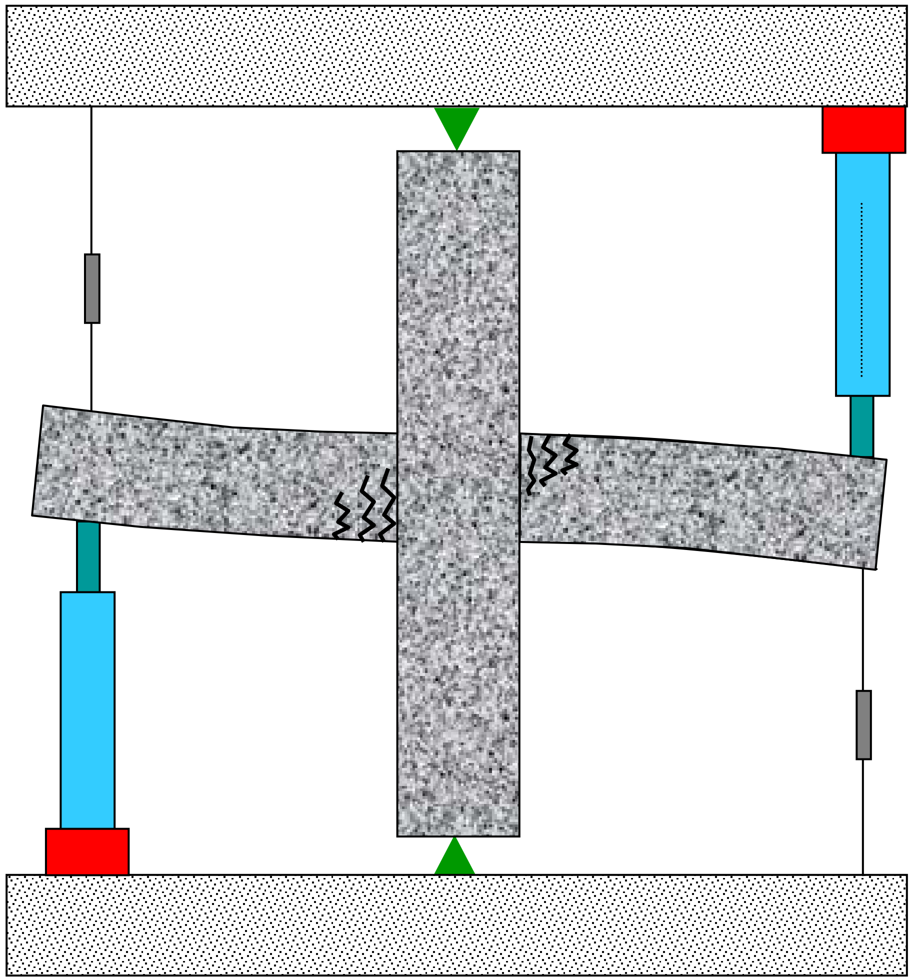
INELASTIC BEHAVIOR OF MATERIALS AND STRUCTURES



Inelastic Behavior of Materials and Structures

- Illustrates inelastic behavior of materials and structures
- Explains why inelastic response may be necessary
- Explains the “equal displacement “ concept
- Introduces the concept of inelastic design response spectra
- Explains how inelastic behavior is built into the *NEHRP Recommended Provisions* and ASCE 7-05

Importance in Relation to ASCE 7-05

- Derivation and explanation of the *response reduction factor, R*
- Derivation and explanation of the *displacement amplification factor,* C_d
- Derivation and explanation of the *overstrength factor,* Ω_o

Inelastic Behavior of Structures

From material

↓

to cross section

↓

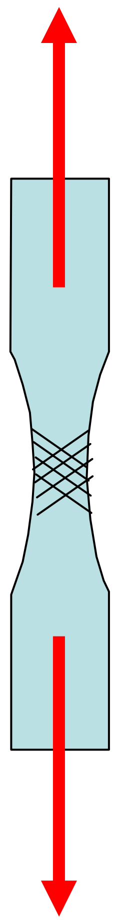
to critical region

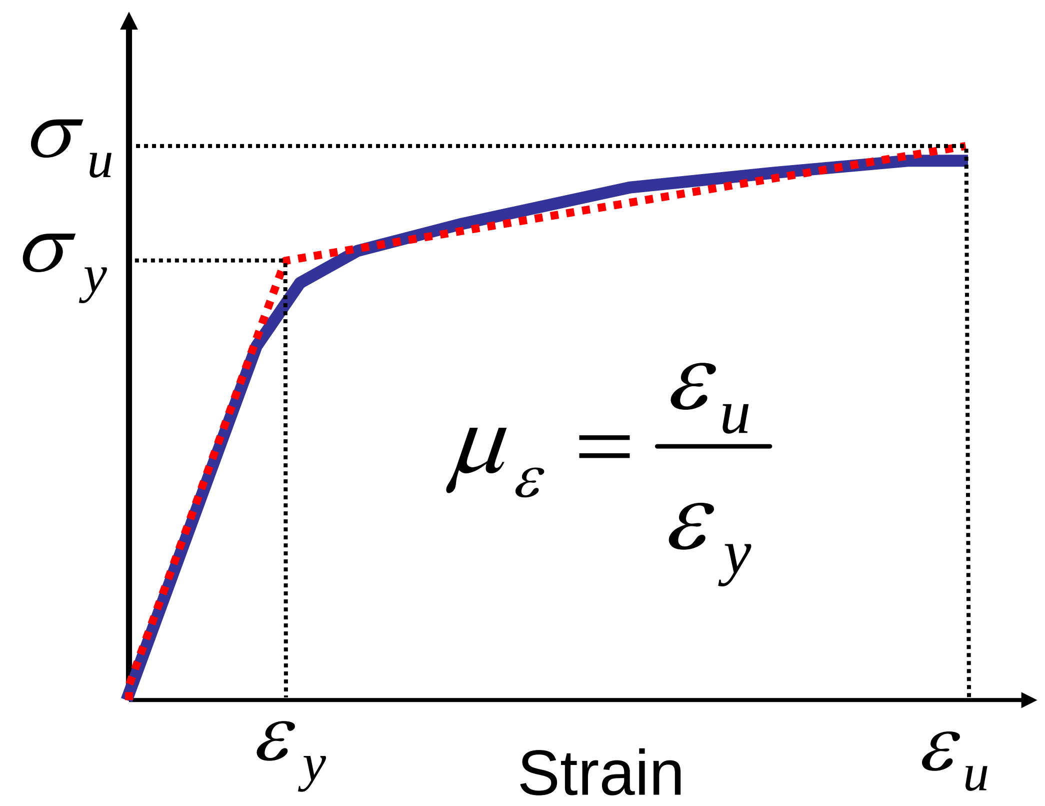
↓

to structure

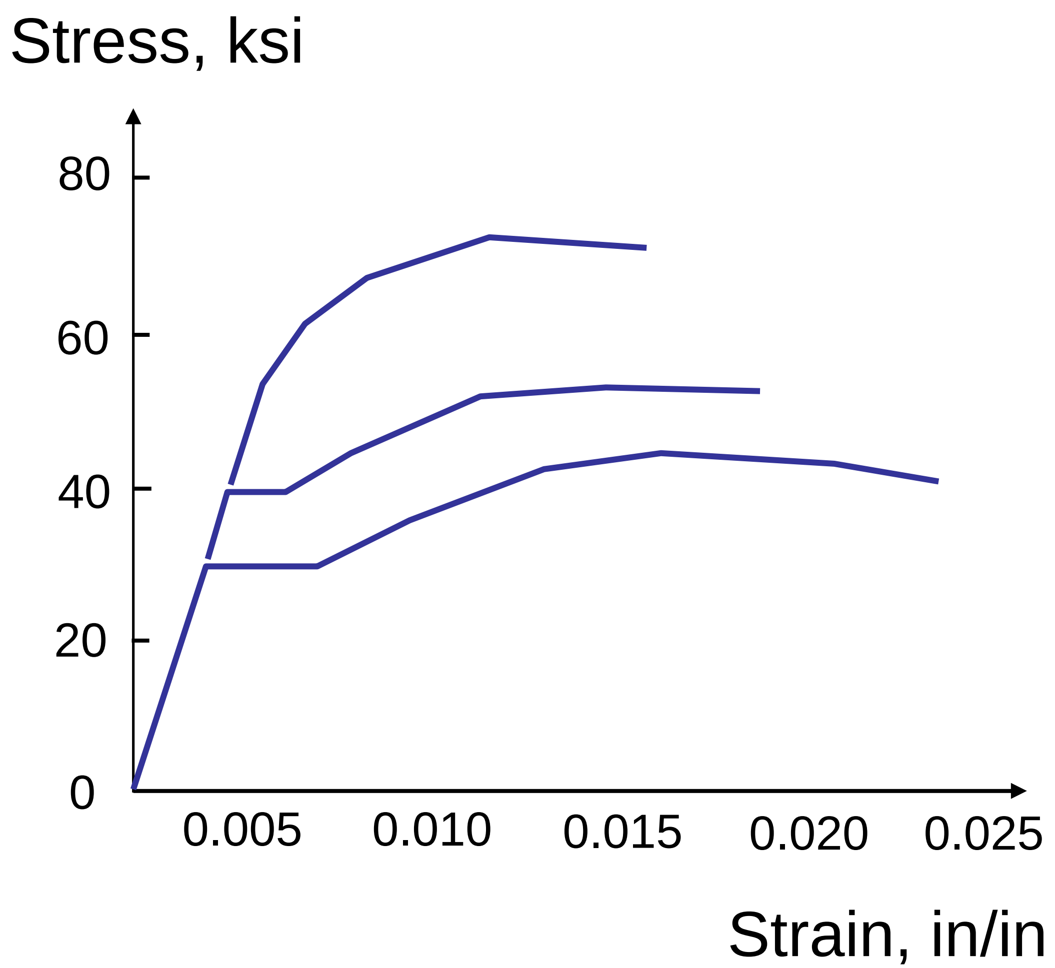
Idealized Inelastic Behavior

From Material…..

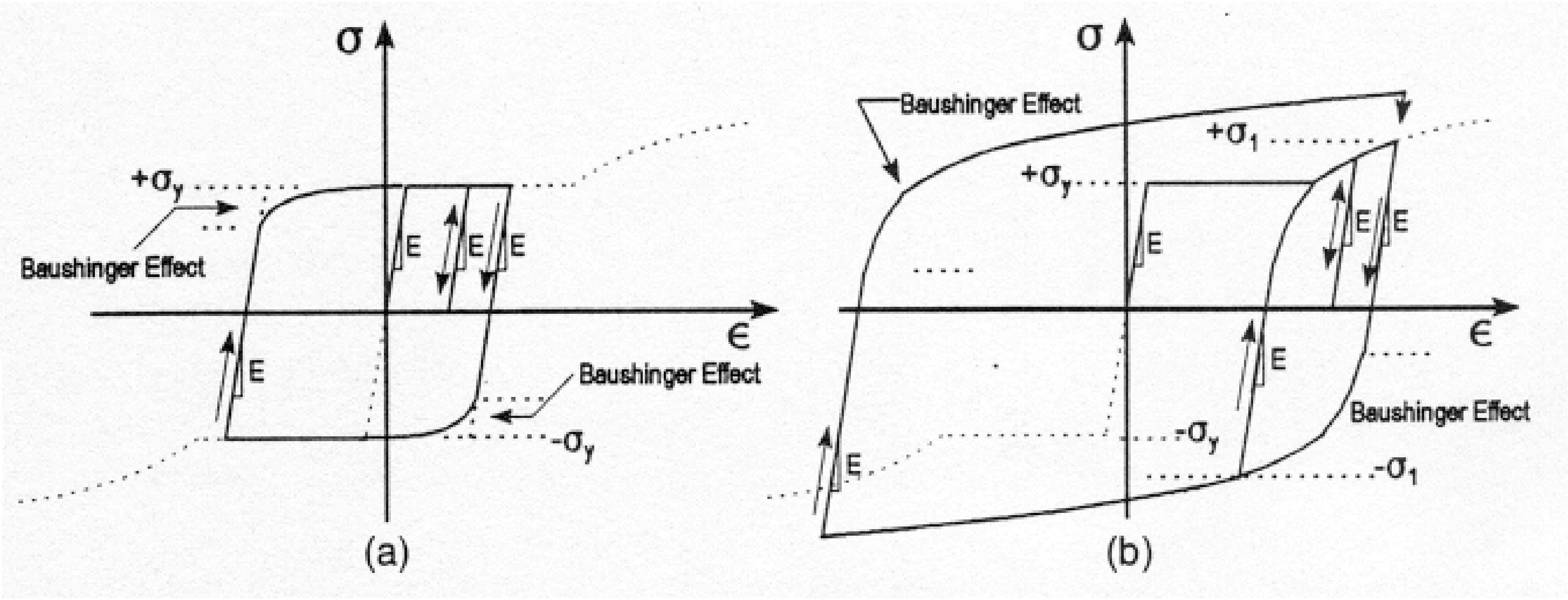




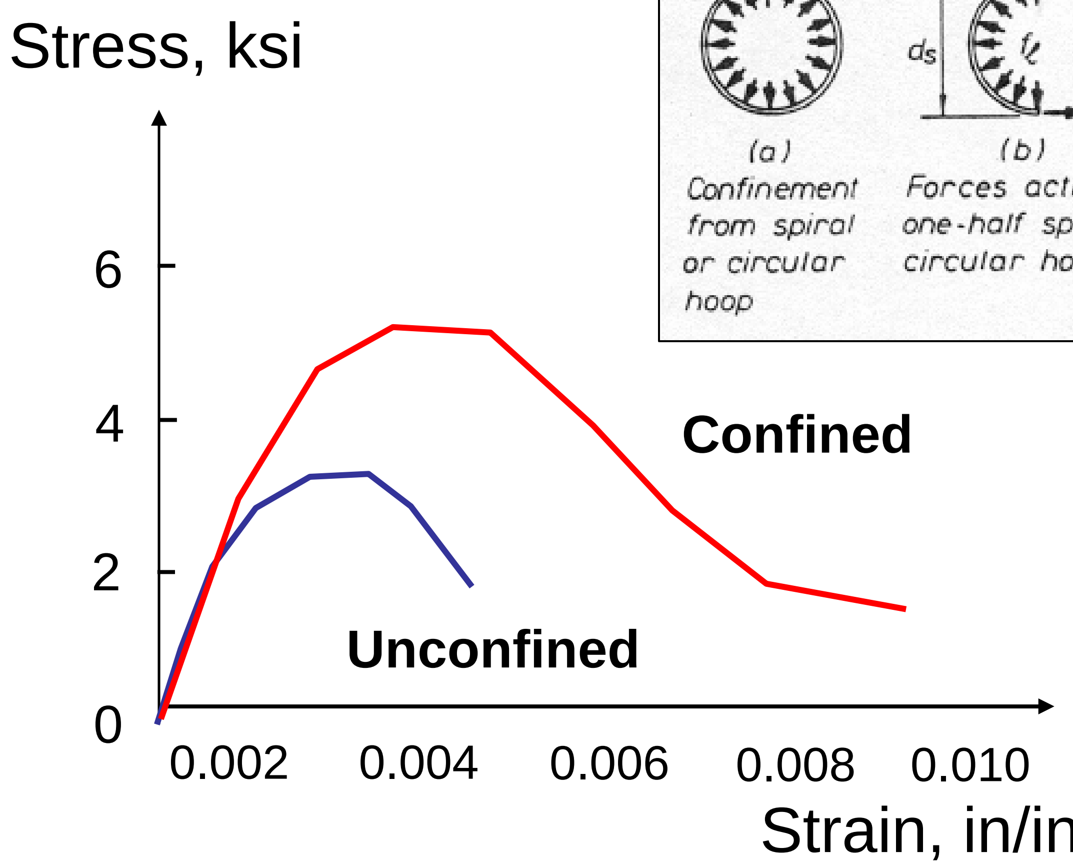
Stress-Strain Relationships for Steel

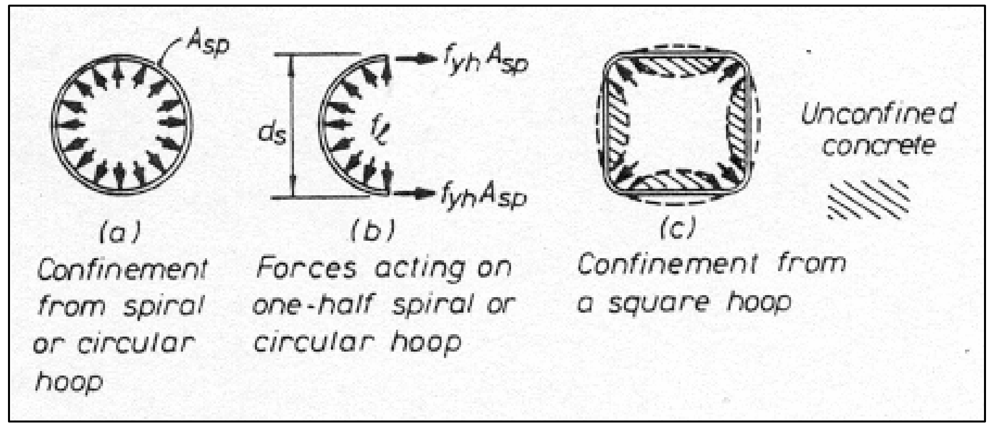


Stress-Strain Relationships for Steel

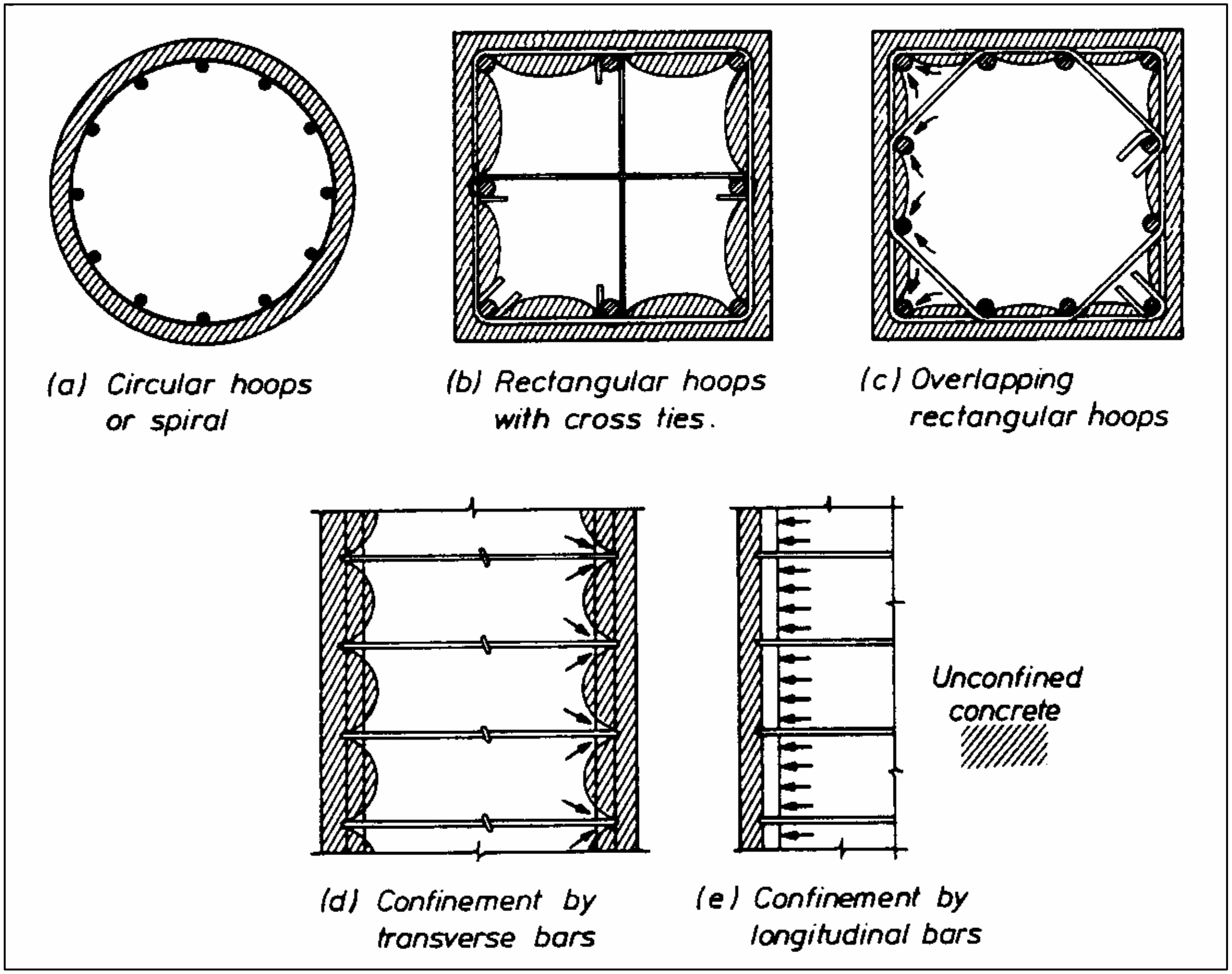


Stress-Strain Relationships for Concrete
(Unconfined and Confined)

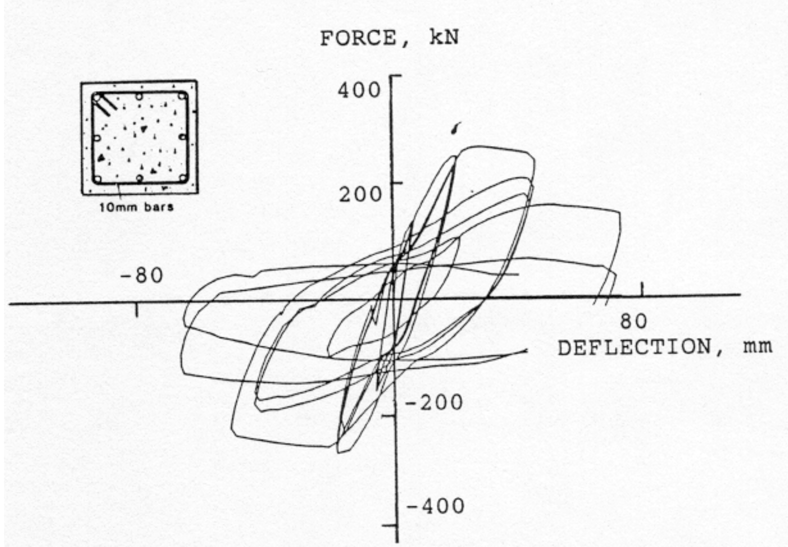




Concrete Confinement

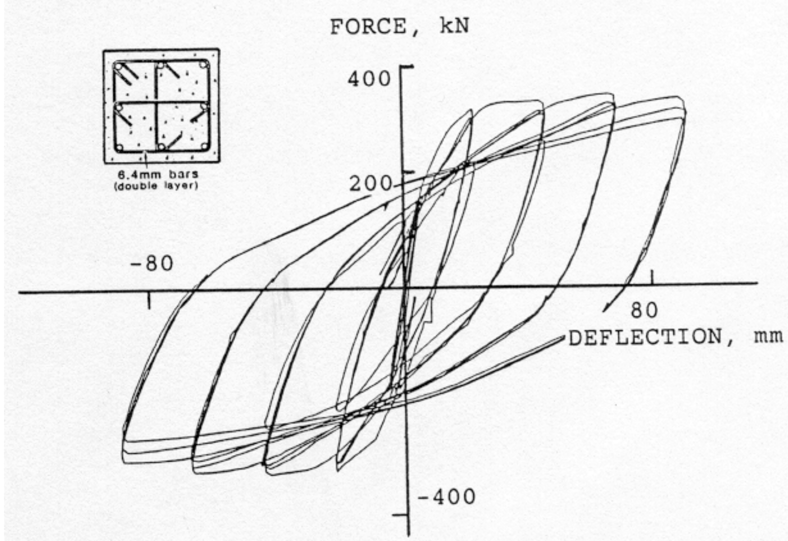


Unconfined



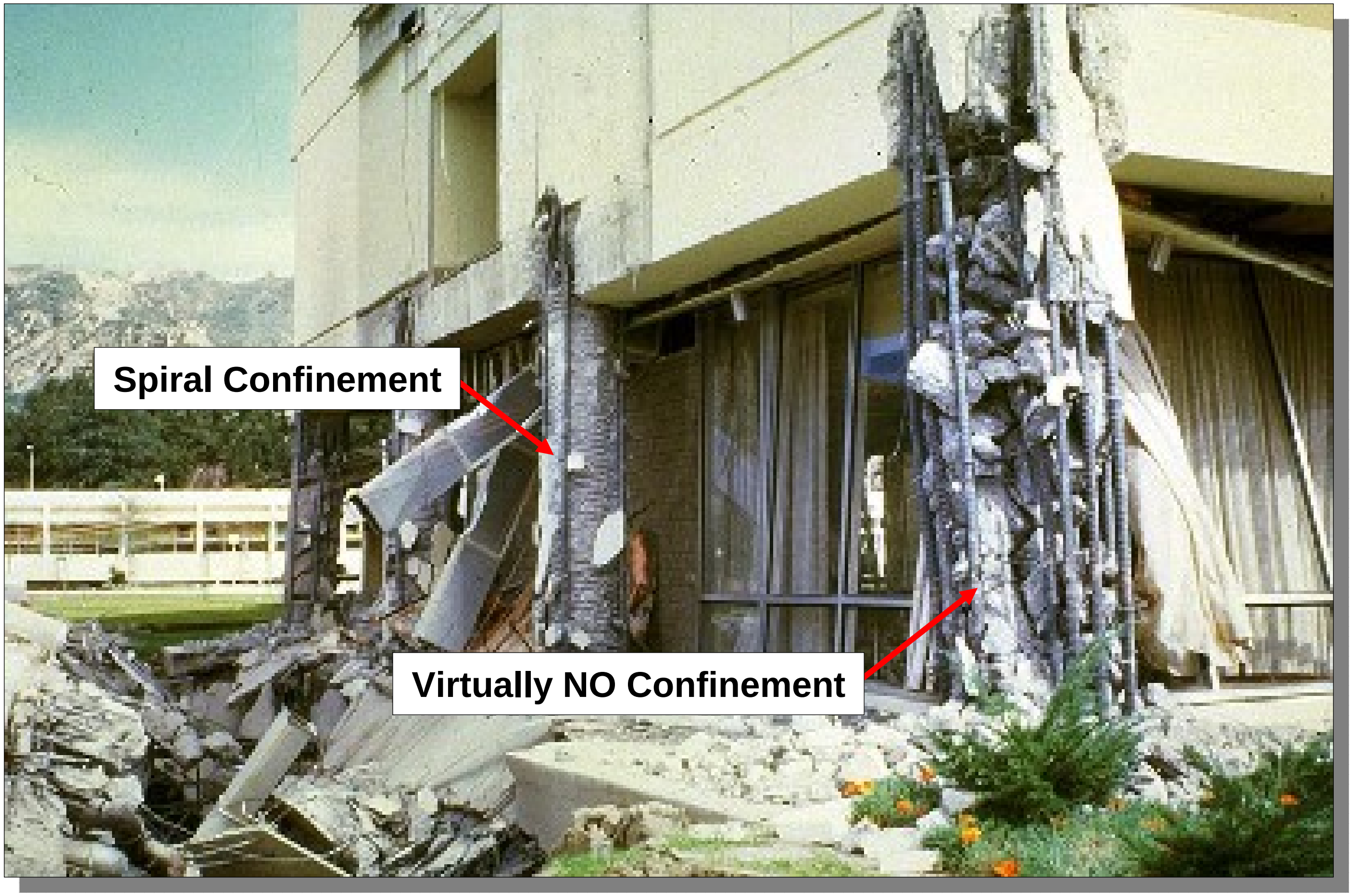
a) Poorly confined column

Confined



b) Well confined column

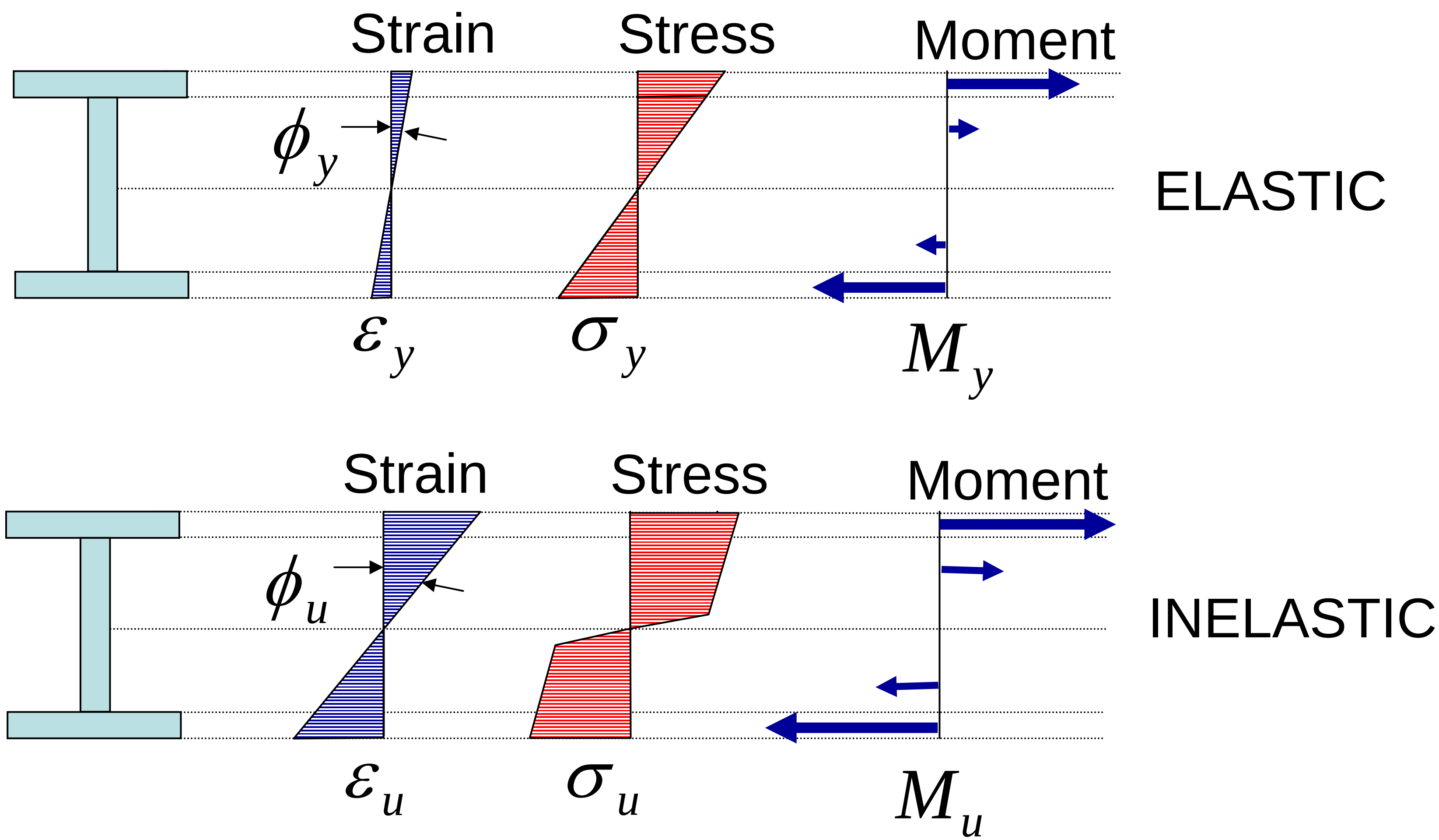
Benefits of Confinement



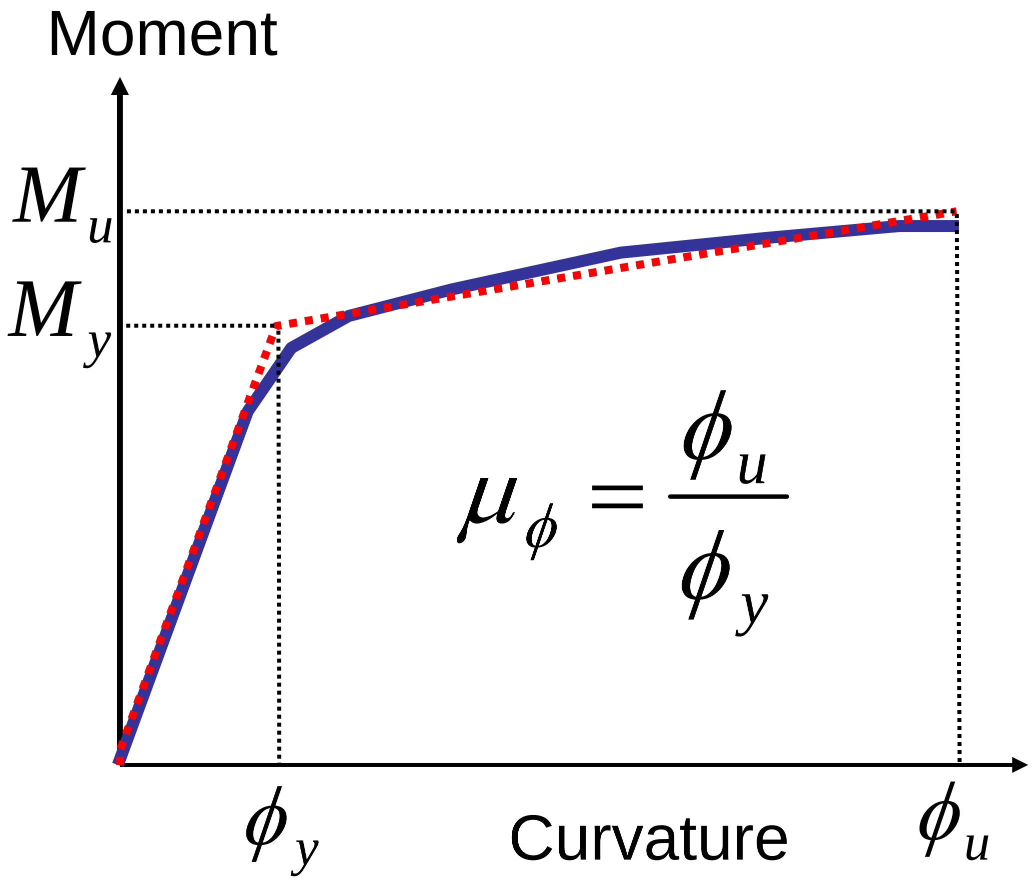
Olive View Hospital, 1971 San Fernando Valley earthquake

Idealized Inelastic Behavior

To Section…..

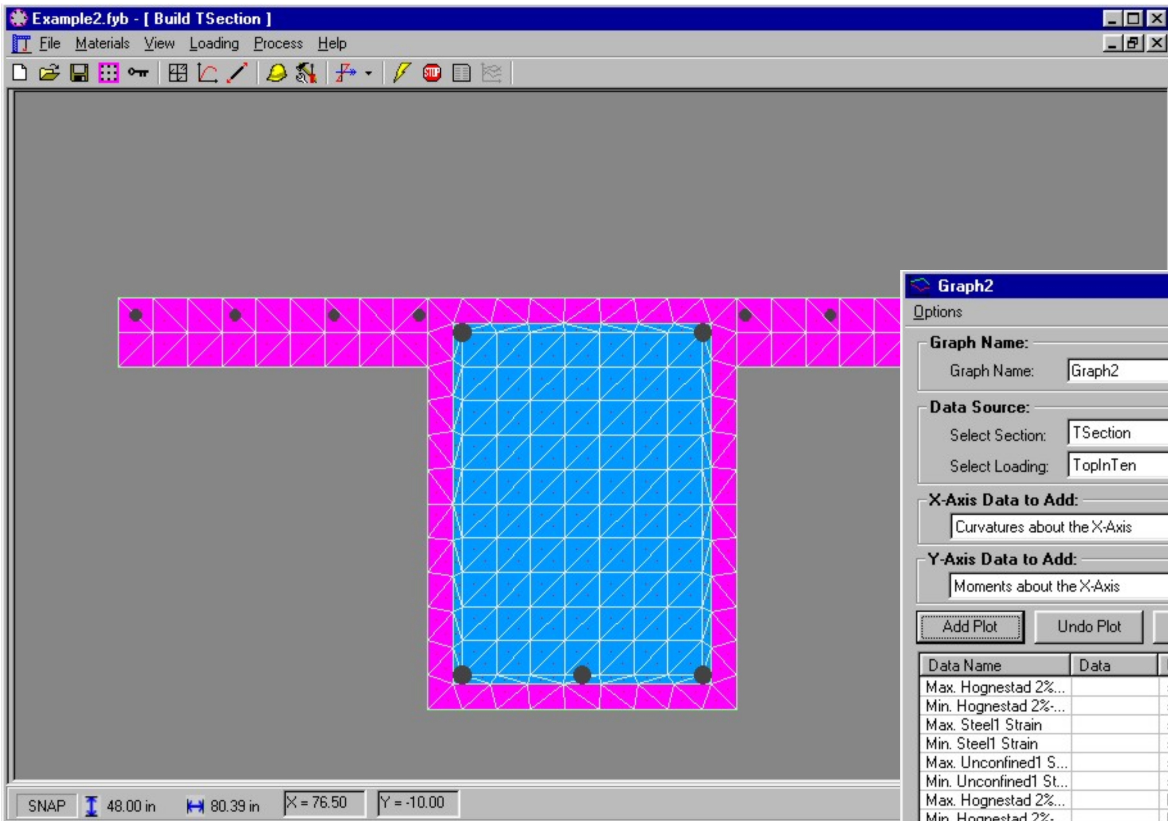


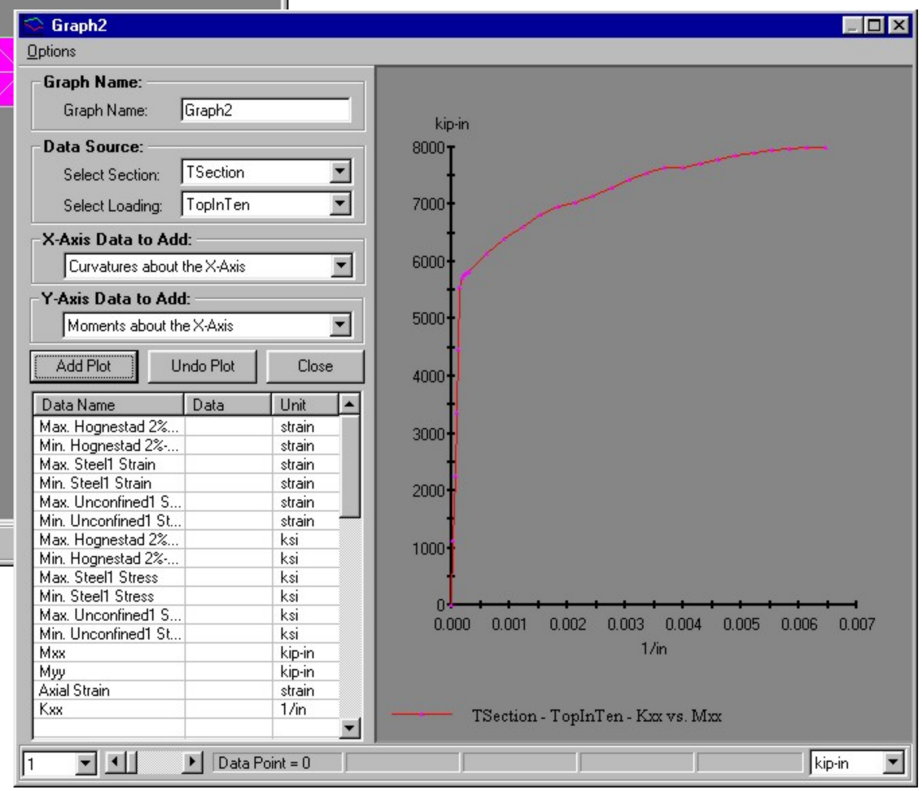
Idealized Inelastic Behavior
To Section…..



NOTE: $\mu_\phi \leq \mu_\varepsilon$

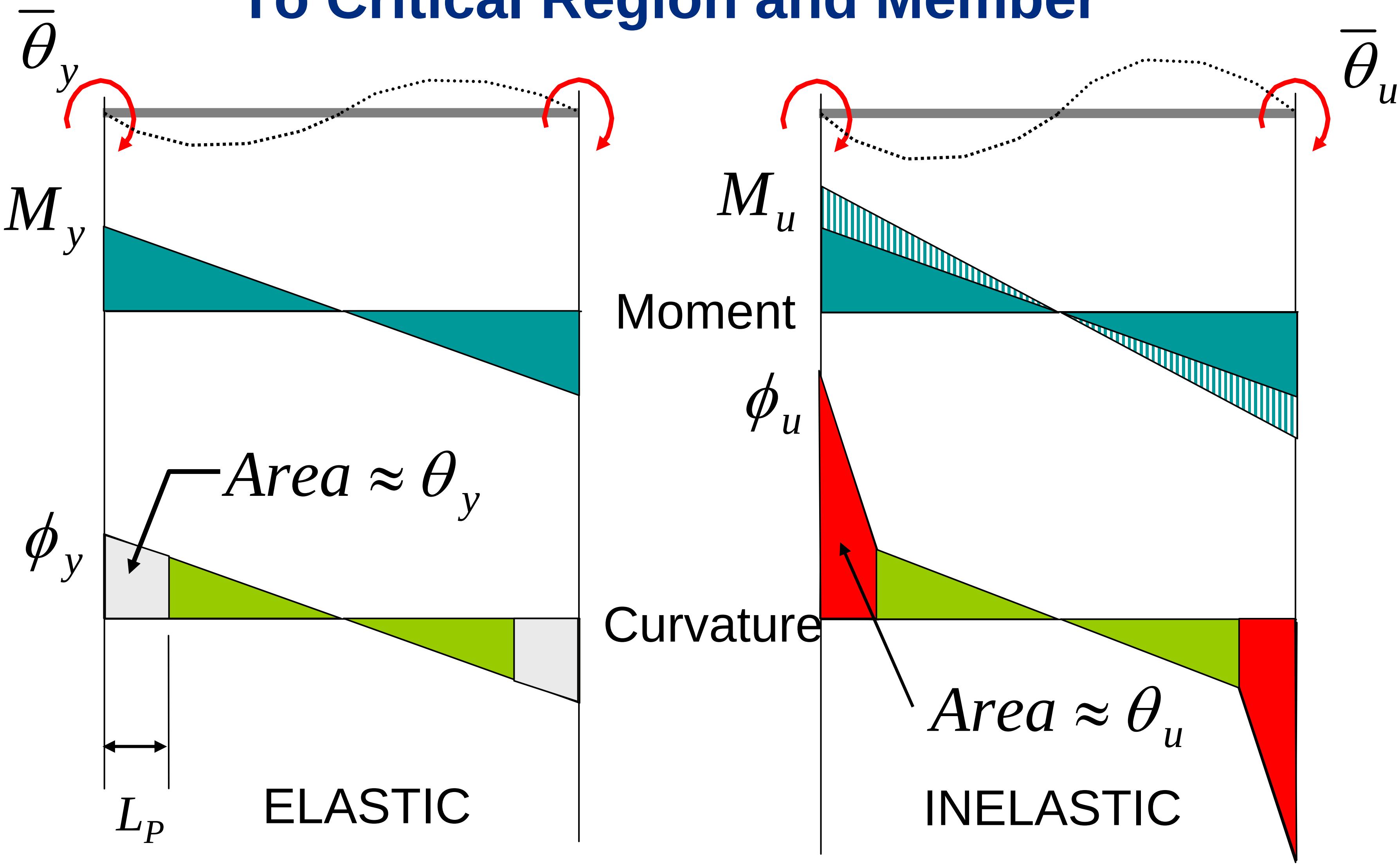
Software for Moment - Curvature Analysis "XTRACT"





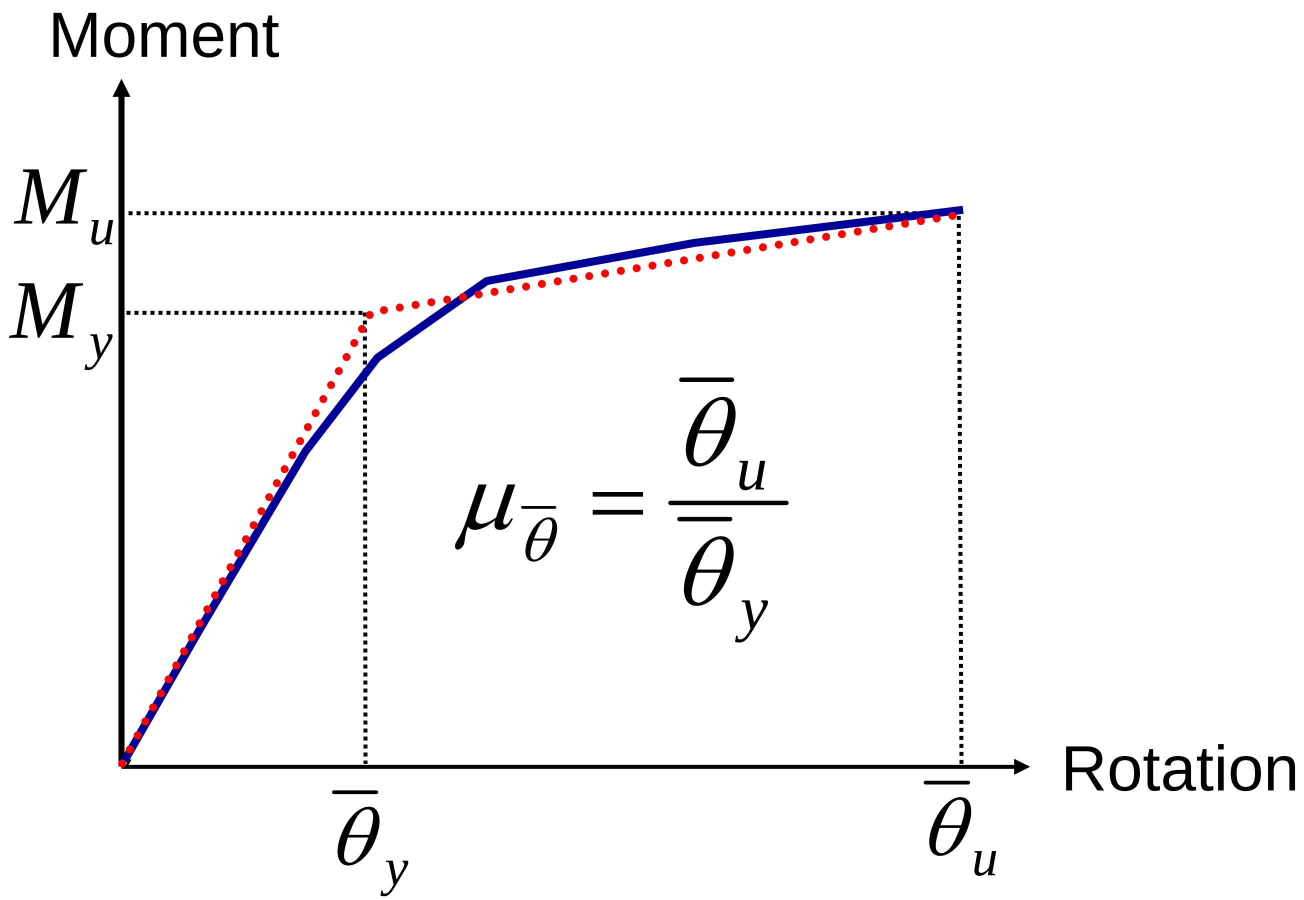
Idealized Inelastic Behavior

To Critical Region and Member



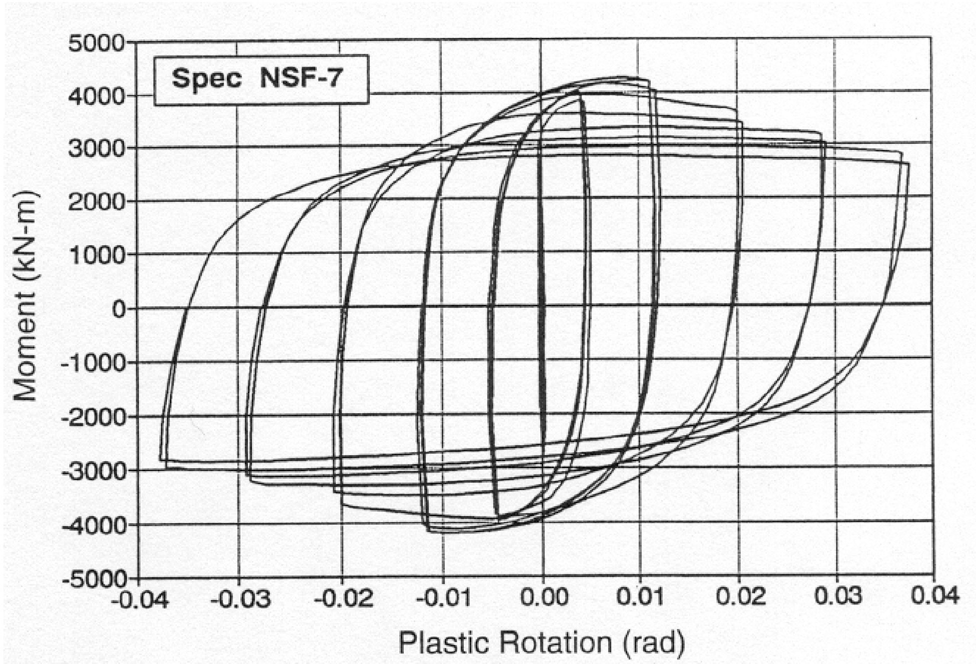
Idealized Inelastic Behavior

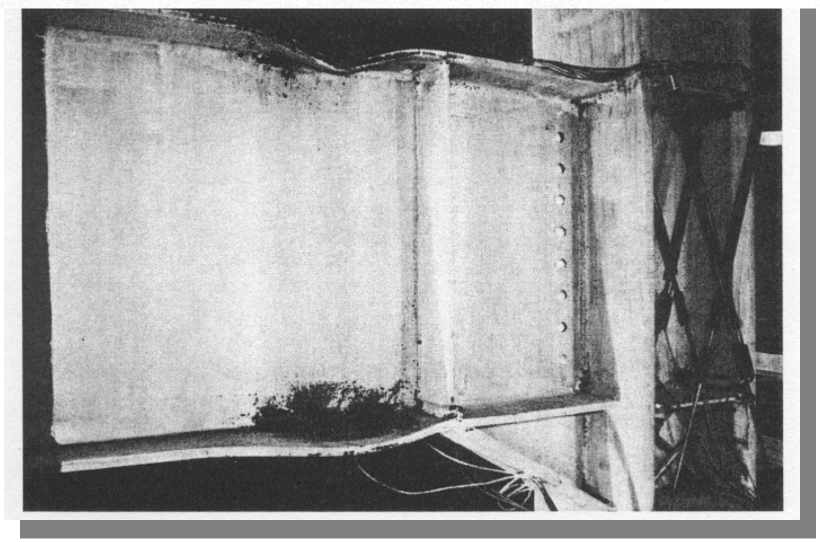
To Critical Region and Member



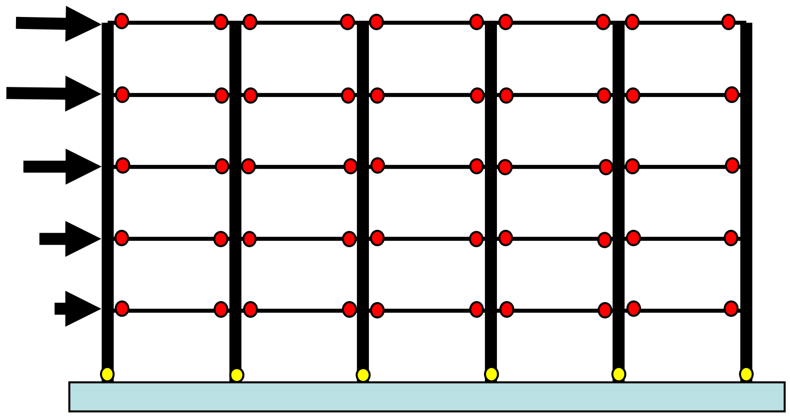
NOTE: $\mu_{\bar{\theta}} \leq \mu_{\theta} \leq \mu_{\phi}$

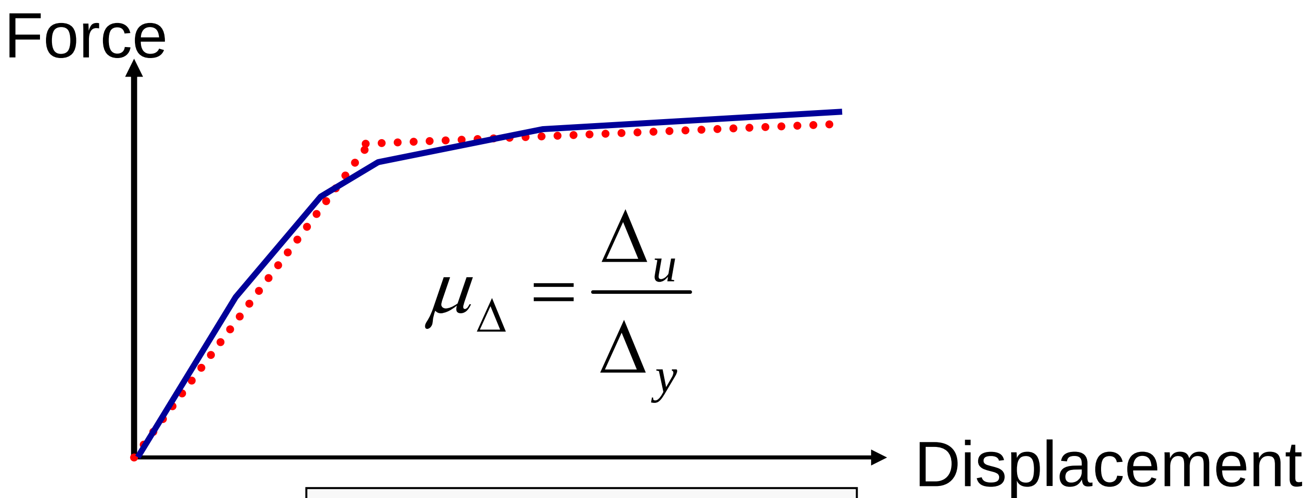
Critical Region Behavior of a Steel Girder





Idealized Inelastic Behavior
To Structure…..





$$\mu_\Delta = \frac{\Delta_u}{\Delta_y}$$

Note: $\mu_\Delta \le \mu_{\bar{\theta}}$

Loss of Ductility Through Hierarchy

Strain μ_{ε}= 100

Curvature μ_{ϕ}= 12 to 20

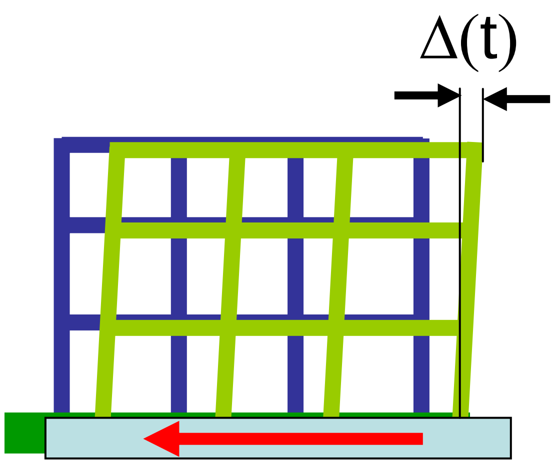
Rotation μ_{θ}= 8 to 14

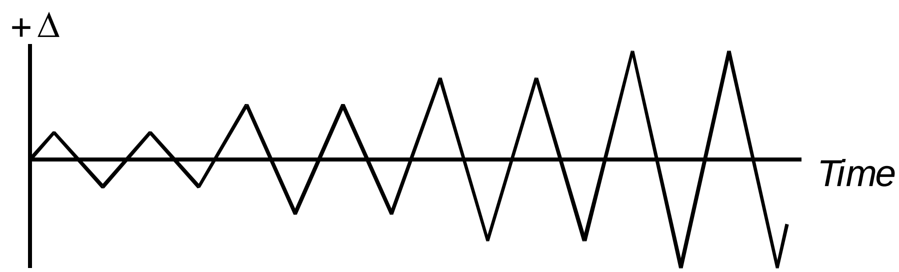
Displacement μ_{Δ}= 4 to 10

Ductility and Energy Dissipation Capacity

- System ductility of 4 to 6 is required for acceptable seismic behavior.
- Good hysteretic behavior requires ductile materials. However, ductility in itself is insufficient to provide acceptable seismic behavior.
- Cyclic energy dissipation capacity is a better indicator of performance.

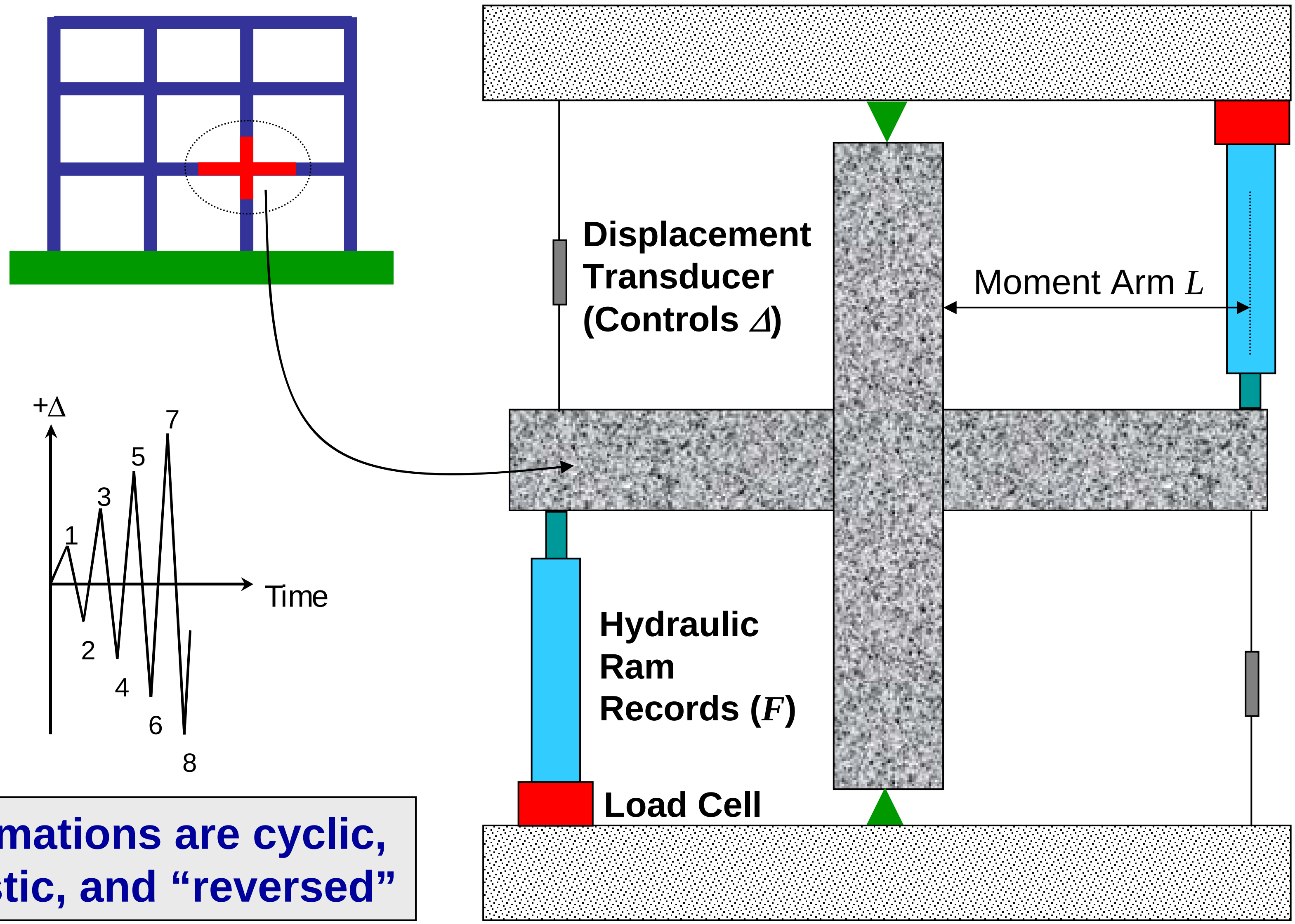
Response Under Reversed Cyclic "Loading"





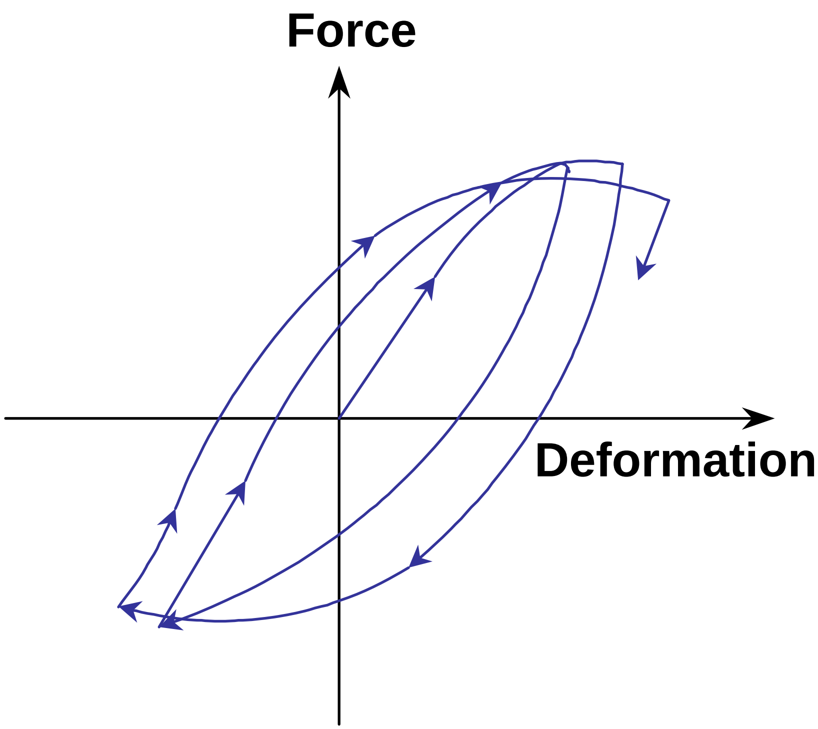
Earthquakes impose *DEFORMATIONS*. Internal forces develop as a result of the deformations.

Laboratory Specimen under Cyclic Deformation Loading

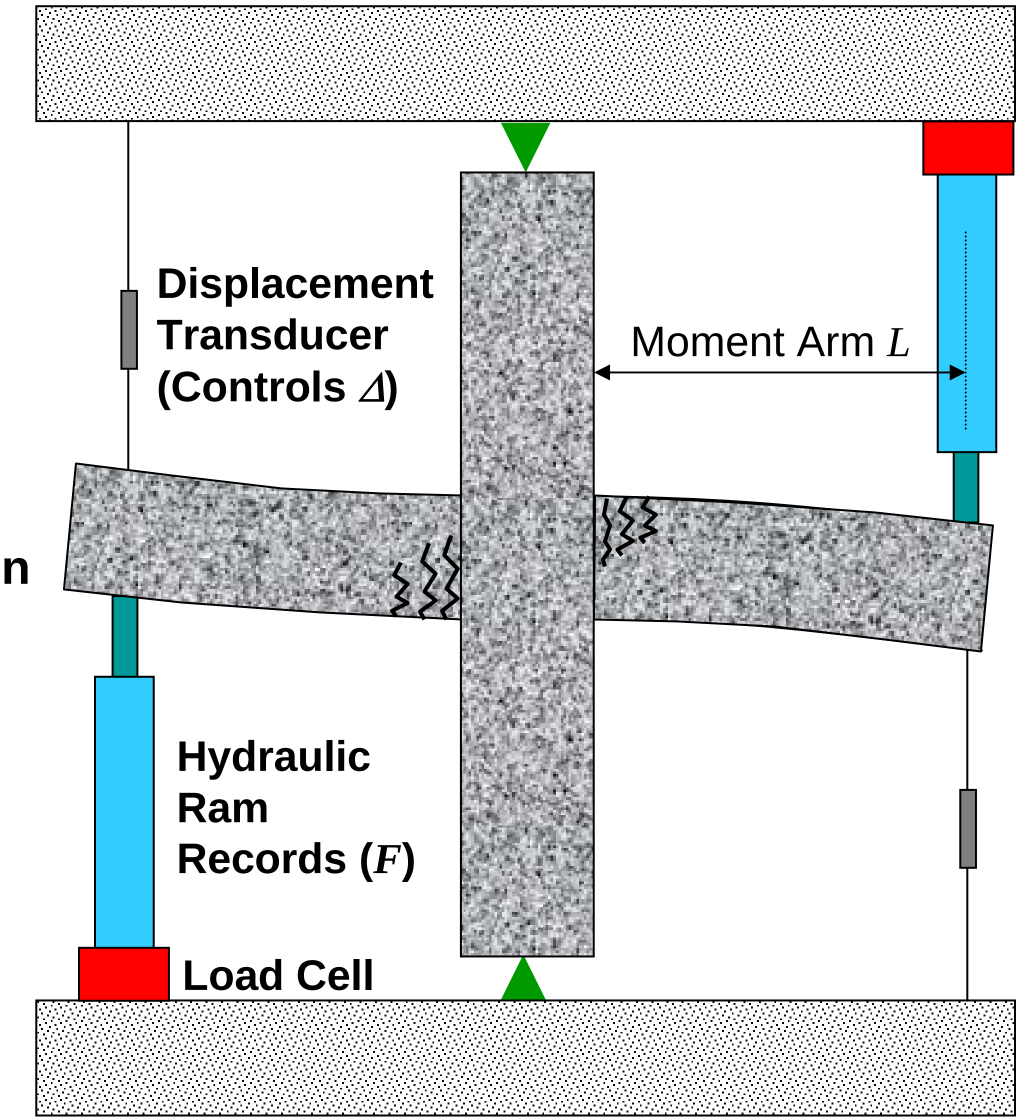


Deformations are cyclic, inelastic, and "reversed"

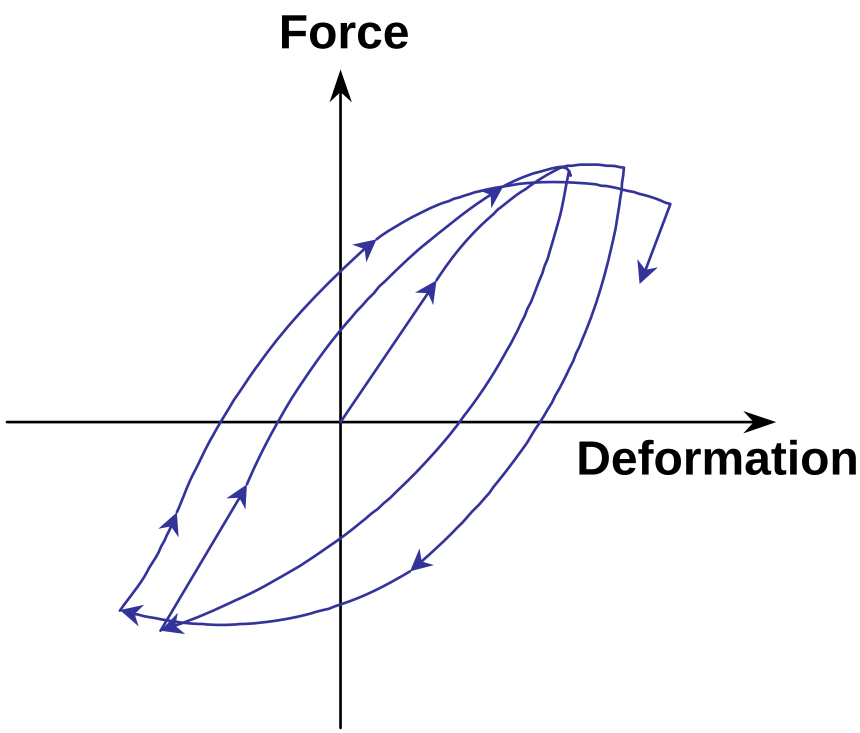
Laboratory Specimen Under Cyclic Deformation Loading



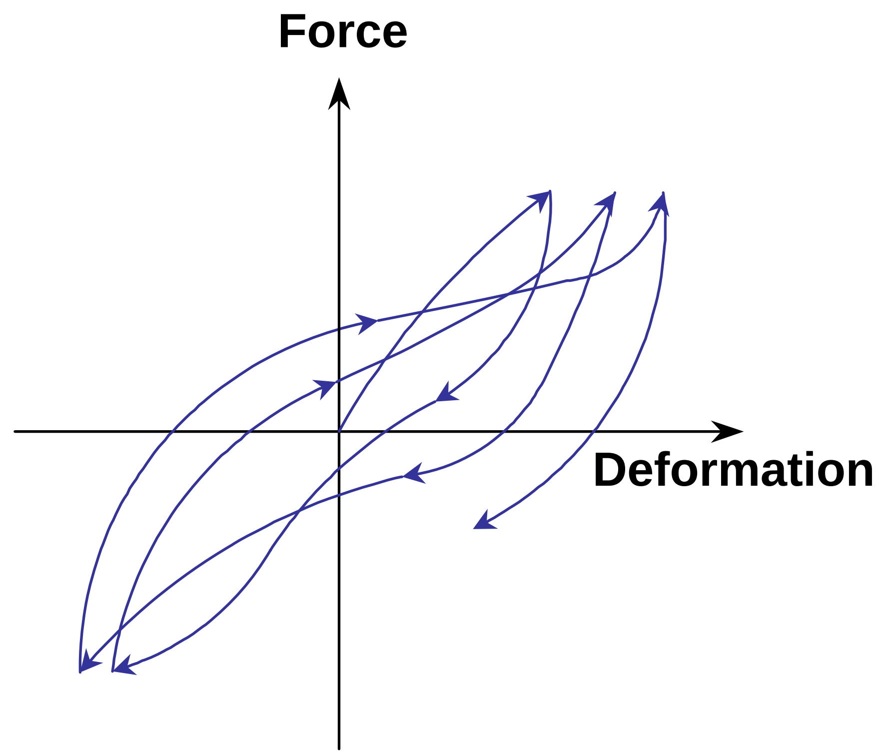
Measured Hysteretic Behavior



Hysteretic Behavior

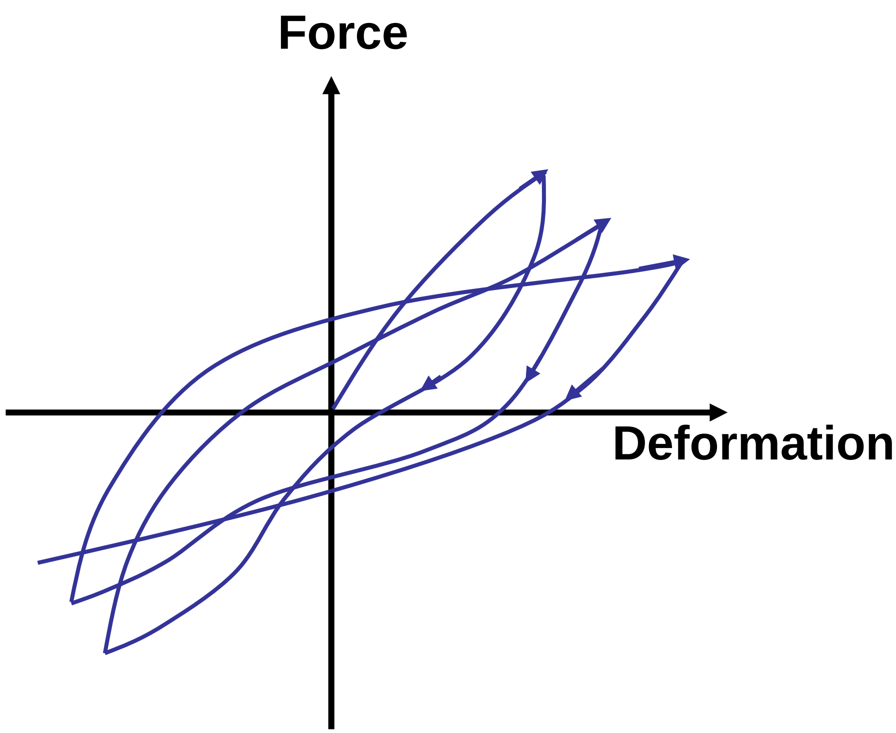


ROBUST
(Excellent)

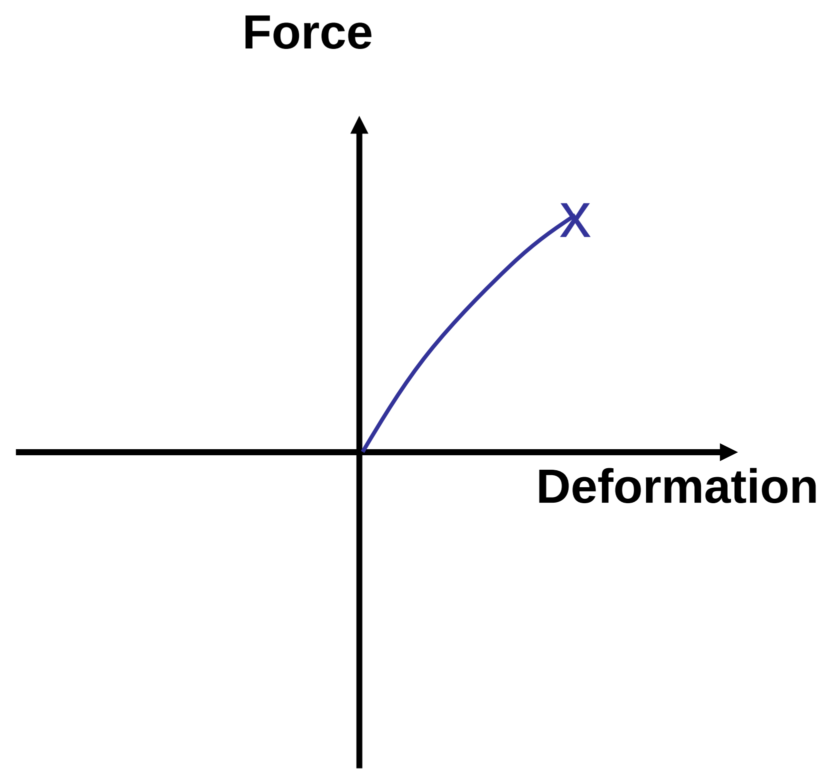


PINCHED
(Good)

Hysteretic Behavior



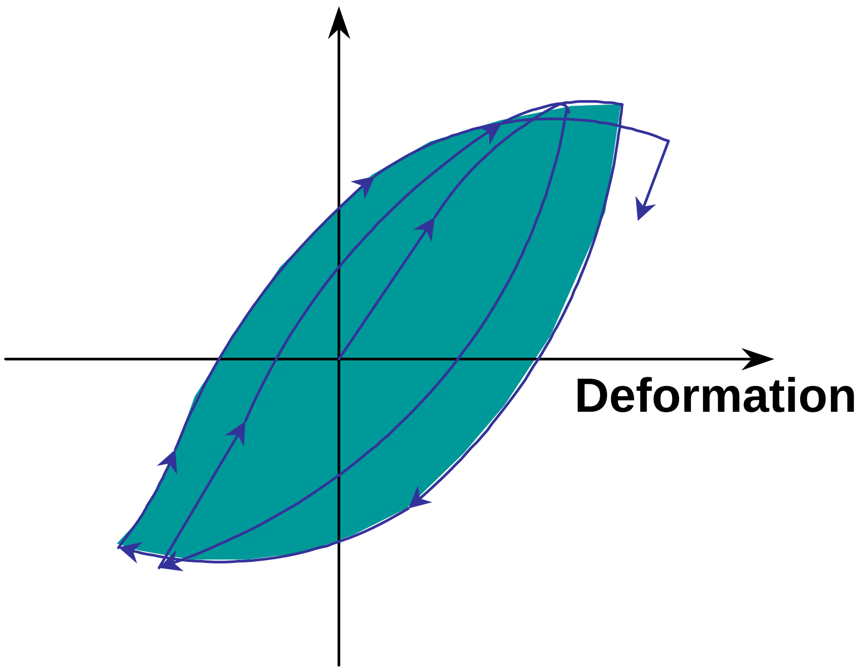
PINCHED (with strength loss)
Poor



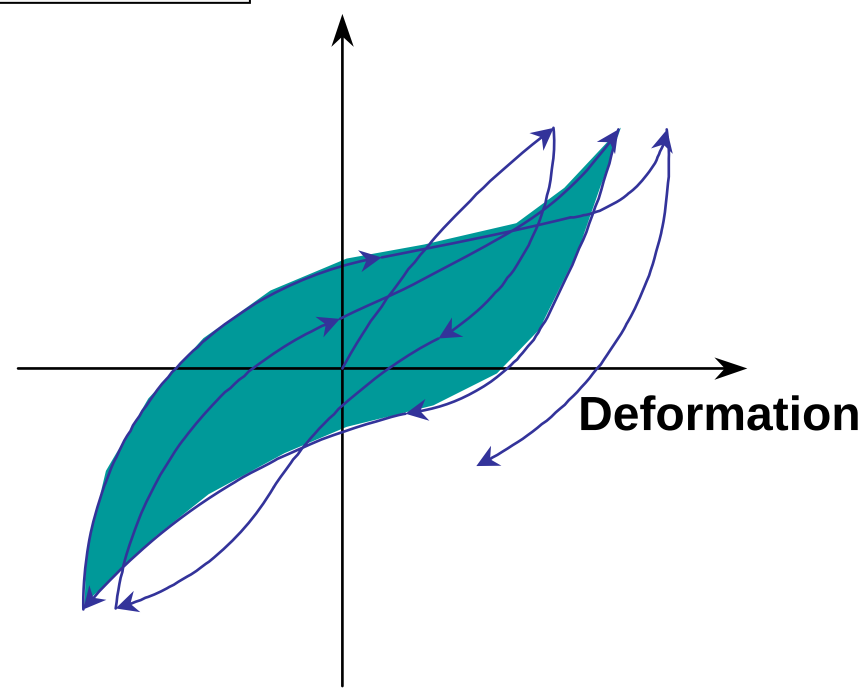
BRITTLE
Unacceptable

Hysteretic Behavior

AREA=
Energy Dissipated



ROBUST



PINCHED (No Strength Loss)

Ductility and Energy Dissipation Capacity

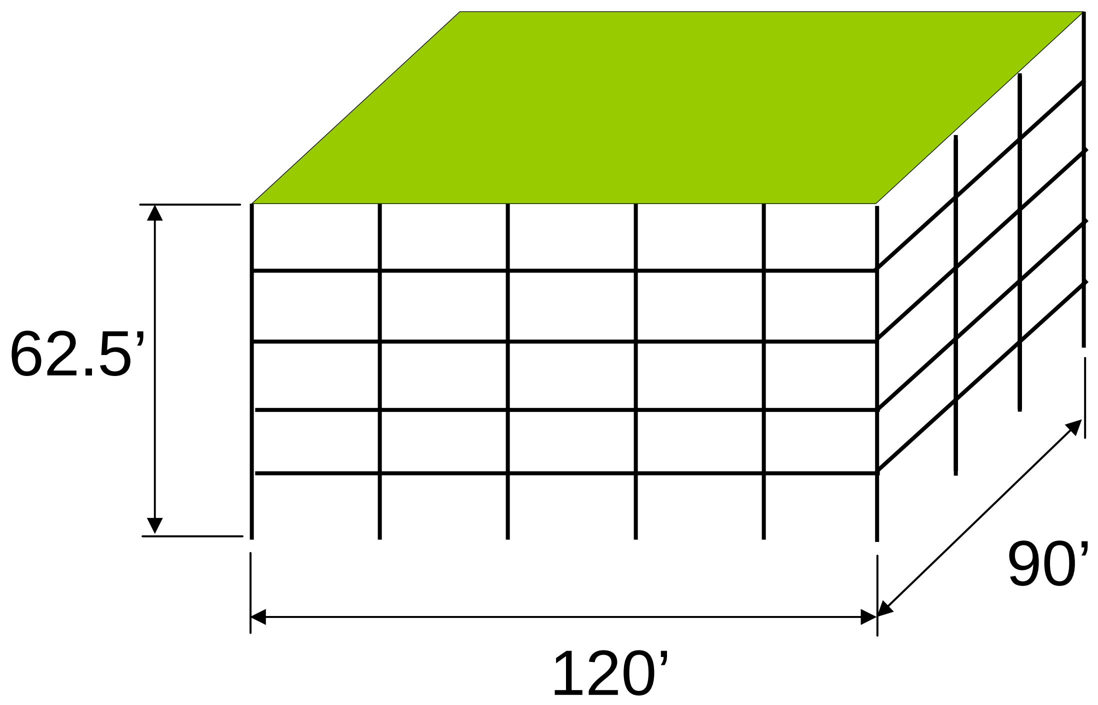
- The structure should be able to sustain several cycles of inelastic deformation without significant loss of strength.
- Some loss of stiffness is inevitable, but excessive stiffness loss can lead to collapse.
- The more energy dissipated per cycle without excessive deformation, the better the behavior of the structure.

Ductility and Energy Dissipation Capacity

- The art of seismic-resistant design is in the details.
- With good detailing, structures can be designed for force levels significantly lower than would be required for elastic response.

Why Is Inelastic Response Necessary?

Compare the Wind and Seismic Design of a Simple Building

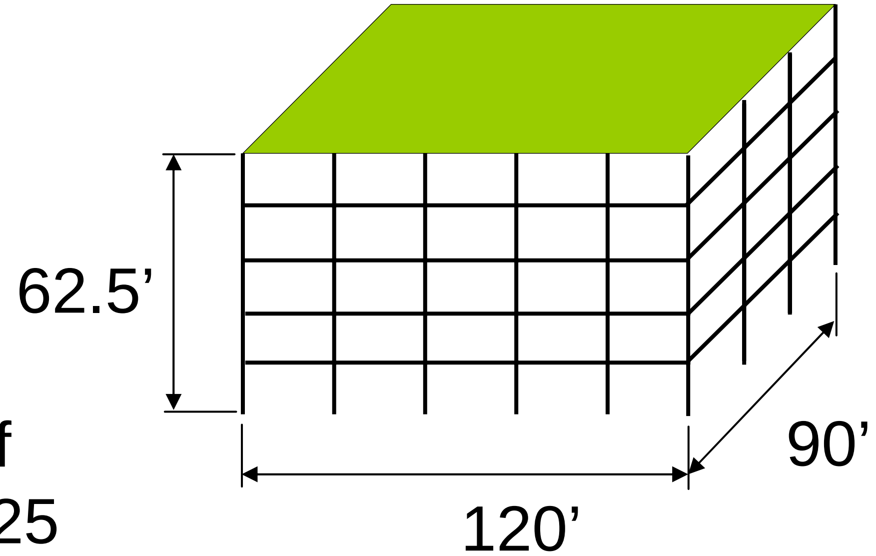


Building properties:
Moment resisting frames
Density ρ = 8 pcf
Period T = 1.0 sec
Damping ξ = 5%
Soil Site Class “B”

Wind:
100 mph Exposure C

Earthquake:
Assume S_{D1} = 0.48g

Wind:



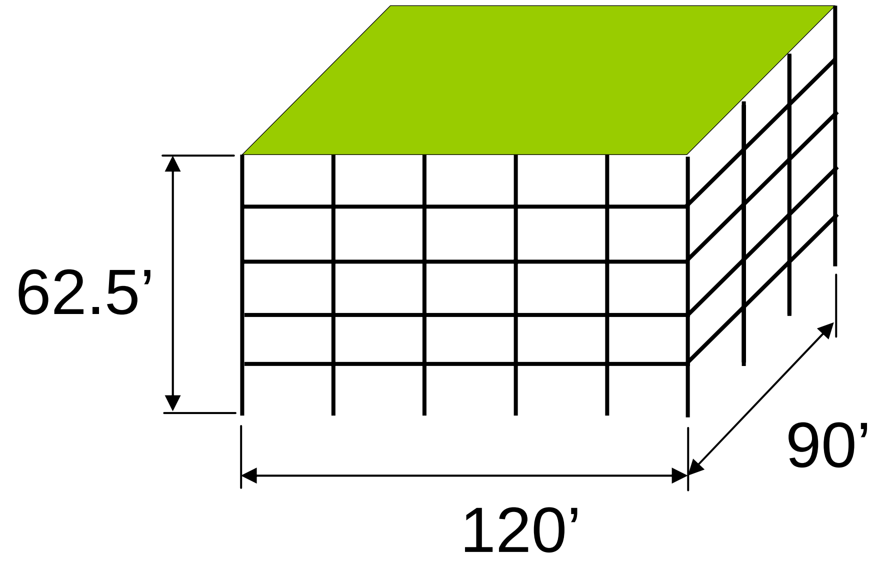
100 mph fastest
Exposure C

Velocity pressure q_s= 25.6 psf
Gust/exposure factor C_e = 1.25
Pressure coefficient C_q = 1.3
Load factor for wind = 1.3

Total wind force on 120-foot face:
V_{W120}= 62.5*120*25.6*1.25*1.3*1.3/1000 = **406 kips**

Total wind force on 90-foot face:
V_{W90} = 62.5*90*25.6*1.25*1.3*1.3/1000 = **304 kips**

Earthquake:



Building weight, W = 120*90*62.5*8/1000 = 5400 kips

$$V_{EQ} = C_S W$$

$$C_S = \frac{S_{D1}}{T(R/I)} = \frac{0.48}{1.0(1.0/1.0)} = 0.480$$

Total ***ELASTIC*** earthquake force (in each direction):
V_{EQ} = 0.480*5400 = **2592 kips**

Comparison: Earthquake vs. Wind

$$\frac{V_{EQ}}{V_{W120}} = \frac{2592}{406} = 6.4$$

$$\frac{V_{EQ}}{V_{W90}} = \frac{2592}{304} = 8.5$$

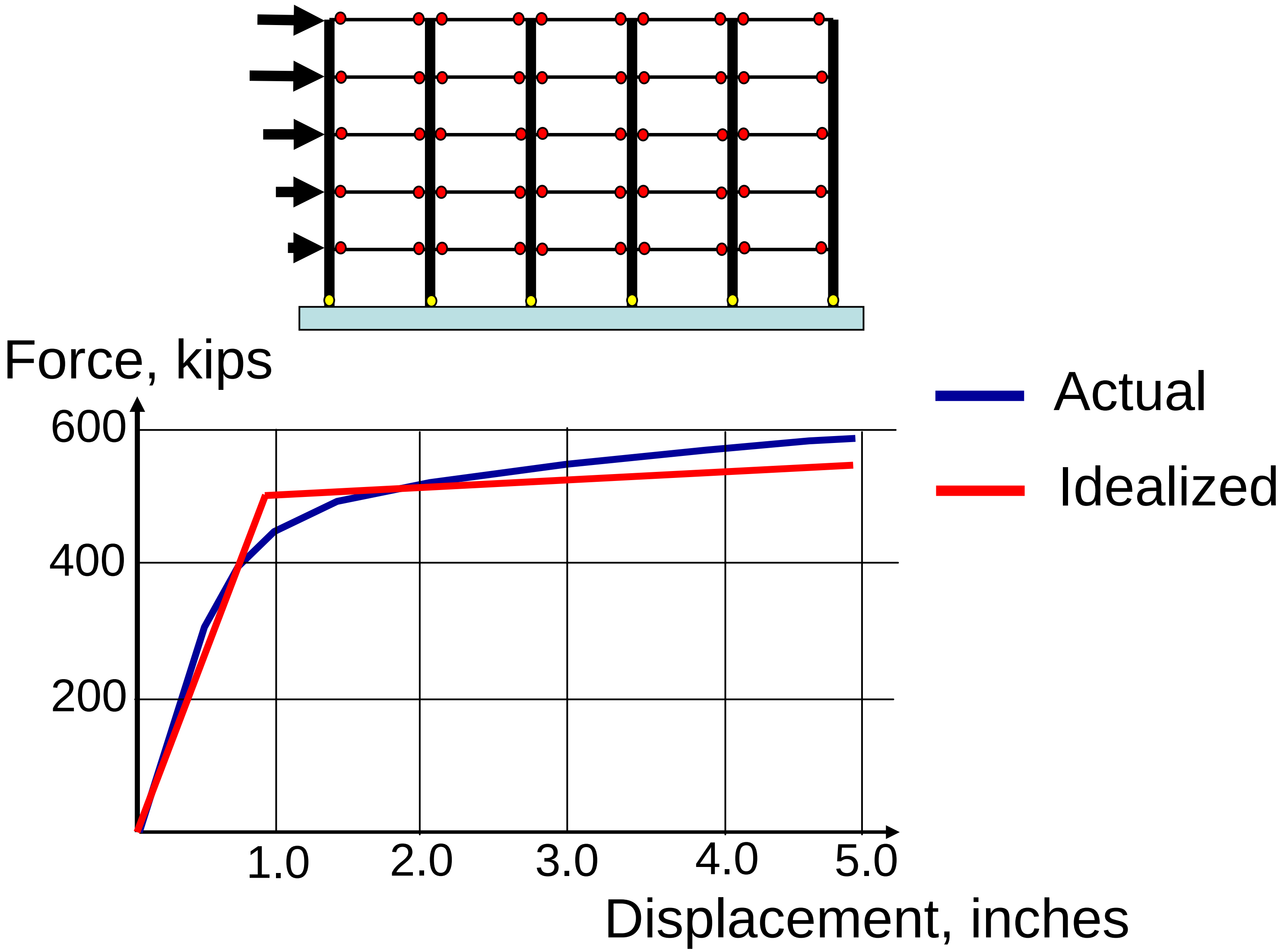
- ELASTIC earthquake forces 6 to 9 times wind!
- Virtually impossible to obtain economical design

How to Deal with Huge Earthquake Force?

- Isolate structure from ground (base isolation)
- Increase damping (passive energy dissipation)
- Allow controlled inelastic response

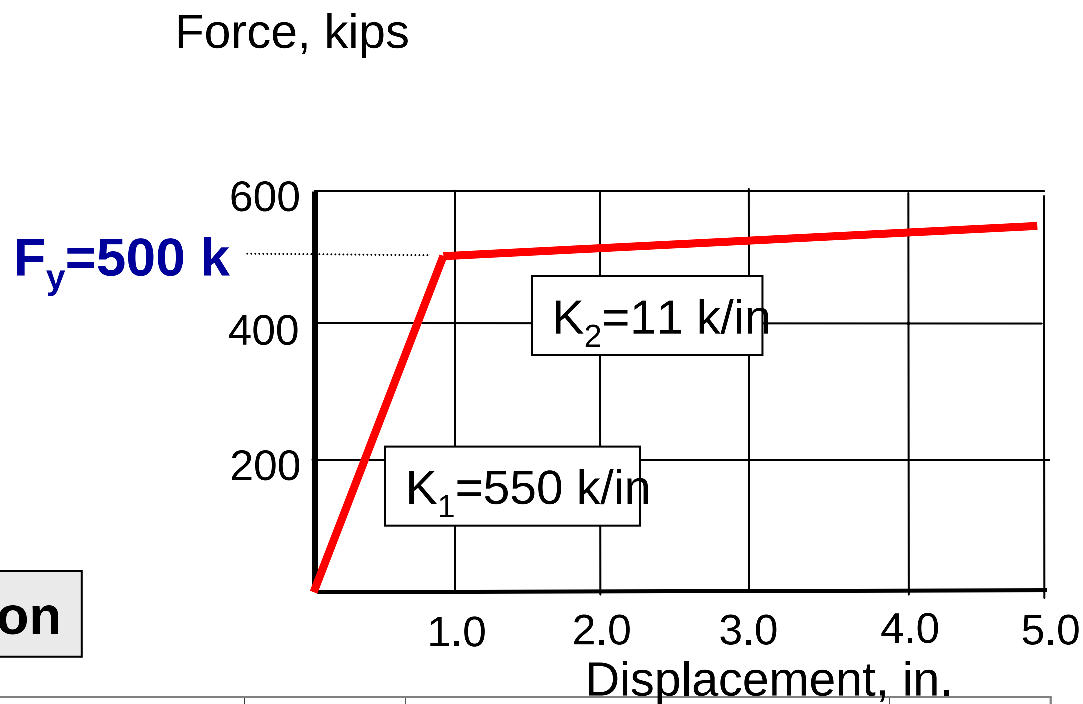
Historically, building codes use **inelastic response procedure**. Inelastic response occurs through structural **damage** (yielding). We must control the damage for the method to be successful.

Assume Frame Is Designed for Wind
"Pushover" Analysis Predicts Strength = 500 k

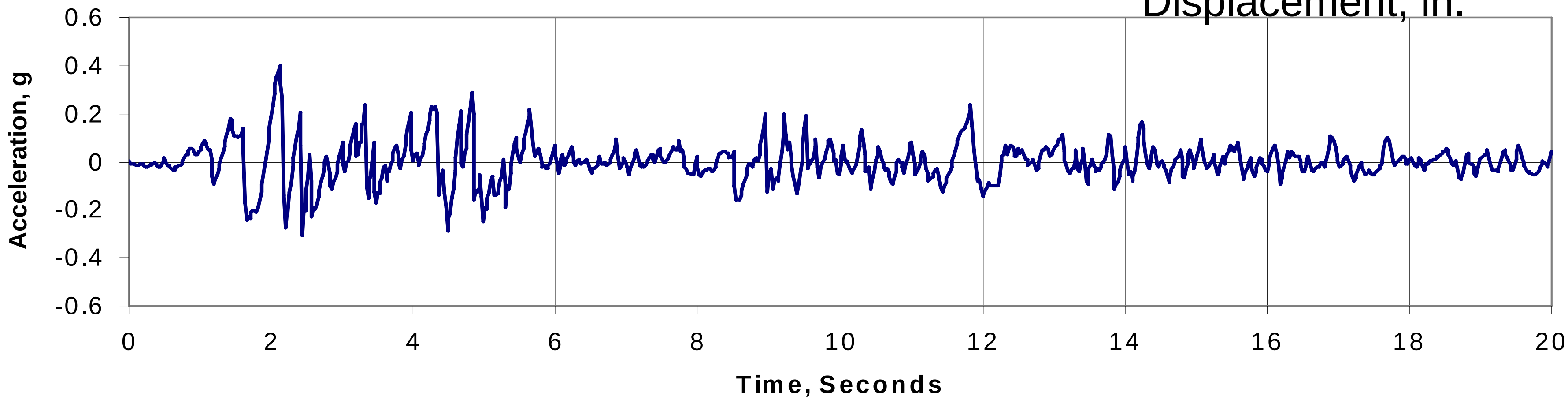


How Will Frame Respond During 0.4g El Centro Earthquake?

Idealized SDOF Model



El Centro Ground Motion



Response Computed by NONLIN

Maximum displacement:

4.79”

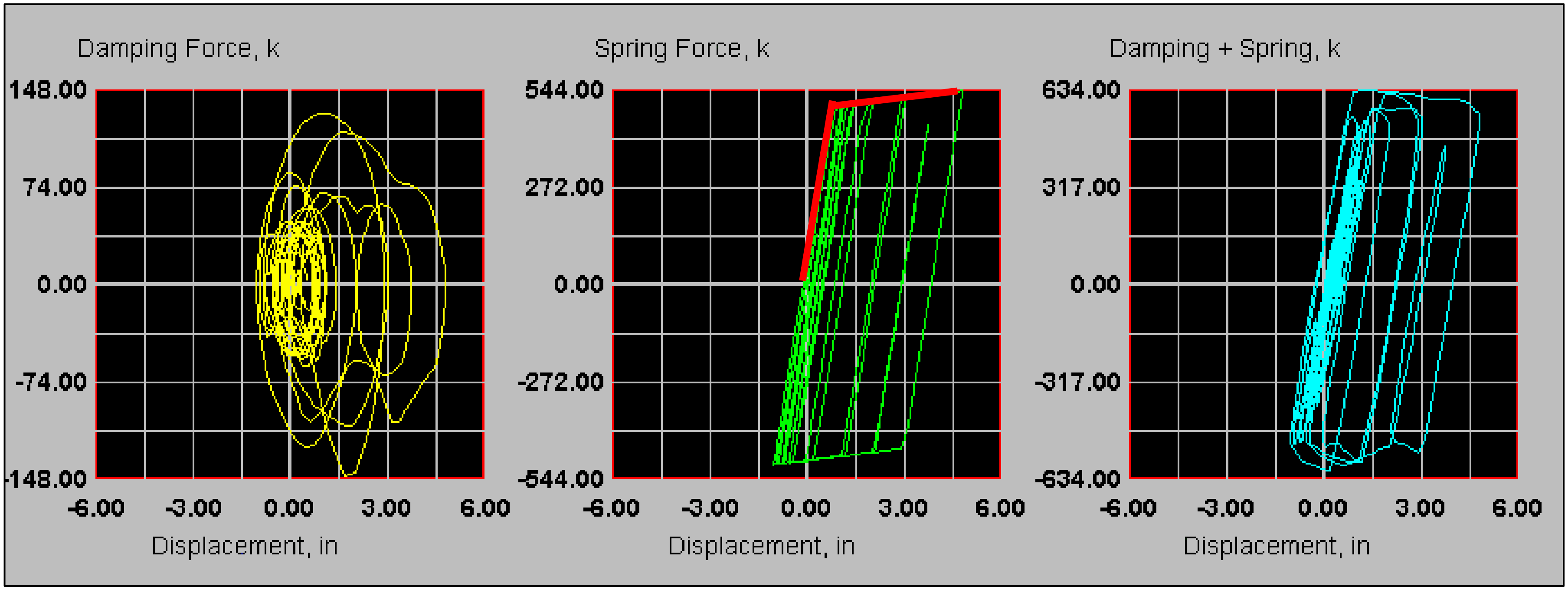
Maximum shear force:

542 k

Number of yield events:

15

Response Computed by NONLIN



Yield displacement = 500/550 = 0.91 inch

Ductility Demand $\equiv \dfrac{\text{Maximum Displacement}}{\text{Yield Displacement}} = \dfrac{4.79}{0.91} = 5.26$

Interim Conclusion (The Good News)

The frame, designed for a wind force that is 15% of the ELASTIC earthquake force, can survive the earthquake if:

- It has the capability to undergo ***numerous cycles of INELASTIC deformation.***
- It has the capability to ***deform at least 5 to 6 times the yield deformation.***
- It suffers ***no appreciable loss of strength.***

REQUIRES ADEQUATE DETAILING

Interim Conclusion (The Bad News)

As a result of the large displacements associated with the inelastic deformations, <u>the structure will suffer considerable structural and nonstructural damage</u>.

- This damage must be controlled by adequate detailing and by limiting structural deformations (drift).

Development of "Equal Displacement" Concept of Seismic Resistant Design

Concept used by:

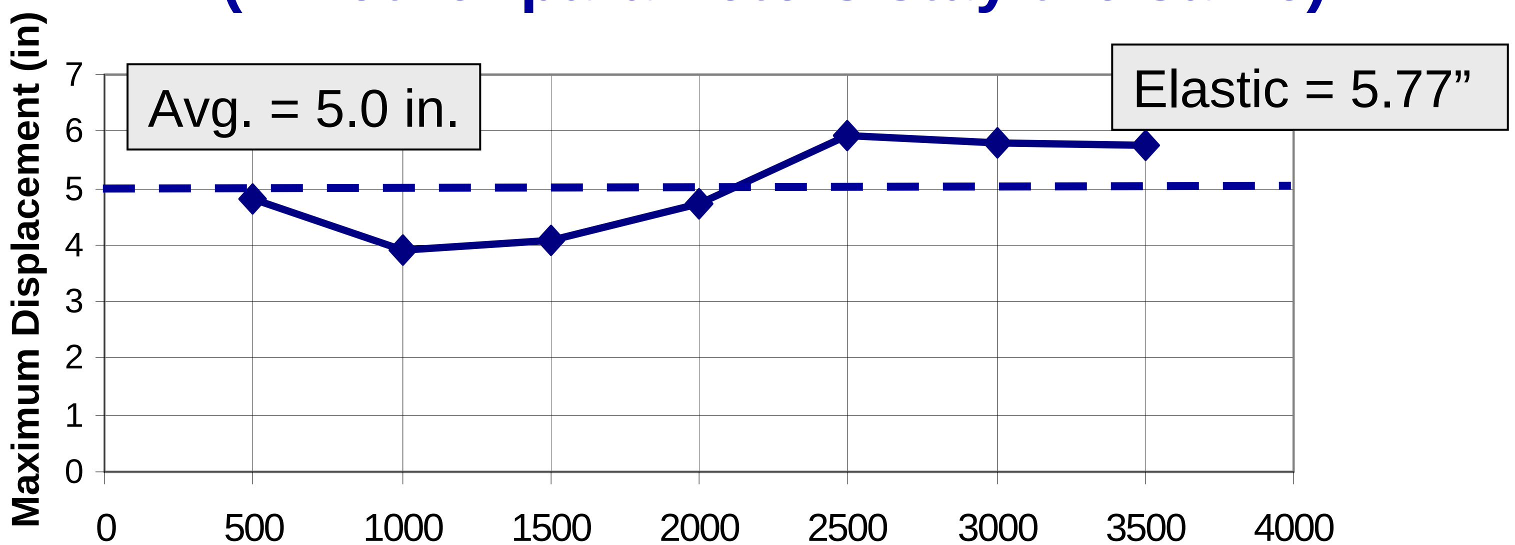
IBC NEHRP ASCE-7	In association with "force based" design concept. Used to predict design forces and displacements
FEMA 273	In association with static pushover analysis. Used to predict displacements at various performance points.

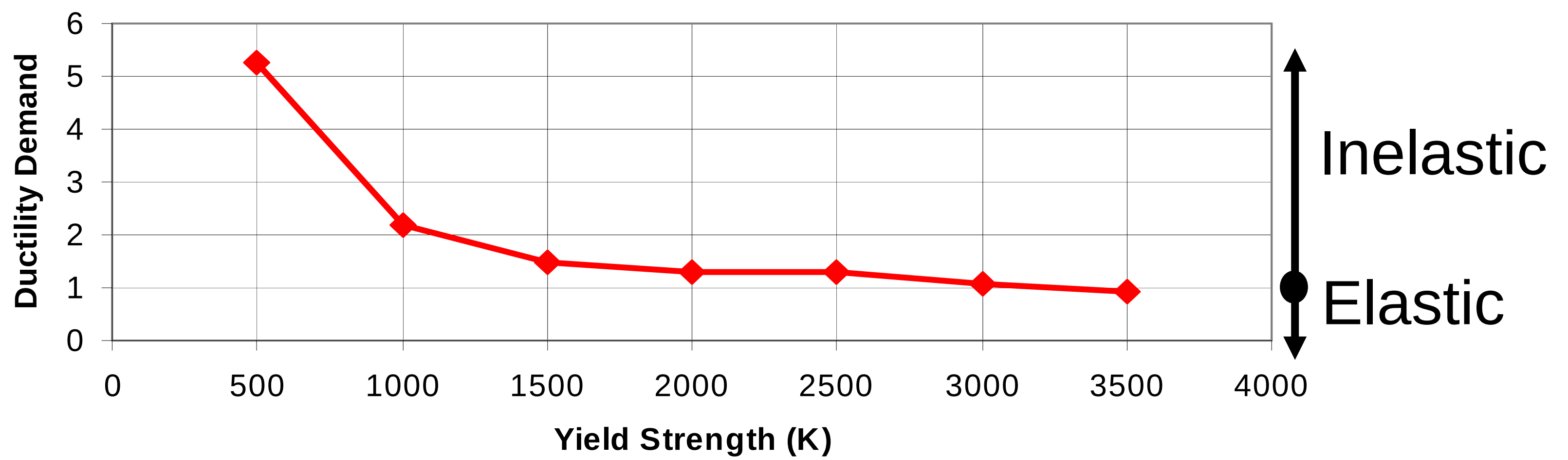
The Equal Displacement Concept

"The displacement of an inelastic system, with stiffness K and strength F_y, subjected to a particular ground motion, is approximately equal to the displacement of the same system responding elastically."

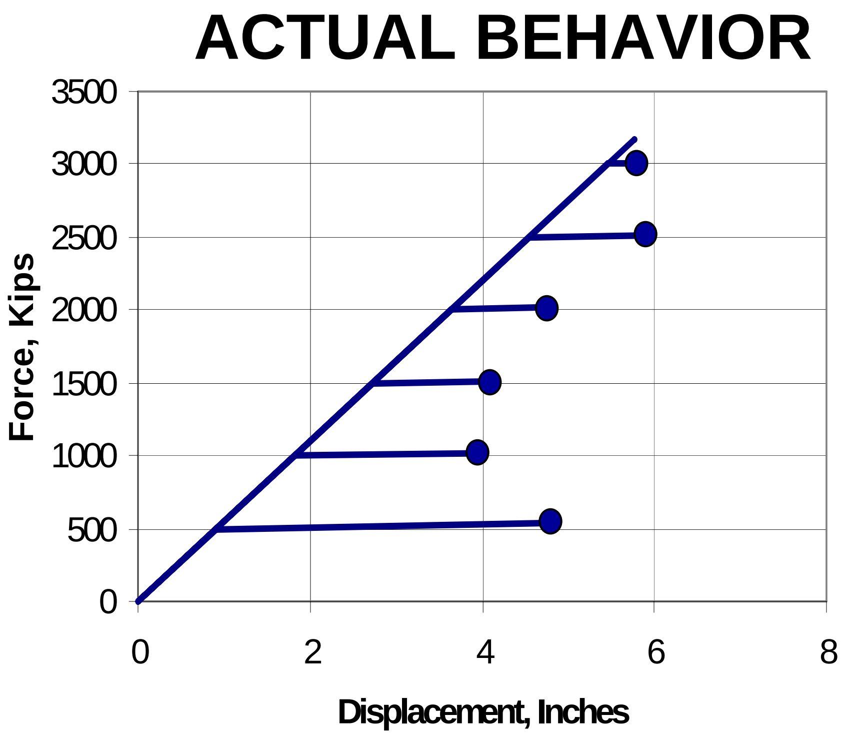
(The displacement of a system is independent of the yield strength of the system.)

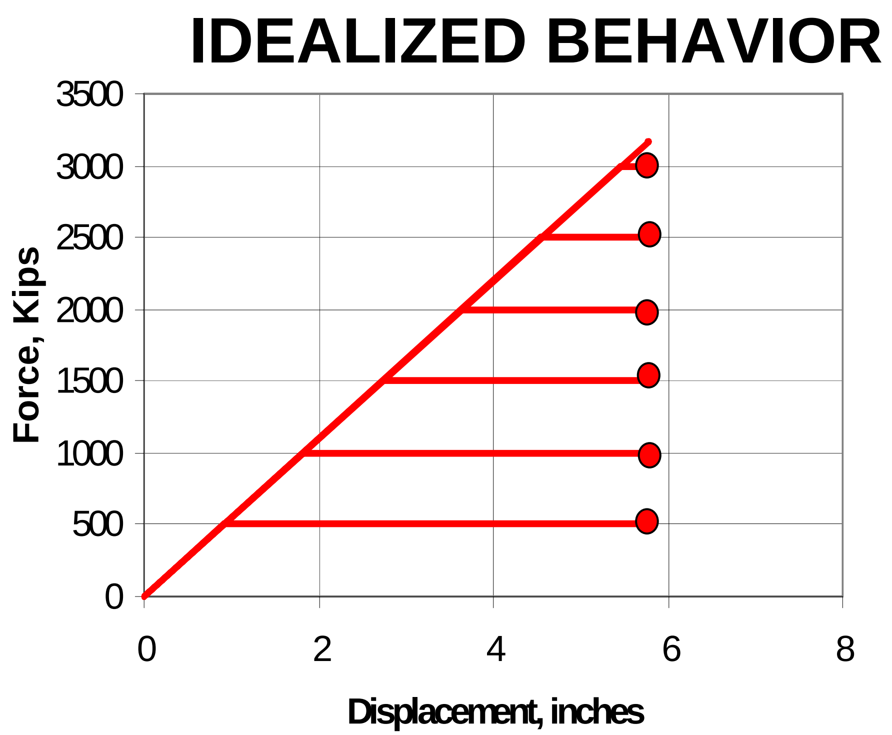
Repeat Analysis for Various Yield Strengths (All other parameters stay the same)





Constant Displacement Idealization of Inelastic Response

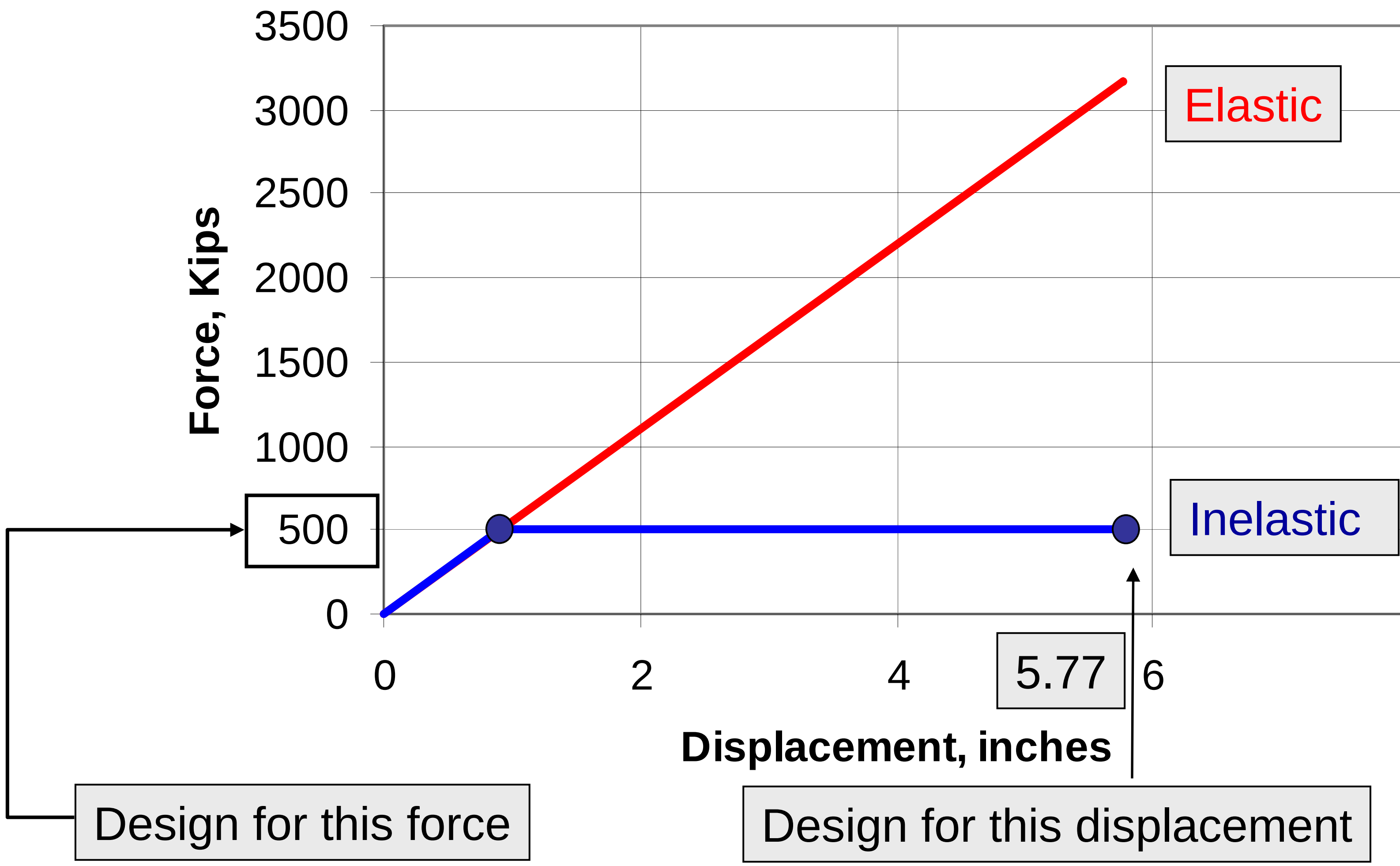




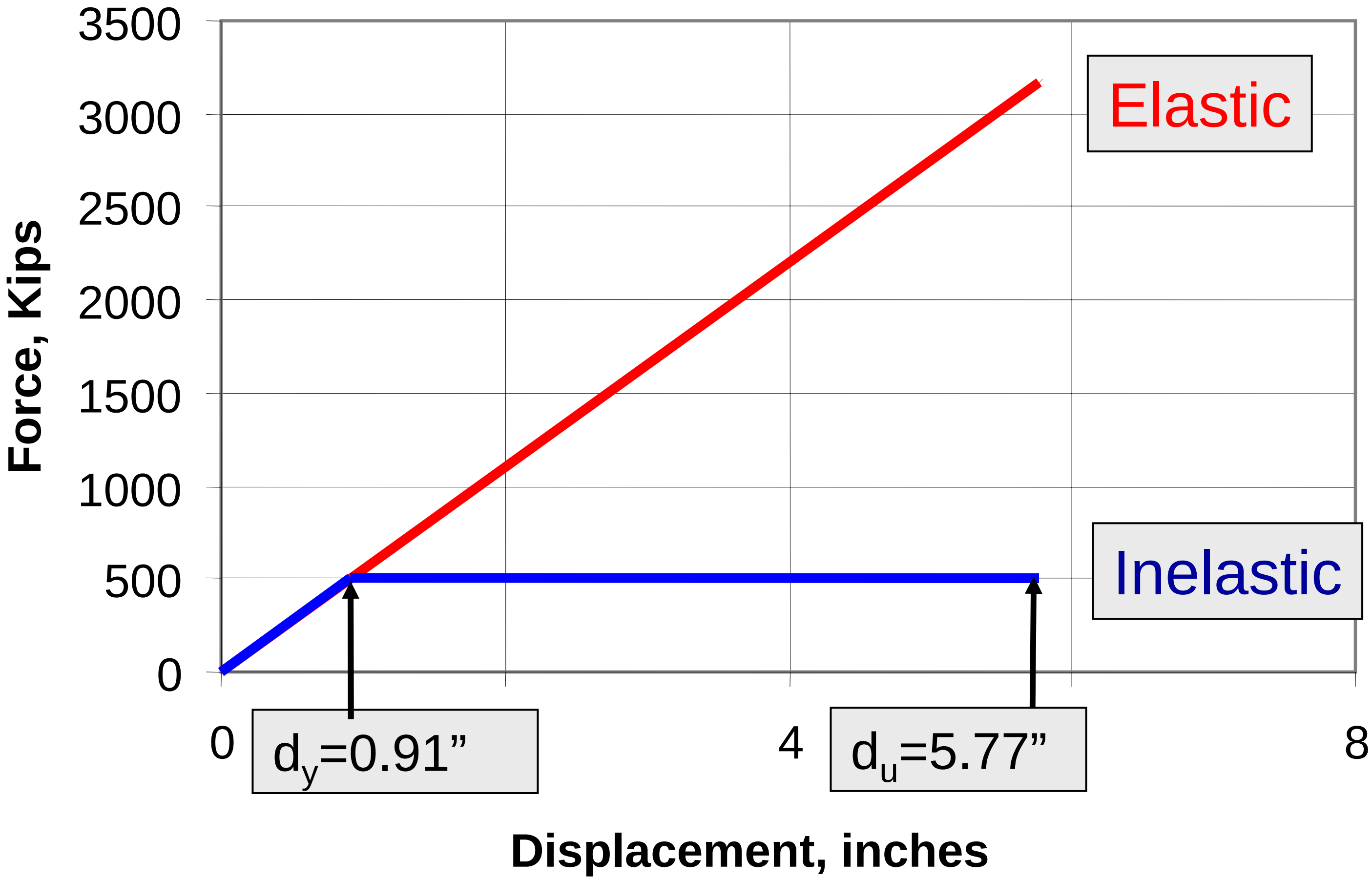
Equal Displacement Idealization of Inelastic Response

- For design purposes, it may be assumed that inelastic displacements are equal to the displacements that would occur during an elastic response.
- The required force levels under inelastic response are much less than the force levels required for elastic response.

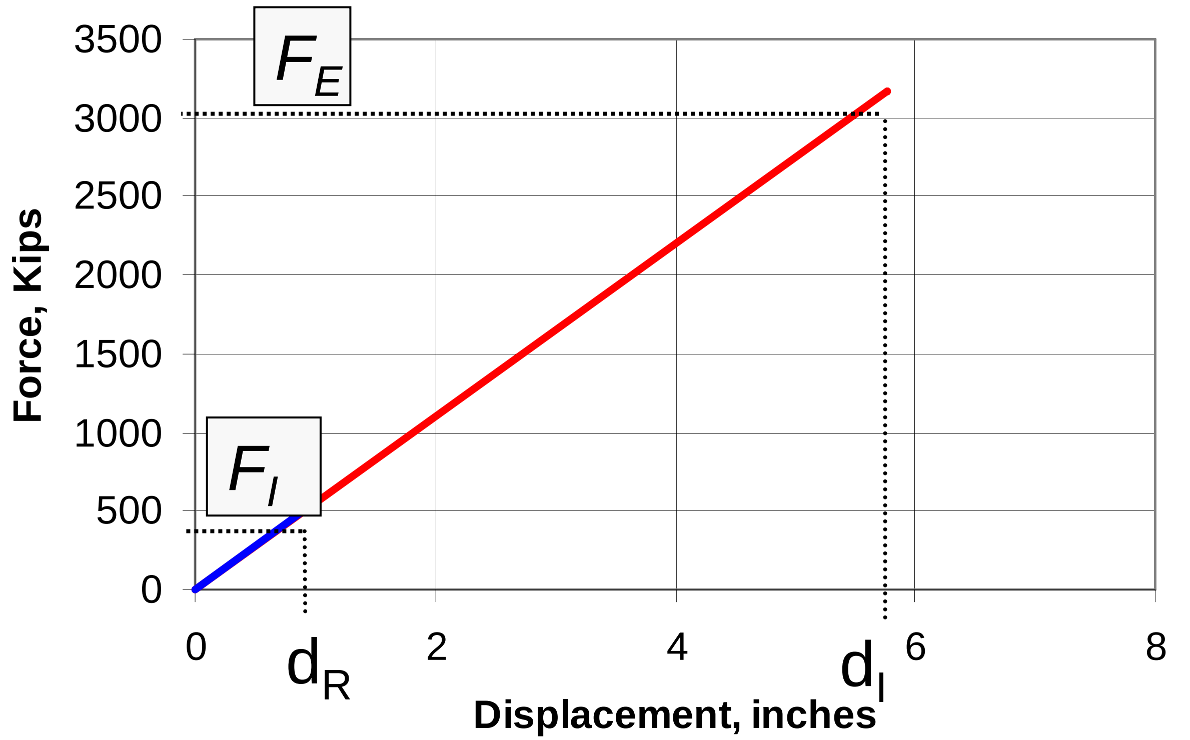
Equal Displacement Concept of Inelastic Design



Equal Displacement Concept of Inelastic Design



Ductility supply MUST BE > ductility demand = $\frac{5.77}{0.91} = 6.34$



Using response spectra, estimate **elastic** force demand $\boldsymbol{F_E}$

Estimate ductility supply, μ, and determine **inelastic** force demand $\boldsymbol{F_I = F_E/\mu}$.. **Design structure for $\boldsymbol{F_{I.}}$**

Compute reduced displacement. $\boldsymbol{d_R}$, and multiply by μ to obtain true inelastic eisplacement, $\boldsymbol{d_{I.}}$ **Check drift using $\boldsymbol{d_{i.}}$**

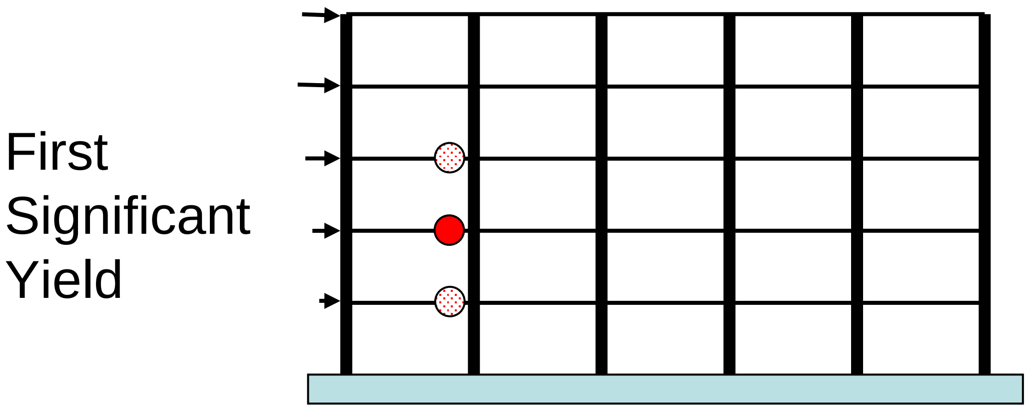
ASCE 7 Approach

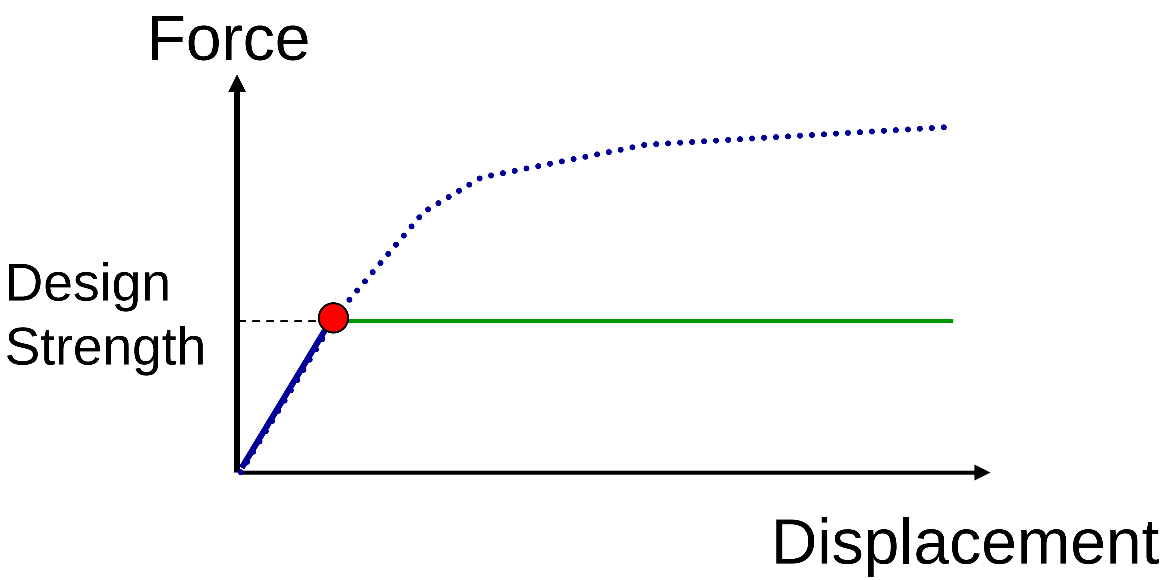
Use basic elastic spectrum but, for strength, divide all pseudoacceleration values by ***R***, a response modification factor that accounts for:

- Anticipated ductility supply
- Overstrength
- Damping (if different than 5% critical)
- Past performance of similar systems
- Redundancy

Ductility/Overstrength

FIRST SIGNIFICANT YIELD

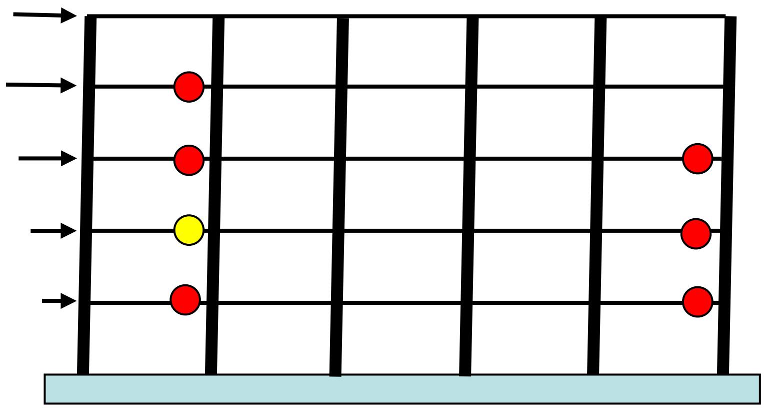


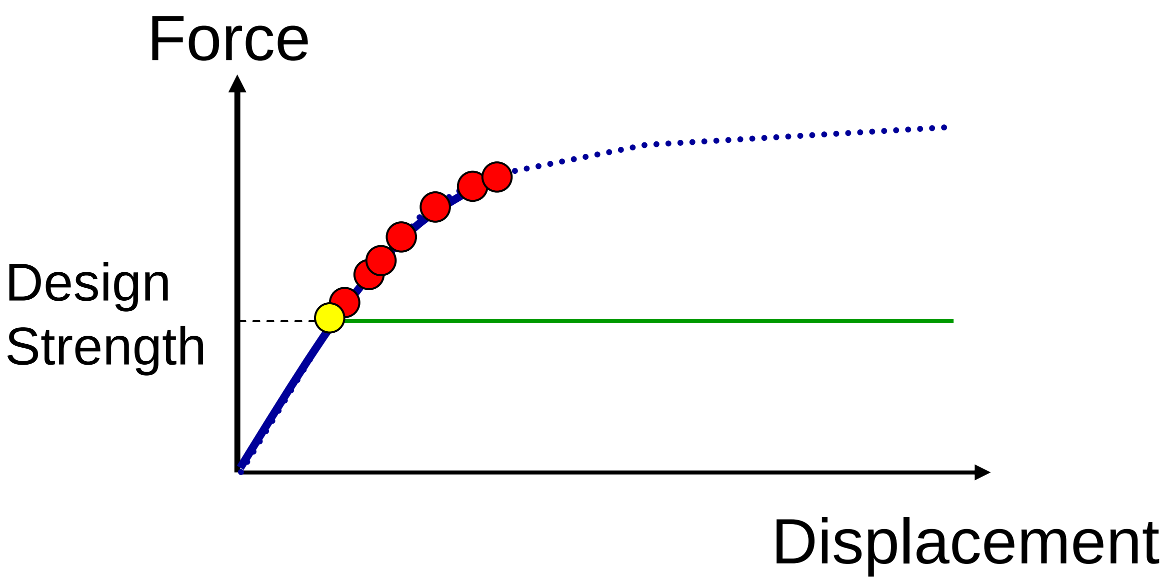


First Significant Yield is the level of force that causes complete plastification of at least the most critical region of the structure (e.g., formation of the first plastic hinge).

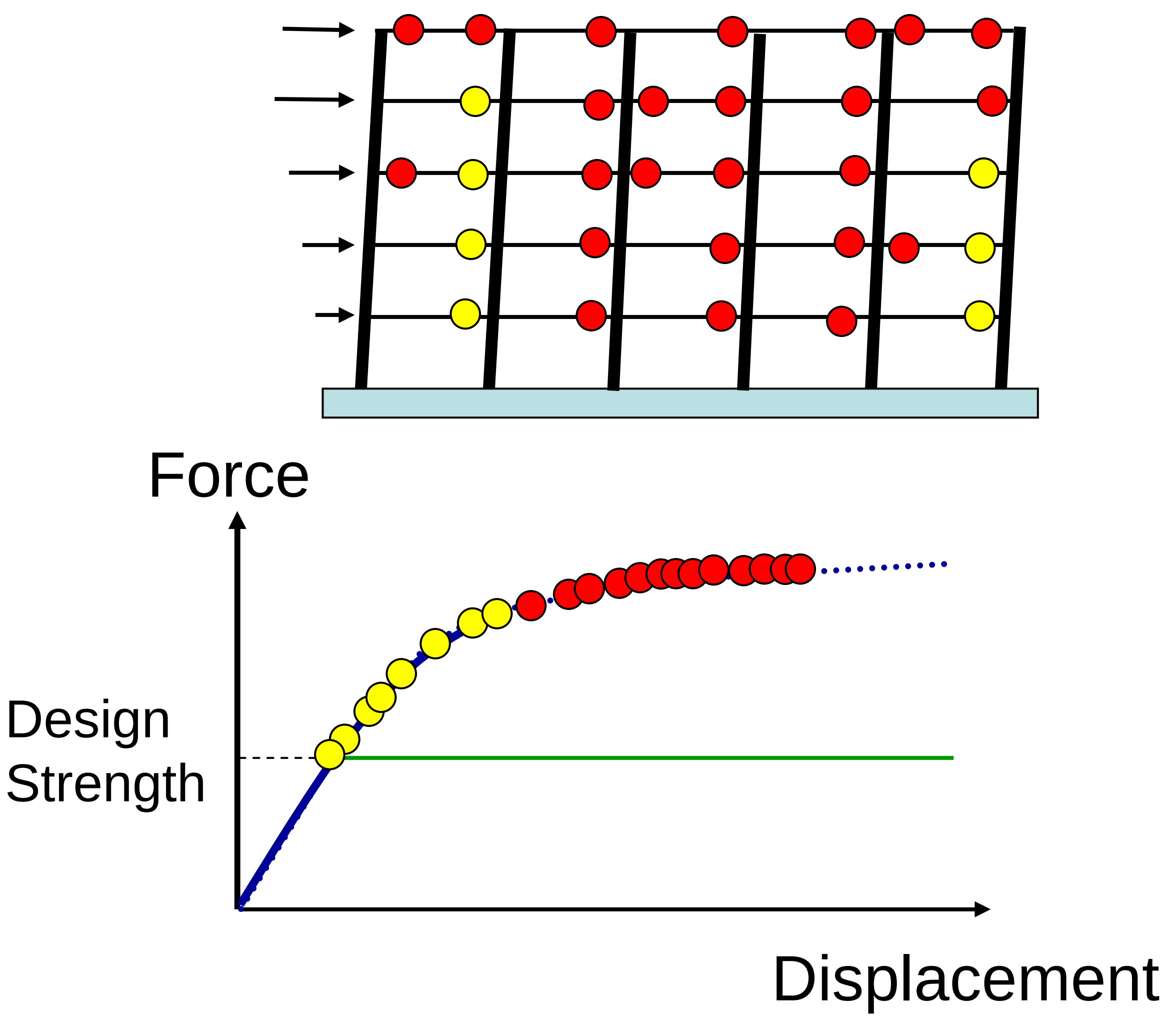
The **design strength** of a structure is equal to the resistance at first significant yield.

Overstrength (1)

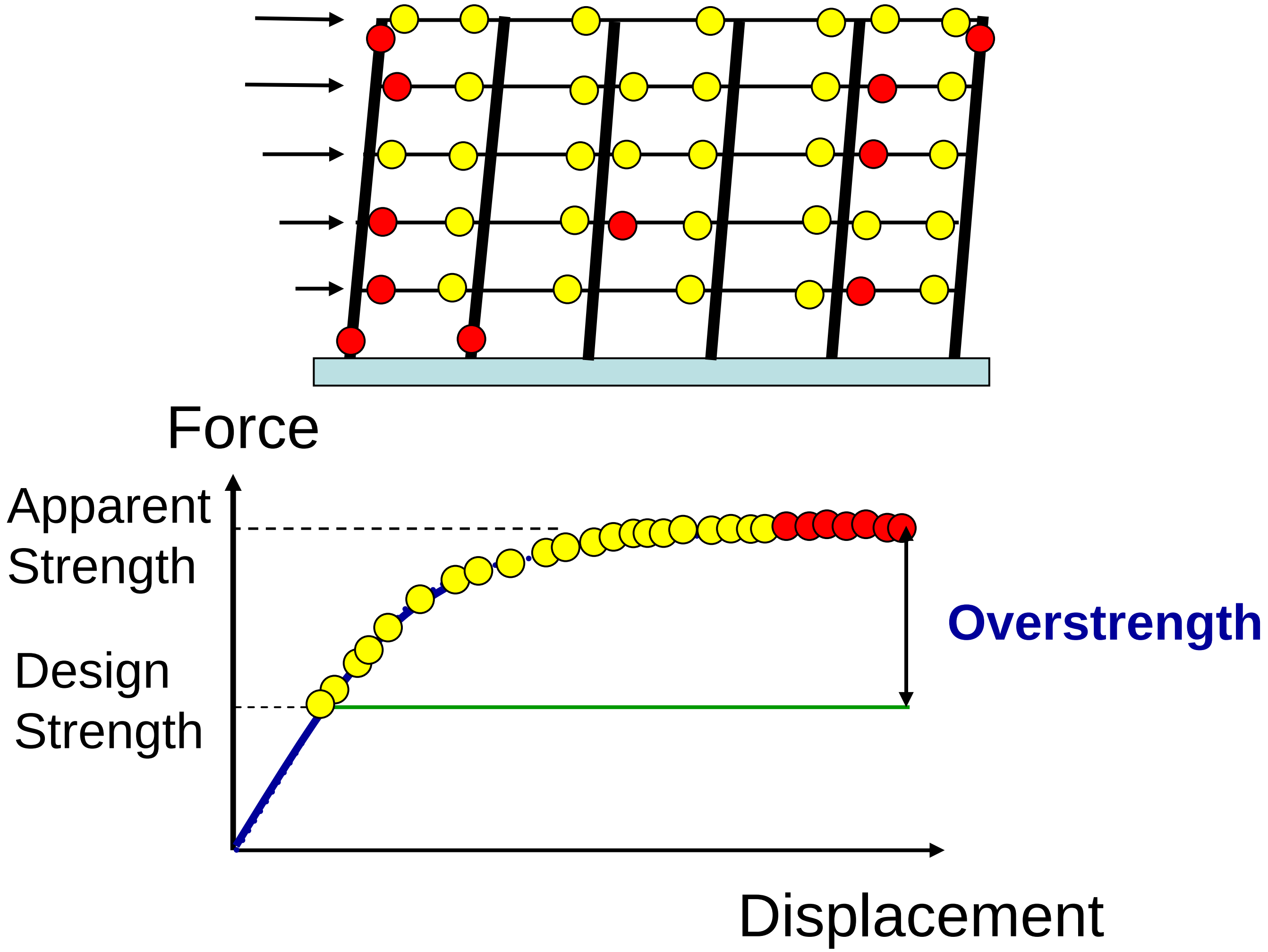




Overstrength (2)



Overstrength (3)

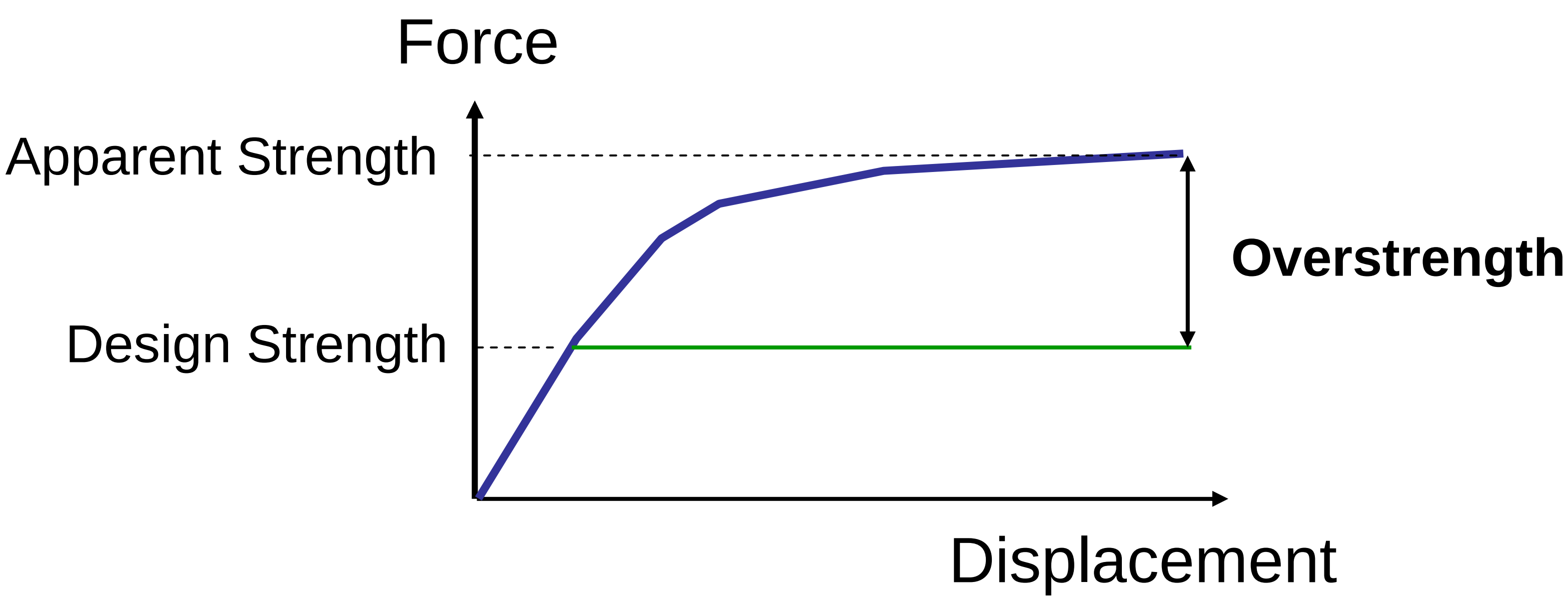


Sources of Overstrength

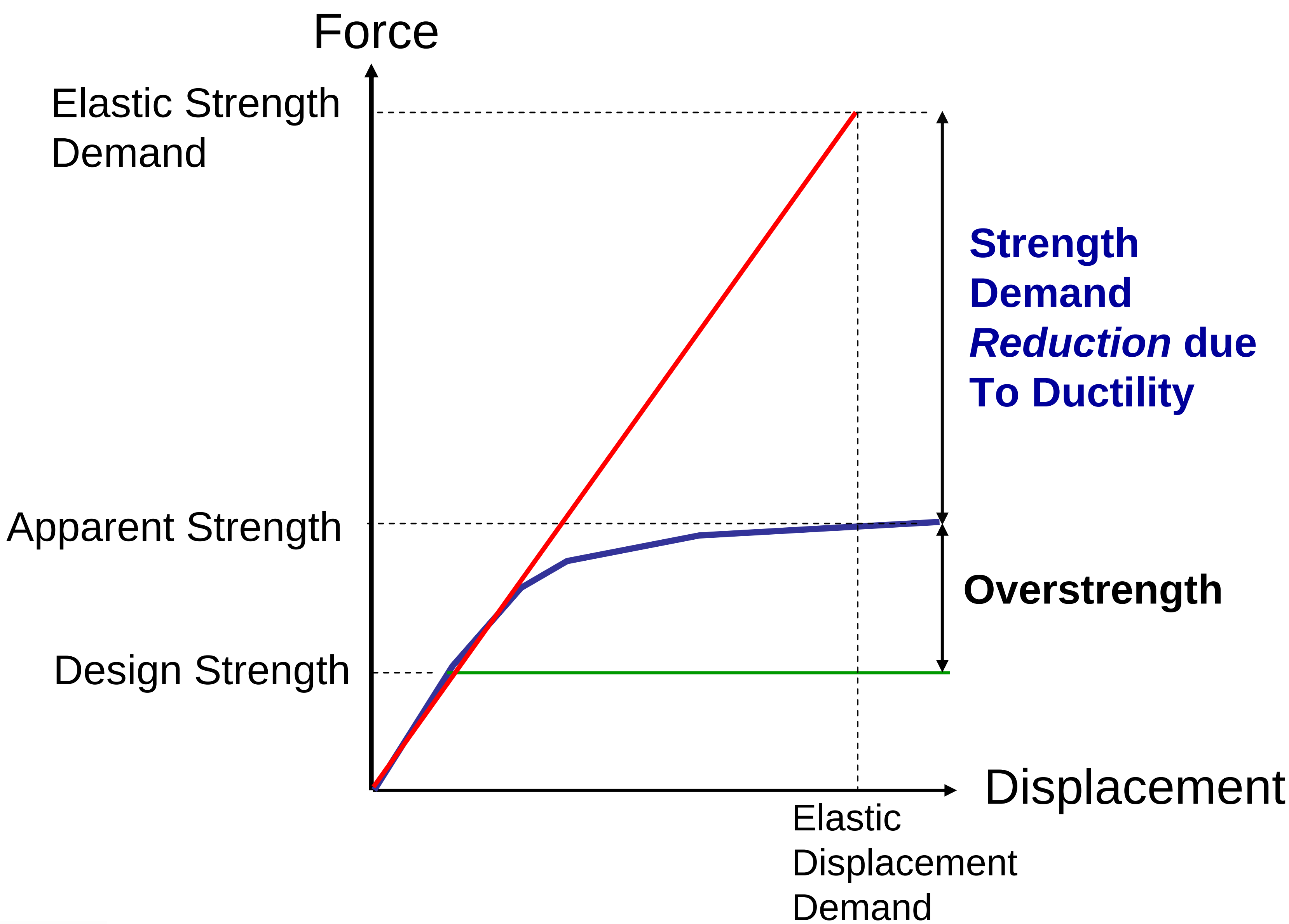
- Sequential yielding of critical regions
- Material overstrength (actual vs specified yield)
- Strain hardening
- Capacity reduction (ϕ) factors
- Member selection

Definition of Overstrength Factor Ω

$$\text{Overstrength Factor } \Omega = \frac{\text{Apparent Strength}}{\text{Design Strength}}$$

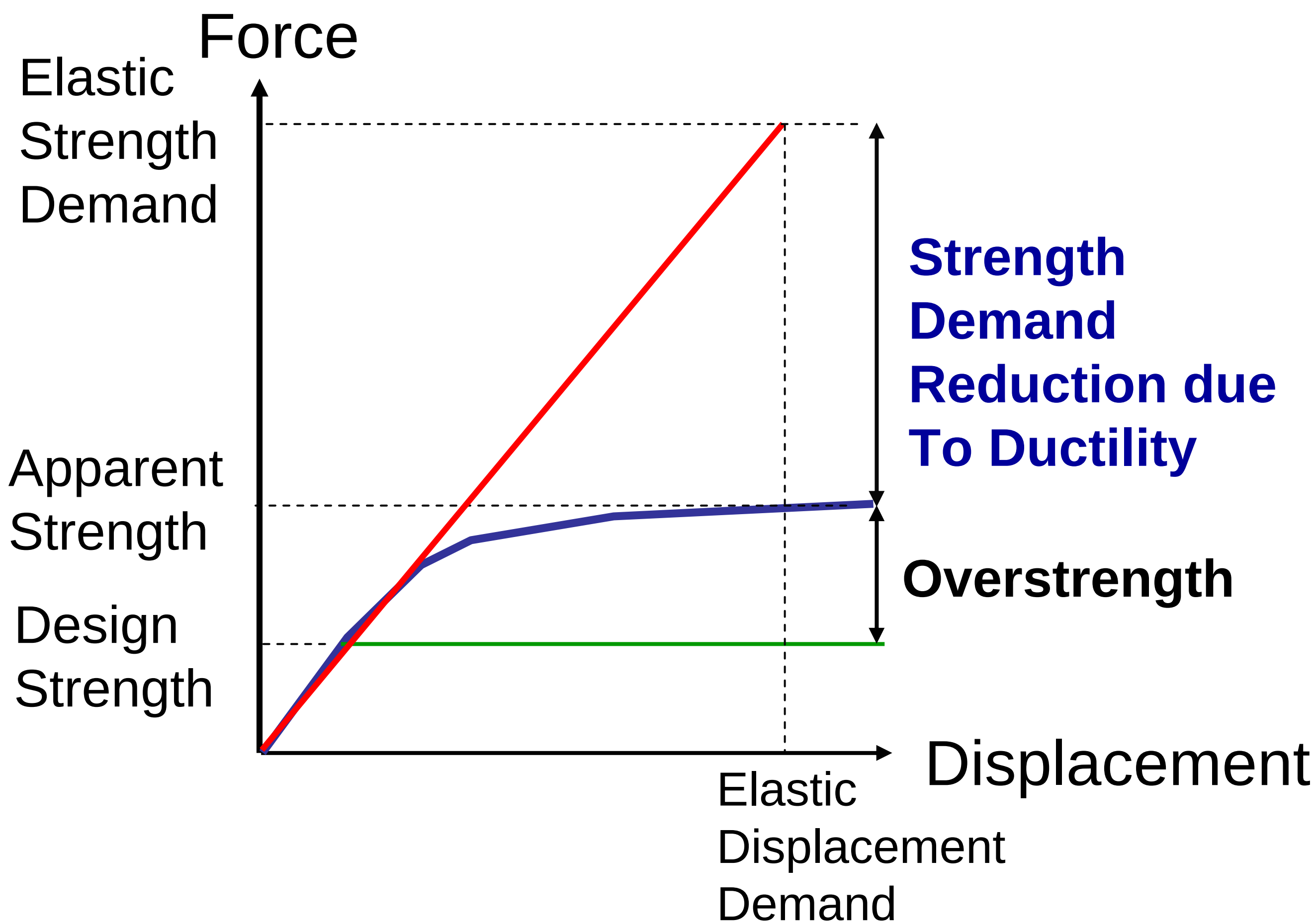


Definition of Ductility Reduction Factor R_d



Definition of Ductility Reduction Factor

$$\text{Ductility Reduction } R_d = \frac{\text{Elastic Strength Demand}}{\text{Apparent Strength}}$$



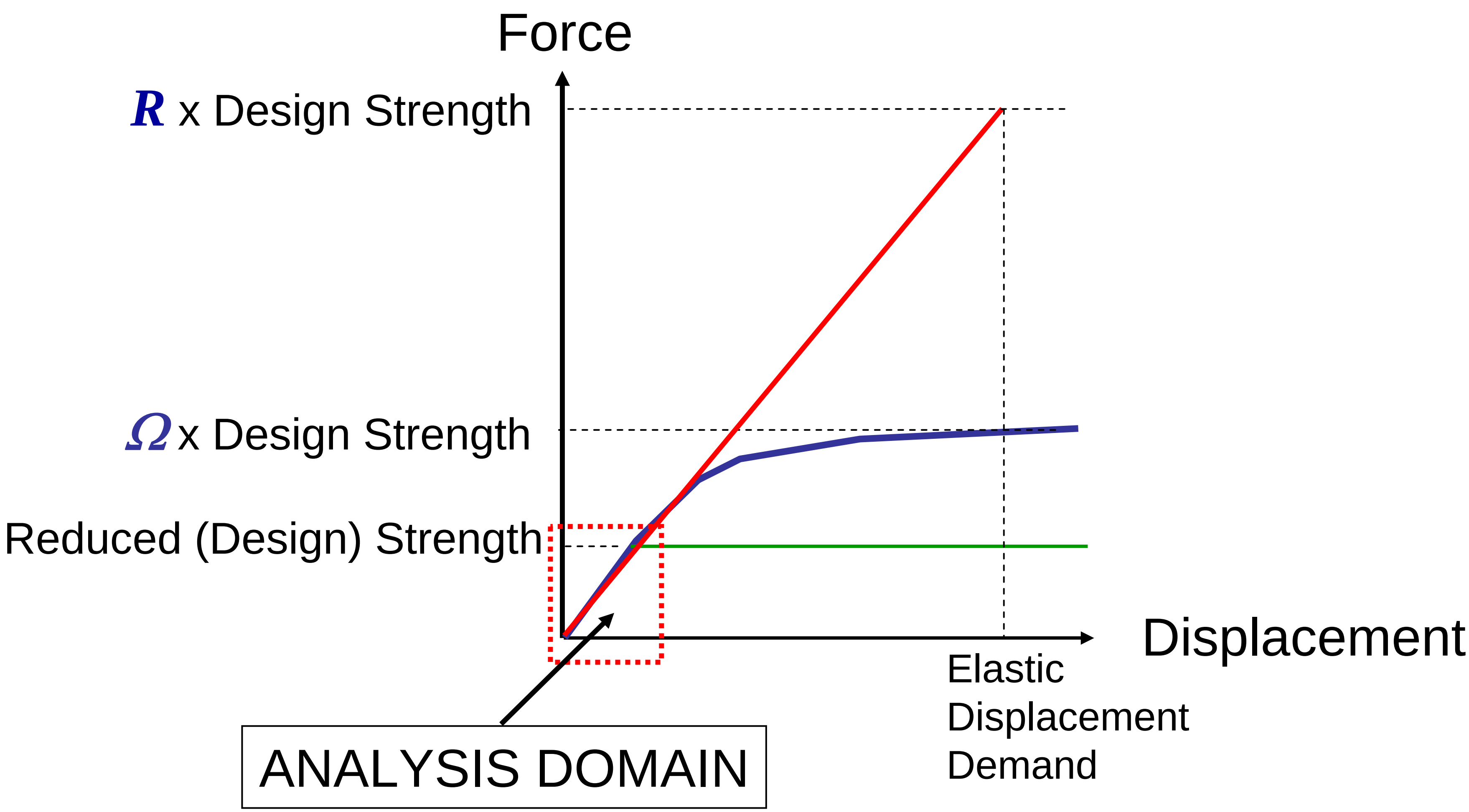
Definition of Response Modification Coefficient R

$$\text{Overstrength Factor } \Omega = \frac{\text{Apparent Strength}}{\text{Design Strength}}$$

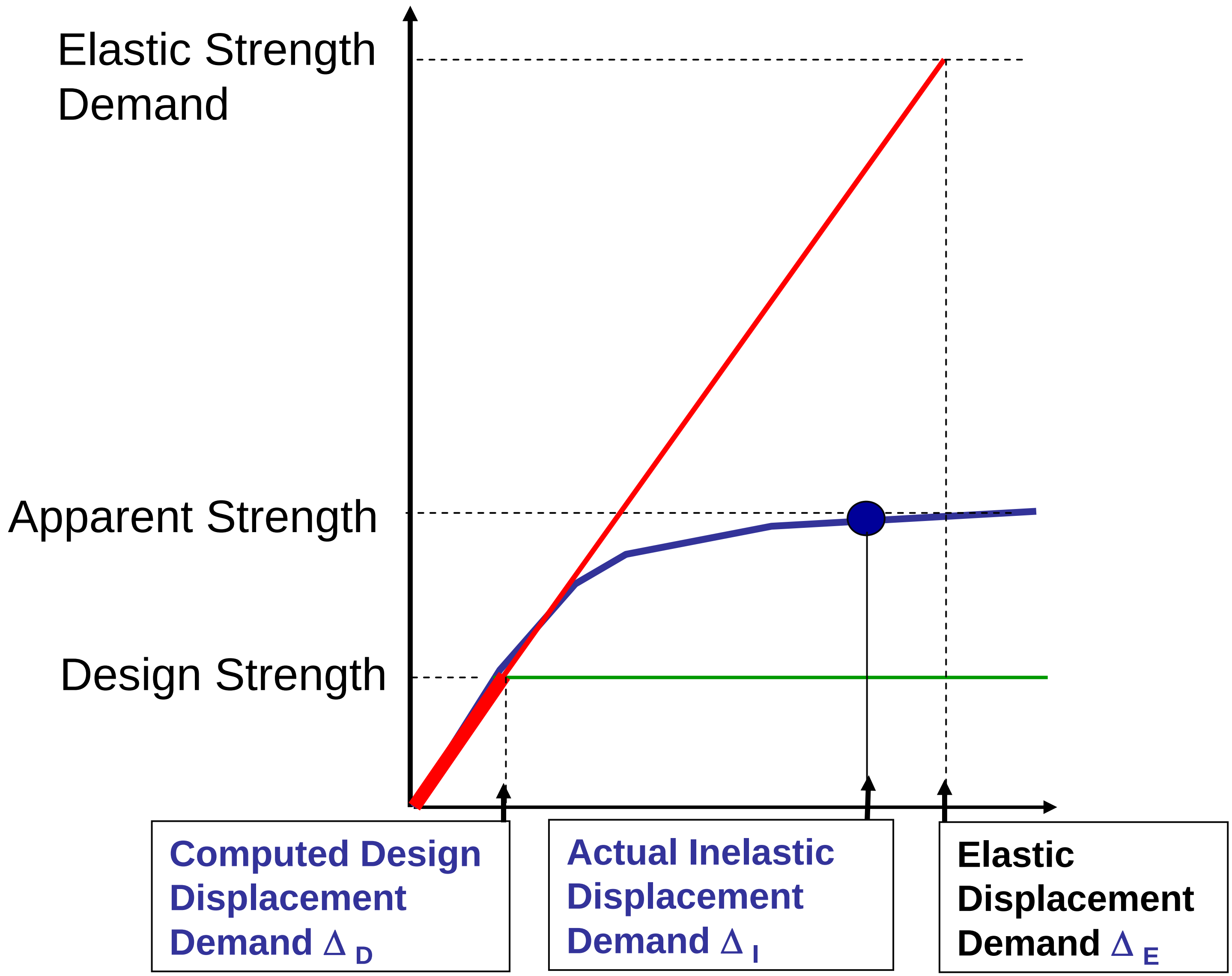
$$\text{Ductility Reduction } R_d = \frac{\text{Elastic Strength Demand}}{\text{Apparent Strength}}$$

$$R = \frac{\text{Elastic Strength Demand}}{\text{Design Strength}} = R_d \, \Omega$$

Definition of Response Modification Coefficient *R*



Definition of Deflection Amplification Factor Coefficient C_d



ASCE 7 Approach for Displacements

Determine design forces: $V = C_s W$, where C_s includes ductility/overstrength reduction factor R.

Distribute forces vertically and horizontally and compute displacements using linear elastic analysis.

Multiply computed displacements by C_d to obtain estimate of true inelastic response.

Examples of Design Factors for Steel Structures ASCE 7-05

	R	Ω_o	R_d	C_d
Special Moment Frame	8	3	2.67	5.5
Intermediate Moment Frame	4.5	3	1.50	4.0
Ordinary Moment Frame	3.5	3	1.17	3.0
Eccentric Braced Frame	8	2	4.00	4.0
Eccentric Braced Frame (Pinned)	7	2	3.50	4.0
Special Concentric Braced Frame	6	2	3.00	5.0
Ordinary Concentric Braced Frame	3.25	2	1.25	3.25
Not Detailed	3	3	1.00	3.0

Note: R_d is ductility demand ONLY IF Ω_o is achieved.

Examples of Design Factors for Reinforced Concrete Structures ASCE 7-05

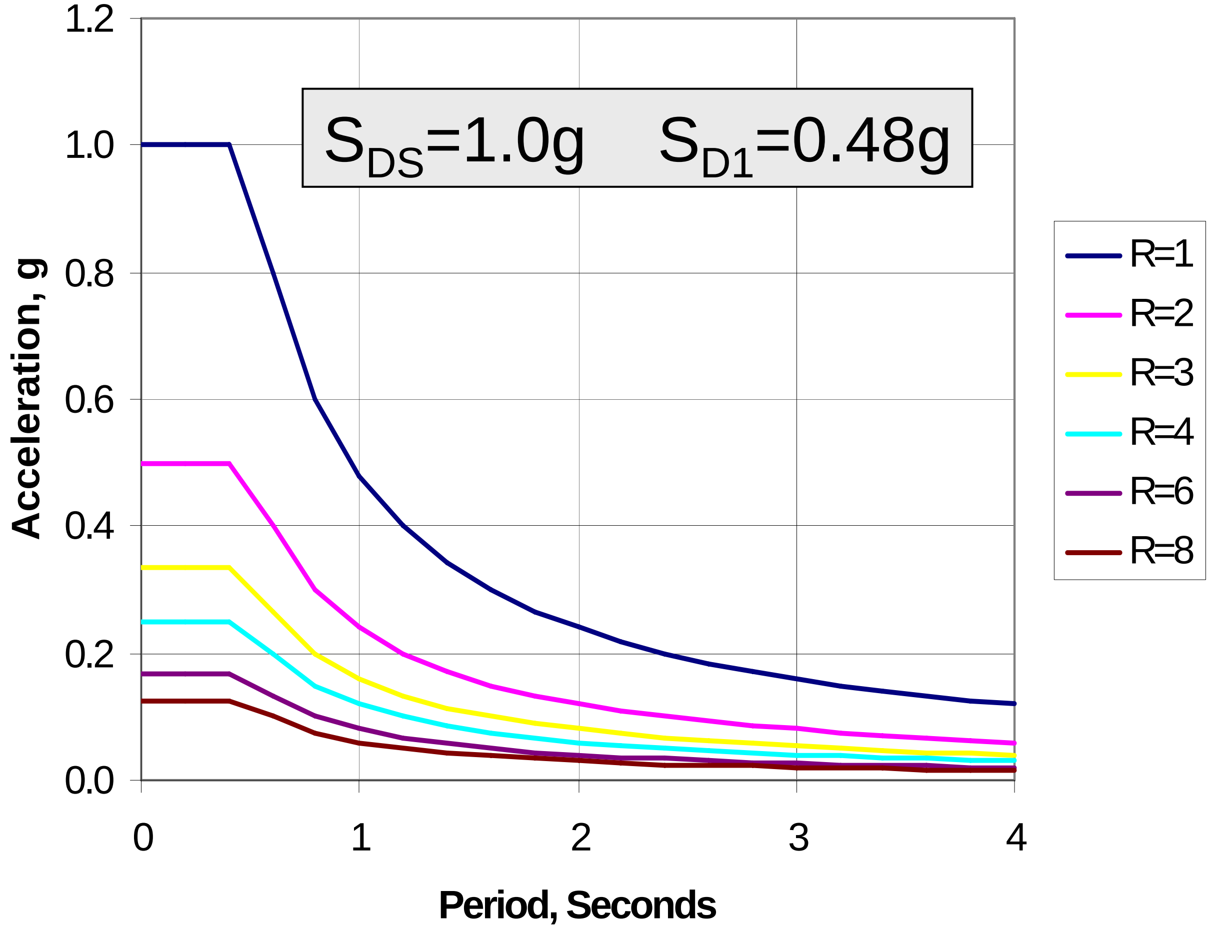
	R	Ω_o	R_d	C_d
Special Moment Frame	8	3	2.67	5.5
Intermediate Moment Frame	5	3	1.67	4.5
Ordinary Moment Frame	3	3	1.00	2.5
Special Reinforced Shear Wall	5	2.5	2.00	5.0
Ordinary Reinforced Shear Wall	4	2.5	1.60	4.0
Detailed Plain Concrete Wall	2	2.5	0.80	2.0
Ordinary Plain Concrete Wall	1.5	2.5	0.60	1.5

Note: R_d is Ductility Demand ONLY IF Ω_o is Achieved.

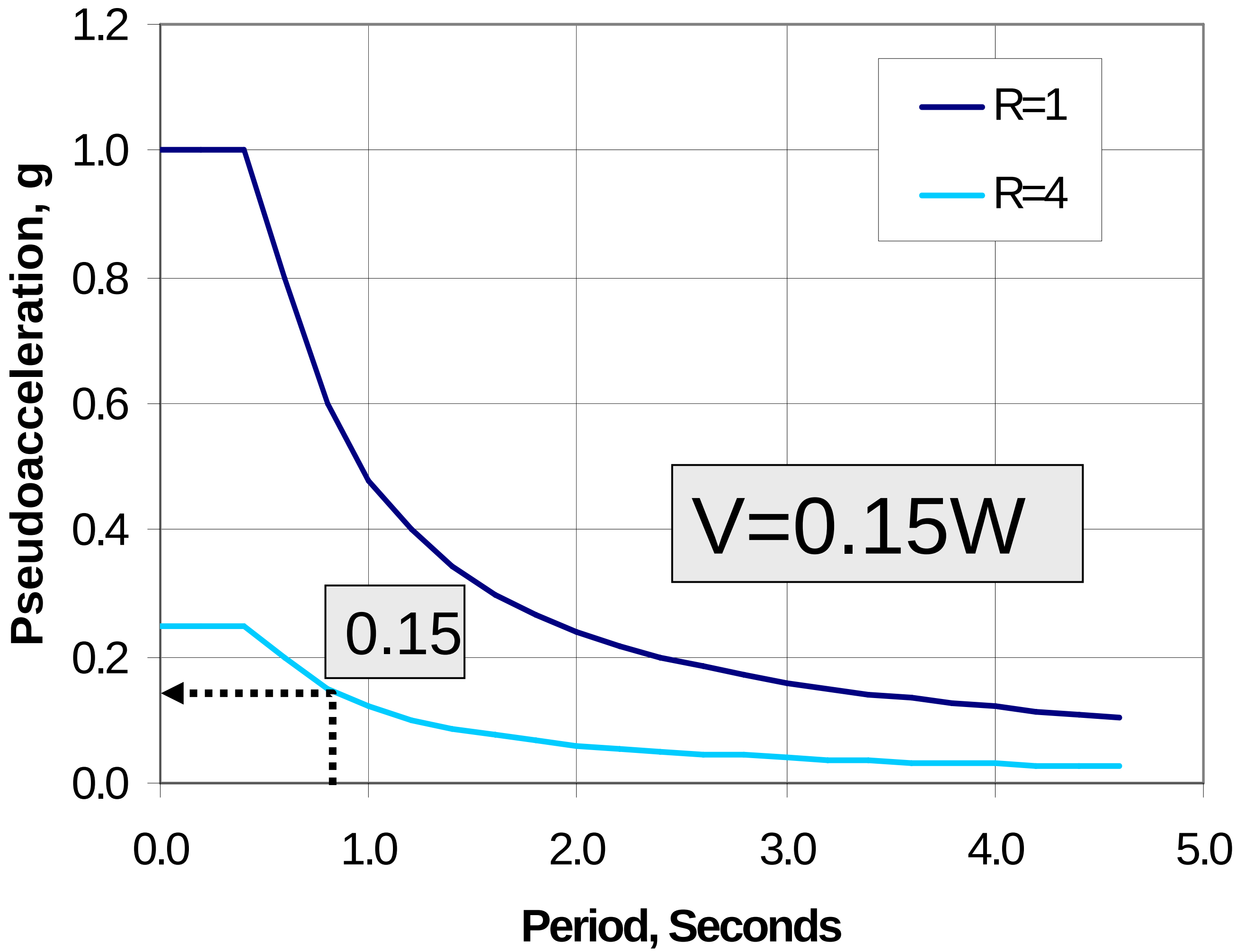
ASCE 7 Elastic Spectra as Adjusted for Ductility and Overstrength

$$C_S = \frac{S_{DS}}{R / I}$$

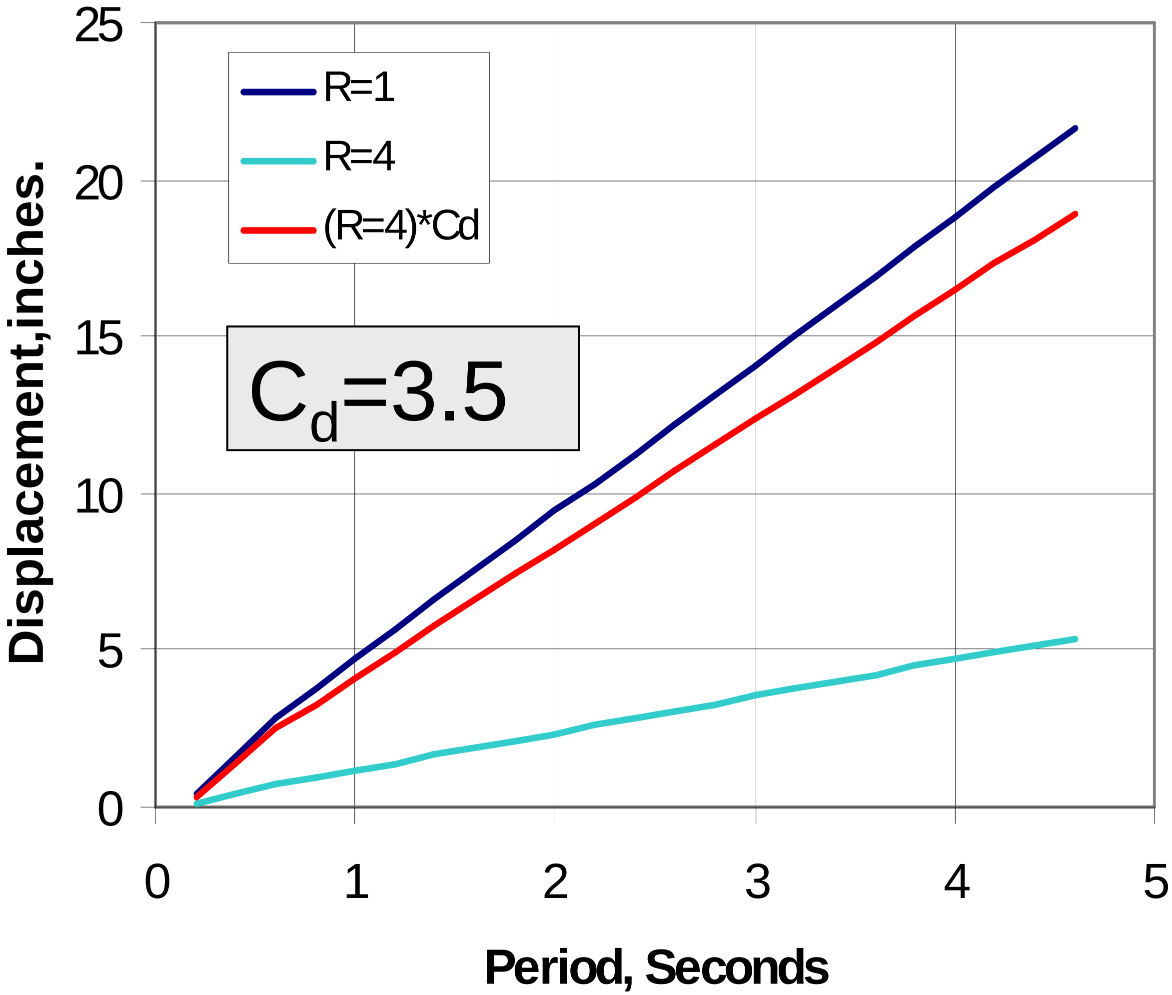
$$C_S = \frac{S_{D1}}{T(R / I)}$$



Using Modified ASCE 7 Spectrum to Determine Force Demand

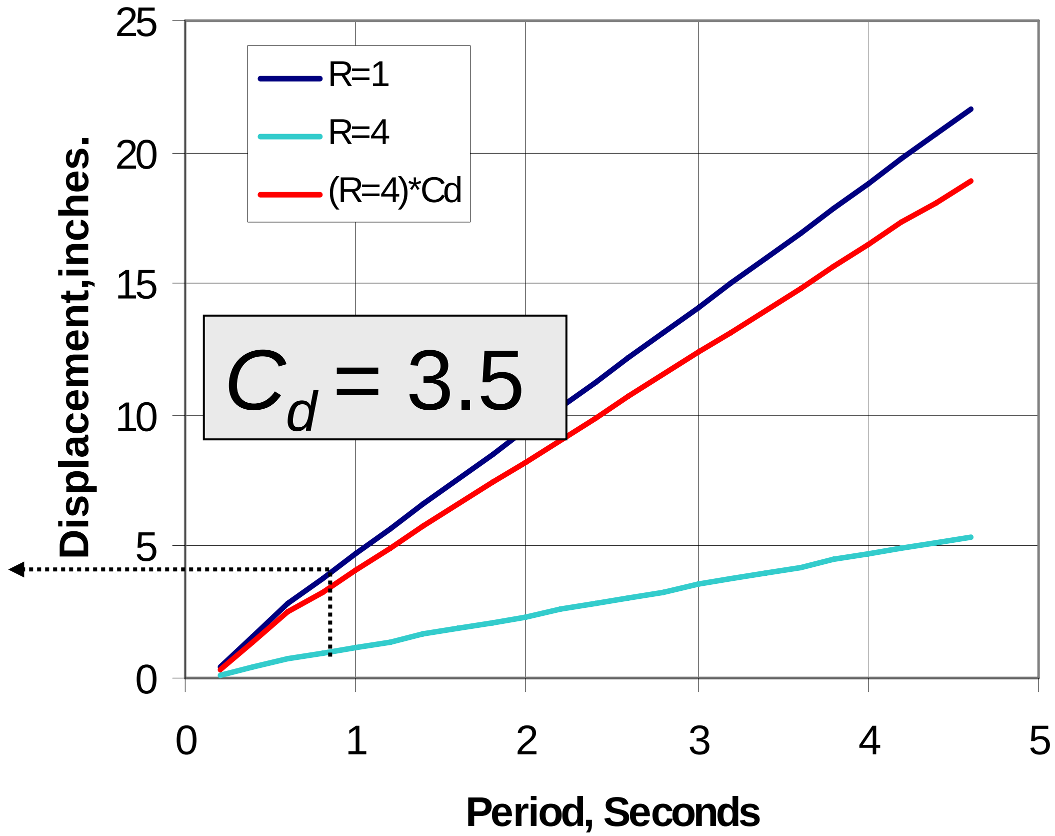


Using Modified ASCE-7 Spectrum to Determine Displacement Demand



Displacements must be multiplied by factor C_d because displacements based on reduced force **would be too low**

$$\Delta_{INELASTIC} = C_d \times \Delta_{REDUCEDELASTIC}$$



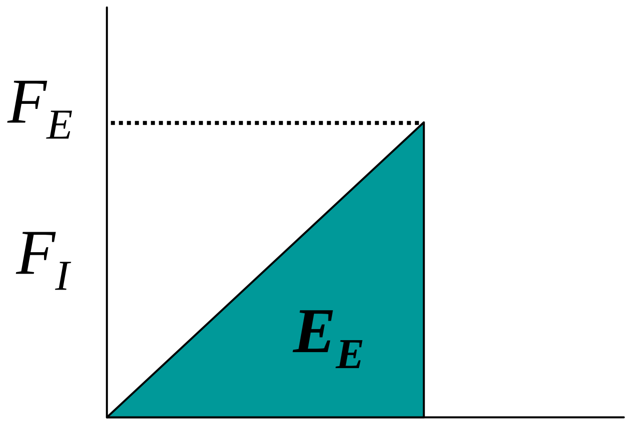
$$C_d = 3.5$$

$$\Delta_{INELASTIC} = 3.65\ in.$$

“Equal displacement” approach may not be applicable at very low period values.

Equal Energy Concept
(Applicable at Low Periods)

ELASTIC ENERGY

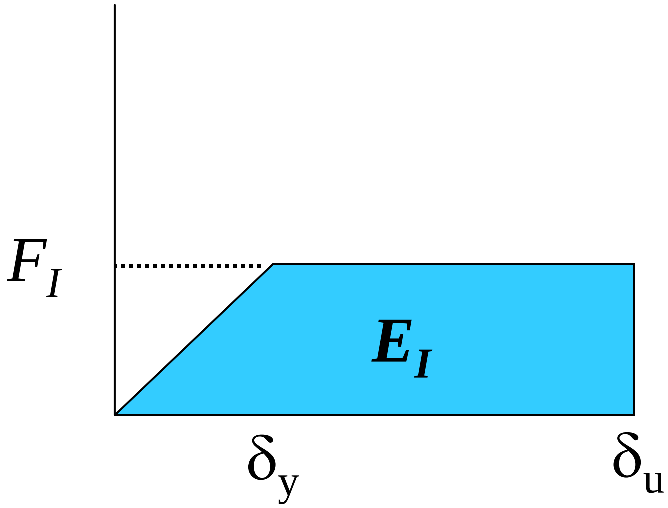


$$\frac{F_E}{F_I}\delta_y$$

$$E_E = 0.5F_E \frac{F_E}{F_I}\delta_y = 0.5\delta_y \frac{F_E^2}{F_I}$$

Equal Energy Concept
(Applicable at Low Periods)

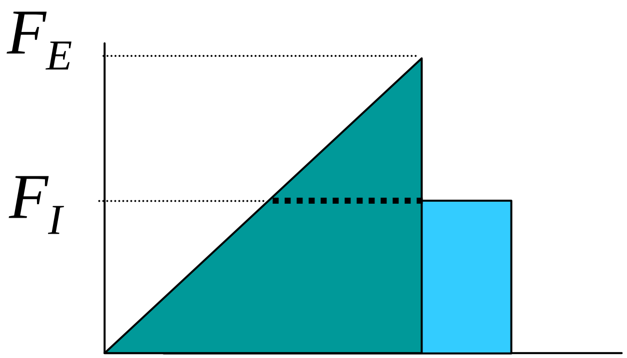
INELASTIC ENERGY



$$E_I = F_I \delta_u - 0.5 F_I \delta_y = F_I \delta_y \left(\mu - 0.5 \right)$$

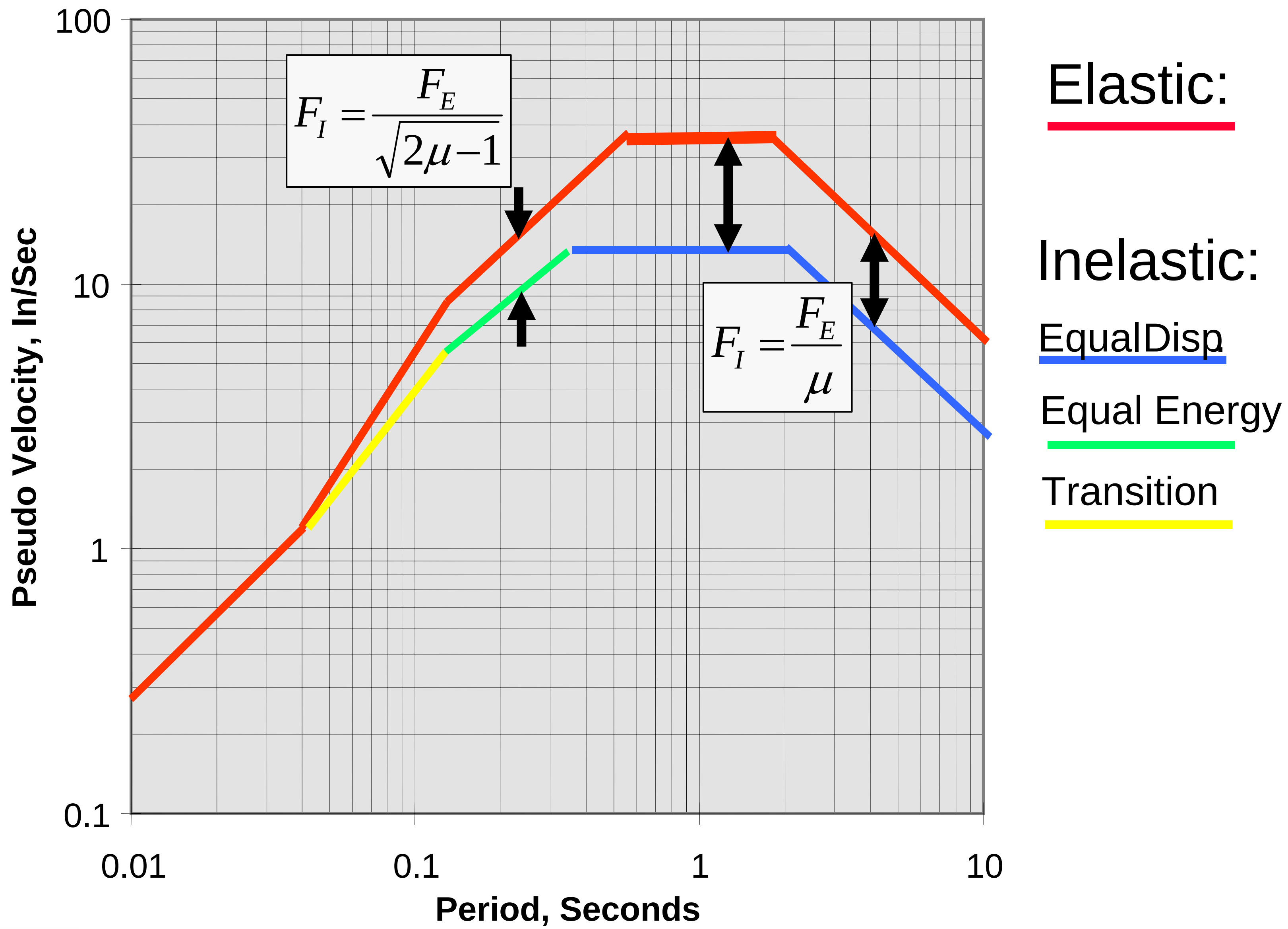
Equal Energy Concept
(Applicable at Low Periods)

Assuming $E_E = E_I$:



$$\frac{F_E}{F_I} = \sqrt{2\mu - 1}$$

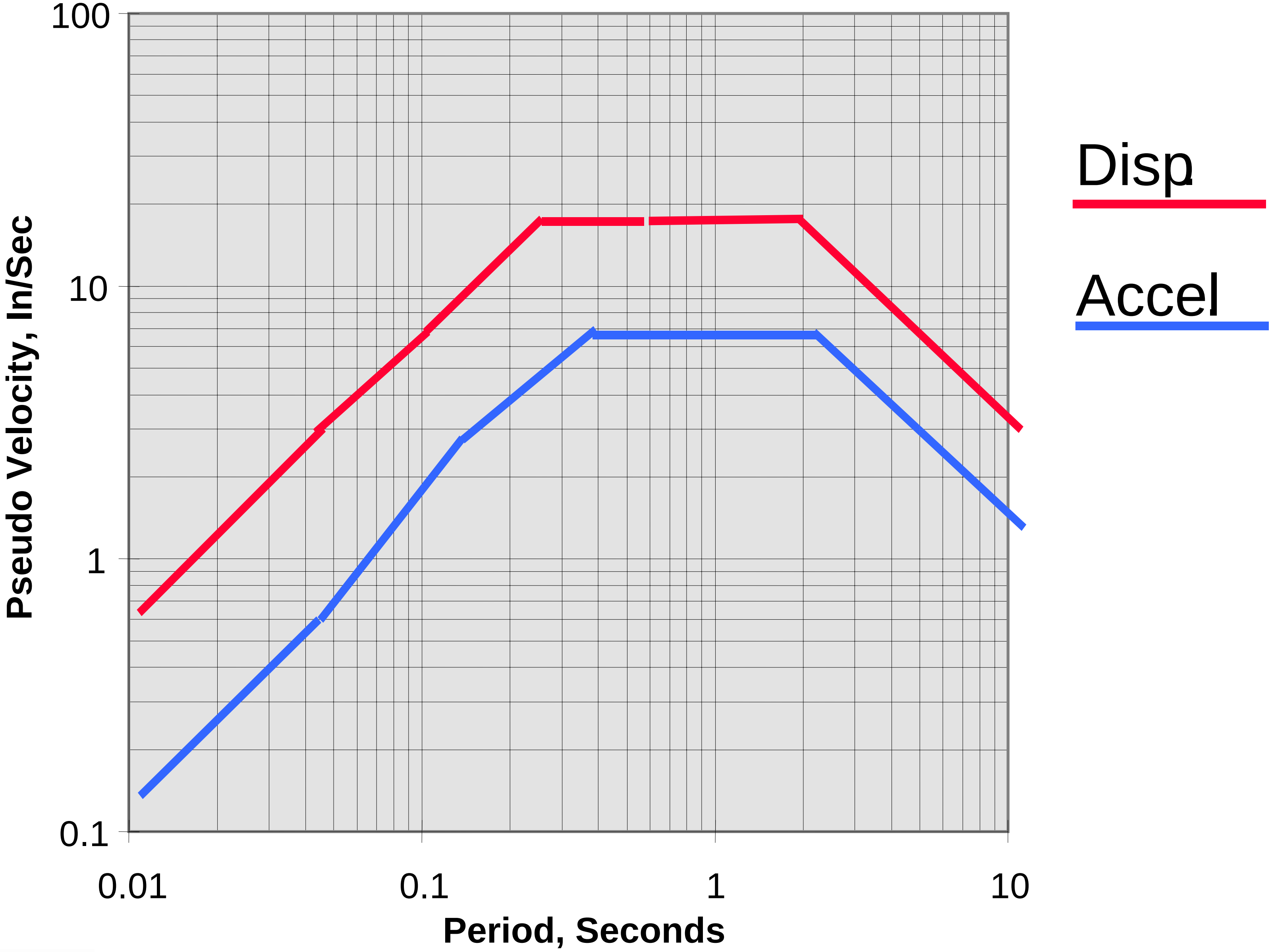
Newmark Inelastic Spectrum (for Psuedoacceleration)



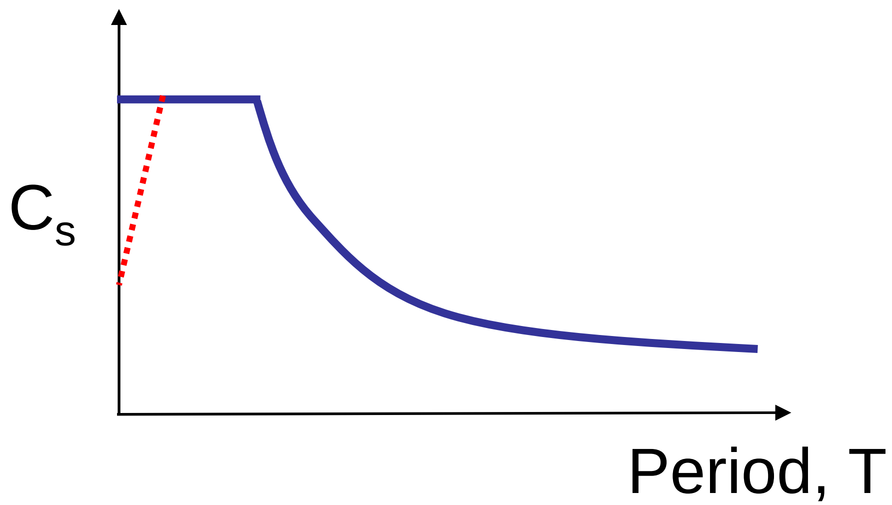
Newmark's
Inelastic Design Response Spectrum

To obtain inelastic displacement spectrum, multiply the spectrum shown in previous slide by μ (for all periods).

Inelastic Design Response Spectrum for Acceleration & Displacement



At very low periods, the ASCE 7 spectrum does not reduce to ground acceleration so this partially compensates for “error” in equal displacement assumption at low period values.



Note: FEMA 273 has explicit modifications for computing “target at low periods.”