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 impaired 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. Behaviour 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. Behaviour of Self-centering Systems

![Figure 7.2 Idealized Seismic Response of Self-Centering Structure (from Christopoulos 2002)](image)

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

![Diagram of Steel Frame](image)
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

<table>
<thead>
<tr>
<th>Response Index</th>
<th>CGD</th>
<th>LANQ</th>
<th>LP1</th>
<th>PCR3</th>
<th>SCOF</th>
<th>ELPF</th>
<th>MEAN</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
<td>(%)</td>
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<tr>
<td>Assumptions</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Preload (lbf)</td>
<td>1.0</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>Residual Drift</td>
<td>1.35</td>
<td>1.37</td>
<td>1.19</td>
<td>1.39</td>
<td>1.40</td>
<td>1.41</td>
<td>1.39</td>
</tr>
<tr>
<td>Maximum Drift</td>
<td>0.80</td>
<td>0.83</td>
<td>0.94</td>
<td>0.98</td>
<td>0.98</td>
<td>0.99</td>
<td>0.98</td>
</tr>
<tr>
<td>Maximum M.A.</td>
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<td>0.23</td>
<td>0.27</td>
<td>0.23</td>
<td>0.27</td>
<td>0.27</td>
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</tr>
<tr>
<td>Acceleration (g)</td>
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<td>0.80</td>
<td>0.79</td>
<td>0.80</td>
<td>0.80</td>
<td>0.79</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

- 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

![Figure 7.27 Ancient Greek Temples a) General View and b) Segmented Column](image)

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
    - NiTi: 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

**Figure 7.20 SMAs Hysteresis Behaviour:** a) for Low Alloying Temperatures and b) for High Alloying Temperatures

**Figure 7.30 SMAs Superelastic Behaviour 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
    - Dissipate energy
  - Disadvantages:
    - Sensitive to fatigue: after large number of loading cycles, SMAs deteriorate into classical plastic behaviour with residual strains
    - Cost

- **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-Storey Test Frame Used for Shake Table Tests of Nitinol](image)

![Figure 7.4: Hysteresis Behavior of Nitinol Wires Recorded During Shake Table Tests](image)
6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):
    • With no preload, wires loose at the end of testing.
    • With a small preload, difficult to achieve uniform response in all braces
    • Large preload applied to Nitinol wires in subsequent seismic tests
    • Axial strain in wires cycled between 2.5% and 6.0% during tests
    • Nitinol continuously cycled in of martensite phase
    • Steel-like hysteresis behaviour with maximum energy dissipation
    • Self-centering capabilities of the Nitinol lost

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6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):

![Hysteresis Loops for All Nitinol Braces from Aiken et al. 1992](image)

Figure 6.1: Hysteresis Loops for All Nitinol Braces from Aiken et al. 1992. Reproduced with the permission of the New Zealand Society for Earthquake Engineering.

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6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):

![Effect of Nitinol Braces on the Seismic Response of Test Frame](image)

Figure 7.3: Effect of Nitinol Braces on the Seismic Response of Test Frame – Zaranda Ground Motion, Sohle: Nitinol Without Postload, Dorns: Nitinol With Postload, Disc-Dash: Raw Frame (from Aiken et al. 1992, reproduced with the permission of the New Zealand Society for Earthquake Engineering).
6. Shape Memory Alloys

- Experimental Studies
  - 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

- Ocel et al. (2004):
  - Investigated cyclic behaviour of steel beam-column connections incorporating Nitinol rods
  - Four Nitinol rods in martensitic phase incorporated as axial elements in connection to dissipate energy
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 300ºC and ¾ of permanent deformations recovered

6. Shape Memory Alloys

• 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 Behaviour**
  - 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

![Diagram of EDR system](image)
7. The Energy Dissipating Restraint (EDR)

- Hysteretic Behaviour

![Hysteretic Behaviour Diagram]

7. The Energy Dissipating Restraint (EDR)

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

![Experimental Studies Image]

7. The Energy Dissipating Restraint (EDR)

- Experimental Studies
  - Aiken et al. (1993):

![Additional Experimental Studies Diagram]
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

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

8. Self-centering Dampers Using Ring Springs

• Experimental Studies with SHAPIA Damper
  – 200-kN capacity prototype damper
  – Characterization Tests
8. Self-centering Dampers Using Ring Springs

• Experimental Studies with SHAPIA Damper
  – Characterization Tests

![Characterization Tests Diagram]

8. Self-centering Dampers Using Ring Springs

• Experimental Studies with SHAPIA Damper
  – Characterization Tests

![Characterization Tests Diagram]

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

![Shake Table Tests Diagram]
8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Shake Table Tests

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
9. Post-tensioned Frame and Wall Systems

- Concrete Frames
  - PRESSS (PREcast Seismic Structural Systems) program

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9. Post-tensioned Frame and Wall Systems

- Concrete Frames
  - PRESSS (PREcast Seismic Structural Systems) program

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9. Post-tensioned Frame and Wall Systems

- Hysteretic Characteristics of Post-Tensioned Energy Dissipating (PTED) Connections
  - Self-centering conditions: $M_a \geq (k_1 - k_2)P_a$
  - $k_1$ = Elastic axial stiffness of ED elements
  - $k_2$ = Post-yield axial stiffness of ED elements
  - $\theta_a$ = Gap opening angle at first yield of ED elements
    (textbook p. 266-268)

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Figure 7.43 Hybrid Connection of Five-Story PRESSS Building: a) Photo at 4%, b) Drift Ratio and c) Force-Deflection Response (courtesy of S. Panapakis)

CRB5000 Introduction to Graduate Research in Structural Engineering
9. Post-tensioned Frame and Wall Systems

- Sectional Analysis of PTED Connections

\[
\varepsilon_{\text{PT}} = \varepsilon_{\text{y}} + \frac{\theta d_s}{L_{\text{sys}}} \left( 1 - \frac{L}{d_s} \right)
\]

\[
\varepsilon_{\text{ED}} = \frac{\theta d_s - d_c}{L_{\text{sys}}}
\]

\[
\varepsilon_{\text{max}} = \left[ \frac{\theta}{L_{\text{sys}}} \right] + \theta \varepsilon_{\text{y}}
\]

9. Post-tensioned Frame and Wall Systems

- 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](image)

9. Post-tensioned Frame and Wall Systems

- Cyclic Modelling of PTED Connections with Equivalent Nonlinear Rotational Springs

![Graph showing cyclic performance](image)
9. Post-tensioned Frame and Wall Systems

• Extension of PTED Model to Constrained Beams

- Model Accounting for Beam Depth

- Larger number of springs
- Fiber elements for gap opening and for beam shear carry

- Beam-Column element
- Rigid links
- Pre-stressed Truss element
9. Post-tensioned Frame and Wall Systems

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

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

- 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

Figure 7.65 Hybrid Post-Tensioned Connection for Steel Frames (after Ricles et al. 2001)
9. Post-tensioned Frame and Wall Systems
- Self-Centering Systems for Steel Structures
  - PTED Connection (Christopoulos et al. 2002a, 2002b)

![Figure 7.6 PTED Connection for Steel Structures (Christopoulos et al. 2002)](image)

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

![Figure 7.69 Concept of Hybrid System Applied on Bridge Floors (after Pedersen et al. 2004)](image)
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