Seismic Design of Shape Memory Alloy Reinforced Concrete Bridge Pier

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Outline

• Current seismic design philosophy
• Performance based seismic design (PBSD)
• PBSD for new materials
• PBSD Example on SMA-RC Pier
• Conclusion
Current Seismic Design Philosophy

Collapse Prevention

“Failure”
Current Seismic Design Philosophy

Successive residual strain accumulation causes large permanent deformation

“Failure”
Current Seismic Design Philosophy

“Success -- ?”
Current Seismic Design Philosophy

- May result in bridge closures
  - Excessive column damage
  - Excessive lateral deflection
  - Limited access; may or may not allow even emergency response vehicles

- Extensive Repairs
  - Patching of spalled concrete
  - Shoring of spans
  - Replacement
  - Disrupts traffic
  - Major economic loss
Improved Seismic Design

- Minimize residual drift
- Minimize repair need
- Keep bridges operational
- Reduce damage to plastic hinges
- Keep an energy dissipating system

Performance Based Design…..
Performance Based Seismic Design

Cracking  Yielding  Spalling  Crushing

Hose et al. 2000

Is it enough to protect our investments? If not, what can we do?
Rocking bridge pier
Innovative Materials

Superelastic Shape Memory Alloy (SMA)

Steel

SMA
Innovative Materials

Reinforced Concrete Columns
➢ Reduced residual deformation

Steel RC Column

SMA RC Column
Performance Based Design of SMA-RC Pier

Select Performance Objectives

Develop Preliminary Design

Assess Performance Capability

Does Performance Meet Objectives?

- Yes: Done
- No: Revise Design

Revise Design

Done
Performance-based Damage States

- Fully Operational
- Operational
- Life Safety
- Collapse
Damage State Development

Selection of Shape Memory Alloy → Design of bridge piers with different SMA → Moment-curvature analysis of different SMA-RC section → Selection of suitable ground motions

IDA of different SMA-RC bridge pier

Capture the different performance limits for each EQ at different intensity

Develop the dynamic pushover curves for each EQ and compute the median, 5 percentile and 95 percentile curves

Obtain the drift limit at different performance levels and determine the suitable distribution

Define drift limits at different performance levels for different SMAs


## Properties of Different SMAs

<table>
<thead>
<tr>
<th>Alloy</th>
<th>εs (%)</th>
<th>E (GPa)</th>
<th>fy (MPa)</th>
<th>f_p1 (MPa)</th>
<th>f_T1 (MPa)</th>
<th>f_T2 (MPa)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA-1 NiTi&lt;sub&gt;45&lt;/sub&gt;</td>
<td>6</td>
<td>62.5</td>
<td>401.0</td>
<td>510</td>
<td>370</td>
<td>130</td>
<td>Alam et al. 2008</td>
</tr>
<tr>
<td>SMA-2 NiTi&lt;sub&gt;45&lt;/sub&gt;</td>
<td>8</td>
<td>68</td>
<td>435.0</td>
<td>535.0</td>
<td>335</td>
<td>170</td>
<td>Ghassemieh et al. 2012</td>
</tr>
<tr>
<td>SMA-3 FeNCATB</td>
<td>13.5</td>
<td>46.9</td>
<td>750</td>
<td>1200</td>
<td>300</td>
<td>200</td>
<td>Tanaka et al. 2010</td>
</tr>
<tr>
<td>SMA-4 CuAlMn</td>
<td>9</td>
<td>28</td>
<td>210.0</td>
<td>275.0</td>
<td>200</td>
<td>150</td>
<td>Shrestha et al. 2013</td>
</tr>
<tr>
<td>SMA-5 FeMnAlNi</td>
<td>6.13</td>
<td>98.4</td>
<td>320.00</td>
<td>442.5</td>
<td>210.8</td>
<td>122</td>
<td>Omori et al. 2011</td>
</tr>
</tbody>
</table>

f<sub>y</sub> (austenite to martensite starting stress); f<sub>p1</sub> (austenite to martensite finishing stress); f<sub>T1</sub> (martensite to austenite starting stress); f<sub>T2</sub> (martensite to austenite finishing stress), ε<sub>s</sub> (superelastic plateau strain length); and E (modulus of elasticity).
Design and Geometry of Bridge Piers

- Diameter: $D = 1.83$ m
- Diameter: $D' = 1.71$ m
- Spars: $16$ mm
- Spacing: $s = 76$ mm
- Longitudinal Reinforcement: 48 @ 29 mm
- Height: $L = 9.14$ m
- Spirals: $16$ M spiral @ 76 mm pitch
- Steel Reinforced Section
- SMA Reinforced Section
## Bridge Pier Configuration

<table>
<thead>
<tr>
<th>Pier</th>
<th>Longitudinal Rebar</th>
<th>$\rho_l$ (%)</th>
<th>Spiral</th>
<th>$\rho_s$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA-RC-1</td>
<td>48-28M</td>
<td>1.12</td>
<td>15M @76 mm</td>
<td>0.70</td>
</tr>
<tr>
<td>SMA-RC-2</td>
<td>48-28M</td>
<td>1.12</td>
<td>15M @76 mm</td>
<td>0.70</td>
</tr>
<tr>
<td>SMA-RC-3</td>
<td>48-20M</td>
<td>1.20</td>
<td>15M @76 mm</td>
<td>0.70</td>
</tr>
<tr>
<td>SMA-RC-4</td>
<td>48-35M</td>
<td>1.75</td>
<td>15M @76 mm</td>
<td>0.70</td>
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<tr>
<td>SMA-RC-5</td>
<td>48-32M</td>
<td>1.46</td>
<td>15M @76 mm</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Capacity Curves

![Graph showing Capacity Curves for SMA-1 to SMA-5.](image)

- **Moment (kN-m)**
  - SMA-1
  - SMA-2
  - SMA-3
  - SMA-4
  - SMA-5

- **Curvature (1/m)**
  - SMA-1
  - SMA-2
  - SMA-3
  - SMA-4
  - SMA-5

- **Base Shear (kN)**
  - SMA-1
  - SMA-2
  - SMA-3
  - SMA-4
  - SMA-5

- **Displacement (m)**
  - SMA-1
  - SMA-2
  - SMA-3
  - SMA-4
  - SMA-5
Finite Element Modeling

Concrete Model

Steel Model
Menegotto and Pinto, 1973

Stress
Strain

SeismoStruct
Validation with Experimental Result

Fig. Comparison of experimental and numerical results (a) SMA-RC (SMA-1) bridge pier (Saiidi and Wang 2006). (b) SMA-RC (SMA-4) beam (Shrestha et al. 2013).
Different Hazard Levels

Spectral Acceleration (g) vs. Time (sec) for 2%/50 Year (Target), 5%/50 Year (Target), 10%/50 Year (Target), 2%/50 Year (Mean), 5%/50 Year (Mean), and 10%/50 Year (Mean).
### Proposed Damage State Framework

<table>
<thead>
<tr>
<th>Damage Parameter</th>
<th>Damage State</th>
<th>Functional Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>DS-1</td>
<td>Immediate</td>
<td>Onset of hairline cracks</td>
</tr>
<tr>
<td>Yielding</td>
<td>DS-2</td>
<td>Limited</td>
<td>Theoretical first yield of longitudinal rebar</td>
</tr>
<tr>
<td>Spalling</td>
<td>DS-3</td>
<td>Service disruption</td>
<td>Onset of concrete spalling</td>
</tr>
<tr>
<td>Core Crushing</td>
<td>DS-4</td>
<td>Life safety</td>
<td>Crushing of core concrete</td>
</tr>
</tbody>
</table>
Maximum Drift Damage States

**Figure.** Dynamic pushover response and different damage states with distribution for SMA-RC-1 for (a) 2% in 50 years (b) 5% in 50 years and (c) 10% in 50 years probability of exceedance.
# Damage States of SMA-RC Bridge Pier

<table>
<thead>
<tr>
<th>Damage State</th>
<th>SMA-1</th>
<th>SMA-2</th>
<th>SMA-3</th>
<th>SMA-4</th>
<th>SMA-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
</tr>
<tr>
<td>2%</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>5%</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>10%</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
</tr>
<tr>
<td>2%</td>
<td>1.68</td>
<td>1.76</td>
<td>1.86</td>
<td>1.66</td>
<td>1.72</td>
</tr>
<tr>
<td>5%</td>
<td>1.72</td>
<td>1.80</td>
<td>2.28</td>
<td>2.42</td>
<td>2.58</td>
</tr>
<tr>
<td>10%</td>
<td>2.28</td>
<td>2.42</td>
<td>2.58</td>
<td>1.74</td>
<td>1.83</td>
</tr>
<tr>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
</tr>
<tr>
<td>2%</td>
<td>2.66</td>
<td>2.79</td>
<td>2.88</td>
<td>2.69</td>
<td>2.77</td>
</tr>
<tr>
<td>5%</td>
<td>2.77</td>
<td>2.87</td>
<td>1.64</td>
<td>1.72</td>
<td>1.80</td>
</tr>
<tr>
<td>10%</td>
<td>2.87</td>
<td>1.64</td>
<td>1.72</td>
<td>1.80</td>
<td>2.52</td>
</tr>
<tr>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
<td>Drift (%)</td>
</tr>
<tr>
<td>2%</td>
<td>5.05</td>
<td>5.68</td>
<td>5.94</td>
<td>5.51</td>
<td>5.91</td>
</tr>
<tr>
<td>5%</td>
<td>5.91</td>
<td>6.05</td>
<td>7.65</td>
<td>7.81</td>
<td>7.94</td>
</tr>
<tr>
<td>10%</td>
<td>6.05</td>
<td>7.65</td>
<td>7.81</td>
<td>7.94</td>
<td>5.56</td>
</tr>
</tbody>
</table>

- **Cracking** DS-1: Uniform
- **Yielding** DS-2: Lognormal
- **Spalling** DS-3: Normal
- **Crushing** DS-4: Gamma
## Maximum Drift Damage States

<table>
<thead>
<tr>
<th>Damage Parameter</th>
<th>Damage State</th>
<th>Functional Level</th>
<th>Maximum Drift (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Probability of Exceedance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10% in 50</td>
</tr>
<tr>
<td><strong>Cracking</strong></td>
<td>DS-1</td>
<td>Fully Operational</td>
<td>0.28</td>
</tr>
<tr>
<td><strong>Yielding</strong></td>
<td>DS-2</td>
<td>Operational</td>
<td>1.86</td>
</tr>
<tr>
<td><strong>Spalling</strong></td>
<td>DS-3</td>
<td>Life safety</td>
<td>2.88</td>
</tr>
<tr>
<td><strong>Crushing</strong></td>
<td>DS-4</td>
<td>Collapse Prevention</td>
<td>5.94</td>
</tr>
</tbody>
</table>
# Residual Drift Damage States

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Functional Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight (DS=1)</td>
<td>Fully Operational</td>
<td>No structural realignment is necessary</td>
</tr>
<tr>
<td>Moderate (DS=2)</td>
<td>Operational</td>
<td>Minor structural repairing is necessary</td>
</tr>
<tr>
<td>Extensive (DS=3)</td>
<td>Life safety</td>
<td>Major structural realignment is required</td>
</tr>
<tr>
<td>Collapse (DS=4)</td>
<td>Collapse</td>
<td>Structure in danger of collapse from earthquake aftershocks</td>
</tr>
</tbody>
</table>
Residual Drift Damage States

Figure. Fragility curves in terms of residual drift at (a) 10% in 50 years (b) 5% in 50 years and (c) 2% in 50 years probability of exceedance.
## Residual Drift Damage States

<table>
<thead>
<tr>
<th>Damage State</th>
<th>Functional Level</th>
<th>Description</th>
<th>Residual Drift, $R_\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight (DS=1)</td>
<td>Fully Operational</td>
<td>No structural realignment is necessary</td>
<td>0.24 0.28 0.33</td>
</tr>
<tr>
<td>Moderate (DS=2)</td>
<td>Operational</td>
<td>Minor structural repairing is necessary</td>
<td>0.48 0.55 0.62</td>
</tr>
<tr>
<td>Extensive (DS=3)</td>
<td>Life safety</td>
<td>Major structural realignment is required</td>
<td>0.73 0.82 0.87</td>
</tr>
<tr>
<td>Collapse (DS=4)</td>
<td>Collapse</td>
<td>Structure in danger of collapse from earthquake aftershocks</td>
<td>1.04 1.16 1.22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probability of Exceedance</th>
<th>10% in 50</th>
<th>5% in 50</th>
<th>2% in 50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slight (DS=1)</td>
<td>0.24</td>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>Moderate (DS=2)</td>
<td>0.48</td>
<td>0.55</td>
<td>0.62</td>
</tr>
<tr>
<td>Extensive (DS=3)</td>
<td>0.73</td>
<td>0.82</td>
<td>0.87</td>
</tr>
<tr>
<td>Collapse (DS=4)</td>
<td>1.04</td>
<td>1.16</td>
<td>1.22</td>
</tr>
</tbody>
</table>
Prediction of Residual Drift

\[ RD = 0.5 \left( \frac{\varepsilon_s}{100} MD^2 \right) - \left( \frac{\varepsilon_s}{100} MD \right) + \left( \frac{1}{\varepsilon_s} \right) \]
**μ-ξ Relationship of SMA-RC Pier**

\[ \xi_{eq} = 5 + \frac{32}{\pi} \left( 1 - \frac{1}{\mu^{0.56}} \right) \]
Define site location and seismic hazard

Select performance level and target residual drift (RD)

Select SMA and calculate maximum drift ($\Delta_m$)

Select yield drift and calculate ductility demand, $\mu = \frac{\Delta_m}{\Delta_y}$

Select initial column parameters

Determine equivalent damping ($\xi_{eq}$)

Determine ductility ($\mu_{eq}$)

Determine effective stiffness

Determine design base shear

Determine design moment

Design bridge pier

Verify shear and moment capacity

Complete structural detailing

Acceptable

Not Acceptable

Verify target RD and MD

PBSD Of SMA-RC Pier

![Flow diagram for PBSD of SMA-RC bridge pier](image)

<table>
<thead>
<tr>
<th>SMA</th>
<th>$\varepsilon_s$ (%)</th>
<th>$A_f$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiTi45</td>
<td>6</td>
<td>-10</td>
</tr>
<tr>
<td>NiTi45</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>FeNCATB</td>
<td>13.5</td>
<td>-62</td>
</tr>
<tr>
<td>CuAlMn</td>
<td>9</td>
<td>-39</td>
</tr>
<tr>
<td>FeMnAlNi</td>
<td>6.13</td>
<td>-50</td>
</tr>
</tbody>
</table>

$RD = 0.5 \left( \frac{\varepsilon_s}{100} \right) \left( \frac{MD}{100} \right) + \left( \frac{1}{\varepsilon_s} \right)$

Performance Level

Residual Drift (%)

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Probability of exceedance in 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Operation</td>
<td>2%</td>
</tr>
<tr>
<td>Operational</td>
<td>5%</td>
</tr>
<tr>
<td>Life safety</td>
<td>10%</td>
</tr>
<tr>
<td>Collapse</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Damage Parameter</th>
<th>SMA-1 Drift (%)</th>
<th>SMA-2 Drift (%)</th>
<th>SMA-3 Drift (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cracking</td>
<td>0.28</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>Yielding</td>
<td>1.68</td>
<td>1.66</td>
<td>2.28</td>
</tr>
<tr>
<td>Spalling</td>
<td>2.66</td>
<td>2.69</td>
<td>1.64</td>
</tr>
<tr>
<td>Crushing</td>
<td>5.05</td>
<td>5.51</td>
<td>7.65</td>
</tr>
</tbody>
</table>
Design of SMA-RC Pier

- Location: Vancouver (Soil Class-C)
- Life Line Bridge
- EQ Return Period: 2475 Yr
- Functional Level: Operational
- Damage Level: Moderate
- Target RD = 0.6%
Define site location and seismic hazard

Select performance level and target residual drift (RD)

Select SMA and calculate maximum drift (Δm)

Select initial column parameters

Select yield drift and calculate ductility demand, $\mu = \Delta_m / \Delta_y$

Determine effective stiffness

Determine design base shear

Determine design moment

Design bridge pier

Verify shear and moment capacity

Verify target RD and MD

Acceptable

Not Acceptable

Complete structural detailing

Full Operation
Operational
Life safety
Collapse

<table>
<thead>
<tr>
<th>Performance Level</th>
<th>Residual Drift (%)</th>
<th>Probability of exceedance in 50 years</th>
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</thead>
<tbody>
<tr>
<td>Full Operation</td>
<td>0.24 0.28 0.33</td>
<td>10% 5% 2%</td>
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<tr>
<td>Operational</td>
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<tr>
<td>Collapse</td>
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<tr>
<td>CuAlMn</td>
<td>9</td>
<td>-39</td>
</tr>
<tr>
<td>FeMnAlNi</td>
<td>6.13</td>
<td>-50</td>
</tr>
</tbody>
</table>

$RD = 0.5 \left( \frac{\varepsilon_s}{100} MD^3 \right) - \left( \frac{\varepsilon_f}{100} MD \right) + \frac{1}{\varepsilon_f}$
Design of SMA-RC Pier

**Figure.** (a) Cross section, (b) elevation and (c) finite element model of SMA-RC bridge pier
Finite Element Modeling

Concrete Model

Steel Model
Menegotto and Pinto, 1973

SMA Model
Auricchio and Sacco [1997]

Stress-Strain diagrams for concrete, steel, and SMA models.
Performance Evaluation

(a) Target Spectra
- ChiChi
- Fruili
- Hollister
- Imperial Valley
- Kobe
- Kocaeli
- Landers
- Loma Prieta
- Northridge
- Trinidad

(b) Residual Drift (%)
- ChiChi
- Fruili
- Hollister
- Imperial Valley
- Kobe
- Kocaeli
- Landers
- Loma Prieta
- Northridge
- Trinidad
- Average
Conclusions

• A new residual drift–based design method
• A comprehensive approach for PBSD of SMA-RC bridge piers
• Meets performance expectations
• Lower residual drift
• Less maintenance cost
Acknowledgement

Natural Sciences and Engineering Research Council of Canada (NSERC)
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University of British Columbia (UBC)
• University Graduate Fellowship (UGF)
Fall 2017 — Making Connections

Thanks for your attention

Q & A

Questions/Comments

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Source: http://www.wsdot.wa.gov/publications/fulltext/Bridge/Shape_Memory.pdf