches to prevent collapse:
  – Goal: prevent loss of life.
  – Estimates of the probability of collapse and develop consensus on acceptable probability.
Self Centering (SC) Seismic-Resistant Structural System Concepts

- Discrete structural members are post-tensioned to pre-compress joints.
- Gap opening at joints at selected earthquake load levels provides softening of lateral force-drift behavior without damage to members.
- PT forces close joints and permanent lateral drift is avoided.
Lateral Force-Drift Behavior Controlled by Gap Opening, not by Member Damage

Steel MRF subassembly with SC connections at 3% drift
Expected Damage for Conventional Steel Frames

Reduced beam section (RBS) beam-column specimen with slab:
(a) at 3% drift, (b) at 4% drift.
Lateral Force-Drift Behavior Controlled by Gap Opening, not by Member Damage

Steel MRF subassembly with SC connections at 3% drift
Comparison of Lateral Force-Drift Behavior

- Conventional system softens by inelastic damage to main structural members producing residual drift
- SC system softens by gap opening and reduced contact area at joints
- SC system energy dissipation is designed feature of system
- Two systems have similar initial stiffness
Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project

- Develop two SC steel frame systems

Moment-resisting frames (SC-MRFs)

Concentrically-braced frames (SC-CBFs).
Research on SC-MRF Systems—Prior Work

PT Strands and Angles
(Ricles et al. 2000)

PT Bars and ED Bars
(Christopoulos et al. 2002)
Beam-Column Connection and Energy Dissipation Details

PT Strands and Web Friction Device (WFD) (Lin et al. 2008)

Used in large-scale SC-MRF tests.
Behavior of SC WFD Connection

- \( MIGO \)
- \( M_d \)
- Gap closing
- Unloading
- \( 3: \) PT strands yield

\[ \theta_r \]

\[ M \]

\[ 2M_F \]
Performance-Based, Probabilistic Seismic Design Procedure

Target Performance

- Damage free for Immediate Occupancy (IO) under Design Basis Earthquake (DBE).
- Collapse Prevention (CP) under the Maximum Considered Earthquake (MCE).
- MCE – 2% probability of exceedance in 50 years.
- DBE – 10% probability of exceedance in 50 years (or 2/3 of MCE).
Performance-Based, Probabilistic Seismic Design Procedure

\[ \theta_{rf, DBE} = \text{roof drift under DBE} \]

\[ \theta_{rf, MCE} = \text{roof drift under MCE} \]
Performance-Based, Probabilistic Seismic Design Procedure

- Reliable estimates of global response $\theta_{rf, DBE}$ and $\theta_{rf, MCE}$ are critical for design procedure.
- Reliable estimates of corresponding local response variables $\theta_{r, DBE}$ and $\theta_{r, MCE}$ are similarly critical.
Large-Scale Hybrid Simulations on SC-MRF

Prototype SC-MRF

- 7x7-bay 4-story
- Office Building in Los Angeles, California
- Stiff Soil

Plan of Building

Elevation of perimeter frame

Composite/non-composite floor system to permit unrestrained gap opening of SC-WFD
Hybrid Simulations

• Direct integration of equations of motion with restoring forces $r(t)$

$$M \cdot \ddot{x}_{i+1} + C \cdot \dot{x}_{i+1} + r_{i+1} = F_{i+1}$$

• Structural system divided into analytical substructure and experimental substructure

• Restoring forces from analytical substructure and experimental structure are combined

$$M \cdot \ddot{x}_{i+1} + C \cdot \dot{x}_{i+1} + r^a_{i+1} + r^e_{i+1} = F_{i+1}$$

analytical structure  experimental structure
Large-Scale Hybrid Simulations on SC-MRF

Tributary Gravity Frames, Seismic Mass, and Inherent Damping as Analytical Substructure

Perimeter SC-MRF as Experimental Substructure

Earthquake Loading Direction
Large-Scale Hybrid Simulations on SC-MRF

Analytical Substructure
- Gravity Columns – column stiffness and axial loads $P$, building mass $m$ and damping.

Experimental Substructure
- Displacements imposed through floor diaphragm system

Horizontal Rigid Link (typ.)
Large-Scale Hybrid Simulations on SC-MRF

0.6-Scale 2-bay 4-story SC-MRF
Experimental Substructure
### Matrix of Simulations

<table>
<thead>
<tr>
<th>Tests</th>
<th>Descriptions</th>
<th>Ground Motion Record</th>
<th>Scale Factor</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>FOE-1</td>
<td>1979 Imperial Valley</td>
<td>H-CXO225</td>
<td>0.700</td>
<td></td>
</tr>
<tr>
<td>FOE-2</td>
<td>1979 Imperial Valley</td>
<td>H-CXO225</td>
<td>1.400</td>
<td></td>
</tr>
<tr>
<td>DBE-1</td>
<td>1979 Imperial Valley</td>
<td>H-ECC002</td>
<td>0.943</td>
<td></td>
</tr>
<tr>
<td>DBE-2</td>
<td>1989 Loma Prieta</td>
<td>SJTE315</td>
<td>-2.234</td>
<td>Hybrid</td>
</tr>
<tr>
<td><strong>DBE-3</strong></td>
<td><strong>1994 Northridge</strong></td>
<td><strong>LOS000</strong></td>
<td><strong>1.182</strong></td>
<td></td>
</tr>
<tr>
<td>MCEs</td>
<td>1994 Northridge</td>
<td>Varied w/ tests</td>
<td>Varied w/ tests</td>
<td></td>
</tr>
<tr>
<td>Aftershocks</td>
<td>1989 Loma Prieta</td>
<td>SJTE315</td>
<td>-2.234</td>
<td></td>
</tr>
</tbody>
</table>
Observed Experimental Response

- No damage in beams and columns, except for yielding at column base.
- No residual drift: self-centering
DBE-3 Simulation Results
DBE-3 Simulation Results

Moment – $\theta_r$ response
Summary and Conclusions from Large-Scale Hybrid Simulations on SC-MRF

• First large-scale simulations on steel SC-MRF system.
• Simulations validated the performance-based design procedure and criteria.
• SC-WFD beam-to-column connections performed well, dissipating energy while maintaining self-centering.
• Demonstrated that SC-MRF system can be designed to be damage free and achieve Immediate Occupancy (IO) performance under DBE.
• Also demonstrated that residual drift and damage of SC-MRF system is minimal under the MCE, achieving Collapse Prevention (CP) performance.
Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems Project: SC-CBF Systems

- Develop SC-CBF concept and configurations.
- Develop performance-based, probabilistic seismic design procedure for SC-CBFs.
- Develop connection and energy dissipation details for SC-CBFs.
- Conduct large-scale laboratory tests of SC-MRFs using NEES facility.

Concentrally-braced frames (SC-CBFs).
Large-Scale Hybrid Simulations on SC-CBF

- Large-scale hybrid simulations of 4-story SC-CBF at Lehigh NEES equipment site are in progress.
Acknowledgement

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