Self-Centering
Earthquake Resisting Systems
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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 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

![Idealized Seismic Response of Self-Centering Structure](from Chryssopoulos 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

![Schematic Diagram](CIE500D "Introduction to Graduate Research in Structural Engineering"

3. Dynamic Response of MDOF Self-centering Systems

![Schematic Diagram](CIE500D "Introduction to Graduate Research in Structural Engineering"
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

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 behaviour
  - 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 7.20 SMAs Hysteresis Behaviour:**

a) Low Alloying Temperatures  
![Graph](image1.png)

b) High Alloying Temperatures  
![Graph](image2.png)

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**Figure 7.30 SMAs Superelastic Behaviour for Intermediate Alloying Temperatures**  
![Graph](image3.png)
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 7.3a: Three-Storey Test Frame Used for Shake Table Studies of Nitinol](image)

![Figure 7.3b: Inclined Load-Displacement Graph of Nitinol Wires](image)
6. Shape Memory Alloys

• Experimental Studies
  – Aiken et al. (1992):
    • With no preload, wires lose 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.

![Graph showing hysteresis loops for Nitinol wires.](image)

Figure 6.1 Hysteresis Loops for All Nitinol Braces (Aiken et al., 1992).

![Graph showing effect of Nitinol braces on seismic response.](image)

Figure 6.2 Effect of Nitinol Braces on the Seismic Response of Test Frame – Zaratula Ground Motion, Shale: Nitinol Welded Perforated, Dome: Nitinol Welded Perforated, Bar: Perforated (from Aiken et al., 1992, reprinted 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

- Experimental Studies
  - 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 300°C and ¾ 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 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
7. The Energy Dissipating Restraint (EDR)

- Hysteretic Behaviour

![Hysteretic Behaviour Diagram]

Figure 7.4a: Hysteretic Loops for Various Configurations of EDR from Nino 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):
    - Same three storey steel frame as for SMA damper tests

![Experimental Studies Photo]

Figure 7.4b: 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):
    - EDR with various configurations

![Experimental Studies Diagrams]
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](image_url)

- Shake Table Tests
  - Single-story 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 a peripheral pinned gravity frame
  - Test frame carry only the lateral inertia forces
  - Lateral load resistance provided by MRF and bracing member

![Shake Table Tests](image_url)
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

![Figure 7.23 Hybrid Connection of Five-Story PRESSS Building: (a) Photo at 4% Drift Ratio and (b) Force-Displacement Response (courtesy of S. Panzarino)]

**Figure 7.23 Hybrid Connection of Five-Story PRESSS Building: (a) Photo at 4% Drift Ratio and (b) Force-Displacement Response (courtesy of S. Panzarino)**

- Hysteretic Characteristics of Post-Tensioned Energy Dissipating (PTED) Connections

  - Self-centering conditions: $M_a = (k_3 - k_1)P_0$
  - $k_3$: Post-yield axial stiffness of ED elements
  - $k_1$: Elastic axial stiffness of ED elements
  - $\theta_a$: Gap opening angle at first yield of ED elements

![Figure 7.24 Self-centering Connections: (a) Generalized Post-Tensioned Connection and (b) Details of Diaphragm and End Connection]

**Figure 7.24 Self-centering Connections: (a) Generalized Post-Tensioned Connection and (b) Details of Diaphragm and End Connection**
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

9. Post-tensioned Frame and Wall Systems
• Cyclic Modelling of PTED Connections with Equivalent Nonlinear Rotational Springs
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 carrying
- Pre-stressed triaxial elements
9. Post-tensioned Frame and Wall Systems

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

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)

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)

9. Post-tensioned Frame and Wall Systems

• Self-Centering Systems for Bridges

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 $0.90$.

![Figure 5.70 General Design Approach for Self-Centering Systems](image-url)

Questions/Discussions