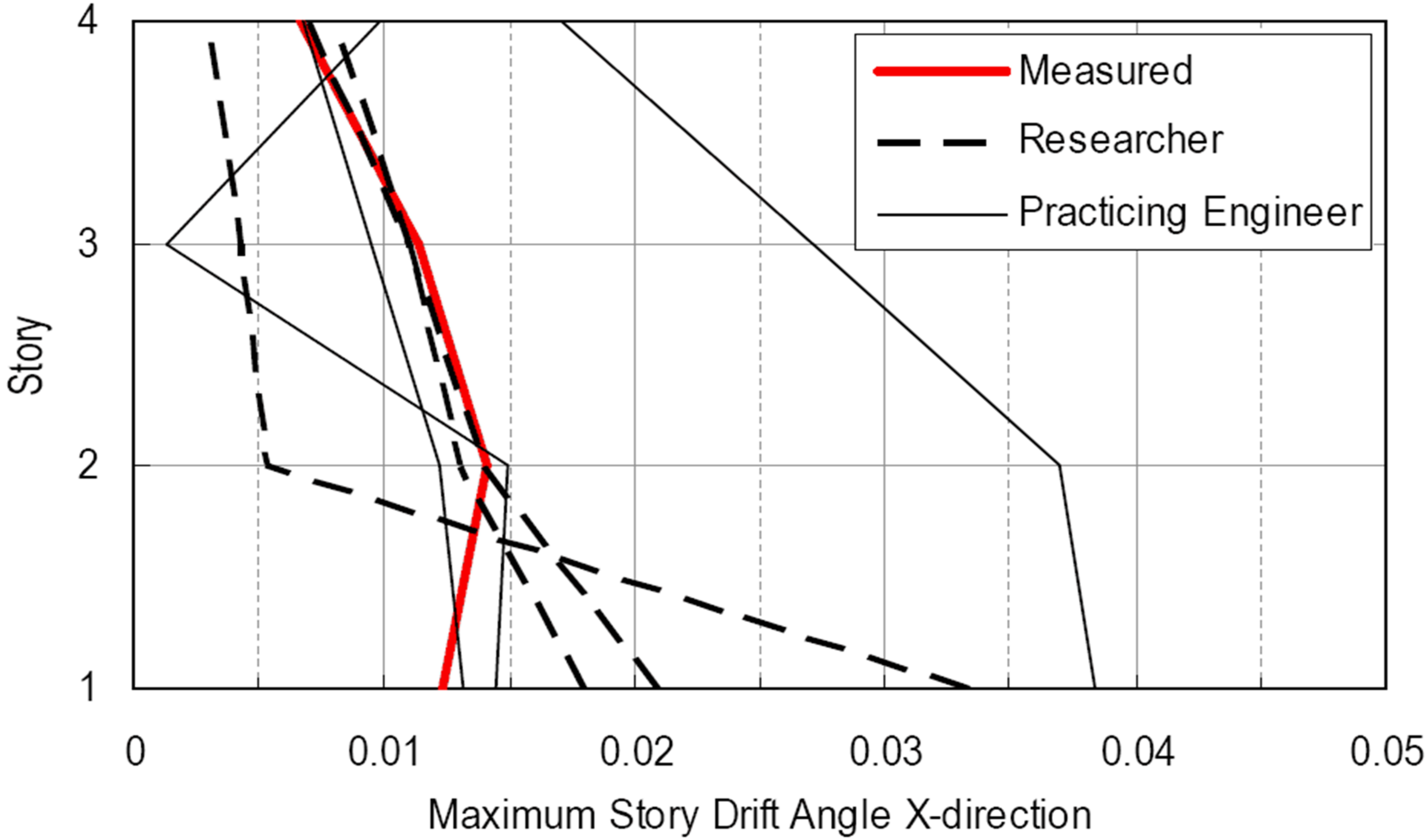
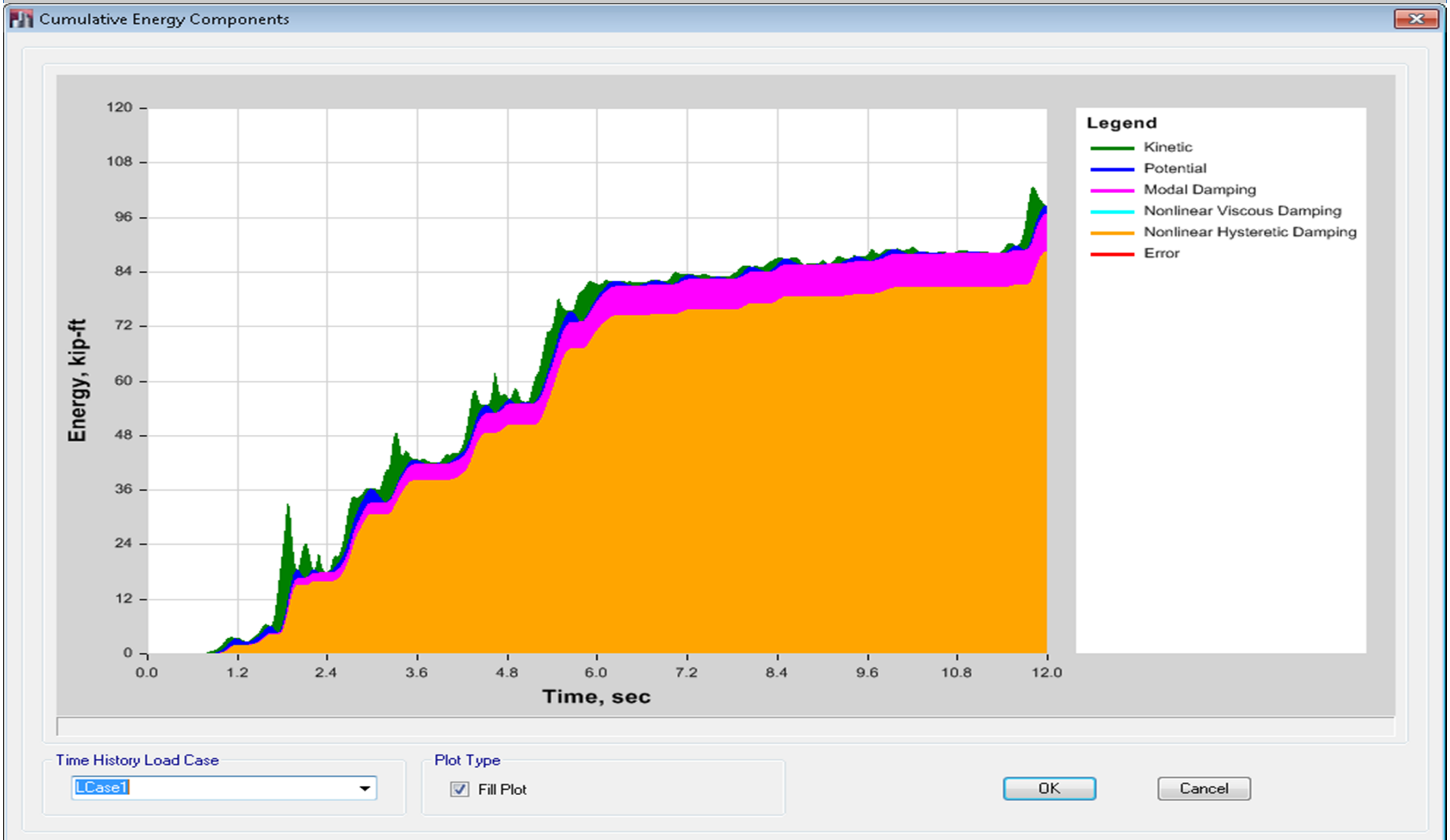

A One-Day Technology Transfer Event
The theory and practice of
PERFORMANCE-BASED DESIGN
THE FUTURE OF EARTHQUAKE ENGINEERING
Instructor: Ashraf Habibullah
President and CEO, Computers & Structures, Inc.

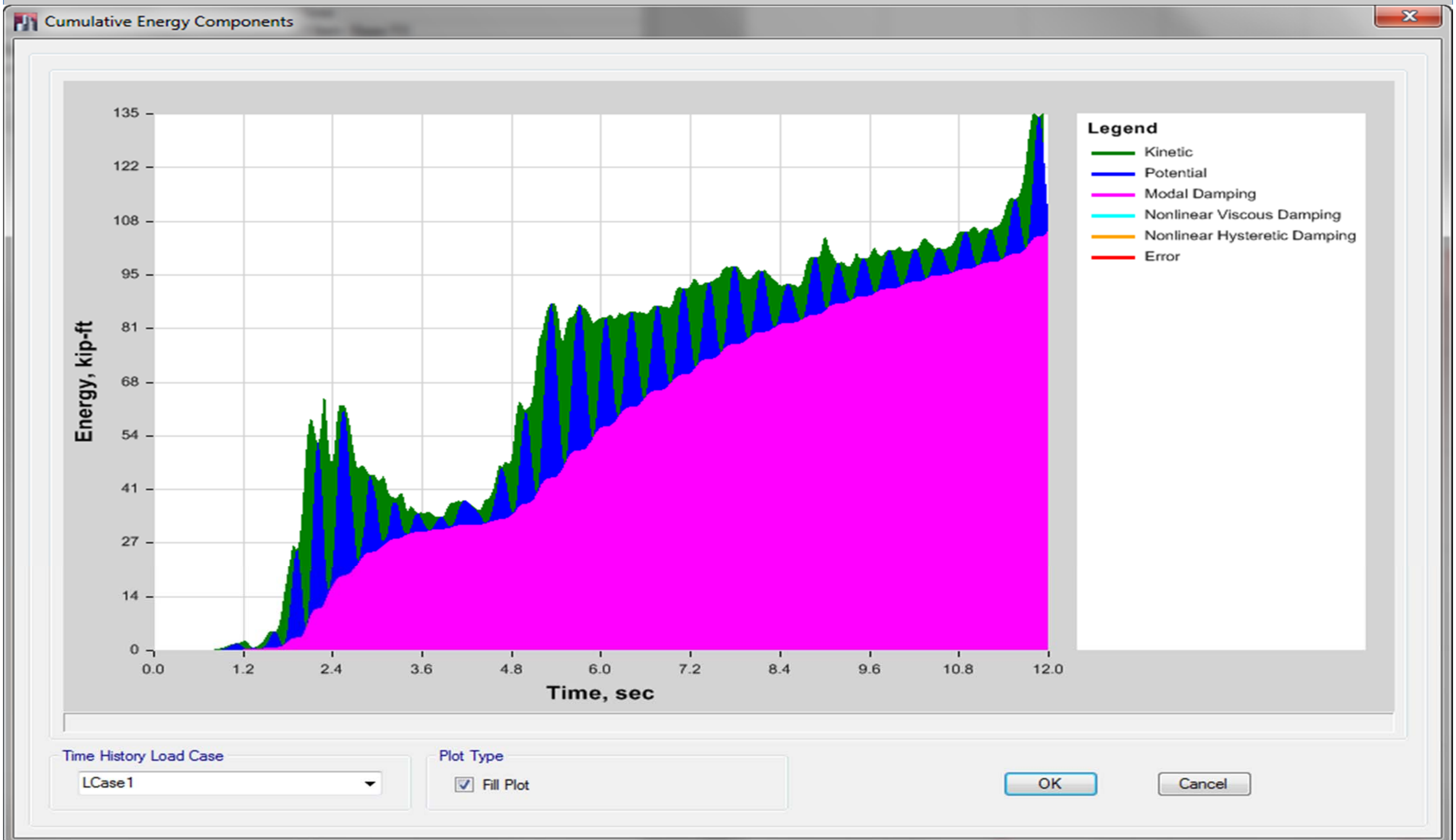

NEW
ANOTHER BREAKTHROUGH FROM RADIO SHACK!
TRS-80 MODEL II
5-Figure Computing Power at a 4-Figure Price!
3450.00

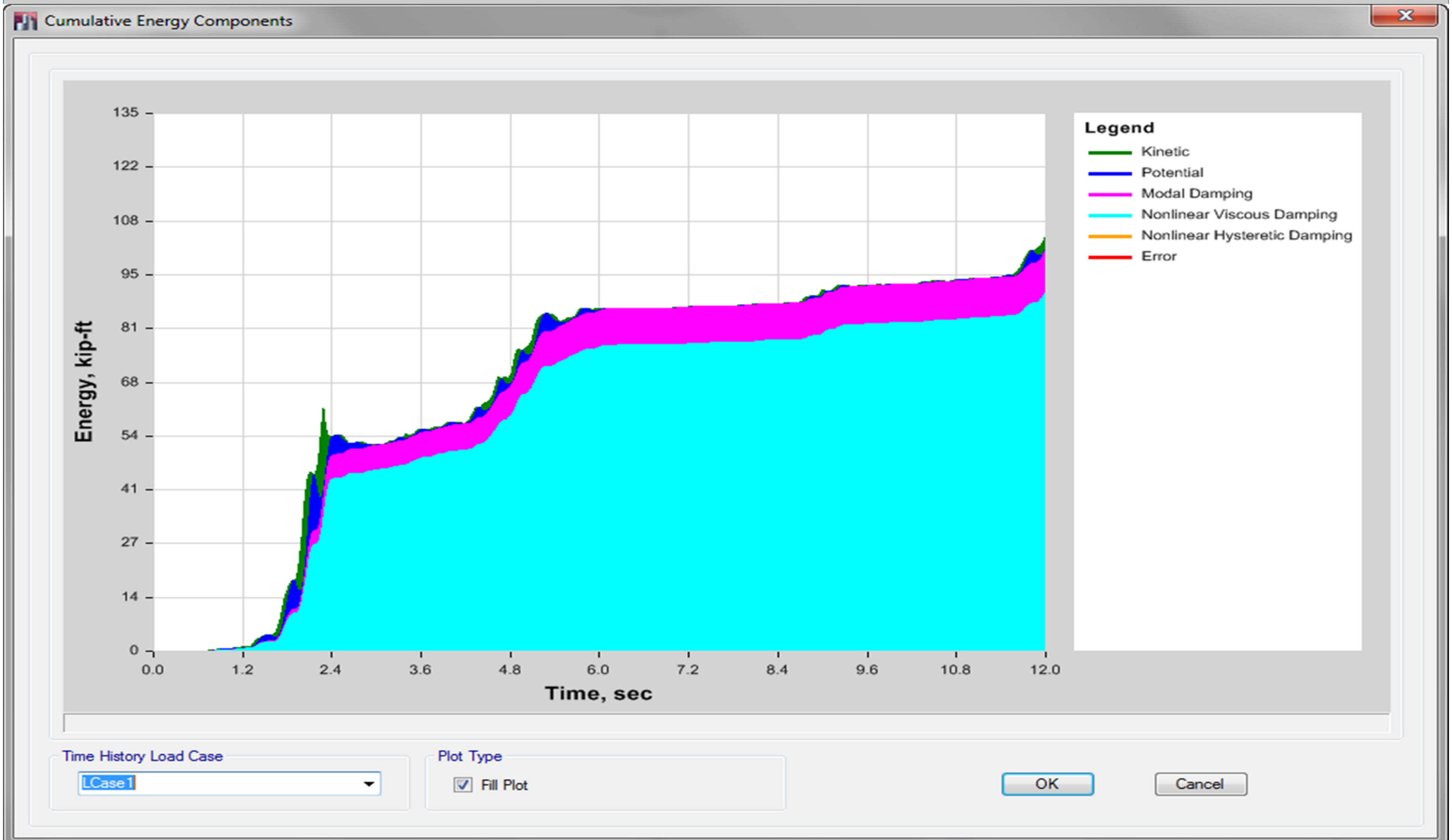
CALCULATED vs MEASURED



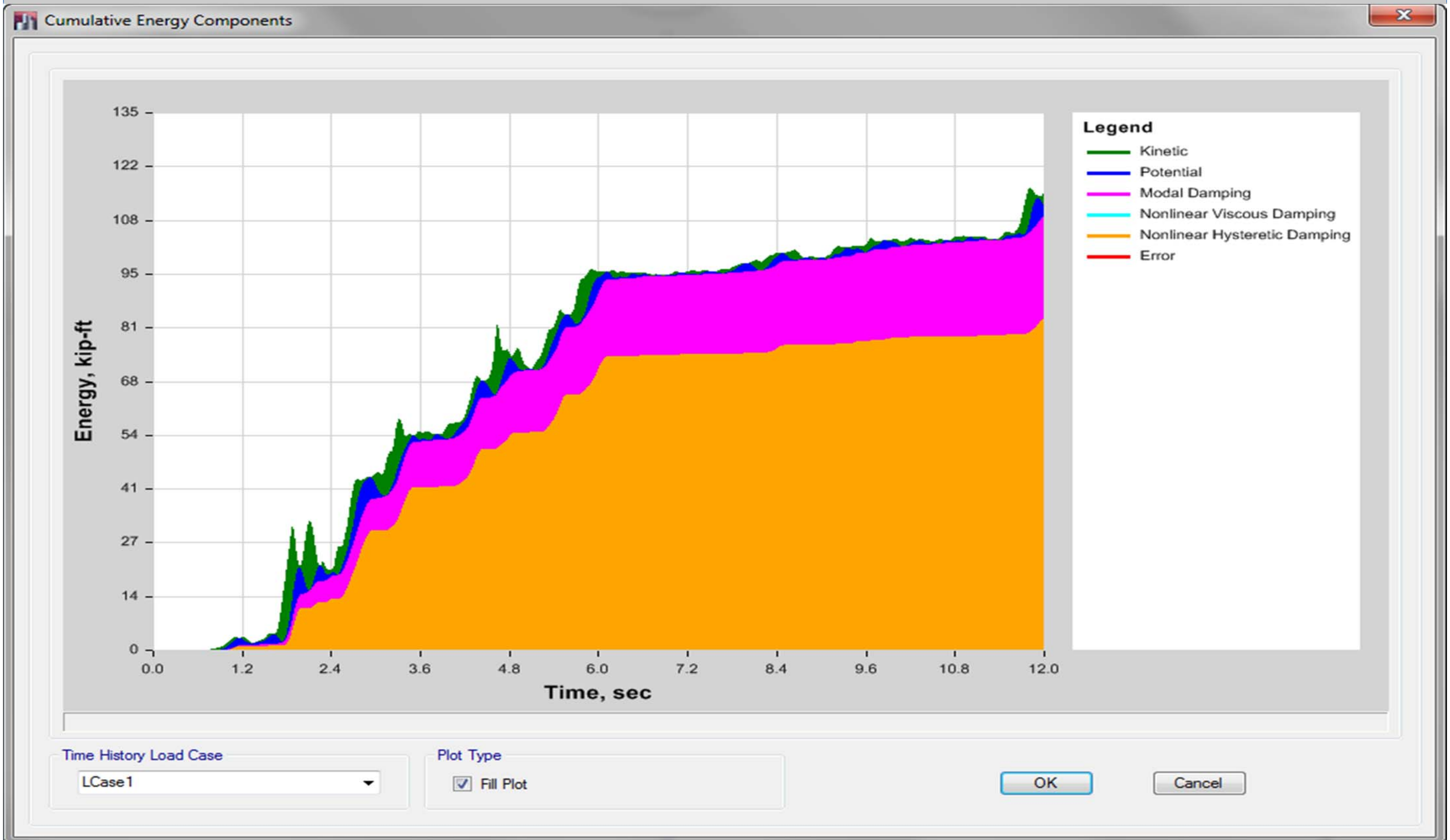
ENERGY DISSIPATION



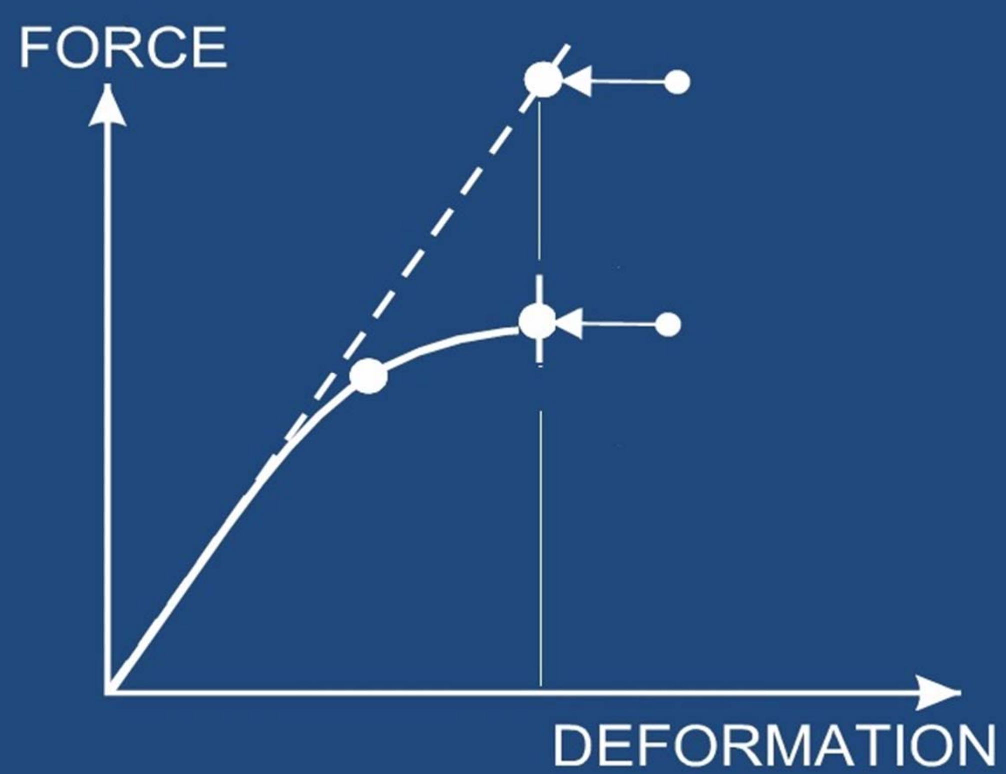

Cumulative Energy Components
Energy, kip-ft
135
122
108
95
81
68
54
41
27
14
0
0.0
1.2
2.4
3.6
4.8
6.0
7.2
8.4
9.6
10.8
12.0
Time, sec
Legend
Kinetic
Potential
Modal Damping
Nonlinear Viscous Damping
Nonlinear Hysteretic Damping
Error
Time History Load Case
LCase1
Plot Type
Fill Plot
OK
Cancel



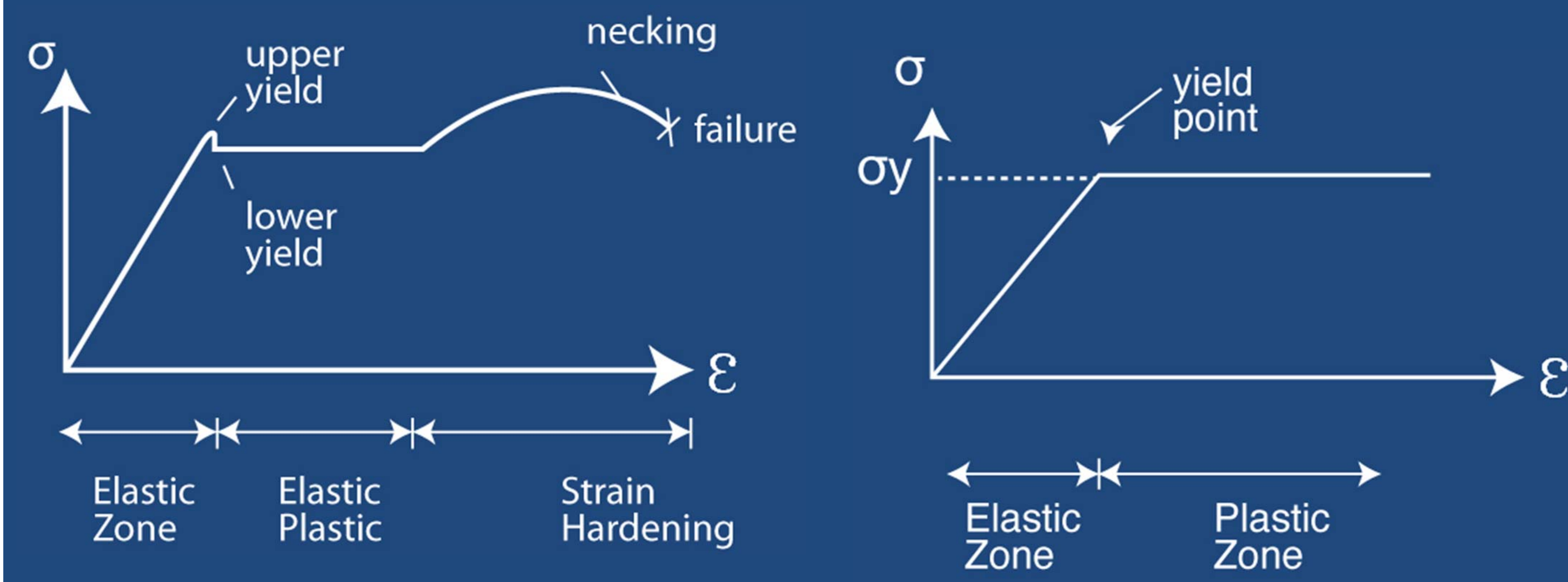
Nonlinear Analysis & Performance Based Design


Cumulative Energy Components
Energy, kip-ft
135
122
108
95
81
68
54
41
27
14
0
0.0
1.2
2.4
3.6
4.8
6.0
7.2
8.4
9.6
10.8
12.0
Time, sec
Legend
Kinetic
Potential
Modal Damping
Nonlinear Viscous Damping
Nonlinear Hysteretic Damping
Error
Time History Load Case
LCase1
Plot Type
Fill Plot
OK
Cancel

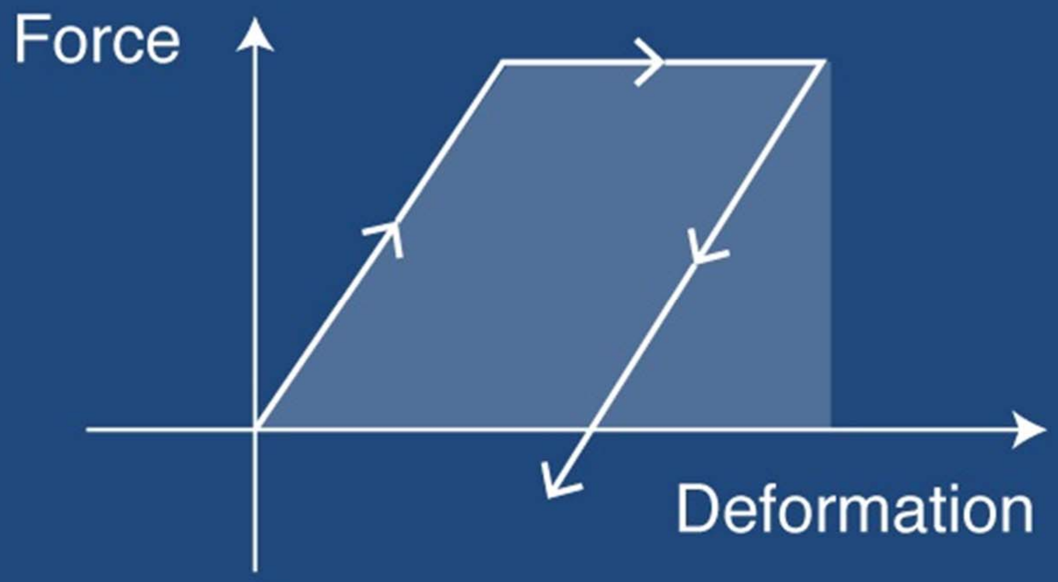
IMPLICIT NONLINEAR BEHAVIOR



STEEL STRESS STRAIN RELATIONSHIPS

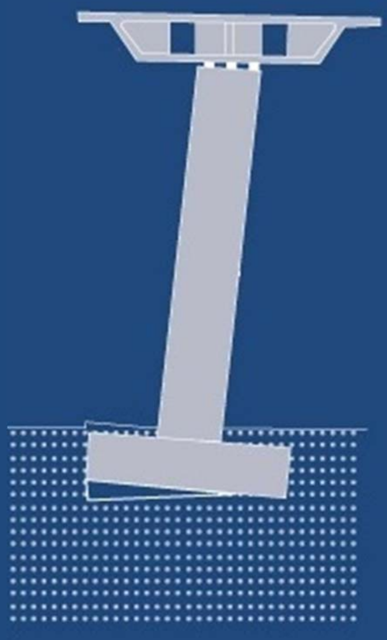


INELASTIC WORK DONE!

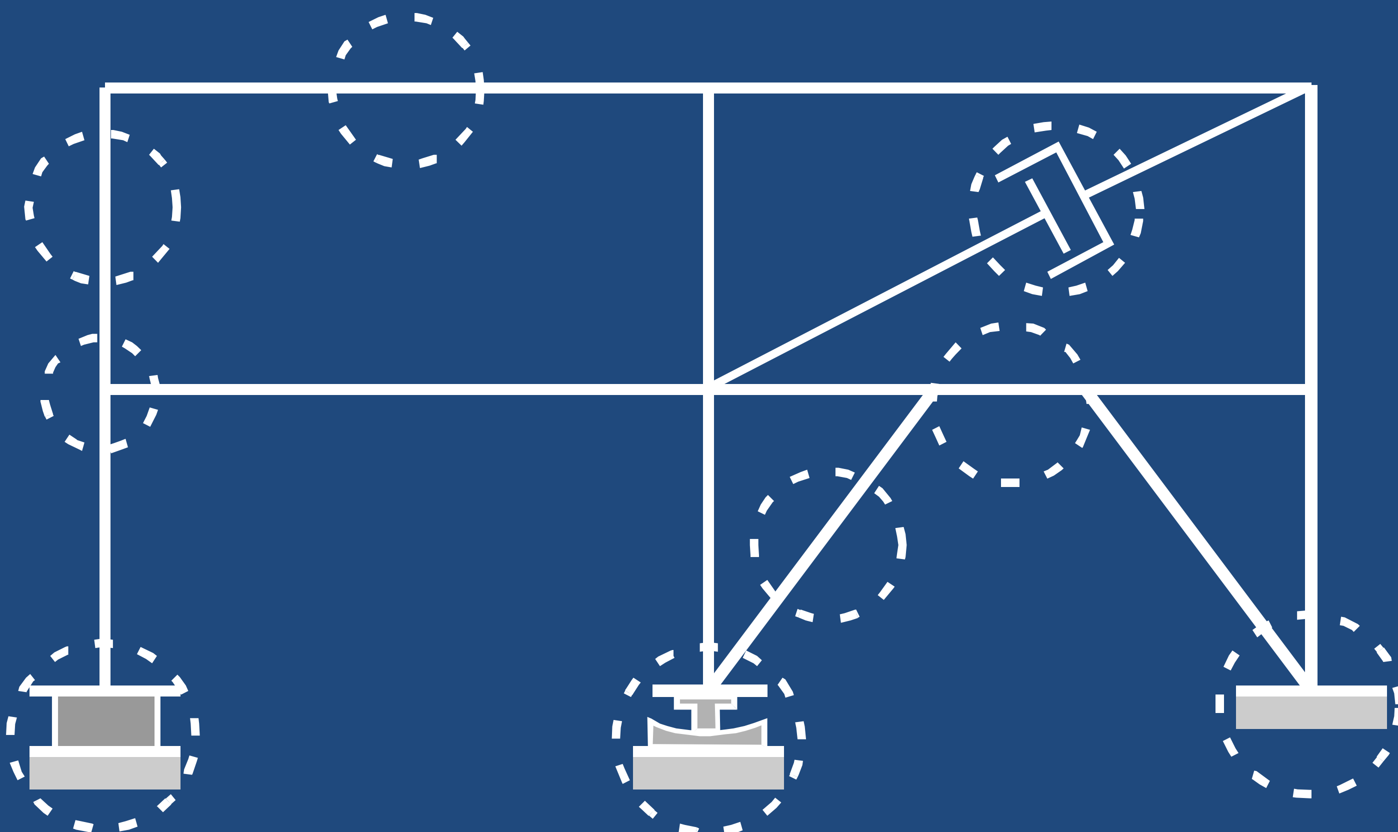


CAPACITY DESIGN

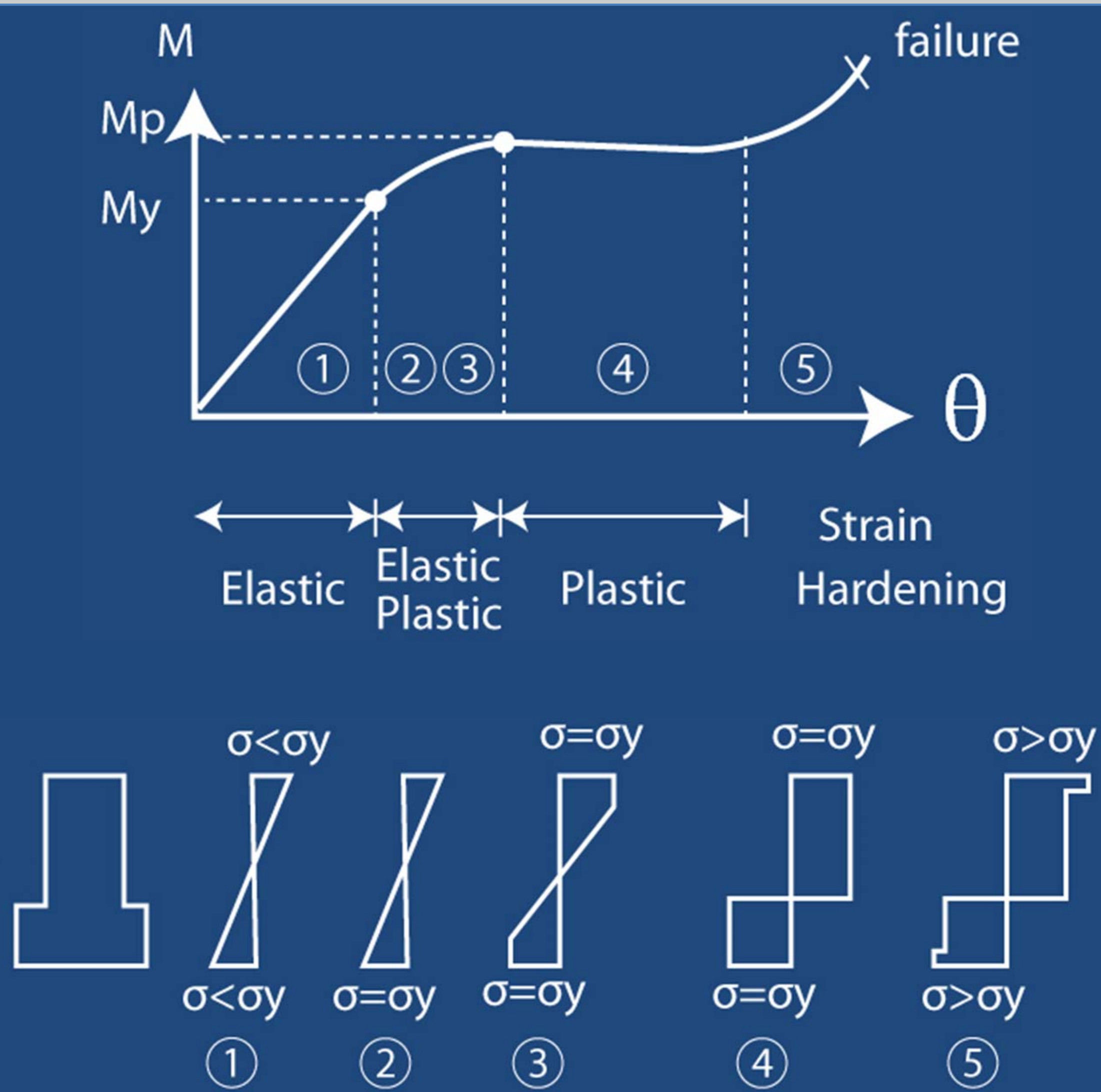
STRONG COLUMNS & WEAK BEAMS IN FRAMES
REDUCED BEAM SECTIONS
LINK BEAMS IN ECCENTRICALLY BRACED FRAMES
BUCKLING RESISTANT BRACES AS FUSES
RUBBER-LEAD BASE ISOLATORS
HINGED BRIDGE COLUMNS
HINGES AT THE BASE LEVEL OF SHEAR WALLS
ROCKING FOUNDATIONS
OVERDESIGNED COUPLING BEAMS
OTHER SACRIFICIAL ELEMENTS



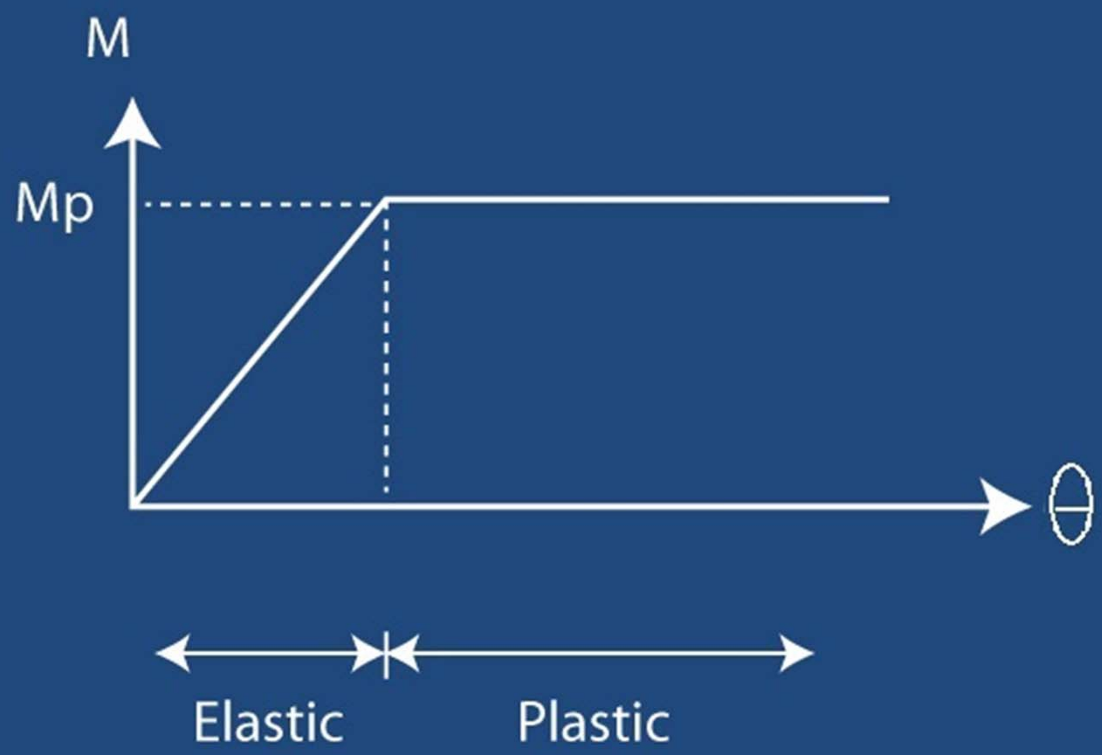
STRUCTURAL COMPONENTS



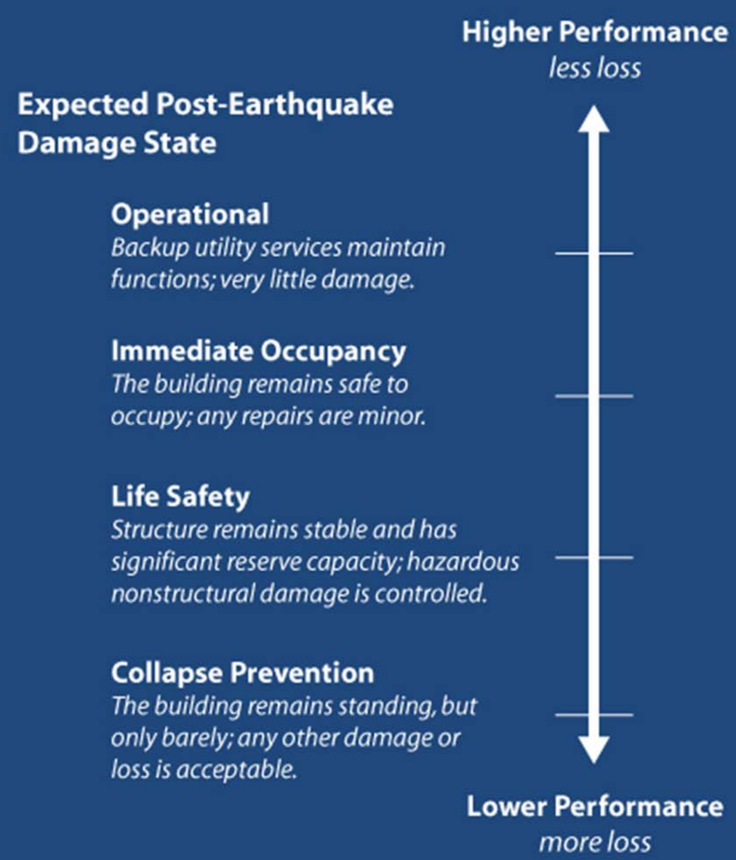
MOMENT ROTATION RELATIONSHIP



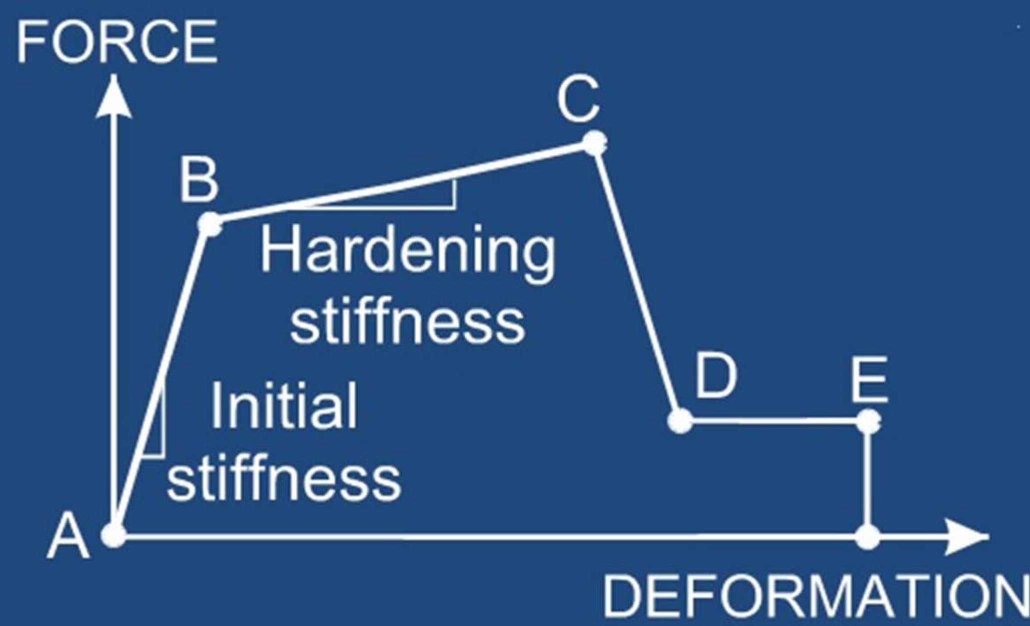
IDEALIZED MOMENT ROTATION



PERFORMANCE LEVELS

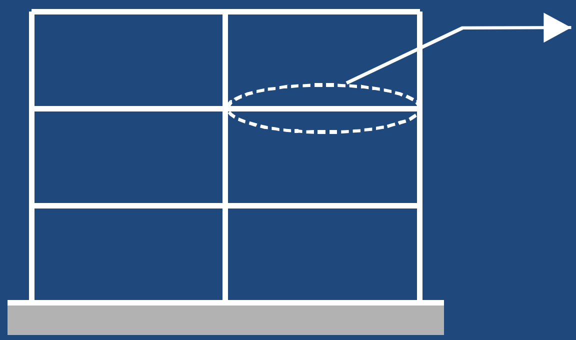


IDEALIZED FORCE DEFORMATION CURVE



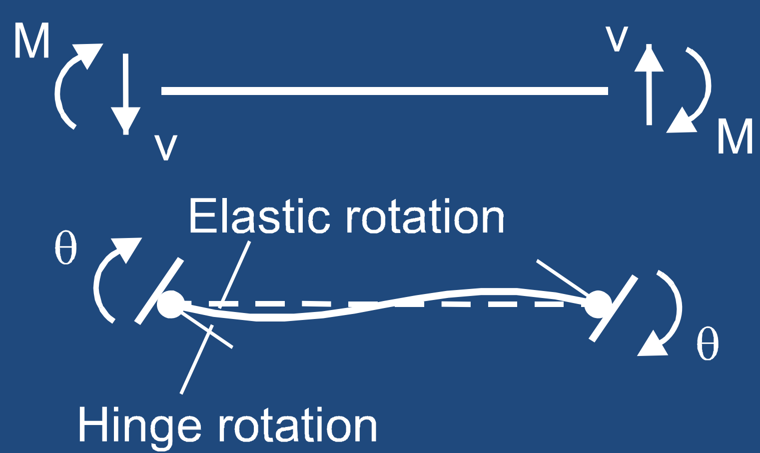
ASCE 41

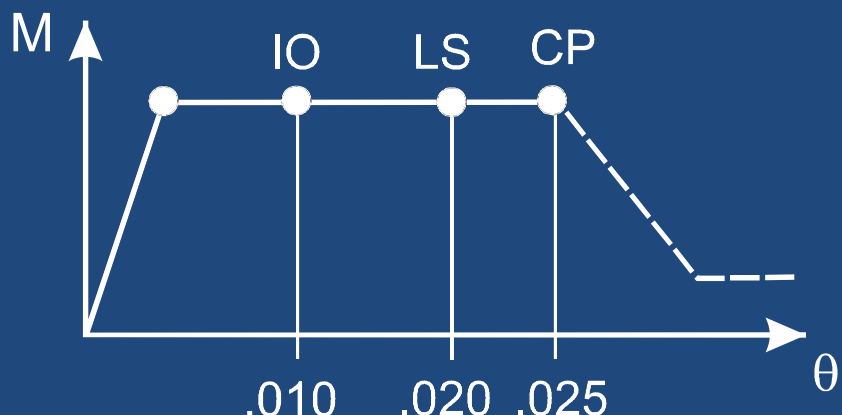
ASCE 41 BEAM MODEL



Performance assessment :

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





ASCE 41 hinge rotation capacities

ASCE 41 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)

STRENGTH vs DEFORMATION

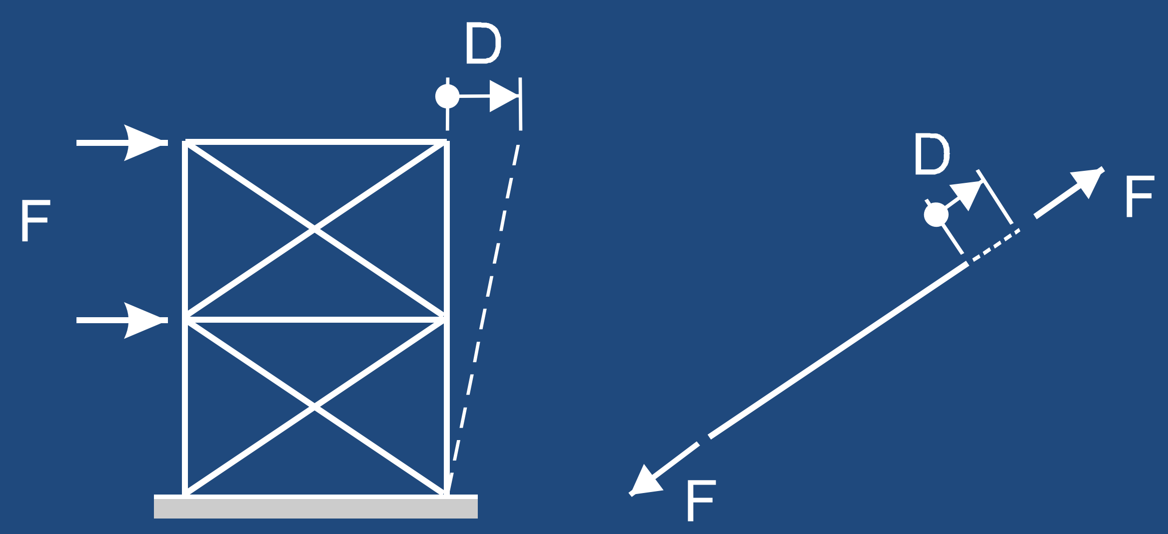
ELASTIC STRENGTH DESIGN - KEY STEPS

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

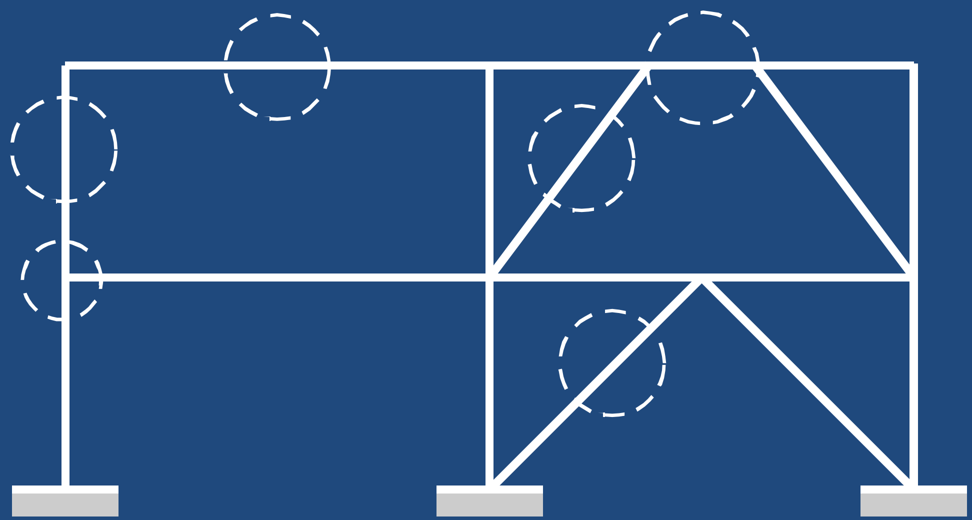
CHOSE PERFORMANCE LEVEL AND DESIGN LOADS – ASCE 41
DEMAND CAPACITY MEASURES – DRIFT/HINGE ROTATION/SHEAR
GET DEFORMATION AND FORCE CAPACITIES
CALCULATE DEFORMATION AND FORCE DEMANDS (RS OR TH)
CALCULATE D/C RATIOS – LIMIT STATES

STRUCTURE and MEMBERS



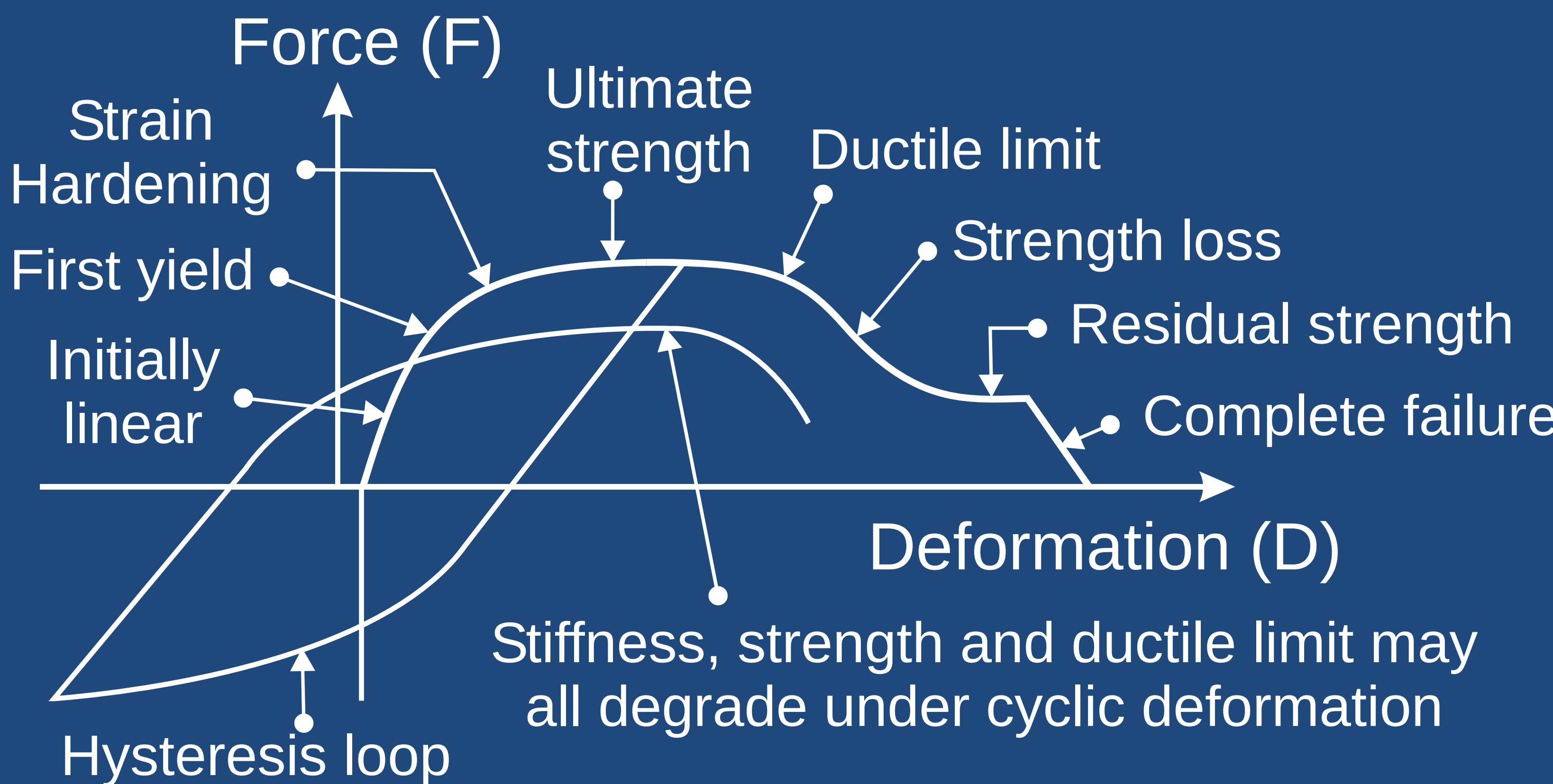
- For a structure, F = load, D = deflection.
- For a component, F depends on the component type, D is the corresponding deformation.
- The <u>component</u> F-D relationships must be known.
- The <u>structure</u> F-D relationship is obtained by structural analysis.

FRAME COMPONENTS

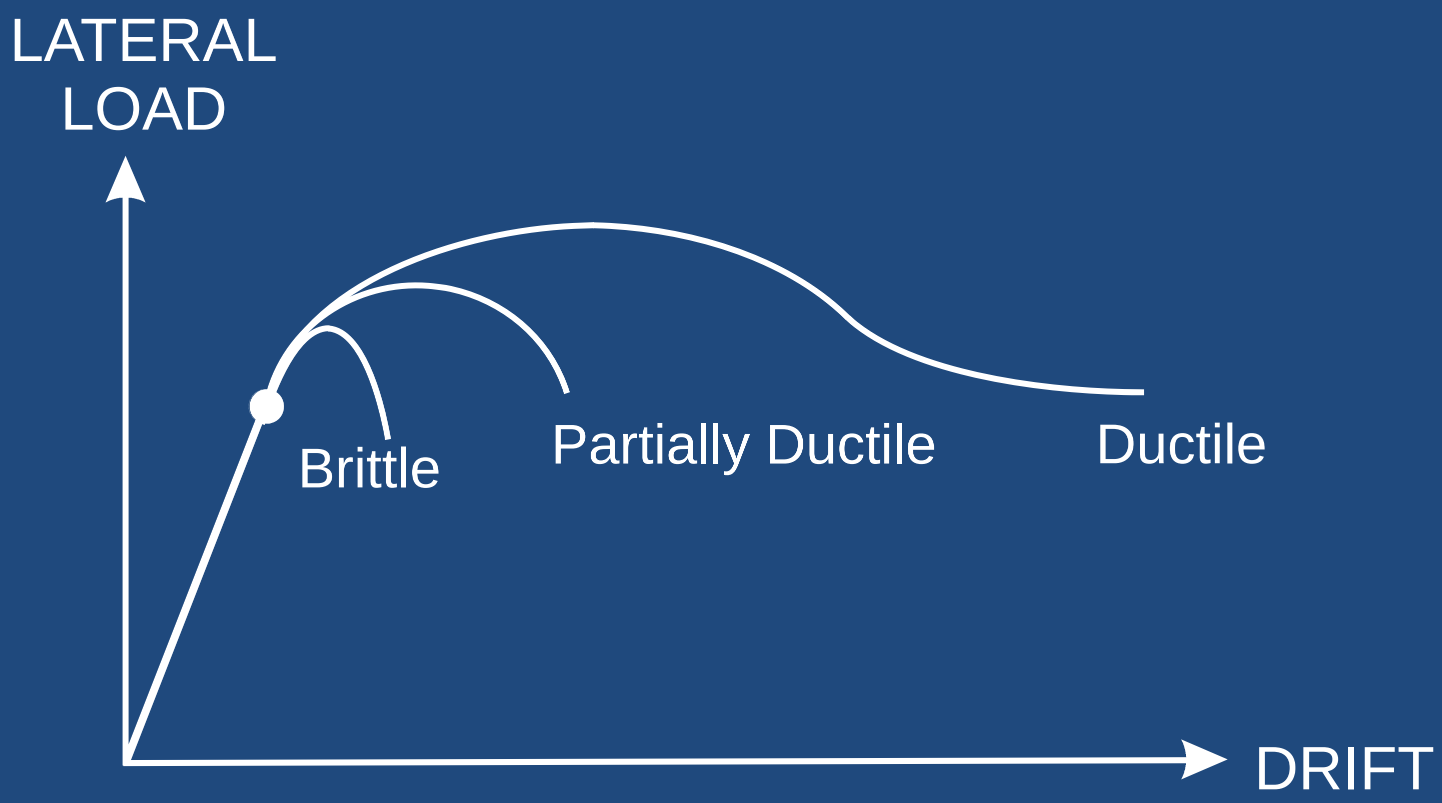


- For each component type we need :
  Reasonably accurate nonlinear F-D relationships.
  Reasonable deformation and/or strength capacities.
- We must choose realistic demand-capacity measures, and it must be feasible to calculate the demand values.
- The best model is the simplest model that will do the job.

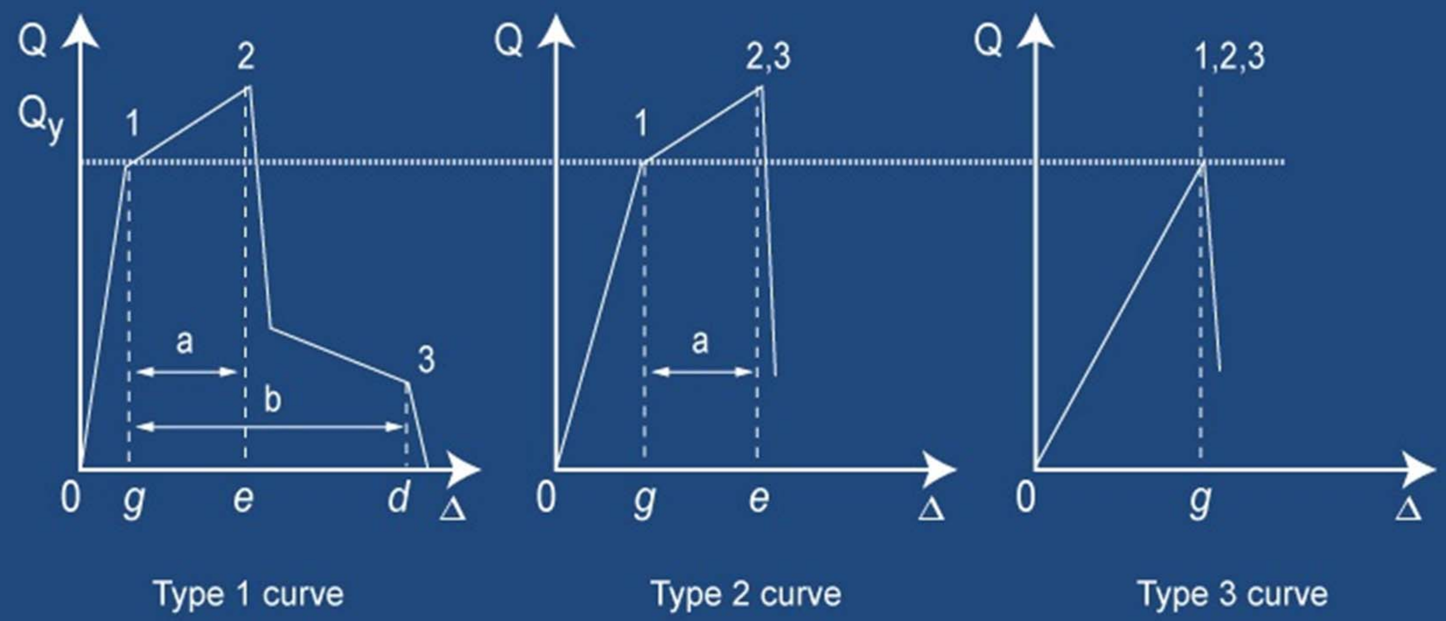
F-D RELATIONSHIP



DUCTILITY



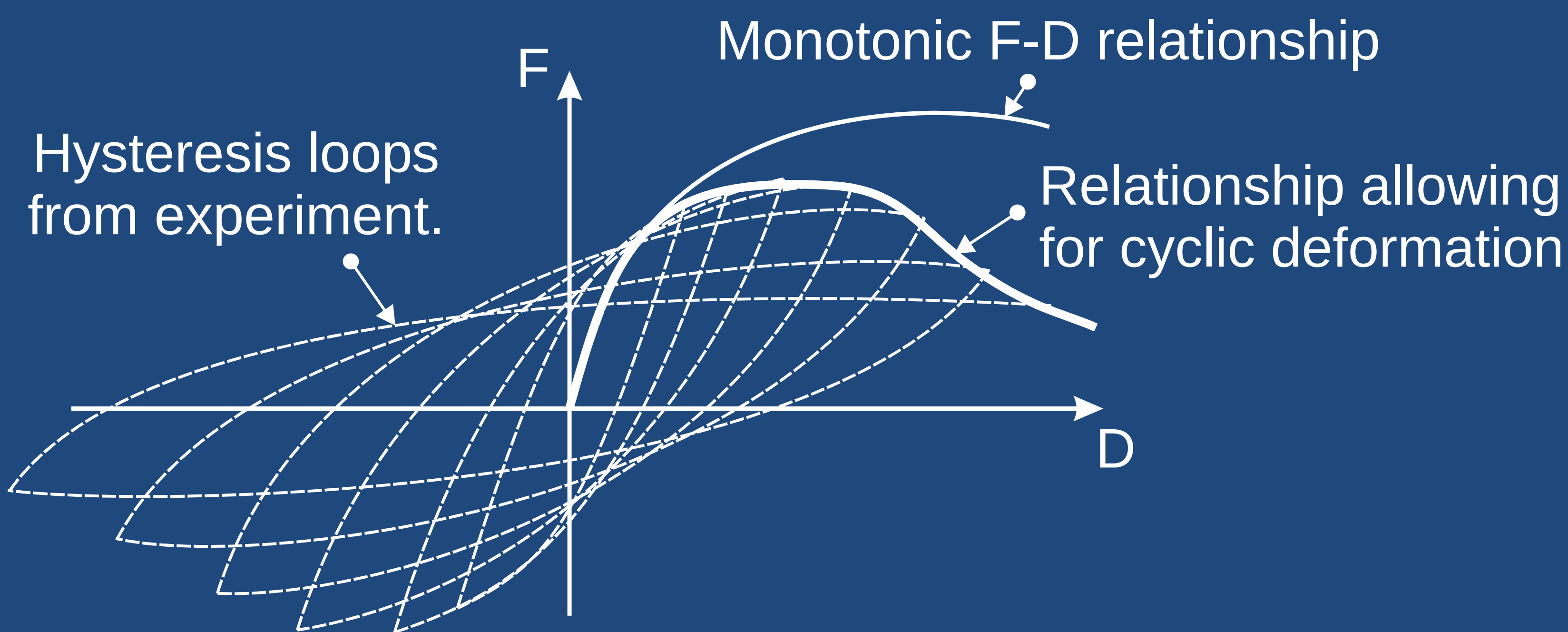
ASCE 41 - DUCTILE AND BRITTLE



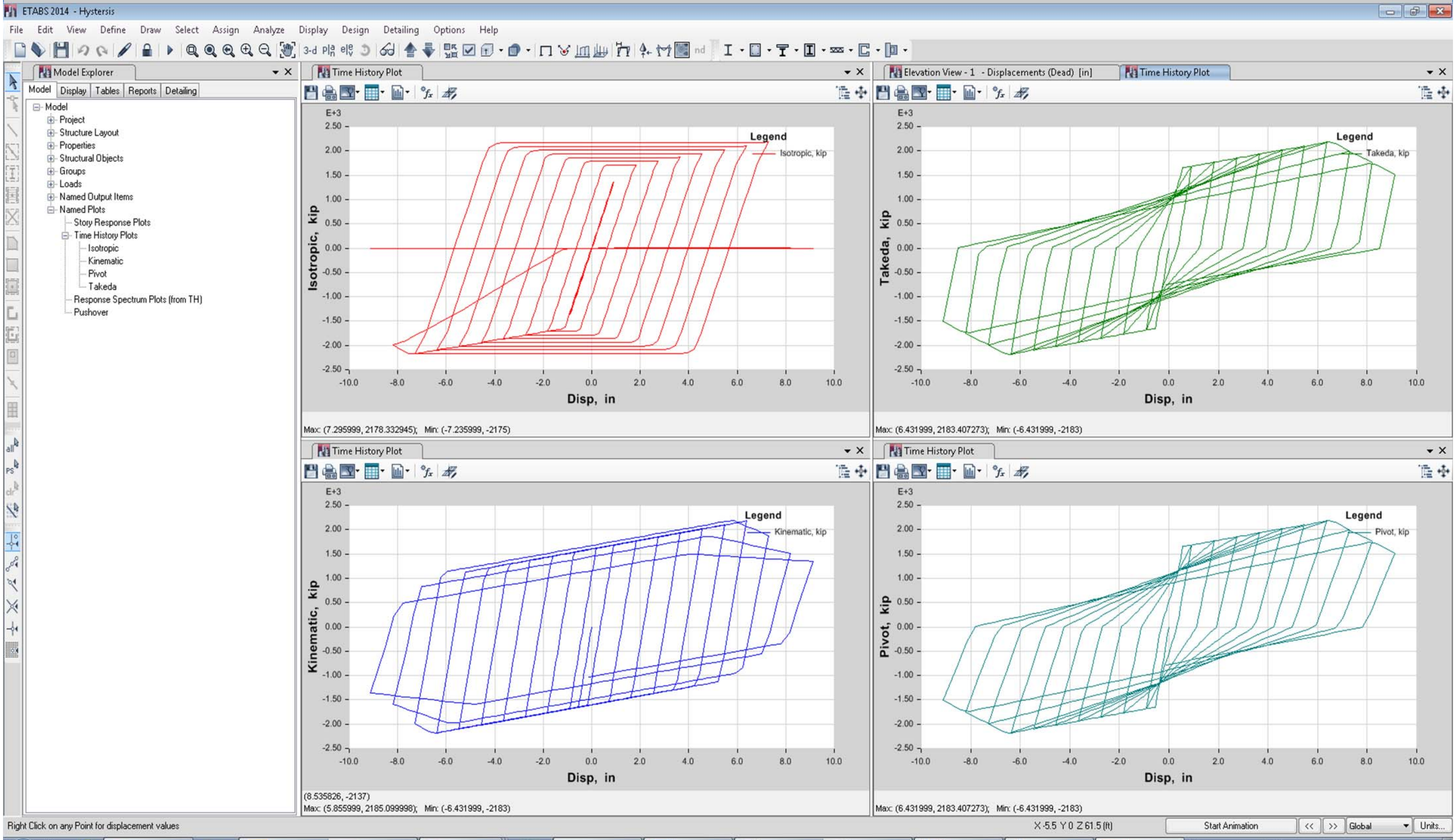
FORCE AND DEFORMATION CONTROL

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

BACKBONE CURVE

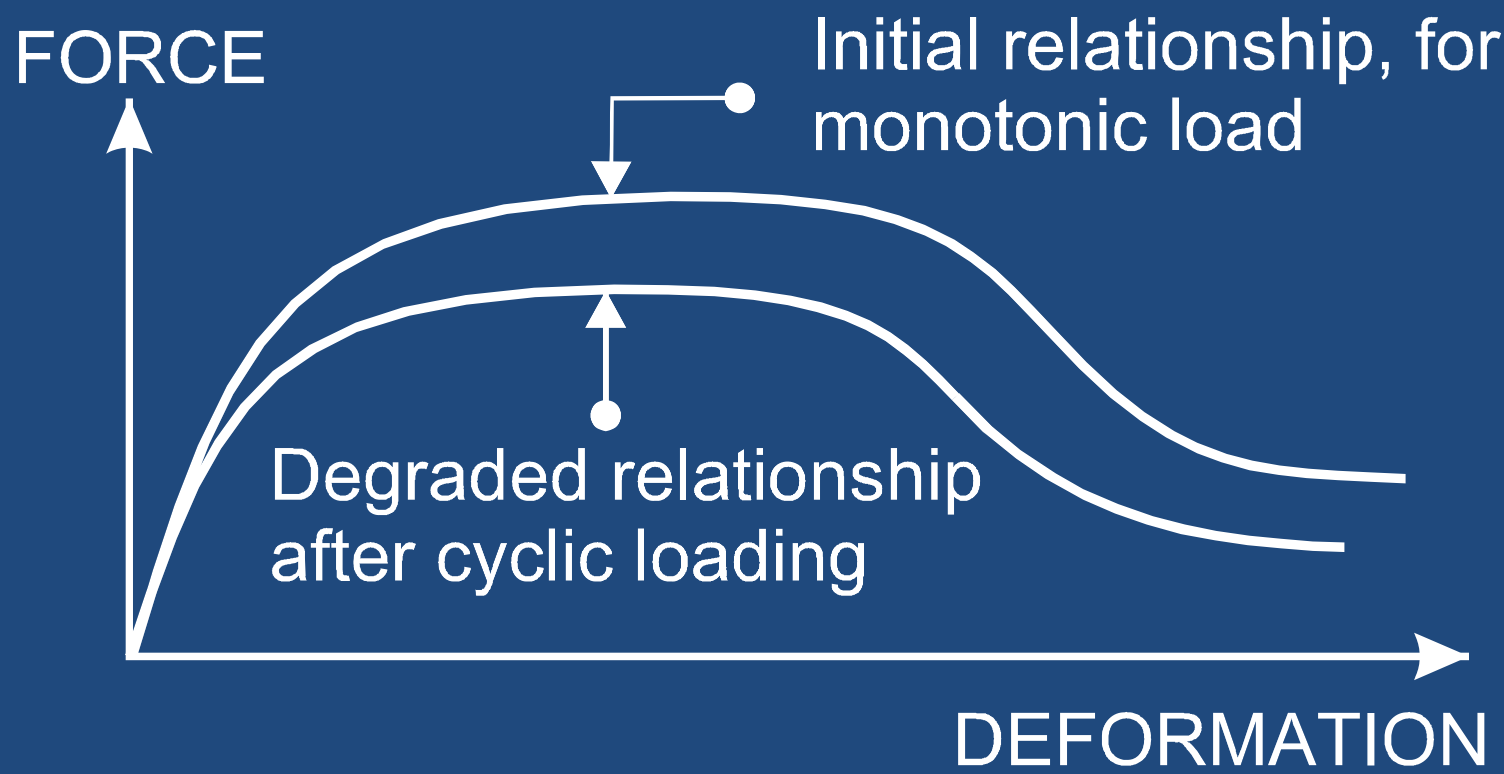


HYSTERESIS LOOP MODELS

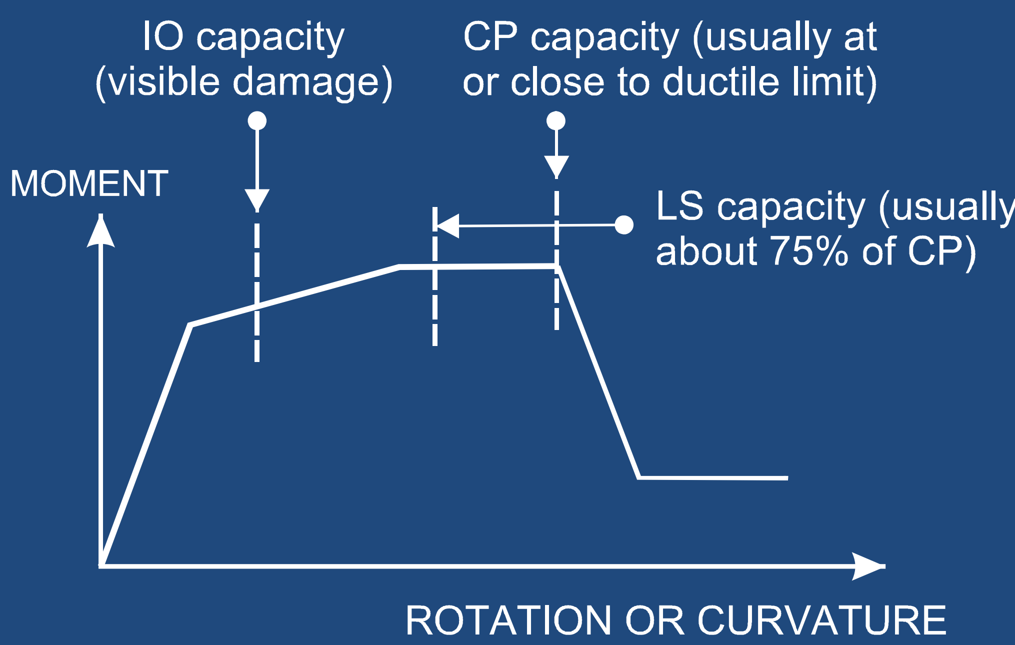


Nonlinear Analysis & Performance Based Design

STRENGTH DEGRADATION

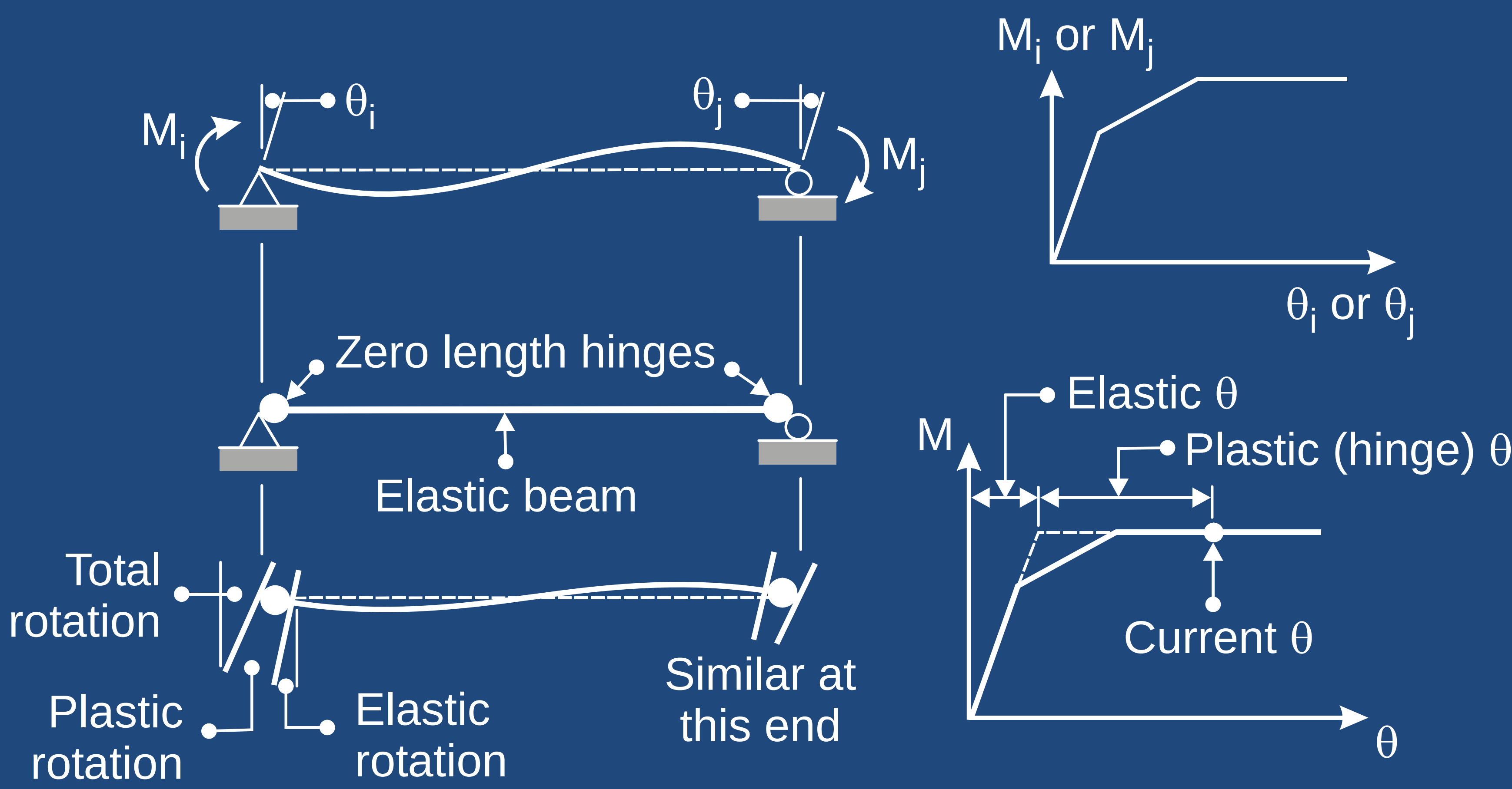


ASCE 41 DEFORMATION CAPACITIES

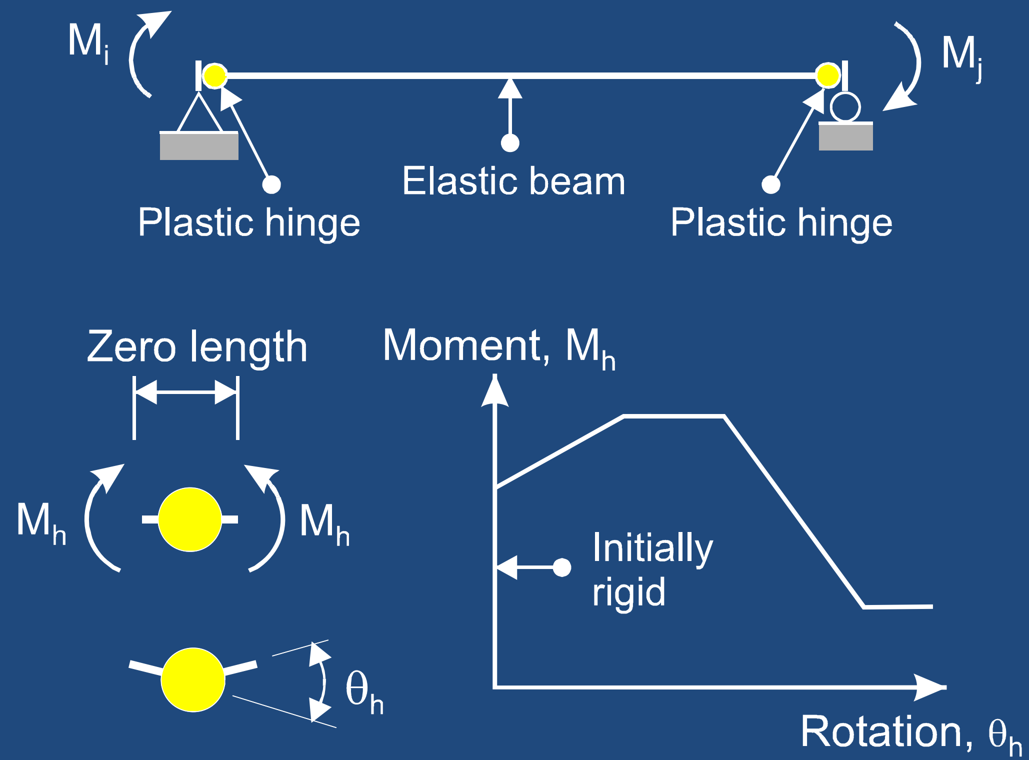


- This can be used for components of all types.
- It can be used if experimental results are available.
- ASCE 41 gives capacities for many different components.
- For beams and columns, ASCE 41 gives capacities only for the chord rotation model.

BEAM END ROTATION MODEL

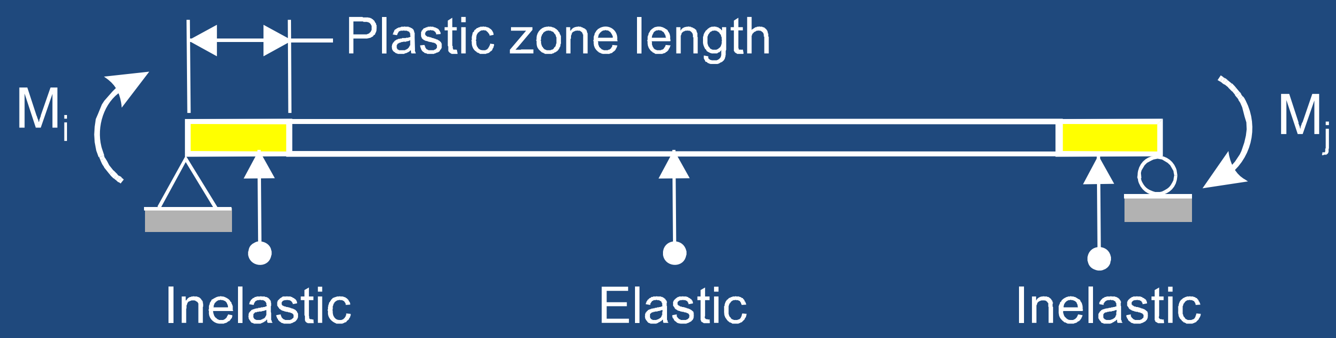


PLASTIC HINGE MODEL



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

PLASTIC ZONE MODEL

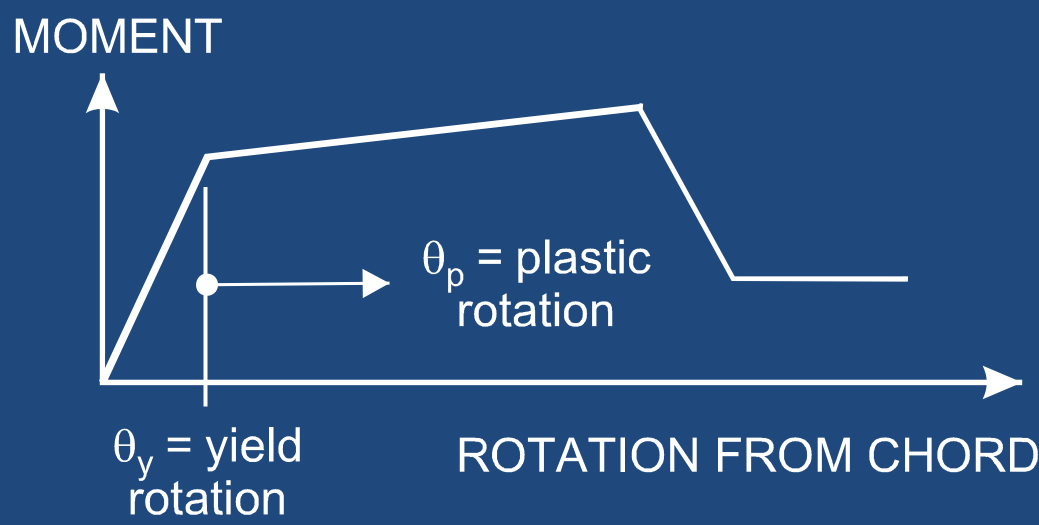


- The inelastic behavior occurs in finite length plastic zones.
- Actual plastic zones usually change length, but models that have variable lengths are too complex.
- The deformation measure for D/C can be :

  - Average curvature in plastic zone.

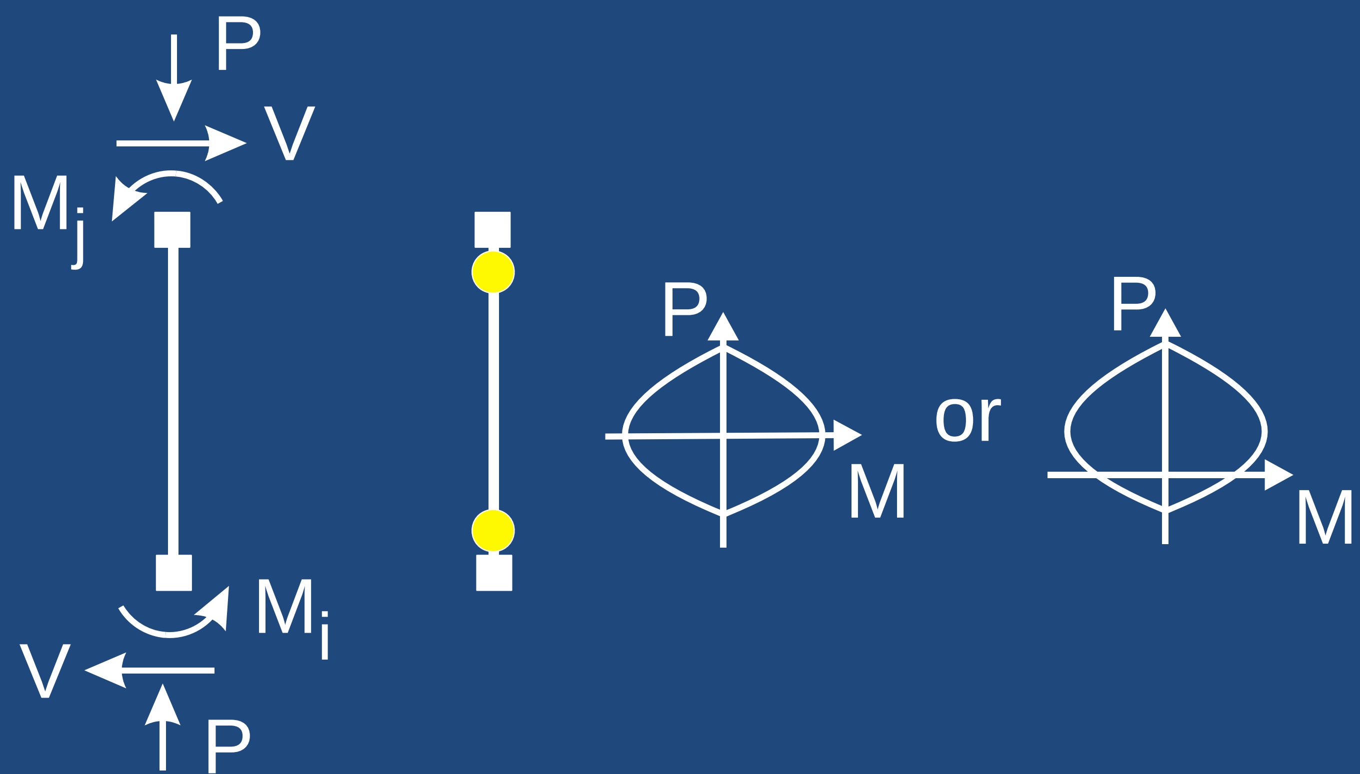
  - Rotation over plastic zone (= average curvature x plastic zone length).

ASCE 41 CHORD ROTATION CAPACITIES

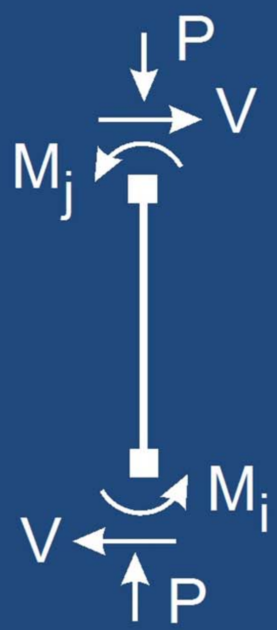


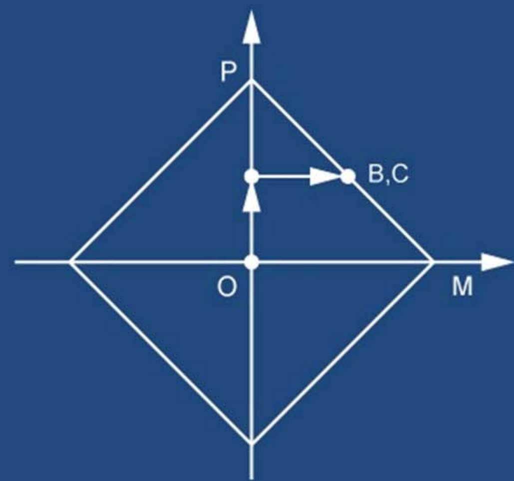
	IO	LS	CP
Steel Beam	$\theta_p/\theta_y = 1$	$\theta_p/\theta_y = 6$	$\theta_p/\theta_y = 8$
RC Beam			
Low shear	$\theta_p = 0.01$	$\theta_p = 0.02$	$\theta_p = 0.025$
High shear	$\theta_p = 0.005$	$\theta_p = 0.01$	$\theta_p = 0.02$

COLUMN AXIAL-BENDING MODEL

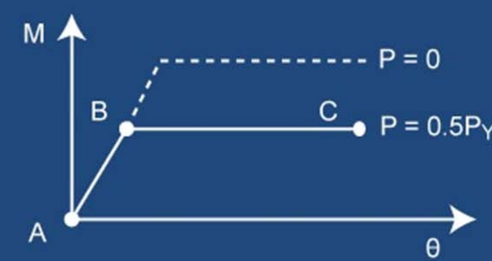


STEEL COLUMN AXIAL-BENDING





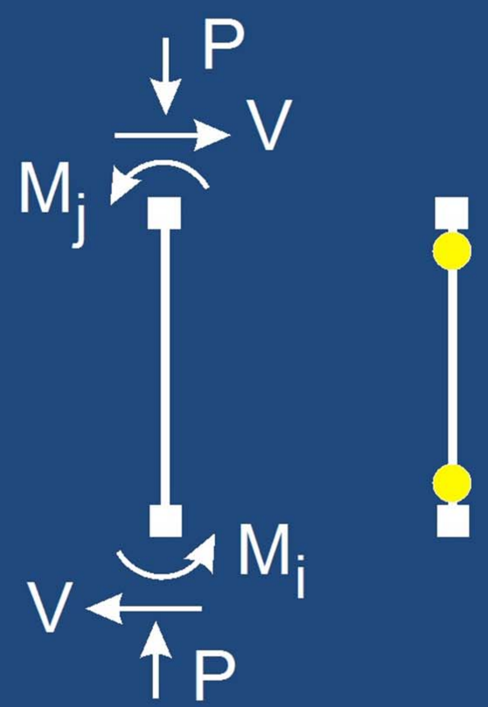
LOAD PATH

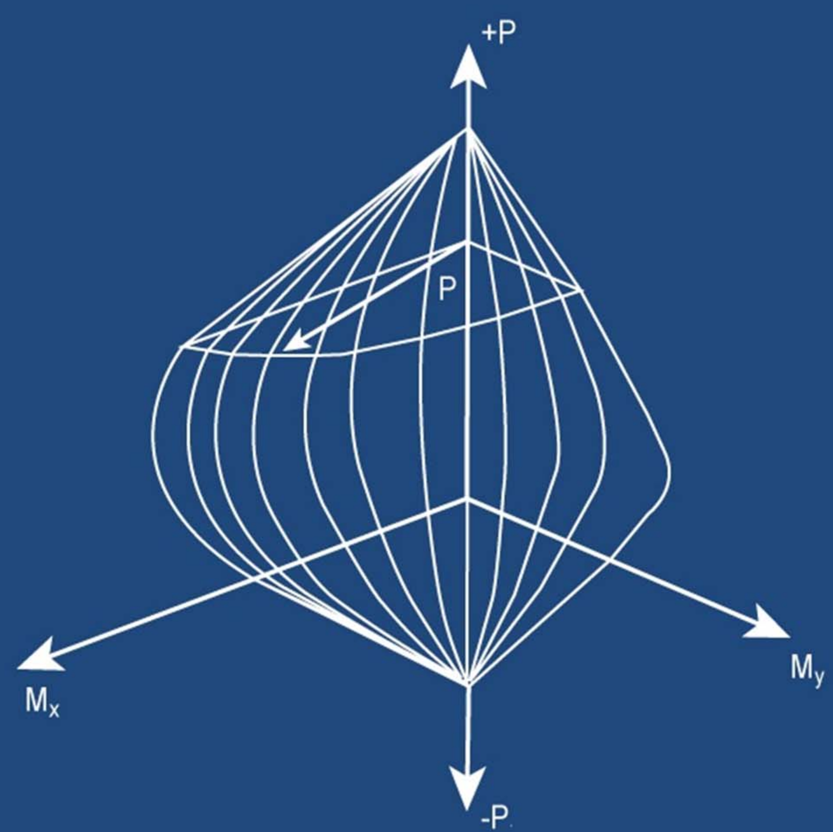


MOMENT ROTATION

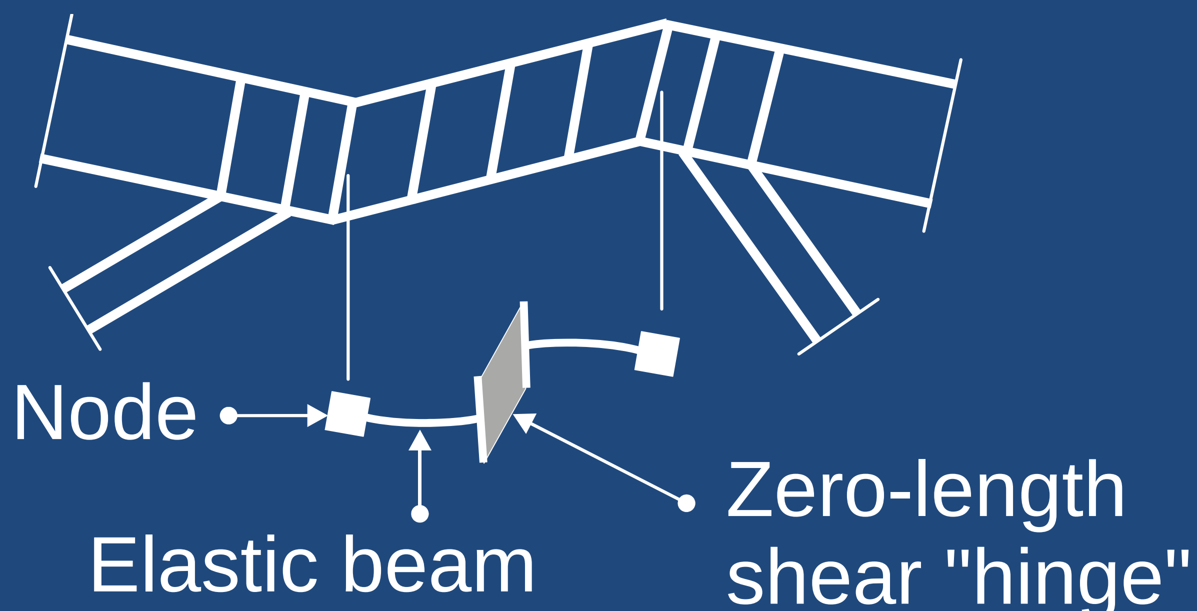
$$M_y = Z F_y \left(1 - P / P_y\right)$$

CONCRETE COLUMN AXIAL-BENDING

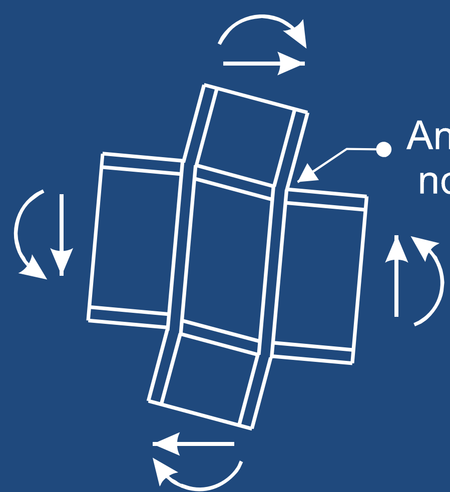




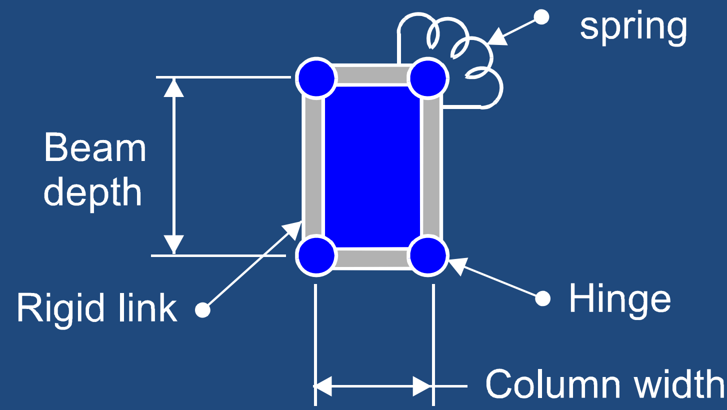
SHEAR HINGE MODEL



PANEL ZONE ELEMENT



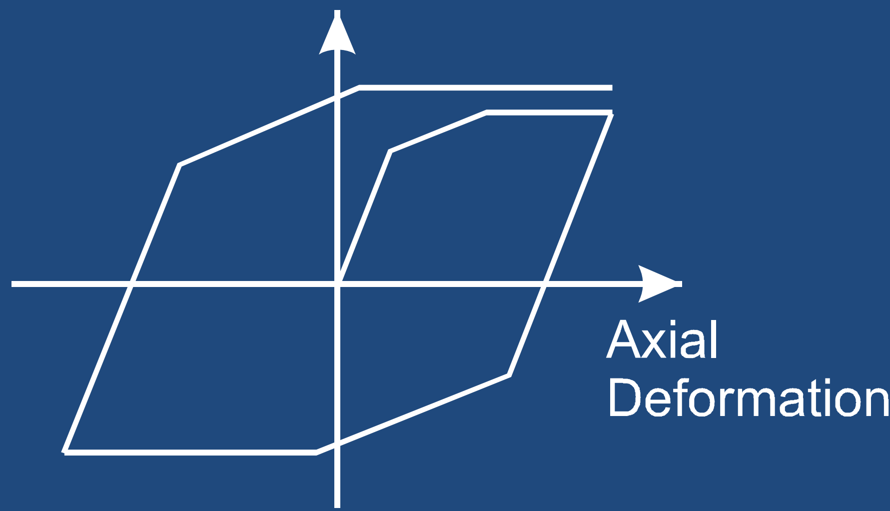
PANEL ZONE DEFORMATION



ANALYSIS MODEL

- Deformation, D = spring rotation = shear strain in panel zone.
- Force, F = moment in spring = moment transferred from beam to column elements.
- Also, F = (panel zone horizontal shear force) x (beam depth).

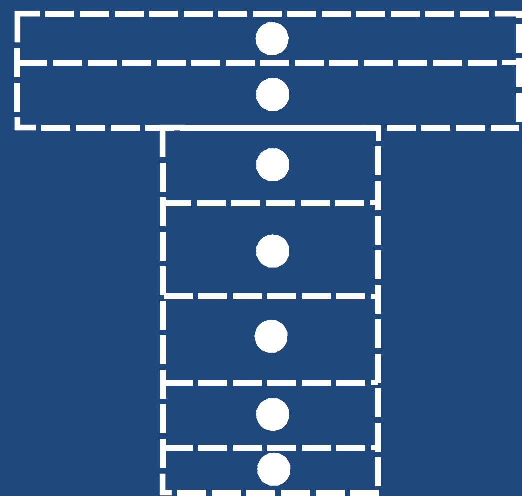
BUCKLING-RESTRAINED BRACE



The BRB element includes “isotropic” hardening.

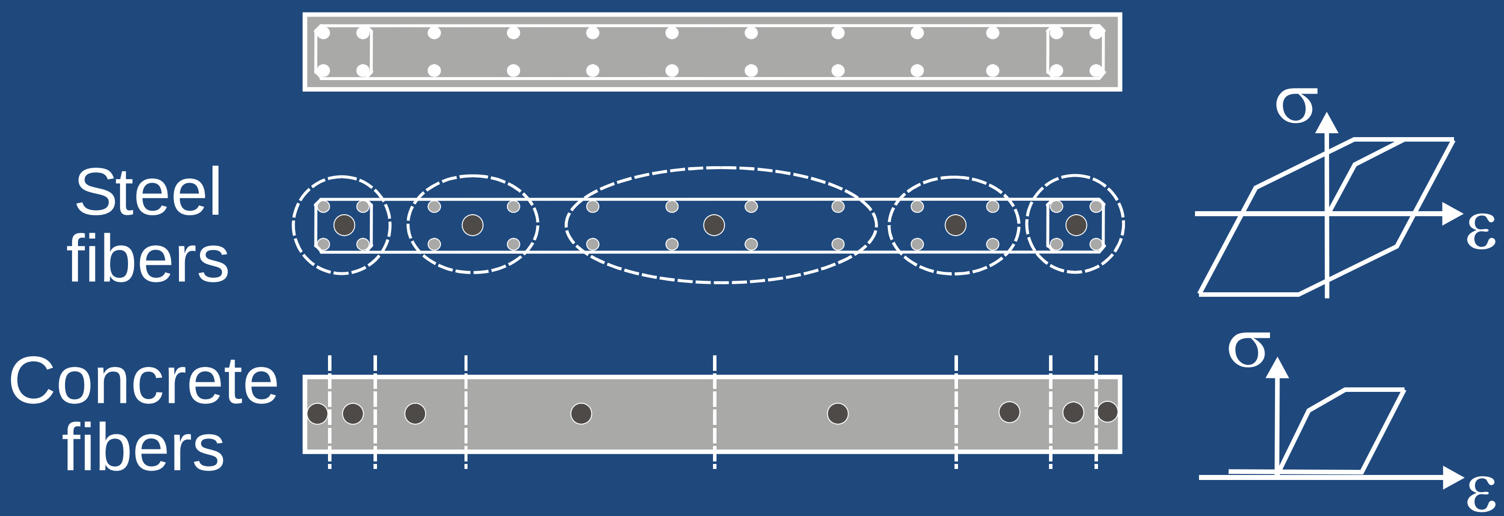
The D-C measure is axial deformation.

BEAM/COLUMN FIBER MODEL

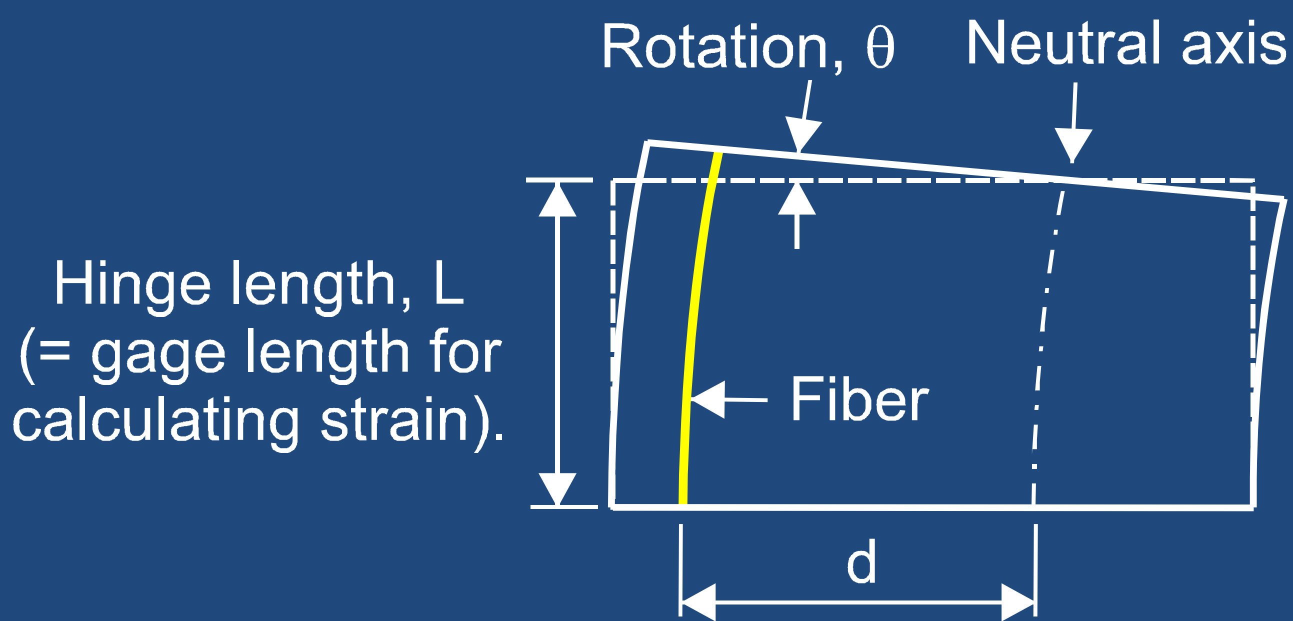


The cross section is represented by a number of uni-axial fibers.
The M-ψ relationship follows from the fiber properties, areas and locations.
Stress-strain relationships reflect the effects of confinement

WALL FIBER MODEL

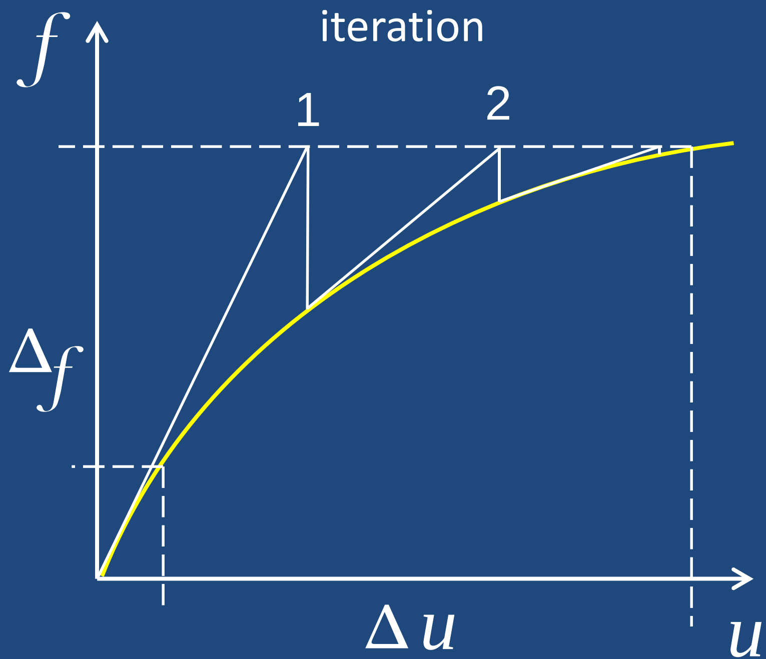


ALTERNATIVE MEASURE - STRAIN

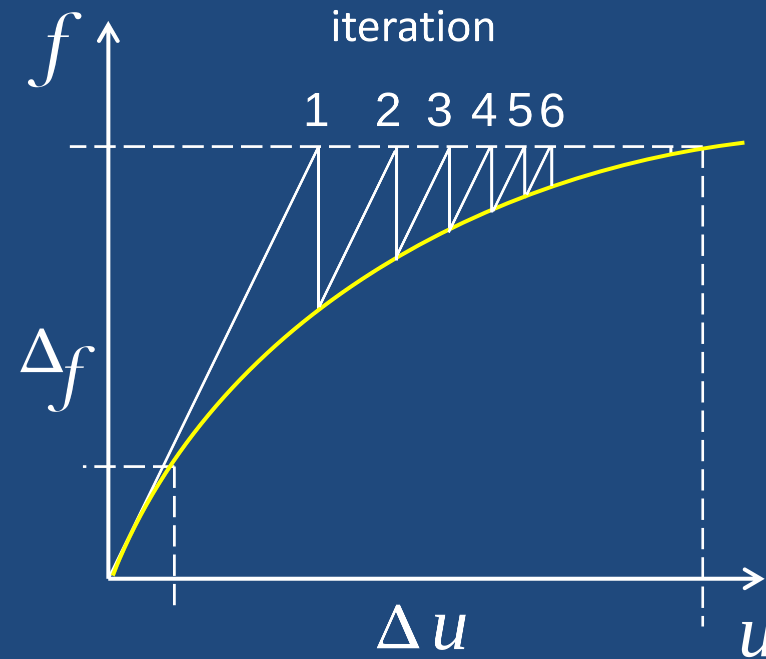


$$\text{Fiber strain} = \frac{\theta\, d}{L}$$

NONLINEAR SOLUTION SCHEMES

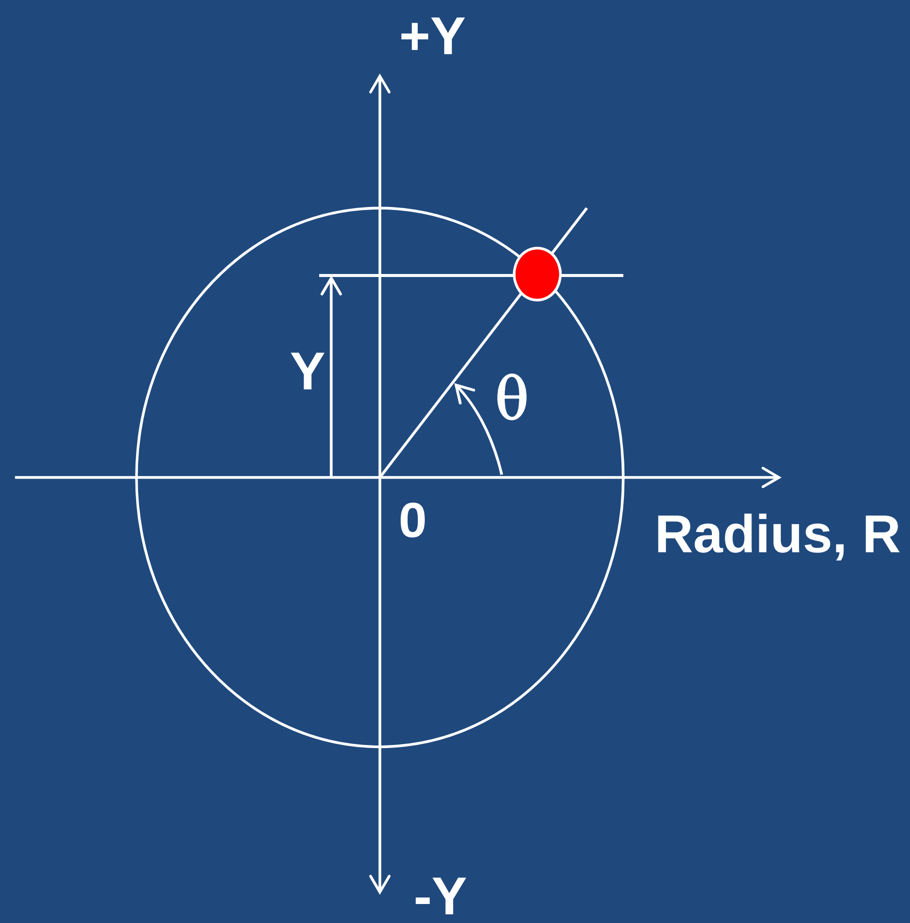


NEWTON – RAPHSON ITERATION

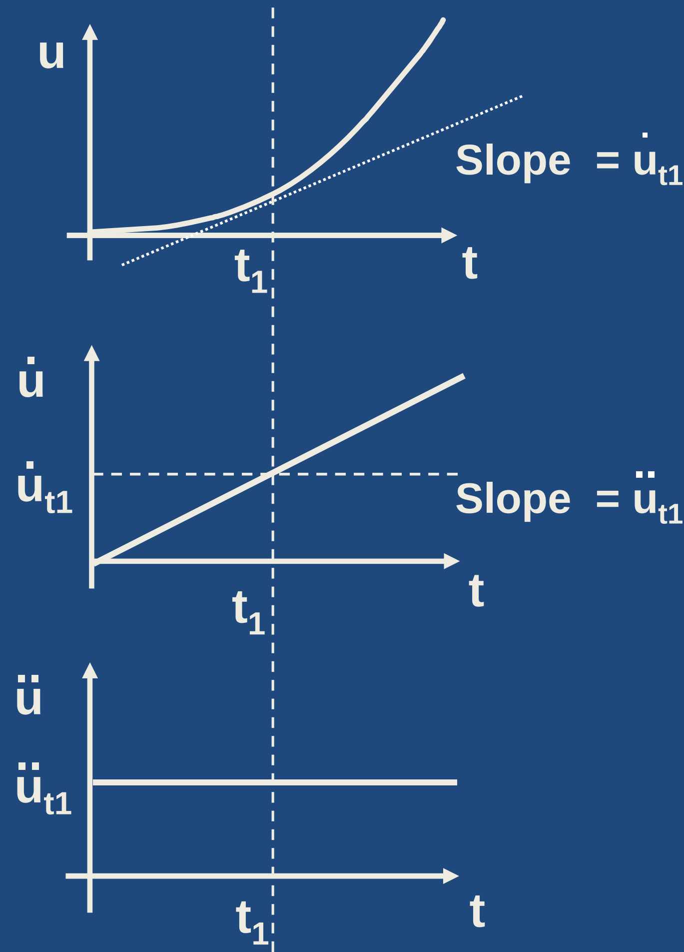


CONSTANT STIFFNESS ITERATION

CIRCULAR FREQUENCY



THE D, V & A RELATIONSHIP

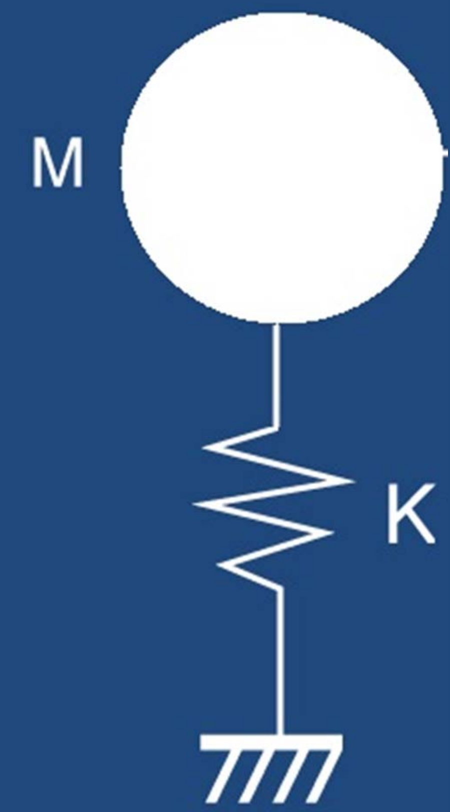


UNDAMPED FREE VIBRATION

$$m\ddot{u} + ku = 0$$

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

$$where \quad \omega = \sqrt{\frac{k}{m}}$$



RESPONSE MAXIMA

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

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

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

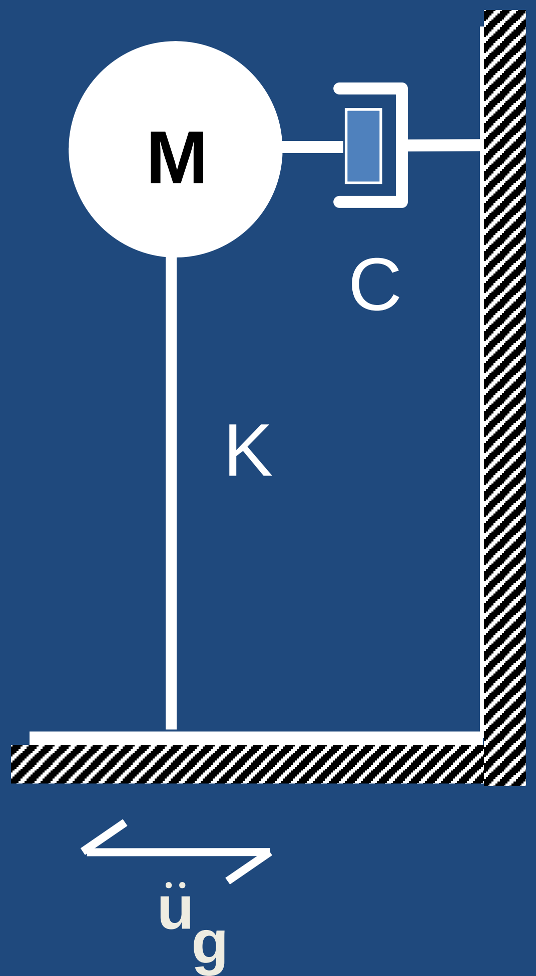
$$\ddot{u}_{max} = -\omega^2 u_{max}$$

BASIC DYNAMICS WITH DAMPING

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

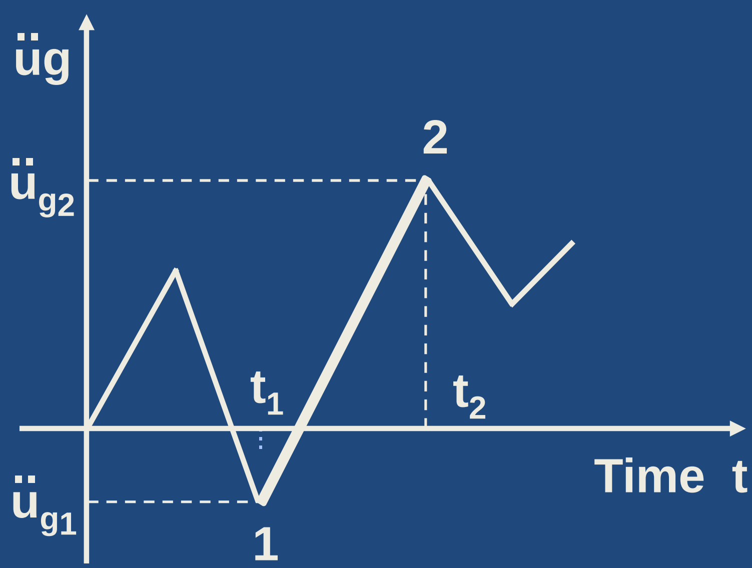
$$M\ddot{u} + C\dot{u} + Ku = -M\ddot{u}_g$$

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



RESPONSE FROM GROUND MOTION

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



DAMPED RESPONSE

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

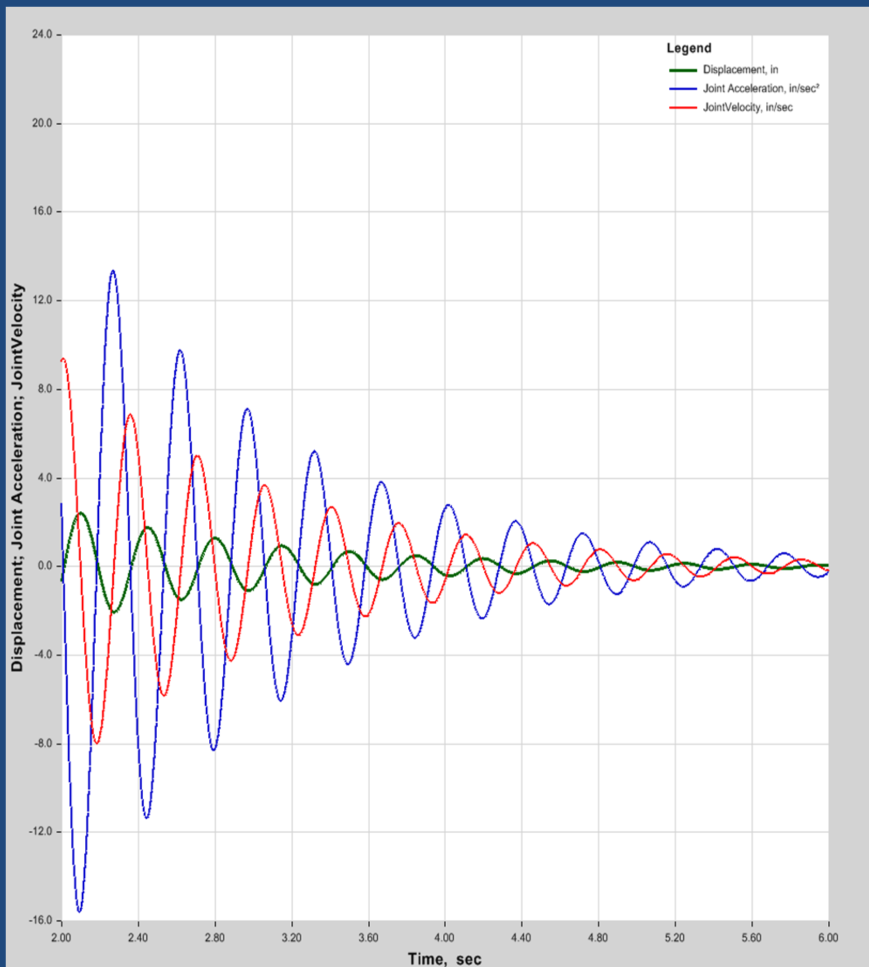
$$+ \frac{1}{\omega_d}[A - \omega^2 u_{t_1} - \xi\omega(\dot{u}_{t_1} + \frac{B}{\omega^2})]\sin\omega_d t\} + \frac{B}{\omega^2}$$

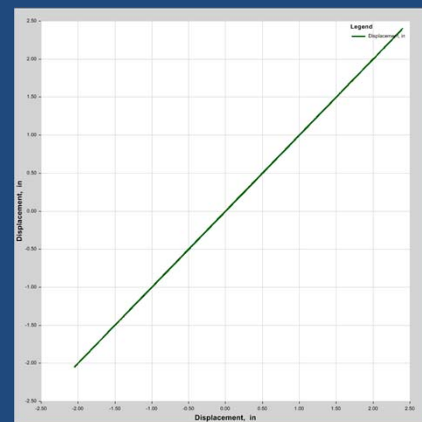
$$u_t = e^{-\xi\omega t}\{[u_{t_1} - \frac{A}{\omega^2} + \frac{2\xi B}{\omega^3}]\cos\omega_d t$$

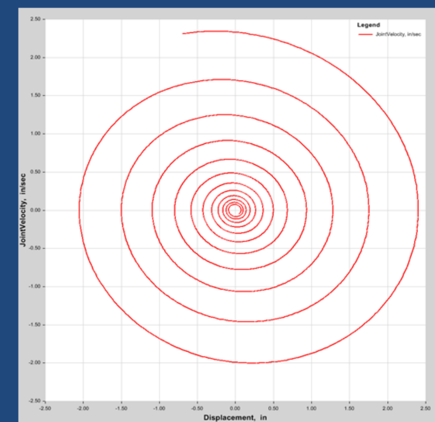
$$+ \frac{1}{\omega_d}[\dot{u}_{t_1} + \xi\omega u_{t_1} - \frac{\xi A}{\omega} + \frac{B(2\xi^2 - 1)}{\omega^2}]\sin\omega_d t\}$$

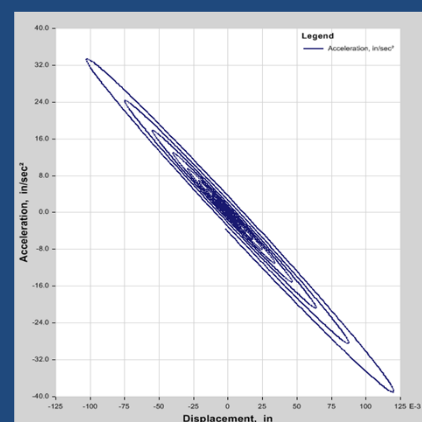
$$+ [\frac{A}{\omega^2} - \frac{2\xi B}{\omega^3} + \frac{Bt}{\omega^2}]$$

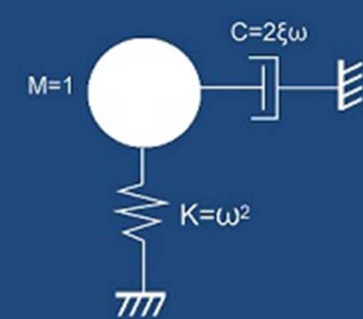
SDOF DAMPED RESPONSE





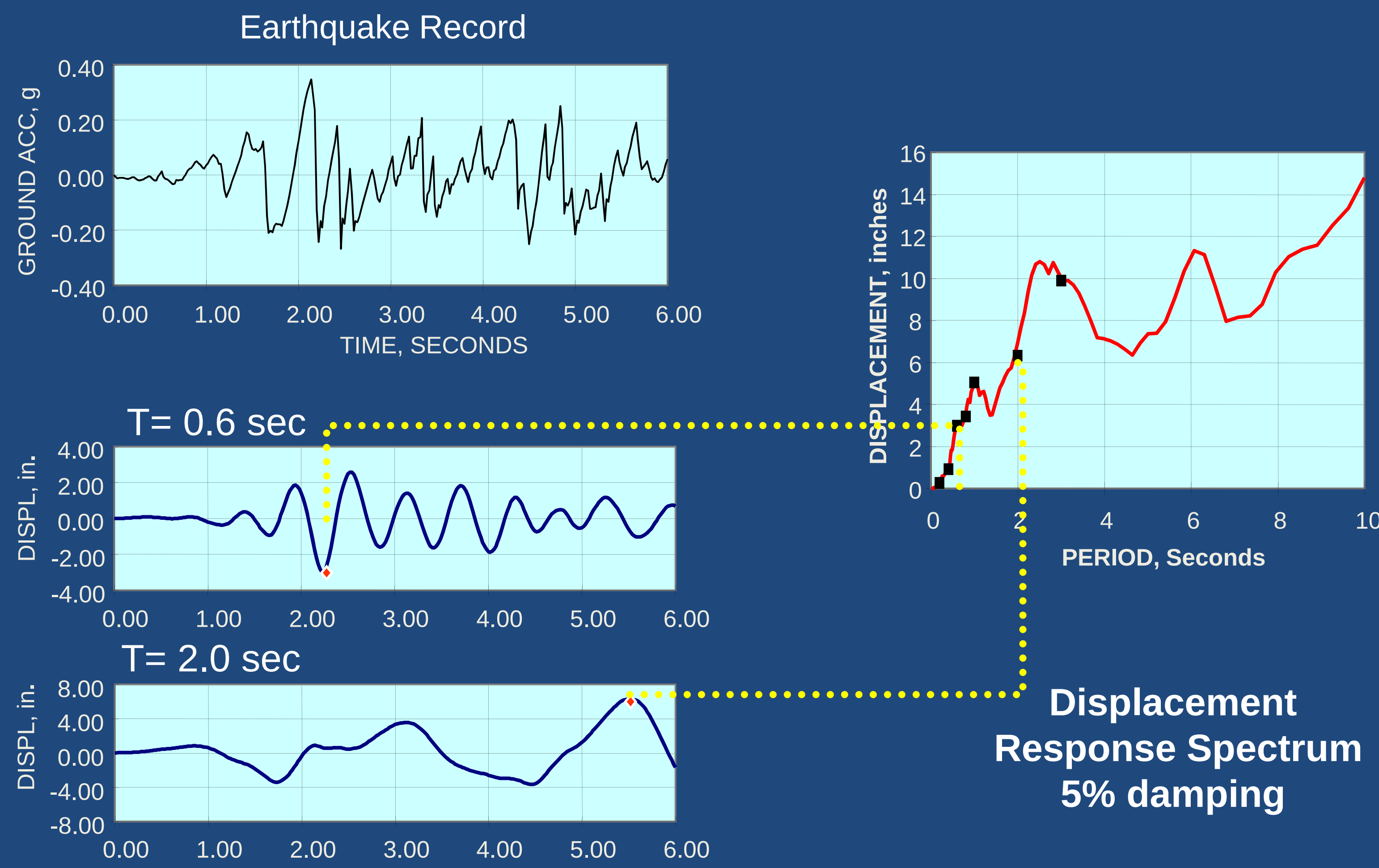




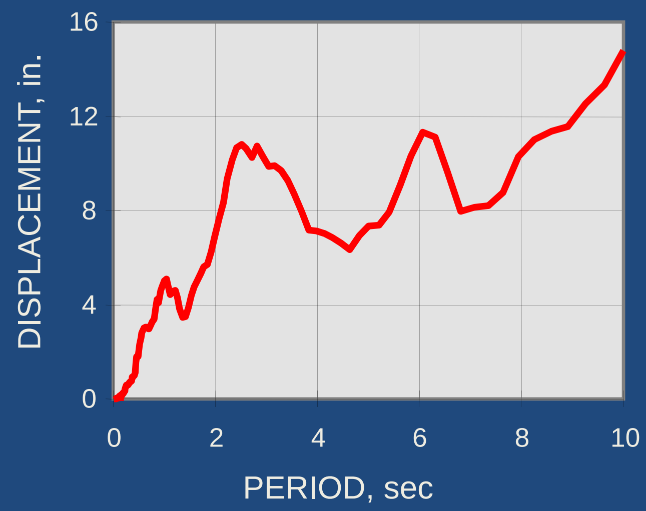


$$\ddot{u}+2\xi\omega u+\omega^2\dot{u} = -\ddot{u}g$$

RESPONSE SPECTRUM GENERATION

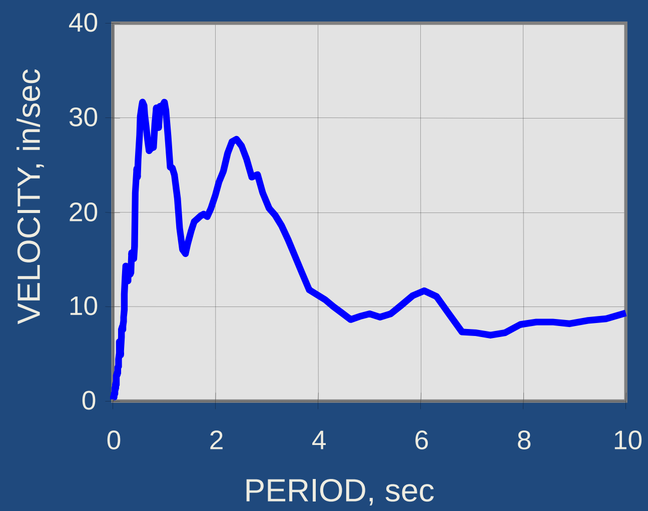


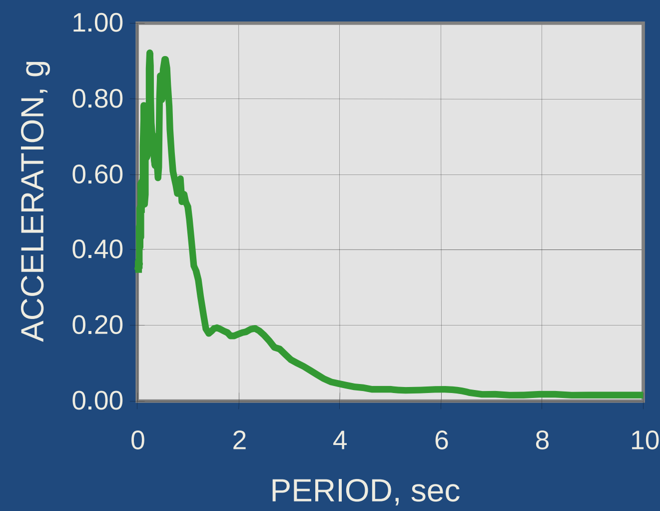
SPECTRAL PARAMETERS



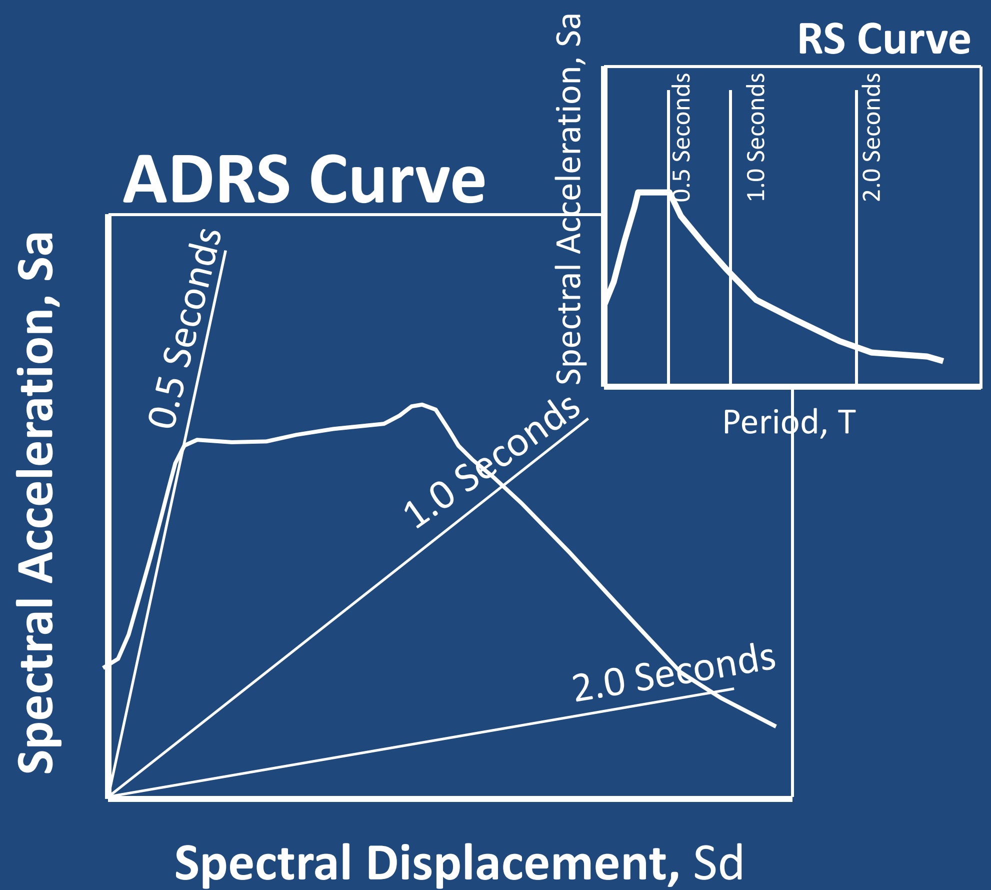
$$PS_V = \omega S_d$$

$$PS_a = \omega PS_v$$

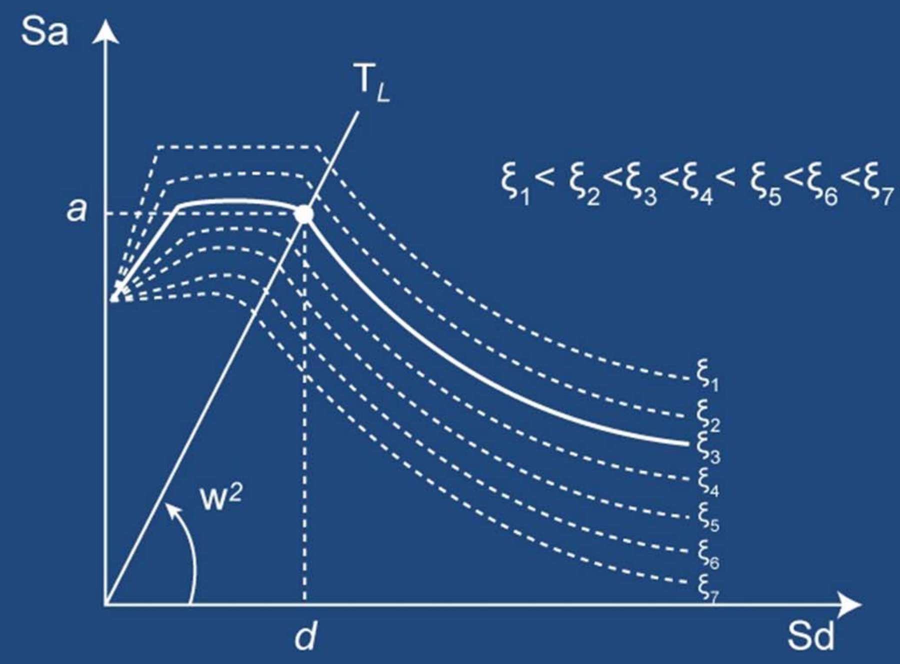




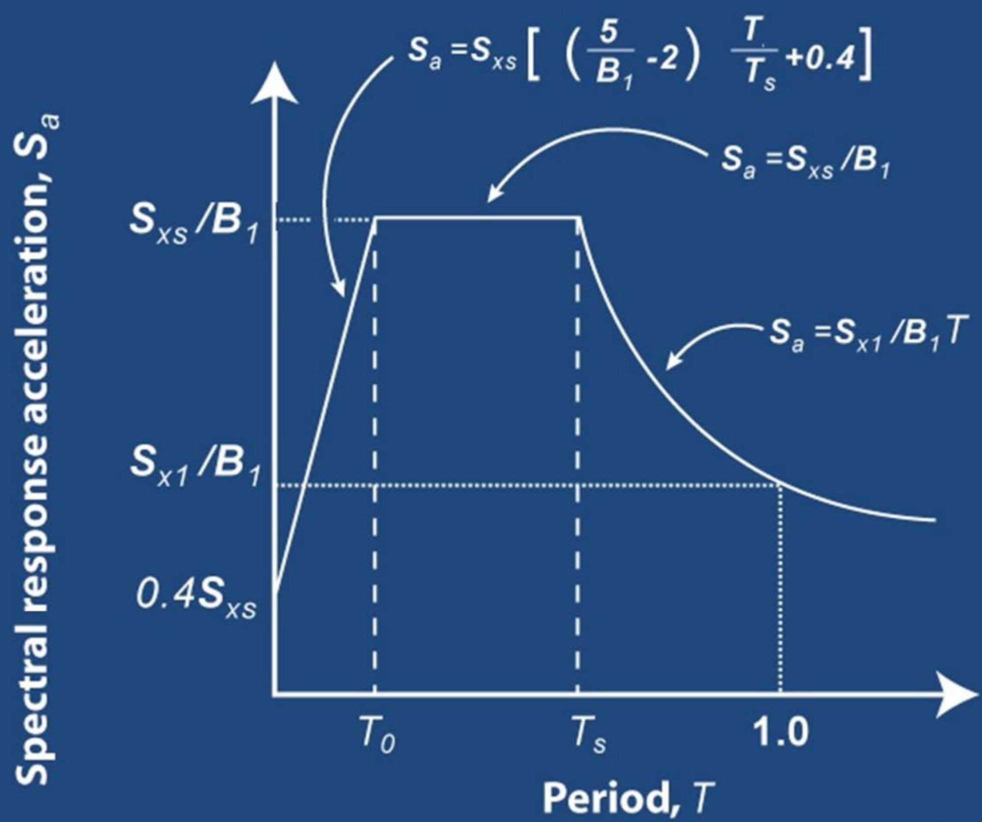
THE ADRS SPECTRUM



THE ADRS SPECTRUM

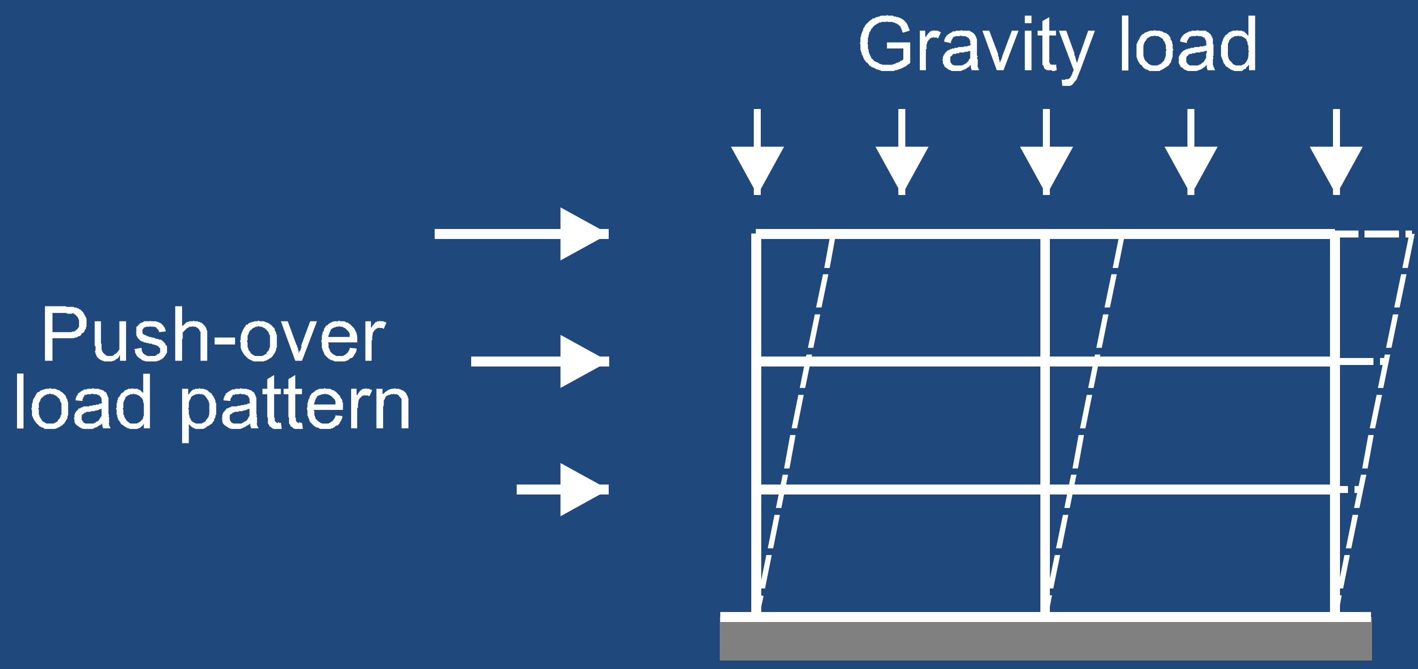


ASCE 7 RESPONSE SPECTRUM

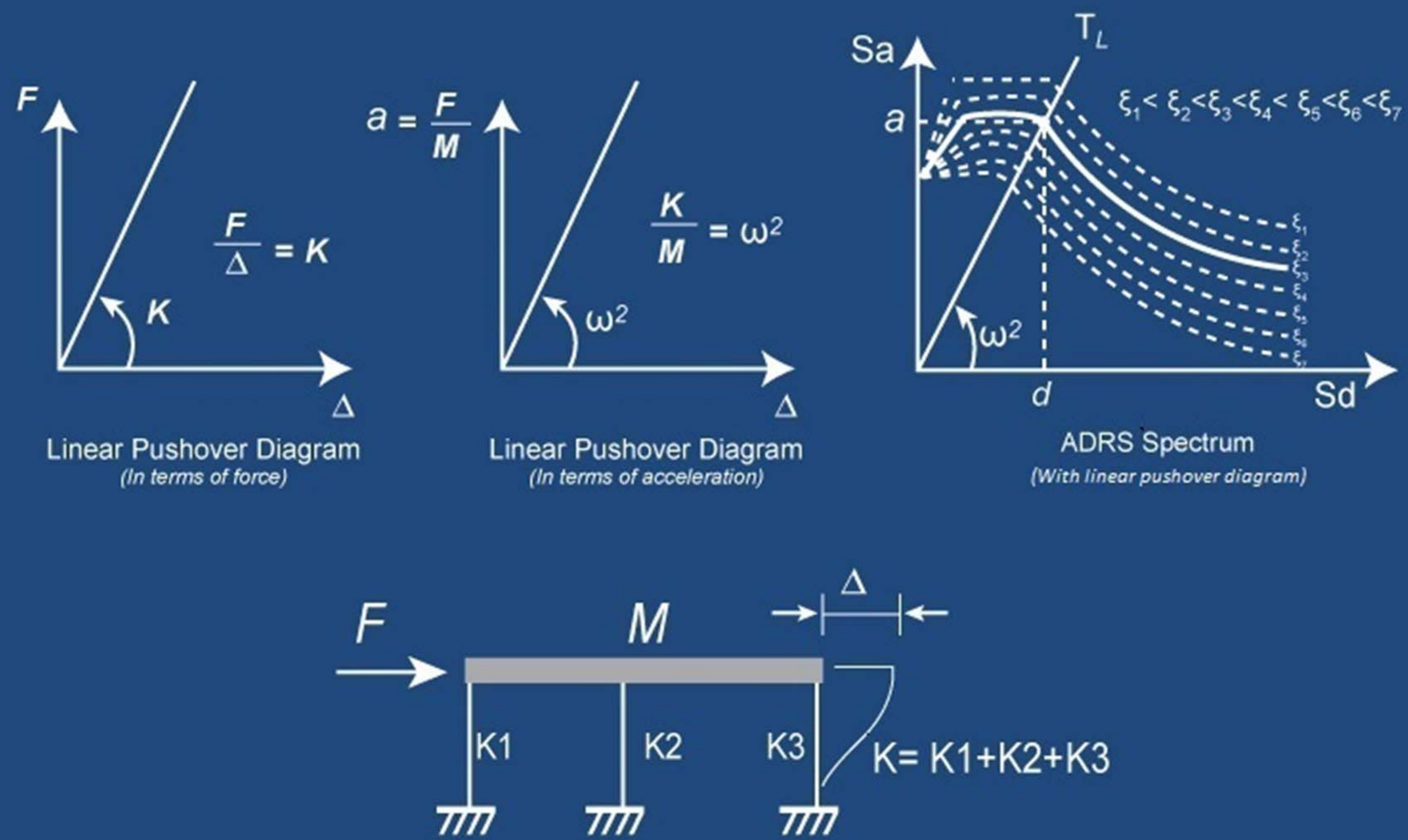


$$B_1 = \frac{4}{5.6 - \log n\,(100\xi)}$$

PUSHOVER

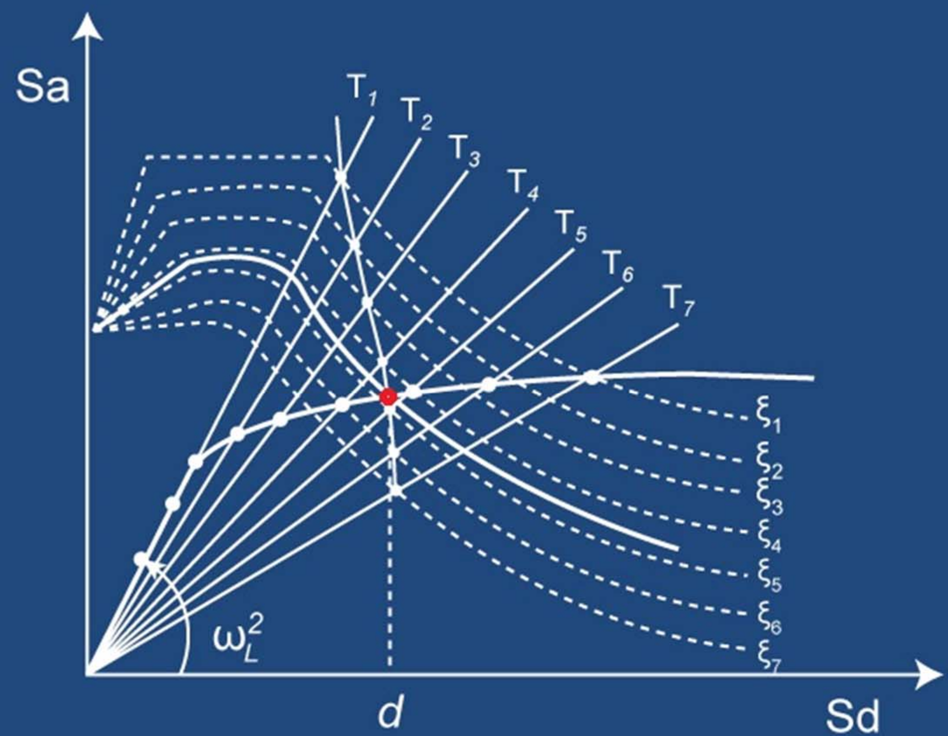


THE LINEAR PUSHOVER



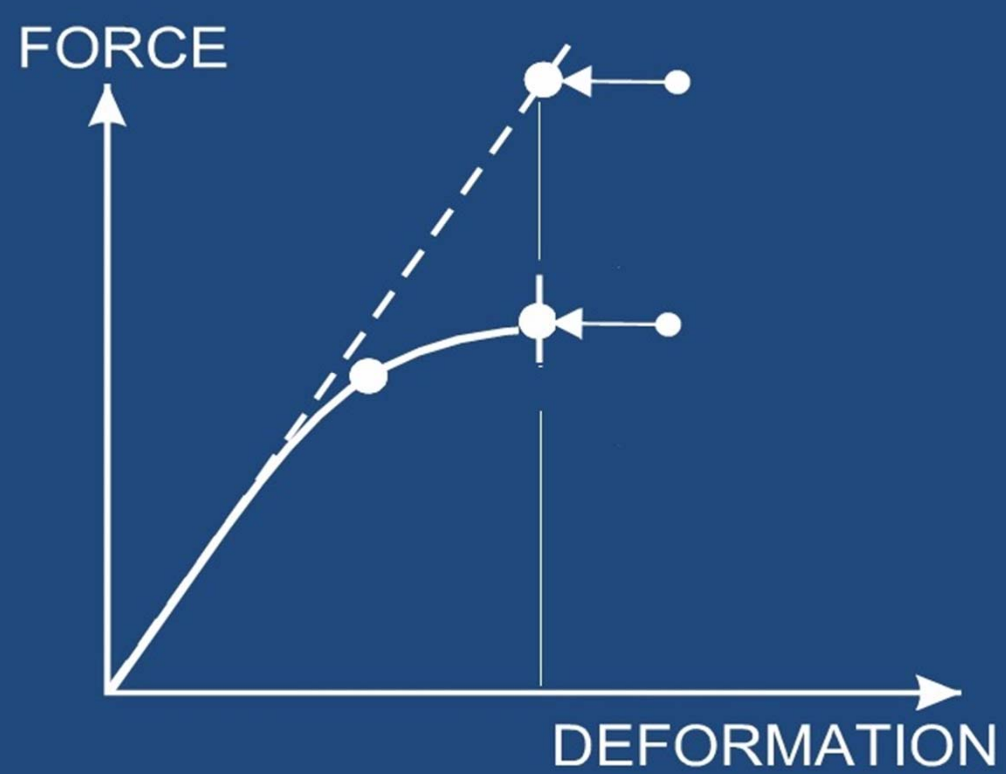
EQUIVALENT LINEARIZATION

How far to push? The Target Point!



موسسه آموزشی و مهندسی ۸۰۸
آموزشهای تخصصی عمران و معماری

DISPLACEMENT MODIFICATION



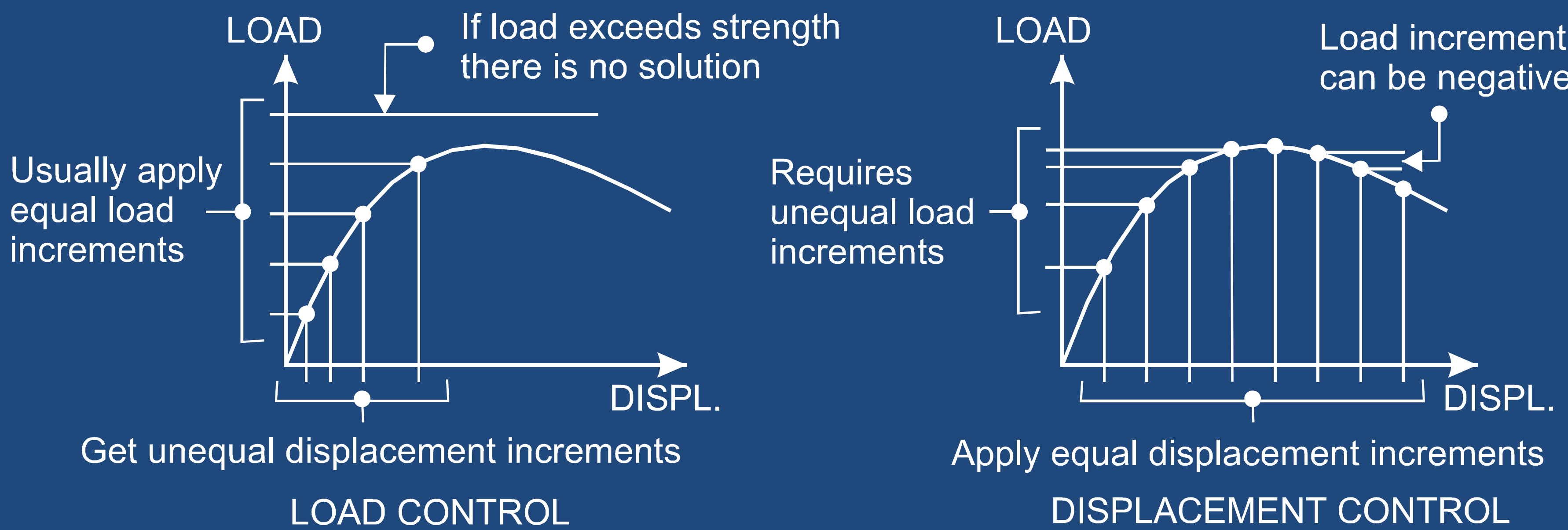
DISPLACEMENT MODIFICATION

Calculating the Target Displacement

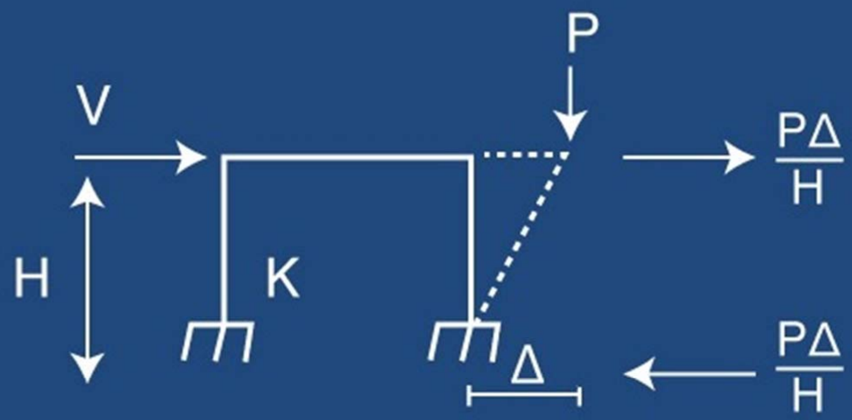
$$\delta = C_0 C_1 C_2 S_a T_e^2 / (4\pi^2)$$

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

LOAD CONTROL AND DISPLACEMENT CONTROL



P-DELTA ANALYSIS

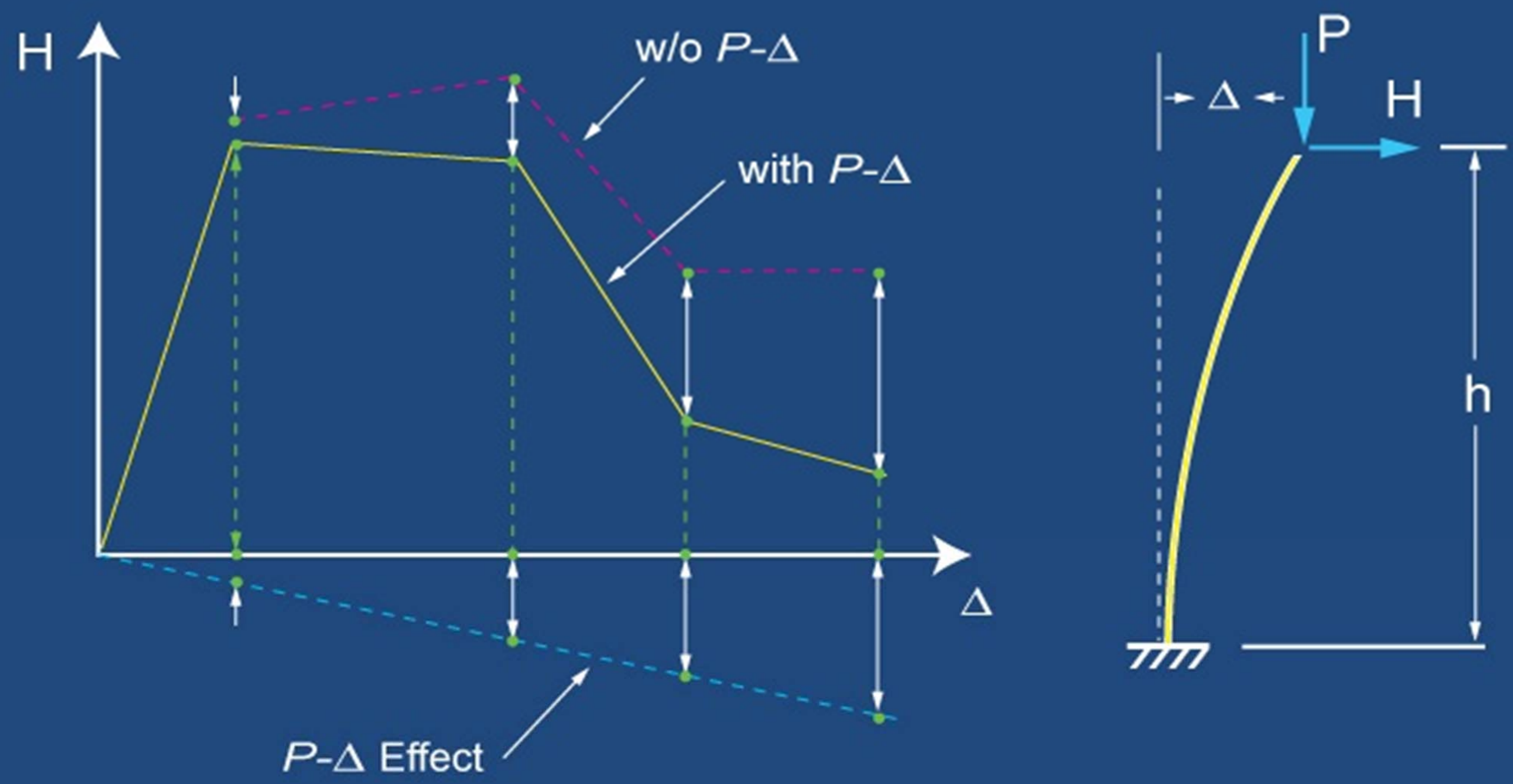


$$V = K\Delta$$

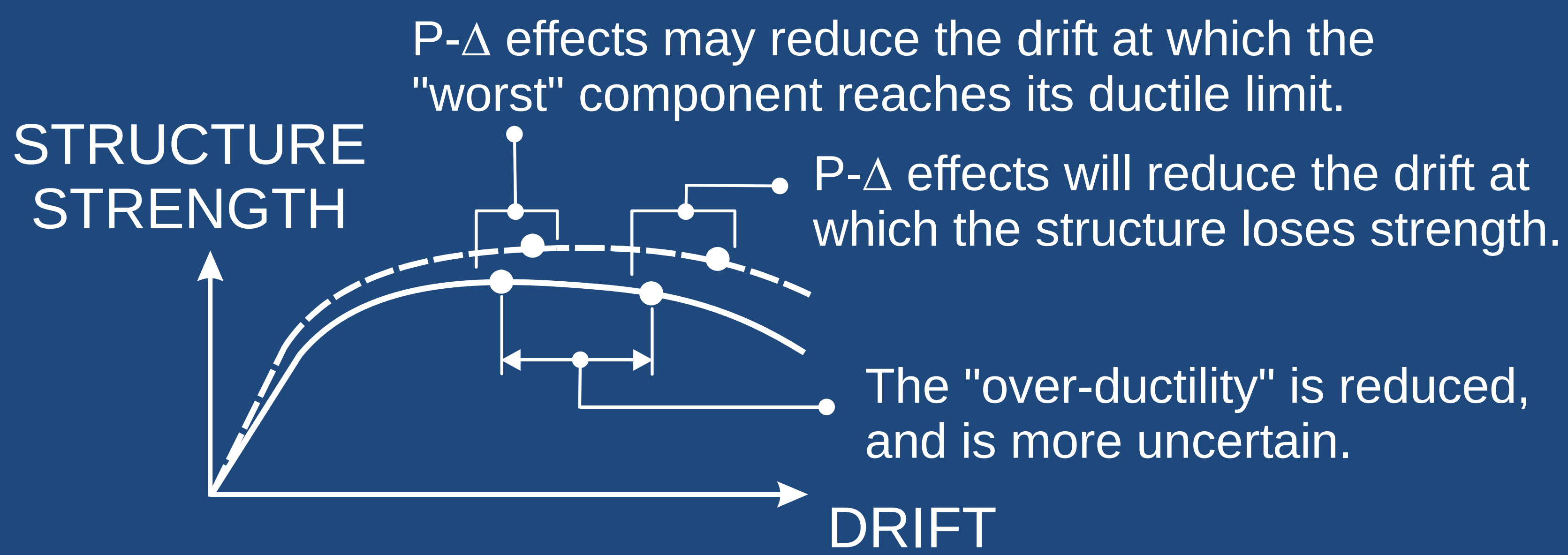
$$V + \frac{P\Delta}{H} = K\Delta$$

$$V = \left(K - \frac{P}{H}\right)\Delta$$

P-DELTA DEGRADES STRENGTH



P-DELTA EFFECTS ON F-D CURVES



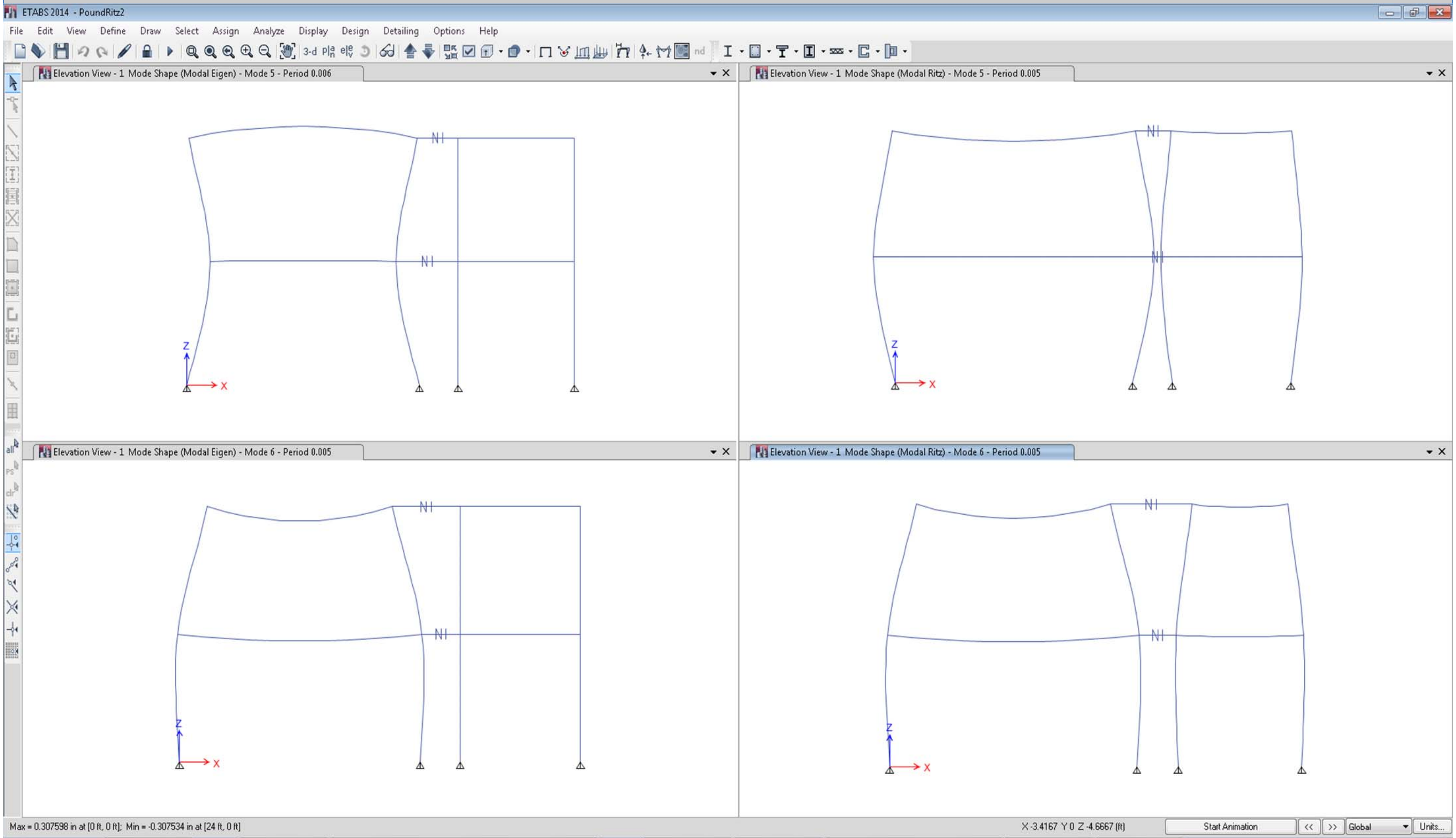
THE FAST NONLINEAR ANALYSIS METHOD (FNA)

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

STRUCTURAL DAMPERS
STRUCTURAL UPLIFT

STRUCTURAL POUNDING
BUCKLING RESTRAINED BRACES

RITZ VECTORS



Nonlinear Analysis & Performance Based Design

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.

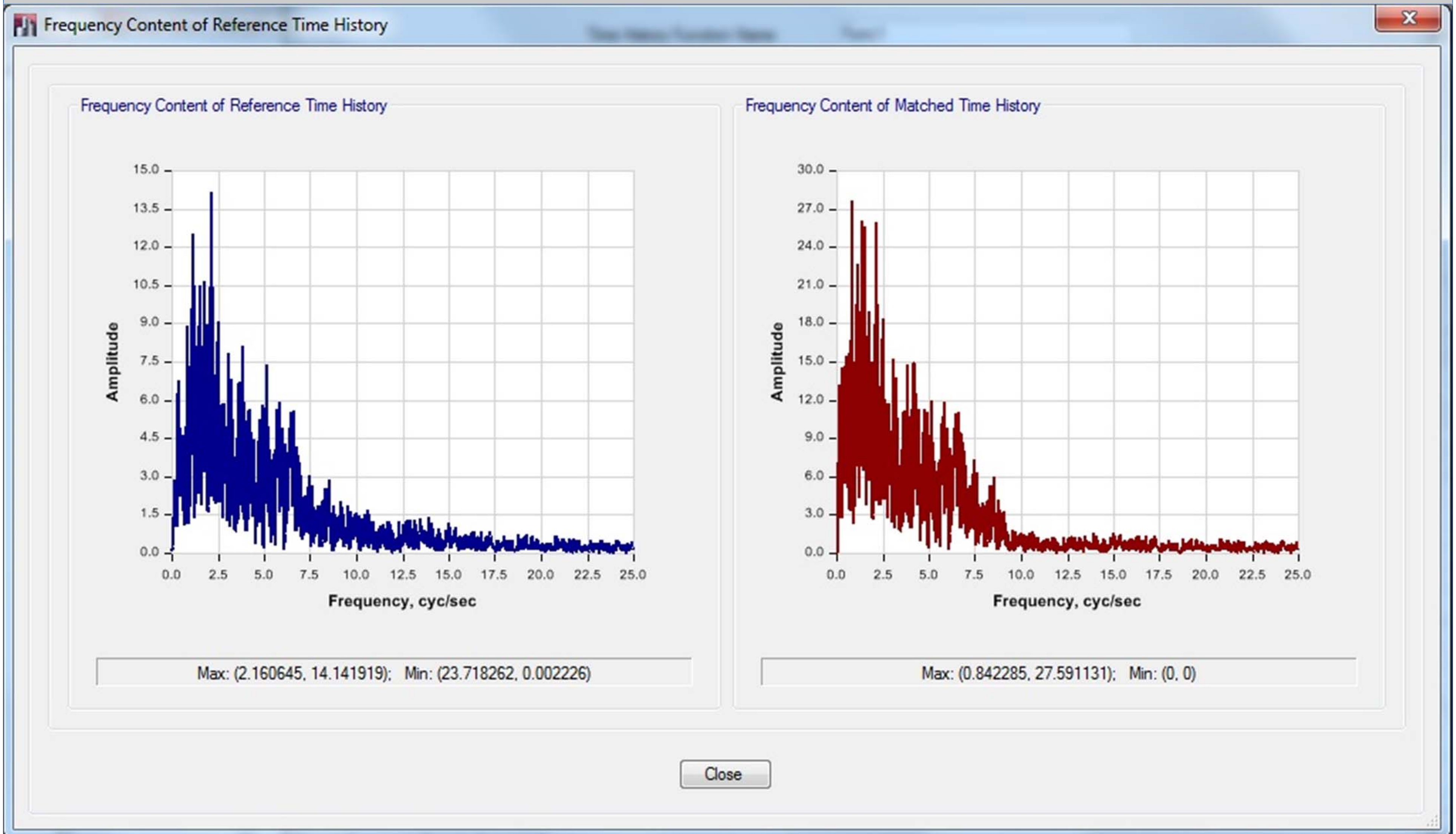
ARTIFICIAL EARTHQUAKES

CREATING HISTORIES TO MATCH A SPECTRUM

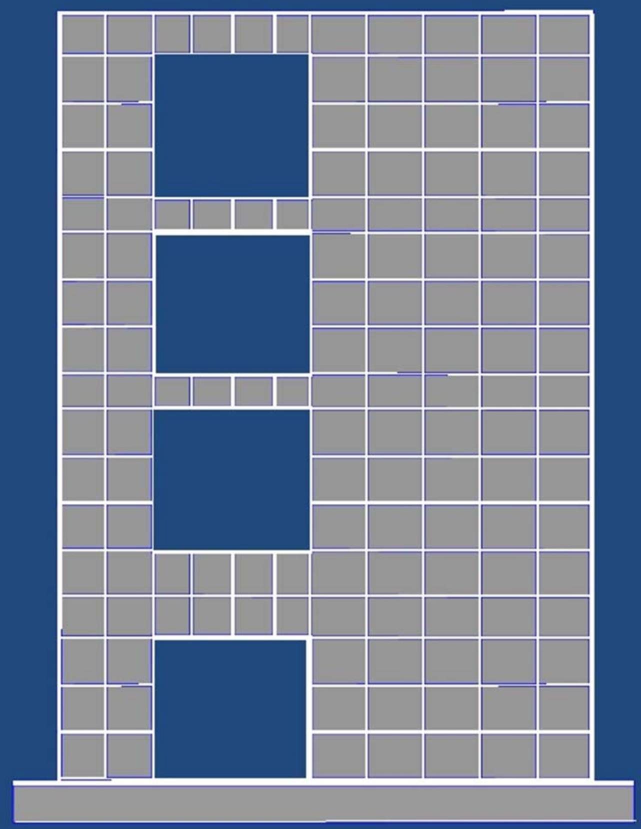
FREQUENCY CONTENTS OF EARTHQUAKES

FOURIER TRANSFORMS

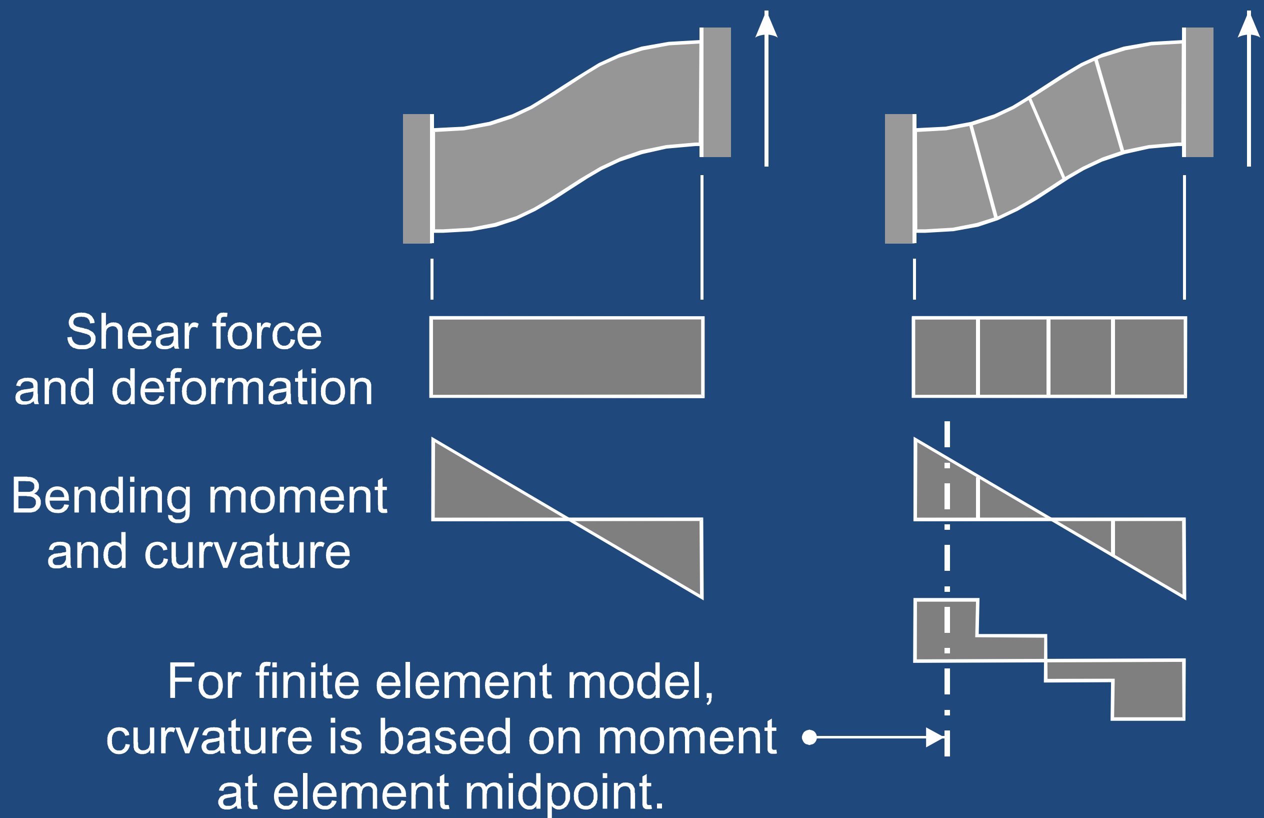
ARTIFICIAL EARTHQUAKES



MESH REFINEMENT

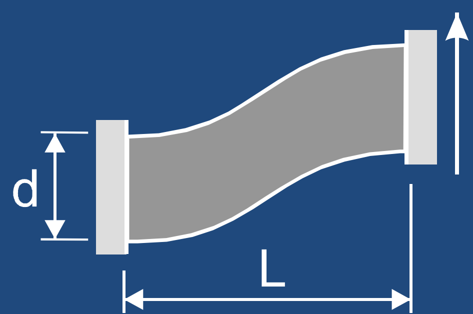


APPROXIMATING BENDING BEHAVIOR



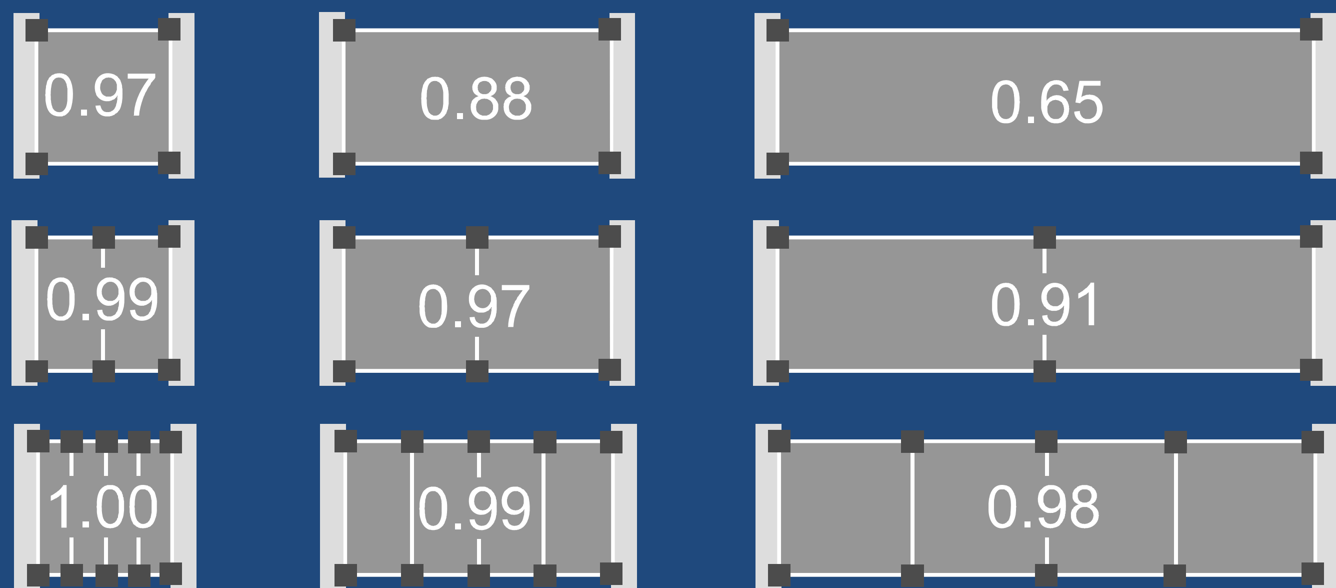
This is for a coupling beam. A slender pier is similar.

ACCURACY OF MESH REFINEMENT

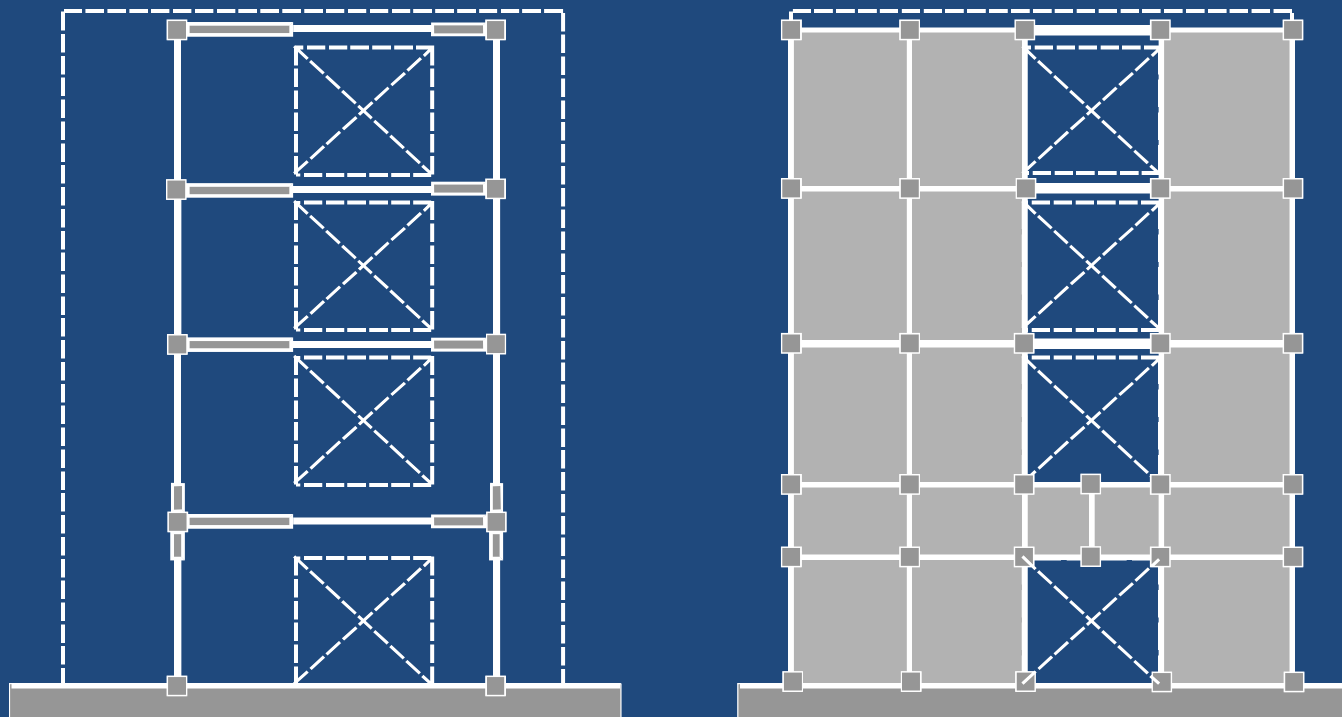


Elastic beam, rectangular section.
Shear modulus, G = 0.4E.
Assume shear area = actual area.

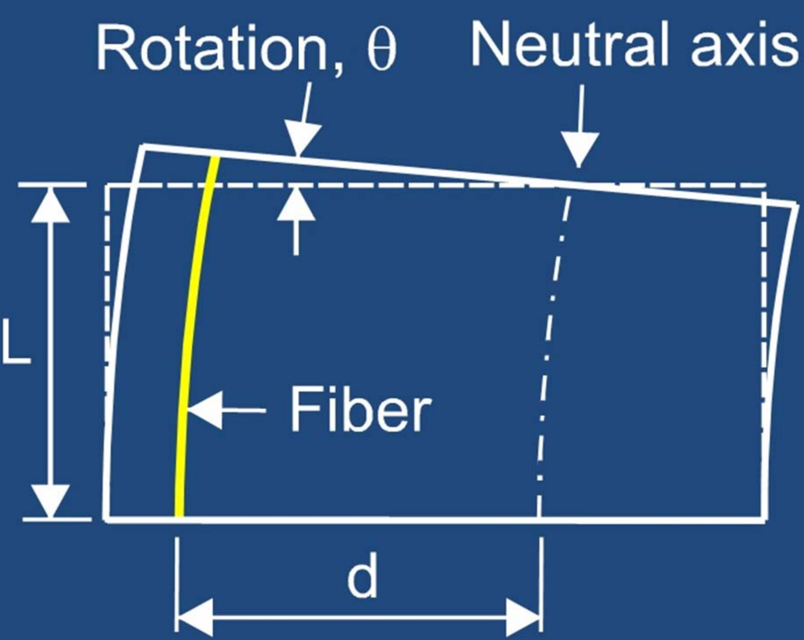
Ratio of finite element deflection to exact deflection for different d/L ratios and numbers of elements.



PIER / SPANDREL MODELS



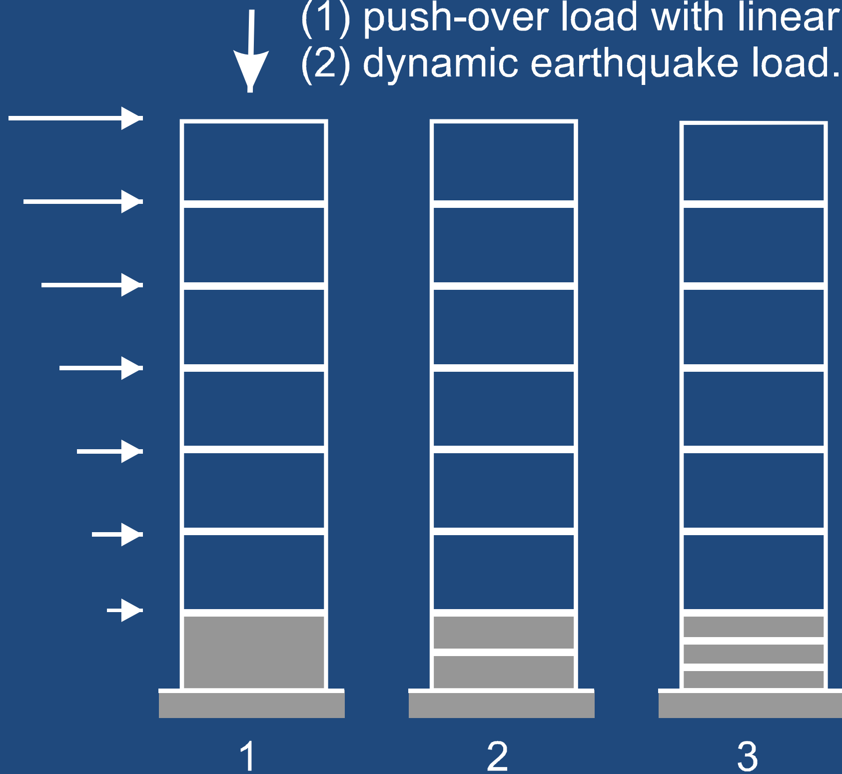
STRAIN & ROTATION MEASURES



$$\text{Fiber strain} = \frac{\theta\, d}{L}$$

STRAIN CONCENTRATION STUDY

Gravity load, followed by :
(1) push-over load with linear variation over height,
(2) dynamic earthquake load.



Number of elements over hinge length

Use hinge length = story height.

Consider different numbers of elements over the hinge length.

Calculate strain at extreme fiber :
(a) In lowest element.
(b) Over story height, using a strain gage.

Calculate rotation over story height, using a rotation gage.

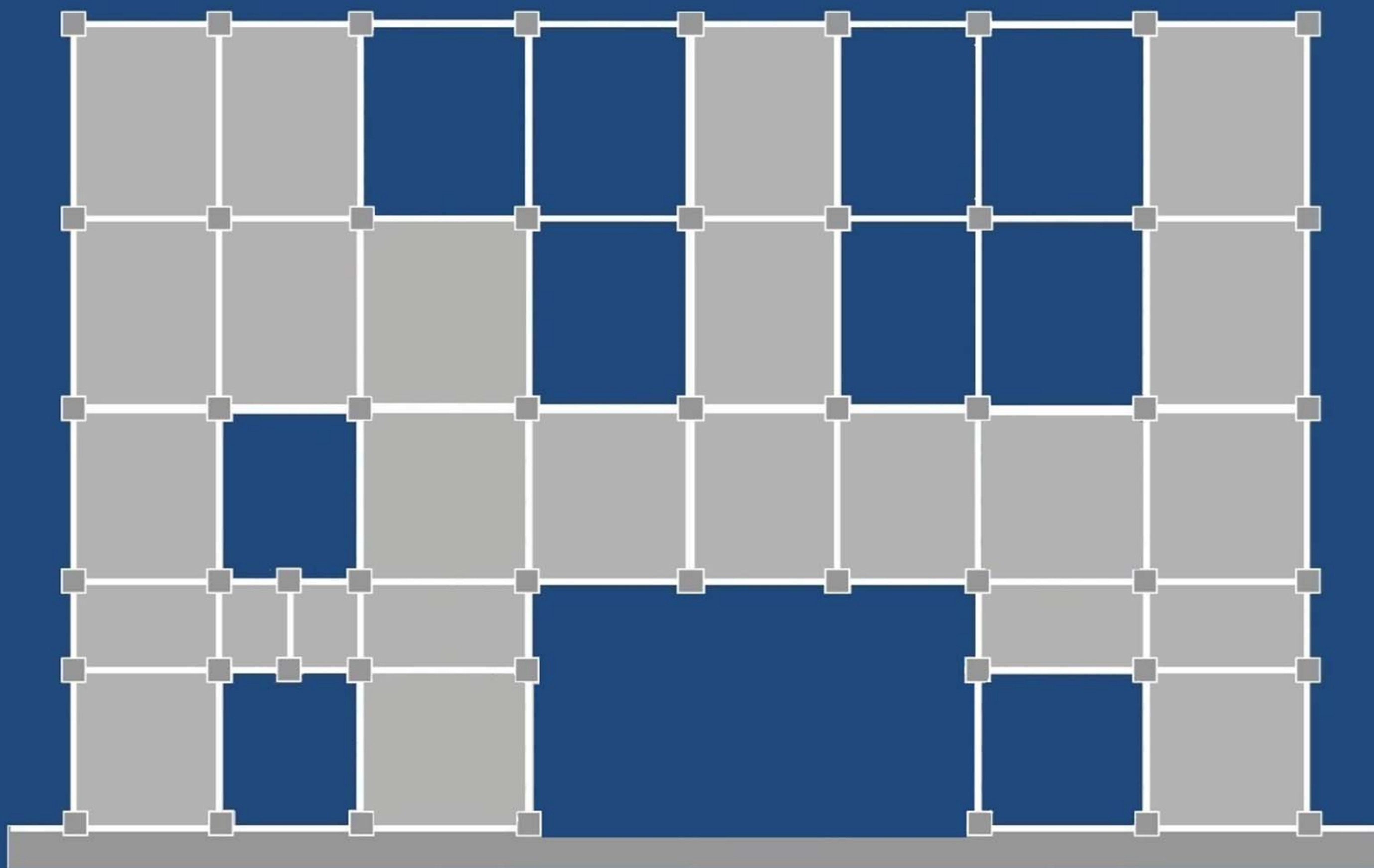
Compare calculated strains and rotations for the 3 cases.

STRAIN CONCENTRATION STUDY

No. of elems	Roof drift	Strain in bottom element	Strain over story height	Rotation over story height
1	2.32%	2.39%	2.39%	1.99%
2	2.32%	3.66%	2.36%	1.97%
3	2.32%	4.17%	2.35%	1.96%

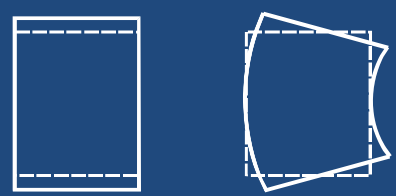
The strain over the story height is insensitive to the number of elements.
Also, the rotation over the story height is insensitive to the number of elements.
Therefore these are good choices for D/C measures.

DISCONTINUOUS SHEAR WALLS

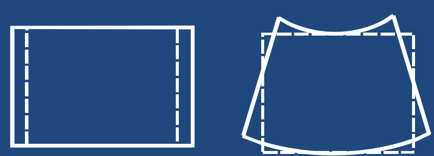


Nonlinear Analysis & Performance Based Design

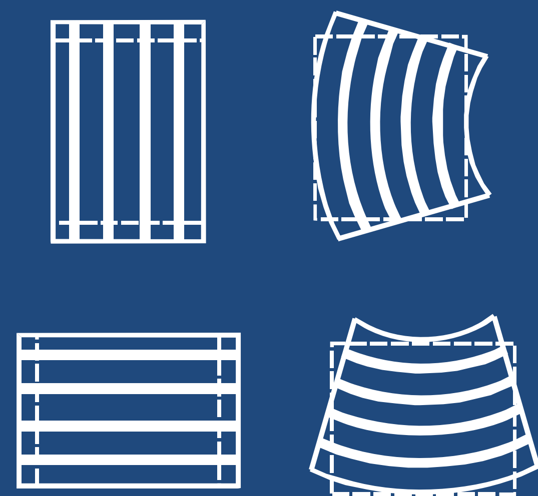
PIER AND SPANDREL FIBER MODELS



Vertical axial and bending

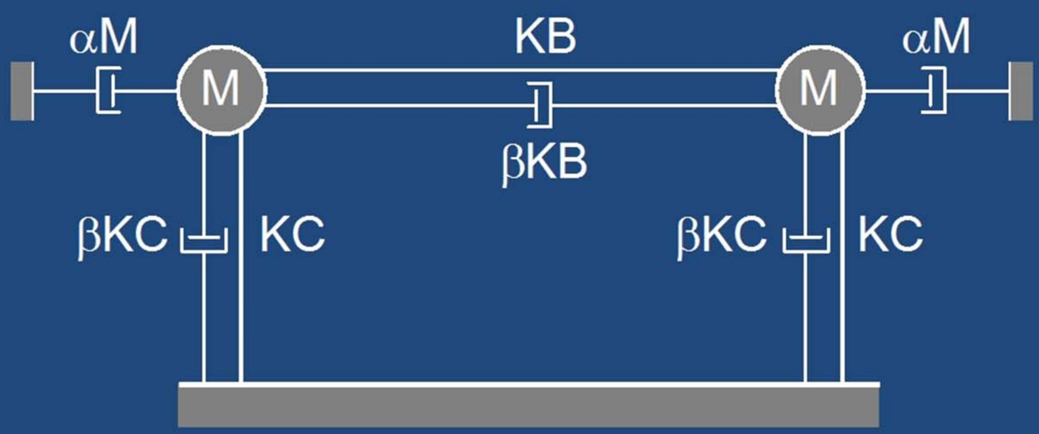


Horizontal axial and bending



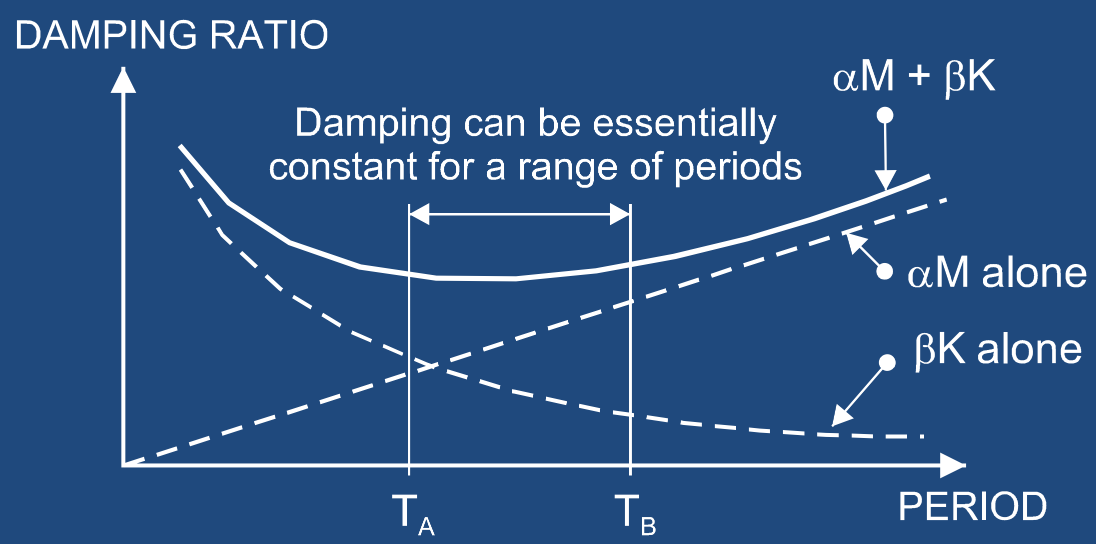
Vertical and horizontal fiber models

RAYLEIGH DAMPING



- The αM dampers connect the masses to the ground. They exert external damping forces. Units of α are 1/T.
- The βK dampers act in parallel with the elements. They exert internal damping forces. Units of β are T.
- The damping matrix is $\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}$.

RAYLEIGH DAMPING



- For linear analysis, the coefficients α and β can be chosen to give essentially constant damping over a range of mode periods, as shown.
- A possible method is as follows :

  Choose T_B = 0.9 times the first mode period.

  Choose T_A = 0.2 times the first mode period.

  Calculate α and β to give 5% damping at these two values.
- The damping ratio is essentially constant in the first few modes.
- The damping ratio is higher for the higher modes.

RAYLEIGH DAMPING

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

$$M\ddot{u}_t + (\alpha M + \beta K)\dot{u} + Ku = 0$$

$$\ddot{u} + \frac{C}{M}\dot{u} + \frac{K}{M}u = 0$$

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = 0 \quad ; \quad 2\xi M\omega = C$$

$$\xi = \frac{C}{2M\omega} = \frac{C}{2M\sqrt{\frac{K}{M}}} = \frac{C}{2\sqrt{KM}} = \frac{\alpha M}{2\sqrt{KM}} + \frac{\beta K}{2\sqrt{KM}}$$

$$\xi = \frac{\alpha}{2\omega} + \frac{\beta\omega}{2}$$

RAYLEIGH DAMPING

Higher Modes (high ω) = β

Lower Modes (low ω) = α

To get ζ from α & β for any $\omega = \sqrt{\frac{K}{M}}$; $T = \frac{2\pi}{\omega}$

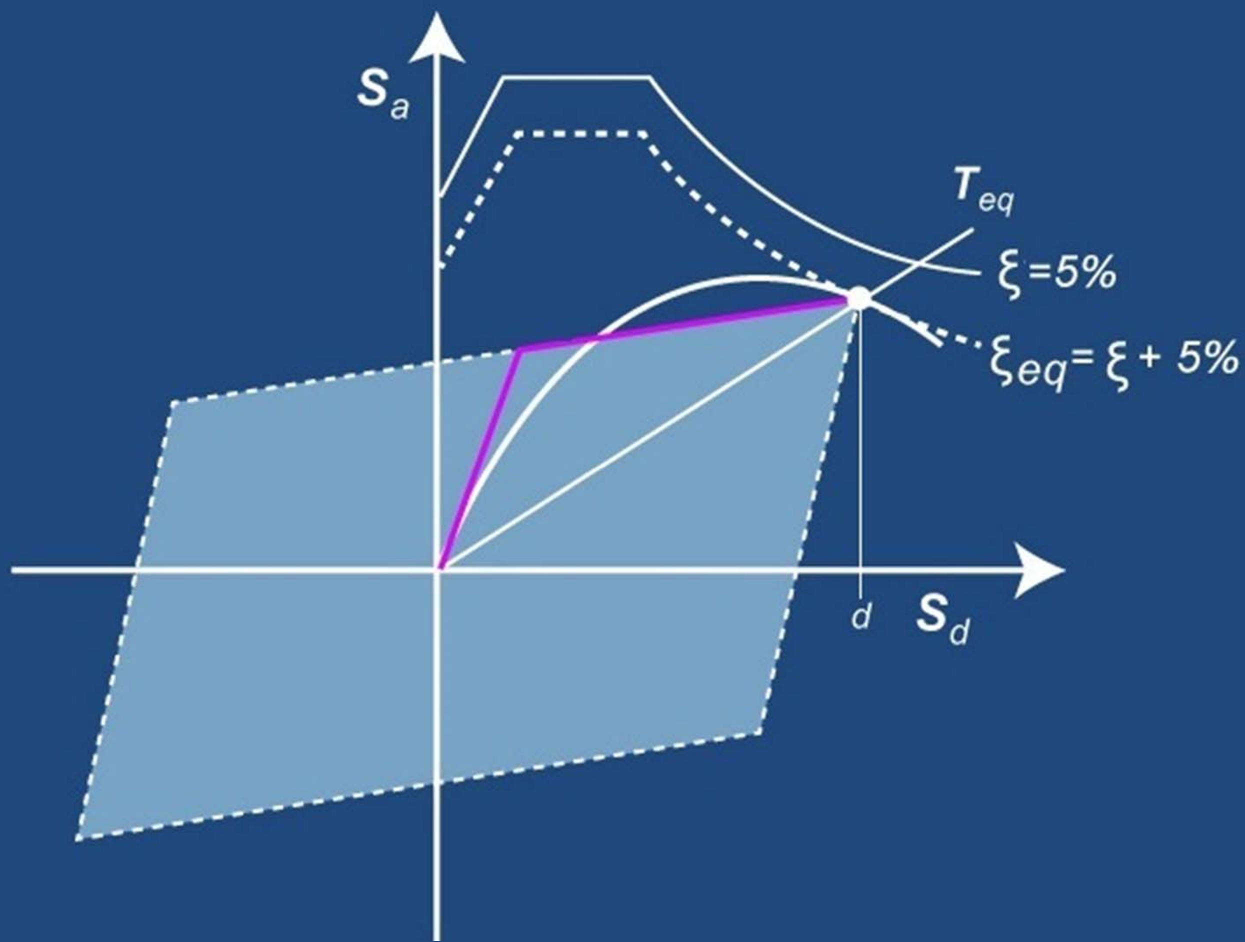
To get α & β from two values of ζ_1 & ζ_2

$$\zeta_1 = \frac{\alpha}{2\omega_1} + \frac{\beta\omega_1}{2}$$

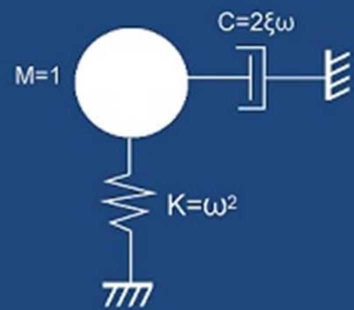
$$\zeta_2 = \frac{\alpha}{2\omega_2} + \frac{\beta\omega_2}{2}$$

Solve for α & β

DAMPING COEFFICIENT FROM HYSTERESIS



DAMPING COEFFICIENT FROM HYSTERESIS



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

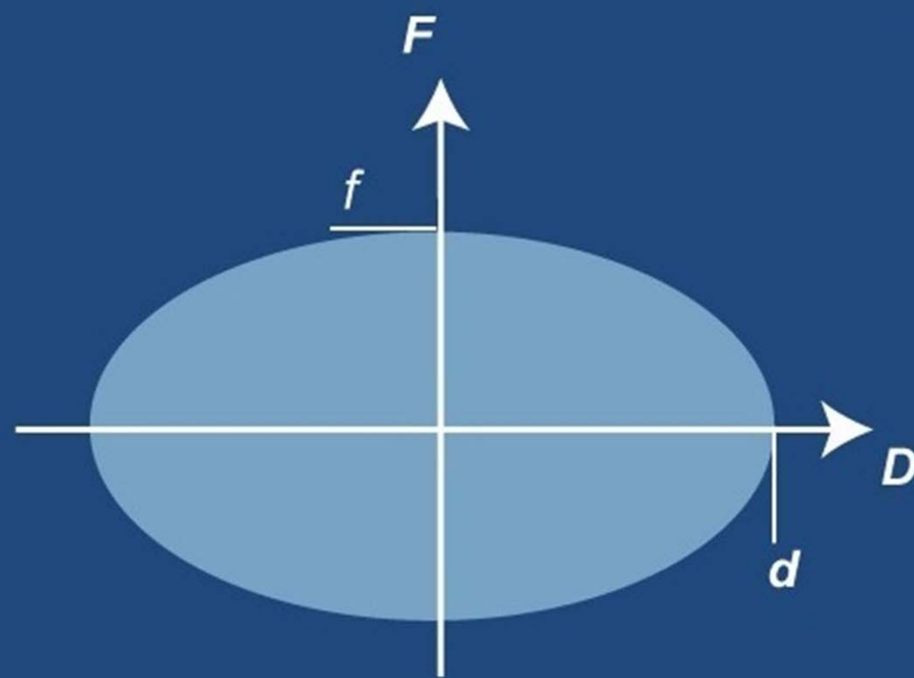
$$u = d \sin \omega t$$

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

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

$$\text{Area} = \pi\ fd$$

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



A BIG THANK YOU!!!

The American Concrete Insitute Awards CSI:

The Charles S. Whitney Medal

"For 30 years of development of world-class computer applications for analysis and design of structures that have changed and modernized structural engineering practice to a level never envisioned just a few decades ago."

- American Concrete Institute Board of Directors, Spring 2011

aci international