Modelling Seismic Isolation and Viscous Damping

Andreas Schellenberg, Ph.D., P.E.
Outline of Presentation

1. Motivation
2. Friction Based Isolators
3. Elastomer Based Isolators
4. Comparison of Modelling Capabilities
5. Viscous Energy Dissipation Devices
6. Example Applications
7. Summary & Conclusions
Motivation

- Research and practice is moving towards Performance-Based Seismic Engineering, which is used as a means of selecting and designing structural systems to resist seismic excitations.

- This creates a need for innovative seismic systems whose response is both robust and optimized to minimize damage in accordance with the defined multi-level performance objectives.
Motivation: Isolation
Motivation: Isolation

- Seismic Isolation is an attractive and efficient approach to enhance structural performance and reduce risks associated with seismic hazards.
- SI provides a means of controlling the demands imposed by an earthquake.
- Concentrate seismic deformation and energy dissipation to one or a few locations.
- The uncertainty associated with their behavior is generally low relative to conventional structural elements.
Motivation: Damping
Motivation: Damping

- Supplemental viscous dampers can also enhance structural performance and reduce risks associated with seismic hazards.
- Supplemental damping provides a means of absorbing energy imposed by an earthquake.
- Concentrate seismic energy dissipation at predetermined fuse locations
- The uncertainty associated with their behavior is generally low relative to conventional structural elements
Motivation: Damping

One or More Outrigger Levels:
- Hybrid BRB/FVD bracing for damping and to limit forces
- Post-tensioning to self-center

Wall base:
- Mixed BRB/FVD bracing for damping and to limit forces
- Post-tensioning and gravity to self-center

“Elastic”

Wall
Friction Based Isolators

EPS

EPS

EPS

EPS

EPS

RJ Watson
The Friction Model

- **Element**
  - flatSliderBearing
  - singleFPBearing
  - TripleFrictionPendulum
  - RJ WatsonEqsBearing

- **FrictionModel**
  - Coulomb
  - VelDependent
  - VelNormalFrcDep
  - VelPressureDep
  - VelDepMultiLinear

frictionModel fnmMdIType? arg1? ...
The Friction Model

Coulomb
VelDependent
VelNormalFrcDep
VelPressureDep
VelDepMultiLinear
Coulomb (Constant) Friction

frictionModel Coulomb $frnTag$ $\mu$

$frnTag$
unique friction model object tag

$\mu$
coefficient of friction

---

coefficient of friction

$\mu$
sliding velocity
VelDependent Friction

\[ \mu = \mu_{Fast} - (\mu_{Fast} - \mu_{Slow}) \cdot e^{-a \cdot V} \]

- $frnTag$: unique friction model object tag
- $\mu_{Slow}$: coefficient of friction at low velocity
- $\mu_{Fast}$: coefficient of friction at high velocity
- $\text{transRate}$: transition rate from low to high velocity

Graph showing the relationship between coefficient of friction and sliding velocity. The graph illustrates the behavior of friction as the sliding velocity increases, with parameters for the experimental data fitting taken into account.
The friction model presented is:

$$\mu_{\text{Fast}} = a_{\text{Fast}} \cdot N^{(n_{\text{Fast}} - 1)}$$

$$\mu_{\text{Slow}} = a_{\text{Slow}} \cdot N^{(n_{\text{Slow}} - 1)}$$

$$a = \alpha_0 + \alpha_1 \cdot N + \alpha_2 \cdot N^2$$

$$\mu = \mu_{\text{Fast}} - (\mu_{\text{Fast}} - \mu_{\text{Slow}}) \cdot e^{-a \cdot V}$$

The figure shows the friction coefficient vs. vertical force with fitted curves. The formulas for fast and slow friction coefficients are given as:

$$\mu_{\text{Fast}} = 17.239 W^{-0.38}$$

$$\mu_{\text{Slow}} = 8.701 W^{-0.34}$$
VelNormalFrcDep Friction

frictionModel VelDepMultiLinear $frnTag -vel $velocityPoints -frn $frictionPoints

$frnTag
unique friction model object tag

$velocityPoints
array of velocity points along friction-velocity curve

$frictionPoints
array of friction points along friction-velocity curve
The Friction Based Elements

- **Element**
  - flatSliderBearing
  - singleFPBearing
  - TripleFrictionPendulum
  - RJ WatsonEqsBearing

- **FrictionModel**
  - Coulomb
  - VelDependent
  - VelNormalFrcDep
  - VelPressureDep
  - VelDepMultiLinear

```
(element eleType? arg1? ...)
```
flatSliderBearing Element

For a two-dimensional problem:

```
<element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -Mz $matTag -orient $x1 $x2 $x3 $y1 $y2 $y3>
  <shearDist $sDratio> <doRayleigh> <mass $m> <-iter $maxIter $tol>
```

For a three-dimensional problem:

```
<element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -T $matTag -My $matTag -Mz $matTag -orient $x1 $x2 $x3 $y1 $y2 $y3>
  <shearDist $sDratio> <doRayleigh> <mass $m> <-iter $maxIter $tol>
```

- `$$eleTag` unique element object tag
- `$$iNode` end nodes
- `$$jNode` tag associated with previously-defined FrictionModel
- `$$frnMdlTag` initial elastic stiffness in local shear direction
- `-P $$matTag` tag associated with previously-defined UniaxialMaterial in axial direction
- `-T $$matTag` tag associated with previously-defined UniaxialMaterial in torsional direction
- `-My $$matTag` tag associated with previously-defined UniaxialMaterial in moment direction around local y-axis
- `-Mz $$matTag` tag associated with previously-defined UniaxialMaterial in moment direction around local z-axis
- `$x1 $x2 $x3` vector components in global coordinates defining local x-axis (optional)
- `$y1 $y2 $y3` vector components in global coordinates defining local y-axis (optional)
- `$sDratio` shear distance from $iNode as a fraction of the element length (optional, default = 0.0)
- `-doRayleigh` to include Rayleigh damping from the bearing (optional, default = no Rayleigh damping contribution)
- `$m` element mass (optional, default = 0.0)
- `$maxIter` maximum number of iterations to undertake to satisfy element equilibrium (optional, default = 20)
- `$tol` convergence tolerance to satisfy element equilibrium (optional, default = 1E-8)
flatSliderBearing Element

depends on FrictionModel

\[
\frac{F_y}{F_x}, \frac{F_z}{F_x}
\]

\[
\mu, \text{kinit}
\]

\[
\text{dy, dz}
\]

\[
\frac{F_z}{F_x}
\]

\[
\frac{F_y}{F_x}
\]

\[
(1-s\text{Dratio})\cdot L
\]

\[
s\text{Dratio}\cdot L
\]

\[
\text{zero length sliding hinge}
\]

\[
\text{rigid}
\]

\[
j\text{Node}
\]

\[
i\text{Node}
\]
For a two-dimensional problem:

```
$element singleFPBearing $eleTag $iNode $jNode $frnMdITag $Reff $kInit -P $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m> <iter $maxIter $tol>
```

For a three-dimensional problem:

```
$element singleFPBearing $eleTag $iNode $jNode $frnMdITag $Reff $kInit -P $matTag -T $matTag -My $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m> <iter $maxIter $tol>
```

- **$eleTag**: unique element object tag
- **$iNode $jNode**: end nodes
- **$frnMdITag**: tag associated with previously-defined FrictionModel
- **$Reff**: effective radius of concave sliding surface
- **$kInit**: initial elastic stiffness in local shear direction
- **-P $matTag**: tag associated with previously-defined UniaxialMaterial in axial direction
- **-T $matTag**: tag associated with previously-defined UniaxialMaterial in torsional direction
- **-My $matTag**: tag associated with previously-defined UniaxialMaterial in moment direction around local y-axis
- **-Mz $matTag**: tag associated with previously-defined UniaxialMaterial in moment direction around local z-axis
- **$x1 $x2 $x3** vector components in global coordinates defining local x-axis (optional)
- **$y1 $y2 $y3** vector components in global coordinates defining local y-axis (optional)
- **$sDratio**: shear distance from iNode as a fraction of the element length (optional, default = 0.0)
- **-doRayleigh**: to include Rayleigh damping from the bearing (optional, default = no Rayleigh damping contribution)
- **$m**: element mass (optional, default = 0.0)
- **$maxIter**: maximum number of iterations to undertake to satisfy element equilibrium (optional, default = 20)
- **$tol**: convergence tolerance to satisfy element equilibrium (optional, default = 1E-8)
singleFPBearing Element

depends on FrictionModel
### TripleFrictionPendulum Element

For a three-dimensional problem:

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>element TripleFrictionPendulum</code></td>
<td>unique element object tag</td>
</tr>
<tr>
<td><code>$seleTag $iNode $jNode $frnTag1 $frnTag2 $frnTag3 $L1 $L2 $L3 $d1 $d2 $d3 $W $uy $kvc $kvt $minFv $tol</code></td>
<td>unique element object tag</td>
</tr>
<tr>
<td><code>$seleTag</code></td>
<td>unique element object tag</td>
</tr>
<tr>
<td><code>$iNode</code></td>
<td>end nodes</td>
</tr>
<tr>
<td><code>$jNode</code></td>
<td>end nodes</td>
</tr>
<tr>
<td><code>$frnTag1, $frnTag2, $frnTag3</code></td>
<td>tags associated with previously-defined <code>FrictionModels</code> at the three sliding interfaces</td>
</tr>
<tr>
<td><code>$L1, $L2, $L3</code></td>
<td>effective radii. Li = R_i - h_i (see Figure 1)</td>
</tr>
<tr>
<td><code>$d1, $d2, $d3</code></td>
<td>displacement limits of pendulums (Figure 1). Displacement limit of the bearing is 2$\sum d1+2d2+2d3+$L1.$d3/$L3-$L1.$d2/$L2</td>
</tr>
<tr>
<td><code>$W</code></td>
<td>lateral force used for the first trial of the first analysis step.</td>
</tr>
<tr>
<td><code>$uy</code></td>
<td>lateral displacement where sliding of the bearing starts. Recommended value = 0.25 to 1 mm. A smaller value may cause convergence problem.</td>
</tr>
<tr>
<td><code>$kvc, $kvt</code></td>
<td>compression k_vc and tension stiffness k_vt of the bearing.</td>
</tr>
<tr>
<td><code>$minFv</code></td>
<td>minimum vertical compression force in the bearing used for computing the horizontal tangent stiffness matrix from the normalized tangent stiffness matrix of the element. $minFv$ is substituted for the actual compressive force when it is less than $minFv$, and prevents the element from using a negative stiffness matrix in the horizontal direction when uplift occurs. The vertical nodal force returned to nodes is always computed from $kvc$ (or $kvt$) and vertical deformation, and thus is not affected by $minFv$.</td>
</tr>
<tr>
<td><code>$tol</code></td>
<td>relative tolerance for checking the convergence of the element. Recommended value = 1.e-10 to 1.e-3.</td>
</tr>
</tbody>
</table>
**TripleFrictionPendulum Element**

\[ L_i = R_i - h_i \]
TripleFrictionPendulum Test
RJ WatsonEqsBearing Element

For a two-dimensional problem:

```
$eleTag RJWatsonEqsBearing $iNode $jNode $fnmEndTag $kInit $k2 $k3 $eta -P $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m> <iter $maxIter $tol>
```

For a three-dimensional problem:

```
$eleTag RJWatsonEqsBearing $iNode $jNode $fnmEndTag $kInit $k2 $k3 $eta -P $matTag -T $matTag -My $matTag -Mz $matTag <orient $x1 $x2 $x3> $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m> <iter $maxIter $tol>
```

- `$eleTag`: unique element object tag
- `$iNode` `$jNode`: end nodes
- `$fnmEndTag`: tag associated with previously-defined FrictionModel
- `$kInit`: initial elastic stiffness in local shear direction
- `$k2`, `$k3`: post yield stiffness of linear hardening component (MER spring)
- `$eta`: exponent of non-linear hardening component
- `-P $matTag`: tag associated with previously-defined UniaxialMaterial in axial direction
- `-T $matTag`: tag associated with previously-defined UniaxialMaterial in torsional direction
- `-My $matTag`: tag associated with previously-defined UniaxialMaterial in moment direction around local y-axis
- `-Mz $matTag`: tag associated with previously-defined UniaxialMaterial in moment direction around local z-axis
- `$x1 $x2 $x3`: vector components in global coordinates defining local x-axis (optional)
- `$y1 $y2 $y3`: vector components in global coordinates defining local y-axis (optional)
- `$sDratio`: shear distance from iNode as a fraction of the element length (optional, default = 0.0)
- `-doRayleigh`: to include Rayleigh damping from the bearing (optional, default = no Rayleigh damping contribution)
- `$m`: element mass (optional, default = 0.0)
- `$maxIter`: maximum number of iterations to undertake to satisfy element equilibrium (optional, default = 20)
- `$tol`: convergence tolerance to satisfy element equilibrium (optional, default = 1E-8)
RJ Watson Eqs Bearing Element

ERADIQUAKE
ISOLATION & FORCE CONTROL BEARING DEVICES

Slide Plate

PTFE/Stainless Interface

MER Spring

Polytron Disc

Masonry Plate
RJ WatsonEqsBearing Element

depends on FrictionModel

\[
\begin{align*}
\frac{F_y}{F_x} &= k_{\text{init}} \\
\frac{F_z}{F_x} &= 1 \\
\frac{k_2 + k_3 \cdot \eta \cdot |d_y|}{F_x} &= 1
\end{align*}
\]

zero length sliding hinge

(1-sDratio) \cdot L

dr 

jNode 

Fy

iNode

sDratio \cdot L

r i g i d
RJ WatsonEqsBearing Test
Important Modelling Considerations

- All the friction based elements need an axial load on them to be able to provide shear resistance -> apply gravity loads
- Due to the vertical-horizontal coupling it is very important to -> provide realistic axial stiffness (not just some large value)
- Shear forces are affected by axial loads and slip rate (for velocity dependent friction models) -> use smaller time step size for dynamic analyses
Important Modelling Considerations

- If there is uplift (and therefore impact) in the friction based bearing elements -> consider using an integration method that provides numerical damping
- If possible (depends on element) -> provide some viscous damping in the axial bearing direction
- Avoid the introduction of artificial viscous damping in the isolation system (i.e. damping leakage) -> avoid using Rayleigh damping in the bearing elements
Elastomer Based Isolators

Bridgestone

DIS

Mageba

High Damping Rubber

Reinforcing Steel Plate

Cover Rubber

Flange

Lead Plug

Natural Rubber
Reinforcing Steel Plate

Cover Rubber

Flange

Shear Force Q (kN)

Shear Displacement X (mm)

Shear Force Q (kN)

Shear Displacement X (mm)
For a two-dimensional problem:

```
 element elastomericBearingPlasticity $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu -P $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

For a three-dimensional problem:

```
 element elastomericBearingPlasticity $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu -P $matTag -T $matTag -My $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

- $eleTag: unique element object tag
- $iNode $jNode: end nodes
- $kInit: initial elastic stiffness in local shear direction
- $fy: yield strength
- $alpha1: post yield stiffness ratio of linear hardening component
- $alpha2: post yield stiffness ratio of non-linear hardening component
- $mu: exponent of non-linear hardening component
- -P $matTag: tag associated with previously-defined UniaxialMaterial in axial direction
- -T $matTag: tag associated with previously-defined UniaxialMaterial in torsional direction
- -My $matTag: tag associated with previously-defined UniaxialMaterial in moment direction around local y-axis
- -Mz $matTag: tag associated with previously-defined UniaxialMaterial in moment direction around local z-axis
- $x1 $x2 $x3: vector components in global coordinates defining local x-axis (optional)
- $y1 $y2 $y3: vector components in global coordinates defining local y-axis (optional)
- $sDratio: shear distance from iNode as a fraction of the element length (optional, default = 0.5)
- -doRayleigh: to include Rayleigh damping from the bearing (optional, default = no Rayleigh damping contribution)
- $m: element mass (optional, default = 0.0)
elastomeric Bearing Plasticity Elem.
elastomericBearingBoucWen Elem.

For a two-dimensional problem:

```
element elastomericBearingBoucWen $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu $eta $beta $gamma -P $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m>
```

For a three-dimensional problem:

```
element elastomericBearingBoucWen $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu $eta $beat $gamma -P $matTag -T $matTag -My $matTag -Mz $matTag <orient $x1 $x2 $x3 $y1 $y2 $y3> <shearDist $sDratio> <doRayleigh> <mass $m>
```

- $eleTag: unique element object tag
- $iNode $jNode: end nodes
- $kInit: initial elastic stiffness in local shear direction
- $fy: yield strength
- $alpha1: post yield stiffness ratio of linear hardening component
- $alpha2: post yield stiffness ratio of non-linear hardening component
- $mu: exponent of non-linear hardening component
- $eta: yielding exponent (sharpness of hysteresis loop corners) (default = 1.0)
- $beta: first hysteretic shape parameter (default = 0.5)
- $gamma: second hysteretic shape parameter (default = 0.5)
- -P $matTag: tag associated with previously-defined UniaxialMaterial in axial direction
- -T $matTag: tag associated with previously-defined UniaxialMaterial in torsional direction
- -My $matTag: tag associated with previously-defined UniaxialMaterial in moment direction around local y-axis
- -Mz $matTag: tag associated with previously-defined UniaxialMaterial in moment direction around local z-axis
- $x1 $x2 $x3: vector components in global coordinates defining local x-axis (optional)
- $y1 $y2 $y3: vector components in global coordinates defining local y-axis (optional)
- $sDratio: shear distance from iNode as a fraction of the element length (optional, default = 0.5)
- -doRayleigh: to include Rayleigh damping from the bearing (optional, default = no Rayleigh damping contribution)
- $m: element mass (optional, default = 0.0)
elastomeric Bearing BoucWen Elem.
elastomeric Bearing Bouc-Wen Elem.

\[(a) \quad \alpha = 0.5 \quad \beta = 0.5 \]
\[(b) \quad \alpha = 0.1 \quad \beta = 0.9 \]
\[(c) \quad \alpha = 0.9 \quad \beta = 0.1 \]

\[(d) \quad \alpha = 0.5 \quad \beta = -0.5 \]
\[(e) \quad \alpha = 0.25 \quad \beta = -0.75 \]
\[(f) \quad \alpha = 0.75 \quad \beta = -0.25 \]

\[(\alpha_{\text{Wen}} = \beta_{\text{OPS}}, \beta_{\text{Wen}} = \gamma_{\text{OPS}}) \quad \text{from Wen, 1976}\]
elastomericX Element

For a 3D problem:

```
element ElastomericX $eleTag $Nd1 $Nd2 $qRubber $uh $Gr $Kbulk $D1 $D2 $ts $tr $n <$x1 $x2 $x3> $y1 $y2
$y3> <$kc> <$PhiM> <$ac> <$sDratio> <$m> <$cd> <$tc>
```

- `$eleTag`: unique element object tag
- `$Nd1 $Nd2`: end nodes
- `$qRubber`: yield strength
- `$uh`: yield deformation
- `$Gr`: shear modulus of elastomeric bearing
- `$Kbulk`: bulk modulus of rubber
- `$D1`: internal diameter
- `$D2`: outer diameter (excluding cover thickness)
- `$ts`: single steel shim layer thickness
- `$tr`: single rubber layer thickness
- `$n`: number of rubber layers
- `$x1 $x2 $x3`: vector components in global coordinates defining local x-axis (optional)
- `$y1 $y2 $y3`: vector components in global coordinates defining local y-axis (optional)
- `$kc`: cavitation parameter (optional, default = 10.0)
- `$PhiM`: damage parameter (optional, default = 0.5)
- `$ac`: strength reduction parameter (optional, default = 1.0)
- `$sDratio`: shear distance from iNode as a fraction of the element length (optional, default = 0.5)
- `$m`: element mass (optional, default = 0.0)
- `$cd`: viscous damping parameter (optional, default = 0.0)
- `$tc`: cover thickness (optional, default = 0.0)
elastomericX Element

- Coupled bidirectional motion in horizontal directions
- Coupling of vertical and horizontal motion
- Cavitation and post-cavitation behavior in tension
- Strength degradation in cyclic tensile loading due to cavitation
- Variation in critical buckling load capacity due to lateral displacement
# LeadRubberX Element

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Nd1$ $Nd2$</td>
<td>end nodes</td>
</tr>
<tr>
<td>$sqLead$</td>
<td>yield strength</td>
</tr>
<tr>
<td>$suh$</td>
<td>yield deformation</td>
</tr>
<tr>
<td>$Gr$</td>
<td>shear modulus of elastomeric bearing</td>
</tr>
<tr>
<td>$Kbulk$</td>
<td>bulk modulus of rubber</td>
</tr>
<tr>
<td>$D1$</td>
<td>internal diameter</td>
</tr>
<tr>
<td>$D2$</td>
<td>outer diameter (excluding cover thickness)</td>
</tr>
<tr>
<td>$ts$</td>
<td>single steel shim layer thickness</td>
</tr>
<tr>
<td>$tr$</td>
<td>single rubber layer thickness</td>
</tr>
<tr>
<td>$n$</td>
<td>number of rubber layers</td>
</tr>
<tr>
<td>$x1$ $x2$ $x3$</td>
<td>vector components in global coordinates defining local x-axis (optional)</td>
</tr>
<tr>
<td>$y1$ $y2$ $y3$</td>
<td>vector components in global coordinates defining local y-axis (optional)</td>
</tr>
<tr>
<td>$kc$</td>
<td>cavitation parameter (optional, default = 10.0)</td>
</tr>
<tr>
<td>$PhiM$</td>
<td>damage parameter (optional, default = 0.5)</td>
</tr>
<tr>
<td>$ac$</td>
<td>strength reduction parameter (optional, default = 1.0)</td>
</tr>
<tr>
<td>$sDratio$</td>
<td>shear distance from iNode as a fraction of the element length (optional, default = 0.5)</td>
</tr>
<tr>
<td>$m$</td>
<td>element mass (optional, default = 0.0)</td>
</tr>
<tr>
<td>$cd$</td>
<td>viscous damping parameter (optional, default = 0.0)</td>
</tr>
<tr>
<td>$tc$</td>
<td>cover thickness (optional, default = 0.0)</td>
</tr>
<tr>
<td>$qL$</td>
<td>density of lead (optional, default = 11200 kg/m³)</td>
</tr>
<tr>
<td>$cL$</td>
<td>specific head of lead (optional, default = 130 N-m/kg oC)</td>
</tr>
<tr>
<td>$kS$</td>
<td>thermal conductivity of steel (optional, default = 50 W/m oC)</td>
</tr>
<tr>
<td>$aS$</td>
<td>thermal diffusivity of steel (optional, default = 1.41e-05 m²/s)</td>
</tr>
</tbody>
</table>
LeadRubberX Element

- Strength degradation in cyclic shear loading due to heating of lead core
- Coupled bidirectional motion in horizontal directions
- Coupling of vertical and horizontal motion
- Cavitation and post-cavitation behavior in tension
- Strength degradation in cyclic tensile loading due to cavitation
- Variation in critical buckling load capacity due to lateral displacement
Lead Rubber Bearing Test
# HDR Element

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$eleTag</td>
<td>unique element object tag</td>
</tr>
<tr>
<td>$Nd1 $Nd2</td>
<td>end nodes</td>
</tr>
<tr>
<td>$qRubber</td>
<td>yield strength</td>
</tr>
<tr>
<td>$uh</td>
<td>yield deformation</td>
</tr>
<tr>
<td>$Gr</td>
<td>shear modulus of elastomeric bearing</td>
</tr>
<tr>
<td>$Kbulk</td>
<td>bulk modulus of rubber</td>
</tr>
<tr>
<td>$D1</td>
<td>internal diameter</td>
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<tr>
<td>$D2</td>
<td>outer diameter (excluding cover thickness)</td>
</tr>
<tr>
<td>$ts</td>
<td>single steel shim layer thickness</td>
</tr>
<tr>
<td>$tr</td>
<td>single rubber layer thickness</td>
</tr>
<tr>
<td>$n</td>
<td>number of rubber layers</td>
</tr>
<tr>
<td>$a1 $a2 $a3 $b1 $b2 $b3</td>
<td>parameters of the Grant model</td>
</tr>
<tr>
<td>$s1 $x2 $x3</td>
<td>vector components in global coordinates defining local x-axis (optional)</td>
</tr>
<tr>
<td>$y1 $y2 $y3</td>
<td>vector components in global coordinates defining local y-axis (optional)</td>
</tr>
<tr>
<td>$kc</td>
<td>cavitation parameter (optional, default = 10.0)</td>
</tr>
<tr>
<td>$PhiM</td>
<td>damage parameter (optional, default = 0.5)</td>
</tr>
<tr>
<td>$ac</td>
<td>strength reduction parameter (optional, default = 1.0)</td>
</tr>
<tr>
<td>$sDratio</td>
<td>shear distance from iNode as a fraction of the element length (optional, default = 0.5)</td>
</tr>
<tr>
<td>$m</td>
<td>element mass (optional, default = 0.0)</td>
</tr>
<tr>
<td>$cd</td>
<td>viscous damping parameter (optional, default = 0.0)</td>
</tr>
<tr>
<td>$tc</td>
<td>cover thickness (optional, default = 0.0)</td>
</tr>
</tbody>
</table>
HDR Element

- Coupled bidirectional motion in horizontal directions
- Degradation of bearing stiffness and damping due to scragging effects in shear
- Coupling of vertical and horizontal motion
- Cavitation and post-cavitation behavior in tension
- Strength degradation in cyclic tensile loading due to cavitation
- Variation in critical buckling load capacity due to lateral displacement
Kikuchi Bearing Element

element KikuchiBearing $eleTag $iNode $jNode -shape $shape -size $size $totalRubber -totalHeight $nMSS $nMSS -matMSS $matMSSTag -limDisp $limDisp -nMNS $nMNS -matMNS $matMNSTag -lambda $lambda -orient <$x1 $x2 $x3> <$yp1 $yp2 $yp3> -mass $m -noPDInput -noTilt -adjustPDOoutput $ci $cj -doBalance $limFo $limFi $nlter

$eleTag unique element object tag
$iNode $jnode end nodes
$shape following shapes are available: round, square
$size diameter (round shape), length of edge (square shape)
$totalRubber total rubber thickness
$totalHeight total height of the bearing (default: distance between iNode and jNode)
$nMSS number of springs in MSS = nMSS
$matMSSTag matTag for MSS
$limDisp minimum deformation to calculate equivalent coefficient of MSS (see note 1)
$nMNS number of springs in MNS = nMNS*nMNS (for round and square shape)
$matMNSTag matTag for MNS
$lambda parameter to calculate compression modulus distribution on MNS (see note 2)
$x1 $x2 $x3 vector components in global coordinates defining local x-axis
$yp1 $yp2 $yp3 vector components in global coordinates defining vector yp which lies in the local x-y plane for the element
$m element mass
-noPDInput not consider P-Delta moment
-noTilt not consider tilt of rigid link
$ci $cj P-Delta moment adjustment for reaction force (default: $ci=0.5, $cj=0.5)
$limFo $limFi $nlter tolerance of external unbalanced force ($limFo), tolerance of internal unbalanced force ($limFi), number of iterations to get rid of internal unbalanced force ($nlter)
Kikuchi Bearing Element

- Multiple Normal Spring (j node)
- Multiple Shear Spring (mid-height)
- Multiple Normal Spring (i node)

Local axes: local x, local y, local z
Kikuchi Bearing Element

Case 1 local-y direction

Case 2 local-y direction

Case 3 local-y direction

Dr = 1.0 m
Dp = 0.2 m
Gr = 0.4 MPa

LR

HDR
Figure 7. Lead–rubber bearing ($S_2 = 5$) shear force–displacement hysteresis loops for cyclic shear tests with different vertical loads: (a) $\sigma = 0$ MPa; (b) $\sigma = 5$ MPa; (c) $\sigma = 10$ MPa; (d) $\sigma = 20$ MPa; and (e) $\sigma = 30$ MPa.
Important Modelling Considerations

- The simpler the element the better the convergence that can be achieved. For the more complex elements that capture axial load effects, temperature dependence or scragging -> use smaller time step size for dynamic analyses.

- Some of the elastomer based elements need an axial load on them to capture effects on shear forces and P-Delta effects -> apply gravity loads.
Important Modelling Considerations

- For all isolators it is very important to -> provide realistic axial stiffness (not just some large value)
- If possible (depends on element) -> provide some viscous damping in the axial bearing direction
- Avoid the introduction of artificial viscous damping in the isolation system (i.e. damping leakage) -> avoid using Rayleigh damping in the bearing elements
## Comparison of Isolator Capabilities

<table>
<thead>
<tr>
<th>Element</th>
<th>Shear Behavior</th>
<th>Shear Coupling</th>
<th>Axial Behavior</th>
<th>Shear and Axial Coupling</th>
<th>Coupled H-V defo</th>
<th>Moment Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastomeric Bearing BW</td>
<td>bouc-wen</td>
<td>yes, circular</td>
<td>any OPS material</td>
<td>under development</td>
<td>no</td>
<td>any OPS material</td>
</tr>
<tr>
<td>Elastomeric Bearing P</td>
<td>bilinear</td>
<td>yes, circular</td>
<td>any OPS material</td>
<td>no</td>
<td>no</td>
<td>any OPS material</td>
</tr>
<tr>
<td>ElastomericX Bearing</td>
<td>bouc-wen</td>
<td>yes, circular</td>
<td>special tension mat</td>
<td>yes</td>
<td>no</td>
<td>elastic</td>
</tr>
<tr>
<td>LeadRubberX Bearing</td>
<td>bouc-wen</td>
<td>yes, circular</td>
<td>special tension mat</td>
<td>yes</td>
<td>no</td>
<td>elastic</td>
</tr>
<tr>
<td>HDR Bearing</td>
<td>Grant et al.</td>
<td>yes, circular</td>
<td>special tension mat</td>
<td>yes</td>
<td>no</td>
<td>elastic</td>
</tr>
<tr>
<td>Kikuchi Bearing</td>
<td>multi-shear-spring</td>
<td>yes, circular</td>
<td>multi-normal-spring</td>
<td>yes</td>
<td>no</td>
<td>multi-normal spring</td>
</tr>
<tr>
<td>Isolator 2-Spring</td>
<td>bilinear</td>
<td>no, 2D only</td>
<td>elastic</td>
<td>yes</td>
<td>yes</td>
<td>no, fixed required</td>
</tr>
<tr>
<td>Flat Slider Bearing</td>
<td>EPP</td>
<td>yes, circular</td>
<td>any OPS material + gap</td>
<td>yes</td>
<td>no</td>
<td>any OPS material</td>
</tr>
<tr>
<td>Single FP Bearing</td>
<td>bilinear</td>
<td>yes, circular</td>
<td>any OPS material + gap</td>
<td>yes</td>
<td>no</td>
<td>any OPS material</td>
</tr>
<tr>
<td>Triple FP Bearing 1</td>
<td>multi-linear plastic</td>
<td>yes, circular</td>
<td>elastic + gap</td>
<td>yes</td>
<td>no</td>
<td>from geometry</td>
</tr>
<tr>
<td>Triple FP Bearing 2</td>
<td>multi-linear plastic</td>
<td>yes, circular</td>
<td>elastic T and C</td>
<td>yes</td>
<td>no</td>
<td>from geometry</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Rayleigh Damping</th>
<th>P-Delta Effects</th>
<th>Nonlinear Hardening</th>
<th>Scragging Effects</th>
<th>Rate Effects</th>
<th>Temp. Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastomeric Bearing BW</td>
<td>off, optional</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>under dev.</td>
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<tr>
<td>Elastomeric Bearing P</td>
<td>off, optional</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>ElastomericX Bearing</td>
<td>on</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>LeadRubberX Bearing</td>
<td>on</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>HDR Bearing</td>
<td>on</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
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<tr>
<td>Kikuchi Bearing</td>
<td>on</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>maybe</td>
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<tr>
<td>Isolator 2-Spring</td>
<td>off, optional</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Flat Slider Bearing</td>
<td>off, optional</td>
<td>yes</td>
<td>n/a</td>
<td>n/a</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Single FP Bearing</td>
<td>off, optional</td>
<td>yes</td>
<td>n/a</td>
<td>n/a</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Triple FP Bearing 1</td>
<td>on</td>
<td>no</td>
<td>yes</td>
<td>n/a</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Triple FP Bearing 2</td>
<td>on</td>
<td>yes</td>
<td>yes</td>
<td>n/a</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>
Fluid Viscous Dampers
Damping Material Models

Element

twoNodeLink
truss
corotTruss

UniaxialMaterial

Elastic
Viscous
ViscousDamper

uniaxialMaterial matType? matTag? arg1? ...
Elastic Uniaxial Material

$$\sigma(t) = E \cdot \varepsilon(t) + \eta \cdot \dot{\varepsilon}(t)$$
Viscous Uniaxial Material

\[ \sigma(t) = C \cdot \dot{\varepsilon}(t)^{\alpha} \]

- $matTag$: integer tag identifying material
- $C$: damping coefficient
- $\alpha$: power factor (=1 means linear damping)
ViscousDamper Uniaxial Material

The ViscousDamper material is based on:

\[ \frac{\dot{F}_d(t)}{K_d} + \text{sign}(F_d(t))\left(\frac{|F_d(t)|}{C_d}\right)^\alpha = \dot{u}_m(t) \]
Viscous Damper Uniaxial Material

**Figure 1**
- $C_d = 280$
- $\alpha = 0.3$

**Figure 2**
- $C_d = 73$
- $\alpha = 0.6$

**Figure 3**
- $C_d = 1018$
- $\alpha = 0.01$

**Figure 4**
- $C_d = 1.2$
- $\alpha = 1.5$
Damper Configurations

- Diagrams showing various damper configurations.
- Dimensions and labels indicating parts and measurements.
- Pre-bent plate, welded details, and plate thickness annotations.
Damper Configurations
Example Application

flatSliderBearing: constant COF 13%

Horizontal Hysteresis Loops

Interaction Surface
Example Application

singleFPBearing: constant COF 13%

Horizontal Hysteresis Loops

Interaction Surface
Example Application

TripleFrictionPendulum: constant COF 4%, 10%, 13%

Horizontal Hysteresis Loops

Interaction Surface
Example Application

RJ WatsonEQSBearing: constant COF 13%
Example Application

elastomericBearingPlasticity: \( f_y = 1.84 \text{ kip} \)
Example Application

elastomeric Bearing Bouc-Wen: $f_y = 1.84$ kip
Example Application

elastomericX: $f_y = 1.84$ kip
Example Application

LeadRubberX: \( qd = 1.66 \text{ kip} \)
Conclusions

- OpenSees already provides a fairly large library of elements and materials that can be used to model isolators and viscous dampers.
- However, isolator capabilities need to be further improved to include important effects such as the coupled vertical-horizontal deformation effects.
- Additional models for capturing temperature effects should be developed.
- Modeling of isolator failures and moat impact needs to be investigated.
Questions?
Thank you!