Self-Centering
Earthquake Resisting Systems

Andre Filiatrault, Ph.D., Eng.

CONTENT

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

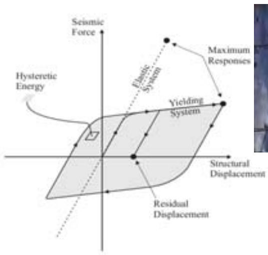


Figure 7.1 Idealized Seismic Response of Yielding Structure (from Christopoulos 2002)

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

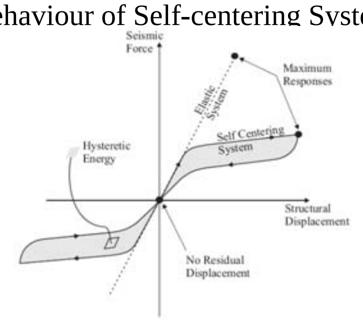
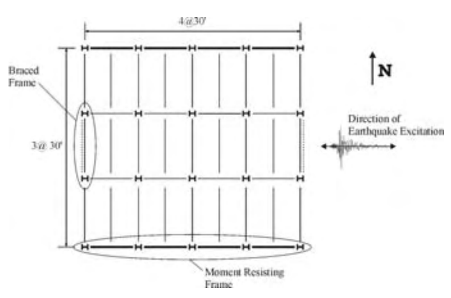


Figure 7.2 Idealized Seismic Response of Self-Centering Structure (from Christopoulos 2002)

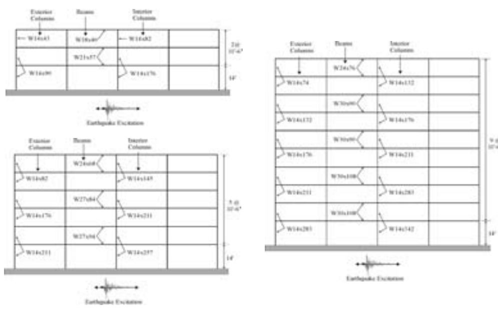
3. Dynamic Response of MDOF Self-centering Systems

- 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

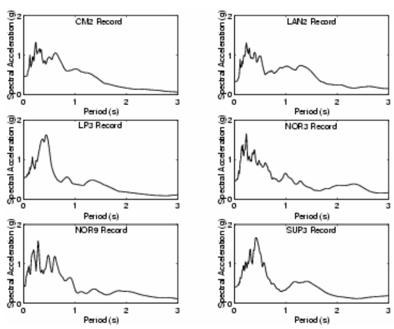
3. Dynamic Response of MDOF Self-centering Systems



3. Dynamic Response of MDOF Self-centering Systems

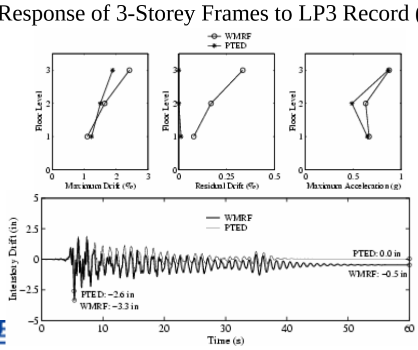


3. Dynamic Response of MDOF Self-centering Systems



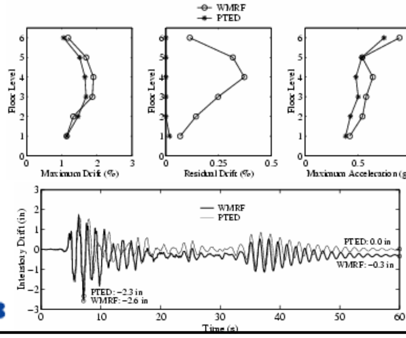
3. Dynamic Response of MDOF Self-centering Systems

- 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)



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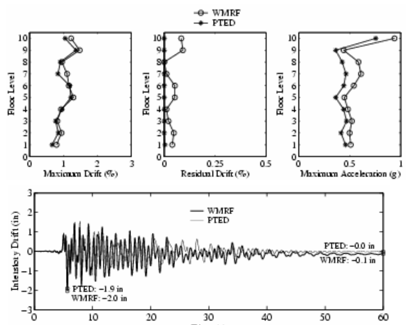
3. Dynamic Response of MDOF Self-centering Systems

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



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3. Dynamic Response of MDOF Self-centering Systems

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

Response Index		CM2	LAN2	LP3	NOR3	NOR9	SUP3	MEAN
Maximum Drift	MRF	1.62	2.32	1.91	1.24	1.50	2.01	1.77
(%)	PTED	1.52	1.77	1.70	1.29	1.45	1.83	1.59
Residual Drift	MRF	0.07	0.18	0.37	0.05	0.18	0.52	0.23
(%)	PTED	0.00	0.13	0.02	0.00	0.02	0.05	0.04
Maximum	MRF	0.85	0.86	0.89	0.79	0.77	0.97	0.86
Acceleration (g)	PTED	0.79	0.80	0.75	0.65	0.60	0.79	0.73
Input Energy	MRF	14990	27670	11110	9134	8456	12460	13970
(kips.in)	PTED	6514	18455	8401	5953	6382	10985	9450
Hysteretic Energy	MRF	7282	17710	5481	2150	2761	7613	7166
(kips.in)	PTED	645	2904	1049	263	384	1847	1182

- 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)

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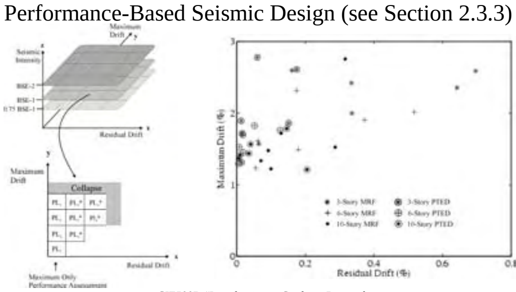
3. Dynamic Response of MDOF Self-centering Systems

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



4. Ancient Applications of Self-centering Systems

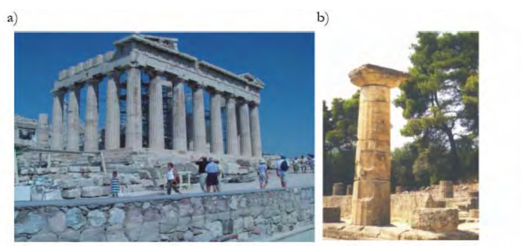
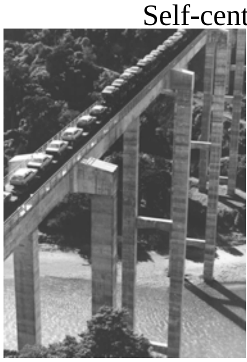
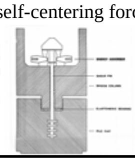


Figure 7.27 Ancient Greek Temple: a) General View and b) Segmental Column

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

6. Shape Memory Alloys

- Superelasticity

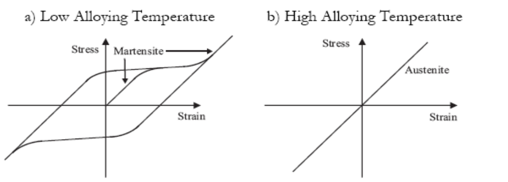


Figure 7.29 SMAs Hysteretic Behaviour: a) for Low Alloying Temperatures and b) for High Alloying Temperatures

6. Shape Memory Alloys

- Superelasticity

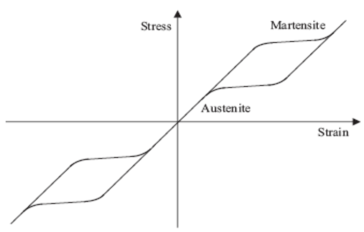
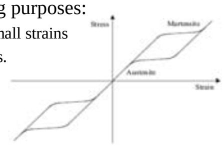


Figure 7.30 SMAs Superelastic Behaviour for Intermediate Alloying Temperatures

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



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

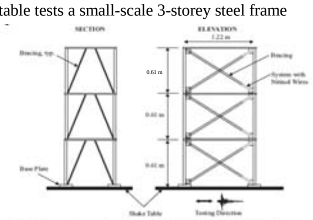
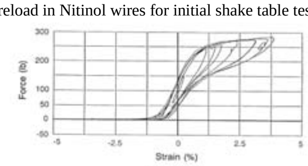


Figure 7.31 Three-Storey Test Frame Used for Shake Table Studies of Nitinol SMA (after Aiken et al. 1992)

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



1 lb = 4.45 N

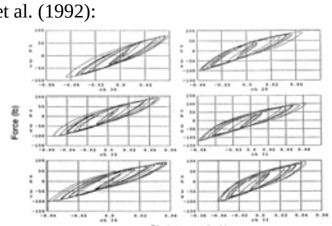
Figure 7.32 Hysteretic Behaviour of Nitinol Wires Recorded During Shake Table Tests (from Aiken et al. 1992, reproduced with the permission of the New Zealand Society for Earthquake Engineering)

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

6. Shape Memory Alloys

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

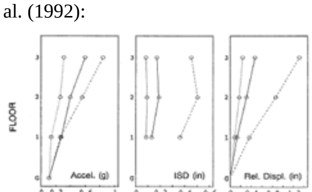


1 inch = 25.4 mm   1 lb = 4.45 N

Figure 7.33 Hysteresis Loops for All Nitinol Braces (from Aiken et al. 1992, reproduced with the permission of the New Zealand Society for Earthquake Engineering)

6. Shape Memory Alloys

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

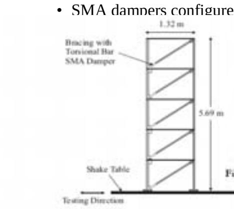


1 inch = 25.4 mm

Figure 7.34 Effect of Nitinol Braces on the Seismic Response of Test Frame – Zacatula Ground Motion, Solid: Nitinol Without Preload, Dotted: Nitinol With Preload, Dot-Dash: Bare 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



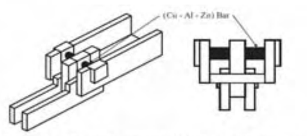


Figure 7.36 Torsional Bar Configuration for SMA Damper (after Witting and Cozzarelli 1992)

Figure 7.35 Five-Storey Test Structure (after Chang et al. 1993)

6. Shape Memory Alloys

- Experimental Studies
  - Witting and Cozzarelli (1992):

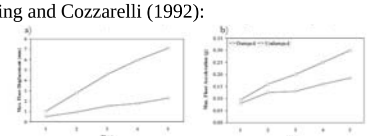


Figure 7.37 Response of Structures for 0.06g El Centro Record: a) Maximum Displacements and b) Maximum Accelerations (after Witting and Cozzarelli 1992)

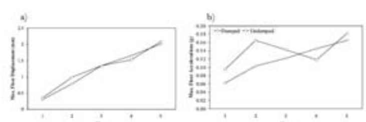
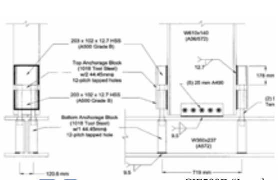
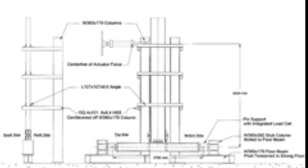


Figure 7.38 Response of Structures for 0.06g Quebec Record: a) Maximum Displacements and b) Maximum Accelerations (after Witting and Cozzarelli 1992

6. Shape Memory Alloys

- 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):

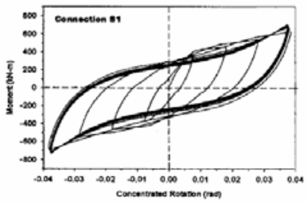
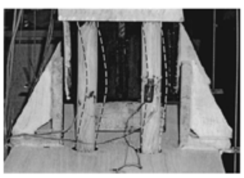


Figure 7.39 Hysteretic Response of a Steel Beam-Column Connection Incorporating Nitinol Bars (from Ocel et al. 2004, reproduced with the permission of the American Society of Civil Engineers)

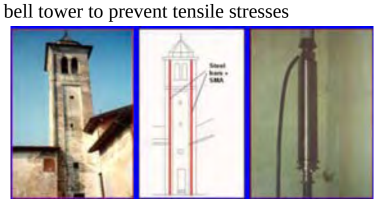
6. Shape Memory Alloys

- 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

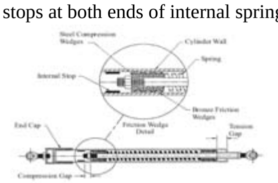
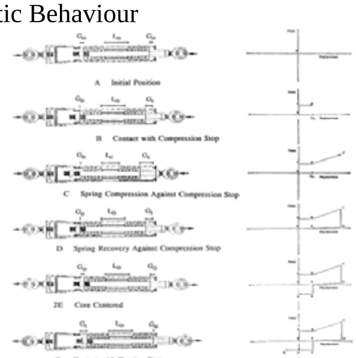


Figure 7.40 Energy Dissipating Restraint (from Nims et al. 1993, reproduced with the permission of the Earthquake Engineering Research Institute)

7. The Energy Dissipating Restraint (EDR)

- Hysteretic Behaviour



7. The Energy Dissipating Restraint (EDR)

- Hysteretic Behaviour

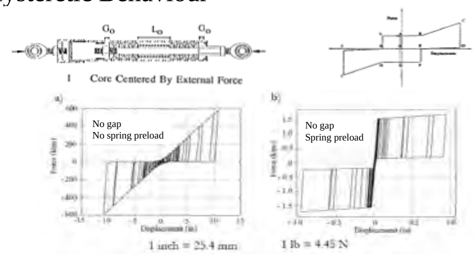


Figure 7.41 Hysteresis Loops for Various Configurations of EDR (from Nims et al. 1993reproduced with the permission of the Earthquake Engineering Research Institute)

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7. The Energy Dissipating Restraint (EDR)

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

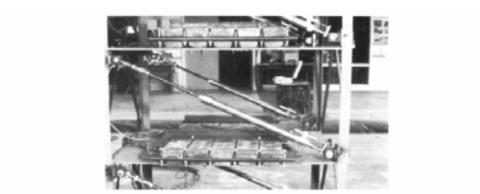

Figure 7.42 Test Frame with EDR (from Aiken et al. 1993, reproduced with the permission of the Earthquake Engineering Research Institute)

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7. The Energy Dissipating Restraint (EDR)

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

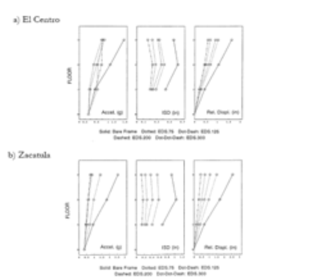

Figure 7.43 Effects of EDRs on the Seismic Response of Test Frame (from Aiken et al. 1993, reproduced with the permission of the Earthquake Engineering Research Institute)

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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

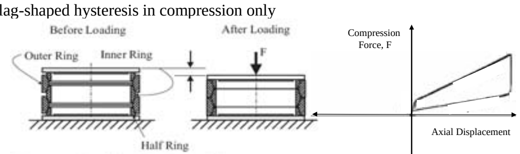


Figure 7.44 Ring Spring Details (after Filiatrault et al. 2000)

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

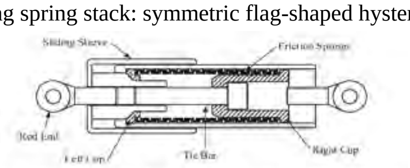


Figure 7.45 200-kN SHAPIA Damper Prototype (after Filiatrault et al. 2000)

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Filiatrault et al (2000)
  - 200-kN capacity prototype damper
  - Characterization Tests

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Characterization Tests

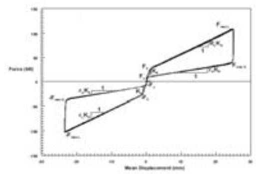


Figure 7.46 Force-Displacement Hysteresis Loops of the SHAPIA Seismic Damper, Sinusoidal Displacement, ±25 mm, 0.5 Hz (after Filiatrault et al. 2000)

Table 7-10: Maximum Values of Response Indices for 10-Storey Frames

Parameter	Numerical values
Elastic stiffness, K_0	23.2 kN/mm
Loading slip stiffness, $r_L K_0$	3.48 kN/mm
Unloading slip stiffness, $r_u K_0$	1.39 kN/mm
Slip force, F_s	28 kN
Residual re-centering force, F_r	9 kN

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Characterization Tests

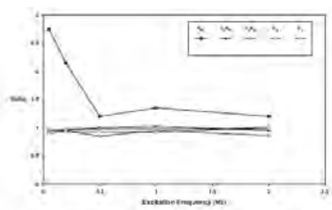


Figure 7.47 Frequency Dependency of SHAPIA Damper Properties (after Filiatrault et al. 2000)

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

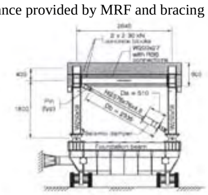


Figure 7.48 Test Structure Incorporating SHAPIA Seismic Damper (Filiatrault et al. 2000, reproduced with the permission of the American Society of Civil Engineers)

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Shake Table Tests

8. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Shake Table Tests

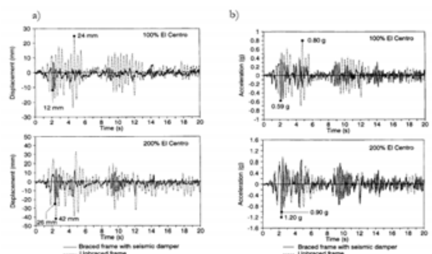


Figure 7.49 Time-History Responses of Frame with Shapia Device: a) Relative Displacement and b) Absolute Acceleration (from Filiatrault et al. 2000, reproduced with the permission of the American Society of Civil Engineers)

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

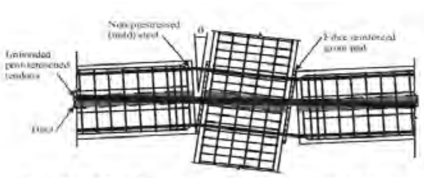


Figure 7.50 Hybrid Frame System (after Stanton and Nakaki 2002)

9. Post-tensioned Frame and Wall Systems

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

9. Post-tensioned Frame and Wall Systems

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

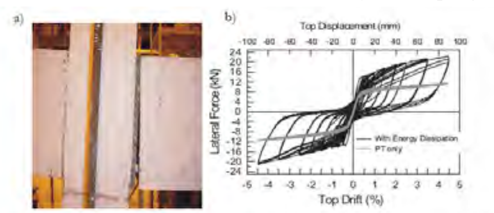


Figure 7.53 Hybrid Connection of Five-Storey PRESSS Building: a) Photo at 4% Drift Ratio and b) Force-Deflection Response (courtesy of S. Pampanin)

9. Post-tensioned Frame and Wall Systems

- Hysteretic Characteristics of Post-Tensioned Energy Dissipating (PTED) Connections
  - Self-centering conditions: $M_A \geq (k_2 - k_3)\theta_B$

k_2 = Elastic axial stiffness of ED elements
k_3 = Post-yield axial stiffness of ED elements
θ_B = Gap opening angle at first yield of ED elements
(textbook p. 256-262)

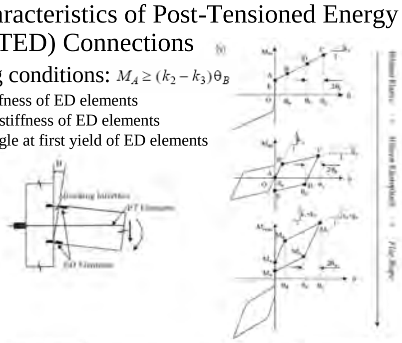
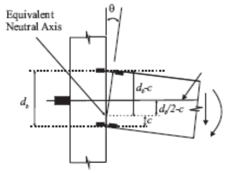


Figure 7.54 Post-Tensioned Connection: a) Generic Post-Tensioned Connection and b) Hysteresis of Post-Tensioned Connection

9. Post-tensioned Frame and Wall Systems

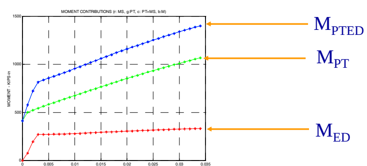
- Sectional Analysis of PTED Connections



PT BARS	ED BARS	COMPRESSION ZONE
$\varepsilon_{PT} = \varepsilon_{in} + \left[\frac{(d_b/2-c)\theta}{L_{PT}}\right]\left(1-\frac{A_{PT}}{A_b}\right)$	$\varepsilon_{ED} = \frac{[\theta(d_b - t_f - c)]}{L_{ED}}$	$\varepsilon_{\max} = c\left(\frac{\theta}{d_b} + \alpha\phi_y\right)$

9. Post-tensioned Frame and Wall Systems

- Sectional Analysis of PTED Connections
  - Construct complete moment-rotation relationship of connection by increasing θ 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

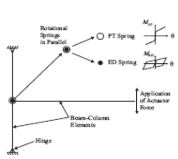


Figure 7.58 Rotational Spring Model for PTED Connections

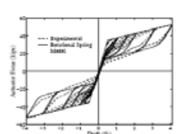
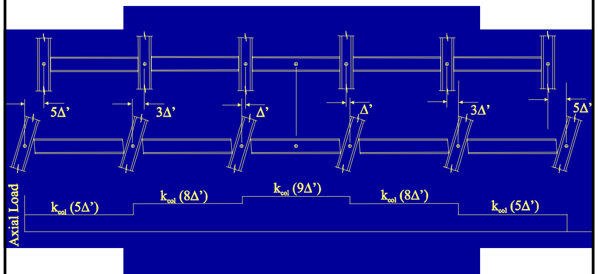


Figure 7.59 Experimental Results and Numerical Cyclic Prediction of Actuator Force versus Interstorey Drift for PTED Exterior Connection (from Christopoulos 2002a)

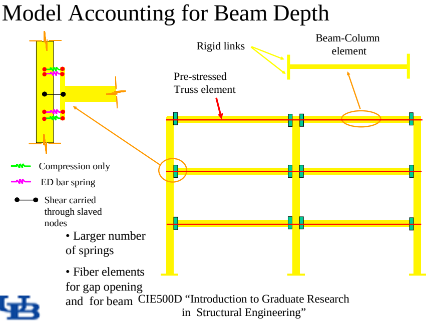
9. Post-tensioned Frame and Wall Systems

- Extension of PTED Model to Constrained Beams



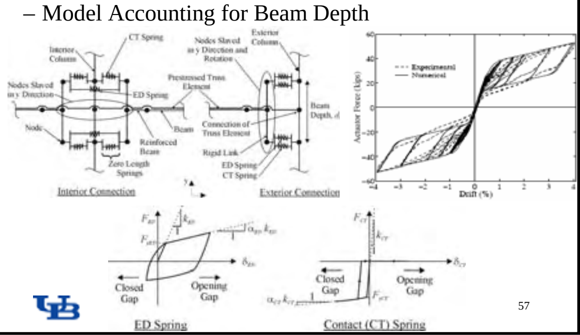
9. Post-tensioned Frame and Wall Systems

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



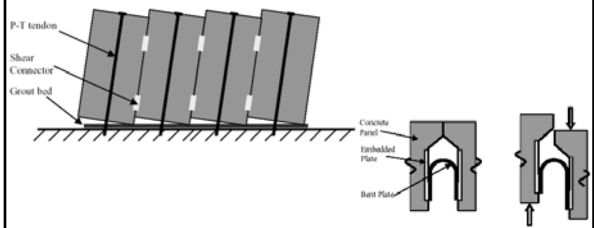
9. Post-tensioned Frame and Wall Systems

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



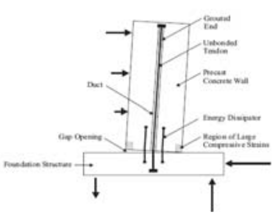
9. Post-tensioned Frame and Wall Systems

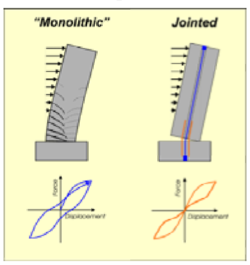
- Concrete Walls
  - Post-Tensioned Rocking Wall System (Stanton et al. 1993)



9. Post-tensioned Frame and Wall Systems

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





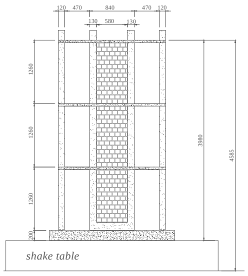
9. Post-tensioned Frame and Wall Systems

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

Extent of damage at 6% drift

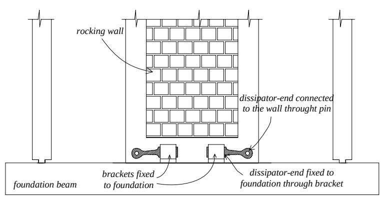
9. Post-tensioned Frame and Wall Systems

- Self-centering Systems for Confined Masonry Walls



9. Post-tensioned Frame and Wall Systems

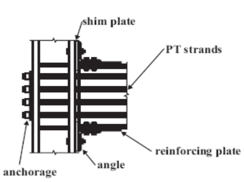
- Self-centering Systems for Confined Masonry Walls



Toranzo1 Toranzo2

9. Post-tensioned Frame and Wall Systems

- Self-Centering Systems for Steel Structures
  - Hybrid Post-Tensioned Connection (Ricles et al. 2001)



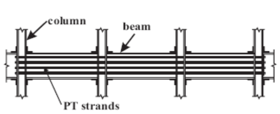


Figure 7.65 Hybrid Post-Tensioned Connection for Steel Frames (after Ricles et al. 2001)

9. Post-tensioned Frame and Wall Systems

- Self-Centering Systems for Steel Structures
  - PTED Connection (Christopoulos et al. 2002a, 2002b)

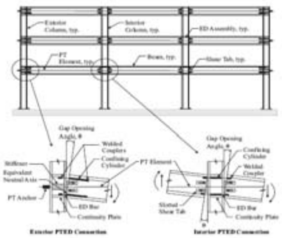
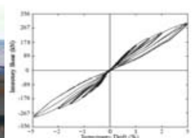
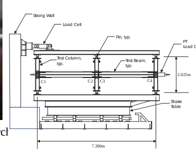


Figure 7.66 PTED Connection for Steel Frames (from Christopoulos et al. 2002)

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

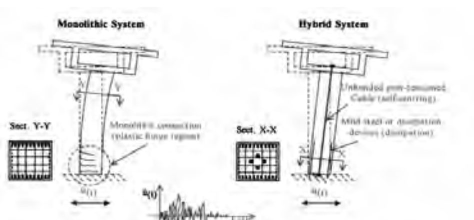


Figure 7.69 Concept of Hybrid System Applied to Bridge Piers (after Palermo et al. 2005)

10. Considerations for the Seismic Design of Self-centering Systems

- If adequate amount of energy dissipation capacity provided to self-centering systems (β = 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 β = 0.75 to 0.90

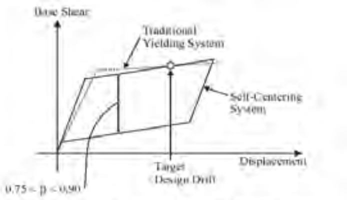


Figure 7.70 General Design Approach for Self-Centering Systems

Questions/Discussions