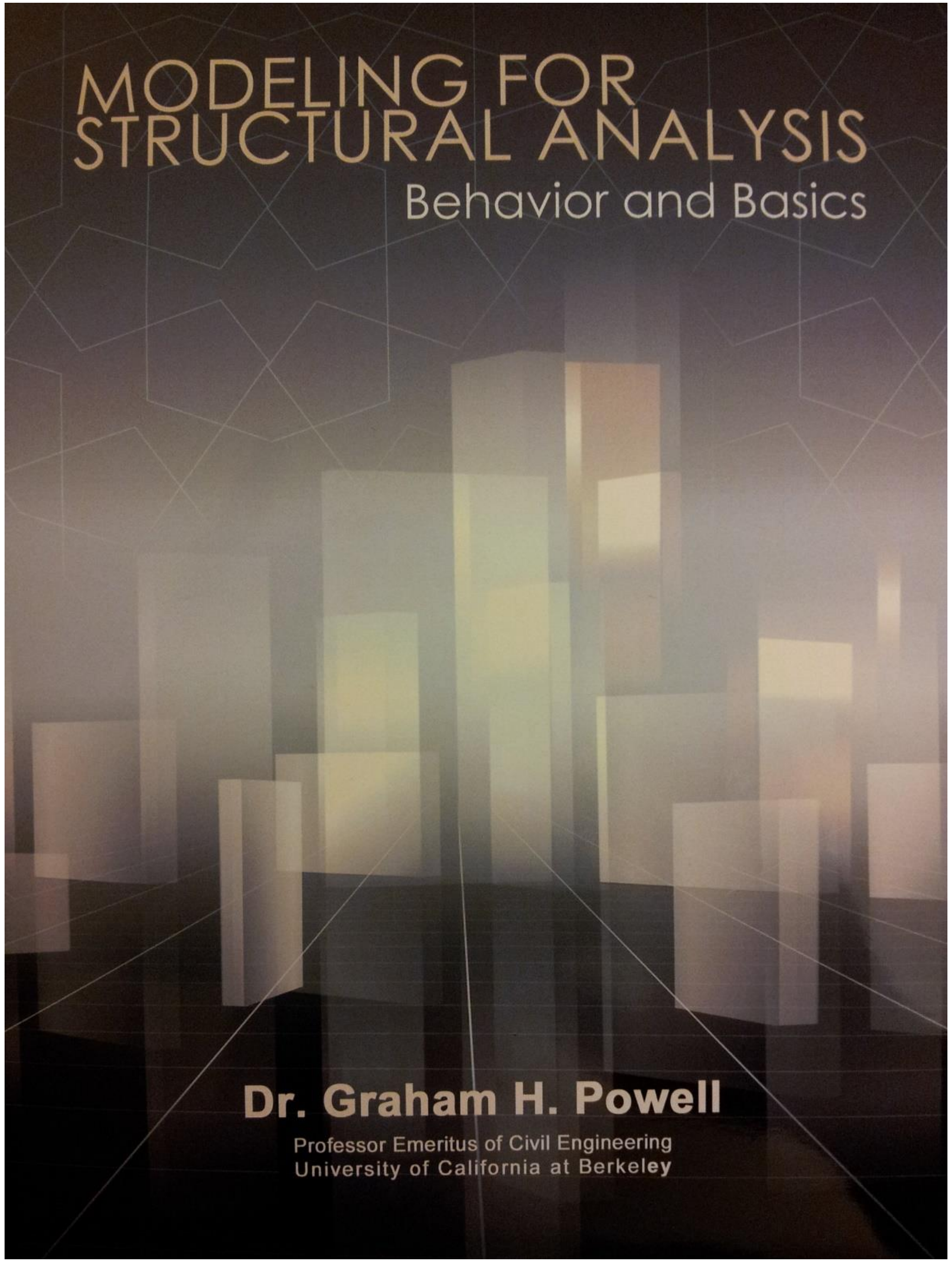
Credits: 3 + 0
PG 2019
Spring 2020 Semester

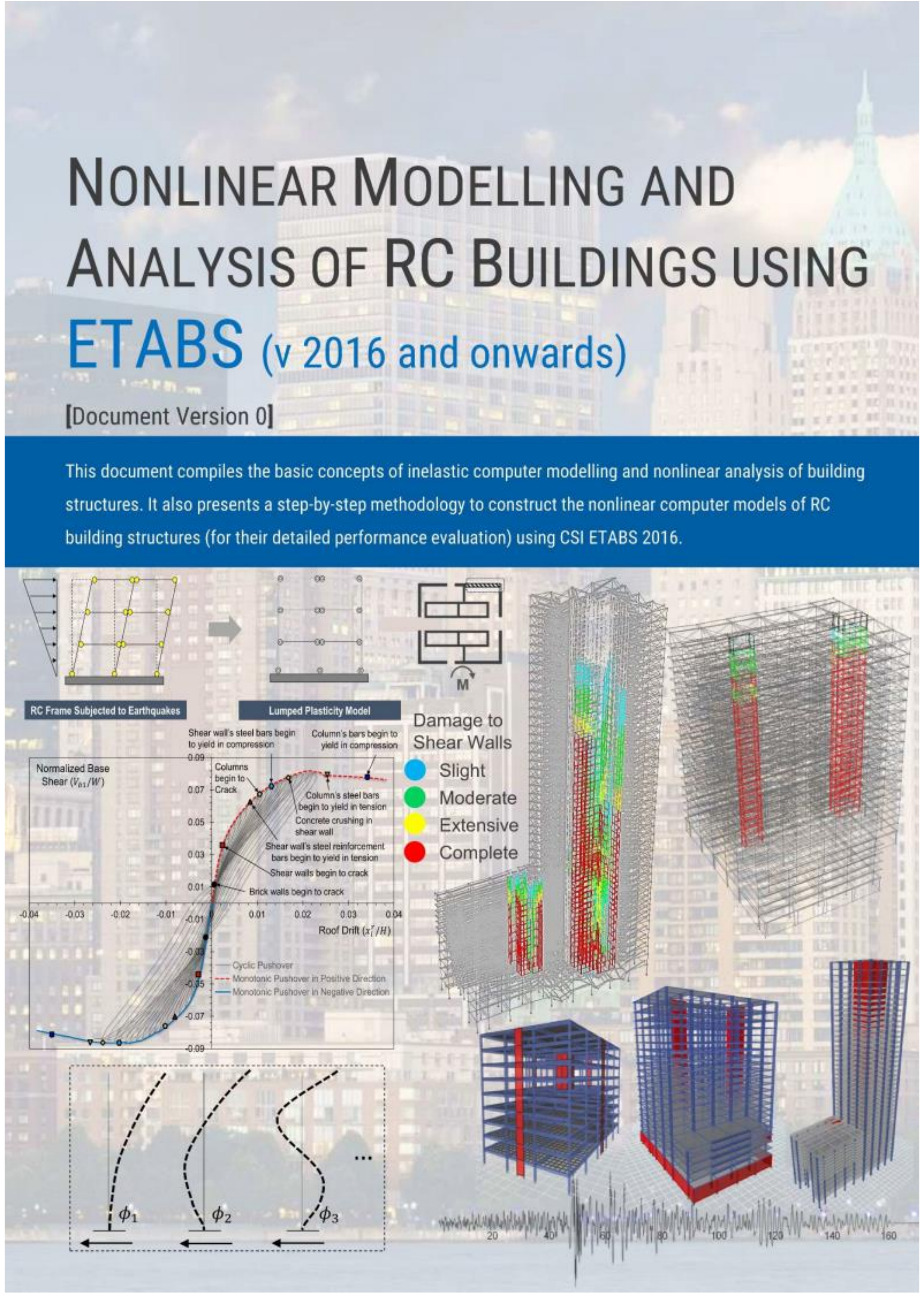
Performance-based Seismic Design of Structures

Fawad A. Najam
Department of Structural Engineering
NUST Institute of Civil Engineering (NICE)
National University of Sciences and Technology (NUST)
H-12 Islamabad, Pakistan
Cell: 92-334-5192533, Email: fawad@nice.nust.edu.pk

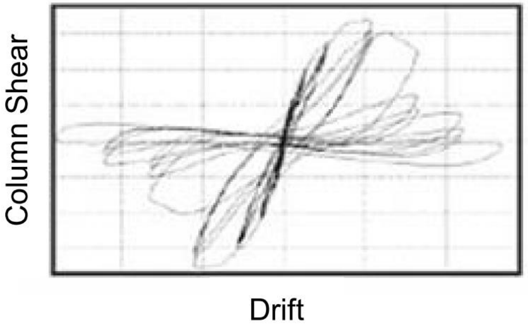
Modeling for Structural Analysis

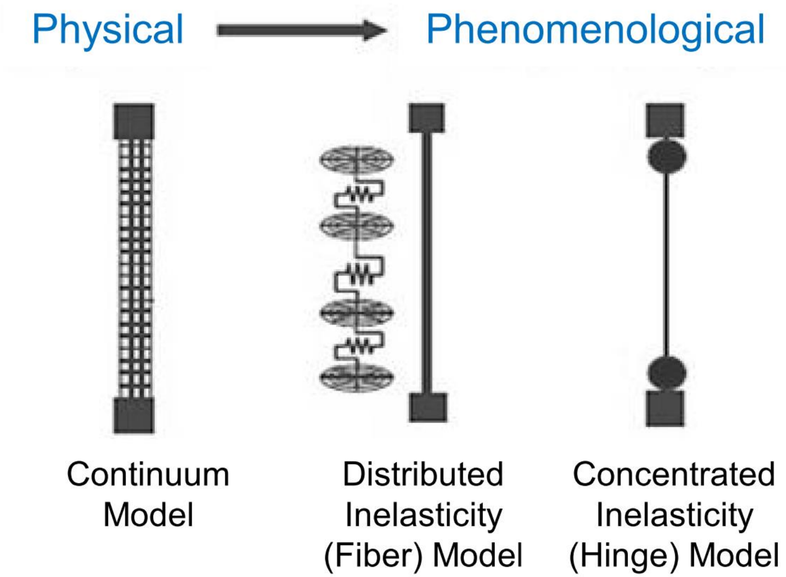
by Graham H. Powell



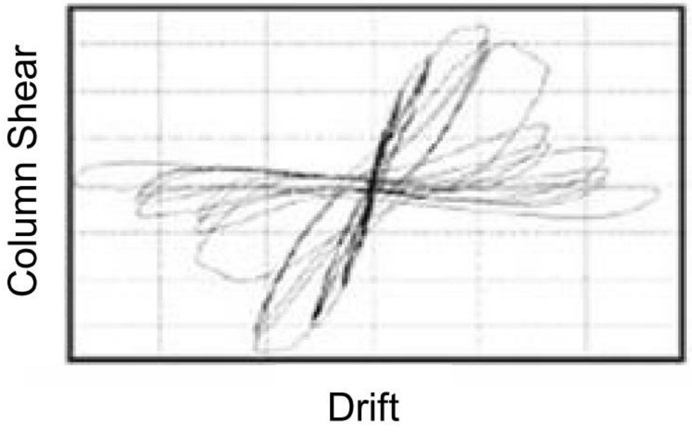


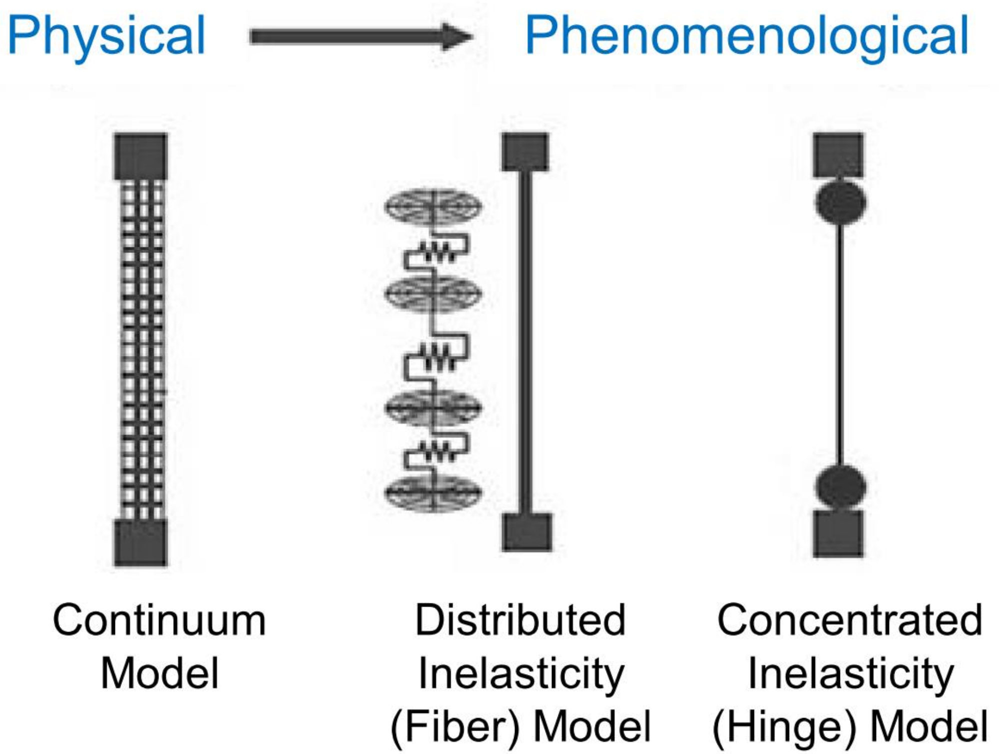
http://structurespro.info/nl-etabs/





Approaches for Nonlinear Modeling of Structures





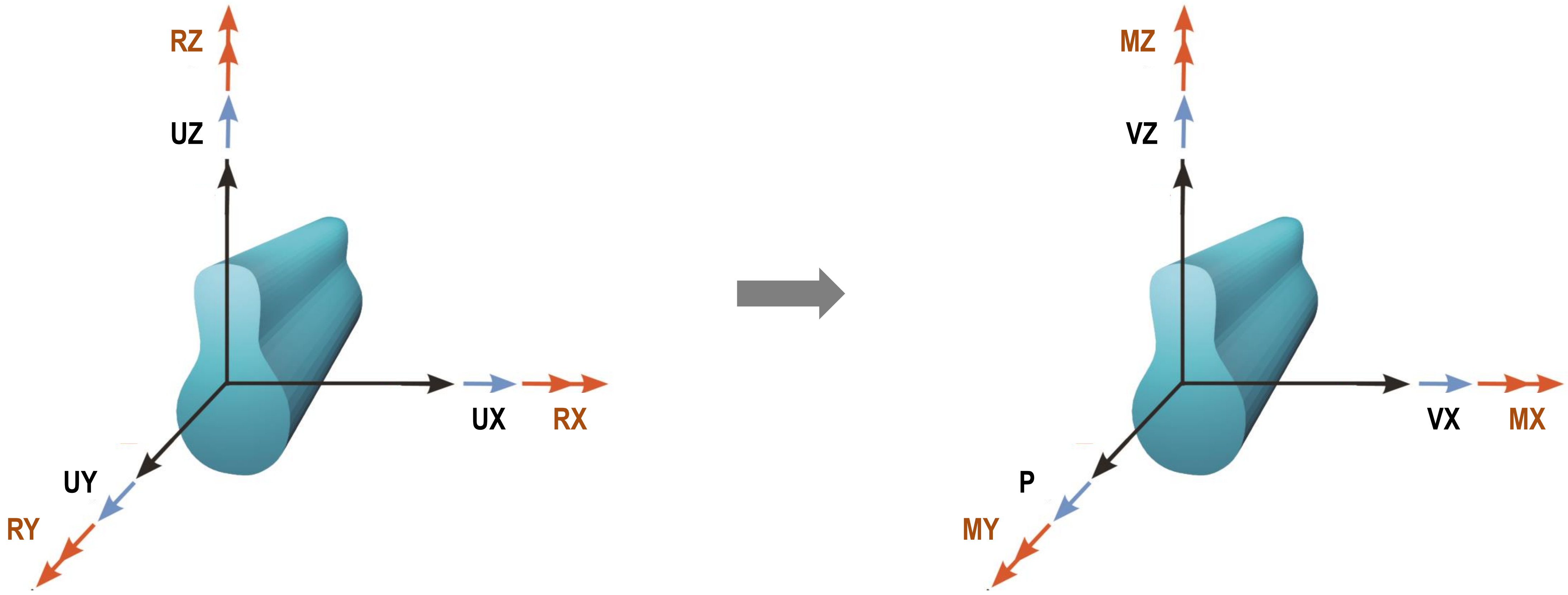
Practical Approaches for Nonlinear Modeling of Structures

Defining Inelastic Behavior at

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

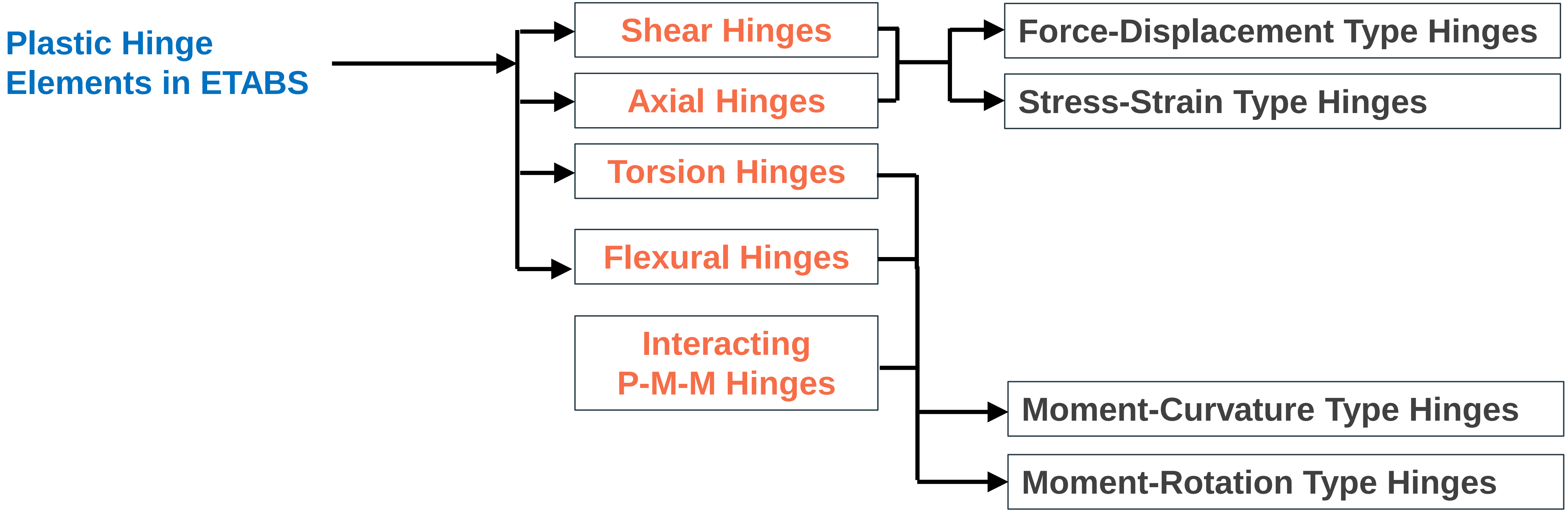
An Introduction to Lumped Plastic Hinge Approach for Nonlinear Modeling of Structural Components

What is a Plastic Hinge?

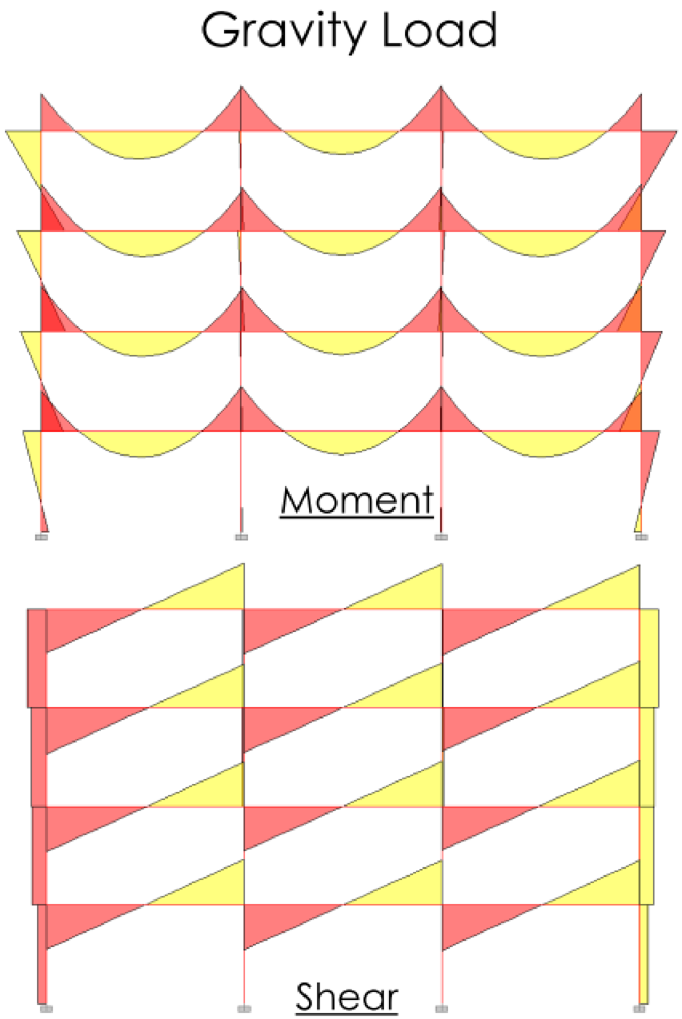


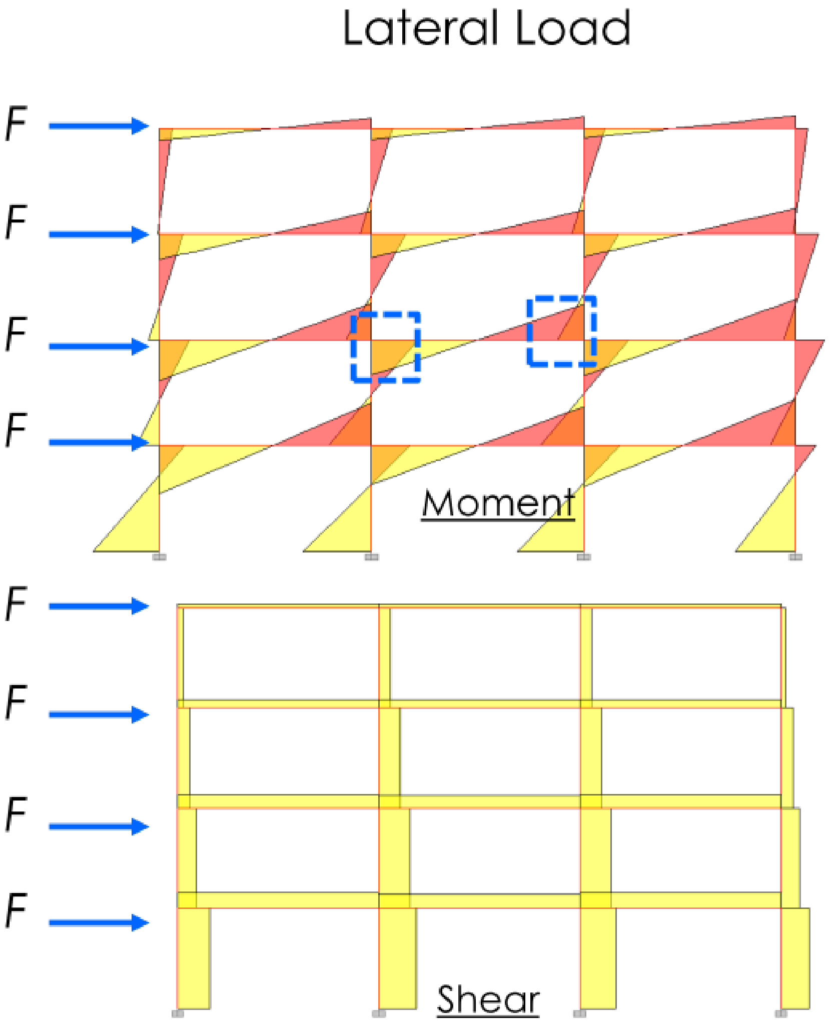
The six degrees-of-freedom and corresponding actions for a node in 3D space.

Plastic Hinge Modeling Approach



Force Distributions on Buildings





Based on Dr. Pramin Norachan, AIT Solutions

Moment-Rotation Plastic Hinge Model for Columns

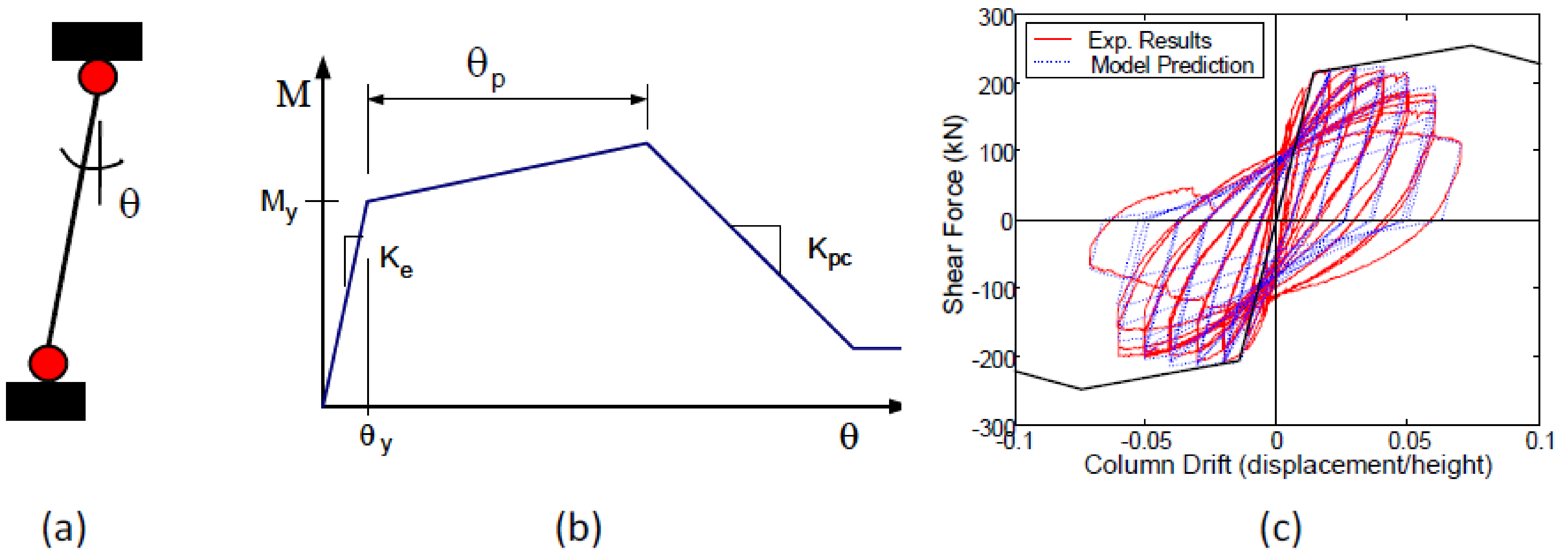
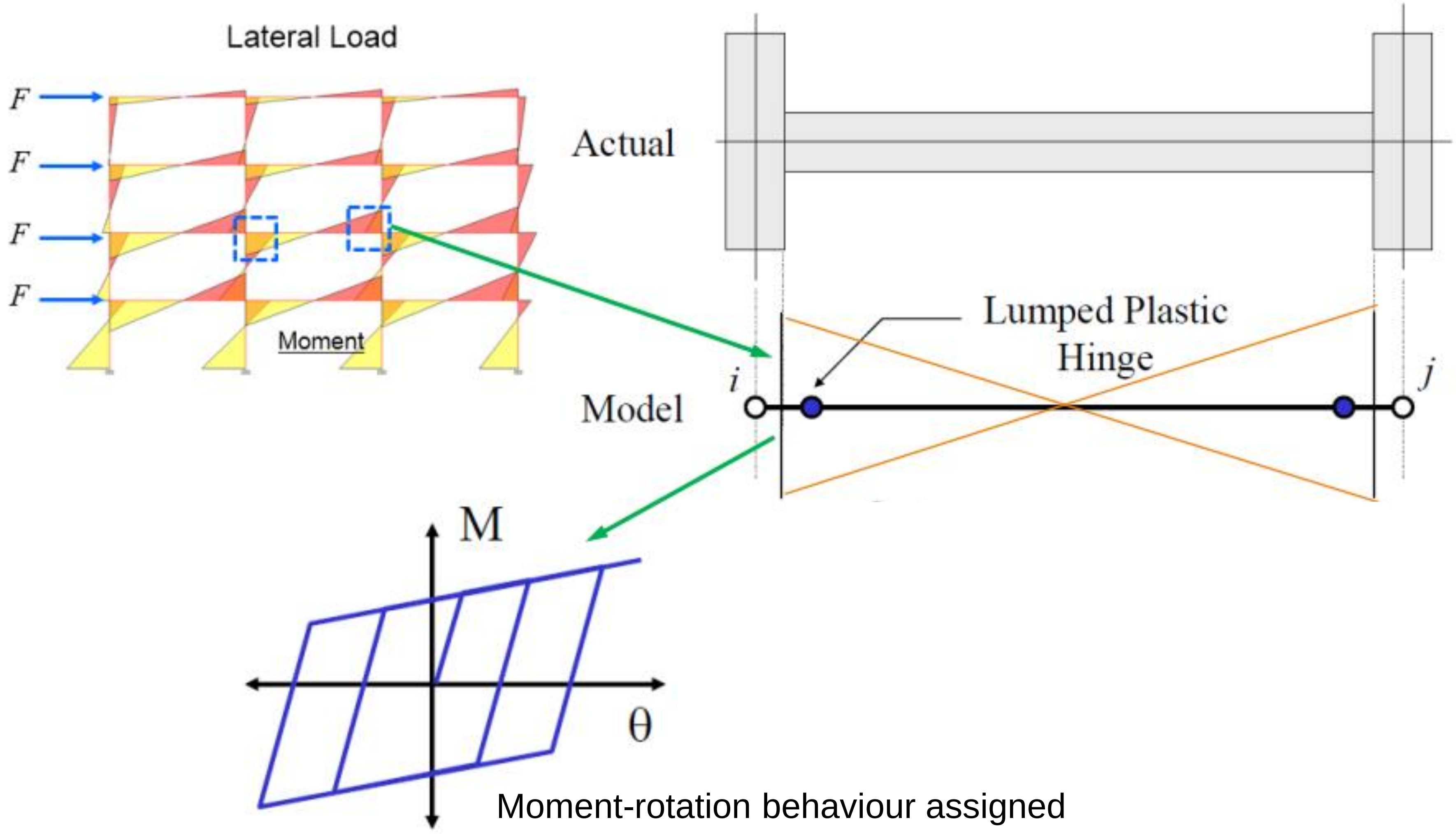


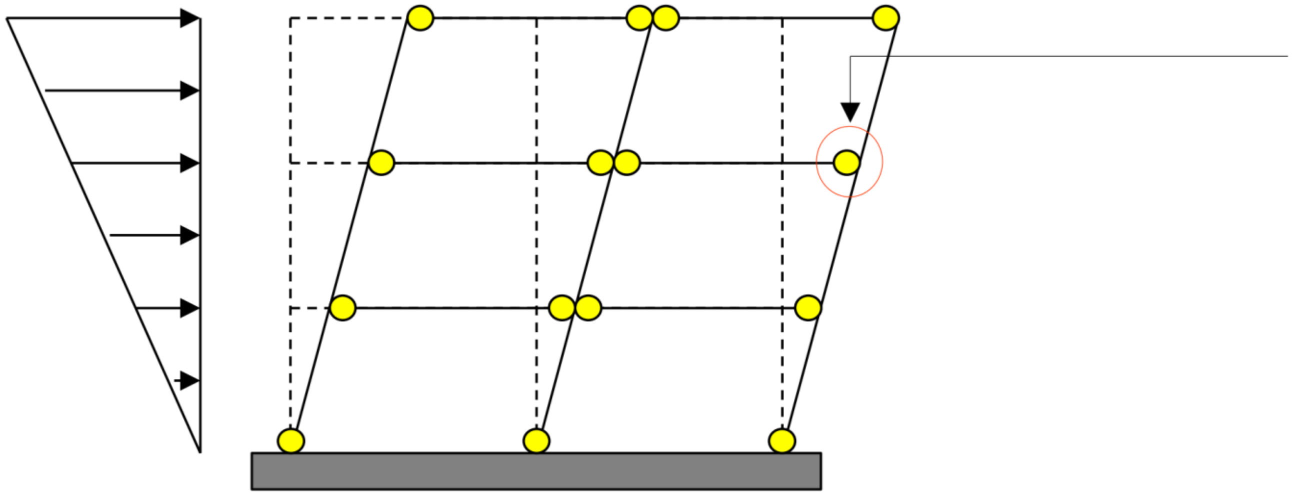
Illustration of modeling components for a reinforced concrete beam-column: (a) inelastic hinge model; (b) initial (monotonic) backbone curve; and (c) cyclic response model (Haselton et al. 2008).

Moment-Rotation Plastic Hinge Model for RC Beams

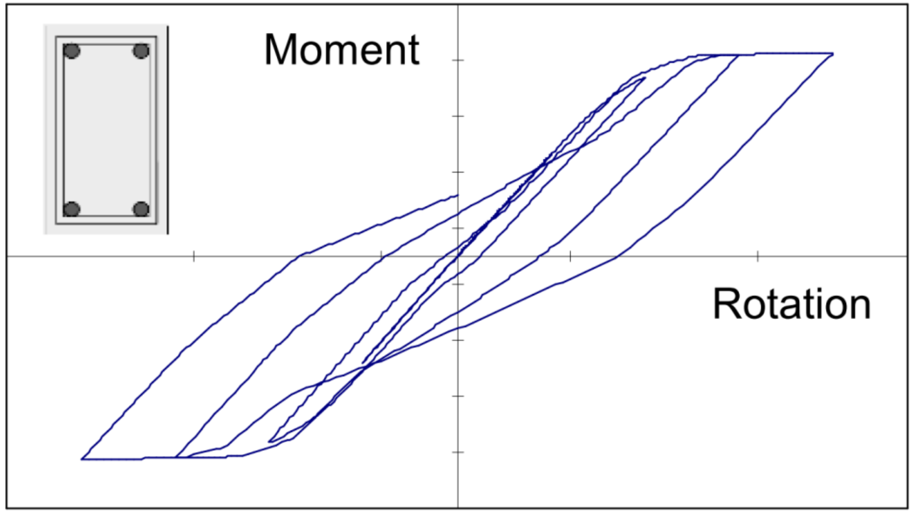


Moment-rotation behaviour assigned
to a plastic hinge element

Moment-Rotation Plastic Hinge Model for RC Beams and Columns



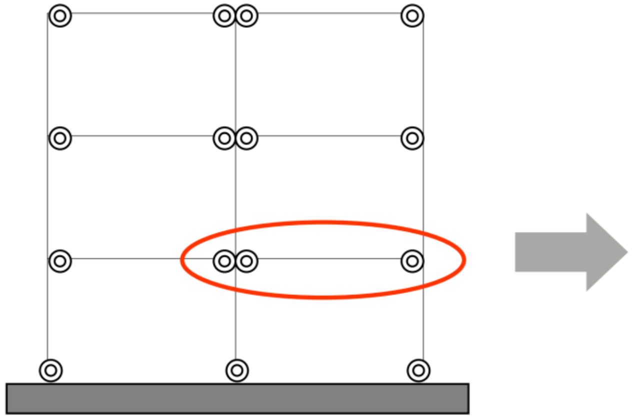
An RC Frame subjected to lateral loads (Beams and ground floor columns are modeled using plastic hinges)

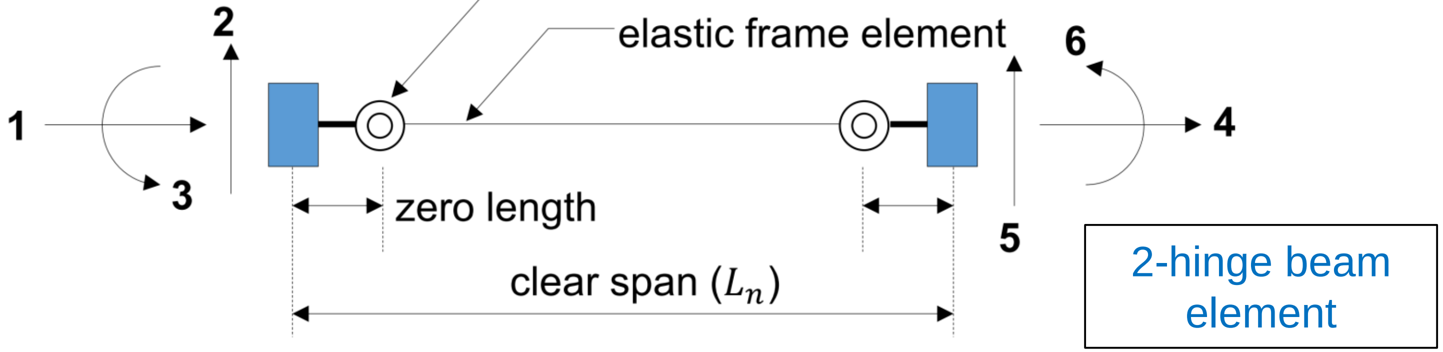


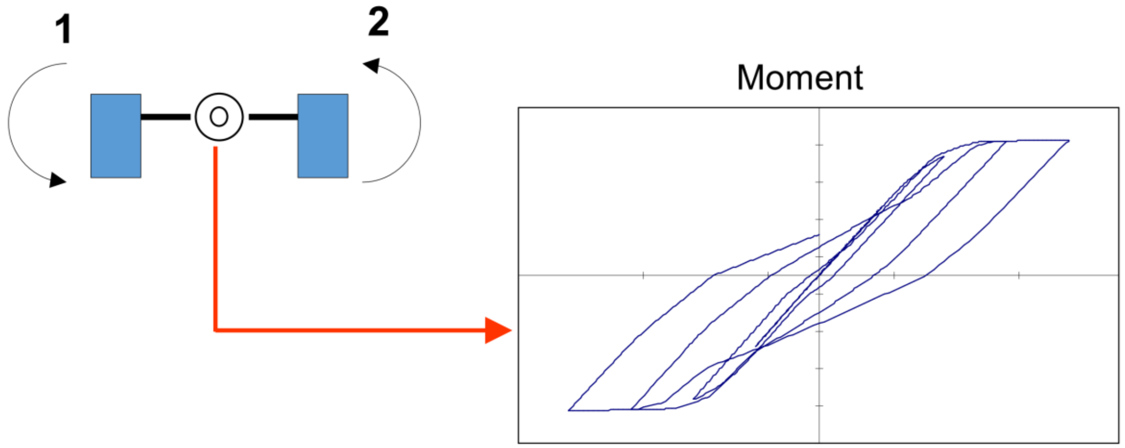
Plastic Hinge in Beams

Seismic energy dissipation mechanism is relied on plastic flexural-deformation of beams and ground floor columns.

Moment-Rotation Plastic Hinge Model for RC Beams and Columns

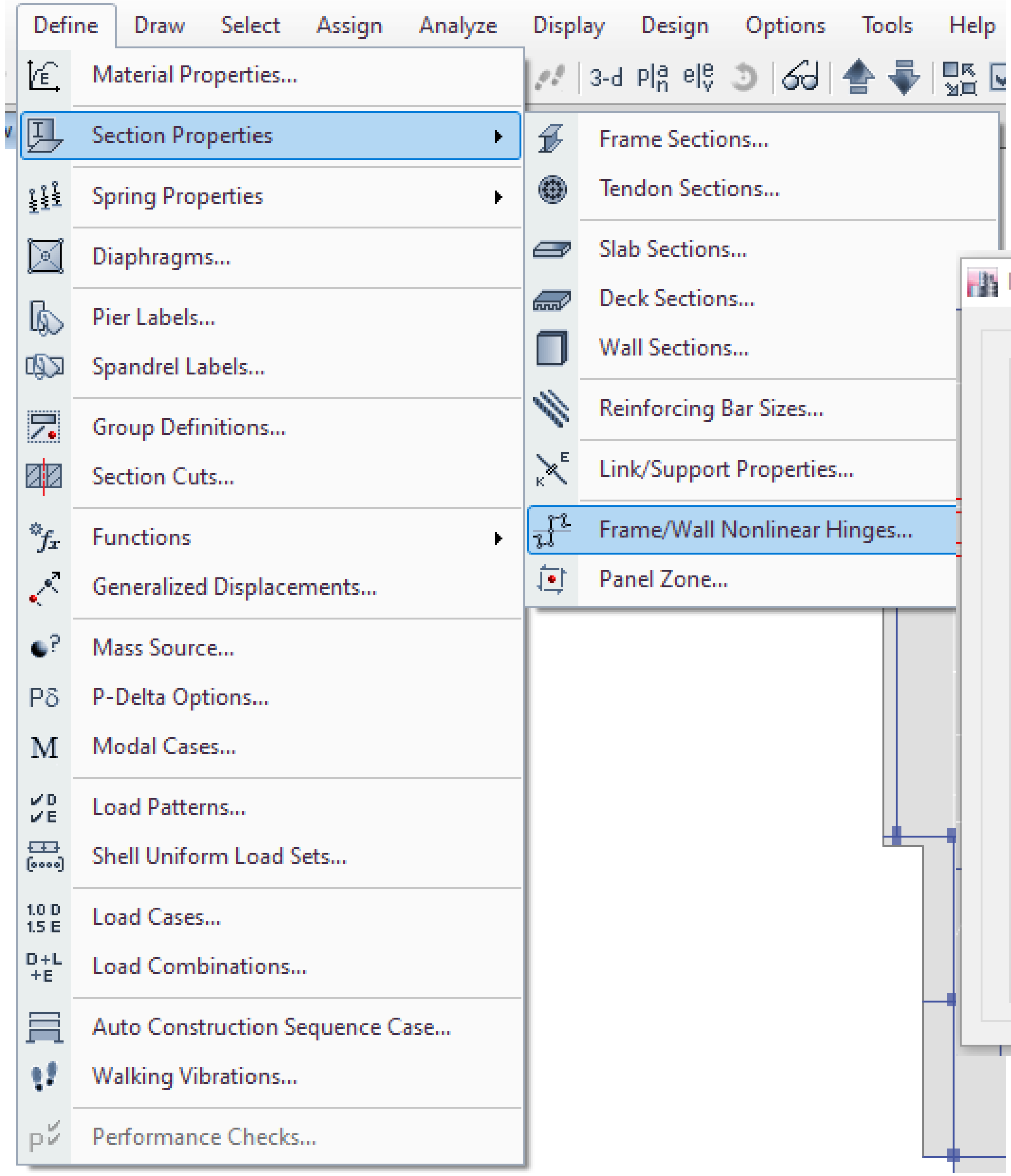


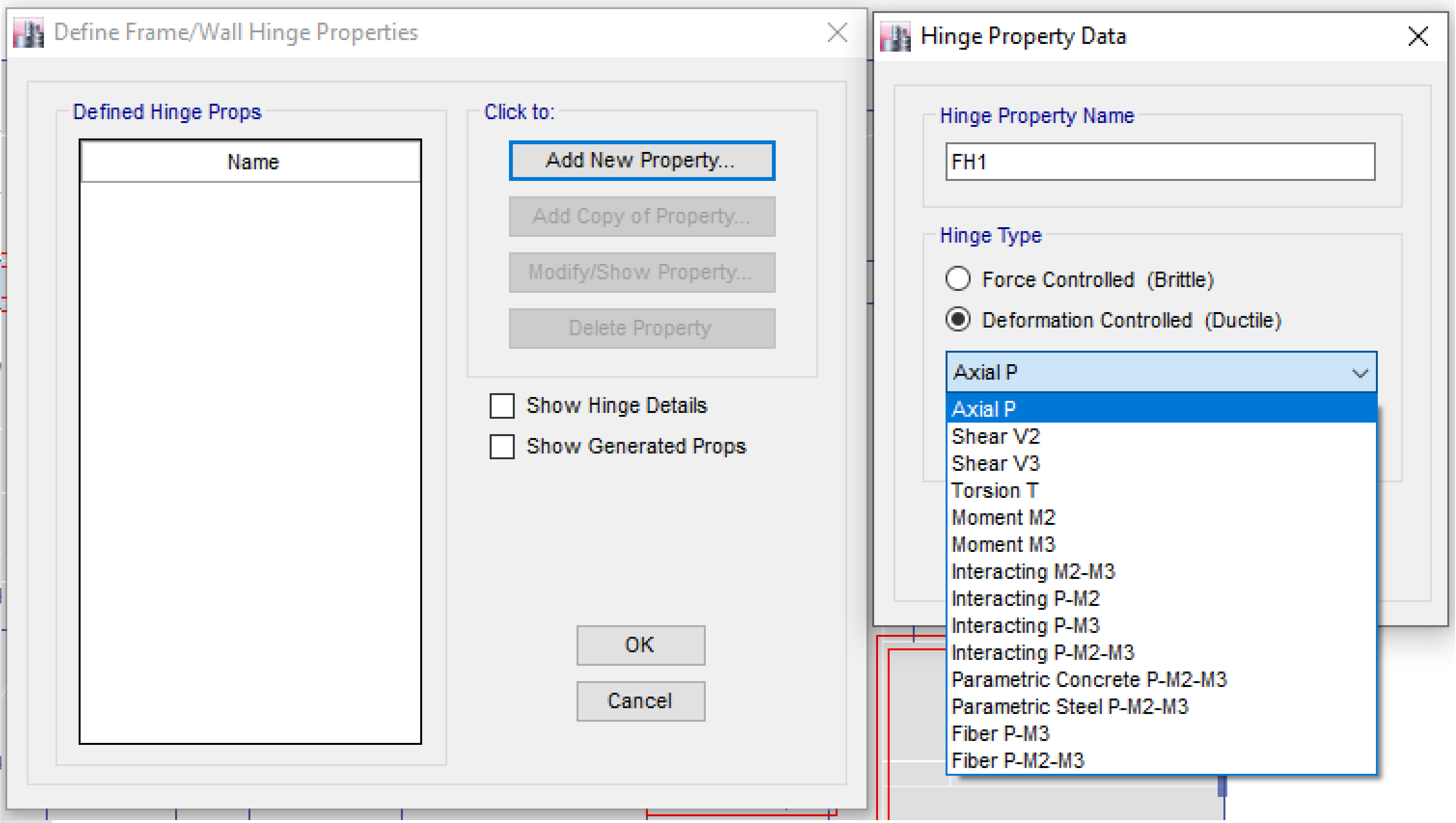


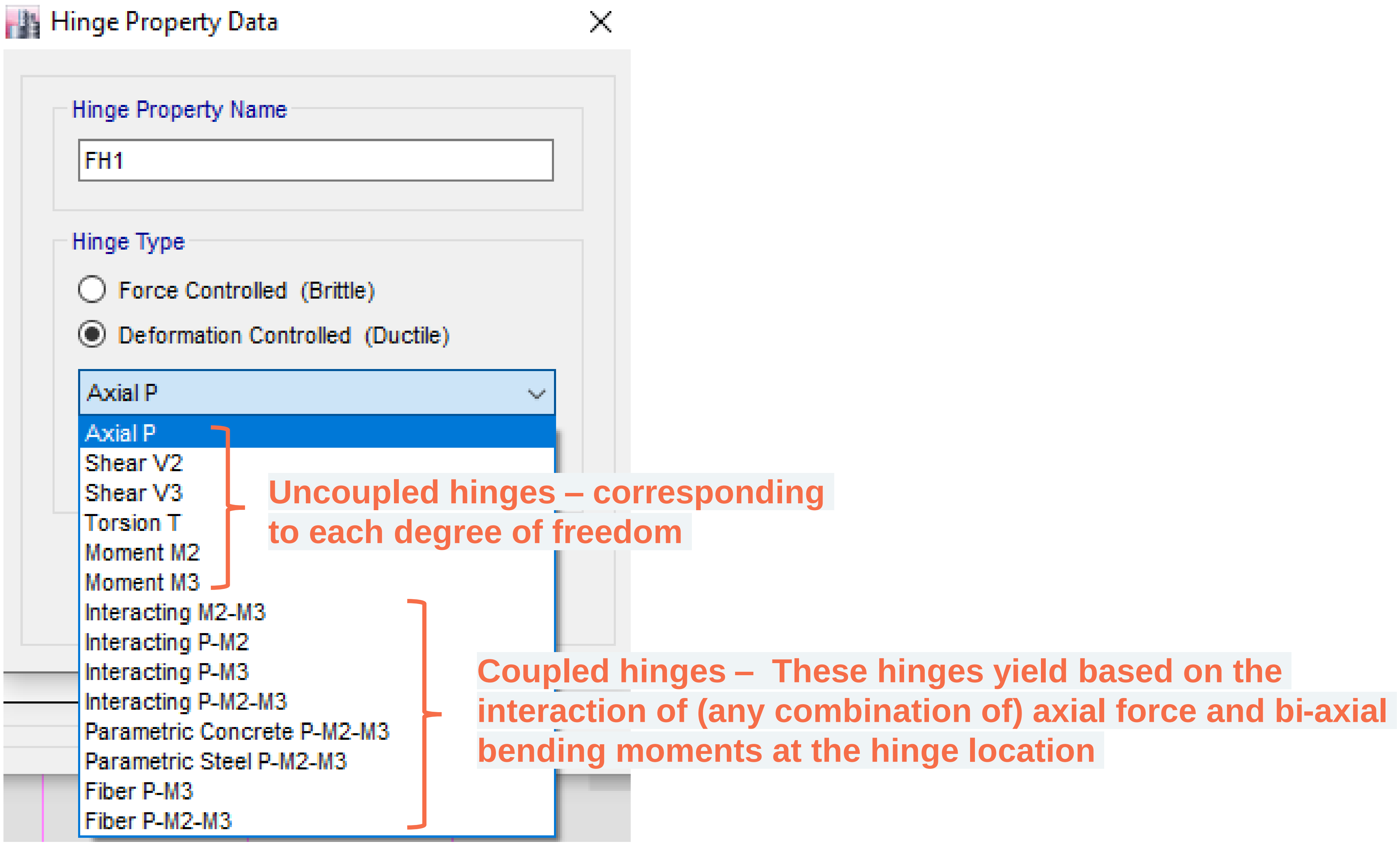
Elastic Frame Element	Uniaxial Nonlinear Rotational Spring
	

An Introduction to Plastic Hinges (and Inelastic Components) in CSI ETABS and CSI PERFORM 3D

Nonlinear Modeling of Structures in ETABS





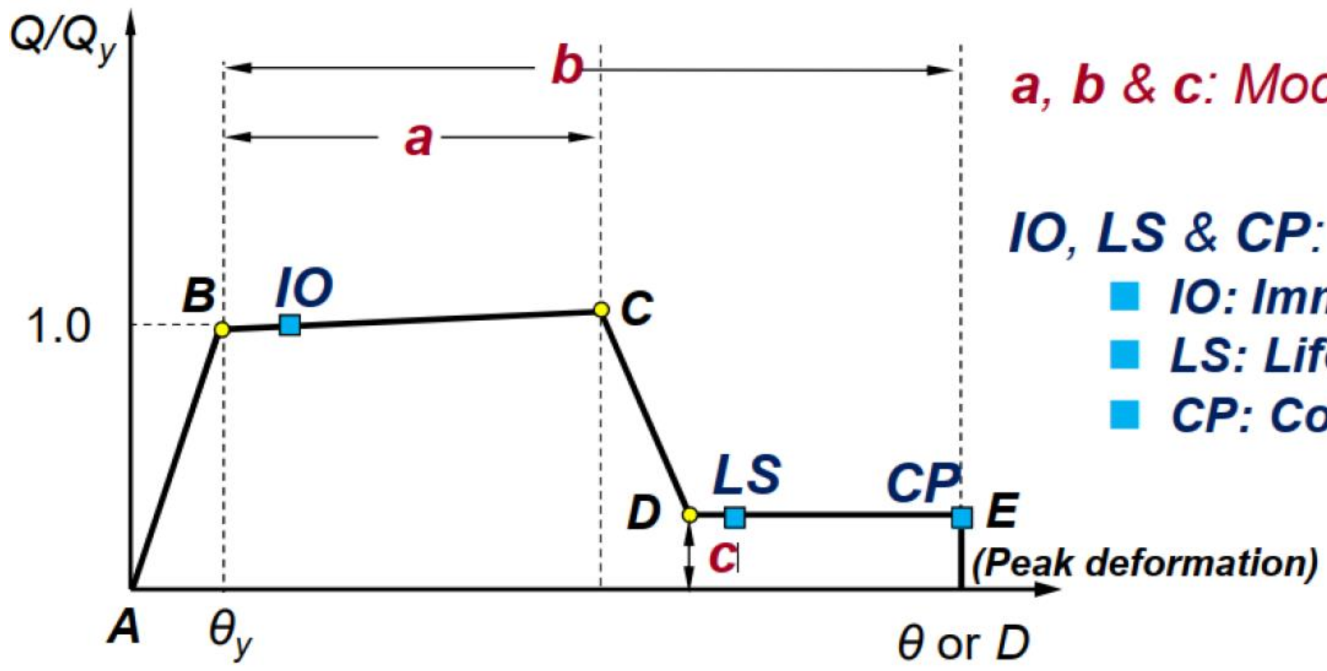

Hinge Property Data
Hinge Property Name
FH1
Hinge Type
Force Controlled (Brittle)
Deformation Controlled (Ductile)
Axial P
Axial P
Shear V2
Shear V3
Torsion T
Moment M2
Moment M3
Interacting M2-M3
Interacting P-M2
Interacting P-M3
Interacting P-M2-M3
Parametric Concrete P-M2-M3
Parametric Steel P-M2-M3
Fiber P-M3
Fiber P-M2-M3
Uncoupled hinges – corresponding to each degree of freedom
Coupled hinges – These hinges yield based on the interaction of (any combination of) axial force and bi-axial bending moments at the hinge location

ASCE 41 Approach for Nonlinear Modeling of Structural Components

ASCE 41 Approach for Nonlinear Modelling of Structural Components

- ASCE/SEI 41 prescribes nonlinear Modeling Parameters(MP) and Acceptance Criteria(AC) for various structural components.
- For Beams and Columns, MP and AC are given as limiting plastic rotations.
- MP are used to build analytical models of structures for seismic evaluation.
- AC provide deformation limits below which member performance is deemed acceptable.

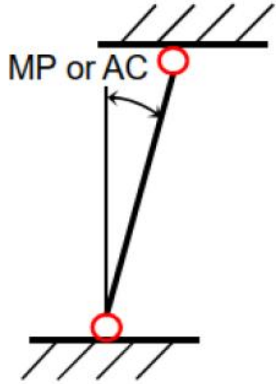
ASCE 41-17 Generalized F-D Relation



***a, b & c**: Modeling Parameters*

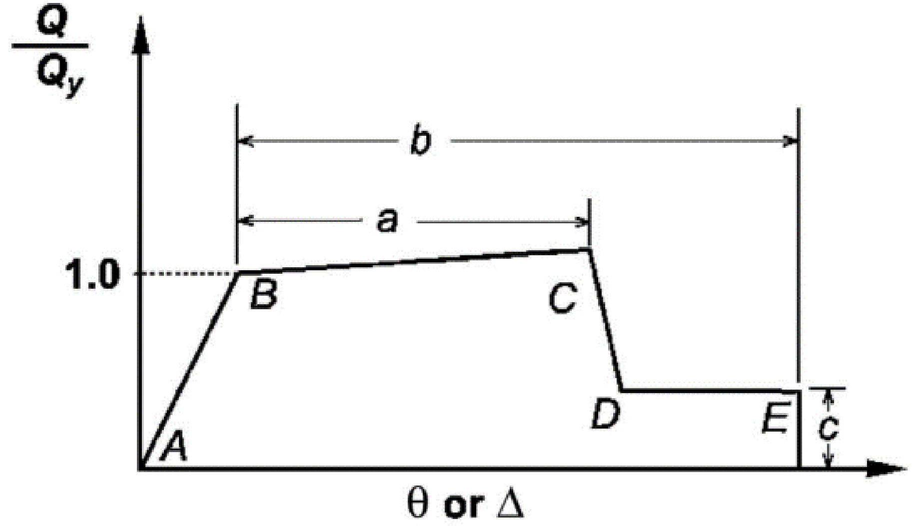
***IO, LS & CP**: Acceptance Criteria*

- ***IO: Immediate Occupancy***
- ***LS: Life Safety***
- ***CP: Collapse Prevention***

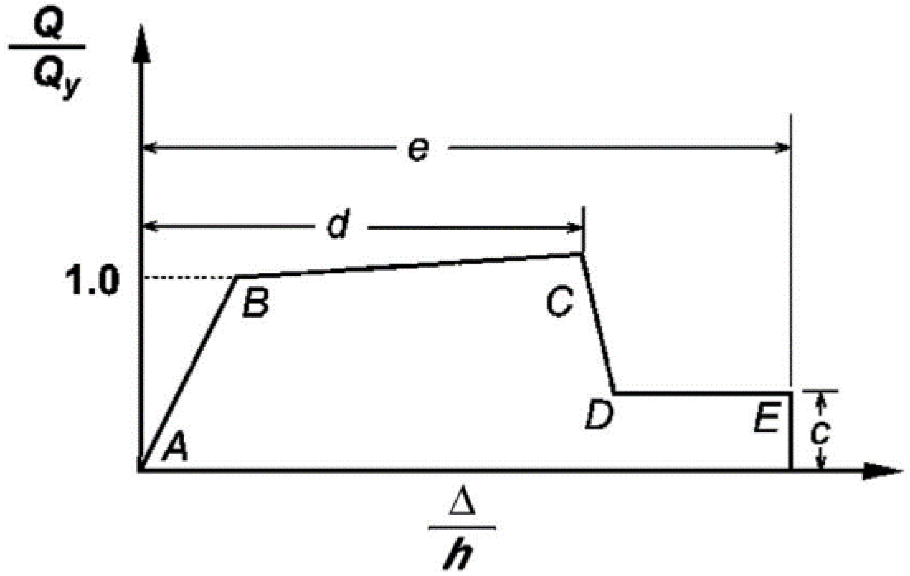


Source: AIT Solutions

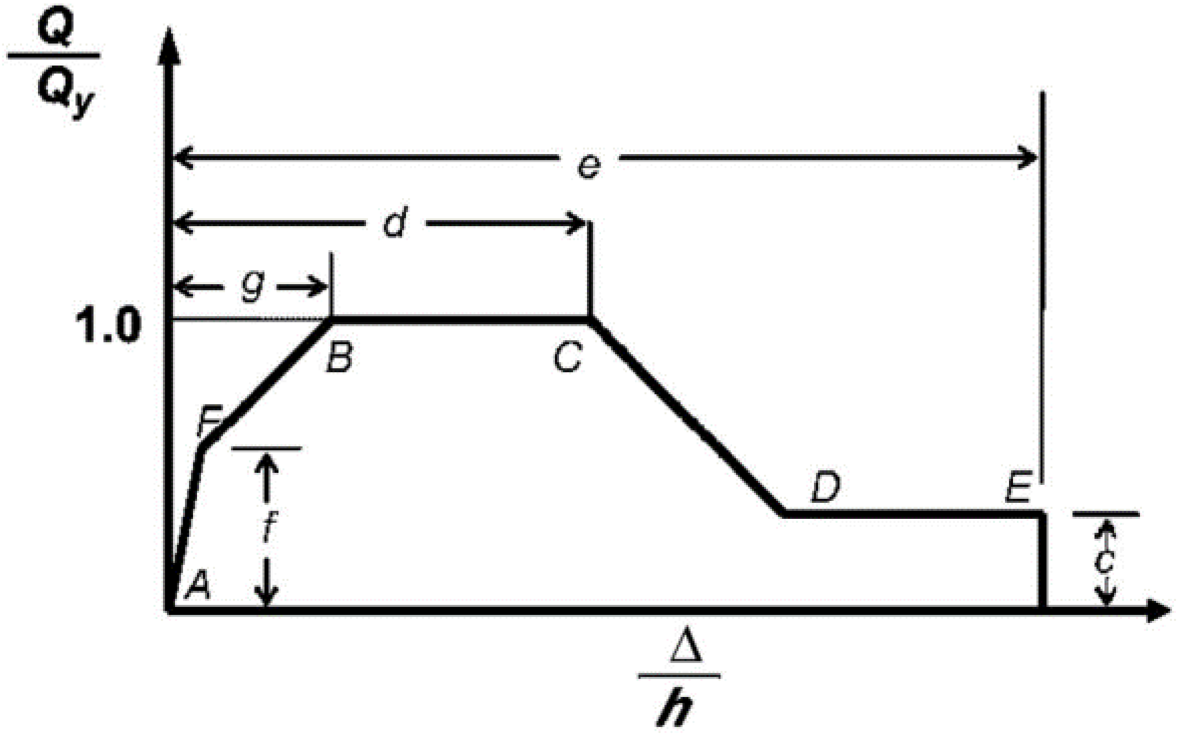
ASCE 41-17 Generalized F-D Relation



(a) Deformation



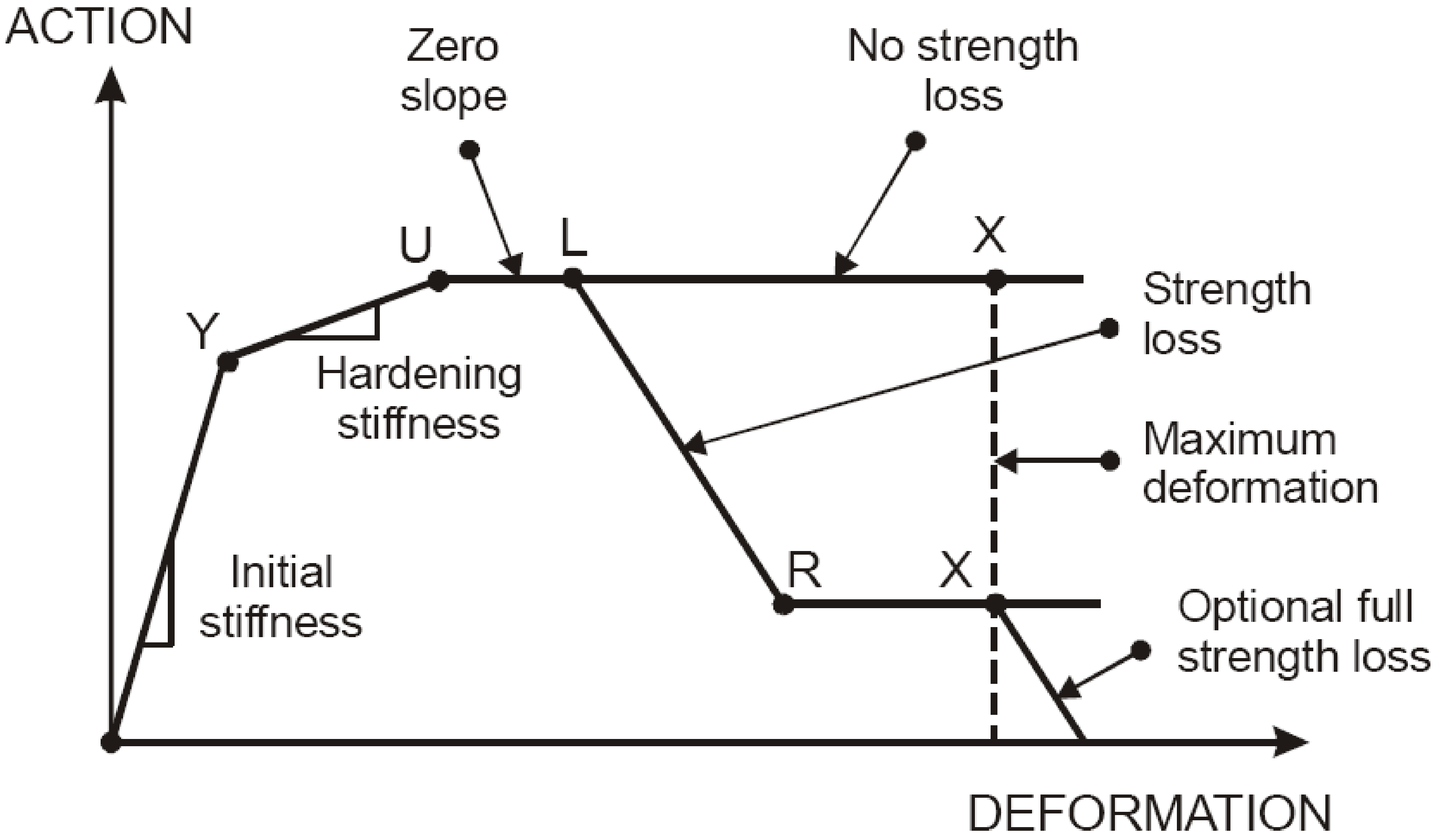
(b) Deformation ratio



(c) Trilinear response-deformation ratio

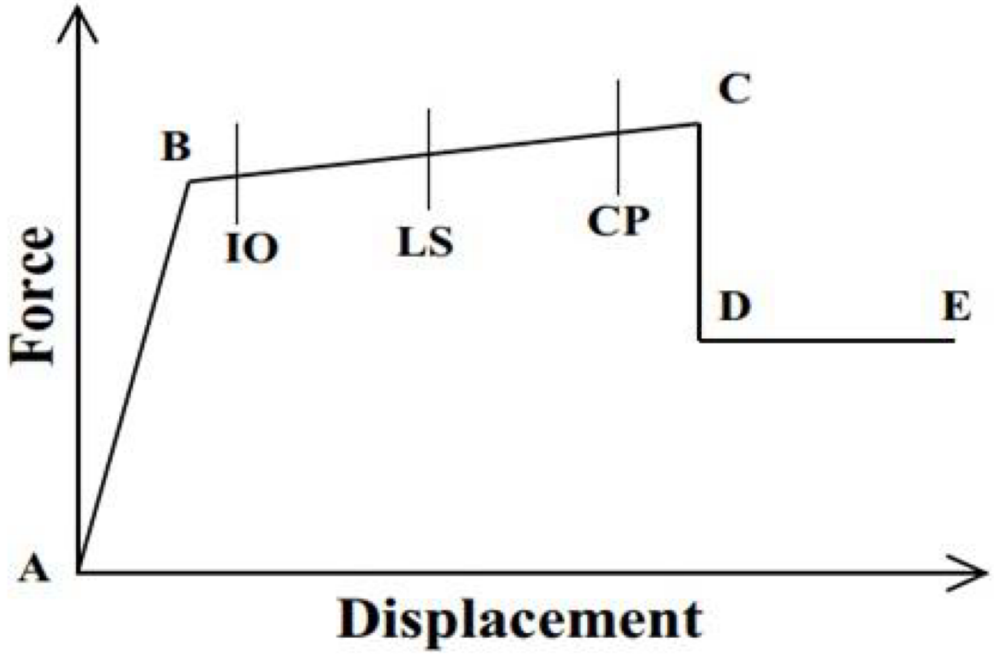
Figure 10-1. Generalized Force–Deformation Relation for Concrete Elements or Components

Basic Force-Deformation Relationship in perform 3d



Hinge Properties

- Five points labeled A, B, C, D, and E are used to define the force deflection behavior of the hinge.



The acceptance criteria (capacities) marked on the force-deformation behavior of hinges.

Hinge Properties

- Point A is always the origin
- Point B represents yielding. No deformation occurs in the hinge up to point B, regardless of the deformation value specified for point B. The displacement (rotation) at point B will be subtracted from the deformations at points C, D, and E. Only the plastic deformation beyond point B will be exhibited by the hinge
- Point C represents the ultimate capacity for Pushover analysis
- Point D represents a residual strength for Pushover analysis
- Point E represents total failure. Beyond point E the hinge will drop load down to point F (not shown) directly below point E on the horizontal axis. To prevent this failure in the hinge, specify a large value for the deformation at point E

RC Beams

Table 10-7. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Beams

Conditions			Modeling Parameters[a]: Plastic Rotation Angle (radians) *a*	Modeling Parameters[a]: Plastic Rotation Angle (radians) *b*	Modeling Parameters[a]: Residual Strength Ratio *c*	Acceptance Criteria[a]: Plastic Rotation Angle (radians), Performance Level IO	LS	CP
Condition i. Beams controlled by flexure[b]								
$\frac{\rho-\rho'}{\rho_{bal}}$	Transverse reinforcement[c]	$\frac{V^d}{b_w d\sqrt{f'_{cE}}}$						
≤0.0	C	≤3 (0.25)	0.025	0.05	0.2	0.010	0.025	0.05
≤0.0	C	≥6 (0.5)	0.02	0.04	0.2	0.005	0.02	0.04
≥0.5	C	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≥0.5	C	≥6 (0.5)	0.015	0.02	0.2	0.005	0.015	0.02
≤0.0	NC	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≤0.0	NC	≥6 (0.5)	0.01	0.015	0.2	0.0015	0.01	0.015
≥0.5	NC	≤3 (0.25)	0.01	0.015	0.2	0.005	0.01	0.015
≥0.5	NC	≥6 (0.5)	0.005	0.01	0.2	0.0015	0.005	0.01
Condition ii. Beams controlled by shear[b]								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.2	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.2	0.0015	0.005	0.01
Condition iii. Beams controlled by inadequate development or splicing along the span[b]								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.0	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.0	0.0015	0.005	0.01
Condition iv. Beams controlled by inadequate embedment into beam–column joint[b]								
			0.015	0.03	0.2	0.01	0.02	0.03

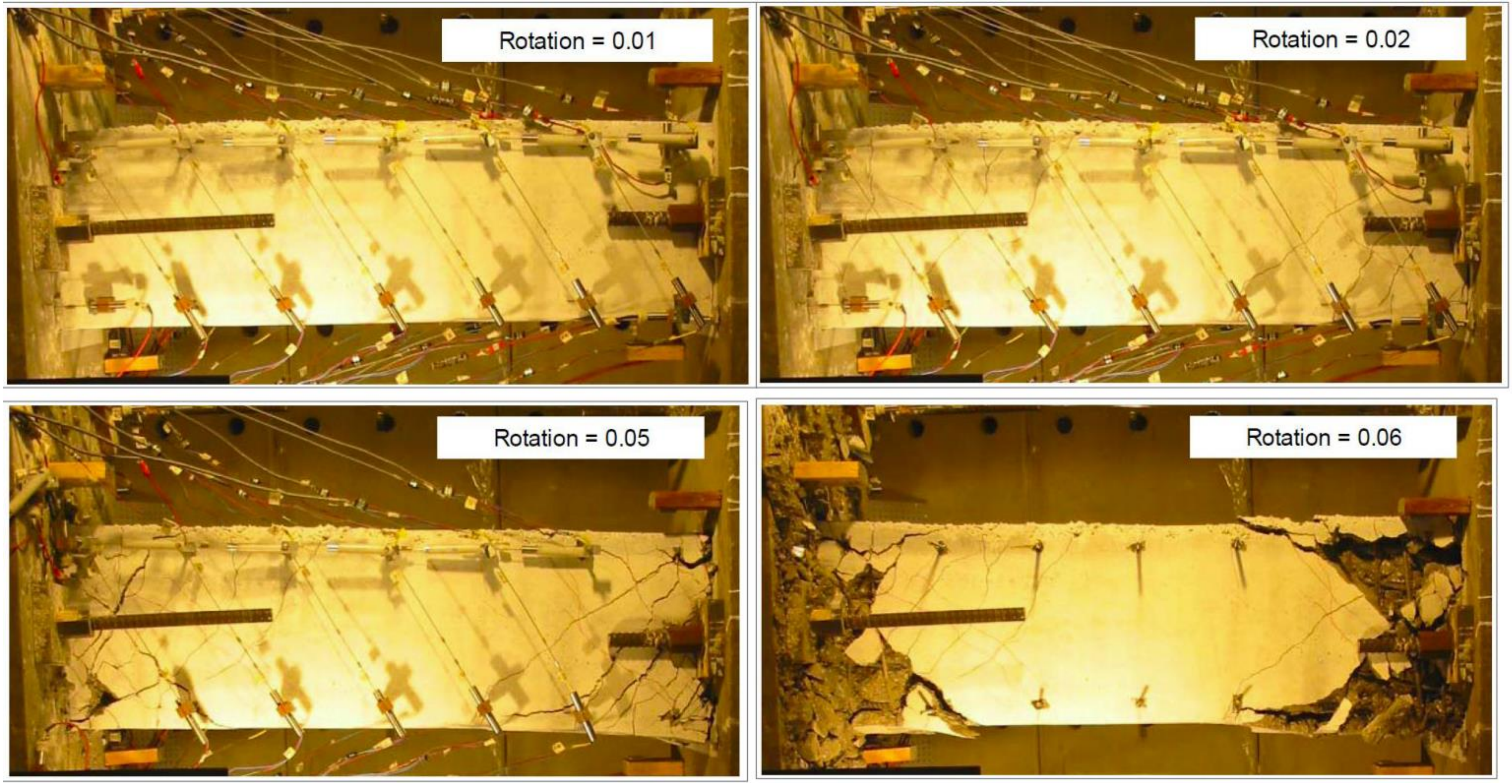
Note: f'_{cE} in lb/in.^{2} (MPa) units.

[a] Values between those listed in the table should be determined by linear interpolation.

[b] Where more than one of conditions i, ii, iii, and iv occur for a given component, use the minimum appropriate numerical value from the table.

[c] "C" and "NC" are abbreviations for conforming and nonconforming transverse reinforcement, respectively. Transverse reinforcement is conforming if, within the flexural plastic hinge region, hoops are spaced at ≤ $d/3$, and if, for components of moderate and high ductility demand, the strength provided by the hoops (V_s) is at least 3/4 of the design shear. Otherwise, the transverse reinforcement is considered nonconforming.

[d] V is the design shear force from NSP or NDP.



Source: UCLA-SGEL Report 2009/06

RC Columns other than Circular with Spiral Reinforcement

Table 10-8. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Columns Other Than Circular with Spiral Reinforcement or Seismic Hoops as Defined in ACI 318

Modeling Parameters	Acceptance Criteria		
	Plastic Rotation Angle (radians)		
	Performance Level		
Plastic Rotation Angles, *a* and *b* (radians) Residual Strength Ratio, *c*	**IO**	**LS**	**CP**
Columns not controlled by inadequate development or splicing along the clear height[a]			
$a = \left(0.042 - 0.043\frac{N_{UD}}{A_g f'_{cE}} + 0.63\rho_t - 0.023\frac{V_{yE}}{V_{ColOE}}\right) \geq 0.0$	$0.15\,a$ ≤ 0.005	$0.5\,b^{b}$	$0.7\,b^{b}$
For $\frac{N_{UD}}{A_g f'_{cE}} \leq 0.5 \left\{ b = \frac{0.5}{5 + \frac{N_{UD}}{0.8 A_g f'_{cE}} \frac{1}{\rho_t} \frac{f'_{cE}}{f_{ytE}}} - 0.01 \geq a^{a} \right.$			
$c = 0.24 - 0.4\frac{N_{UD}}{A_g f'_{cE}} \geq 0.0$			
Columns controlled by inadequate development or splicing along the clear height[c]			
$a = \left(\frac{1}{8}\frac{\rho_t f_{ytE}}{\rho_l f_{ylE}}\right) \begin{matrix} \geq 0.0 \\ \leq 0.025^{d} \end{matrix}$	0.0	$0.5\,b$	$0.7\,b$
$b = \left(0.012 - 0.085\frac{N_{UD}}{A_g f'_{cE}} + 12\rho_t^{\,e}\right) \begin{matrix} \geq 0.0 \\ \geq a \\ \leq 0.06 \end{matrix}$			
$c = 0.15 + 36\rho_t \leq 0.4$			

Notes: ρ_t shall not be taken as greater than 0.0175 in any case nor greater than 0.0075 when ties are not adequately anchored in the core. Equations in the table are not valid for columns with ρ_t smaller than 0.0005.
V_{yE}/V_{ColOE} shall not be taken as less than 0.2.
N_{UD} shall be the maximum compressive axial load accounting for the effects of lateral forces as described in Eq. (7-34). Alternatively, it shall be permitted to evaluate N_{UD} based on a limit-state analysis.

[a] b shall be reduced linearly for $N_{UD}/(A_g f'_{cE}) > 0.5$ from its value at $N_{UD}/(A_g f'_{cE}) = 0.5$ to zero at $N_{UD}/(A_g f'_{cE}) = 0.7$ but shall not be smaller than a.
[b] $N_{UD}/(A_g f'_{cE})$ shall not be taken as smaller than 0.1.
[c] Columns are considered to be controlled by inadequate development or splices where the calculated steel stress at the splice exceeds the steel stress specified by Eq. (10-1a) or (10-1b). Modeling parameter for columns controlled by inadequate development or splicing shall never exceed those of columns not controlled by inadequate development or splicing.
[d] a for columns controlled by inadequate development or splicing shall be taken as zero if the splice region is not crossed by at least two tie groups over its length.
[e] ρ_t shall not be taken as greater than 0.0075.

RC Circular Columns with Spiral Reinforcement

Table 10-9. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Circular Columns with Spiral Reinforcement or Seismic Hoops as Defined in ACI 318

Modeling Parameters	Acceptance Criteria		
	Plastic Rotation Angle (radians)		
	Performance Level		
Plastic Rotation Angles, *a* and *b* (radians) Residual Strength Ratio, *c*	IO	LS	CP
Columns not controlled by inadequate development or splicing along the clear height[a]			
$a = \left(0.06 - 0.06\frac{N_{UD}}{A_g f'_{cE}} + 1.3\rho_t - 0.037\frac{V_{yE}}{V_{ColOE}}\right) \geq 0.0$	$0.15\,a$ ≤ 0.005	$0.5\,b$[b]	$0.7\,b$[b]
For $\frac{N_{UD}}{A_g f'_{cE}} \leq 0.5 \left\{ b = \frac{0.65}{5 + \frac{N_{UD}}{0.8 A_g f'_{cE}} \frac{1}{\rho_t} \frac{f'_{cE}}{f_{ytE}}} - 0.01 \geq a \right.$[a]			
$c = 0.24 - 0.4\frac{N_{UD}}{A_g f'_{cE}} \geq 0.0$			
Columns controlled by inadequate development or splicing along the clear height[c]			
$a = \left(\frac{1}{8}\frac{\rho_t f_{ytE}}{\rho_l f_{ylE}}\right) \begin{matrix} \geq 0.0 \\ \leq 0.025 \end{matrix}$[d]	0.0	$0.5\,b$	$0.7\,b$
$b = \left(0.012 - 0.085\frac{N_{UD}}{A_g f'_{cE}} + 12\rho_t\right.$[e]$\left.\right) \begin{matrix} \geq 0.0 \\ \geq a \\ \leq 0.06 \end{matrix}$			
$c = 0.15 + 36\rho_t \leq 0.4$			

Notes: ρ_t shall not be taken as greater than 0.0175 in any case nor greater than 0.0075 when ties are not adequately anchored in the core.

Equations in the table are not valid for columns with ρ_t smaller than 0.0005.

V_{yE}/V_{ColOE} shall not be taken as less than 0.2.

N_{UD} shall be the maximum compressive axial load accounting for the effects of lateral forces as described in Eq. (7-34). Alternatively, it shall be permitted to evaluate N_{UD} based on a limit-state analysis.

[a] *b* shall be reduced linearly for $N_{UD}/(A_g f'_{cE}) > 0.5$ from its value at $N_{UD}/(A_g f'_{cE}) = 0.5$ to zero at $N_{UD}/(A_g f'_{cE}) = 0.7$ but shall not be smaller than *a*.

[b] $N_{UD}/(A_g f'_{cE})$ shall not be taken as smaller than 0.1.

[c] Columns are considered to be controlled by inadequate development or splices where the calculated steel stress at the splice exceeds the steel stress specified by Eq. (10-1a) or (10-1b). Modeling parameter for columns controlled by inadequate development or splicing shall never exceed those of columns not controlled by inadequate development or splicing.

[d] *a* for columns controlled by inadequate development or splicing shall be taken as zero if the splice region is not crossed by at least two tie groups over its length.

[e] ρ_t shall not be taken as greater than 0.0075.

RC Beam-Column Joints

Table 10-11. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Beam–Column Joints

Conditions			Modeling Parameters[a]			Acceptance Criteria[a]		
			Plastic Rotation Angle (radians)		Residual Strength Ratio	Plastic Rotation Angle (radians)		
						Performance Level		
			a	*b*	*c*	IO	LS	CP
Condition i. Interior joints (Note: For classification of joints, refer to Fig. 10-3)								
$\frac{P^b}{A_g f'_{cE}}$	Transverse reinforcement[c]	$\frac{V^d}{V_J}$						
≤0.1	C	≤1.2	0.015	0.03	0.2	0.0	0.02	0.03
≤0.1	C	≥1.5	0.015	0.03	0.2	0.0	0.015	0.02
≥0.4	C	≤1.2	0.015	0.025	0.2	0.0	0.015	0.025
≥0.4	C	≥1.5	0.015	0.2	0.2	0.0	0.015	0.02
≤0.1	NC	≤1.2	0.005	0.2	0.2	0.0	0.015	0.02
≤0.1	NC	≥1.5	0.005	0.015	0.2	0.0	0.01	0.015
≥0.4	NC	≤1.2	0.005	0.015	0.2	0.0	0.01	0.015
≥0.4	NC	≥1.5	0.005	0.015	0.2	0.0	0.01	0.015
Condition ii. Other joints (Note: For classification for joints, refer to Fig. 10-3)								
$\frac{P^b}{A_g f'_{cE}}$	Transverse reinforcement[c]	$\frac{V^d}{V_J}$						
≤0.1	C	≤1.2	0.01	0.02	0.2	0.0	0.015	0.02
≤0.1	C	≥1.5	0.01	0.015	0.2	0.0	0.01	0.015
≥0.4	C	≤1.2	0.01	0.02	0.2	0.0	0.015	0.02
≥0.4	C	≥1.5	0.01	0.015	0.2	0.0	0.01	0.015
≤0.1	NC	≤1.2	0.005	0.01	0.2	0.0	0.0075	0.01
≤0.1	NC	≥1.5	0.005	0.01	0.2	0.0	0.0075	0.01
≥0.4	NC	≤1.2	0.0	0.0075	0.0	0.0	0.005	0.0075
≥0.4	NC	≥1.5	0.0	0.0075	0.0	0.0	0.005	0.0075

[a] Values between those listed in the table should be determined by linear interpolation.
[b] P is the design axial force on the column above the joint calculated using limit-state analysis procedures in accordance with Section 10.4.2.4, and A_g is the gross cross-sectional area of the joint.
[c] "C" and "NC" are abbreviations for conforming and nonconforming transverse reinforcement. Joint transverse reinforcement is conforming if hoops are spaced at $\leq h_c/2$ within the joint. Otherwise, the transverse reinforcement is considered nonconforming.
[d] V is the design shear force from NSP or NDP, and V_n is the shear strength for the joint. The shear strength should be calculated according to Section 10.4.2.3.

Two-way Slabs and Slab-Column Connections

Table 10-15. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Two-Way Slabs and Slab–Column Connections

		Modeling Parameters[a]			Acceptance Criteria[a]		
					Plastic Rotation Angle (radians)		
					Performance Level		
		Plastic Rotation Angle (radians)		Residual Strength Ratio		Secondary	
Conditions		***a***	***b***	***c***	**IO**	**LS**	**CP**
Condition i. Reinforced concrete slab–column connections[b]							
$\frac{V_g}{V_o}$[c]	Continuity reinforcement[d]						
0	Yes	0.035	0.05	0.2	0.01	0.035	0.05
0.2	Yes	0.03	0.04	0.2	0.01	0.03	0.04
0.4	Yes	0.02	0.03	0.2	0	0.02	0.03
≥0.6	Yes	0	0.02	0	0	0	0.02
0	No	0.025	0.025	0	0.01	0.02	0.025
0.2	No	0.02	0.02	0	0.01	0.015	0.02
0.4	No	0.01	0.01	0	0	0.008	0.01
0.6	No	0	0	0	0	0	0
>0.6	No	0	0	0	—[e]	—[e]	—[e]
Condition ii. Post-tensioned slab–column connections[b]							
$\frac{V_g}{V_o}$[c]	Continuity reinforcement[d]						
0	Yes	0.035	0.05	0.4	0.01	0.035	0.05
0.6	Yes	0.005	0.03	0.2	0	0.025	0.03
>0.6	Yes	0	0.02	0.2	0	0.015	0.02
0	No	0.025	0.025	0	0.01	0.02	0.025
0.6	No	0	0	0	0	0	0
>0.6	No	0	0	0	—[e]	—[e]	—[e]
Condition iii. Slabs controlled by inadequate development or splicing along the span[b]							
		0	0.02	0	0	0.01	0.02
Condition iv. Slabs controlled by inadequate embedment into slab–column joint[b]							
		0.015	0.03	0.2	0.01	0.02	0.03

[a] Values between those listed in the table shall be determined by linear interpolation.
[b] Where more than one of conditions i, ii, iii, and iv occur for a given component, use the minimum appropriate numerical value from the table.
[c] V_g is the gravity shear acting on the slab critical section as defined by ACI 318, and V_o is the direct punching shear strength as defined by ACI 318.
[d] "Yes" shall be used where the area of effectively continuous main bottom bars passing through the column cage in each direction is greater than or equal to $0.5V_g/(\phi f_y)$. Where the slab is post-tensioned, "Yes" shall be used where at least one of the post-tensioning tendons in each direction passes through the column cage. Otherwise, "No" shall be used.
[e] Action shall be treated as force controlled.

Plastic Hinge Modeling of RC Beams using ETABS

Option 1: Manual Definition of Hinge Properties for Every Hinge Type

Option 2: Automatic Definition of Hinge Properties by the Program

ASCE 41-17 Modelling Parameters and Acceptance Criteria - RC Beams

Table 10-7. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures—Reinforced Concrete Beams

Conditions			Modeling Parameters[a]: Plastic Rotation Angle (radians) *a*	Modeling Parameters[a]: Plastic Rotation Angle (radians) *b*	Modeling Parameters[a]: Residual Strength Ratio *c*	Acceptance Criteria[a]: Plastic Rotation Angle (radians), Performance Level IO	LS	CP
Condition i. Beams controlled by flexure[b]								
$\frac{\rho-\rho'}{\rho_{bal}}$	Transverse reinforcement[c]	$\frac{V^d}{b_w d\sqrt{f'_{cE}}}$						
≤0.0	C	≤3 (0.25)	0.025	0.05	0.2	0.010	0.025	0.05
≤0.0	C	≥6 (0.5)	0.02	0.04	0.2	0.005	0.02	0.04
≥0.5	C	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≥0.5	C	≥6 (0.5)	0.015	0.02	0.2	0.005	0.015	0.02
≤0.0	NC	≤3 (0.25)	0.02	0.03	0.2	0.005	0.02	0.03
≤0.0	NC	≥6 (0.5)	0.01	0.015	0.2	0.0015	0.01	0.015
≥0.5	NC	≤3 (0.25)	0.01	0.015	0.2	0.005	0.01	0.015
≥0.5	NC	≥6 (0.5)	0.005	0.01	0.2	0.0015	0.005	0.01
Condition ii. Beams controlled by shear[b]								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.2	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.2	0.0015	0.005	0.01
Condition iii. Beams controlled by inadequate development or splicing along the span[b]								
Stirrup spacing ≤ $d/2$			0.0030	0.02	0.0	0.0015	0.01	0.02
Stirrup spacing > $d/2$			0.0030	0.01	0.0	0.0015	0.005	0.01
Condition iv. Beams controlled by inadequate embedment into beam–column joint[b]								
			0.015	0.03	0.2	0.01	0.02	0.03

Note: f'_{cE} in lb/in.^{2} (MPa) units.

[a] Values between those listed in the table should be determined by linear interpolation.

[b] Where more than one of conditions i, ii, iii, and iv occur for a given component, use the minimum appropriate numerical value from the table.

[c] "C" and "NC" are abbreviations for conforming and nonconforming transverse reinforcement, respectively. Transverse reinforcement is conforming if, within the flexural plastic hinge region, hoops are spaced at ≤ $d/3$, and if, for components of moderate and high ductility demand, the strength provided by the hoops (V_s) is at least 3/4 of the design shear. Otherwise, the transverse reinforcement is considered nonconforming.

[d] V is the design shear force from NSP or NDP.

ASCE 41-17 Modelling Parameters and Acceptance Criteria for RC Beams

In order to obtain the modeling parameters & acceptance criteria for a particular reinforced concrete beam, the following three quantities are required in the Table 10-7 of ASCE 41-17.

(a) $\frac{\rho-\rho'}{\rho_{bal}}$

(b) The information whether the transverse reinforcement is "conforming" or not, and

(c) $\frac{V}{b_w\, d\, \sqrt{f_{cE}'}}$

Where;

ρ = Tensile reinforcement ratio.

ρ' = Compression reinforcement ratio.

ρ_{bal} = Balanced reinforcement ratio.

f_{cE}' = Expected concrete strength.

V = Design shear force of the beam.

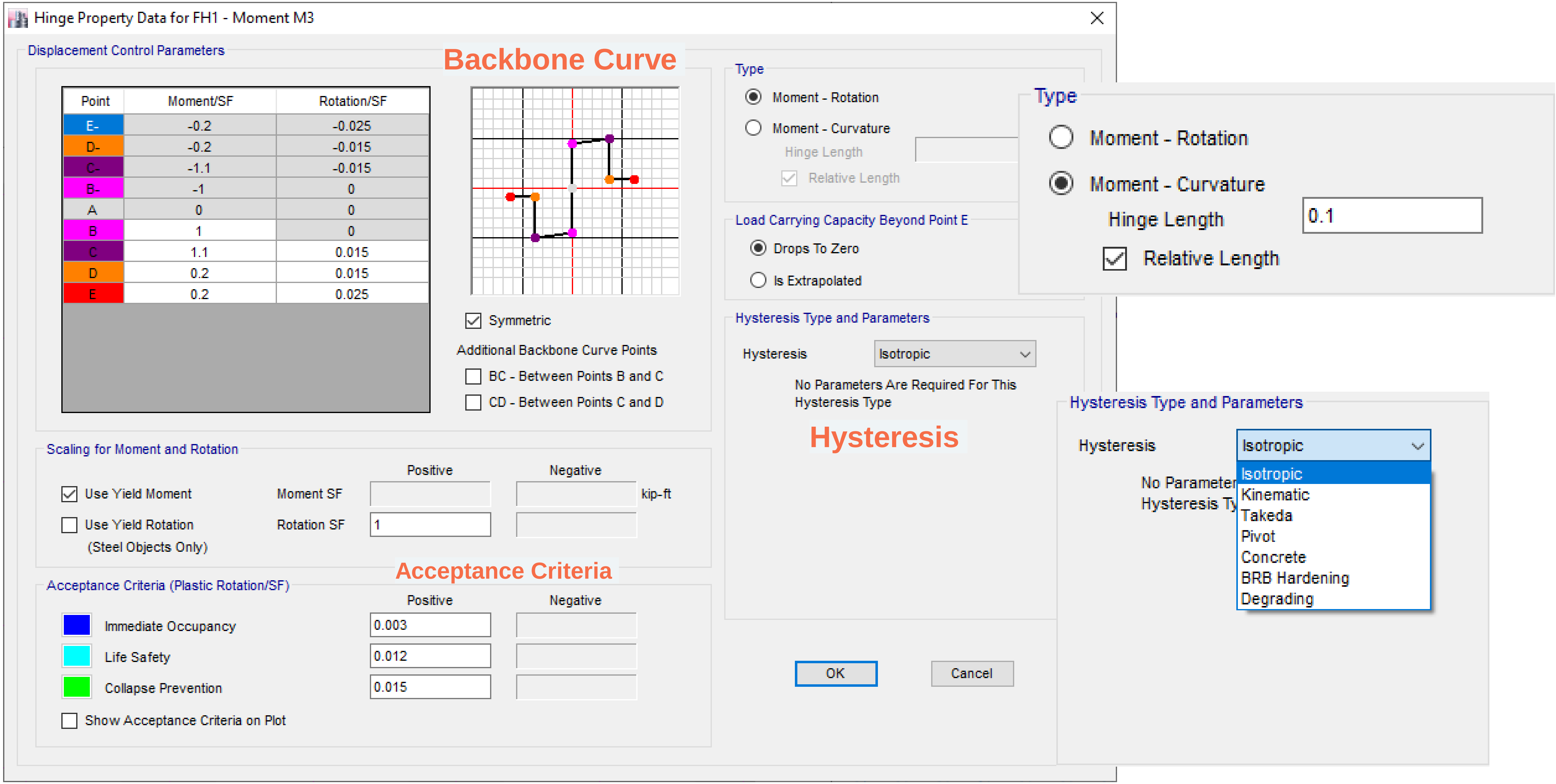
b_w = Width of the beam cross-section.

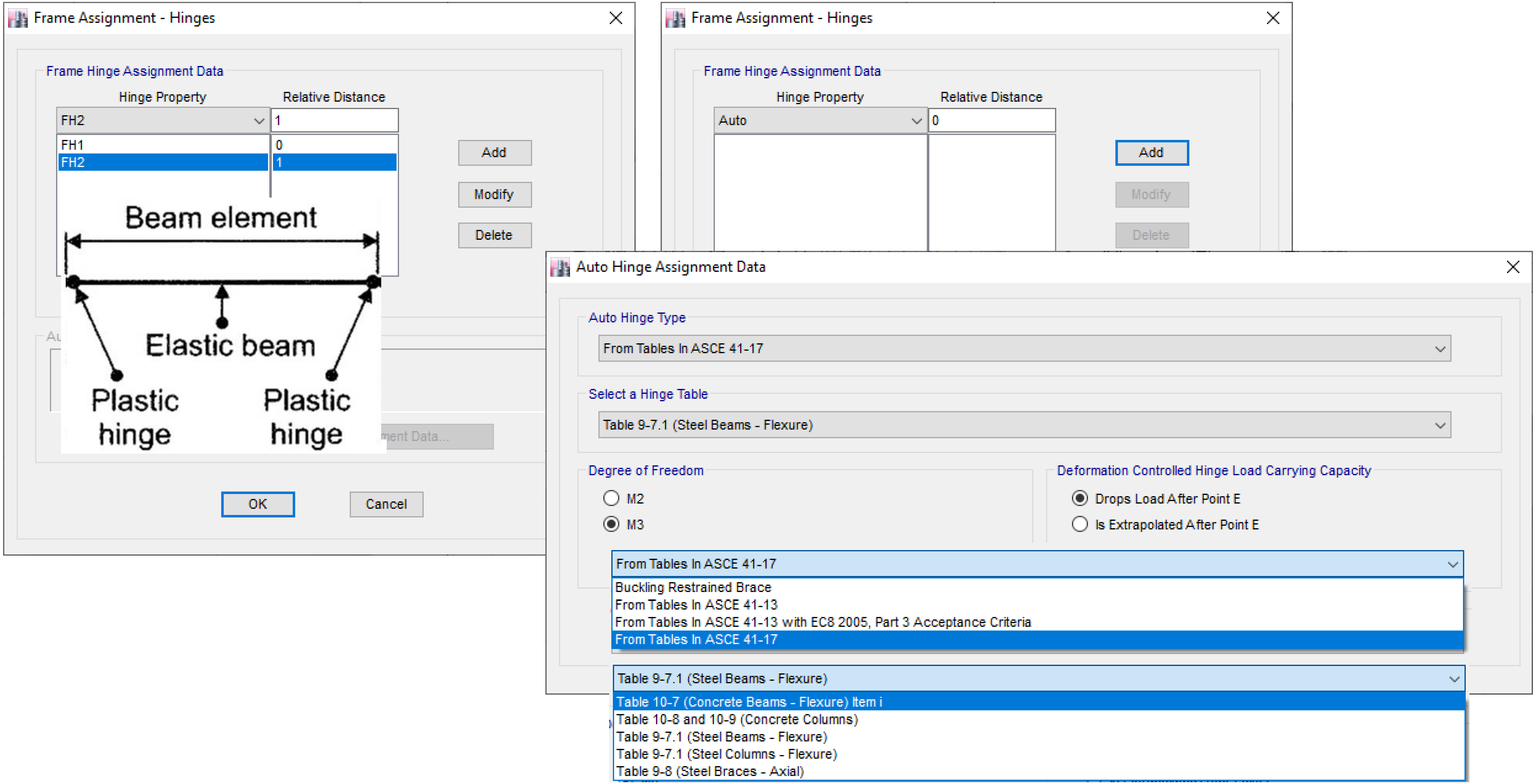
d = Depth of the beam cross-section.

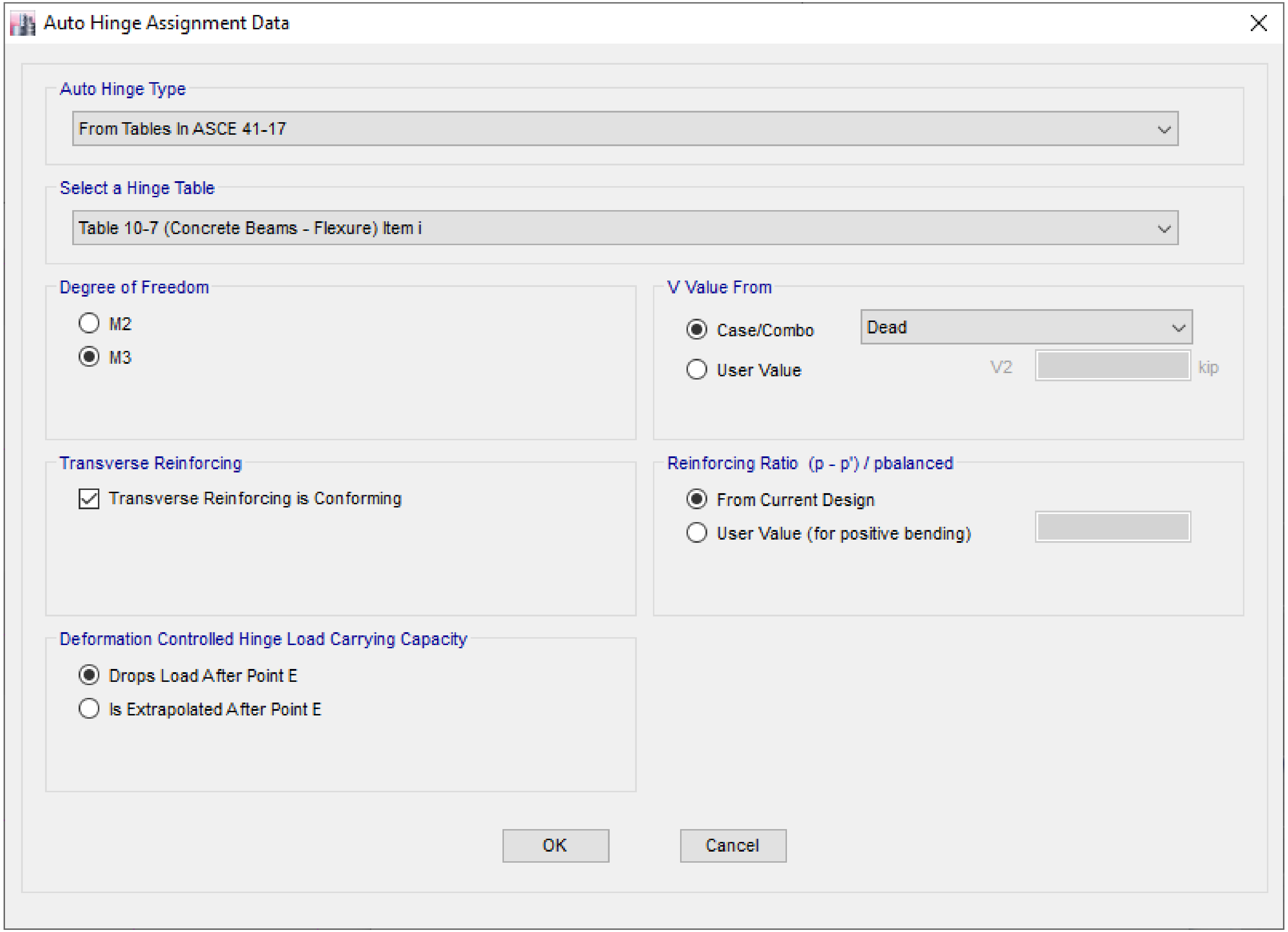
The design longitudinal reinforcements (top and bottom) can be used to determine the factor $\frac{\rho-\rho'}{\rho_{bal}}$.

In the transverse reinforcement column of Table 10-7, the symbols "C" and "NC" are abbreviations for conforming and nonconforming transverse reinforcement, respectively. Transverse reinforcement is conforming if, within the flexural plastic hinge region, hoops are spaced at ≤ d/3, and if, for components of moderate and high ductility demand, the strength provided by the hoops (V_s) is at least 3/4 of the design shear. Otherwise, the transverse reinforcement is considered nonconforming. The design shear reinforcement can be checked to confirm whether they are C or NC.

V is the design shear from the nonlinear static or dynamic procedures.


Hinge Property Data for FH1 - Moment M3
Displacement Control Parameters
Backbone Curve
Point
Moment/SF
Rotation/SF
E- -0.2 -0.025
D- -0.2 -0.015
C- -1.1 -0.015
B- -1 0
A 0 0
B 1 0
C 1.1 0.015
D 0.2 0.015
E 0.2 0.025
Symmetric
Additional Backbone Curve Points
BC - Between Points B and C
CD - Between Points C and D
Scaling for Moment and Rotation
Positive
Negative
Use Yield Moment
Moment SF
kip-ft
Use Yield Rotation
Rotation SF
1
(Steel Objects Only)
Acceptance Criteria
Acceptance Criteria (Plastic Rotation/SF)
Positive
Negative
Immediate Occupancy
0.003
Life Safety
0.012
Collapse Prevention
0.015
Show Acceptance Criteria on Plot
Type
Moment - Rotation
Moment - Curvature
Hinge Length
Relative Length
Load Carrying Capacity Beyond Point E
Drops To Zero
Is Extrapolated
Hysteresis Type and Parameters
Hysteresis
Isotropic
No Parameters Are Required For This
Hysteresis Type
Hysteresis
OK
Cancel
Type
Moment - Rotation
Moment - Curvature
Hinge Length
0.1
Relative Length
Hysteresis Type and Parameters
Hysteresis
Isotropic
No Parameter
Hysteresis Ty
Isotropic
Kinematic
Takeda
Pivot
Concrete
BRB Hardening
Degrading


Frame Assignment - Hinges
Frame Hinge Assignment Data
Hinge Property
Relative Distance
FH2
1
FH1
0
FH2
1
Add
Modify
Delete
Beam element
Elastic beam
Plastic hinge
Plastic hinge
OK
Cancel
Frame Assignment - Hinges
Frame Hinge Assignment Data
Hinge Property
Relative Distance
Auto
0
Add
Modify
Delete
Auto Hinge Assignment Data
Auto Hinge Type
From Tables In ASCE 41-17
Select a Hinge Table
Table 9-7.1 (Steel Beams - Flexure)
Degree of Freedom
M2
M3
Deformation Controlled Hinge Load Carrying Capacity
Drops Load After Point E
Is Extrapolated After Point E
From Tables In ASCE 41-17
Buckling Restrained Brace
From Tables In ASCE 41-13
From Tables In ASCE 41-13 with EC8 2005, Part 3 Acceptance Criteria
From Tables In ASCE 41-17
Table 9-7.1 (Steel Beams - Flexure)
Table 10-7 (Concrete Beams - Flexure) Item i
Table 10-8 and 10-9 (Concrete Columns)
Table 9-7.1 (Steel Beams - Flexure)
Table 9-7.1 (Steel Columns - Flexure)
Table 9-8 (Steel Braces - Axial)



Auto Hinge Assignment Data
Auto Hinge Type
From Tables In ASCE 41-17
Select a Hinge Table
Table 10-7 (Concrete Beams - Flexure) Item i
Degree of Freedom
M2
M3
V Value From
Case/Combo
Dead
User Value
V2
kip
Transverse Reinforcing
Transverse Reinforcing is Conforming
Reinforcing Ratio (p - p') / pbalanced
From Current Design
User Value (for positive bending)
Deformation Controlled Hinge Load Carrying Capacity
Drops Load After Point E
Is Extrapolated After Point E
OK
Cancel

Seismic Design Shear (V) in Plastic Hinge Regions

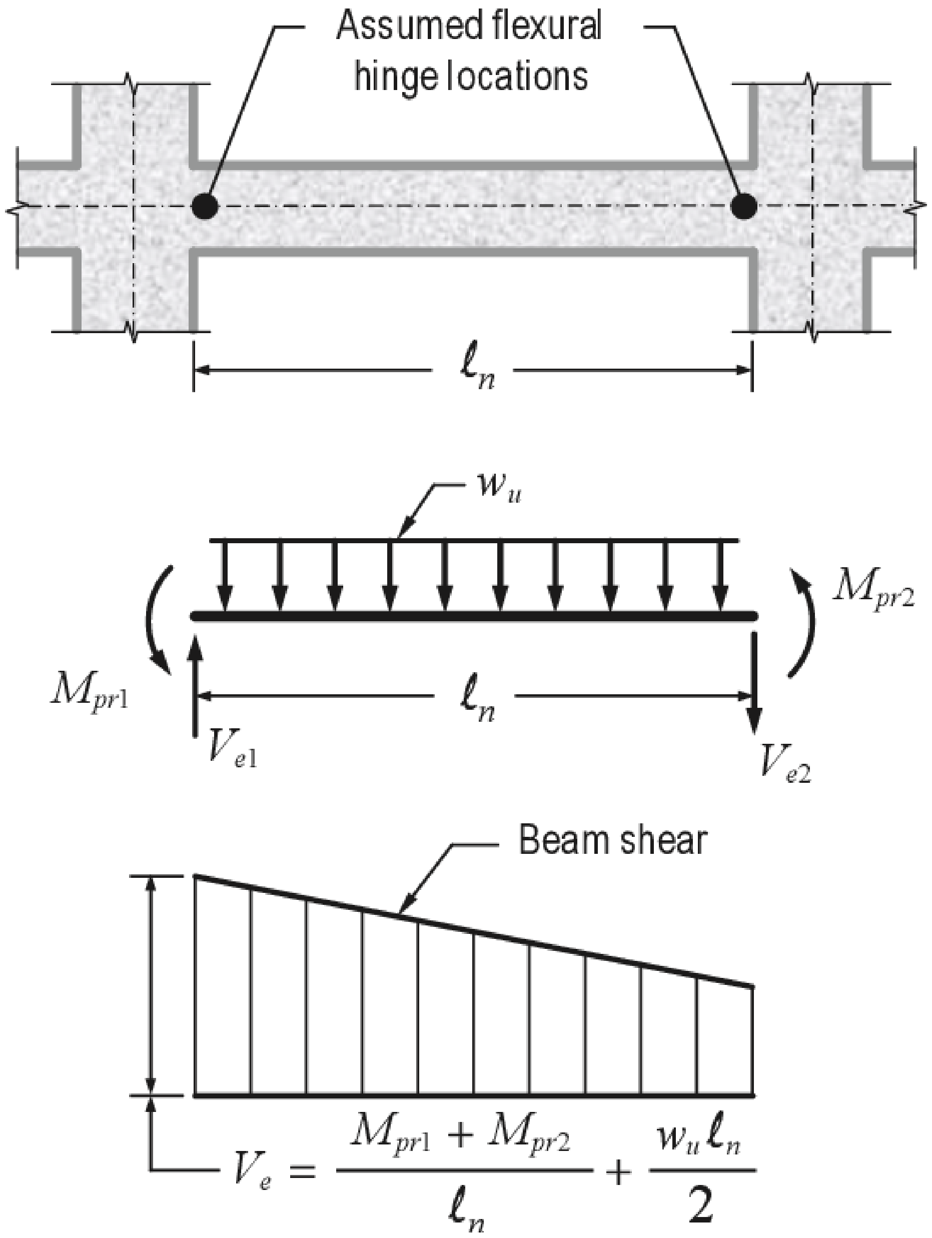
- Ductile response requires that members yield in flexure, and that shear failure be avoided. Shear failure is avoided through use of a capacity-design approach. The general approach is to identify flexural yielding regions, design those regions for code-required moment strengths, and then calculate design shears based on equilibrium assuming the flexural yielding regions develop probable moment strengths.

- Seismic design shear (V) in plastic hinge regions is associated with maximum inelastic moments that can develop at the ends of members when the longitudinal tension reinforcement is in the strain hardening range (assumed to develop $1.25\ f_y$) This moment level is labeled as probable flexural strength, M_{pr}.

- Probable moment strength is calculated from conventional flexural theory considering the as- designed cross section, using ϕ = 1.0, and assuming reinforcement yield strength equal to at least $1.25 f_y$.

Beam Shear Demand (based on Capacity Design Approach)

- Assuming beam is yielding in flexure, beam end moments are set equal to probable moment strengths.
- Design shear is based on the probable moment to maintain the moment equilibrium. This is worst case scenario for shear.
- ACI 318 defines probable moment strength as moment strength of a member, determined using the properties of the member at the joint faces assuming a tensile stress in longitudinal bars of "at least $1.25\ f_y$" and a strength reduction factor ϕ = 1.0.
- Controlling Load Combination $1.2D + E_v + (1.0\ or\ 0.5)L + 0.2\ S$



SUMMARY – Beam Shear Demand (based on Capacity Design Approach)

- A capacity design approach is used to guide the design of a special moment frame.
- The process begins by identifying where inelastic action is intended to occur. For a special moment frame, this is intended to be predominantly in the form of flexural yielding of the beams.
- The building is analyzed under the design loads to determine the required flexural strengths at beam plastic hinges, which are almost always located at the ends of the beams.
- Beam sections are designed so that the reliable flexural strength is at least equal to the factored design moment, that is, $\phi M_n > M_u$
- Once the beam is proportioned, the plastic moment strengths of the beam can be determined based on the expected material properties and the selected cross section. ACI 318 uses the probable moment strength M_{pr} for this purpose.
- Probable moment strength is calculated from conventional flexural theory considering the as-designed cross section, using ϕ = 1.0, and assuming reinforcement yield strength equal to at least $1.25\ f_y$.
- The probable moment strength is used to establish requirements for beam shear strength, beam-column joint strength, and column strength as part of the capacity-design process. Because the design of other frame elements depends on the amount of beam flexural reinforcement, the designer should take care to optimize each beam and minimize excess capacity.

Probable Moment Strength, M_{pr}

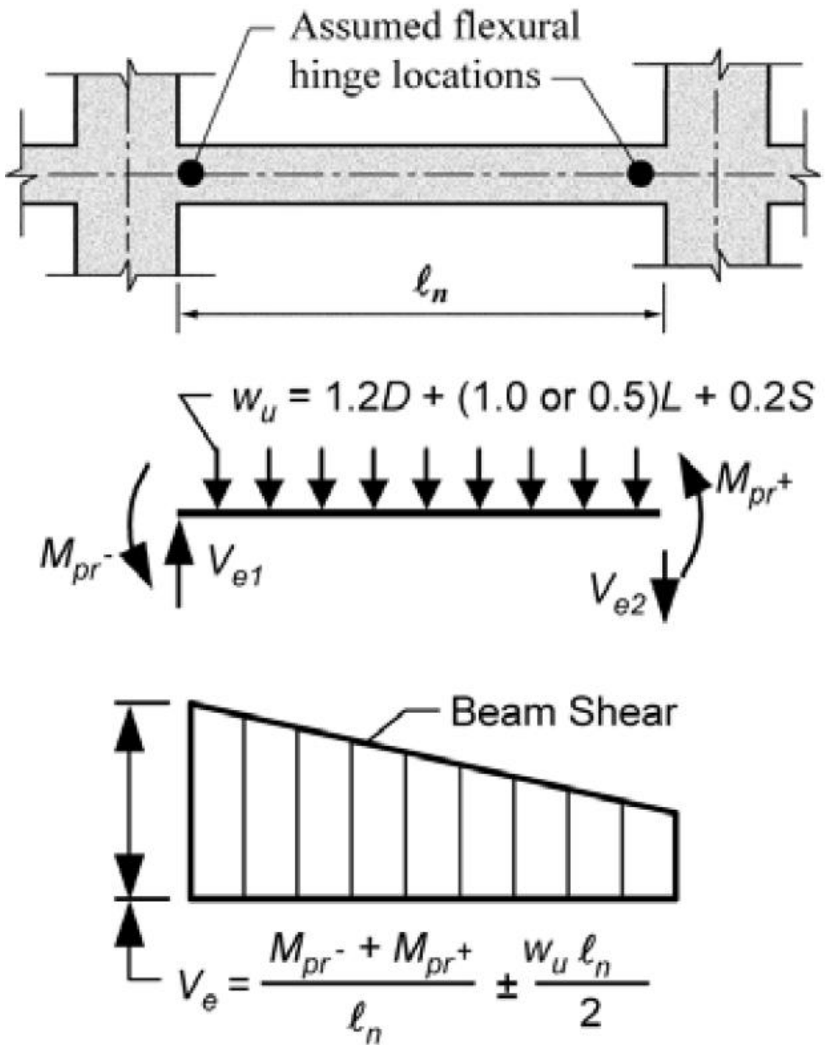
- The overstrength factor 1.25 is thought to be a low estimate of the actual overstrength that might occur for a beam. Reinforcement commonly used in the U.S. has an average yield stress about 15 percent higher than the nominal value (f_y), and it is not unusual for the actual tensile strength to be 1.5 times the actual yield stress. Thus, if a reinforcing bar is subjected to large strains during an earthquake, stresses well above 1.25 f_y are likely.

- The main reason for estimating beam flexural over-strength conservatively is to be certain there is sufficient strength elsewhere in the structure to resist the forces that develop as the beams yield in flexure. The beam overstrength is likely to be offset by overstrength throughout the rest of the building as well.

- The factor 1.25 in ACI 318 was established recognizing all these effects.

Beam Design Shear (in SMRFs)

- Figure illustrates this approach applied to a beam. A free body diagram of the beam is isolated from the frame, and is loaded by factored gravity loads (using the appropriate load combinations defined by ASCE 7) as well as the moments and shears acting at the ends of the beam.
- Assuming the beam is yielding in flexure, the beam end moments are set equal to the probable moment strengths M_{pr}.
- The design shears are then calculated as the shears required to maintain moment equilibrium of the free body (that is, summing moments about one end to obtain the shear at the opposite end).
- This approach is intended to result in a conservatively high estimate of the design shears. For a typical beam in a special moment frame, the resulting beam shears do not trend to zero near mid-span, as they typically would in a gravity-only beam. Instead, most beams in a special moment frame will have non-reversing shear demand along their length. If the shear does
- reverse along the span, it is likely that non-reversing beam plastic hinges will occur.
- Typical practice for gravity-load design of beams is to take the design shear at a distance d away from the column face. For special moment frames, the shear gradient typically is low such that the design shear at d is only marginally less than at the column face. Thus, for simplicity the design shear value usually is evaluated at the column face.



Beam shears are calculated based on provided probable moment strengths combined with factored gravity loads.

SUMMARY – Beam Shear Demand (based on Capacity Design Approach)

In summary, the value of V can be determined as follows.

$$V = \frac{M_{pr1} + M_{pr2}}{l} + \frac{w_u \times l}{2}$$

Where

l = Span length of the beam.

w_u = Ultimate factored load on that beam.

M_{pr1} = Probable moment at one end of beam.

M_{pr2} = Probable moment at other end of beam.

D = Dead load on the beam.

L = Live load on the beam.

S = Snow load on the beam if any.

E_v = Equivalent static load for the vertical component of earthquake.

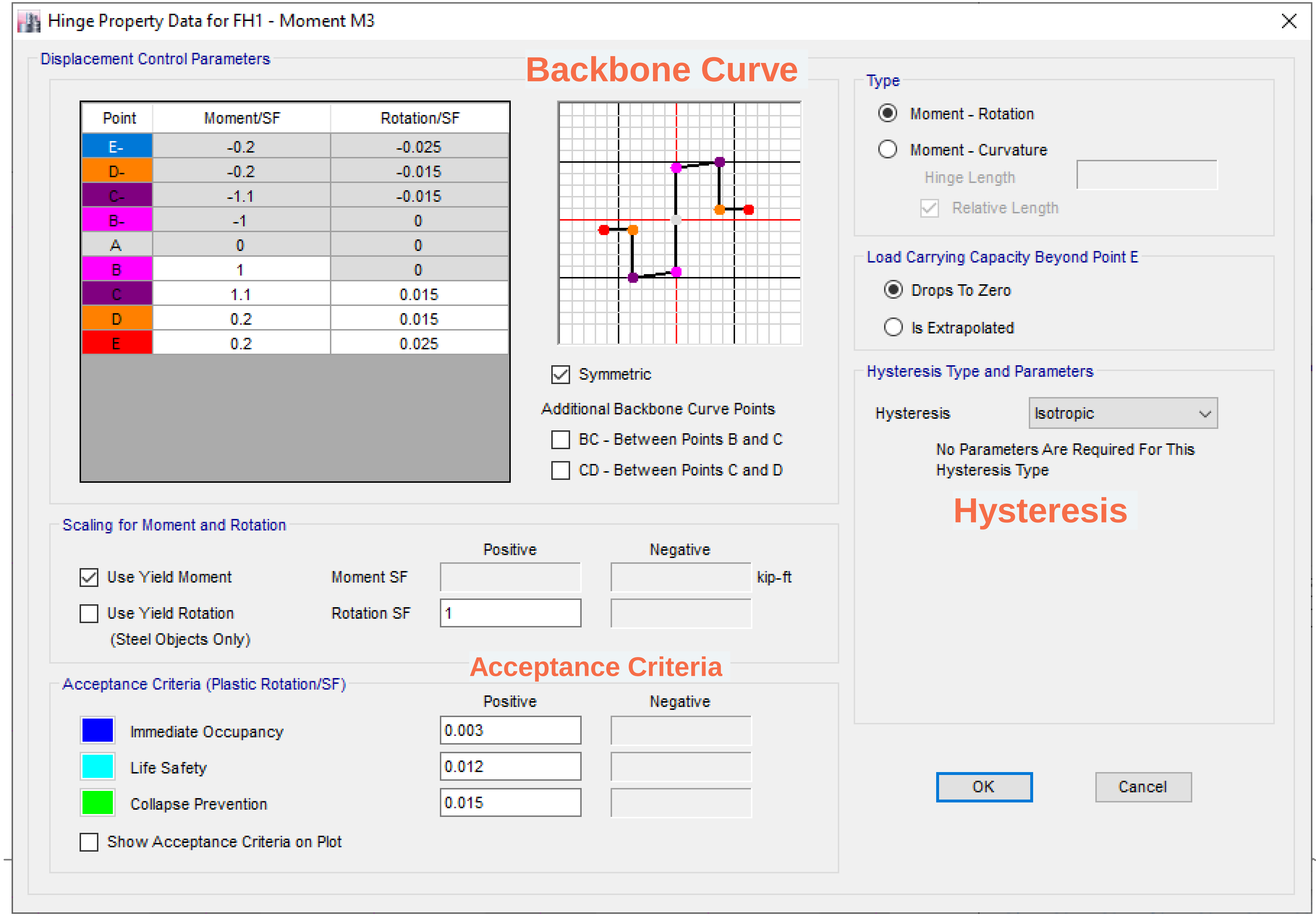
The value of E_v depends on the seismic code used for the analysis and design.

For UBC 97, $E_v = 0.5\, C_a\, I\, D$, where C_a is the seismic coefficient and I is the importance factor.

The ultimate factored load on the beam should be coming from the following load combination:

$$1.2\,D + E_v + (1 \text{ or } 0.5)L + 0.2\,S$$

Definition of M3 Plastic Hinges for Beams (Manual vs. Automatic)



All Inputs Required:

- Yield Moment (M_y)
- Yield Rotation (θ_y)
- MPs: a, b, c
- AC: IO, LS, CP
- $\frac{\rho-\rho'}{\rho_{bal}}$
- Shear reinforcement C/NC
- $\frac{V}{b_w d \sqrt{f'_{cE}}}$
- Hysteretic Model (and its parameters)

Definition of M3 Plastic Hinges for Beams (Manual vs. Automatic)

OPTION 1

1) Define and assign new beam sections based on difference in reinforcement [to automatically determine M_y for M-θ curve and determine $(\rho - \rho')/\rho_{bal})$ factor for using in Table 10-7, ASCE 7-16].
2) Manually determine V using Excel sheet. Run the gravity load analysis first to extract the maximum shear in all beams.
3) Select beams of same type and use Auto option to define PHs.
4) Give manually calculated V (maximum value for one type of beams) from the Excel Sheet. [Same type = Beams having same cross-section size, reinforcement and span (as the V value will depend on span also)].
5) Use "From Current Design" for $(\rho - \rho')/\rho_{bal}$ factor.
6) Manually modify each generated PH to remove moment over-strength and assign suitable hysteretic model.
7) Repeat steps 3 to 6 for each type of beams.

OPTION 2

1) Define and assign new beam sections based on difference in reinforcement [to automatically determine M_y for M-θ curve].
2) For the same type of beams, manually define one PH using a, b, c, IO, LS and CP from the Excel sheet. Select “Use Yield Moment” for the scale factor of moment. Select a suitable hysteretic model. [Same type = Beams governed by the same row in Table 10-7, ASCE 7-16].
3) Manually select all beams which should be assigned the same M-θ curve and IO, LS and CP [i.e. which belong to same row in Table 10-7, ASCE 7-16] and assign that pre-defined PH. Software will generate PHs for all beams with same M-θ curve, IO, LS and CP, and hysteretic behaviour but the M_y will be different for each single beam depending upon its reinforcement.
4) Repeat step 3 for all beam types (corresponding to same row of Table 10-7, ASCE 7-16).

Definition of M3 Plastic Hinges for Beams

OPTION 1
Effort Required vs. Saved

1) Define and assign new beam sections based on difference in reinforcement.
2) Run the gravity load analysis to extract the maximum shear in all beams.
3) Fill the Excel sheet with all details of beams (cross-section, reinforcement, spans and V from gravity load combination)
4) No need to manually define Master PHs
5) Selecting same type of beams (Same type = Beams having same cross-section size, reinforcement and span (as the V value will depend on span also)].
6) More number of beam "types".

7) Give manually calculated V while defining Auto PHs
8) Manually modify each generated PH to remove moment over-strength and assign suitable hysteretic model.

OPTION 2
Effort Required vs. Saved

1) Define and assign new beam sections based on difference in reinforcement.
2) Run the gravity load analysis to extract the maximum shear in all beams.
3) Fill the Excel sheet with all details of beams (cross-section, reinforcement, spans and V from gravity load combination).
4) Define 1 master PH for each type of beams.
5) Selecting same type of beams [Same type = Beams governed by the same row in Table 10-7, ASCE 7-16].
6) Less number of beam "types".

7) No need to manually give V while defining PHs.
8) No need to manually modify each generated PH to remove moment over-strength and assign suitable hysteretic model.

ETABS Demonstration on

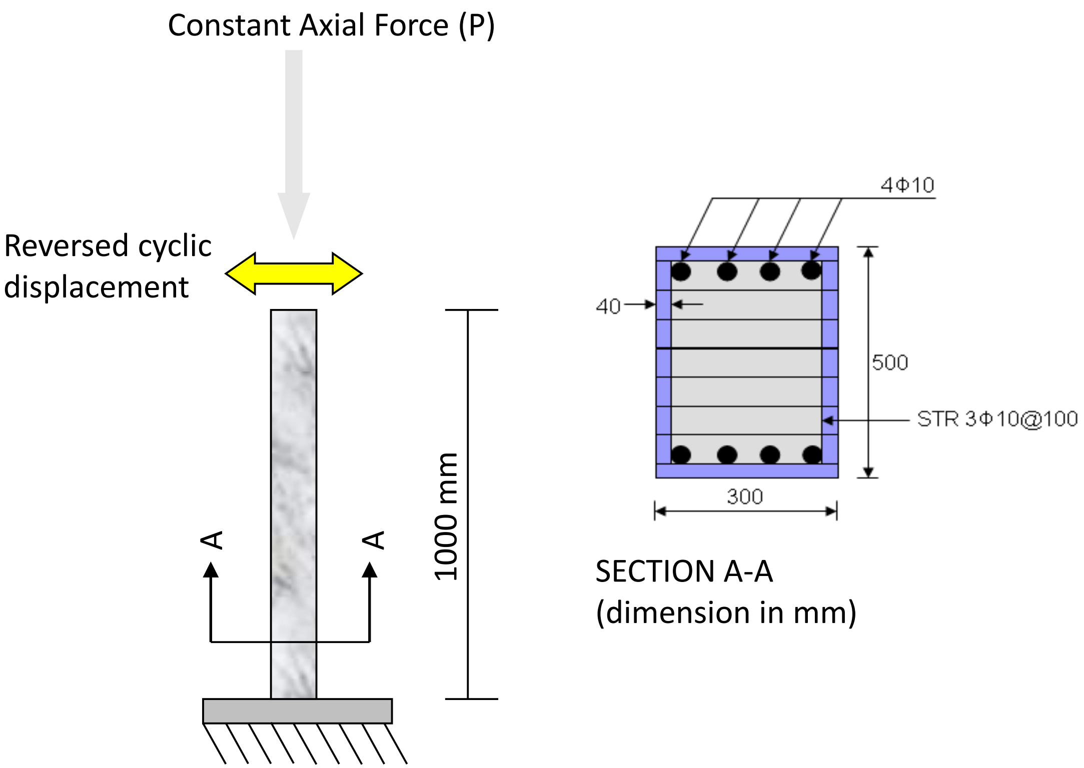
Moment-Rotation Type Plastic Hinge Modeling of RC Beams

Plastic Hinge Modeling of RC Columns using ETABS

Option 1: Manual Definition of Hinge Properties for Every Hinge Type

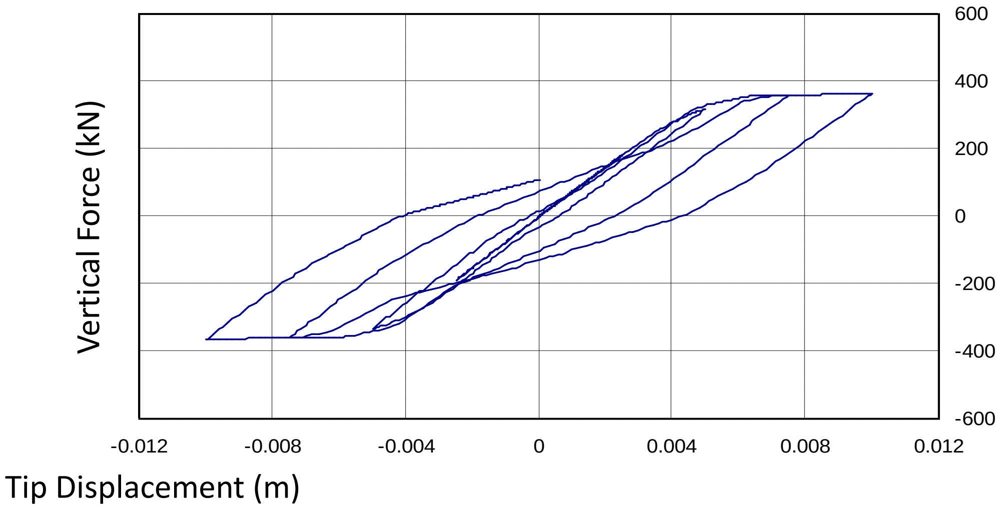
Option 2: Automatic Definition of Hinge Properties by the Program

Analytical Plastic Hinge Response

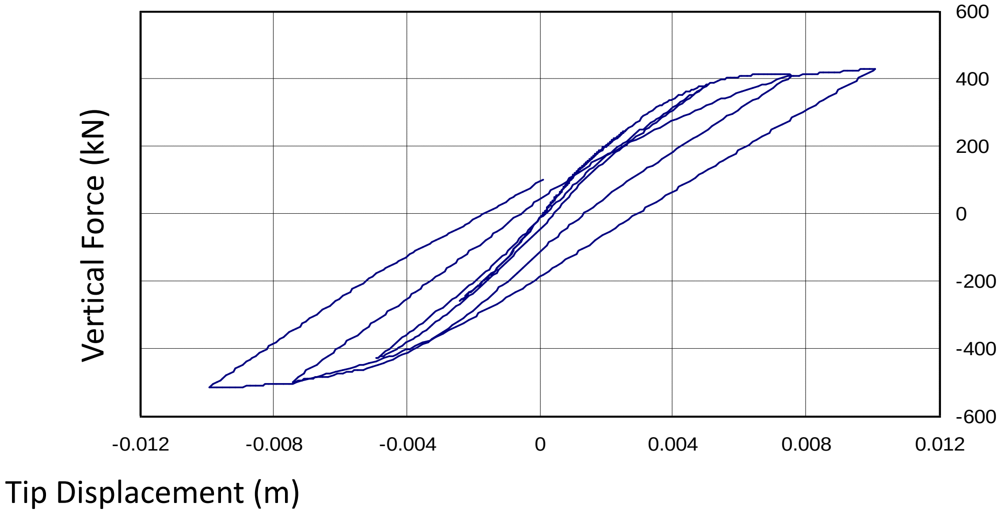


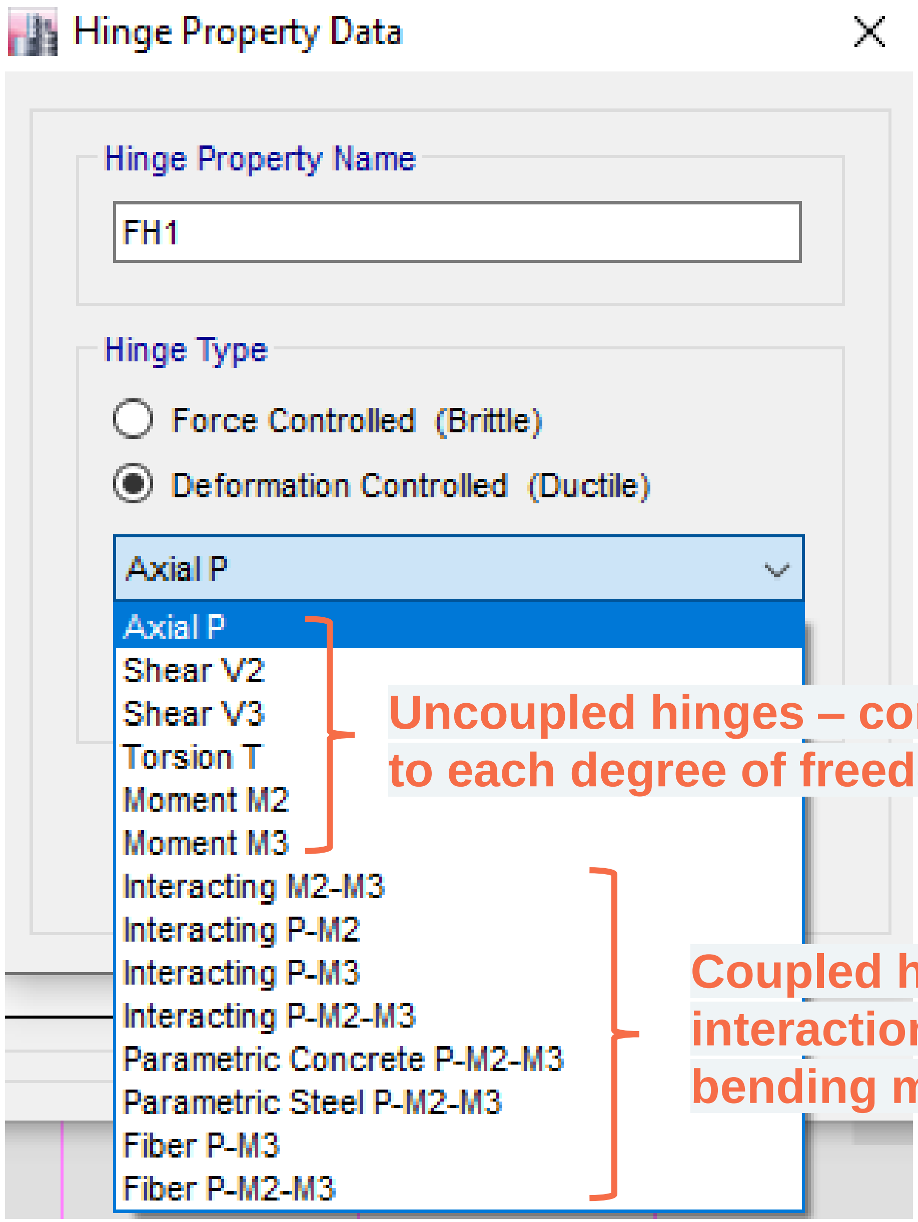
SECTION A-A
(dimension in mm)

CASE A – [P = 0 kN]



CASE B – [P = 100 kN]





Uncoupled hinges – corresponding to each degree of freedom

Coupled hinges – These hinges yield based on the interaction of (any combination of) axial force and bi-axial bending moments at the hinge location

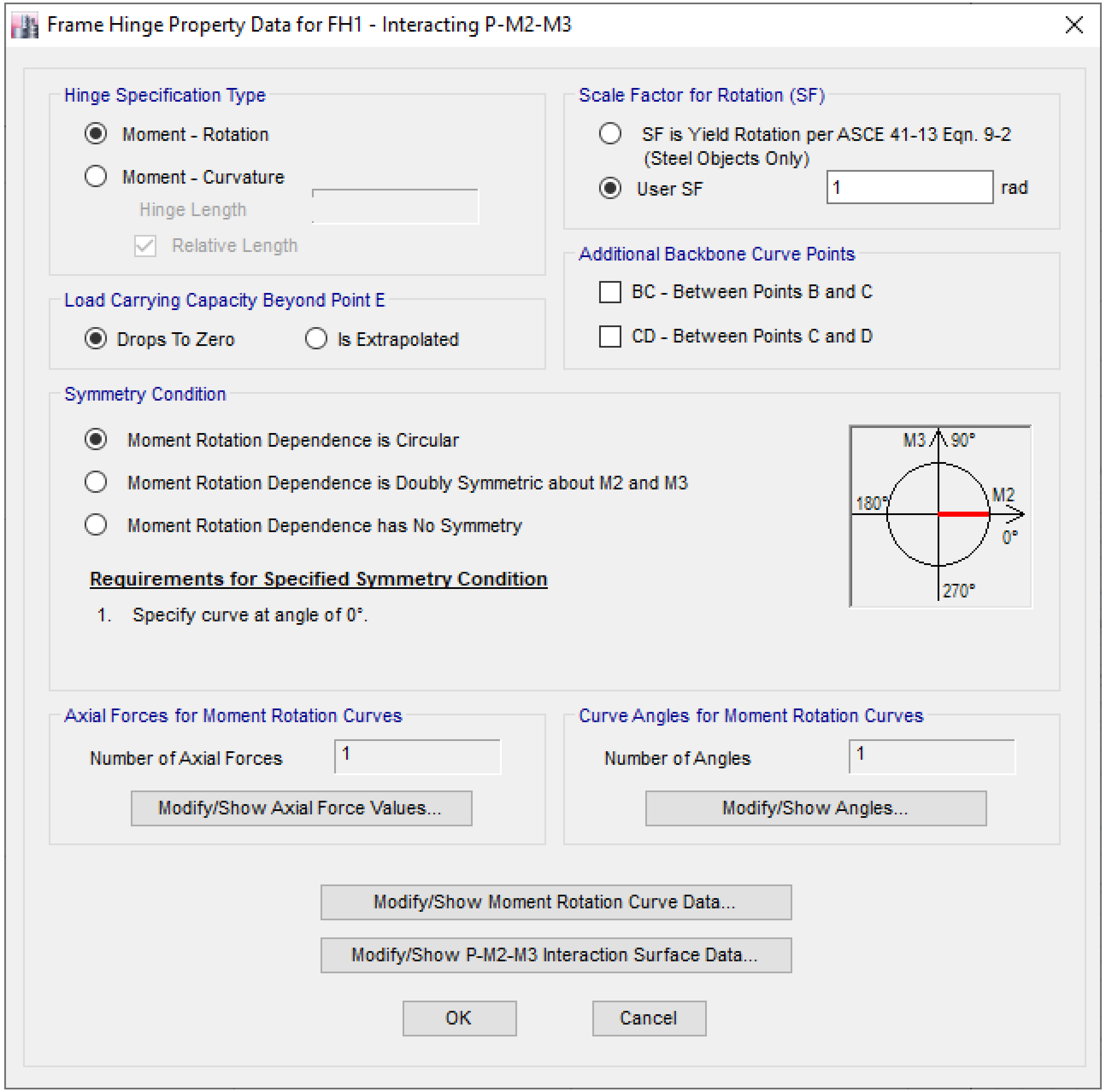
Interacting Plastic Hinges

- Interacting Hinge Types
  - M2-M3 Hinge Rotation and Curvature Types
  - P-M2 Hinge Rotation and Curvature Types
  - P-M3 Hinge Rotation and Curvature Types
  - P-M2-M3 Hinge Rotation and Curvature Type
  - V2-V3 Shear Hinge (Not available in ETABS)
  - Fiber P-M2-M3 Hinge

Moment vs. Rotation

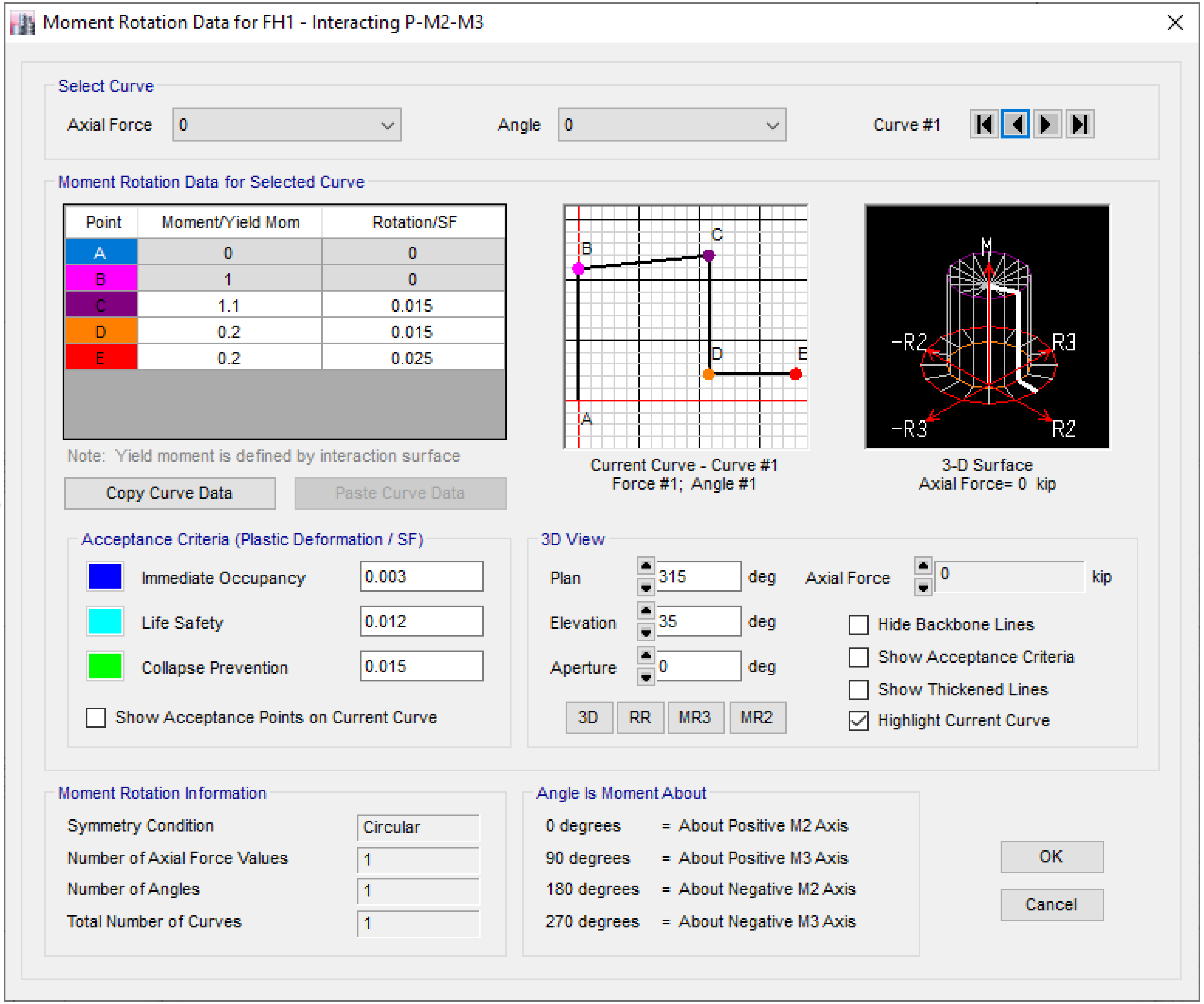
Behaviour for P-M2-M3

Interacting Hinges

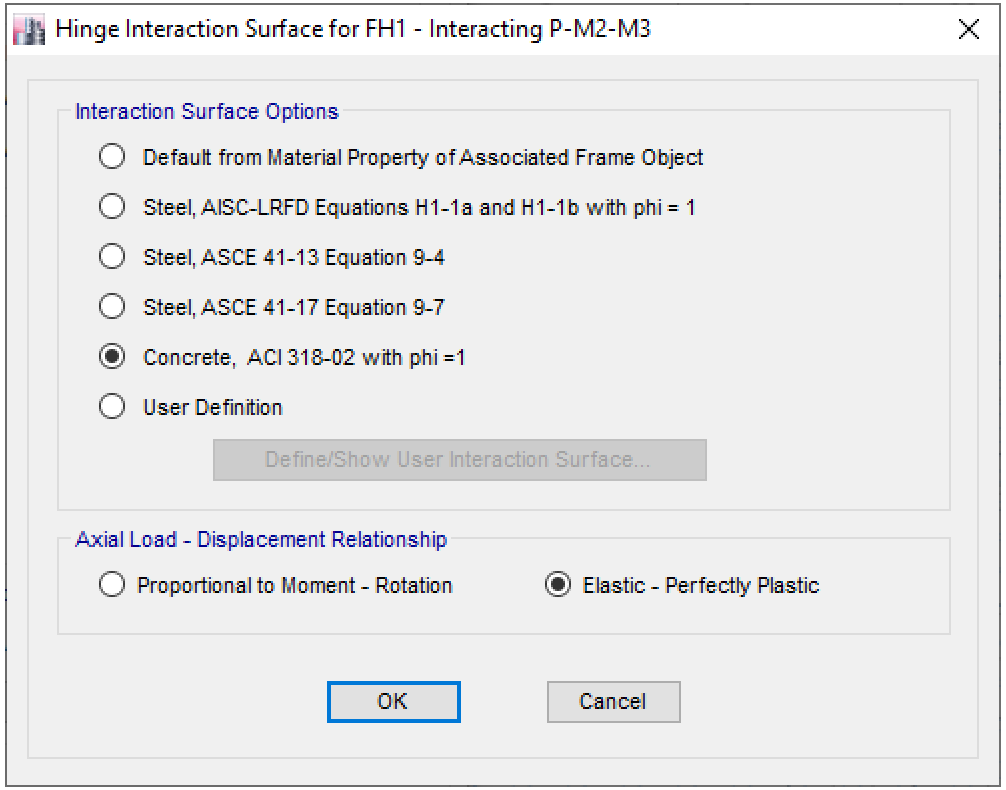


Moment vs. Rotation Behaviour

(Defined as a function of Axial Force and Angle)



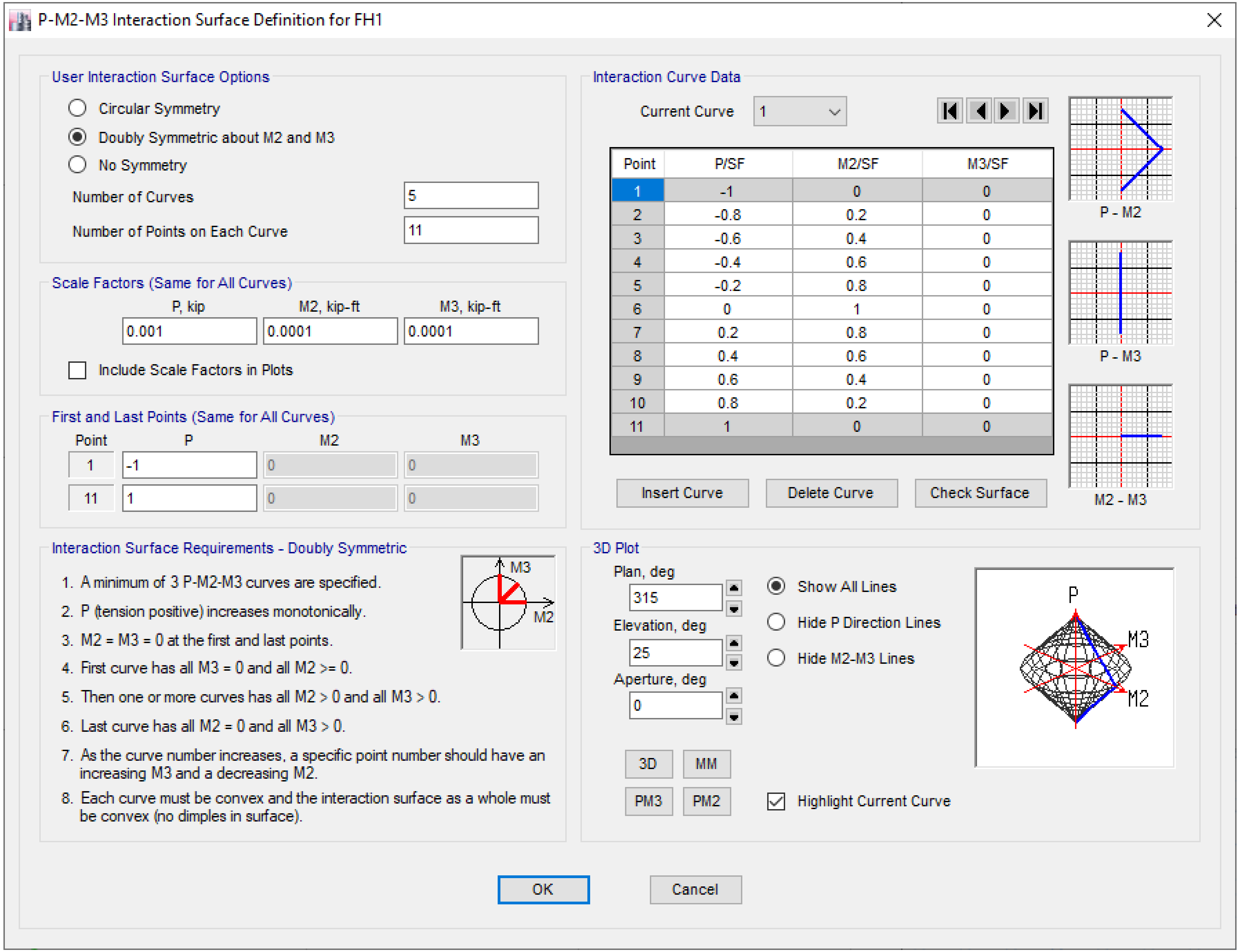
Hinge Interaction Surface



User-defined

Hinge Interaction

Surface



Types of P-M2-M3 Hinges

- Normally the hinge properties for each of the six degrees of freedom are uncoupled from each other. However, you have the option to specify coupled axial-force/bi-axial-moment behavior.
- This is called a P-M2-M3 or PMM hinge. Three types are available. In summary:
  - **a) Isotropic P-M2-M3 hinge:** This hinge can handle complex and unsymmetrical PMM surfaces and can interpolate between multiple moment-rotation curves. Two-dimensional subsets of the hinge are available. It is limited to isotropic hysteresis, which may not be suitable for some structures.
  - **b) Parametric P-M2-M3 hinge:** This hinge is limited to doubly symmetric section properties and uses a simple parametric definition of the PMM surface. Hysteretic energy degradation can be specified, making it more suitable than the isotropic hinge for extensive cyclic loading.
  - **c) Fiber P-M2-M3 hinge.** This is the most realistic hinge, but may require the most computational resources in terms of analysis time and memory usage. Various hysteresis models are available and they can be different for each material in the hinge.

Isotropic P-M2-M3 Hinge

- This hinge can handle complex and unsymmetrical PMM surfaces and can interpolate be tween multiple moment-rotation curves. It is limited to isotropic hysteresis, which may not be suitable for some structures.
- Three additional coupled hinges are avail able as sub sets of the PMM hinge: P-M2, P-M3, and M2-M3 hinges.

Isotropic P-M2-M3 Hinges - Interaction (Yield) Surface

- For the PMM hinge, you specify an interaction (yield) surface in three-dimensional P-M2-M3 space that represents where yielding first occurs for different combinations of axial force P, minor moment M2, and major moment M3.
- The surface is specified as a set of P-M2-M3 curves, where P is the axial force (tension is positive), and M2 and M3 are the moments. For a given curve, these moments may have a fixed ratio, but this is not necessary.
- The following rules apply:
  - All curves must have the same number of points.
  - For each curve, the points are ordered from most negative (compressive) value of P to the most positive (tensile).
  - The three values P, M2 and M3 for the first point of all curves must be identical, and the same is true for the last point of all curves.
  - When the M2-M3 plane is viewed from above (looking toward compression), the curves should be defined in a counter-clock wise direction.
  - The sur face must be con vex. This means that the plane tangent to the surface at any point must be wholly outside the surface. If you define a surface that is not convex, the program will automatically increase the radius of any points which are “pushed in” so that their tangent planes are outside the surface. A warning will be issued during analysis that this has been done.
- You can explicitly define the interaction surface, or let the program calculate it using one of the following formulas:
  - Steel, AISC-LRFD Equations H1-1a and H1-1b with phi = 1
  - Steel, FEMA-356 Equation 5-4
  - Concrete, ACI 318-02 with phi = 1
- You may look at the hinge properties for the generated hinge to see the specific surface that was calculated by the program.

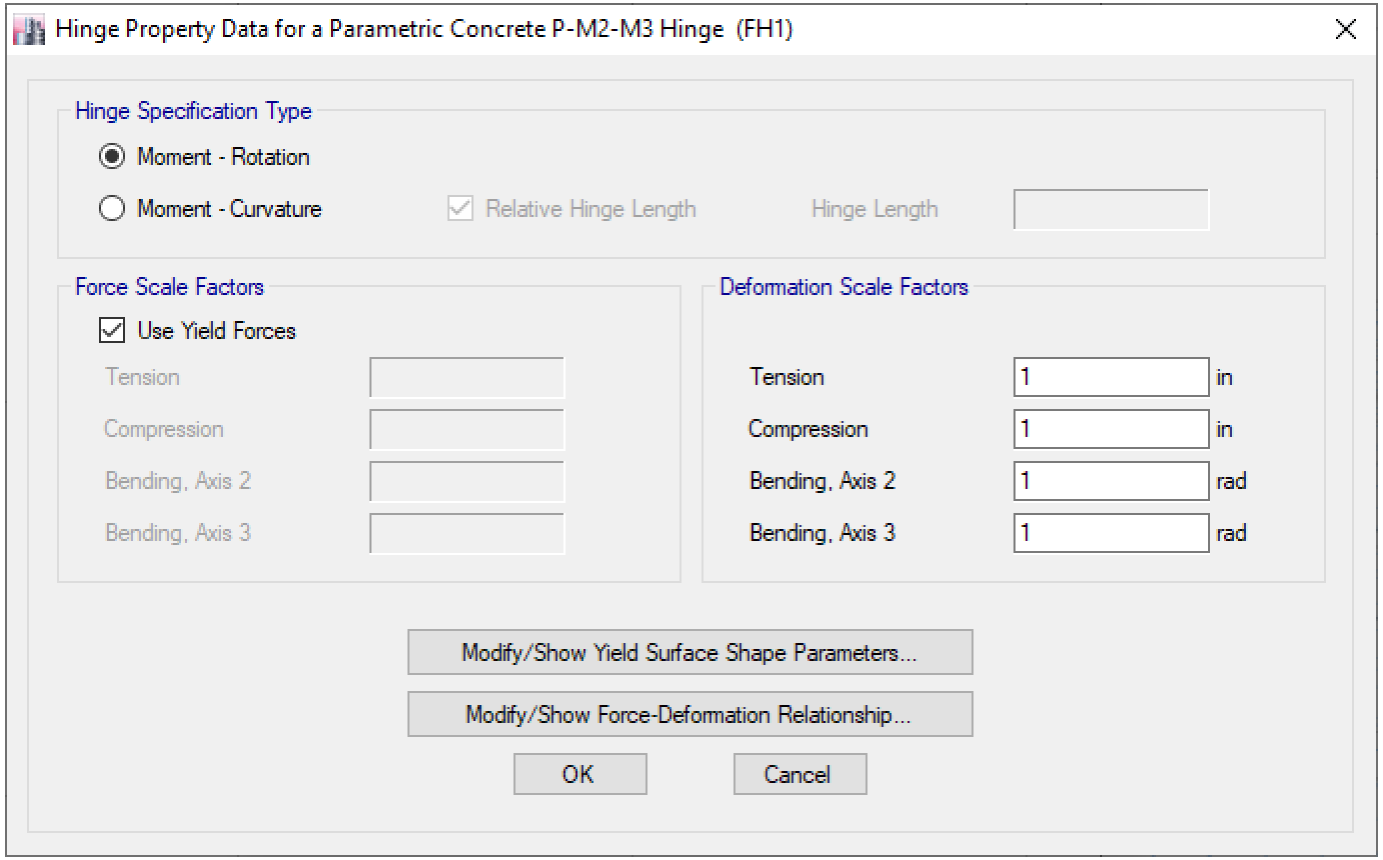
Isotropic P-M2-M3 Hinges - Moment-Rotation Curves

- For PMM hinges you specify one or more moment/plastic-rotation curves corresponding to different values of P and moment angle q. The moment angle is measured in the M2-M3 plane, where 0° is the positive M2 axis, and 90° is the positive M3 axis. You may specify one or more axial loads P and one or more moment angles q.
- During analysis, once the hinge yields for the first time, i.e., once the values of P, M2 and M3 first reach the interaction surface, a net moment-rotation curve is interpolated to the yield point from the given curves. This curve is used for the rest of the analysis for that hinge.
- If the values of P, M2, and M3 change from the values used to interpolate the curve, the curve is adjusted to provide an energy equivalent moment-rotation curve. This means that the area under the moment-rotation curve is held fixed, so that if the resultant moment is smaller, the ductility is larger. This is consistent with the underlying stress strain curves of axial “fibers” in the cross section.
- As plastic deformation occurs, the yield surface changes size according to the shape of the M-Rp curve, depending upon the amount of plastic work that is done. You have the option to specify whether the surface should change in size equally in the P, M2, and M3 directions, or only in the M2 and M3 directions. In the latter case, axial deformation behaves as if it is perfectly plastic with no hardening or collapse.

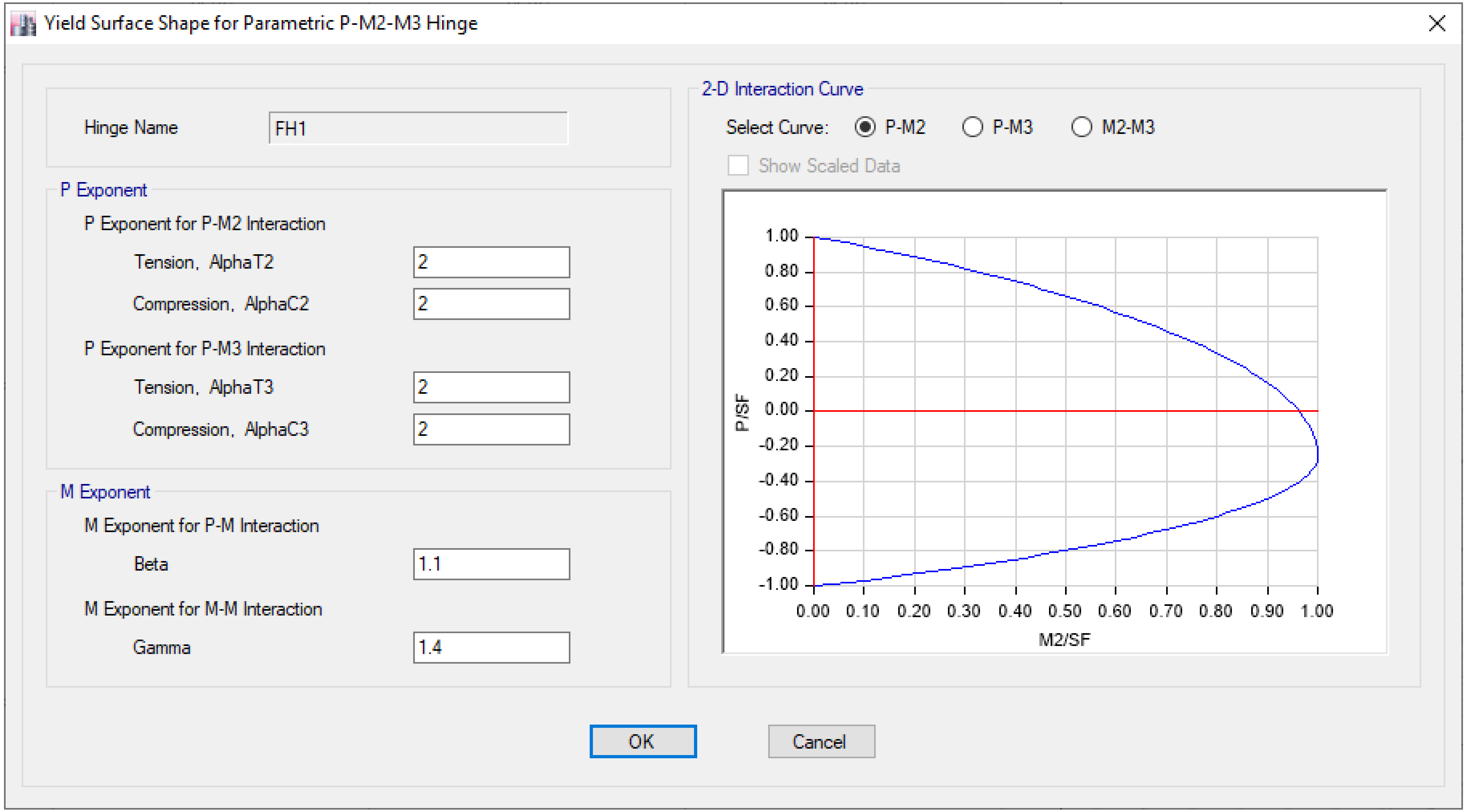
Parametric P-M2-M3 Hinge

- This hinge is limited to doubly symmetric section properties and uses a simple parametric definition of the PMM surface. Hysteretic energy degradation can be specified, making it more suitable than the isotropic hinge for extensive cyclic loading.
- Two versions of the hinge are available, one for steel frame sections, and one for reinforced-concrete frame sections.
- Currently this hinge is only available in ETABS, and will be added to SAP2000 and CSI Bridge in subsequent versions.
- The description and theory for this hinge formulation are presented in the Technical Note "Parametric P-M2-M3 Hinge Model". This document can be found in the Manuals subfolder where the soft ware is installed on your computer. It can be accessed from inside the software using the menu command Help > Documentation > Technical Notes.
- Detailed descriptions of the input values needed to define the properties for either the steel or concrete hinge are available from the Help facility within the software.
- This can be accessed using the menu command Help > Product Help, or pressing the F1 key at any time.

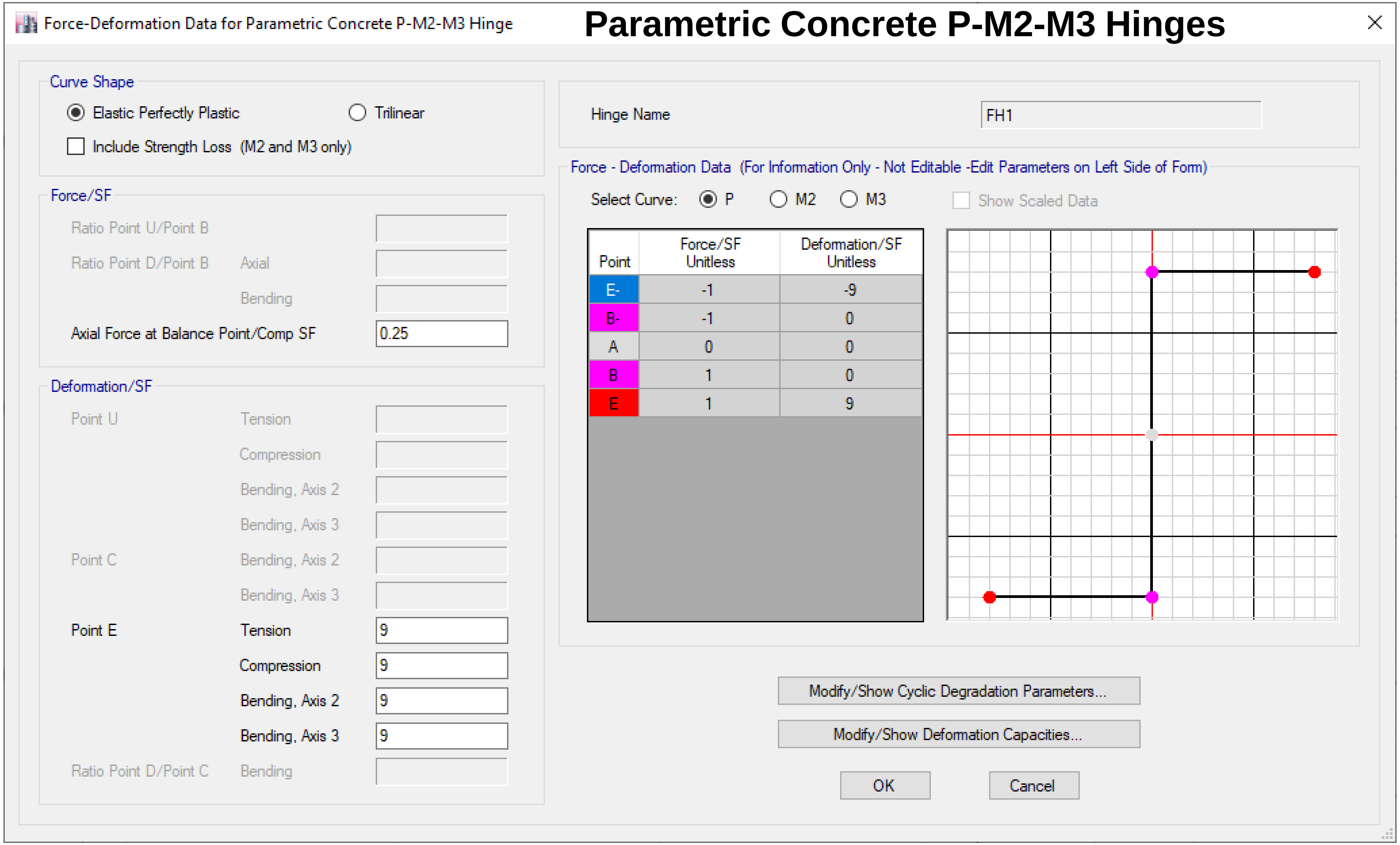
Parametric Concrete P-M2-M3 Hinges



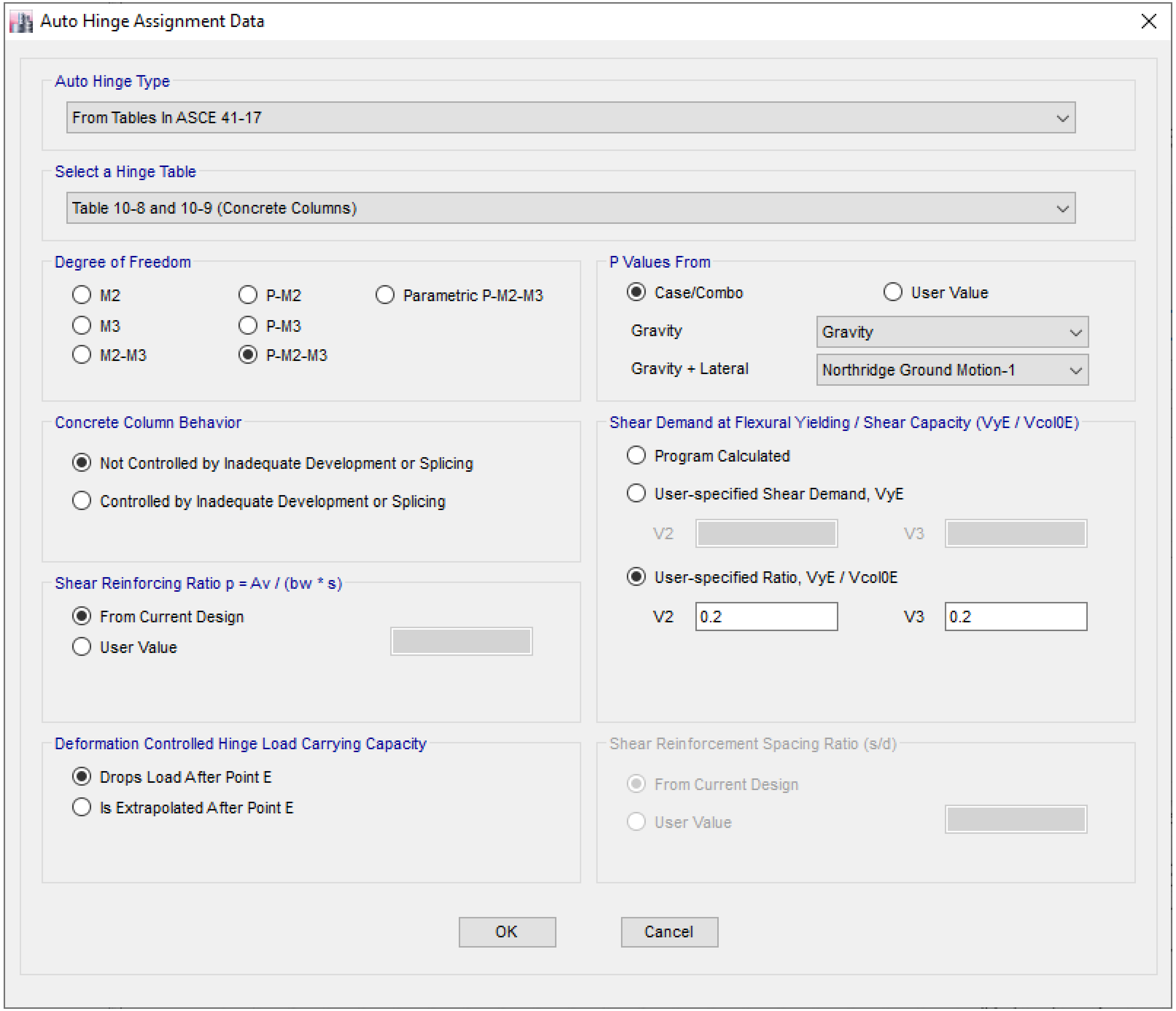
Parametric Concrete P-M2-M3 Hinges



Parametric Concrete P-M2-M3 Hinges



Automatic Definition of Column Hinge Properties



ETABS Demonstration on

Moment-Rotation Type Plastic Hinge Modeling of RC Columns

Thank you