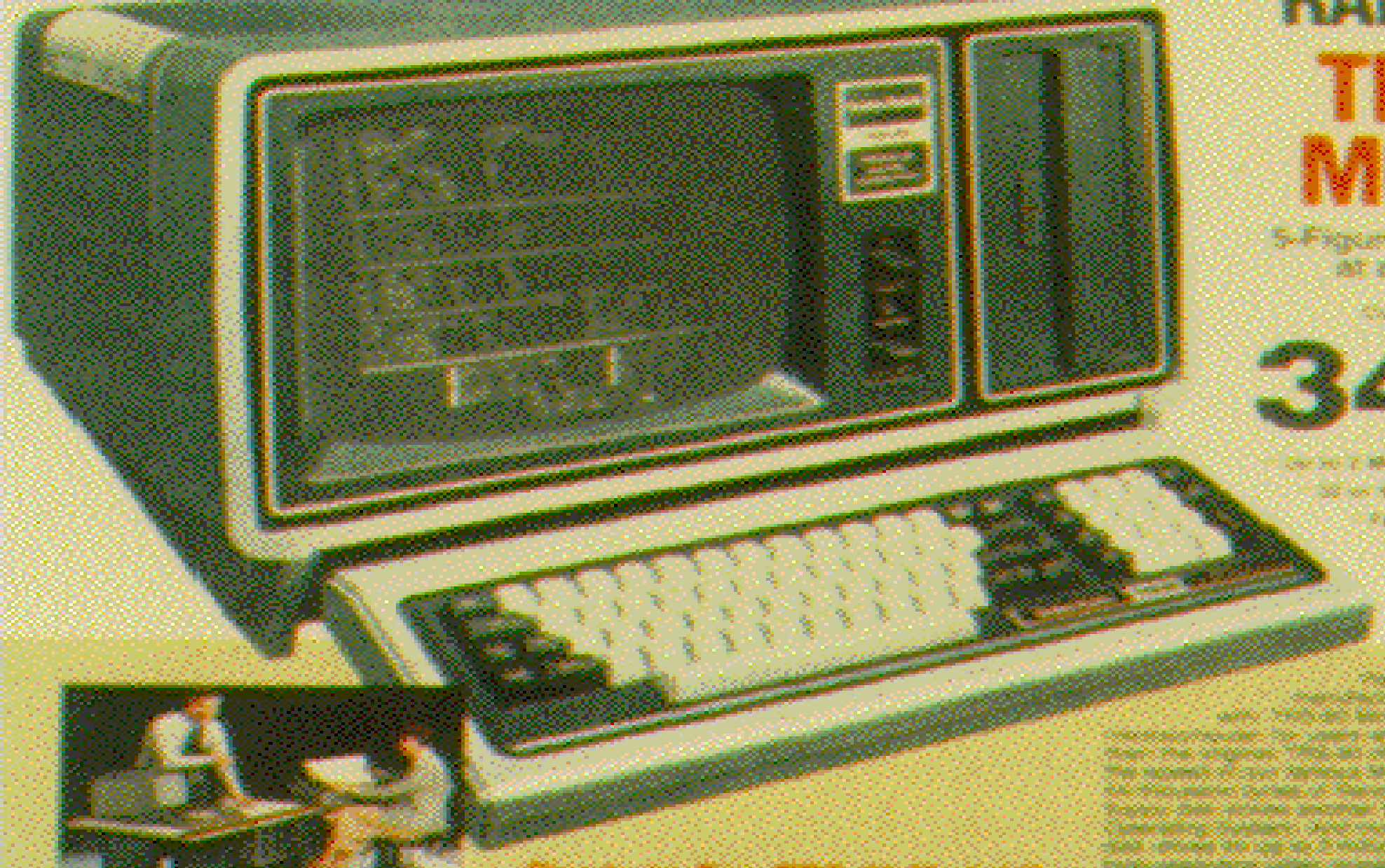
The theory and practice of PERFORMANCE-BASED DESIGN

THE FUTURE OF EARTHQUAKE ENGINEERING

Ashraf Habibullah
President and CEO, Computers & Structures, Inc.

NEW ANOTHER BREAKTHROUGH FROM RADIO SHACK!

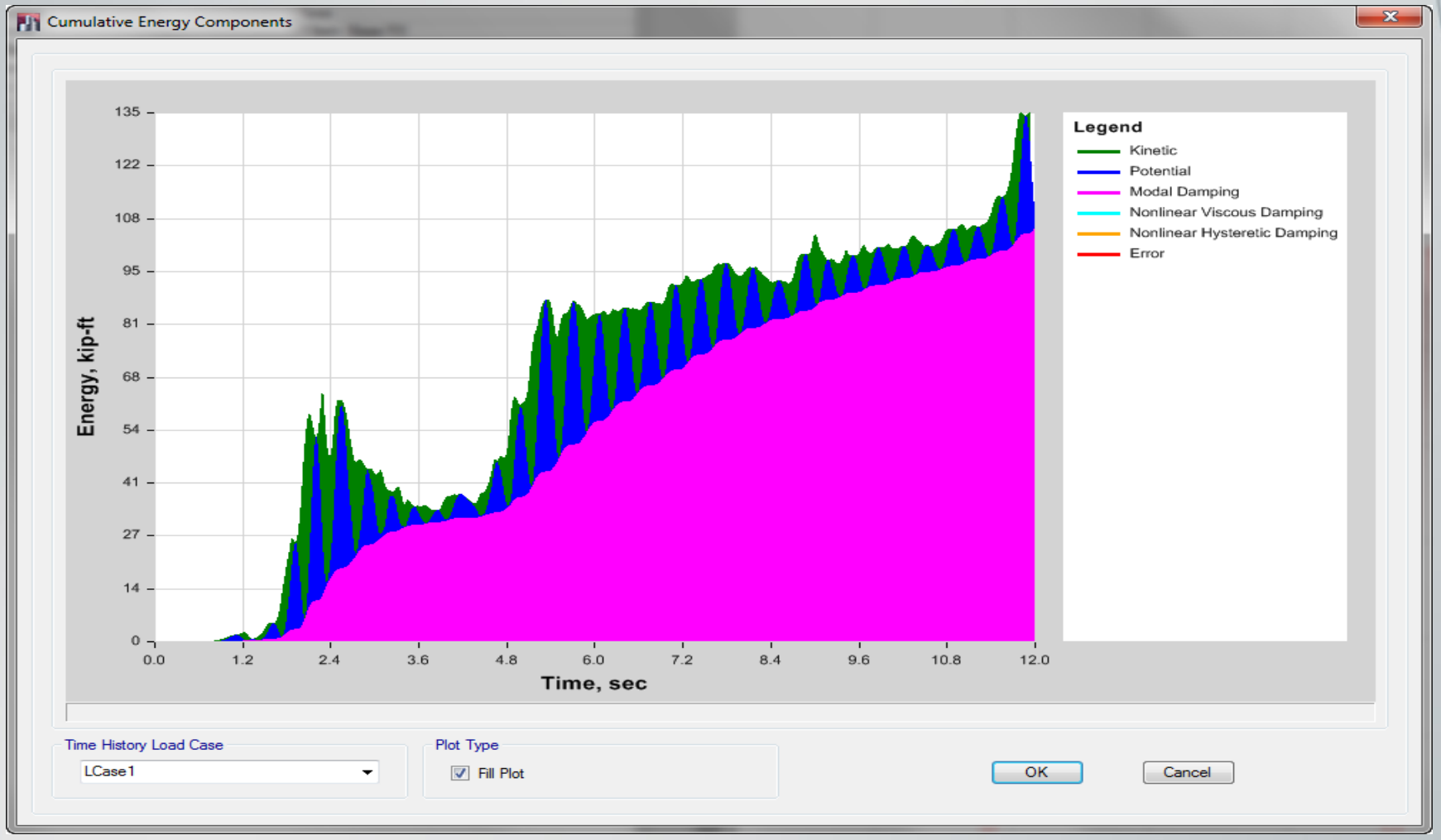


TRS-80 MODEL II

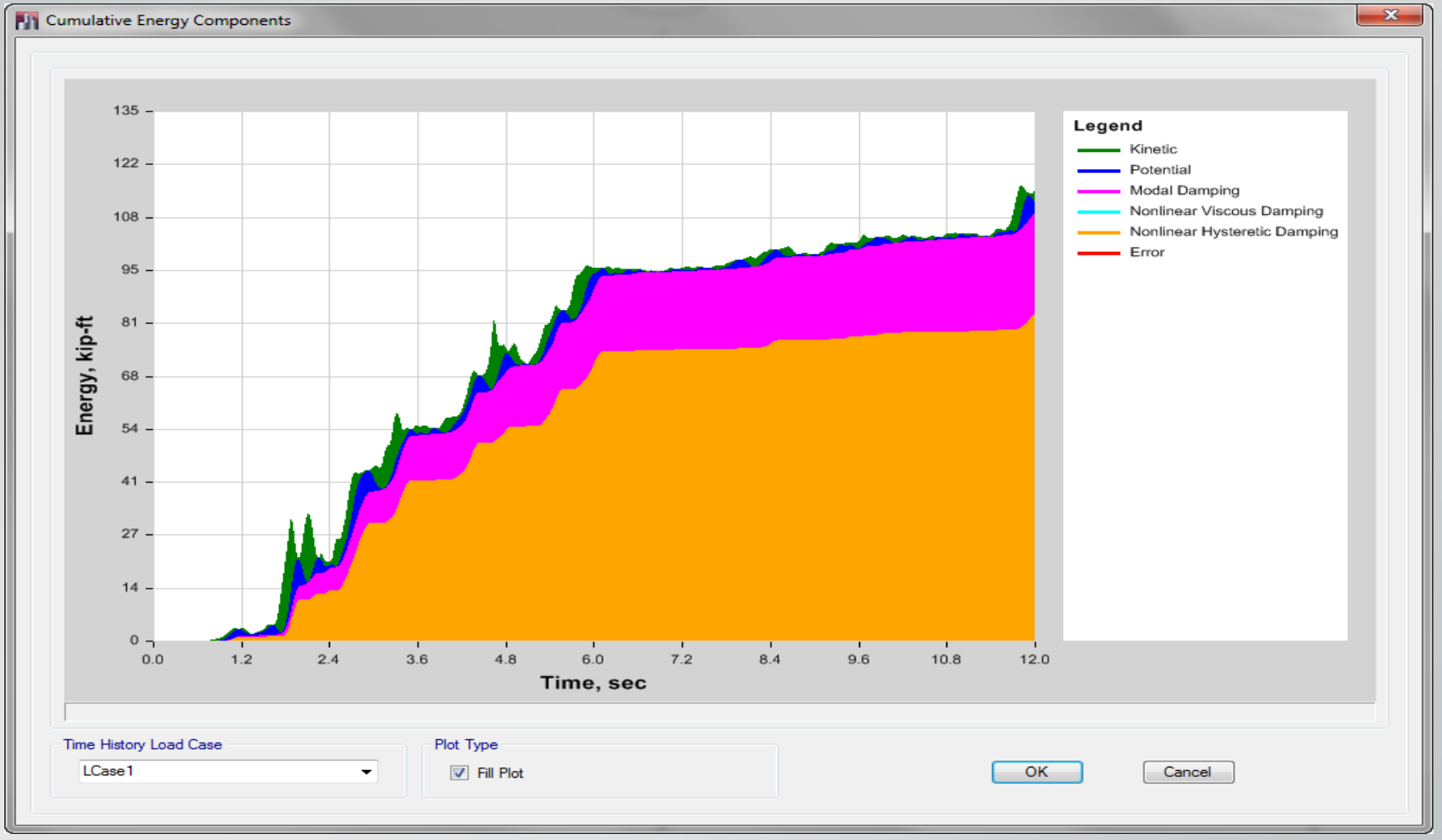
5-Figure Computing Power at a 4-Figure Price*

3450.00

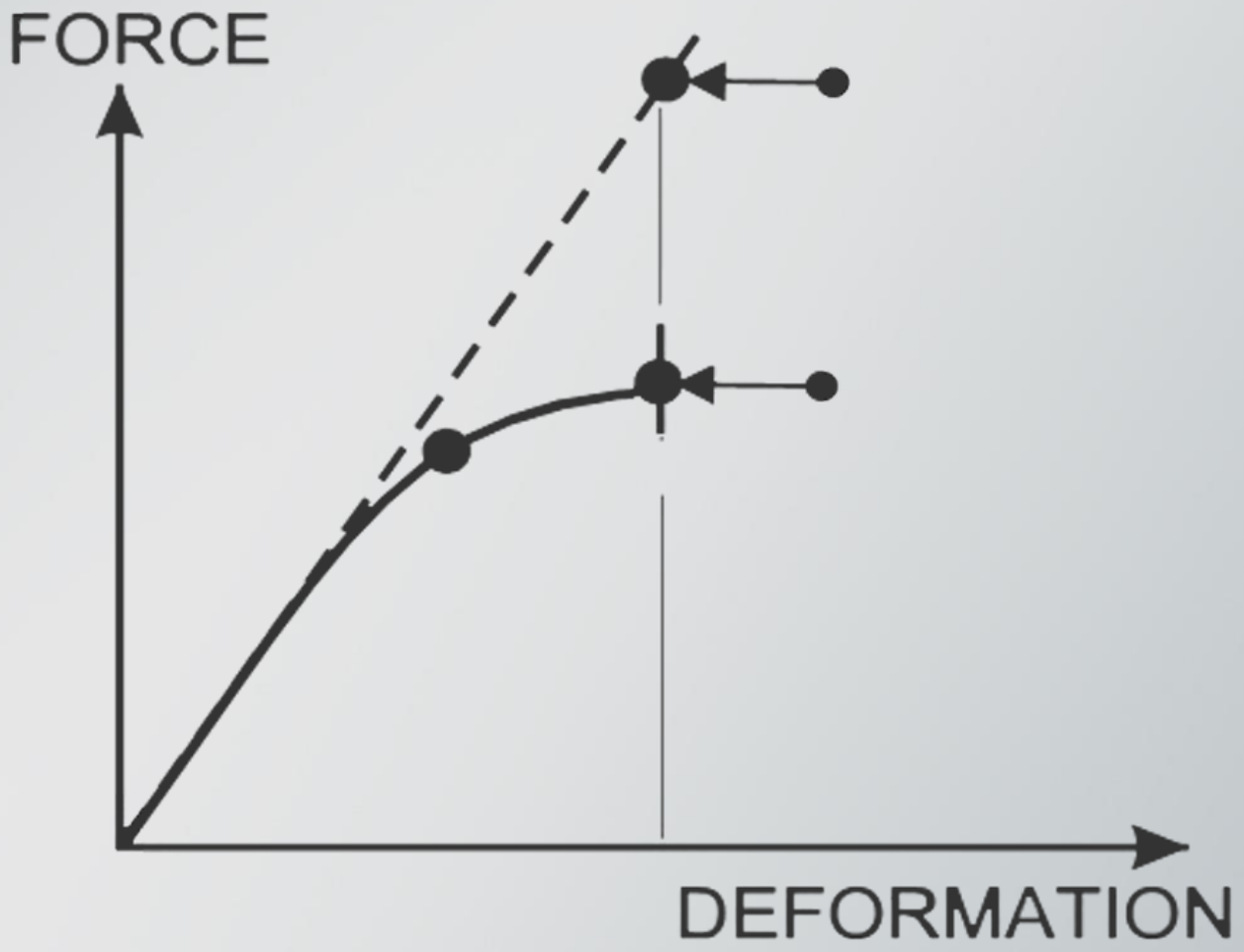
ENERGY DIAGRAM



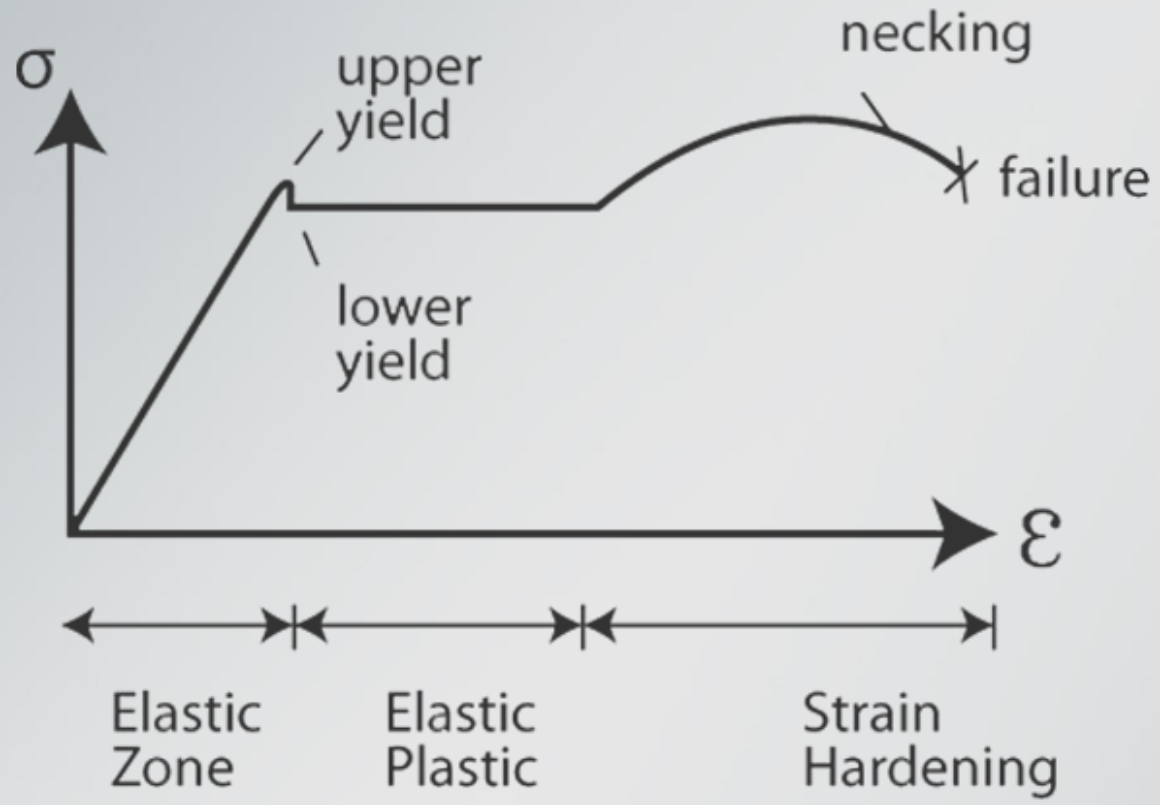
ENERGY DIAGRAM w/ HYSTERETIC

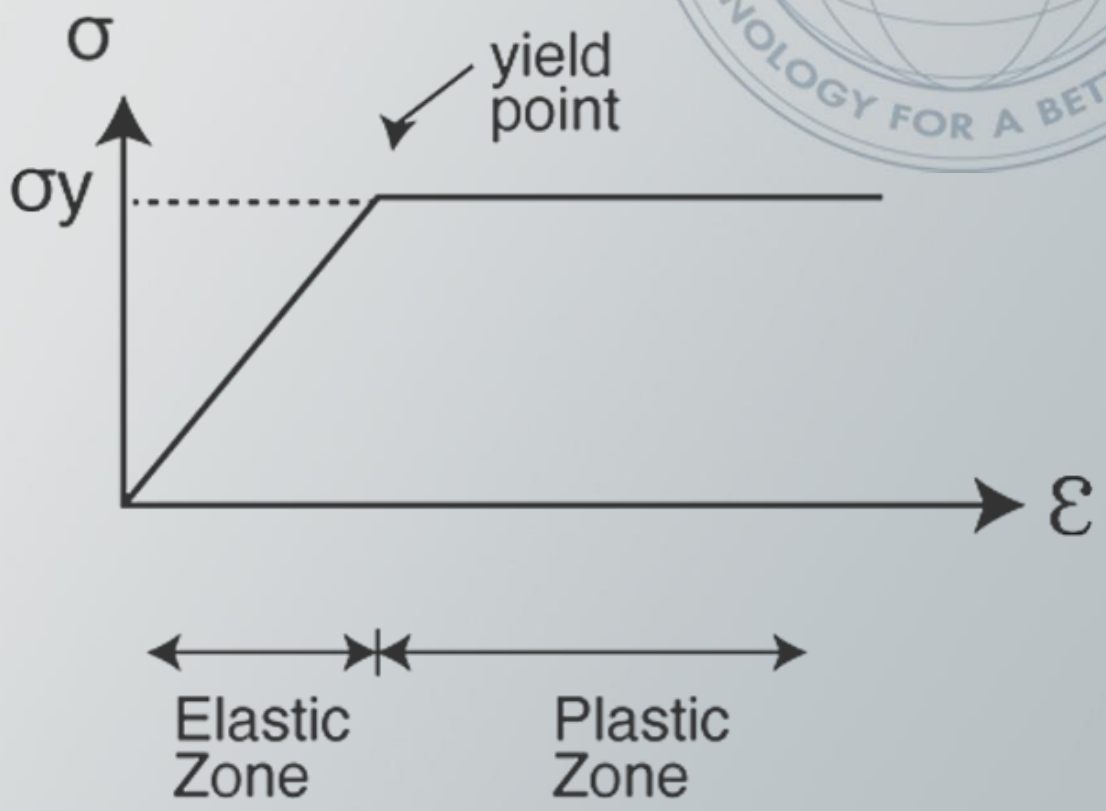


IMPLIED NONLINEAR BEHAVIOR

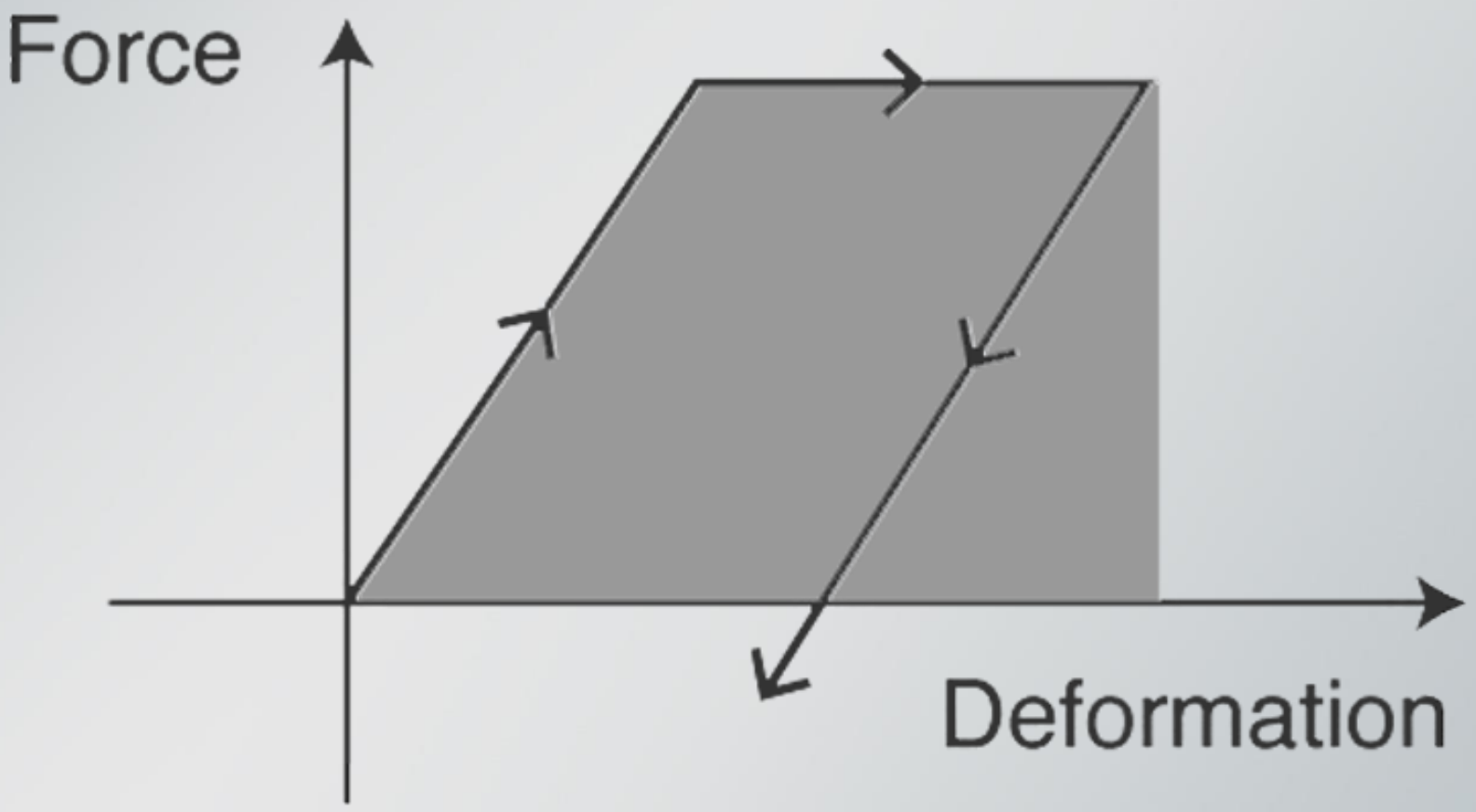


STEEL STRESS STRAIN RELATIONSHIPS

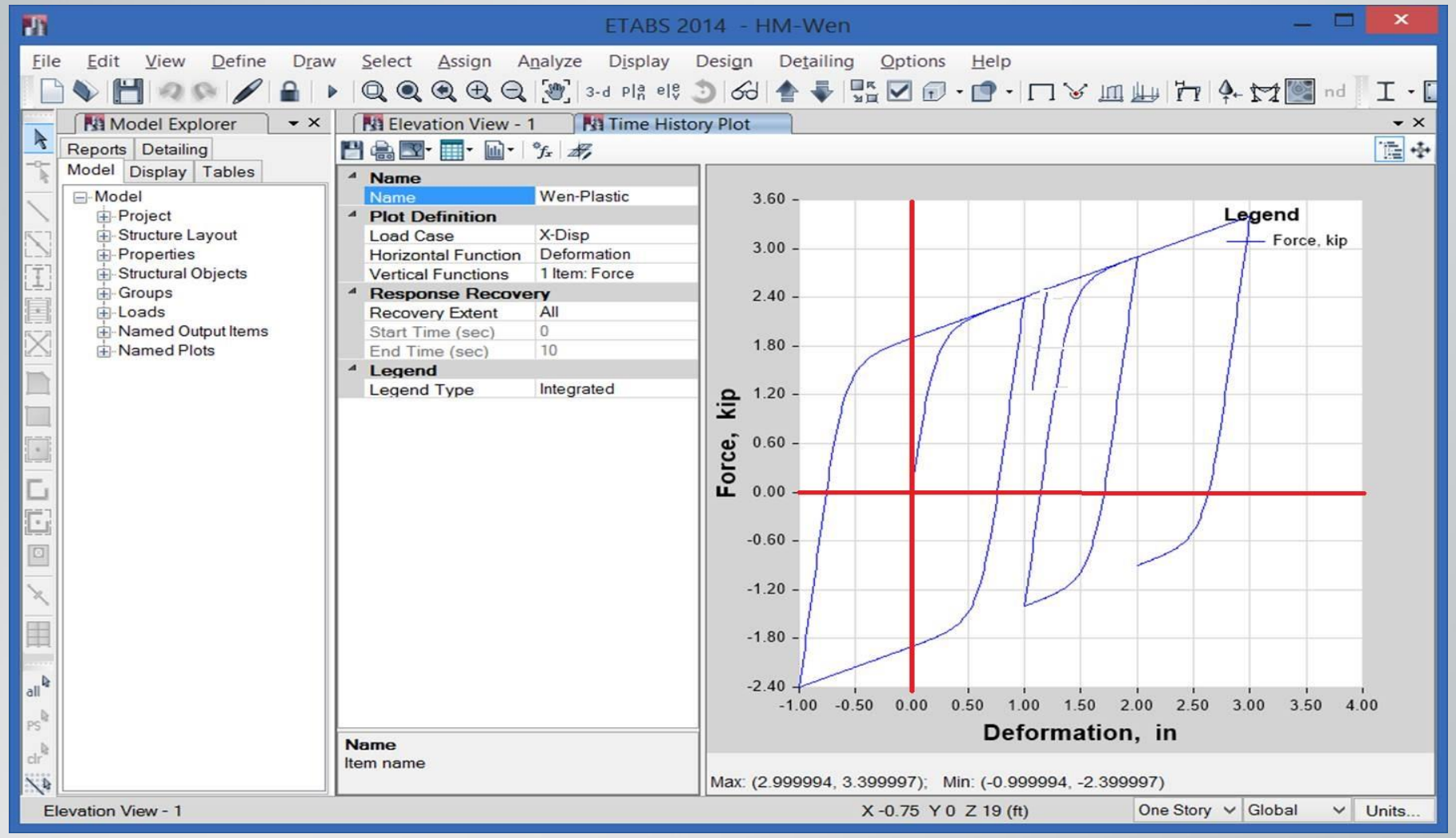




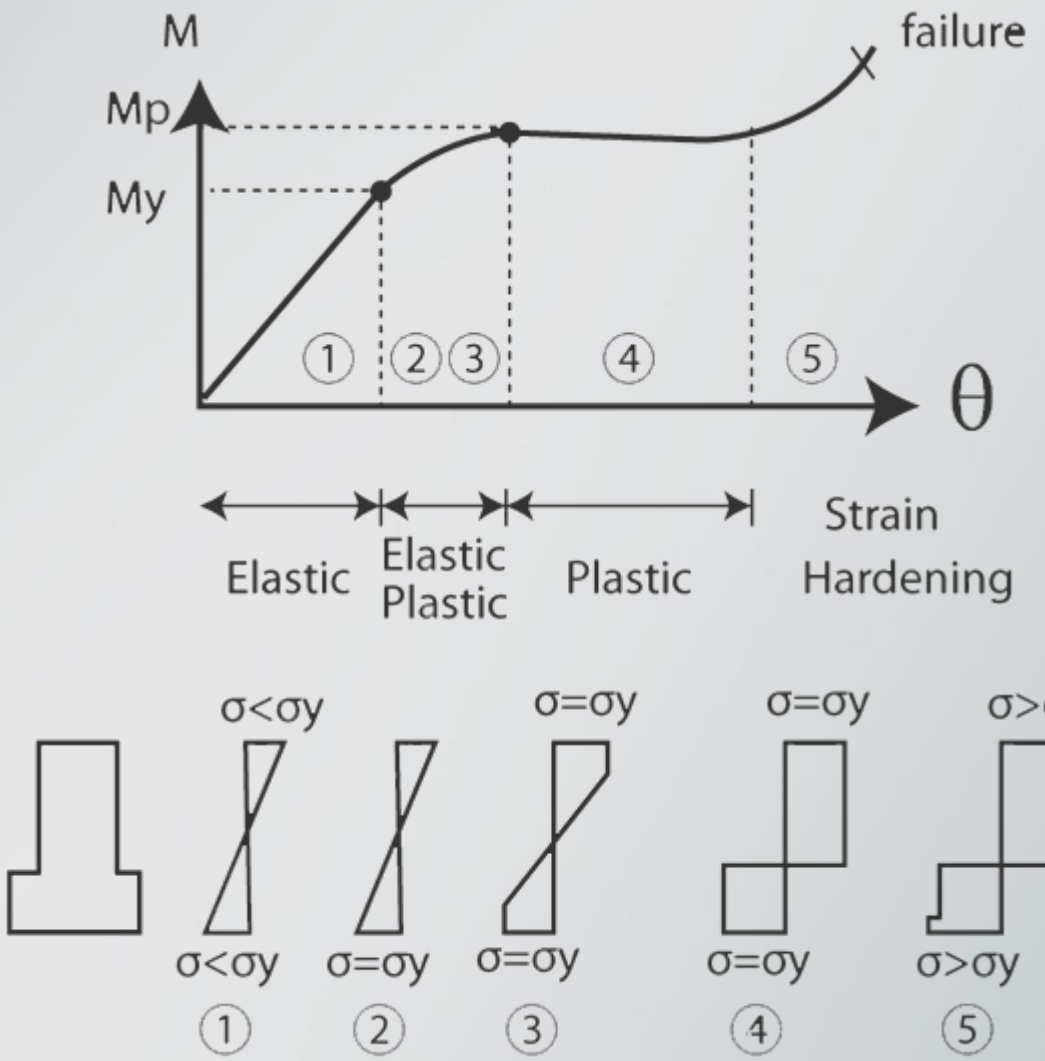
INELASTIC WORK DONE



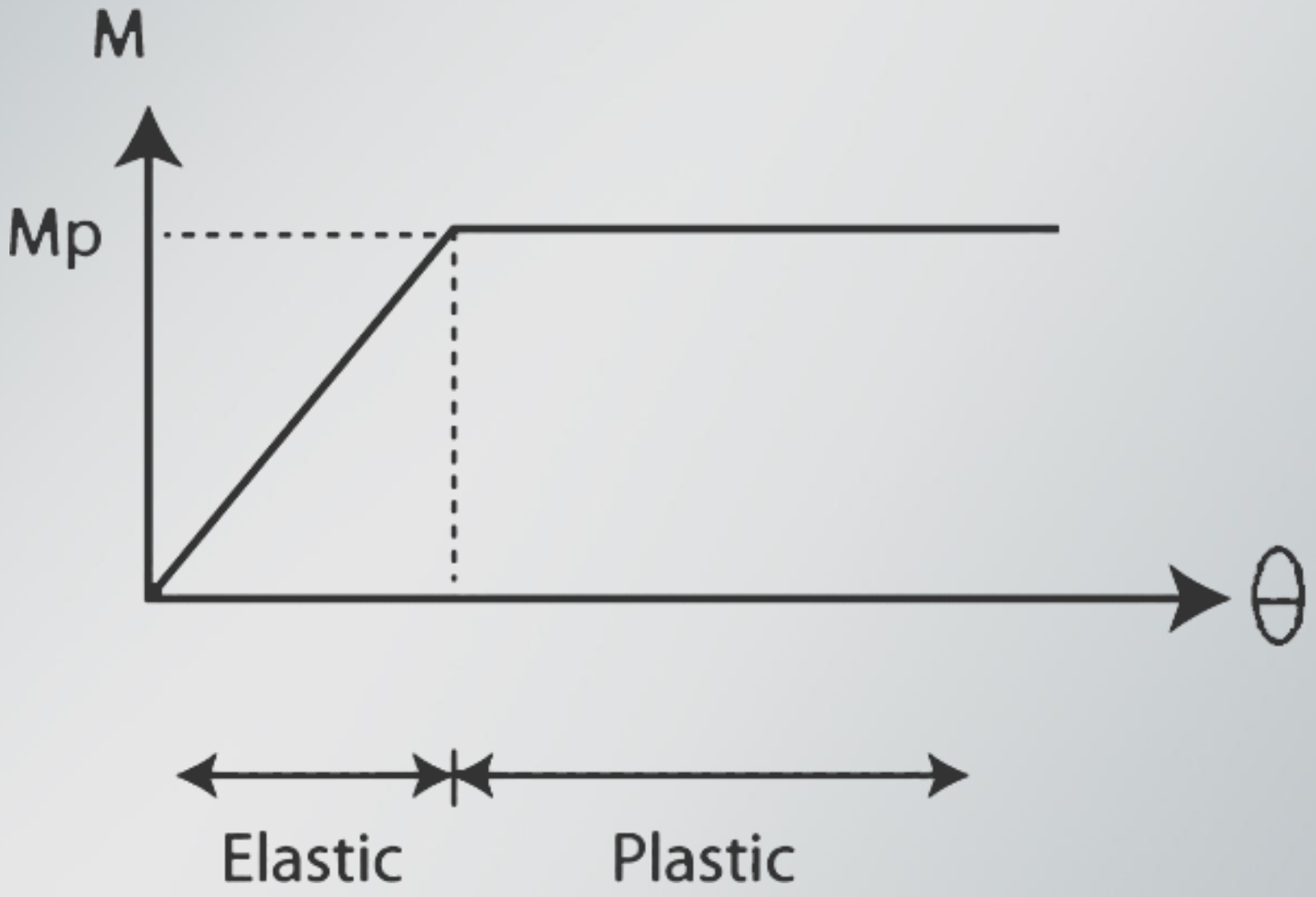
HYSTERETIC BEHAVIOR



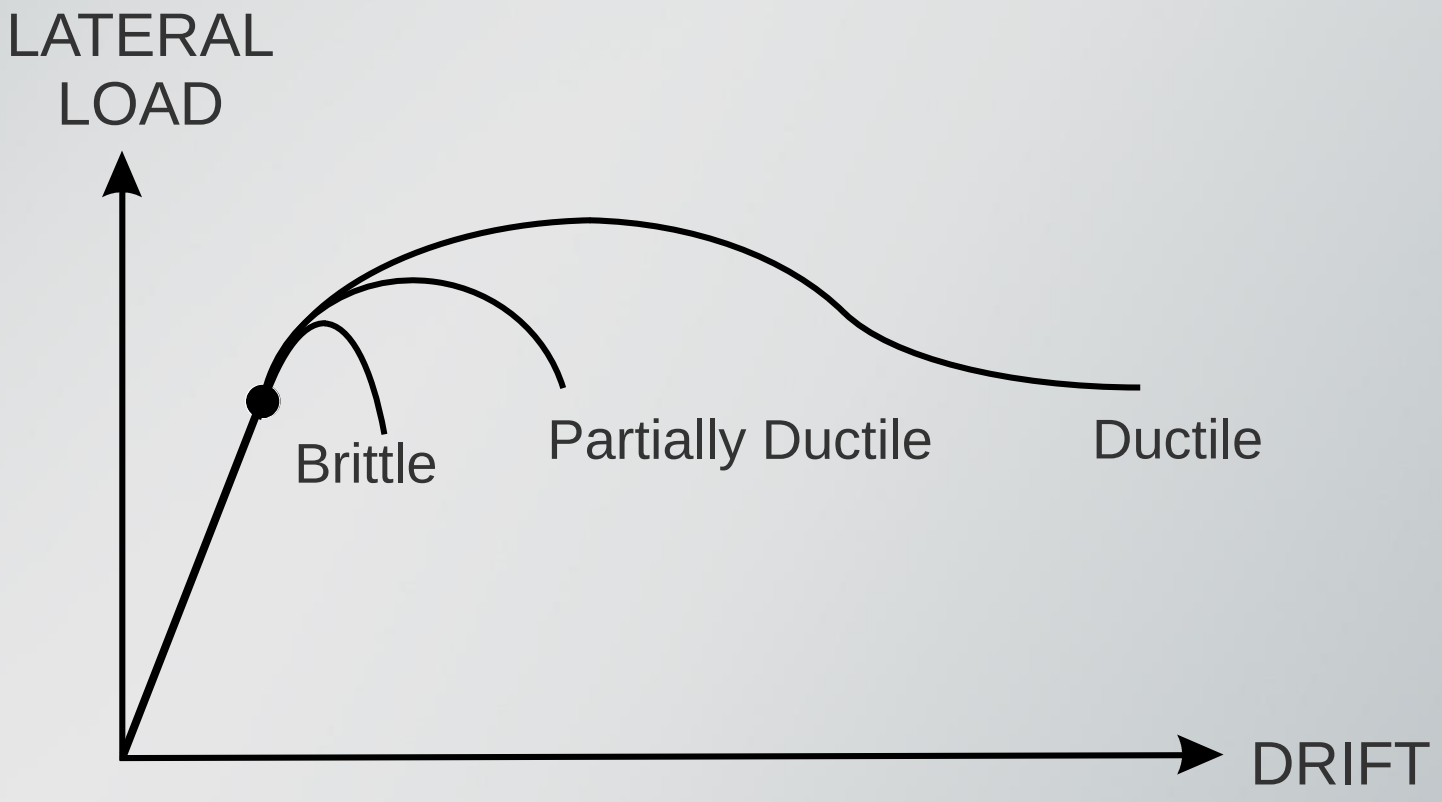
MOMENT ROTATION RELATIONSHIP



IDEALIZED MOMENT ROTATION

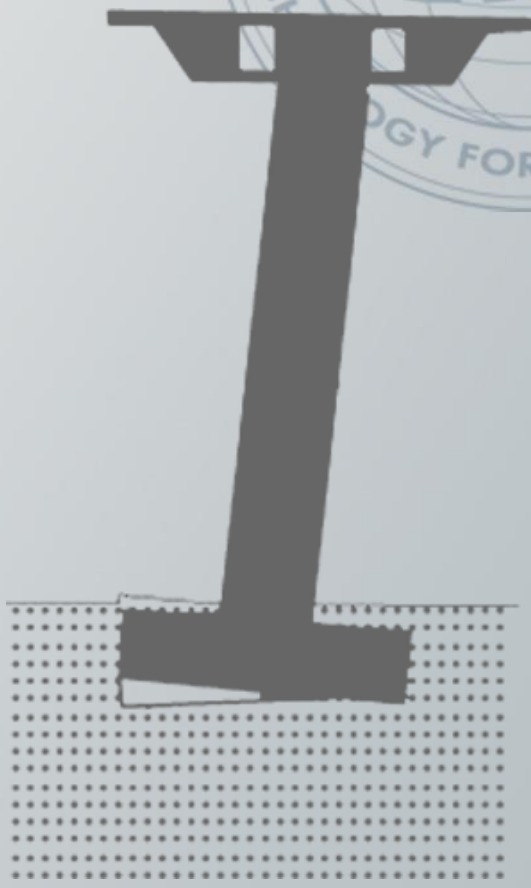


DUCTILITY

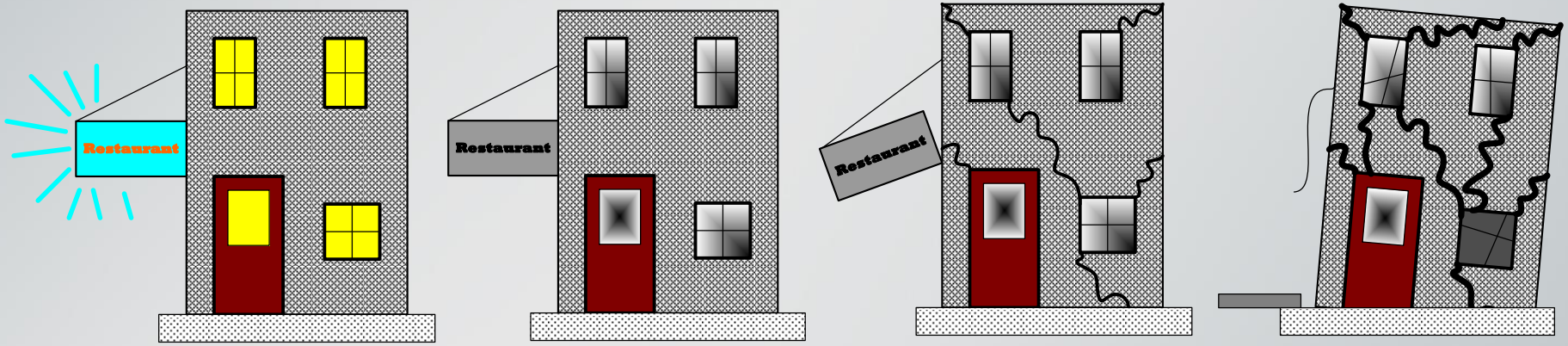


CAPACITY DESIGN

- STRONG COLUMNS & WEAK BEAMS IN FRAMES
- REDUCED BEAM SECTIONS
- LINK BEAMS IN ECCENTRICALLY BRACED FRAMES
- BUCKLING RESISTANT BRACES AS FUSES
- RUBBER-LEAD BASE ISOLATORS
- HINGED BRIDGE COLUMNS
- HINGES AT THE BASE LEVEL OF SHEAR WALLS
- ROCKING FOUNDATIONS
- OVERDESIGNED COUPLING BEAMS
- OTHER SACRIFICIAL ELEMENTS



PERFORMANCE LEVELS



Operational

Immediate Occupancy

Life Safety

Collapse Prevention

Less Damage

More Damage

Ref: FEMA 451 B

PERFORMANCE LEVELS

Higher Performance
less loss

Expected Post-Earthquake Damage State

Operational
Backup utility services maintain functions; very little damage.

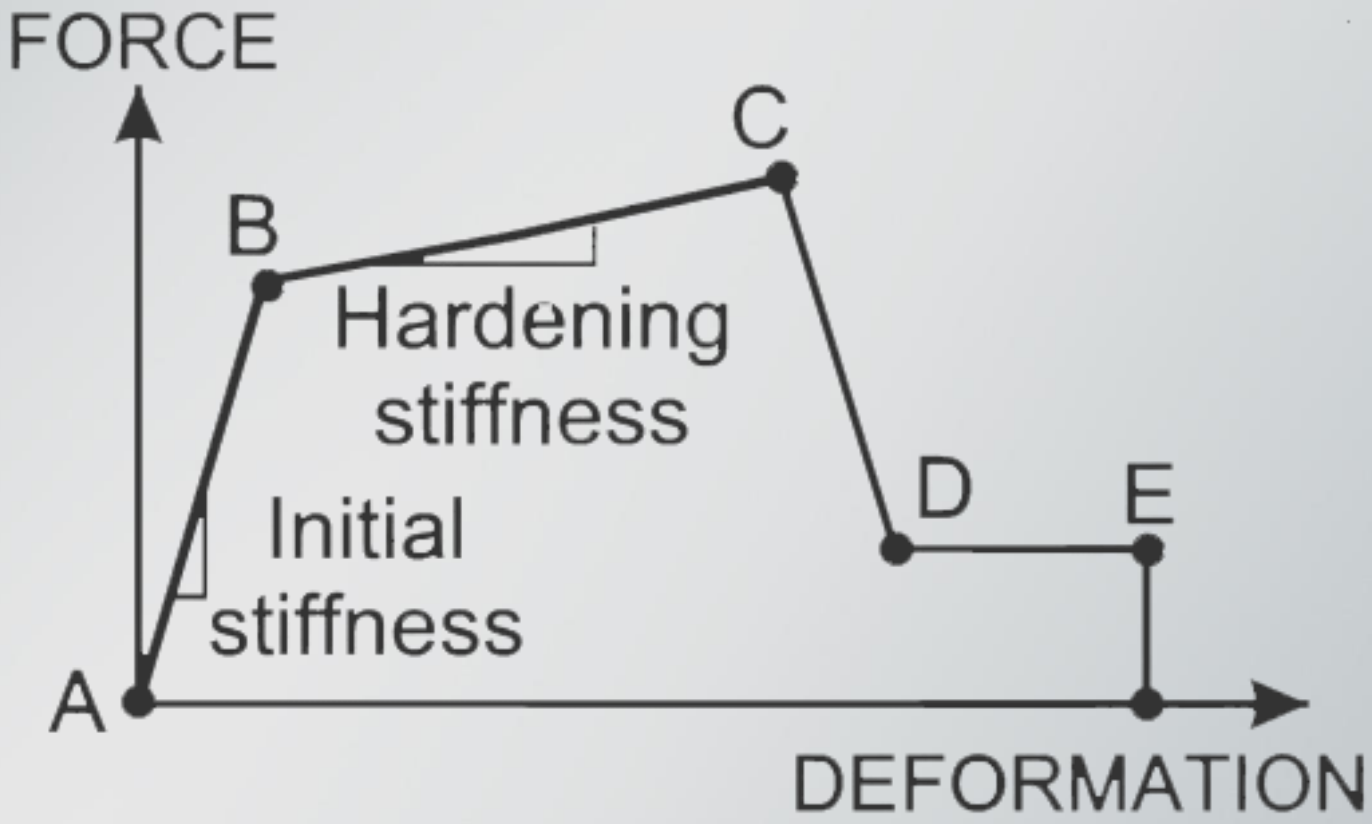
Immediate Occupancy
The building remains safe to occupy; any repairs are minor.

Life Safety
Structure remains stable and has significant reserve capacity; hazardous nonstructural damage is controlled.

Collapse Prevention
The building remains standing, but only barely; any other damage or loss is acceptable.

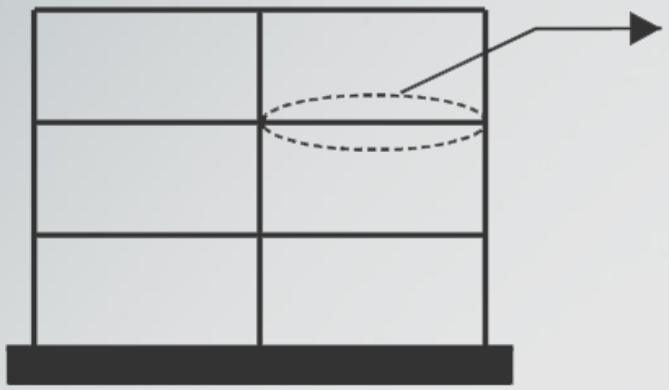
Lower Performance
more loss

IDEALIZED FORCE DEFORMATION CURVE



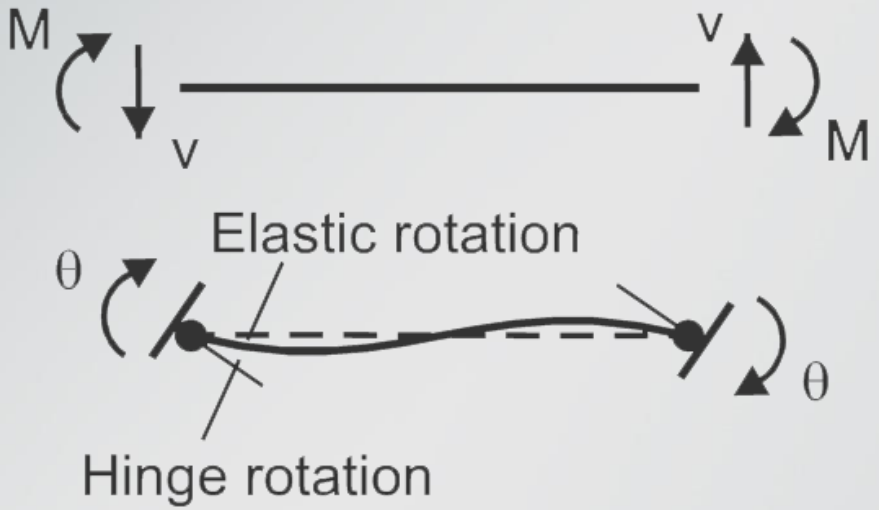
ASCE 41

ASCE 41 BEAM MODEL



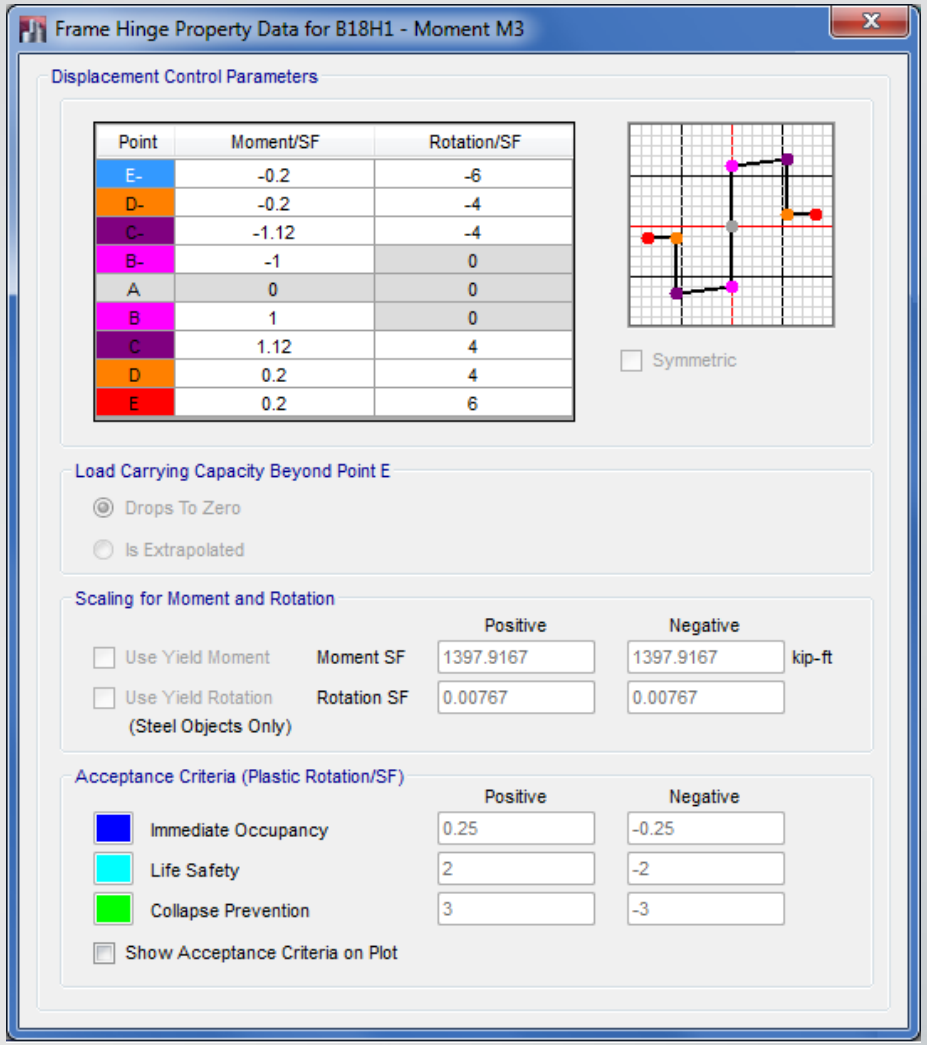
Performance assessment :

Bending behavior is ductile.
Use hinge rotation D/C ratio.



ASCE 41 hinge rotation capacities

ASCE 41 MOMENT HINGE



Point	Moment/SF	Rotation/SF
E-	-0.2	-6
D-	-0.2	-4
C-	-1.12	-4
B-	-1	0
A	0	0
B	1	0
C	1.12	4
D	0.2	4
E	0.2	6

STRENGTH vs. DEFORMATION

ELASTIC STRENGTH DESIGN - KEY STEPS

CHOSE DESIGN CODE AND EARTHQUAKE LOADS
DESIGN CHECK PARAMETERS STRESS/BEAM MOMENT
GET ALLOWABLE STRESSES/ULTIMATE– PHI FACTORS
CALCULATE STRESSES – LOAD FACTORS (ST RS TH)
CALCULATE STRESS RATIOS

INELASTIC DEFORMATION BASED DESIGN -- KEY STEPS

CHOSE PERFORMANCE LEVEL AND DESIGN LOADS – ASCE 41
DEMAND CAPACITY MEASURES – DRIFT/HINGE ROTATION/SHEAR
GET DEFORMATION AND FORCE CAPACITIES
CALCULATE DEFORMATION AND FORCE DEMANDS (RS OR TH)
CALCULATE D/C RATIOS – LIMIT STATES

ASCE 41 ASSESSMENT OPTIONS

- Linear Static Analysis
- Linear Dynamic Analysis (Response Spectrum or Time History Analysis)
- Nonlinear Static Analysis (Pushover Analysis)
- Nonlinear Dynamic Time History Analysis (NDI or FNA)

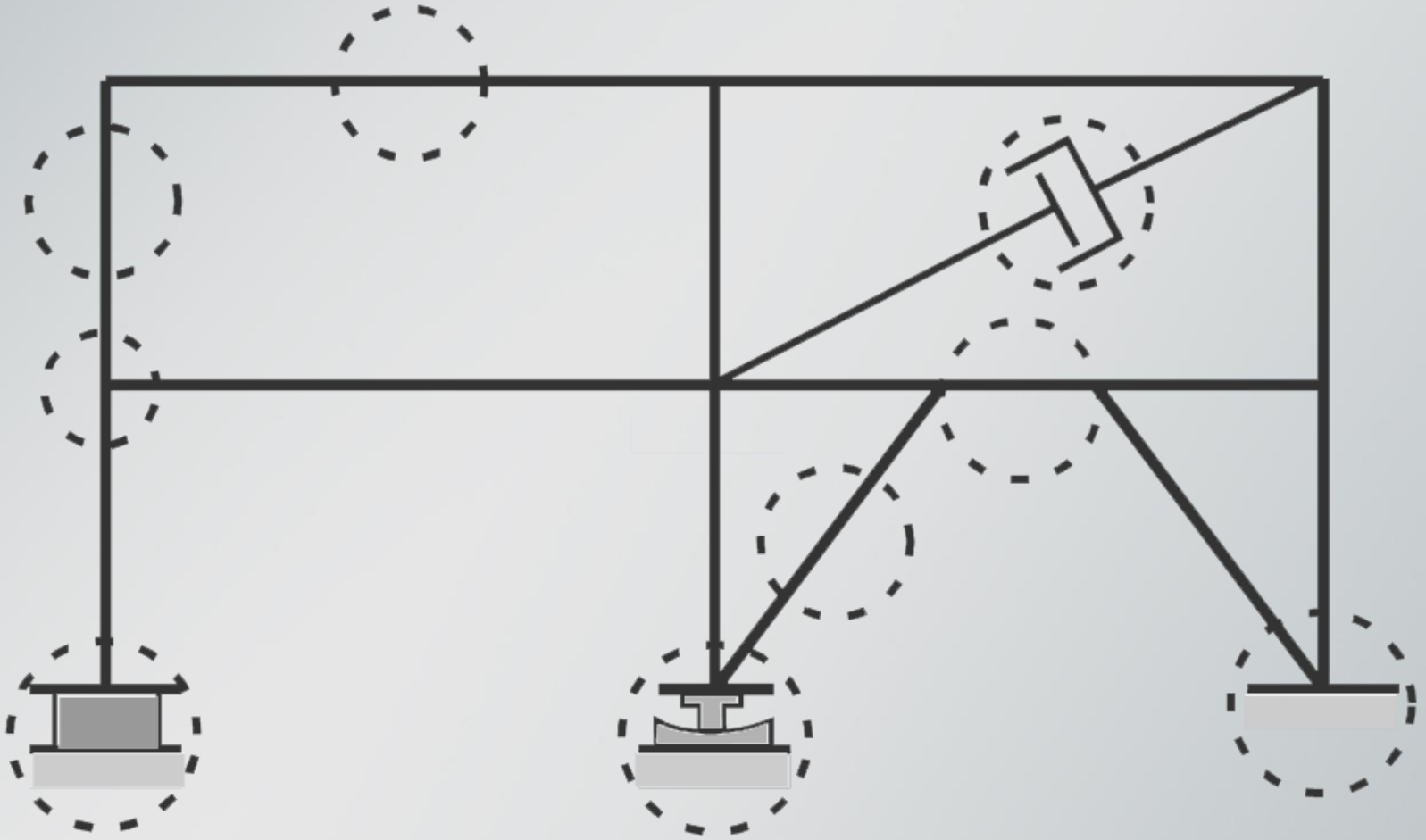
PERFORMANCE PARAMETERS

BRIDGE CATEGORIES
LIFELINE BRIDGES
MAJOR-ROUTE BRIDGES
OTHER BRIDGES

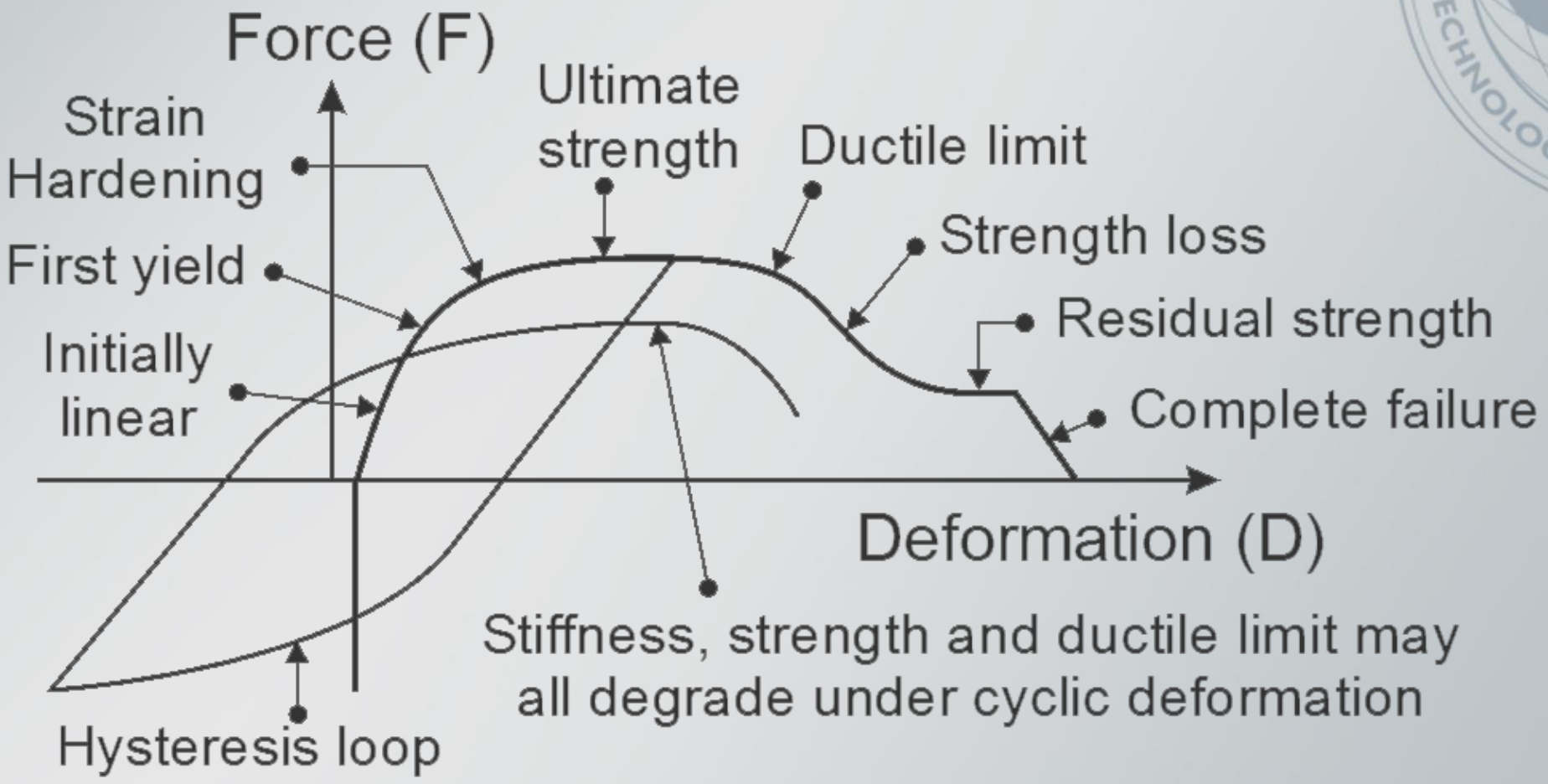
PERFORMANCE LEVELS	
SERVICE	**DAMAGE**
IMMEDIATE	MINIMAL DAMAGE
LIMITED	REPAIRABLE DAMAGE
SERVICE DISRUPTION	EXTENSIVE DAMAGE
LIFE SAFETY	PROBABLE REPLACEMENT

GROUND MOTION LEVELS	
PROBABILITY IN 50 YEARS	**RETURN PERIOD**
10%	475 YEARS
5%	975 YEARS
2%	2475 YEARS

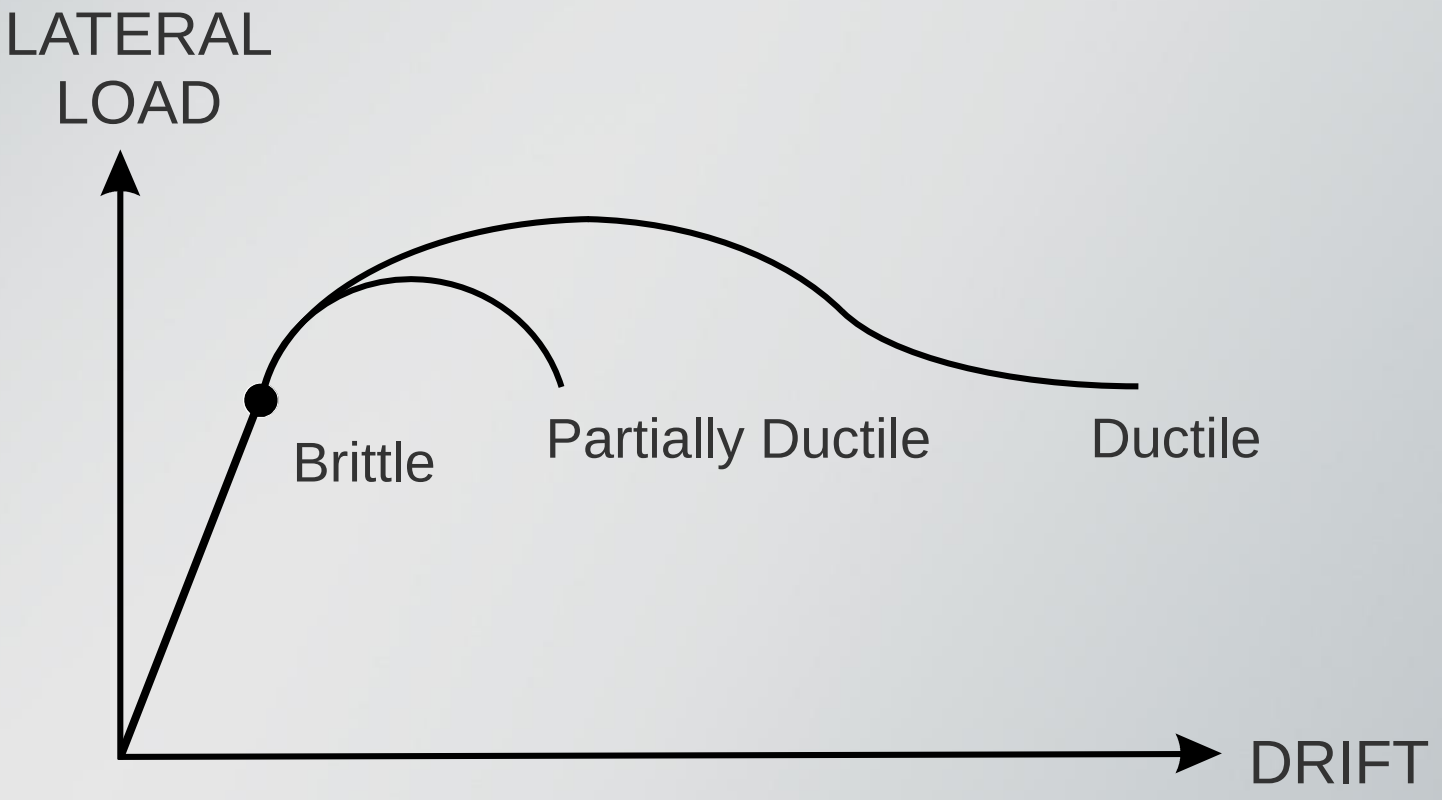
STRUCTURAL COMPONENTS



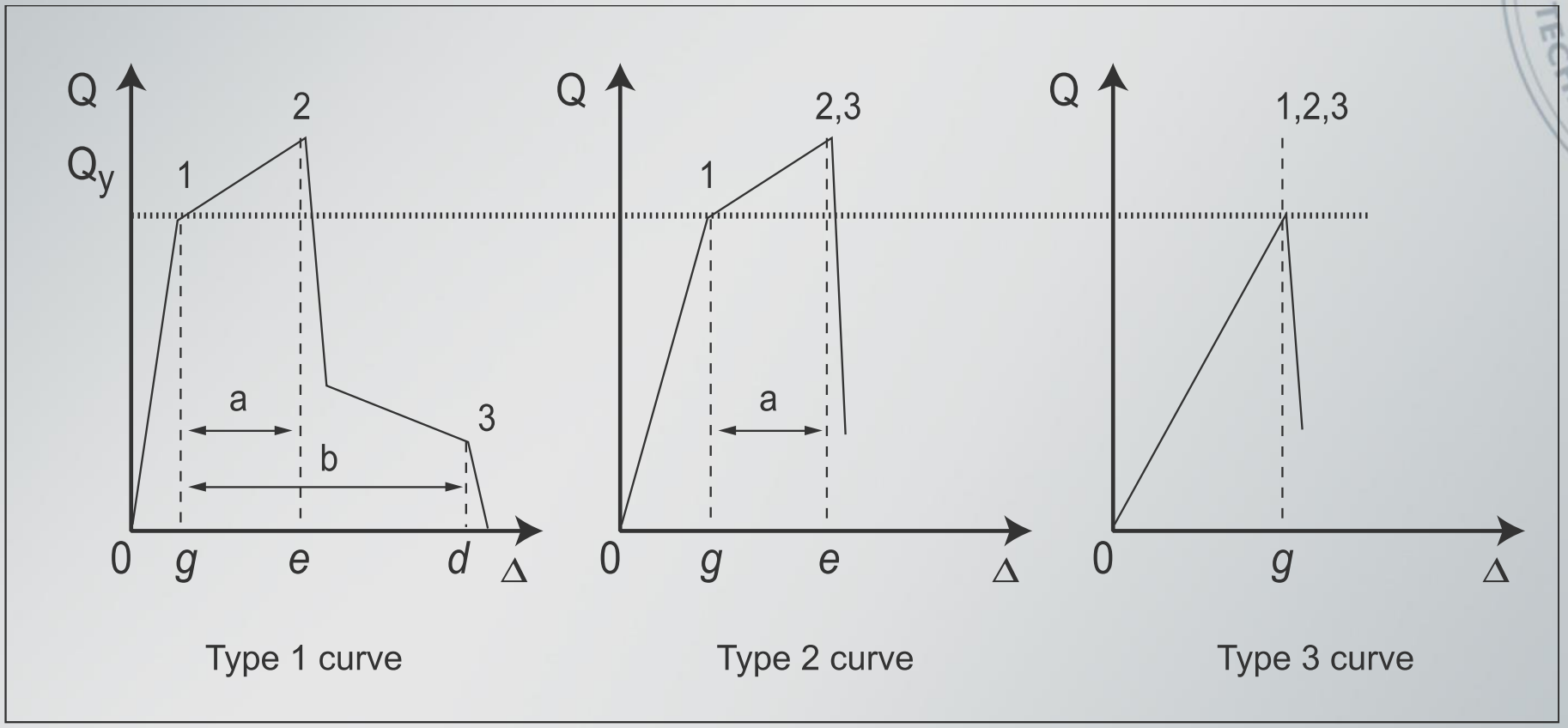
F-D RELATIONSHIP



DUCTILITY



ASCE 41 – DUCTILE AND BRITTLE



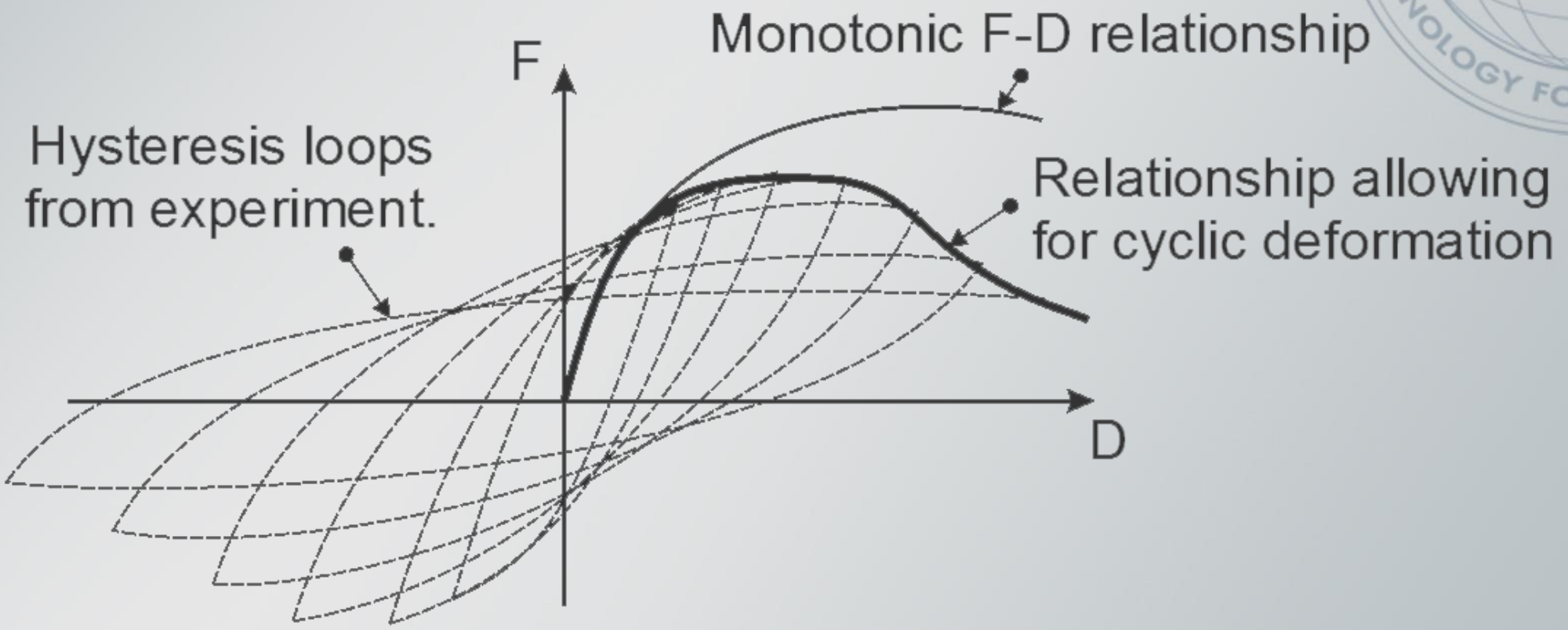
Component Force Versus Deformation Curves

FORCE AND DEFORMATION CONTROL

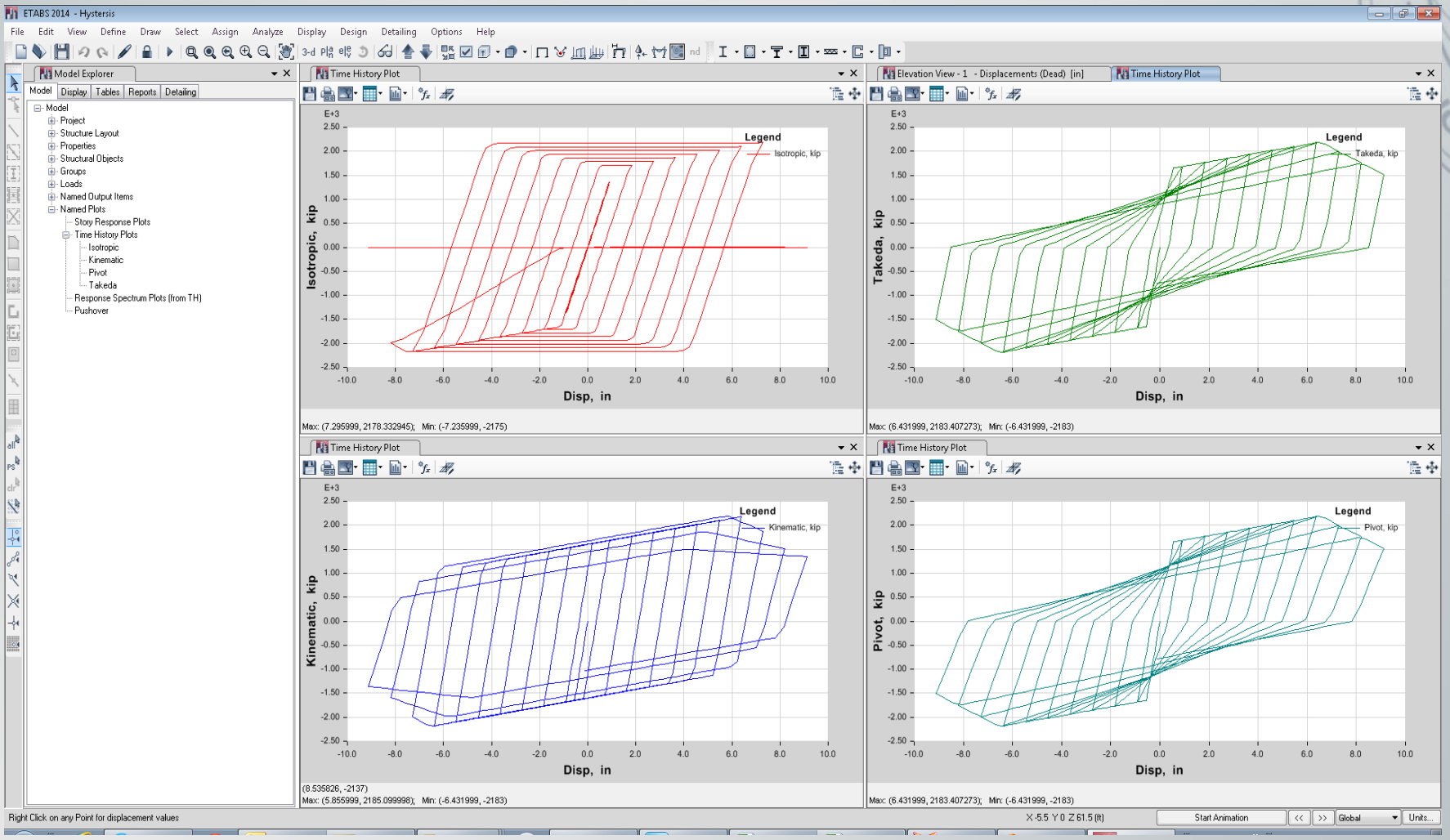
Table C2-1 Examples of Possible Deformation-Controlled and Force-Controlled Actions

Component	Deformation-Controlled Action	Force-Controlled Action
Moment Frames		
• Beams	Moment (M)	Shear (V)
• Columns	M	Axial load (P), V
• Joints	--	V[1]
Shear Walls	M, V	P
Braced Frames		
• Braces	P	--
• Beams	--	P
• Columns	--	P
• Shear Link	V	P, M
Connections	P, V, M[3]	P, V, M
Diaphragms	M, V[2]	P, V, M

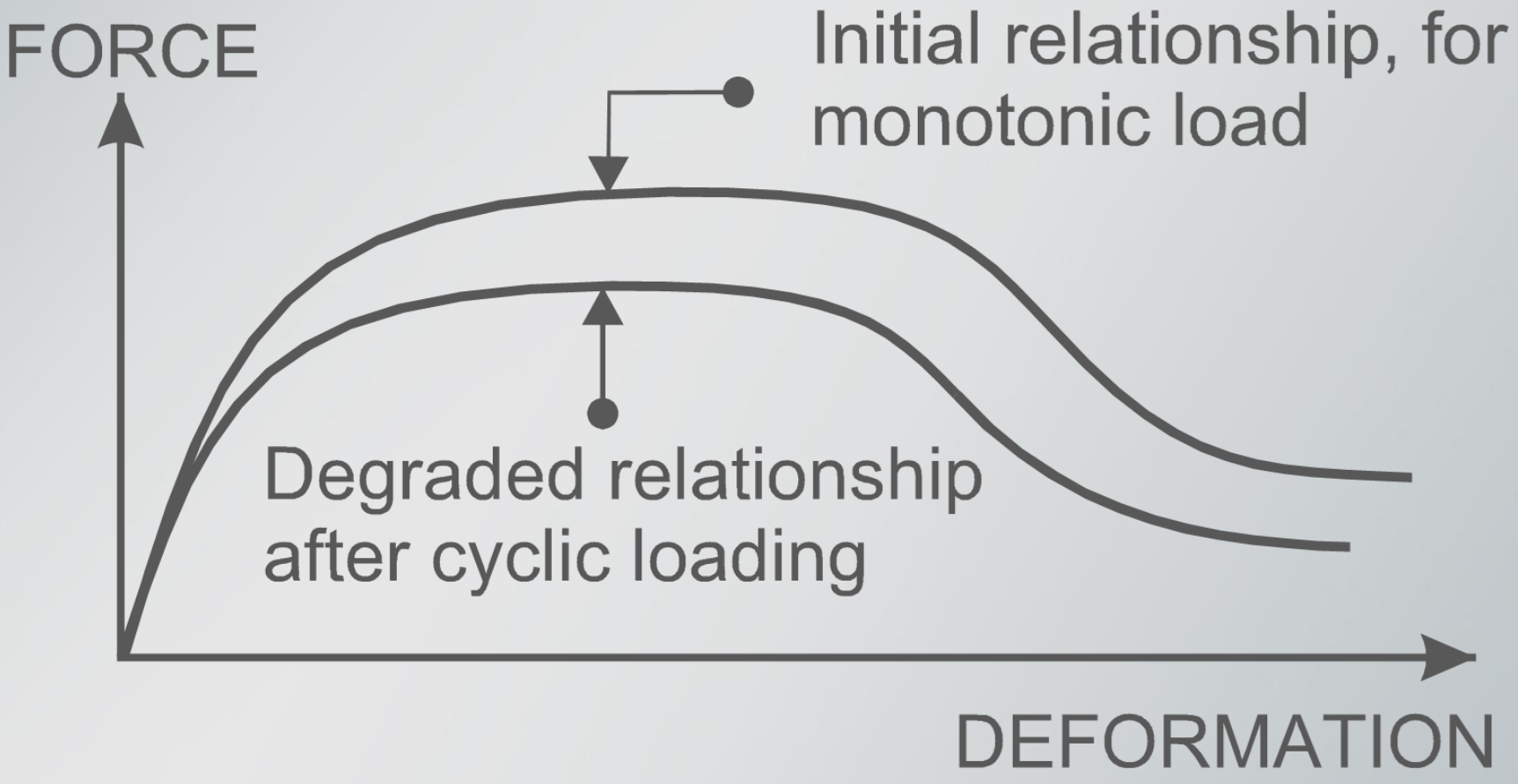
BACKBONE CURVE



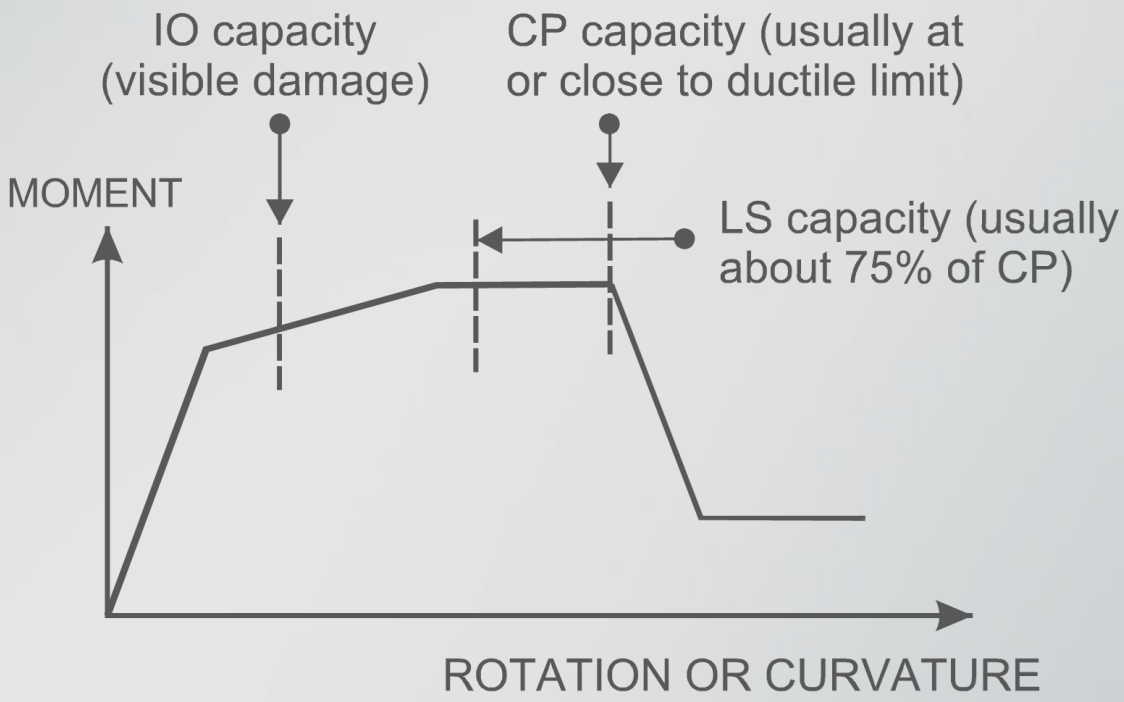
HYSTERESIS LOOP MODELS



STRENGTH AND DEGRADATION

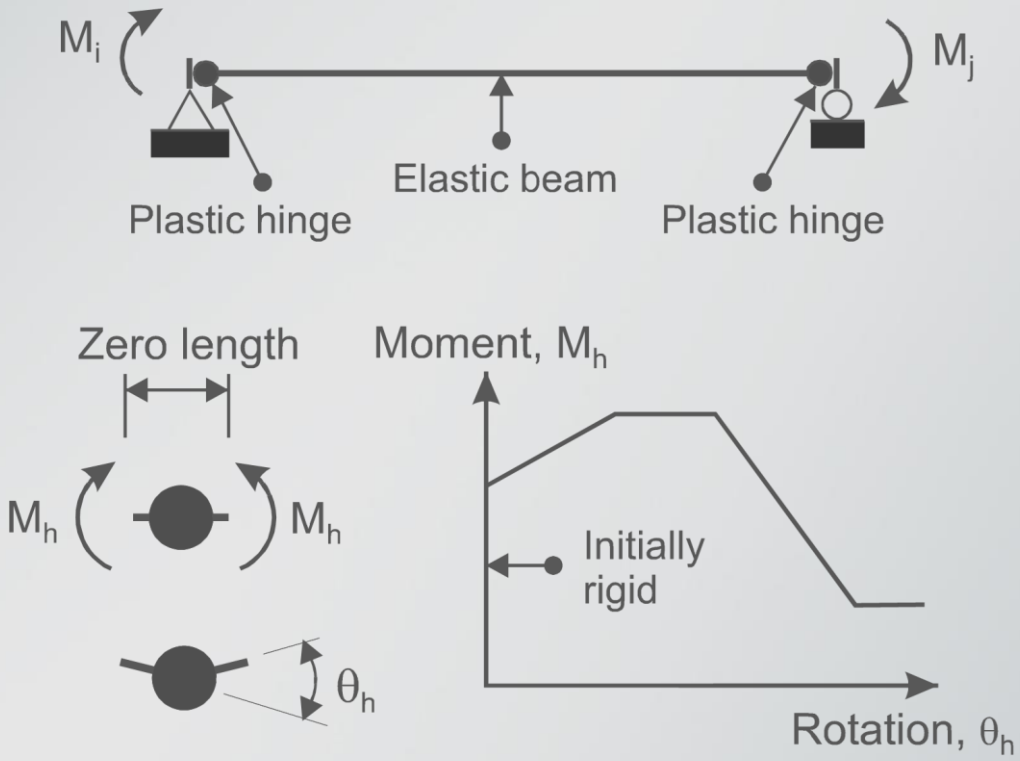


ASCE 41 DEFORMATION CAPACITIES



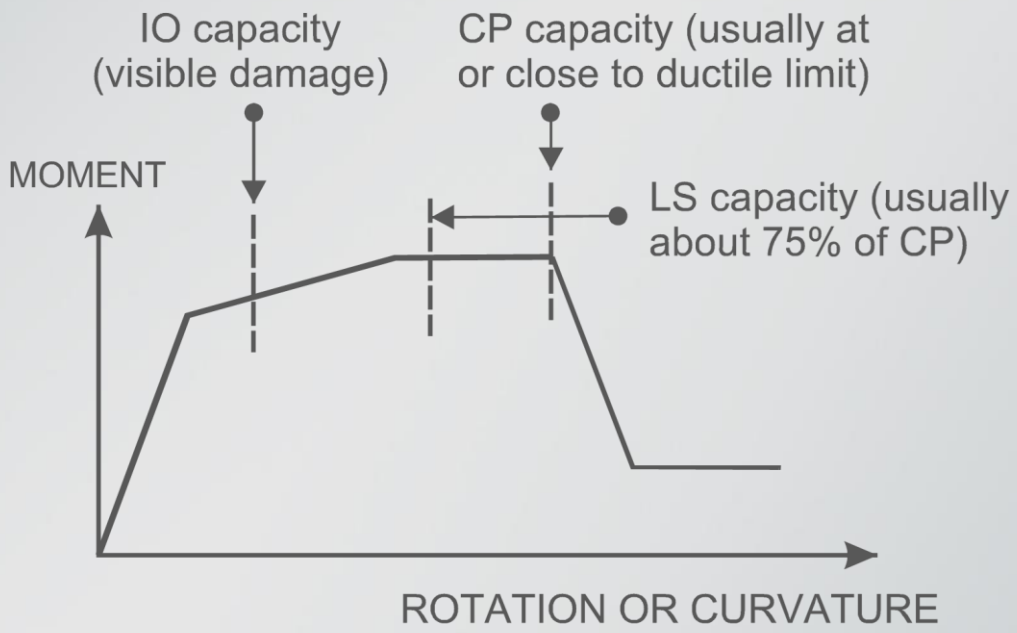
- This can be used for components of all types.
- It can be used if experimental results are available.
- ASCE 41 gives capacities for many different components.

PLASTIC HINGE MODEL



- It is assumed that all inelastic deformation is concentrated in zero-length plastic hinges.
- The deformation measure for D/C is hinge rotation.

ASCE 41 ROTATION CAPACITIES



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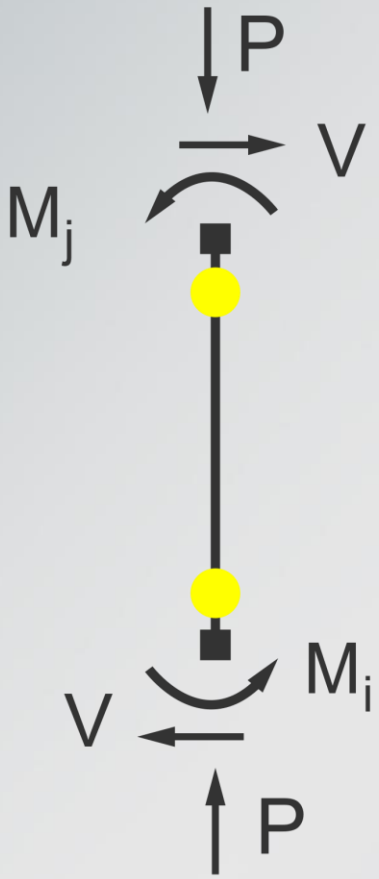
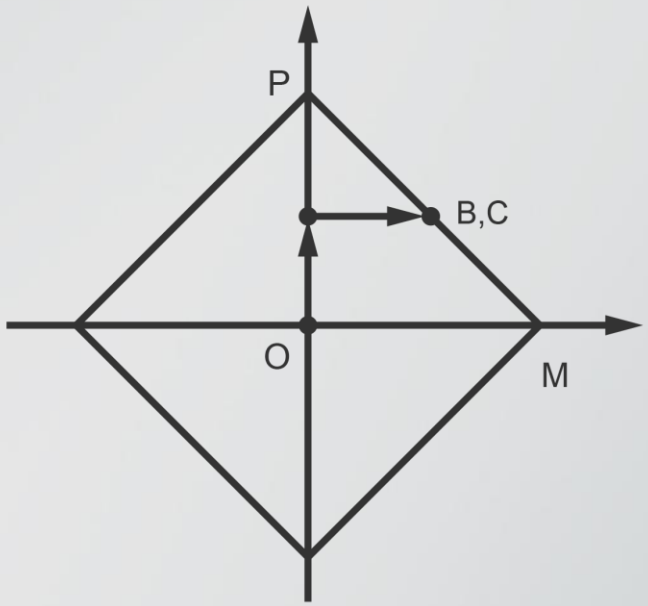
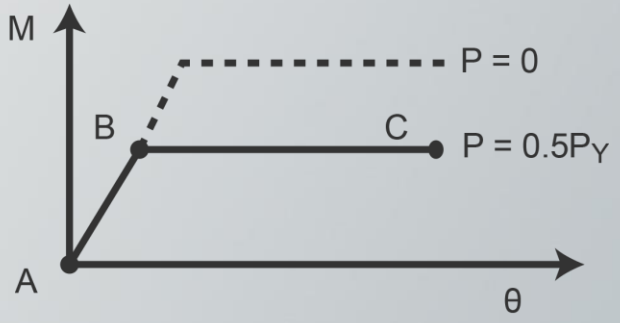
STEEL COLUMN AXIAL-BENDING





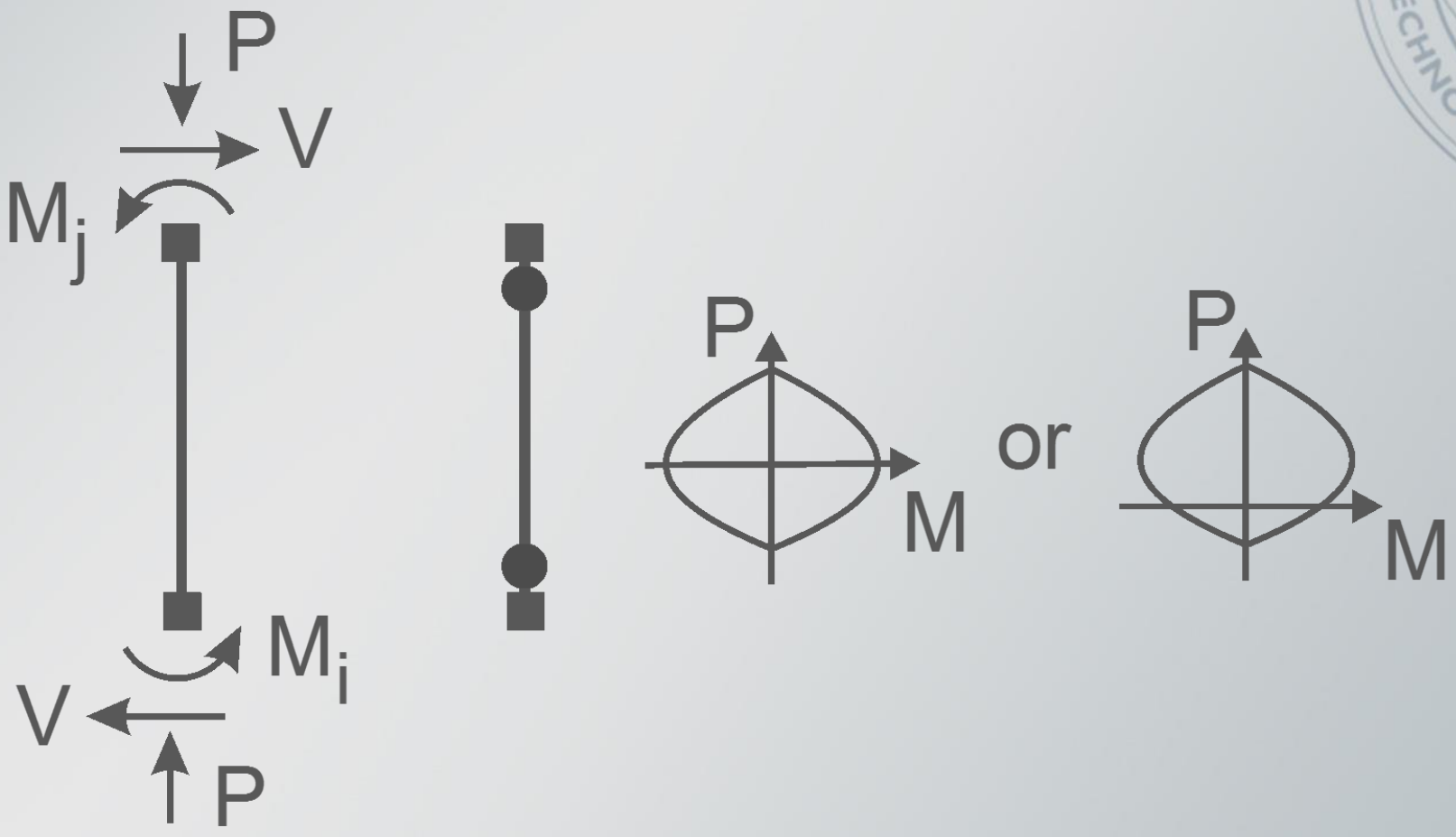
Load Path



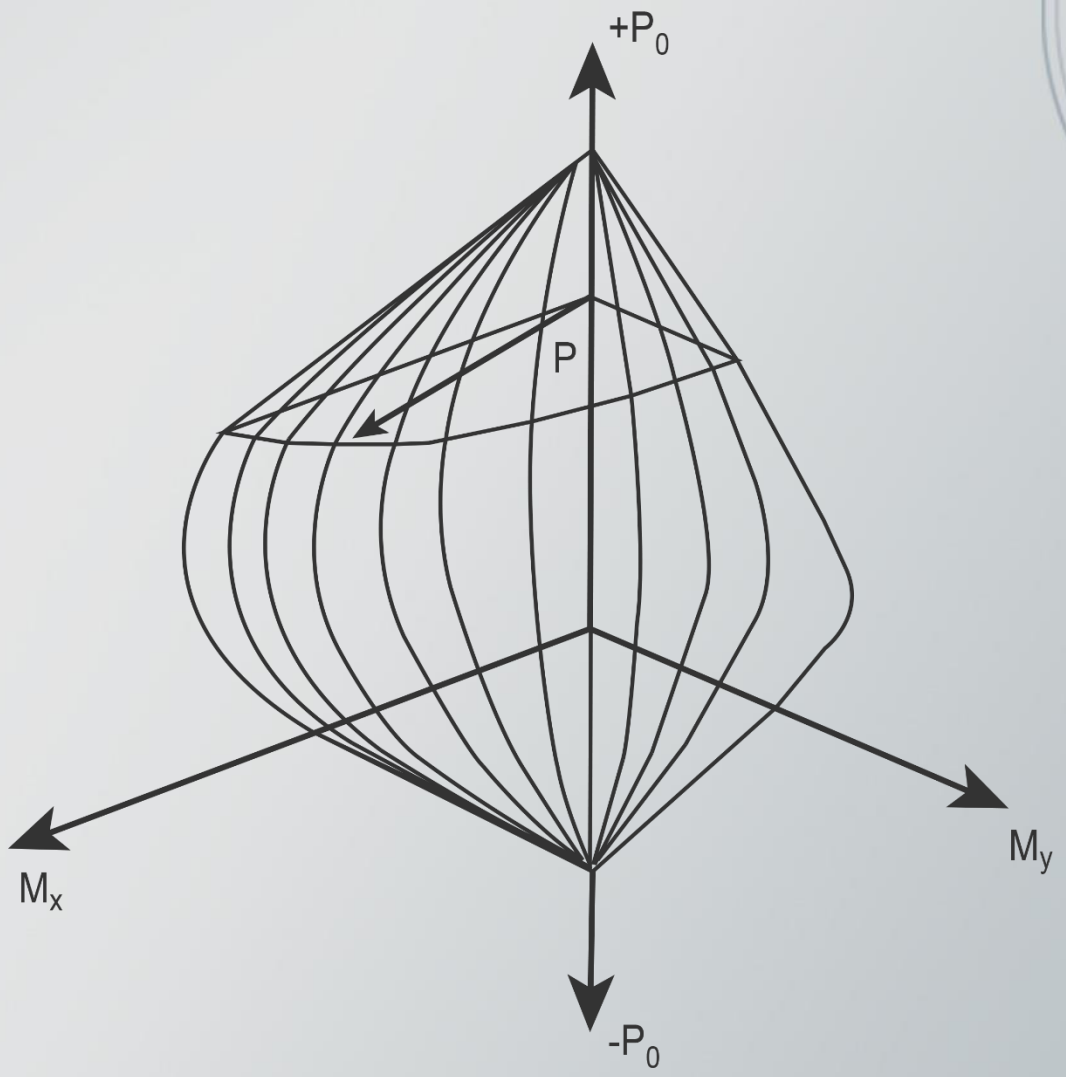
Moment Rotation

$$M_y = ZF_y(1-P/P_y)$$

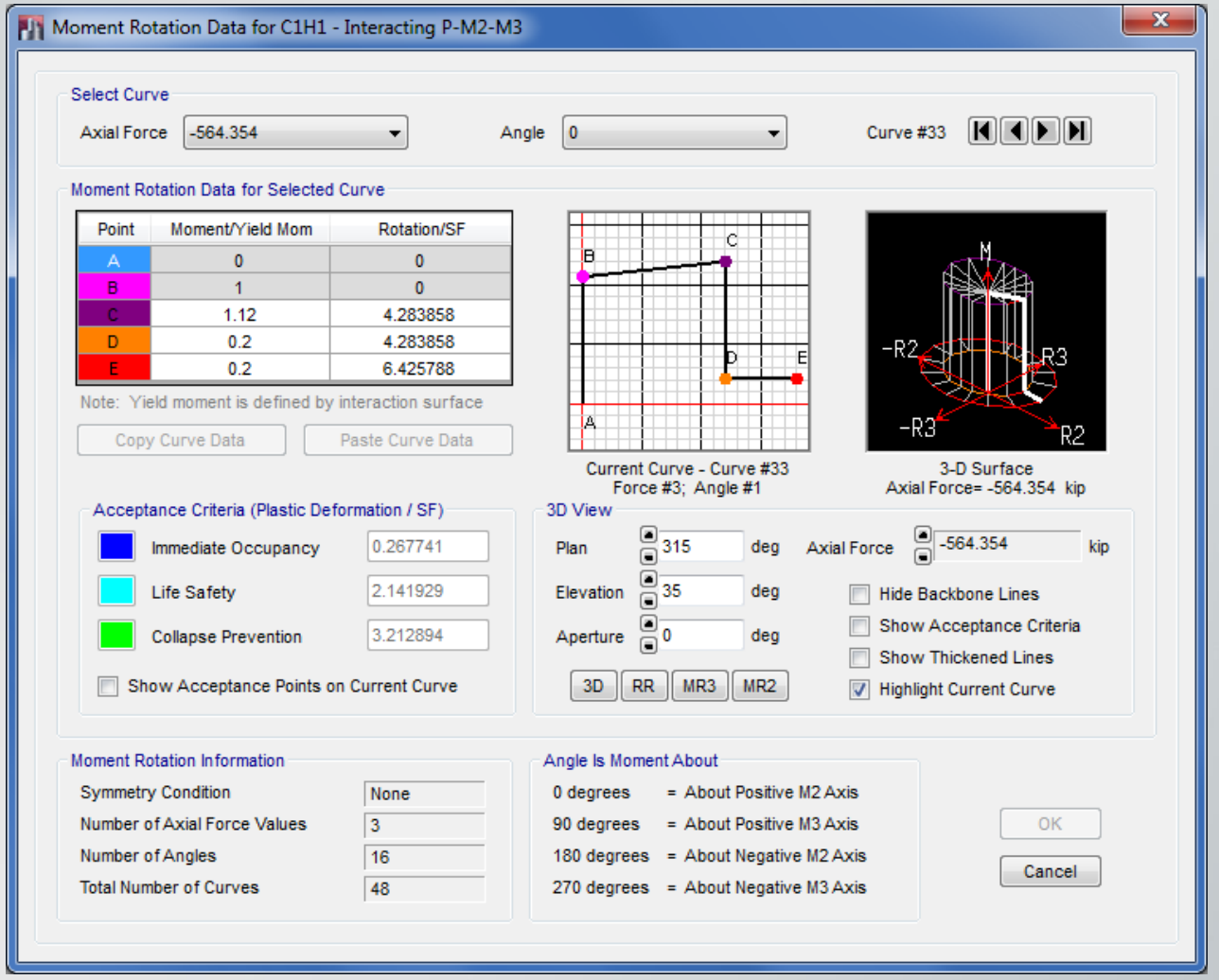
COLUMN AXIAL-BENDING MODEL



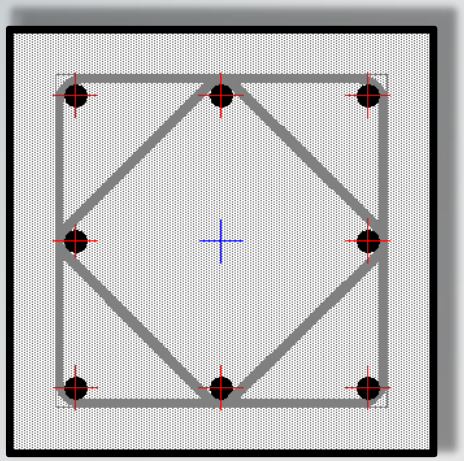
CONCRETE COLUMN AXIAL-BENDING



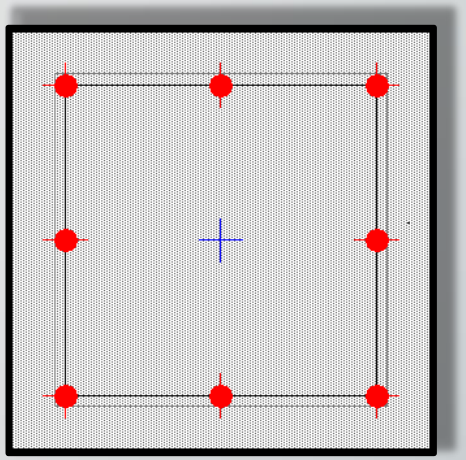
FEMA PMM HINGE



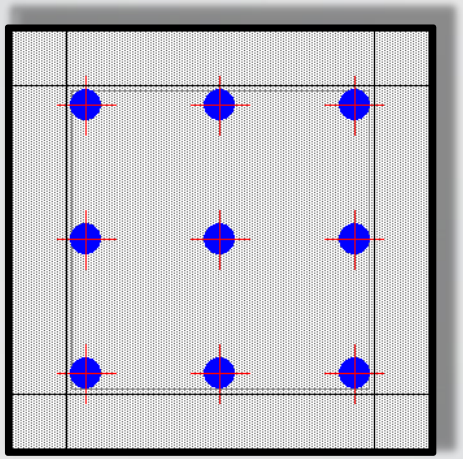
CONCRETE COLUMN FIBER HINGE MODEL



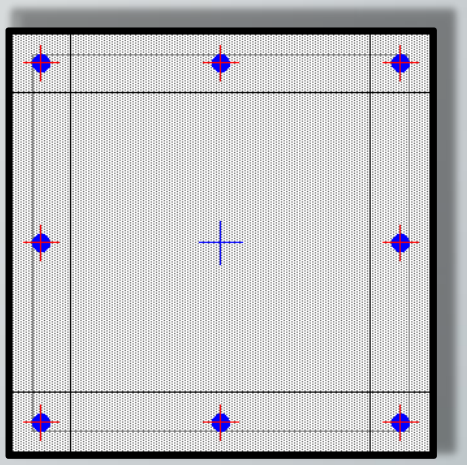
Reinforced Concrete Column



Steel Rebar Fibers

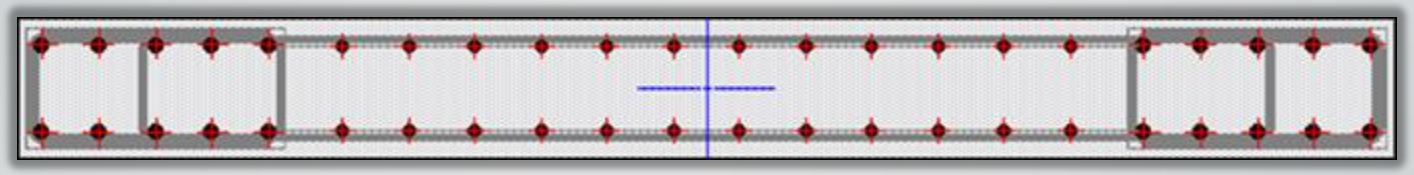


Confined Concrete Fibers

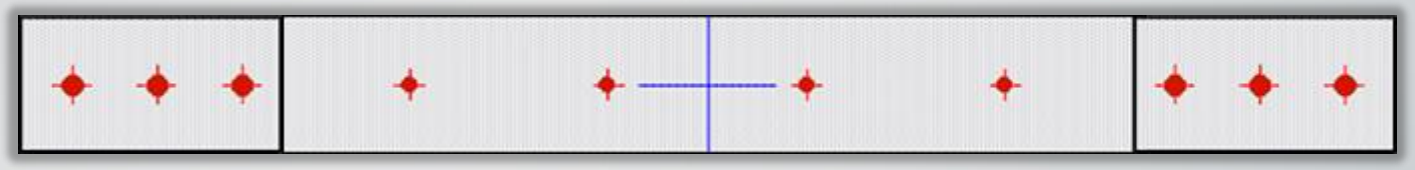


Unconfined Concrete Fibers

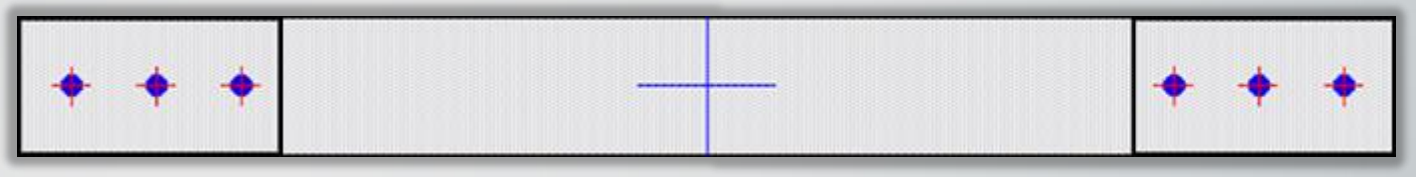
SHEAR WALL FIBER HINGE MODEL



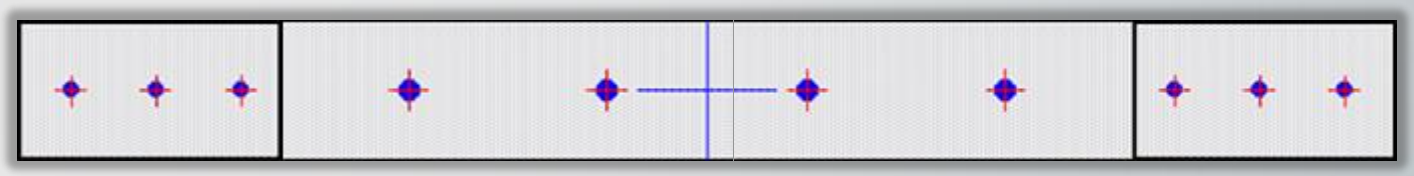
Reinforcement Layout



Steel Fibers

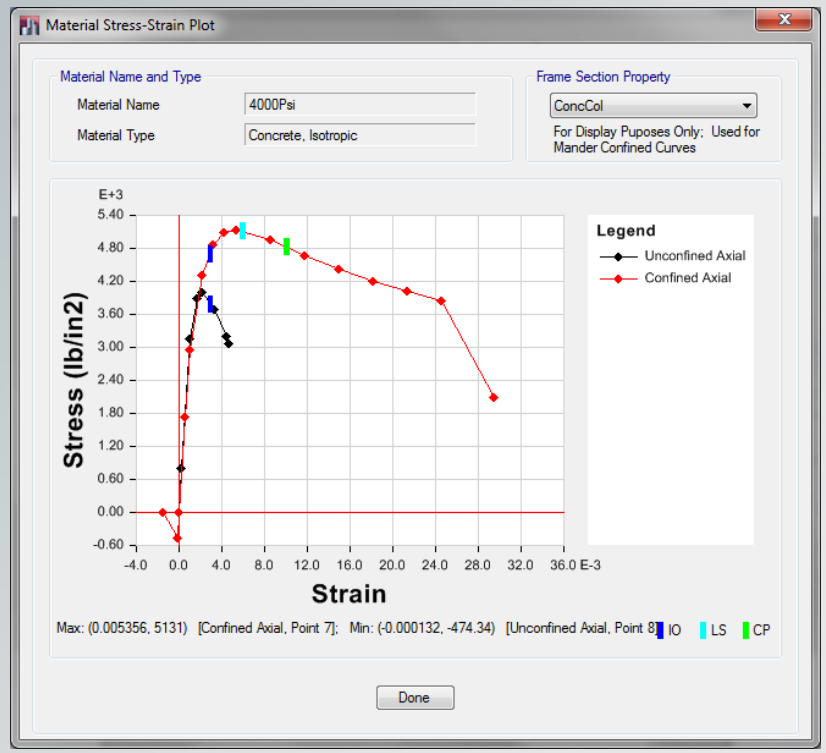


Confined Concrete Fibers

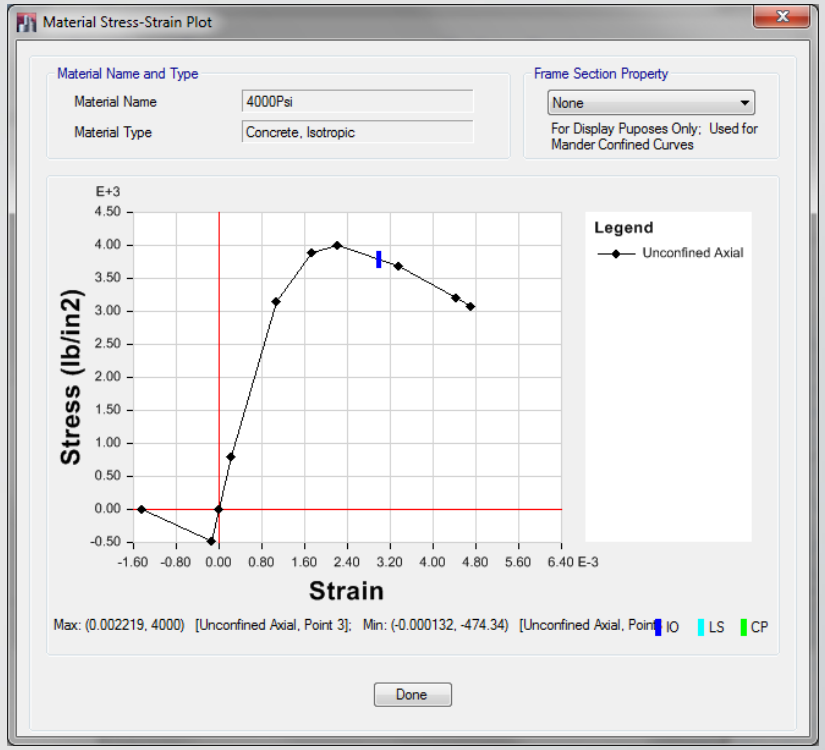


Unconfined Concrete Fibers

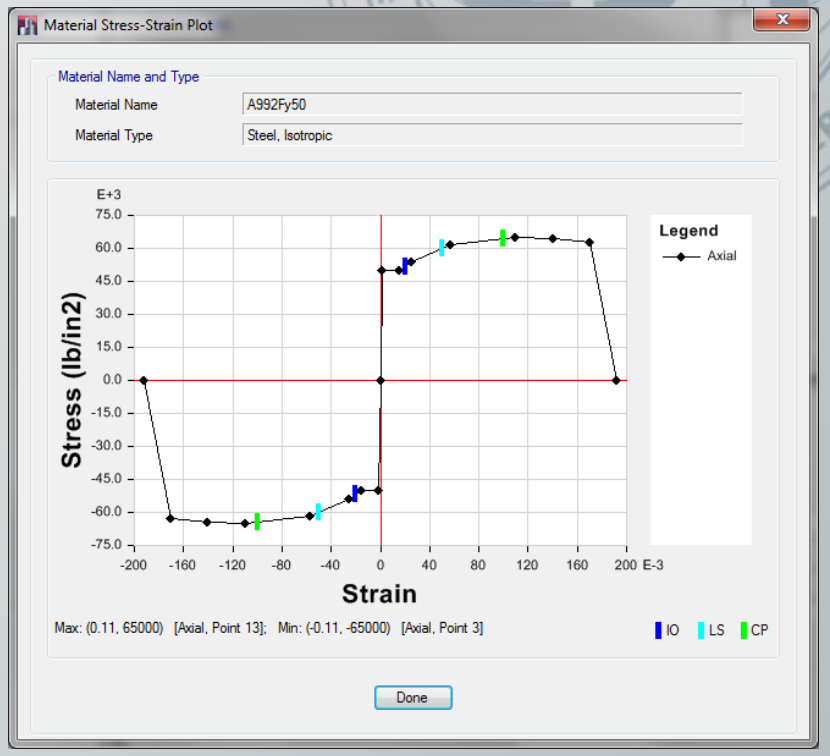
MATERIAL STRESS-STRAIN CURVES



Unconfined and Confined Concrete
(Compared)



Confined Concrete

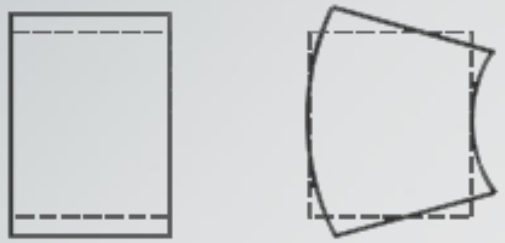


Steel

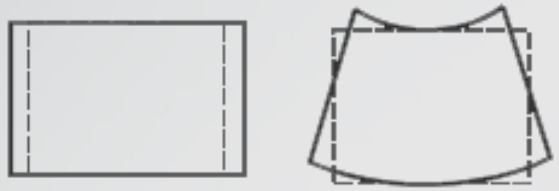
STRAIN AS PERFORMANCE MEASURE

Strain	Limit
Fully confined concrete compressive strain	0.015
Unconfined concrete compressive strain	0.005
Rebar tensile strain	0.05
Rebar compressive strain	0.02

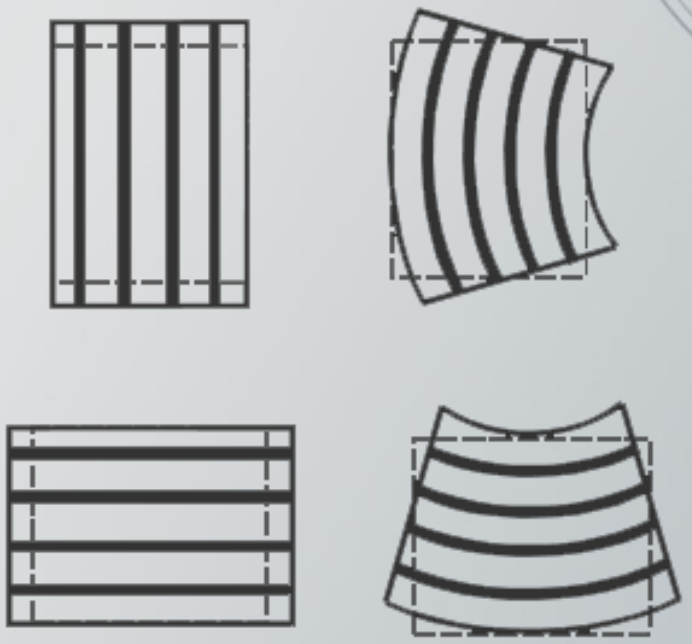
PIER AND SPANDREL FIBER MODELS



Vertical axial and bending

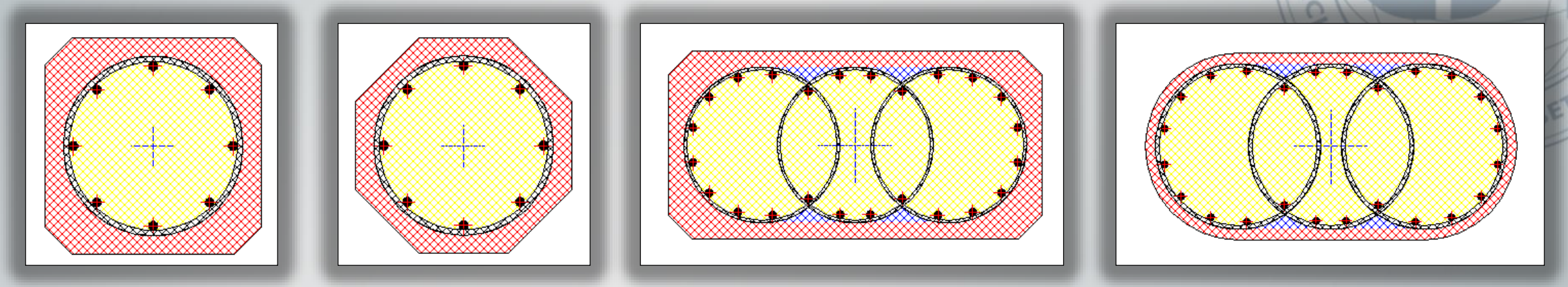


Horizontal axial and bending

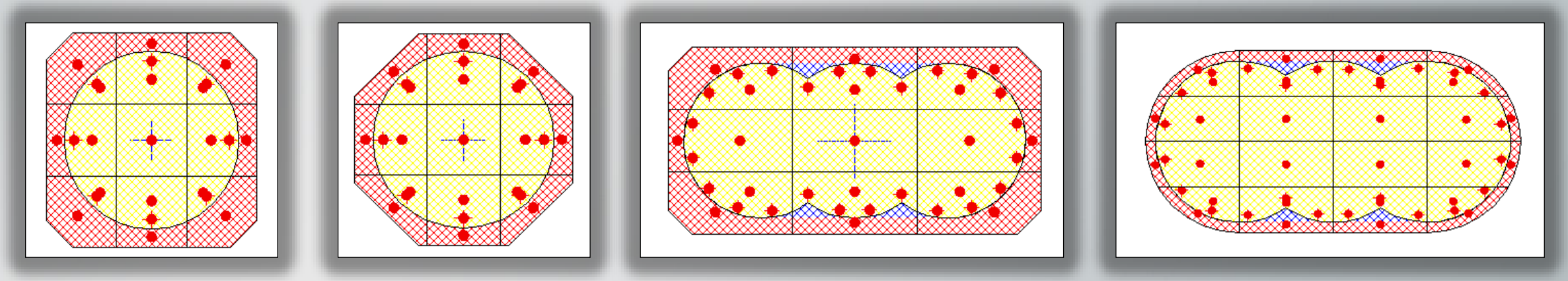


Vertical and horizontal fiber models

BRIDGE SECTIONS AND FIBER MODELS

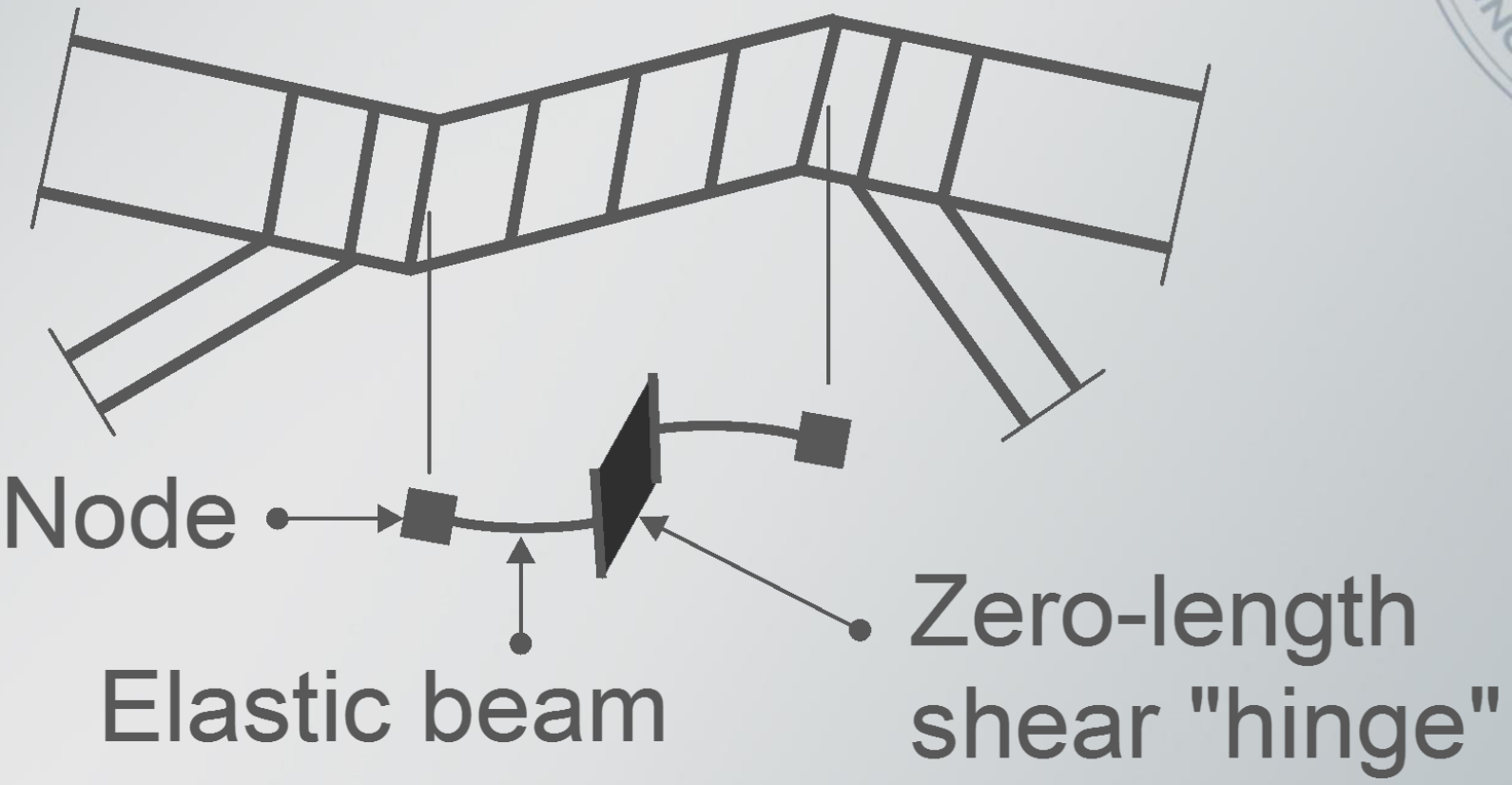


BRIDGE CROSS SECTIONS

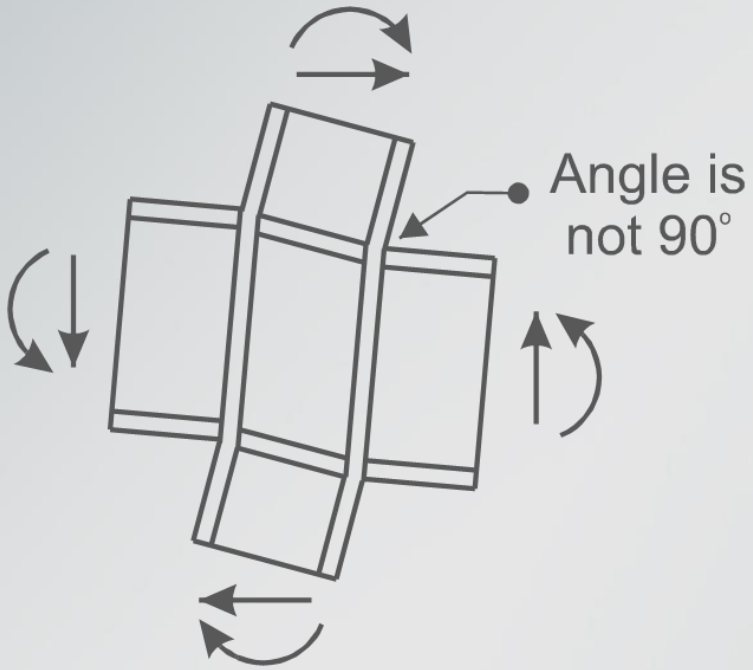


FIBER MODELS OF CROSS SECTIONS

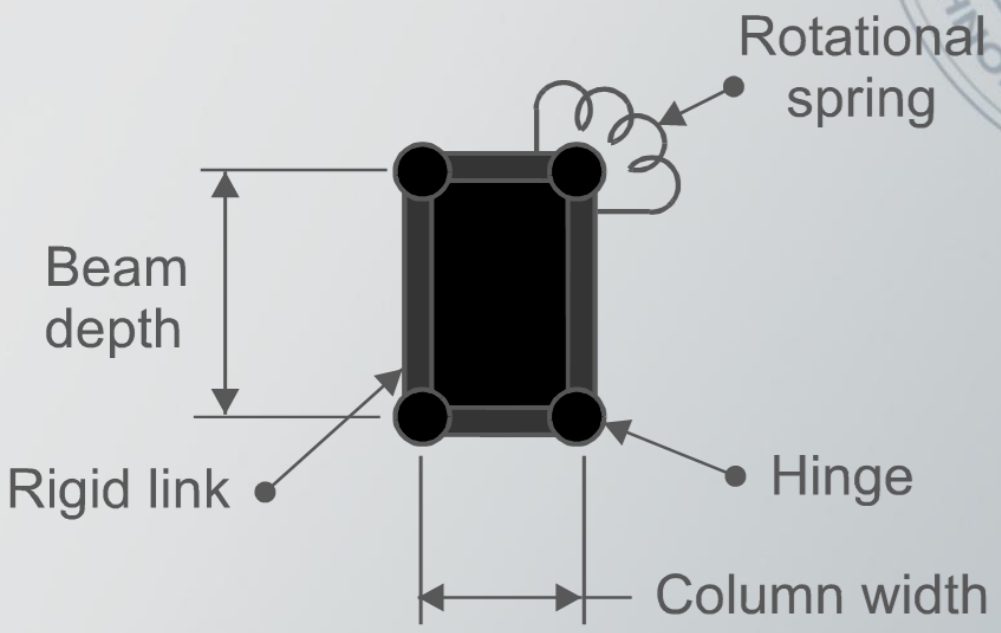
SHEAR HINGE MODEL



PANEL ZONE ELEMENT

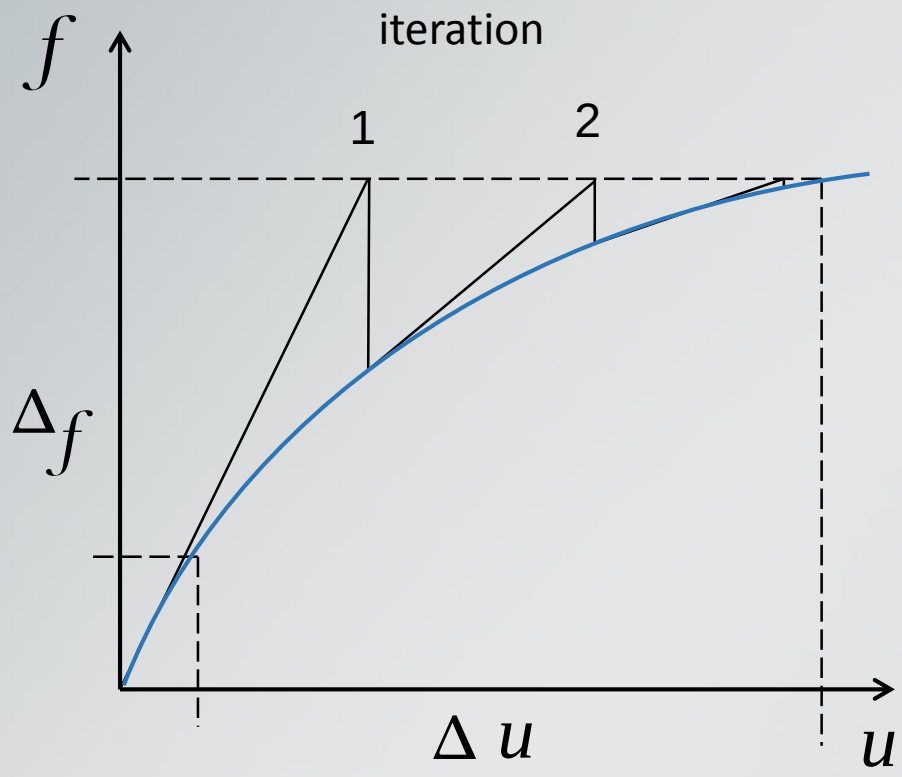


PANEL ZONE DEFORMATION

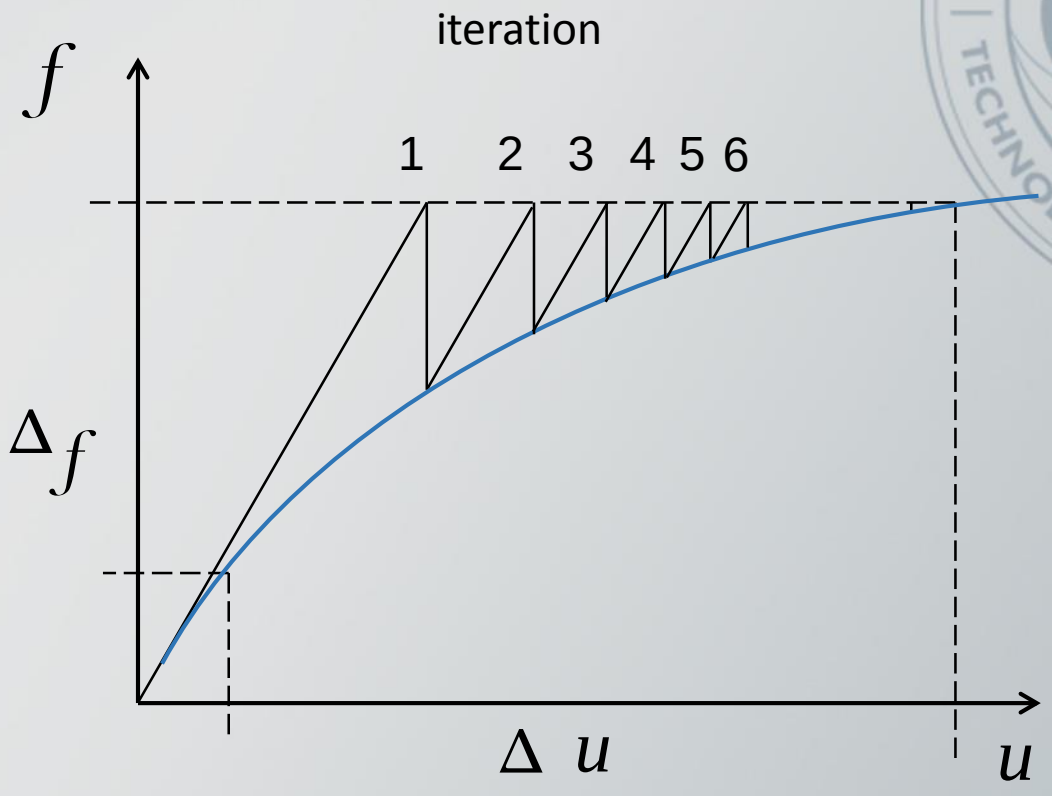


ANALYSIS MODEL

NONLINEAR SOLUTION SCHEMES



NEWTON – RAPHSON ITERATION



CONSTANT STIFFNESS ITERATION

THE POWER OF RITZ VECTORS

APPROXIMATELY THREE TIMES FASTER THAN THE CALCULATION OF EXACT EIGENVECTORS

IMPROVED ACCURACY WITH A SMALLER NUMBER OF VECTORS

CAN BE USED FOR NONLINEAR ANALYSIS TO CAPTURE LOCAL RESPONSE

FAST NONLINEAR ANALYSIS (FNA)

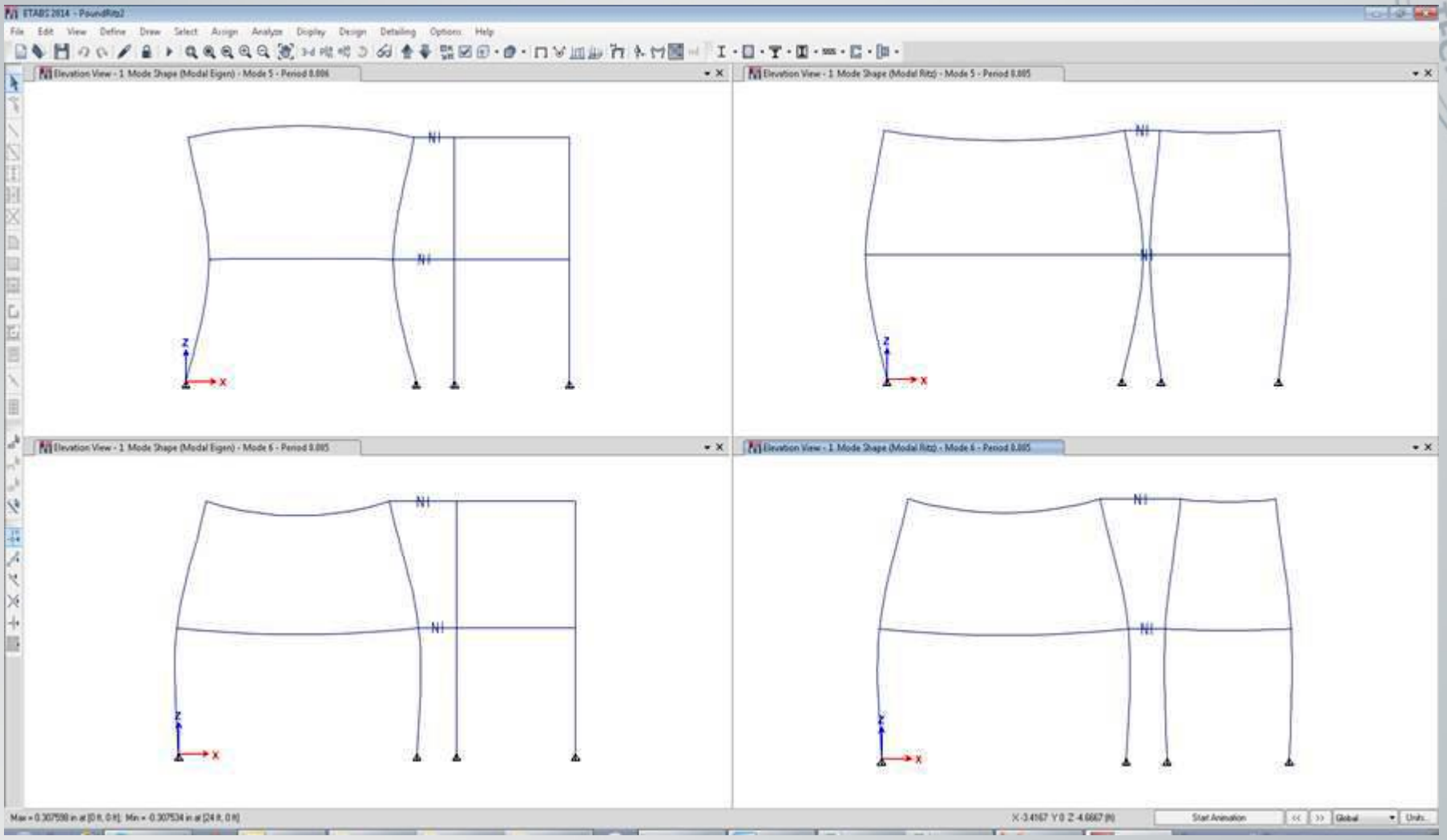
DISCRETE NONLINEARITY

FRAME AND SHEAR WALL HINGES
BASE ISOLATORS (RUBBER & FRICTION)

STRUCTURAL DAMPERS
STRUCTURAL UPLIFT

STRUCTURAL POUNDING
BUCKLING RESTRAINED BRACES

RITZ VECTORS



FNA ADVANTAGES

MODAL SOLUTION - NO STIFFNESS REDUCTION
CLOSED FORM SOLUTION – VERY FAST

TIME STEP INDEPENDENT
CAPTURES HIGH FREQUENCY RESPONSE

RITZ VECTORS CALCULATED ONCE
MULTIPLE TIME HISTORIES ARE FAST

FNA KEY POINT

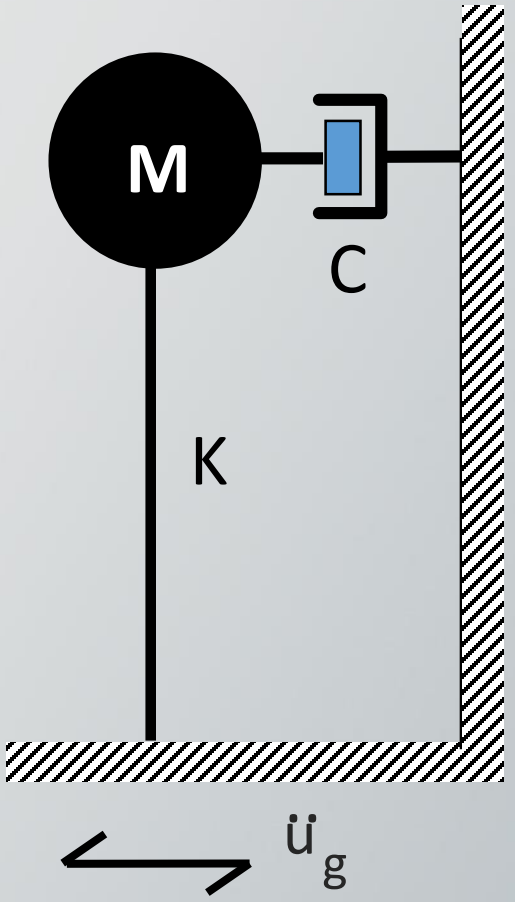
The Ritz modes generated by the nonlinear deformation loads are used to modify the basic structural modes whenever the nonlinear elements go nonlinear.

DYNAMIC EQUILIBRIUM EQUATIONS

$$M\ddot{u}_t + C\dot{u} + Ku = 0$$

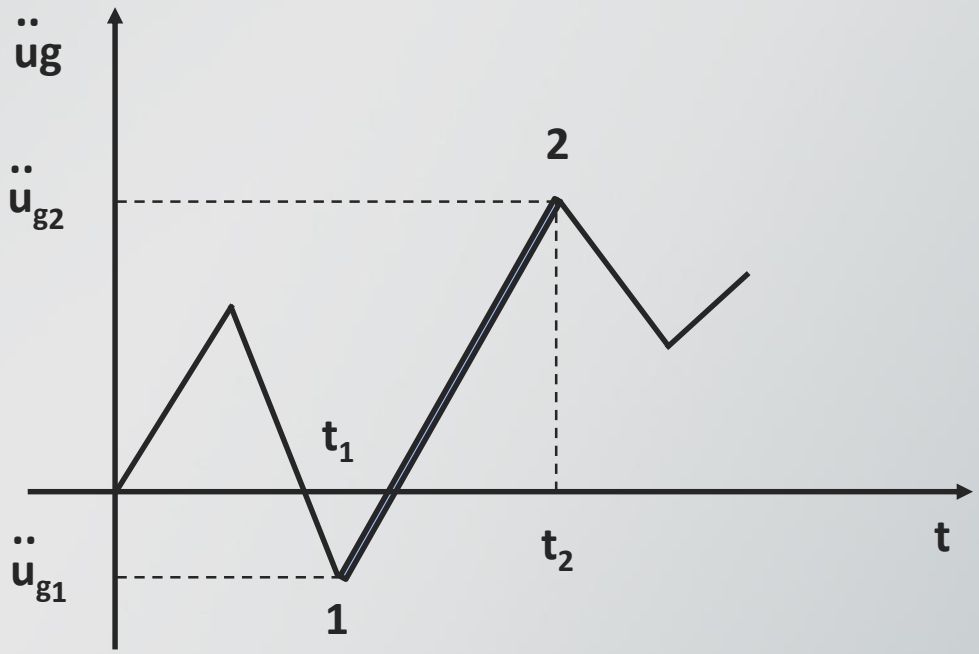
$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g$$

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = -\ddot{u}_g$$



RESPONSE FROM GROUND MOTION

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = A + B\,t = -\ddot{u}_g$$



CLOSED FORM DAMPED RESPONSE

$$\dot{u}_t = e^{-\xi\omega t}\{ [\dot{u}_{t_1} - \frac{B}{\omega^2}] \cos \omega_d t$$

$$+ \frac{1}{\omega_d} [A - \omega^2 u_{t_1} - \xi\omega(\dot{u}_{t_1} + \frac{B}{\omega^2})] \sin \omega_d t \} + \frac{B}{\omega^2}$$

$$u_t = e^{-\xi\omega t}\{ [u_{t_1} - \frac{A}{\omega^2} + \frac{2\xi B}{\omega^3}] \cos \omega_d t$$

$$+ \frac{1}{\omega_d} [\dot{u}_{t_1} + \xi\omega u_{t_1} - \frac{\xi A}{\omega} + \frac{B(2\xi^2 - 1)}{\omega^2}] \sin \omega_d t \}$$

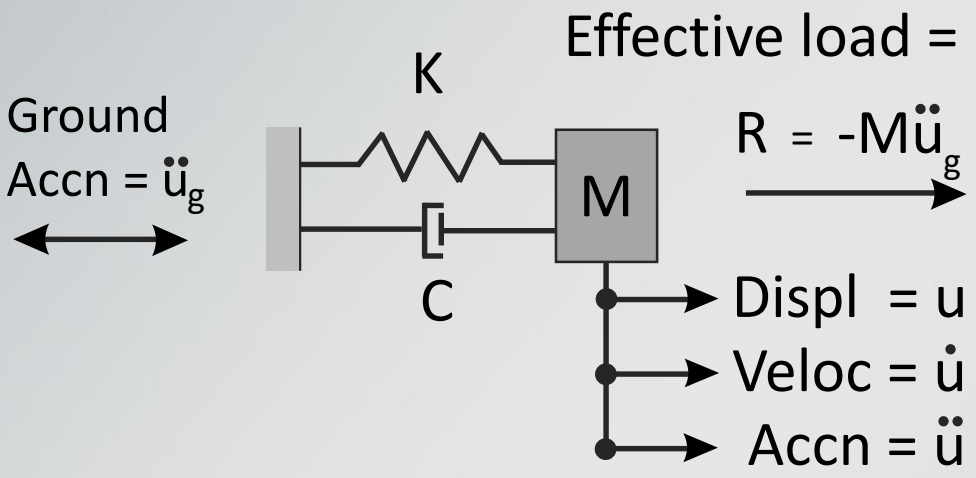
$$+ [\frac{A}{\omega^2} - \frac{2xB}{\omega^3} + \frac{Bt}{\omega^2}]$$

UNDAMPED RESPONSE

$$u_t = \left[u_{t_1} - \frac{A}{\omega^2}\right]\cos \omega t + \frac{1}{\omega}\left[\dot{u}_{t_1} - \frac{B}{\omega^2}\right]\sin \omega t + \frac{1}{\omega^2}(A + Bt)$$

$$u_t = \left[\dot{u}_{t_1} - \frac{B}{\omega^2}\right]\cos \omega t + \frac{1}{\omega}\left[A - \omega^2 u_{t_1}\right]\sin \omega t + \frac{B}{\omega^2}$$

STEP BY STEP DYNAMIC ANALYSIS



- At any point in time, dynamic equilibrium is :

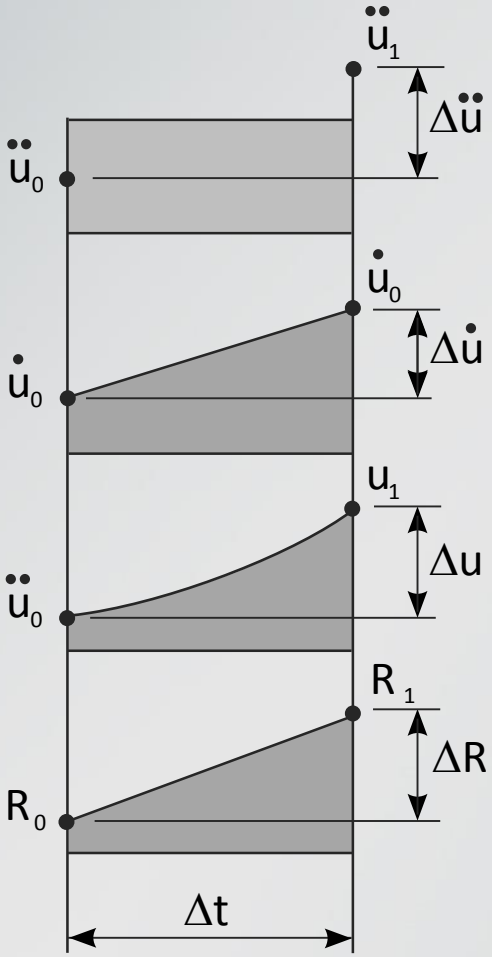
$$M\ddot{u} + C\dot{u} + Ku = R$$

- Over a time step, Δt, dynamic equilibrium is :

$$M\,\Delta\ddot{u} + C\,\Delta\dot{u} + K\,\Delta u = \Delta R$$

- This equation can be solved by step-by-step methods.
- There is one equation with three unknowns (Δu, $\Delta\ddot{u}$, $\Delta\dot{u}$), so assumptions must be made and the solution is approximate.

STEP-BY-STEP INTEGRATION (CAA)



Equilibrium :

$$M\,\Delta\ddot{u} + C\,\Delta\dot{u} + K\,\Delta u = \Delta R$$

From Kinematics :

$$\Delta\dot{u} = \frac{\Delta t}{2}(\ddot{u}_0 + \ddot{u}_1) = \frac{\Delta t}{2}(2\ddot{u}_0 + \Delta\ddot{u})$$

$$\Delta u = \frac{\Delta t}{2}(\dot{u}_0 + \dot{u}_1) = \frac{\Delta t}{2}(2\dot{u}_0 + \Delta\dot{u})$$

Hence get effective stiffness and load :

$$K_{eff} = \frac{4}{\Delta t^2}M + \frac{2}{\Delta t}C + K$$

$$\Delta R_{eff} = -M\ddot{u}_g + M(2\ddot{u}_0 + \frac{4}{\Delta t}\dot{u}_0) + 2C\dot{u}_0$$

Solve $K_{eff}\Delta u = \Delta R_{eff}$ Then :

$$\Delta\dot{u} = -2\dot{u}_0 + \frac{2}{\Delta t}\Delta u$$

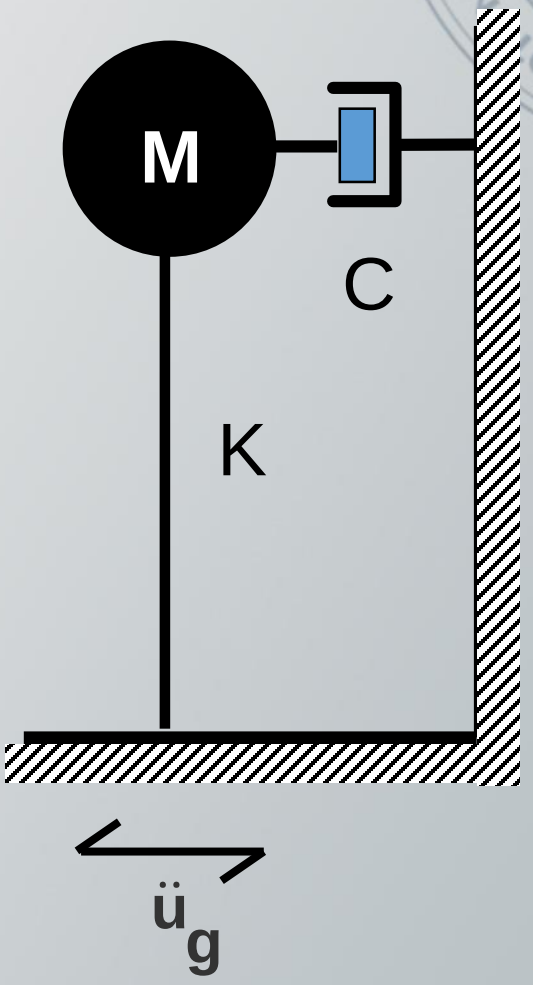
$$\Delta\ddot{u} = -2\ddot{u}_0 + \frac{2}{\Delta t}\Delta\dot{u}$$

BASIC DYNAMICS WITH DAMPING

$$M\ddot{u}_t + C\dot{u} + Ku = 0$$

$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g$$

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = -\ddot{u}_g$$



RESPONSE MAXIMA

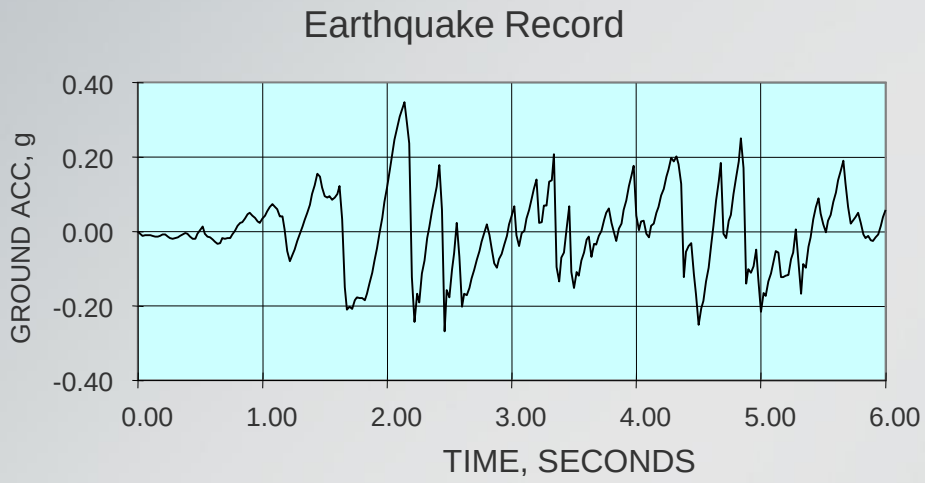
$$u_t = u_0 \cos(\omega t)$$

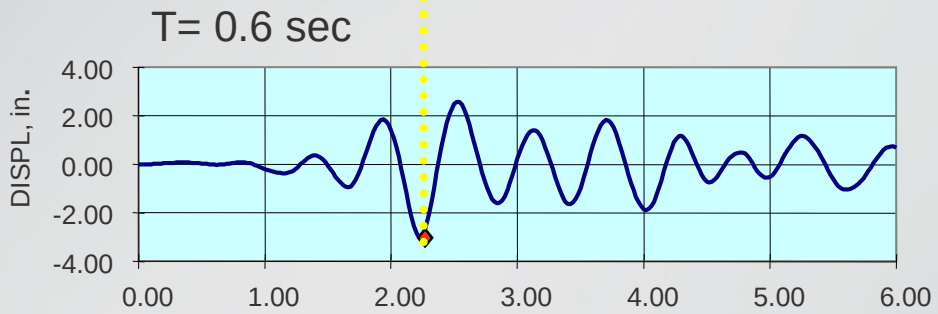
$$\dot{u}_t = -\omega u_0 \sin(\omega t)$$

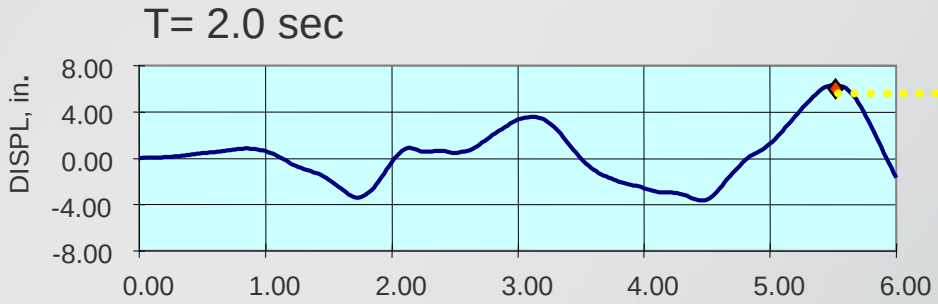
$$\ddot{u}_t = -\omega^2 u_0 \cos(\omega t)$$

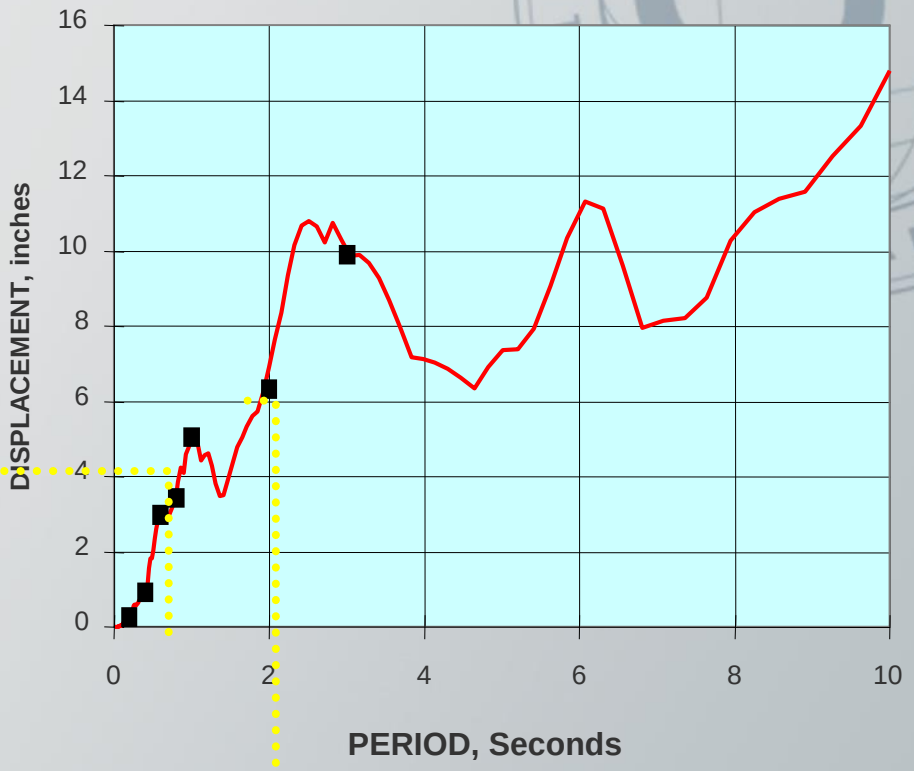
$$\ddot{u}_{max} = -\omega^2 u_{max}$$

RESPONSE SPECTRUM GENERATION



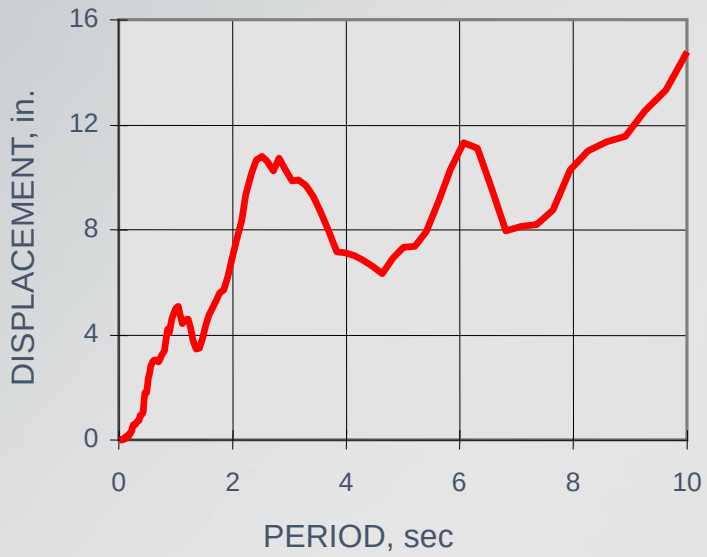






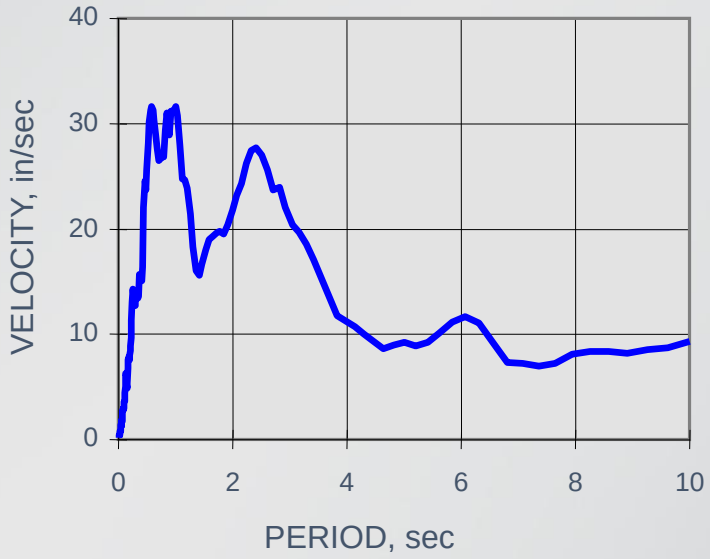
Displacement Response Spectrum 5% damping

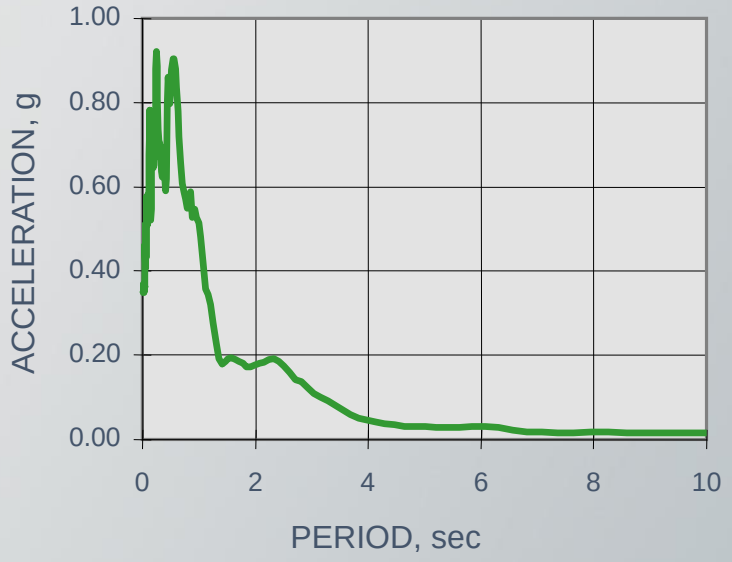
SPECTRAL PARAMETERS



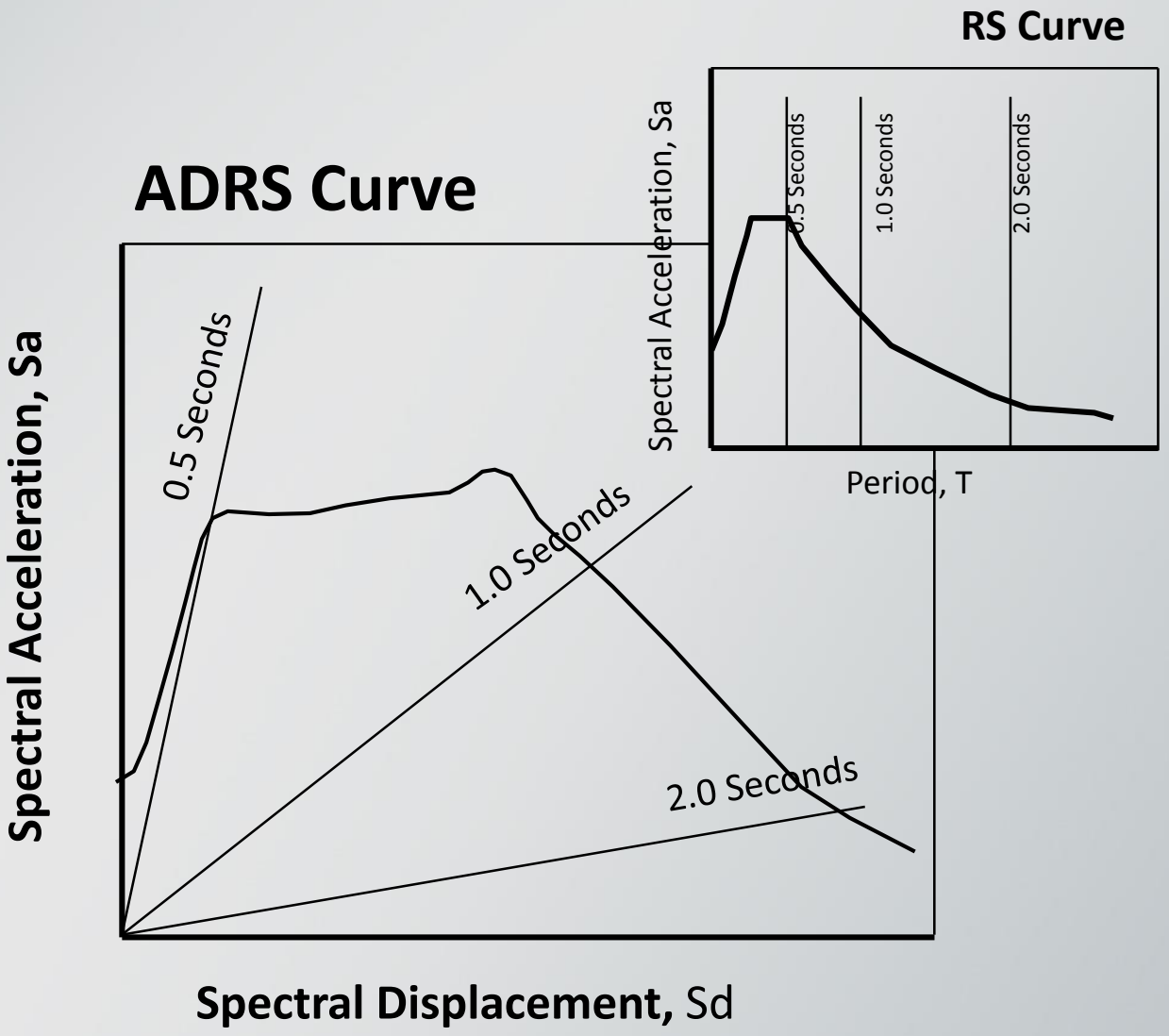
$$PS_V = \omega S_d$$

$$PS_a = \omega PS_v$$

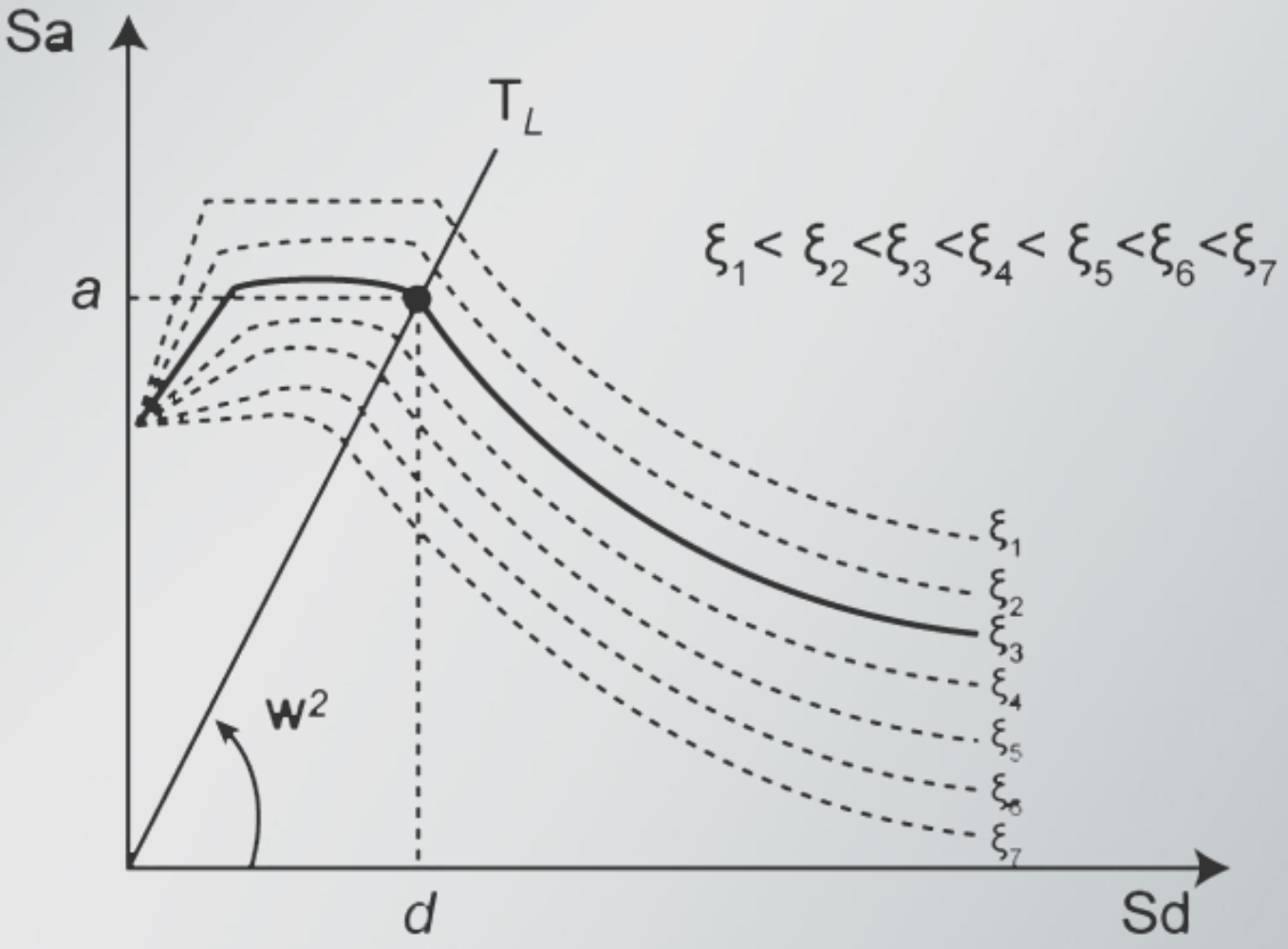




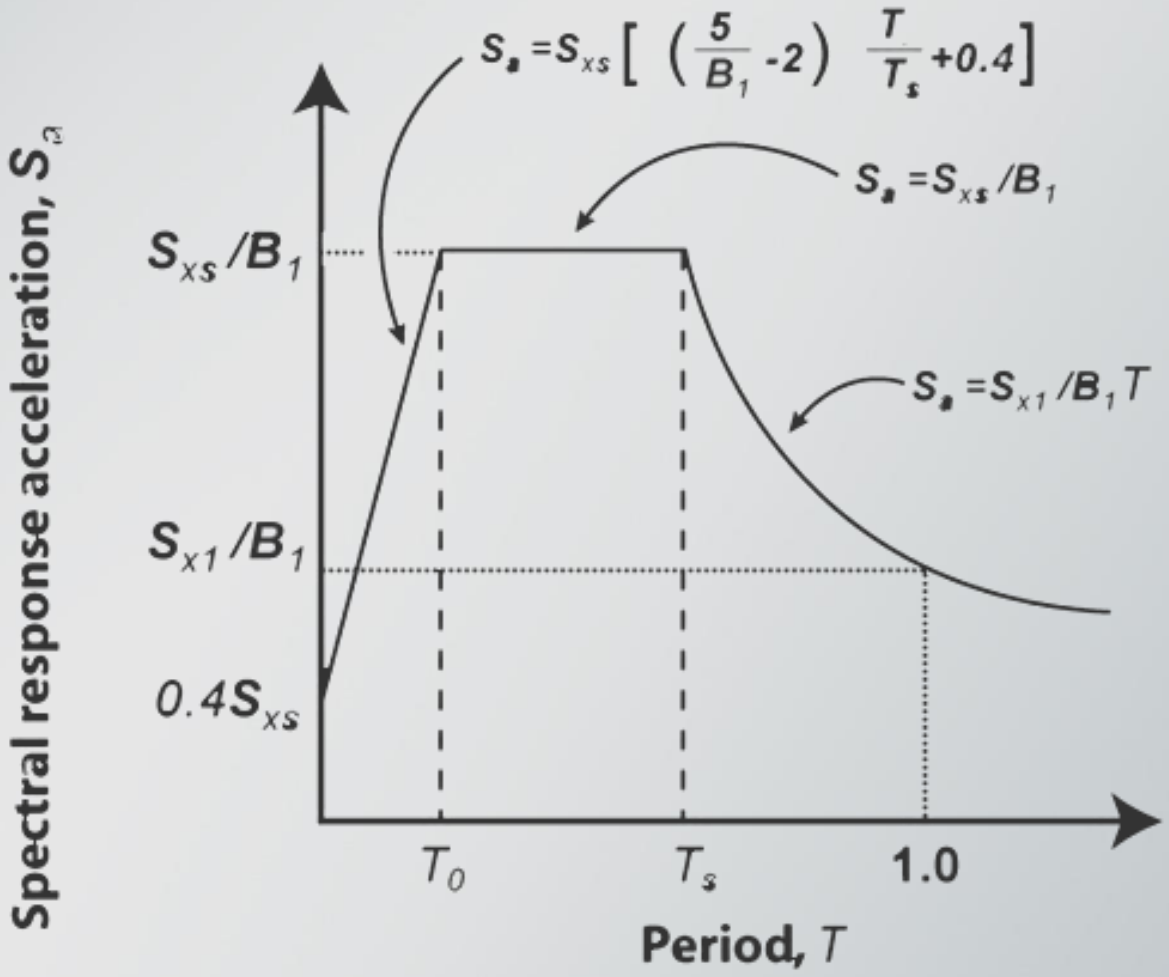
THE ADRS SPECTRUM



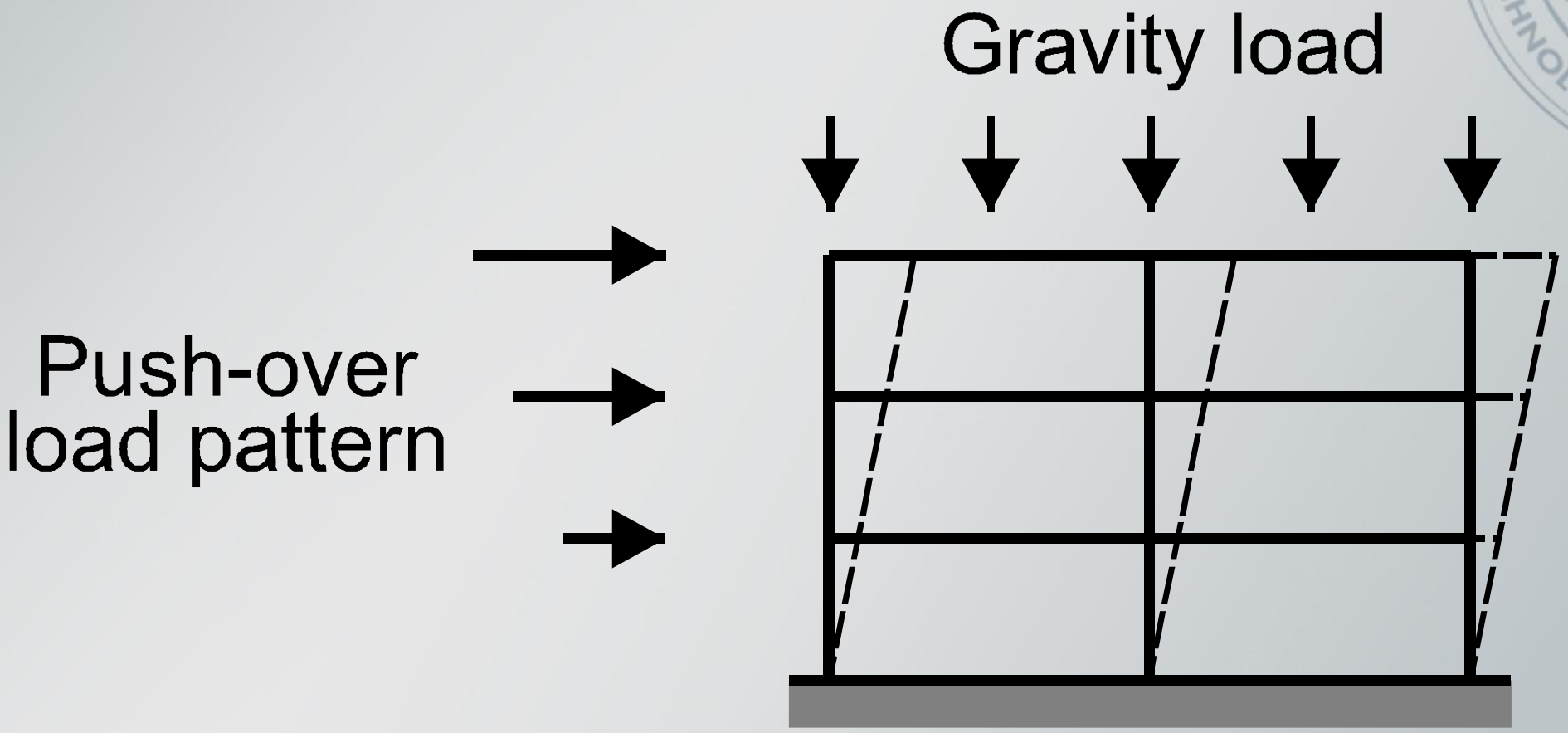
THE ADRS SPECTRUM



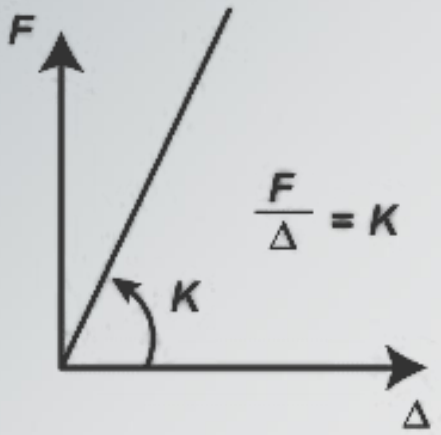
ASCE 7 RESPONSE SPECTRUM



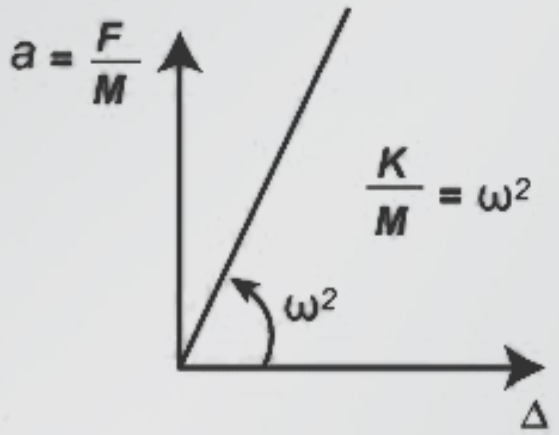
PUSHOVER



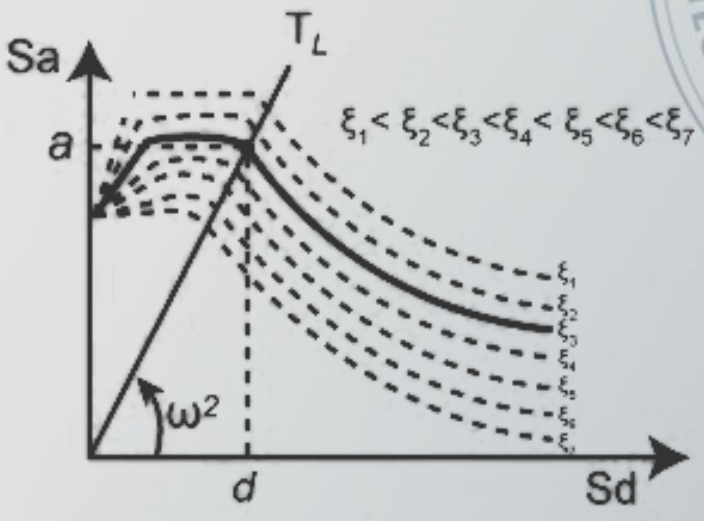
THE LINEAR PUSHOVER



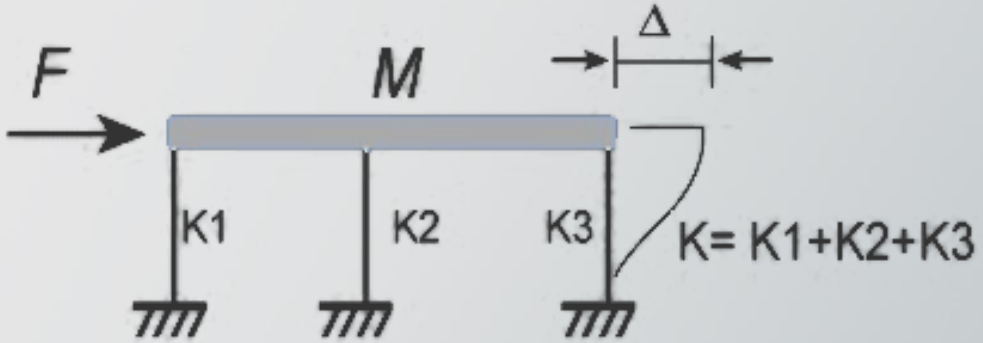
Linear Pushover Diagram
(In terms of force)



Linear Pushover Diagram
(In terms of acceleration)

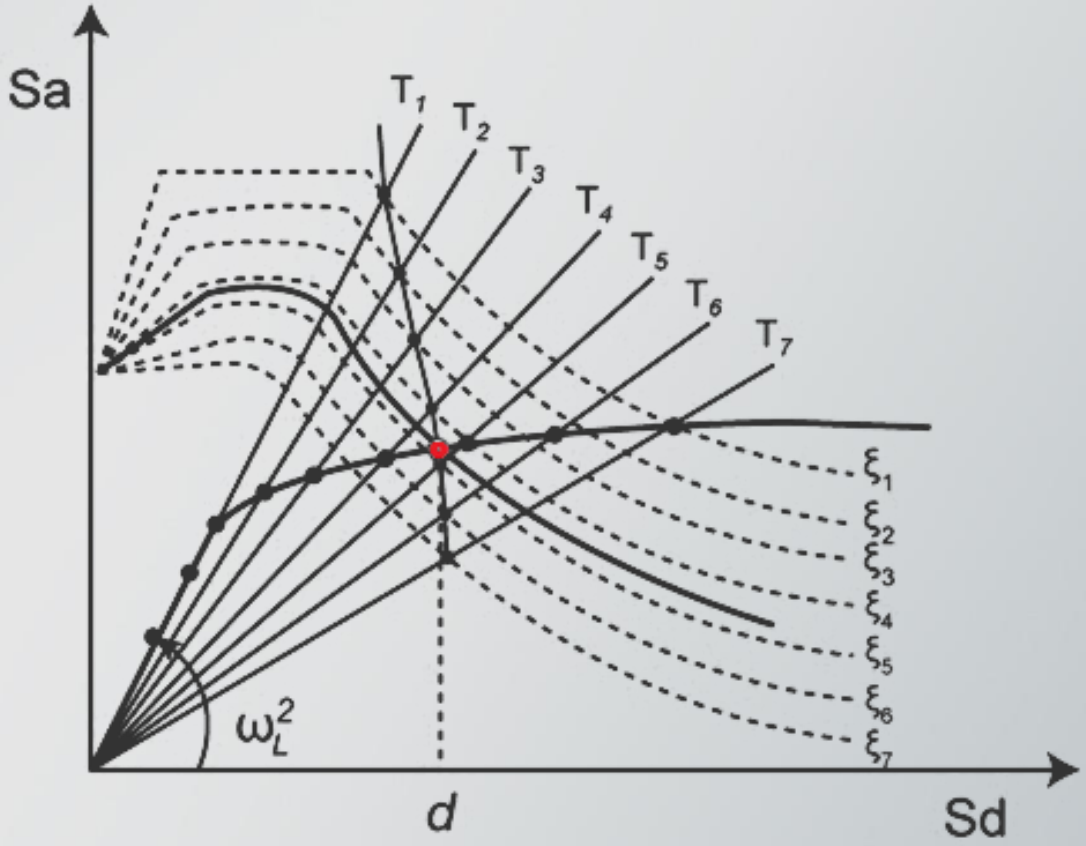


ADRS Spectrum
(With linear pushover diagram)

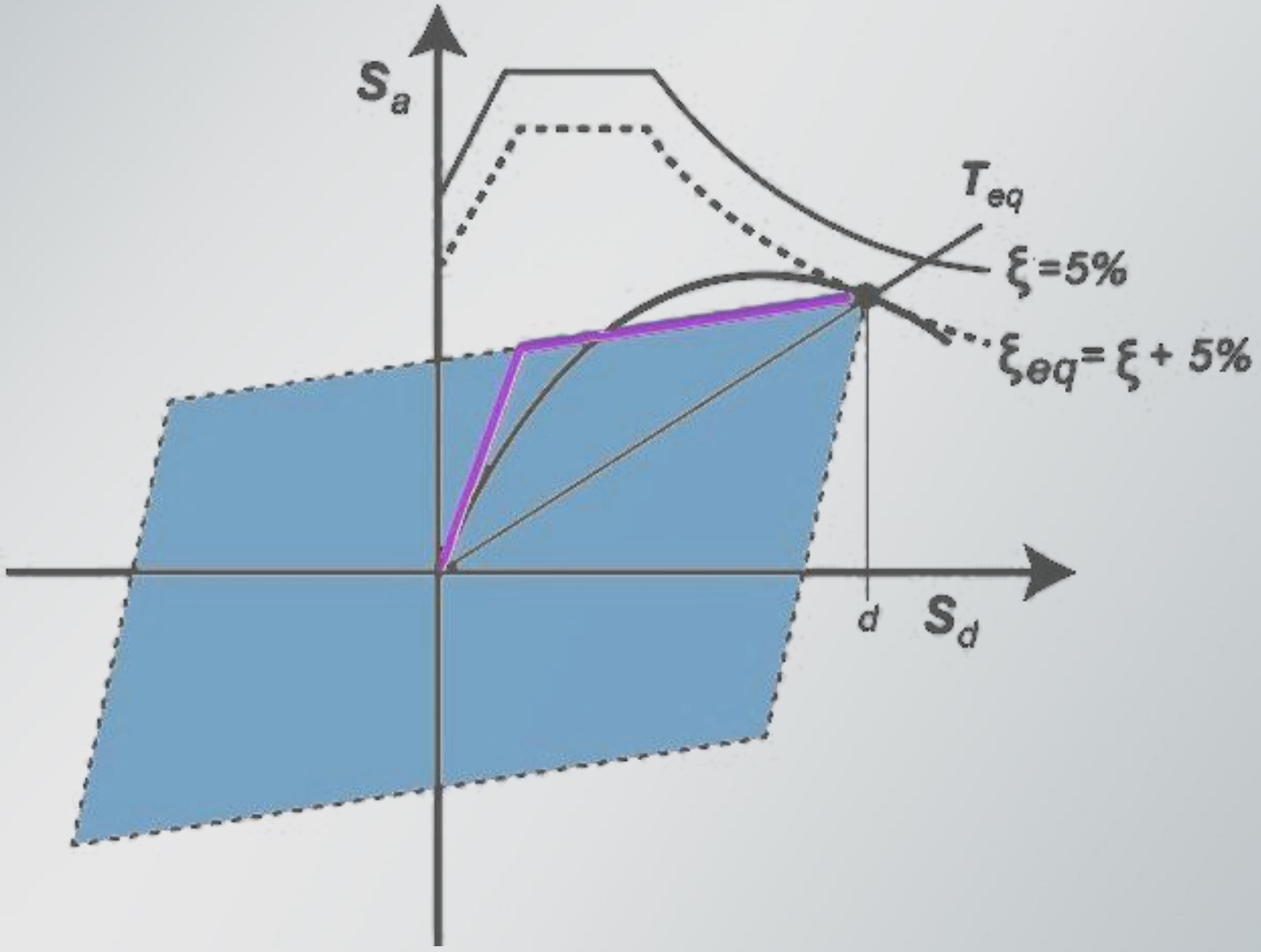


EQUIVALENT LINEARIZATION

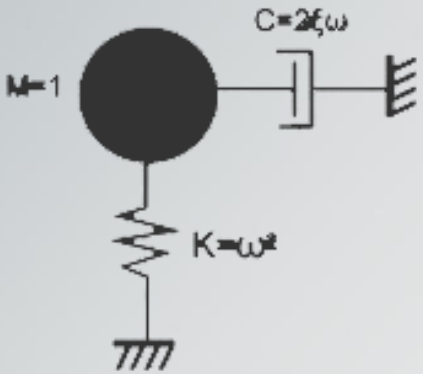
How far to push? The Target Point!



DAMPING COEFICIENT FROM HYSTERESIS



DAMPING COEFICIENT FROM HYSTERESIS



$$\ddot{u} + 2\xi\omega u + \omega^2 \dot{u} = -\ddot{u}g$$

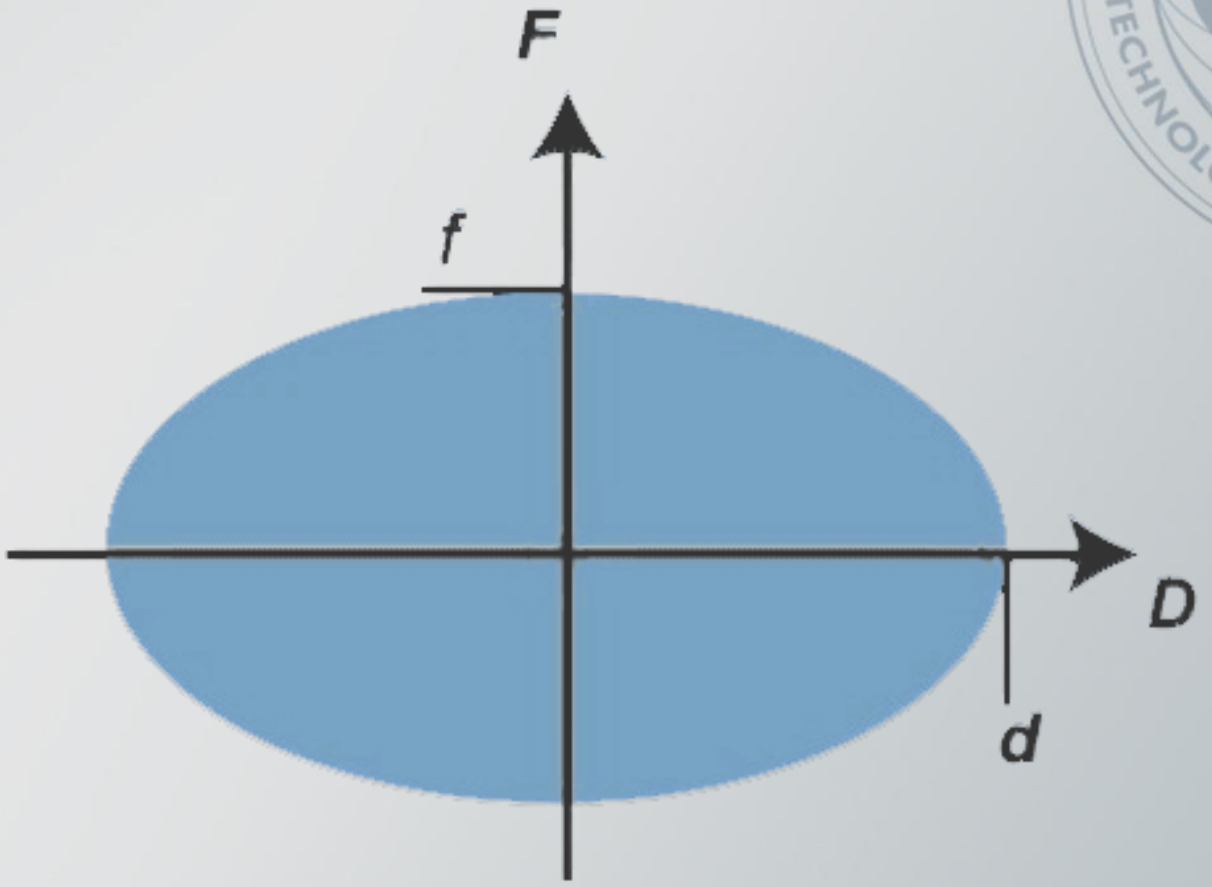
$$u = d \sin \omega t$$

$$\dot{u} = d\,\omega \cos\omega t$$

$$f = (2\xi\omega)\,(d\omega)$$

$$\text{Area} = \pi f d$$

$$= 2\pi\xi\omega^2 d^2$$



DISPLACEMENT MODFICATION

Calculating the Target Displacement

$$\delta = C_0 \, C_1 \, C_2 \, S_a \, T_e^{\,2} / (4\pi^2)$$

C_0 Relates spectral to roof displacement
C_1 Modifier for inelastic displacement
C_2 Modifier for hysteresis loop shape

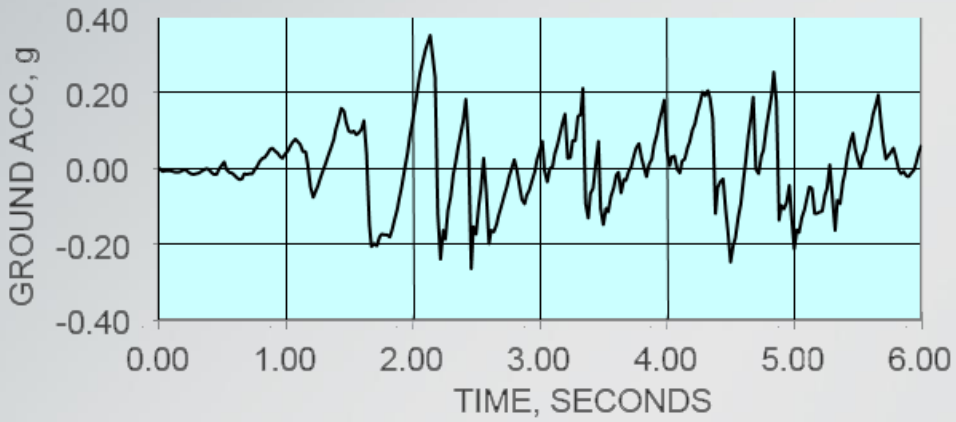
ARTIFICIAL EARTHQUAKES

CREATING HISTORIES TO MATCH A SPECTRUM

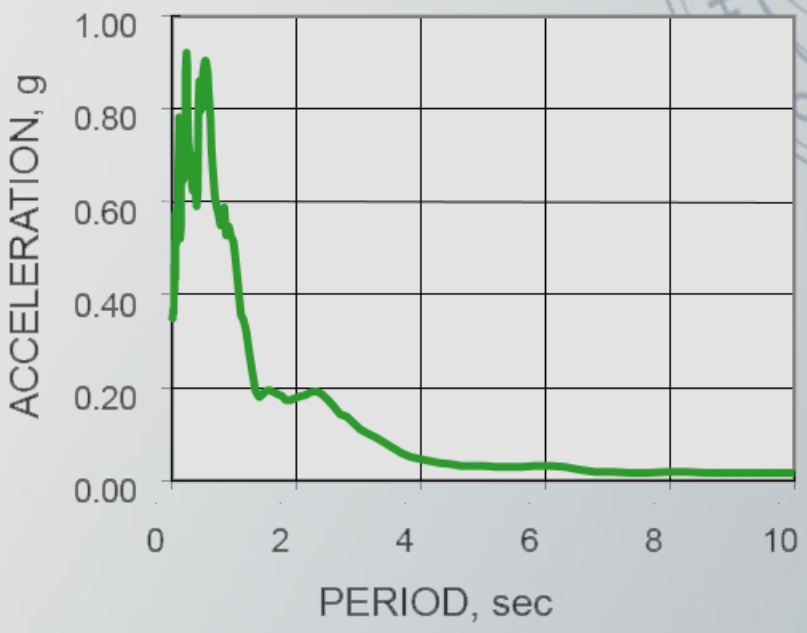
FREQUENCY CONTENTS OF EARTHQUAKES

FOURIER TRANSFORMS

MATCHING THE SPECTRUM

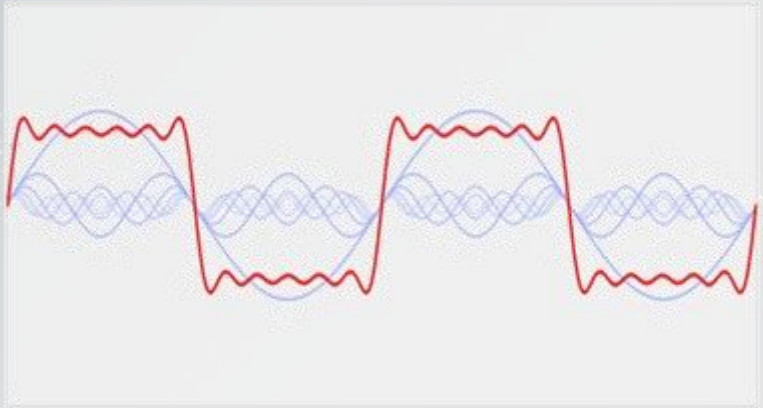


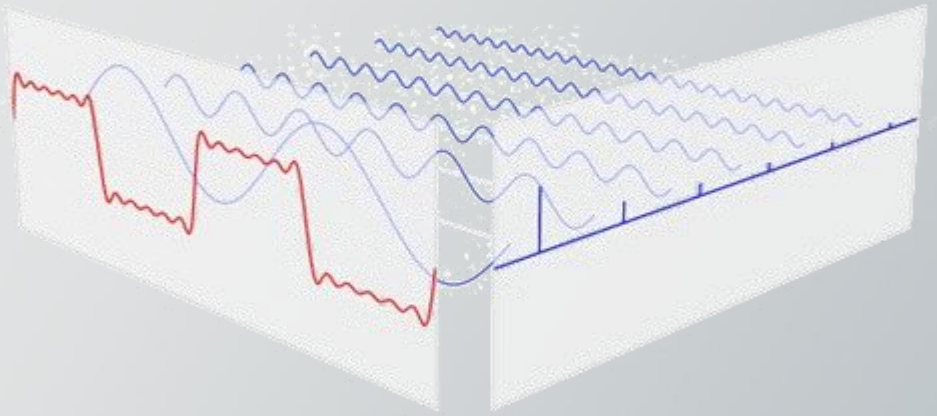
Seed Earthquake Record



Spectrum to be matched

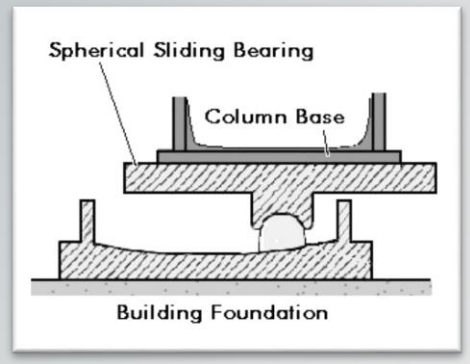
FOURIER TRANSFORMS

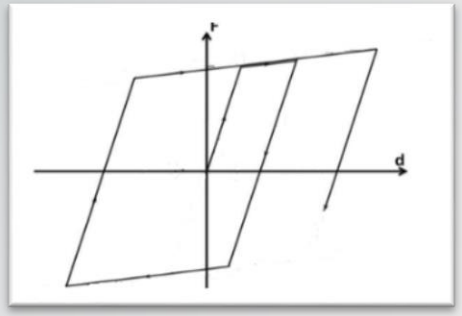




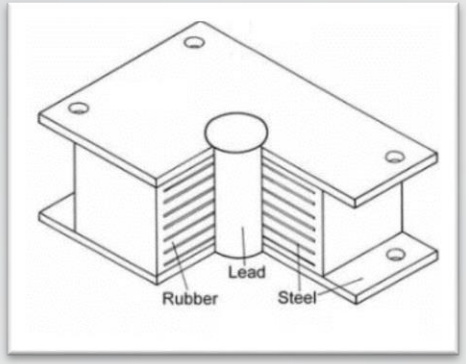
ENERGY DISSIPATION DEVICES

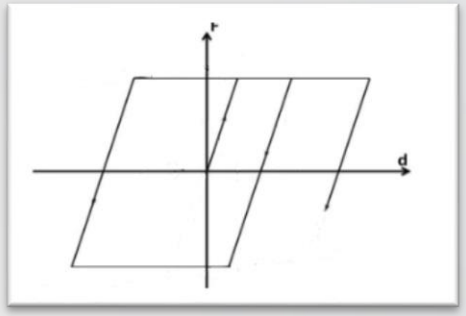
Friction Isolator



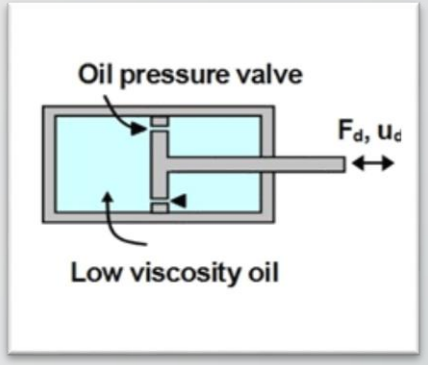


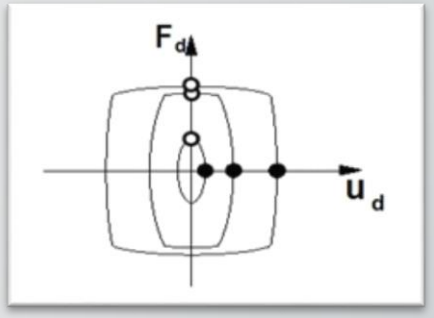
Rubber Isolator



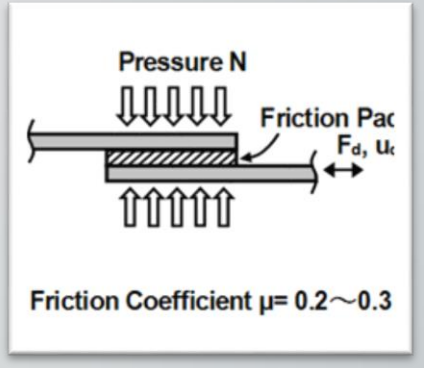


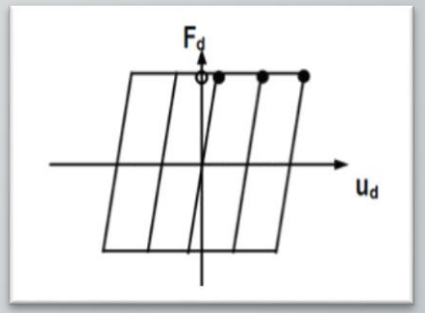
Oil Damper



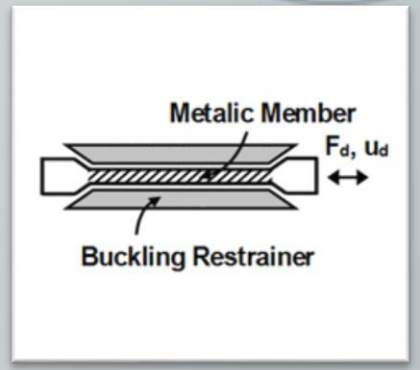


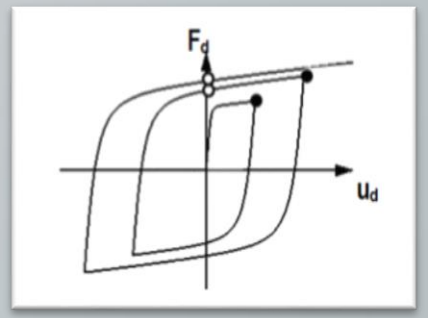
Friction Damper





Buckling-Restrained Brace (BRB)

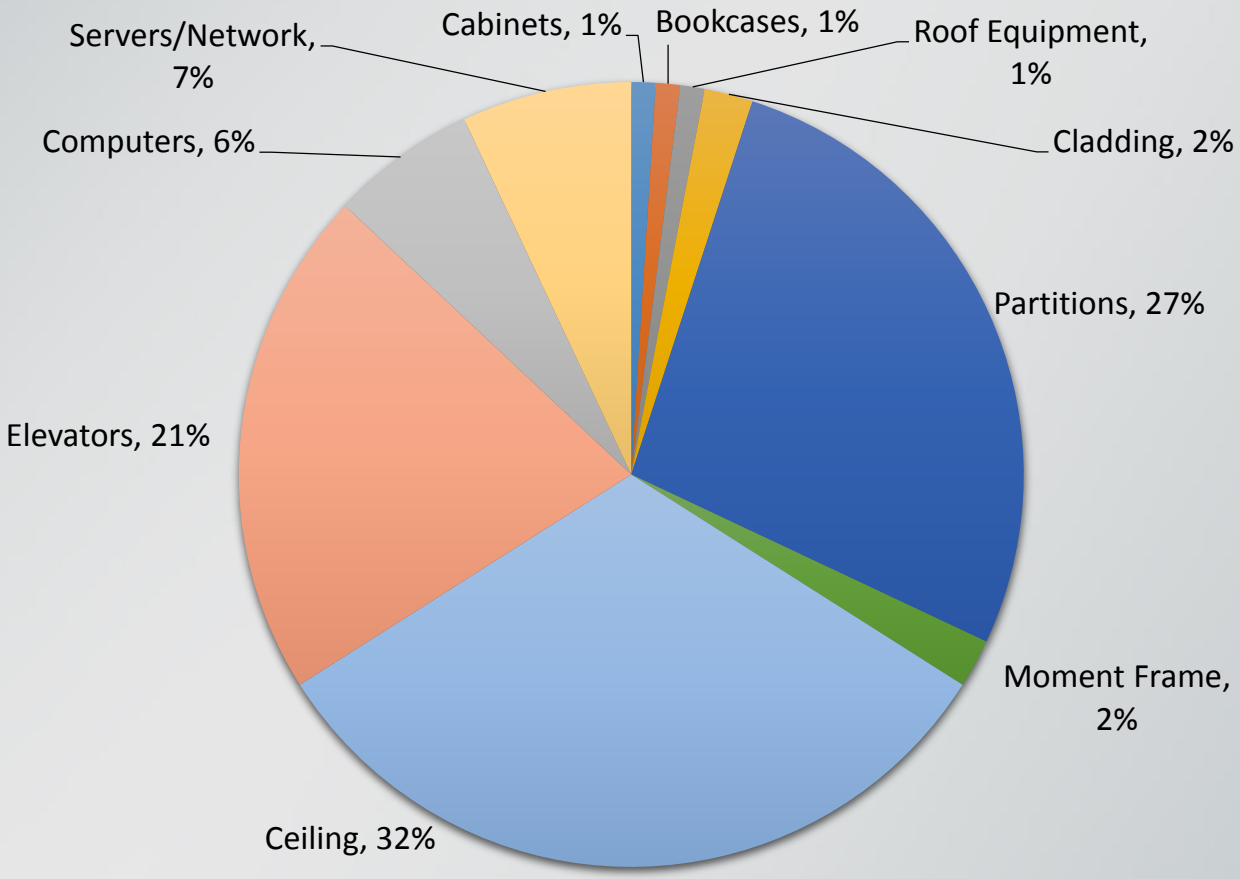




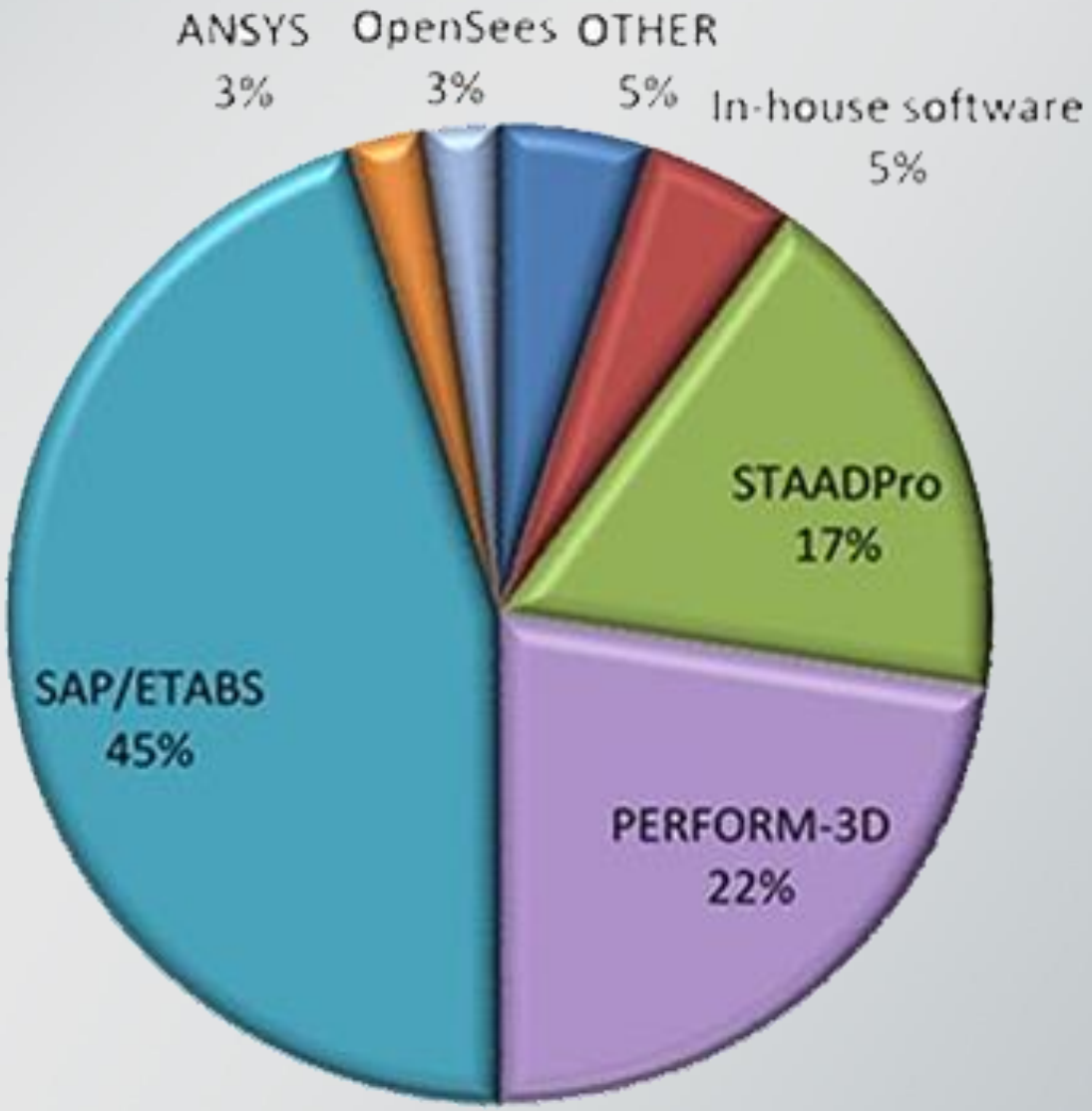
RATING FOR SEISMIC PERFORMANCE

CoRE Rating	Safety	Reparability	Functionality
5-Star	Life Safe	Loss <5%	Occupiable Immediately Functional < 72 hours
4-Star	Life Safe	Loss <10%	Occupiable Immediately Functional < 1 month
3-star	Life Safe	Loss <20%	Occupiable < 1 month Functional < 6 months
Certified	Life Safe	Not estimated	Not estimated
Not Certified	Life Safety Hazard	Not estimated	Not estimated

DAMAGE ANALYSIS



NONLINEAR ANALYSIS SURVEY



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