Credits: 3 + 0
PG 2019
Spring 2020 Semester

Performance-based Seismic Design of Structures

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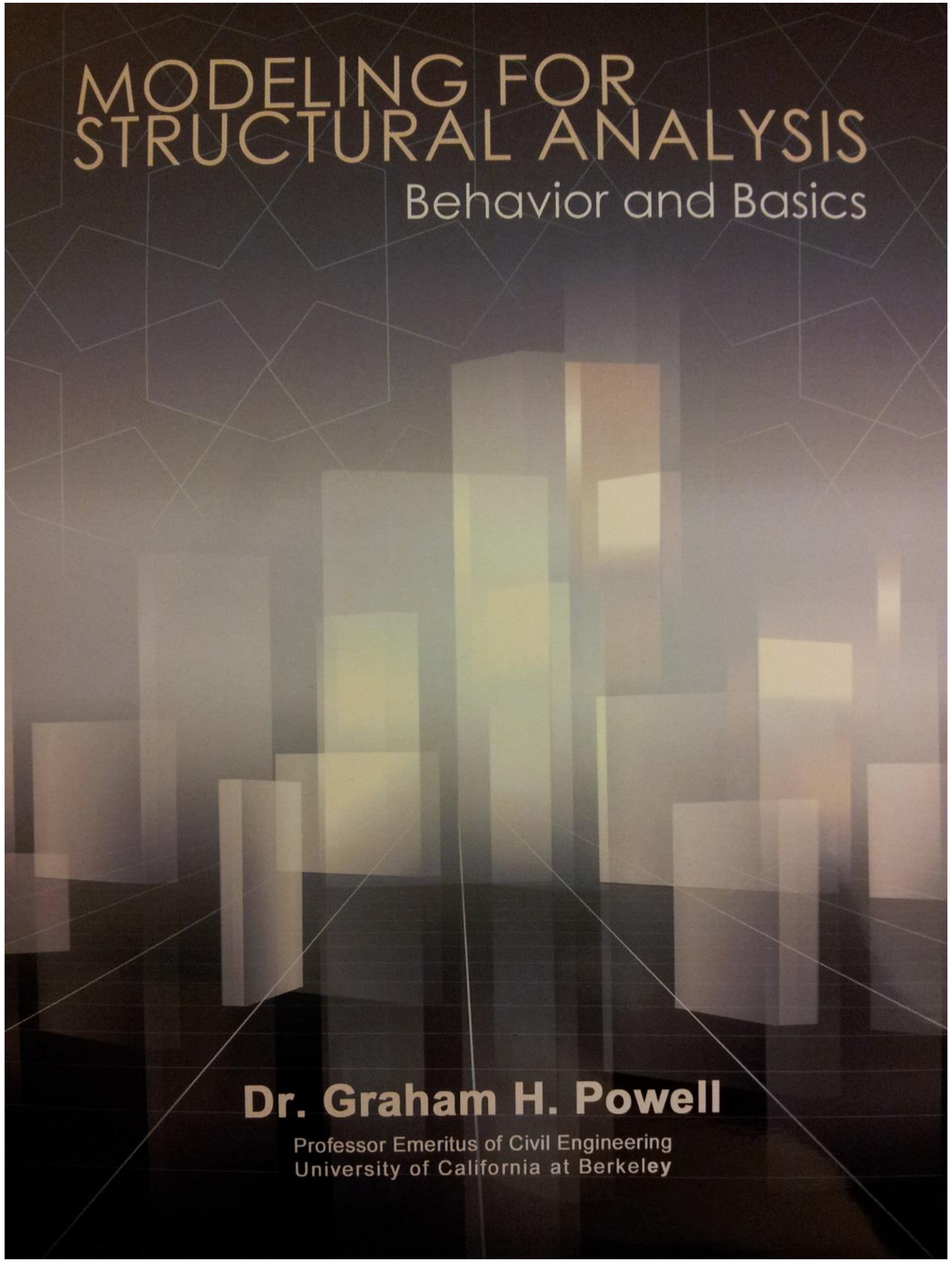
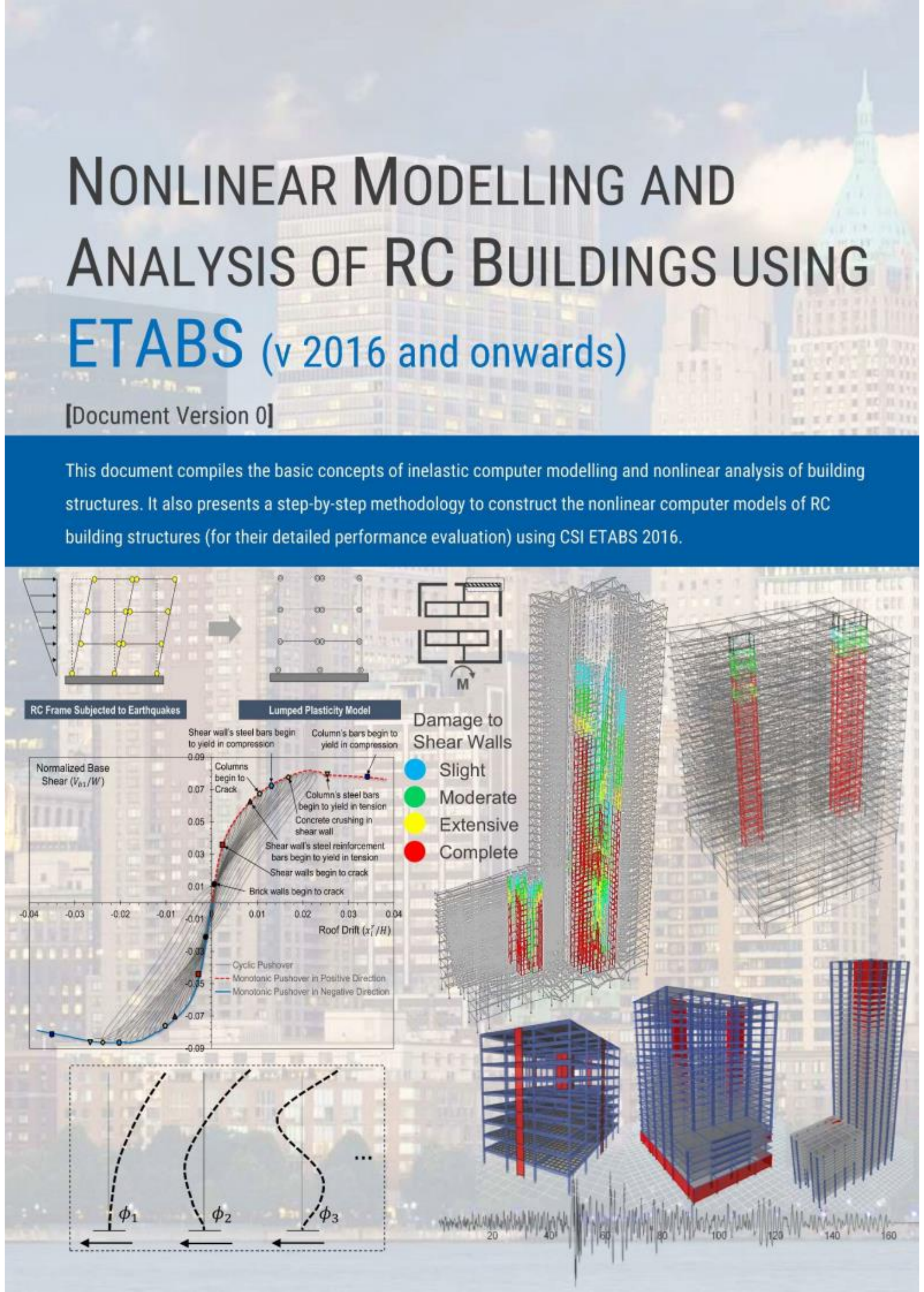
Modeling for Structural Analysis

by Graham H. Powell





http://structurespro.info/nl-etabs/

Practical Approaches for Nonlinear Modeling of Structures

Defining Inelastic Behavior at

- **Nonlinear Modeling of Materials** → **Material Level** → **Fiber Modeling Approach**
- **Nonlinear Modeling of Cross-sections** → **Cross-section Level**
- **Nonlinear Modeling of Members** → **Member Level**

Cross-section Level and **Member Level** → **Plastic Hinge Modeling Approach**

An Introduction to Fiber Modeling Approach for Nonlinear Modeling of Structural Components

Fiber Modeling Approach

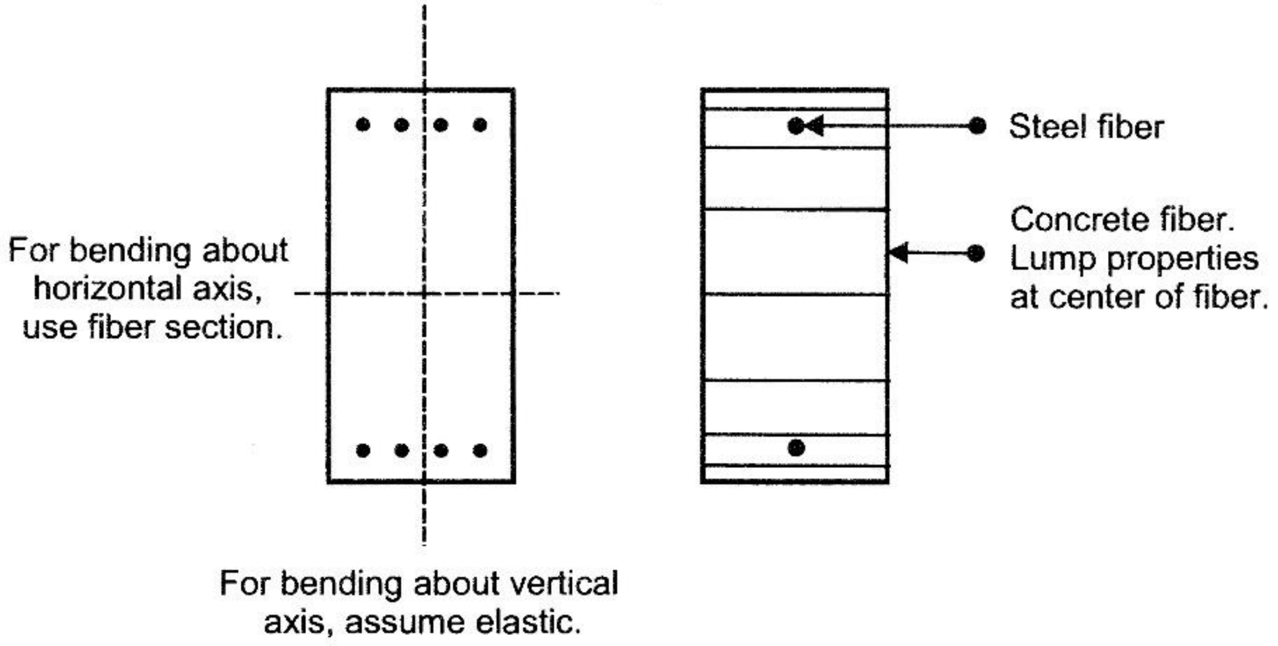
- In this approach, the cross-section of a structural member is divided into a number of uniaxial "**fibers**" running along the larger dimension of the member.
- Each particular fiber is assigned a uniaxial stress-strain relationship capturing various aspects of material nonlinearity in that fiber.
- While using this approach for beams, columns or walls, the **length of fiber segments** is also defined which can either be the full length of the member or some fraction of the full length.
- A complete beam, column or wall element may be made up of several fiber segments.
- For reinforced concrete members, a fiber segment comprises of several fibers of concrete and steel (for rebars) with their respective **stress-strain relationships**.
- The fiber modeling can also account for axial-flexural interaction and hence for axial deformation caused by bending in columns and shear walls.
- The shear behavior in beams, columns and shear walls need to be modeled (elastic or inelastic) separately.

Fiber Modeling Approach

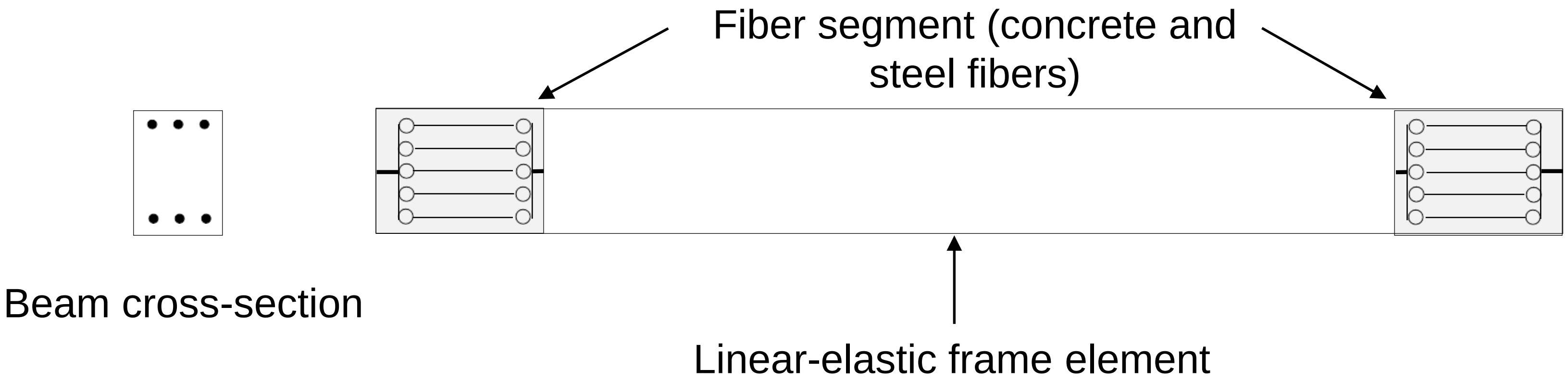
- Fiber hinges (P-M3 or P-M2-M3) can be defined, which are a collection of material points over the cross section.
- Each point represents a tributary area and has its own stress-strain curve.
- Plane sections are assumed to remain planar for the section, which ties together the behavior of the material points.
- Fiber hinges are often more realistic than force-moment hinges, but are more computationally intensive.

Fiber Model of Reinforced Concrete Beams

(a) Fiber section of a reinforced concrete beam (Modified from Powell [2006])



(b) Fiber segments at both ends of a reinforced concrete beam with Linear-elastic frame element in-between. The length of fiber segments is a small fraction of the total beam length.



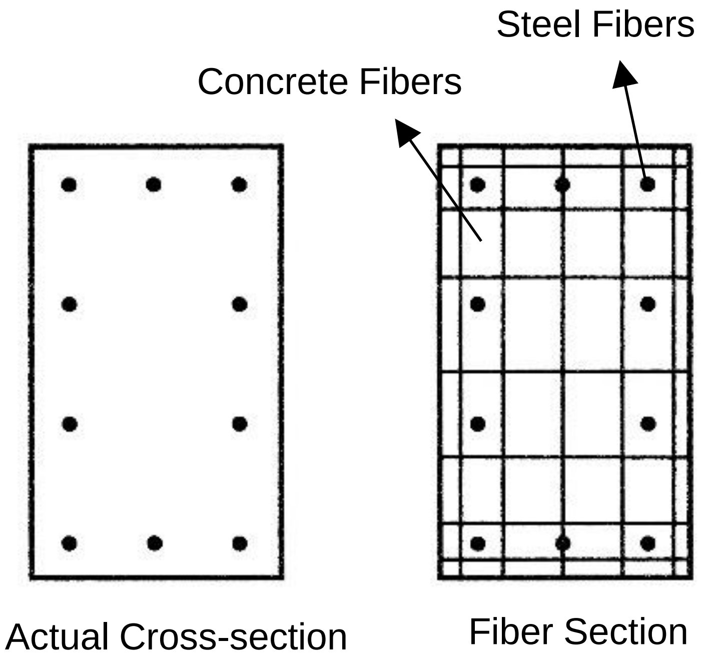
Fiber Model of Reinforced Concrete Beams

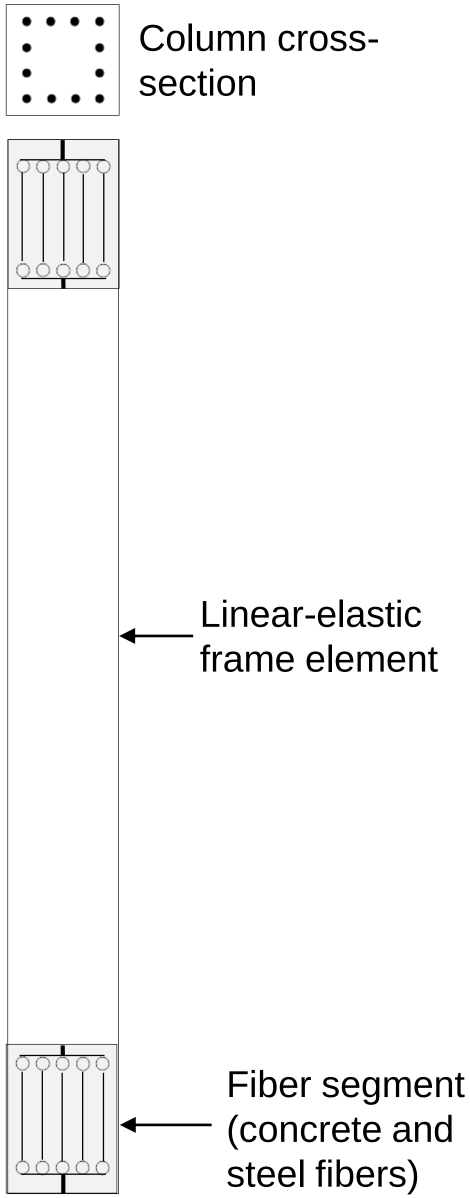
- A common assumption for a beam is that there is **inelastic bending in only one direction.**
- To model bending behavior in the vertical direction, fibers are needed only through the depth of the beam, as indicated in the figure.
- For horizontal bending an elastic bending stiffness is specified (i.e., an EI value). For vertical bending the fiber model determines EI. For horizontal bending the model assumes that there is no P-M interaction. It also assumes that there is **no coupling between vertical and lateral bending** [Powell 2006].

Fiber Model of Reinforced Concrete Columns

- A fiber model for a column must usually account for biaxial bending. Hence, fibers are needed, as indicated in Figure 1-3. This type of model accounts for P-M-M interaction.

- For both beams and columns, the behavior in torsion is usually assumed to be elastic, and also to be uncoupled from the axial and bending behavior.





Fiber Model of Reinforced Concrete Shear Walls

A shear wall has bending in two directions, namely in-plane and out-of-plane. Often it is accurate enough to consider inelastic behavior only for in-plane bending (membrane behavior), and to assume that the behavior is elastic for out-of-plane bending (plate bending behavior). In this case the fiber model can be similar to that for a beam, with fibers only for membrane behavior, as shown in Figure below.

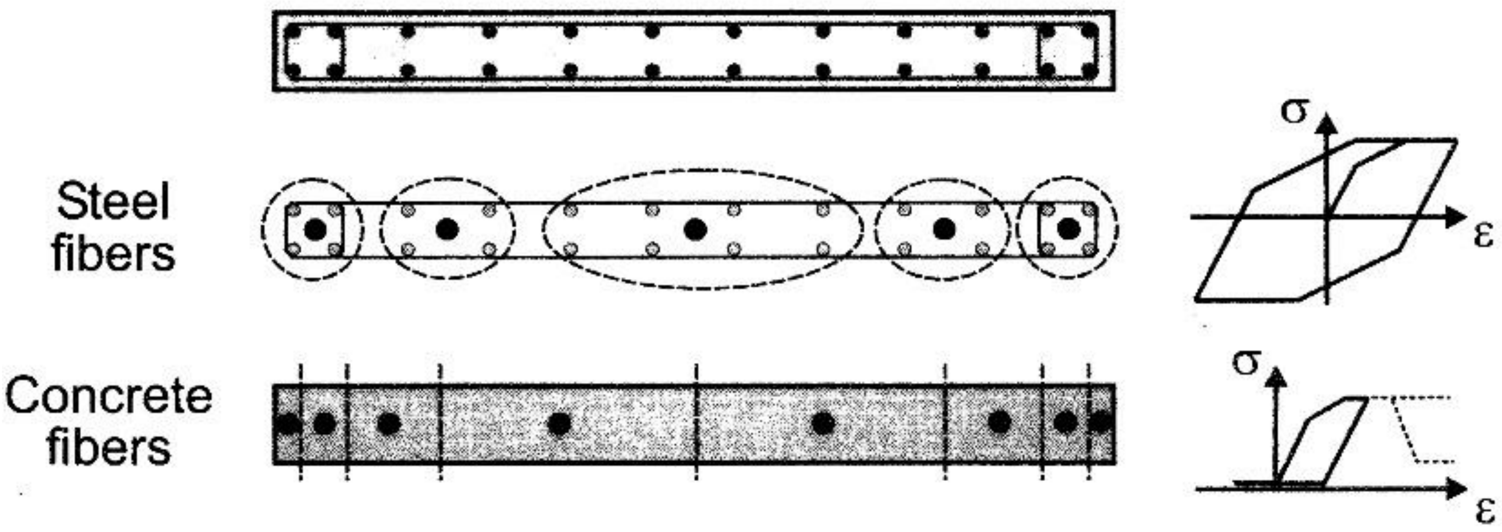
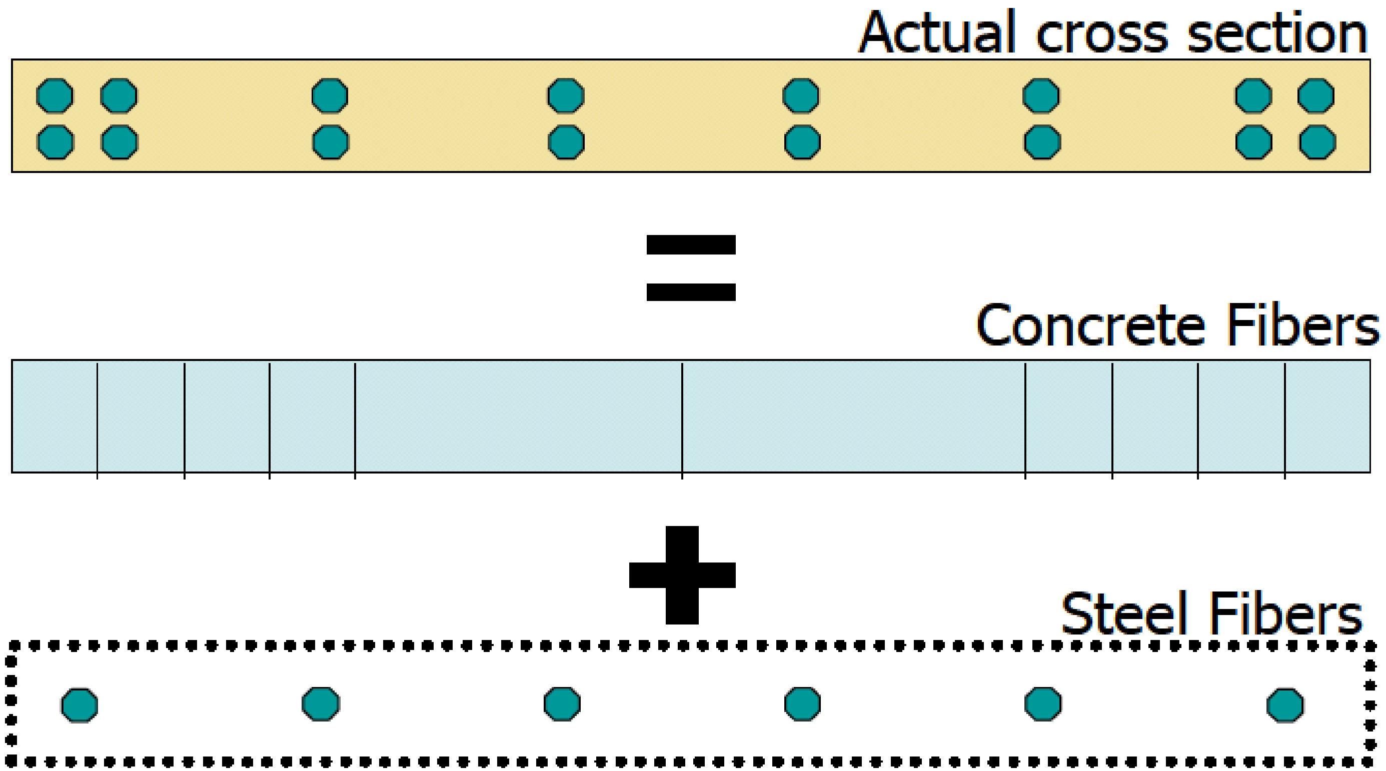


Figure 5.21 Fiber Section for Membrane Behavior of a Wall

Shear Wall Fiber Cross Section



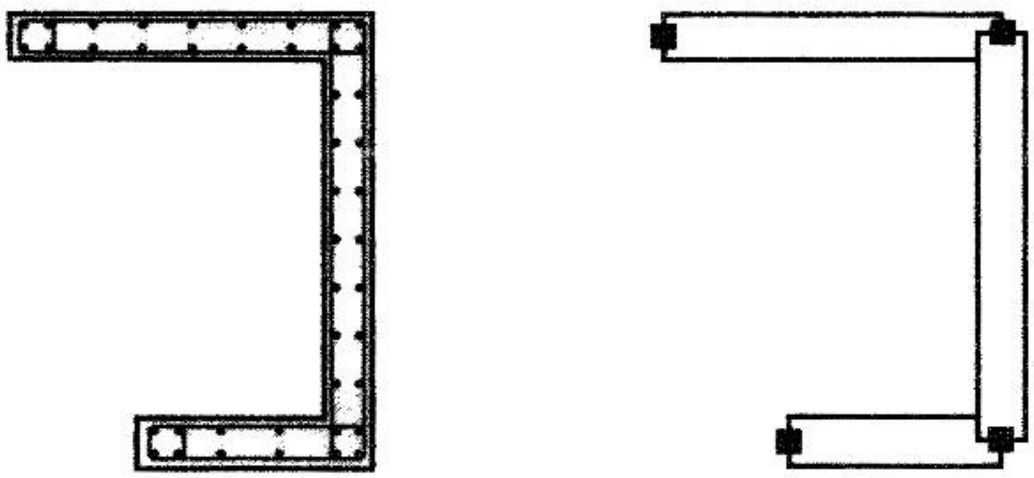
Fiber Model of Reinforced Concrete Shear Walls

- As with a beam, an effective EI is specified for out-of-plane bending, and there is no coupling between membrane and plate bending effects.

- If inelastic plate bending is to be considered, there must also be fibers through the wall thickness. In this case the fiber model is similar to that for a column.

Fiber Model of Reinforced Concrete Shear Walls

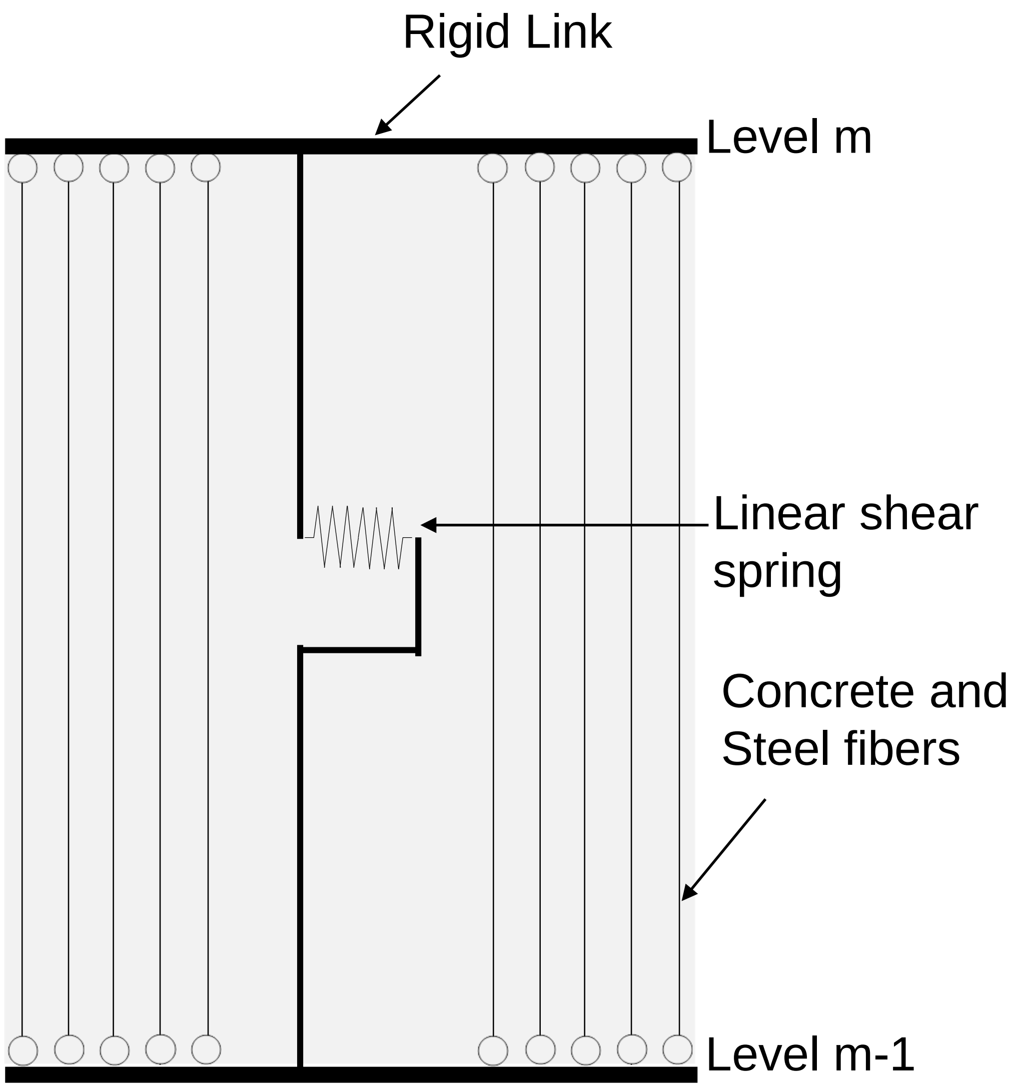
The cross section in Figure (a) could be treated as a single section, rather like a column. However, this is likely to be inaccurate because it does not allow for warping of the cross section. For a fiber section it is usual to assume that plane sections remain plane. This can be reasonable for a plane wall, even if it is quite wide, but it can be incorrect for an open, thin-walled section. It is more accurate to divide the section into plane parts, as in Figure (b).



(a) Wall cross section (b) Model with plane walls

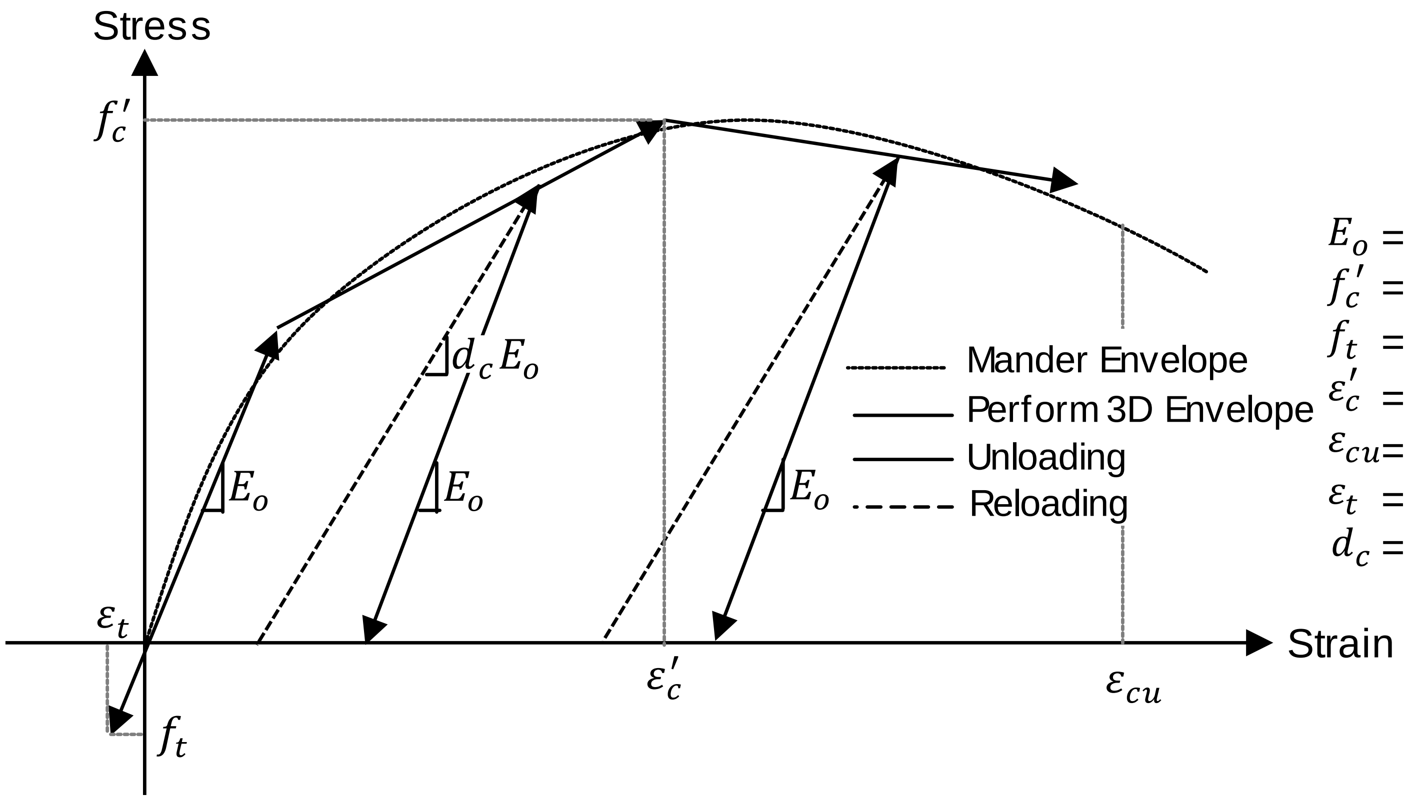
Figure 5.22 Wall Section Modeled as Several Plane Walls

MVLEM for RC Walls



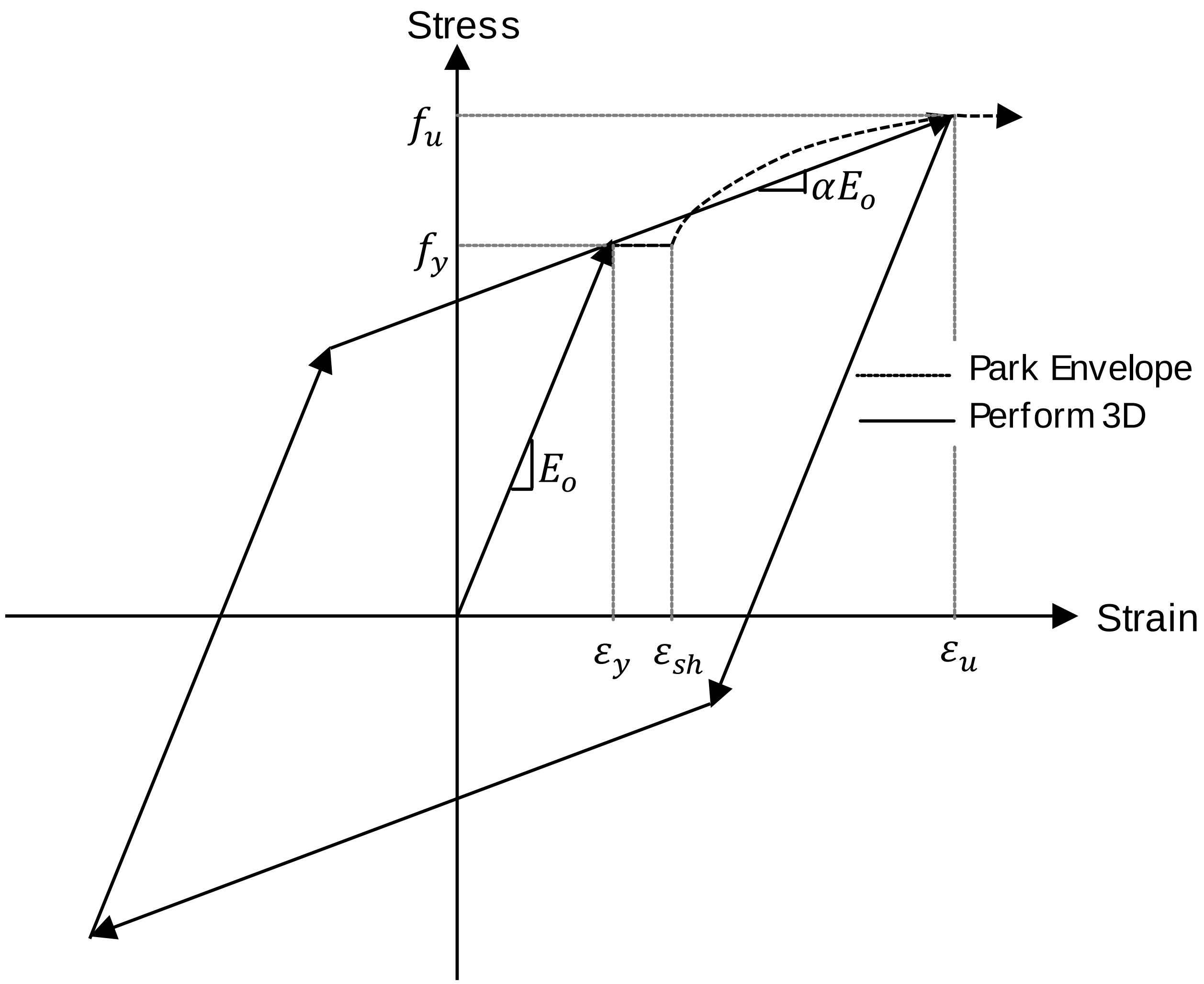
Nonlinear Modeling of Materials (for Fiber Modeling of Members)

Stress-strain Model for Concrete



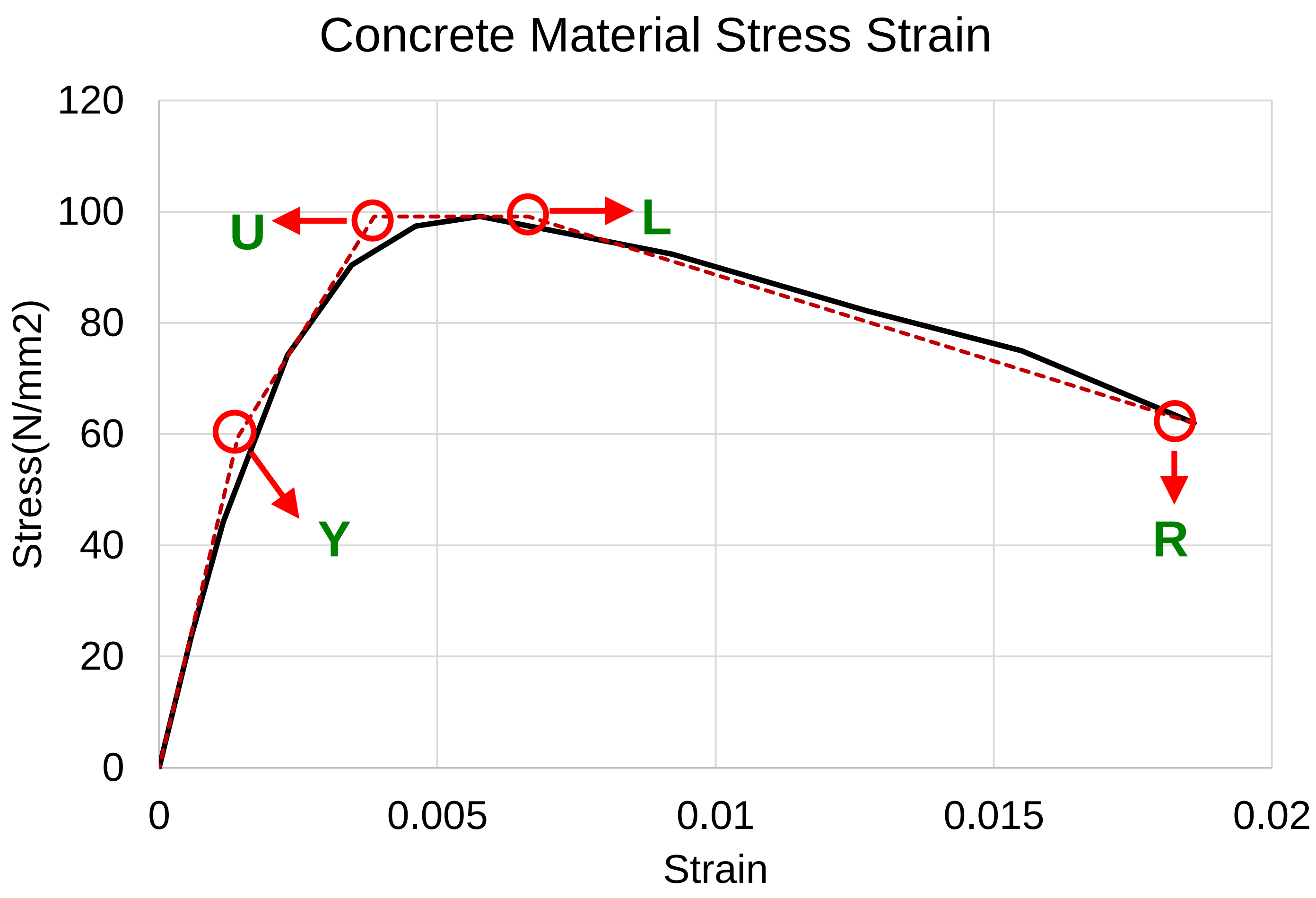
E_o = Tangent modulus of elasticity
f_c' = Compressive strength of unconfined concrete
f_t = Tensile strength of concrete = $0.33\sqrt{f_c'}\ MPa$
ε_c' = Strain at f_c'
ε_{cu}= Ultimate strain capacity
ε_t = Tensile strain capacity
d_c = Energy dissipation factor for reloading

Stress-strain Model for Steel



E_o = Modulus of elasticity
α = Ratio of initial stiffness to post-yield stiffness
f_y = Rebar yield stress
f_u = Rebar ultimate stress capacity
ε_y = Rebar yield strain
ε_{sh} = Strain in rebar at the onset of strain hardening
ε_u = Rebar ultimate strain capacity

Concrete Material Stress Strain Model in PERFORM 3D (YULRX)

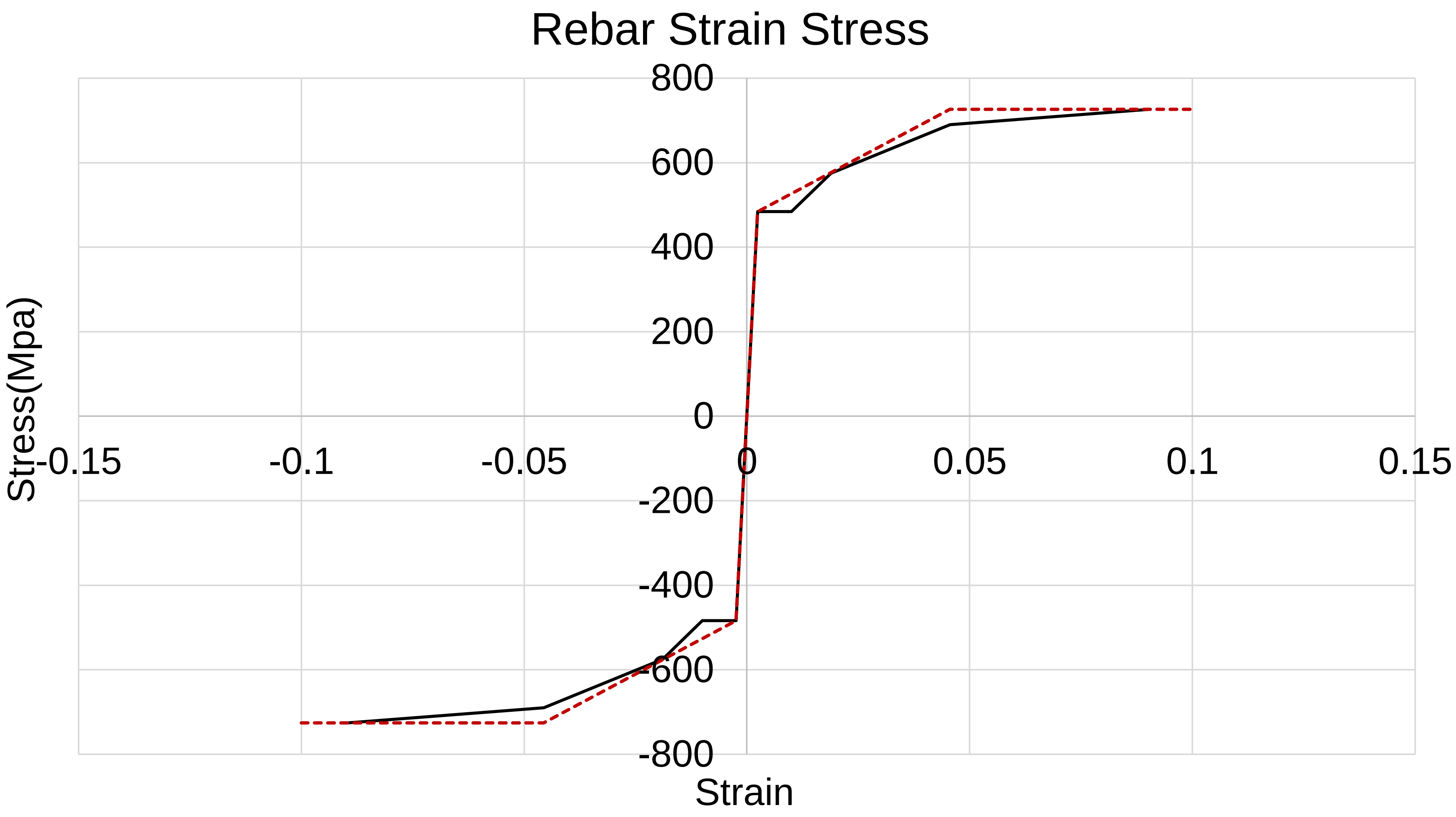


Y:($0.6\ f_{cc}/E_c$, $0.6f_{cc}$)

U:($0.75\ \varepsilon_c$, $0.6f_{cc}$)

L:($1.25\ \varepsilon_c$, $0.6f_{cc}$)

Rebar Material Stress Strain



Nonlinear Material Properties

These properties are used in the nonlinear modeling of elements while using the

- **Fiber Hinges**

  Fiber hinges are used to define the coupled axial force and bi-axial bending behavior at locations along the length of a frame element. The hinges can be defined manually, or created automatically.

  For each fiber in the cross section at a fiber hinge, the material direct nonlinear stress-strain curve is used to define the axial $\sigma_{11} - \varepsilon_{11}$ relationship. Summing up the behavior of all the fibers at a cross section and multiplying by the hinge length gives the axial force-deformation and bi-axial moment-rotation relationships. The $\sigma_{11} - \varepsilon_{11}$ is the same whether the material is Uniaxial, Isotropic, Orthotropic, or Anisotropic. Shear behavior is not considered in the fibers. Instead, shear behavior is computed for the frame section as usual using the linear shear modulus G.

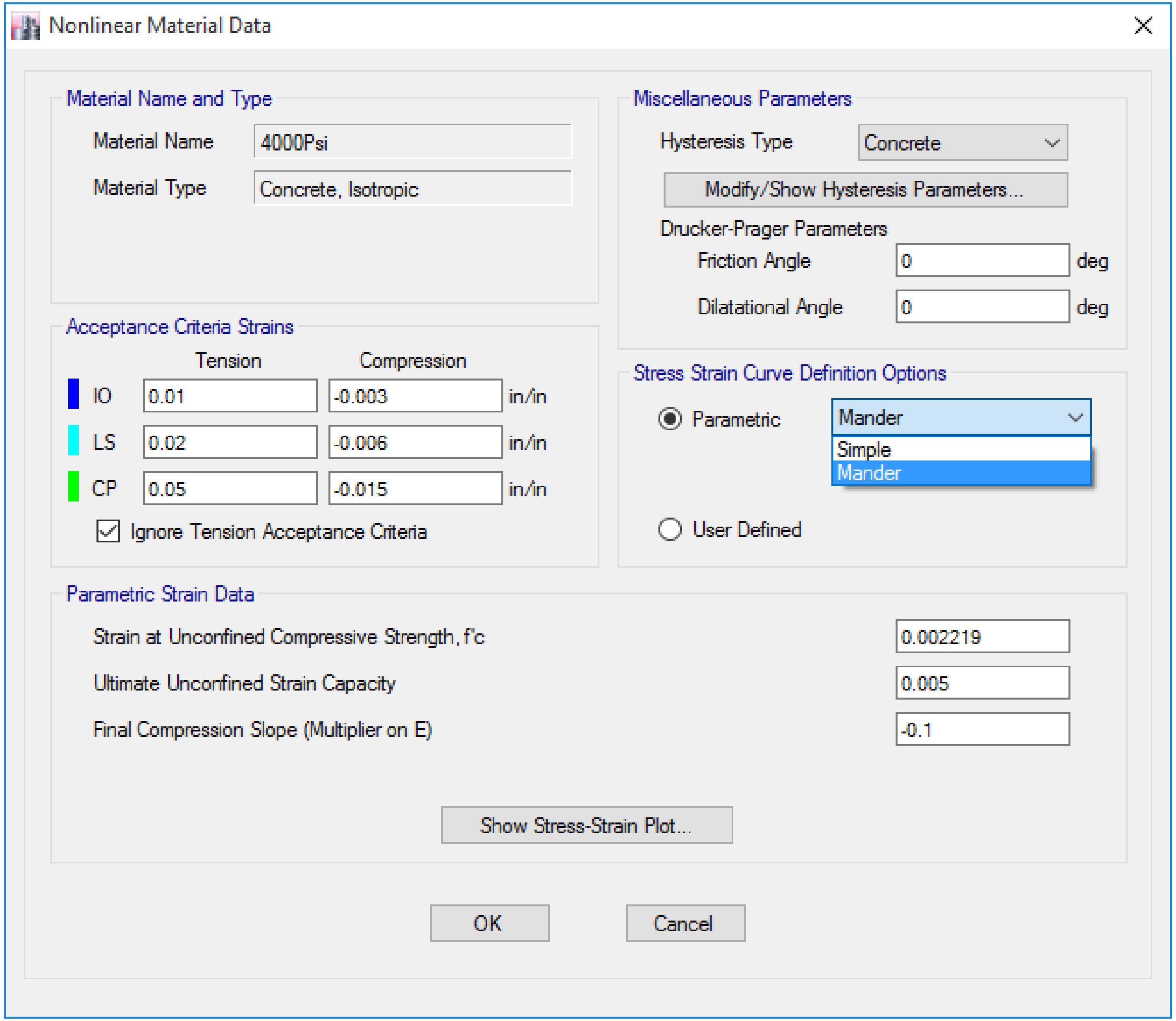
- **Layered Shell Element**

  The Shell element with the layered section property may consider linear, nonlinear, or mixed material behavior. For each layer, you select a material, a material angle, and whether each of the in-plane stress-strain relationships are linear, nonlinear, or inactive (zero stress).

Nonlinear Material Properties

Used in the nonlinear modeling of elements using the

- **Fiber Hinges**
- **Layered Shell Element**

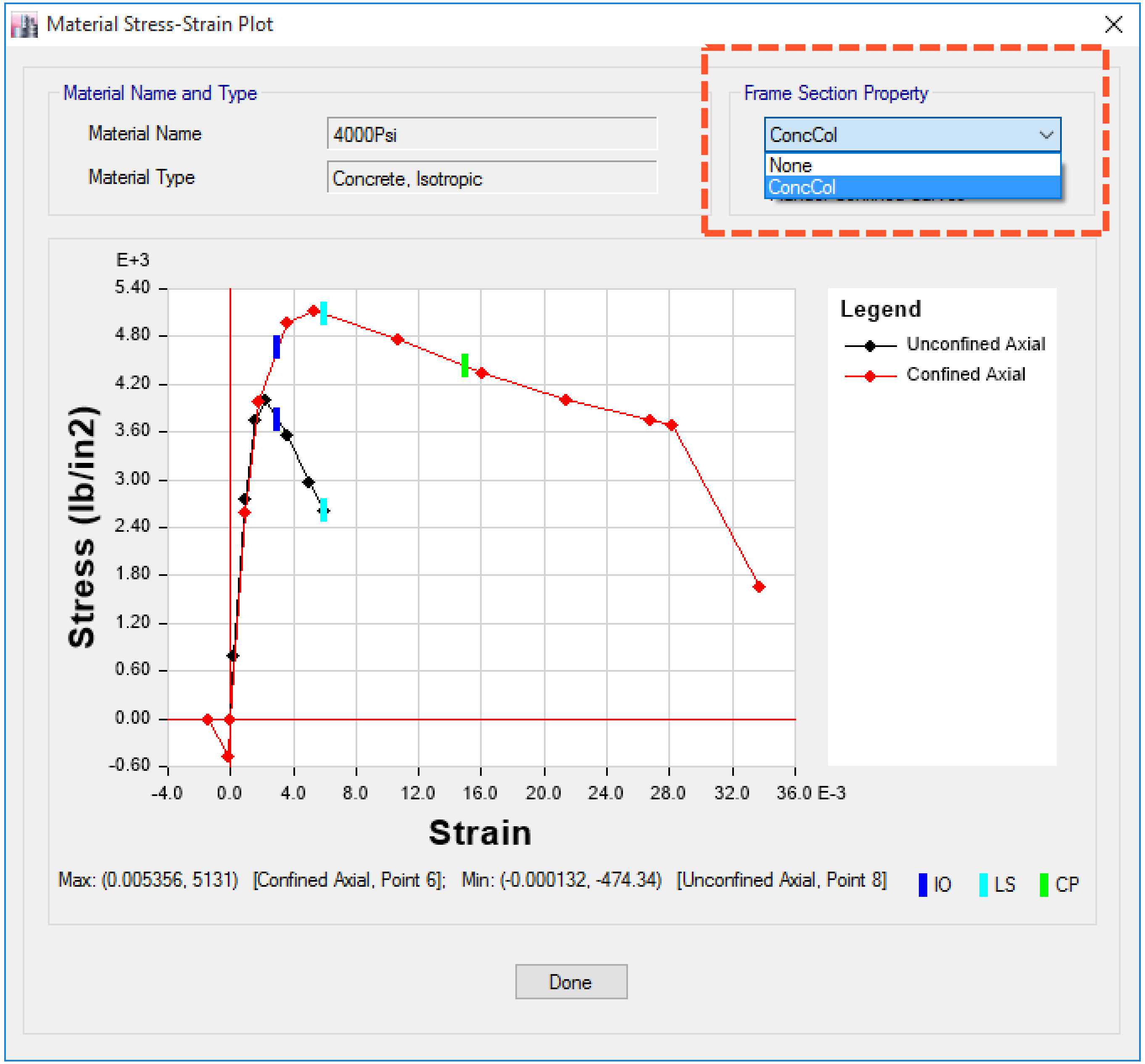


Acceptance Criteria

- Three points labeled IO, LS and CP are used to define the acceptance criteria for the hinge
- IO- Immediate Occupancy
- LS- Life Safety
- CP-Collapse Prevention

Mander Confined and Unconfined Concrete Model in Tension and Compression

A shear stress-strain curve is computed internally from the direct stress-strain curve. The assumption is made that shearing behavior can be computed from tensile and compressive behavior acting at 45° to the material axes using Mohr's circle in the plane.



Mander's (1988) Unconfined Concrete Model

The Mander unconfined concrete stress-strain curve is defined by the following equations:

For $\varepsilon \leq 2\varepsilon'_c$ (curved portion),

$$f = \frac{f'_c x r}{r - 1 + x^r}$$

where

$$x = \varepsilon / \varepsilon'_c$$

$$r = \frac{E}{E - (f'_c / \varepsilon'_c)}$$

For $2\varepsilon'_c < \varepsilon \leq \varepsilon_u$ (linear portion),

$$f = \left(\frac{2 f'_c r}{r - 1 + 2^r}\right)\left(\frac{\varepsilon_u - \varepsilon}{\varepsilon_u - 2\varepsilon'_c}\right)$$

where r is as defined previously for the curved portion of the curve.

The tensile yield stress for the Mander unconfined curve is taken at $7.5\sqrt{f'_c}$ in psi.

ε = Concrete strain

f = Concrete stress

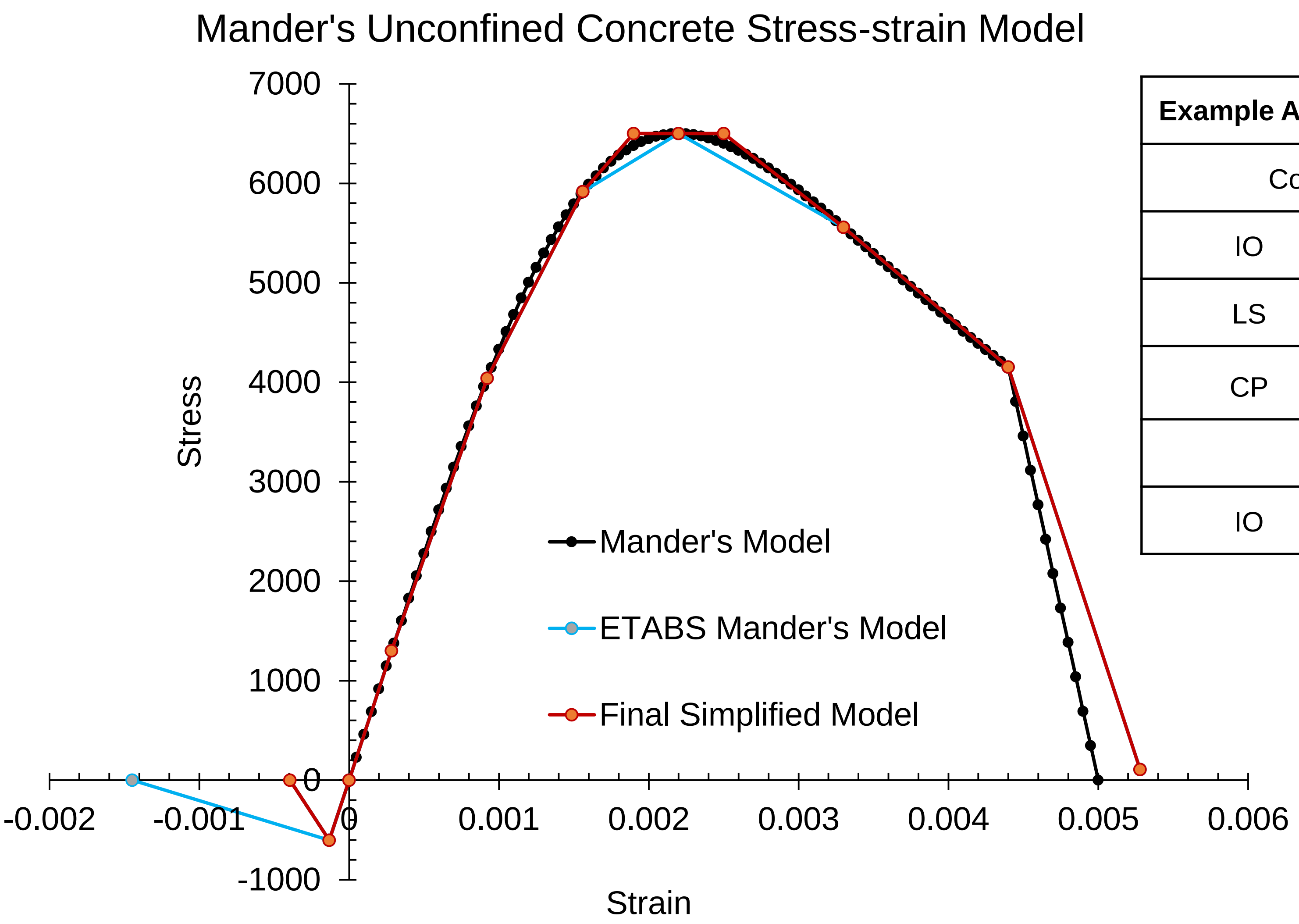
E = Modulus of elasticity

f'_c = Concrete compressive strength

ε'_c = Concrete strain at f'_c

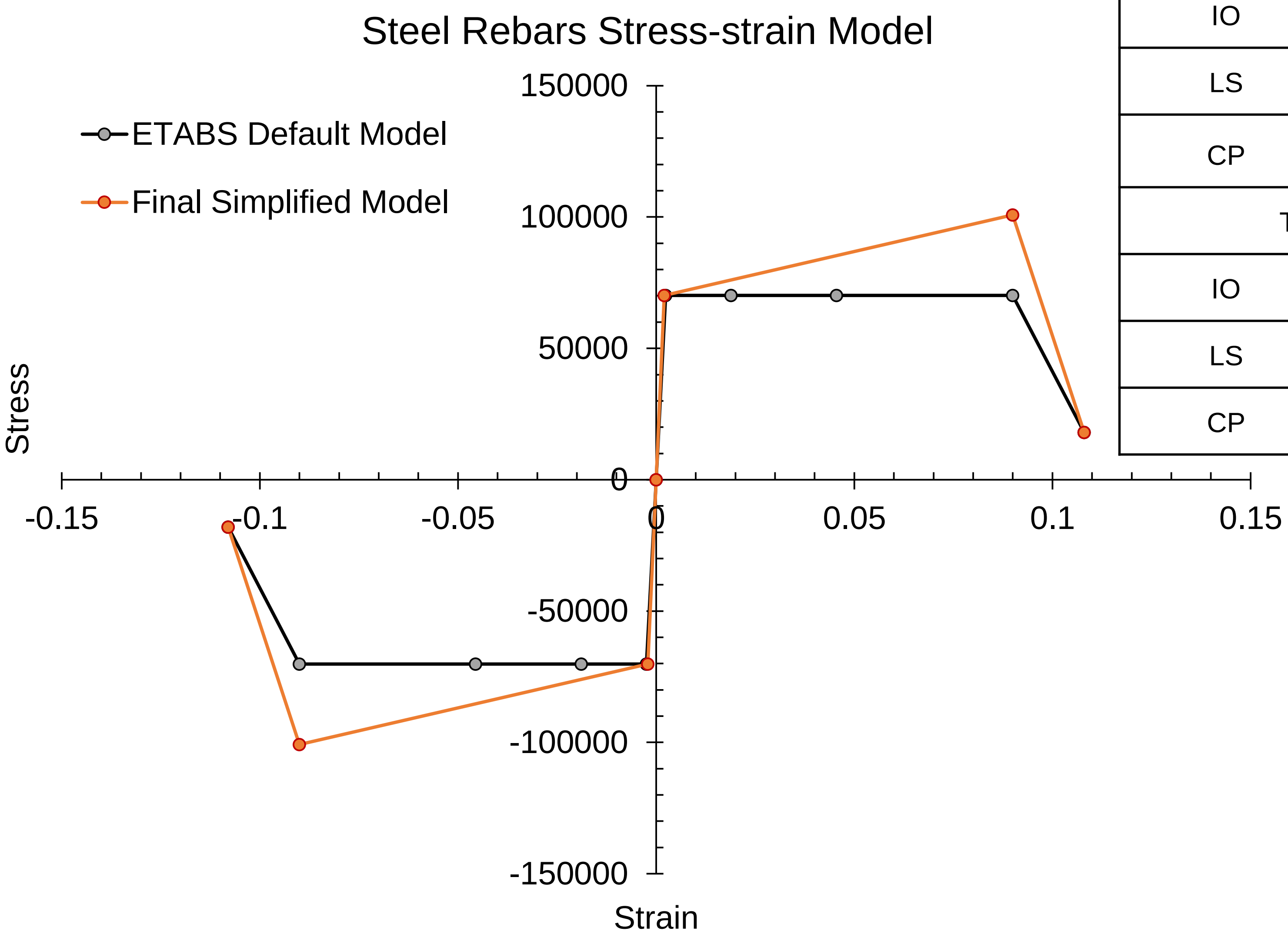
ε_u = Ultimate concrete strain capacity

Mander’s (1988) Unconfined Concrete Model



Example Acceptance Criteria		Description
Compression		
IO	-0.00092	Onset of compression cracking
LS	-0.0022	Peak stress achieved
CP	-0.003	Onset of significant strength degradation
Tension		
IO	0.000132	Onset of tensile cracking

An Example Steel Model



Example Acceptance Criteria		Description
Compression		
IO	0.002069	Onset of compression yielding
LS	0.004138	2 times of compression yielding
CP	0.006207	3 times of compression yielding
Tension		
IO	0.002069	Onset of tensile yielding
LS	0.006207	3 times of tensile yielding
CP	0.010345	5 times of tensile yielding

ASCE 41-17 Lower-bound and Expected Material Capacities

Table 10-1. Factors to Translate Lower-Bound Material Properties to Expected Strength Material Properties

Material Property	Factor
Concrete compressive strength	1.50
Reinforcing steel tensile and yield strength	1.25
Connector steel yield strength	1.50

Table 10-2. Default Lower-Bound Compressive Strength of Structural Concrete, lb/in.^{2} (MPa)

Time Frame	Footings	Beams	Slabs	Columns	Walls
1900–1919	1,000 to 2,500 (7 to 17)	2,000 to 3,000 (14 to 21)	1,500 to 3,000 (10 to 21)	1,500 to 3,000 (10 to 21)	1,000 to 2,500 (7 to 17)
1920–1949	1,500 to 3,000 (10 to 21)	2,000 to 3,000 (14 to 21)	2,000 to 3,000 (14 to 21)	2,000 to 4,000 (14 to 28)	2,000 to 3,000 (14 to 21)
1950–1969	2,500 to 3,000 (17 to 21)	3,000 to 4,000 (21 to 28)	3,000 to 4,000 (21 to 28)	3,000 to 6,000 (21 to 40)	2,500 to 4,000 (17 to 28)
1970–present	3,000 to 4,000 (21 to 28)	3,000 to 5,000 (21 to 35)	3,000 to 5,000 (21 to 35)	3,000 to 10,000 (21 to 70)	3,000 to 5,000 (21 to 35)

ASCE 41-17 Lower-bound and Expected Material Capacities

Table 10-3. Default Lower-Bound Tensile and Yield Properties of Reinforcing Steel for Various Periods

		Structural[a]	Intermediate[a]	Hard[a]				
	Grade	**33**	**40**	**50**	**60**	**65**	**70**	**75**
	Minimum Yield, lb/in.^{2} (MPa)	**33,000 (230)**	**40,000 (280)**	**50,000 (350)**	**60,000 (420)**	**65,000 (450)**	**70,000 (485)**	**75,000 (520)**
Year	**Minimum Tensile, lb/in.^{2} (MPa)**	**55,000 (380)**	**70,000 (485)**	**80,000 (550)**	**90,000 (620)**	**75,000 (520)**	**80,000 (550)**	**100,000 (690)**
1911–1959		x	x	x		x		
1959–1966		x	x	x	x	x	x	x
1966–1972			x	x	x	x	x	
1972–1974			x	x	x	x	x	
1974–1987			x	x	x	x	x	
1987–present			x	x	x	x	x	x

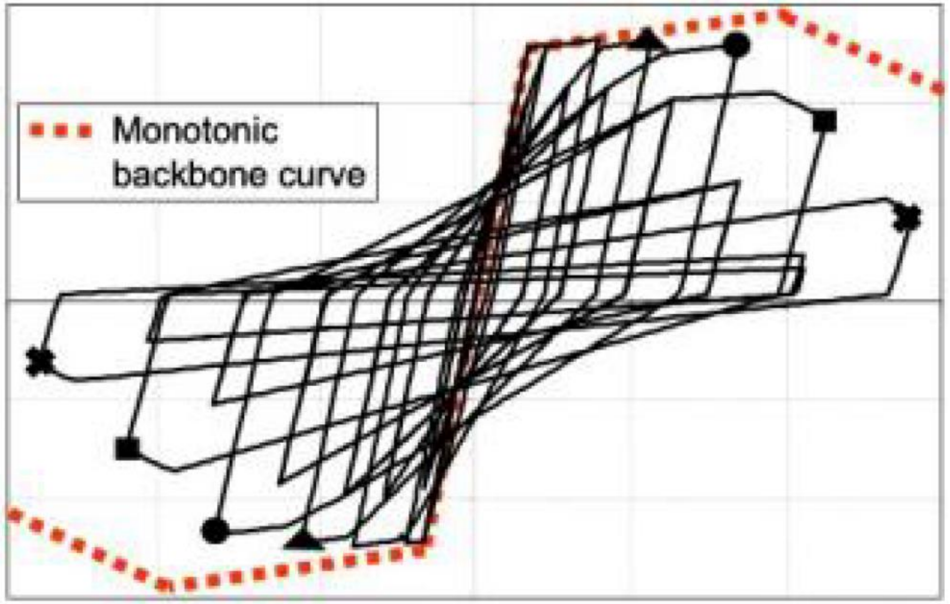
Note: An entry of "x" indicates that the grade was available in those years.
[a] The terms "structural," "intermediate," and "hard" became obsolete in 1968.

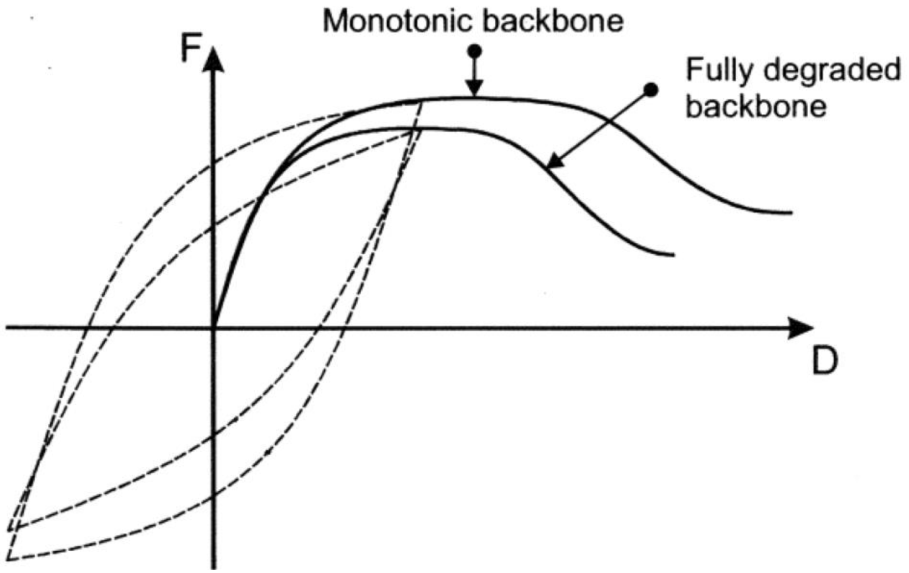
Modeling of Hysteretic Behavior and Options Available in ETABS

Modeling of Hysteresis Behavior of Inelastic Components

Option 1: Explicit Modeling of Hysteresis Behavior

- Cyclic and in-cycle degradation explicitly modeled during analysis.
- The initial backbone curve as a reference boundary surface.
- Backbone curve hardens/softens as a function of damage.
- A set of rules is needed to defined how the degradation will occur and on what parameters this degradation will depend
- This modeling option is not available in commercial software but research-based software like Opensees have options to model components with explicitly consider hysteresis behavior.

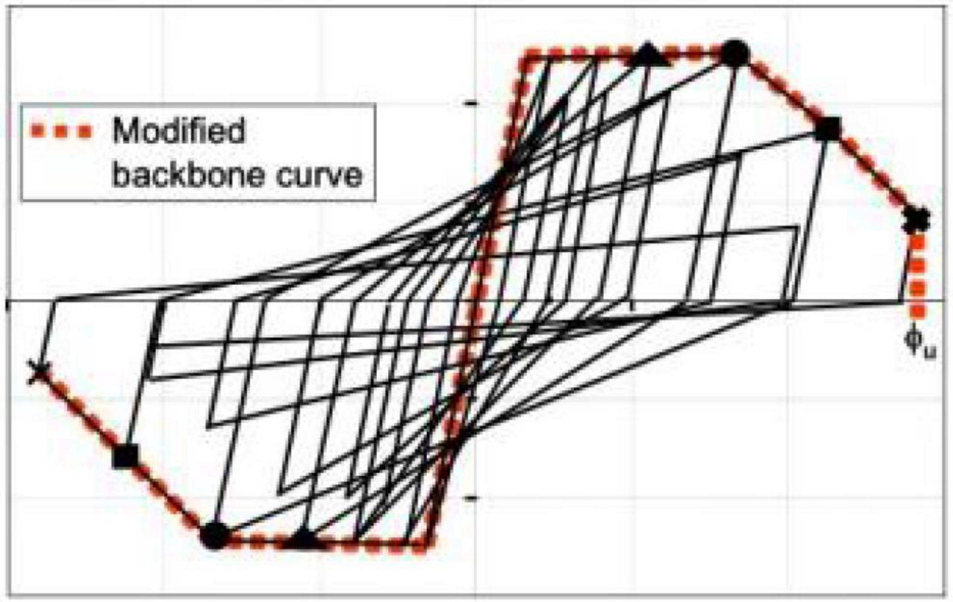


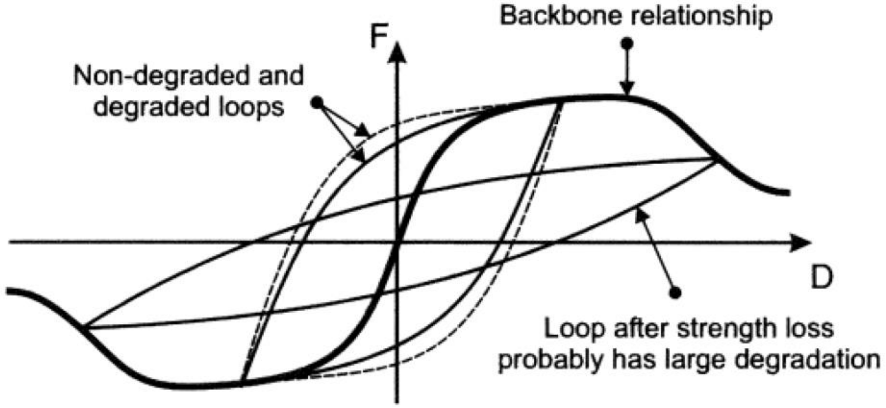


Modeling of Hysteresis Behavior of Inelastic Components

Option 2: Degradation of Backbone

- Use of cyclic envelope (skeleton) curve as a modified initial backbone curve.
- Ductility degradation and cyclic strength degradation are already incorporated in the backbone.
- Hysteretic loops will be anchored to the backbone.
- A set of rules is needed to define how loops will form and how much energy will be dissipated by the component





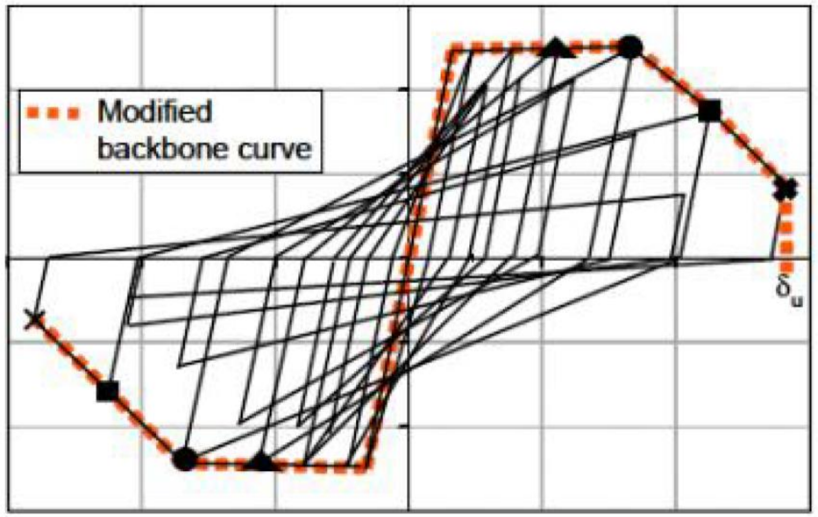
Modeling of Hysteresis Behavior

Generalized Component Response

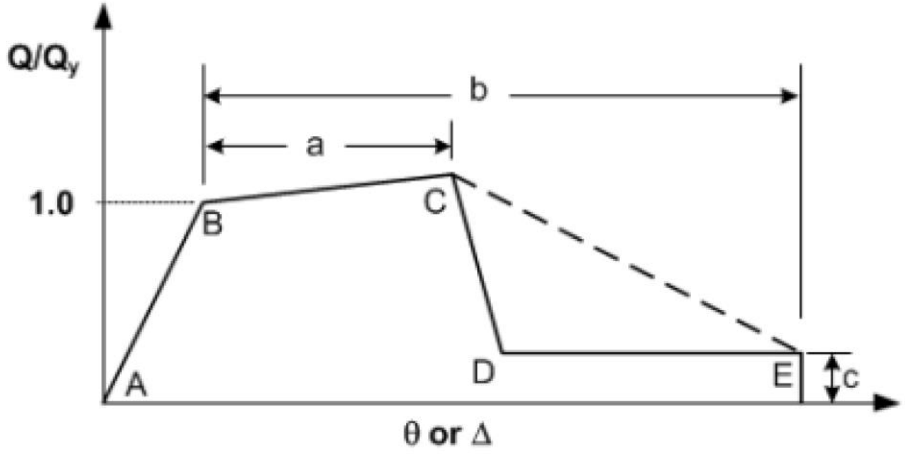
Response curves in ASCE 41 are essentially the same as "Option 2”.

- Cyclic envelope fit to cyclic test data
- ASCE 41 (FEMA 273) originally envisioned for static pushover analysis without any cyclic deformation in the analysis.

- Option 2/ASCE 41: reasonable for most Commercial analysis programs that cannot simulate cyclic degradation of the backbone curve.
- Post-Peak Response: dashed line connecting points C-E in ASCE 41 response curve is more reasonable representation of post-peak (softening) response

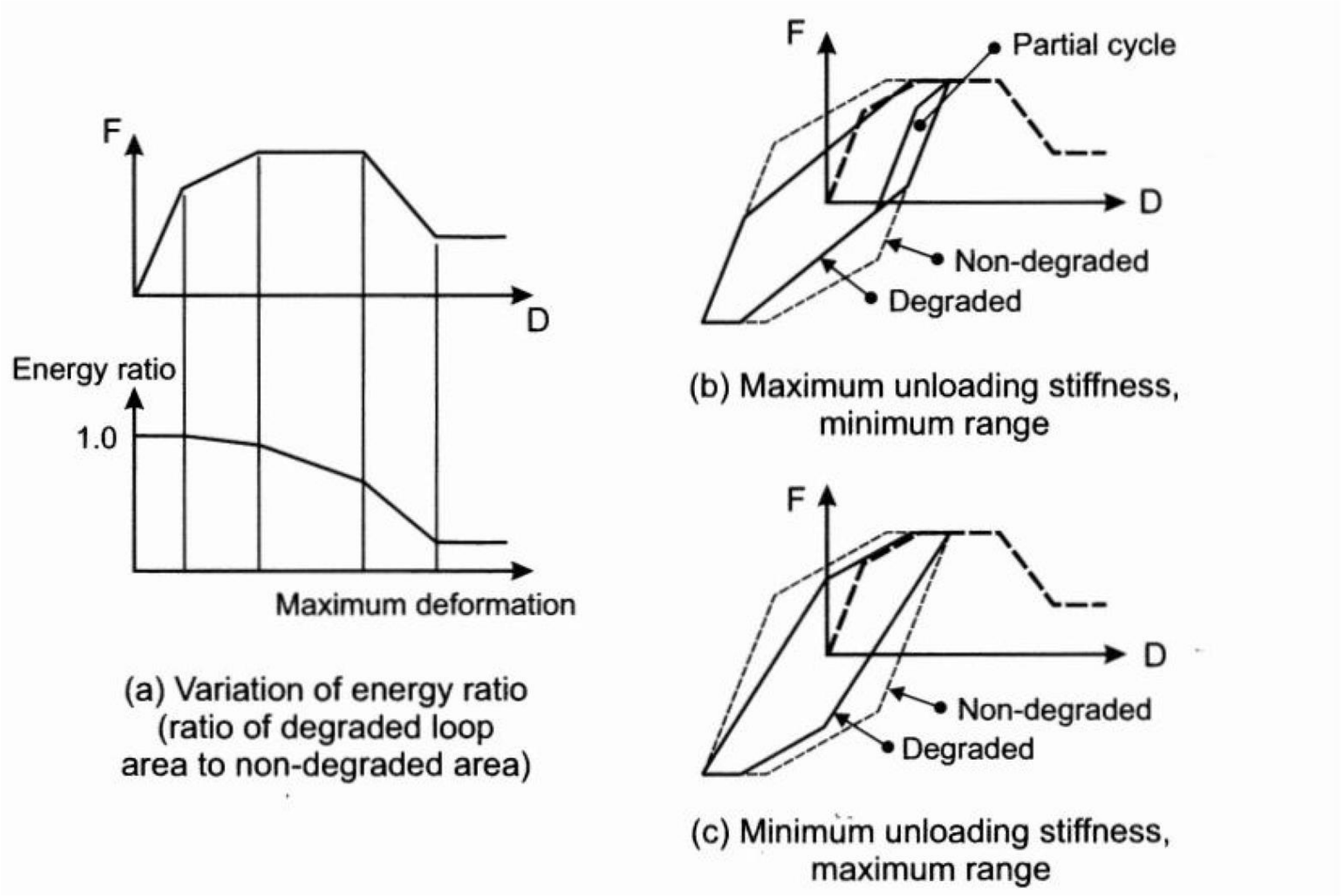


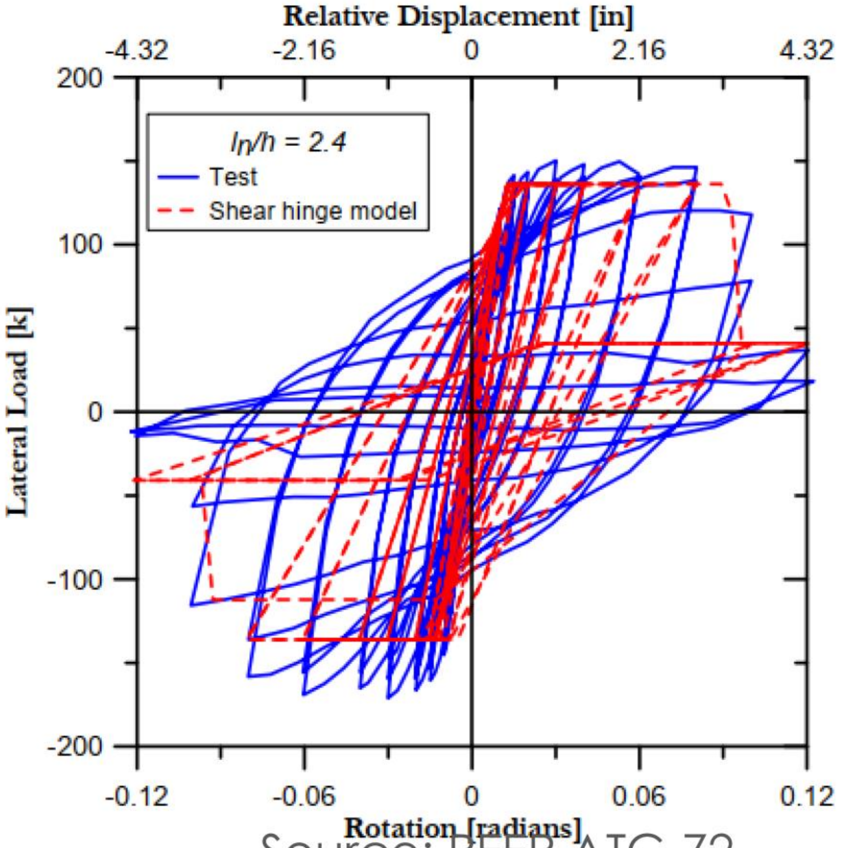
(b) Option 2 – modified backbone curve = envelope curve



ASCE 41 (and related models)

Energy Degradation in Perform 3D and ETABS

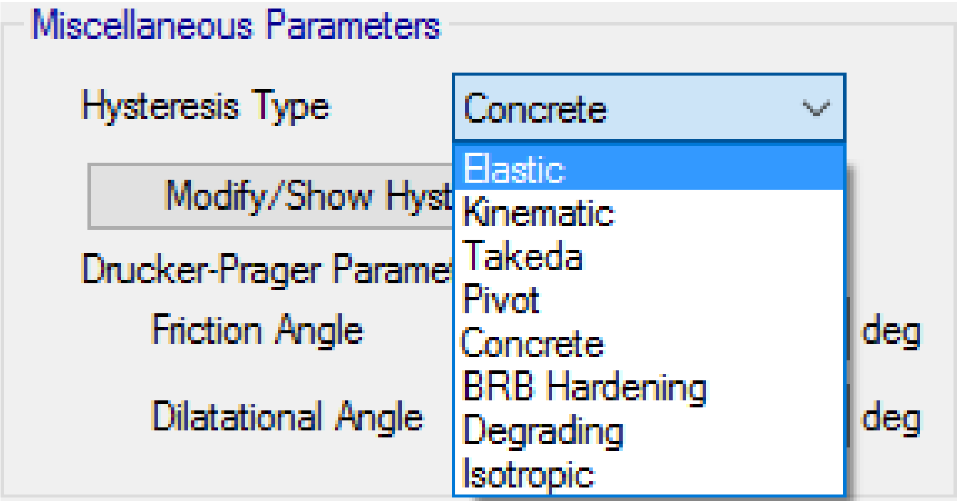




Source: PEER ATC-72

General Hysteretic Behaviors in ETABS

Hysteresis is the process of energy dissipation through deformation (displacement), as opposed to viscosity which is energy dissipation through deformation rate (velocity). Hysteresis is typical of solids, whereas viscosity is typical of fluids, although this distinction is not rigid.



Several **hysteresis models** are available to define the nonlinear stress-strain behavior when load is reversed or cycled.

For the most part, these models differ in the **amount of energy they dissipate in a given cycle of deformation**, and how the energy dissipation behavior changes with an increasing amount of deformation.

Hysteretic Models

Each hysteresis model may be used for the following purposes:

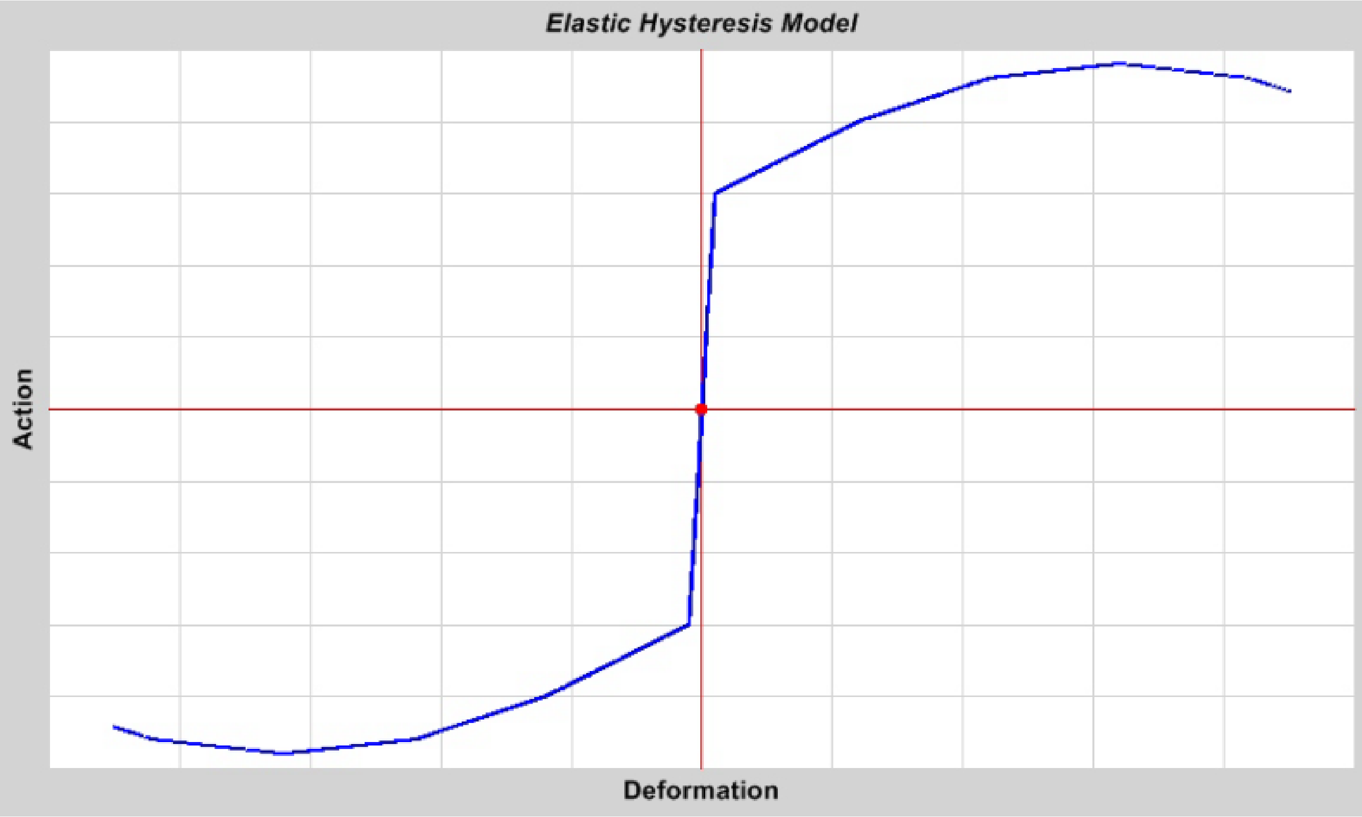
- **Material stress-strain behavior**, affecting frame fiber hinges and layered shells that use the material
- Single degree-of-freedom **frame hinges**, such as M3 or P hinges. Interacting hinges, such as P-M3 or P-M2-M3, currently use the isotropic model
- **Link/support elements** of type multi-linear plasticity.

Backbone Curve (Action vs. Deformation)

- For each material, hinge, or link degree of freedom, a **uniaxial action vs. deformation curve** defines the non-linear behavior under monotonic loading in the positive and negative directions.
- Here action and deformation are an energy conjugate pair as follows:
  - For materials, stress vs. strain
  - For hinges and multi-linear links, force vs. deformation or moment vs. rotation, depending upon the degree of freedom to which it is applied
- For each model, the uniaxial action-deformation curve is given by a set of points that you define. This curve is called the **backbone curve**.

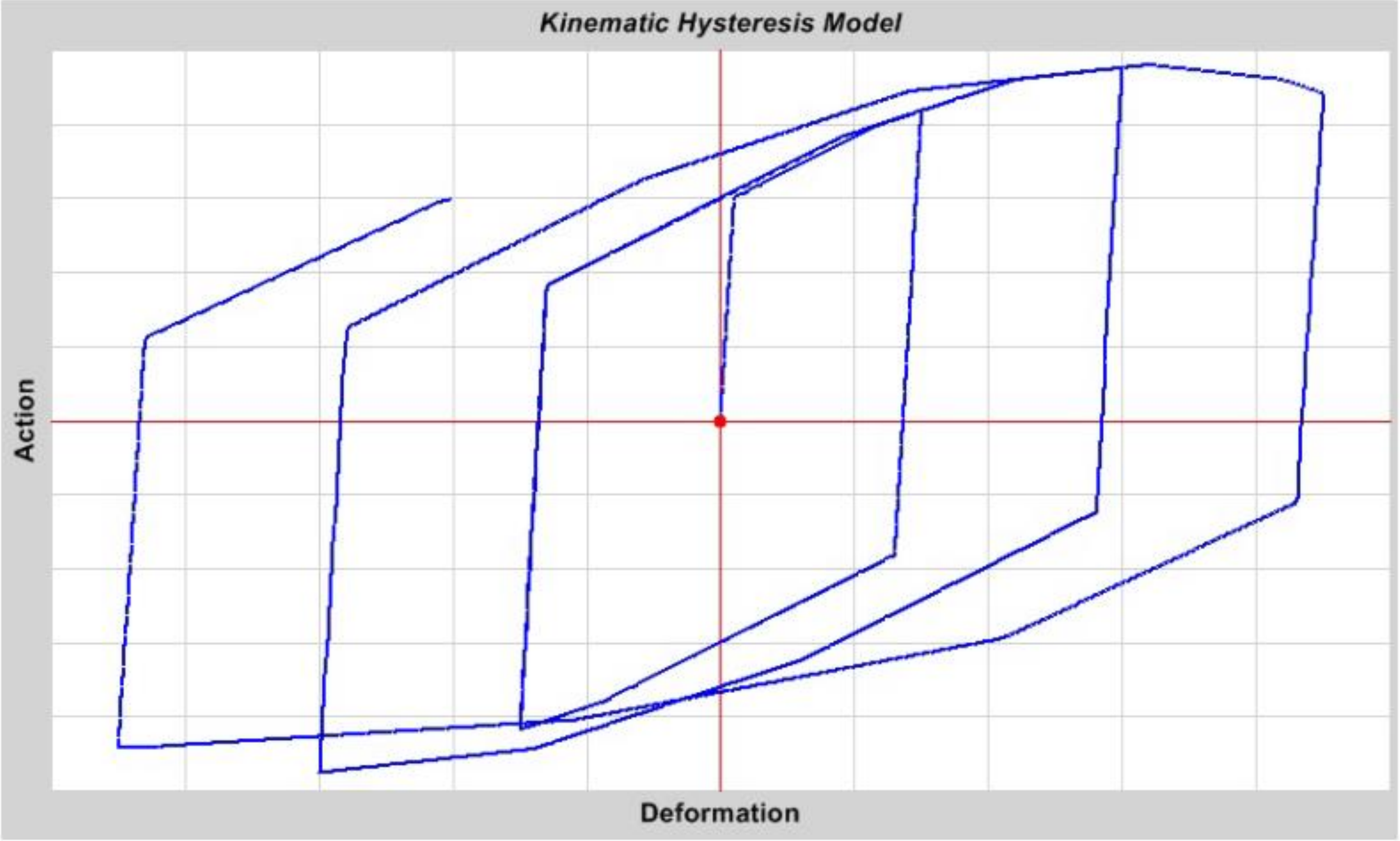
Elastic Hysteresis Model

The behavior is ***nonlinear but also elastic***. This means that the material always loads and unloads along the backbone curve, and no energy is dissipated.



Kinematic Hysteresis Model

This model is based upon kinematic hardening behavior that is commonly observed in metals, ***and it is the default hysteresis model for all metal materials*** in the program. This model dissipates a significant amount of energy, and is appropriate for ductile materials.

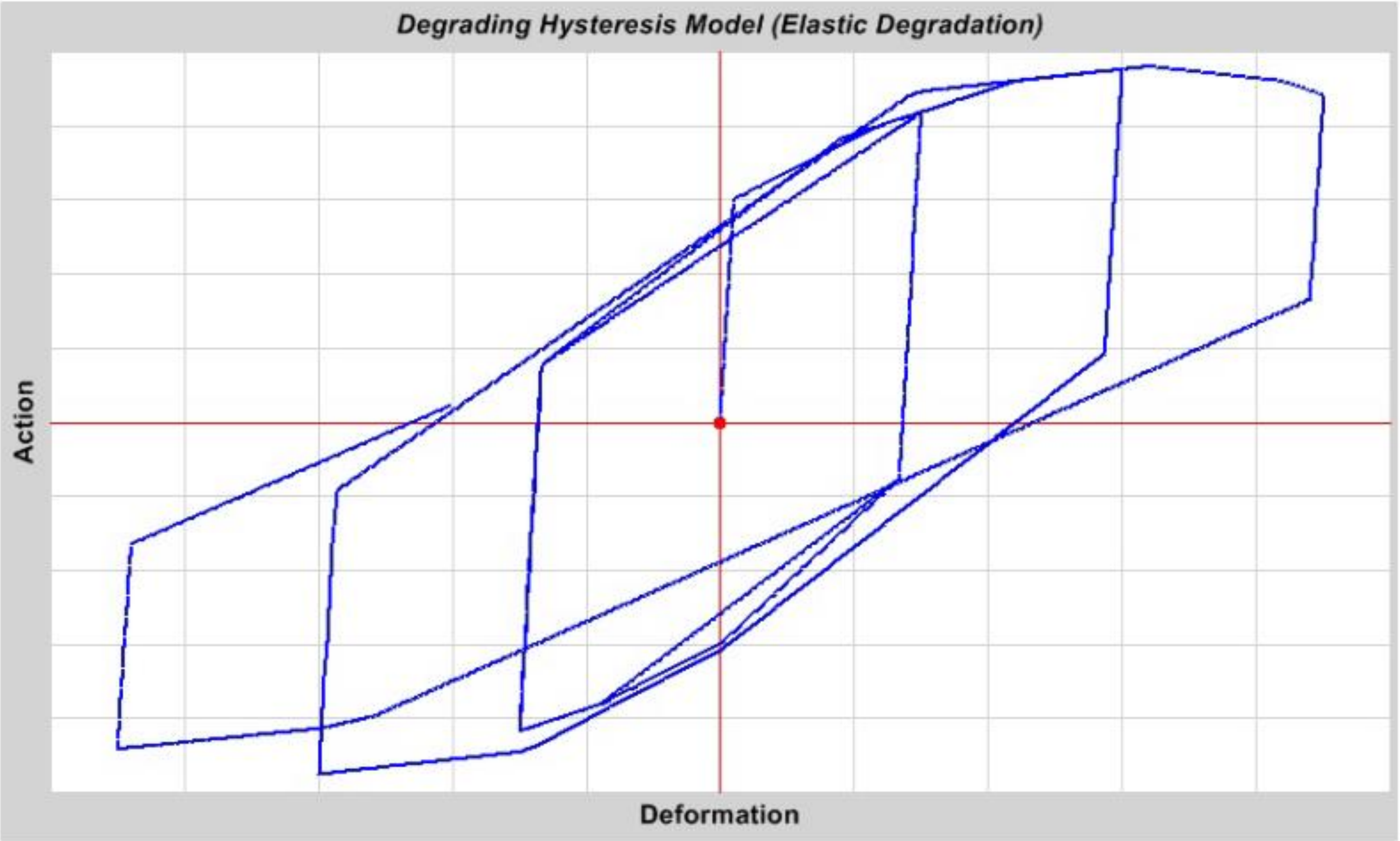


No additional parameters are required for this model.

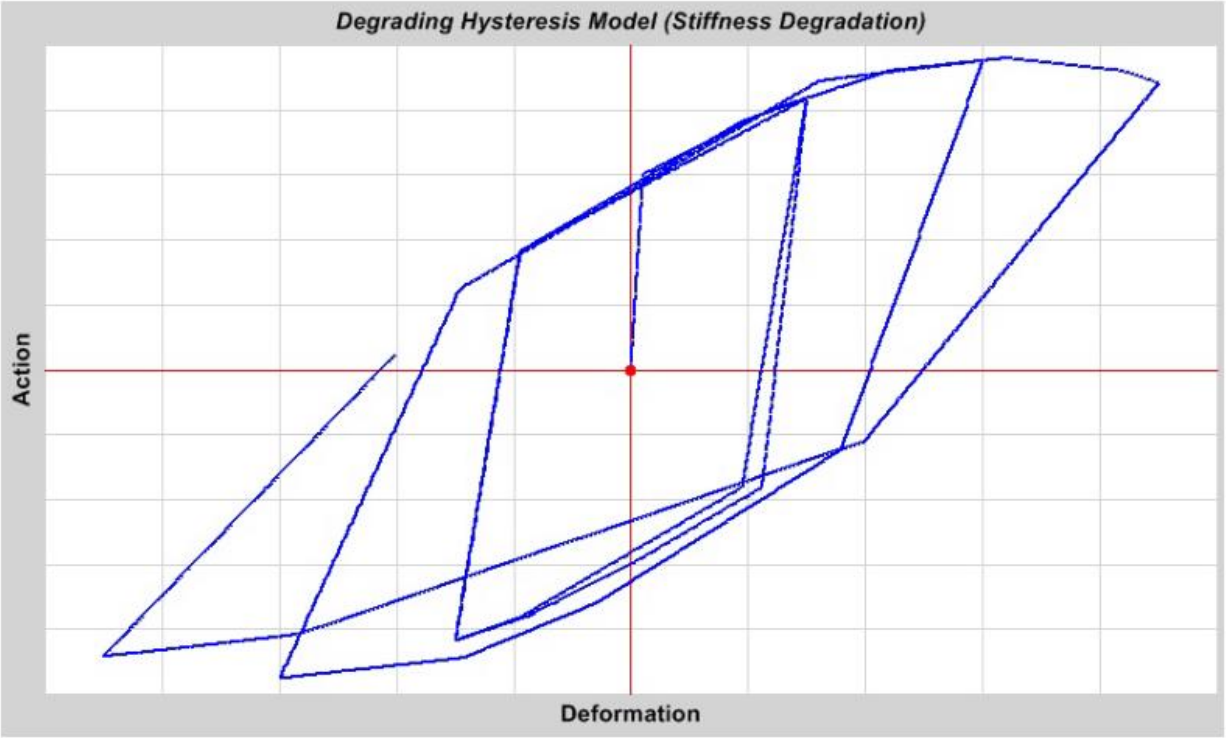
Upon unloading and reverse loading, the curve follows a path made of segments parallel to and of the same length as the previously loaded segments and their opposite-direction counterparts until it rejoins the backbone curve when loading in the opposite direction.

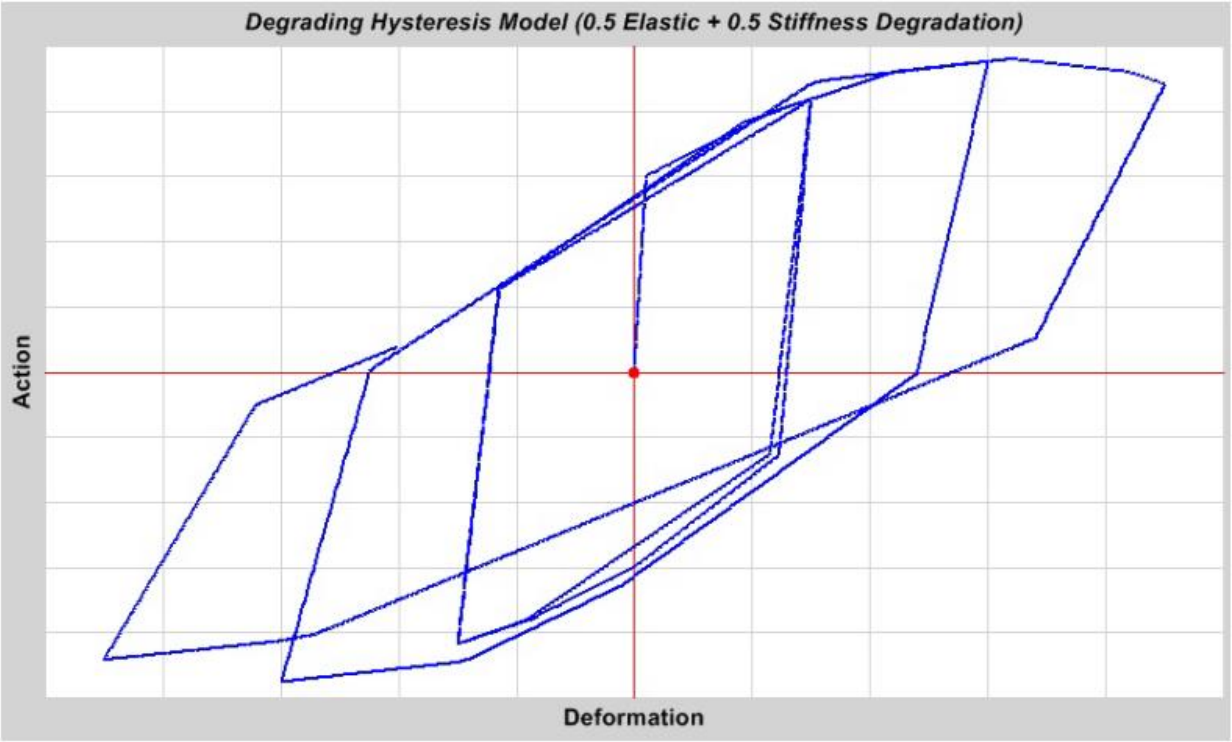
Degrading Hysteresis Model

This model is very similar to the Kinematic model, but uses a degrading hysteretic loop that accounts for decreasing energy dissipation and unloading stiffness with increasing plastic deformation.



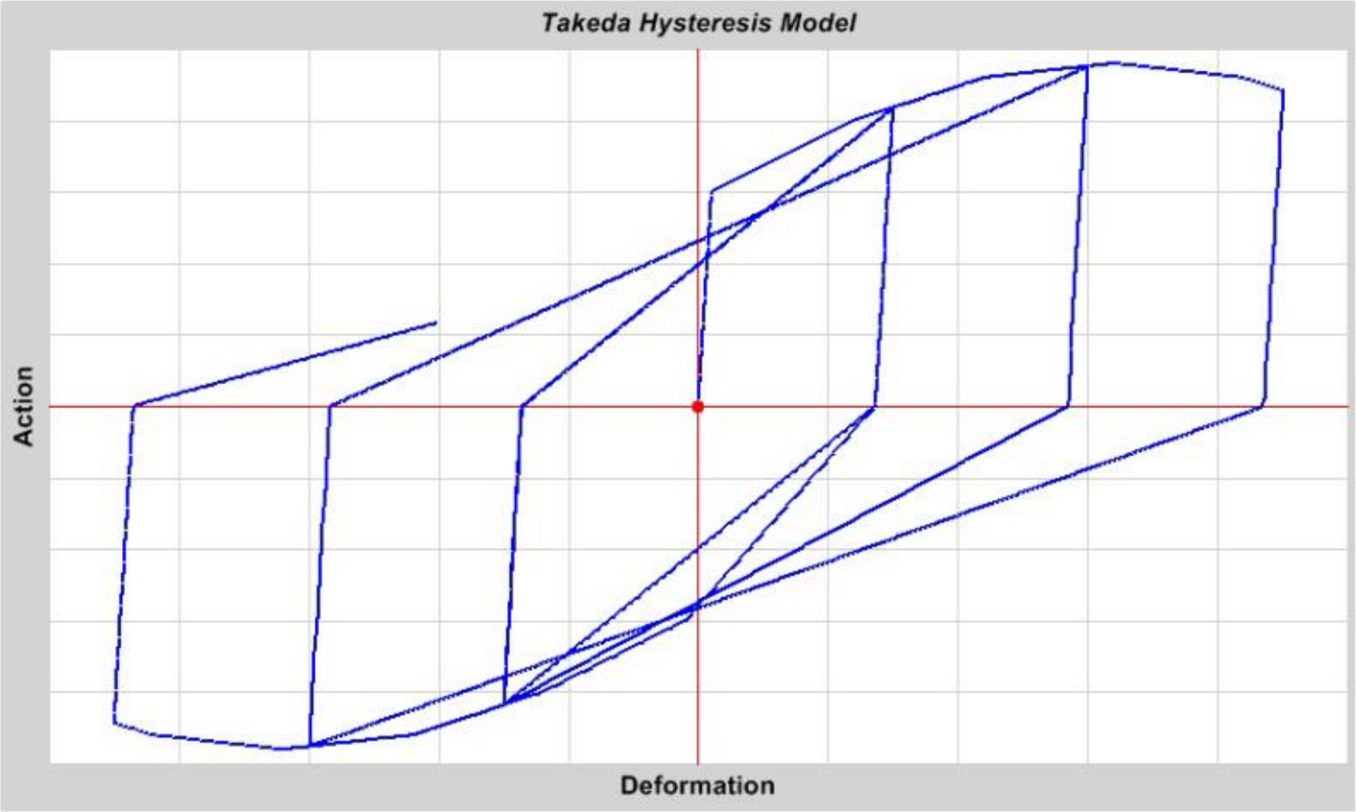
Degrading Hysteresis Model





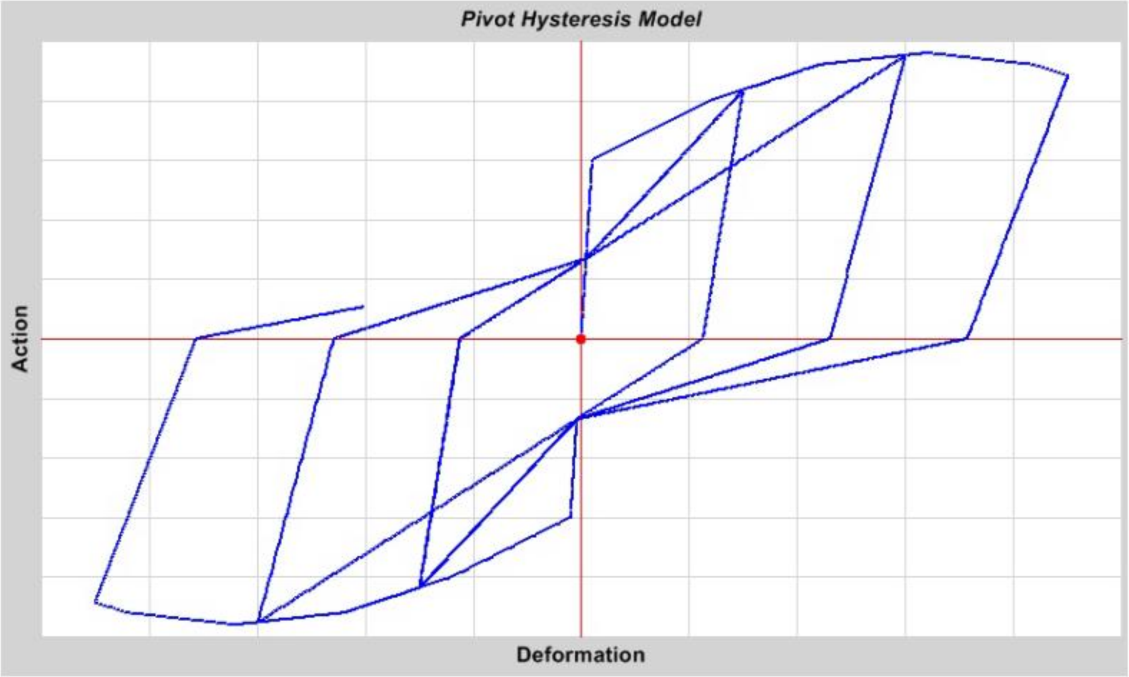
Takeda Hysteresis Model

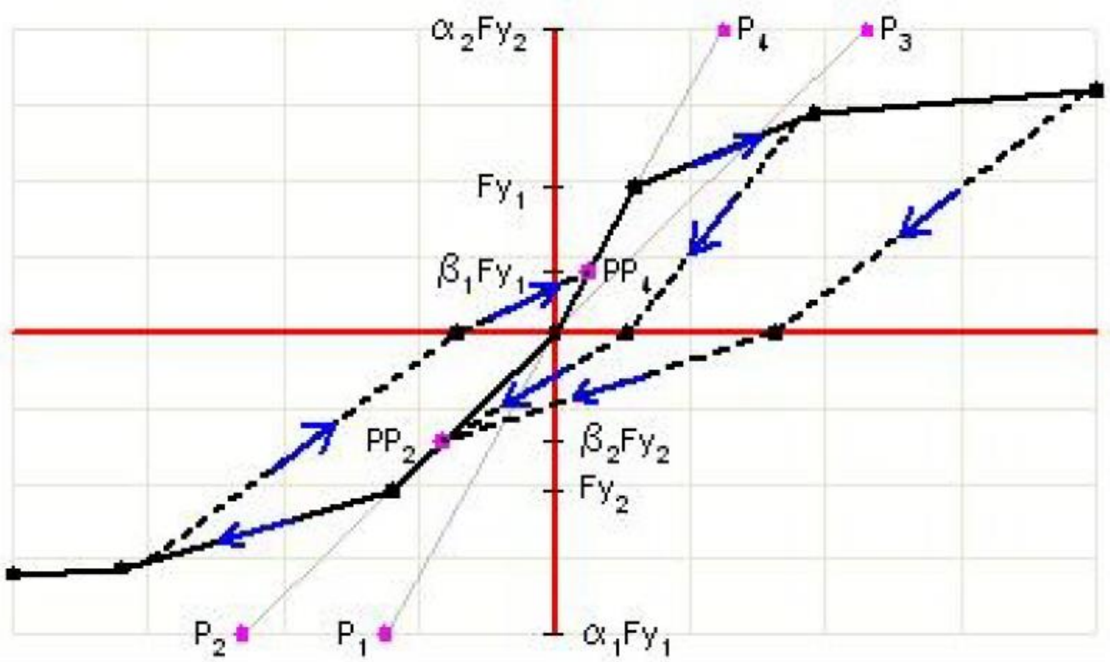
This model is very similar to the kinematic model, but uses a degrading hysteretic loop based on the Takeda model, as described in Takeda, Sozen, and Nielsen (1970). This simple model requires no additional parameters, and is ***more appropriate for reinforced concrete*** than for metals. Less energy is dissipated than for the kinematic model.



Pivot Hysteresis Model

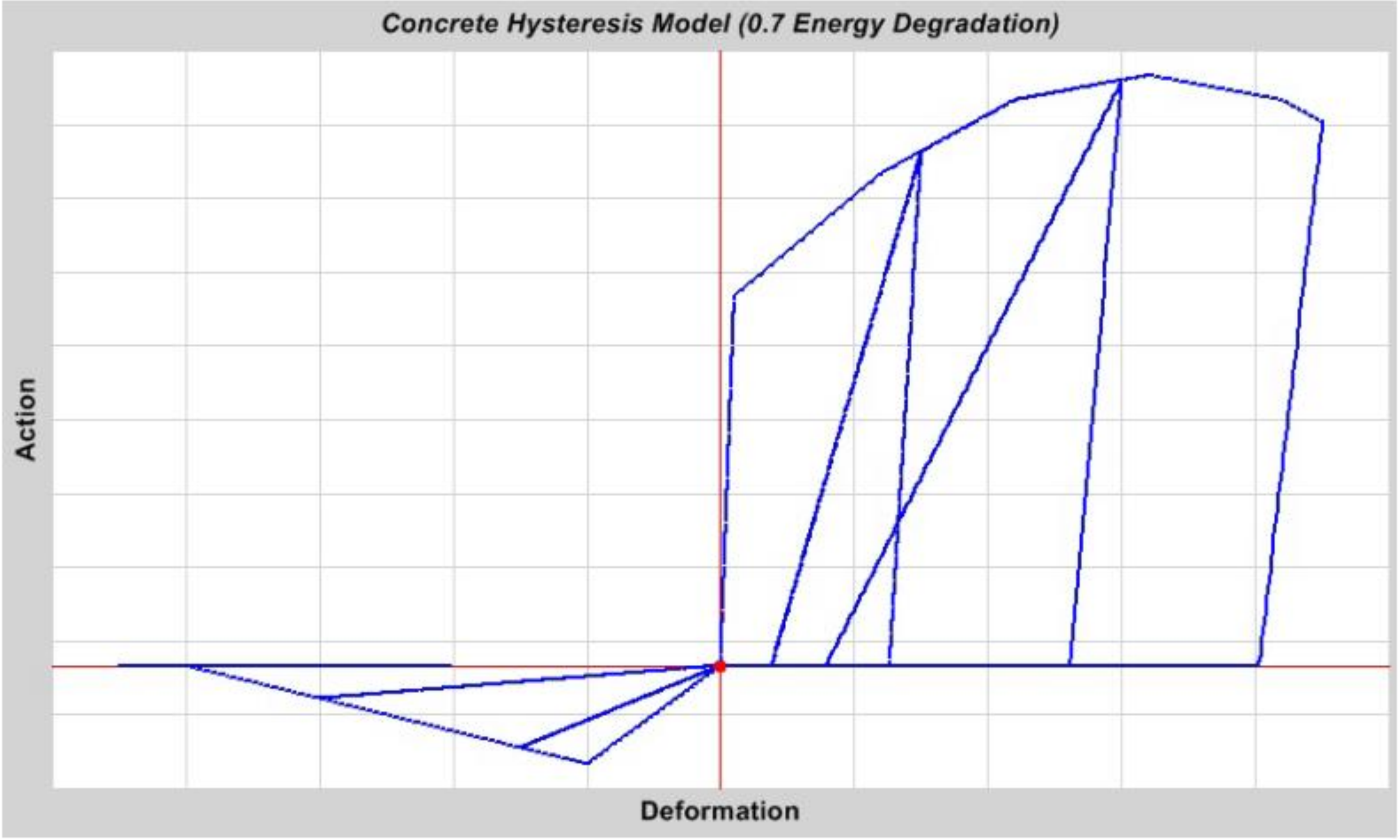
This model is similar to the Takeda model, but has additional parameters to control the degrading hysteretic loop. It is particularly well suited for reinforced concrete members, and is based on the observation that unloading and reverse loading tend to be directed toward specific points, called ***pivots points***, in the action-deformation plane. The most common use of this model is for moment-rotation. This model is fully described in Dowell, Seible, and Wilson (1998).





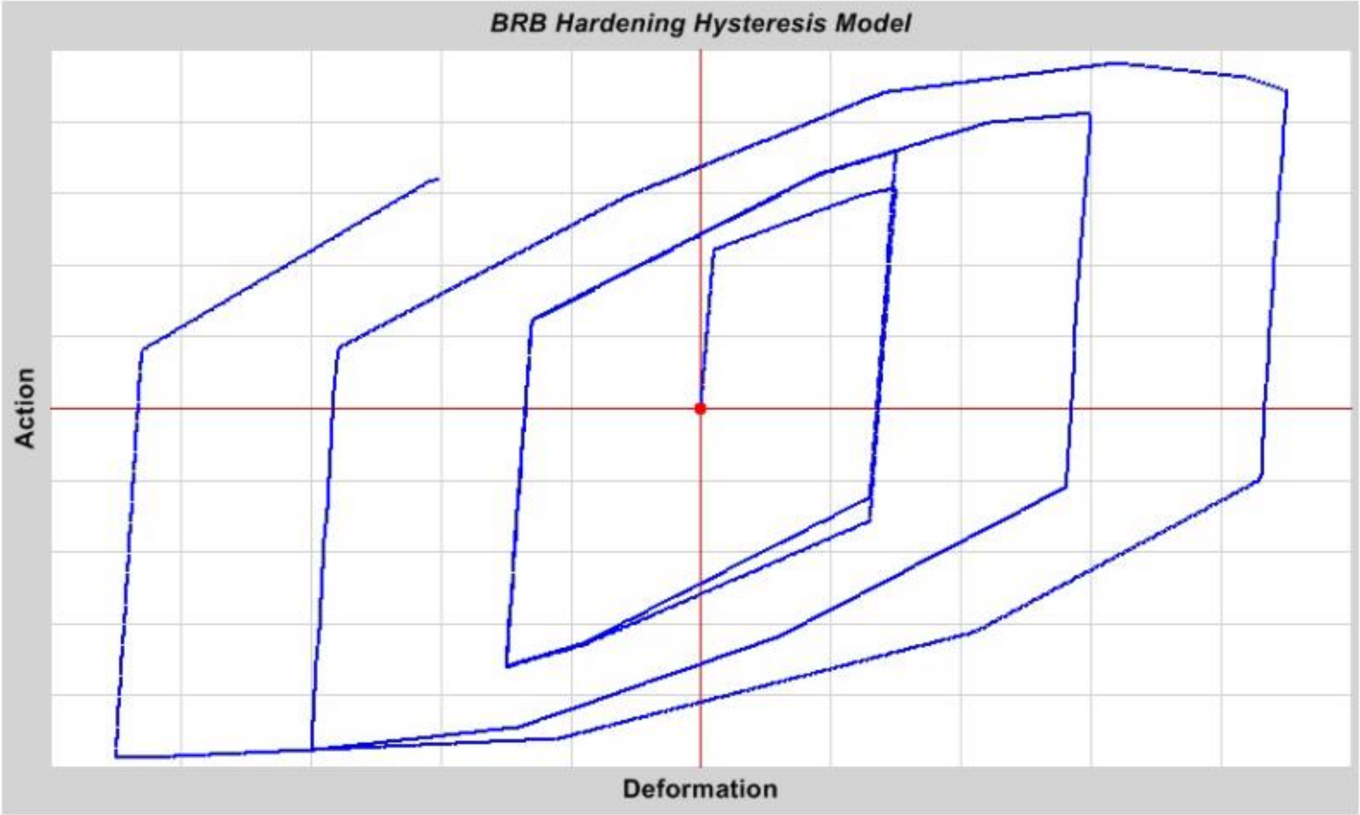
Concrete Hysteresis Model

This model is ***intended for unreinforced concrete*** and similar materials, and is the default model for concrete and masonry materials in the program. Tension and compression behavior are independent and behave differently.



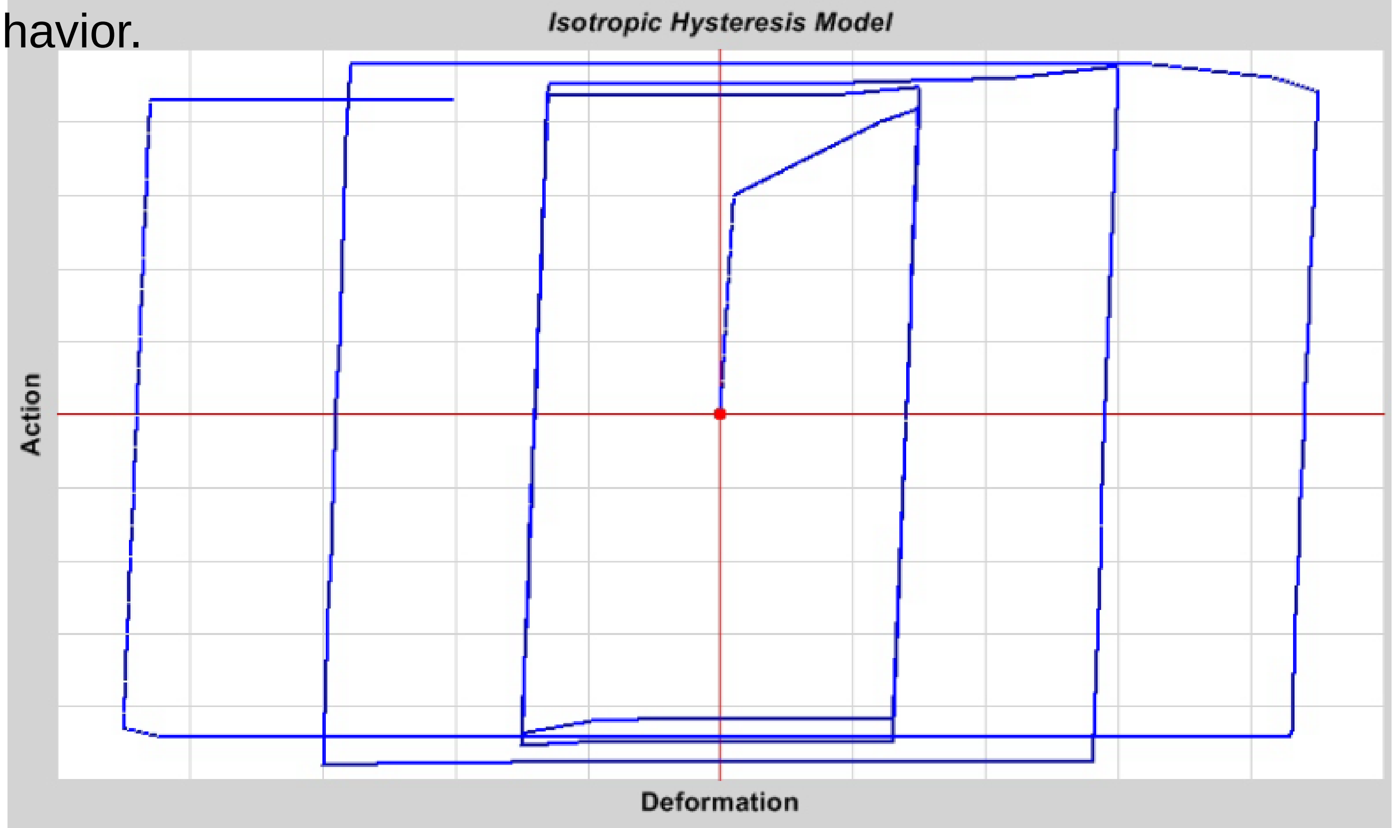
BRB Hardening Hysteresis Model

This model is similar to the kinematic model, but accounts for the increasing strength with plastic deformation that is typical of ***buckling-restrained braces***, causing the backbone curve, and hence the hysteresis loop, to ***progressively grow in size***. It is in tended primarily for use with axial behavior, but can be applied to any degree of freedom.



Isotropic Hysteresis Model

This model is, in a sense, ***the opposite of the kinematic model***. Plastic deformation in one direction "pushes" the curve for the other direction away from it, so that both directions increase in strength simultaneously. Unlike the BRB hardening model, the backbone curve itself does not increase in strength, only the unloading and reverse loading behavior.



Modified Darwin-Pecknold Concrete Model

- A **two-dimensional nonlinear concrete material model** is available for use in the layered shell. This model is based on the **Darwin-Pecknold model**, with consideration of Vecchio-Collins behavior.
- This model represents the concrete compression, cracking, and shear behavior under both monotonic and cyclic loading, and considers the stress-strain components $\sigma_{11} - \varepsilon_{11}$, $\sigma_{22} - \varepsilon_{22}$ and $\sigma_{33} - \varepsilon_{33}$.
- A state of plane stress is assumed.

ETABS Demonstration on

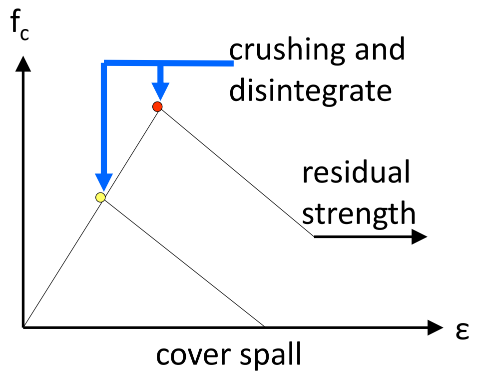
Nonlinear Modeling of Materials

(Fibers)

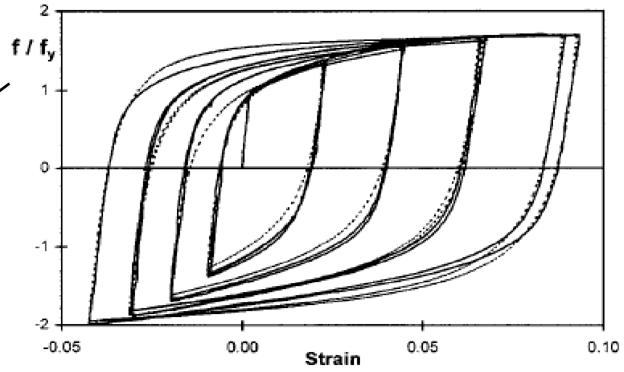
General Guidelines for Fiber Modeling in ETABS

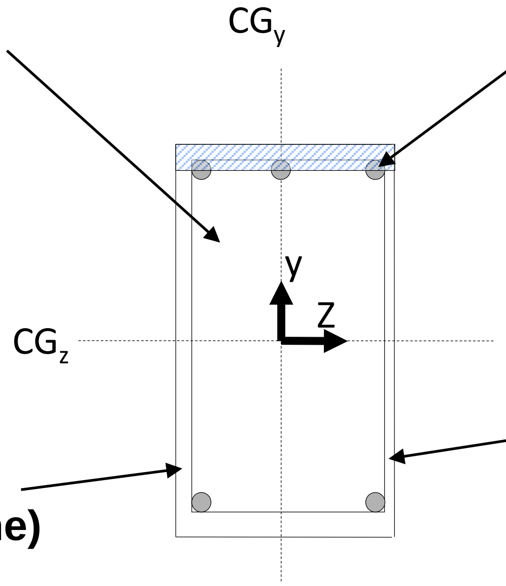
Inelastic Material Functions – RC Beams

Core Concrete (Confined Zone)



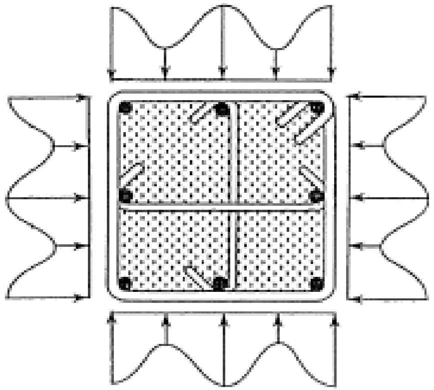
Main Steel= energy dissipater





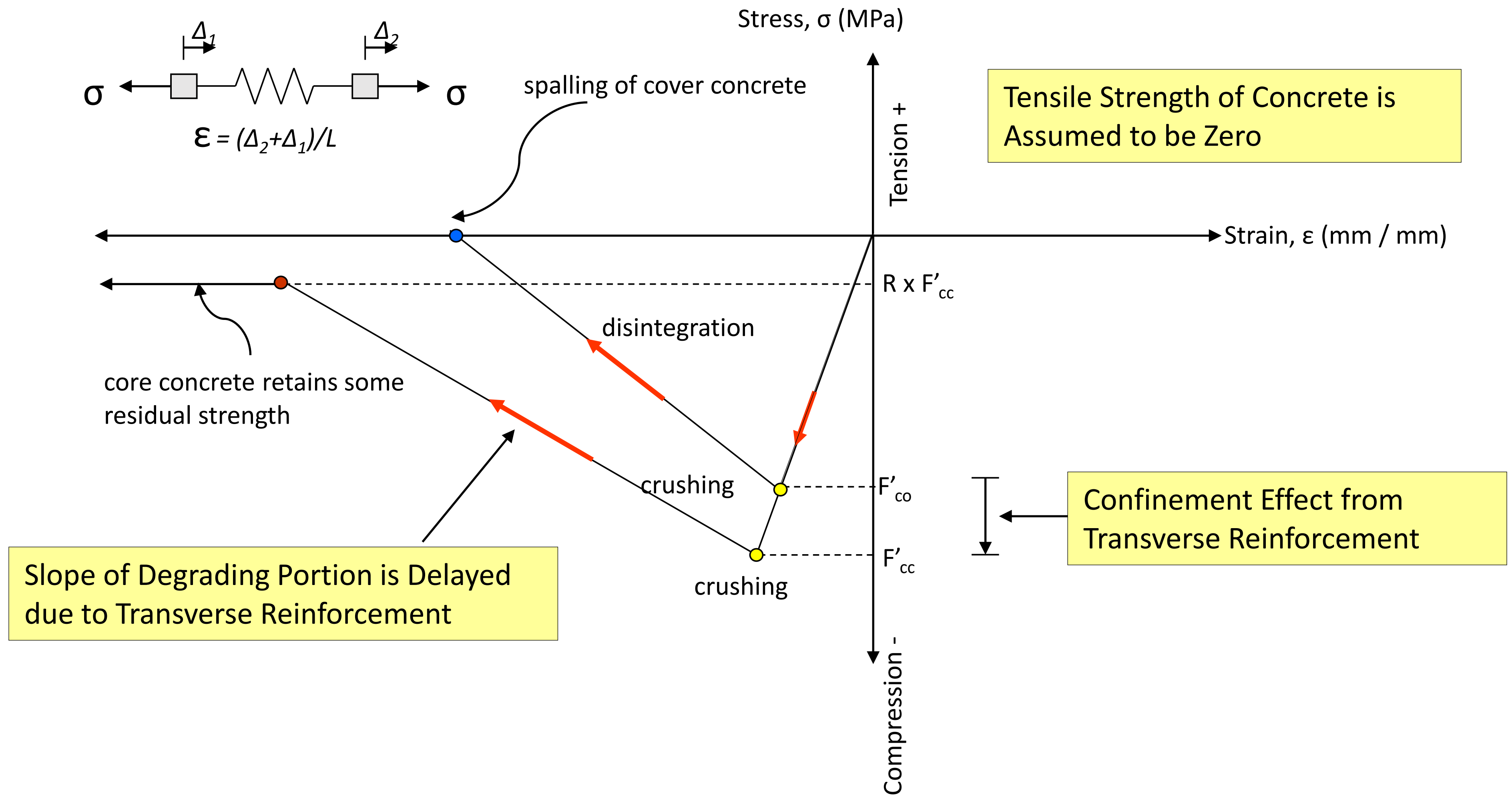
Cover Concrete (Unconfined Zone)

STIRRUP = confinement + shear capacity

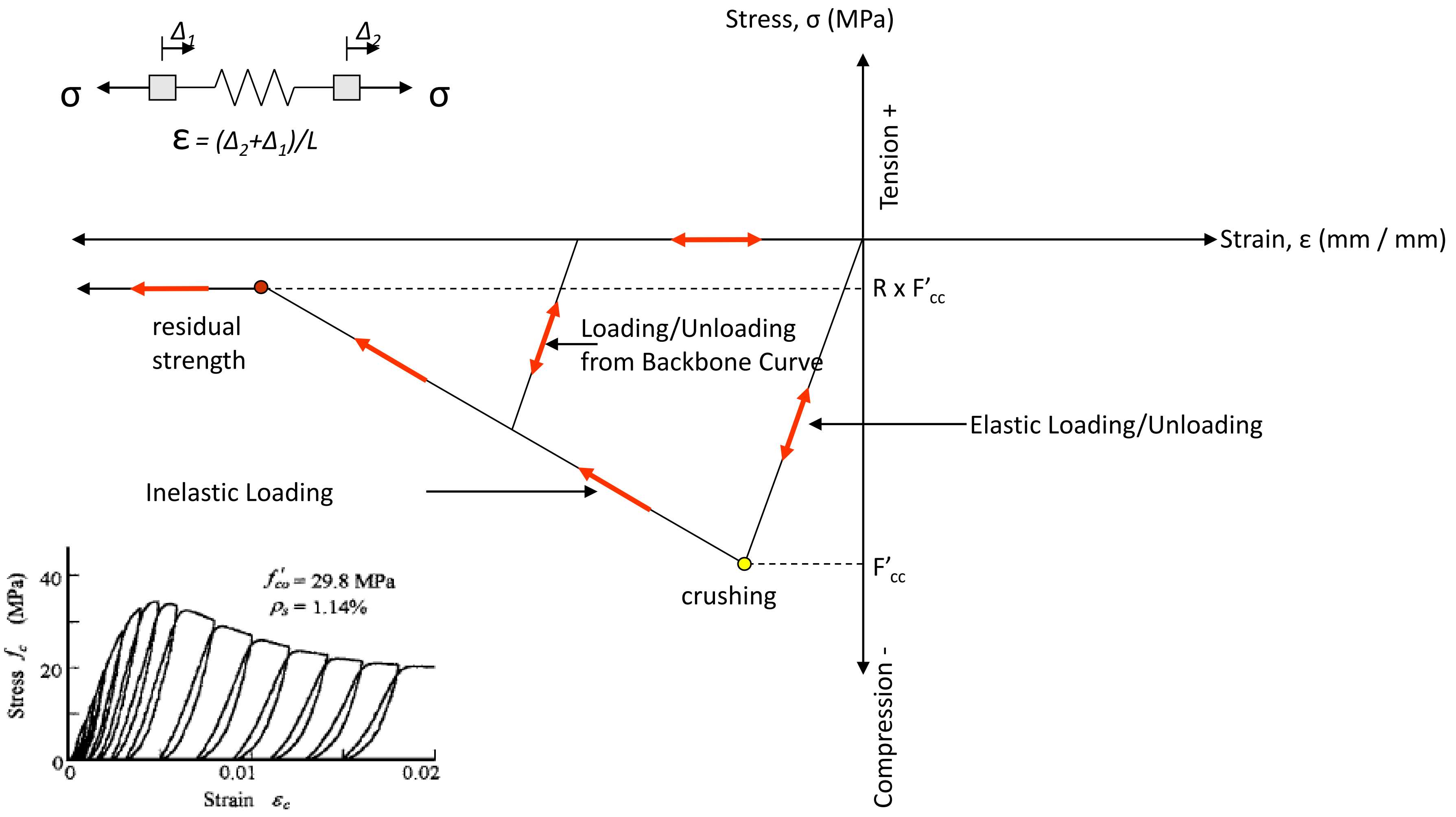


A Beam Cross Section

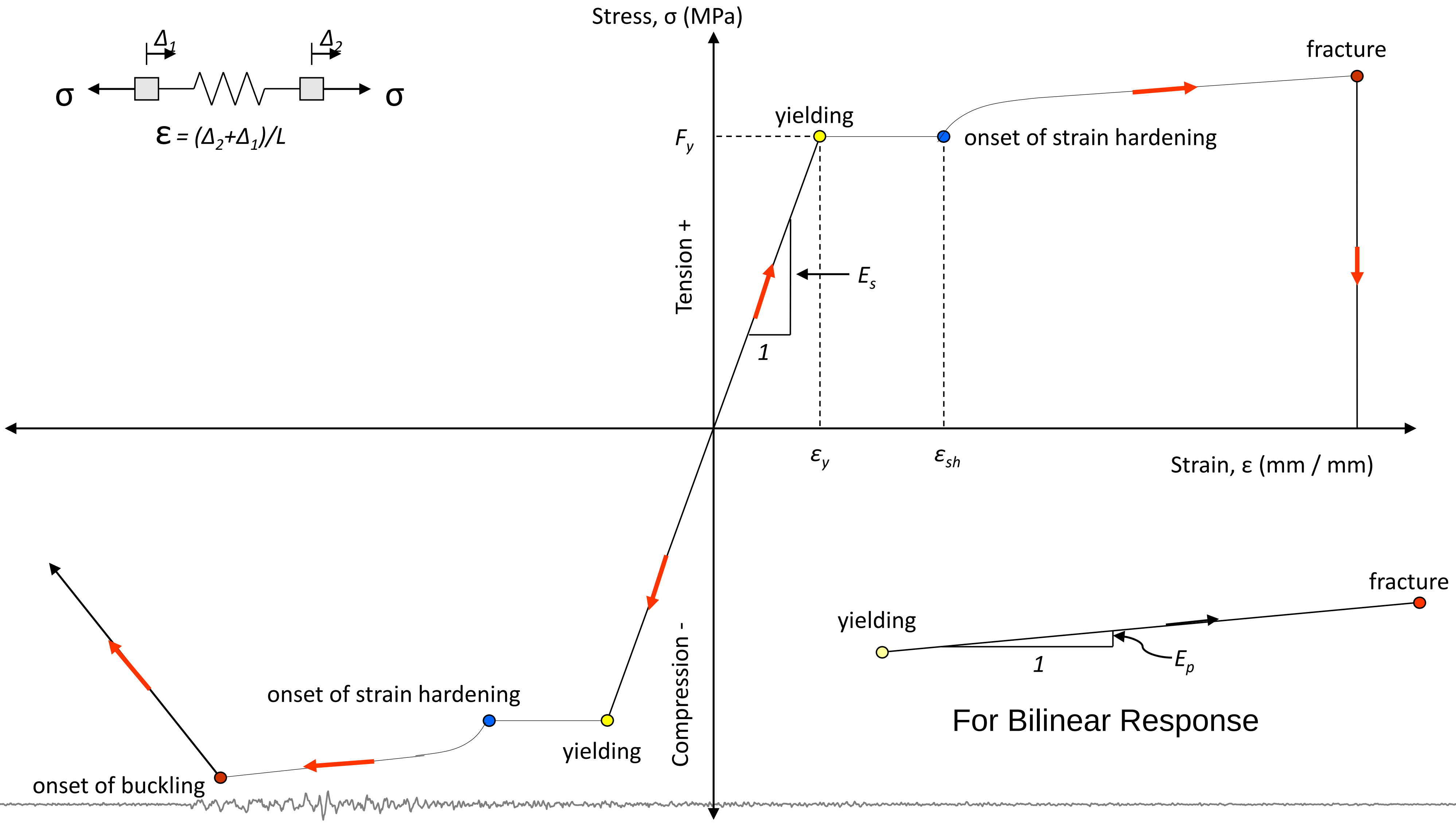
Core/Cover Concrete – Monotonic Response



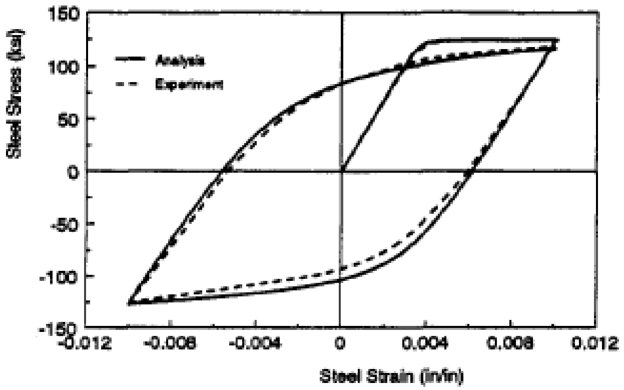
Core/Cover Concrete – Hysteretic Response

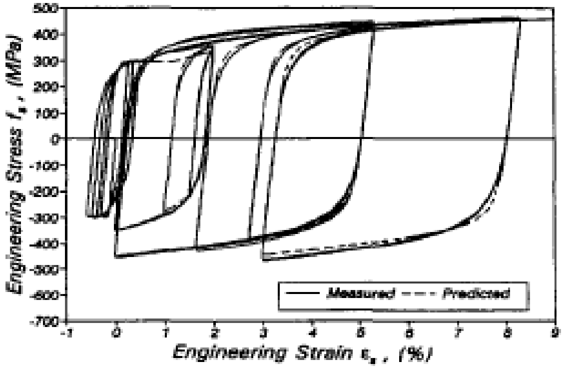


Steel Reinforcement – Monotonic Response



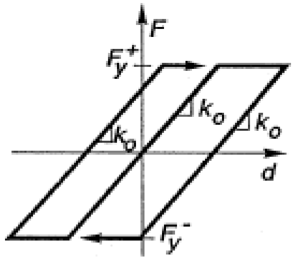
Steel Reinforcement – Hysteretic Response



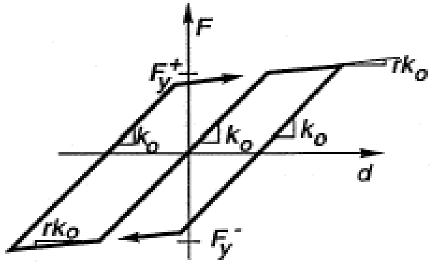


Hysteretic response of reinforcing steel

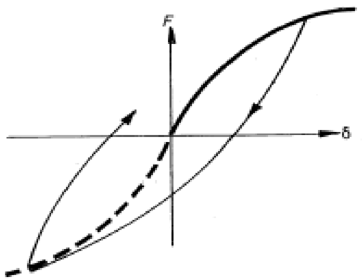
[L.L. Dodd and J.I. Restrepo-Posada, 1995]



EPP-Model

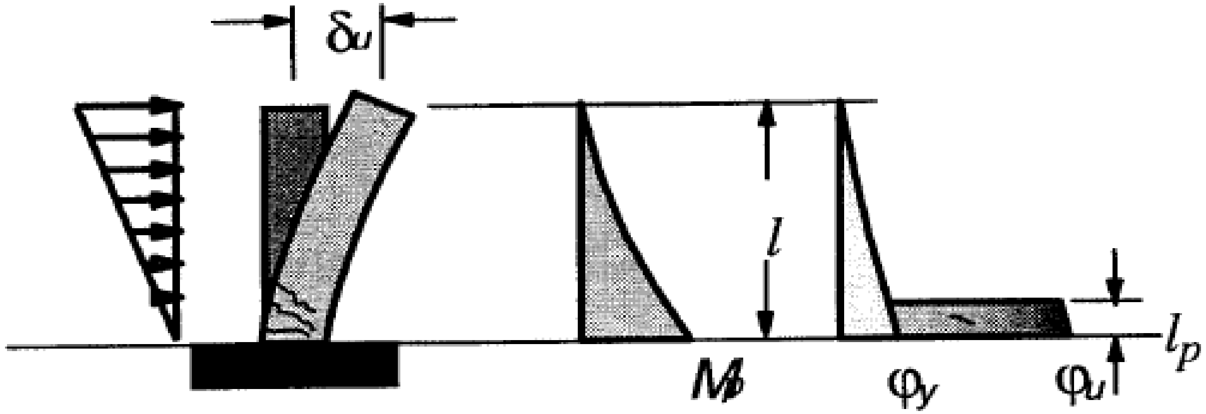


Bilinear Model (Clough)



Ramberg-Osgood Model

Equivalent Plastic Hinge Length, L_{PH}



Concept of “Equivalent Plastic Hinge Length, L_{PH}”

$$\theta_{PH} = \int_{PH-length} \phi(x)dx \approx \phi_{max} L_{PH}$$

Empirical equations for L_{ph} can be found in the literature

$$L_{PH} = 0.08L + 0.022 d_b F_y$$

[Paulay and Priestley, 1992]

Equivalent Plastic Hinge Length, L_{PH}

The plastic zone (or plastic length) has remained an area of detailed research in last 2 to 3 decades. Several guidelines are available to estimate the length or zone where the concentrated inelastic action can be assumed. One such guideline is as follows.

$$L_p = 0.08\,L + 0.022\,f_{ye}\,d_{bl} \geq 0.044\,f_{ye}\,d_{bl} \qquad \text{(MPa)}$$

Where

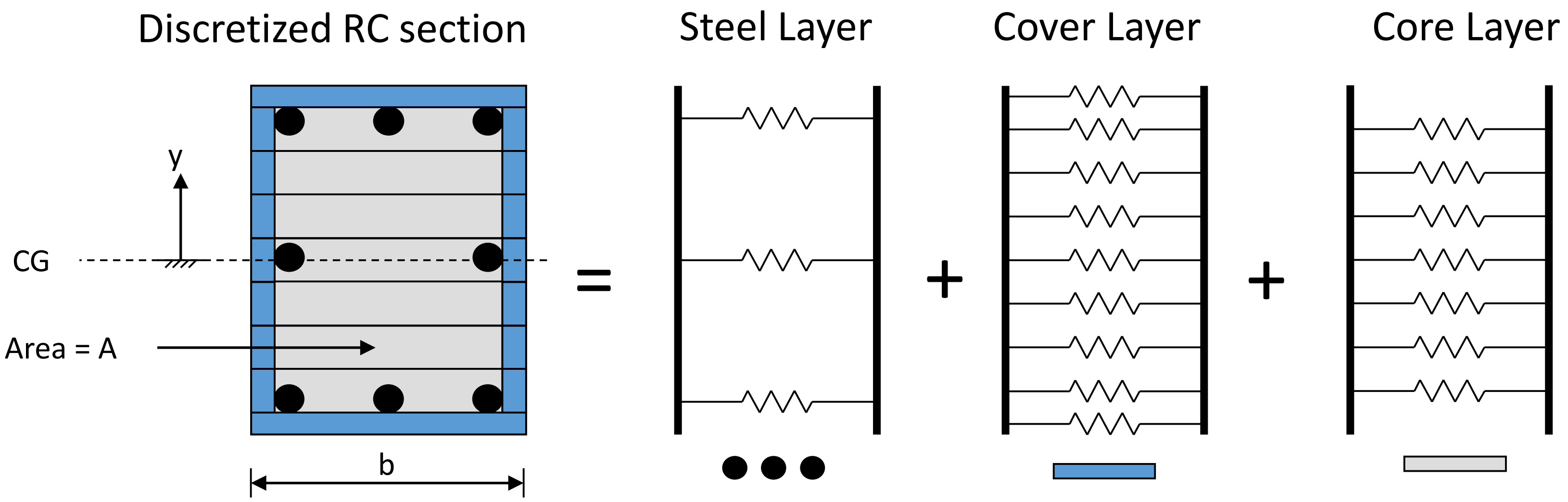
L_p = plastic hinge length.

L = Distance from the critical section of plastic hinge to the point of contraflexure.

f_{ye} = Expected yield strength of longitudinal reinforcement.

d_{bl} = Diameter of longitudinal reinforcement.

Fiber Section Model – RC Beams



- An RC section can be represented by sub-divided layers (fibers). Each layers is modeled using uniaxial nonlinear springs which, in turn, classified into 3 groups according to their material hysteretic response, i.e., steel springs, cover-concrete springs, and core-concrete springs.
- Theoretical formulation of the fiber section model can be explained through the following equations.

$$N = \int f_s(\varepsilon) b\,dy$$

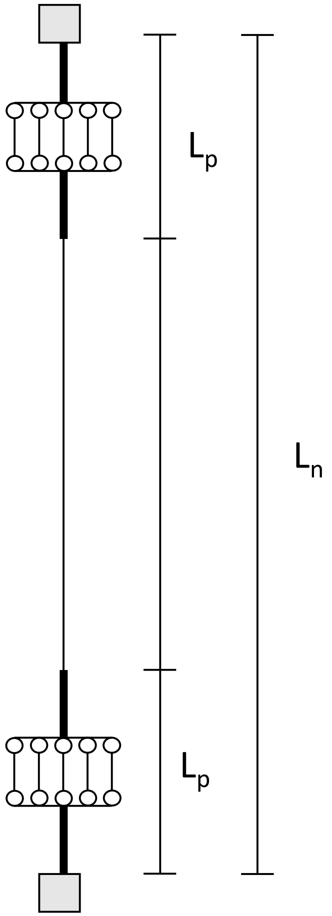
$$N = \sum_{i=1}^{n} \left(f_s(\varepsilon) A_{fiber} \right)_i$$

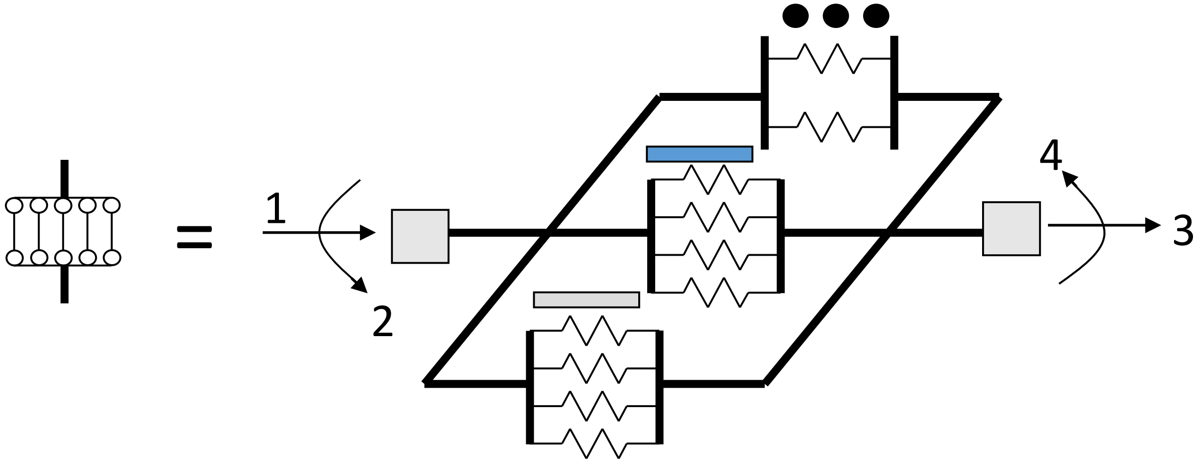
$$M = \int f_s(\varepsilon) y b\,dy$$

$$M = \sum_{i=1}^{n} \left(f_s(\varepsilon) y_{cg} A_{fiber} \right)_i$$

$$K_{spring} = \frac{EA}{L} = \frac{E_t A_{fiber}}{L_{PH}}$$

Fiber Section Model





- —/\/\/\— = uniaxial nonlinear spring.
- Axial stiffness of each spring is defined by area of fiber, equivalent plastic hinge length, and tangent stiffness of the corresponding material.
- To define the tangent stiffness, material hysteretic model as discussed earlier can be directly assign to these springs.

Material Models for Concrete and Steel

- Concrete
    - Mander’s (unconfined and confined) model can be used.
    - Confinement effect should be considered in cross-section.
    - Use tri-linear backbone curve.
    - Tensile strength may be neglected.
    - Concrete hysteresis model can be used.

- Reinforcing Steel
    - Use bi-linear or tri-linear backbone curve.
    - 1% of strain hardening can be used.
    - Kinematic Hysteresis model can be used.

ETABS Demonstration on

Fiber Modeling of RC Beams

ETABS Demonstration on

Fiber Modeling of RC Columns

ETABS Demonstration on

Fiber Modeling of RC Shear Walls

Thank you