Uniaxial Material Model for Reinforcing Steel Incorporating Buckling and Low-Cycle Fatigue

Jon Mohle and Sashi Kunnath

UC DAVIS
UNIVERSITY OF CALIFORNIA

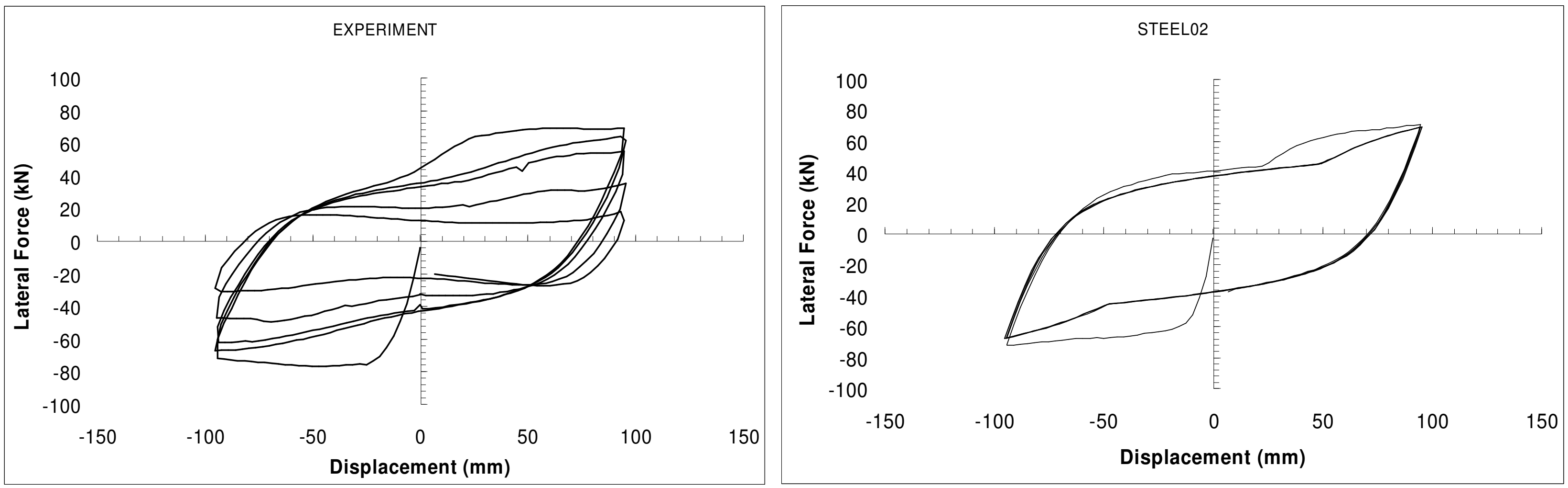
Background and Motivation

- Simulation of degrading behavior of RC structures to enable the prediction of post-yield damage states through collapse is critical to PEER performance-based methodology.
- Use of existing steel material models (Steel01, Steel02) in OpenSees within the framework of a fiber section does not capture degrading behavior

Background and Motivation

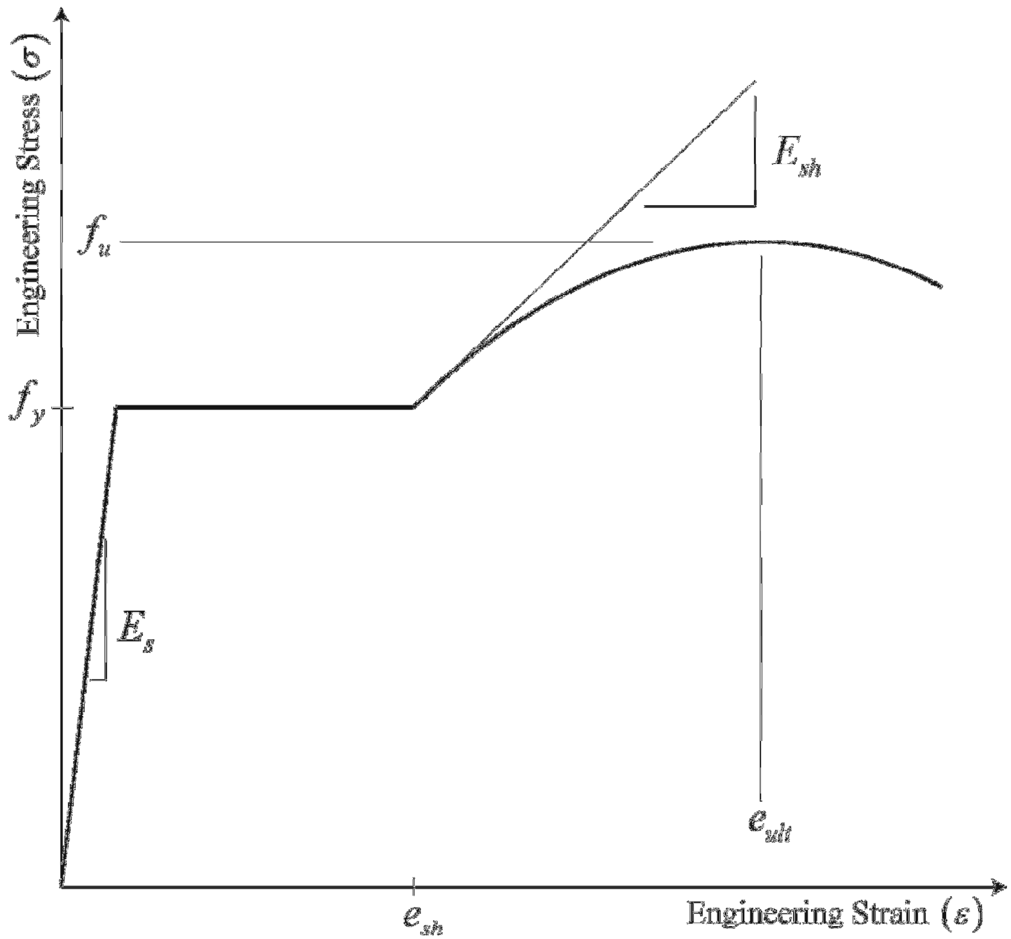
Observed response of a bridge column subjected to constant-amplitude cyclic loading

Simulated response using OpenSees with Steel02



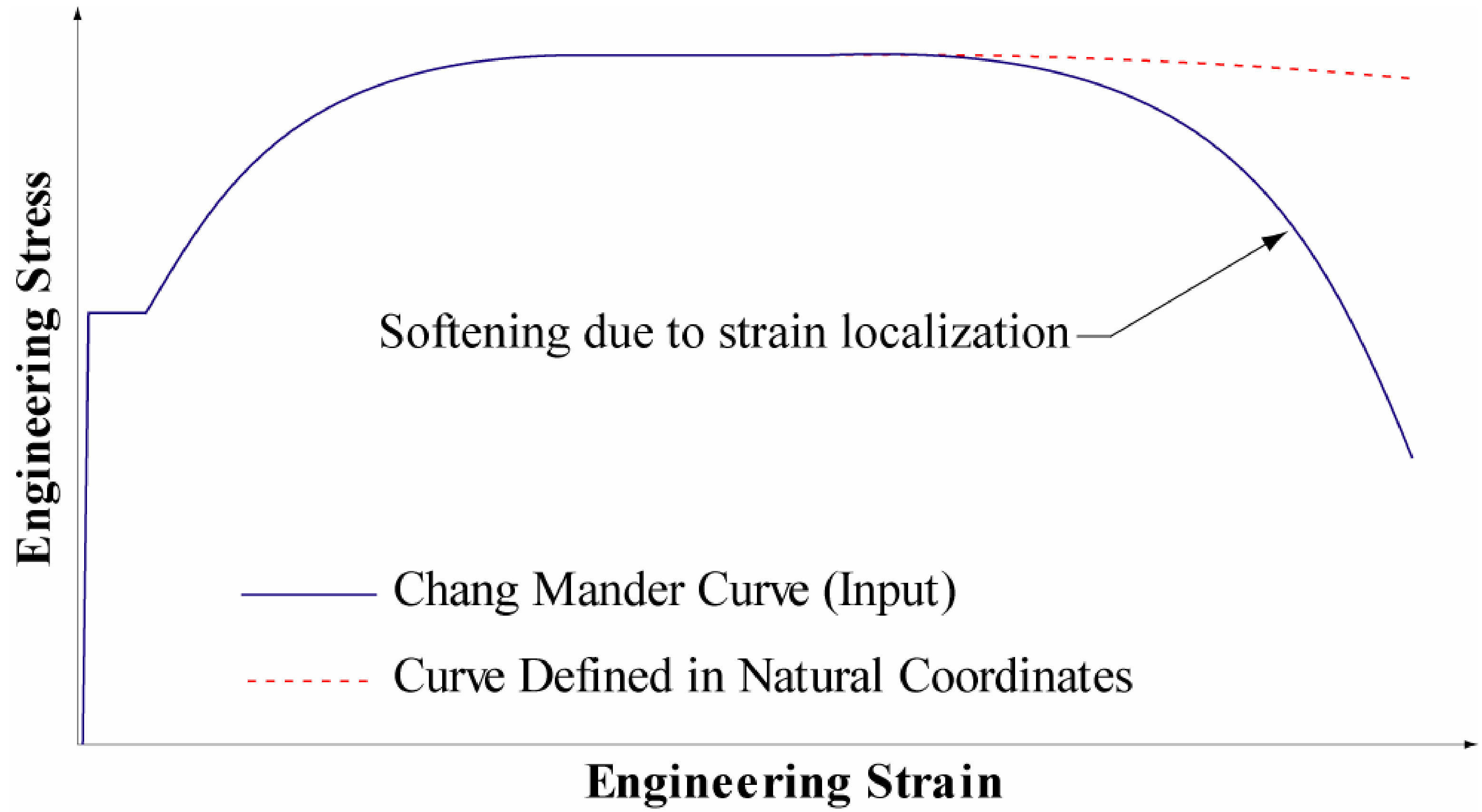
Need for a material model that incorporates buckling, strength deterioration, and failure resulting from low-cycle fatigue

Stress-Strain Envelope



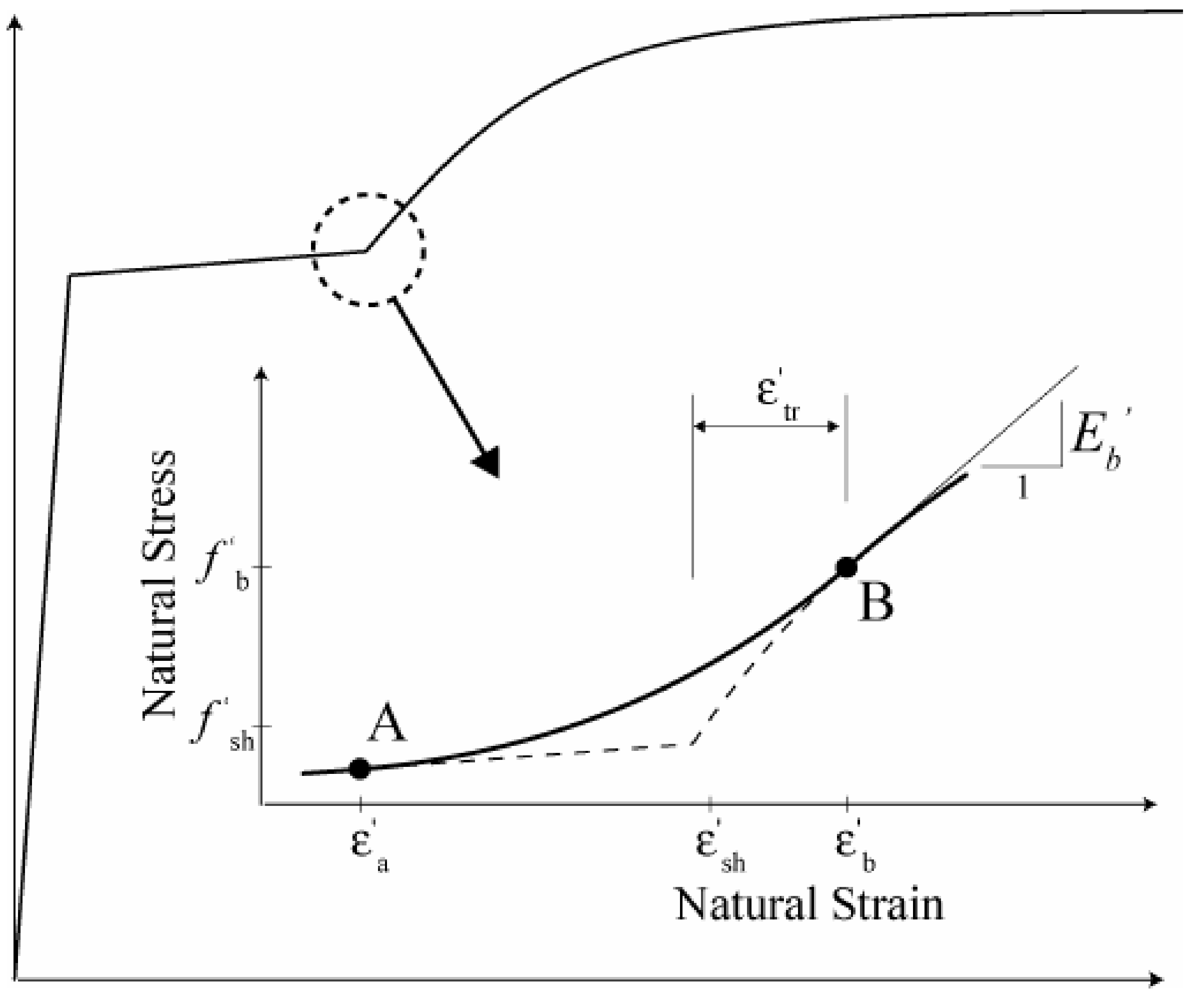
- Note: Envelope is non-symmetric in tension and compression
- Compression envelope is generated automatically – accounting for change in effective bar area
- Cyclic behavior adapted from Chang & Mander (1994)

Representation in Natural Stress-Strain Space



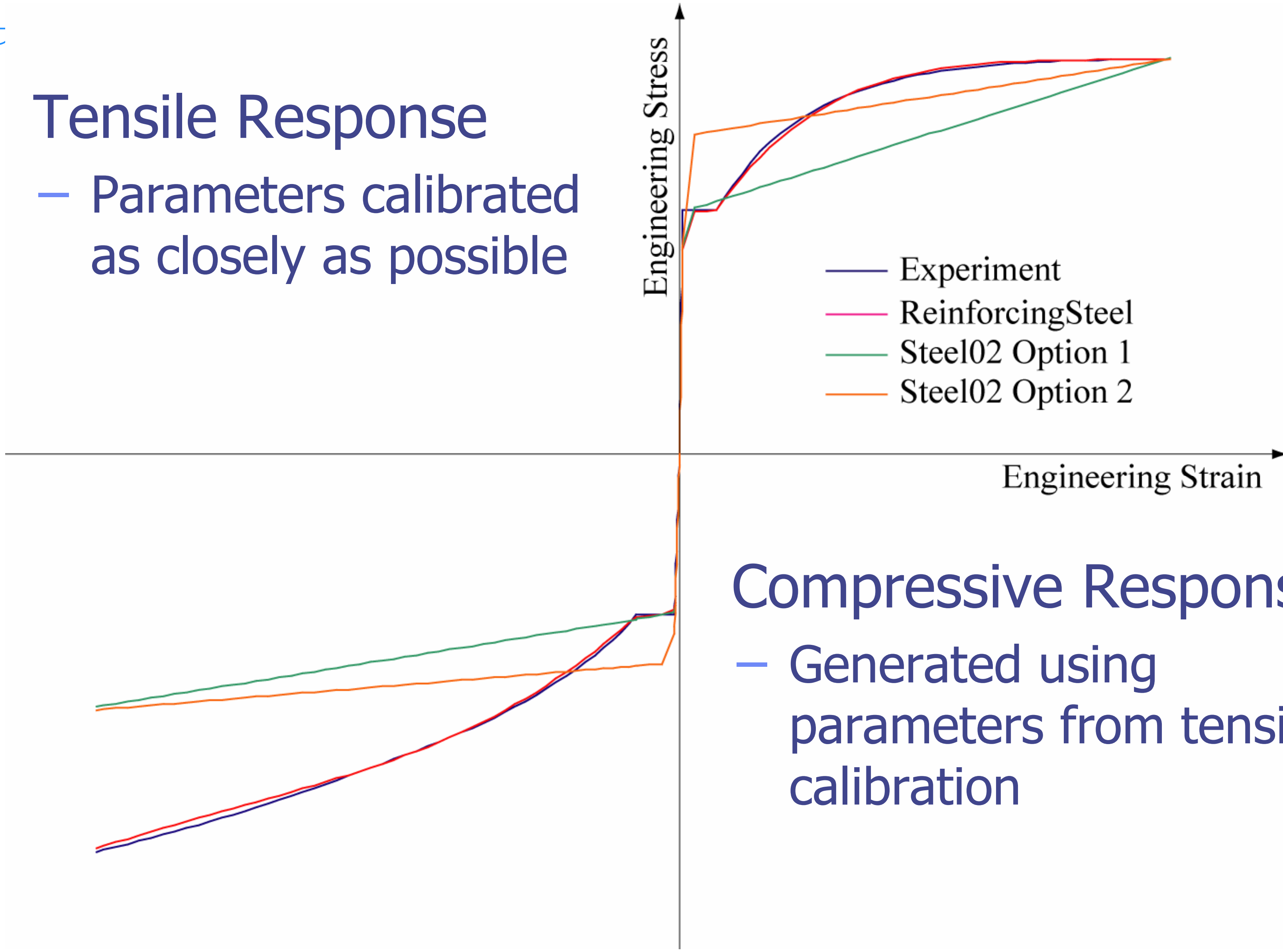
- Tensile Curve Converted to Natural Stress-Strain Space
- Single Curve Represents Both Tension and Compressive Response (tensile and compressive response non-symmetric)

Smoothed Hardening Transition



- Continuous slope for improved convergence

Monotonic Material Model Calibration



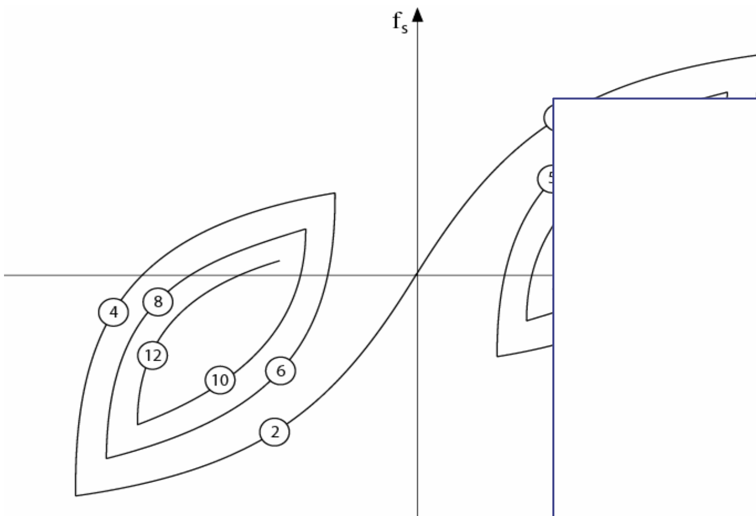
Tensile Response

– Parameters calibrated as closely as possible

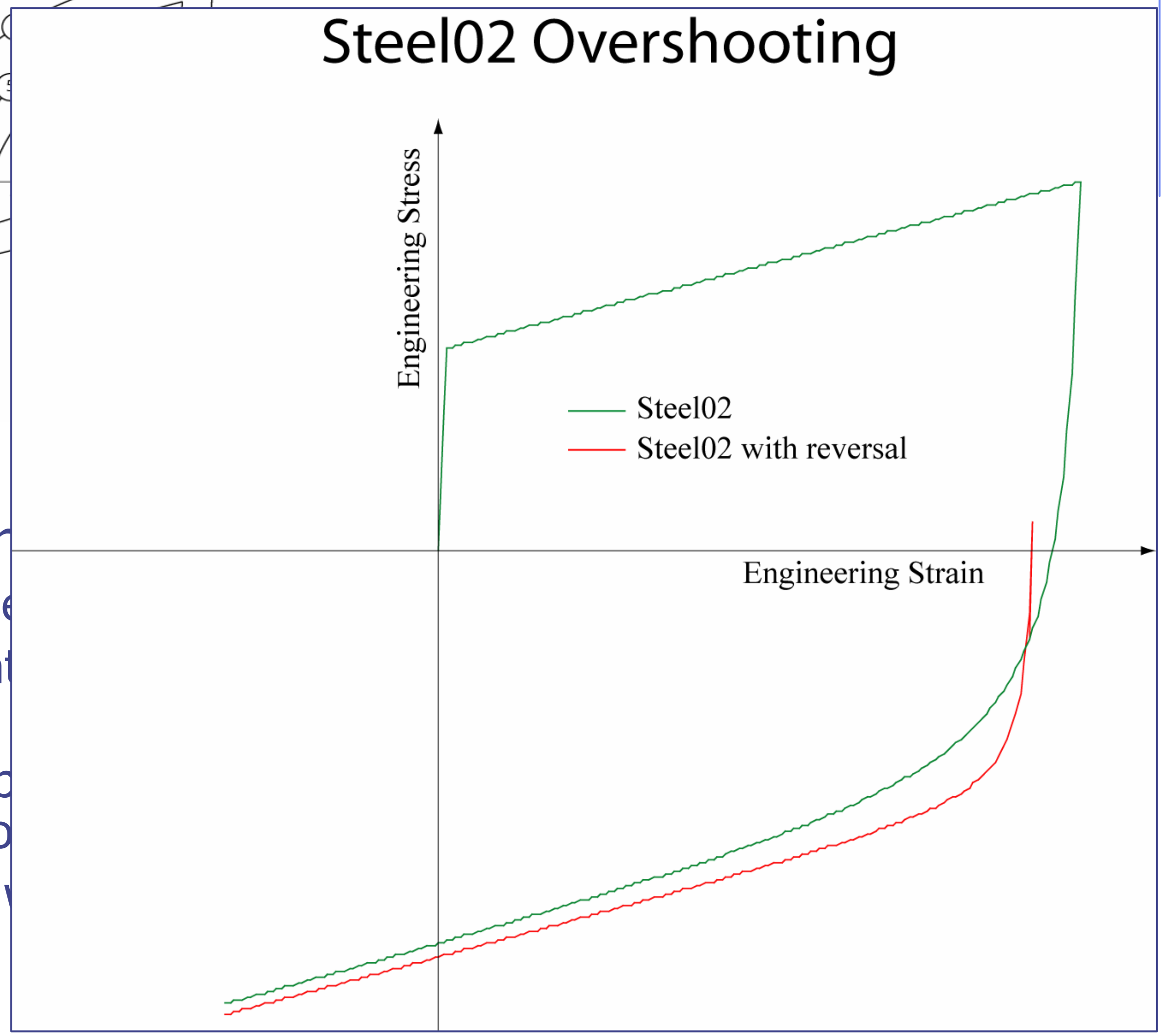
Compressive Response

– Generated using parameters from tensile calibration

Cyclic Behavior

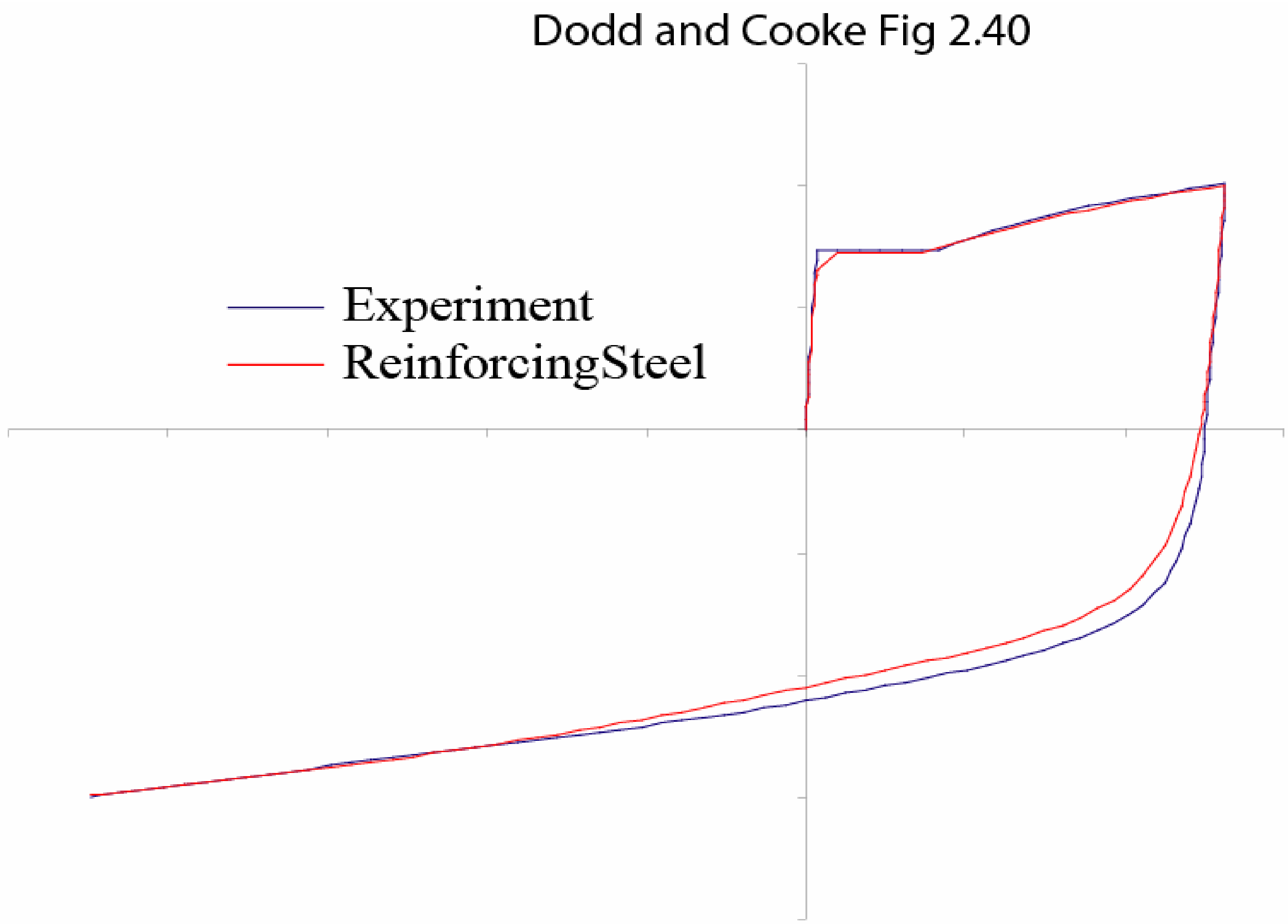


- Steel02 has the Equivalent of 4 reversal branches

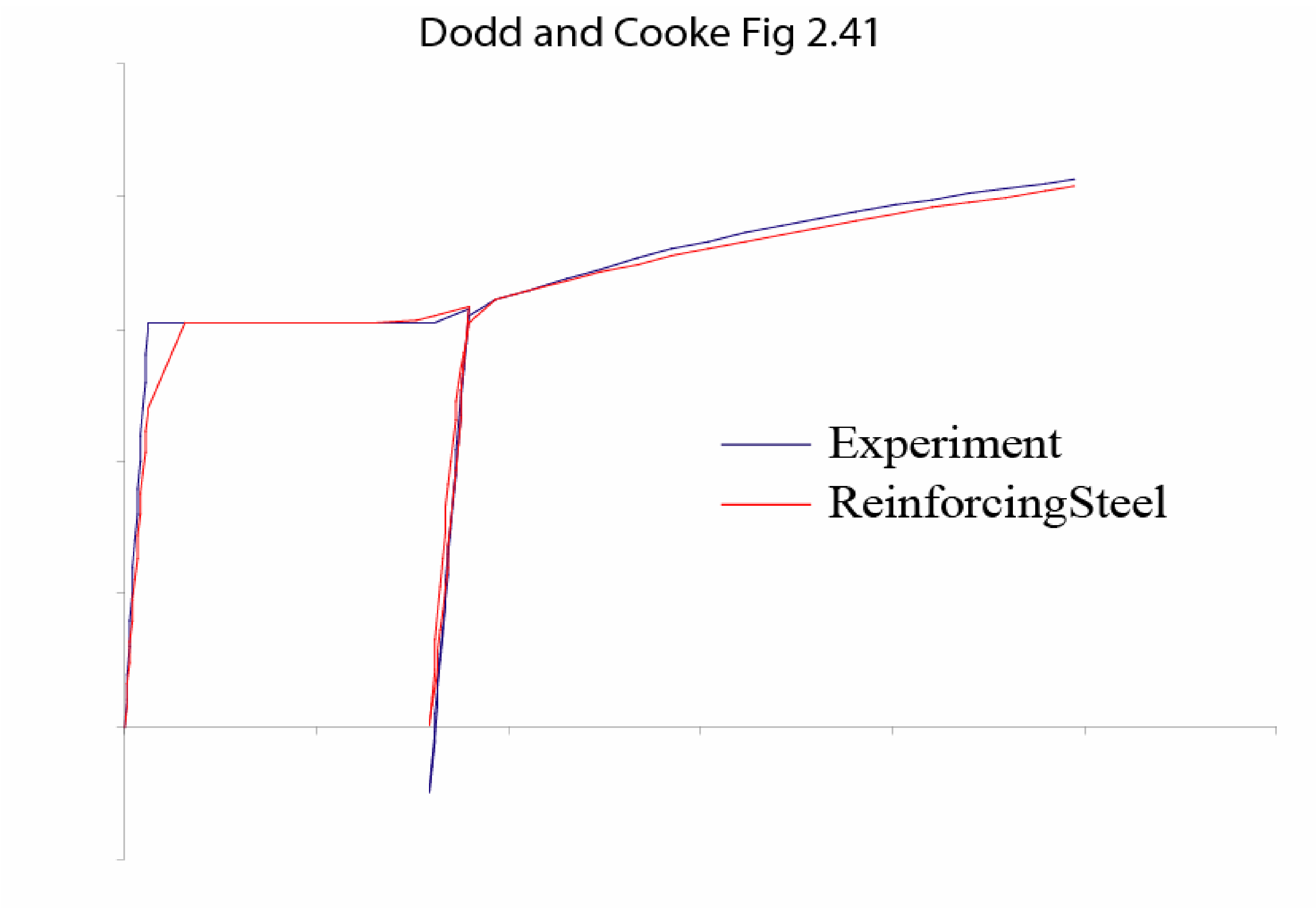


- Reasons for added br
  - Ran EQ time historie
  - Observed significant overshooting
  - Having at least 16 b minimized overshoo
  - Currently compiled

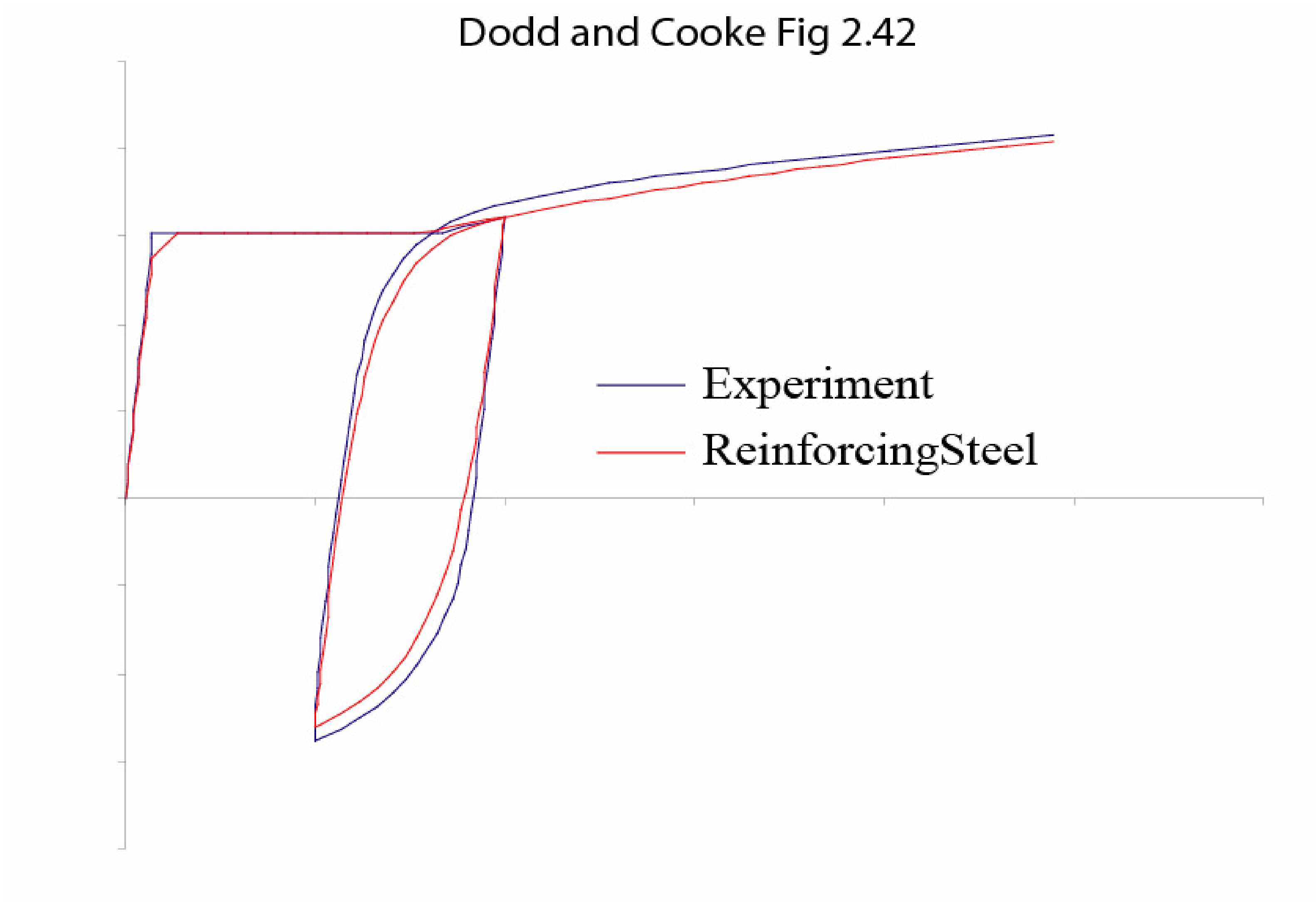
Calibration of Menegotto Pinto Constants



Calibration of Menegotto Pinto Constants

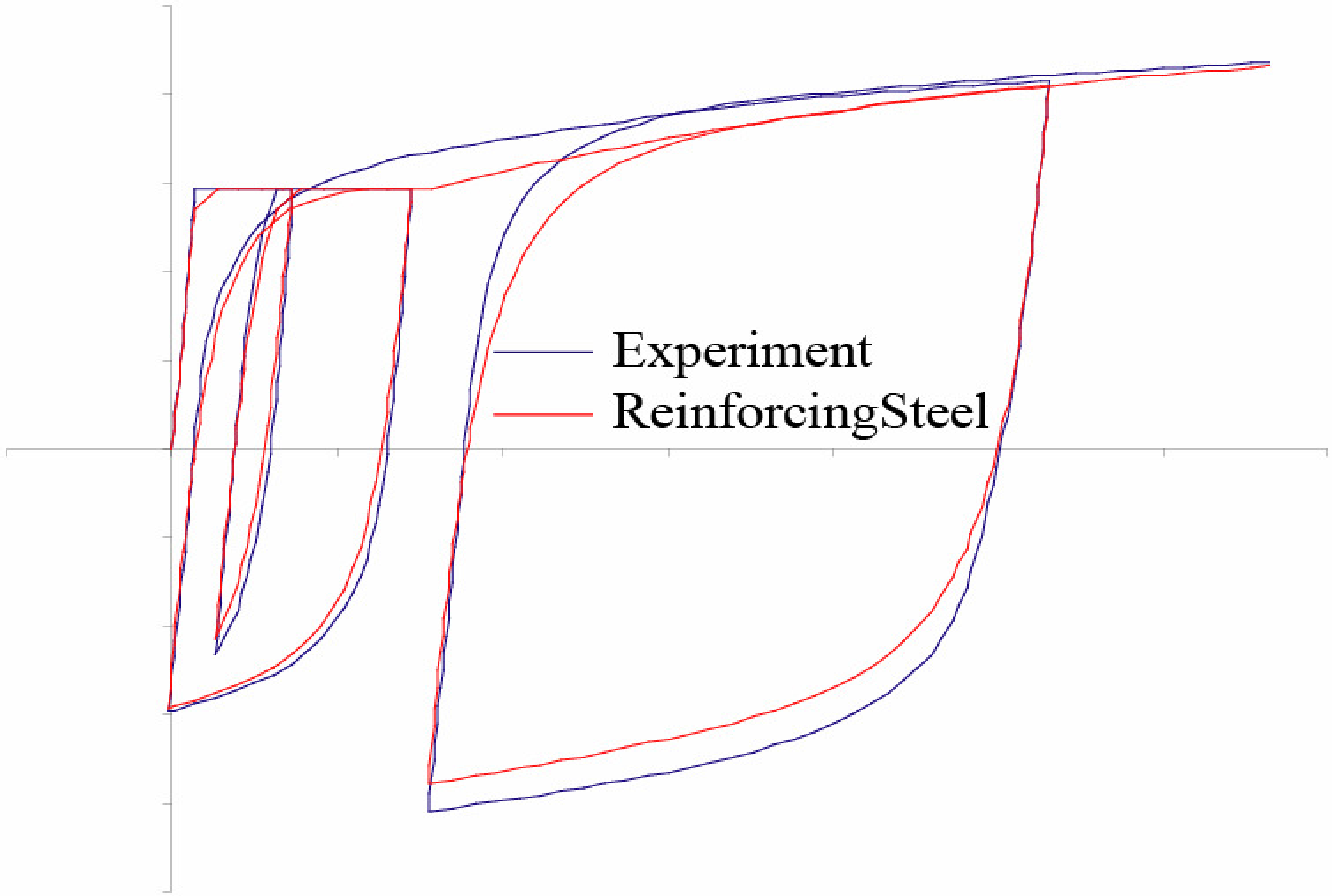


Calibration of Menegotto Pinto Constants



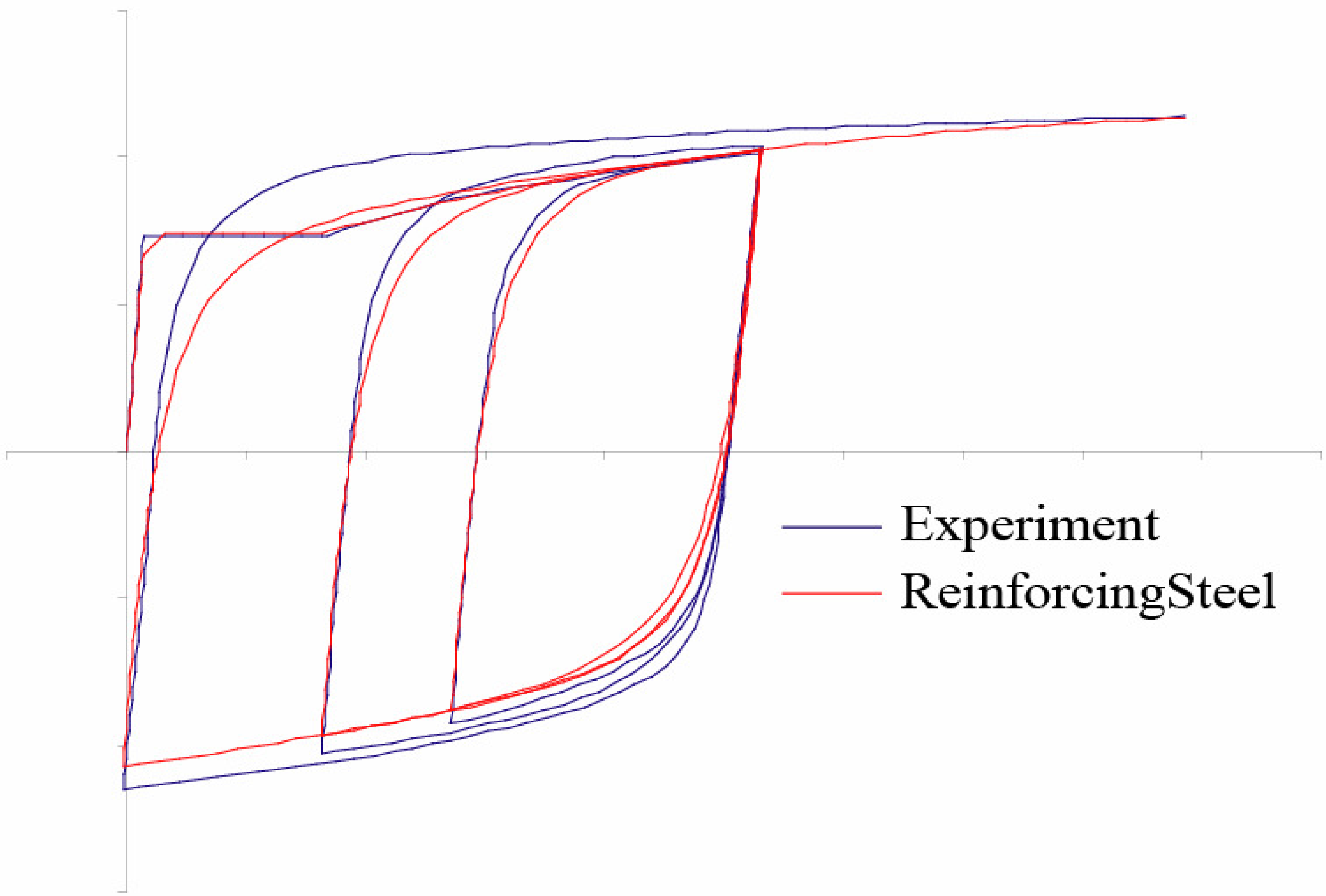
Calibration of Menegotto Pinto Constants

Dodd and Cooke Fig 2.43

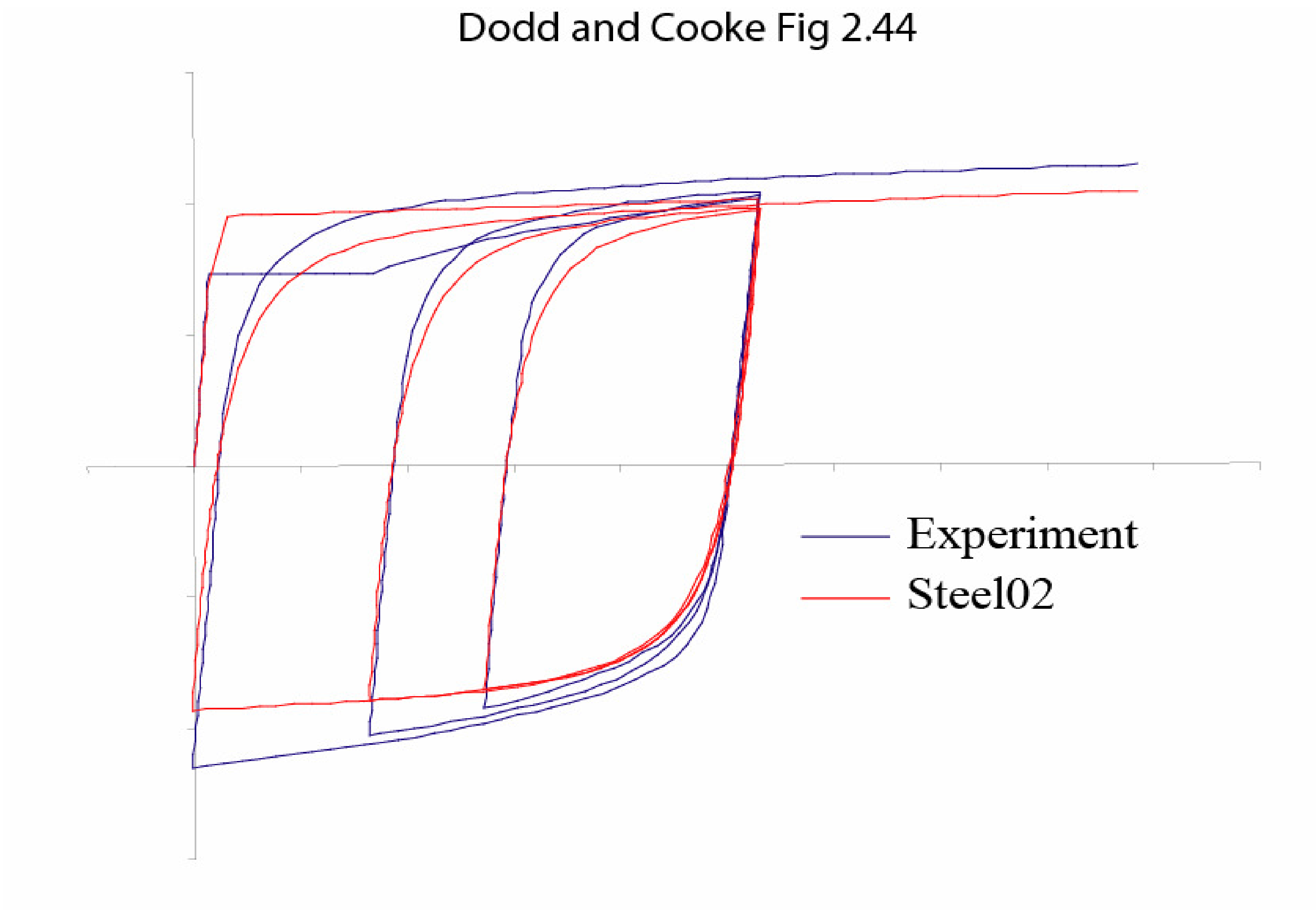


Calibration of Menegotto Pinto Constants

Dodd and Cooke Fig 2.44

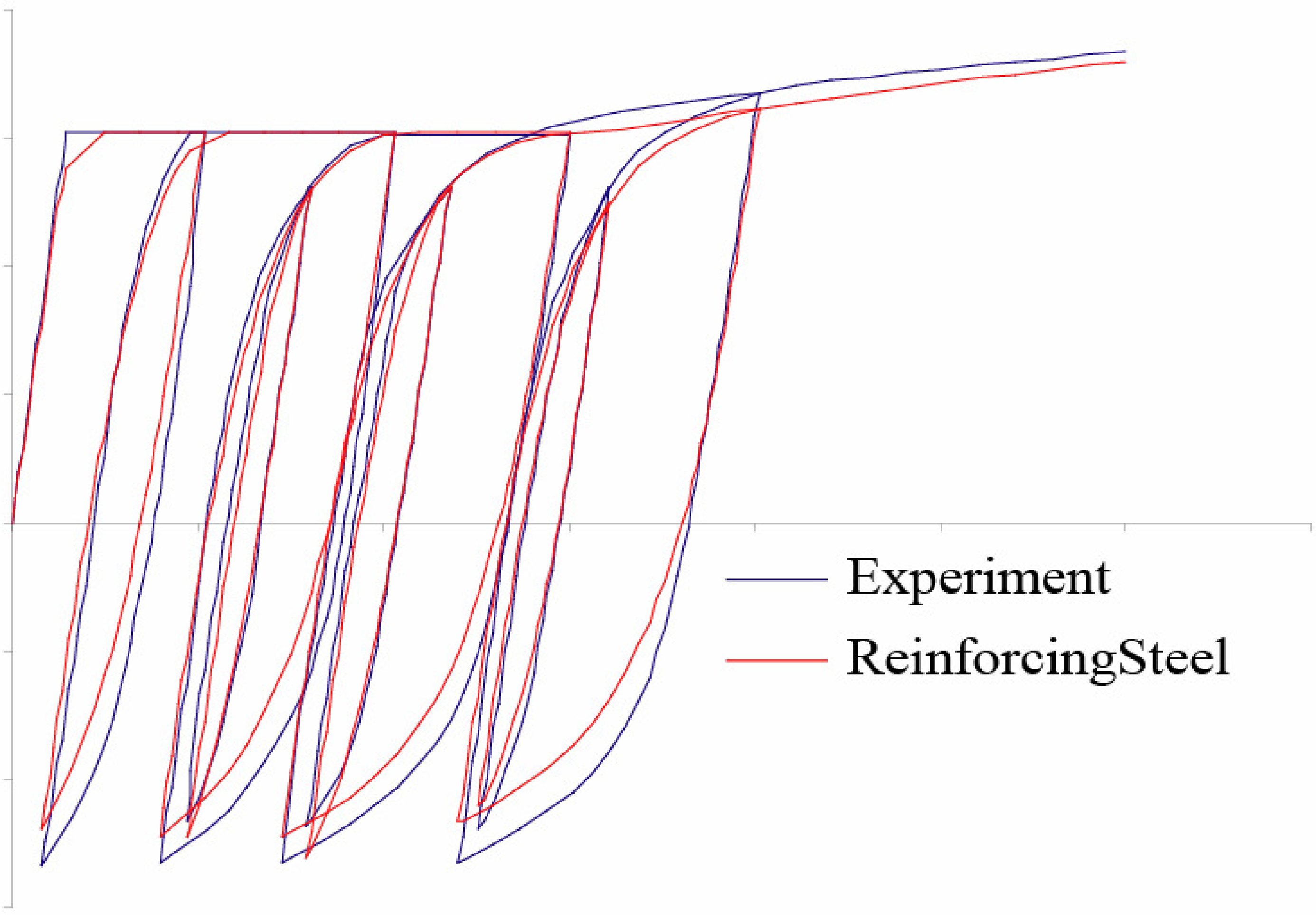


Steel02 (default) No Isotropic Hardening

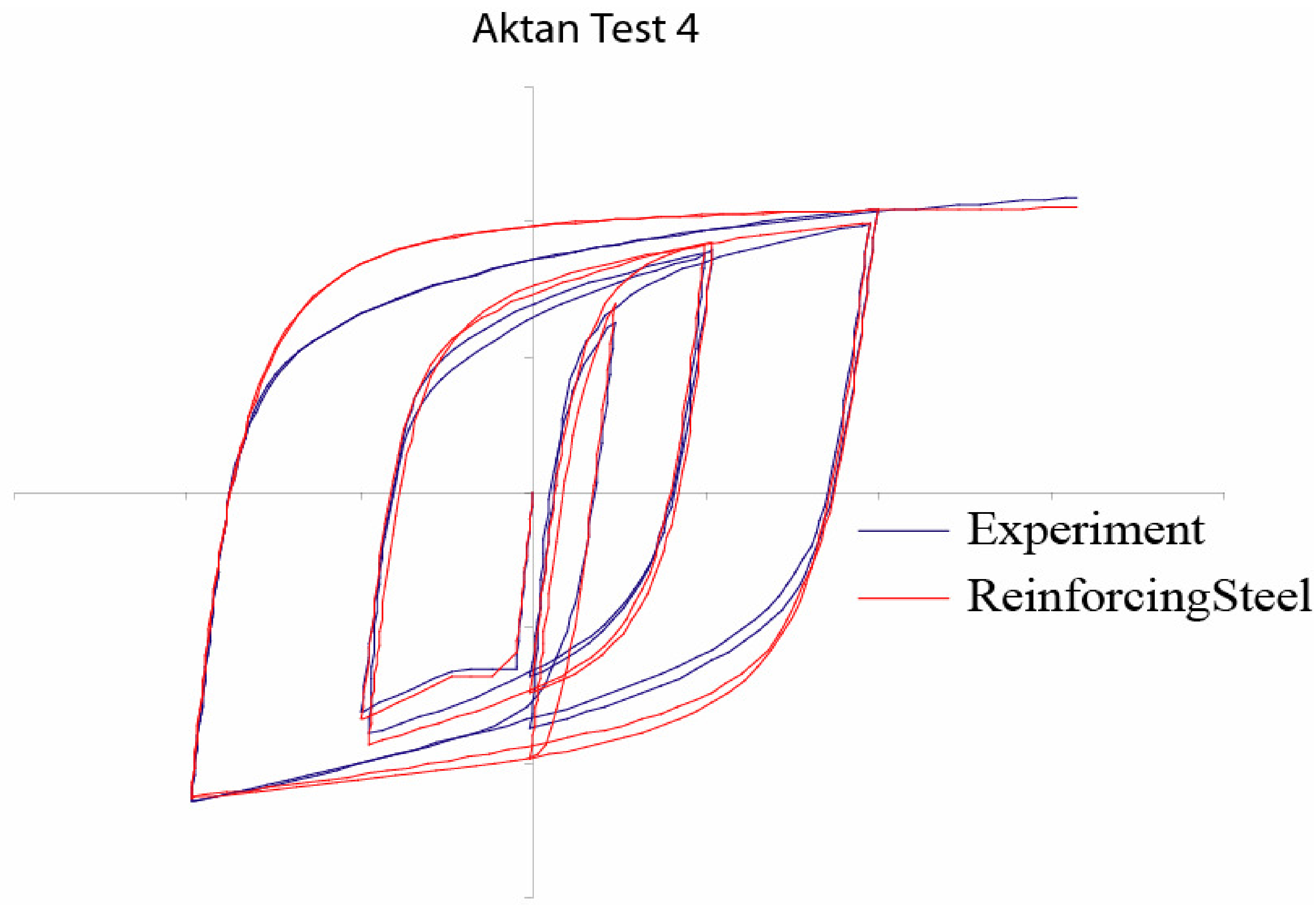


Calibration of Menegotto Pinto Constants

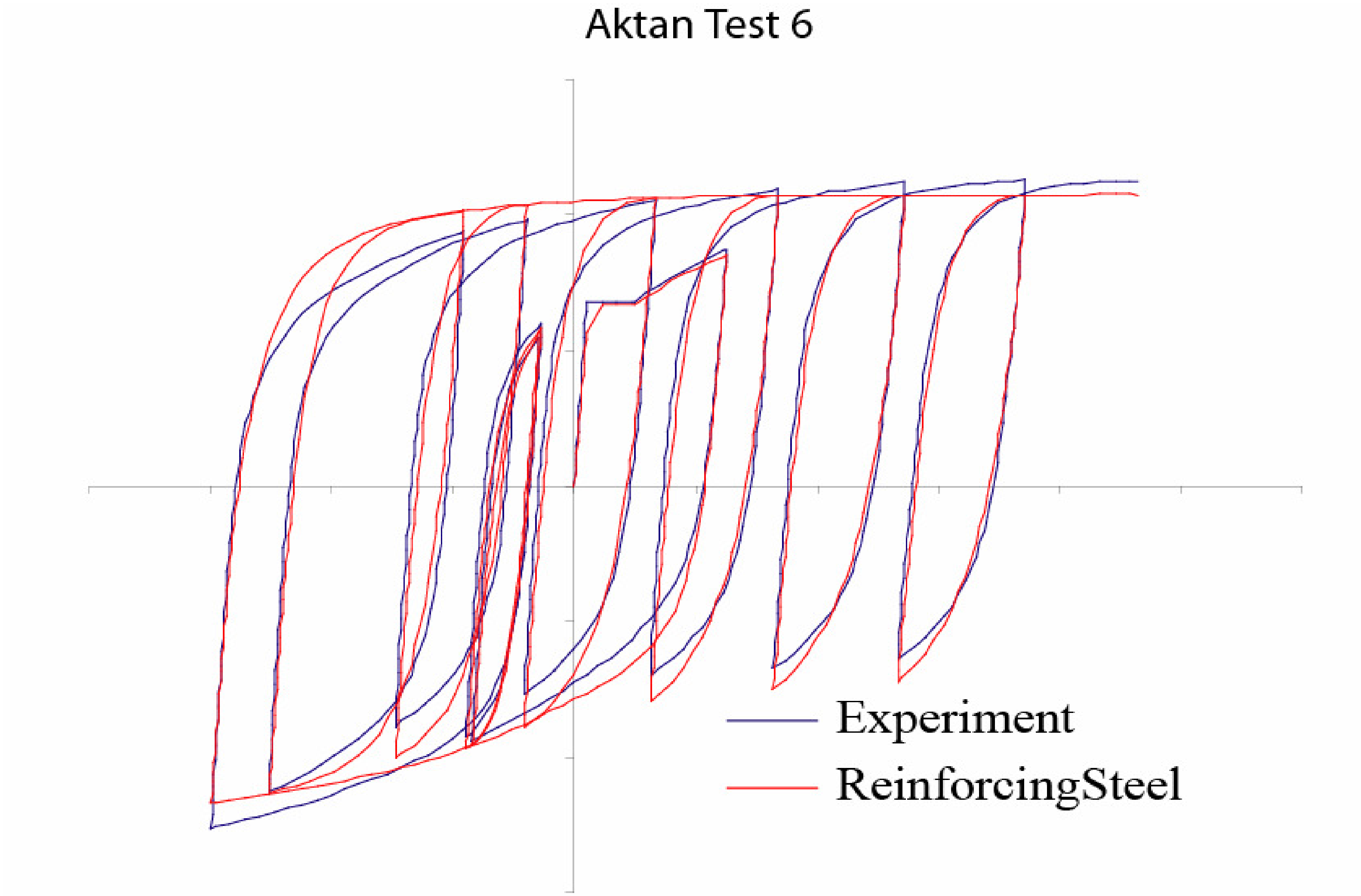
Dodd and Cooke Fig 2.45



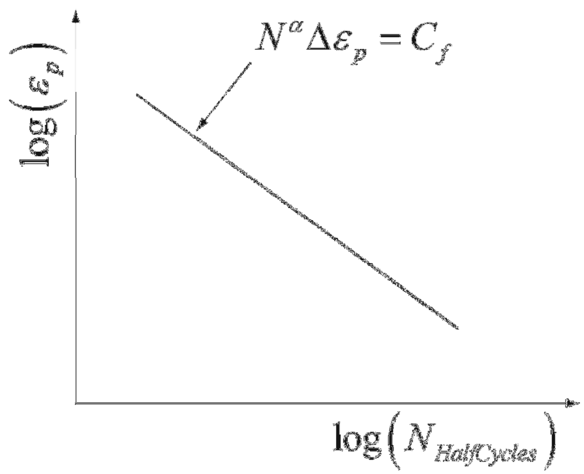
Calibration of Menegotto Pinto Constants



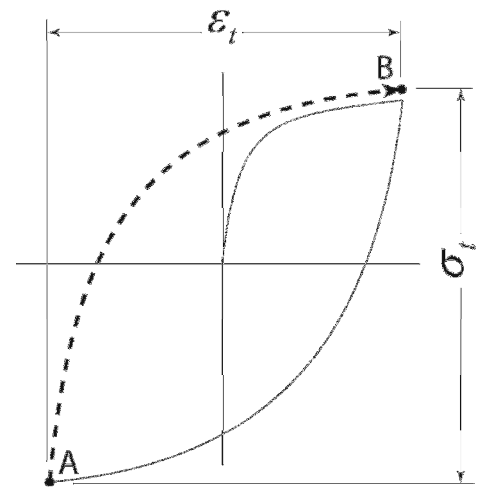
Calibration of Menegotto Pinto Constants



Low-Cycle Fatigue and Fracture: Notation



Coffin-Manson Constants



$$\varepsilon_p = \varepsilon_t - \frac{\sigma_t}{E_s}$$

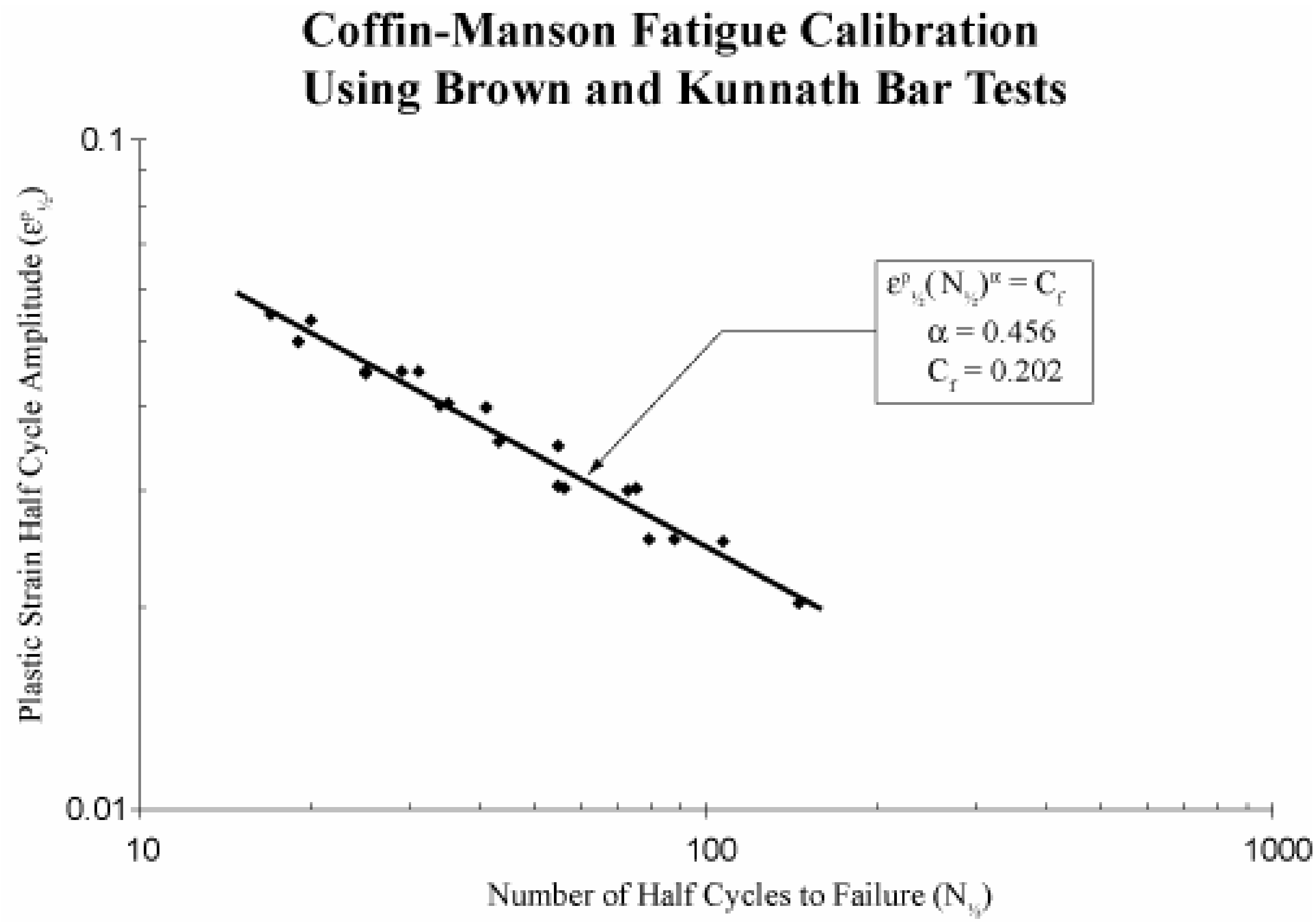
Half-cycle terms defined

C_f and α are factors used to relate the number of half cycles to fracture to the plastic strain half cycle amplitude. The total half cycle strain amplitude is the change in strain from reversal A to reversal B.

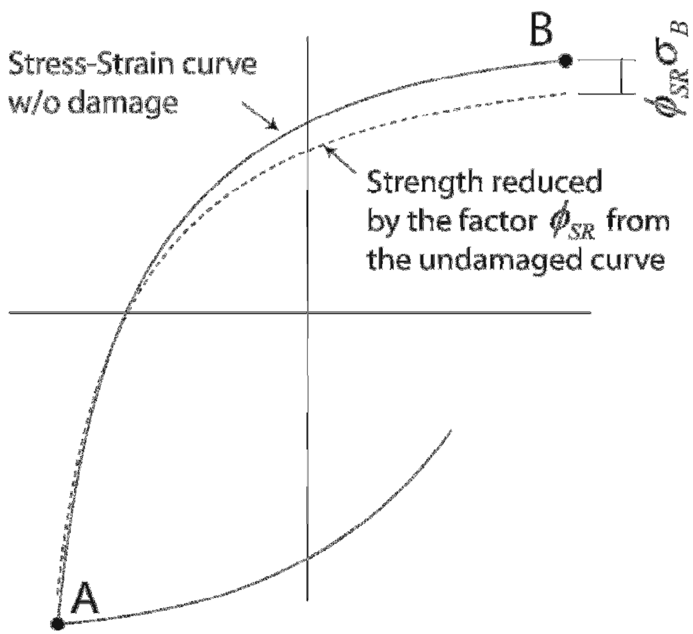
C_f and α are used to define a cumulative damage factor, D: $D = \sum\left(\frac{\Delta\varepsilon_p}{C_f}\right)^{\frac{1}{\alpha}}$

Fatigue Calibration

- Number of cycles to failure vs Average strain amplitude



Cyclic Degradation



Another parameter is used to describe loss in strength due to damage or other phenomenon resulting in softening due to plastic reversals. The degradation is currently assumed to have a simple linear relationship with D which correlates strength degradation from an undamaged state to the cumulative damage factor.

$$\phi_{SR} = K_1 D$$

Alternately this simple linear equation can be rewritten in a way that makes the strength degradation independent of the number of half cycles to failure. Keeping the failure and degradation terms independent is convenient for calibration.

$$\phi_{SR} = \sum \left(\frac{\Delta \varepsilon_p}{C_d} \right)^{\frac{1}{\alpha}}$$

The constants K_1 and C_d can be related as follows:

$$C_d = \frac{C_f}{K_1^{\alpha}}$$

Calibration of Cyclic Degradation

$$\phi_{SR} = \sum \left(\frac{\Delta \varepsilon_p}{C_d} \right)^{\frac{1}{\alpha}}$$

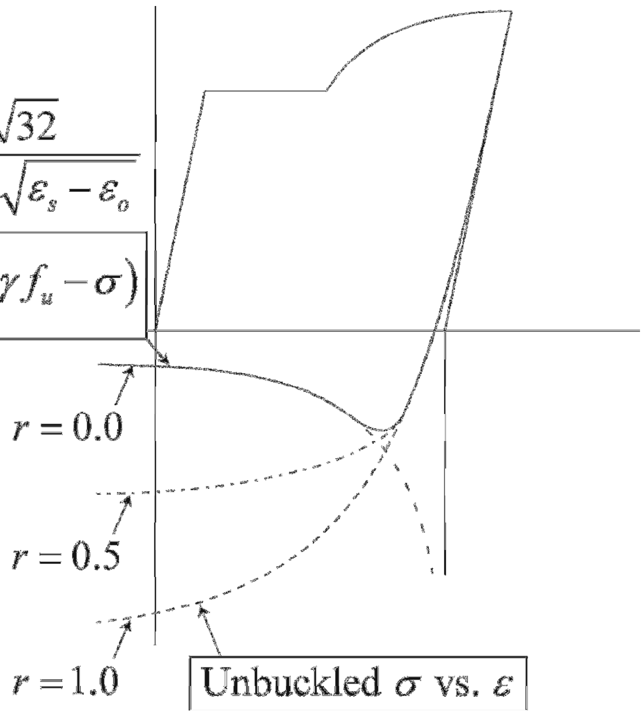
- Constant α and C_d calibrated using Newton search
- Measured stress was compared with model prediction at peak reversals (constant amplitude tests)
- Minimize Sum of the difference squared
- Calibration results:
  - $\alpha=0.451$ ⟷ $\alpha=0.456$
  - $C_d=0.477$

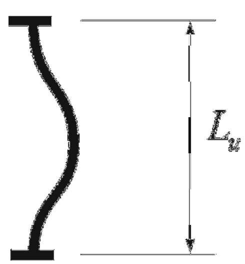
Note Similarity to Coffin-Manson Calibration

Gomes Appleton Buckling Behavior

$$\Omega_b = \beta \frac{\sqrt{32}}{3\pi l_{SR}\sqrt{\varepsilon_s - \varepsilon_o}}$$

$$\boxed{\sigma_b = \gamma f_u - \frac{\Omega_b + \gamma}{1+\gamma}(\gamma f_u - \sigma)}$$





d_b = Bar Diameter

L_u = Unsuported Length

$$l_{SR} = \frac{L_u}{d_b}$$

β is an amplification factor to scale the buckling curve.

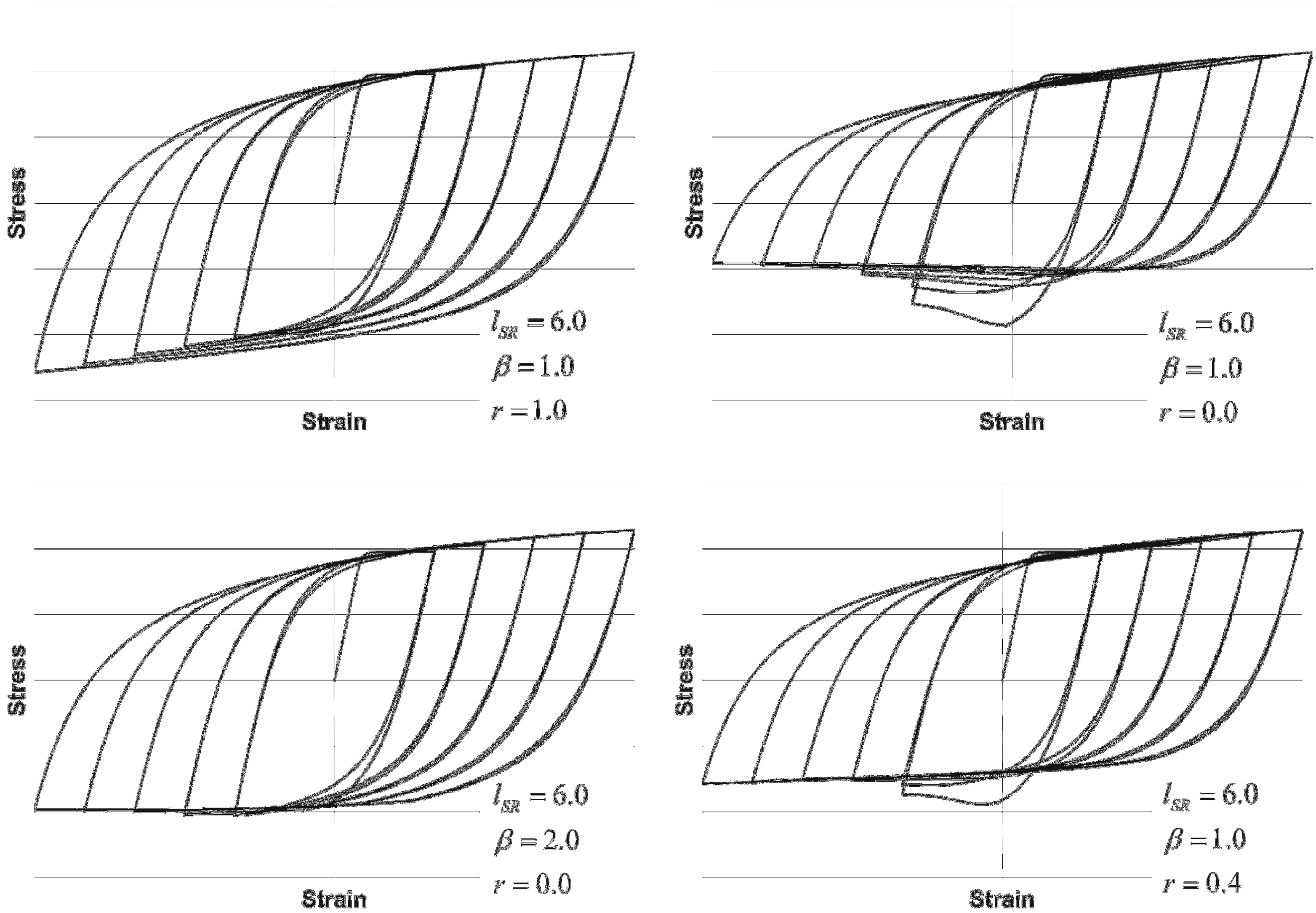
The *r* factor adjusts the curve between the buckled and the unbuckled profile. The variable r can only be a real number between 0.0 and 1.0.

The γ factor is the positive stress location that the buckling factor is taken about. γ should be between 0.0 and 1.0.

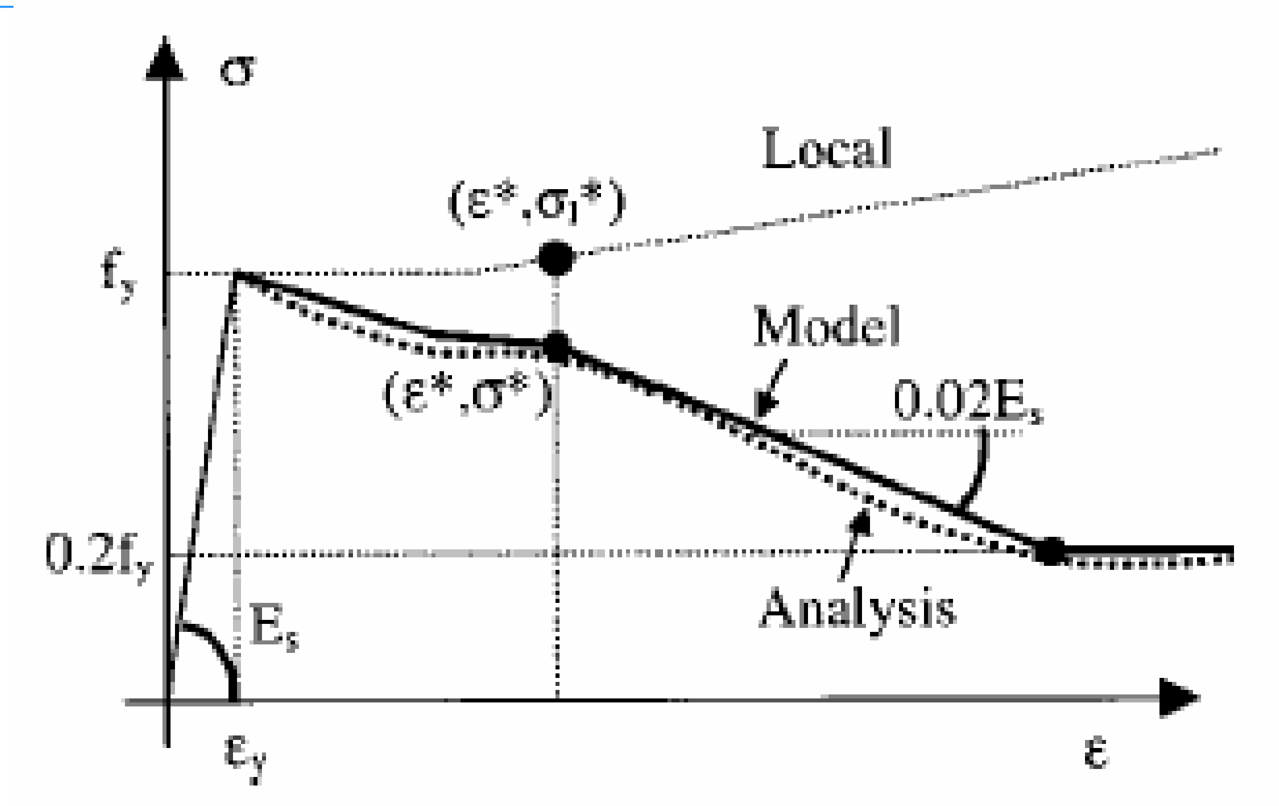
Suggested initial values:

$\beta = 1.0$
$r = 0.4$
$\gamma = 0.5$

Gomes Appleton



Dhakal-Maekawa Buckling Behavior



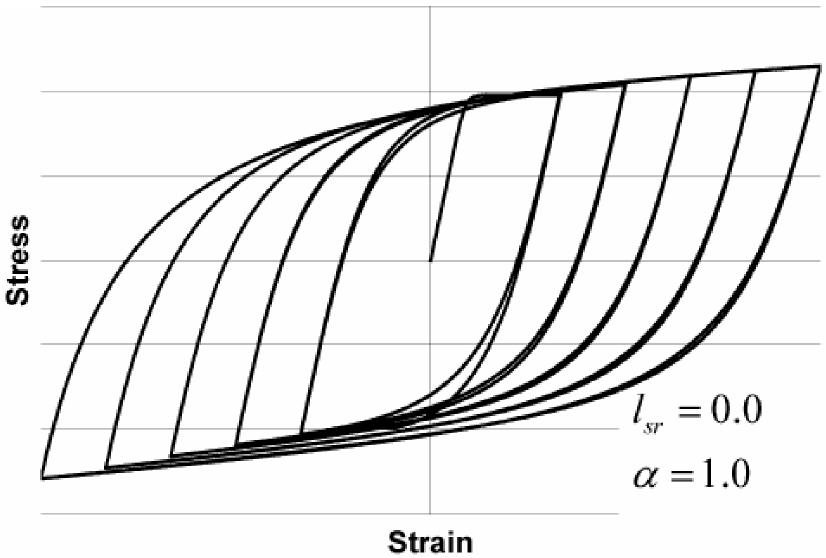
$$\frac{\varepsilon^*}{\varepsilon_y} = 55 - 2.3\sqrt{\frac{f_y}{100}\frac{L}{D}}; \quad \varepsilon^*/\varepsilon_y \geq 7$$

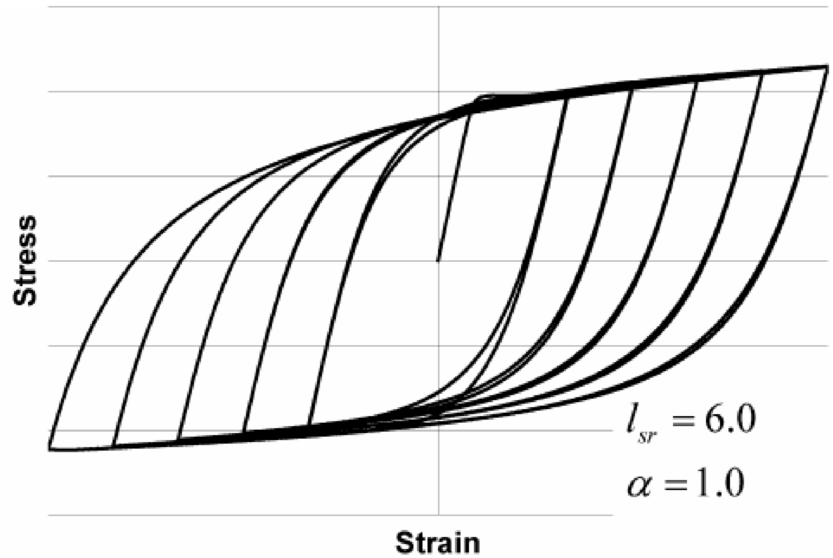
$$\frac{\sigma^*}{\sigma_l^*} = \alpha\left(1.1 - 0.016\sqrt{\frac{f_y}{100}\frac{L}{D}}\right); \quad \sigma^* \geq 0.2 f_y$$

$$\frac{\sigma}{\sigma_l} = 1 - \left(1 - \frac{\sigma^*}{\sigma_l^*}\right)\left(\frac{\varepsilon - \varepsilon_y}{\varepsilon^* - \varepsilon_y}\right); \quad \text{for } \varepsilon_y < \varepsilon \leq \varepsilon^*$$

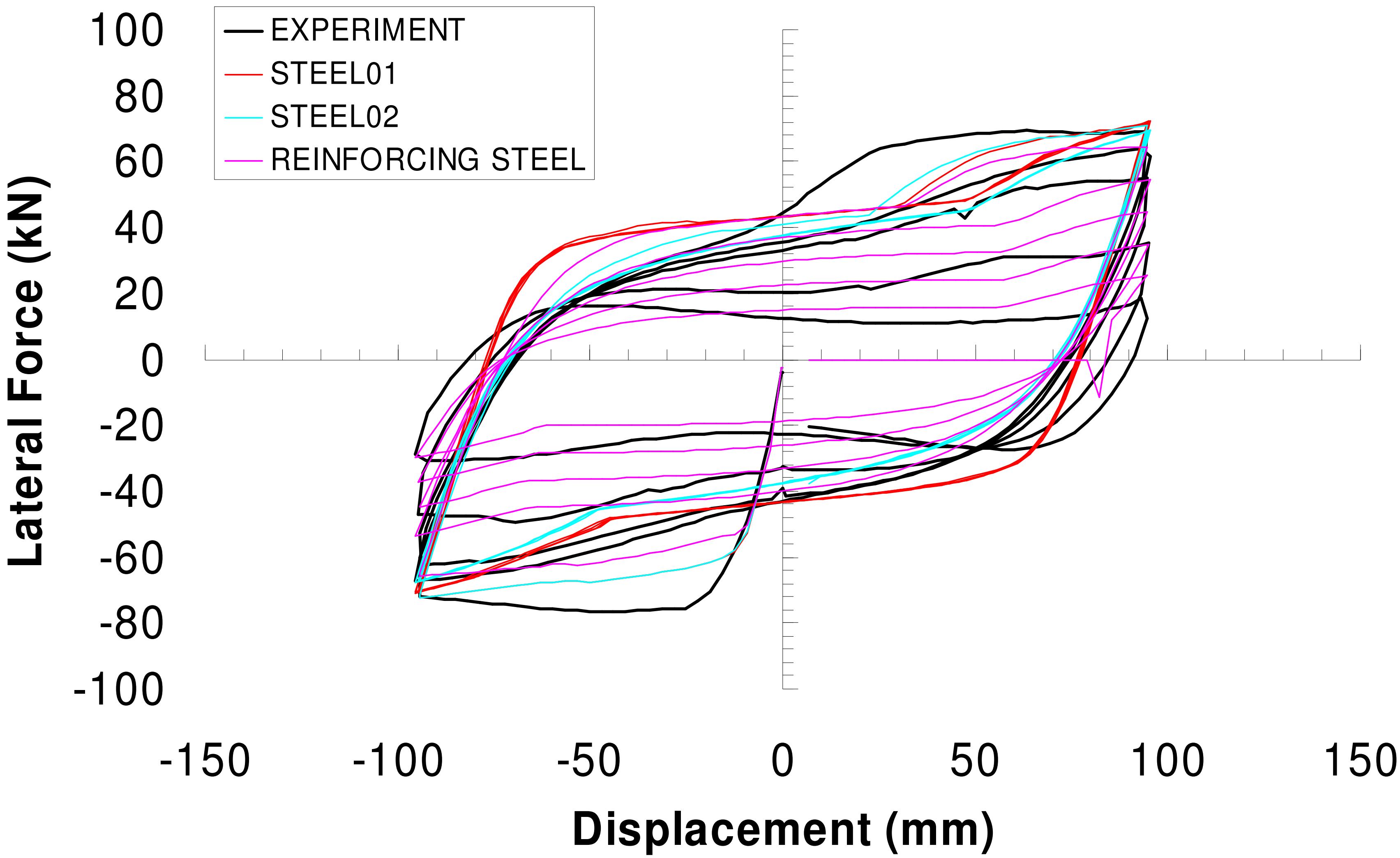
$$\sigma \geq 0.2 f_y; \quad \sigma = \sigma^* - 0.02 E_s(\varepsilon - \varepsilon^*); \quad \text{for } \varepsilon > \varepsilon^*$$

Dhakal-Maekawa





Column Simulation – Force Based Beam



OpenSees Implementation

uniaxialMaterial *ReinforcingSteel* $matTag $fy $fu $Es $Esh $esh $eult
< -GABuck $lsr $beta $r $gama >
< -DMBuck $lsr < $alpha > >
< -CMFatigue $Cf $alpha $Cd >
< -MPCurveParams $MP1 $MP2 $MP3 >

Modeling Tips

1. Remember that the material is a single base material with many modifiers. Fatigue and buckling is not automatic.
2. You may get softening in tension but not in compression (without buckling)
3. This material is not symmetrical and will amplify convergence problems. Use less integration points in the NL beam column.
4. Member behavior is mesh biased, more integration points will give higher local curvature. This will increase fatigue, buckling etc. We recommend using beam with hinges so you have control over the hinge length.

Modeling Tips

5. Start with the base model, get it to run, then add the other features one at a time
6. If you get a message "trial strain too large..." you are approaching a compressive strain of 1.0 in one or more fibers, the results are invalid, something is wrong.
7. This material is more complicated and uses more logic and memory. It will be slightly slower than Steel02
8.

References

- Chang, G. and Mander, J. (1994). Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity. NCEER Technical Report 94-0006.
- Gomes, A., and Appleton, J. (1997). "Nonlinear cyclic stress-strain relationship of reinforcing bars including buckling." Eng. Struct., 19(10), 822–826.
- Brown, J. and Kunnath, S.K. (2000). Low Cycle Fatigue Behavior of Longitudinal Reinforcement in Reinforced Concrete Bridge Columns. NCEER Technical Report 00-0007.