Application of Shape Memory Alloys Using OpenSEES

Dr. Reginald DesRoches
School of Civil & Environmental Engineering
Atlanta, GA 30332-0355

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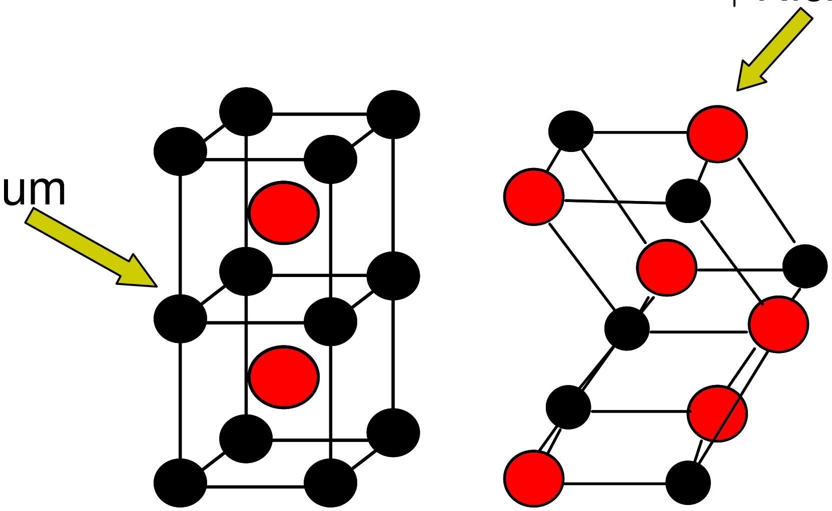
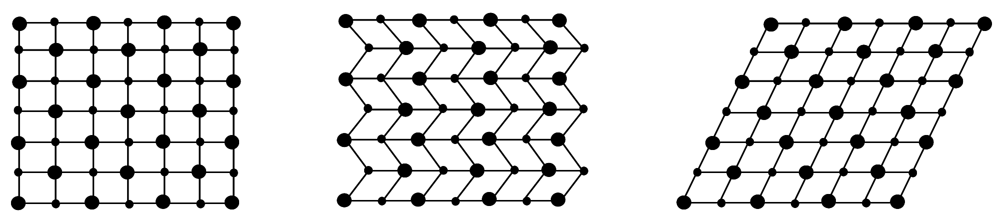
Outline of Presentation

- Background on Shape Memory Alloys
- Modeling Methods for SMAs
- Applications
  - Bridge Restrainers
  - Braced-Frame Steel Buildings
  - SMA Beam Column Connections
- OpenSEES Development Work
  - PR Connections
  - SMA Connections
  - Energy Recorders

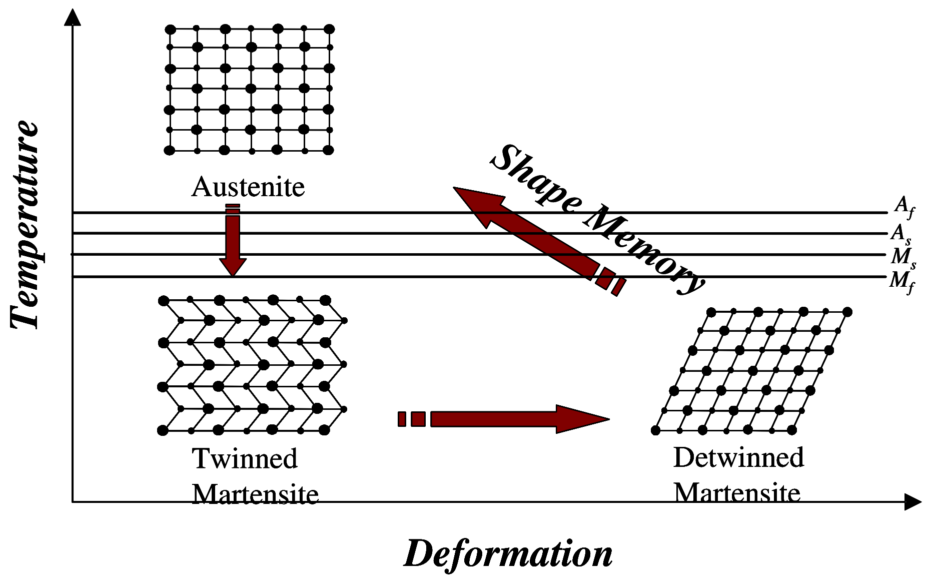
Shape Memory Alloys

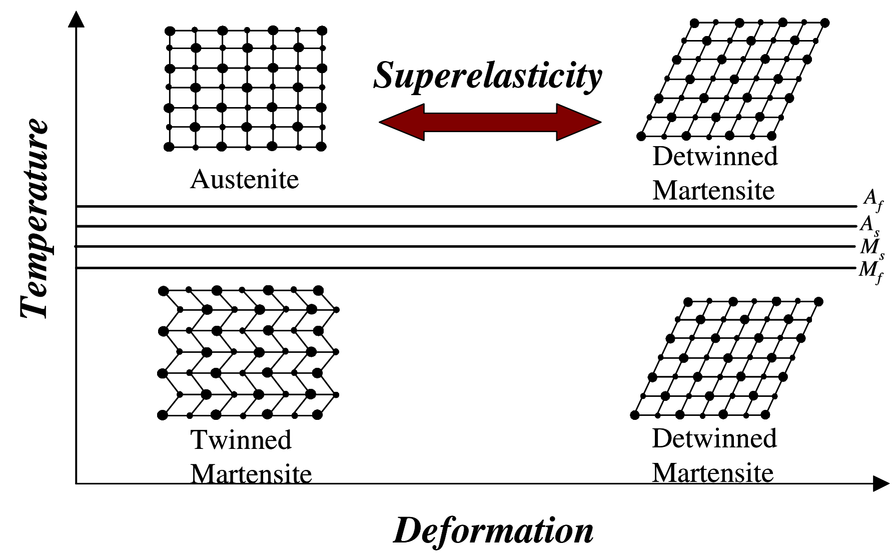
- SMAs were first discovered in 1951
- Further publicized after the discovery of Ni-Ti alloy in 1963
- SMAs have two main phases: Austenite and Martensite
- Austenite phase is symmetric, while martensite phase is less symmetric
- Phase transformation occurs either thermally of mechanically





Shape Memory Alloys



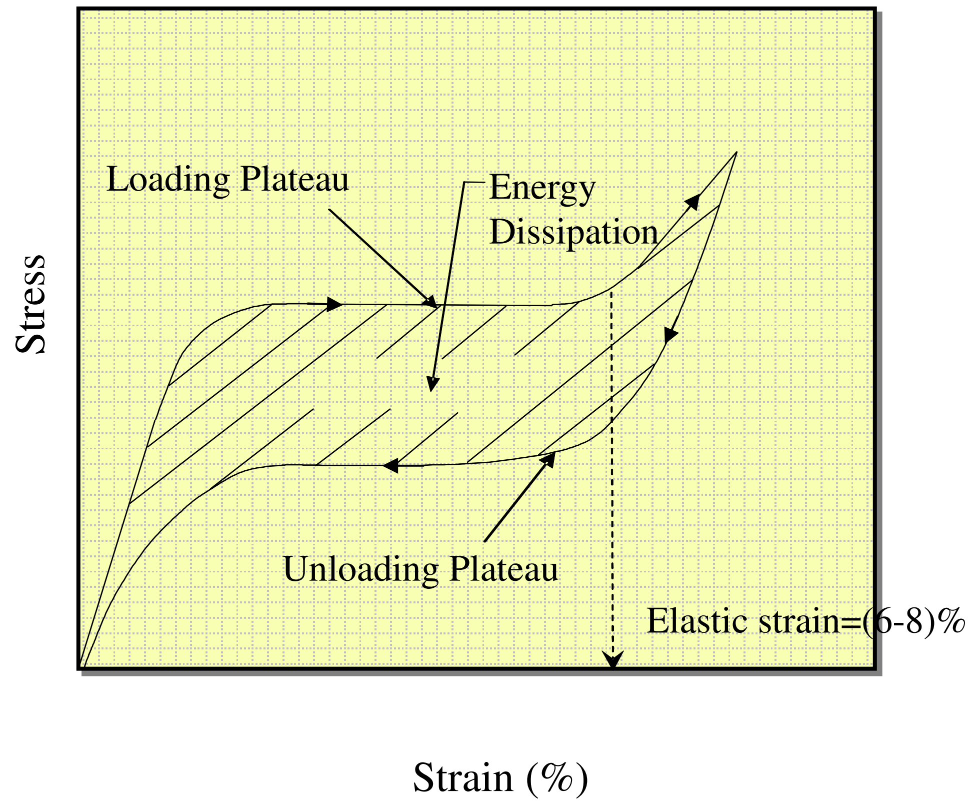


- Four transformation temperatures control the phase transformation
- At temperatures below M_f the alloy is 100% martensite (Shape memory effect)
- At temperatures above A_f the alloy is 100% austenite (Superelasticity effect)

Superelastic SMAs

Superelastic SMAs are characterized by:

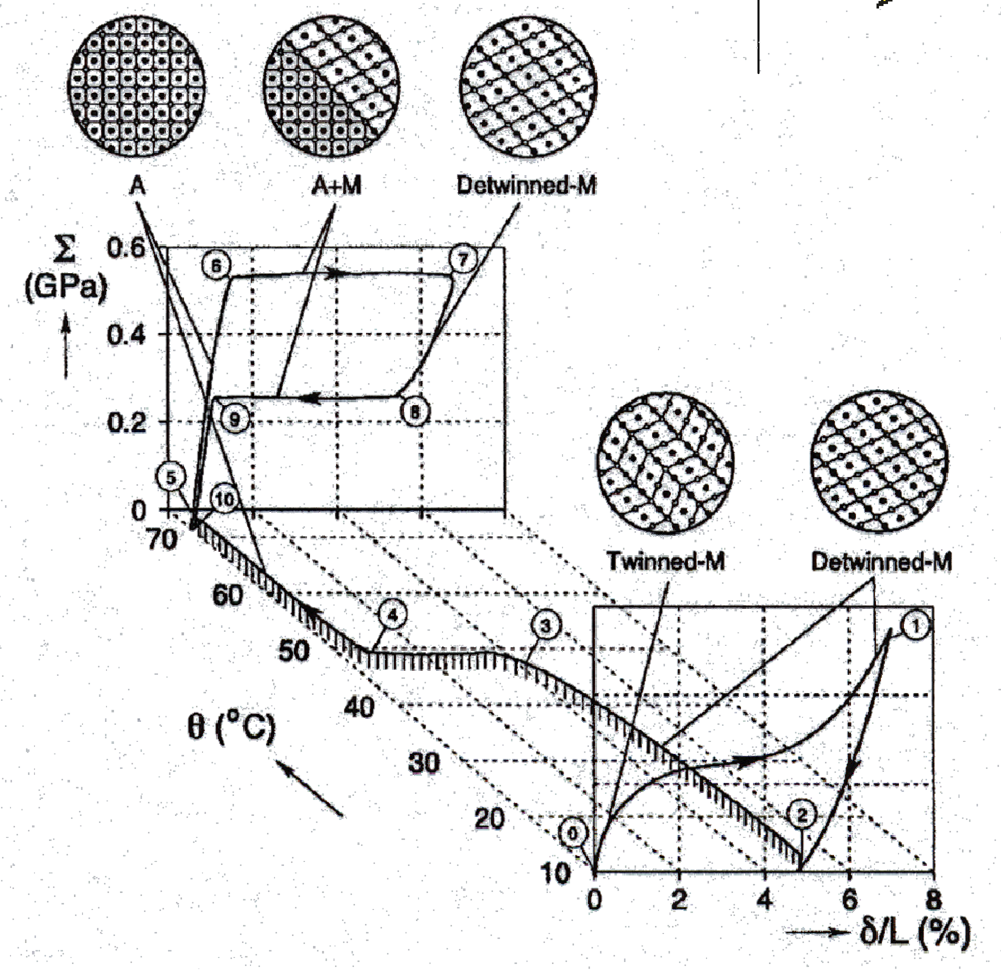
1) Excellent recentering capability
2) Controlled level of force at moderate strain levels
3) Strain hardening at large strain levels
4) Hysteretic energy dissipation
5) Excellent corrosion resistance
6) High fatigue strength



Shape Memory Alloys

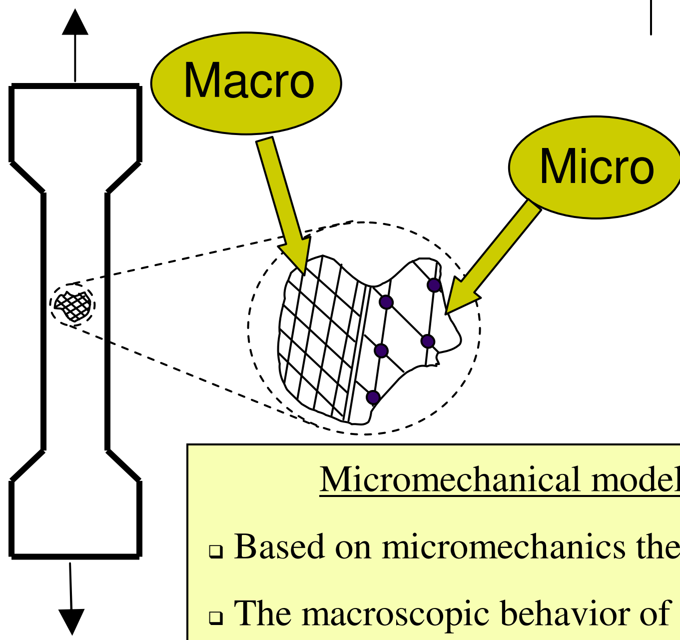
Mechanical Behavior

Property	Austenite	Martensite
Modulus of Elasticity	30-83 GPa	21-41 GPa
Yield Strength	195-690 MPa	70-140 MPa
Ultimate Tensile Strength	895-1900 MPa	895-1900 MPa
Elongation at Failure	Approx. 25%	Approx. 25%
Recoverable Strain	Up to 8%	Up to 8%
Poisson Ratio	0.33	0.33



Shape Memory Alloys : Modeling

Types of Models



Phenomenological models

Reproduce a specific phenomenon w/o describing the microstructural behavior

Experimental-based

- Built on curve fitting of experimental data
- Requires few material constants

Thermomechanical-based

- Built on thermodynamics theory
- "Internal State Variable" models
- Requires greater number of material constants

Micromechanical models

- Based on micromechanics theory
- The macroscopic behavior of the material is related to its micromechanical state
- In the case of thermoelastic MT, there are two main mechanisms:

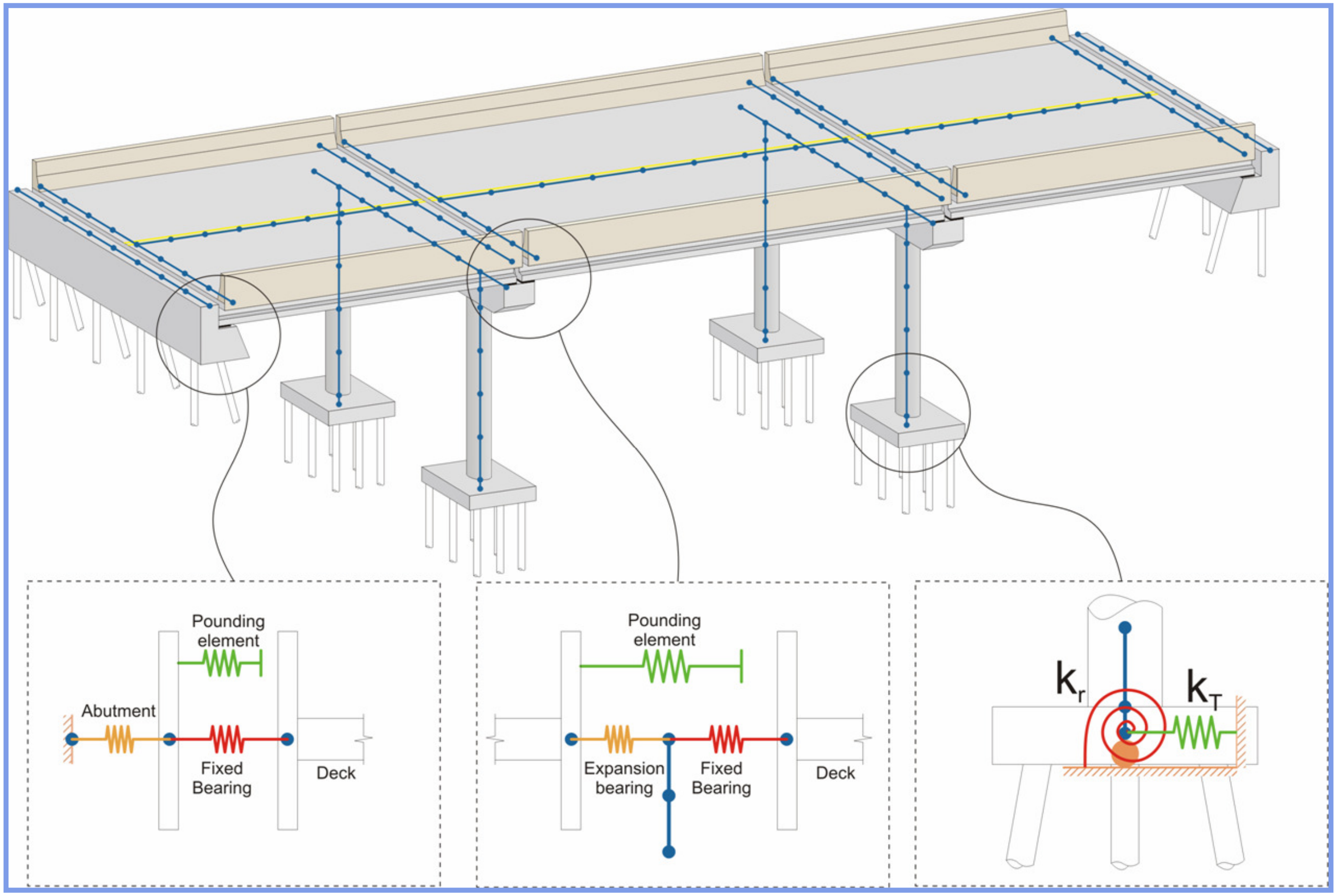
  a) Formulation of martensite variants

  b) Reorientation of martensite variants
- Requires a great number of material constants

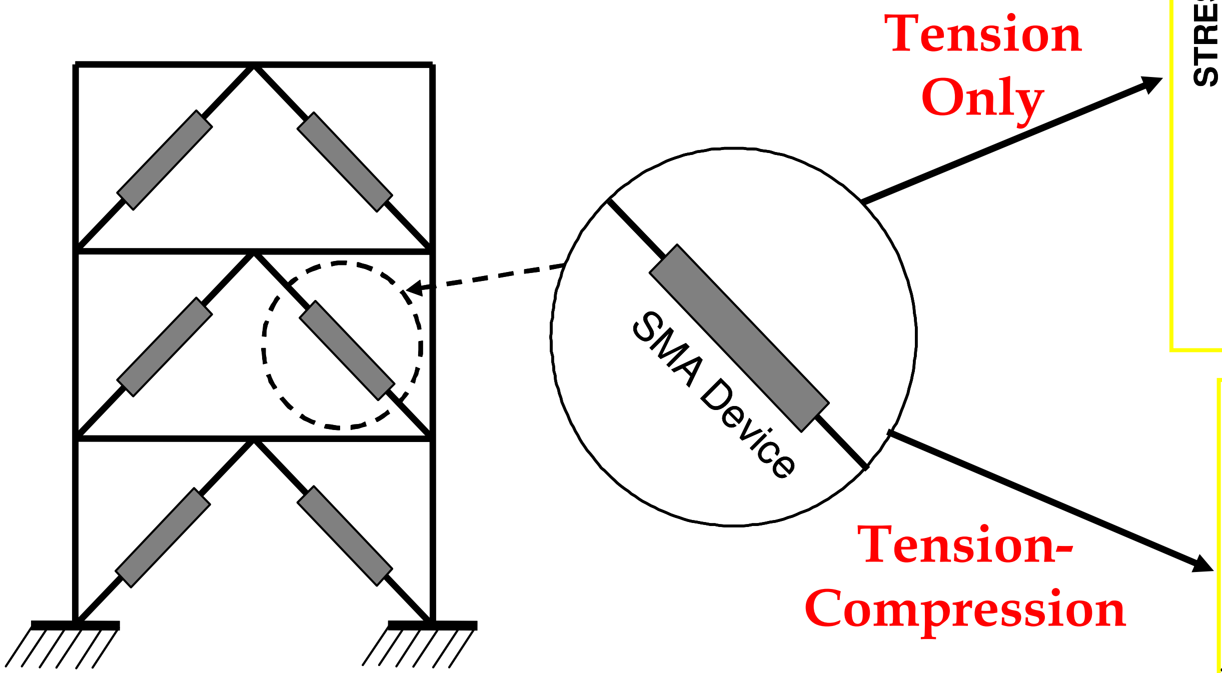
Potential Civil Engineering Applications

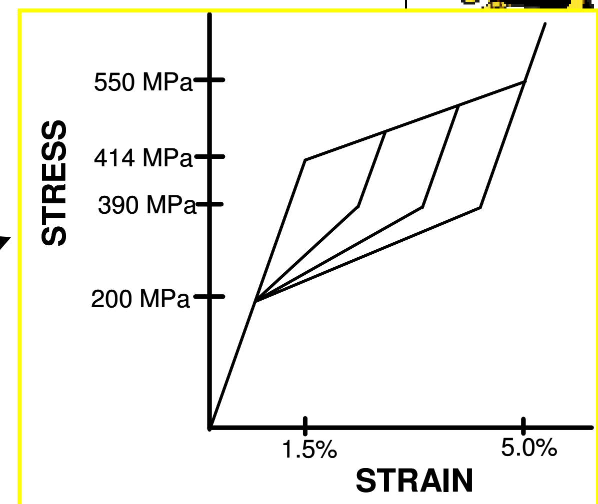
- Use of martensitic and/or superelastic shape memory alloys for restrainer cables in multi-span bridge systems
- Use of martensitic shape memory alloys in partially restrained beam-column connections
- Use of superelastic shape memory alloys as bracing systems in steel frame structures

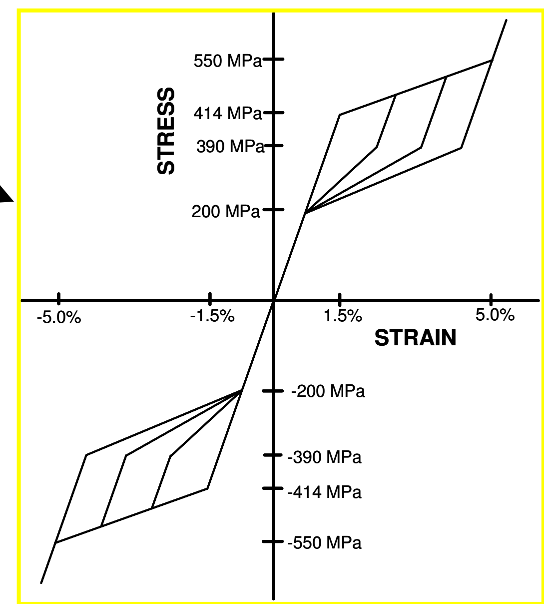
SMA Bridge Restrainers



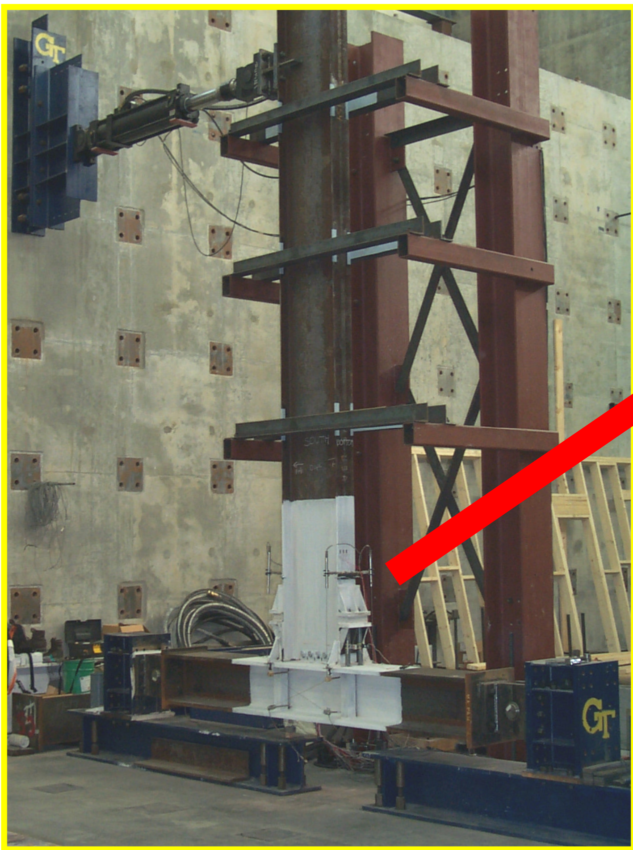
Smart Bracing System







SMA Beam-Column Connection



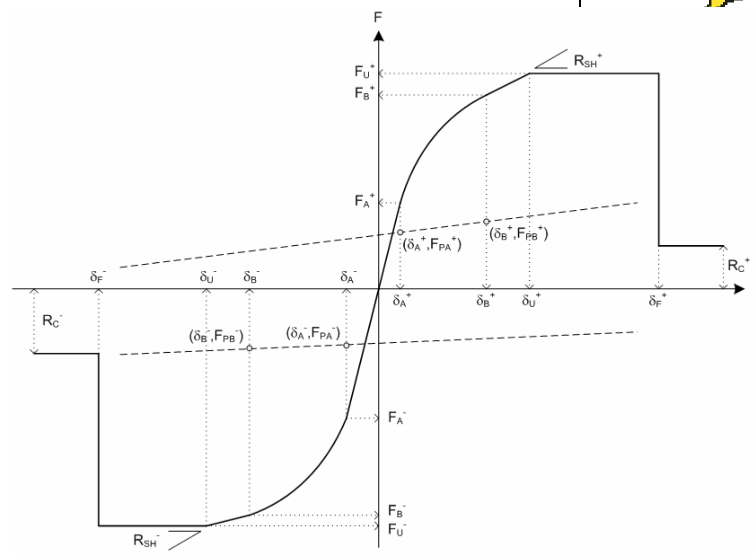
1.4375"

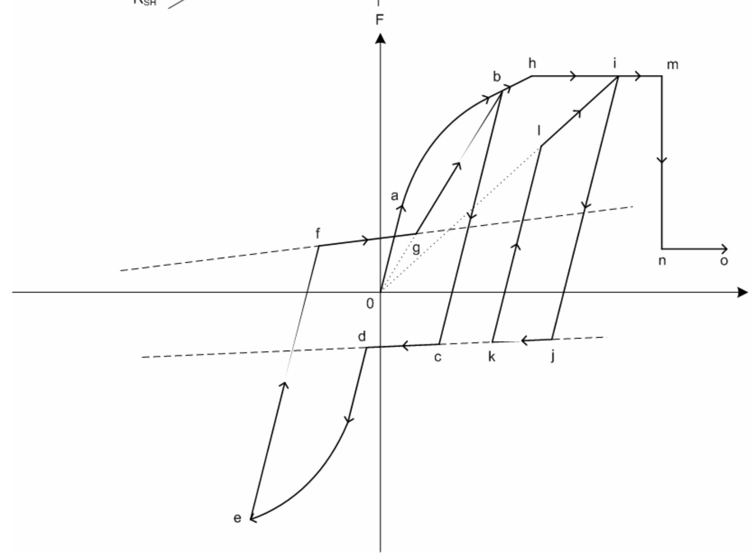
OpenSees Development for SMA Connections

- Force-Deformation relationships for
  - Partially restrained connections
  - Shape memory alloys: Superelastic effect
- Recorders for
  - Energy calculations: Strain, kinetic and damping energy
- Tcl Scripts for automation of
  - Model generation
  - Analysis procedures
  - Calculation of various response quantities

Force-Deformation Relationships
PR Connections - I

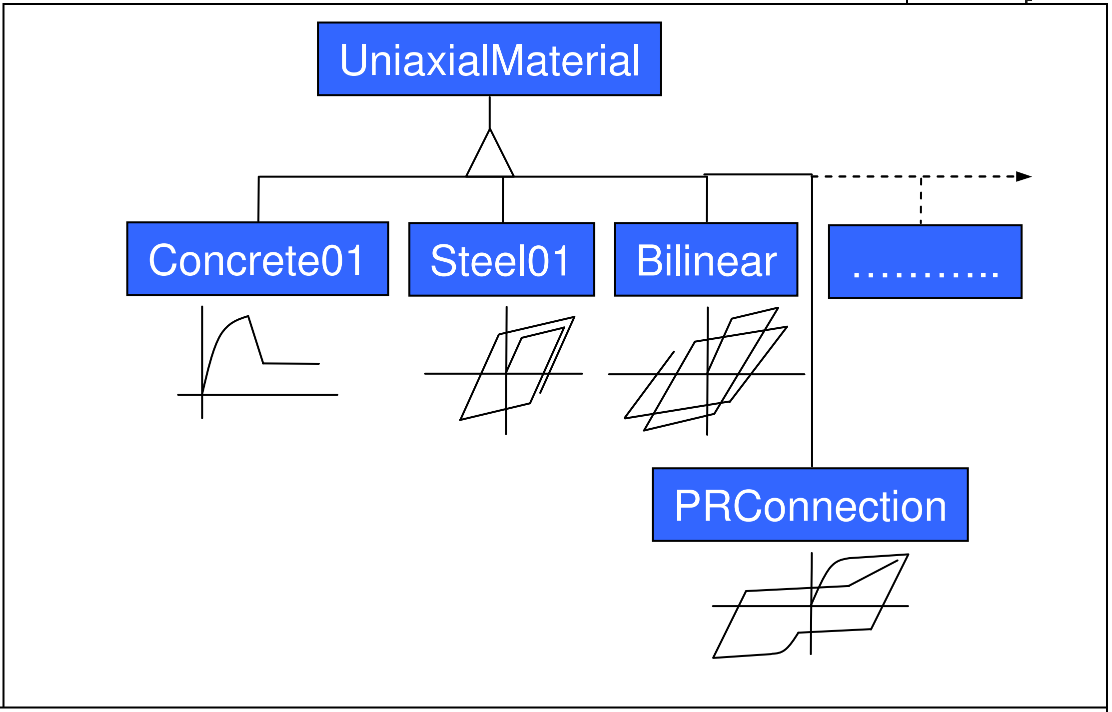
- PR connection model
  - Developed during SAC studies by Maison and Kasai (1998)
- Key features:
  - Backbone envelope curve representing the monotonic loading behavior
  - Slip plateau to model hysteretic pinching
  - Reduced reloading stiffness with increasing rotation history
  - Limited strain hardening leading to a finite ultimate moment capacity
  - Finite ultimate deformation capacity





Force-Deformation Relationships PR Connections - II

- OpenSees UniaxialMaterial class is extended by implementing a child class for:
  - PRConnection

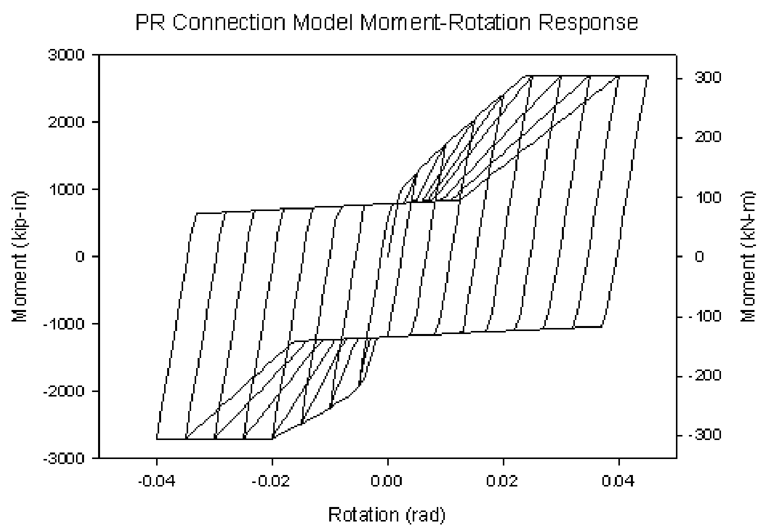


New Command:

```
uniaxialMaterial PRConnection $matTag $pUA $pMA
   $pUB $pMB $pShr $pN $pMU $pMApinch <$pMBpinch
   $nMA $nUB $nMB $nShr $nN $nMU $nMApinch
   $nMBpinch>
```

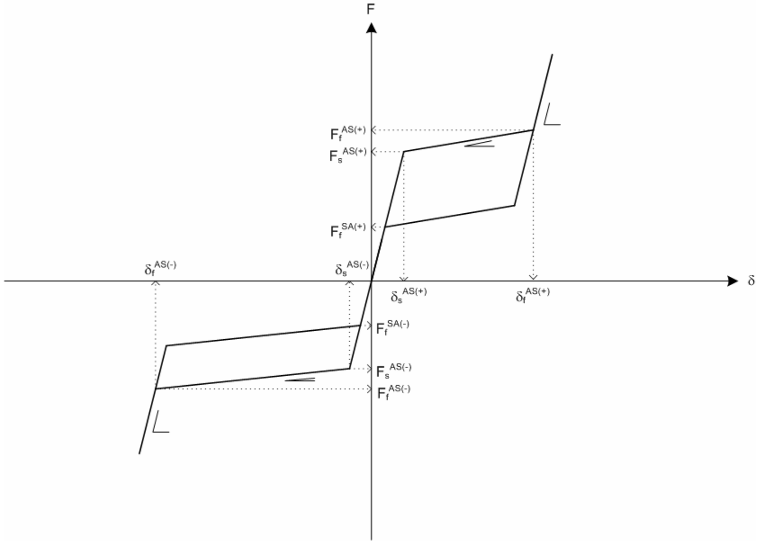
Force-Deformation Relationships PR Connections - III

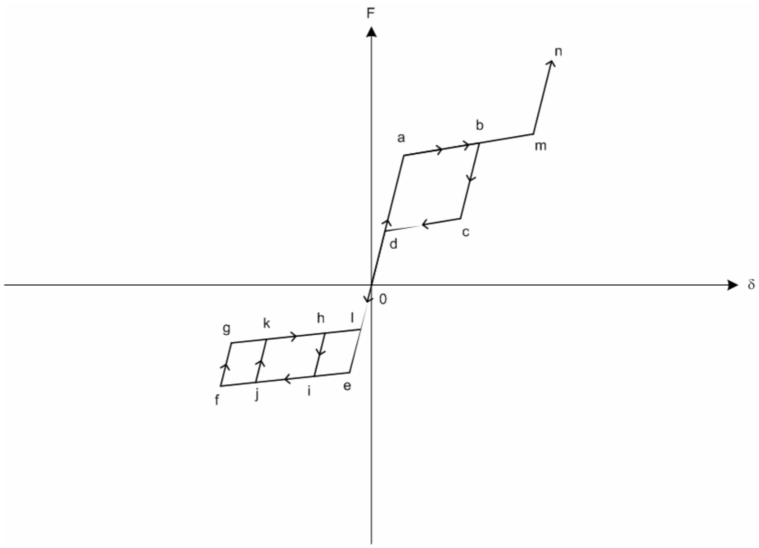
- PRConnection uniaxial material is used to model
  - Top & bottom seat angle connections
  - Composite connections
  - T-Stub connections



Force-Deformation Relationships
Superelastic SMAs - I

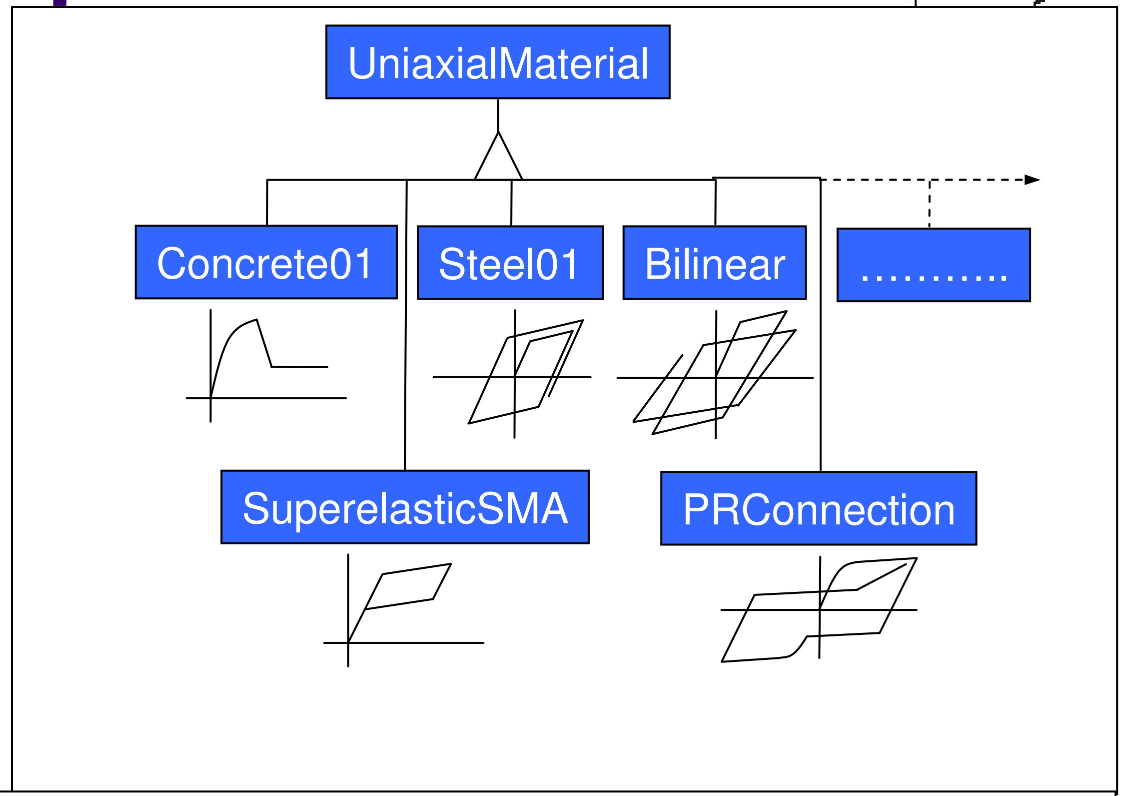
- Superelastic SMA Model
  - Based on phenomonological model developed by DesRoches and Delemont (2002)
- Key Features
  - Different properties under tension and compression
  - Loading and unloading plateaus where transformation from austenite to martensite and vice versa takes place, leading to flag shaped hysteresis
  - Elastic deformation of fully transformed martensite





Force-Deformation Relationships Superelastic SMAs - II

- OpenSees UniaxialMaterial class is extended by implementing child classes for:
  - SuperelasticSMA

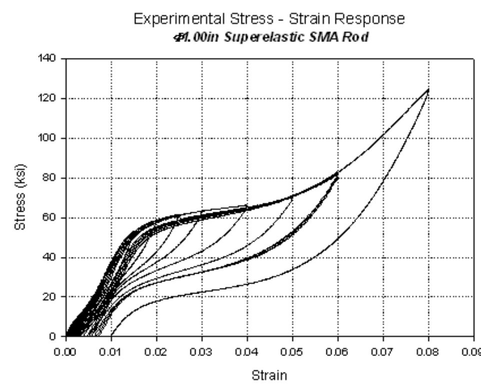


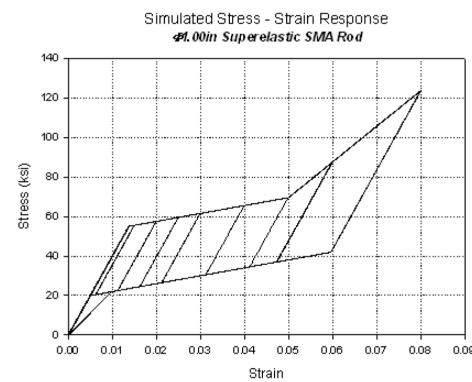
New Command:

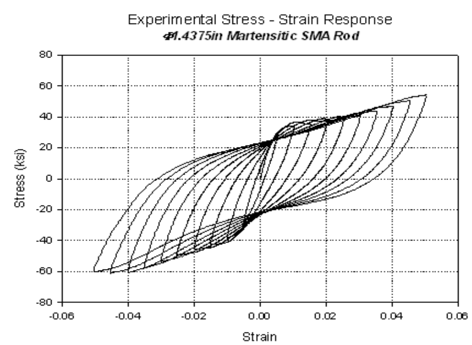
```
uniaxialMaterial SuperelasticSMA $matTag $E
   $pLoadingPlateauStress $pUnloadingPlateauStress
   $pLoadingPlateauSR $pTransformationStrain $pMartensiteSR
   <$nLoadingPlateauStress $nUnloadingPlateauStress
   $nLoadingPlateauSR $nTransformationStrain $nMartensiteSR>
```

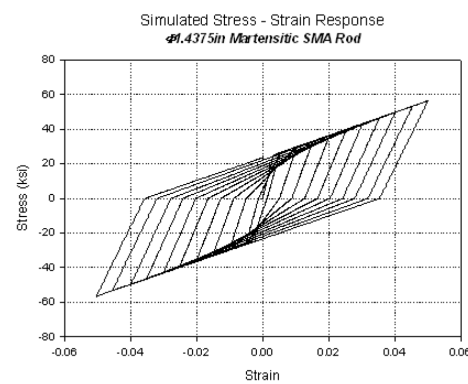
Force-Deformation Relationships SMA Connection - I

- Already built in and newly developed material models are calibrated using experimental data
  - SuperelasticSMA uniaxial material model for superelastic effect
  - Hysteretic uniaxial material model for martensitic SMA behavior



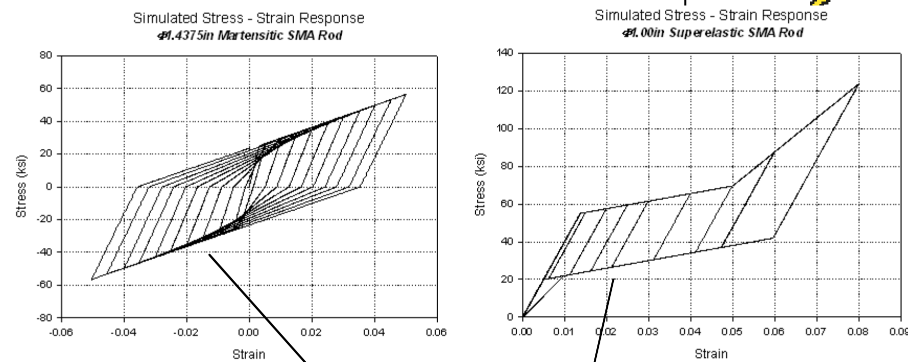


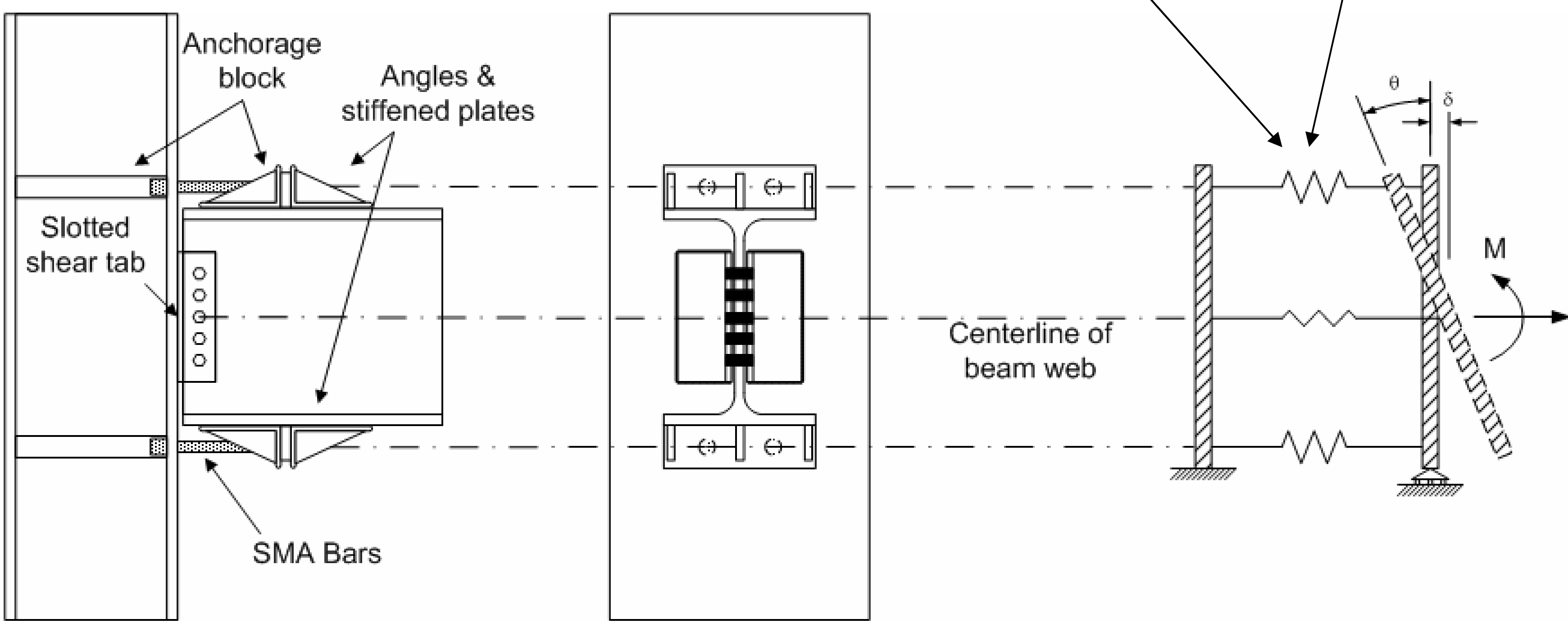




Force-Deformation Relationships SMA Connection - II

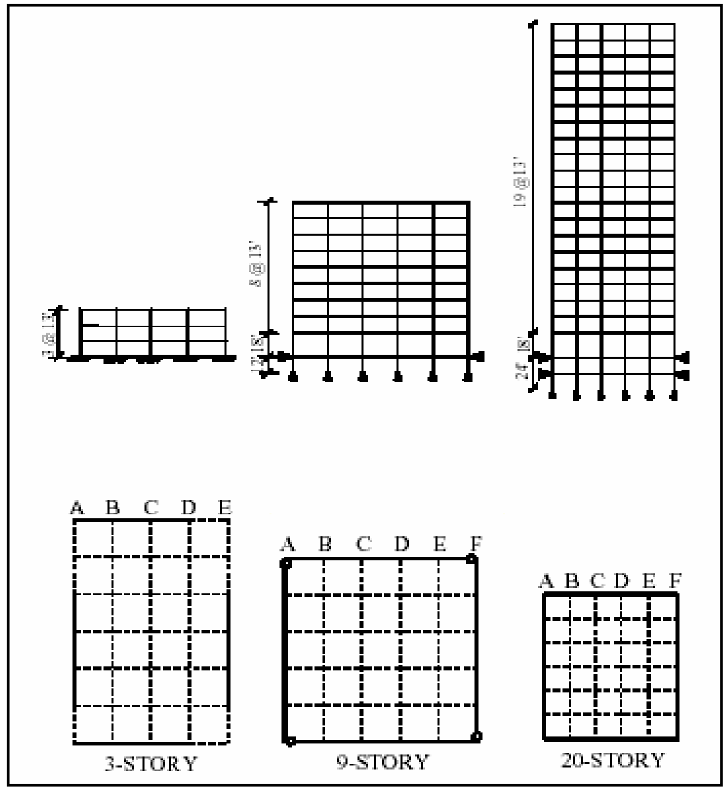
- A fiber connection model is built to predict the response of SMA connections with superelastic and martensitic SMA connecting elements
  - Used in probabilistic seismic demand analysis of steel frames with SMA connections





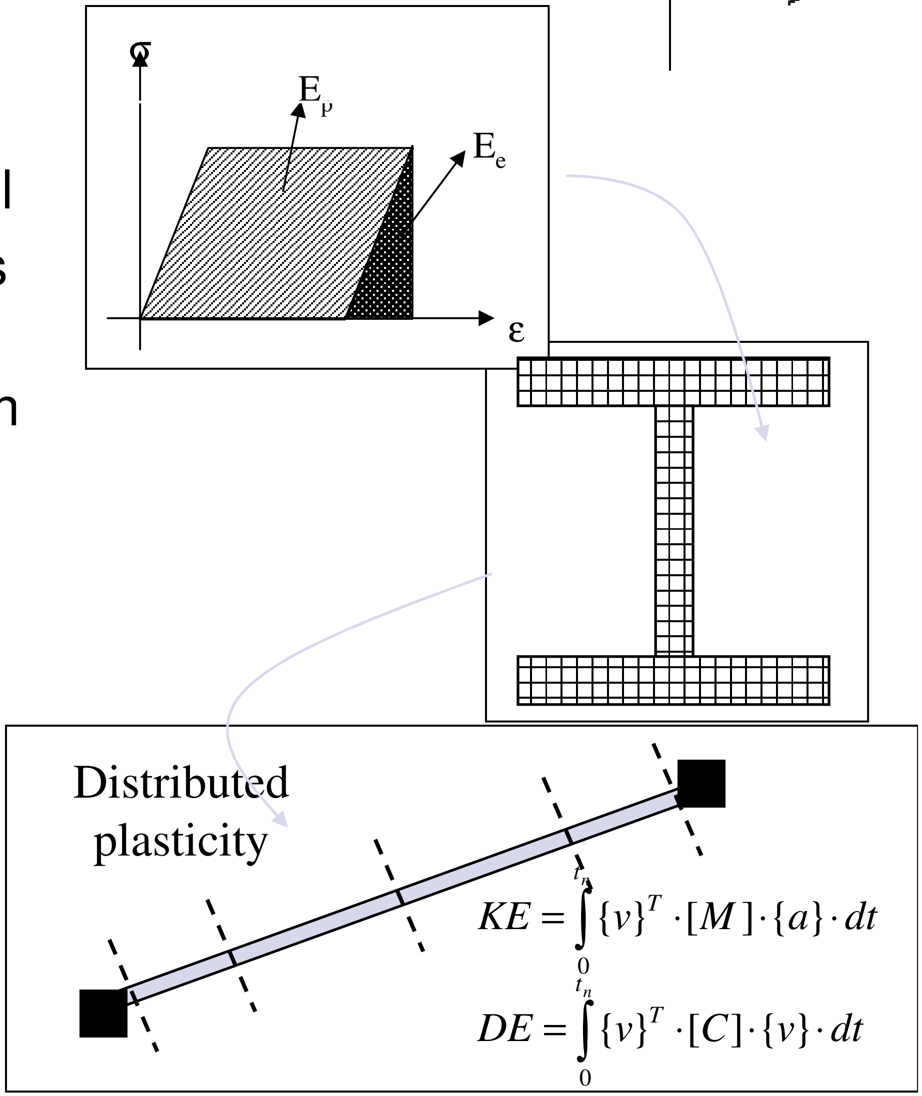
Model Buildings and Ground Motions

- Model buildings
  - 3-, 9- and 20-story SAC model buildings
  - Representative of regular SMRFs
  - Pre- and post-Northridge designs available for various locations:
    - Los Angeles
    - Seattle
    - Boston



Recorders
Energy Calculations - I

- Strain Energy Calculations
  - Elastic and plastic deformations are separable at the material level
  - The energy dissipated in a fiber is integrated along the fiber section
  - The energy dissipated in a section is integrated along the length of the element
- Kinetic Energy Calculations
  - Done at the element level with numerical integration
- Damping Energy Calculations
  - Done at the element level with numerical integration

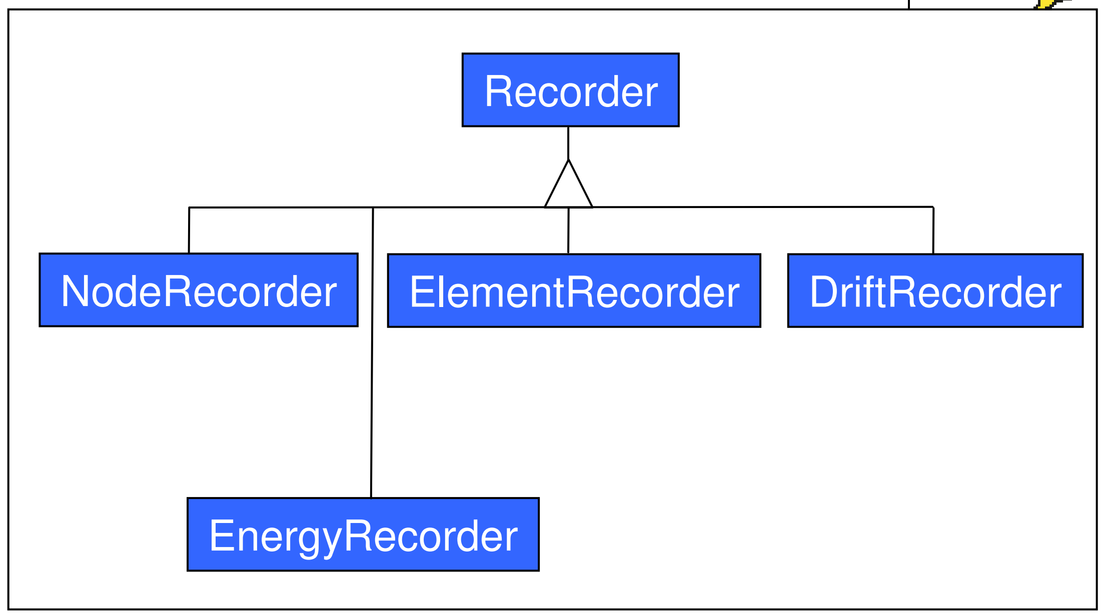


$$KE = \int_0^{t_n} \{v\}^T \cdot [M] \cdot \{a\} \cdot dt$$

$$DE = \int_0^{t_n} \{v\}^T \cdot [C] \cdot \{v\} \cdot dt$$

Recorders
Energy Calculations - II

- OpenSees Recorder class is extended by implementing a child class for
  - EnergyRecorder
- Elements modified to use energy recorder:
  - elasticBeamColumn
  - nonlinearBeamColumn
  - zeroLengthSection

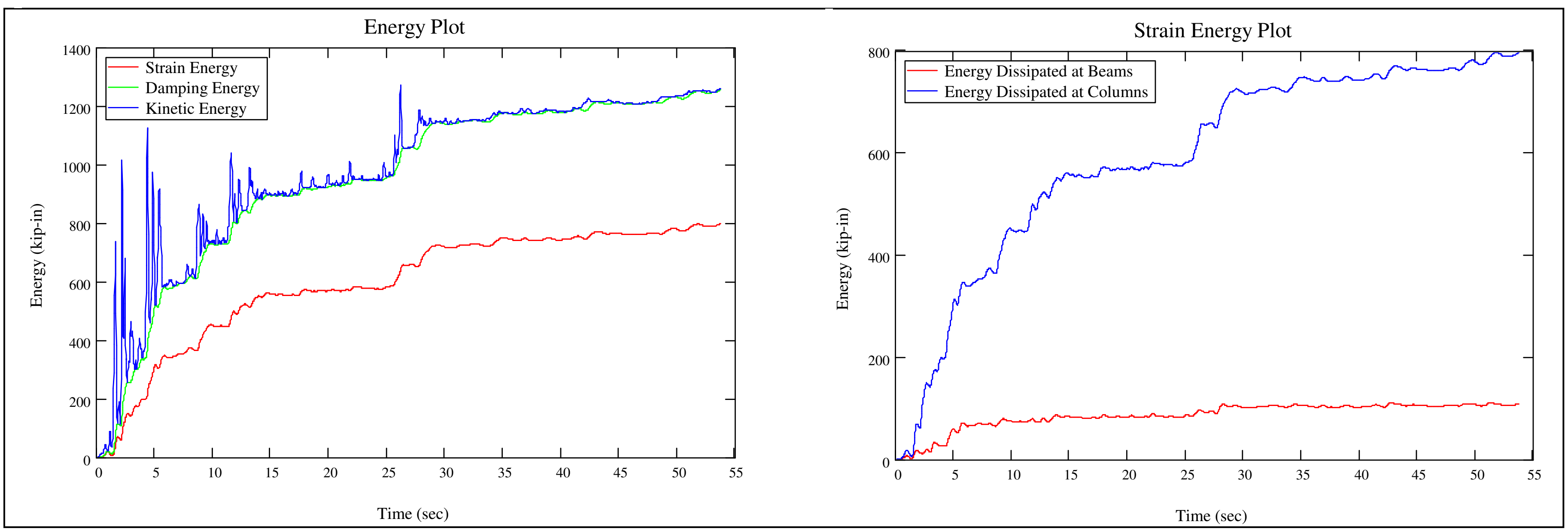


New Command:

```
recorder Energy <-file $fileName> <-time> <-ele ($ele1 $ele2
   ...)>  <-node ($node1 $node2 ...)> <-eleRange $startEle
   $endEle>         <-nodeRange $startNode $endNode> <-
   elementRegion $regTag>         <-nodeRegion $regTag> <-ele
   all> <-node all> <-cumulative> $eType
```

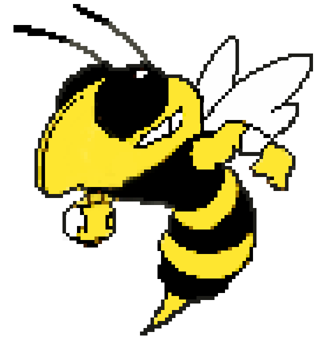
Recorders
Energy Calculations - III

- Adds the ability to record (during a time history analysis)
  - Energy dissipated at each (group of) element
  - Strain (elastic and dissipated), kinetic, damping and total energy quantities



Tcl Script: Adaptive Models & Post-Processing

- Tasks automated using Tcl scripts:
  - Model generation with different types of connection models
  - Determination of constants for Rayleigh damping
  - Determination of PGA and S_a of ground acceleration records
  - Incremental Dynamic Analysis (IDA)
  - Determination of steady state response (residual/permanent forces & deformations) of the model after a time history analysis
  - Post-processing of various response quantites:
    - Response maxima at element (e.g. max moment), floor (e.g. max floor acceleration), and structure (e.g. max interstory drift) during a time history analysis
    - Base shear & fundamental period time histories
    - Normalized hysteretic energy of structural members



Thank you!