Performance Modeling Strategies for Modern Reinforced Concrete Bridge Columns

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UW-PEER Structural Performance Database

- Nearly 500 Columns
  - spiral or circular hoop-reinforced columns (~180)
  - rectangular reinforced columns (~300)
- Column geometry, material properties, reinforcing details, loading
- Digital Force-Displacement Histories
- Observations of column damage
- http://nisee.berkeley.edu/spd
- User's Manual (Berry and Eberhard, 2004)

Objective of Research

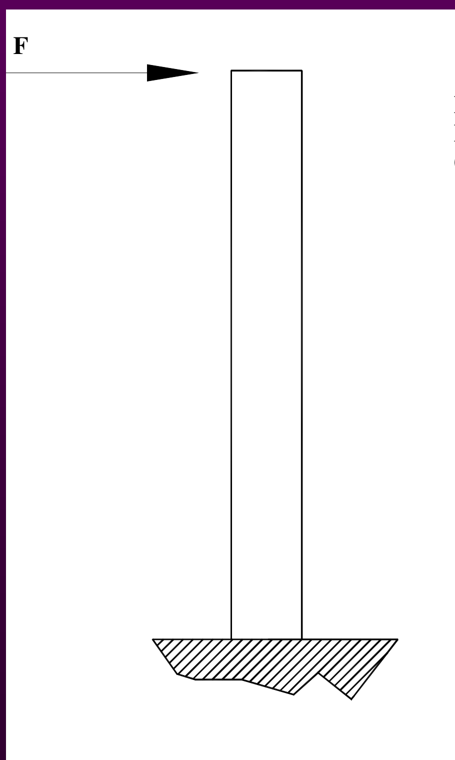
Develop, calibrate, and evaluate column modeling strategies that are capable of accurately modeling bridge column behavior under seismic loading.

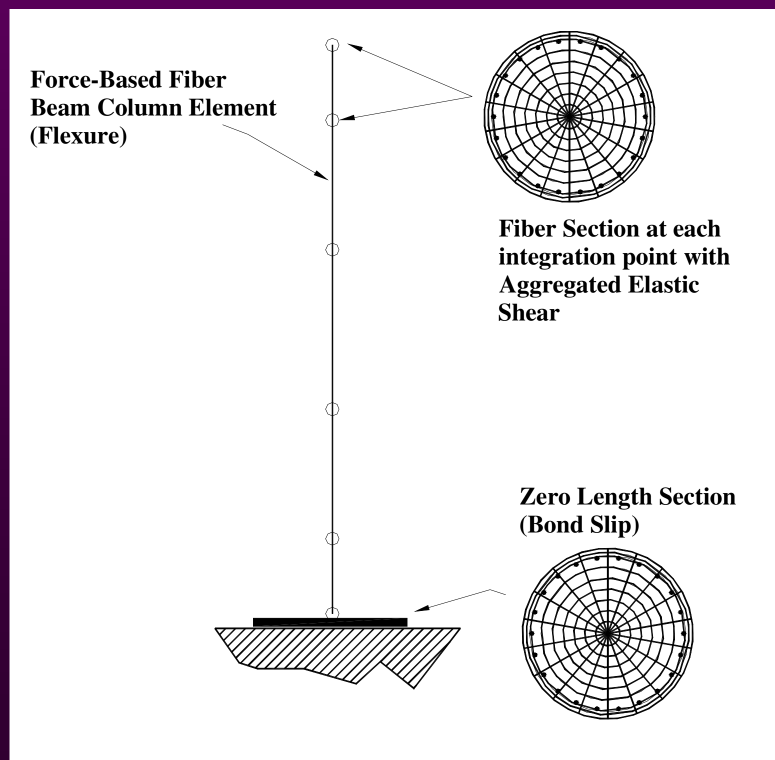
– Global deformations
– Local deformations (strains and rotations)
– Progression of damage

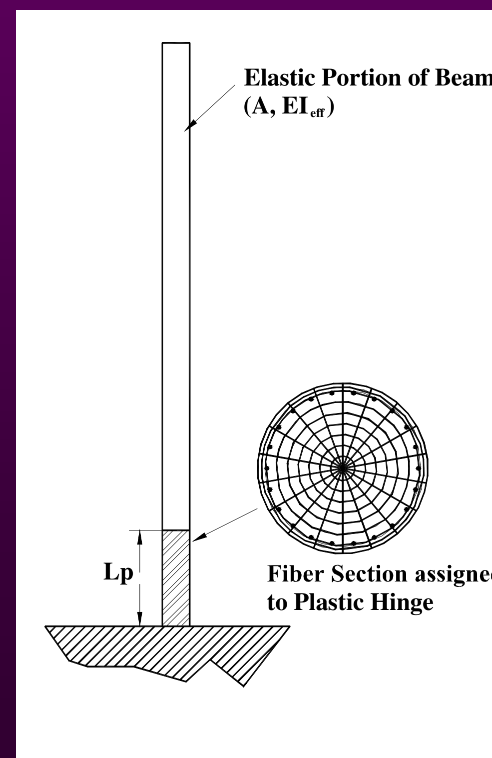
Advanced Modeling Strategies

Distributed-Plasticity

Lumped-Plasticity



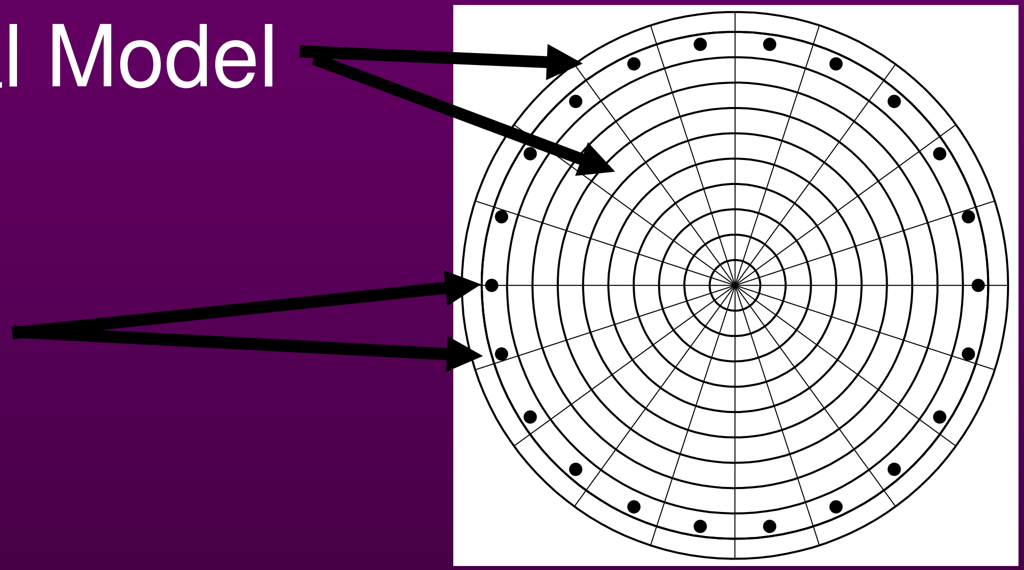




Cross-Section Modeling

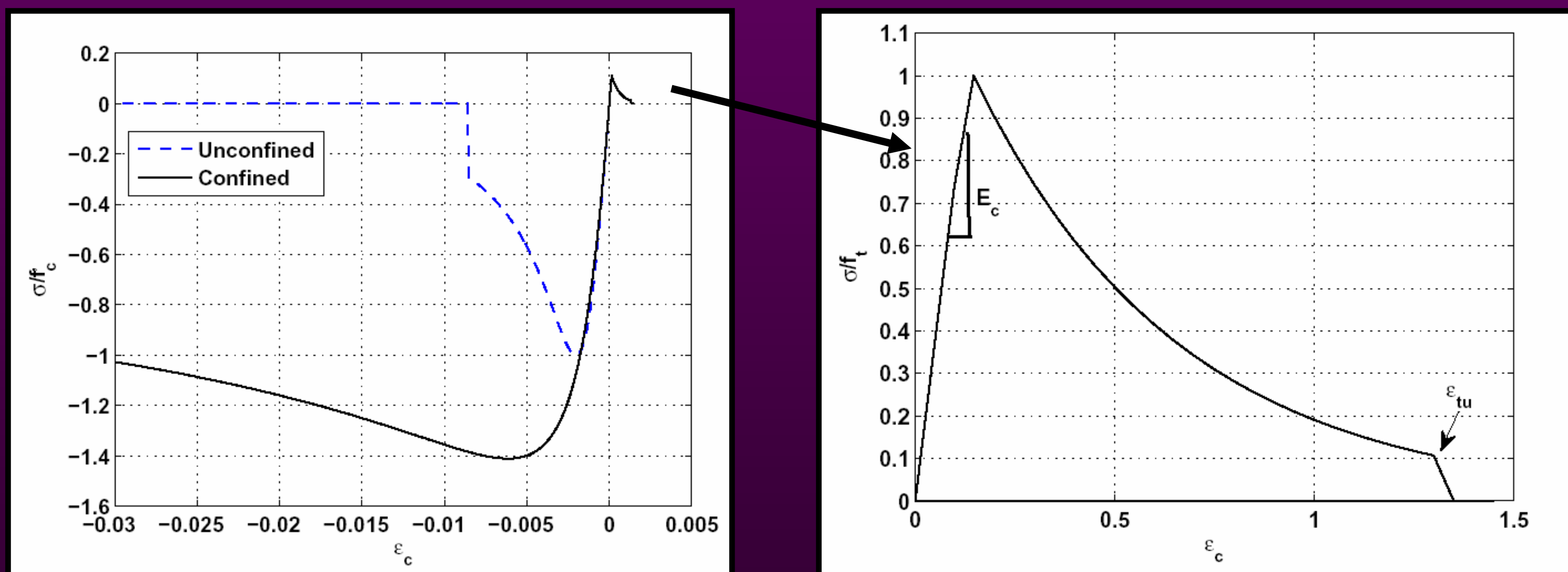
Cross-Section Modeling Components

- Concrete Material Model
- Reinforcing Steel Material Model
- Cross-Section Discretization Strategy

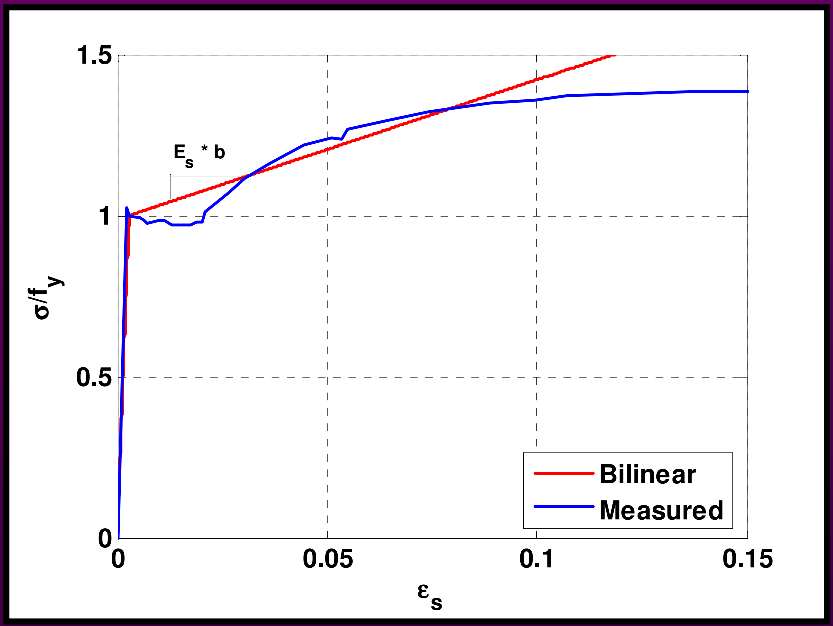


Concrete Material Model

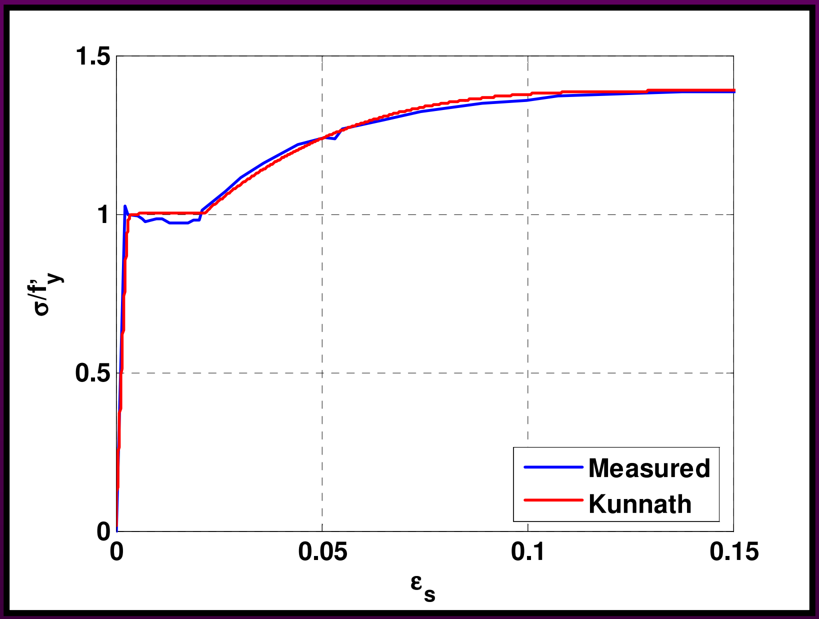
Popovic’s Curve with Mander et. al. Constants and Added Tension Component (Concrete04)



Reinforcing Steel Material Models



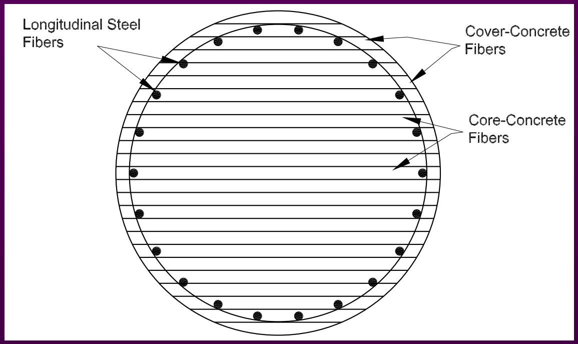
Giufre-Menegotto-Pinto
(Steel02)

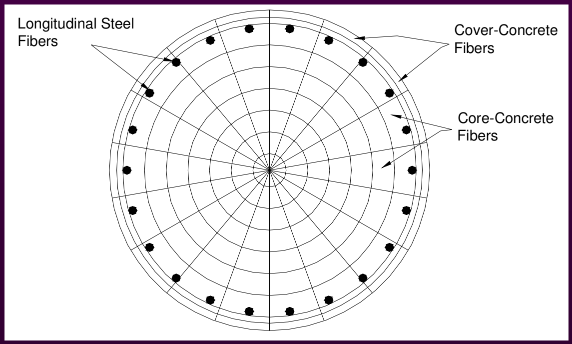


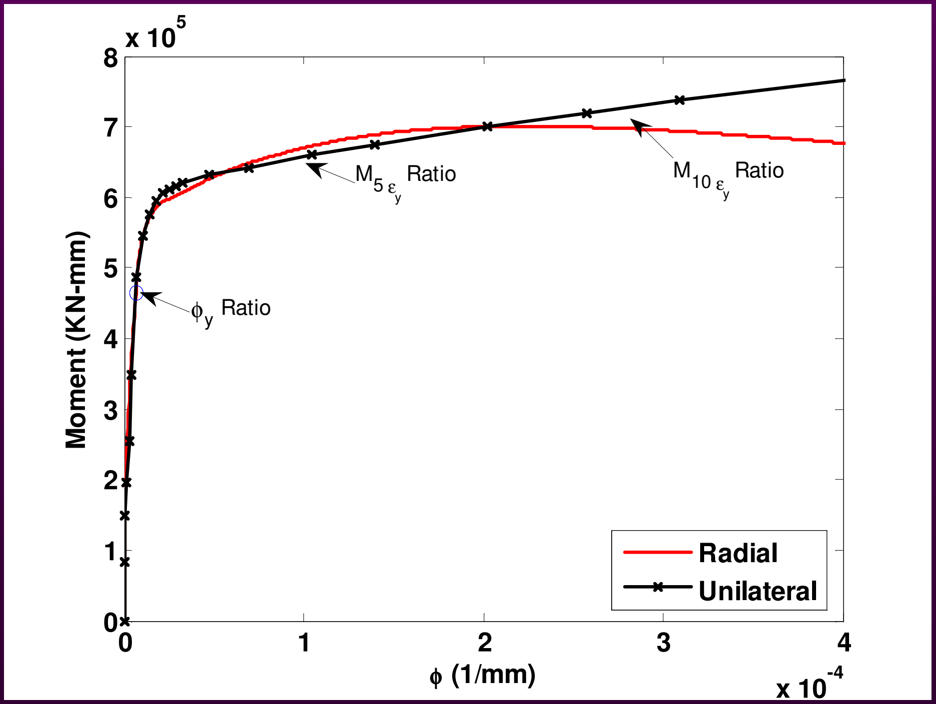
Mohle and Kunnath
(ReinforcingSteel)

Section Fiber Discretization

- Objective: Use as few fibers as possible to eliminate the effects of discretization

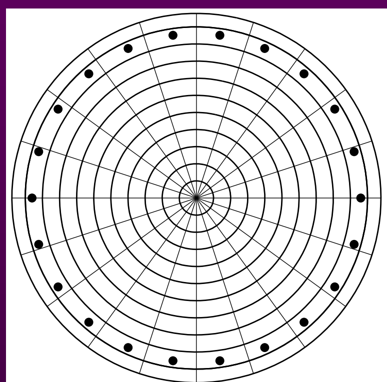






Cross-Section Fiber Discretization

Uniform (220 Fibers)



Confined

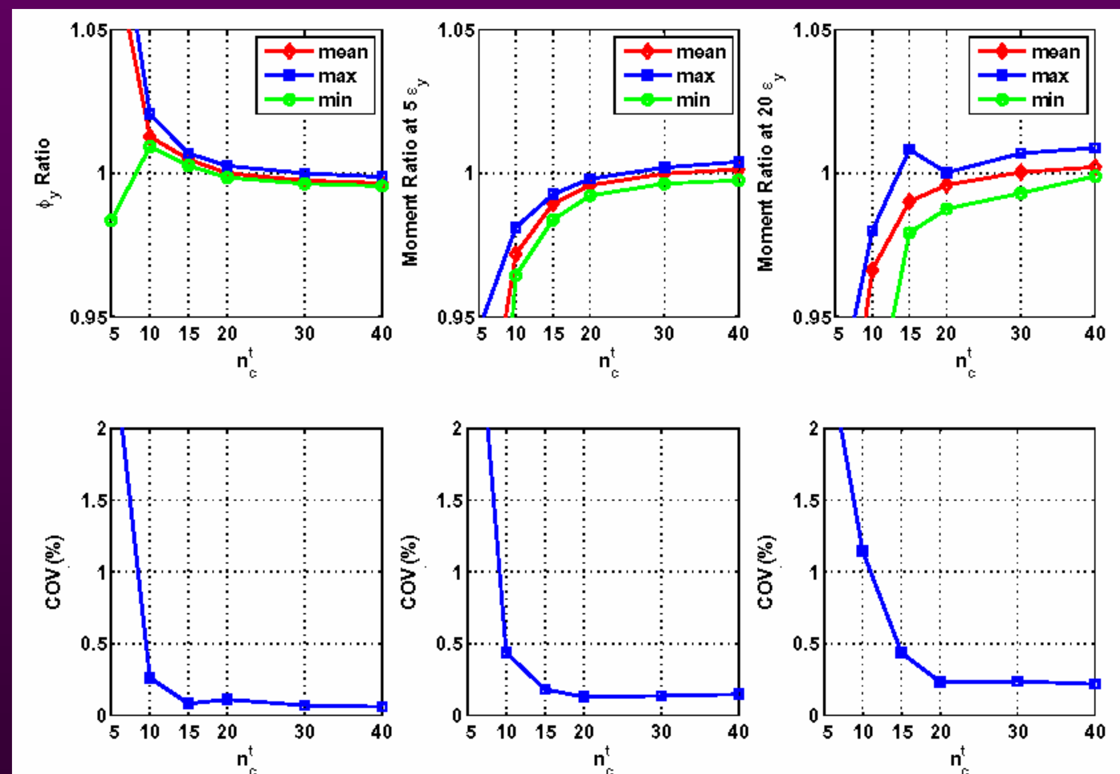
$$n_c^r = 10$$

$$n_c^t = 20$$

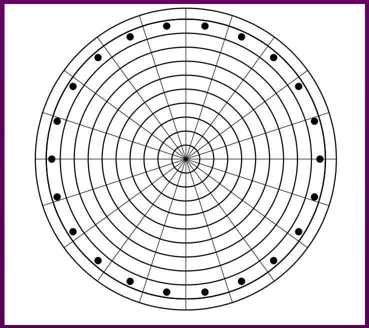
Unconfined

$$n_u^r = 1$$

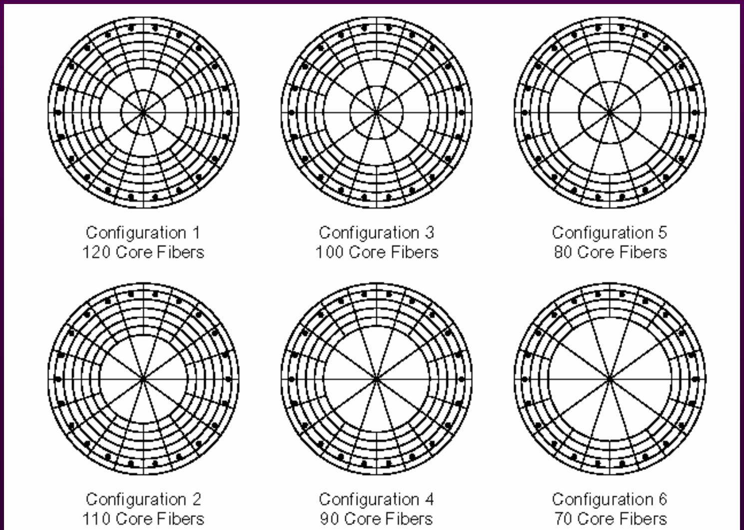
$$n_u^t = 20$$



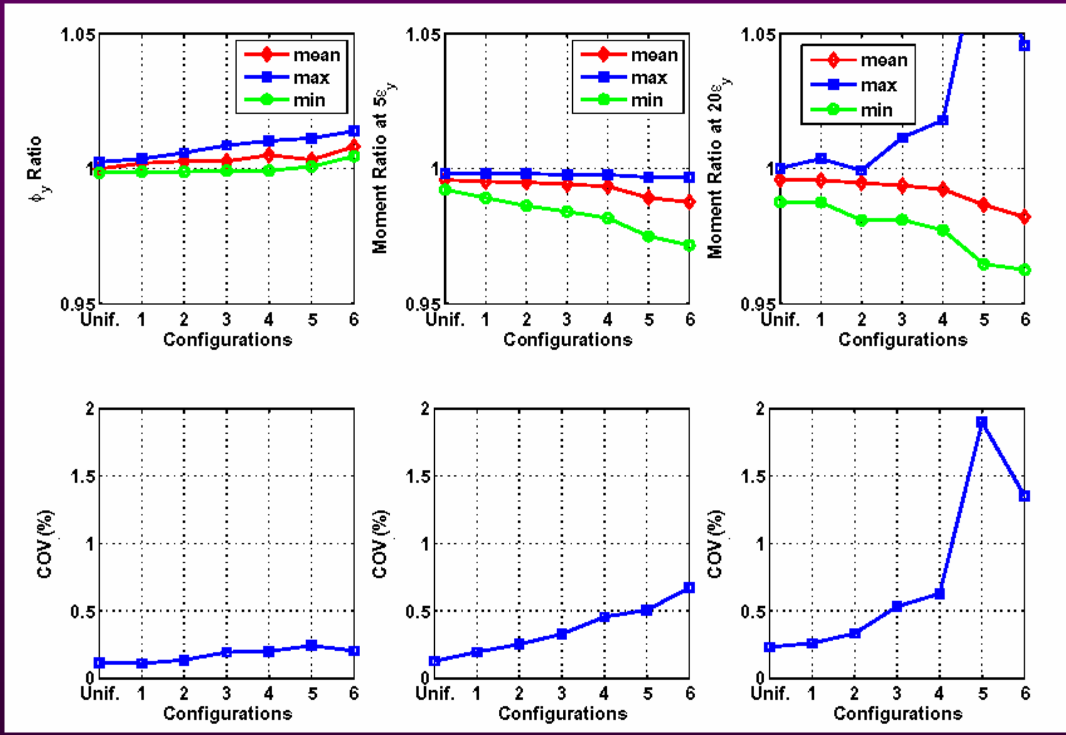
Reduced Fiber Discretization



Uniform (220 Fibers)

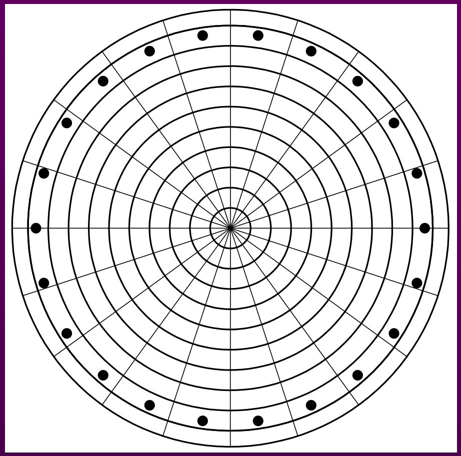


Nonuniform Strategies

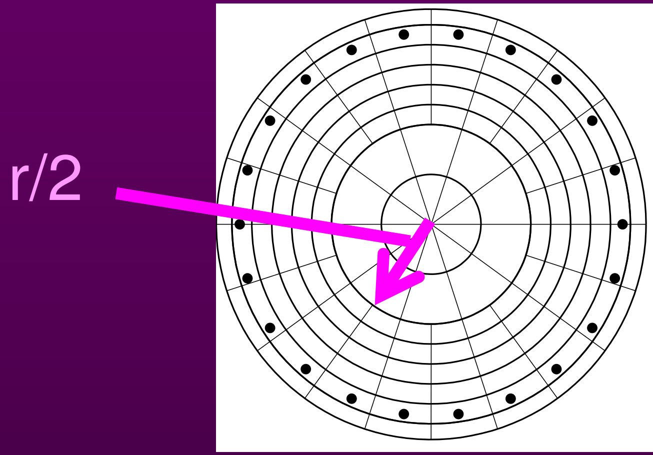


Cross-Section Fiber Discretization

Uniform (220 Fibers)



Reduced (140 Fibers)



Uniform (220 Fibers)

Confined

$$n_c^r = 10$$

$$n_c^t = 20$$

Unconfined

$$n_u^r = 1$$

$$n_u^t = 20$$

Reduced (140 Fibers)

Confined

$$n_{fine}^r = 5$$

$$n_{fine}^t = 20$$

$$n_{coarse}^r = 2$$

$$n_{coarse}^t = 10$$

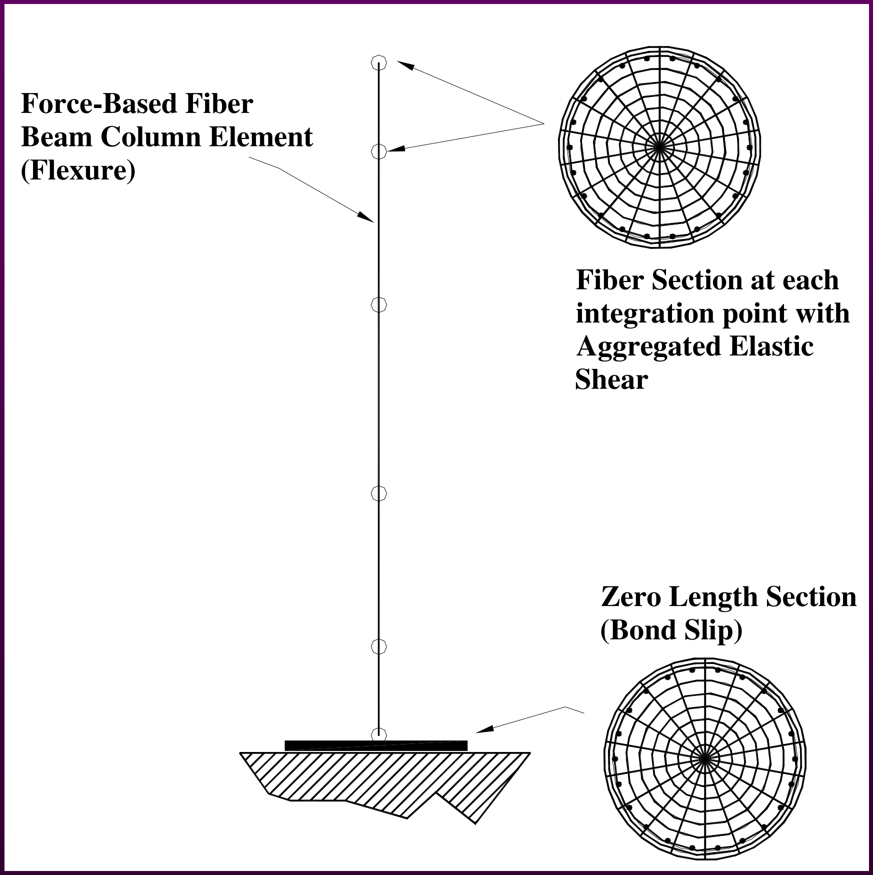
Unconfined

$$n_u^r = 1$$

$$n_u^t = 20$$

Modeling with Distributed-Plasticity Element

Model Components

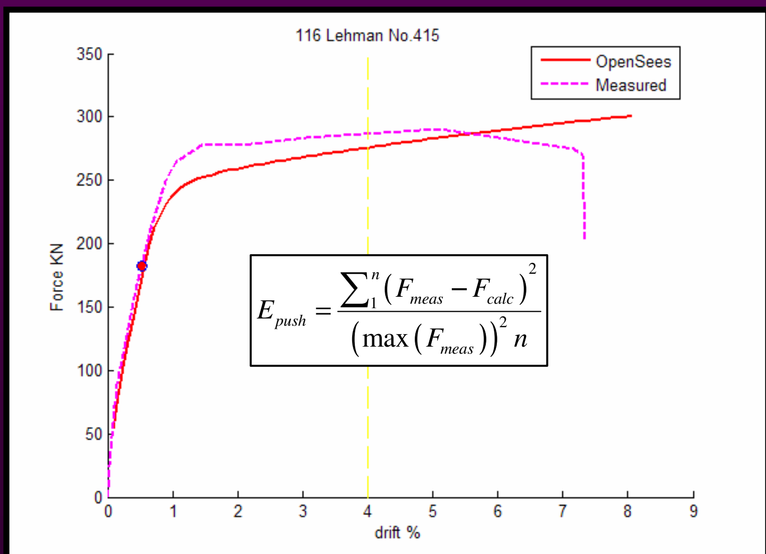


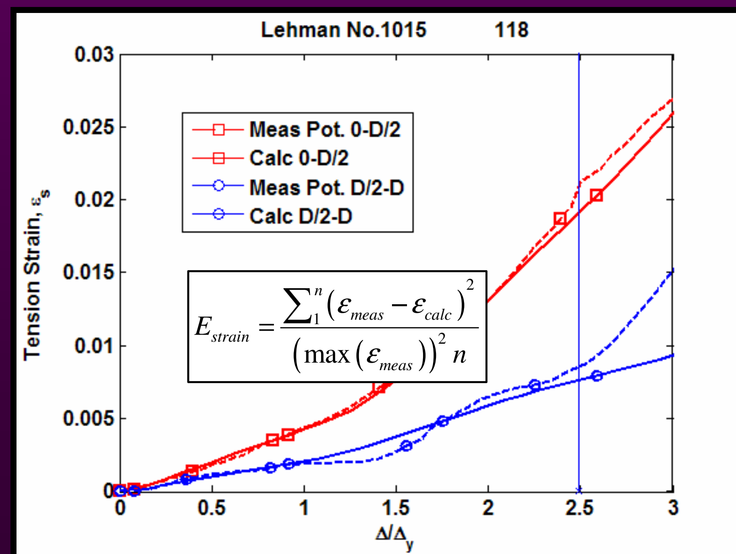
- **Flexure Model (Force-Based Beam-Column)**
  - *nonlinearBeamColumn*
  - Fiber section
  - Popovics Curve (Mander constants)
  - Giufre-Menegotto-Pinto (***b***)
  - Number of Integration Points (*Np*)
- **Anchorage-Slip Model**
  - *zeroLengthSection*
  - Fiber section
  - Reinforcement tensile stress-deformation response from Lehman et. al. (1998) bond model (λ)
  - Effective depth in compression (d_{comp})
- **Shear Model**
  - *section Aggregator*
  - Elastic Shear (γ)

Model Optimization

- Objective: Determine model parameters such that the error between measured and calculated global and local responses are minimized.

$$E_{total} = \text{mean}\left(E_{push}\right) + \frac{\kappa_1}{2}\text{mean}\left(E_{strain}^{(0-D/2)}\right) + \frac{\alpha_2}{2}\text{mean}\left(E_{strain}^{(D/2-D)}\right)$$

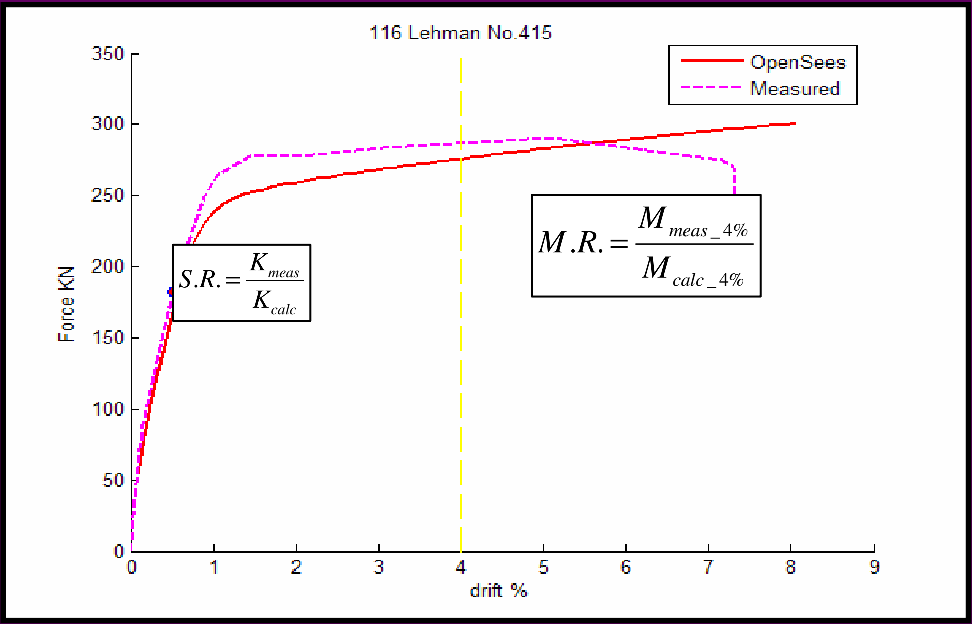




Model Evaluation

Optimized Model:

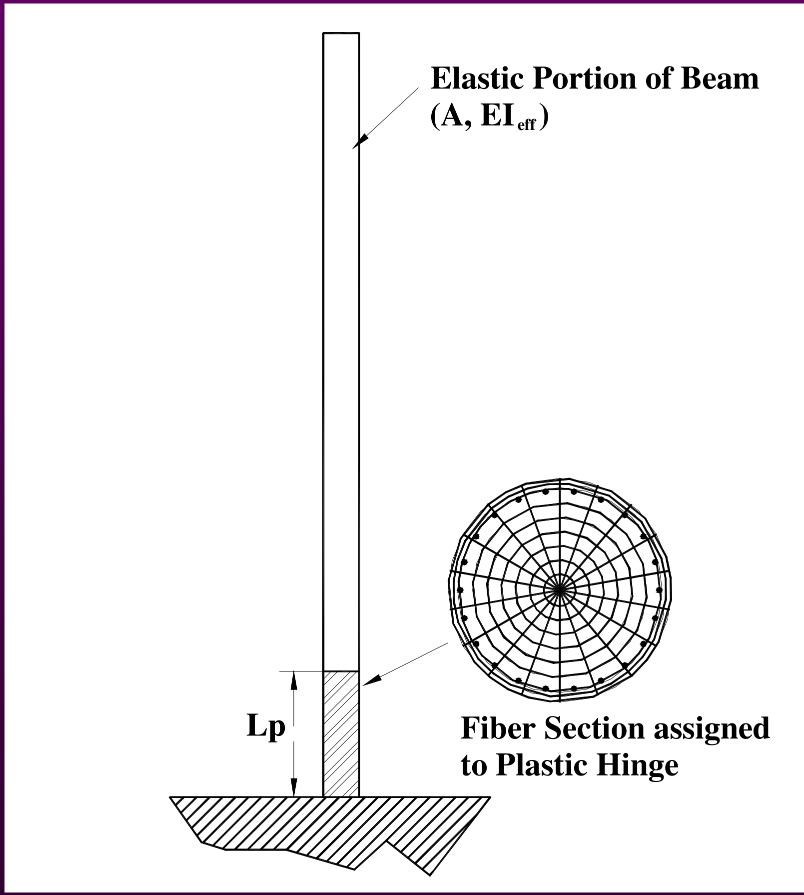
- Strain Hardening Ratio, *b = 0.01*
- Number of Integration Points, $N_p = 5$
- Bond-Strength Ratio, *λ = 0.875*
- Bond-Compression Depth,
- d_{comp} =1/2 N.A. Depth at 0.002 comp strain
- Shear Stiffness *γ* = 0.4



	E_{total}	E_{push}	$E_{strain}^{(0-D/2)}$	$E_{strain}^{(D/2-D)}$	$S.R.$	$M.R.$
mean	14.89	6.73	7.78	14.4	1.02	1.03
cov (%)	–	–	–	–	15	8

Modeling with Lumped-Plasticity Element

Lumped-Plasticity Model



- Hinge Model Formulation:
  - *beamwithHinges3*
  - Force Based Beam Column Element with Integration Scheme Proposed by Scott and Fenves, 2006.
  - Fiber Section
- Elastic Section Properties
  - Elastic Area, *A*
  - Effective Section Stiffness, EI_{eff}
- Calculated Plastic-Hinge Length
  - L_p

Section Stiffness Calibration

	Stiffness Ratio Stats	
$EI_{eff} =$	$\alpha_g^{calc} E_c I_g$	$\alpha_{\sec}^{calc} EI_{\sec}$
mean	1.00	1.00
cov (%)	19	16

$$\alpha_g^{calc} = 0.1 + 0.034\frac{L}{D} + 1.35\frac{P}{A_g f'_c} \leq 1.0$$

$$\alpha_{sec}^{calc} = 0.45 + 0.087\frac{L}{D} \leq 1.0$$

Plastic-Hinge Length Calibration

$$L_p = 0.05L + 0.1\frac{f_y d_b}{\sqrt{f'_c}} \leq \frac{L}{4}$$

$$\epsilon_{bb}^{calc} = 0.046 + 0.25\rho_{eff} \leq 0.15$$

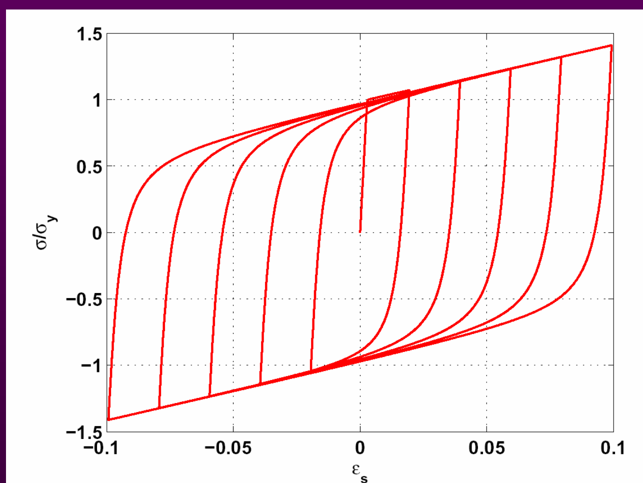
Plastic-Hinge Length	E_{total}	Pushover Accuracy			Damage Estimates					
		E_{push}	M.R.	D.R.	ϵ_{bb}		$\frac{\Delta_{bb}^{meas}}{\Delta_{bb}^{calc}}$	ϵ_{sp}		$\frac{\Delta_{sp}^{meas}}{\Delta_{sp}^{mean}}$
	mean	mean	mean	mean	mean	cov	cov	mean	cov	cov
Selected Optimal $0.05L + 0.1\frac{f_y d_b}{\sqrt{f'_c}} \leq L/4$	8.32	8.08	1.05	-1.23	0.082	0.299	0.237	0.008	0.482	0.350
Priestley et al. (1996) $0.08L + 0.022 f_y d_b \leq 0.044 f_y d_b$	8.87	8.32	1.06	-1.49	0.070	0.349	0.281	0.007	0.465	0.359
Mattock (1967) $0.05L + 0.5D$	8.96	8.41	1.07	-1.56	0.058	0.323	0.291	0.006	0.424	0.353

Cyclic Response

Cyclic Material Response

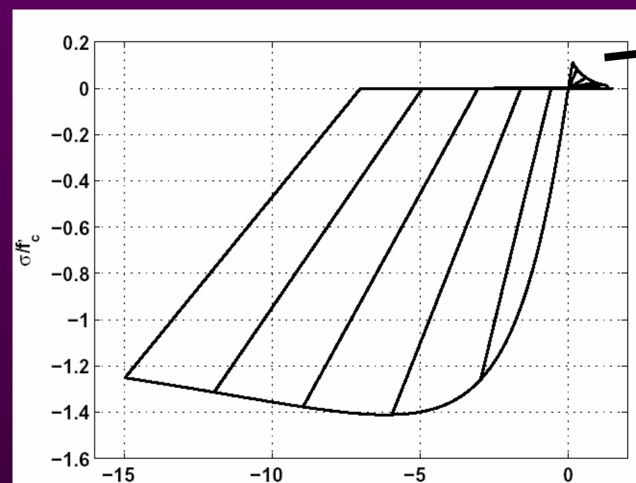
- **Cyclic response of the fiber-column model depends on the cyclic response of the material models.**

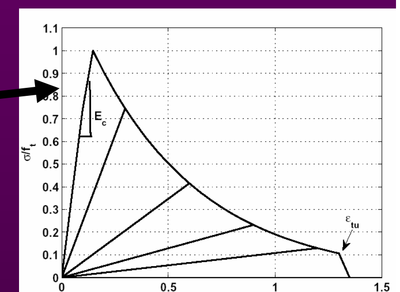
Reinforcing Steel



Giufre-Menegotto-Pinto (with Bauschinger Effect)
Steel02

Confined and Unconfined Concrete



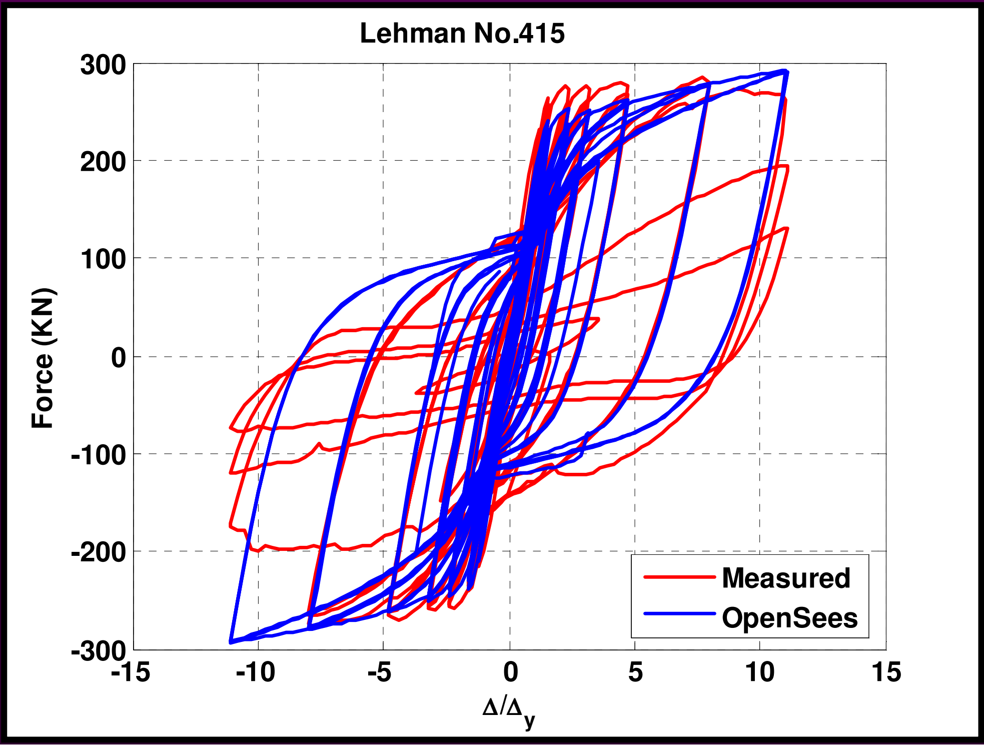


Karsan and Jirsa with Added Tension Component
Concrete04

- **Current Methodologies**
  - **Do not account for cyclic degradation steel**
  - **Do not account for imperfect crack closure**

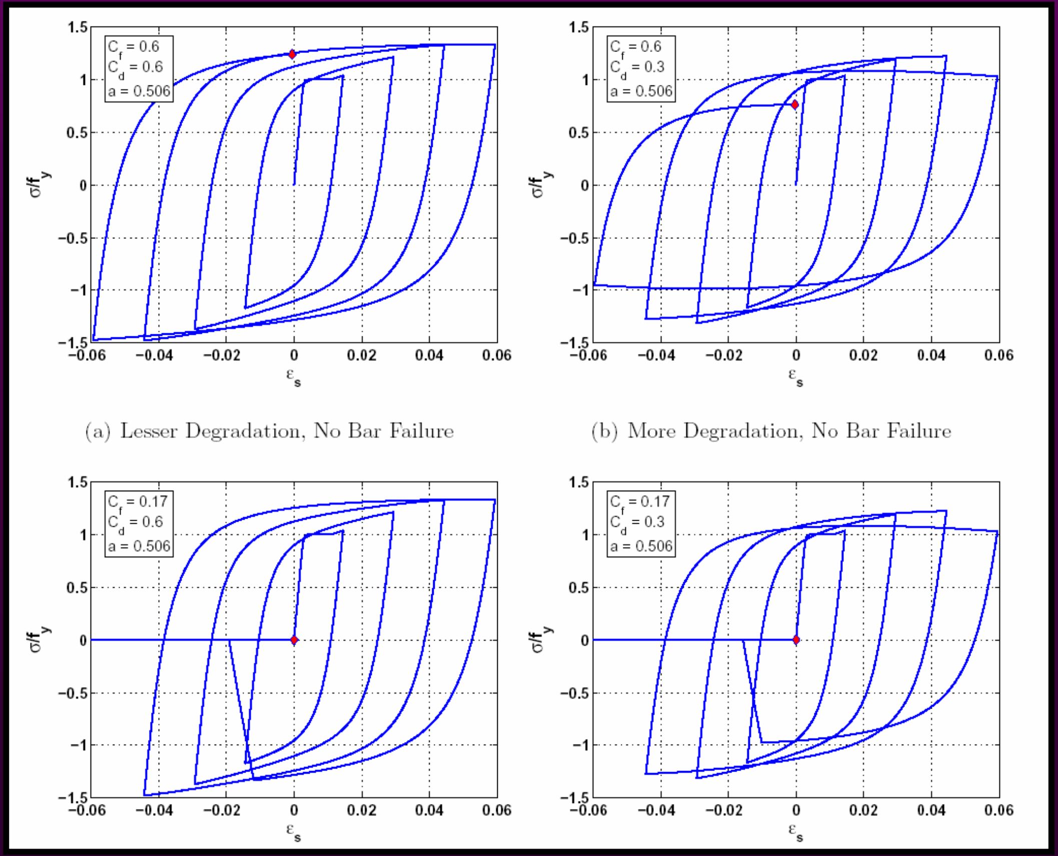
Evaluation of Response

	Lumped-Plasticity	Distributed-Plasticity
	E_{force} (%)	E_{force} (%)
mean	16.13	15.66
min	6.63	6.47
max	44.71	46.05



Kunnath and Mohle Steel Material Model

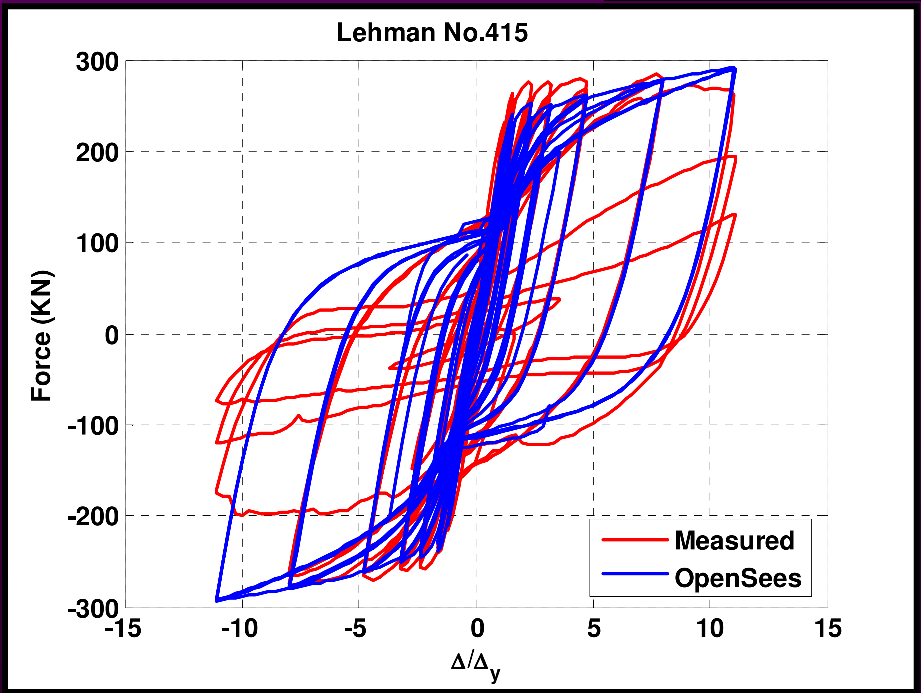
- Cyclic degradation according to Coffin and Manson Fatigue.
- Model parameters:
  - Ductility Constant, C_f
  - Strength Reduction Constant, C_d



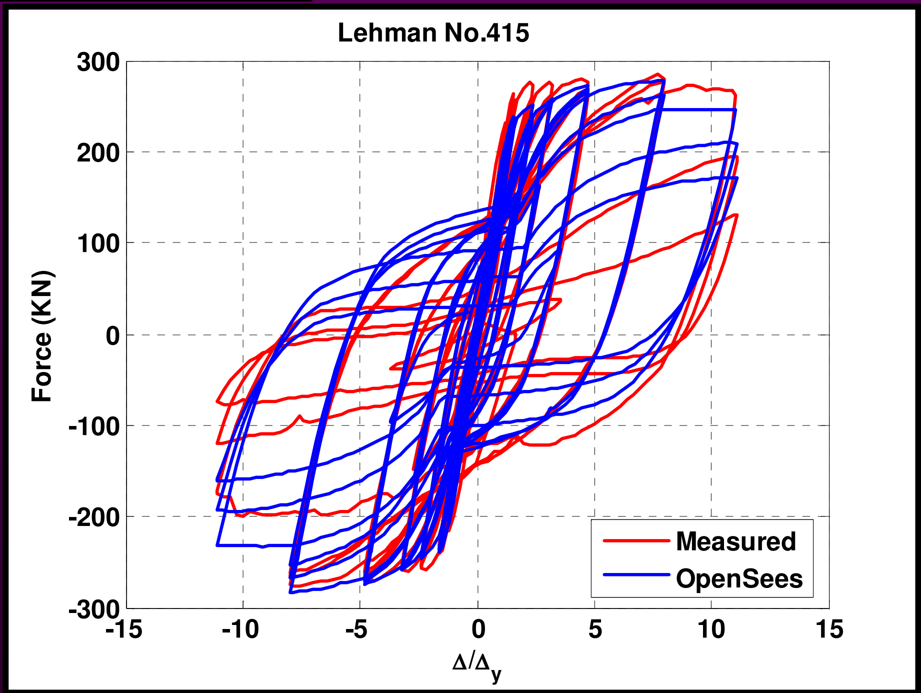
Preliminary Study with Kunnath Steel Model

- **Ductility Constant, C_f=0.4**
- **Strength Reduction Constant, C_d=0.4**

	Giufre-Menegotto-Pinto	Kunnath and Mohle
	E_{force} (%)	E_{force} (%)
mean	16.13	11.98
min	6.63	5.15
max	44.71	29.45



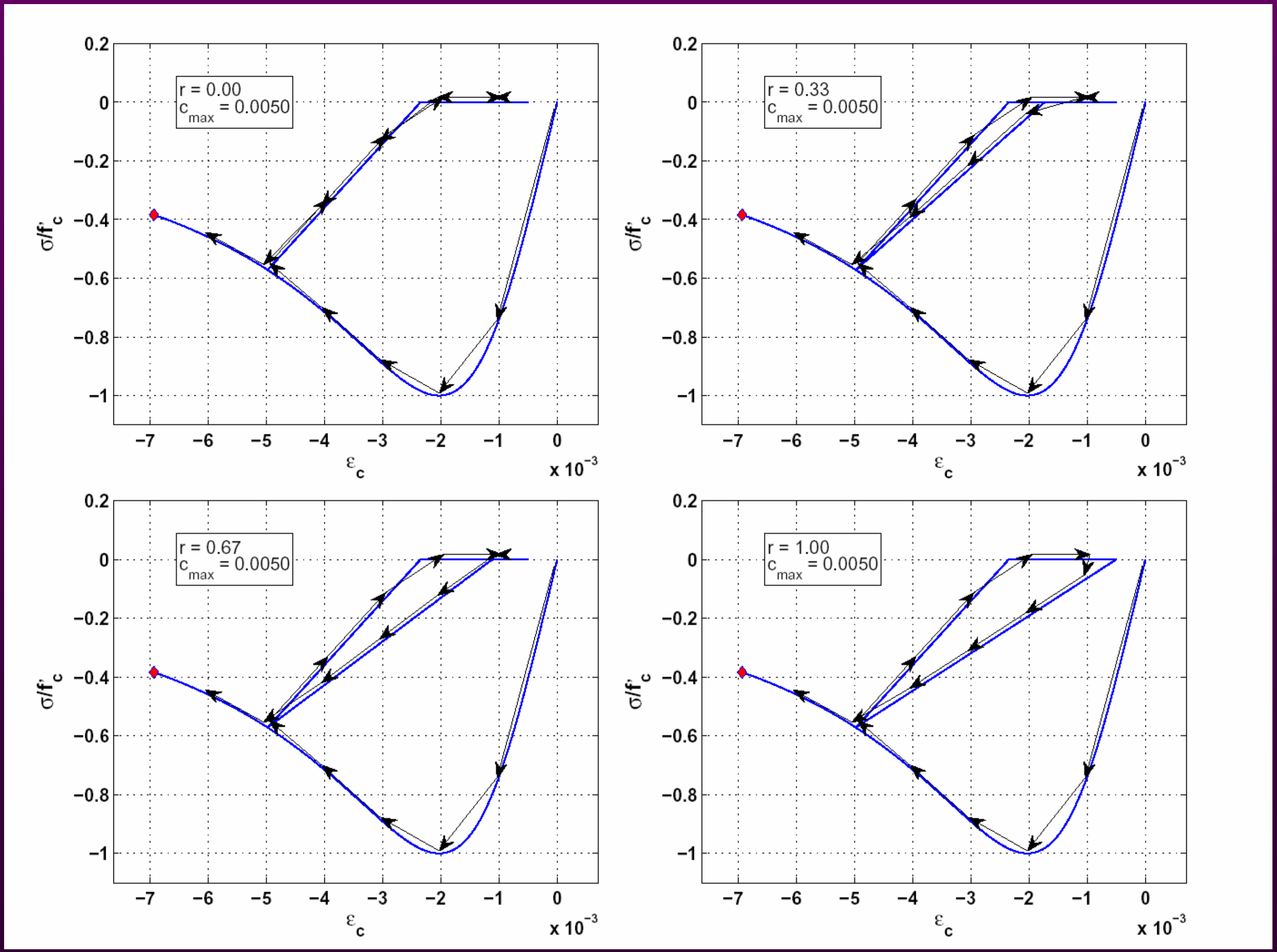
Giufre-Menegotto-Pinto (with Bauschinger Effect)



Kunnath and Mohle (2006)

Continuing Work

Imperfect Crack Closure



Prediction of Flexural Damage

- Drift Ratio Equations
- Distributed-Plasticity Modeling Strategy
- Lumped-Plasticity Modeling Strategy

Key Statistics

Fragility Curves

Design Recommendations

Evaluation of Modeling-Strategies for Complex Loading

- Bridge Bent (Purdue, 2006)
- Unidirectional and Bi-directional Shake Table (Hachem, 2003)

Thank you