Modelling Seismic Isolation and Viscous Damping

Andreas Schellenberg, Ph.D., P.E.

Open System for Earthquake Engineering Simulation
Pacific Earthquake Engineering Research Center

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

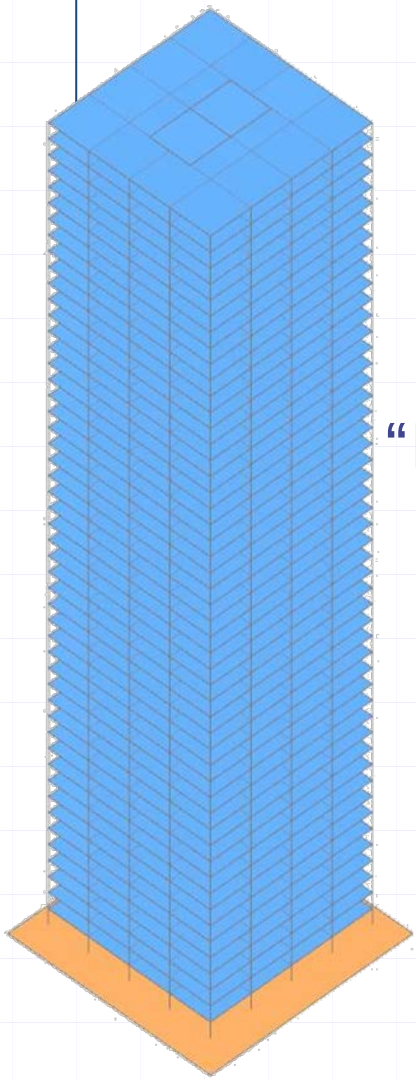
- Seismic Isolation is an attractive and efficient approach to enhance structural performance and reduce risks associated with seismic hazards.
- SI provides a means of controlling the demands imposed by an earthquake.
- Concentrate seismic deformation and energy dissipation to one or a few locations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

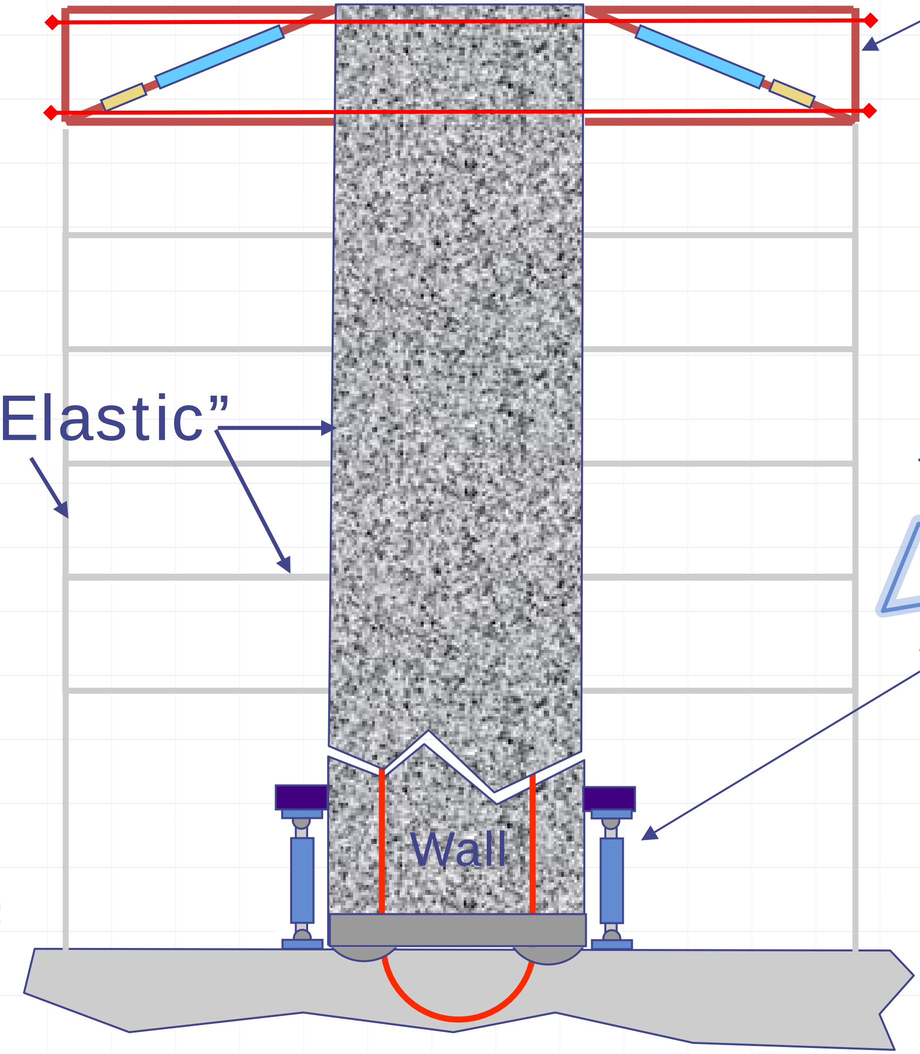
Motivation: Damping

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

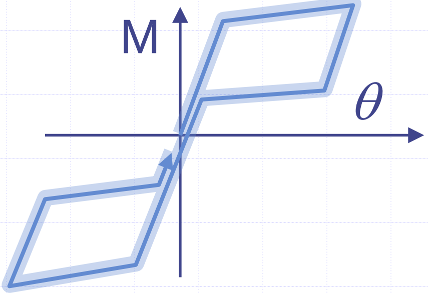
Motivation: Damping





One or More Outrigger Levels:

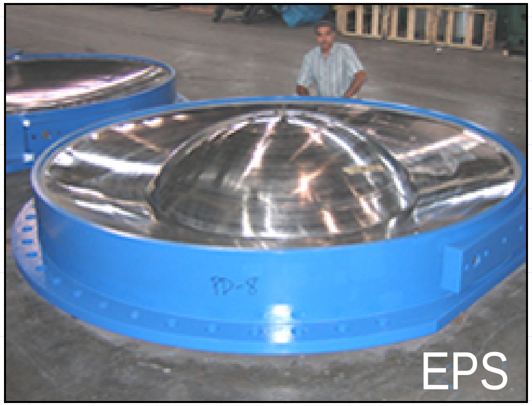
- Hybrid BRB/FVD bracing for damping and to limit forces
- Post-tensioning to self-center



Wall base:

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

Friction Based Isolators


EPS

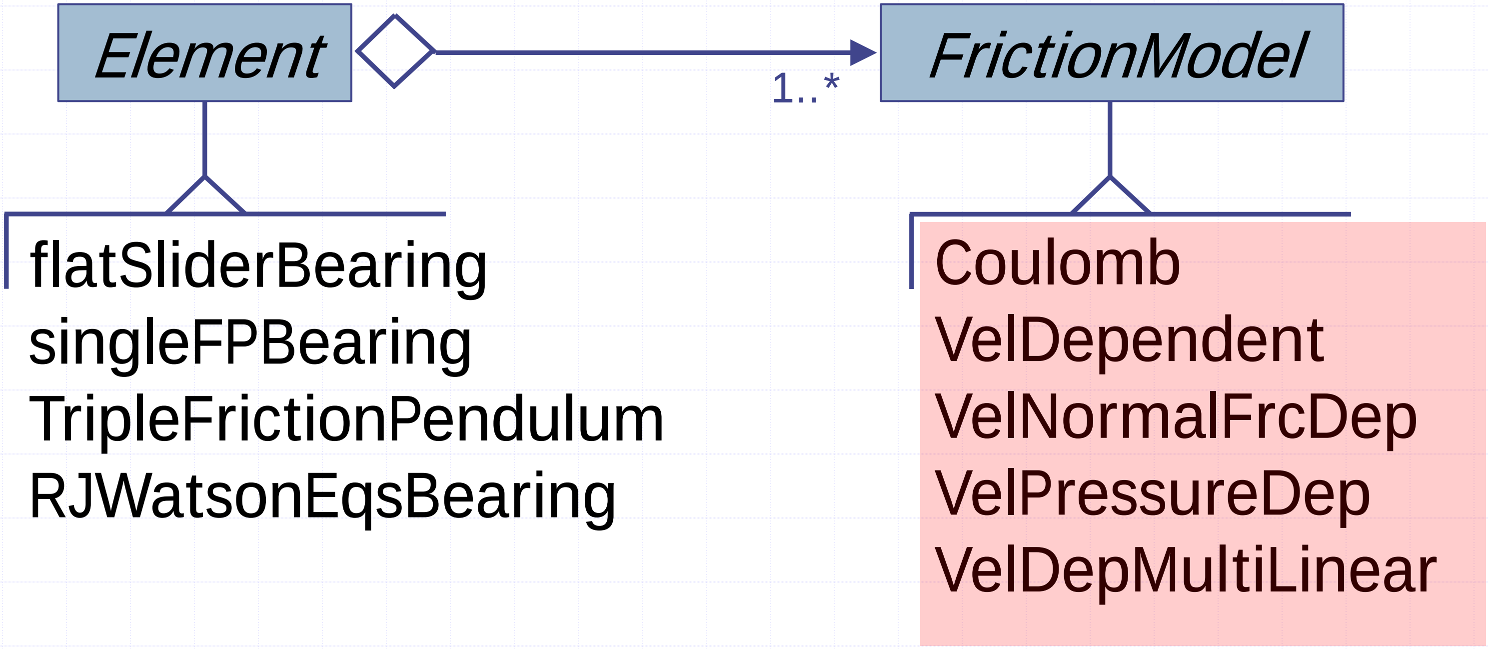

EPS


EPS


EPS


RJ Watson

The Friction Model

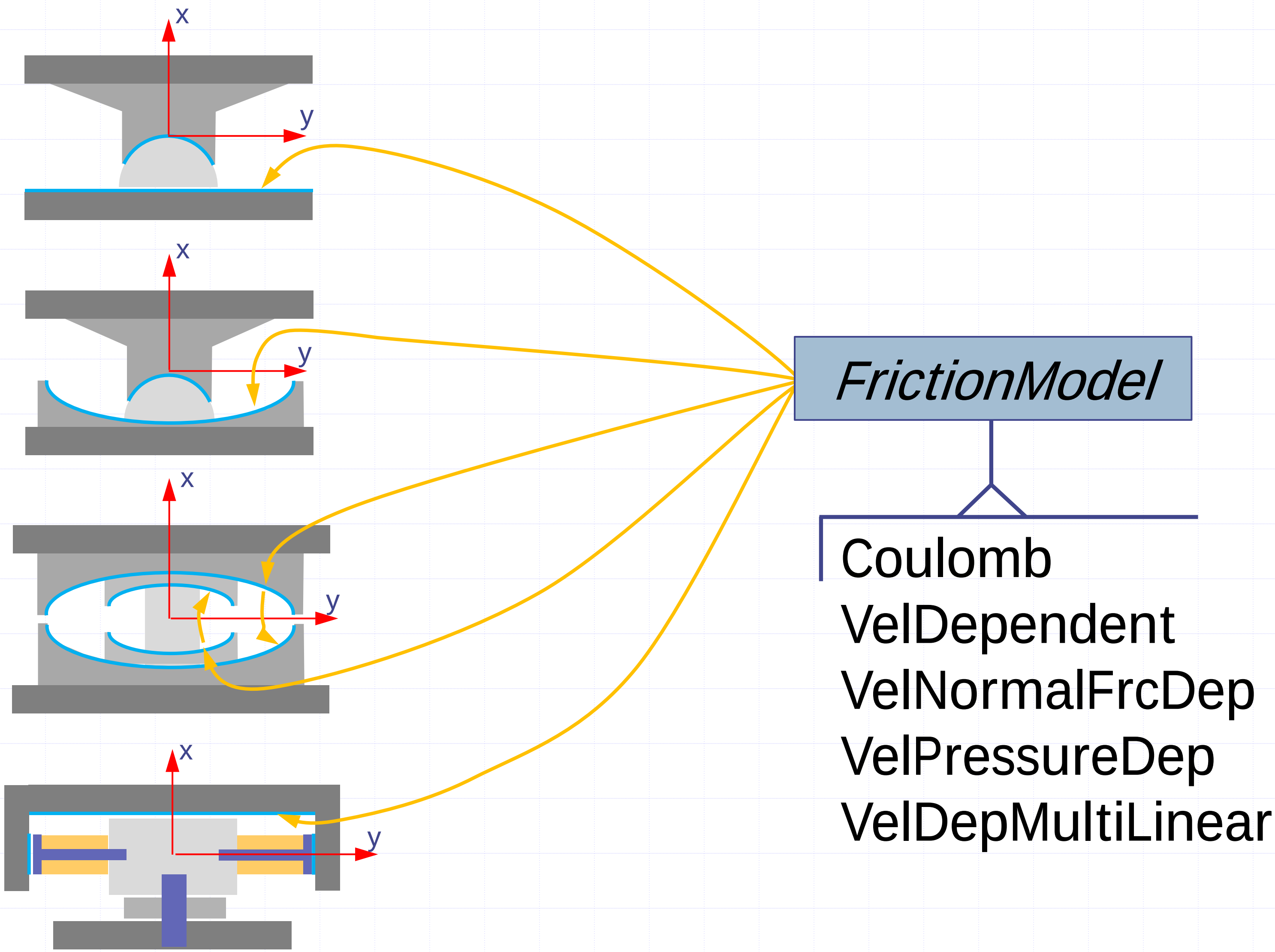


flatSliderBearing
singleFPBearing
TripleFrictionPendulum
RJWatsonEqsBearing

Coulomb
VelDependent
VelNormalFrcDep
VelPressureDep
VelDepMultiLinear

frictionModel frnMdlType? arg1? ...

The Friction Model



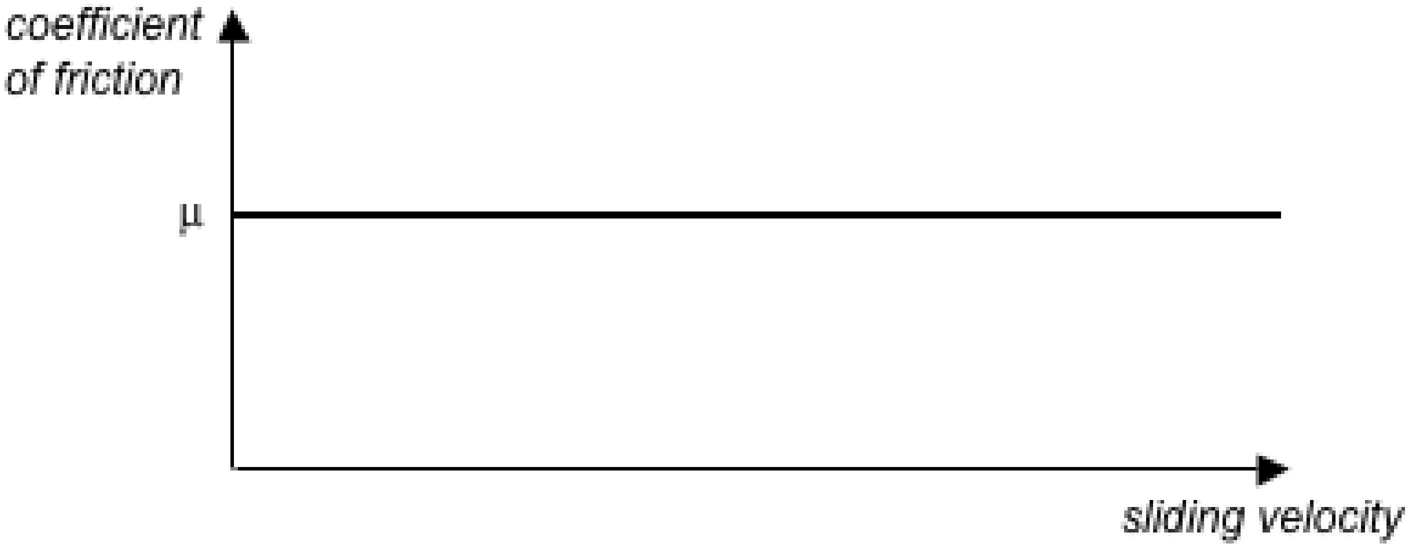
FrictionModel

Coulomb
VelDependent
VelNormalFrcDep
VelPressureDep
VelDepMultiLinear

Coulomb (Constant) Friction

```
frictionModel Coulomb $frnTag $mu
```

$frnTag	unique friction model object tag
$mu	coefficient of friction

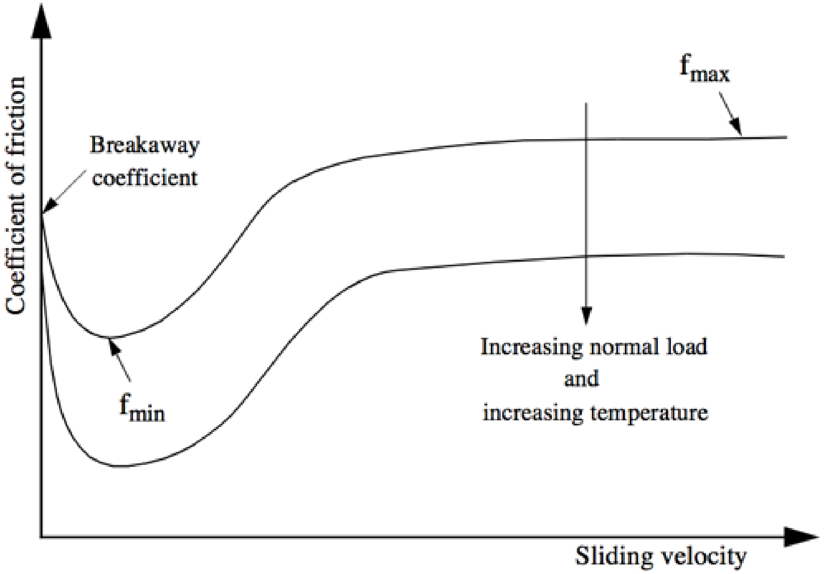


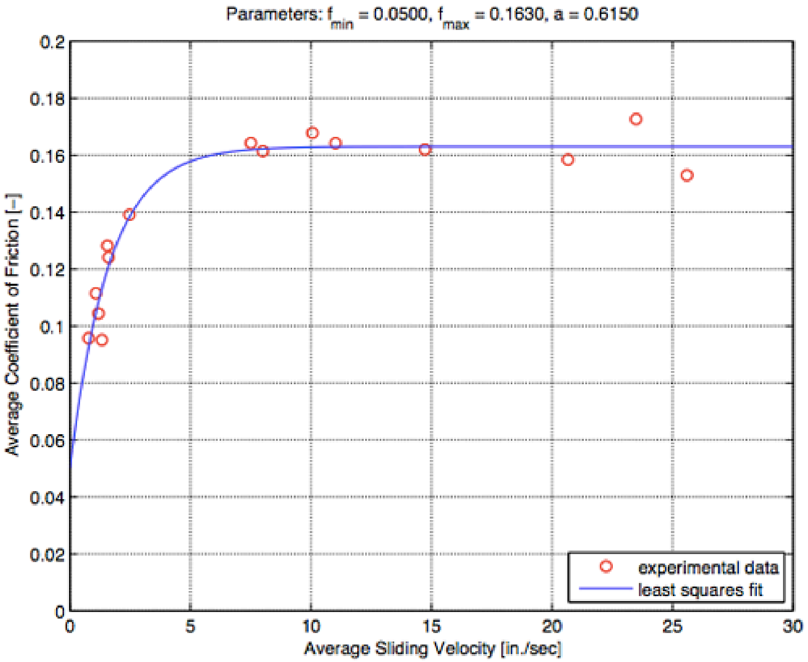
VelDependent Friction

```
frictionModel VelDependent $frnTag $muSlow $muFast $transRate
```

$frnTag	unique friction model object tag
$muSlow	coefficient of friction at low velocity
$muFast	coefficient of friction at high velocity
$transRate	transition rate from low to high velocity

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





VelNormalFrcDep Friction

frictionModel VelNormalFrcDep $frnTag $aSlow $nSlow $aFast $nFast $alpha0 $alpha1 $alpha2 $maxMuFact

$frnTag	unique friction model object tag
$aSlow	constant for coefficient of friction at low velocity
$nSlow	exponent for coefficient of friction at low velocity
$aFast	constant for coefficient of friction at high velocity
$nFast	exponent for coefficient of friction at high velocity
$alpha0	constant rate parameter coefficient
$alpha1	linear rate parameter coefficient
$alpha2	quadratic rate parameter coefficient
$maxMuFact	factor for determining the maximum coefficient of friction. This value prevents the friction coefficient from exceeding force becomes very small. The ma μFast, for example μ ≤ $maxMuFa

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

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

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

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

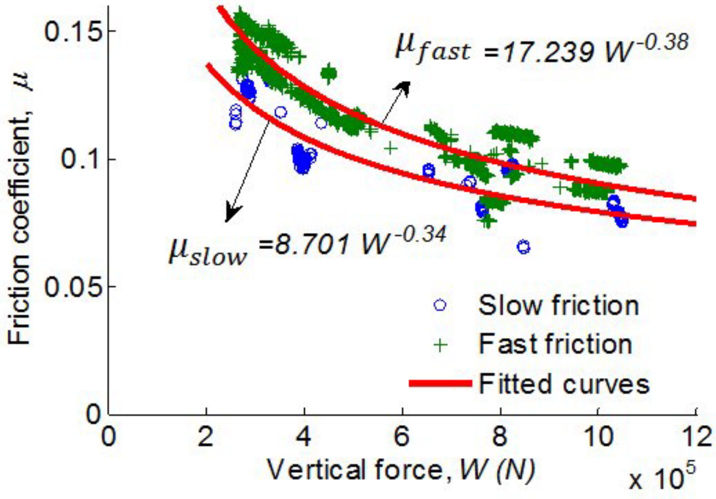
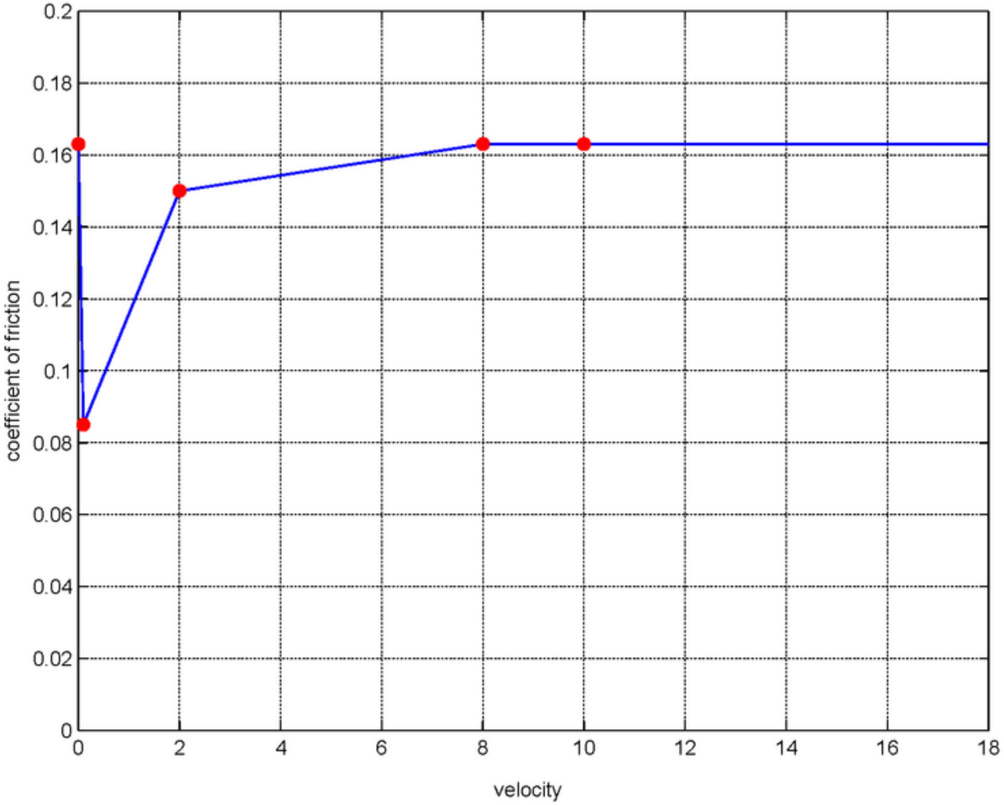


Figure 3: Friction coefficient vs. vertical force

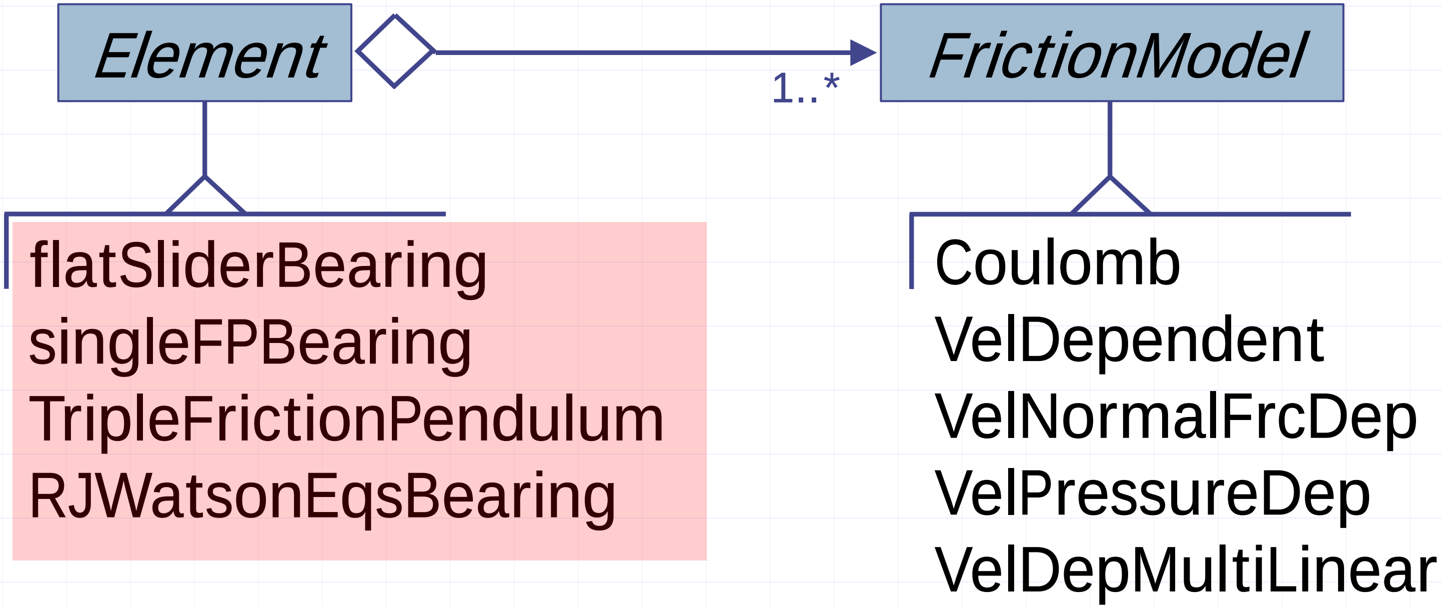
VelNormalFrcDep Friction

```
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

1..*

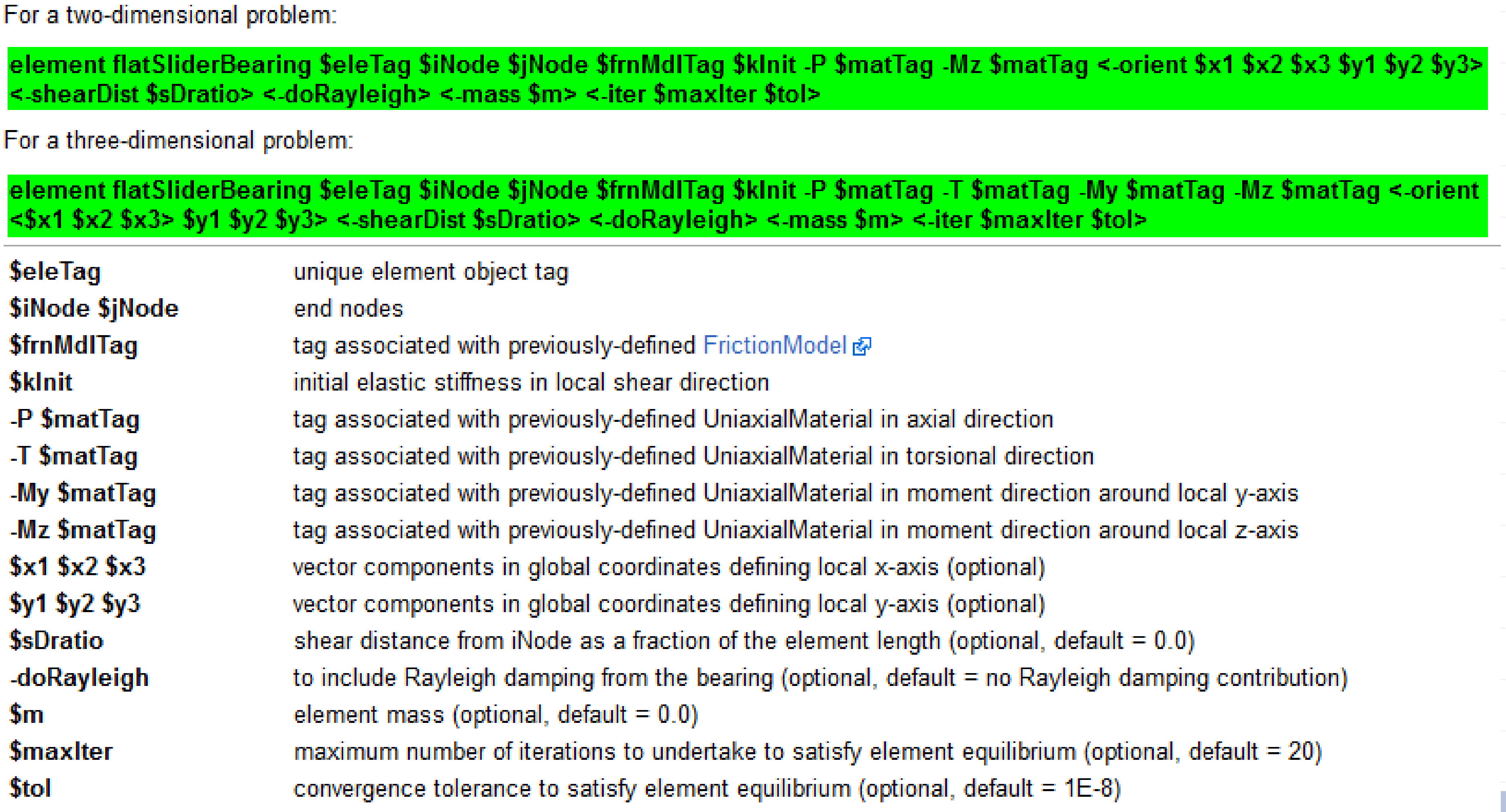
FrictionModel

flatSliderBearing
singleFPBearing
TripleFrictionPendulum
RJWatsonEqsBearing

Coulomb
VelDependent
VelNormalFrcDep
VelPressureDep
VelDepMultiLinear

element eleType? arg1? ...

flatSliderBearing Element



For a two-dimensional problem:

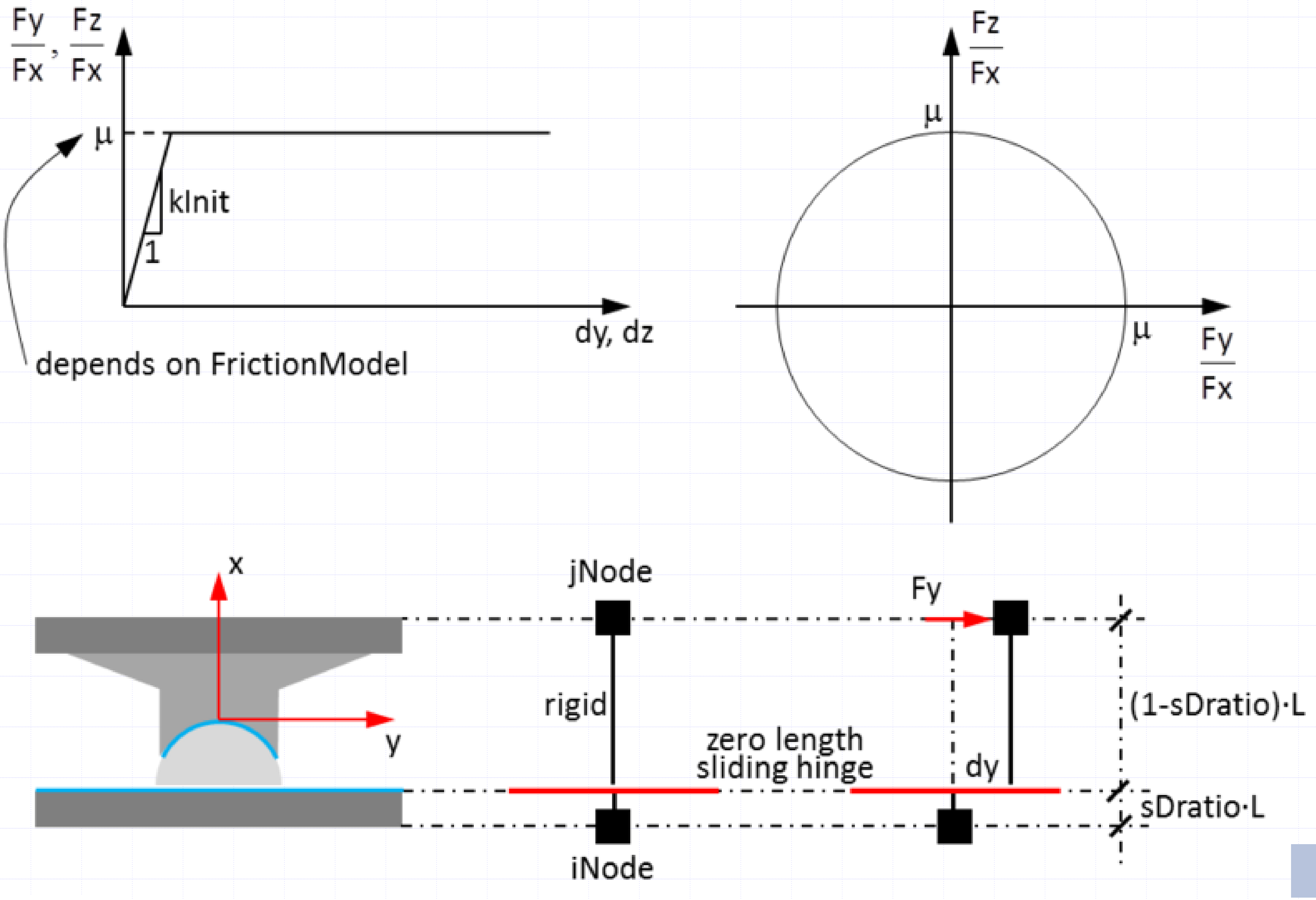
```
element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

For a three-dimensional problem:

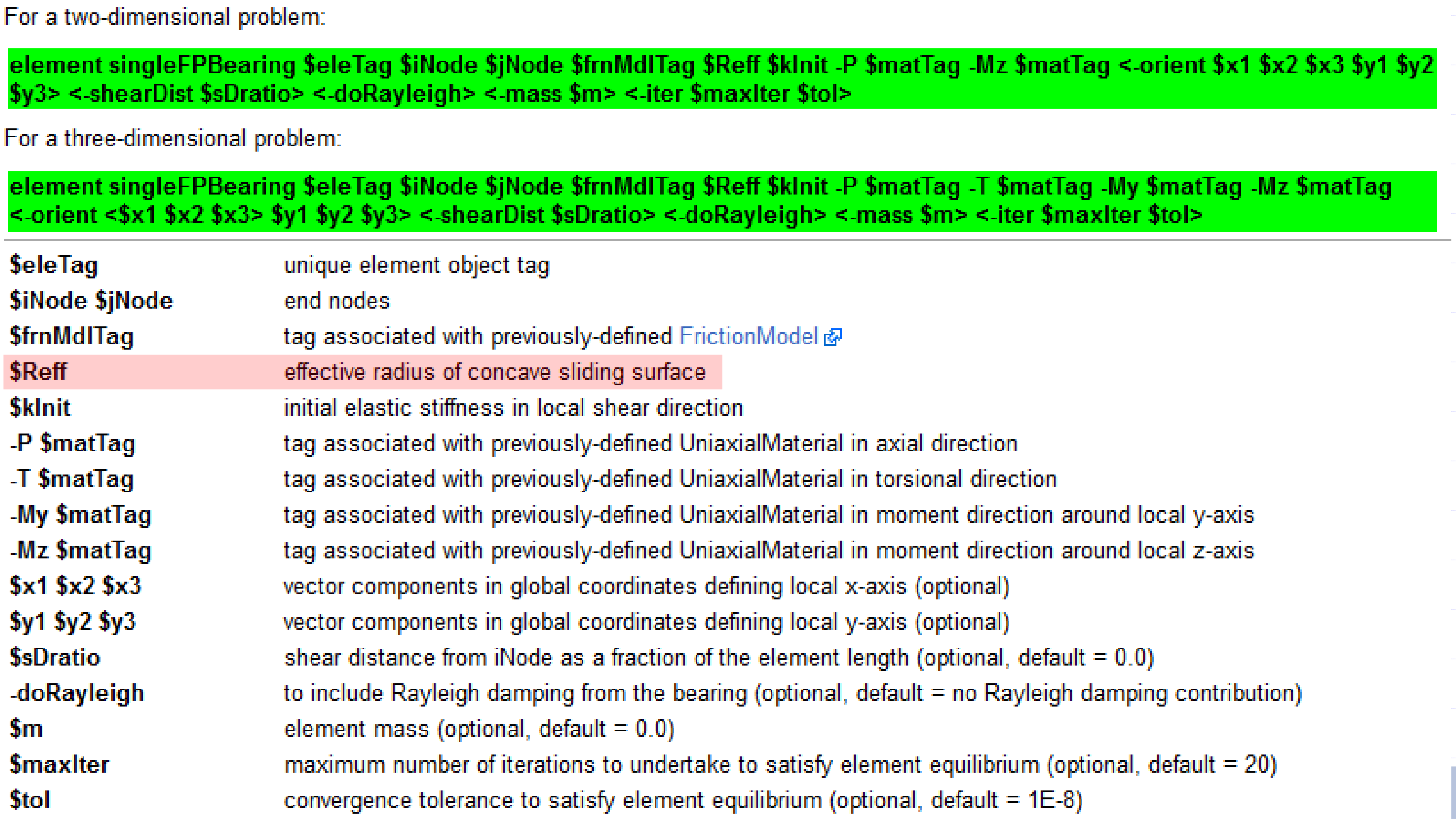
```
element flatSliderBearing $eleTag $iNode $jNode $frnMdlTag $kInit -P $matTag -T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

$eleTag	unique element object tag
$iNode $jNode	end nodes
$frnMdlTag	tag associated with previously-defined FrictionModel
$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)

flatSliderBearing Element



singleFPBearing Element



For a two-dimensional problem:

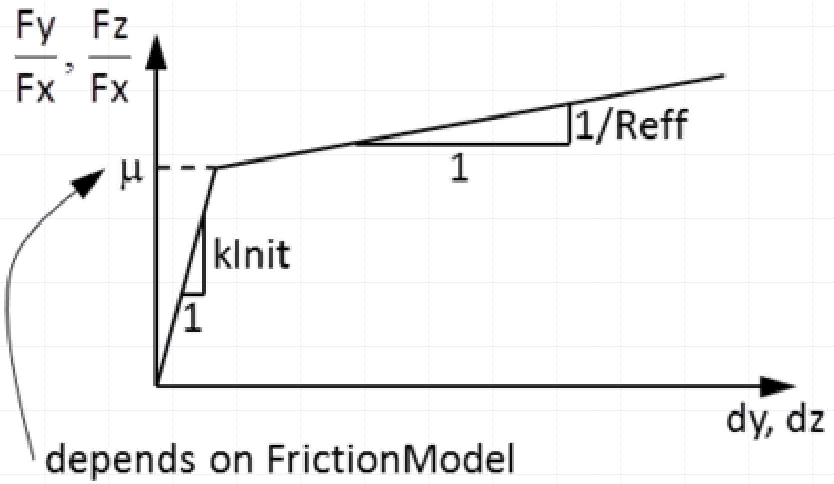
```
element singleFPBearing $eleTag $iNode $jNode $frnMdlTag $Reff $kInit -P $matTag -Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

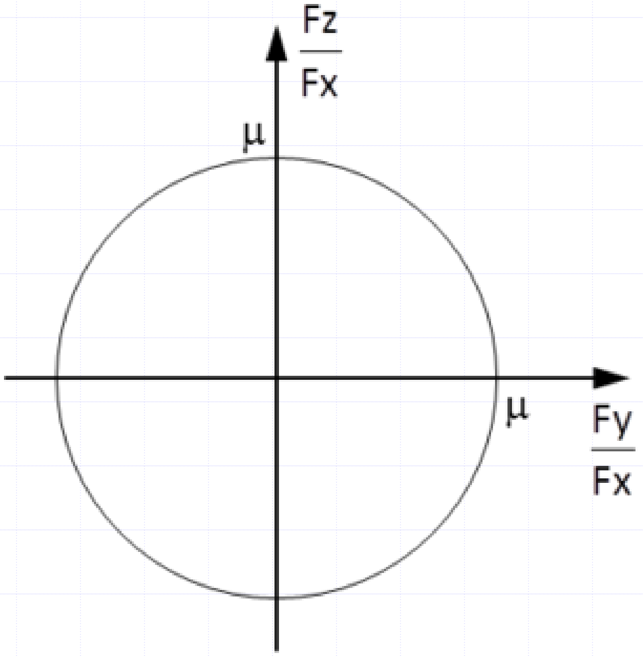
For a three-dimensional problem:

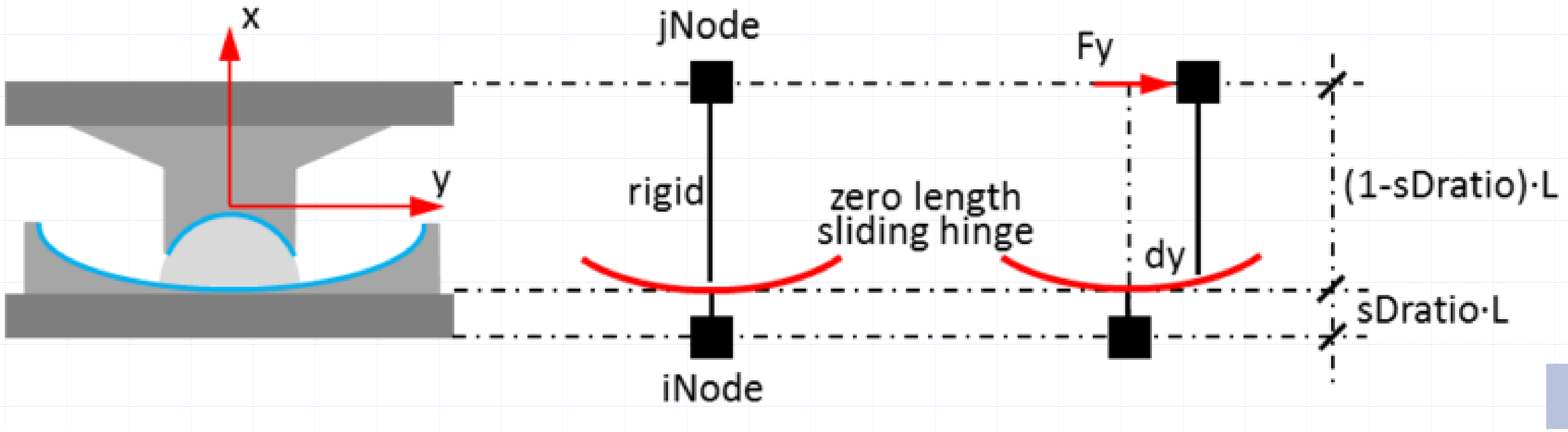
```
element singleFPBearing $eleTag $iNode $jNode $frnMdlTag $Reff $kInit -P $matTag -T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

$eleTag	unique element object tag
$iNode $jNode	end nodes
$frnMdlTag	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)

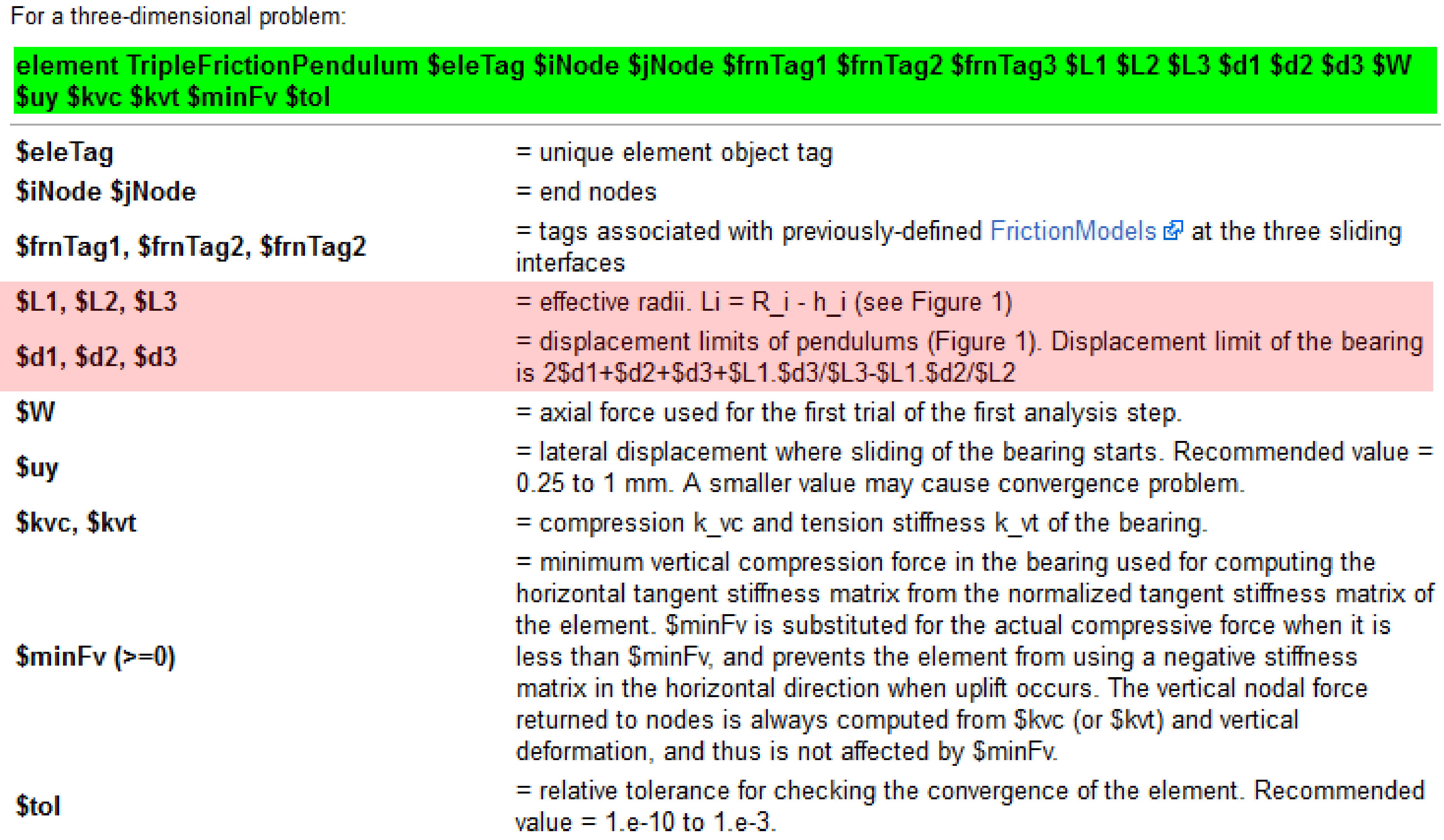
singleFPBearing Element







TripleFrictionPendulum Element

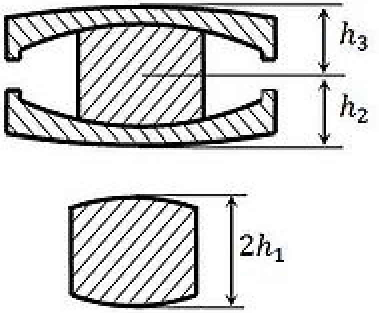


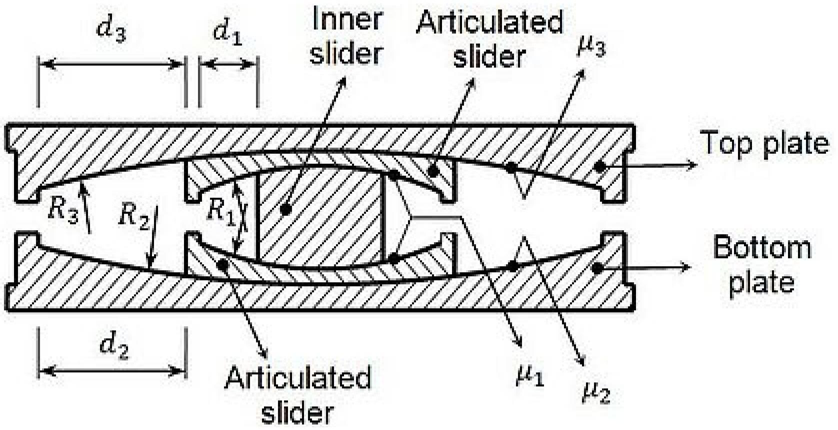
For a three-dimensional problem:

```
element TripleFrictionPendulum $eleTag $iNode $jNode $frnTag1 $frnTag2 $frnTag3 $L1 $L2 $L3 $d1 $d2 $d3 $W
$uy $kvc $kvt $minFv $tol
```

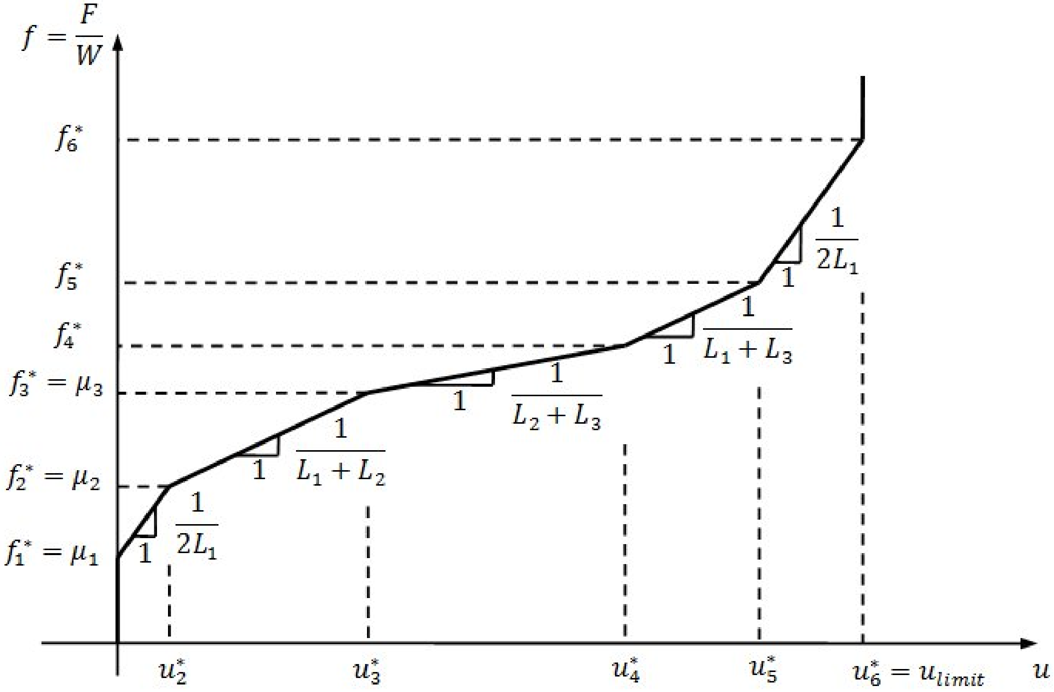
$eleTag	= unique element object tag
$iNode $jNode	= end nodes
$frnTag1, $frnTag2, $frnTag2	= tags associated with previously-defined FrictionModels at the three sliding interfaces
$L1, $L2, $L3	= effective radii. Li = R_i - h_i (see Figure 1)
$d1, $d2, $d3	= displacement limits of pendulums (Figure 1). Displacement limit of the bearing is 2$d1+$d2+$d3+$L1.$d3/$L3-$L1.$d2/$L2
$W	= axial force used for the first trial of the first analysis step.
$uy	= lateral displacement where sliding of the bearing starts. Recommended value = 0.25 to 1 mm. A smaller value may cause convergence problem.
$kvc, $kvt	= compression k_vc and tension stiffness k_vt of the bearing.
$minFv (>=0)	= 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.
$tol	= relative tolerance for checking the convergence of the element. Recommended value = 1.e-10 to 1.e-3.

TripleFrictionPendulum Element



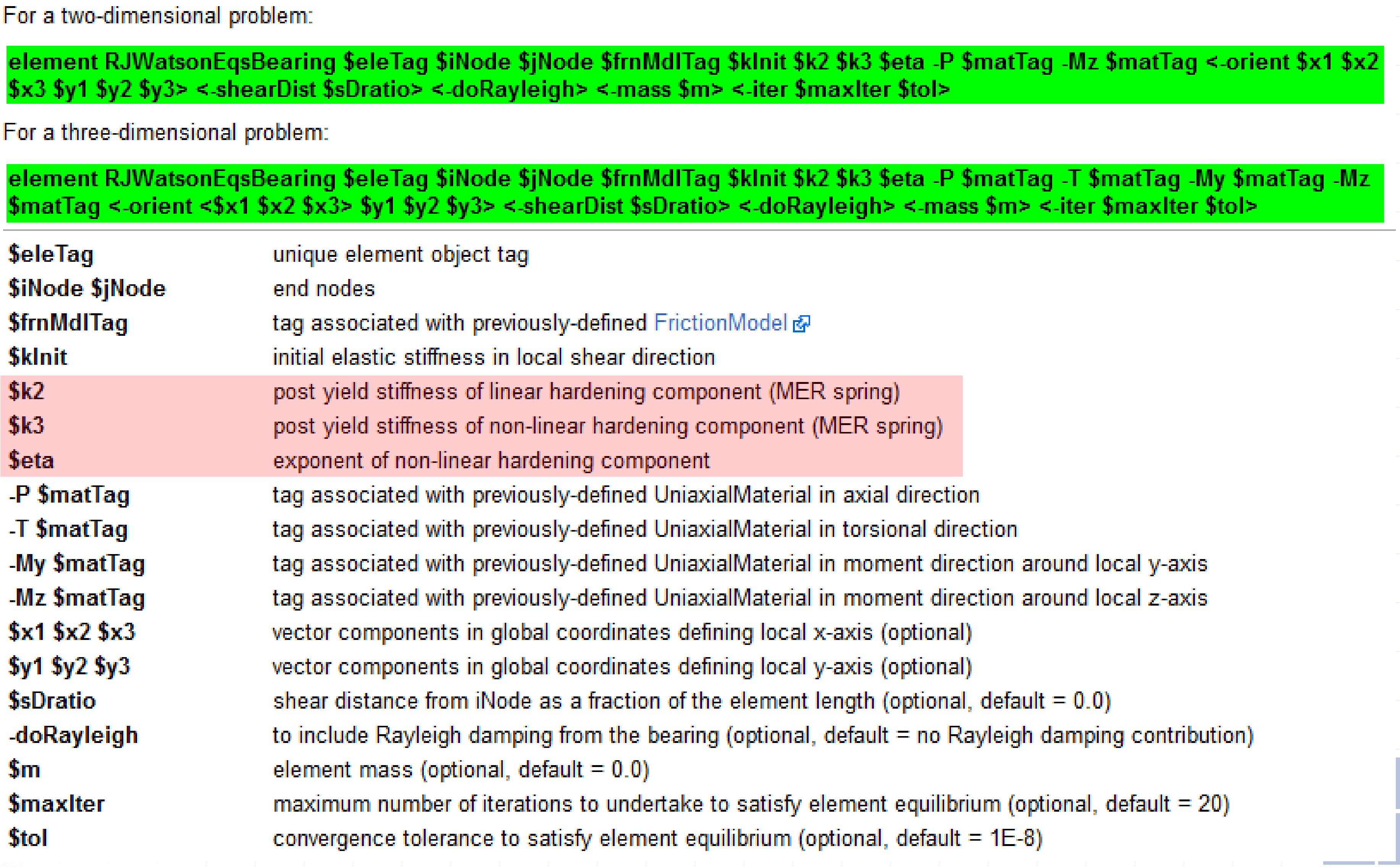


$$L_i = R_i - h_i$$



TripleFrictionPendulum Test

RJWatsonEqsBearing Element



For a two-dimensional problem:

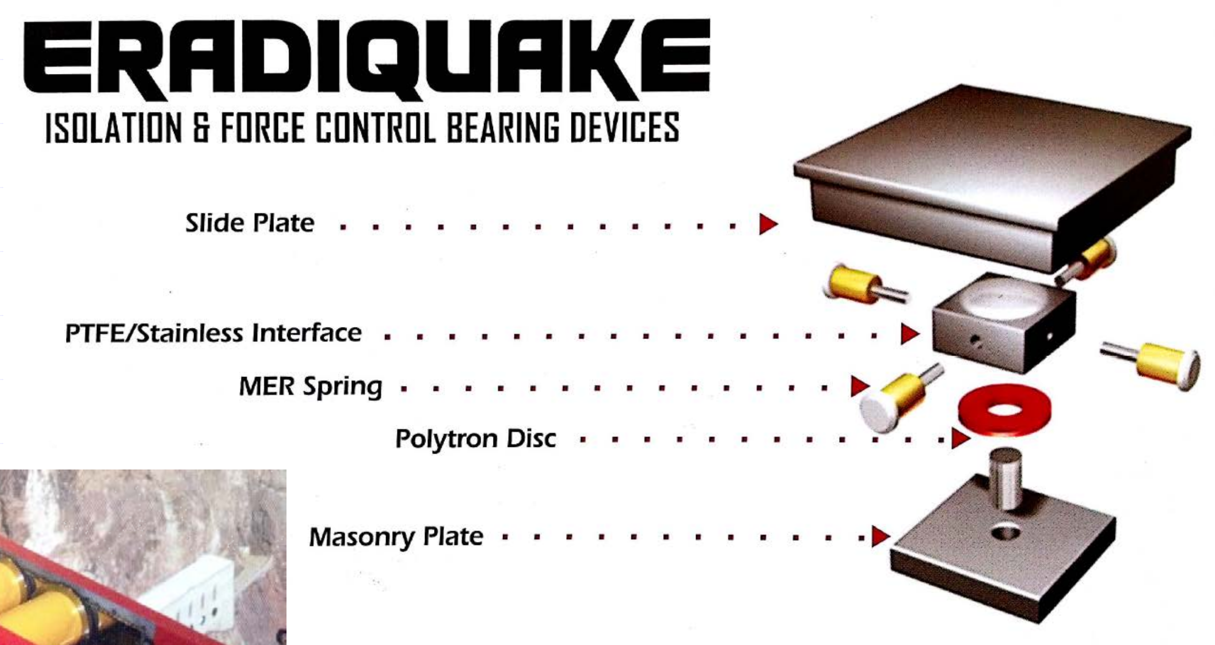
```
element RJWatsonEqsBearing $eleTag $iNode $jNode $frnMdlTag $kInit $k2 $k3 $eta -P $matTag -Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

For a three-dimensional problem:

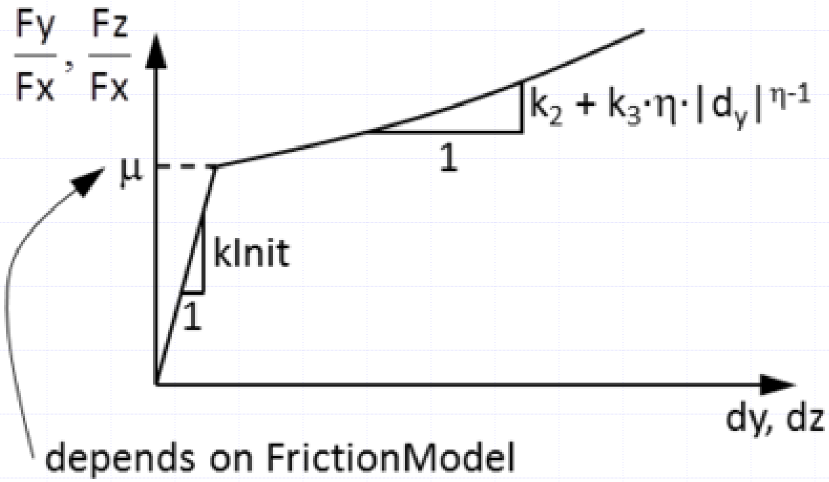
```
element RJWatsonEqsBearing $eleTag $iNode $jNode $frnMdlTag $kInit $k2 $k3 $eta -P $matTag -T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m> <-iter $maxIter $tol>
```

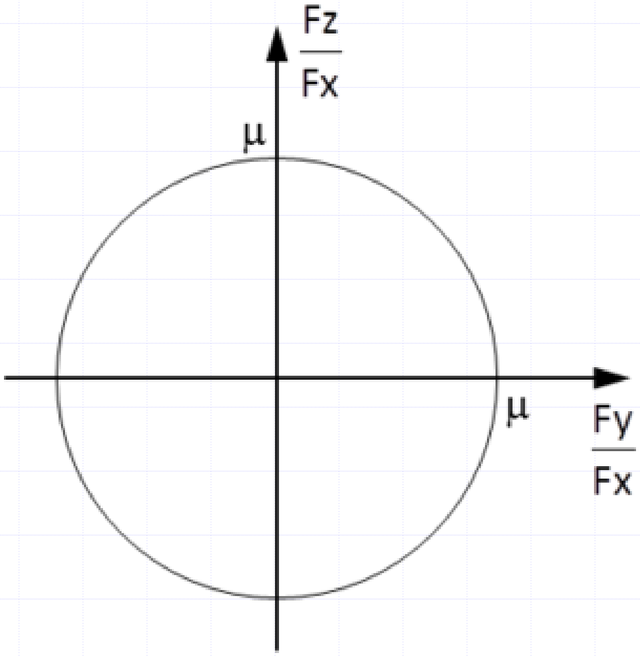
$eleTag	unique element object tag
$iNode $jNode	end nodes
$frnMdlTag	tag associated with previously-defined FrictionModel
$kInit	initial elastic stiffness in local shear direction
$k2	post yield stiffness of linear hardening component (MER spring)
$k3	post yield stiffness of non-linear hardening component (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)

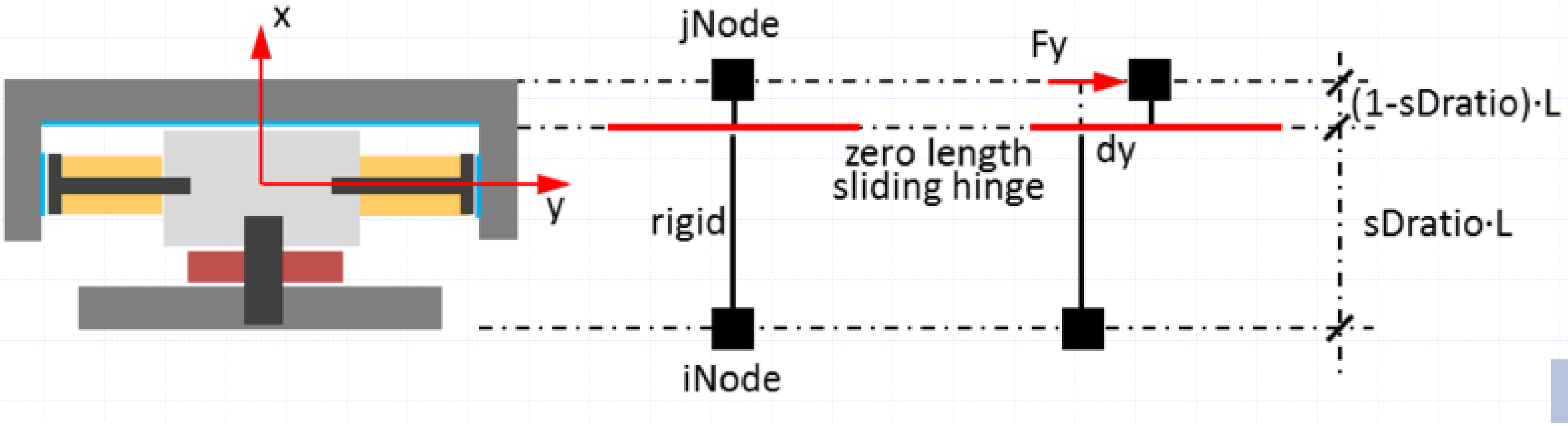
RJWatsonEqsBearing Element



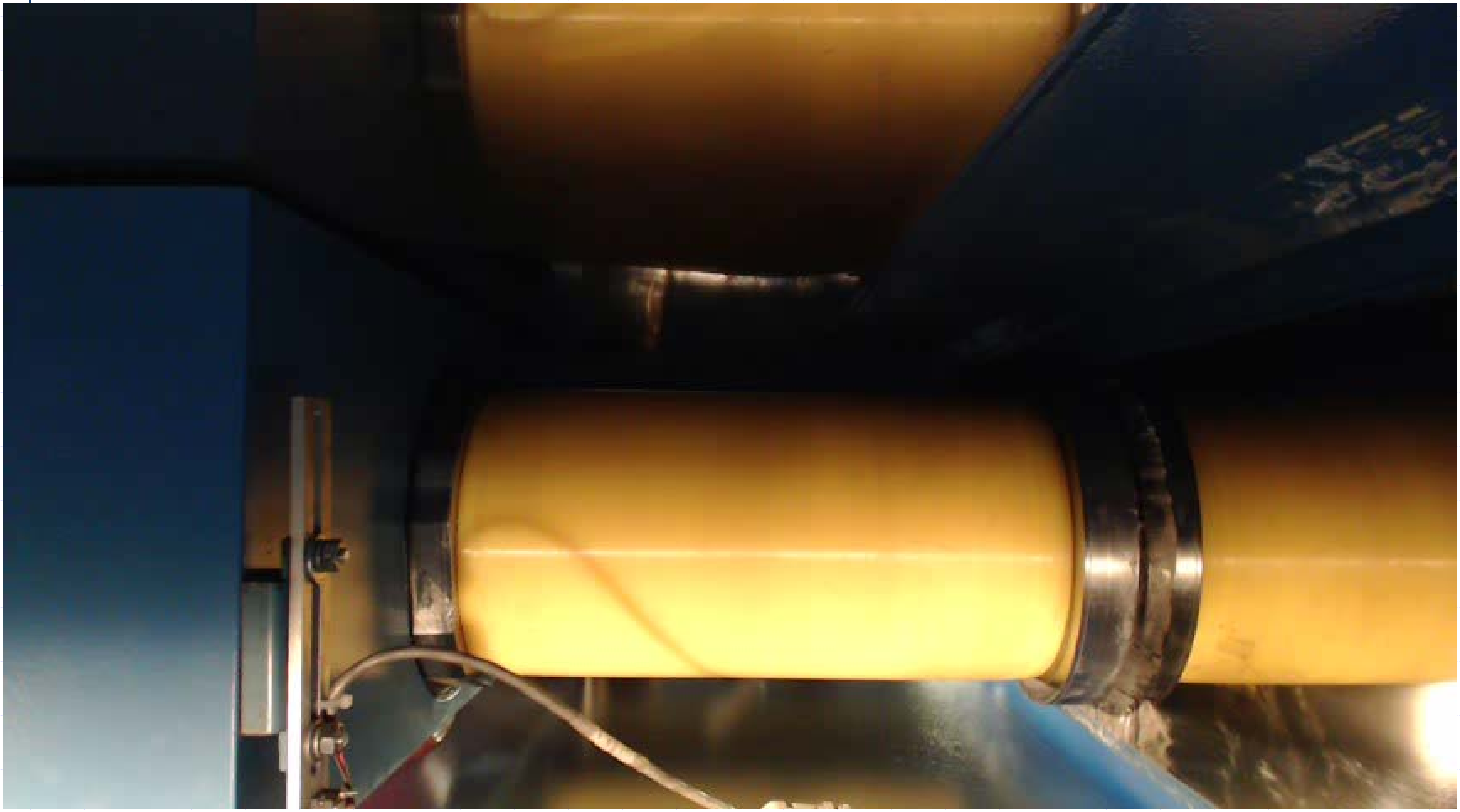
RJWatsonEqsBearing Element







RJWatsonEqsBearing Test



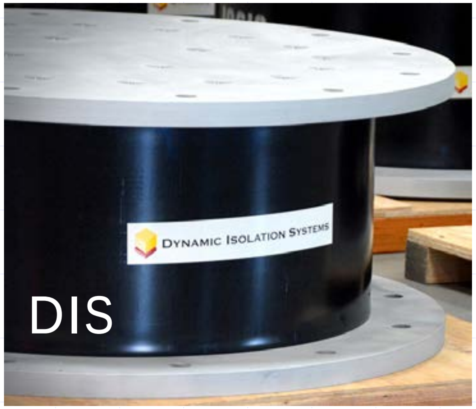
Important Modelling Considerations

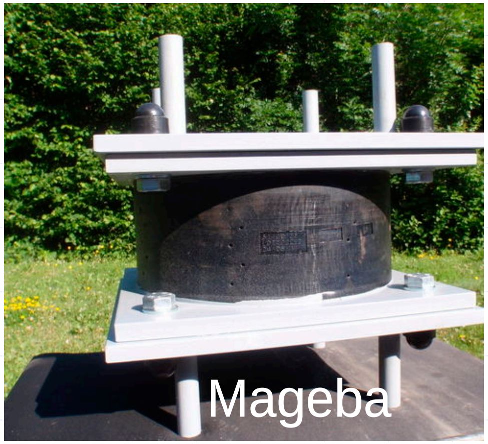
- All the friction based elements need an axial load on them to be able to provide shear resistance -> apply gravity loads
- Due to the vertical-horizontal coupling it is very important to -> provide realistic axial stiffness (not just some large value)
- Shear forces are affected by axial loads and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

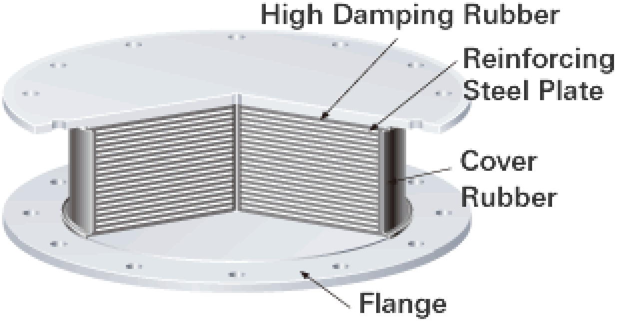
Important Modelling Considerations

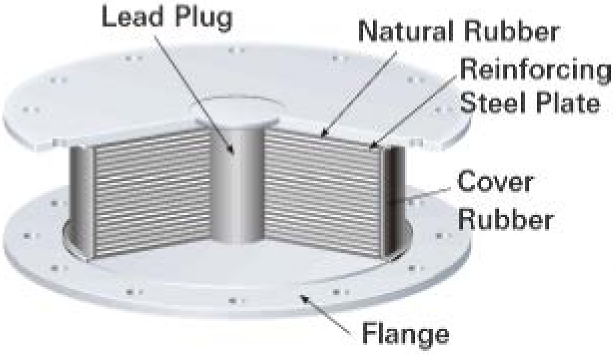
- If there is uplift (and therefore impact) in the friction based bearing elements-> consider using an integration method that provides numerical damping
- If possible (depends on element) -> provide some viscous damping in the axial bearing direction
- avoid the introduction of artificial viscous damping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

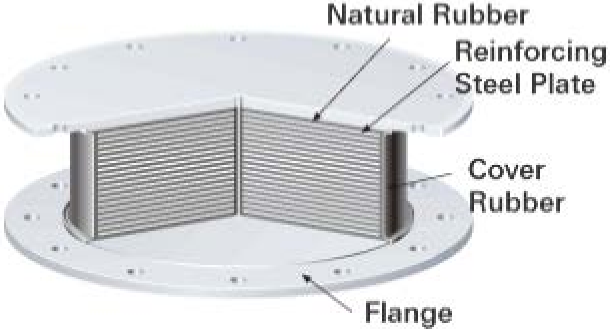
Elastomer Based Isolators

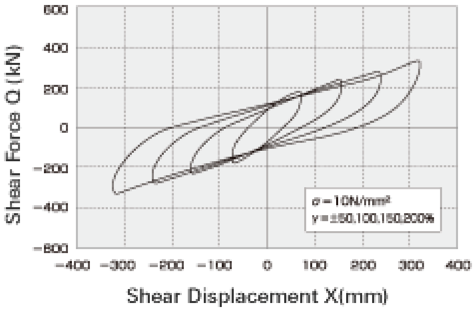


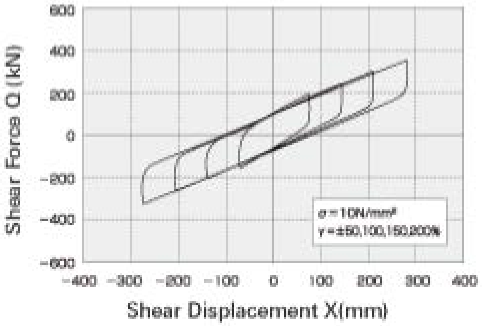


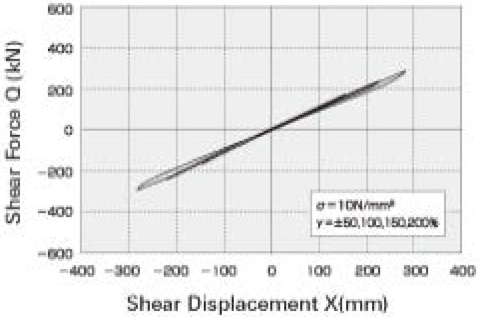




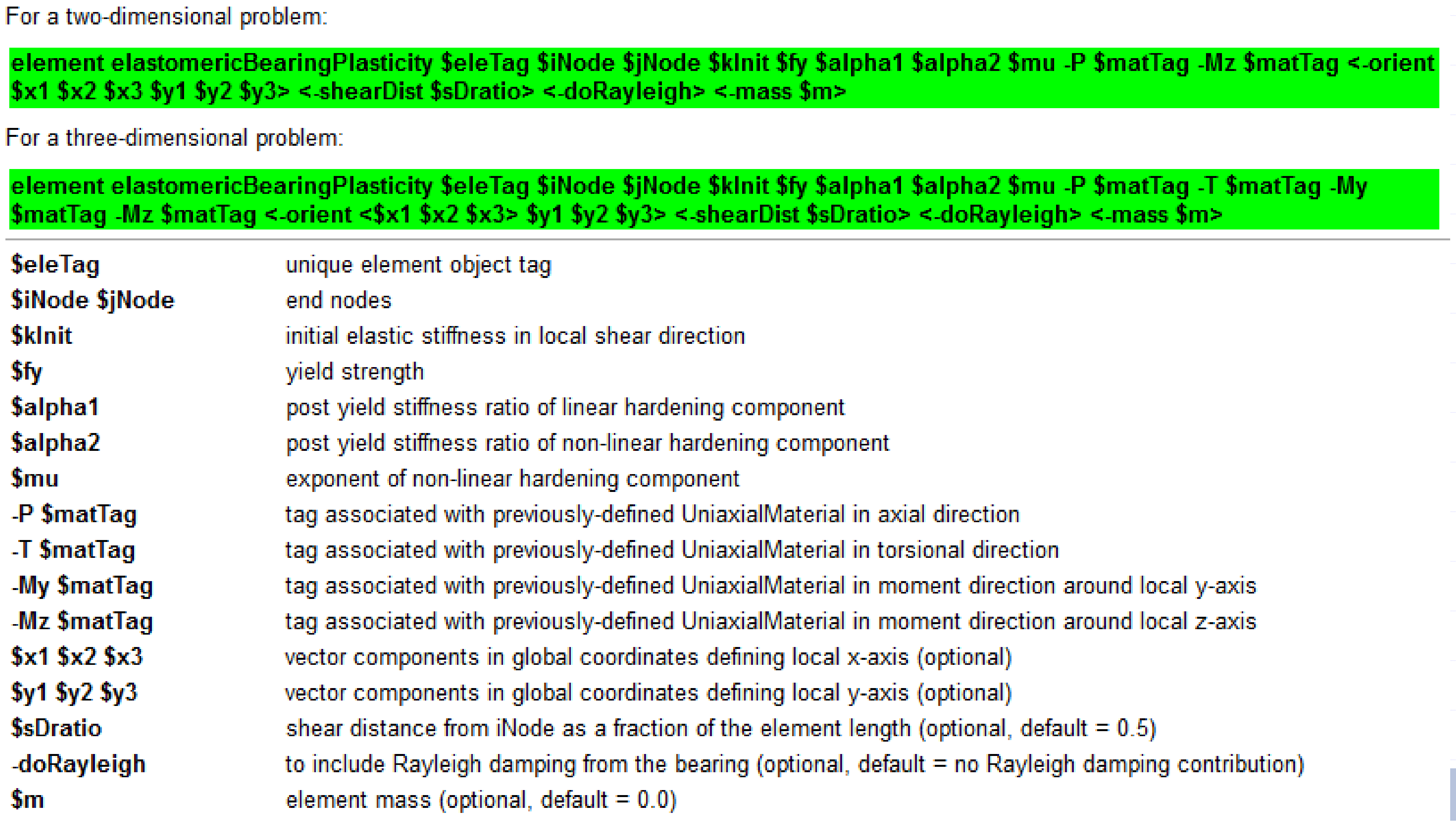








elastomericBearingPlasticity Elem.



For a two-dimensional problem:

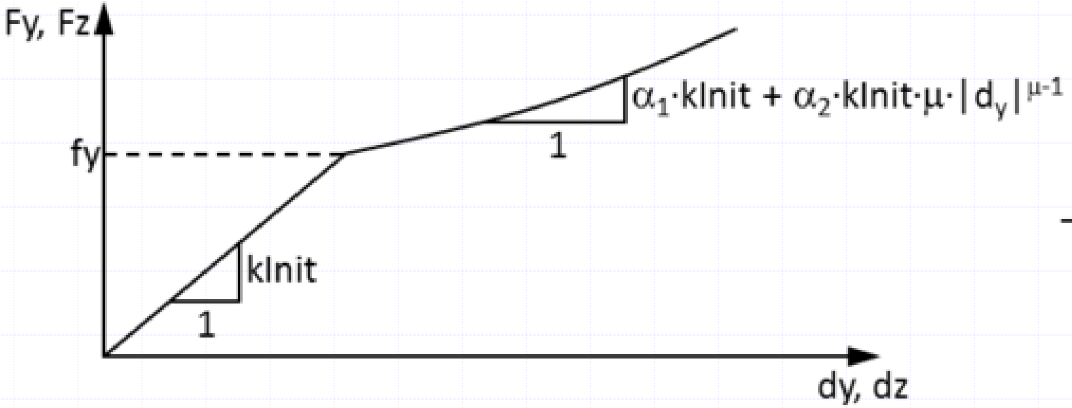
```
element elastomericBearingPlasticity $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu -P $matTag -Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

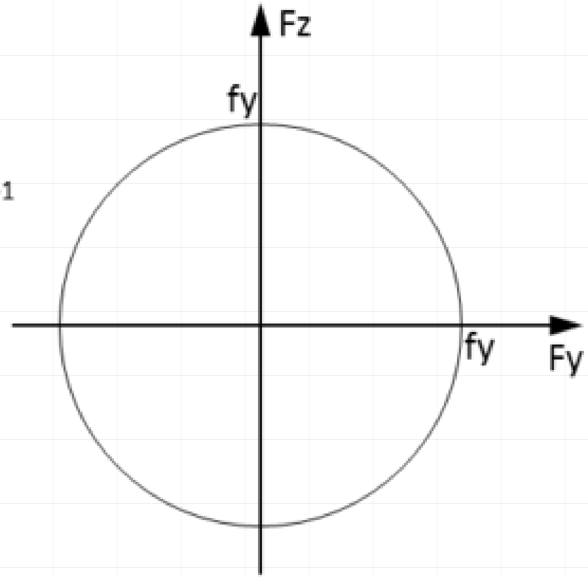
For a three-dimensional problem:

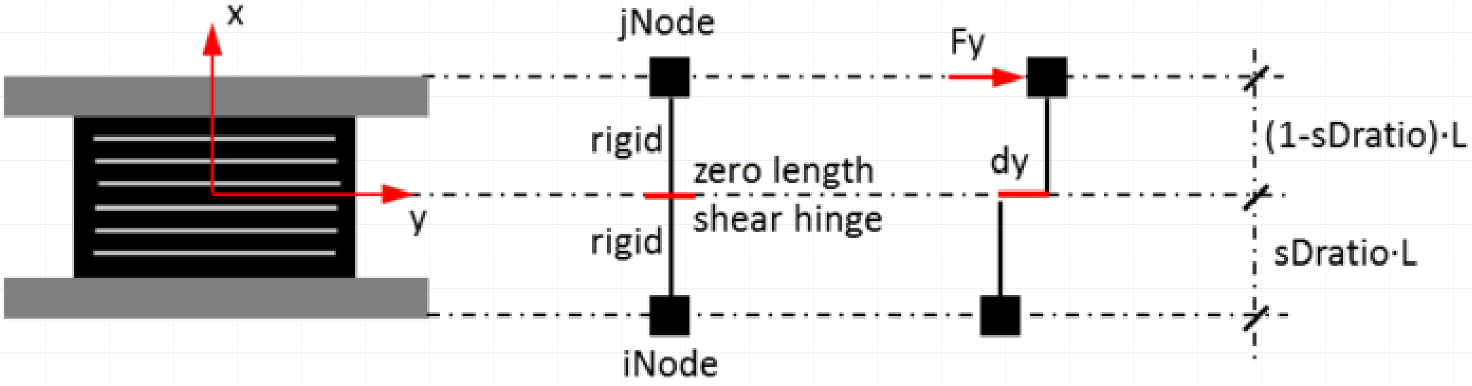
```
element elastomericBearingPlasticity $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu -P $matTag -T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

$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)

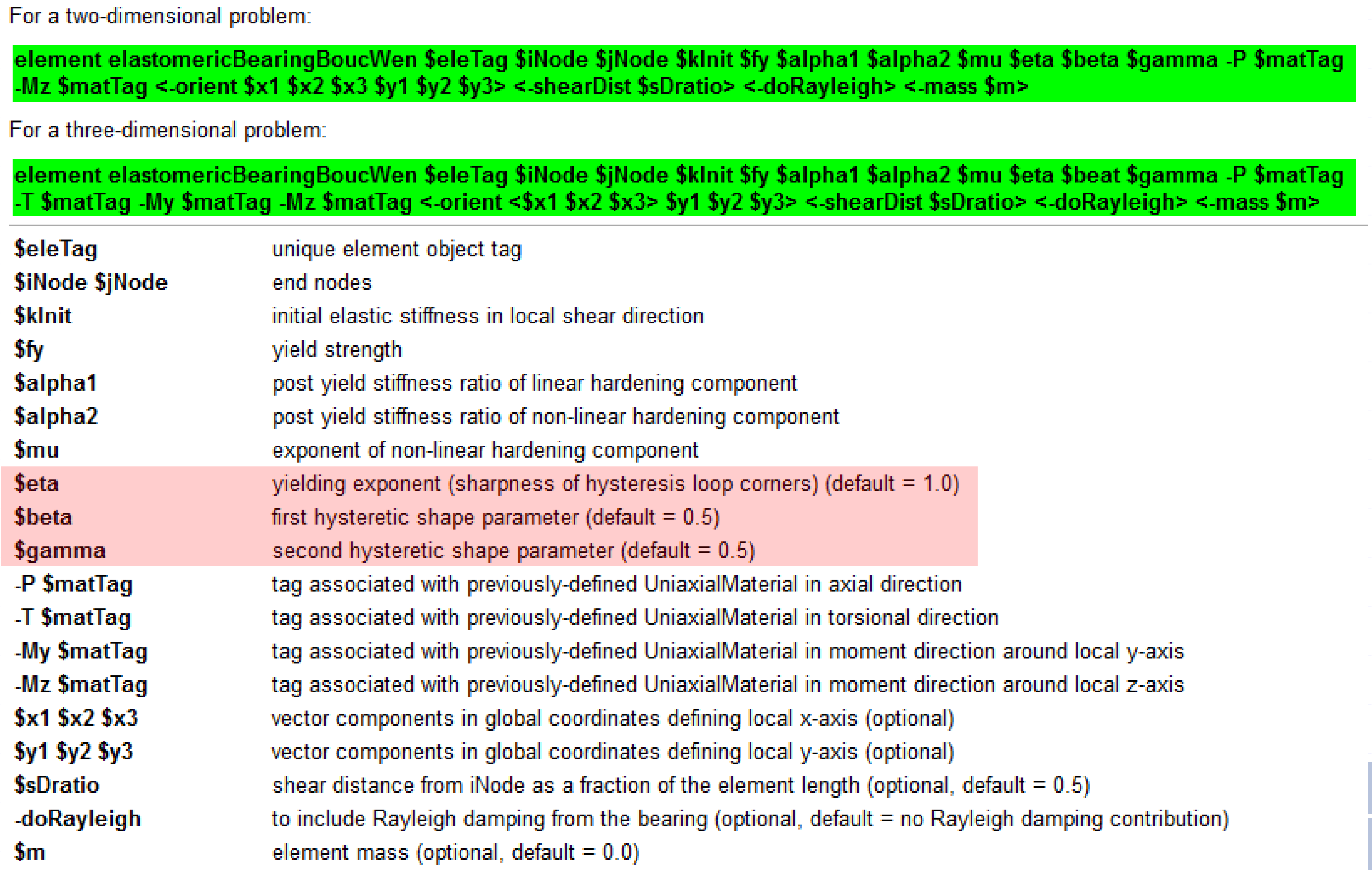
elastomericBearingPlasticity Elem.







elastomericBearingBoucWen Elem.



For a two-dimensional problem:

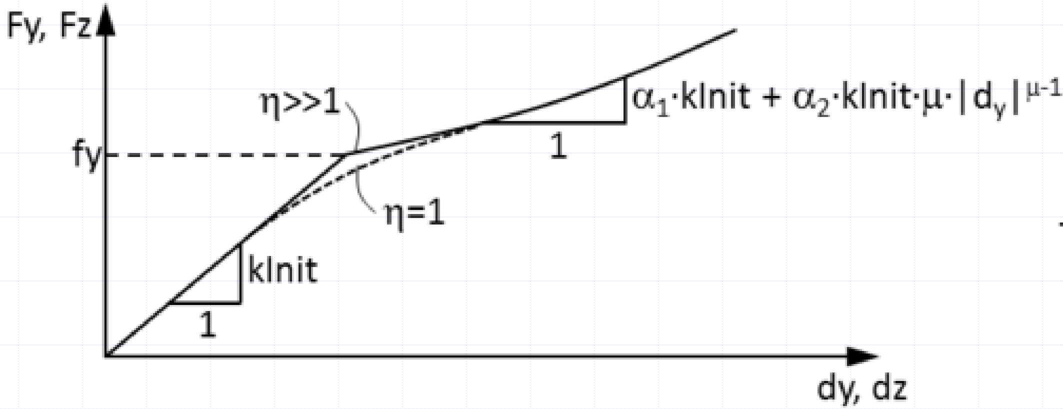
```
element elastomericBearingBoucWen $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu $eta $beta $gamma -P $matTag
-Mz $matTag <-orient $x1 $x2 $x3 $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

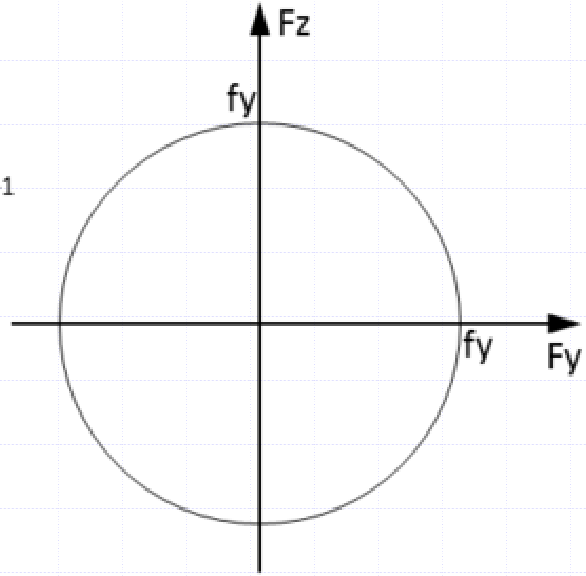
For a three-dimensional problem:

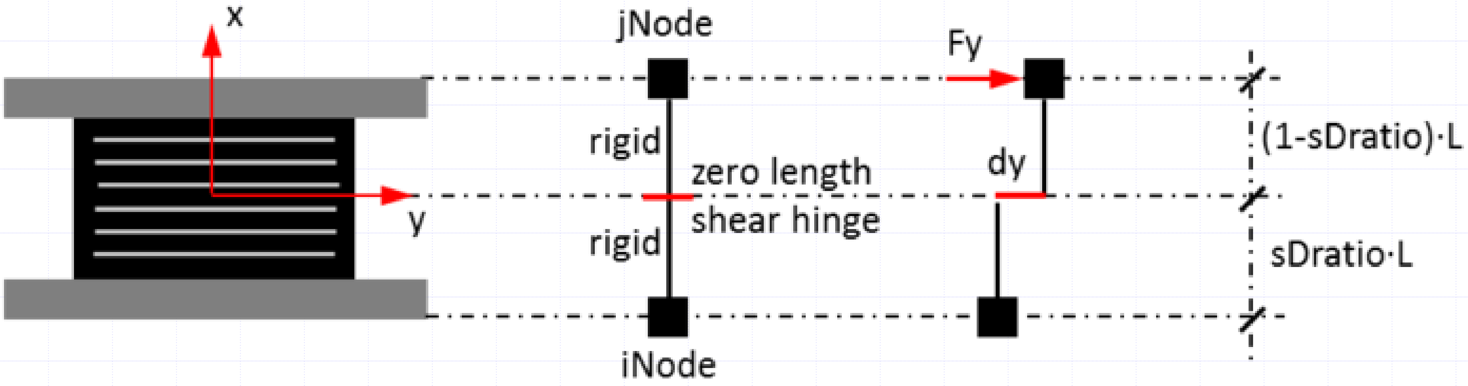
```
element elastomericBearingBoucWen $eleTag $iNode $jNode $kInit $fy $alpha1 $alpha2 $mu $eta $beat $gamma -P $matTag
-T $matTag -My $matTag -Mz $matTag <-orient <$x1 $x2 $x3> $y1 $y2 $y3> <-shearDist $sDratio> <-doRayleigh> <-mass $m>
```

$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)

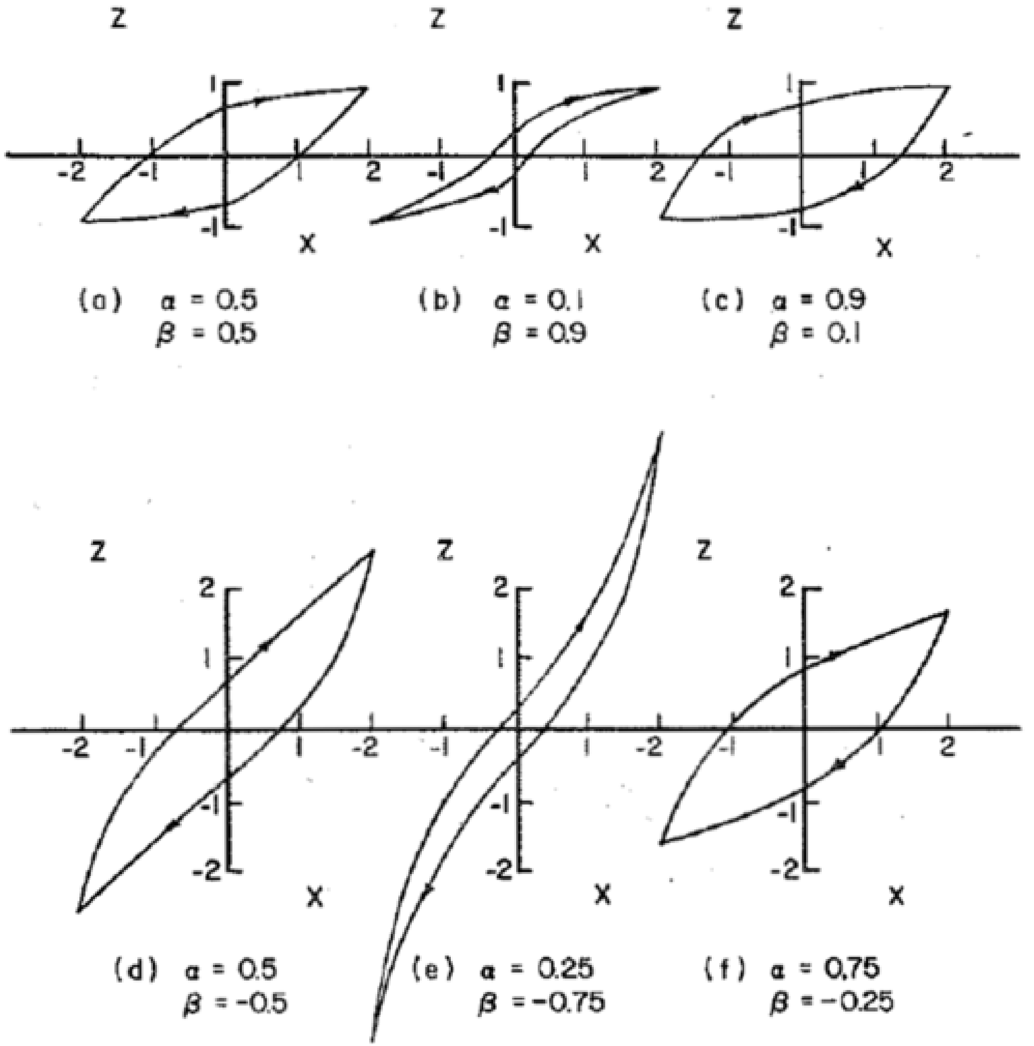
elastomericBearingBoucWen Elem.





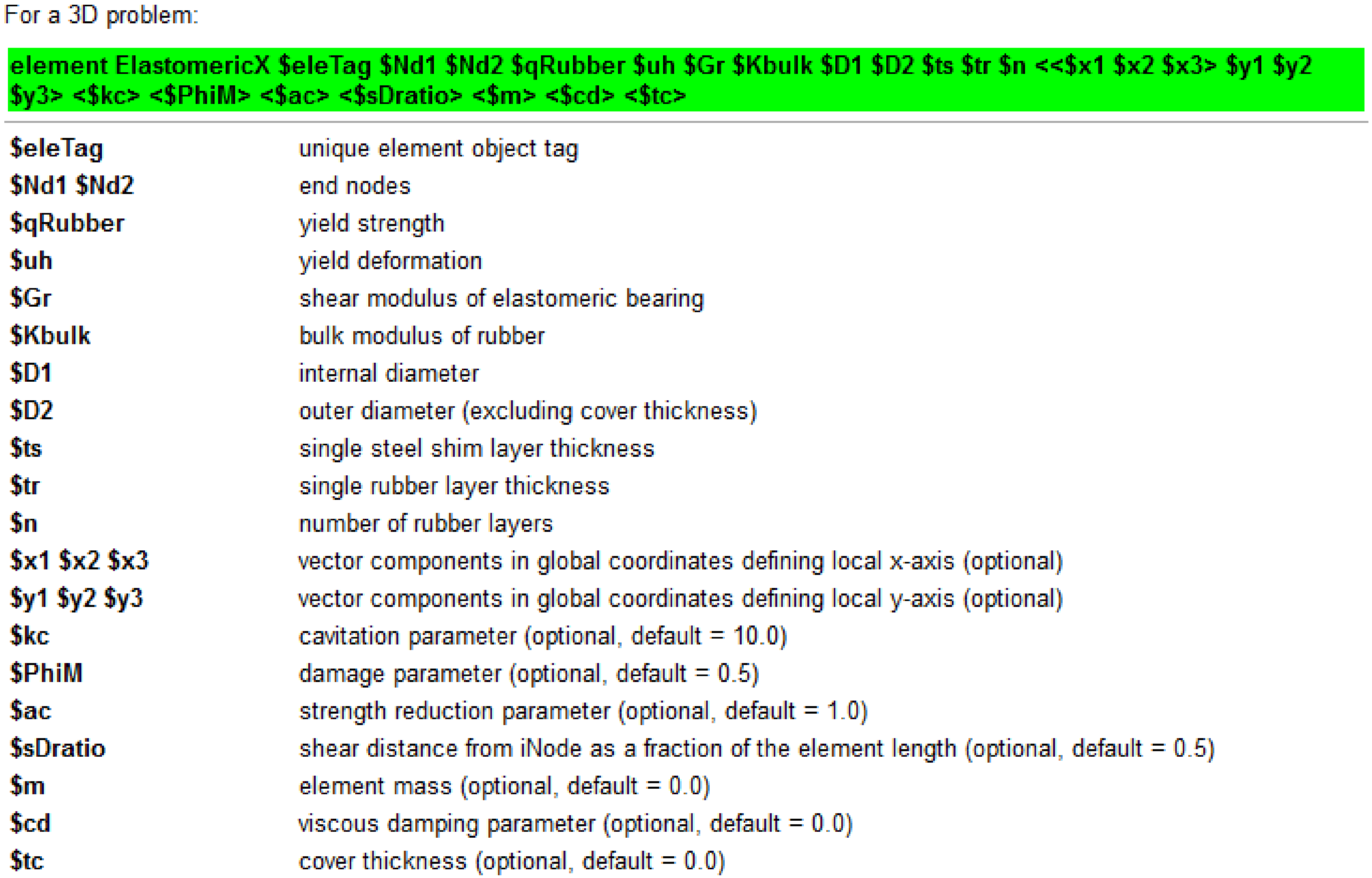


elastomericBearingBoucWen Elem.



$(\alpha_{Wen} = \beta_{OPS}, \beta_{Wen} = \gamma_{OPS})$ from Wen, 1976

elastomericX Element



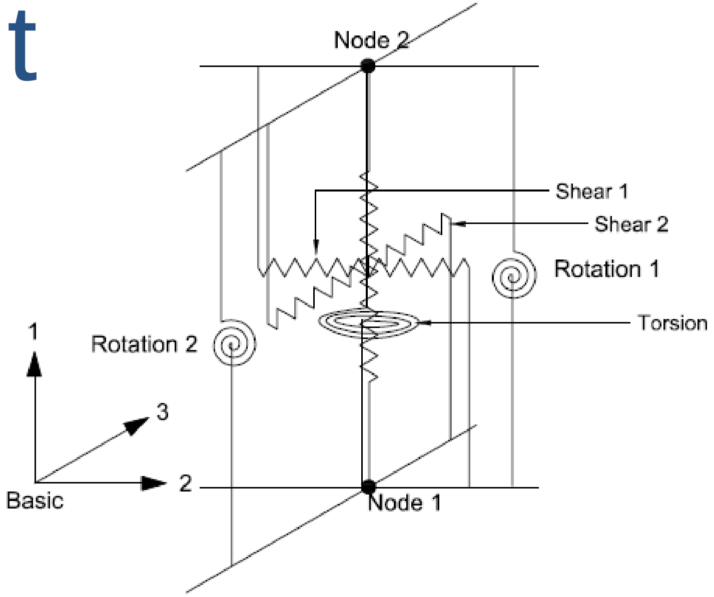
For a 3D problem:

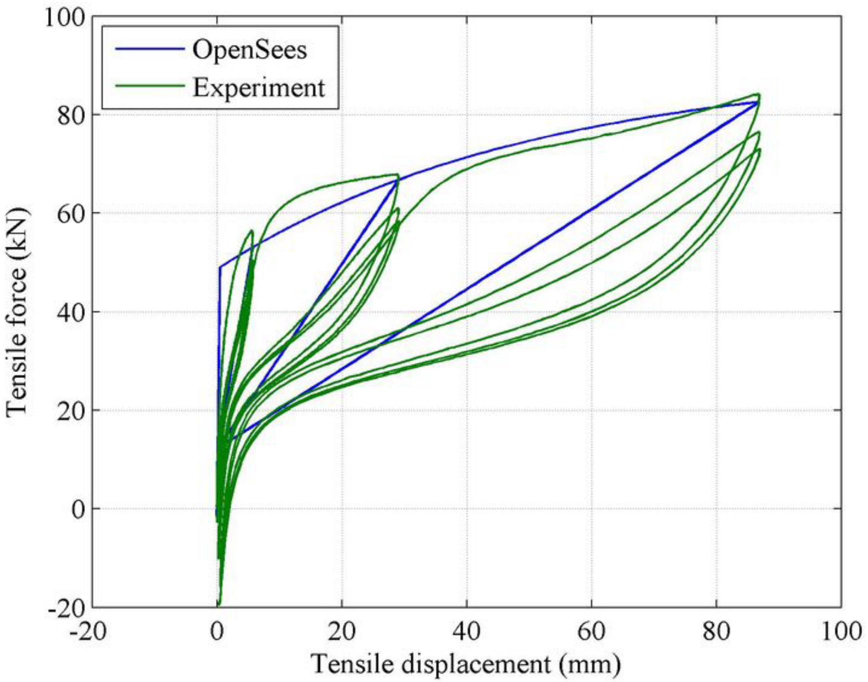
```
element ElastomericX $eleTag $Nd1 $Nd2 $qRubber $uh $Gr $Kbulk $D1 $D2 $ts $tr $n <<$x1 $x2 $x3> $y1 $y2 $y3> <$kc> <$PhiM> <$ac> <$sDratio> <$m> <$cd> <$tc>
```

$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)

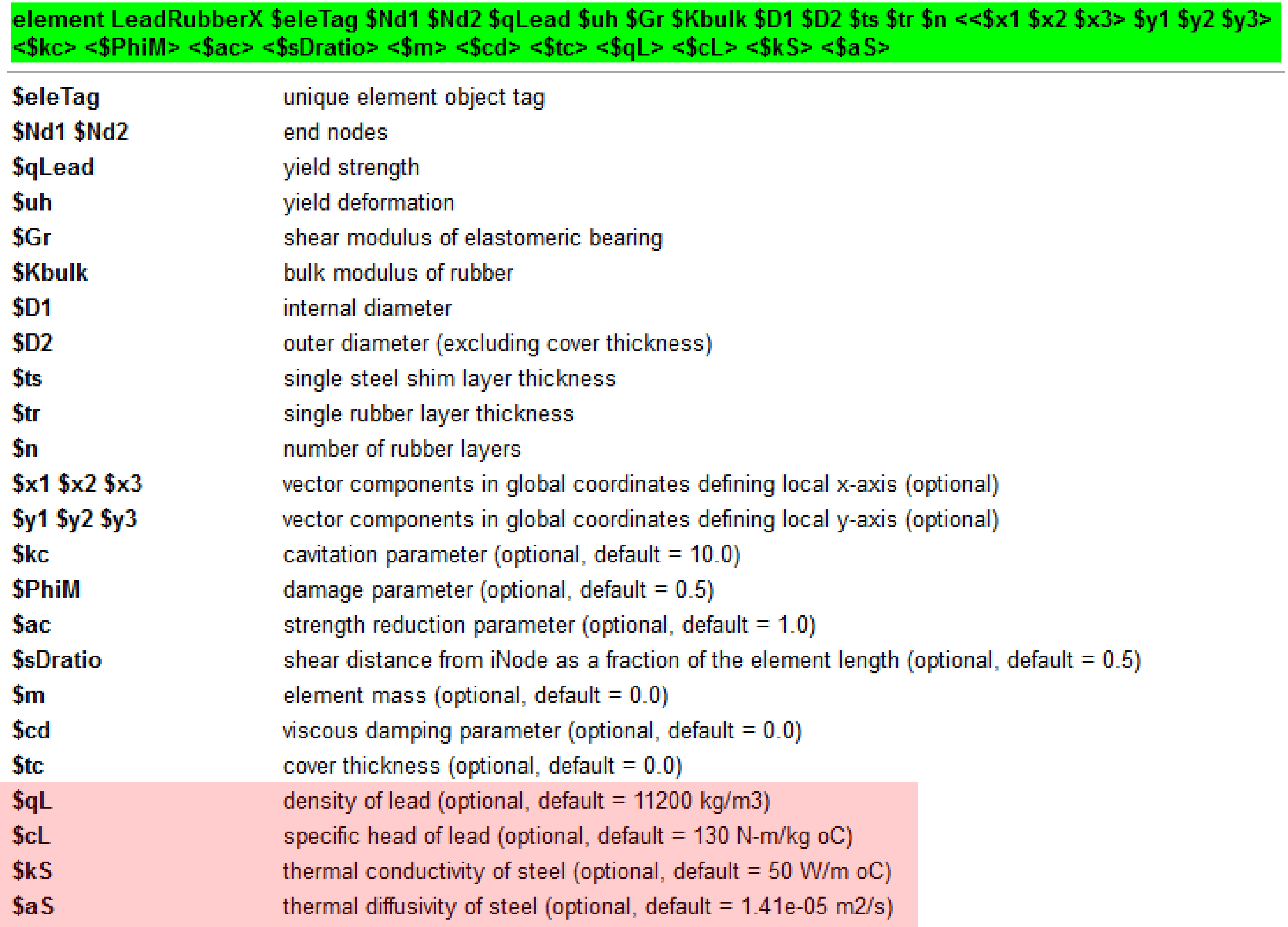
elastomericX Element

- 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

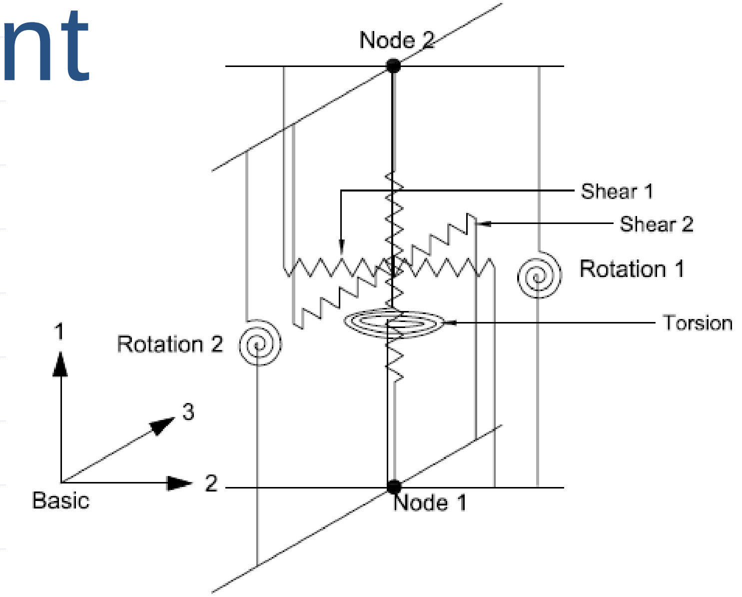


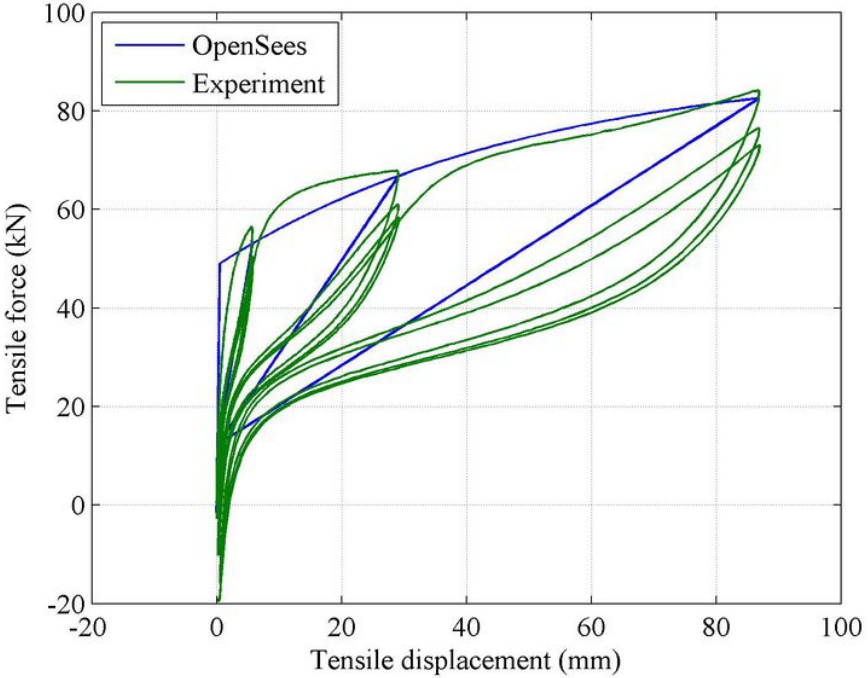
```
element LeadRubberX $eleTag $Nd1 $Nd2 $qLead $uh $Gr $Kbulk $D1 $D2 $ts $tr $n <<$x1 $x2 $x3> $y1 $y2 $y3>
<$kc> <$PhiM> <$ac> <$sDratio> <$m> <$cd> <$tc> <$qL> <$cL> <$kS> <$aS>
```

$eleTag	unique element object tag
$Nd1 $Nd2	end nodes
$qLead	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)
$qL	density of lead (optional, default = 11200 kg/m3)
$cL	specific head of lead (optional, default = 130 N-m/kg oC)
$kS	thermal conductivity of steel (optional, default = 50 W/m oC)
$aS	thermal diffusivity of steel (optional, default = 1.41e-05 m2/s)

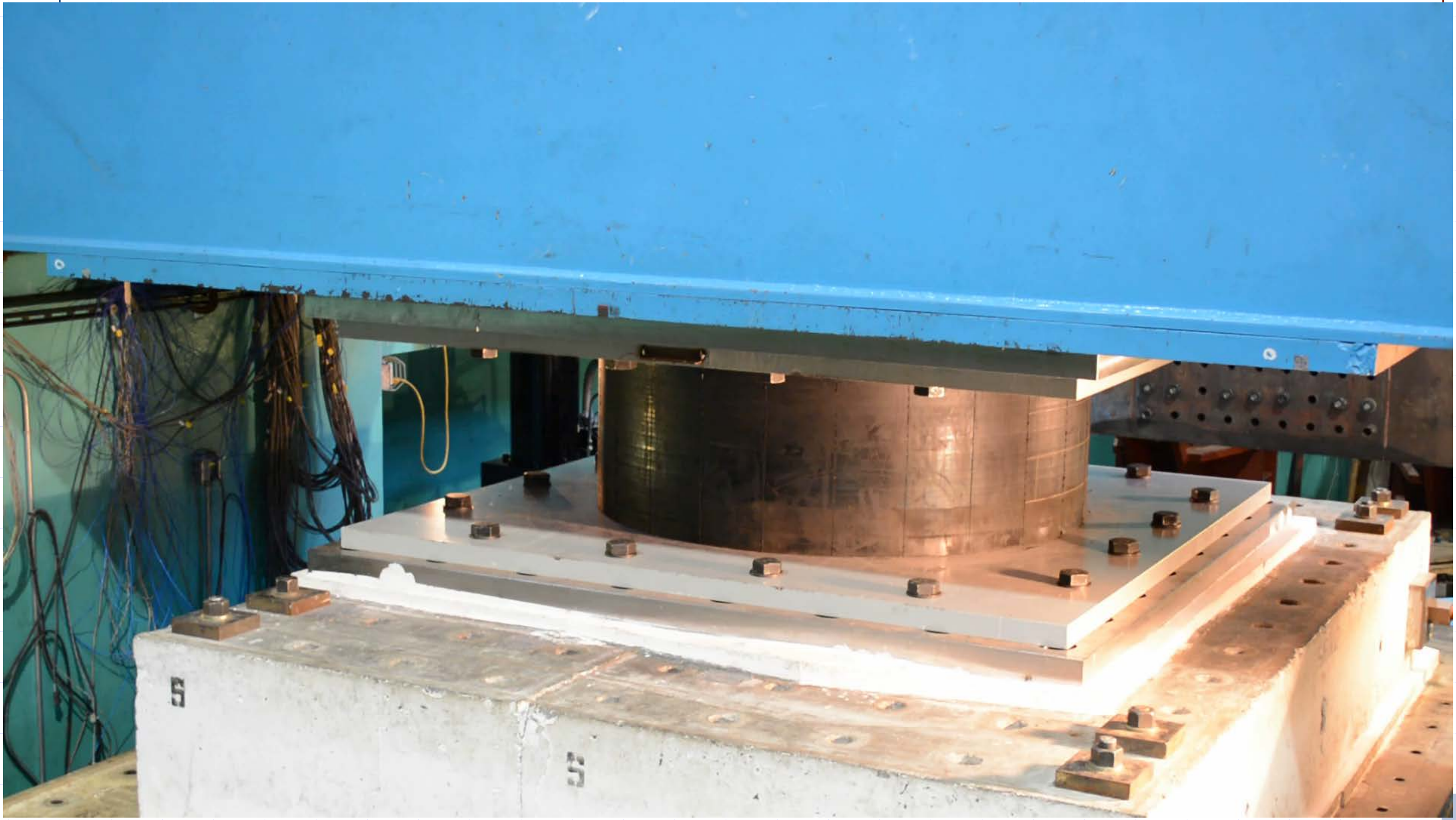
LeadRubberX Element

- 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

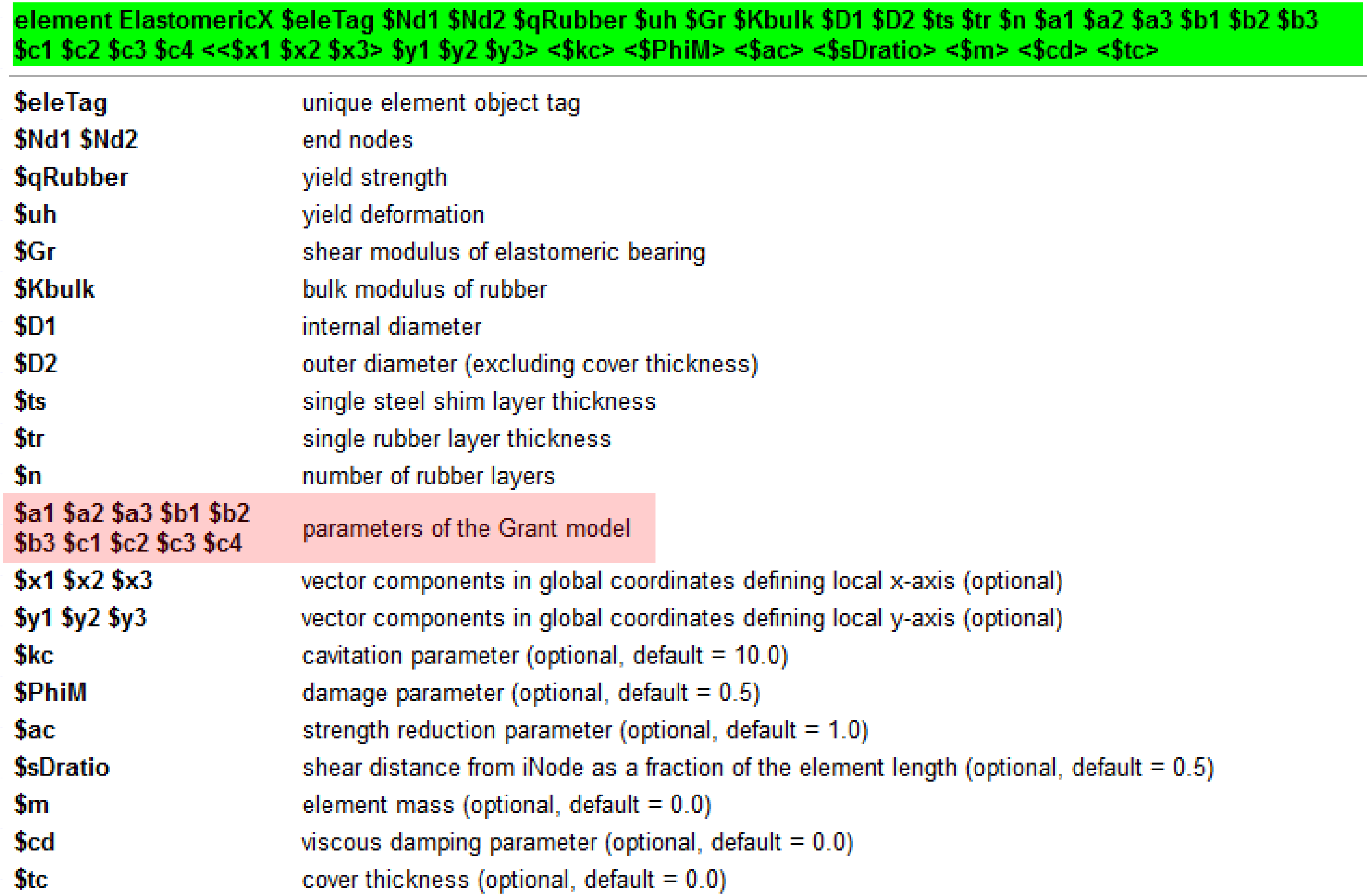




Lead Rubber Bearing Test



HDR Element

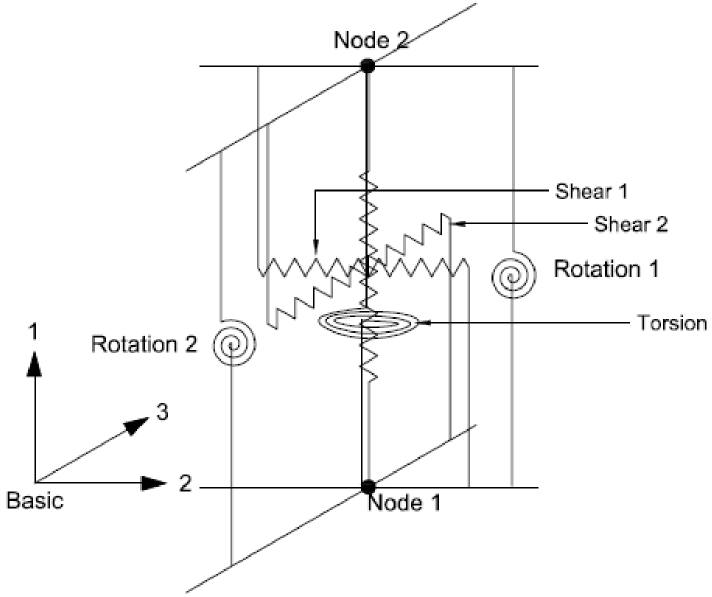


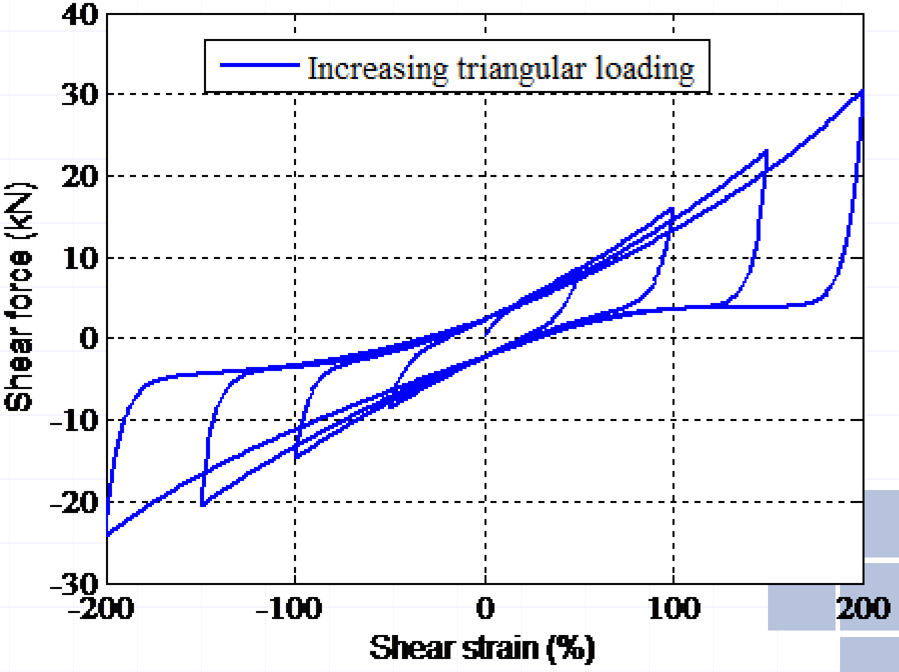
```
element ElastomericX $eleTag $Nd1 $Nd2 $qRubber $uh $Gr $Kbulk $D1 $D2 $ts $tr $n $a1 $a2 $a3 $b1 $b2 $b3
$c1 $c2 $c3 $c4 <<$x1 $x2 $x3> $y1 $y2 $y3> <$kc> <$PhiM> <$ac> <$sDratio> <$m> <$cd> <$tc>
```

$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
$a1 $a2 $a3 $b1 $b2 $b3 $c1 $c2 $c3 $c4	parameters of the Grant model
$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)

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



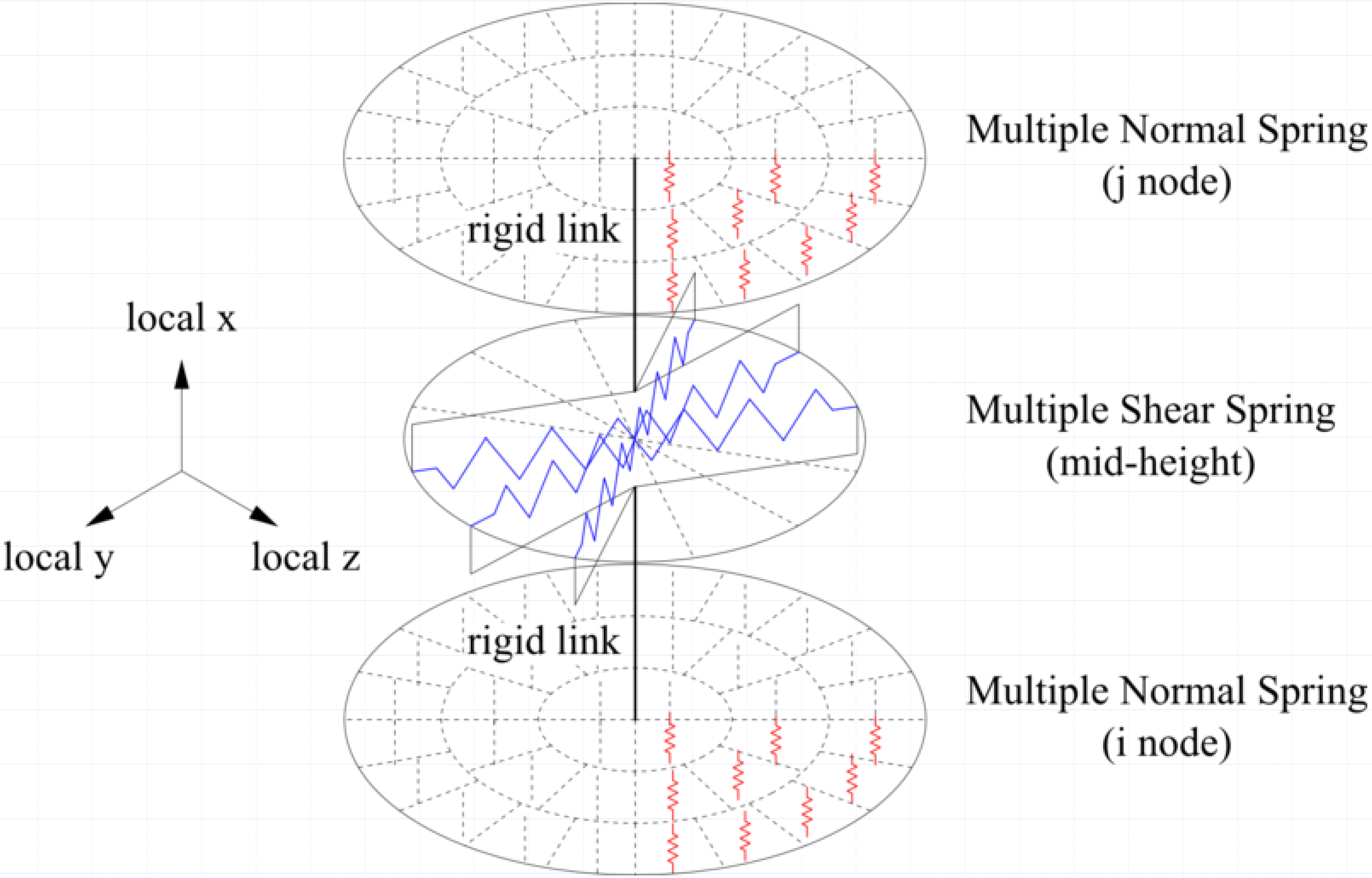


KikuchiBearing Element

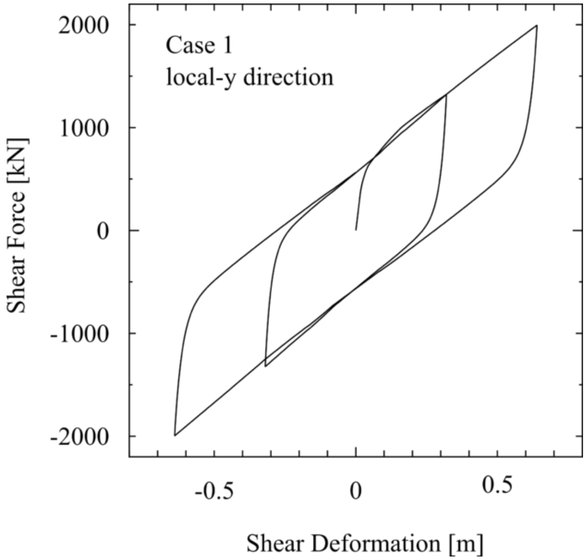
```
element KikuchiBearing $eleTag $iNode $jNode -shape $shape -size $size $totalRubber <-totalHeight $totalHeight>
-nMSS $nMSS -matMSS $matMSSTag <-limDisp $limDisp> -nMNS $nMNS -matMNS $matMNSTag <-lambda
$lambda> <-orient <$x1 $x2 $x3> $yp1 $yp2 $yp3> <-mass $m> <-noPDInput> <-noTilt> <-adjustPDOutput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

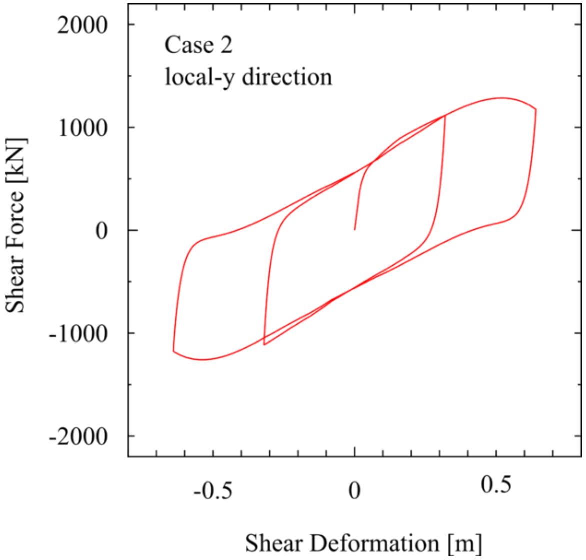
$eleTag	unique element object tag
$inode $jnode	end nodes
$shape	following shapes are available: **round**, **square**
$size	diameter (round shape), length of edge (square shape)
$totalRubber	total rubber thickness
$totalHeight	total height of the bearing (defaulut: distance between iNode and jNode)
$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 $nIter	tolerance of external unbalanced force (**$limFo**), tolorance of internal unbalanced force (**$limFi**), number of iterations to get rid of internal unbalanced force (**$nIter**)

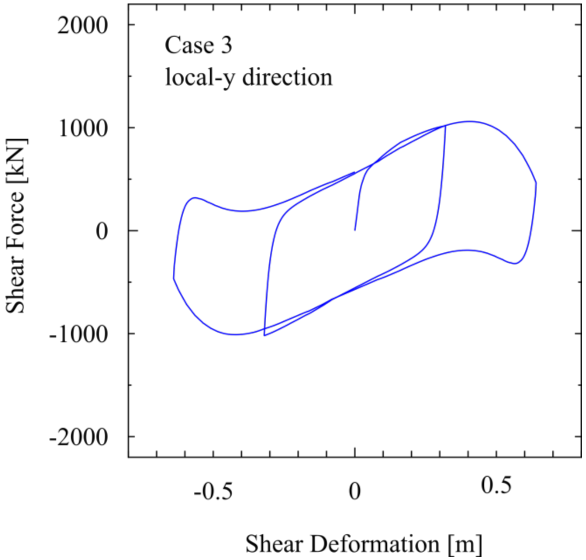
KikuchiBearing Element

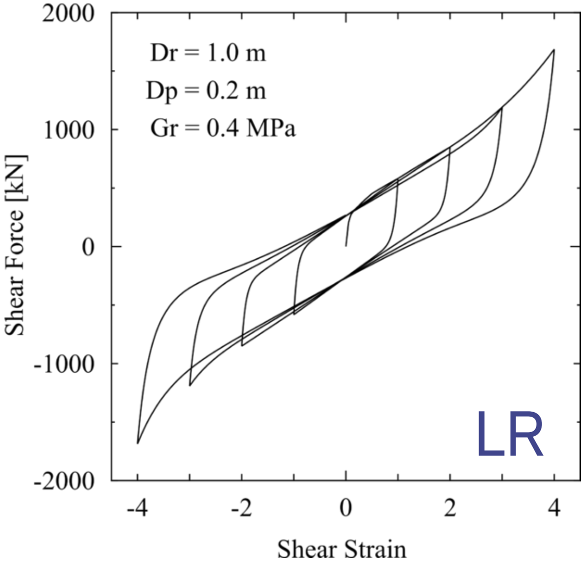


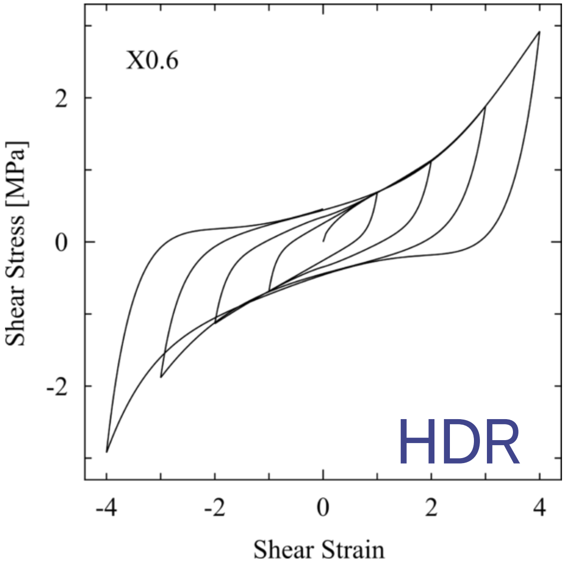
KikuchiBearing Element











Lead Rubber Bearing Tests

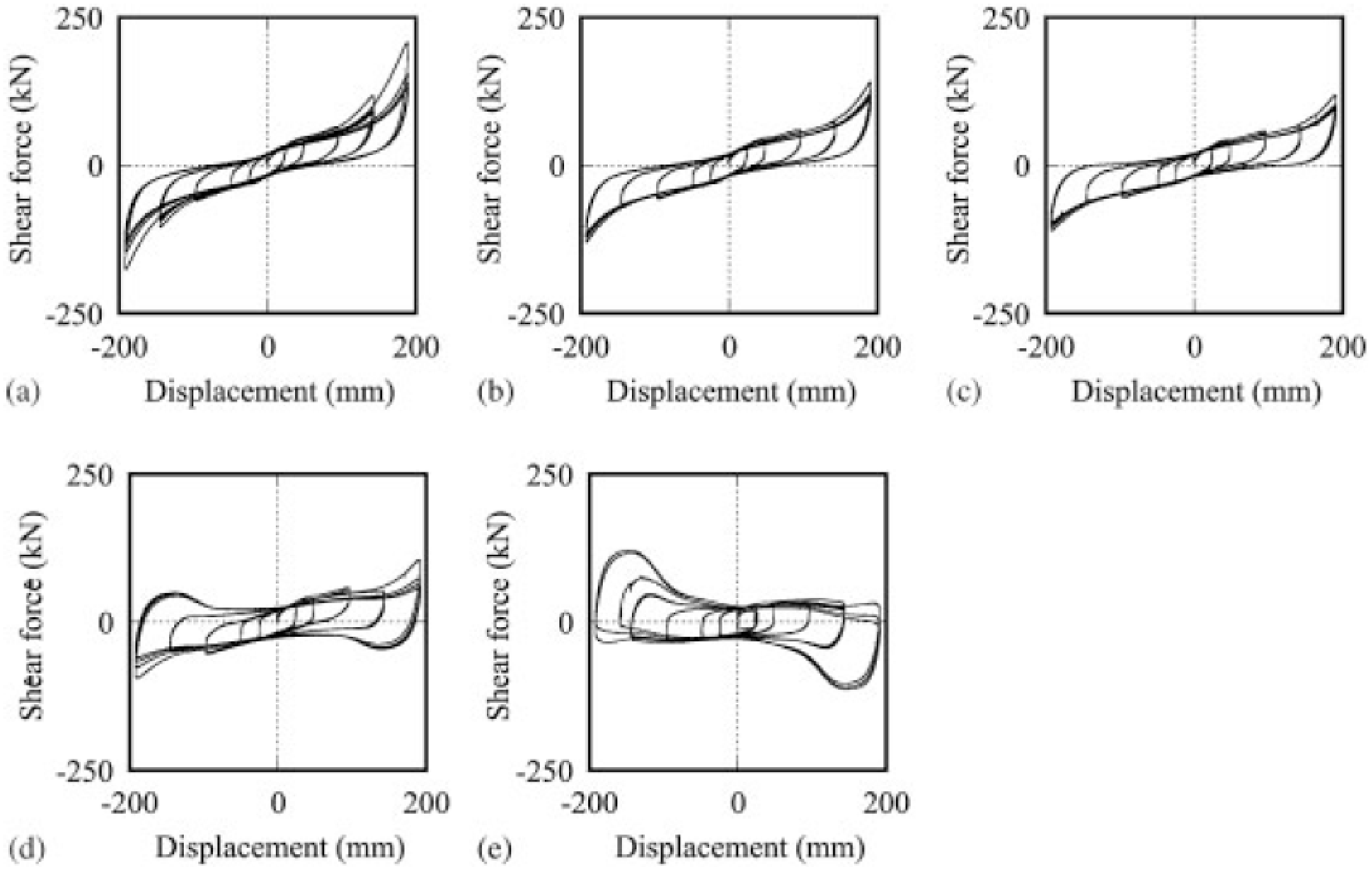


Figure 7. Lead–rubber bearing ($S_2 = 5$) shear force–displacement hysteresis loops for cyclic shear tests with different vertical loads: (a) $\sigma = 0$ MPa; (b) $\sigma = 5$ MPa; (c) $\sigma = 10$ MPa; (d) $\sigma = 20$ MPa; and (e) $\sigma = 30$ MPa.

Yamamoto, Kikuchi, Ueda and Aiken, EESD 2009

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

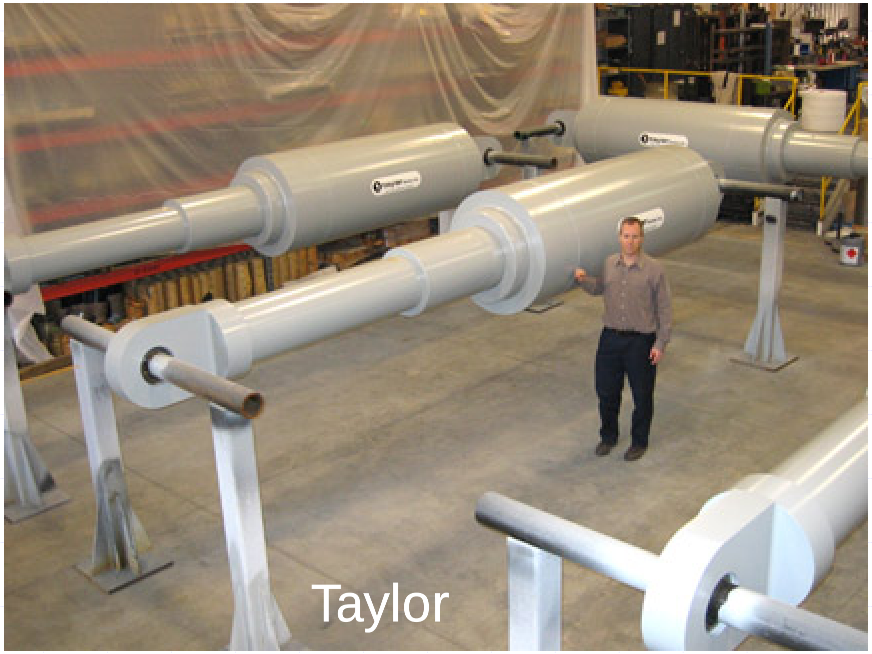
- For all isolators it is very important to -> provide realistic axial stiffness (not just some large value)
- If possible (depends on element) -> provide some viscous damping in the axial bearing direction
- Avoid the introduction of artificial viscous damping in the isolation system (i.e. damping leakage)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

Comparison of Isolator Capabilities

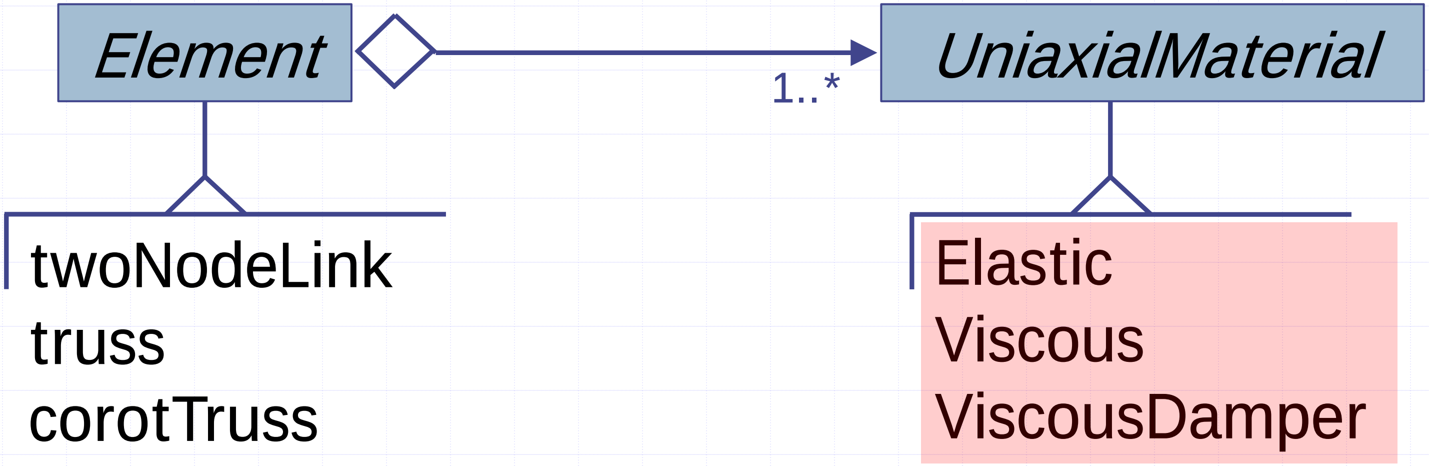
Element	Shear Behavior	Shear Coupling	Axial Behavior	Shear and Axial Coupling	Coupled H-V defo	Moment Behavior
Elastomeric Bearing BW	bouc-wen	yes, circular	any OPS material	under development	no	any OPS material
Elastomeric Bearing P	bilinear	yes, circular	any OPS material	no	no	any OPS material
ElastomericX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

Element	Rayleigh Damping	P-Delta Effects	Nonlinear Hardening	Scragging Effects	Rate Effects	Temp. Effects
Elastomeric Bearing BW	off, optional	yes	yes	no	no	under dev.
Elastomeric Bearing P	off, optional	yes	yes	no	no	no
ElastomericX Bearing	on	no	no	no	no	no
LeadRubberX Bearing	on	no	no	no	yes	yes
HDR Bearing	on	no	yes	yes	no	no
Kikuchi Bearing	on	yes	yes	yes	no	maybe
Isolator 2-Spring	off, optional	yes	no	no	no	no
Flat Slider Bearing	off, optional	yes	n/a	n/a	yes	no
Single FP Bearing	off, optional	yes	n/a	n/a	yes	no
Triple FP Bearing 1	on	no	yes	n/a	no	no
Triple FP Bearing 2	on	yes	yes	n/a	yes	no

Fluid Viscous Dampers



Damping Material Models



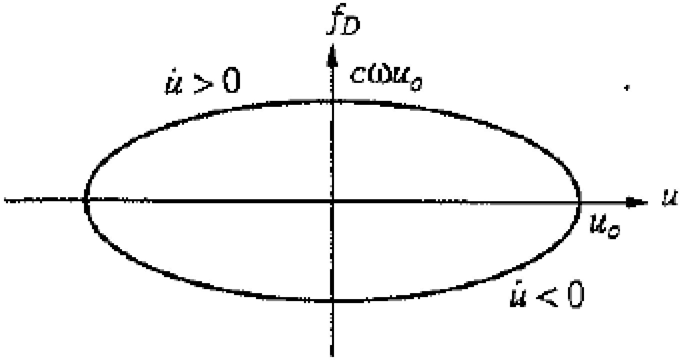
uniaxialMaterial matType? matTag? arg1? ...

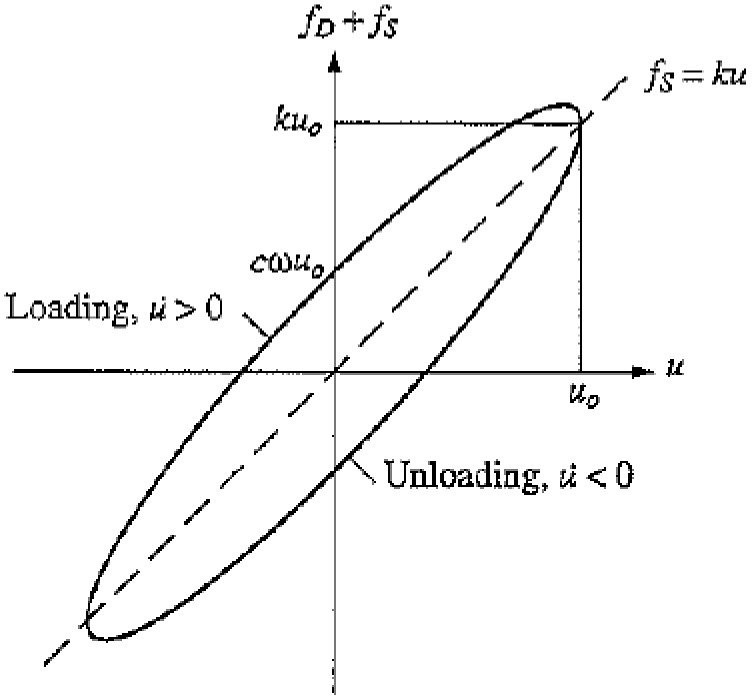
Elastic Uniaxial Material

```
uniaxialMaterial Elastic $matTag $E <$eta> <$Eneg>
```

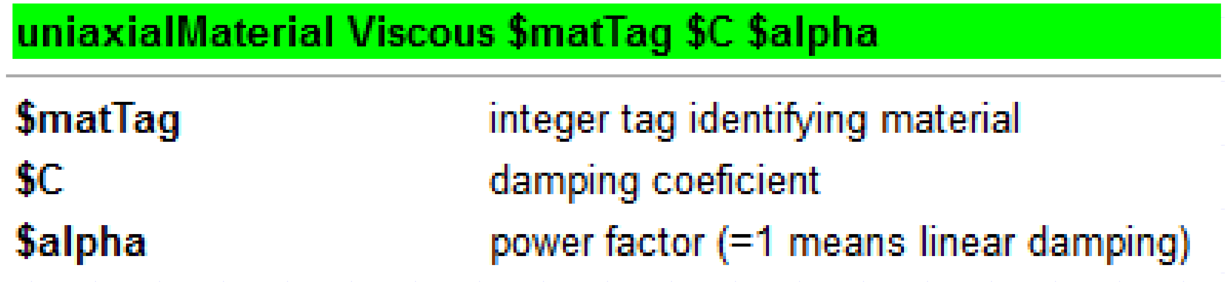
$matTag	integer tag identifying material
$E	tangent
$eta	damping tangent (optional, default=0.0)
$Eneg	tangent in compression (optional, default=E)

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





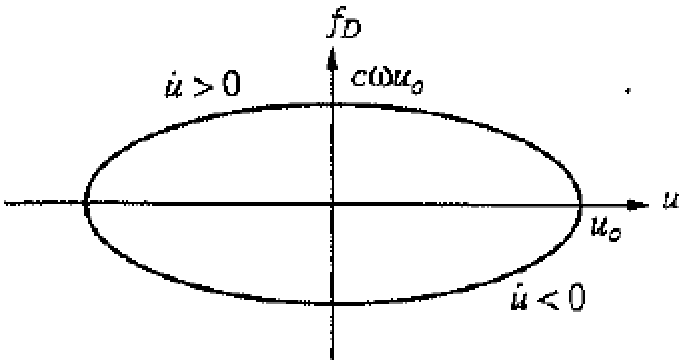
Viscous Uniaxial Material



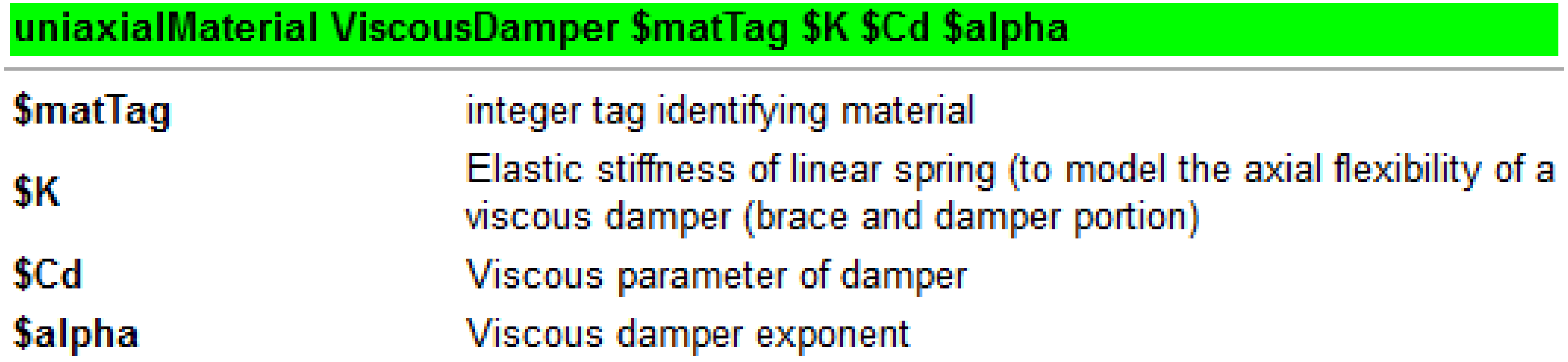
```
uniaxialMaterial Viscous $matTag $C $alpha
```

$matTag	integer tag identifying material
$C	damping coeficient
$alpha	power factor (=1 means linear damping)

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



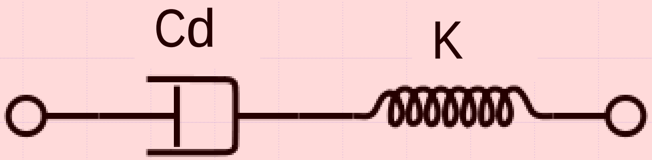
ViscousDamper Uniaxial Material



`uniaxialMaterial ViscousDamper $matTag $K $Cd $alpha`

$matTag	integer tag identifying material
$K	Elastic stiffness of linear spring (to model the axial flexibility of a viscous damper (brace and damper portion)
$Cd	Viscous parameter of damper
$alpha	Viscous damper exponent

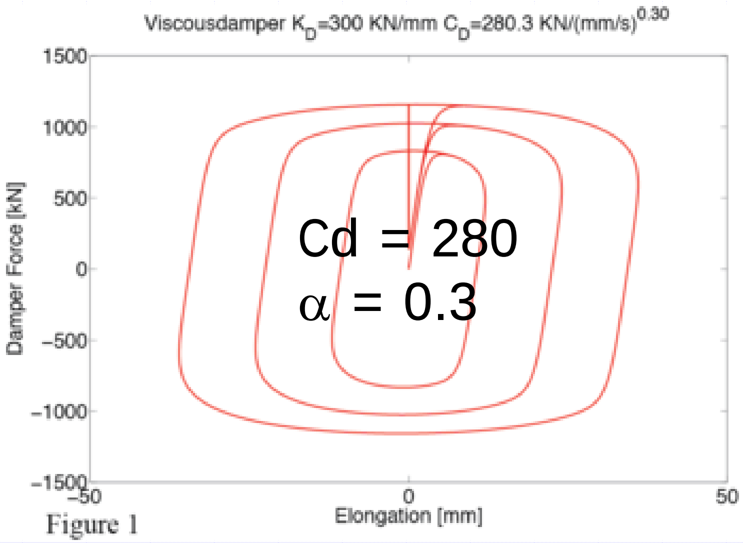
The ViscousDamper material is based on:



Maxwell material model

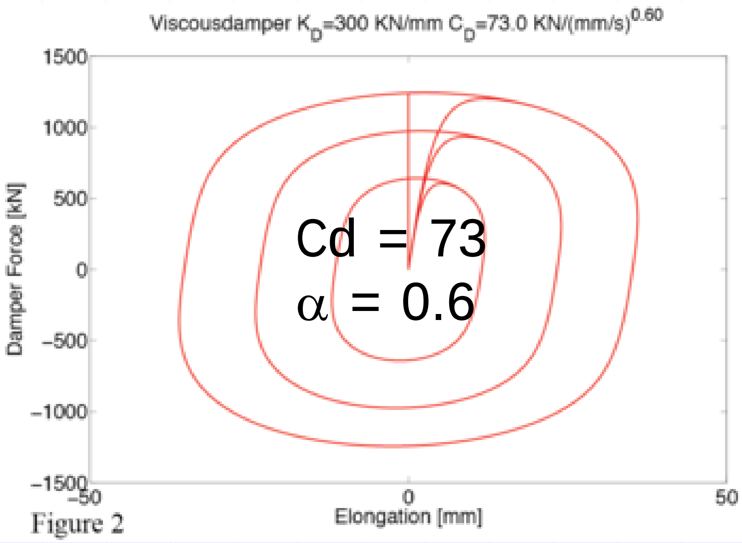
$$\frac{\dot{F}_d(t)}{K_d} + \operatorname{sign}(F_d(t))\left(\frac{|F_d(t)|}{C_d}\right)^{\frac{1}{\alpha}} = \dot{u}_m(t)$$

ViscousDamper Uniaxial Material


Viscousdamper K_D=300 KN/mm C_D=280.3 KN/(mm/s)$^{0.30}$

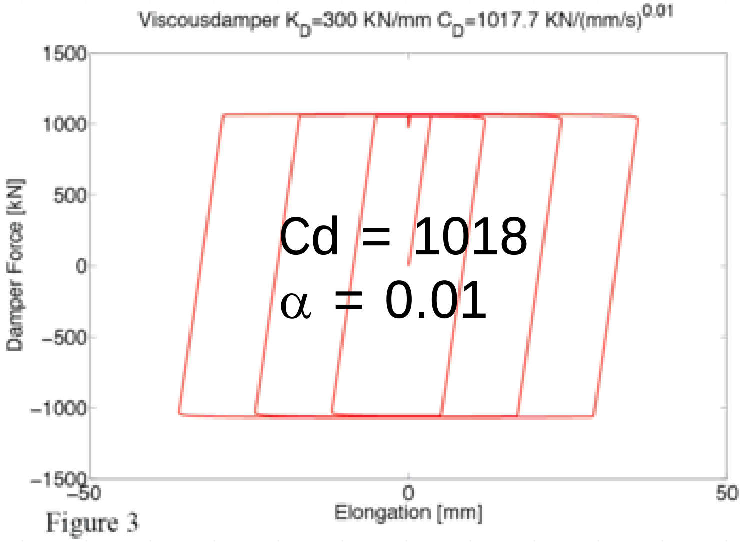
Cd = 280
α = 0.3

Figure 1


Viscousdamper K_D=300 KN/mm C_D=73.0 KN/(mm/s)$^{0.60}$

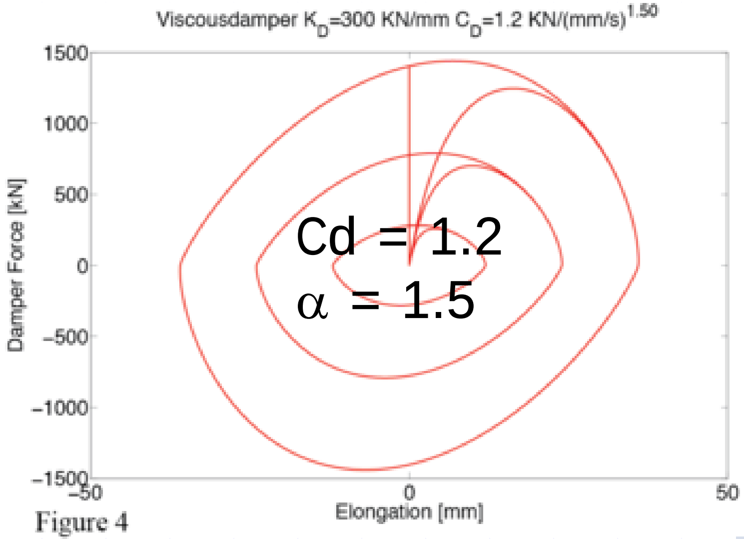
Cd = 73
α = 0.6

Figure 2


Viscousdamper K_D=300 KN/mm C_D=1017.7 KN/(mm/s)$^{0.01}$

Cd = 1018
α = 0.01

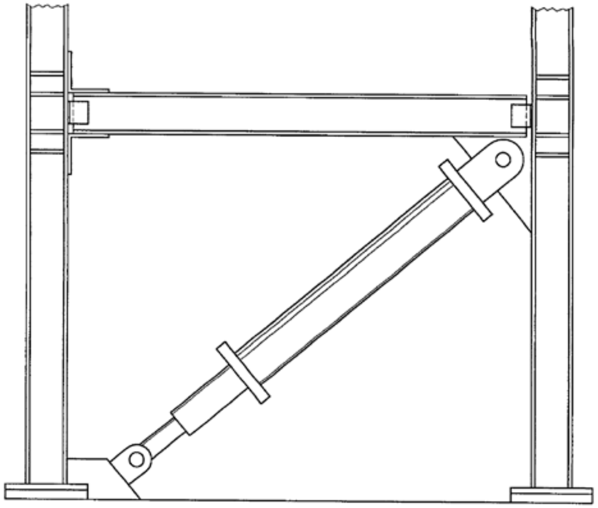
Figure 3

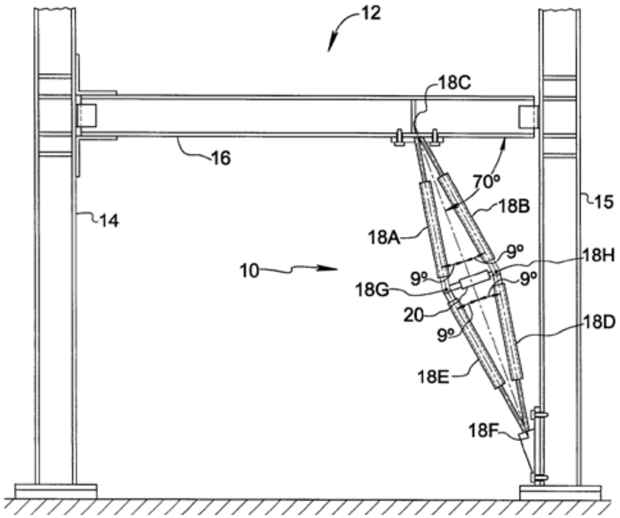

Viscousdamper K_D=300 KN/mm C_D=1.2 KN/(mm/s)$^{1.50}$

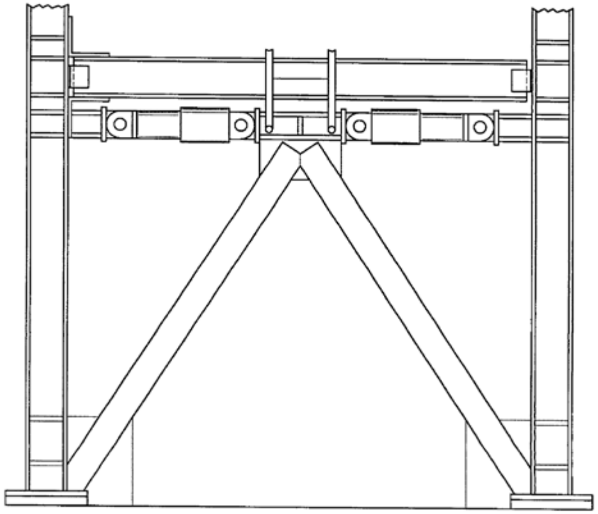
Cd = 1.2
α = 1.5

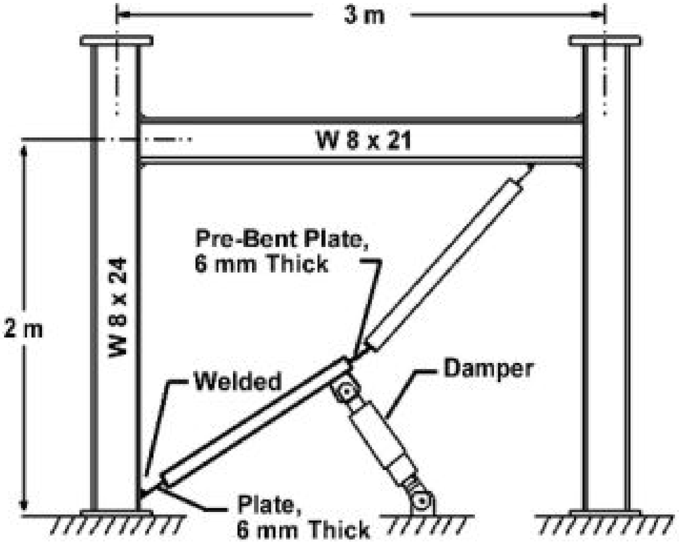
Figure 4

Damper Configurations

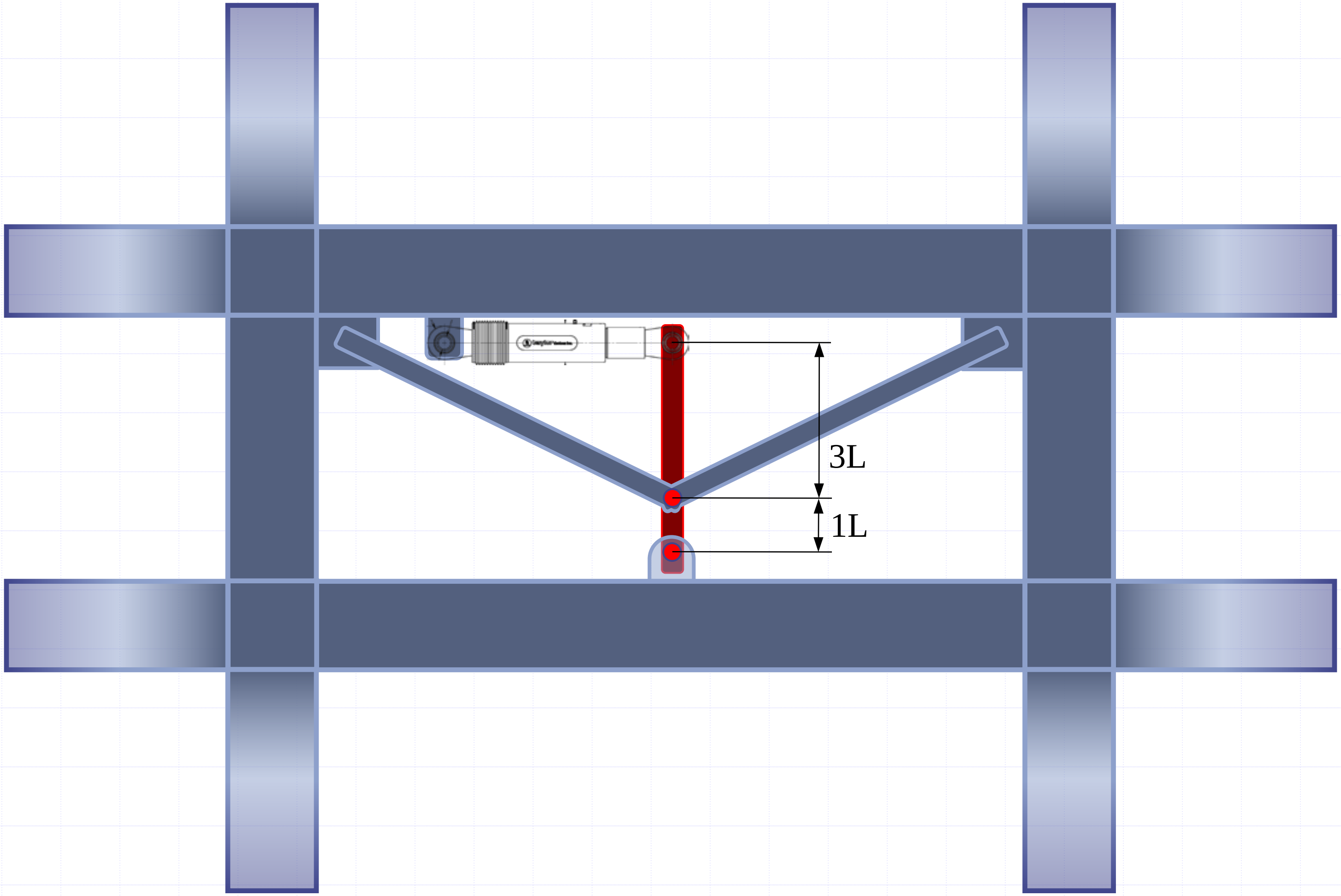






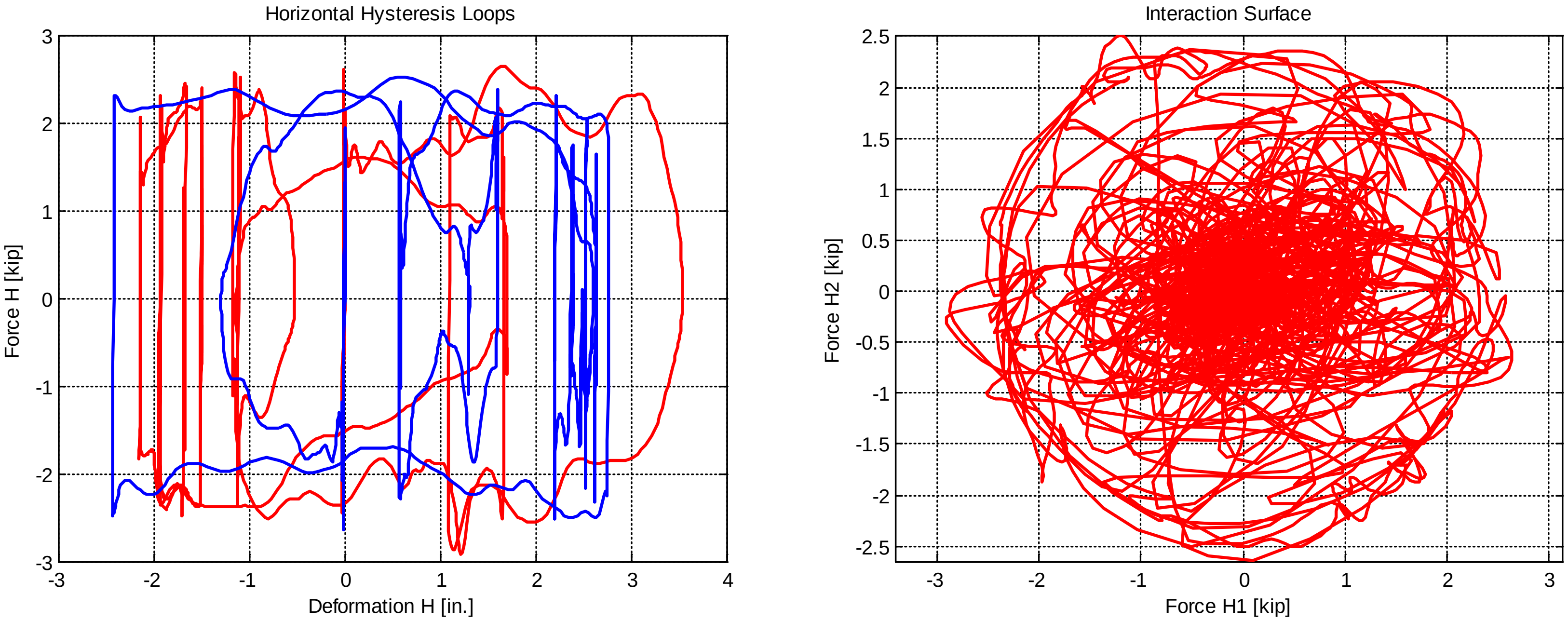


Damper Configurations



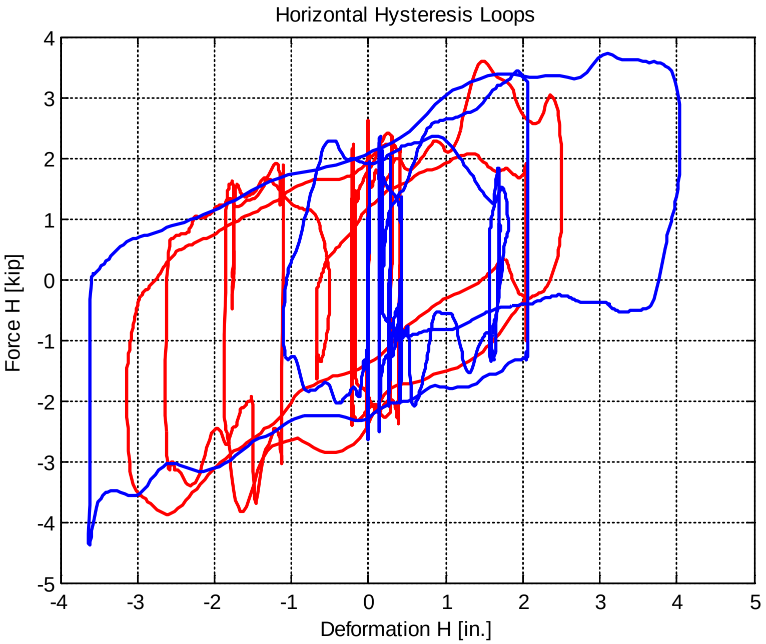
Example Application

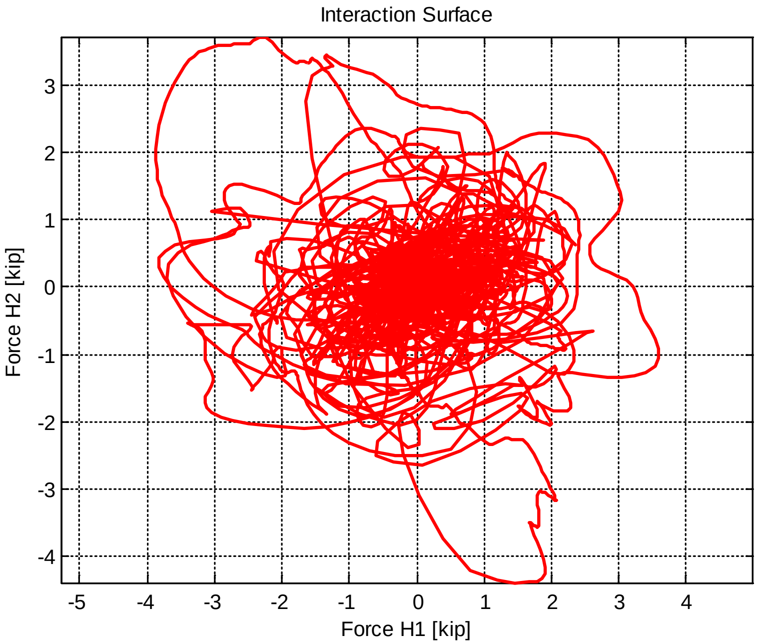
flatSliderBearing: constant COF 13%



Example Application

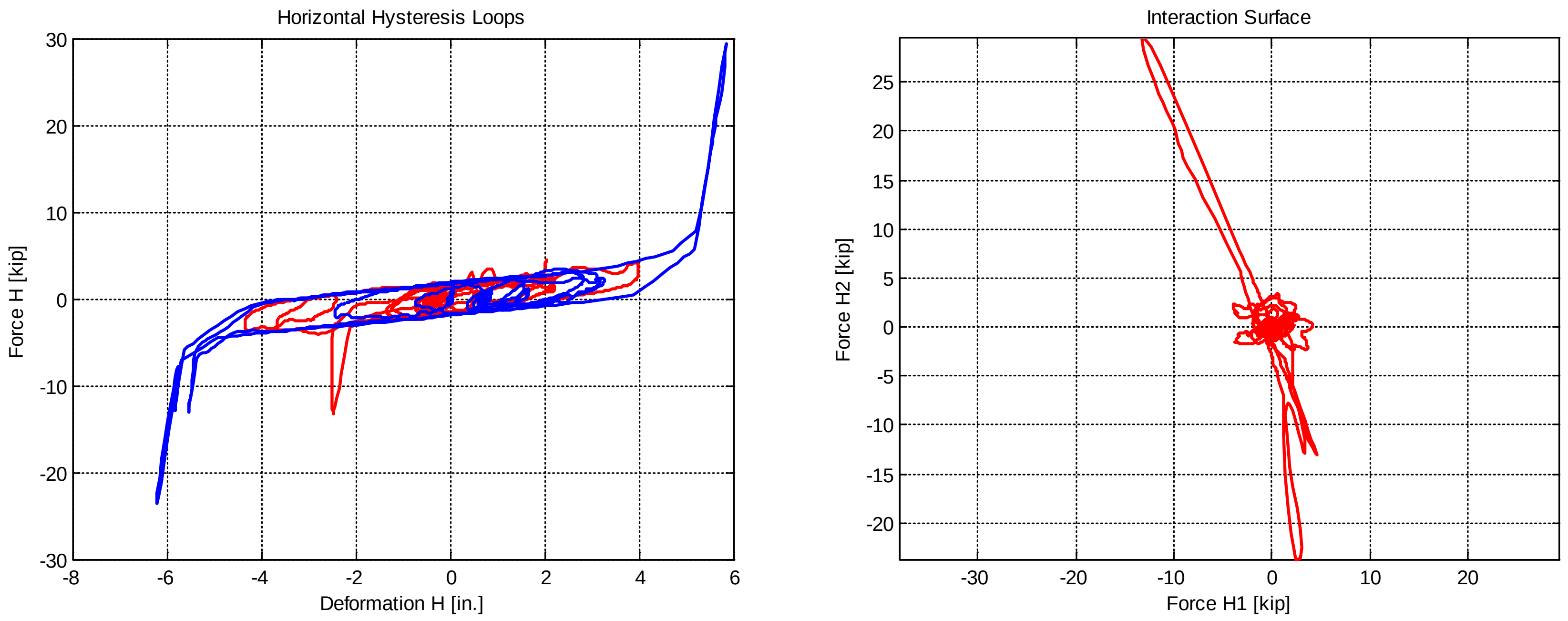
singleFPBearing: constant COF 13%





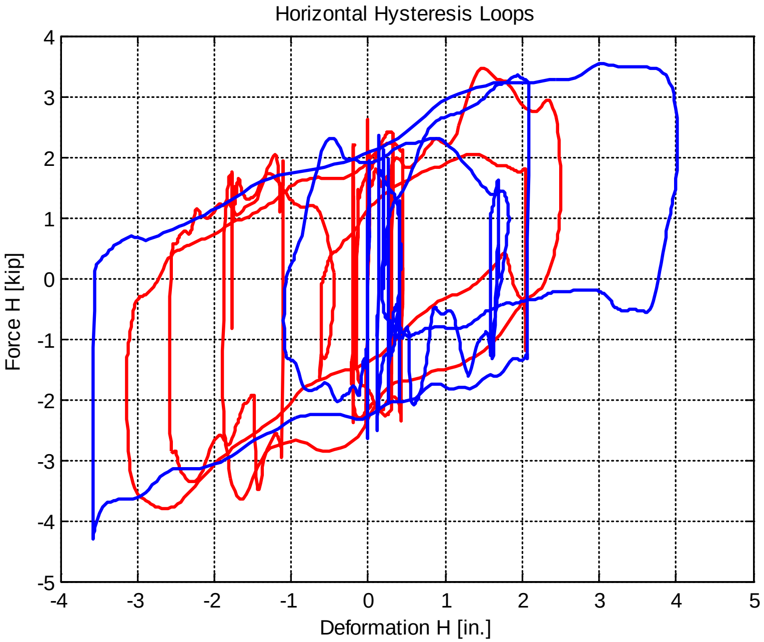
Example Application

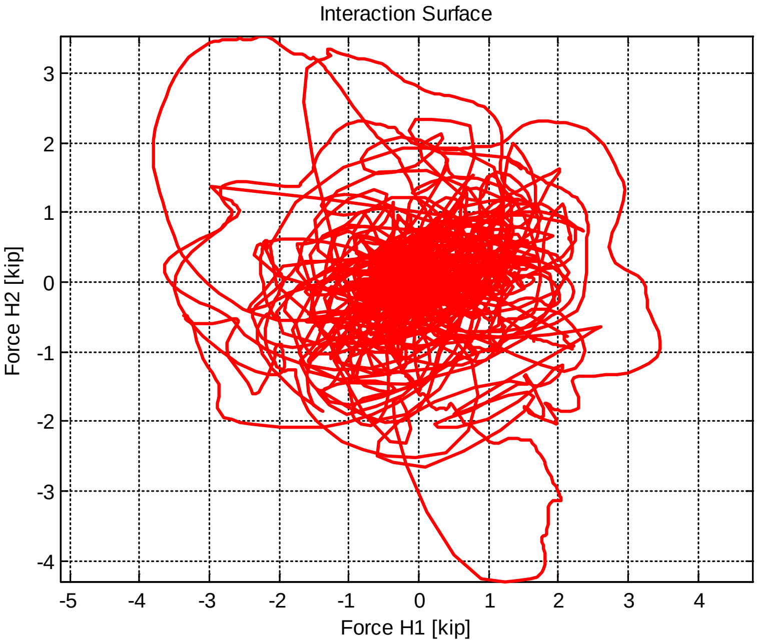
TriplFrictionPendulum: constant COF 4%, 10%, 13%



Example Application

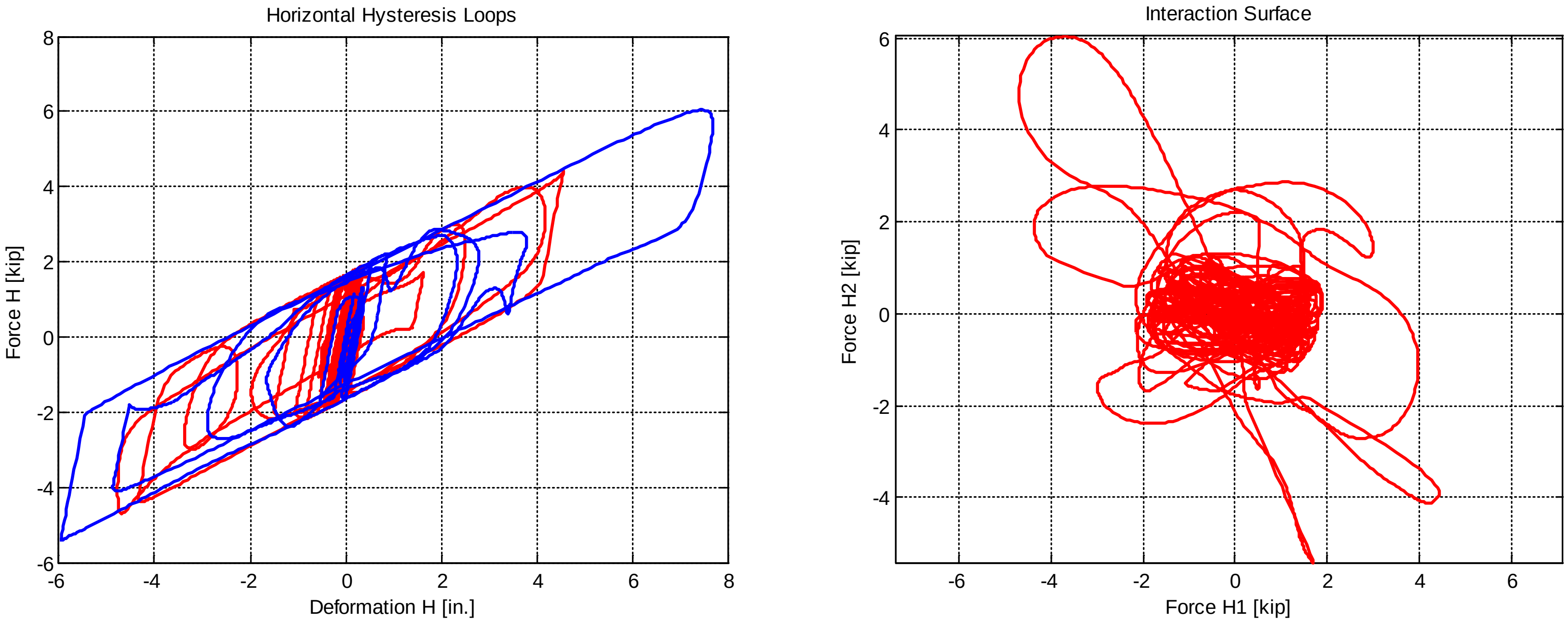
RJWatsonEQSBearing: constant COF 13%


Horizontal Hysteresis Loops


Interaction Surface

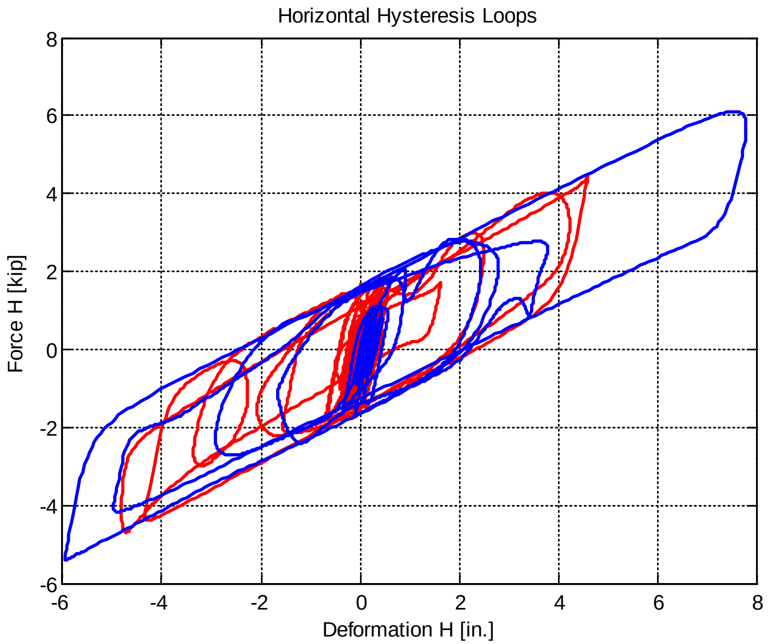
Example Application

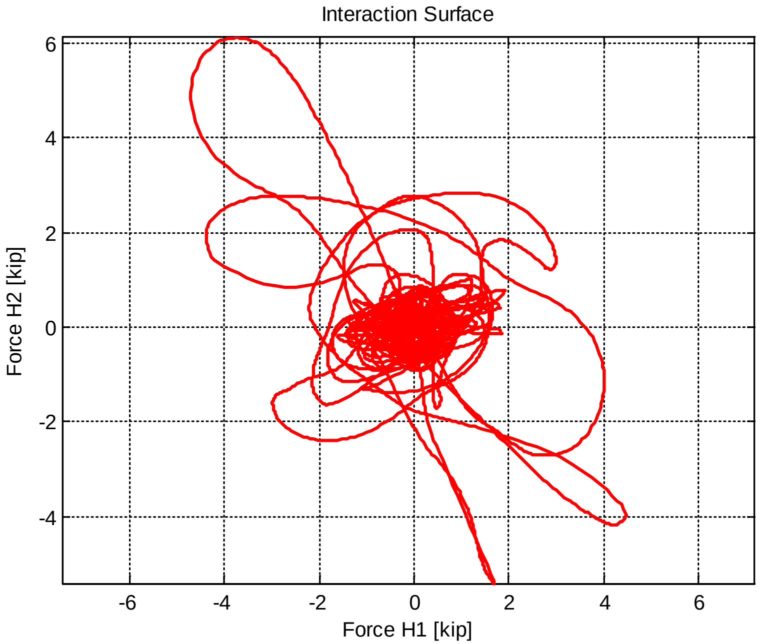
elastomericBearingPlasticity: fy = 1.84 kip



Example Application

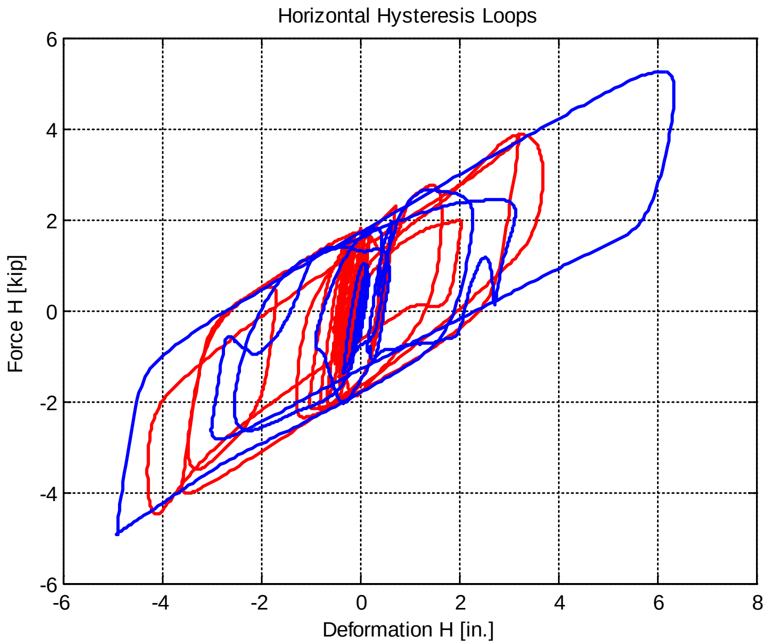
elastomericBearingBoucWen: fy = 1.84 kip

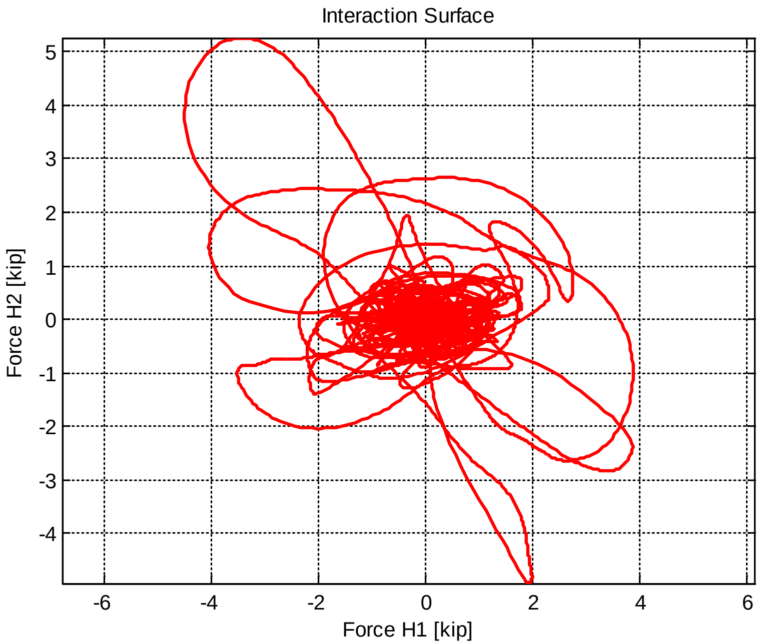




Example Application

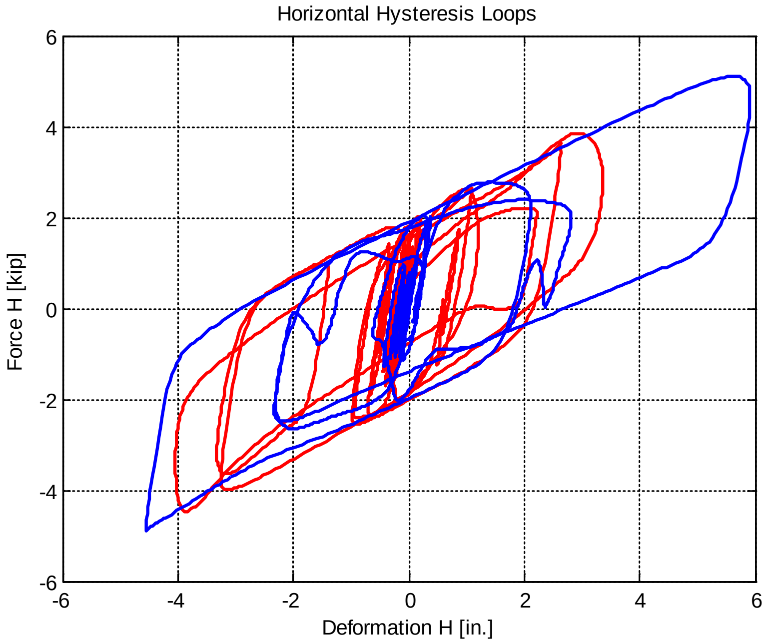
elastomericX: fy = 1.84 kip

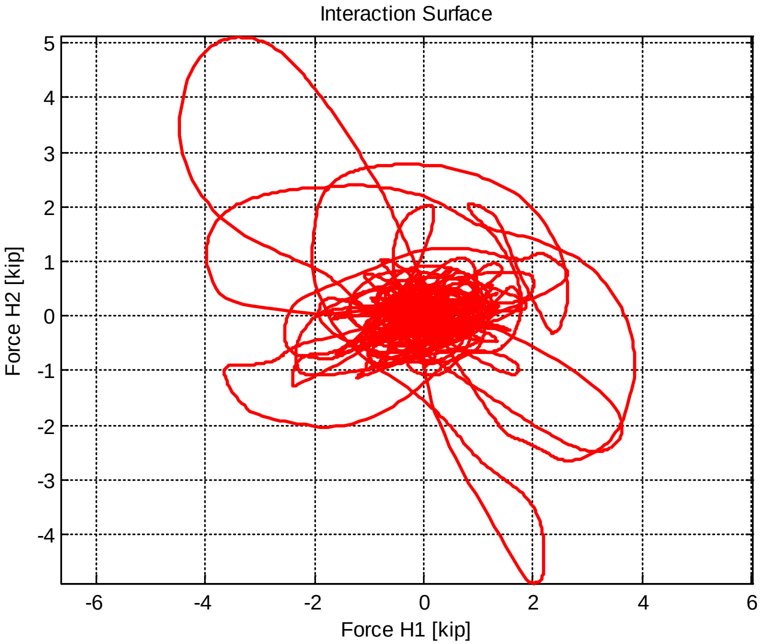




Example Application

LeadRubberX: qd = 1.66 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!