Chapter 12
Self-Centering 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

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; and
    - 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) (see Chapter 2).
- 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)
CIE 626 Structural Control
Chapter 12 – Self-Centering Systems
3. Dynamic Characteristics of Self-centering Systems

- Priestley and Tao (1993):
  - Compared seismic response of SDOF systems with bilinear elastic hysteresis and bilinear elastoplastic systems.
  - Despite total lack of hysteretic energy absorption in bilinear elastic model, displacement for medium/long period structures, response < 35% larger than elastoplastic of same period.
3. Dynamic Characteristics of Self-centering Systems

• Brewer (1993):
  – Investigated response of 5 and 15-storey frames.
  – Three connection hysteretic models: bilinear elastic, bilinear degrading and bilinear elastoplastic.
  – 15-storey building: similar maximum roof drifts regardless of connection hysteretic model.
  – 5-storey building: larger roof drifts bilinear elastic system.
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Definition of Hysteretic Models:
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Derivation of Closed-Form Frequency Response Solution:

![Diagram of a base excited nonlinear SDOF oscillator](image)

*Figure 7.4 Base Excited Nonlinear SDOF Oscillator*
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Derivation of Closed-Form Frequency Response Solution:
    - General solution obtained in Section 5.4.1

\[
\sigma^2 = \begin{cases} 
1 \pm \frac{A_{exc}}{\bar{A}} & \text{for } \bar{A} < 1 \\
\bar{C}(A) \pm \sqrt{\left(\frac{A_{exc}}{\bar{A}}\right)^2 - \bar{S}^2(A)} & \text{for } \bar{A} > 1 
\end{cases}
\]

where \( A_{exc} \) is the normalized excitation amplitude:

\[
A_{exc} = \frac{m a_g}{F_y} \quad \bar{A} = \frac{A}{x_y}
\]
3. Dynamic Characteristics of Self-centering Systems

\[
\bar{C}(A) = \frac{C(A)}{A} \quad \text{(7.4)}
\]

\[
\bar{S}(A) = \frac{S(A)}{A}
\]

where \( A \) is the steady-state amplitude of the response, and where \( S(A) \) and \( C(A) \) are defined by:

\[
S(A) = \frac{1}{\pi} \int_{0}^{2\pi} f(A \cos \theta, \alpha, \beta) \sin \theta d\theta \quad \text{(7.5)}
\]

\[
C(A) = \frac{1}{\pi} \int_{0}^{2\pi} f(A \cos \theta, \alpha, \beta) \cos \theta d\theta \quad \text{(7.6)}
\]

and where:

\[
\bar{A} = \frac{A}{x_y} \quad \text{(7.7)}
\]
It can be shown that:

\[ \bar{C}(A) = \Omega_1 + \Omega_2 + \Omega_3 + \Omega_4 \]  

(7.12)

where \( \Omega_1 \) through \( \Omega_4 \) are given by:

\[ \Omega_1 = \left( \frac{1}{A} - 1 \right)(1 - \alpha) \sin \theta_1 + \frac{\theta_1}{2} + \frac{\sin(2 \theta_1)}{4} \]

\[ \Omega_2 = \frac{1}{A}(1 - \alpha - \beta + \alpha \beta)(\sin \theta_2 - \sin \theta_1) + \alpha \left( \frac{(\theta_2 - \theta_1)}{2} + \frac{\sin(2 \theta_2) - \sin(2 \theta_1)}{4} \right) \]

(7.13)

\[ \Omega_3 = \frac{\theta_3 - \theta_2}{2} + \frac{\sin(2 \theta_3) - \sin(2 \theta_2)}{4} \]

\[ \Omega_4 = \frac{1}{A}(1 - \alpha) \sin \theta_3 + \alpha \left( \frac{\pi - \theta_3}{2} - \frac{\sin(2 \theta_3)}{4} \right) \]

and where:

\[ \theta_1 = \cos \left( 1 - \frac{\beta}{A} \right) \]

\[ \theta_2 = \cos \left( 1 - \frac{\beta}{A} \right) \]

(7.14)

\[ \theta_3 = \cos \left( \frac{1}{A} \right) \]

and:

\[ \bar{S}(A) = \frac{\Lambda}{A} \left( 1 - \frac{1}{A} \right) \]

(7.15)

where

\[ \Lambda = \frac{\pi - 2}{\pi} \beta (1 - \alpha) \]

(7.16)
3. Dynamic Characteristics of Self-centering Systems

Resonance occurs in this system when $\sigma^2$ has a double root in the second expression of Equation (7.2), which in turn occurs when:

$$\bar{S}(A) = (A_{exc}/\bar{A})^2 = (x_{st}/A)^2$$

and:

$$|\bar{S}(A)| = |x_{st}/A|$$

From Equation (7.17) it can be deduced that for an excitation amplitude of $x_{st}$ the normalized steady-state amplitude at resonance $\bar{A}^*$ is:

$$\bar{A}^* = \frac{|\Lambda|}{|\Lambda| - A_{exc}}$$

Since in this derivation $A$ has been implicitly defined as positive, unbounded resonance occurs for $A_{exc} \geq |\Lambda|$, which results in the following condition on the system yield force $F_y$ in order to avoid unbounded response at resonance:

$$F_y > \frac{\pi m a_g}{2 \beta (1 - \alpha)}$$

where, as defined earlier, $a_g$ is the amplitude of the base acceleration.

It can be seen in Equation (7.20) that increasing $\alpha$ or reducing $\beta$ requires a higher system strength to assure a bounded response at resonance.
3. Dynamic Characteristics of Self-centering Systems

Figure 7.5 Comparison between Theoretical Flag-shaped Frequency Response Curve and Numerical Integration for $A_{exc} = 0.25$, $\alpha = 0.05$ and $\beta = 0.5$
3. Dynamic Characteristics of Self-centering Systems

\[ A_{exc} = \frac{ma_g}{F_y} \]

Figure 7.6 Effect of Increasing Amplitude of Excitation on Flag-shaped Frequency Response Curve for \( \alpha = 0.10 \) and \( \beta = 0.8 \)
3. Dynamic Characteristics of Self-centering Systems

Figure 7.7 Effect of Post-Yielding Stiffness Coefficient $\alpha$ on Flag-shaped Frequency Response Curve for $A_{exc} = 0.25$ and $\beta = 0.6$
3. Dynamic Characteristics of Self-centering Systems

Figure 7.8 Effect of Energy Dissipation Coefficient $\beta$ on Flag-shaped Frequency Response Curve for $A_{exc} = 0.20$ and $\alpha = 0.05$
3. Dynamic Characteristics of Self-centering Systems

Figure 7.9 Comparison Between Elastoplastic and Flag-Shaped Hysteresis Frequency Response Curves
3. Dynamic Characteristics of Self-centering Systems

• Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  – Stability Analysis of Frequency Response:
    • Study of small amplitude and phase perturbations at location of vertical tangency of frequency response curve.
    • See textbook (p. 205) for derivation.
    • Solution: intermediate solution branch always unstable.
3. Dynamic Characteristics of Self-centering Systems

• Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  – Stability Analysis of Frequency Response:

![Diagram](image)

Figure 7.10 Stability of Frequency Response Branches for $\alpha = 0.10$ and $\beta = 0.8$
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Jump Phenomenon:

![Diagram showing the jump phenomenon in frequency response curves](image)

Figure 7.13 Jump Phenomenon in Flag-shaped Frequency Response Curves
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Numerical Verification of Jump Phenomenon:

![Graph showing frequency response](image)

*Figure 7.14 Comparison of Results of Time Integration for Increasing and Decreasing Harmonic Sweeps with Flag-shaped Frequency Response Curve, $\alpha = 0.10$, $\beta = 0.8$, $A_{exc} = 0.50$*
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Theoretical versus “Likely” Frequency Response:
    - Two stable branches attained only by slowly sweeping excitation frequency.
    - Stable branch of higher amplitude can only be achieved if slowly decrease of excitation frequency.
    - Perturbations in excitation signal cause jump to lower stable branch.
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Theoretical versus “Likely” Frequency Response:

![Graphs showing dynamic response](image)

Figure 7.15 Jump Phenomenon for Large Decrease of Excitation Frequency: a) Time-trace of amplitude and b) State-Space Representation
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Theoretical versus “Likely” Frequency Response:
    - Unlikely that seismic excitation will be stationary, with slowly decreasing frequency harmonic loading.
    - Likely frequency response curve of a flag-shape system defined by lowest stable amplitude branch for all excitation frequencies.
3. Dynamic Characteristics of Self-centering Systems

- Frequency Response of Analogous SDOF Flag-Shaped Hysteretic Systems
  - Theoretical versus “Likely” Frequency Response:

![Graph showing theoretical and likely frequency response of self-centering systems.]

*Figure 7.16 Theoretical Frequency Response Curves of Flag-Shaped and Elastoplastic Systems and Likely Response of Flag-Shaped System*
4. Seismic Response of Self-centering SDOF Systems

Seismic Response of Self-Centering SDOF Systems

- Normalized Equations of Motion:

\[
mx'' + cx' + F(x) = -mx_g
\]

where \( m \) is the mass of the system, \( c \) is the viscous damping coefficient, and \( F(x) \) is the nonlinear restoring force defined by the hysteretic model of the system. The displacement, velocity, and acceleration of the system relative to the ground are denoted by \( x, \dot{x}, \) and \( \ddot{x} \), respectively. The ground acceleration is designated by \( \dddot{x}_g \).

For small inherent damping, two key parameters can be used to define the dynamic response of a nonlinear SDOF system: the initial period \( T_0 \) and the strength ratio \( \eta \):

\[
T_0 = 2\pi \sqrt{\frac{m}{k_0}}
\]

\[
\eta = \frac{F_y}{mg}
\]

where \( k_0 \) is the initial stiffness of the system, \( F_y \) is the yield force, and \( g \) is the acceleration of gravity.
• **Seismic Response of Self-Centering SDOF Systems**

  – **Normalized Equations of Motion:**

    Using Equation (7.41), Equation (7.42) can be rewritten as:

    \[
    \ddot{x} + 2\xi_0 \left(\frac{2\pi}{T_0}\right) \dot{x} + \left(\frac{2\pi}{T_0}\right)^2 \tilde{f}(x) = -\ddot{x}_g
    \]  

    with \(\xi_0\) denoting the initial fraction of critical damping of the system,

    \[
    \xi_0 = \frac{c}{2\sqrt{k_0m}}
    \]  

    and \(\tilde{f}(x)\) representing the nonlinear pseudo-restoring force (normalized by the stiffness) of the system (see Figure 7.3):

    \[
    \tilde{f}(x) = \frac{F(x)}{k_0}
    \]  

    The yield displacement \(x_y\) of the system is given by:

    \[
    x_y = \frac{F_y}{k_0} = \tilde{f}_y
    \]  

    as shown in Figure 7.3.
4. Seismic Response of Self-centering SDOF Systems

- Normalized Equations of Motion:

With this formulation, for a given critical damping ratio $\xi_0$, initial period $T_0$ and strength level $\eta$, the SDOF system is completely defined for the case when the restoring force-displacement relationship is bilinear elastoplastic (Figure 7.3a) and requires only the additional parameters $\alpha$ and $\beta$ to be assigned, if the restoring force-displacement relationship exhibits a flag-shaped hysteresis (Figure 7.3b).
• Seismic Response of Self-Centering SDOF Systems
  – System Response Indices:
    • The maximum displacement ductility $\mu_A$:
      \[
      \mu_A = \frac{\max|x(t)|}{x_y}, \quad 0 \leq t \leq t_D
      \]  (7.50)
      where $t_D$ is the total duration of the seismic input.
      In performance-based earthquake engineering, the maximum inelastic displacement, which is an indirect measure of the maximum strains developed at critical sections in the structure, is an important response index to determine damage to structures under seismic loading.
    • The normalized maximum absolute acceleration:
      \[
      a_{max} = \frac{\max|\ddot{x}(t) + \ddot{x}_g(t)|}{g}, \quad 0 \leq t \leq t_D
      \]  (7.51)
      This index is a measure of the damage potential to acceleration-sensitive nonstructural components, as well as an indicator of potential injury to occupants during an earthquake event. In addition, this response index is a direct indicator of the force level induced into the system by the seismic input.
4. Seismic Response of Self-centering SDOF Systems

- Seismic Response of Self-Centering SDOF Systems
  - System Response Indices:

    - The normalized maximum absorbed energy:
      \[
      E_{abs} = \frac{\max |E_a(t)|}{x_y m g}, \quad 0 \leq t \leq t_D
      \]  
      (7.52)
      This index is a measure of potential structural damage including duration effects.

    - The normalized residual displacement:
      \[
      x_{res} = \frac{|x(t_D)|}{x_y}
      \]  
      (7.53)
      This index is an indicator of the structural damage sustained after an earthquake and of the extent of repair costs. Residual displacements are only computed for the bilinear elastoplastic hysteretic model (see Figure 7.3a). The flag-shaped hysteretic model (see Figure 7.3b), by virtue of its self-centering characteristics, does not sustain any residual displacements.
• Seismic Response of Self-Centering SDOF Systems
  – Ground Motions Considered in Parametric Study:

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Magnitude</th>
<th>Station</th>
<th>Epicentral Distance (km)</th>
<th>Soil Type</th>
<th>Duration (s)</th>
<th>Scaling Amplitude</th>
<th>Scaled PGA (g)</th>
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<td>2.2</td>
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<td>Glendale - Las Palmas</td>
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<td>L.A. - Hollywood Stor. F.F.</td>
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<td>D</td>
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<td>Capitola</td>
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4. Seismic Response of Self-centering SDOF Systems

- Seismic Response of Self-Centering SDOF Systems
  - Ground Motions Considered in Parametric Study:

![Graph showing elastic acceleration response spectra of twenty scaled records.

Figure 7.17 Elastic Acceleration Response Spectra of Twenty Scaled Records]
• Seismic Response of Self-Centering SDOF Systems
  – Range of Key System and Hysteretic Parameters:

<table>
<thead>
<tr>
<th>$T_0$ (s)</th>
<th>$\eta$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
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Table 7-2: SDOF System Values Used in Study
• Seismic Response of Self-Centering SDOF Systems
  – Mean Response of Flag-Shaped SDOF Hysteretic Systems:

  • Mean displacement ductility generally increases for decreasing values of initial period and decreasing values of strength ratio, $\eta$.
  • Mean displacement ductility is reduced in all cases for increasing values of $\alpha$ and $\beta$.
  • Reduction more significant for low period structures ($T < 1.0 \text{ s}$) and for structures with lower strength ratio, $\eta$.

Figure 7.18 Mean Displacement Ductility for Flag-Shaped Hysteretic Systems
• Seismic Response of Self-Centering SDOF Systems
  – Mean Response of Flag-Shaped SDOF Hysteretic Systems:

• When $\alpha$ is increased, accelerations of systems with lower values of $\eta$ are increased.
• Seismic Response of Self-Centering SDOF Systems
  – Mean Response of Bilinear Elastoplastic Hysteretic Systems:

  • Mean displacement ductility increases for decreasing values of initial period and decreasing values of the strength ratio, \( \eta \).

Figure 7.22 Response of Elastoplastic Systems: a) Mean Displacement Ductility, b) Mean Maximum Accelerations, c) Mean Normalized Absorbed Energy, and d) Normalized Residual Displacements
4. Seismic Response of Self-centering SDOF Systems

- Seismic Response of Self-Centering SDOF Systems
- Comparative Response of Flag-Shaped and Elastoplastic Hysteretic Systems:

![Graph showing ratios of mean displacement ductility of flag shaped systems to mean displacement ductility of elastoplastic systems.](image-url)

Figure 7.23 Ratios of Mean Displacement Ductility of Flag Shaped Systems to Mean Displacement Ductility of Elastoplastic Systems
4. Seismic Response of Self-centering SDOF Systems

- Seismic Response of Self-Centering SDOF Systems
  - Comparative Response of Flag-Shaped and Elastoplastic Hysteretic Systems:
    - For each EP system, at least one FS system of similar initial period and strength ratio achieves equal or smaller displacement ductility.
    - Intermediate values of \( \alpha \) and \( \beta \) achieve this performance level.
    - Maximum absolute accelerations similar for low values of \( \alpha \).
    - For larger values of \( \alpha \), maximum accelerations are larger for FS systems, especially for systems with lower strength ratios.
    - Energy absorbed significantly larger for EP systems, especially for low values of \( \alpha \).
4. Seismic Response of Self-centering SDOF Systems

- Seismic Response of Self-Centering SDOF Systems
  - Comparative Response of Flag-Shaped and Elastoplastic Hysteretic Systems:

<table>
<thead>
<tr>
<th>System</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\eta$</th>
<th>$\Delta_y$ (mm)</th>
<th>$F_y$ (kN)</th>
<th>$\Delta_{max}$ (mm)</th>
<th>$A_{max}$ (g)</th>
<th>$E_{abs}$ (kN.mm x 10$^6$)</th>
<th>$\Delta_{res}$ (mm)</th>
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<td>3924</td>
<td>124.7</td>
<td>0.13</td>
<td>2.00</td>
<td>22.9</td>
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<td>0.10</td>
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<td>0.20</td>
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<td>0.10</td>
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<td>0.07</td>
<td>17.5</td>
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</table>
5. 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.
5. Dynamic Response of MDOF Self-centering Systems
5. Dynamic Response of MDOF Self-centering Systems
5. Dynamic Response of MDOF Self-centering Systems

- Response of 3-Storey Frames to LP3 Record (0.5 g)
• 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>CM2</th>
<th>LAN2</th>
<th>LP3</th>
<th>NOR3</th>
<th>NOR9</th>
<th>SUP3</th>
<th>MEAN</th>
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<td>Maximum Drift (%)</td>
<td>MRF</td>
<td>1.62</td>
<td>2.32</td>
<td>1.91</td>
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<td>0.02</td>
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<td>0.02</td>
<td>0.05</td>
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<td>0.79</td>
<td>0.77</td>
<td>0.97</td>
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<td>0.75</td>
<td>0.65</td>
<td>0.60</td>
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<td>11110</td>
<td>9134</td>
<td>8456</td>
<td>12460</td>
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<td></td>
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<td>6514</td>
<td>18455</td>
<td>8401</td>
<td>5953</td>
<td>6382</td>
<td>10985</td>
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<td>Hysteretic Energy (kips.in)</td>
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<td>2150</td>
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<td>PTED</td>
<td>645</td>
<td>2904</td>
<td>1049</td>
<td>263</td>
<td>384</td>
<td>1847</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).
• Explicit Consideration of Residual Deformations in Performance-Based Seismic Design (see Section 2.3.3)
6. Ancient Applications of Self-centering Systems

Figure 7.27 Ancient Greek Temple: a) General View and b) Segmental Column
7. 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).
8. 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.
8. Shape Memory Alloys

• Superelasticity

Figure 7.29 SMAs Hysteretic Behaviour: a) for Low Alloying Temperatures and b) for High Alloying Temperatures
8. Shape Memory Alloys

• Superelasticity

Figure 7.30 SMAs Superelastic Behaviour for Intermediate Alloying Temperatures
8. 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; and
    - Cost ≈ US $20-60 / kg.
8. 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.
8. 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.

![Graph showing hysteretic behavior of Nitinol wires.](image)

**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)

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Chapter 12 – Self-Centering Systems
8. 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.
8. Shape Memory Alloys

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

![Hysteresis Loops for All Nitinol Braces](image)

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)
8. Shape Memory Alloys

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

![Graph showing the effect of Nitinol Braces on the Seismic Response of Test Frame.](image)

*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)*
8. 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.
8. Shape Memory Alloys

- Experimental Studies

  - Witting and Cozzarelli (1992):

![Graphs showing maximum displacements and accelerations](image)

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

![Graphs showing maximum displacements and accelerations](image)

**Figure 7.38** Response of Structures for 0.06g Quebec Record: a) Maximum Displacements and b) Maximum Accelerations (after Witting and Cozzarelli 1992)
8. 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.
8. 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)
8. 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.
8. Shape Memory Alloys

- Experimental Studies
  - Youssef et al. (2008):
    - Concrete beam-column joints reinforced with Nitinol rebars.
    - Flag-shaped force-displacement with small residual displacements.
    - Plastic hinging developed away from the column face.
8. Shape Memory Alloys

- Experimental Studies
  - Attanasi and Auricchio (2011):
  - Superelastic Seismic Isolation System
    - Flat slider device & SMA coil springs restraining devices.

![Figure 15](image_url)

**FIGURE 15** Superelastic isolator device: 3D view.
8. Shape Memory Alloys

• Structural Implementations
  – Seismic retrofit of historical Bell-Tower of the S. Giorgio in Trignano Church in S. Martino in Rio, Italy:
    • Damaged after 10/15/1996 Modena and Reggio earthquake.
    • Nitinol wires introduced and prestressed through masonry walls of bell tower to prevent tensile stresses.
8. 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.
9. 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.
9. The Energy Dissipating Restraint (EDR)

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

• Hysteretic Behaviour
9. The Energy Dissipating Restraint (EDR)

- Hysteretic Behaviour

![Diagram of EDR system]

- No gap
- No spring preload

![Graphs of EDR system behavior]

- a) No gap
- b) Spring preload

1 inch = 25.4 mm
1 lb = 4.45 N
9. The Energy Dissipating Restraint (EDR)

• Experimental Studies
  – Aiken et al. (1993):
    • Same three storey steel frame as for SMA damper tests.
9. The Energy Dissipating Restraint (EDR)

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

![Diagram showing effects of EDRs on seismic response of test frame.]

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)
10. 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.
10. Self-centering Dampers Using Ring Springs

- **SHAPIA Damper**
  - Originally 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.
10. Self-centering Dampers Using Ring Springs

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

- Experimental Studies with SHAPIA Damper
  - Characterization Tests:

![Graph of force-displacement hysteresis loops for SHAPIA seismic damper, sinusoidal displacement, ±25 mm, 0.5 Hz (after Filiatrault et al. 2000)](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Numerical values</th>
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<tr>
<td>Elastic stiffness, $K_0$</td>
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<tr>
<td>Loading slip stiffness, $r_L K_0$</td>
<td>3.48 kN/mm</td>
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<td>Unloading slip stiffness, $r_U K_0$</td>
<td>1.39 kN/mm</td>
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<td>Slip force, $F_s$</td>
<td>28 kN</td>
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<tr>
<td>Residual re-centering force, $F_c$</td>
<td>9 kN</td>
</tr>
</tbody>
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Figure 7.46 Force-Displacement Hysteresis Loops of the SHAPIA Seismic Damper, Sinusoidal Displacement, ±25 mm, 0.5 Hz (after Filiatrault et al. 2000)
10. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Characterization Tests:

![Graph showing frequency dependency of SHAPIA Damper properties](image)

*Figure 7.47 Frequency Dependency of SHAPIA Damper Properties (after Filiatrault et al. 2000)*
• 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.
10. Self-centering Dampers Using Ring Springs

- Experimental Studies with SHAPIA Damper
  - Shake Table Tests:
• 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)
11. 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.
11. Post-tensioned Frame and Wall Systems

• Concrete Frames
  – PRESSS (PREcast Seismic Structural Systems) program:
11. 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)
• 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.
  \( \theta_B \) = 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
11. 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.
11. Post-tensioned Frame and Wall Systems

- Cyclic Modeling of PTED Connections with Equivalent Nonlinear Rotational Springs
11. Post-tensioned Frame and Wall Systems

• Concrete Walls
  – Post-Tensioned Rocking Wall System (Stanton et al. 1993):
11. Post-tensioned Frame and Wall Systems

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

• Concrete Walls
  – Jointed Cantilever Wall System (Restrepo 2002):

  ![Extent of damage at 6% drift](image)
11. Post-tensioned Frame and Wall Systems

• Self-centering Systems for Confined Masonry Walls
11. Post-tensioned Frame and Wall Systems

• Self-centering Systems for Confined Masonry Walls
11. Post-tensioned Frame and Wall Systems

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

![Diagram of hybrid post-tensioned connection]

Figure 7.65 Hybrid Post-Tensioned Connection for Steel Frames (after Ricles et al. 2001)
11. Post-tensioned Frame and Wall Systems

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

![Diagram of PTED Connection for Steel Frames](image)

Figure 7.66 PTED Connection for Steel Frames (from Christopoulos et al. 2002)
11. Post-tensioned Frame and Wall Systems

- Self-Centering Systems for Steel Structures
  - PTED Connection (Christopoulos et al. 2002a, 2002b):
    - System Testing
11. Post-tensioned Frame and Wall Systems

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

• Self-Centering Systems for Steel Structures
  – Self-Centering Energy Dissipating (SCED) 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.

11. Post-tensioned Frame and Wall Systems

- Post-Tensioned Rocking Frames

http://www.popularmechanics.com/technology/engineering/architecture/earthquake-proof-building-that-is-built-to-collapse
11. 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)
11. Post-tensioned Frame and Wall Systems

- Hybrid Self-Centering Systems for Bridges

![Diagram of Hybrid Self-Centering Systems](image)

HYBRID SLIDING-ROCKING POST-TENSIONED SEGMENTAL BRIDGES: LARGE-SCALE QUASI-STATIC AND SHAKE TABLE TESTING

P. Sideris, A. J. Aref & A. Filiatrault
University at Buffalo – The State University of New York, U.S.A.

15 WCEE LUSCA 2012
11. Post-tensioned Frame and Wall Systems

- Hybrid Self-Centering Systems for Bridges
12. 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