Introduction to Self-Centering Earthquake Resisting Systems

Andre Filiatrault, Ph.D., Eng.

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8. Self-centering Dampers Using Ring Springs
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1. Introduction

- With current design approaches, most structural systems are designed to respond beyond the elastic limit and eventually to develop a mechanism involving ductile inelastic response in specific regions of the structural system while maintaining a stable global response and avoiding loss of life
- Resilient communities expect buildings to survive a moderately strong earthquake with no disturbance to business operation
- Repairs requiring downtime may no longer be tolerated in small and moderately strong events
1. Introduction

• Current Seismic Design Philosophy
  – Performance of a structure typically assessed based on maximum deformations
  – Most structures designed according to current codes will sustain residual deformations in the event of a design basis earthquake (DBE)
  – Residual deformations can result in partial or total loss of a building:
    • static incipient collapse is reached
    • structure appears unsafe to occupants
    • response of the system to a subsequent earthquake or aftershock is impeded by the new at rest position
  – Residual deformations can result in increased cost of repair or replacement of nonstructural elements
  – Residual deformations not explicitly reflected in current performance assessment approaches.
  – Framework for including residual deformations in performance-based seismic design and assessment proposed by Christopoulos et al. (2003)
  – Chapter presents structural self-centering systems possessing characteristics that minimize residual deformations and are economically viable alternatives to current lateral force resisting systems

2. Behavior of Self-centering Systems

• Optimal earthquake-resistant system should:
  – Incorporate nonlinear characteristics of yielding or hysteretically damped structures: limiting seismic forces and provide additional damping
  – Have self-centering properties: allowing structural system to return to, or near to, original position after an earthquake
  – Reduce or eliminate cumulative damage to main structural elements.
2. Behavior of Self-centering Systems

Figure 7.2 Idealized Seismic Response of Self-Centering Structure (from Christopoulos 2002)

3. Dynamic Response of MDOF Self-centering Systems

- Response of 3, 6, 10-storey Steel Frames
- Self-centering Frames with Post-Tensioned Energy Dissipating (PTED) Connections vs. Welded Moment Resisting Frames (WMRF)
- Beam and Column Sections designed according to UBC 97 for a Seismic Zone 4 (Los Angeles)
- Special MRF, assuming non-degrading idealized behavior for welded MRFs
- A992 Steel, with RBS connections
- Hinging of beams and P-M interaction included
- 2% viscous damping assigned to 1st and (N-1)th modes
- 6 historical ground motions scaled to match code spectrum
- 20 second zero acceleration pad at end of records
3. Dynamic Response of MDOF Self-centering Systems

- Response of 3-Storey Frames to LP3 Record (0.5 g)
3. Dynamic Response of MDOF Self-centering Systems

- Response of 6-Storey Frames to LP3 Record (0.5 g)

- Response of 10-Storey Frames to LP3 Record (0.5 g)

- Response of 6-Storey Frames to Ensemble of 6 Records

- PTED Frames:
  - similar maximum drifts as WMRFs (for all records)
  - limited residual drift at base columns unlike welded frame
  - similar maximum accelerations as WMRFs (for all records)
3. Dynamic Response of MDOF Self-centering Systems

- Explicit Consideration of Residual Deformations in Performance-Based Seismic Design (see Section 2.3.3)

4. Ancient Applications of Self-centering Systems

![Ancient Greek Temples](image)

Figure 7.27: Ancient Greek Temples: a) General View and b) Segmented Column

5. Early Modern Applications of Self-centering Systems

- South Rangitikei River Railroad Bridge, New Zealand, built in 1981
- Piers: 70 m tall, six spans prestressed concrete hollow-box girder, overall span: 315 m
- Rocking of piers combined with energy dissipation devices (torsional dampers)
- Gravity provides self-centering force
6. Shape Memory Alloys

- **Superelasticity**
  - Shape Memory Alloys (SMAs): class of materials able to develop superelastic behavior
  - SMAs are made of two or three different metals
    - Nitinol: 49% of Nickel and 51% of Titanium.
    - Copper and zinc can also be alloyed to produce superelastic properties.
    - Depending on temperature of alloying, several molecular rearrangements of crystalline structure of alloy are possible
  - Low alloying temperatures: martensitic microstructure
  - High alloying temperatures austenitic microstructure

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Figure 7.29 SMA Hysteresis Behavior: a) for Low Alloying Temperatures and b) for High Alloying Temperatures

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Figure 7.30 SMA Superelastic Behavior for Intermediate Alloying Temperatures
6. Shape Memory Alloys

• Superelasticity
  – Advantages for supplemental damping purposes:
    • Exhibits high stiffness and strength for small strains
    • It becomes more flexible for larger strains.
    • Practically no residual strain and
    • Dissipates energy
  – Disadvantages:
    • Sensitive to fatigue: after large number of loading cycles, SMAs deteriorate into classical plastic behavior with residual strains
    • Cost

6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):
    • Studied experimentally the use of Nitinol as energy dissipating element
    • Shake table tests a small-scale 3-storey steel frame

Figure 7.3: Three-story Test Frame Used for Shake Table Studies of Nitinol SMAs (Lamb, 1992, UC Berkeley)

6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):
    • Nitinol wires incorporated at each end of the cross braces
    • Nitinol loaded in tension only
    • No preload in Nitinol wires for initial shake table tests

Figure 7.4: Hysteresis of Nitinol Wires - Recorded during Shake Tests (Pruzan et al., 1980, Seismic Research Center, University of New Mexico, Federal Seismic Safety Program)
6. Shape Memory Alloys

- Experimental Studies
  - Aiken et al. (1992):

![Diagrams](image1)

- Witting and Cozzarelli (1992):
  - Shake table tests on 2/5-scale steel frame incorporating Cu-Zn-Al SMA dampers installed as diagonal braces
  - SMA dampers configured as a torsion bar system

![Diagrams](image2)

- Ocel et al. (2004):
  - Investigated cyclic behavior of steel beam-column connections incorporating Nitinol rods
  - Four Nitinol rods in martensitic phase incorporated as axial elements in connection to dissipate energy

![Diagrams](image3)
6. Shape Memory Alloys

- Experimental Studies
  - Ocel et al. (2004):
    - Nitinol rods re-heated above alloying temperature
    - Re-generate austenitic microstructure and recover initial shape
    - Rods heated for 8 minutes at 300°C and ⅔ of permanent deformations recovered

- Structural Implementations
  - Seismic retrofit of historical San Giorgio bell tower, Italy
    - Damaged after 1996 Modena and Reggio earthquake
    - Nitinol wires introduced and prestressed through masonry walls of bell tower to prevent tensile stresses
6. Shape Memory Alloys

• Structural Implementations
  – Seismic rehabilitation of Upper Basilica di San Francesco in Assisi, Italy
    • Damaged by the 1997-98 Marche and Umbria earthquakes
    • Nitinol wires used in post-tensioning rods

7. The Energy Dissipating Restraint (EDR)

• Hysteretic Behavior
  – Manufactured by Fluor Daniel, Inc.
  – Originally developed for support of piping systems
  – Principal components:
    • internal spring, steel compression wedges, bronze friction wedges, stops at both ends of internal spring, external cylinder

7. The Energy Dissipating Restraint (EDR)

• Hysteretic Behavior
  [Diagram showing the components and behavior of the EDR]
7. The Energy Dissipating Restraint (EDR)

- Hysteretic Behavior

\[\text{Figure 7.4: Hysteretic loops for various configurations of EDR (from above, reproduced with the permission of the Earthquake Engineering Research Institute)}\]

7. The Energy Dissipating Restraint (EDR)

- Experimental Studies
  - Aiken et al. (1993):
    - Same three-storey steel frame as for SMA damper tests

\[\text{Figure 7.6: Test Frame with EDR (from Aiken et al., 1993, reproduced with the permission of the Earthquake Engineering Research Institute)}\]

7. The Energy Dissipating Restraint (EDR)

- Experimental Studies
  - Aiken et al. (1993):
8. Self-centering Dampers Using Ring Springs

- Description of Ring Springs (Friction Springs)
  - Outer and inner stainless steel rings with tapered mating surfaces
  - When spring column loaded in compression, axial displacement and sliding of rings on conical friction surfaces
  - Outer rings subjected to circumferential tension (hoop stress)
  - Inner rings experience compression
  - Special lubricant applied to tapered surfaces
  - Small amount of pre-compression applied to align rings axially as column stack
  - Flag-shaped hysteresis in compression only

[Diagram of Ring Spring Details]

- Flag-shaped hysteresis in compression only

Compression Force, \( F \)
Axial Displacement

8. Self-centering Dampers Using Ring Springs

- SHAPIA Damper
  - Manufactured by Spectrum Engineering, Canada
  - Ring spring stack restrained at ends by cup flanges
  - Tension and compression in damper induces compression in ring spring stack: symmetric flag-shaped hysteresis

[Diagram of SHAPIA Damper Prototype]

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Characterization Tests

[Table 7.6: Material Values of Damage Indicators for SHAPIA Damper]

<table>
<thead>
<tr>
<th>Material Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_D )</td>
<td>Tensile</td>
</tr>
<tr>
<td>( R_C )</td>
<td>Compressive</td>
</tr>
<tr>
<td>( R_S )</td>
<td>Shear</td>
</tr>
<tr>
<td>( R_F )</td>
<td>Friction</td>
</tr>
<tr>
<td>( R_T )</td>
<td>Torsional</td>
</tr>
<tr>
<td>( R_M )</td>
<td>Magnetization</td>
</tr>
</tbody>
</table>
8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Characterization Tests

![Diagram of SHAPIA Damper](image1)

![Diagram of Experimental Setup](image2)

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Shake Table Tests
    - Single-storey moment-resisting plane frame: height of 1.8 m and bay width of 2.9 m
    - Column base was linked to pin base. Weight simulated by four concrete blocks (30 kN each) linked horizontally to upper beam.
    - Concrete blocks were supported vertically by peripheral pinned gravity frame.
    - Test frame carry only the lateral inertia forces.
    - Lateral load resistance provided by MRF and bracing member.

![Graph of Frequency Dependency](image3)

![Graph of Time History Response](image4)
9. Post-tensioned Frame and Wall Systems

- Concrete Frames
  - PRESSS (PREcast Seismic Structural Systems) program
    - Use of unbonded post-tensioning elements to develop self-centering hybrid precast concrete building systems

![Image of Hybrid Frame System](after Preumont and Nakato, 2002)

Figure 9.10 Hybrid Frame System (after Preumont and Nakato, 2002)

CIE500D “Introduction to Graduate Research in Structural Engineering”
9. Post-tensioned Frame and Wall Systems

- Hysteretic Characteristics of Post-Tensioned Energy Dissipating (PTED) Connections
  - Self-centering conditions: $M_c = (k_1 - k_2)P_B$
    - $k_1$ = Elastic axial stiffness of ED elements
    - $k_2$ = Post-yield axial stiffness of ED elements
    - $\theta_b$ = Gap opening angle at first yield of ED elements
    (textbook p. 256-262)

- Sectional Analysis of PTED Connections
  - Construct complete moment-rotation relationship of connection by increasing $\theta$ and computing the corresponding moment
  - Separate PT and ED contributions

- Graph showing moment-rotation relationship for PTED connections.
9. Post-tensioned Frame and Wall Systems

- Cyclic Modelling of PTED Connections with Equivalent Nonlinear Rotational Springs

- Extension of PTED Model to Constrained Beams
  - Model Accounting for Beam Depth
9. Post-tensioned Frame and Wall Systems

- Extension of PTED Model to Constrained Beams
  - Model Accounting for Beam Depth

9. Post-tensioned Frame and Wall Systems

- Concrete Walls
  - Post-Tensioned Rocking Wall System (Stanton et al. 1993)

9. Post-tensioned Frame and Wall Systems

- Concrete Walls
  - Jointed Cantilever Wall System (Restrepo 2002)
9. Post-tensioned Frame and Wall Systems

- Concrete Walls
  - Jointed Cantilever Wall System (Restrepo 2002)

Extent of damage at 6% drift

9. Post-tensioned Frame and Wall Systems

- Self-centering Systems for Confined Masonry Walls

9. Post-tensioned Frame and Wall Systems

- Self-centering Systems for Confined Masonry Walls
9. Post-tensioned Frame and Wall Systems
• Self-Centering Systems for Steel Structures
  – Hybrid Post-Tensioned Connection (Ricles et al. 2001)

![Image of Hybrid Post-Tensioned Connection](image1)

9. Post-tensioned Frame and Wall Systems
• Self-Centering Systems for Steel Structures
  – PTED Connection (Christopoulos et al. 2002a, 2002b)

![Image of PTED Connection](image2)

9. Post-tensioned Frame and Wall Systems
• Self-Centering Systems for Steel Structures
  – PTED Connection (Christopoulos et al. 2002a, 2002b)

![Image of PTED Connection](image3)
11. Post-tensioned Frame and Wall Systems

- Shake table testing of PTED frame (Wang and Filiatrault 2008)

11. Post-tensioned Frame and Wall Systems

- Self-Centering Systems for Steel Structures
  - Friction Damped PT Frame (Kim and Christopoulos 2008)
  - ED bars replaced by Friction Energy Dissipating (FED) connections made of Non Asbestos Organic (NAO) brake lining pads on stainless steel

- Self-Centering Energy Dissipating Bracing System (Christopoulos et al. 2008)
  - Two bracing members, tensioning system, energy dissipating system, guiding elements
11. Post-tensioned Frame and Wall Systems
   • Application to wood structures
     – Beam-to-column subassemblies using Laminated Veneer Lumber (LVL)
     – Unbonded post-tensioned tendons and either external or internal energy dissipaters

9. Post-tensioned Frame and Wall Systems
   • Self-Centering Systems for Bridges

10. Considerations for the Seismic Design of Self-centering Systems
    • If adequate amount of energy dissipation capacity provided to self-centering systems ($\beta = 0.75$ to $0.90$), maximum displacement similar to traditional systems of similar initial stiffness
    • General design approach for self-centering systems:
      – Derive lateral design forces for an equivalent traditional system
      – Transform traditional system into self-centering system with equal strength at the target design drift
      – Design self-centering system for similar initial stiffness to traditional system with $\beta = 0.75$ to $0.90$
Questions/Discussions