Computational and Experimental Investigation of Circular Bridge Columns of Different Sizes

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Outline

- Tasks
- Background
- Computational Model
- Physical Models and Calibration
- Conclusions and Future Tasks

Tasks

- Perform a literature review of tests and models for circular RC columns with confining media accounting for size effect.
- Develop a theoretical model for confined RC circular sections addressing the **size effect** in a rigorous manner.
- Develop a computational model with nonlinear **3D FEM** for confined RC circular sections.
- Calibrate the models using past tests of circular columns of different sizes.
- Compare the models to recent tests in Japan and UC-San Diego and upcoming tests at UC-Berkeley.
- Implement a 3D constitutive model of confined RC sections, based on the 3D FE model, into OpenSees.

Background
Size Effect in RC

G_{fc} = Compressive fracture energy as a material property

- Energy released per area of crack propagation
- More research for estimating the tensile fracture energy
- Affected by max. aggregate size, aggregate content, aggregate fineness modulus, cement type, w/c, … etc.
- Needs to be determined through testing or empirically, e.g.
  - ✓ Mizuno, Nakamura, Higai (1999): $G_{fc} = 8.8\sqrt[3]{f_c'}$
  - ✓ Lertsrisakulrat, Watanabe, Matsuo, Niwa (2000): $G_{fc} = 0.99\sqrt[3]{f_c'^2}$
- Energy released within a plastic hinge of length *Lp* :

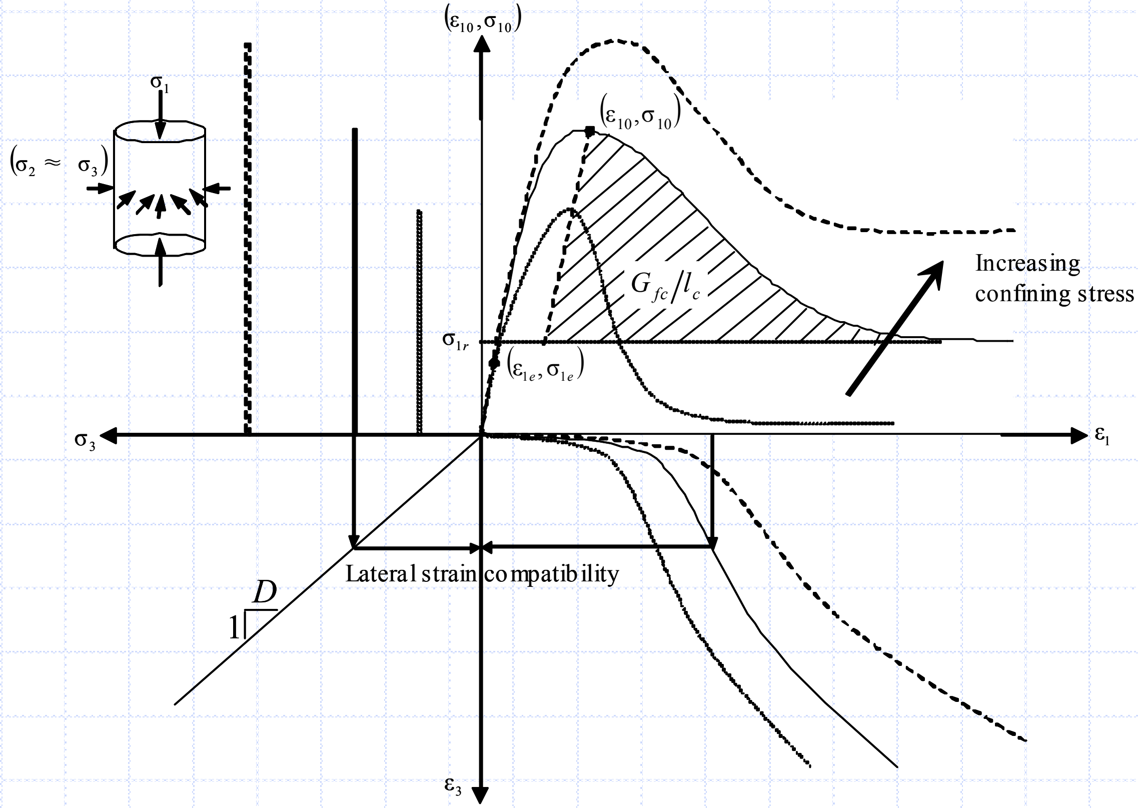
$$G_{fc} / L_p = \int \sigma(\varepsilon) \cdot d\varepsilon$$

- Shows size dependence – inverse relationship between toughness and characteristic length
- Simplified assumption for pure axial compression but not straight forward for combined forces (P, V, M)

Computational Model

Confinement in RC Material (**ConcreteBLE**)

- Family of stress-strain curves (σ_1, ε_1)
- Parametrized by $\varphi = \sigma_3 / f_c'$
- Softening conserves fracture energy, G_{fc}
- Enforces lateral strain compatibility with confining media
- Use of Leon-Pramono failure criterion



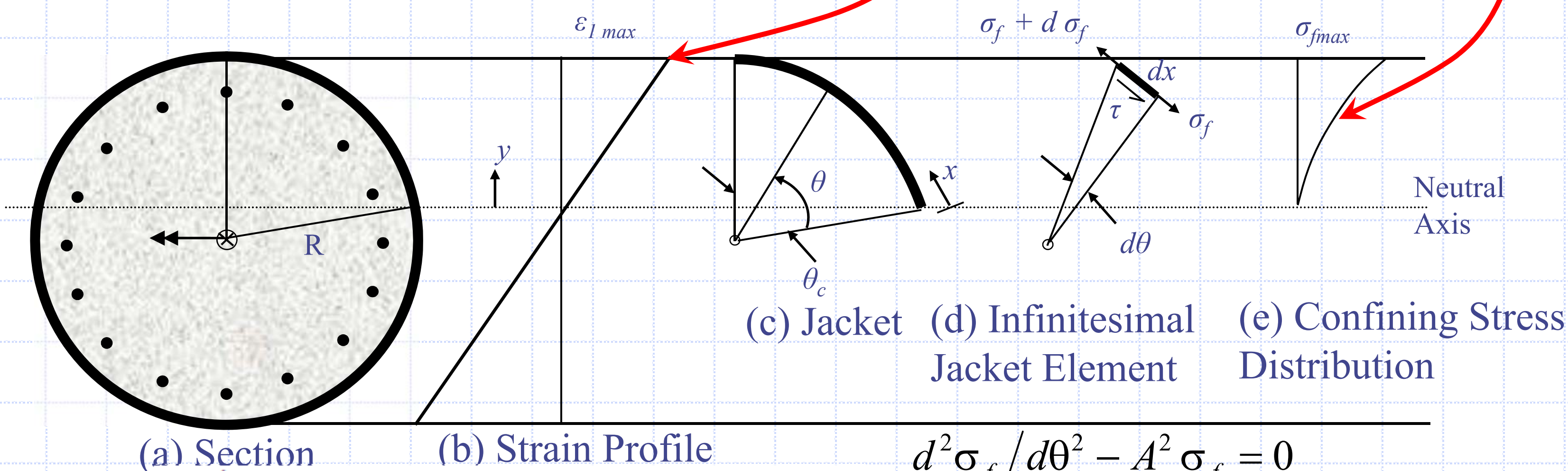
Computational Model

Confinement in RC Section (**RCFiber**)

Depending on location of fiber in cross-section

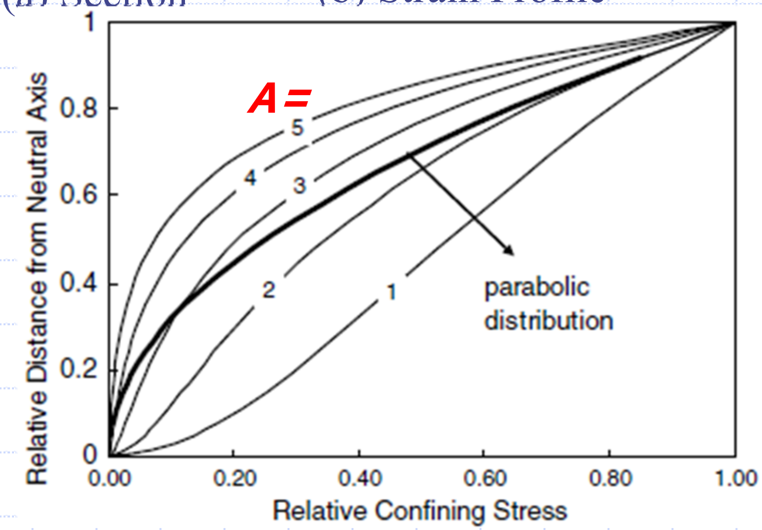
$$\sigma_f = \sigma_{f\max} \sinh(A\theta)/\sinh(A\theta_c)$$

Strain compatibility enforced HERE



$$d^2\sigma_f / d\theta^2 - A^2\sigma_f = 0$$

$$A^2 = (R^2 G_a)/(E_f t_f t_a)$$

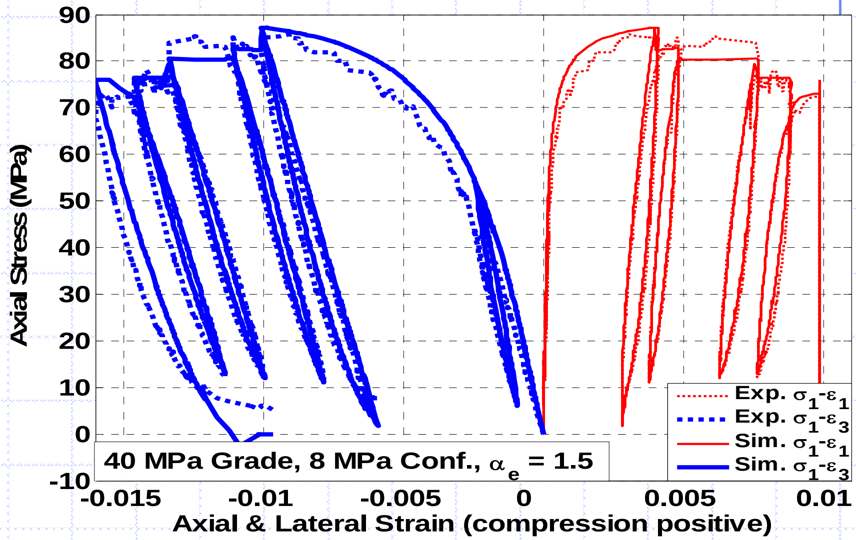


Confining stress distribution for different values of bond parameter (A)

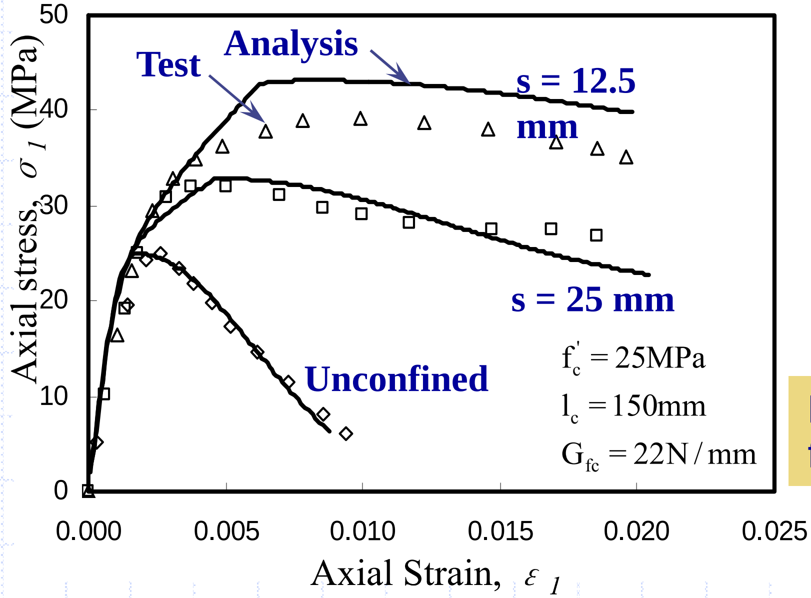
Computational Model

Cyclic Loading & Confinement in RC

- Unloading-reloading rules [Lokuge et al, 2004]
- Stress-strain relationship invariant in principal shear space
- Modified to account for variable confinement and hysteretic energy-based envelope reduction factor



Experimental [Lokuge et al, 2004] vs. simulated axial and lateral stress-strain response

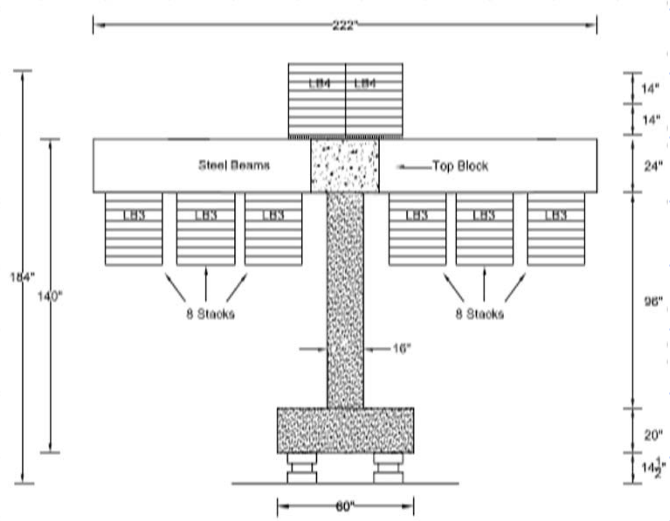


Envelope experimental [Ahmad & Shah, 1982] validation for unconfined cylinders and confined with tie spacing = s

Physical Models and Calibration
Outline

- UCB
  - Columns made of pressurized grout
    - ✓ Cyclic testing w/ variable axial load

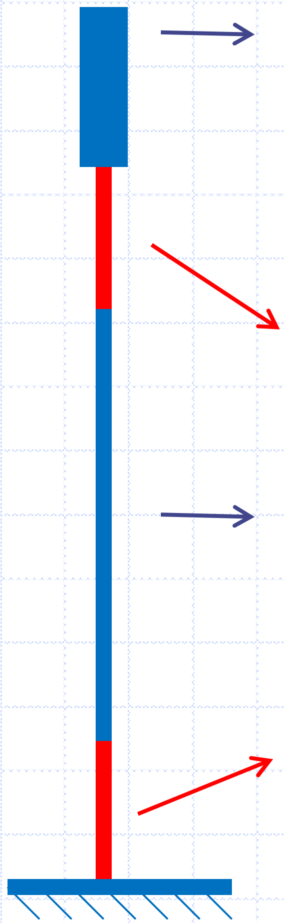
  - Scaled columns under hrz. & vl. motion
    - ✓ 2D seismic testing
  - 1/3-Scale of UCSD column
    - ✓ 1D seismic testing



- UCSD
  - Full-scale column
    - ✓ 1D seismic testing

Physical Models and Calibration
Modeling Assumptions

Each section has 4 “NonlinearBeamColumn” elements with 3 integration points



“Mass-Block”
- ❑ 25% of column height
- ❑ Standard fiber section with Concrete02
- ❑ Confinement by Mander, Park and Priestly (1988)
- ❑ Length scale increased 3x (EI_{eff} increased 3^4 = 81x)
- ❑ Manual input of top mass weight and moment of inertia

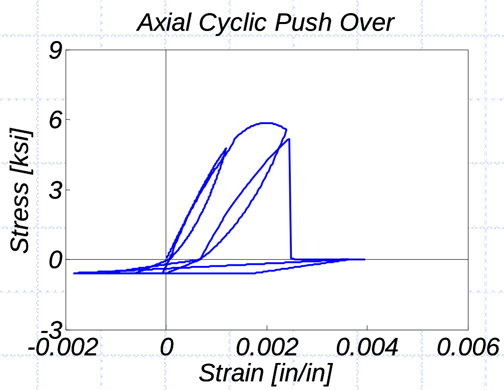
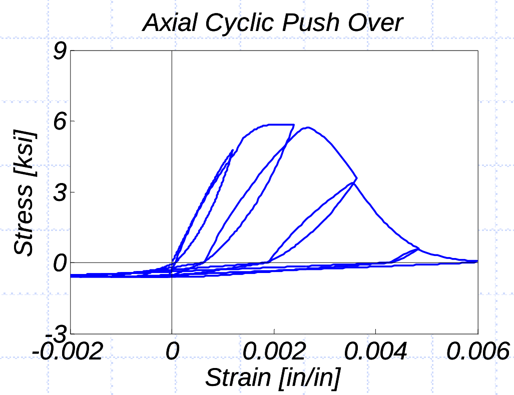
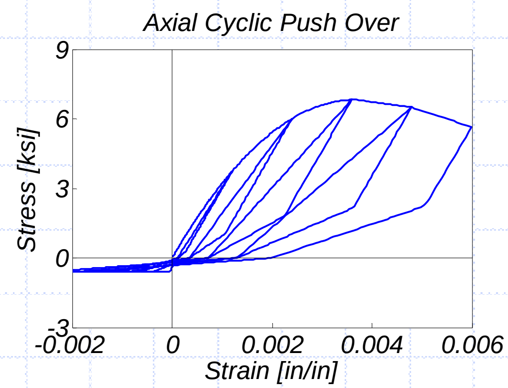
“Plastic Hinge”
- ❑ 20% of column height
- ❑ RCFiber section with ConcreteBLE

“Elastic Section”
- ❑ 60% of column height
- ❑ Standard fiber section with Concrete02
- ❑ Confinement by Mander, Park and Priestly (1988)

“Plastic Hinge”
- ❑ 20% of column height
- ❑ RCFiber section with ConcreteBLE

Physical Models and Calibration

Modeling Assumptions

<table>
<tr><th colspan="2">ConcreteBLE & RCFiber Section</th><th>Concrete02 & Standard Fiber Section</th></tr>
<tr><td>Full Scale</td><td>1/3 Scale</td><td>Scale Independent</td></tr>
<tr><td>
</td><td>
</td><td>
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Full Scale refers to 24’ tall, 4’ diameter, lateral hoops #5 @ 6.25”

Physical Models and Calibration
UCB – Scaled columns made of pressurized grout

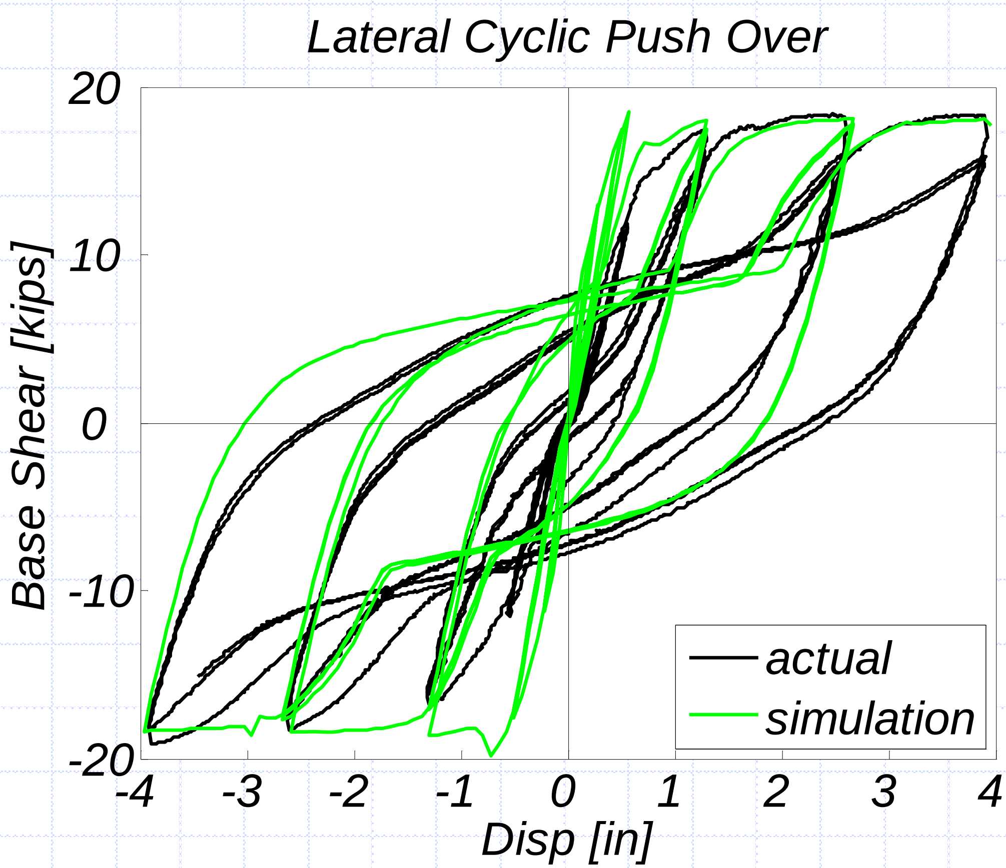
- No coarse aggregate
- Comparison with conventional mix design
- Cyclic Loading

Specimen	Material	Longitudinal Reinforcement	Spiral Transverse Reinforcement	Axial Load [Kips]
1	**Grout**	**(6)#6**	**#4@3"**	**0.0**
2	Concrete	(6)#6	#4@3"	0.0
3	**Grout**	**(6)#6**	**#4@3"**	**300.0**
4	Concrete	(6)#6	#4@3"	300.0
5	Grout	(6)#6	#4@2"	300.0



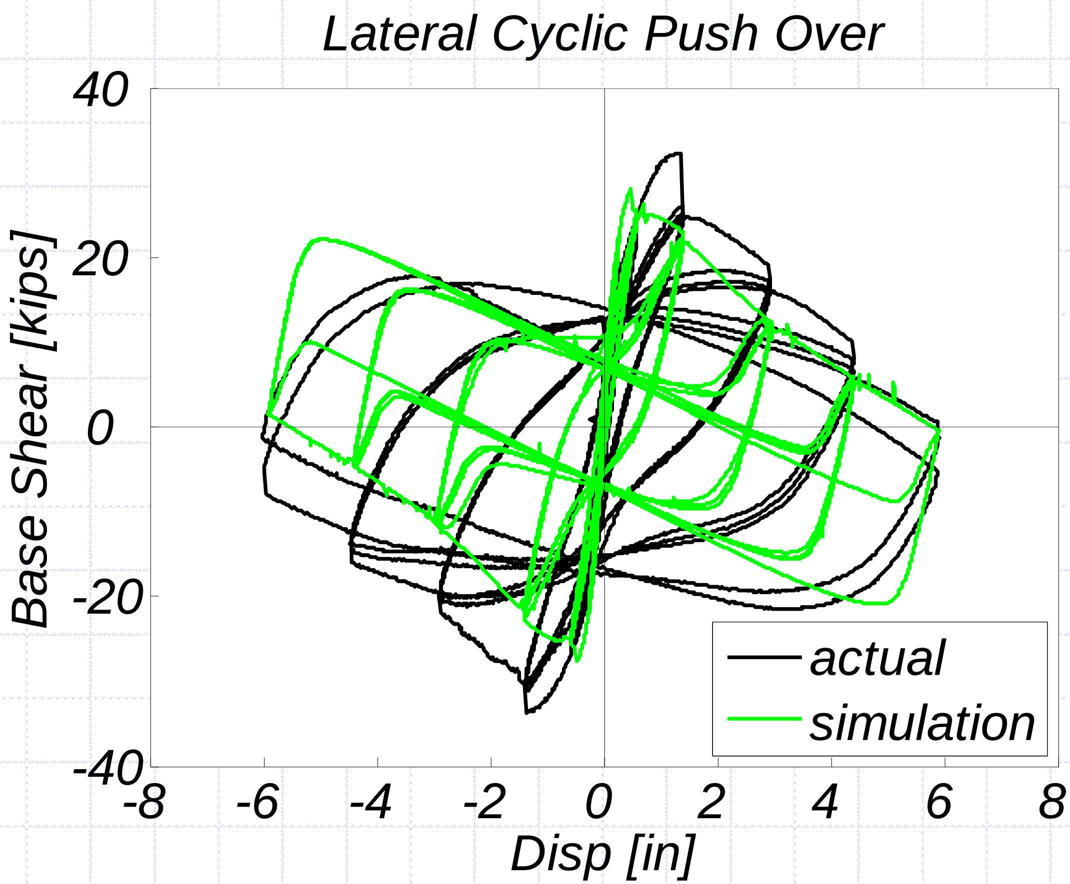

Physical Models and Calibration
UCB – Scaled columns made of pressurized grout

- Grout **specimen 1** - no added axial load
- Modeling - linear geometric transformation



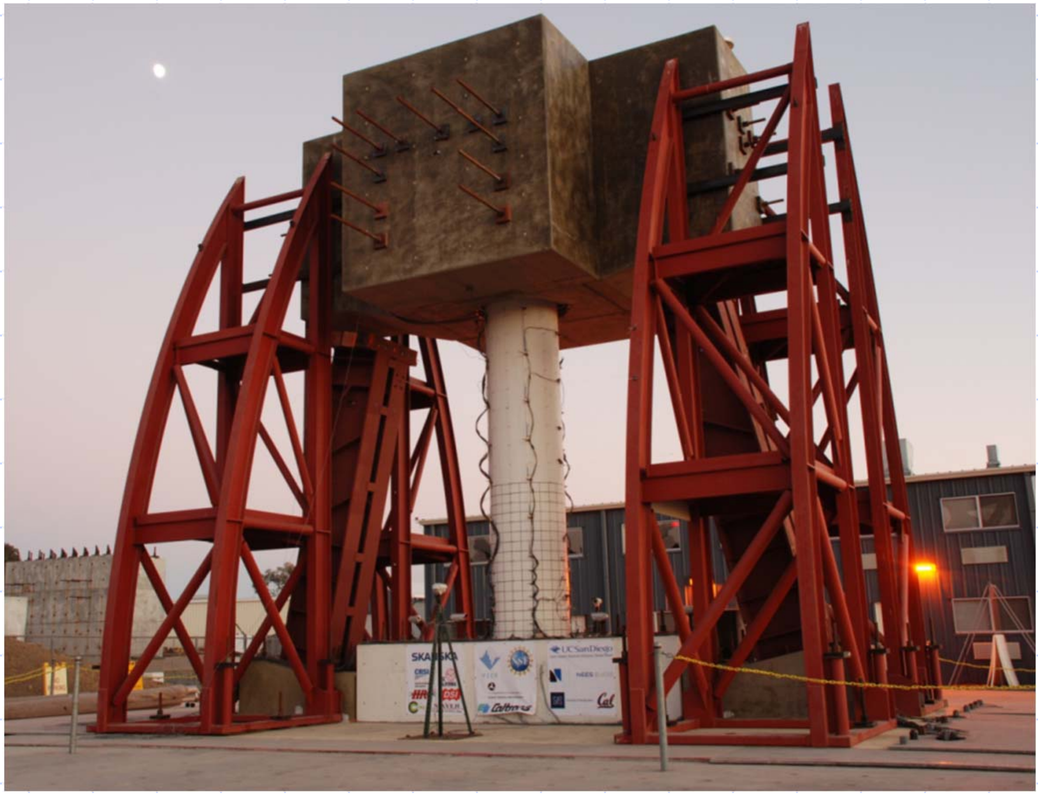
Physical Models and Calibration
UCB – Scaled columns made of pressurized grout

- Grout **specimen 3** - 300 kip axial load
- Modeling – corotational geometric transformation



Physical Models and Calibration
UCSD – Full-scale column

- PI: Prof. Jose Restrepo
- Unidirectional
- Full scale - 24′ height 4′ diameter



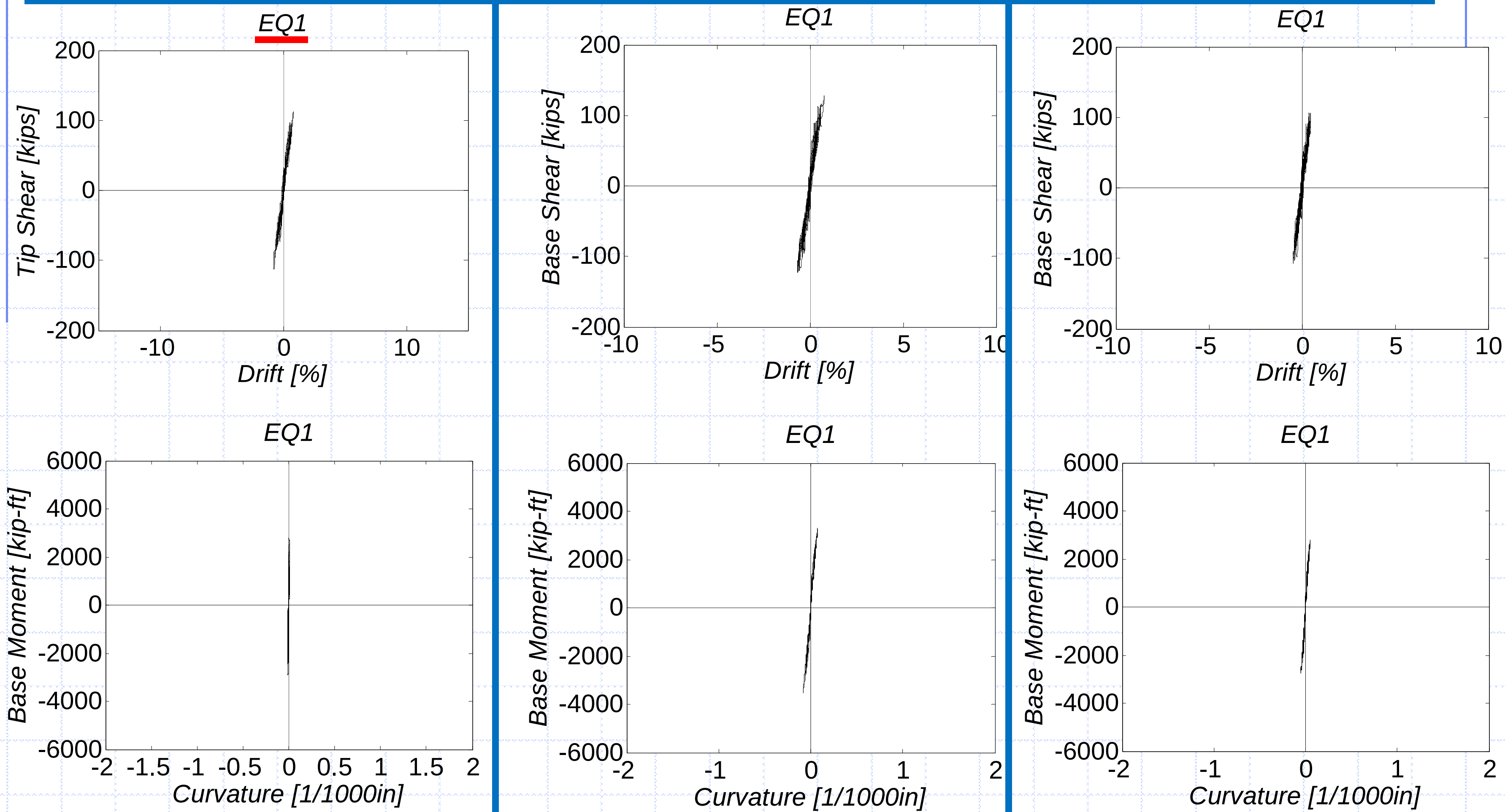
Physical Models and Calibration
UCSD – Full-scale column

Comparison of:

- Experimental Response
- Concrete02 with Standard Fiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation

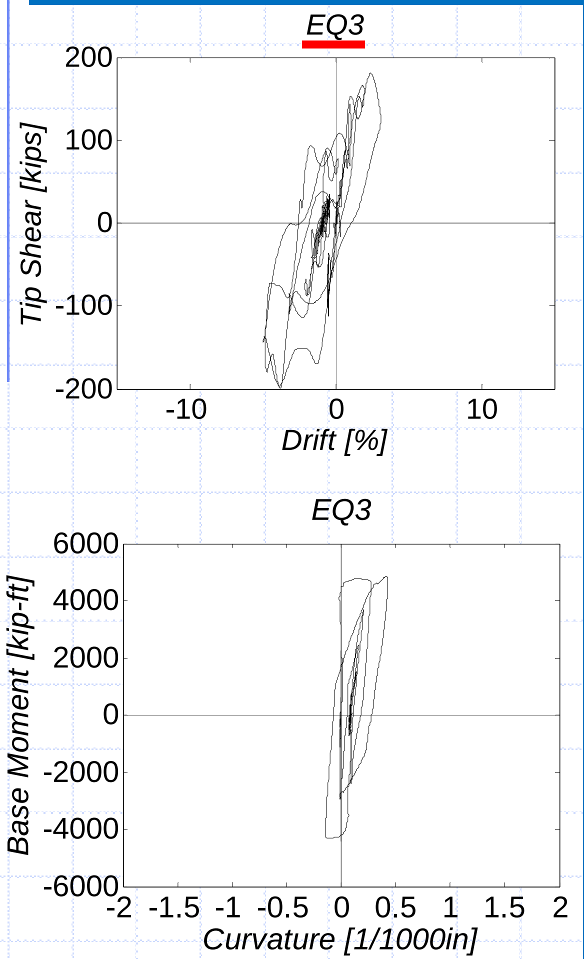
Physical Models and Calibration
UCSD – Full-scale column

Experimental Response | **Concrete02 + Fiber** | **ConcreteBLE + RCFiber**

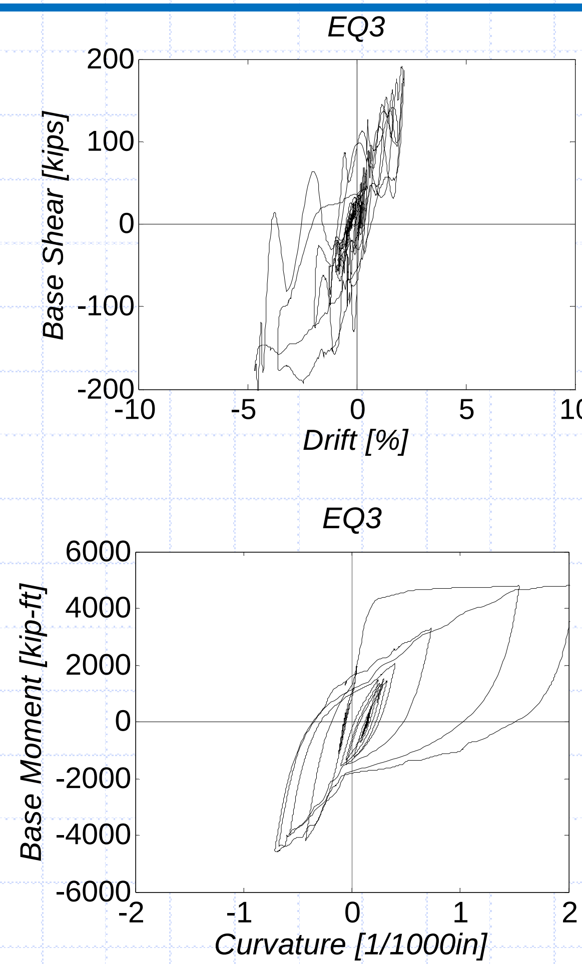


Physical Models and Calibration
UCSD – Full-scale column

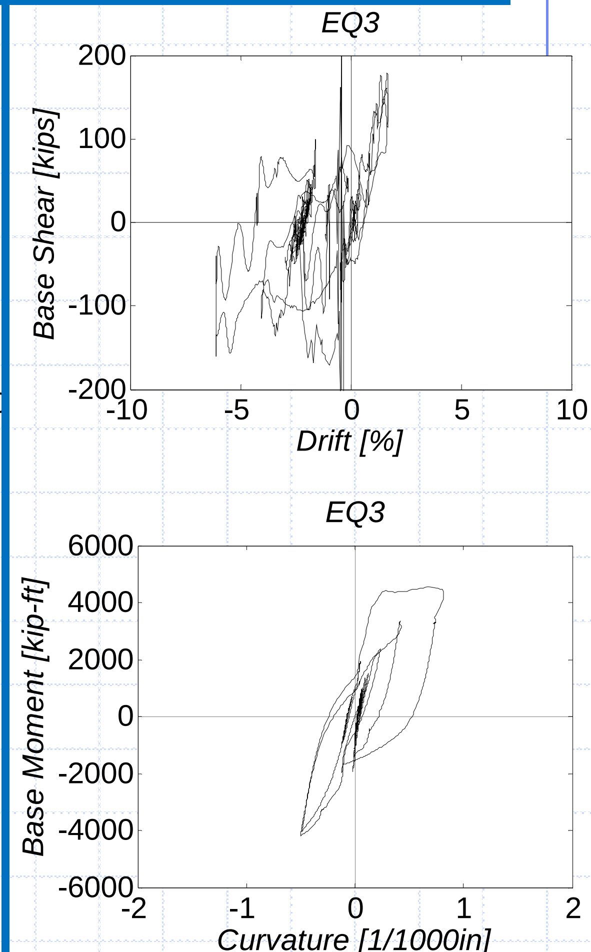
Experimental Response



Concrete02 + Fiber

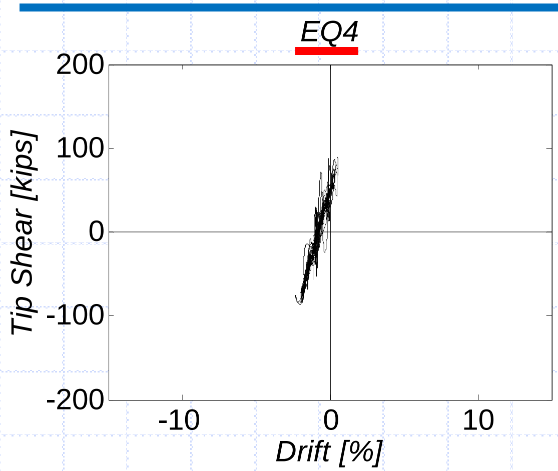


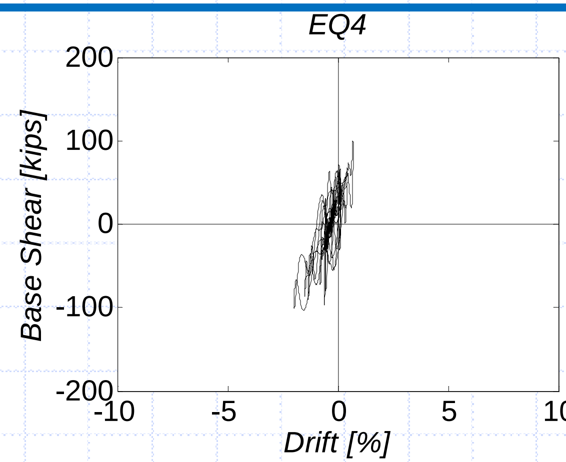
ConcreteBLE + RCFiber

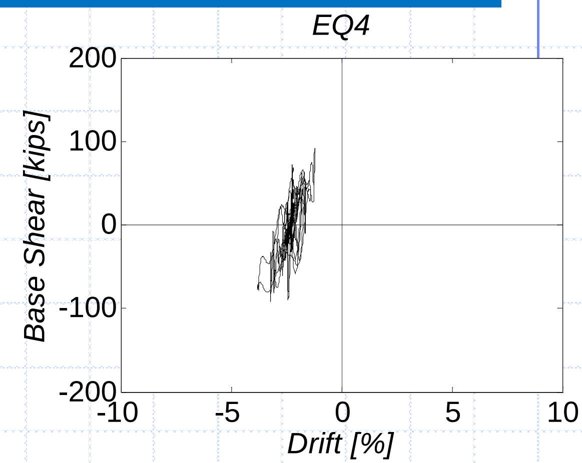


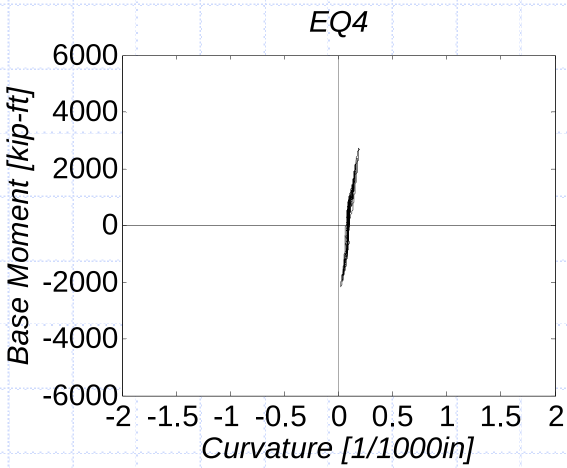
Physical Models and Calibration
UCSD – Full-scale column

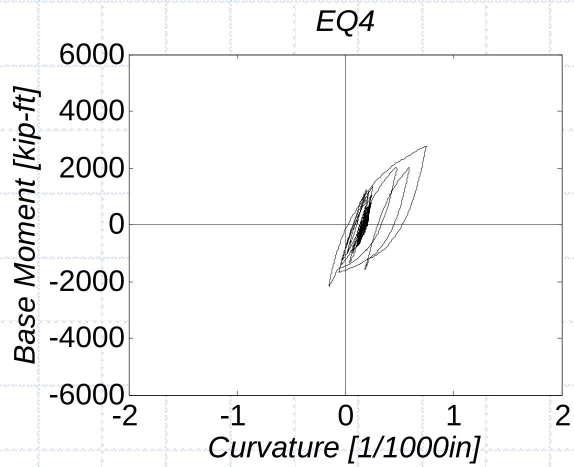
Experimental Response	Concrete02 + Fiber	ConcreteBLE + RCFiber

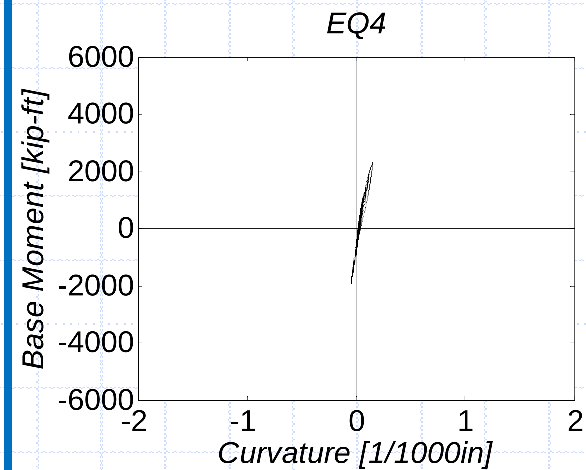








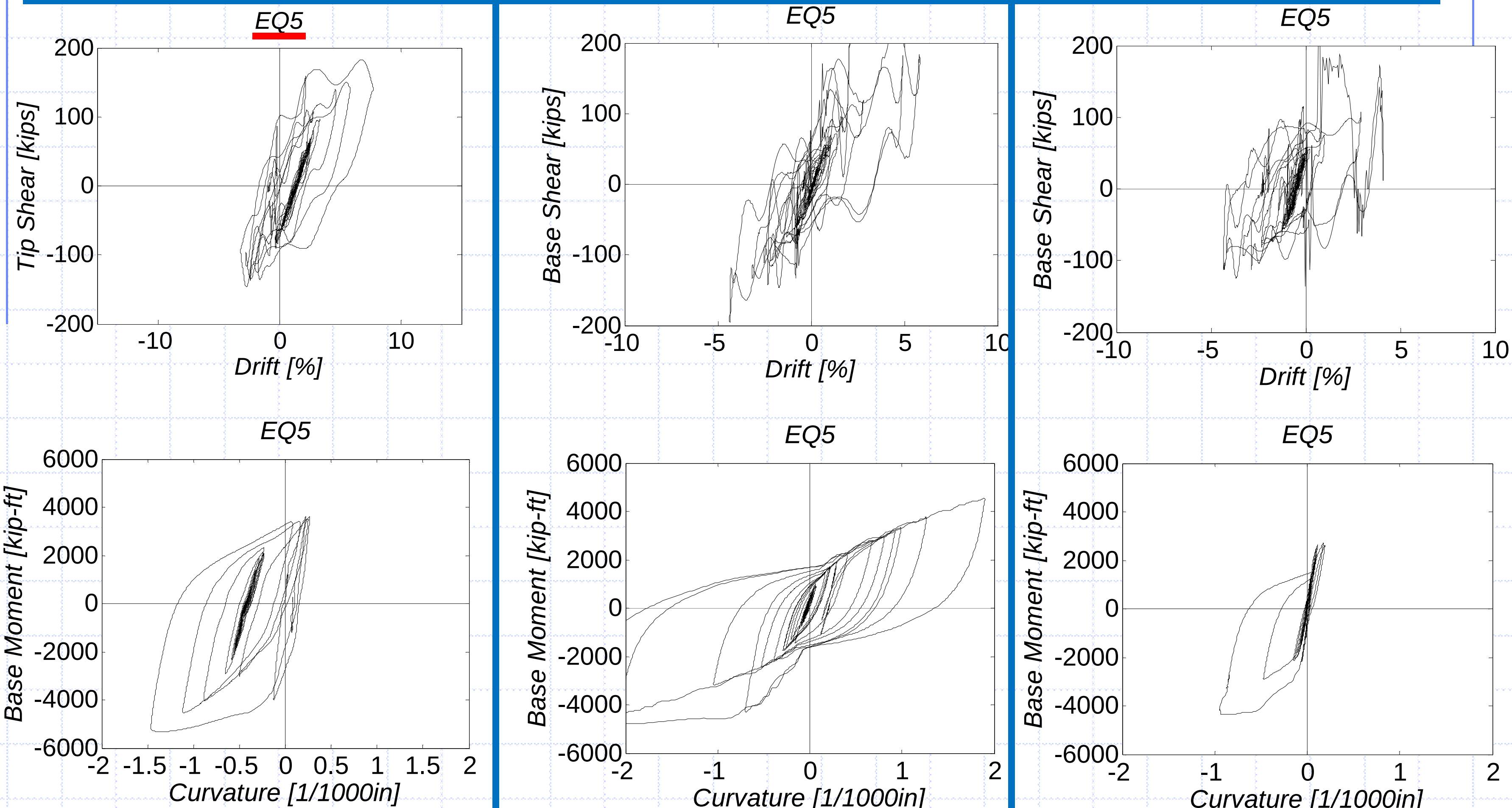




Physical Models and Calibration

UCSD – Full-scale column

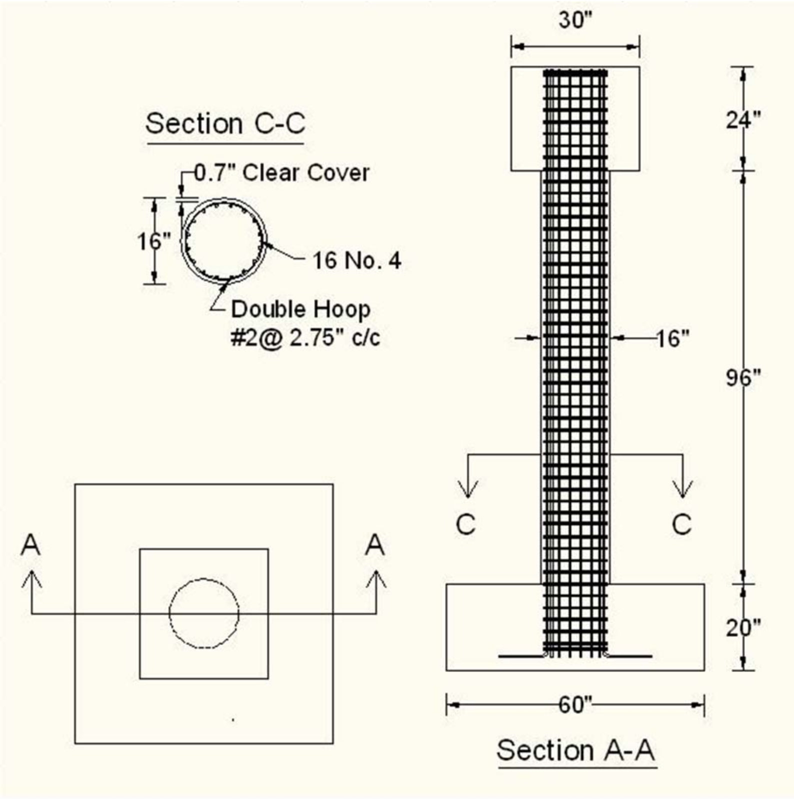
Experimental Response	Concrete02 + Fiber	ConcreteBLE + RCFiber

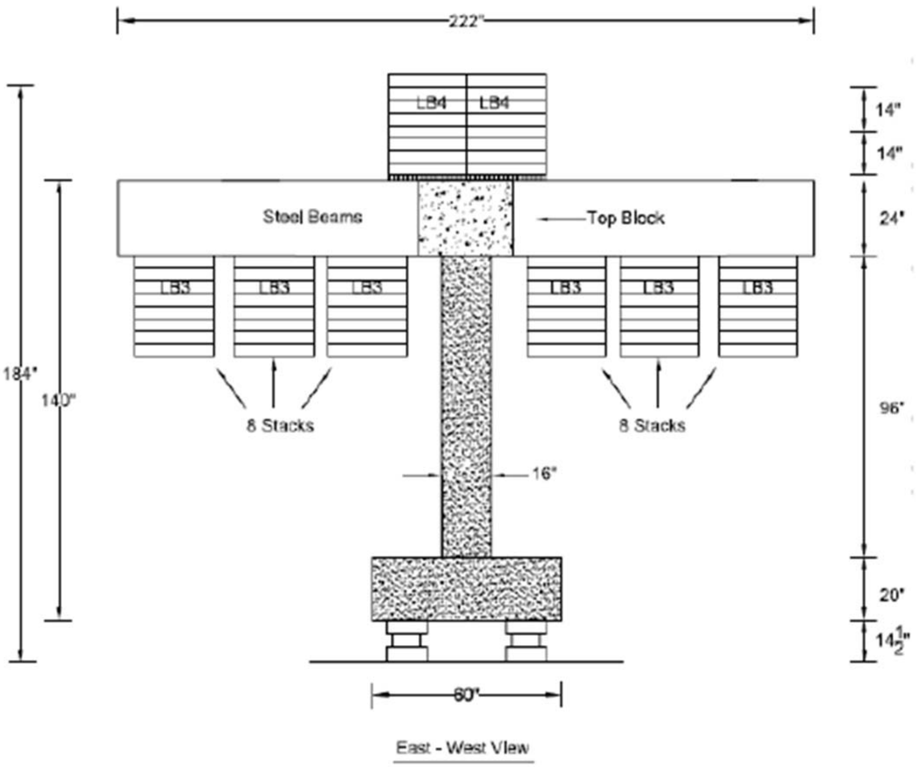


Physical Models and Calibration

UCB – 1/3-Scale of UCSD column

- Unidirectional
- 1/3 scale - 8′ height 16″ diameter





Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Element	Description	UCSD	UC Berkeley	Scaling Factor
Column Height, $H_{Column}(in.)$	*Between footing and column top*	288	96	$S=\frac{288}{96}=3$
Column Diameter, $D_{Column}(in.)$	*Include clear cover*	48	16	$S=\frac{48}{16}=3$
Axial Load Ratio, $\rho_{Axial}(\%)$	$\rho_{axial}=P_{axial}/(A_g f'_c)$	5.34%	5.51%	$S=\frac{5.34}{5.51}=0.97$
Superstructure Mass, $M_{Super}(kips)$	$M_{topblock}+M_{beams}+M_{lead\ blocks}$	521.9	62.585	$S^2=\frac{521.9}{62.585}=8.34,\ S=2.9$
Longitudinal Steel Ratio, $\rho_L(\%)$	$\rho_L=A_{st}/A_g$	1.55	1.59	$S=\frac{1.55}{1.59}=0.98$
Volumetric Transverse Steel Ratio $\rho_V(\%)$	$\rho_V=(4A_V)/(D_{core}s)$	0.953	0.976	$S=\frac{0.953}{0.976}=0.98$
Longitudinal Rebar Area, $A_b(in^2.)$	$UCSD=\#11,\ UCBerkeley=\#4$	1.56	0.20	$S^2=\frac{1.56}{0.20}=7.8,\ S=2.8$
Transverse Reinforcement Area $A_V(in^2.)$	$UCSD=2\#5,\ UCBerkeley=2\#2$	0.62	0.098	$S^2=\frac{0.62}{0.098}=6.33,\ S=2.5$
Transverse Reinforcement Spacing $s(in.)$	*Considering effect of both Seggregation and Buckling*	6	2.75	$S=\frac{6.0}{2.75}=2.2$
Center of Mass Elevation, $y_{CM}(in.)$	*Measured above Footing Top*	288	102	$S=\frac{288}{102}=2.8$
Moment of Inertia, $I(kips\text{-}in\text{-}sec^2)$	**See Calculations*	8778	223	$S^4=\frac{8778}{223}=39.4,\ S=2.5$

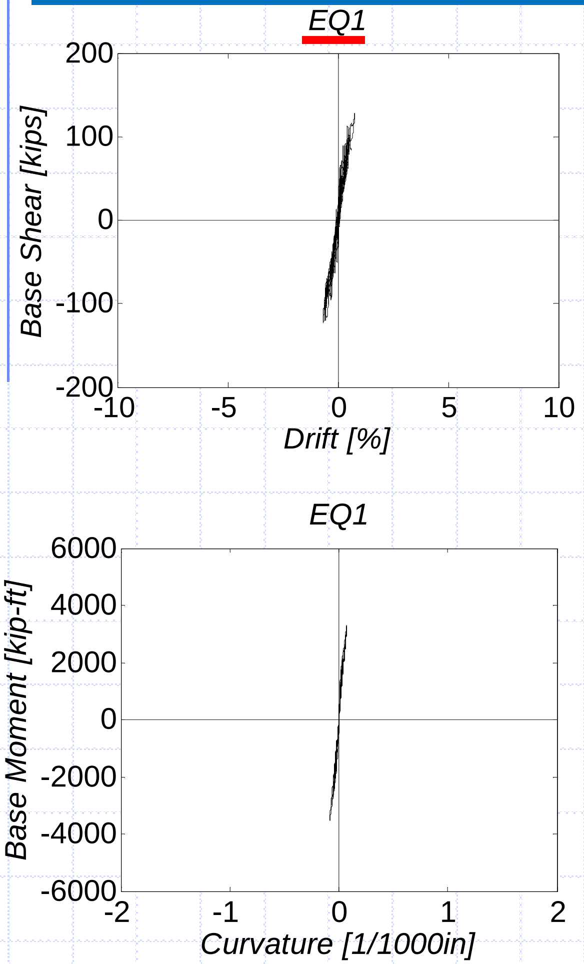
Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

Comparison of:

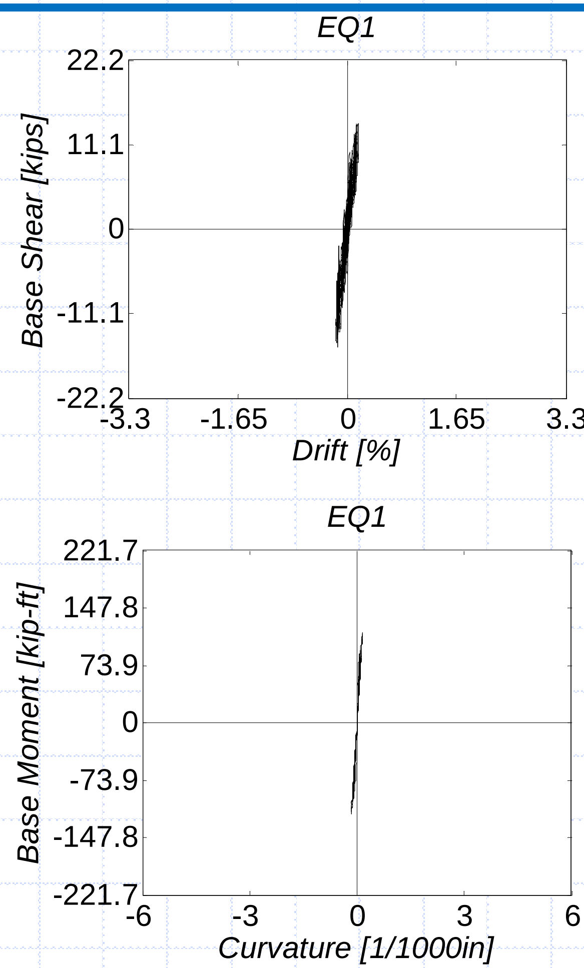
- Concrete02 with Standard Fiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation
- ConcreteBLE with RCFiber Section Simulation, Length Scaled by 1/3

Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

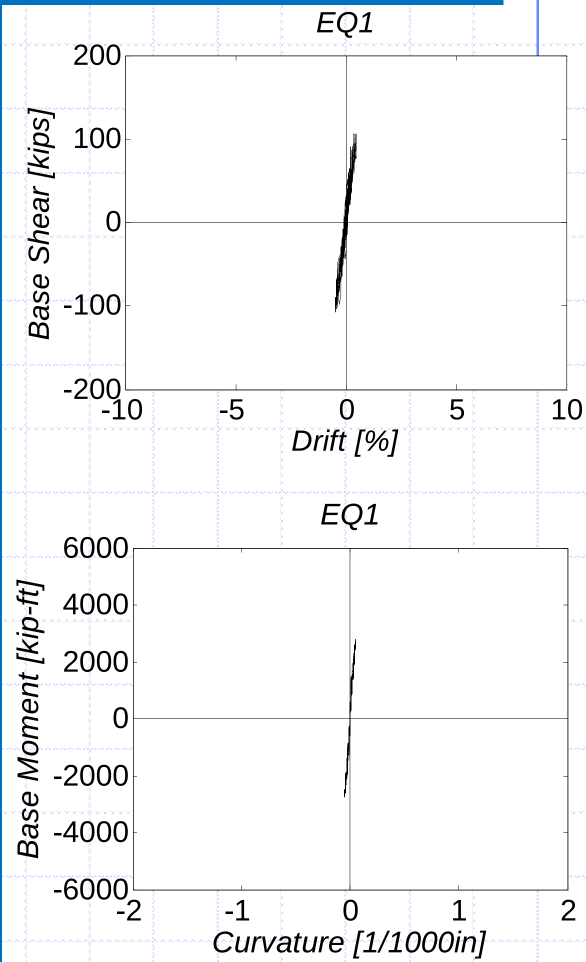
Concrete02 + Fiber



ConcreteBLE + RCFiber (1/3)

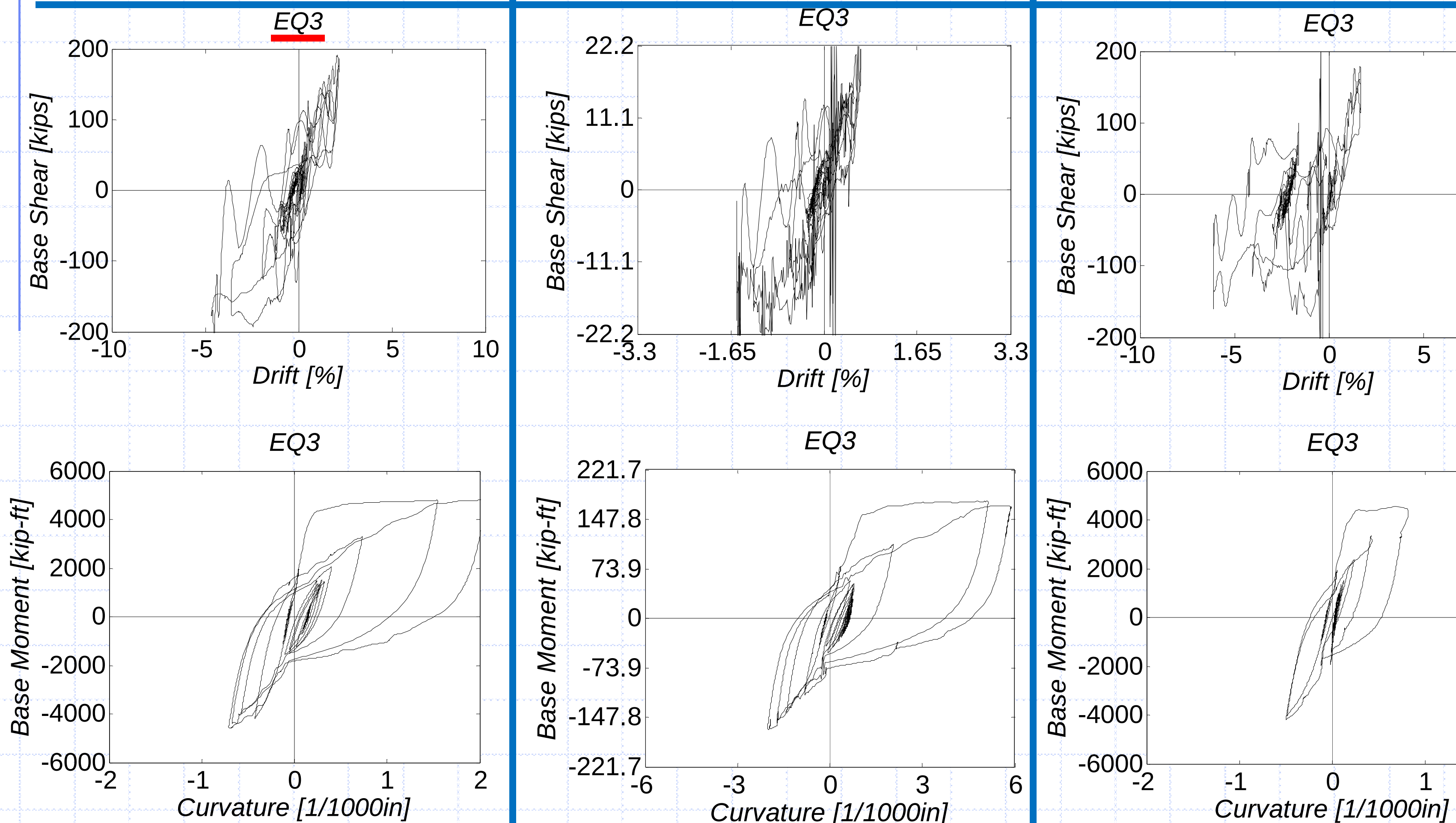


ConcreteBLE + RCFiber



Physical Models and Calibration
UCB – 1/3-Scale of UCSD column

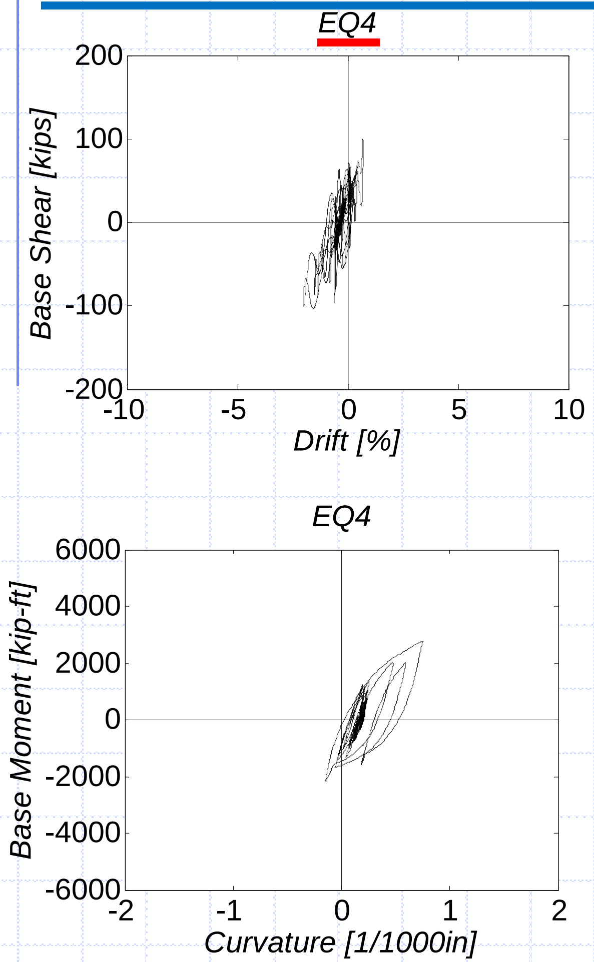
Concrete02 + Fiber | **ConcreteBLE + RCFiber (1/3)** | **ConcreteBLE + RCFiber**



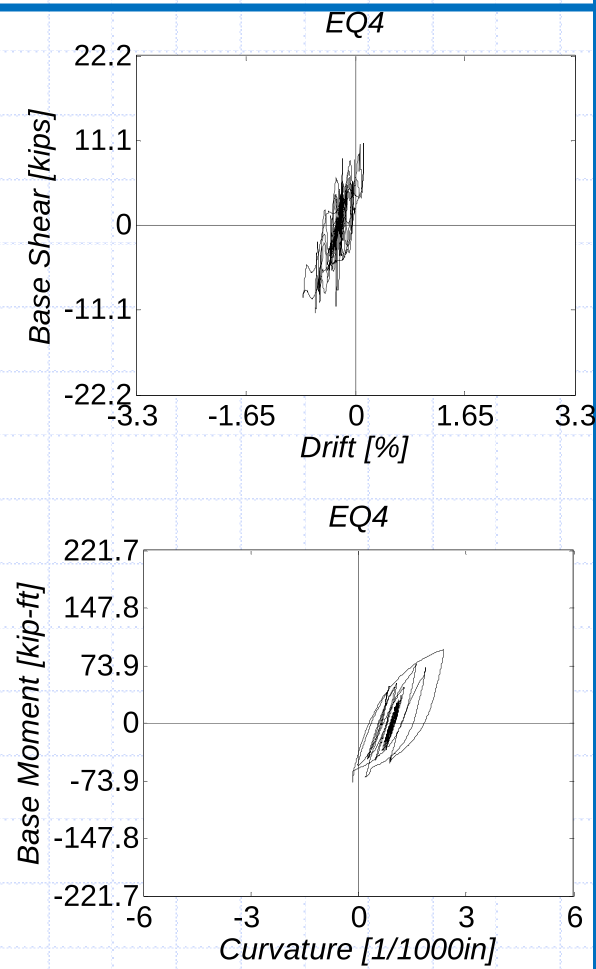
Physical Models and Calibration

UCB – 1/3-Scale of UCSD column

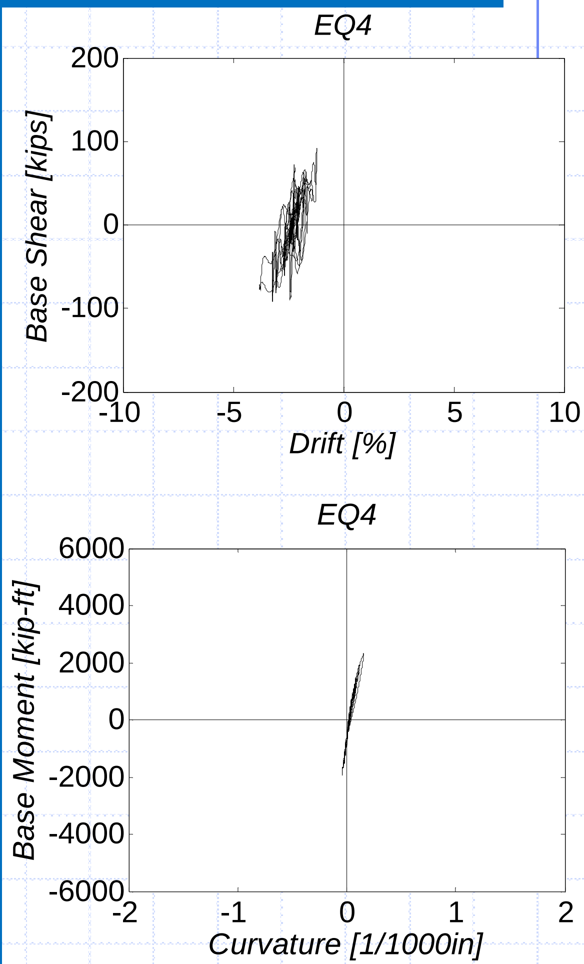
Concrete02 + Fiber



ConcreteBLE + RCFiber (1/3)



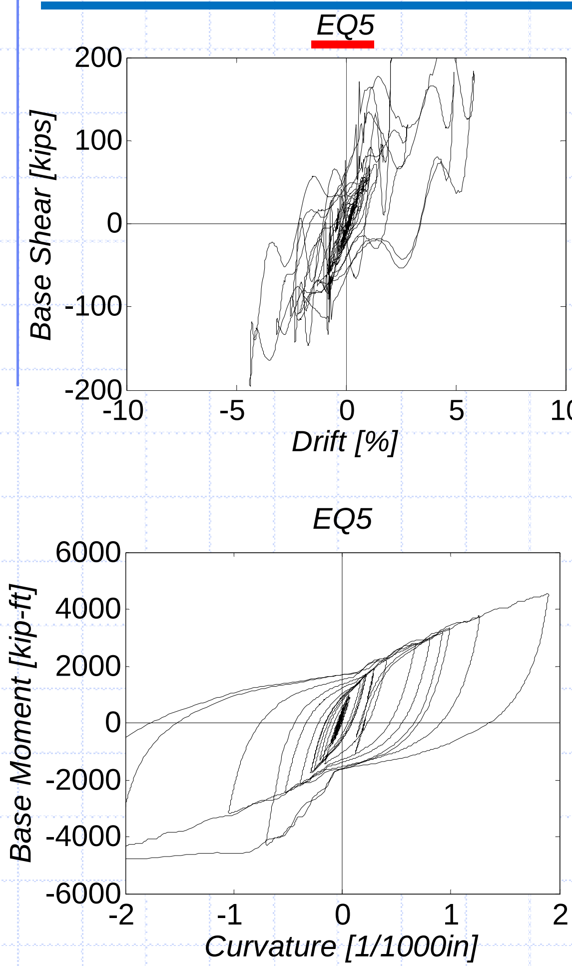
ConcreteBLE + RCFiber



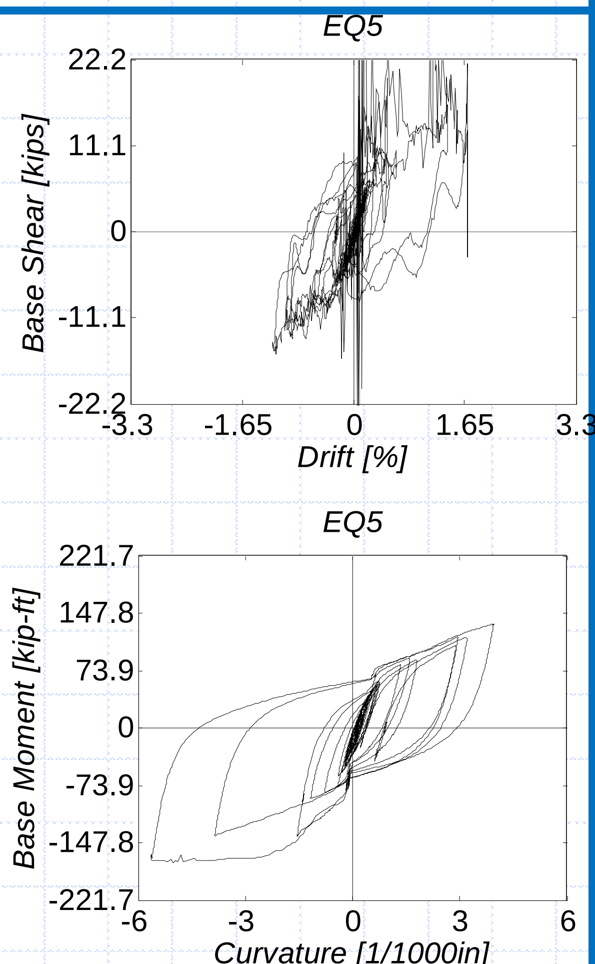
Physical Models and Calibration

UCB – 1/3-Scale of UCSD column

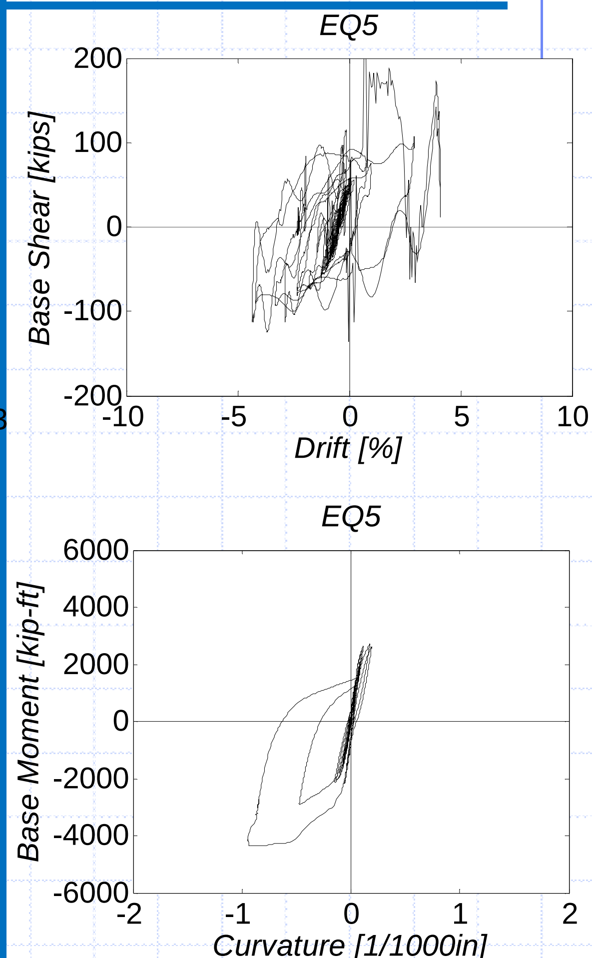
Concrete02 + Fiber



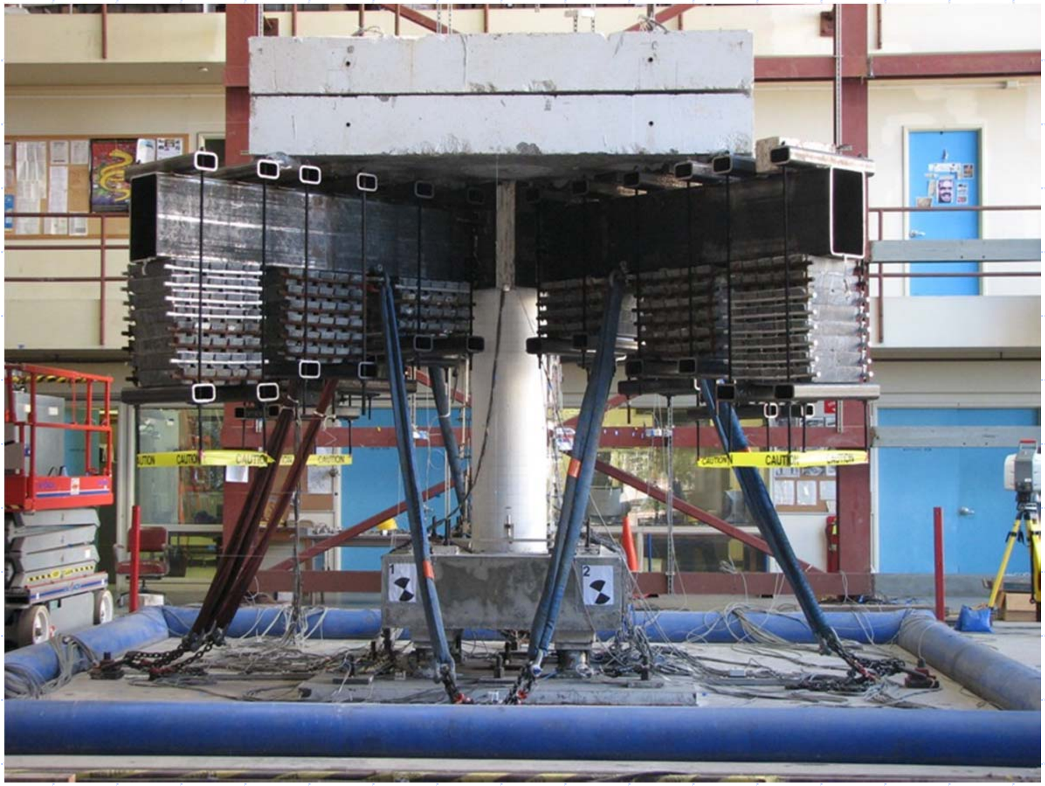
ConcreteBLE + RCFiber (1/3)



ConcreteBLE + RCFiber

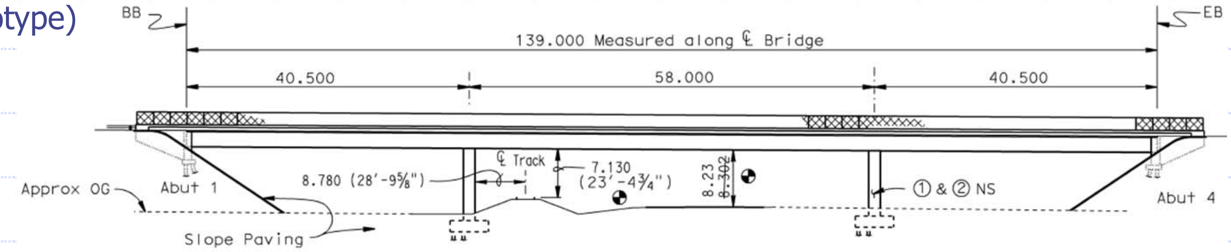


Physical Models and Calibration
UCB – Scaled columns under hrz. & vl. motion



Two specimens (SP1, SP2)

- ¼-scale Plumas Arboga Overhead (Prototype)
- Aspect Ratio = 3.5 : D=20”, h=70”
- Axial Load Ratio = 6.8%
- 2D excitation = X+Z, Northridge EQ
- ρ_V =0.55% (SP1), 0.36% (SP2)

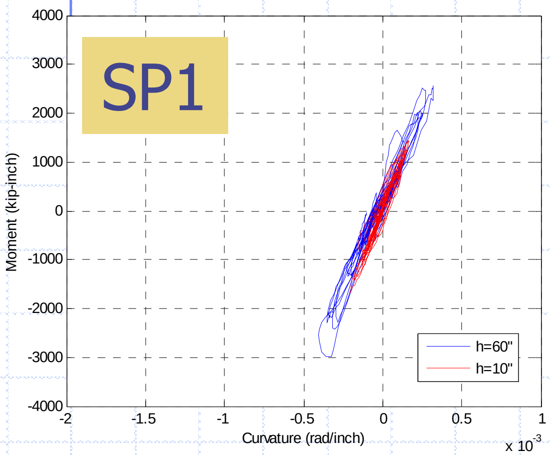


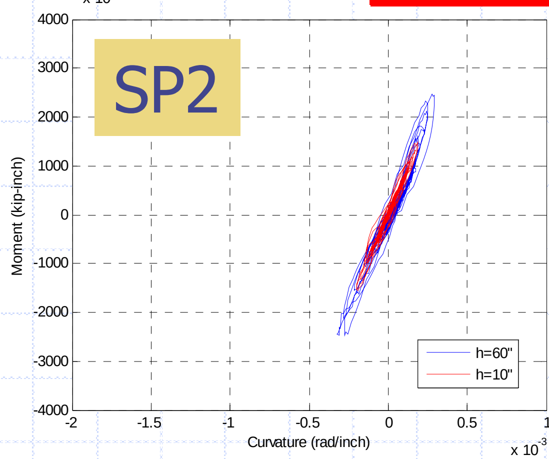
Physical Models and Calibration

UCB – Scaled columns under hrz. & vl. motion

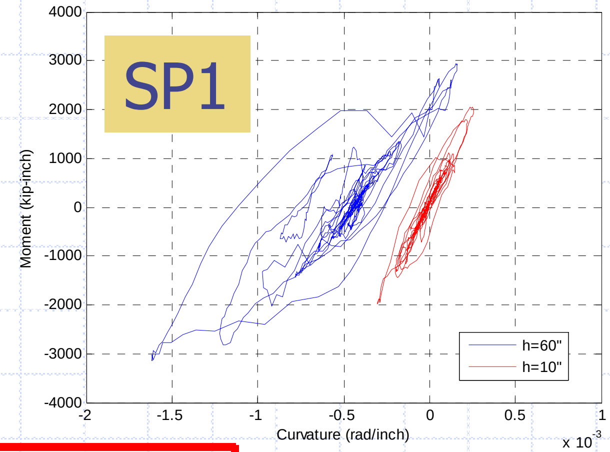
Sample Test Results

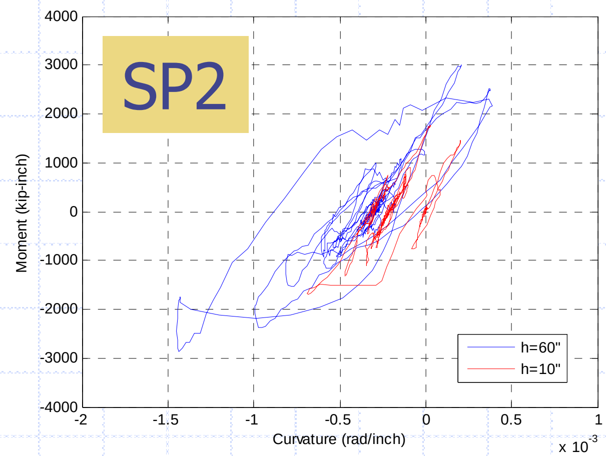
Moment-Curvature at h=10” and 60”
70% Northridge EQ (1-7 and 2-7)





Moment-Curvature at h=10” and 60”
125% Northridge EQ (1-9 and 2-9)





Conclusions and Future Tasks

- Accounting for concrete softening behavior and real-time confining pressures give a more realistic response.
- Results from scaled specimens in physical testing show more relative energy dissipation than larger prototypes.
- Size effect should be accounted for in modeling.
- The new material and fiber section models consider explicit parameters that depend on the size of the modeled column. Further calibration is still needed.
- Damage models should be calibrated and implemented for different mix designs and confinement conditions.

Conclusions and Future Tasks

- Complete physical testing of the 1/3-model (concrete casting is taking place TODAY!)
- Further calibration of the material and fiber section models is underway
- Comparison between findings and code provisions (e.g. ACI, AASHTO, CALTRANS)
- Release ConcreteBLE material, RCFiber section and Damage models in the next version of OpenSees