The Promise of Smart Materials in Earthquake Resistant Design

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Seismic Hazard in CA (USGS)

• **Los Angeles Area**
  • Within the next 30 years the probability is:
    – 60% that an earthquake measuring magnitude 6.7
    – 46% that an earthquake measuring magnitude 7
    – 31% that an earthquake measuring magnitude 7.5

• **San Francisco Bay Area**
  • Within the next 30 years the probability is:
    – 72% that an earthquake measuring magnitude 6.7
    – 51% that an earthquake measuring magnitude 7
    – 20% that an earthquake measuring magnitude 7.5
Vulnerability in Los Angeles

- LA races to fix vulnerable buildings before next major earthquake

Earthquake experts say that as many as 50 brittle concrete buildings in the city of L.A., housing thousands of people, could collapse in an earthquake. Which buildings collapse depends in part on where the earthquake strikes and how big it is.

LA Times, January 2018
A 2015 study found that the risk of potential collapse for pre-1994 steel-frame buildings could be five times as much as expected: roughly 50 percent instead of 10 percent.

NY Times, June 2018
Advances in Materials Science & Nanotechnology

- High Performance Composites
- Carbon Nanotubes
- Carbon Fiber Reinforced Plastics
- Piezoelectric Materials
- Self-healing materials
- Magnetostrictive fluids
- Shape Memory Materials
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- Carbon Fiber Reinforced Plastics
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- Self-healing materials
- Magnetostrictive fluids
- **Shape Memory Materials**
Shape Memory Alloys (SMAs)

- SMAs are unique metallic alloys which can undergo large deformation, but revert back to their original undeformed shape through either the shape memory effect or the superelastic effect.
- Solid state phase change (molecular re-arrangement)
- Nitinol (Nickel Titanium) is one of the most common types of SMAs used in the United States
- Numerous applications currently exist in the medical, aerospace, and commercial fields.

- Cell Phone Antennas
- Medical Stents
- Golf Clubs
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Medical Stents

Cell Phone Antennas

Golf Clubs
Advantages of SMAs

• **SMAs have several characteristics important for seismic applications in structural engineering:**
  - Recentering capability (small residual strains)
  - Hysteretic damping
  - Formation of stress plateaus (loading and unloading)
  - “Strain hardening” at large strain levels
  - Repeatability

• **Challenges**
  - Limited understanding of relationship between micro- and macro- properties
  - Lack of knowledge in regards to size effects, reliability, temperature dependence
  - Current material models too complex
  - Need effective ways and shapes to use SMAs in structures
SMA in EQ Resistant Design

Material Characterization
Mechanical Behavior
SMA Modeling
Application Analysis
Application Testing

Nano- Micro- Macro- Component Full-scale
Due to the thermo-elastic nature of SMAs an increase in temperature acts as a decrease in stress.
NiTi SMA: Superelastic Behavior

Martensite is stress-induced if loaded at temperature above Af. However, upon release of stress, the martensite becomes unstable, resulting in the “superelastic” effect.
Types of Fabrication

• As-cast microstructure not acceptable for most applications
• Further working required to achieve final balance of properties
  ▪ Hot Working
  ▪ Cold Working
  ▪ Heat Treatment
• The processing is key to the final properties of the material or component
# Properties of NiTi SMAs

<table>
<thead>
<tr>
<th>Properties</th>
<th>NiTi SMA</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Austenite</td>
<td>Martensite</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>30-85 GPa</td>
<td>20-40 GPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>195-700 MPa</td>
<td>70-140 MPa</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>800-2000 MPa</td>
<td></td>
</tr>
<tr>
<td>Recoverable Elongation</td>
<td>6-8% typically</td>
<td></td>
</tr>
<tr>
<td>Elongation to Failure</td>
<td>~25% (up to 50%)</td>
<td></td>
</tr>
<tr>
<td>Machinability</td>
<td>Difficult</td>
<td>Good</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td>Excellent</td>
<td>Fair</td>
</tr>
</tbody>
</table>
Materials Characterization

- **Hot-rolled Ni-rich large diameter NiTi bars**
  - Ti-50.90 at %Ni
  - 12.7 mm, 19.1 mm, and 31.8 mm

- **Looked at the effect of various heat treatments and amount of deformation processing**
  - Transmission electron microscopy (TEM)
  - Electron Backscatter Diffraction (EBSD)
  - Differential Scanning Calorimetry (DSC)
  - Hardness

- **Collaborative effort with Materials Science**

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Focus on the mechanical properties of NiTi SMAs

- Forward Transformation Stress, $\sigma_L$
- Reverse Transformation Stress, $\sigma_{UL}$
- Recentering Capability, $\varepsilon_R$
- Equivalent Viscous Damping, $\zeta_{eq}$
Mechanical Behavior 1-inch Superelastic Bar
Mechanical Behavior & Size Effects

• Same hot rolled NiTi superelastic bars
• Focused on scaling effects (i.e., coupon vs. full-scale)
• Connect mechanical behavior with underlying material characterization results
• All specimens underwent a two part annealing process: 350 °C for 30 minutes machined and then annealed for 300 °C for 1.5 hours.
• Loadings:
  ▪ Monotonic
  ▪ Cyclic (20 Cycles to 6% strain)
  ▪ Earthquake (Quasi-static)
  ▪ Earthquake (Dynamic)

Superelastic Bar Size Effects

- Larger bar sizes result in a decrease in the hysteresis and transformation stress.
- Equivalent viscous damping is almost double for wire specimens compared to the bar specimen at large strain values.
- Recentering is not affected by bar size.
Dynamic Test Results

7.1 mm Rod
Quasi-static 0.025 hz

Strain (in/in)

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07

Stress (ksi)

0 20 40 60 80 100 120

Stress (MPa)

0 100 200 300 400 500 600 700 800

$\sigma_L = 50 $ ksi  $\varepsilon_R = .317\%$

$\sigma_{UL} = 30 $ ksi  $\xi_{eq} = 3.87\%$

Max=0.3%/sec

7.1 mm Rod
Dynamic 1.0 hz

Strain (in/in)

0.00 0.01 0.02 0.03 0.04 0.05 0.06 0.07

Stress (ksi)

0 20 40 60 80 100 120

Stress (MPa)

0 100 200 300 400 500 600 700 800

$\sigma_L = 59.97 $ ksi  $\varepsilon_R = .200\%$

$\sigma_{UL} = 47.11 $ ksi  $\xi_{eq} = 1.82\%$

Max=12%/sec
Modeling of SMA Behavior

• Use constitutive models to represent the stress-strain behavior of SMAs

• Three main types of models:
  – Experimental phenomenological
    • Fitting experimental results with few material constants needed
    • Able to implement in current analysis platforms (i.e. OpenSEES)
  – Thermomechanical phenomenological
    • Predict behavior based on an energy balance between phases
    • Provides a good description of the physical phenomenon
  – Micromechanical
    • Describe physical phenomenon for a small volume of material and combine results to determine the global behavior
    • Requires a large number of material constants
• One-dimensional thermomechanical model (Tanaka et al., 1995)
• Captures the austenitic and martensitic behaviors
• Captures the sublooping and cyclic loading effects in SMAs
• The constitutive behavior is governed by the following equation:

$$\sigma^o = D\varepsilon^o + \Theta T^o + \Omega \xi^o$$

• Martensitic fraction during the forward and reverse transformations:

$$\xi = 1 - \xi_{Ao} \exp [b_M c_M (M_s - T) + b_M \sigma]$$

$$\xi = \xi_{Mo} \exp [b_A c_A (A_s - T) + b_A \sigma]$$
Phenomenological Models

- Six parameters needed
- Constant loading and unloading plateaus
- Does not account for internal cycling
- Captures hardening as a result of the formation of stress-induced martensite

- Six parameters needed
- Variable loading and unloading plateaus based on strain level
- Accounts for internal cycling using trigger-line
- Captures hardening as a result of the formation of stress-induced martensite
Model Comparison

- **Simplified Model**
  - Elongation (inches): 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5
  - Force (kips): 0, 500, 1000, 1500, 2000, 2500, 3000, 3500

- **Trigger-line Model**
  - Elongation (inches): 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5
  - Force (kips): 0, 500, 1000, 1500, 2000, 2500, 3000, 3500

- **Thermomechanical Model**
  - Elongation (inches): 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5
  - Force (kips): 0, 500, 1000, 1500, 2000, 2500, 3000, 3500

- **Thermomechanical Model (Cyclic SMA Behavior)**
  - Elongation (inches): 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5
  - Force (kips): 0, 500, 1000, 1500, 2000, 2500, 3000, 3500
SMA Devices Developed

Various Devices: Energy dissipation in seismic events
Major loadings: Uniaxial tension/compression; Torsion; Bending
Rings and S-Shaped Elements
Applications of Shape Memory Alloys

- Smart Beam-Column Connections
  - Recentering Connection
- SMA Bracing Systems
  - Articulated Quadrilateral
  - Tension/Compression Brace
  - *SMA Ring*
- SMA Bridge Restrainer Cables
- Full Scale Test of Nonductile RC Bldg
SMA Recentering Connection

Reduced scale interior beam-column connection

W12x14 beams, W8x67 (A572 Grade 50)

1/2” f, 18” long NiTi tendons
SMA Beam-Column Connection

~25 ft

~20 ft

SAC Protocol
SMA Beam-Column Connection

Analytical Model of 3 Story Building

- 3-story PR frame located in Los Angeles
- Composite and top and seat angle connections
- Fundamental period = 1.27 s

Uniaxial constitutive model developed by Fugazza and implemented in to OpenSEES
Analysis of SMA Connections

Counted Statistics of Peak Inter-Story Drift Angles
LA 3 Story, PR vs. SMA Connections

Counted Statistics of Residual Inter-Story Drift Angles
LA 3 Story, PR vs. SMA Connections

Unseating of Bridge Spans

1989 Loma Prieta Earthquake

1994 Northridge Earthquake

1995 Kobe Earthquake
Large-Scale Testing of SMA Recentering Devices

- Using NEESR-0420347 Test Set-up
- 4 span ⅛ scale bridge
- 2 device configurations
Large-Scale Testing of SMA Recentering Devices

- 1 in² of SMA at each deck-abutment connection
- 5 nitinol cables per side
- 320-wire cable using 0.028” (0.711 mm) diameter wires
Large-Scale Testing of SMA Recentering Devices
Shape Memory Alloys - Prestraining

- Larger resisting forces
- No-sack
- Larger Damping
Test Comparison (SMA Cable Restrainers)

- As-Built
- SMA Restrainers

Peak Hinge Opening
Hinge Opening with SMA Restrainers

South Hinge Opening (0.09 g)

-0.6
-0.4
-0.2
0
0.2
0.4
0.6

Time (sec)

Hinge Opening (in)

As-Built
No-Prestrain
Prestrain

0.50 in
0.22 in
0.08 in

SMA-based seismic bracing system

- SMA ring

SMA-based Superelastic Link

Elastic Link
Test setup and instrumentation

- SMA ring and steel connections
- Turnbuckle and custom-made load cell
Cyclic testing (video)
Deformed SMA ring

- 2% story drift
- 2.5% story drift
- 3% story drift
- 3.5% story drift
Responses in the diagonal direction

Deformation (mm) vs. Tensile force (kN)

SMA + Cable = System
Responses in the lateral direction

![Diagram showing lateral force and story drift with graph of lateral force vs. story drift for different systems: Cable and SMA.](image)
Full Scale Test of SMA Bracing in Nonductile RC Building
Full Scale Test of SMA Bracing in Nonductile RC Building
UCLA Mobile Shaker
### Instrumentation

<table>
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<tr>
<th>DAQ</th>
<th>Accelerometer model</th>
<th># of sensors</th>
<th># of accel. channels</th>
<th>Total # of channels</th>
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<tbody>
<tr>
<td>CABLED</td>
<td>Kinemetrics ES-T</td>
<td>33</td>
<td>33</td>
<td>60 cabled</td>
</tr>
<tr>
<td></td>
<td>Kinemetrics ES-U (3-axis)</td>
<td>9</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>WIRELESS</td>
<td>Silicon Designs 2012-002</td>
<td>14</td>
<td>14</td>
<td></td>
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<tr>
<td></td>
<td><em>Martlet</em> integrated accelerometer (1 or 2 axes)</td>
<td>38</td>
<td>46</td>
<td>66 wireless</td>
</tr>
<tr>
<td></td>
<td>Crossbow CXL01LF1</td>
<td>6</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
• Tested a structure designed using the 1963 ACI-318.

• Typical of older RC construction in the central and eastern US.

• Pull out of bars in the beam-column connections

• Lap splice failure in the column bottom
Retrofit with SMA Braces in the First Story:

Linear Inertial Shaker ("AstroBoy")
The reaction weight, including the yellow slip table, is approximately 8898 kg.

LEGEND:
- 1.2m length of rail weighing 79 kg
- 2.4m length of rail weighing 157 kg
- 3.6m length of rail weighing 238 kg

Shaker Base Plate (3684 kg)
Hydraulic Actuator (weight = 318 kg)
Service Manifold (weight = 272 kg)
Innovative SMA Devices:

- The brace device (a) consisted of an SMA component – wires (c) or rods (d) – housed inside two A500 steel hollow structural section (HSS) tubes.
Individual Brace Tests
Shaker Tests of a SMA Braced RC Frame

![Image of shaker test setup]

**Test Number** | **Shaker Vibration Type**
--- | ---
1 | El Centro scaled to 1"
2 | El Centro scaled to 2"
3 | El Centro scaled to 4"
4 | El Centro scaled to 6"
5 | El Centro scaled to 8"
6 | El Centro scaled to 10"
7 | El Centro scaled to 12"
8 | Pulse 4"
9 | Pulse 8"
10 | Pulse 12"
11 | Double Pulses 16"
12 | Double Pulses 20"
13 | Double Pulses 26"
Videos of the Tested Frames under Shaker Vibration

- SMA-braced frame
- As-built frame
Responses of SMA Wire Braced RC Frame
Opportunities for Smart Materials

• New materials (i.e. SMA) provide the opportunity for significantly enhanced behavior (damping and recentering), are scalable, require no maintenance, and are largely frequency independent.

• These materials/systems can provide enhanced performance well beyond life safety.

• Quality of shape memory alloys continues to improve, while cost continues to go down.

• New alloy types continue to come to market (Fe, Cu).

• Increased accessibility to new forms and shapes for SMAs

• Challenges continue to exists: temperature dependence, difficulty in machining, cost.
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Questions?