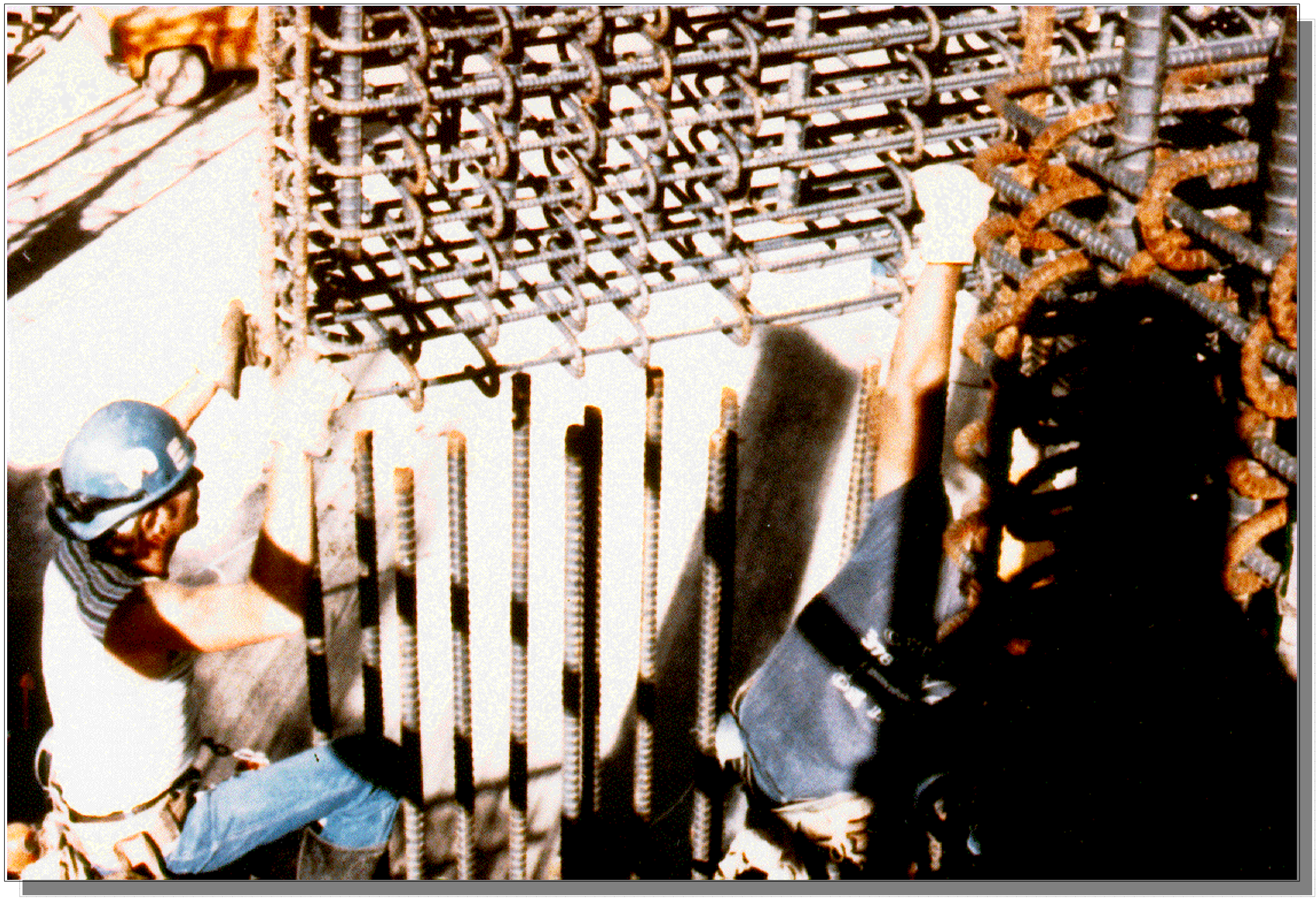
SEISMIC DESIGN OF REINFORCED CONCRETE STRUCTURES



NEHRP Recommended Provisions Concrete Design Requirements

- Context in the *NEHRP Recommended Provisions*
- Concrete behavior
- Reference standards
- Requirements by Seismic Design Category
- Moment resisting frames
- Shear walls
- Other topics
- Summary

Context in *NEHRP Recommended Provisions*

Design basis: Strength limit state

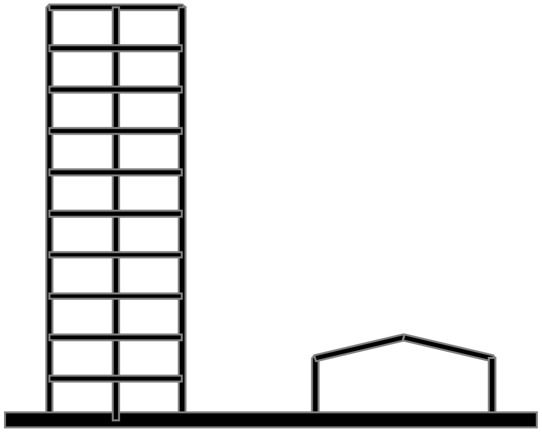
<u>Using *NEHRP Recommended Provisions*</u>:

Structural design criteria:	**Chap. 4**
Structural analysis procedures:	**Chap. 5**
Components and attachments:	**Chap. 6**
Design of concrete structures:	**Chap. 9 and ACI 318**

Seismic-Force-Resisting Systems
Reinforced Concrete

Unbraced frames (with rigid “moment resisting” joints):

- Three types
  - Ordinary
  - Intermediate
  - Special



R/C shear walls:

- Ordinary
- Special

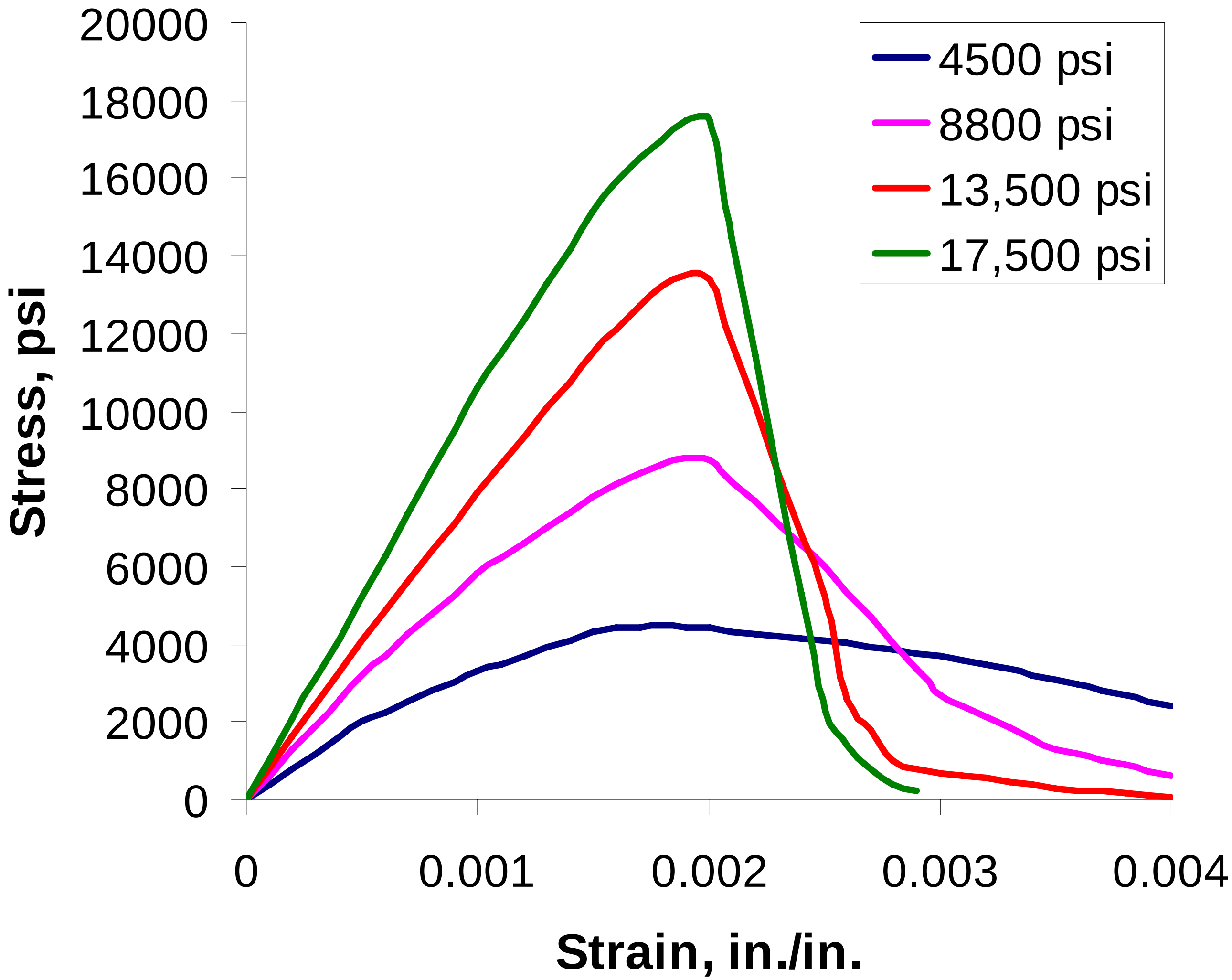
Precast shear walls:

- Special
- Intermediate
- Ordinary

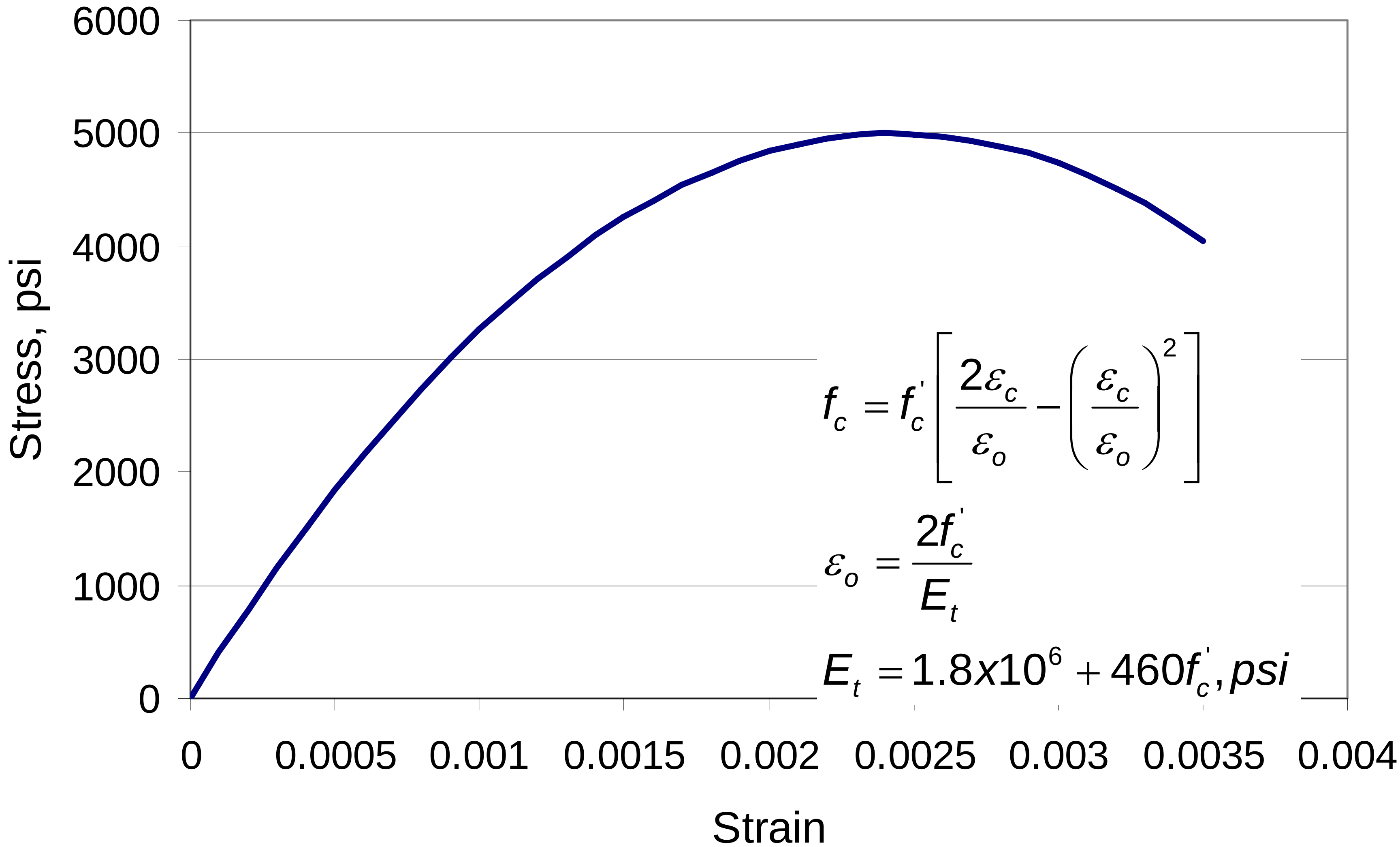
NEHRP Recommended Provisions Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**

Unconfined Concrete Stress-Strain Behavior



Idealized Stress-Strain Behavior of Unconfined Concrete

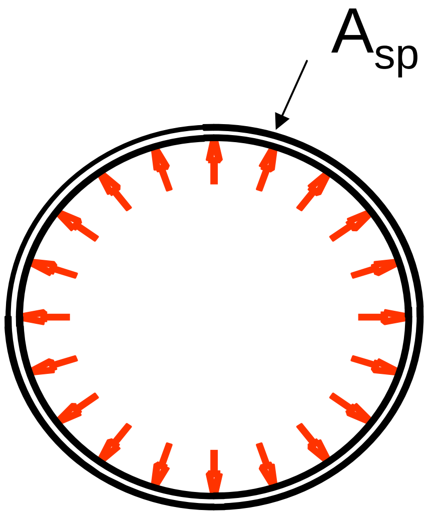


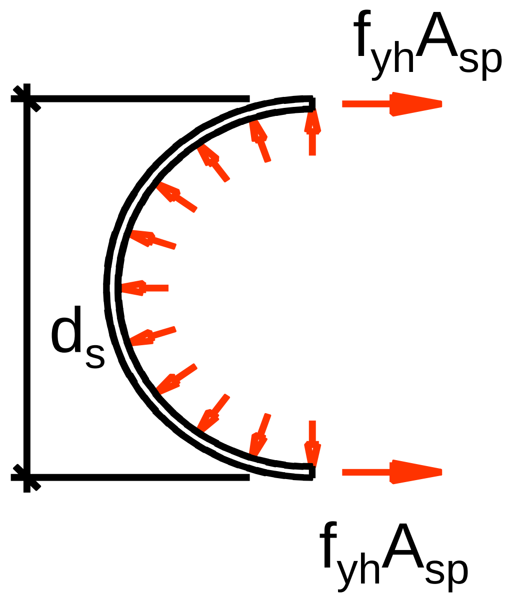
$$f_c = f_c^{'}\left[\frac{2\varepsilon_c}{\varepsilon_o} - \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right]$$

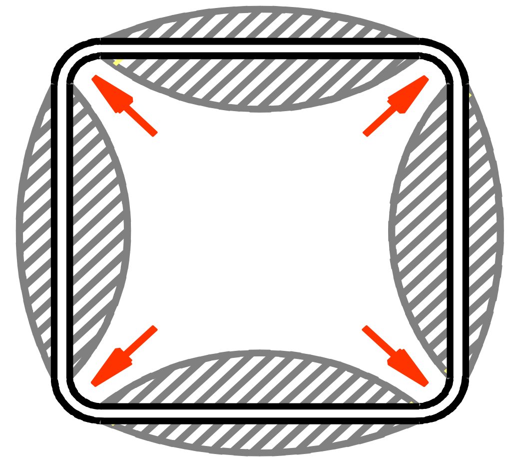
$$\varepsilon_o = \frac{2f_c^{'}}{E_t}$$

$$E_t = 1.8x10^6 + 460f_c^{'}, psi$$

Confinement by Spirals or Hoops





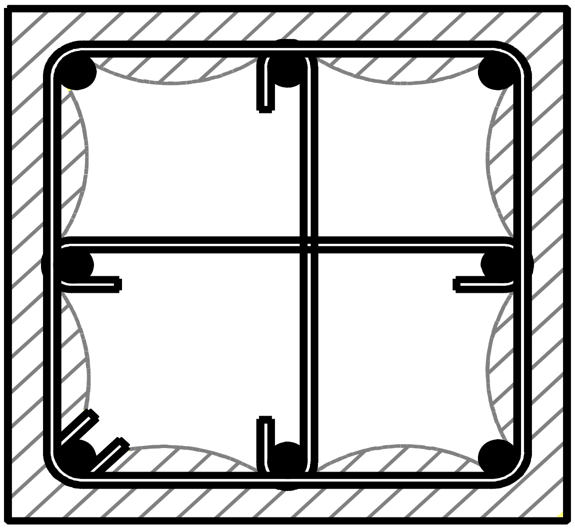


Confinement from spiral or circular hoop

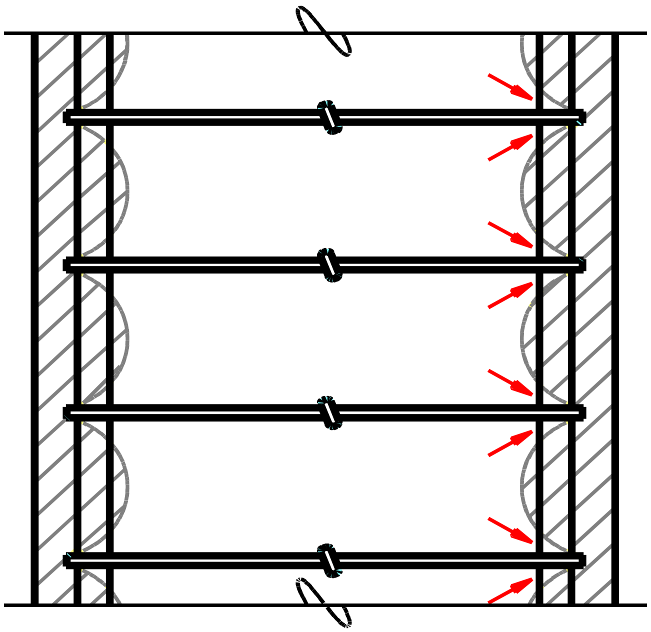
Forces acting on 1/2 spiral or circular hoop

Confinement from square hoop

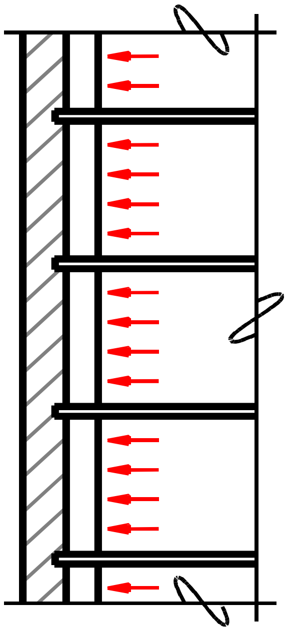
Confinement



Rectangular hoops with cross ties



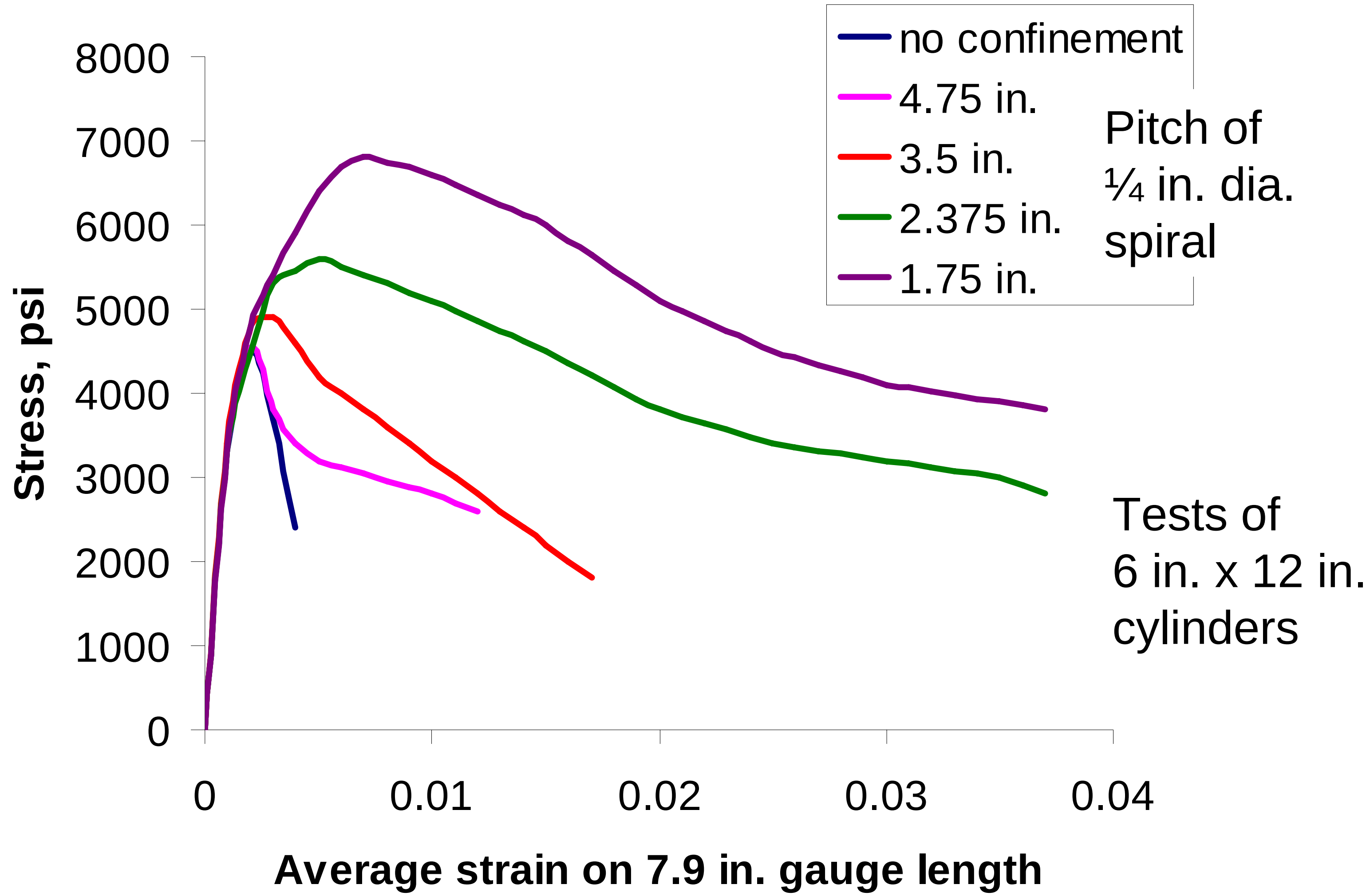
Confinement by transverse bars



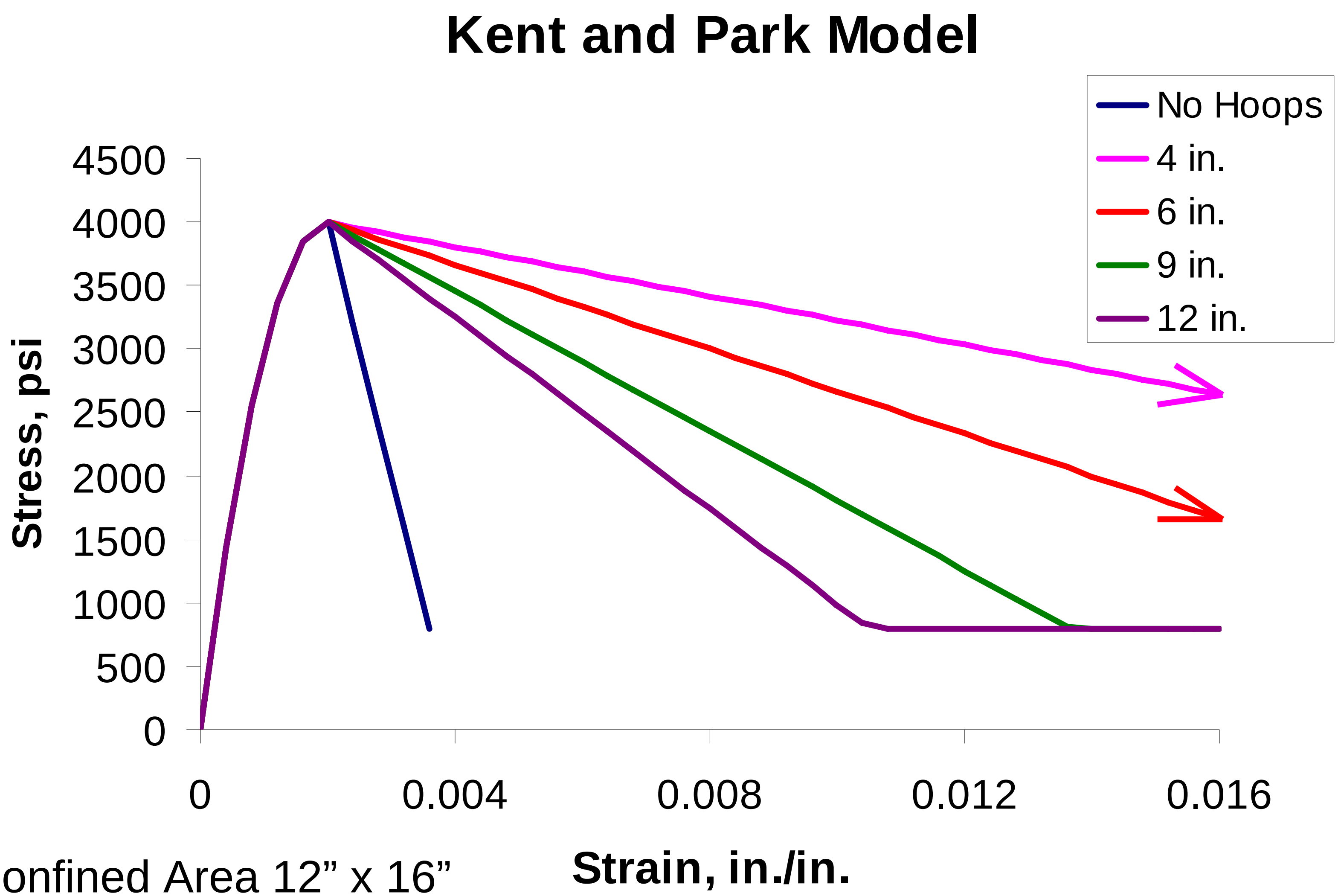
Confinement by longitudinal bars

Opened 90° hook on hoops

Confined Concrete Stress-Strain Behavior

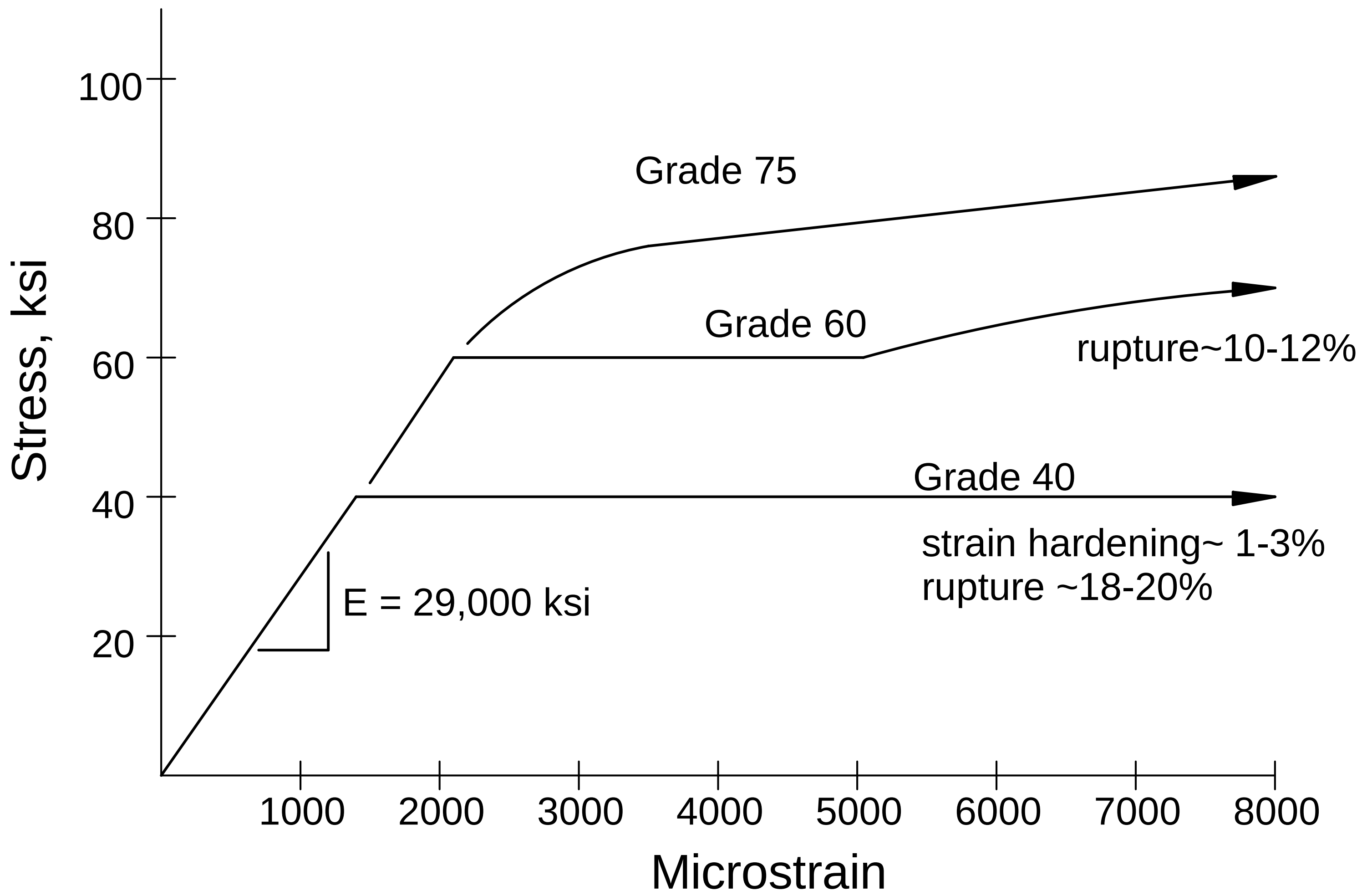


Idealized Stress-Strain Behavior of Confined Concrete

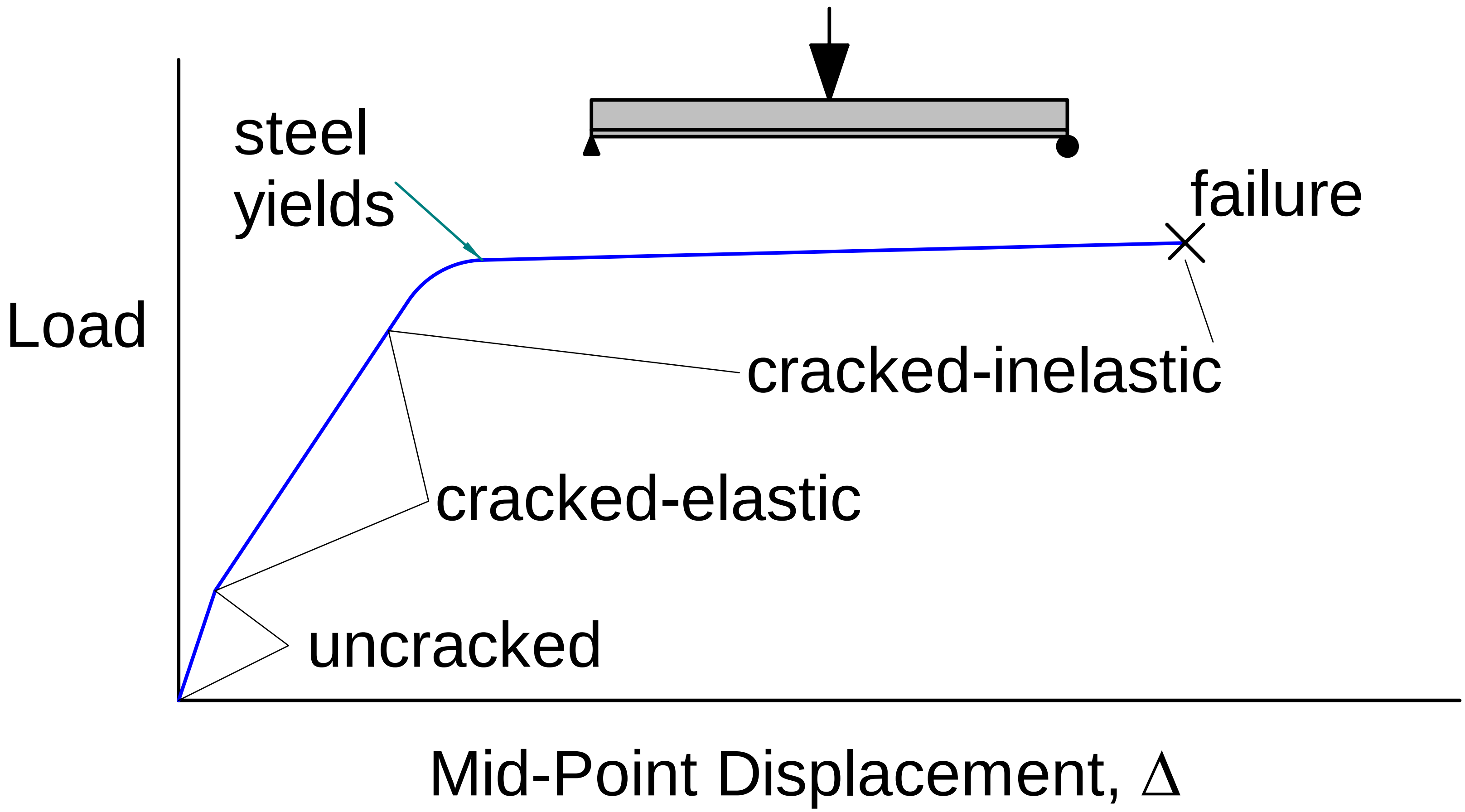


Confined Area 12” x 16”

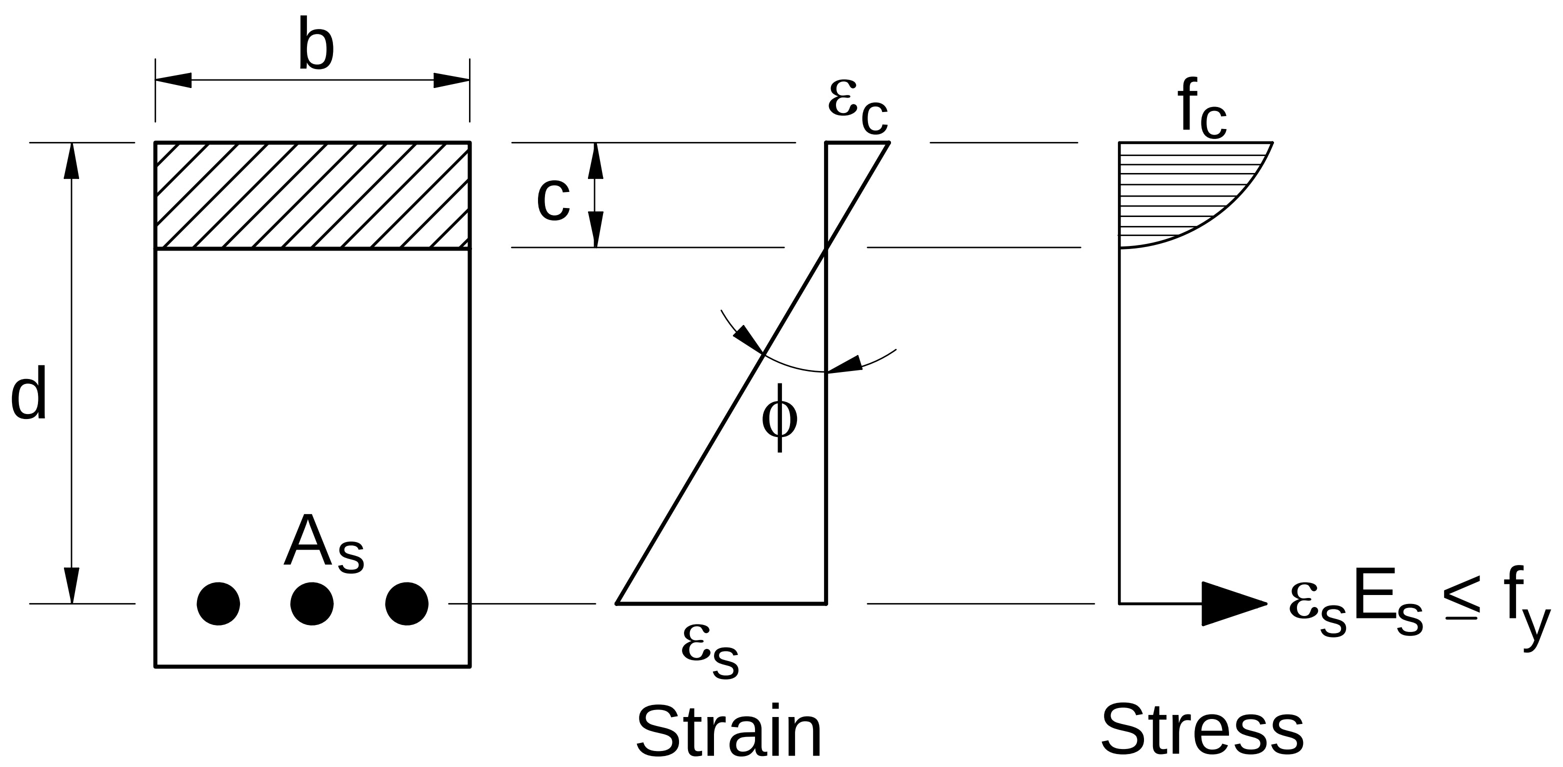
Reinforcing Steel Stress-Strain Behavior



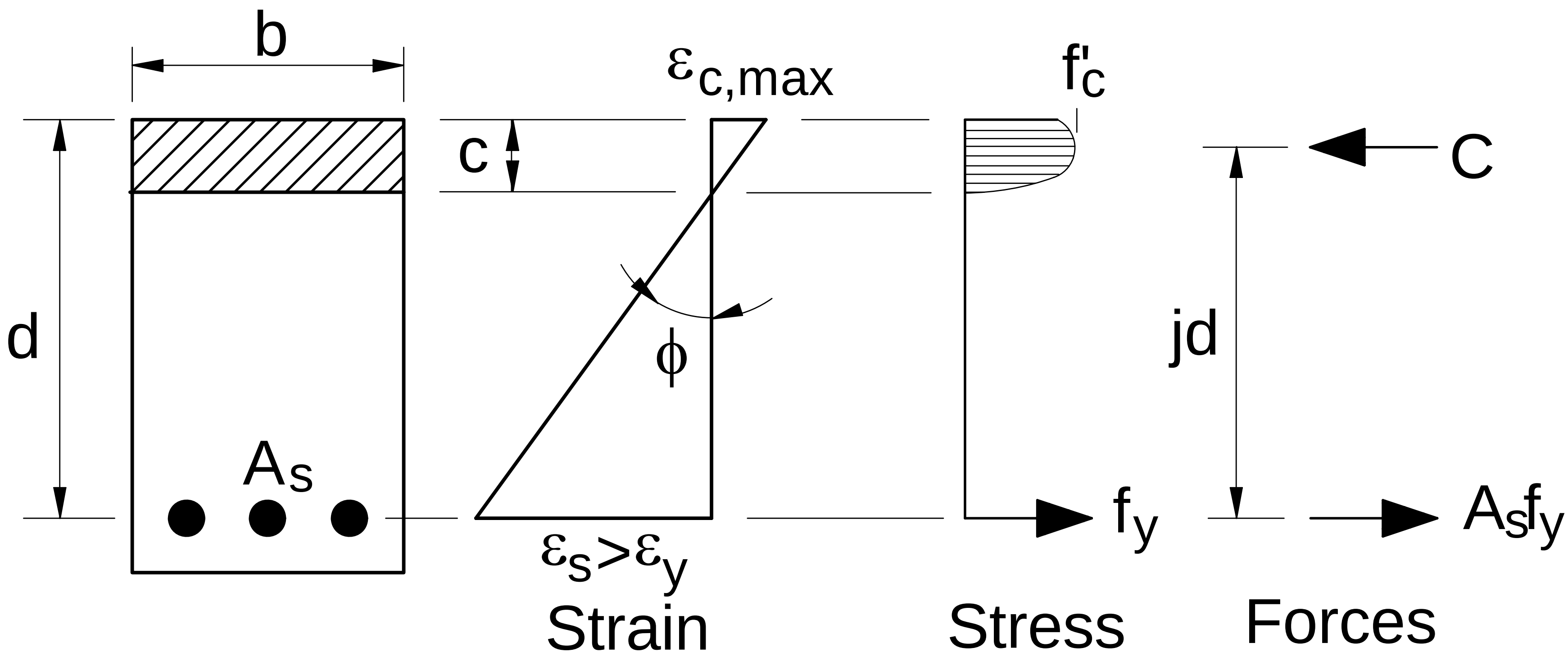
Reinforced Concrete Behavior



Behavior Up to First Yield of Steel

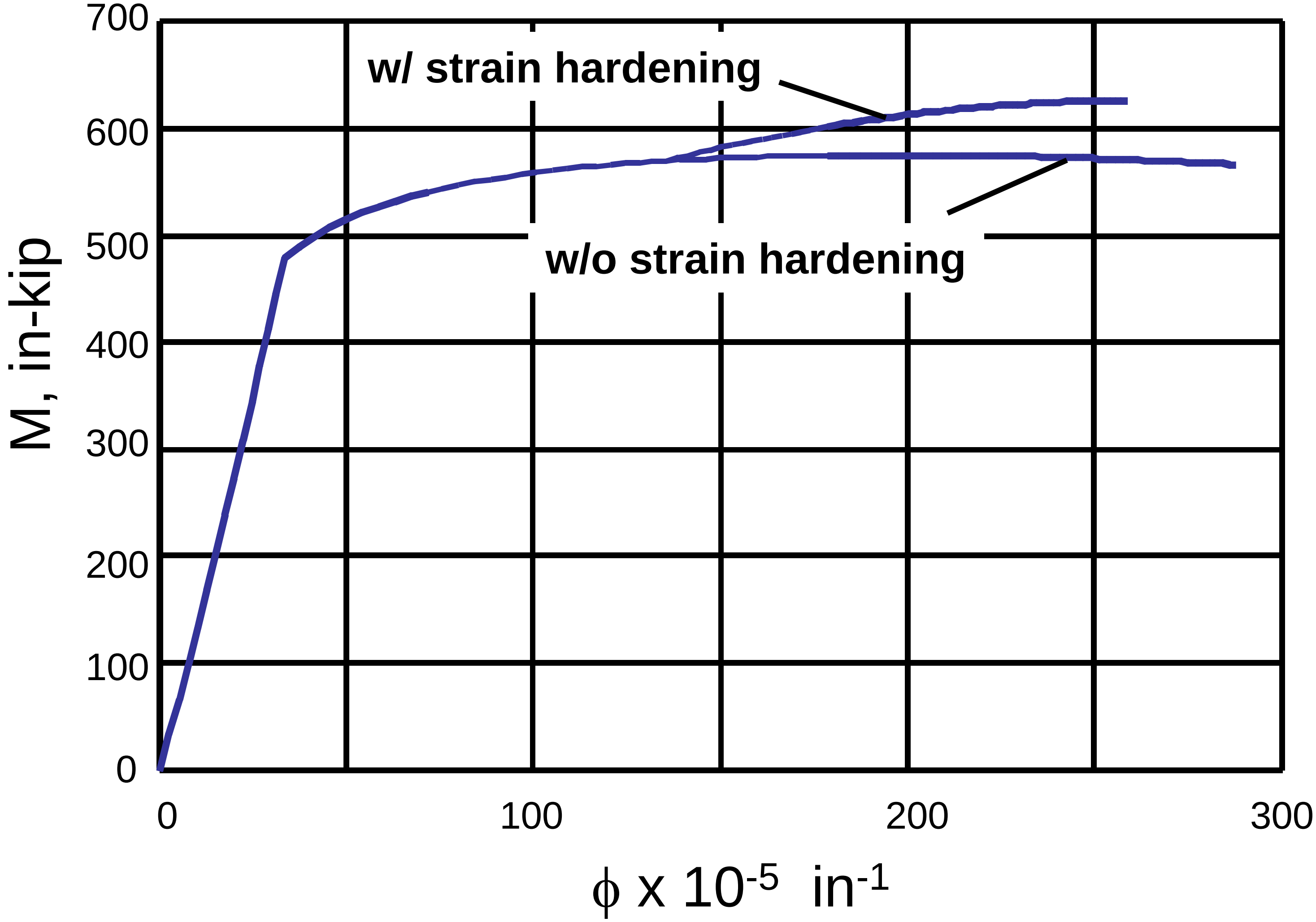


Behavior at Concrete Crushing



$$M_n = A_s f_y jd$$

Typical Moment Curvature Diagram



$f'_c = 4$ ksi

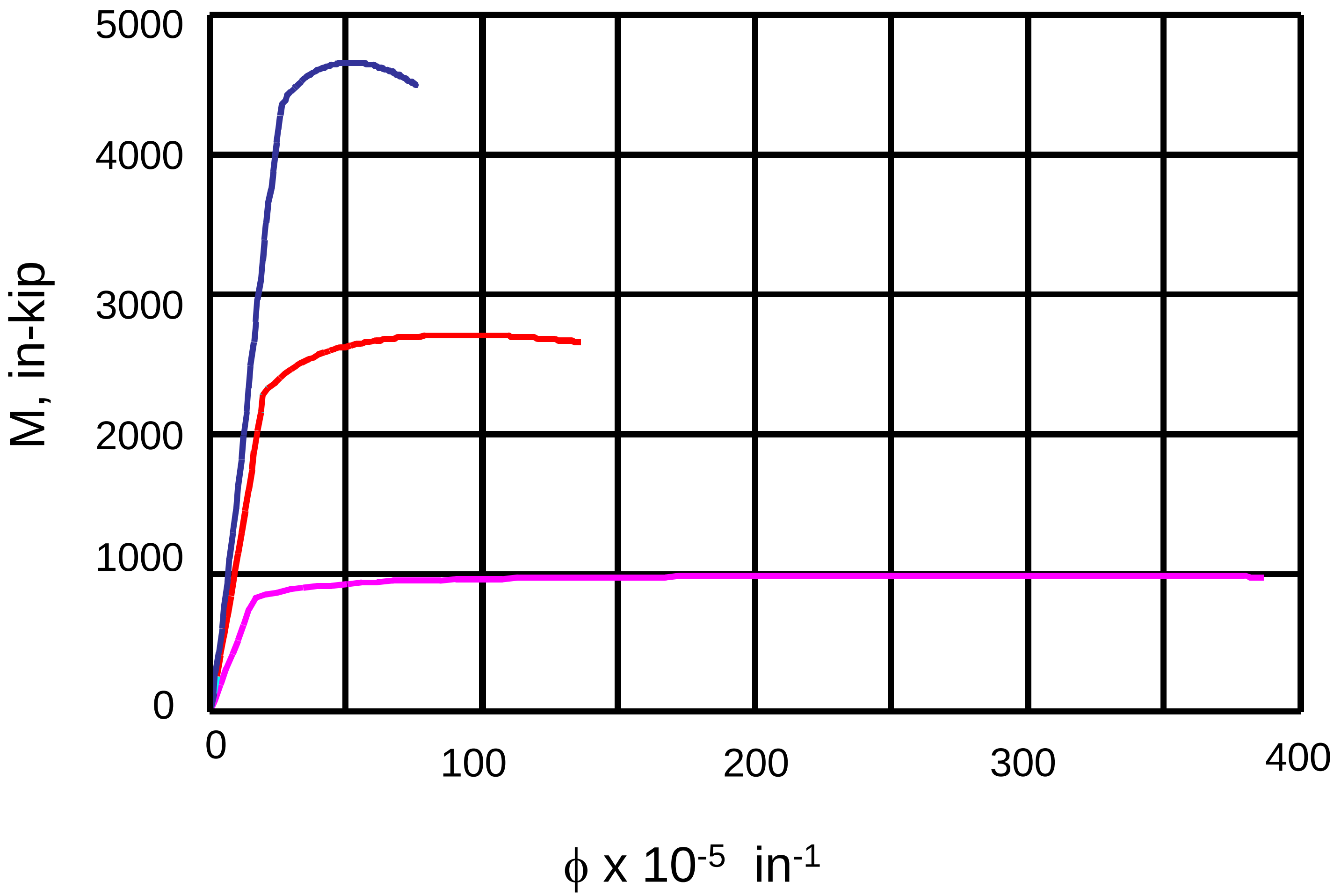
$f_y = 60$ ksi

$b = 8$ in

$d = 10$ in

$\rho = 0.0125$

Influence of Reinforcement Ratio



f'$_c$ = 4 ksi

f$_y$ = 60 ksi

b = 10 in

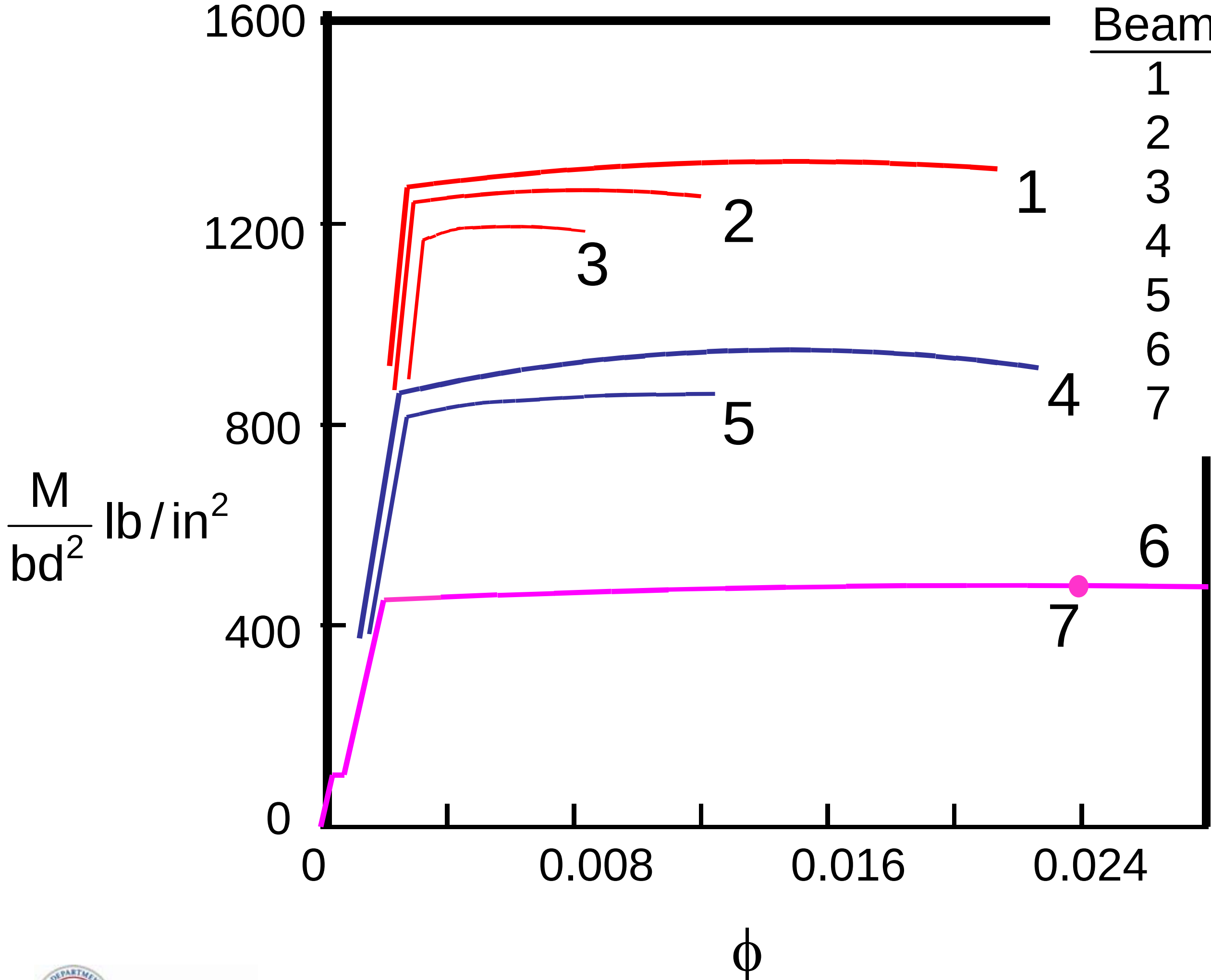
d = 18 in

ρ = 2.5%

ρ = 1.5%

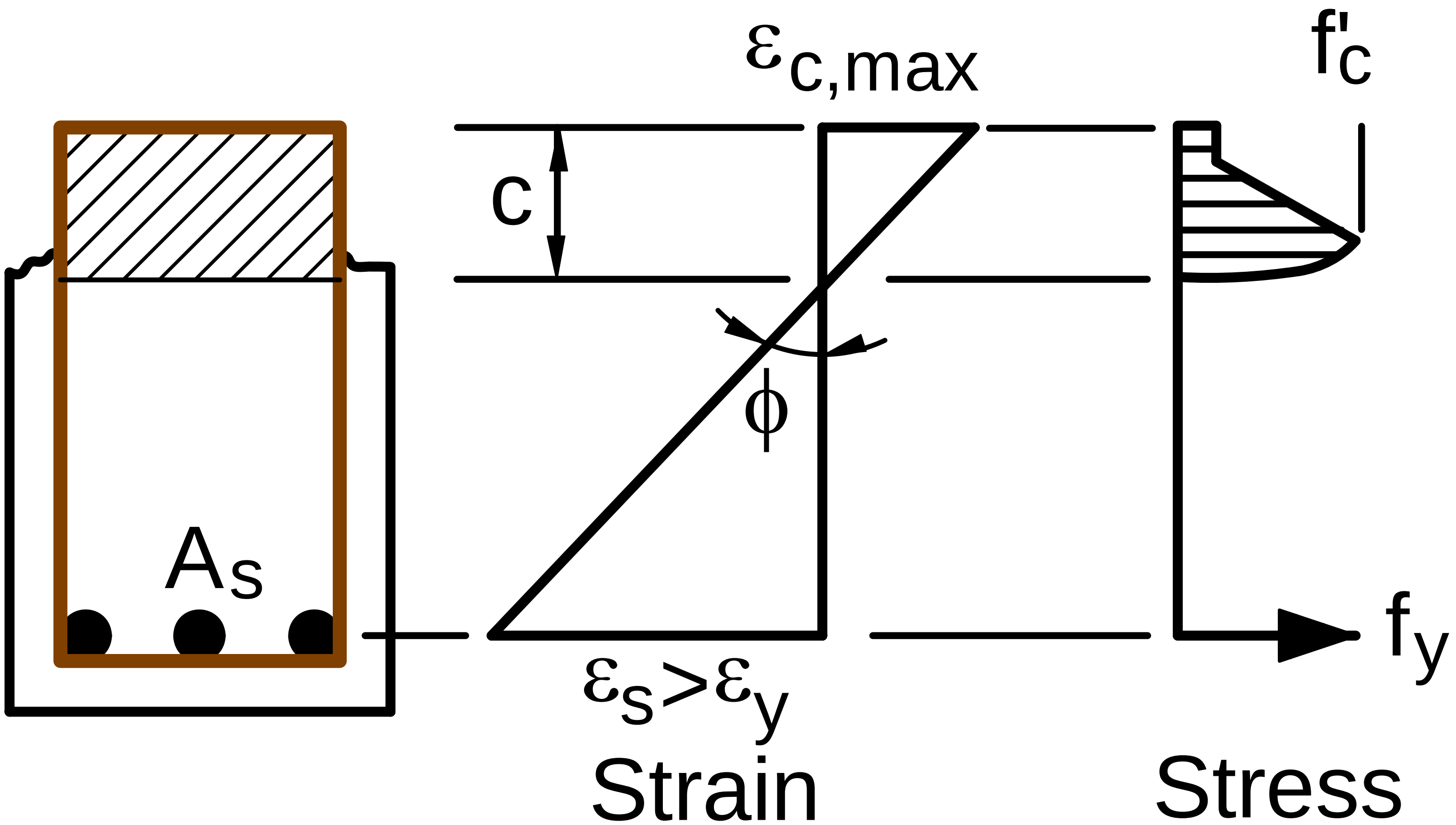
ρ = 0.5%

Influence of Compression Reinforcement

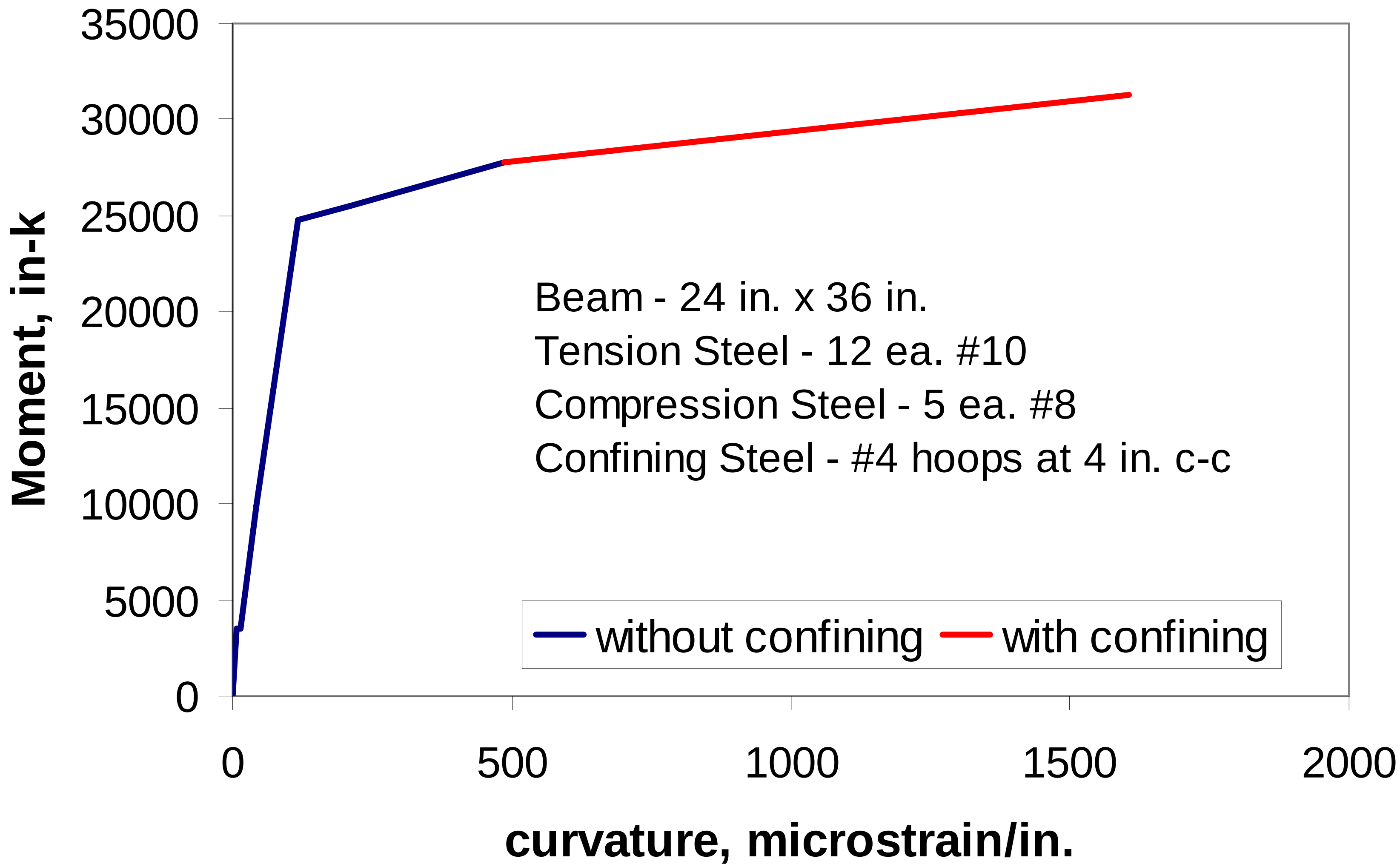


Beam	ρ	ρ'
1	0.0375	0.0250
2	0.0375	0.0125
3	0.0375	0
4	0.0250	0.0125
5	0.0250	0
6	0.0125	0.0125
7	0.0125	0

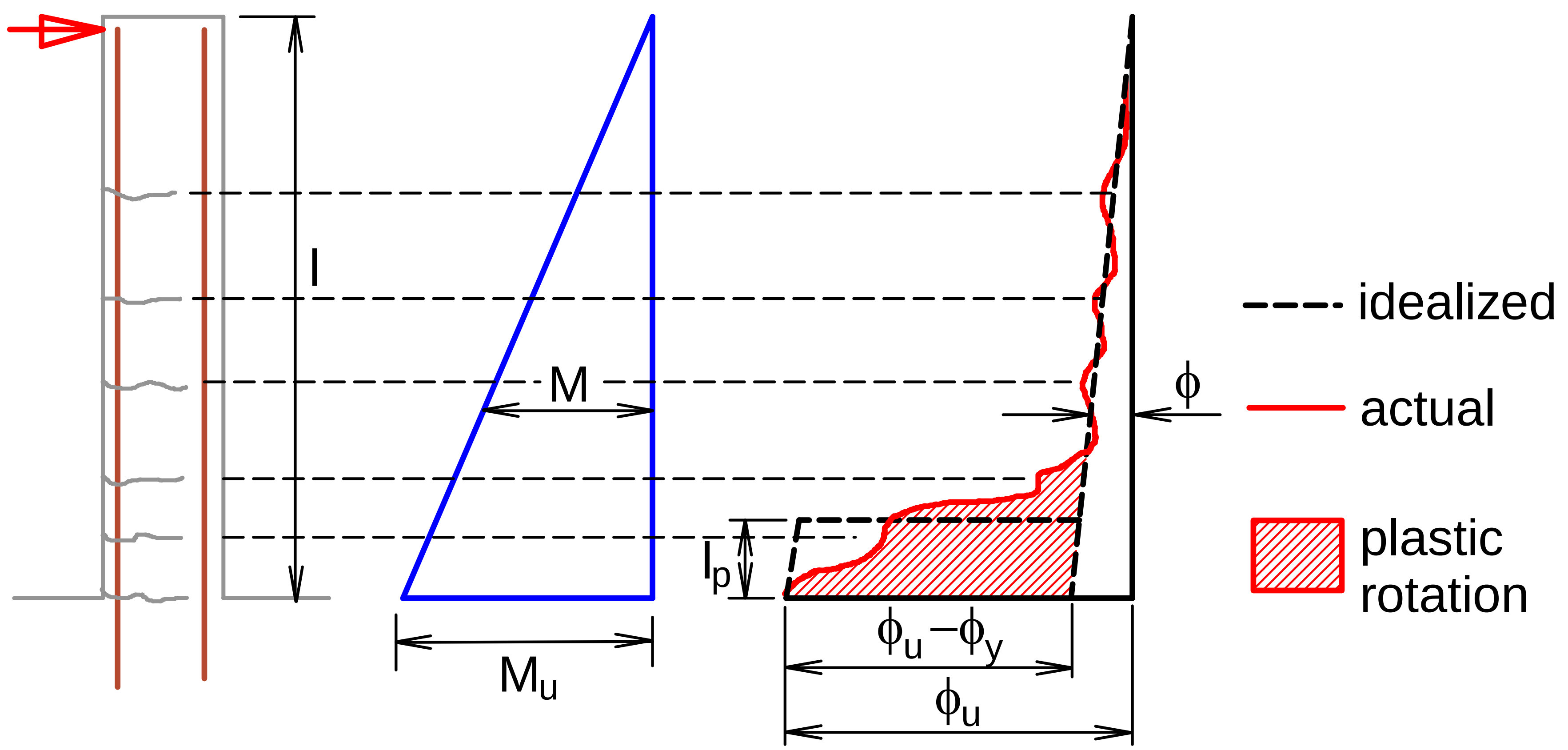
Moment-Curvature with Confined Concrete



Moment-Curvature with Confined Concrete



Plastic Hinging



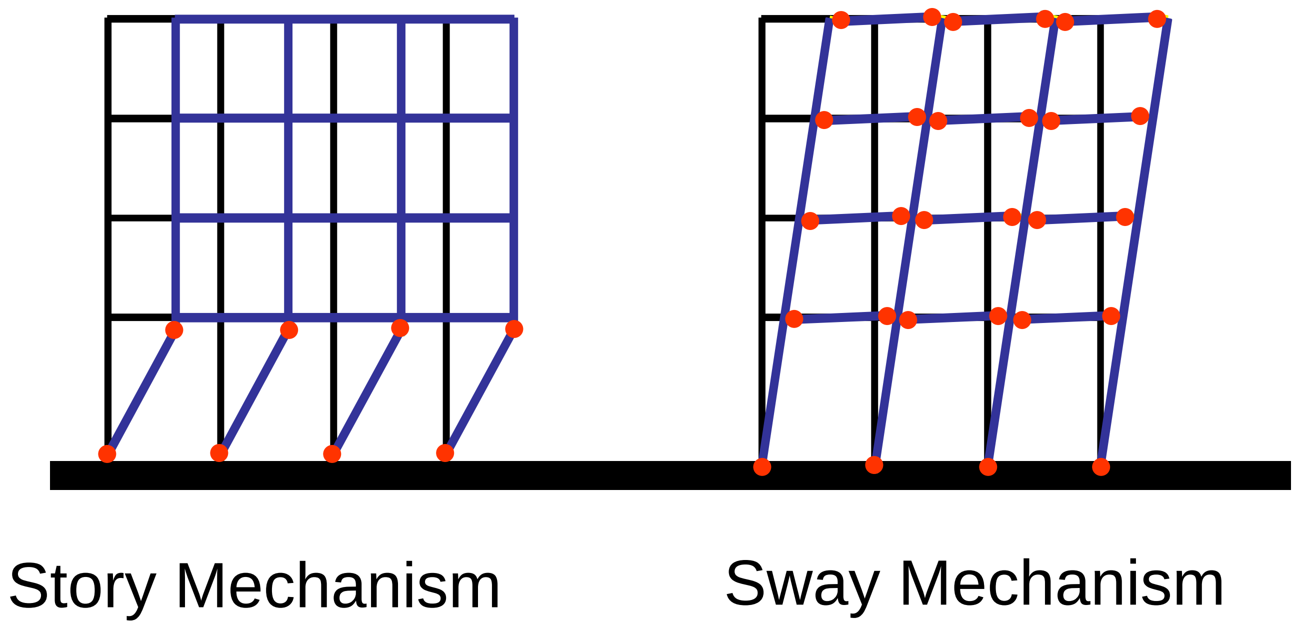
Strategies to Improve Ductility

- Use low flexural reinforcement ratio
- Add compression reinforcement
- Add confining reinforcement

Other Functions of Confining Steel

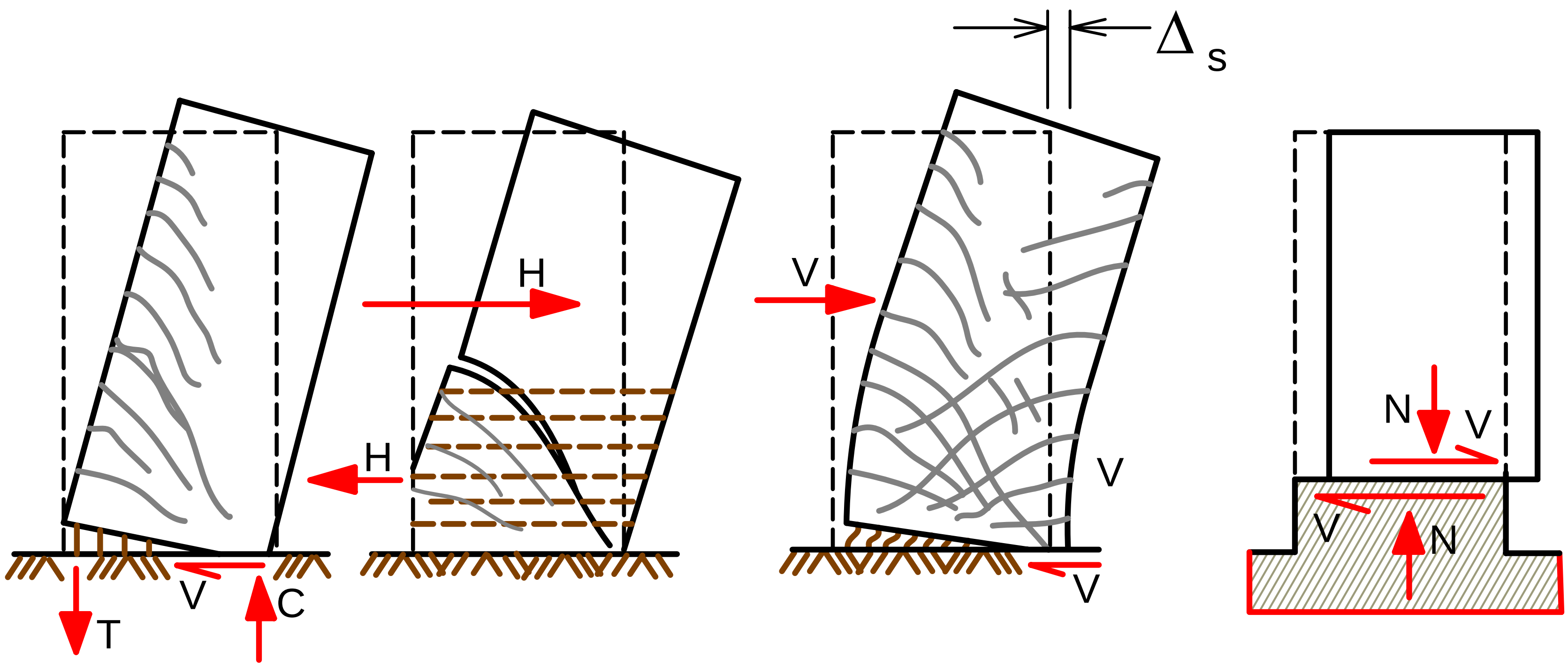
- **Acts as shear reinforcement**
- **Prevents buckling of longitudinal reinforcement**
- **Prevents bond splitting failures**

Structural Behavior
Frames



Story Mechanism

Structural Behavior - Walls



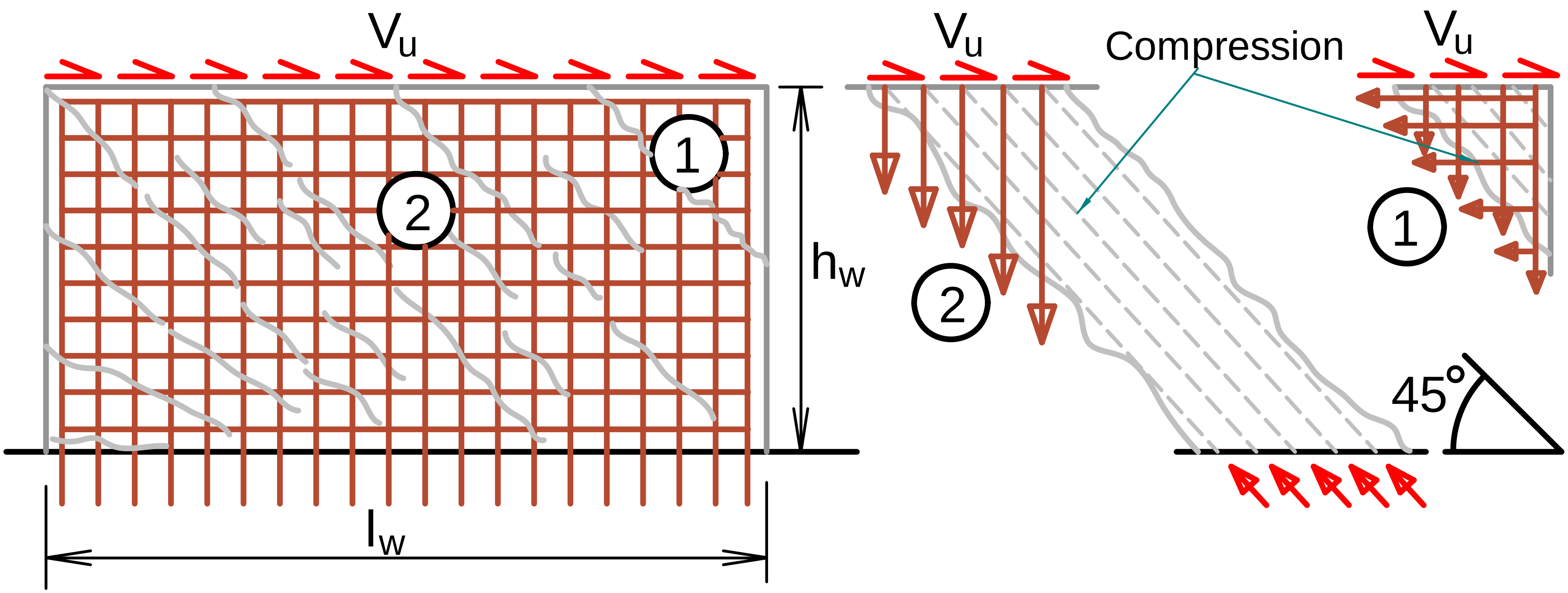
Flexural failure

Horizontal tension

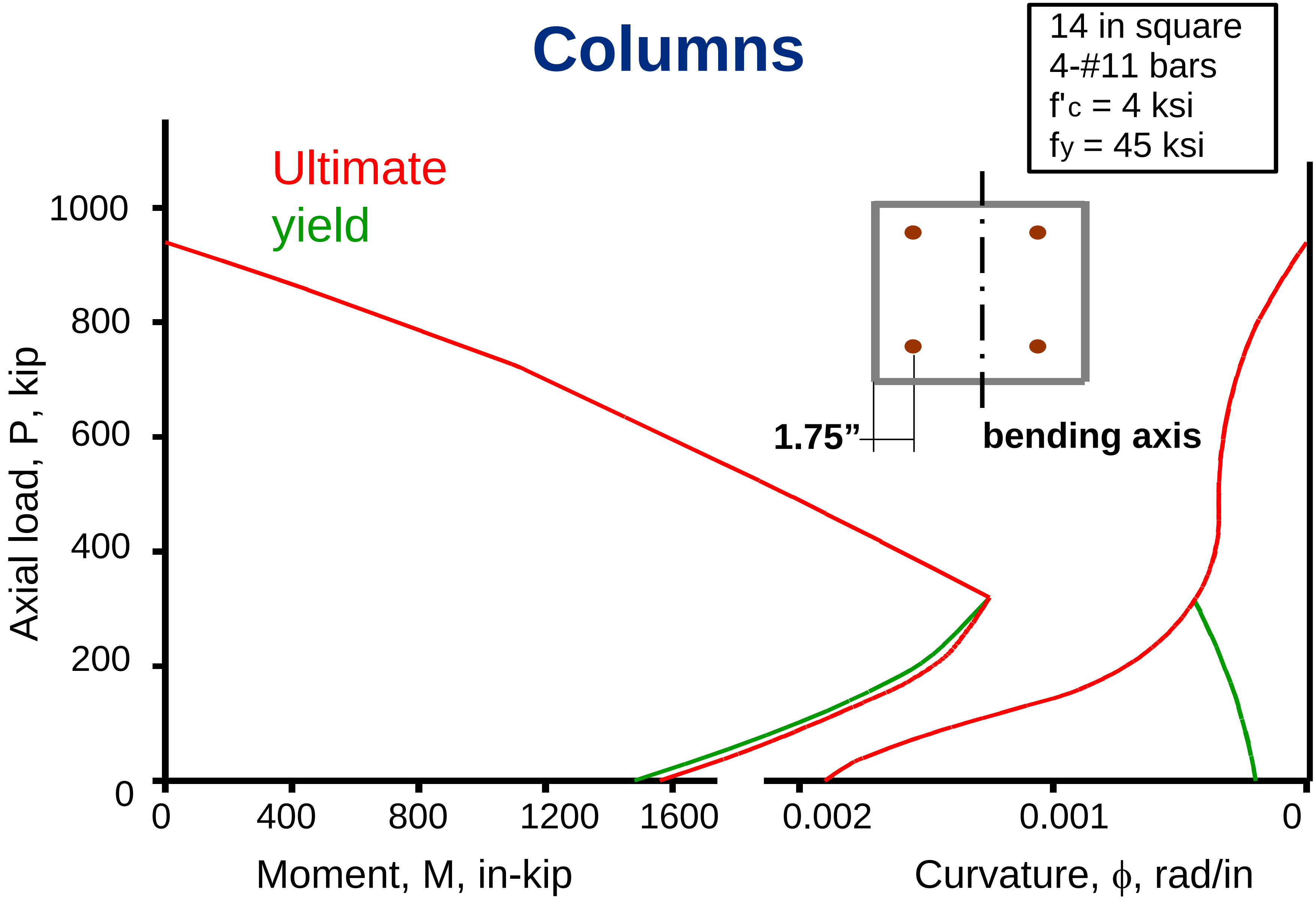
Sliding on flexural cracks

Sliding on construction joint

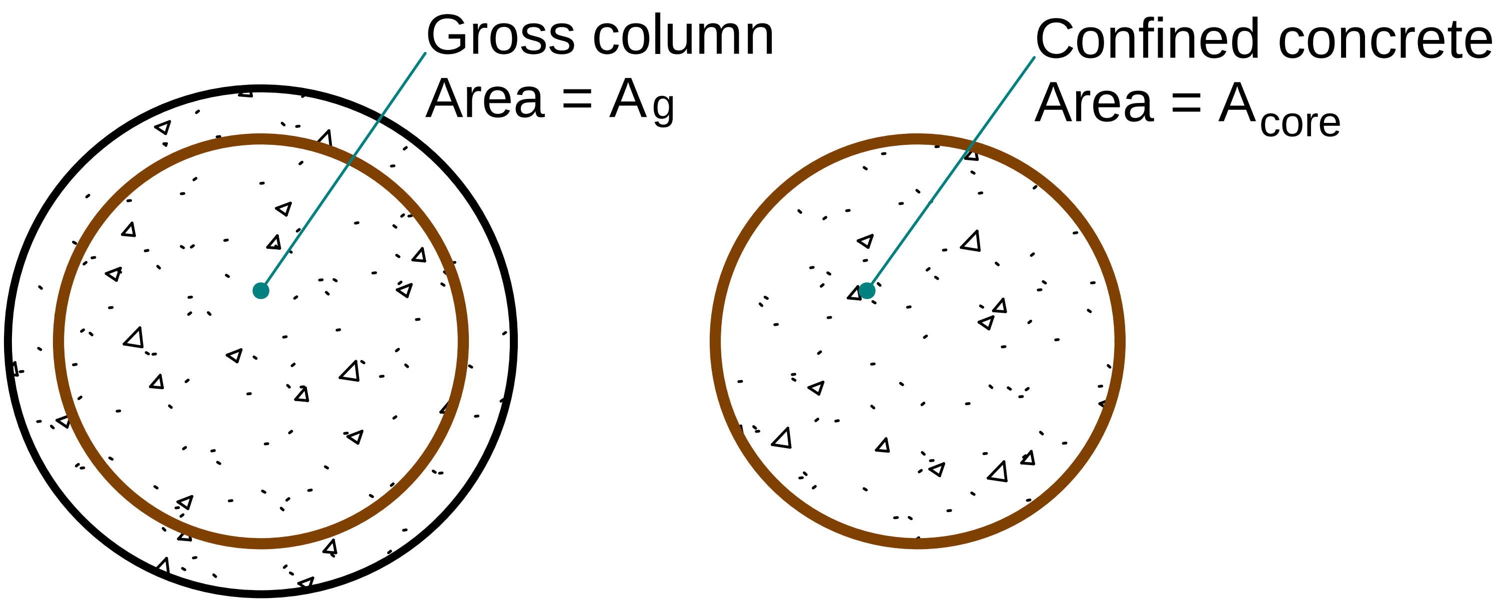
Structural Behavior
Walls



Structural Behavior
Columns



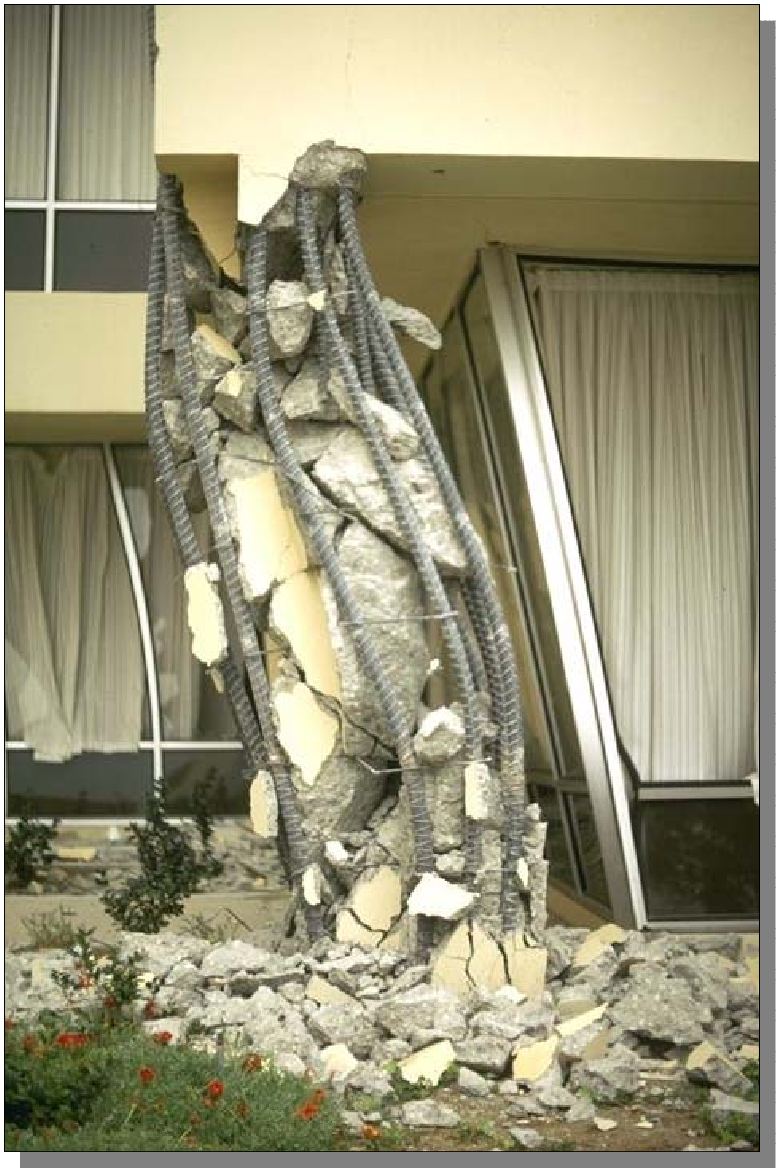
Influence of Hoops on Axial Strength



Before spalling-
$P = A_g f'_c$

After spalling-
$P = A_{core}(f'_c + 4 f_{lat})$

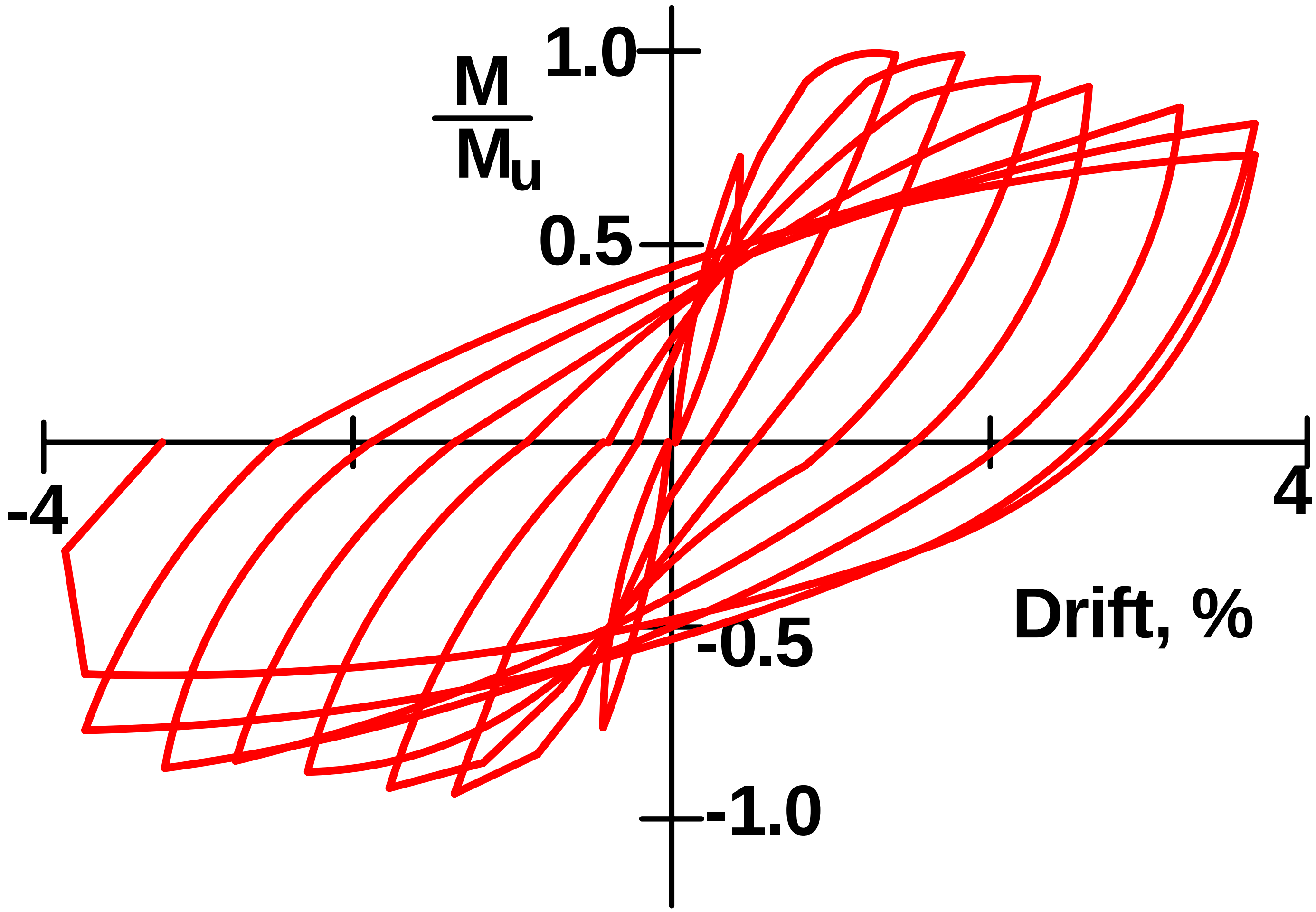
After spalling ≥ Before spalling



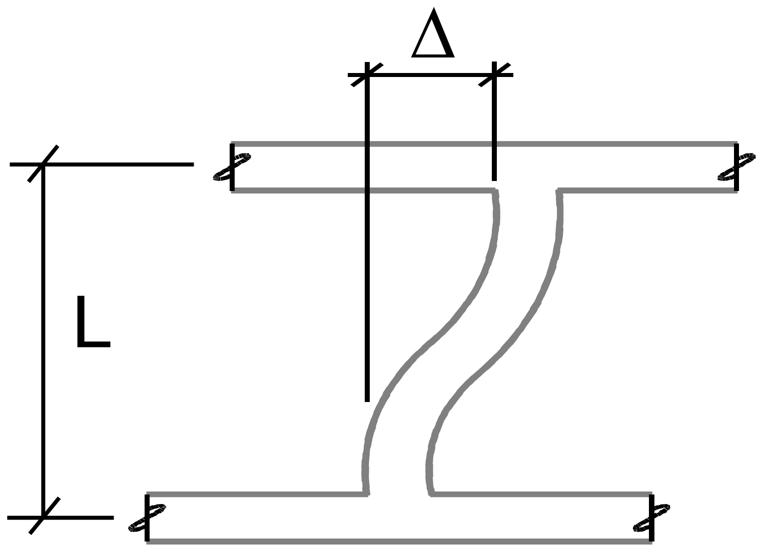
Column with Inadequate Ties

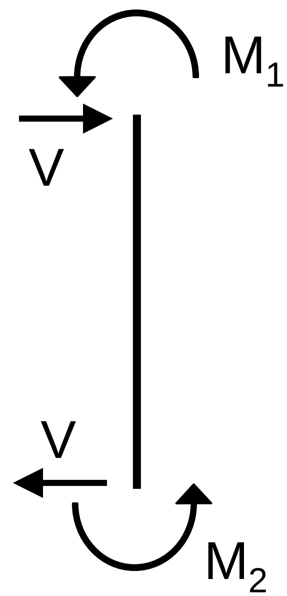
Well Confined Column

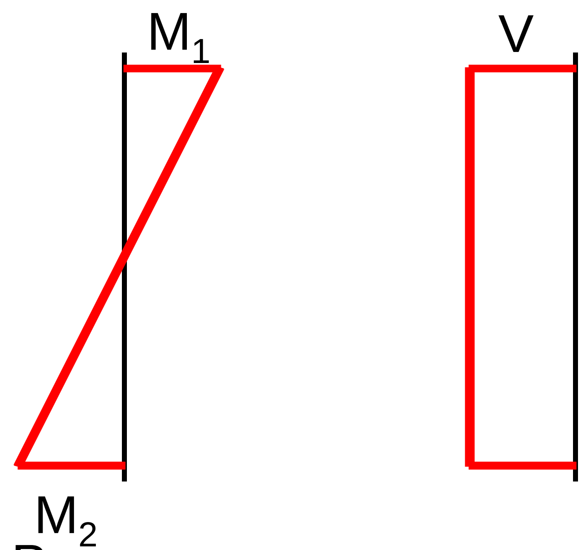
Hysteretic Behavior of Well Confined Column



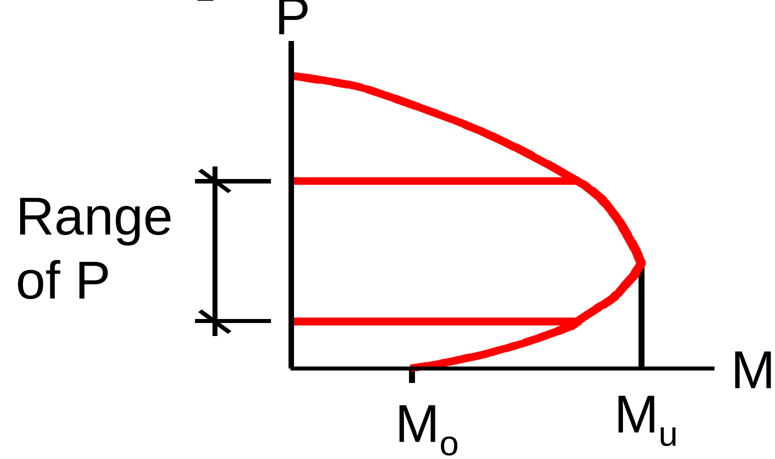
Structural Behavior
Columns





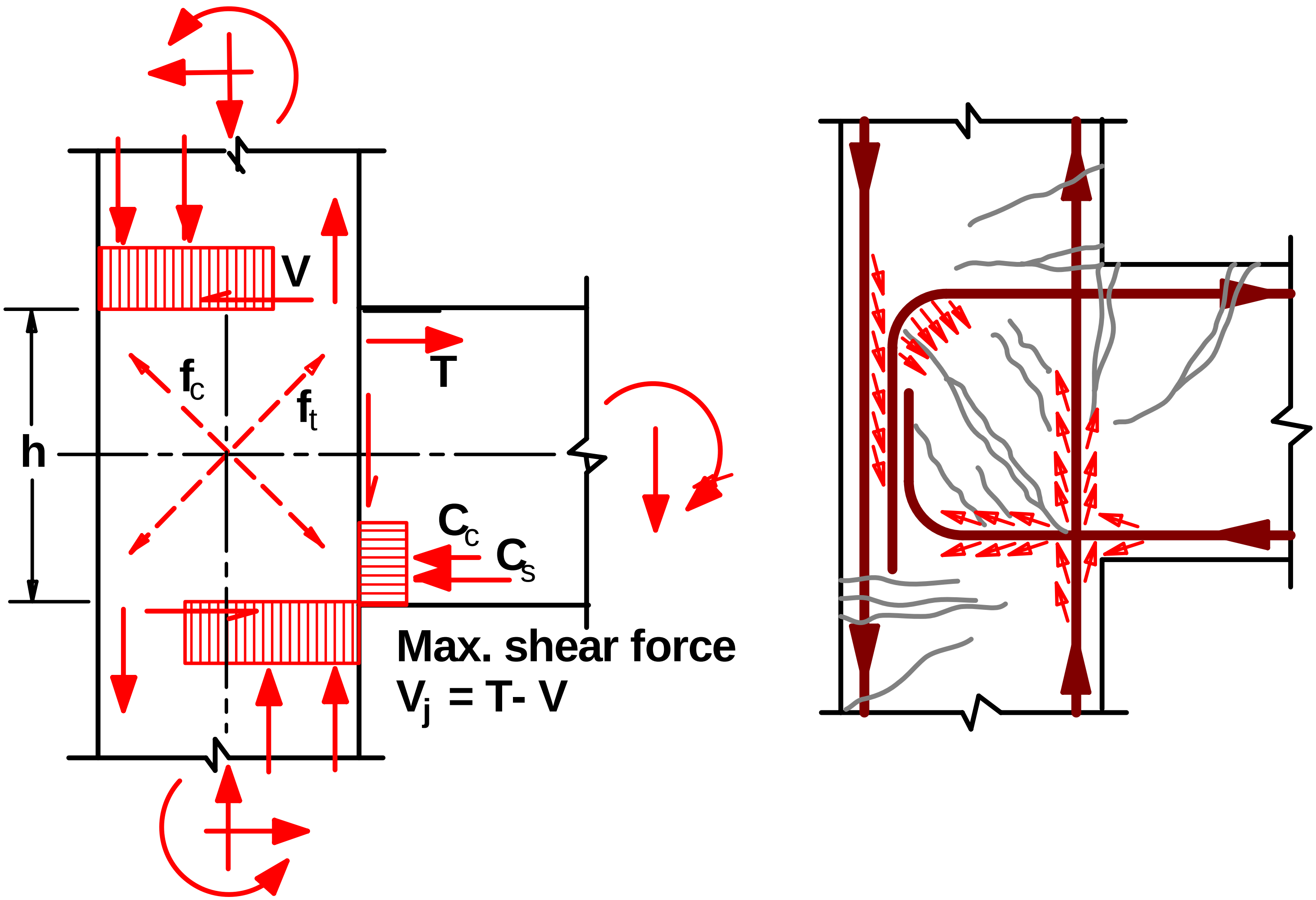


$$V = \frac{M_1 + M_2}{L} = \frac{2M_u}{L}$$

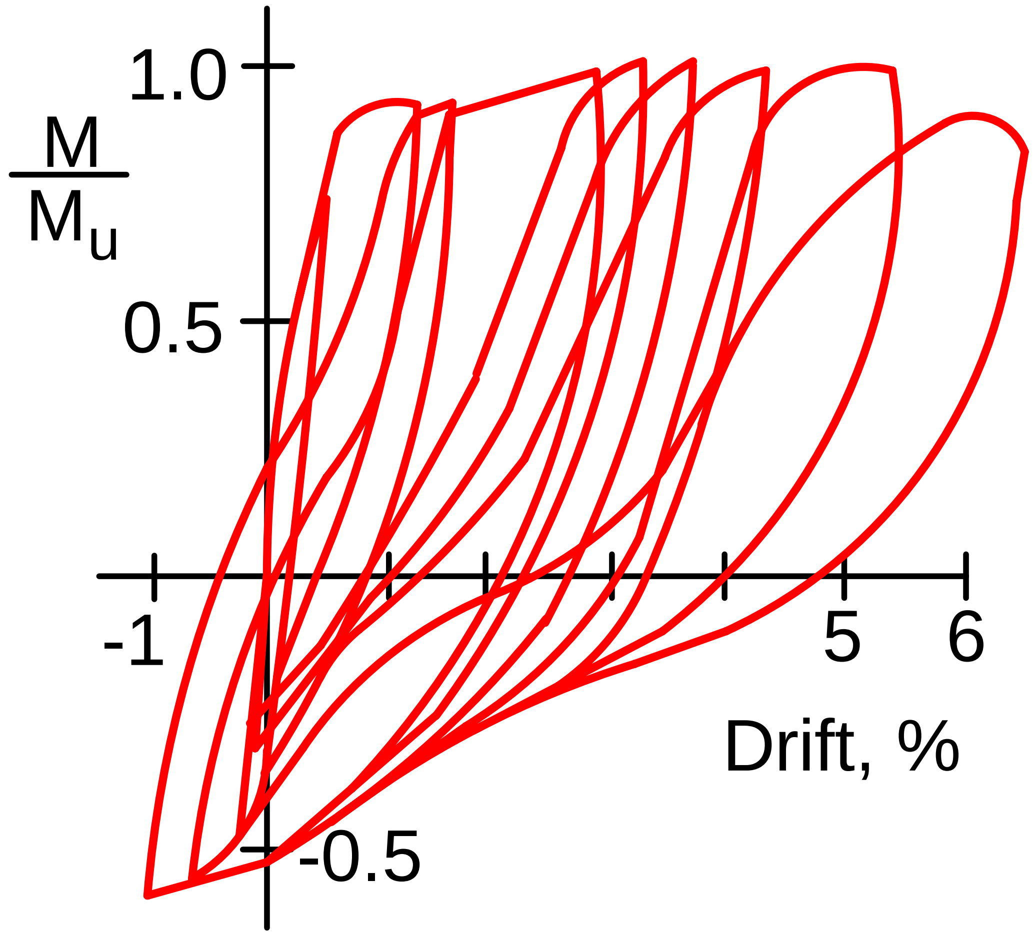


Column Shear Failure

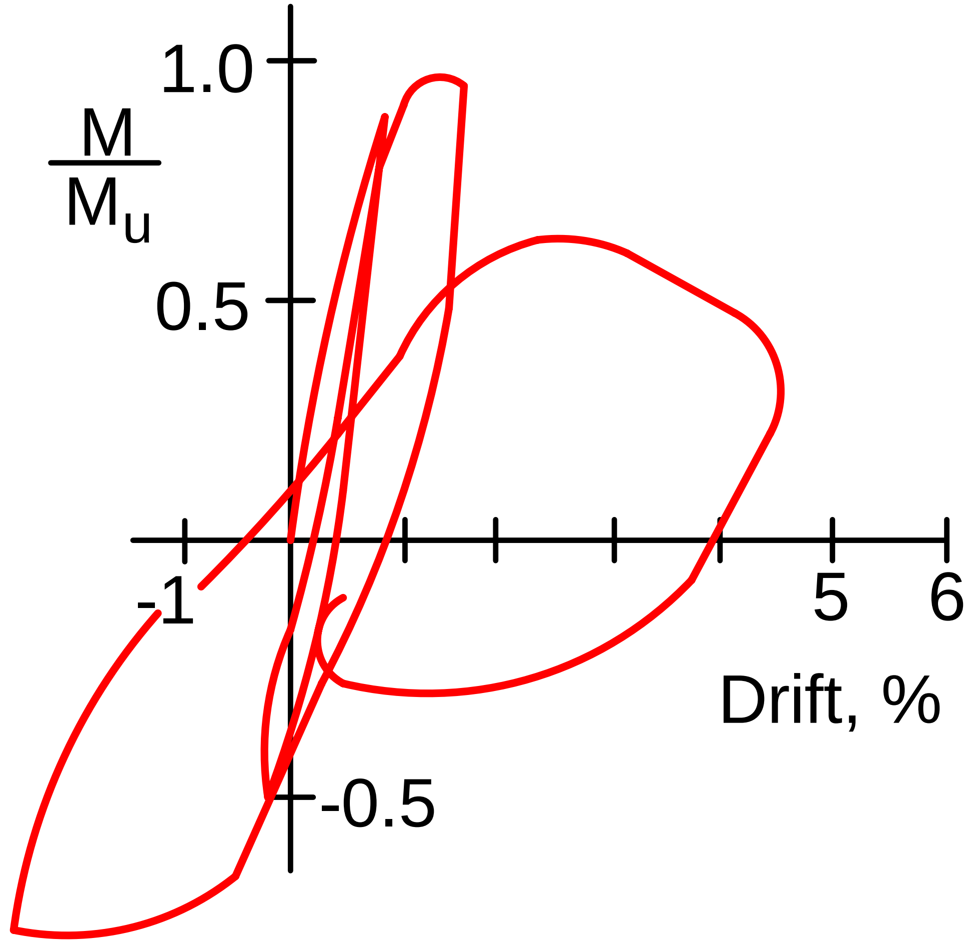
Structural Behavior
Joints



Hysteretic Behavior of Joint with Hoops



Hysteretic Behavior of Joint with No Hoops



Joint Failure – No Shear Reinforcing

Anchorage Failure in Column/Footing Joint

Summary of Concrete Behavior

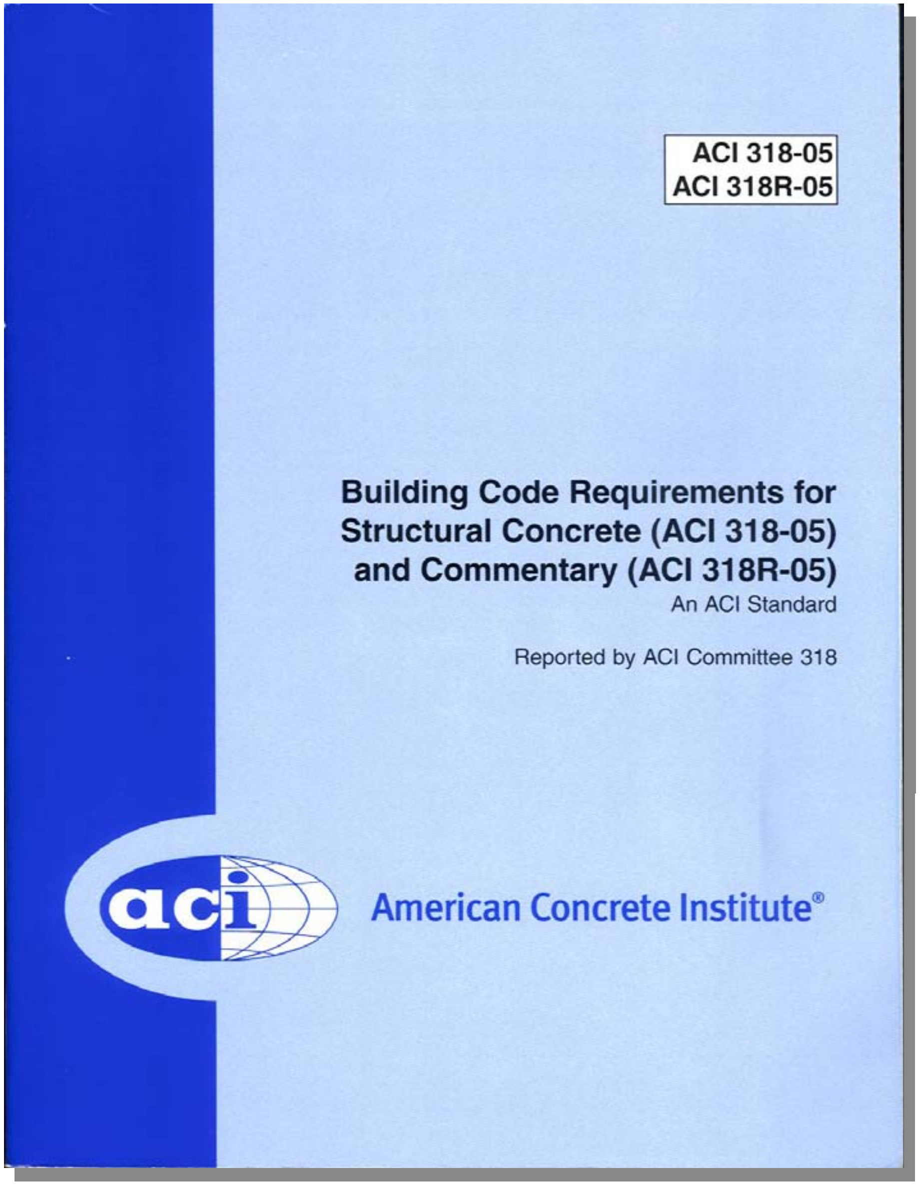
- **Compressive Ductility**
  - Strong in compression but brittle
  - Confinement improves ductility by
    - Maintaining concrete core integrity
    - Preventing longitudinal bar buckling
- **Flexural Ductility**
  - Longitudinal steel provides monotonic ductility at low reinforcement ratios
  - Transverse steel needed to maintain ductility through reverse cycles and at very high strains (hinge development)

Summary of Concrete Behavior

- **Damping**
  - Well cracked: moderately high damping
  - Uncracked (e.g. prestressed): low damping
- **Potential Problems**
  - Shear failures are brittle and abrupt and must be avoided
  - Degrading strength/stiffness with repeat cycles
    - Limit degradation through adequate hinge development

NEHRP Recommended Provisions Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**
- **Reference standards**


ACI 318-05
ACI 318R-05
Building Code Requirements for
Structural Concrete (ACI 318-05)
and Commentary (ACI 318R-05)
An ACI Standard
Reported by ACI Committee 318
aci
American Concrete Institute®

ACI 318-05

Use of Reference Standards

- **ACI 318-05**
  - Chapter 21, Special Provisions for Seismic Design
- **NEHRP Chapter 9, Concrete Structures**
  - General design requirements
  - Modifications to ACI 318
  - Seismic Design Category requirements
  - Special precast structural walls
  - Untopped precast diaphragms (Appendix to Ch.9)

Detailed Modifications to ACI 318

- Modified definitions and notations
- Scope and material properties
- Special moment frames
- Special shear walls
- Special and intermediate precast walls
- Foundations
- Anchoring to concrete

NEHRP Recommended Provisions Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**
- **Reference standards**
- **Requirements by Seismic Design Category**

Design Coefficients - Moment Resisting Frames

Seismic Force Resisting System	Response Modification Coefficient, R	Deflection Amplification Factor, C_d
Special R/C Moment Frame	8	5.5
Intermediate R/C Moment Frame	5	4.5
Ordinary R/C Moment Frame	3	2.5

Design Coefficients
Shear Walls (Bearing Systems)

Seismic Force Resisting System	Response Modification Coefficient, R	Deflection Amplification Factor, C_d
Special R/C Shear Walls	5	5
Ordinary R/C Shear Walls	4	4
Intermediate Precast Shear Walls	4	4
Ordinary Precast Walls	3	3

Design Coefficients
Shear Walls (Frame Systems)

Seismic Force Resisting System	Response Modification Coefficient, R	Deflection Amplification Factor, C_d
Special R/C Shear Walls	6	5
Ordinary R/C Shear Walls	5	4.5
Intermediate Precast Shear Walls	5	4.5
Ordinary Precast Walls	4	4

Design Coefficients
Dual Systems with Special Frames

Seismic Force Resisting System	Response Modification Coefficient, R	Deflection Amplification Factor, C_d
Dual System w/ Special Walls	8 (7)	6.5 (5.5)
Dual System w/ Ordinary Walls	6	5

(ASCE 7-05 values where different)

Frames

Seismic Design Category	Minimum Frame Type	ACI 318 Requirements
A and B	Ordinary	Chapters 1 thru 18 and 22
C	Intermediate	ACI 21.2.1.3 and ACI 21.12
D, E and F	Special	ACI 21.2.1.4 and ACI 21.2, 21.3, 21.4, and 21.5

Reinforced Concrete Shear Walls

Seismic Design Category	Minimum Wall Type	ACI 318 Requirements
A, B and C	Ordinary	Chapters 1 thru 18 and 22
D, E and F	Special	ACI 21.2.1.4 and ACI 21.2 and 21.7

Precast Concrete Shear Walls

Seismic Design Category	Minimum Wall Type	ACI 318 Requirements
A and B	Ordinary	Chapters 1 thru 18 and 22
C	Intermediate	ACI 21.2.1.3 and ACI 21.13
D, E and F	Special	ACI 21.2.1.4 and ACI 21.2, 21.8

Additional *Provisions* Requirements

- **Category C**
  - Discontinuous members
  - Plain concrete
    - Walls
    - Footings
    - Pedestals (not allowed)

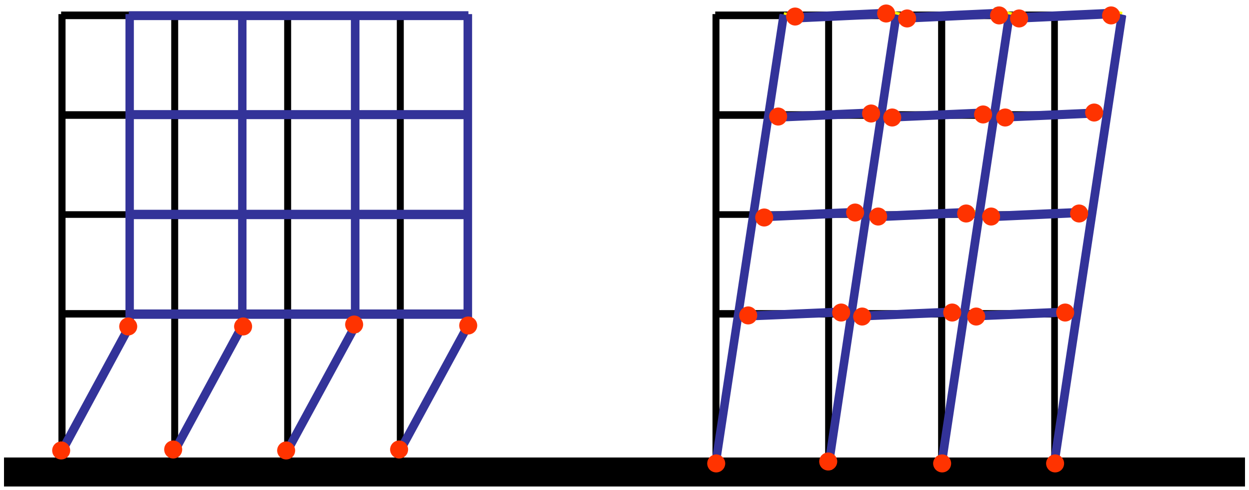
NEHRP Recommended Provisions
Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**
- **Reference standards**
- **Requirements by Seismic Design Category**
- **Moment resisting frames**

Performance Objectives

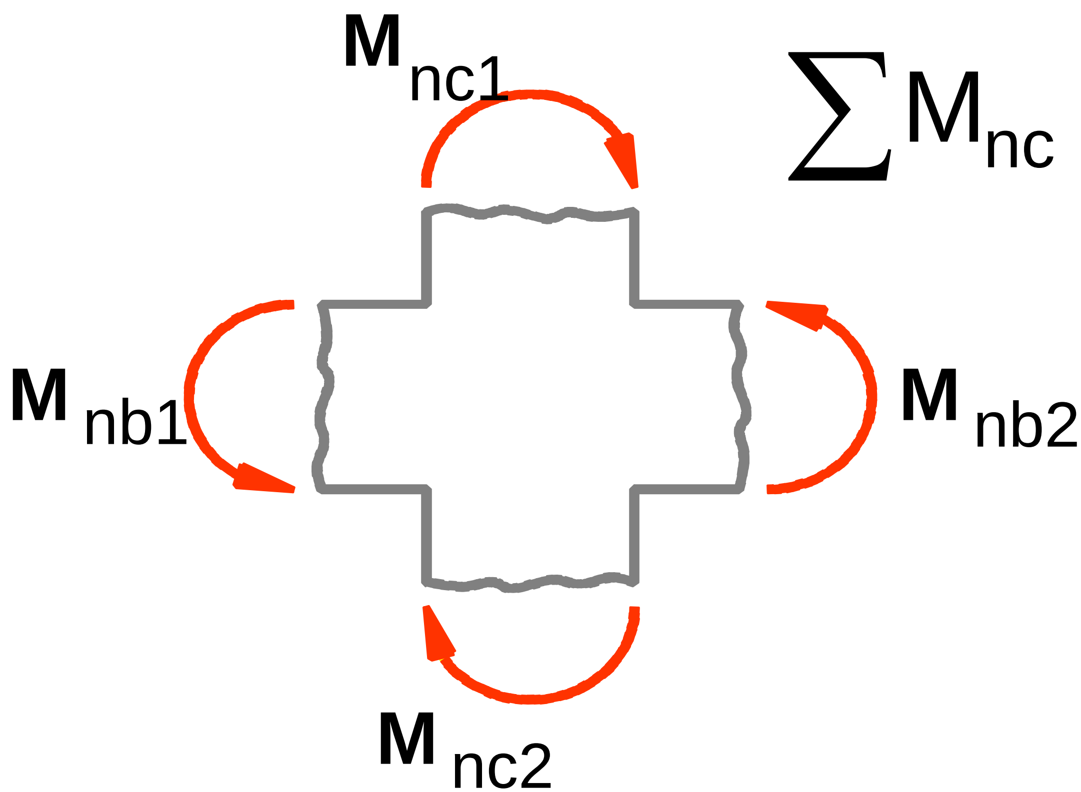
- **Strong column**
  - Avoid story mechanism
- **Hinge development**
  - Confined concrete core
  - Prevent rebar buckling
  - Prevent shear failure
- **Member shear strength**
- **Joint shear strength**
- **Rebar development**

Frame Mechanisms
"strong column – weak beam"



Story mechanism Sway mechanism

Required Column Strength

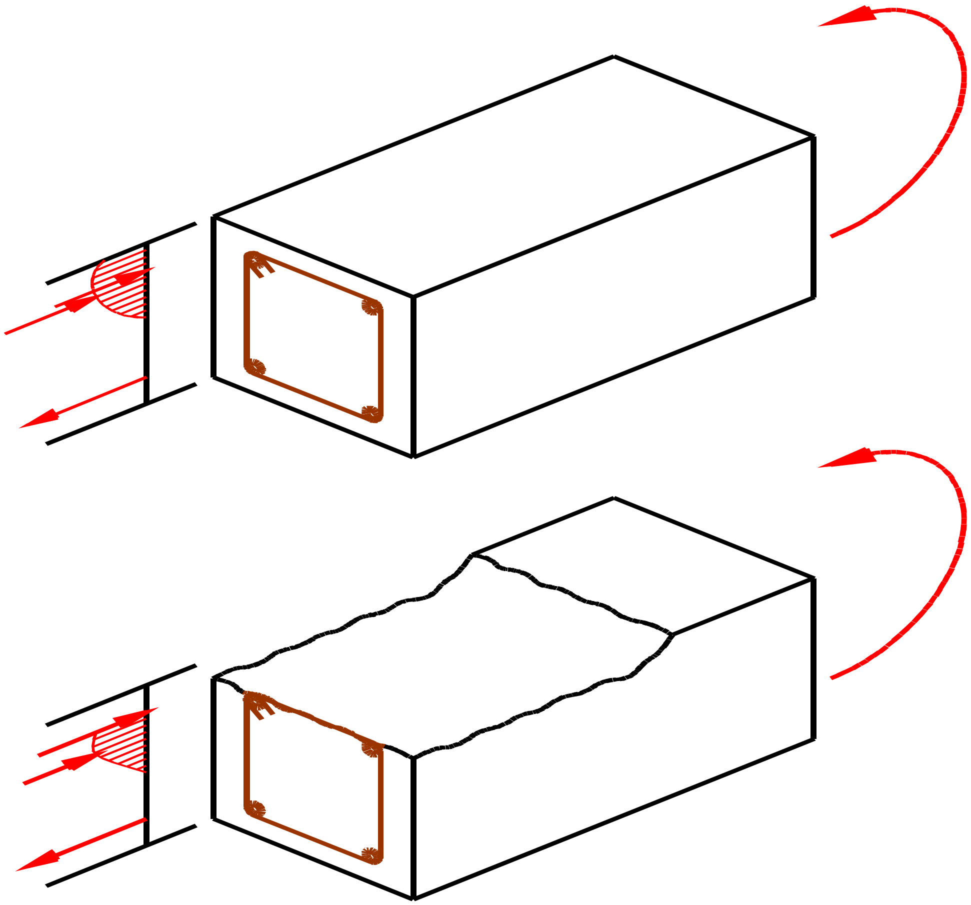


$$\sum M_{nc} \geq 1.2 \sum M_{nb}$$

Hinge Development

- **Tightly Spaced Hoops**
  - Provide confinement to increase concrete strength and usable compressive strain
  - Provide lateral support to compression bars to prevent buckling
  - Act as shear reinforcement and preclude shear failures
  - Control splitting cracks from high bar bond stresses

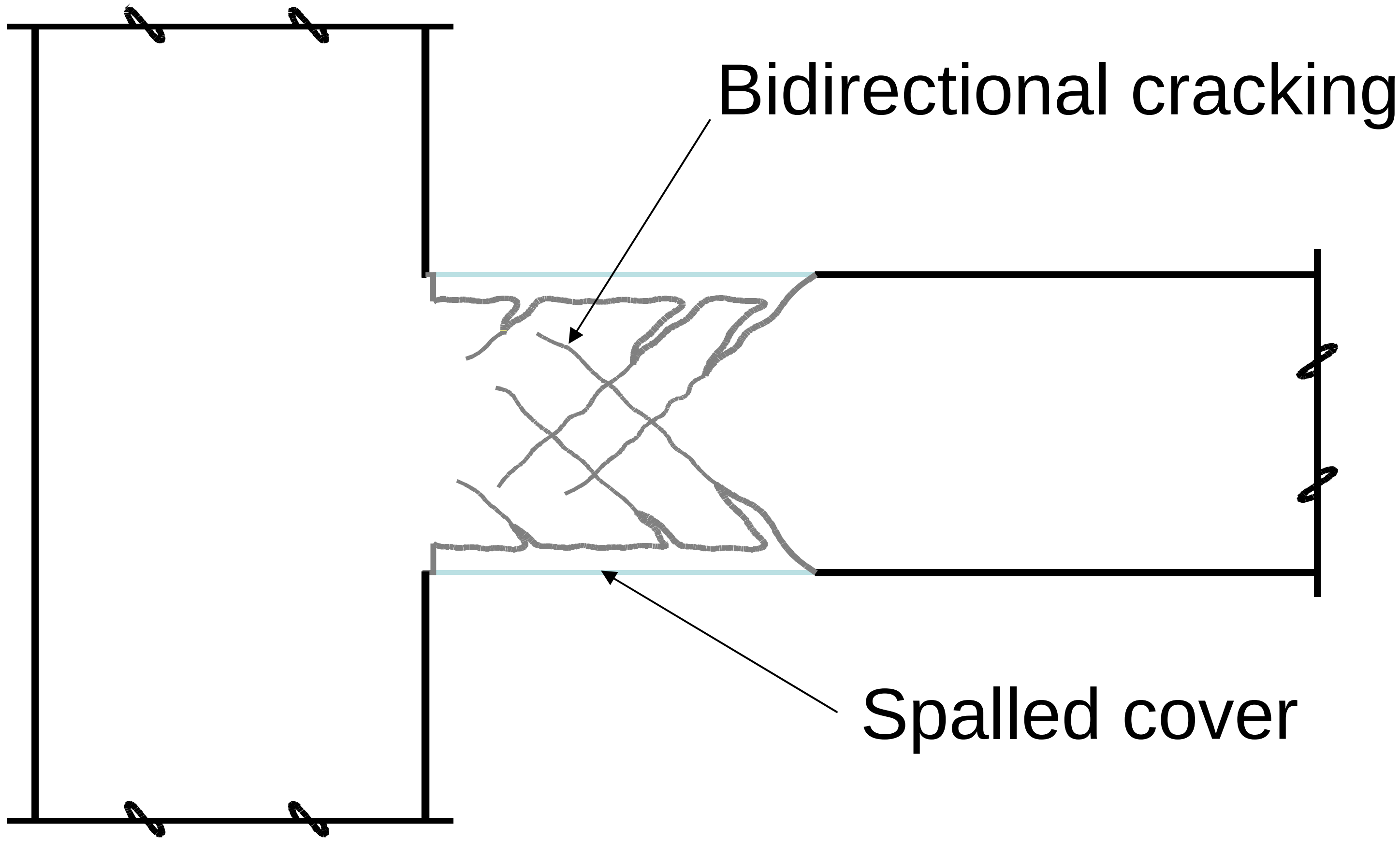
Hinge Development



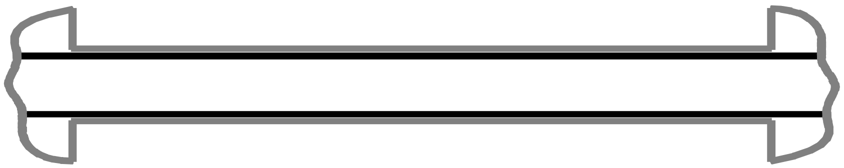
Before spalling

After spalling

Hinge Development

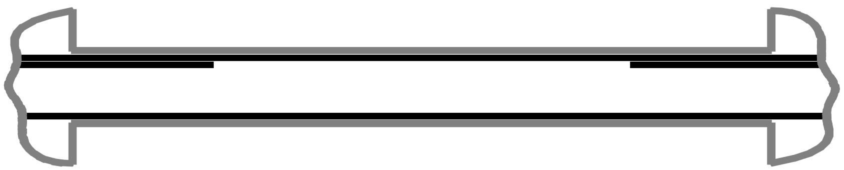


ACI 318-05, Overview of Frames:
Beam Longitudinal Reinforcement

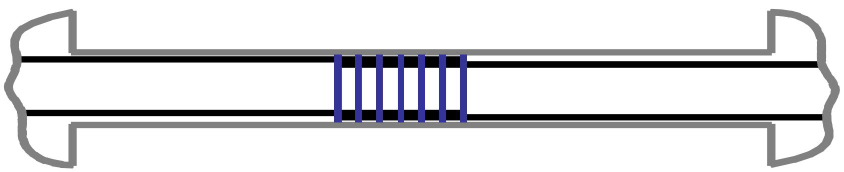


$$200/f_y \le \rho \le 0.025$$

At least 2 bars continuous top & bottom

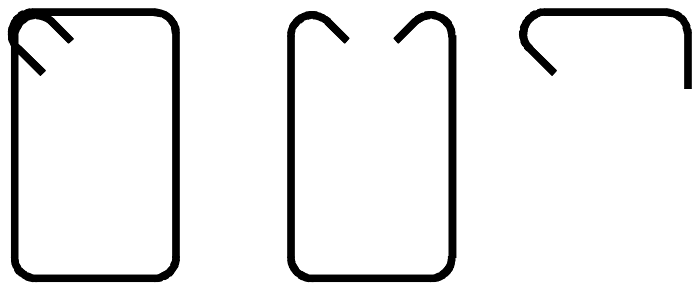


Joint face M_n^+ not less than 50% M_n^-
Min. M_n^+ or M_n^- not less than 25% max. M_n at joint face



Splice away from hinges and enclose within hoops or spirals

ACI 318-05, Overview of Frames:
Beam Transverse Reinforcement

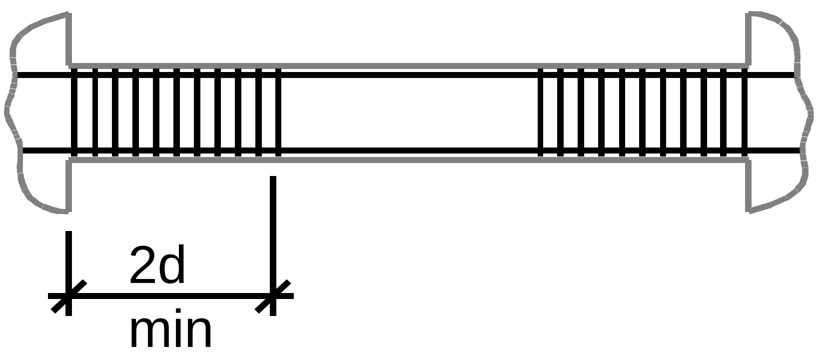


Closed hoops at hinging regions with “seismic” hook

135º hook, $6d_h \geq 3$” extension

Maximum spacing of hoops:

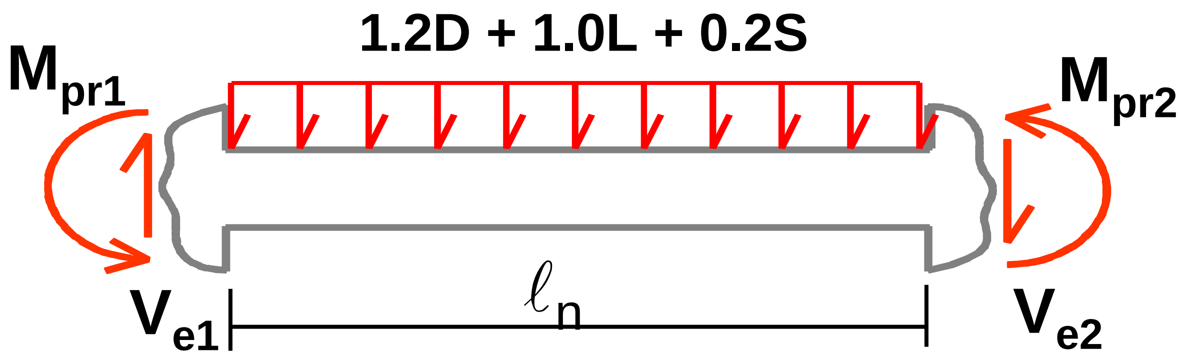
$d/4$ $8d_b$ $24d_h$ 12”



Longitudinal bars on perimeter tied as if column bars

Stirrups elsewhere, $s \leq d/2$

ACI 318-05, Overview of Frames:
Beam Shear Strength



$M_{pr} = M_n$ with

$f_s = 1.25 f_y, \quad \phi = 1.0$

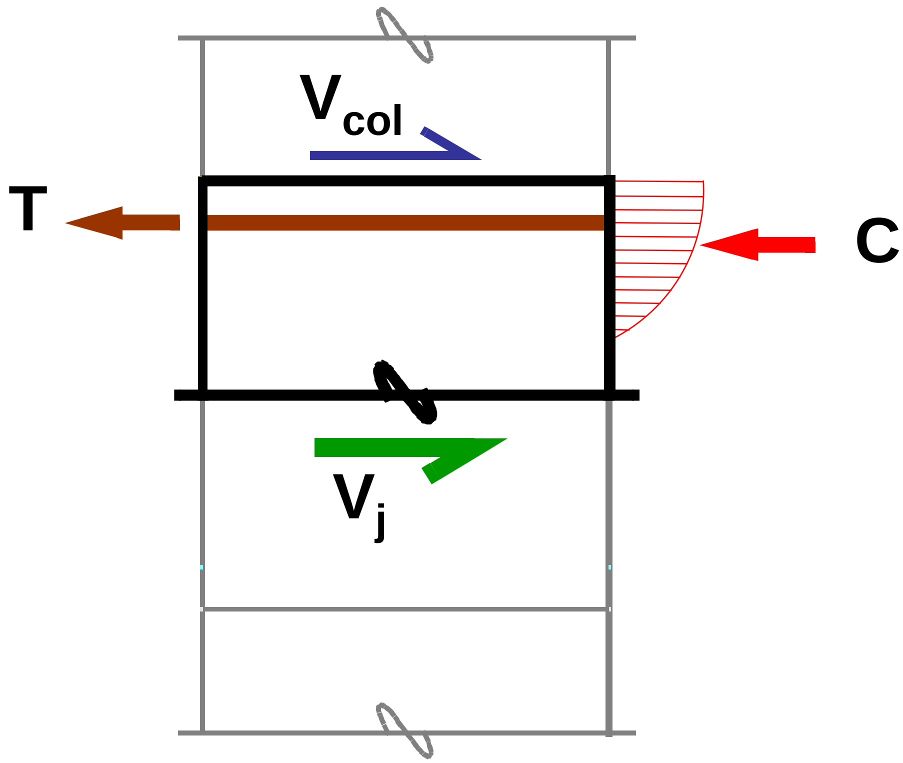
$$V_e = \frac{M_{pr1} + M_{pr2}}{\ell_n} \pm \frac{w_u \ell_n}{2} \geq V_e \text{ by analysis}$$

If earthquake-induced shear force $> \frac{1}{2} V_e$

and $P_u < \frac{A_g f_c'}{20}$

then $V_c = 0$

ACI 318-05, Overview of Frames:
Beam-Column Joint



$$V_j = T + C - V_{col}$$

$$T = 1.25 f_y A_{s,top}$$

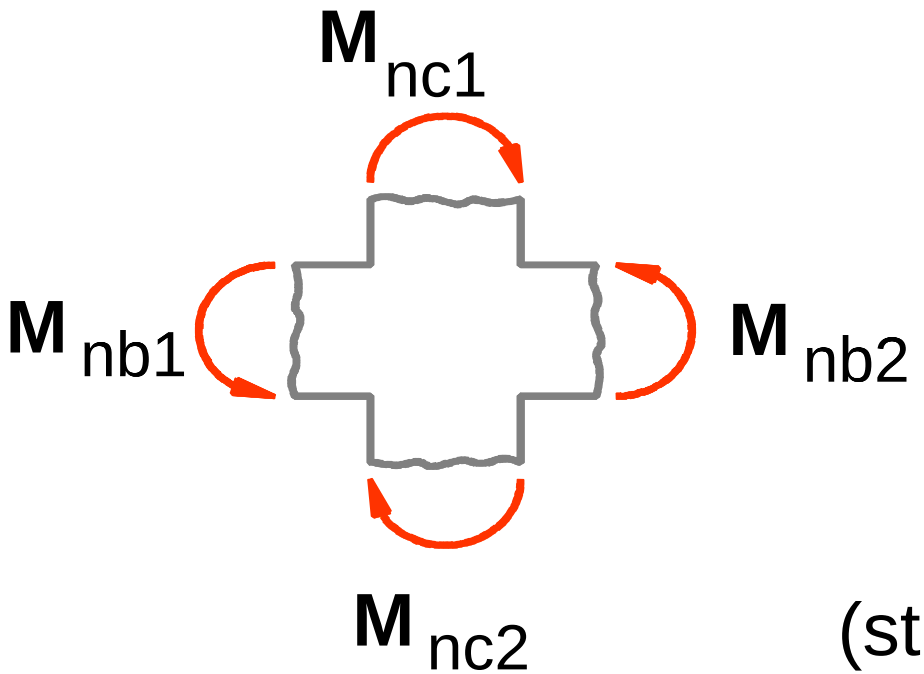
$$C = 1.25 f_y A_{s,bottom}$$

ACI 318-05, Overview of Frames:
Beam-column Joint

$$V_n = \begin{Bmatrix} 20 \\ 15 \\ 12 \end{Bmatrix} \sqrt{f'_c} A_j$$

- **V_n controls size of columns**
- **Coefficient depends on joint confinement**
- **To reduce shear demand, increase beam depth**
- **Keep column stronger than beam**

ACI 318-05: Overview of Frames:
Column Longitudinal Reinforcement



$$0.01 \le \rho \le 0.06$$

$$\sum M_{nc} \ge 1.2 \sum M_{nb}$$

At joints
(strong column-weak beam)

M_{nc} based on factored axial force,
consistent with direction of lateral forces

ACI 318-05, Overview of Frames:
Column Transverse Reinforcement at Potential Hinging Region

Spirals

$$\rho_s = 0.45\left(\frac{A_g}{A_{ch}} - 1\right)\frac{f'_c}{f_{yt}}$$

and

$$\rho_s \ge 0.12\frac{f'_c}{f_{yt}}$$

Hoops

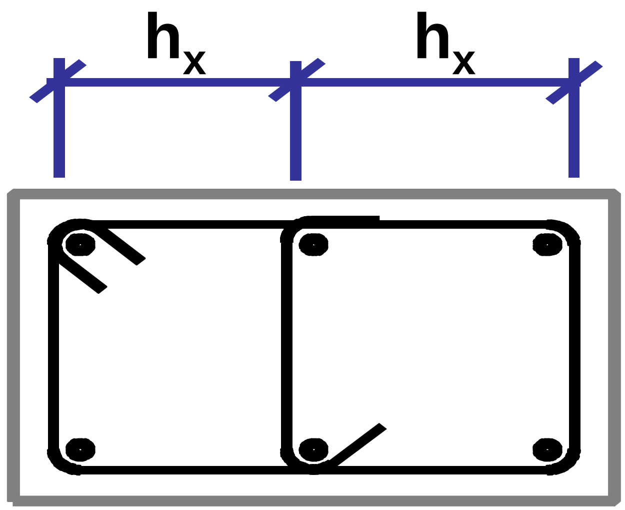
$$A_{sh} \ge 0.3\left(sb_c\frac{f'_c}{f_{yt}}\right)\left(\frac{A_g}{A_{ch}} - 1\right)$$

and

$$A_{sh} \ge 0.09sb_c\frac{f'_c}{f_{yt}}$$

ACI 318-05, Overview of Frames:

Column Transverse Reinforcement at Potential Hinging Region



$$s_o = 4 + \left(\frac{14 - h_x}{3} \right)$$

Spacing shall not exceed the smallest of:

b/4 or 6 d_b or s_o (4" to 6")

Distance between legs of hoops or crossties, $h_x \leq 14"$

ACI 318-05, Overview of Frames:
Potential Hinge Region

- **For columns supporting stiff members such as walls, hoops are required over full height of column if**

$$P_e > \frac{f'_c A_g}{10}$$

- **For shear strength- same rules as beams (concrete shear strength is neglected if axial load is low and earthquake shear is high)**
- **Lap splices are not allowed in potential plastic hinge regions**

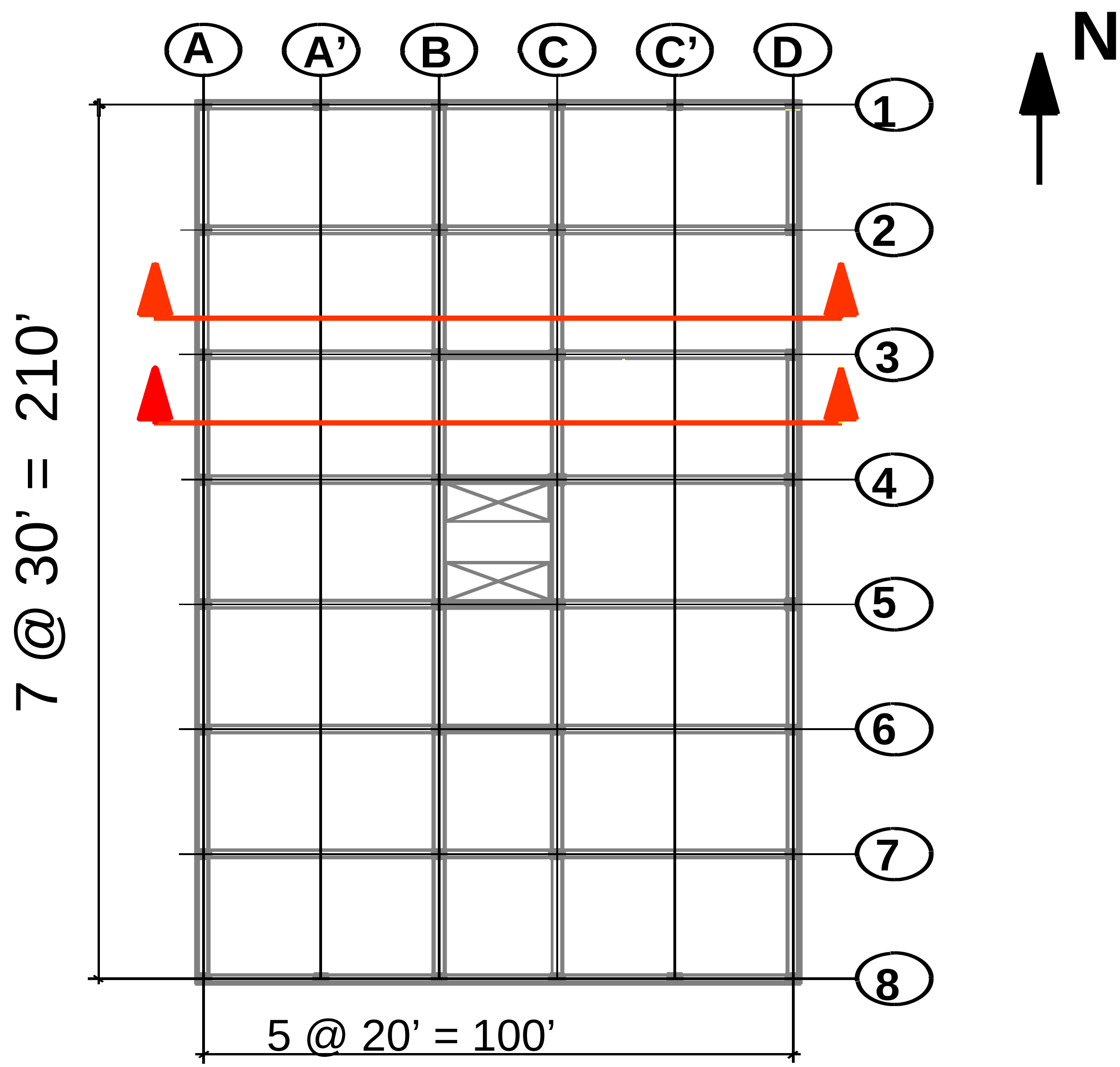
Splice in Hinge Region

Terminating bars

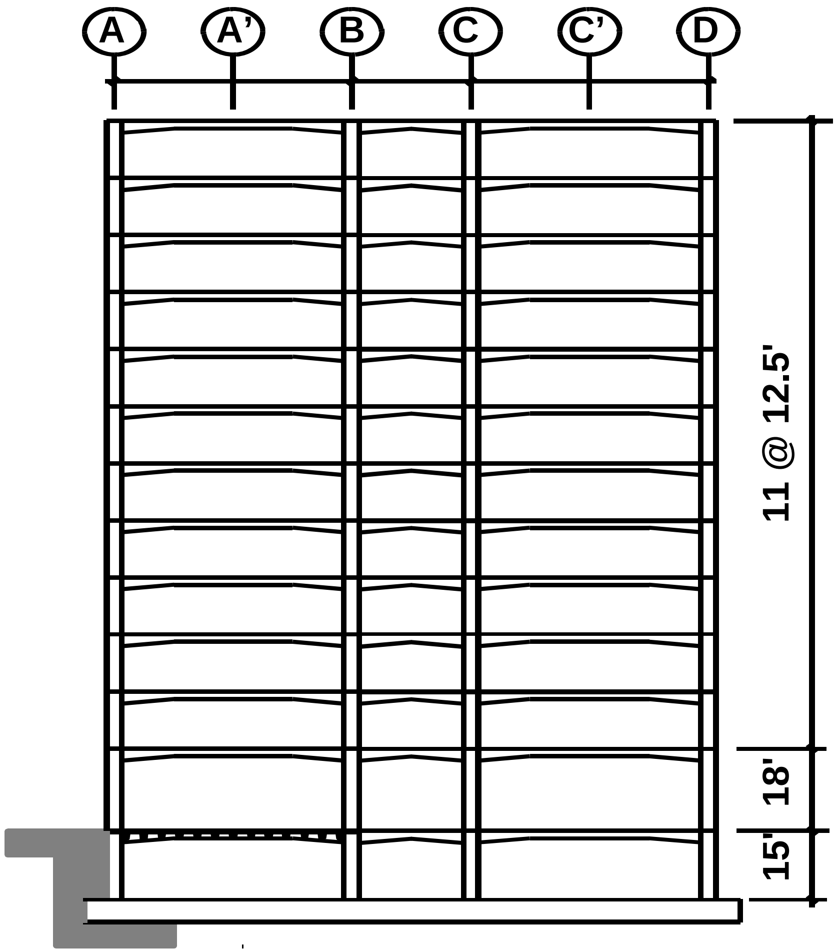
ACI 318-05, Overview of Frames:
Potential Hinge Region

$$\ell_o \geq \begin{Bmatrix} d \\ \\ \dfrac{clear\ height}{6} \\ \\ 18'' \\ \\ \end{Bmatrix}$$

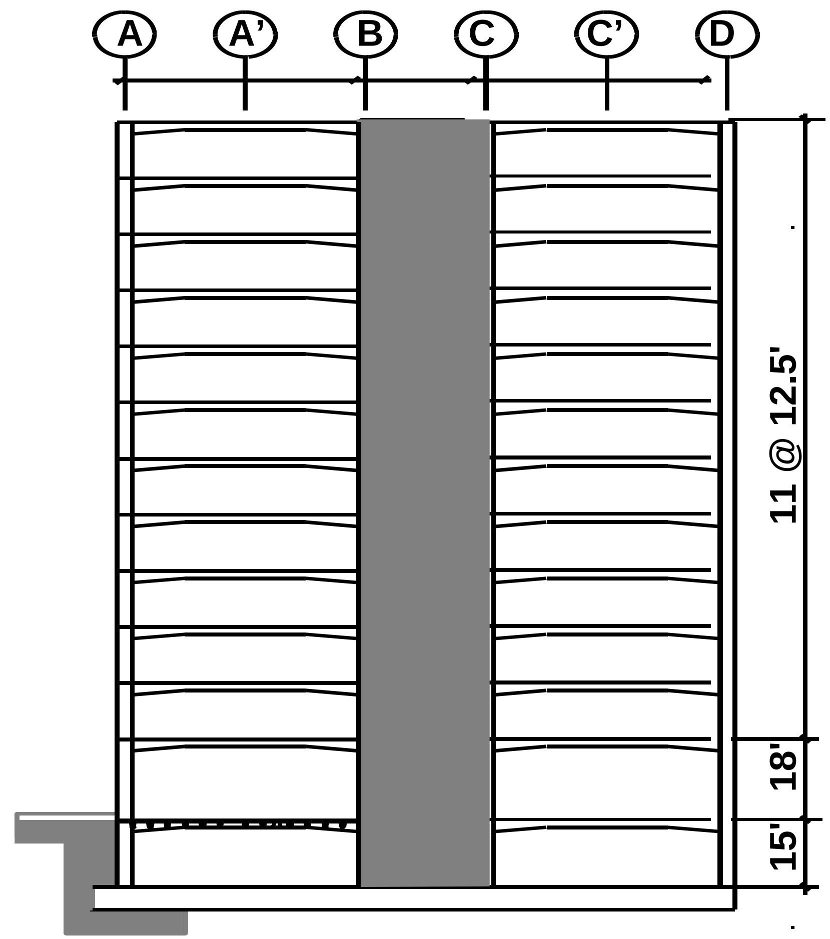
Moment Frame Example



Frame Elevations

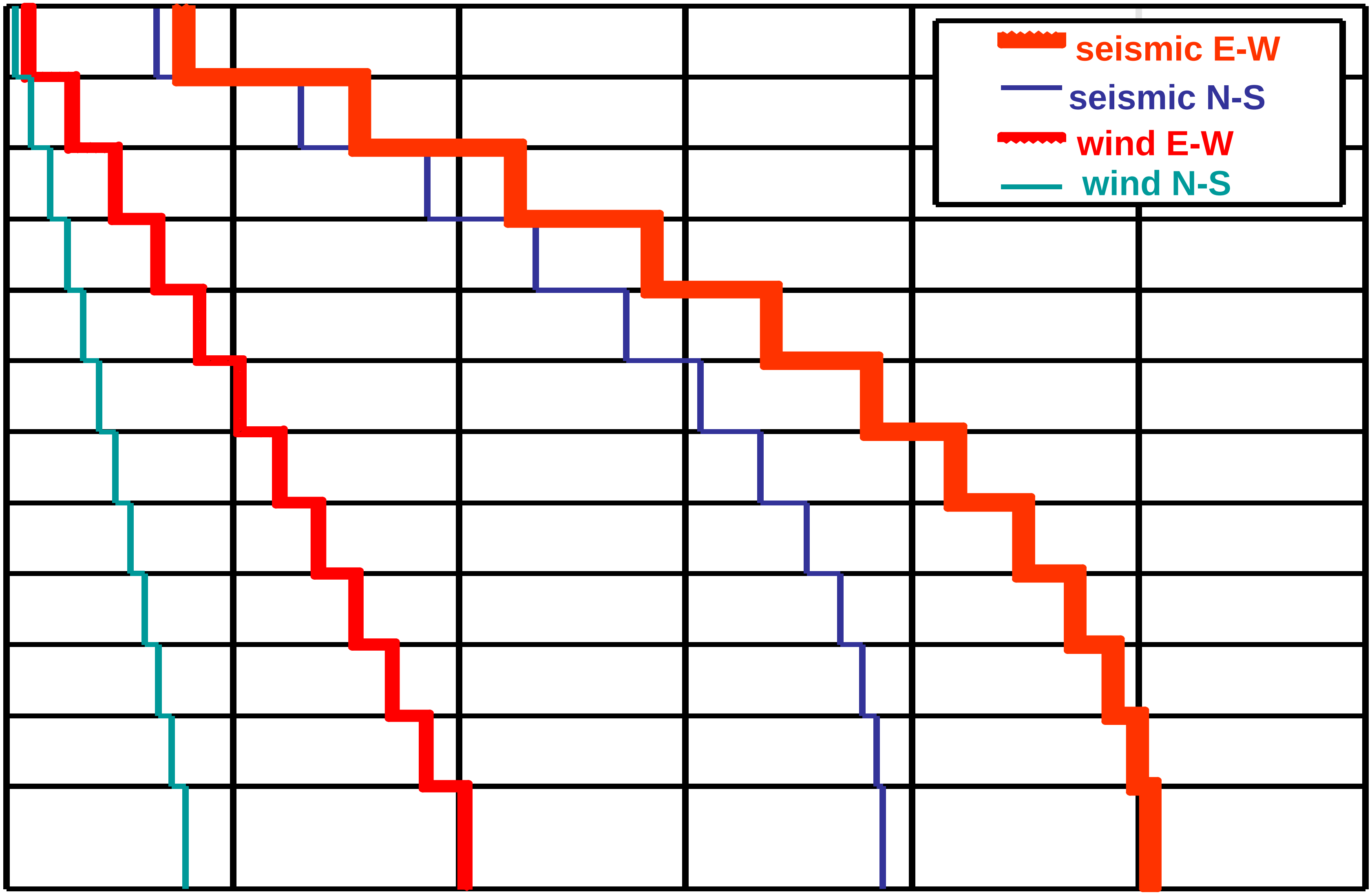


Column Lines 2 and 7

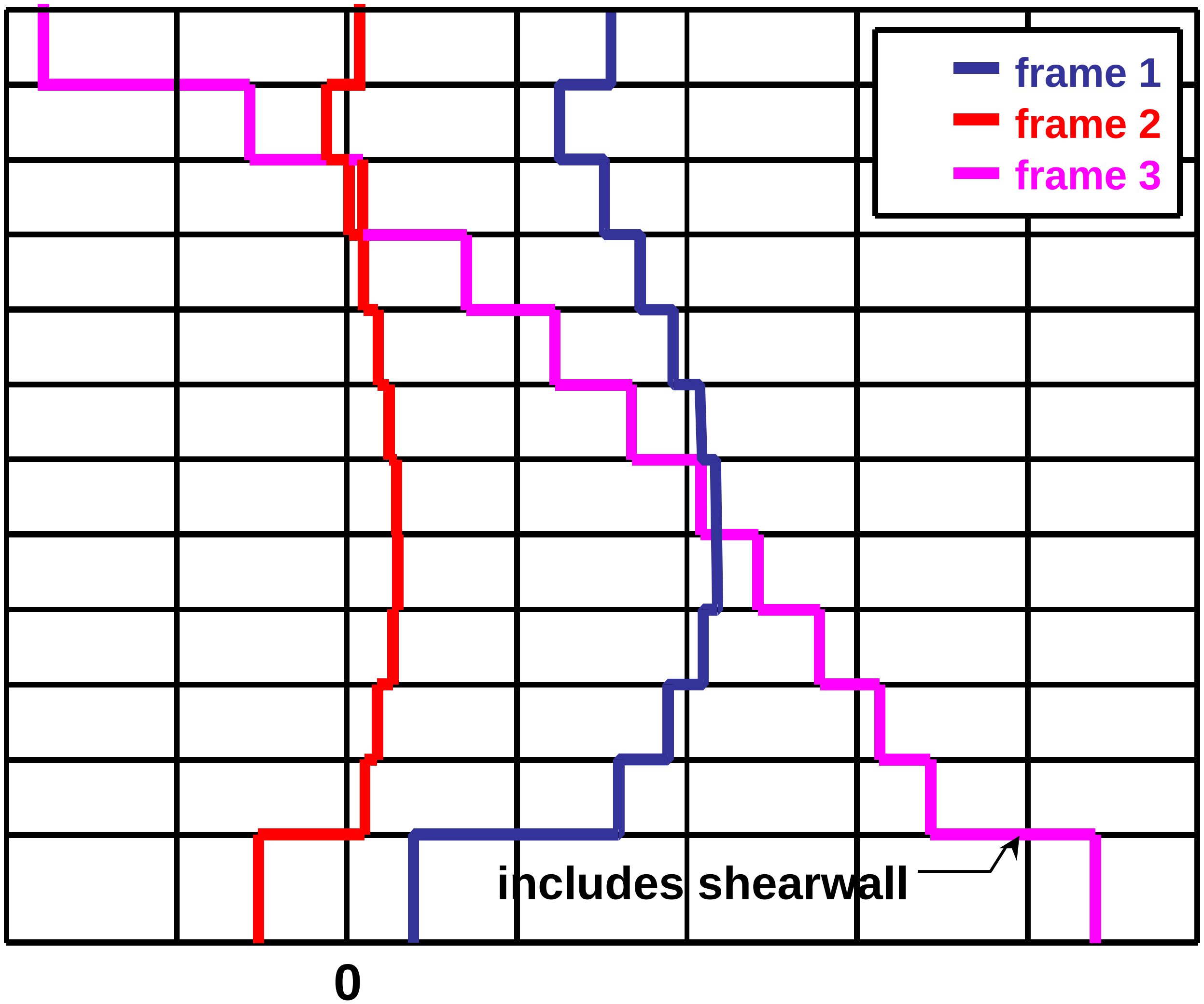


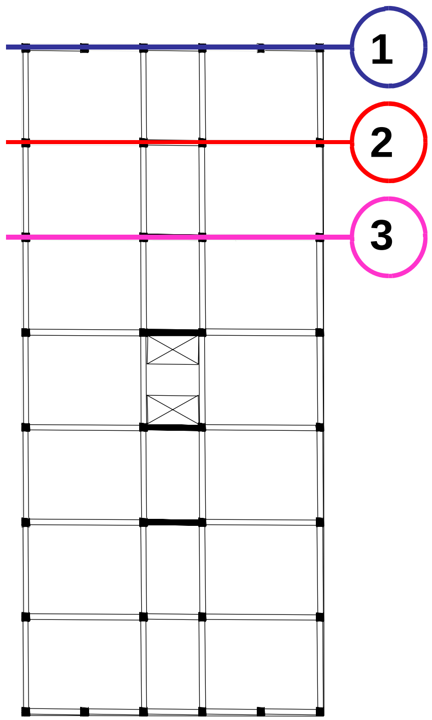
Column Lines 3 to 6

Story Shears: Seismic vs Wind

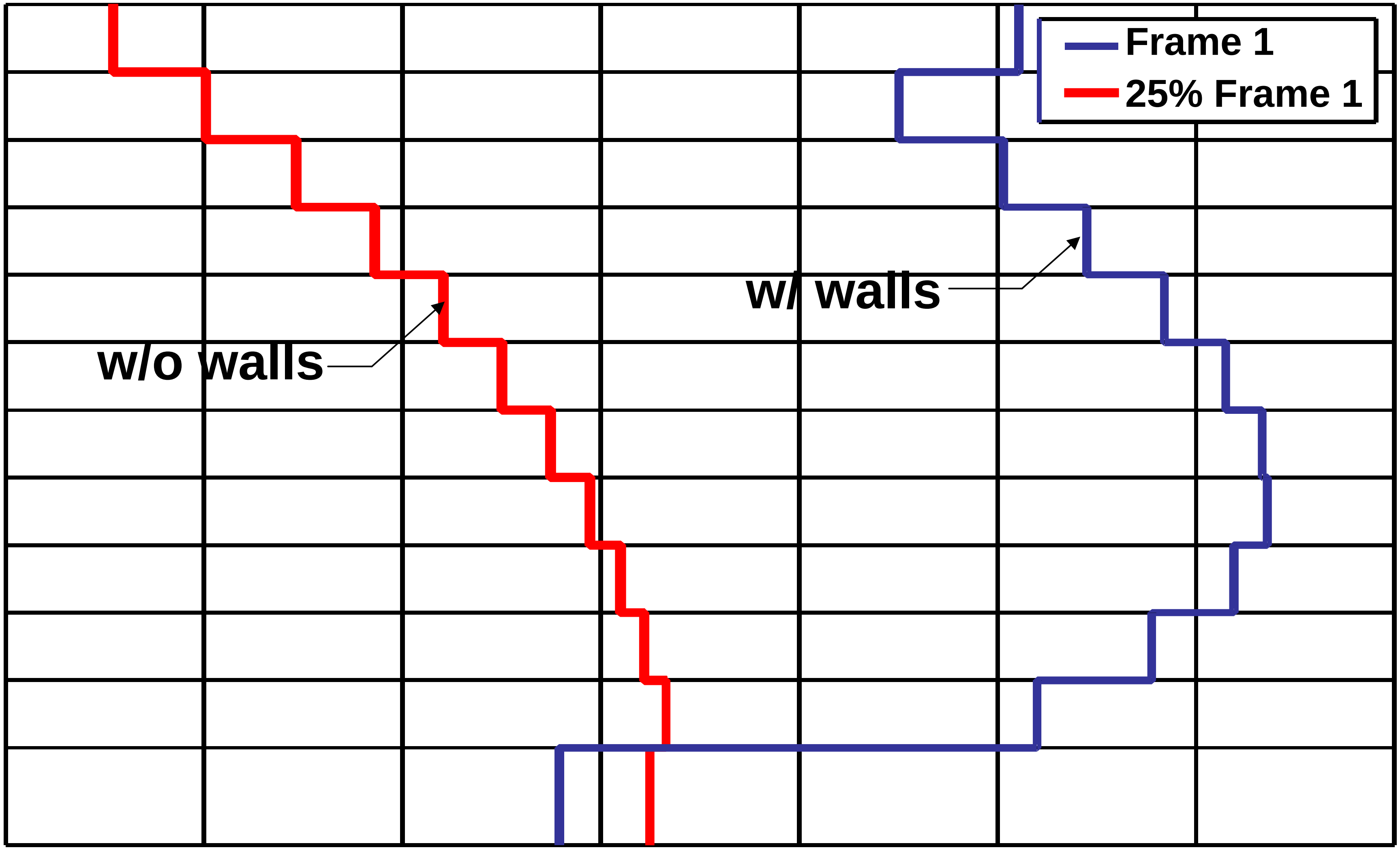


Story Shears: E-W Loading

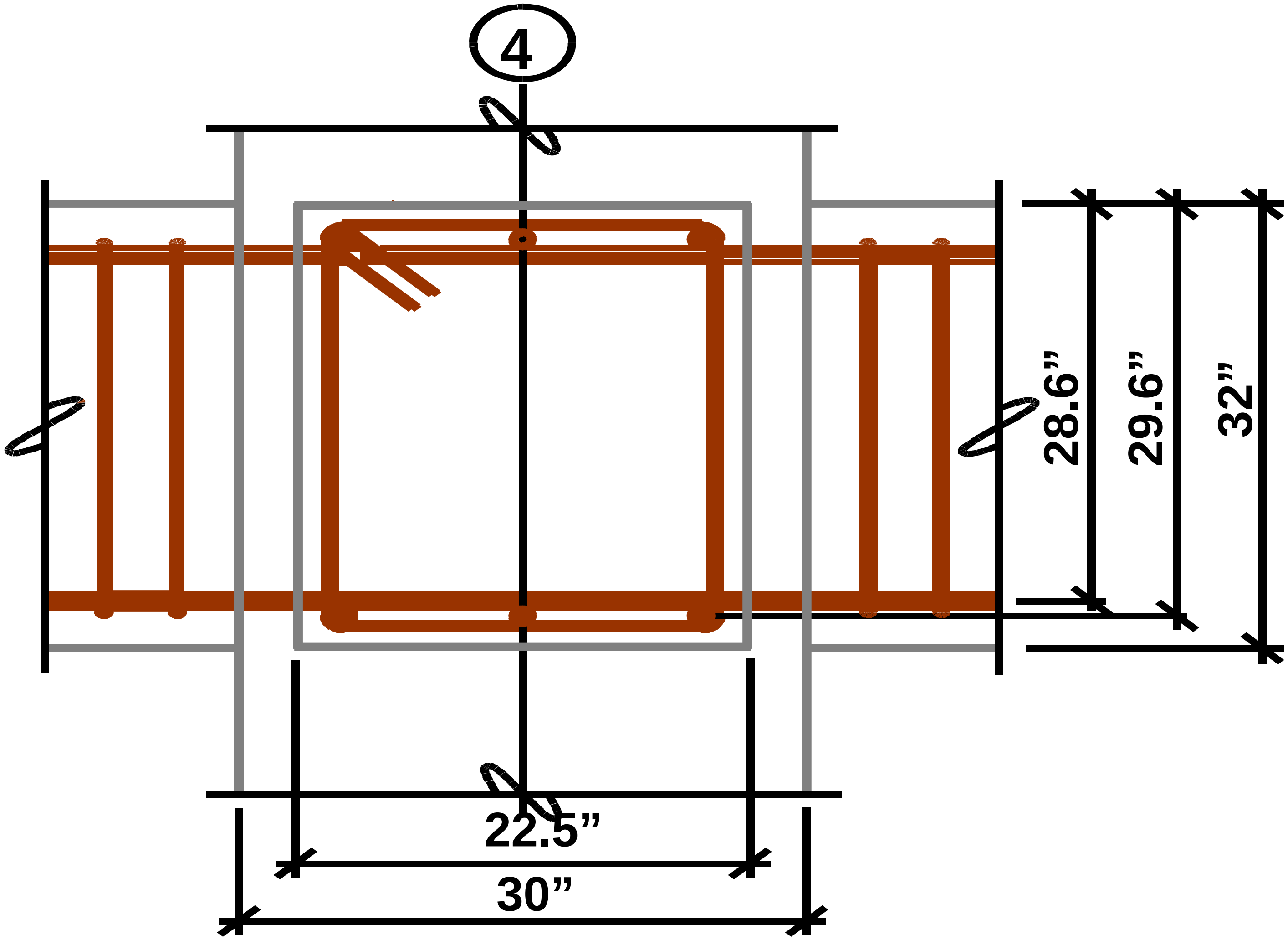




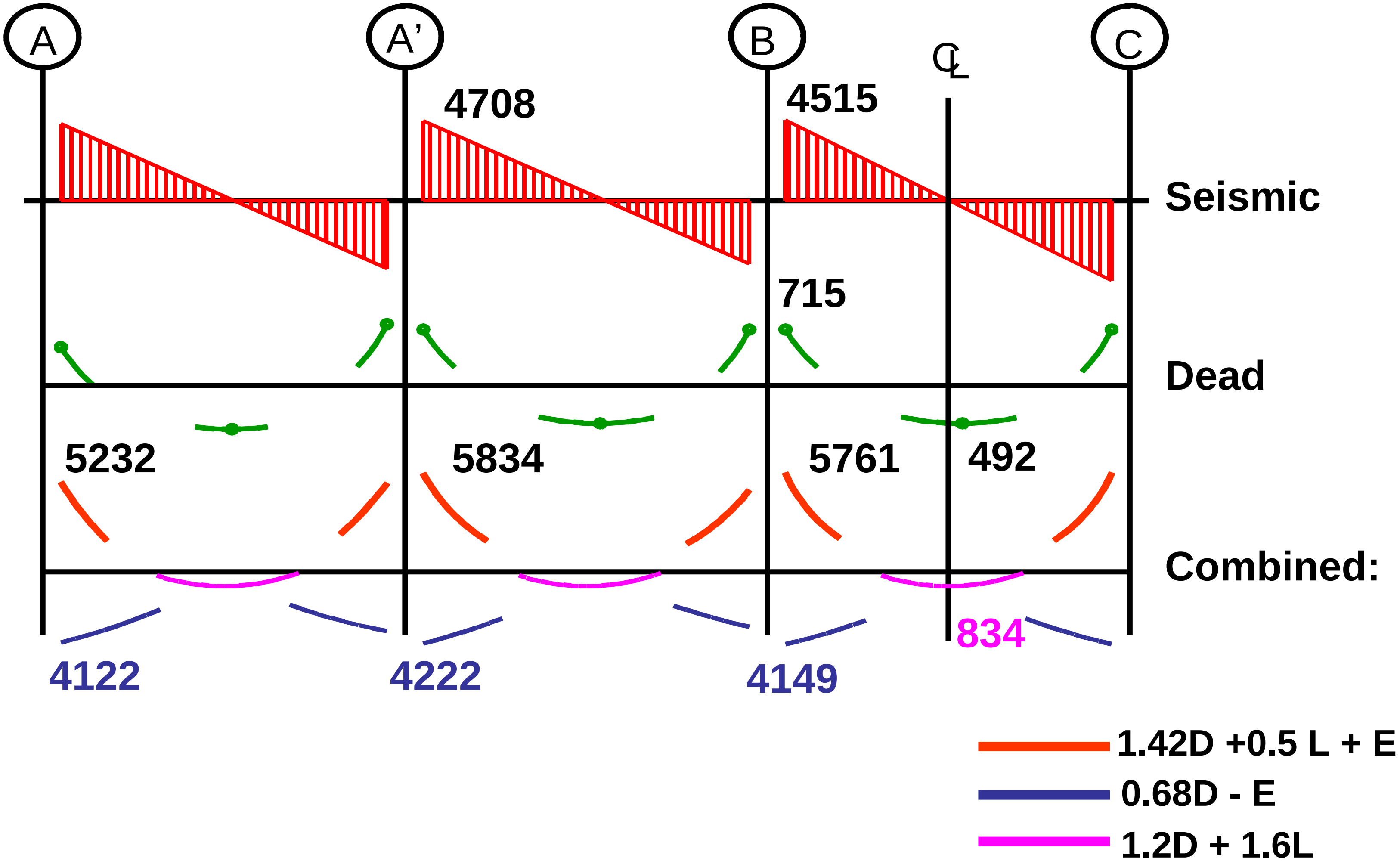
Story Shears: 25% rule



Layout of Reinforcement



Bending Moment Envelopes: Frame 1 Beams



Beam Reinforcement: Longitudinal

Max negative M_u = 5834 in-kips

b = 22.5" d = 29.6" f'_c = 4 ksi f_y = 60 ksi

$$A_{s\,req'd} = \frac{M_u/\phi}{f_y(0.875d)} = \frac{5834/0.9}{60 \cdot 0.875 \cdot 29.6} = 4.17 in^2$$

Choose: 2 #9 and 3 #8 A_s = 4.37 in^2

$\rho = 0.0066 < 0.025$ OK

ϕM_n = 6580 in-kips OK

Beam Reinforcement: Longitudinal (continued)

Positive M_u at face of column = 4222 in-kips (greater than ½(5834) = 2917)

b for negative moment is the sum of the beam width (22.5 in.) plus 1/12 the span length (20 ft x 12 in./ft)/12, b = 42.5 in.

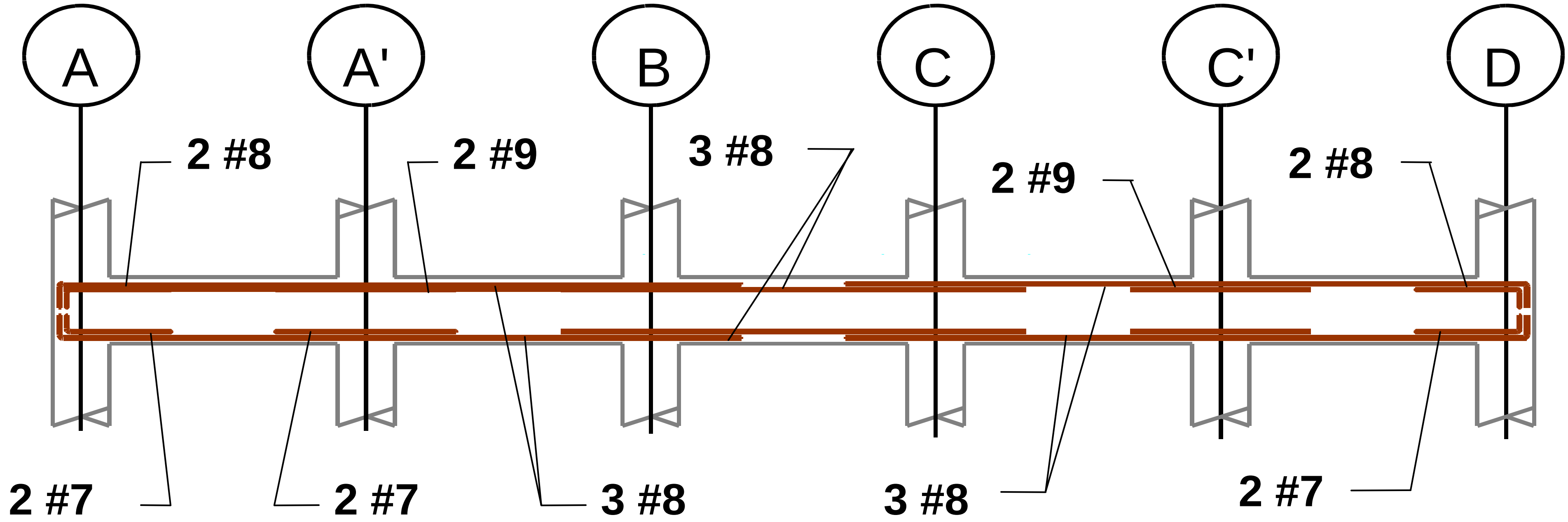
$$A_{s\ req'd} = \frac{M_u/\phi}{f_y(0.9d)} = \frac{4222/0.9}{60 \cdot 0.9 \cdot 29.6} = 2.94 in^2$$

Beam Reinforcement: Longitudinal (continued)

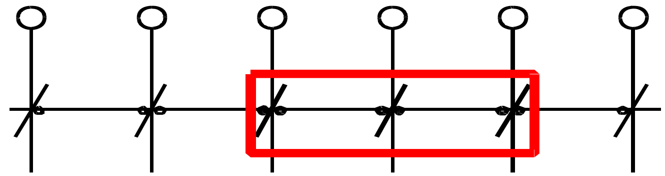
Choose 2 #7 and 3 #8 $A_s = 3.57 \text{ in}^2$
$\phi M_n = 5564$ in-kips   OK

Run 3 #8s continuous top and bottom
$\phi M_n = 3669$ in-kips
This moment is greater than:
25% of max negative $M_n = 1459$ in-kips
Max required $M_u = 834$ in-kips

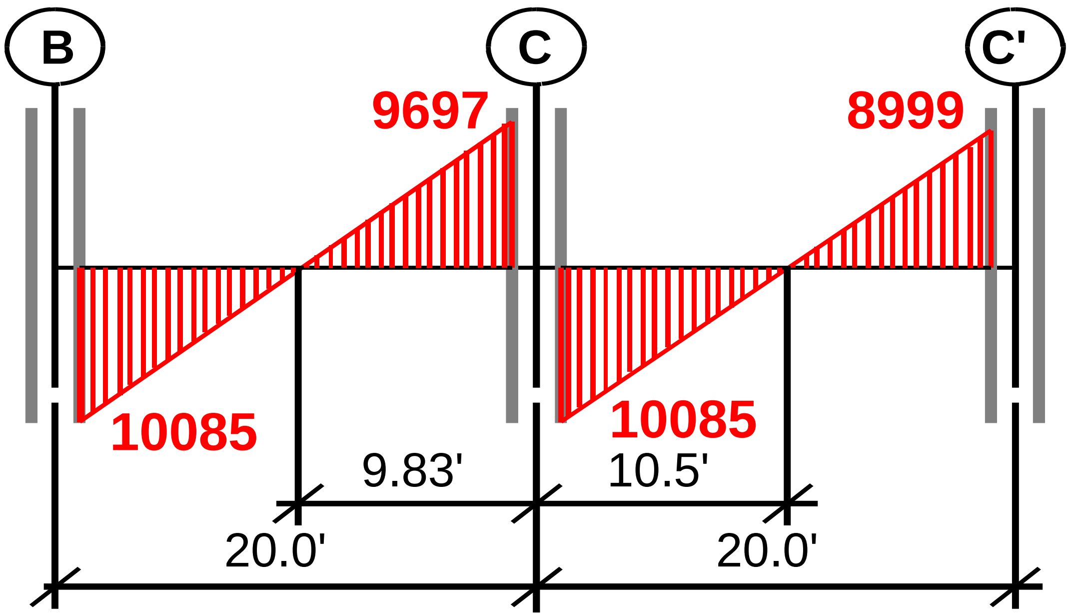
Beam Reinforcement: Preliminary Layout



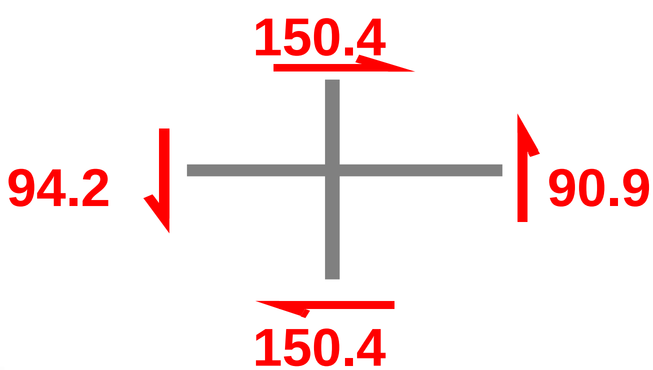
Moments for Computing Shear



Hinging mechanism

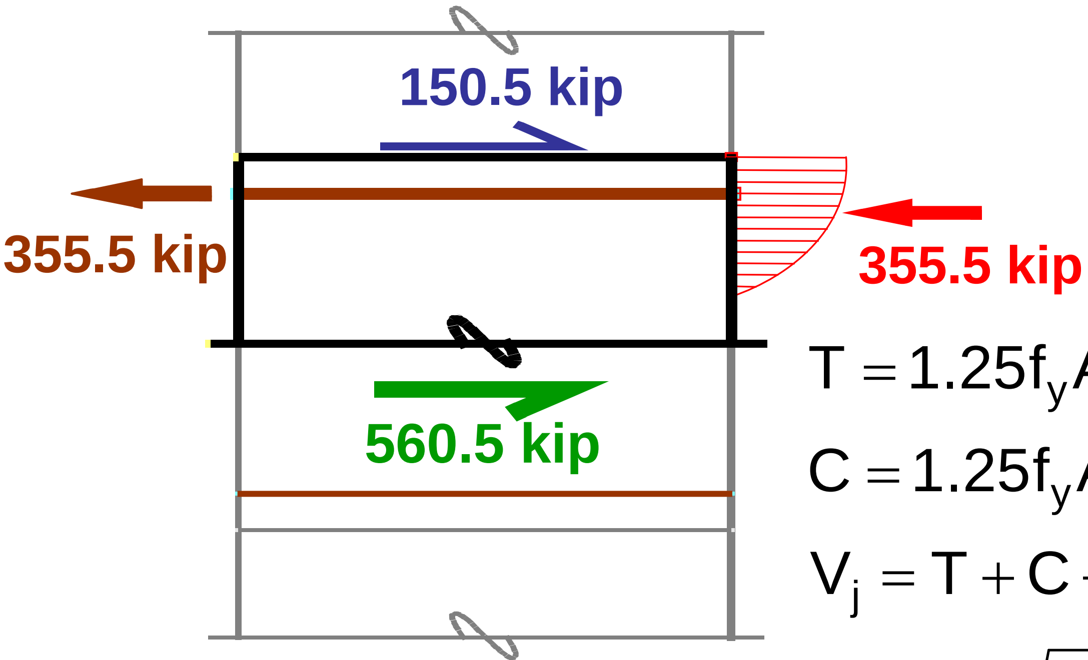


Plastic moments (in-kips)



Girder and column shears (kips)

Joint Shear Force



$$T = 1.25 f_y A_{s,top} = 355.5 \text{ kips}$$

$$C = 1.25 f_y A_{s,bot} = 355.5 \text{ kips}$$

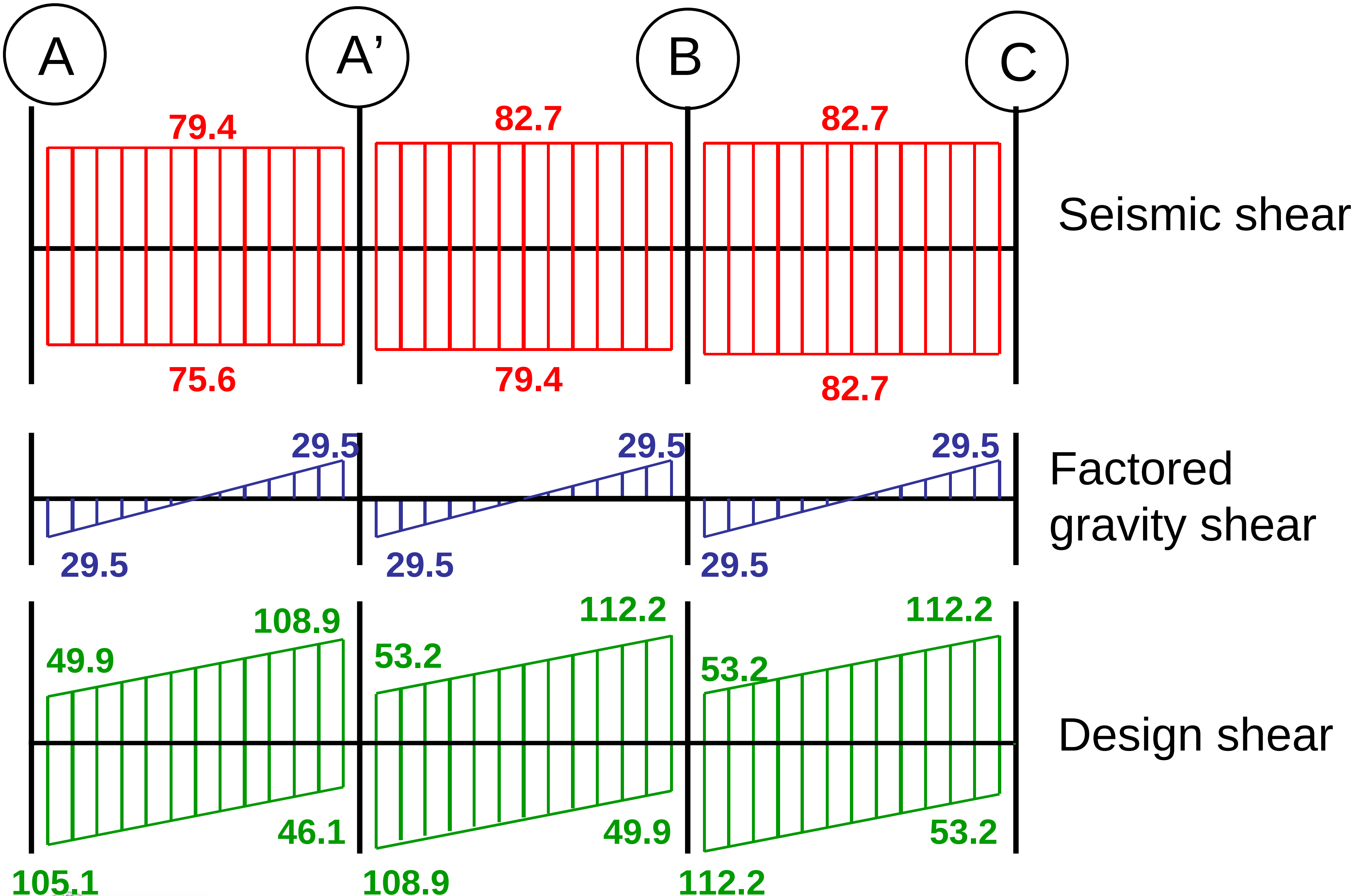
$$V_j = T + C - V_{col} = 560.5 \text{ kips}$$

$$v_j = 15\sqrt{f'_c} = 949 \text{ psi}$$

$$V_n = v_j A_j = 949 \cdot 30 \cdot 30 = 854 \text{ kips}$$

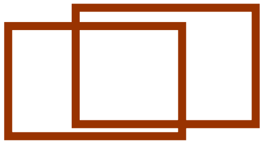
$$\phi V_n = 0.85 \cdot 854 = 726 \text{ kips} > 560.5 \text{ kips}$$

Beam Shear Force



Beam Reinforcement: Transverse

$V_{seismic} > 50\% \, V_u$ therefore take $V_c = 0$
82.7 kips = 73%(112.2)

Use 4 legged #3 stirrups 

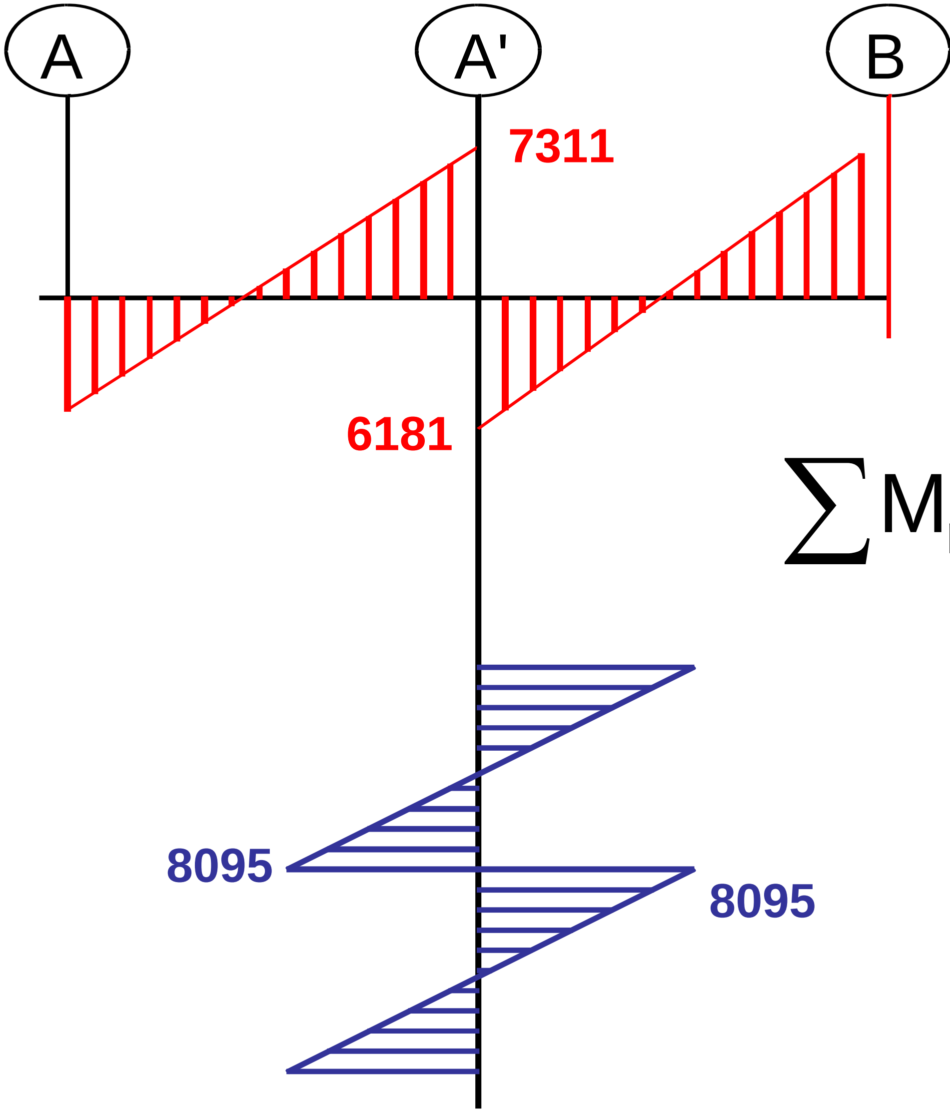
$$V_s = \frac{A_v f_y d}{s}$$

At ends of beam s = 5.5 in.
Near midspan s = 7.0 in.

Beam Reinforcement: Transverse

- **Check maximum spacing of hoops within plastic hinge length (2d)**
  - $d/4 = 7.4$ in.
  - $8d_b = 7.0$ in.
  - $24d_h = 9.0$ in.

Column Design Moments



Girder moments
(Level 7)

$$\sum M_{nc} = 1.2(7311 + 6181)$$
$$= 16190 \text{ in} - \text{k}$$

Column moments
(Level 7)

Column Design Moments

$$\text{if} \quad P_u > \frac{f'_c A_g}{10}$$

$$\sum M_{nc} > 1.2 \sum M_{nb}$$

Distribute relative to stiffness of columns above and below:

M_{nc} = 8095 in-kips (above)
M_{nc} = 8095 in-kips (below)

Design Strengths

Design Aspect	Strength Used
Beam rebar cutoffs	Design strength
Beam shear reinforcement	Maximum probable strength
Beam-column joint strength	Maximum probable strength
Column flexural strength	1.2 times nominal strength
Column shear strength	Maximum probable strength

Column Transverse Reinforcement

$$A_{sh} = 0.3\left(sb_c \frac{f'_c}{f_{yt}}\right)\left[\left(\frac{A_g}{A_{ch}}\right) - 1\right]$$

and

$$A_{sh} = 0.09 sb_c \frac{f'_c}{f_{yt}}$$

A_g = gross area of column
A_{ch} = area confined within the hoops
b_c = transverse dimension of column core measured center to center of outer legs

Second equation typically governs for larger columns

Column Transverse Reinforcement

Maximum spacing is smallest of:

- One quarter of minimum member dimension
- Six times the diameter of the longitudinal bars
- s_o calculated as follows:

$$s_o = 4 + \frac{14 - h_x}{3}$$

h_x = maximum horizontal center to center spacing of cross-ties or hoop legs on all faces of the column, not allowed to be greater the 14 in.

Column Transverse Reinforcement

For max s = 4 in.

$$A_{sh} = 0.3\left(sb_c \frac{f'_c}{f_{yt}}\right)\left[\left(\frac{A_g}{A_{ch}}\right) - 1\right] = 0.3\left(4 \cdot 26.5 \cdot \frac{4}{60}\right)\left(\frac{900}{702} - 1\right)$$

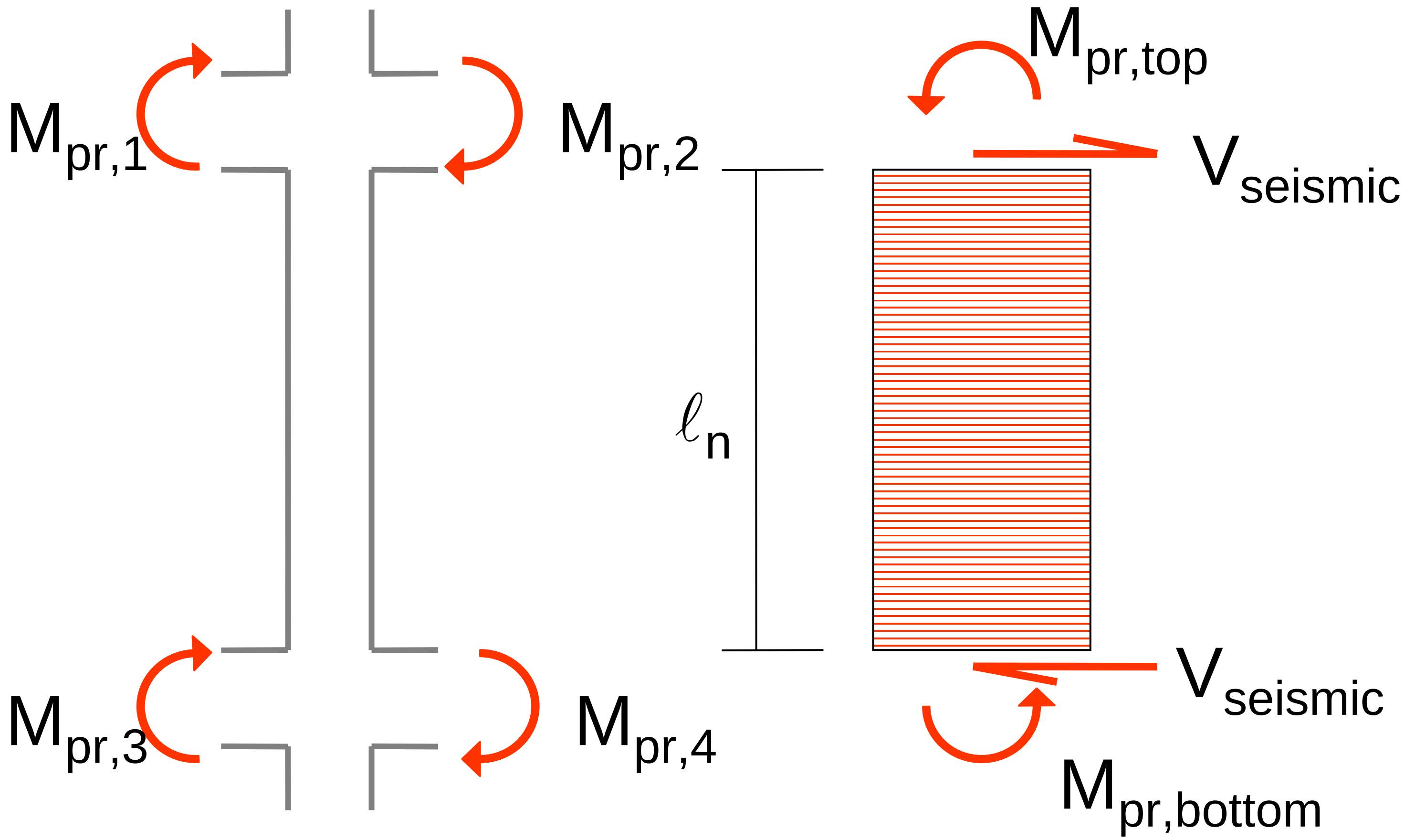
$$A_{sh} = 0.60 \text{ in}^2$$

and

$$A_{sh} = 0.09 sb_c \frac{f'_c}{f_{yt}} = 0.09 \cdot 4 \cdot 26.5 \cdot \frac{4}{60} = 0.64 \text{ in}^2$$

Use 4 legs of #4 bar – A_{sh} = 0.80 in^2

Determine Seismic Shear



Column Transverse Reinforcement Shear Demand from M_{pr} of Beams

$M_{pr,1}$ = 9000 in-k (2 #9 and 3 #8)
$M_{pr,2}$ = 7460 in-k (2 #7 and 3 #8)

Assume moments are distributed equally above and below joint

$$V_{seismic} = \frac{8230 \cdot 2}{(12.5 \cdot 12) - 32} = 139 \text{ kips}$$

Note $V_{seismic}$~100%V_u

$$V_c = 0, if\ P_{\min} < \frac{f'_c A_g}{20} = 180\ kips$$

For 30 in. square column
P_{min} = 266 kips OK

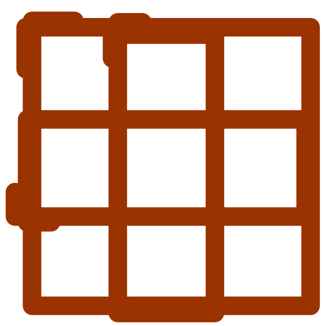
Column Transverse Reinforcement Shear Demand from M_{pr} of Beams

$$\phi V_c = \phi 2\lambda\sqrt{f'_c}bd = 0.75\cdot 2\cdot 0.85\sqrt{4000}\cdot 30\cdot 27.5 = 66.5\text{ kips}$$

$$\phi V_{s,required} = 139 - 66.5 = 72.5\text{ kips}$$

$$\phi V_{s,provided} = \phi\frac{A_v f_y d}{s} = 0.75\frac{4\cdot 0.2\cdot 60\cdot 29.6}{4} = 266.4\text{ kips}$$

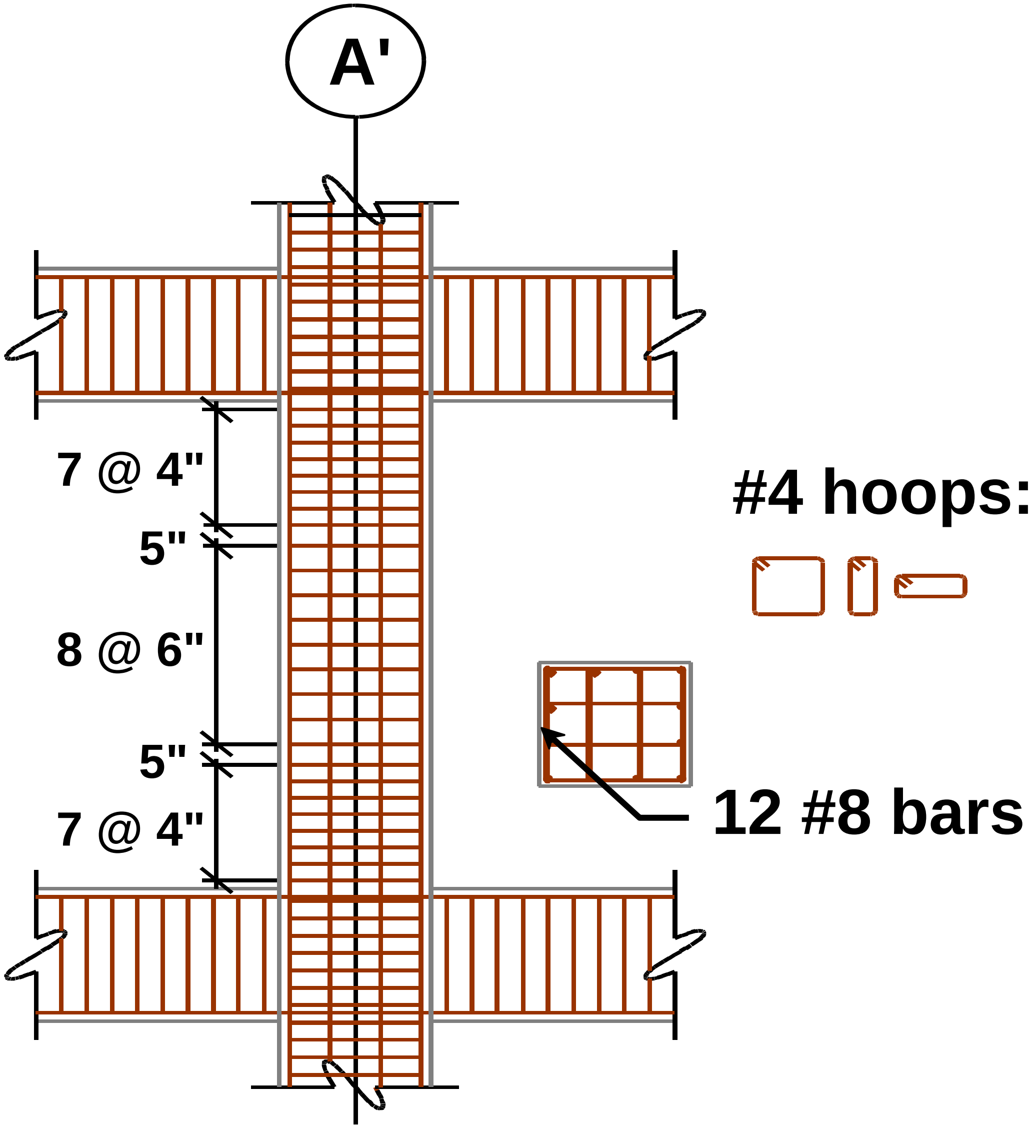
Hoops



4 legs #4

s = 4”

Column Reinforcement



Levels of Seismic Detailing for Frames

Issue	Ordinary	Intermediate	Special
Hinge development and confinement		minor	full
Bar buckling		lesser	full
Member shear		lesser	full
Joint shear	minor	minor	full
Strong column			full
Rebar development	lesser	lesser	full
Load reversal	minor	lesser	full

NEHRP Recommended Provisions Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**
- **Reference standards**
- **Requirements by Seismic Design Category**
- **Moment resisting frames**
- **Shear walls**

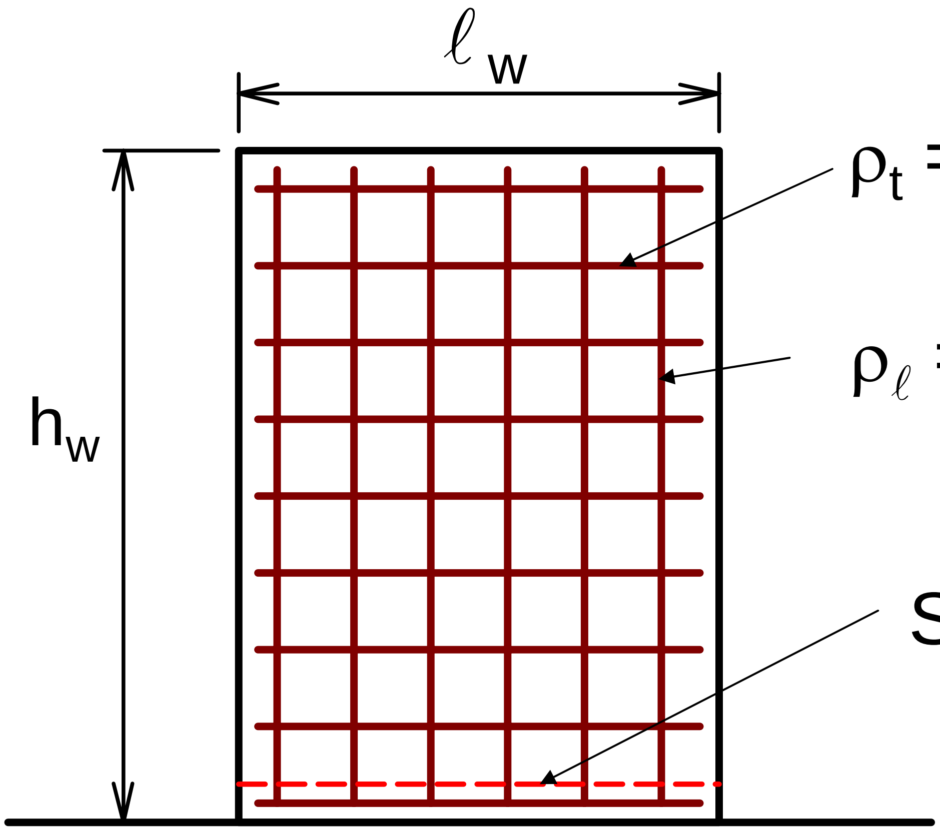
Performance Objectives

- **Resist axial forces, flexure and shear**
- **Boundary members**
  - Where compression strains are large, maintain capacity
- **Development of rebar in panel**
- **Discontinuous walls: supporting columns have full confinement**

Design Philosophy

- **Flexural yielding will occur in predetermined flexural hinging regions**
- **Brittle failure mechanisms will be precluded**
  - Diagonal tension
  - Sliding hinges
  - Local buckling

ACI 318-05, Overview of Walls: General Requirements



ρ_t = parallel to shear plane

ρ_ℓ = perpendicular to shear plane

Shear plane, A_{cv} = web thickness x length of wall

ACI 318-05, Overview of Walls: General Requirements

- ρ_ℓ and ρ_t not less than 0.0025 unless $V_u < A_{cv}\sqrt{f'_c}$

  then as allowed in 14.3
- Spacing not to exceed 18 in.
- Reinforcement contributing to V_n shall be continuous and distributed across the shear plane

ACI 318-05, Overview of Walls: General Requirements

- **Two curtains of reinforcing required if:**

$$V_u > 2A_{cv}\sqrt{f'_c}$$

- **Design shear force determined from lateral load analysis**

ACI 318-05, Overview of Walls: General Requirements

- **Shear strength:**

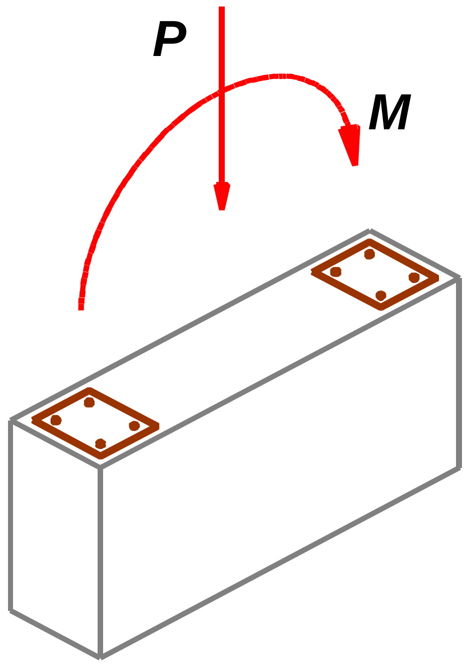
$$V_n = A_{cv}\left(\alpha_c\sqrt{f'_c} + \rho_t f_y\right)$$

α_c = 3.0 for $h_w/\ell_w \leq 1.5$
α_c = 2.0 for $h_w/\ell_w \geq 2.0$
Linear interpolation between

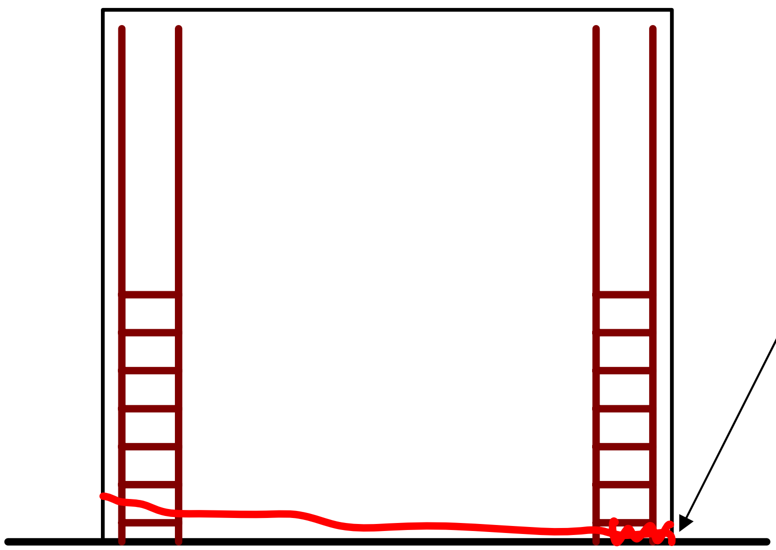
- **Walls must have reinforcement in two orthogonal directions**

ACI 318-05, Overview of Walls: General Requirements

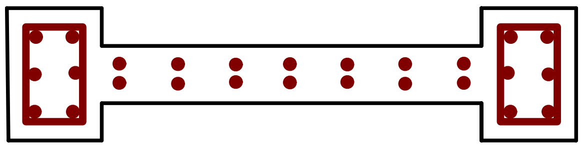
- **For axial load and flexure, design like a column to determine axial load – moment interaction**



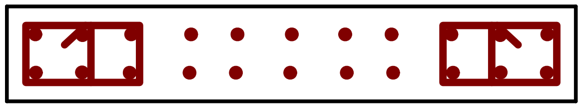
ACI 318-05, Overview of Walls: Boundary Elements



For walls with a high compression demand at the edges – Boundary Elements are required



Widened end with confinement



Extra confinement and/or longitudinal bars at end

ACI 318-05, Overview of Walls: Boundary Elements

- **Boundary elements are required if:**

$$c \geq \frac{\ell_w}{600\left(\delta_u / h_w\right)}$$

δ_u = Design displacement

c = Depth to neutral axis from strain compatibility analysis with loads causing δ_u

ACI 318-05, Overview of Walls: Boundary Elements

- **Where required, boundary elements must extend up the wall from the critical section a distance not less than the larger of:**

$$\ell_w \quad \text{or} \quad M_u/4V_u$$

ACI 318-05: Overview of Walls Boundary Elements

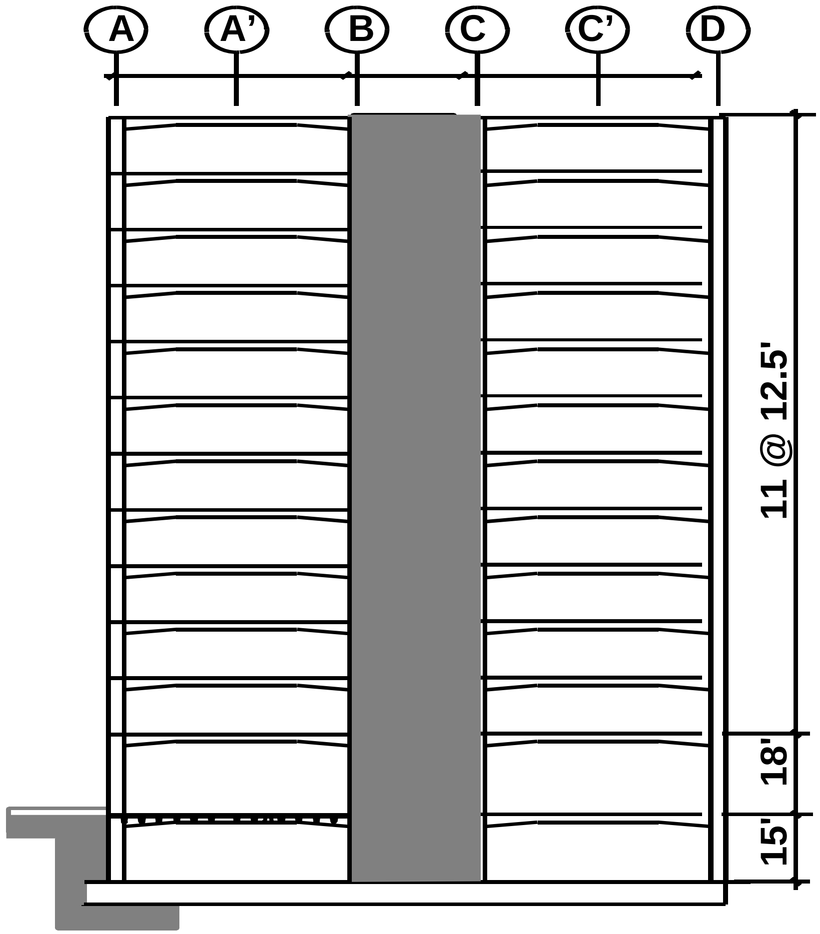
- **Boundary elements are required where the maximum extreme fiber compressive stress calculated based on factored load effects, linear elastic concrete behavior and gross section properties, exceeds 0.2 f'_c**

- **Boundary element can be discontinued where the compressive stress is less than 0.15f'_c**

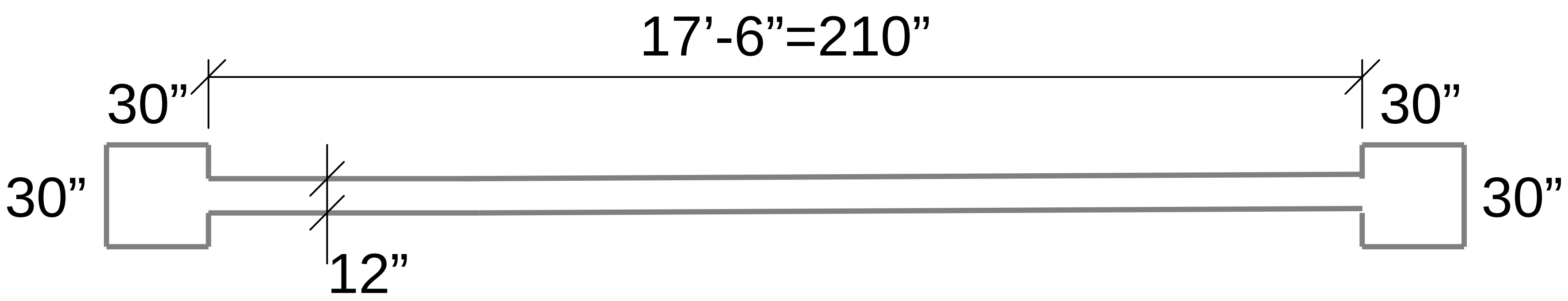
ACI 318-05: Overview of Walls Boundary Elements

- Boundary elements must extend horizontally not less than the larger of c/2 or $c\text{-}0.1\ell_w$
- In flanged walls, boundary element must include all of the effective flange width and at least 12 in. of the web
- Transverse reinforcement must extend into the foundation

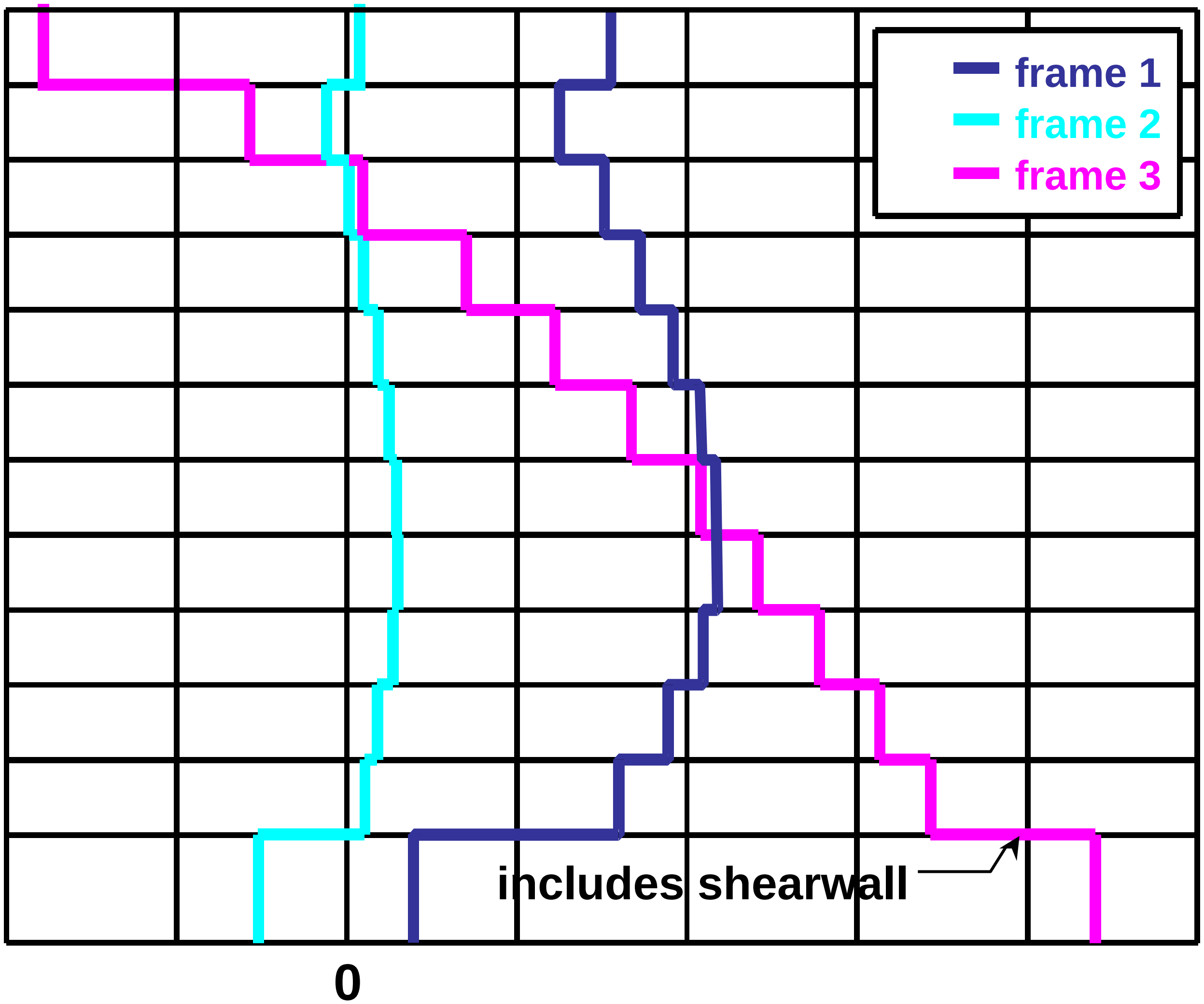
Wall Example

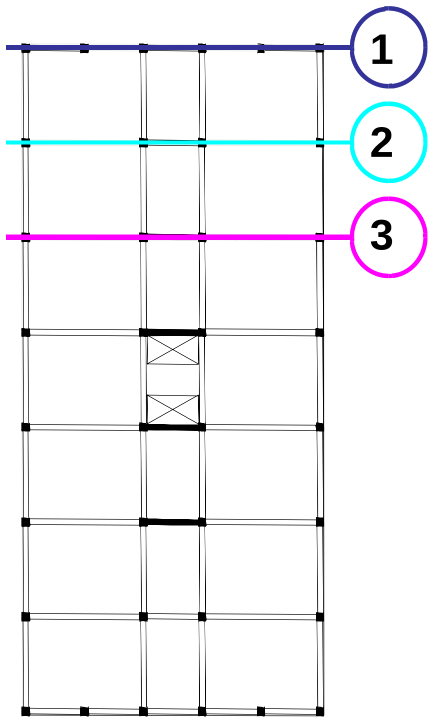


Wall Cross-Section



Story Shears
E-W Loading





Boundary Element Check

Required if: $f_c > 0.2 f_c^{'}$ based on gross concrete section

Axial load and moment are determined based on factored forces, including earthquake effects

At ground P_u = 5550 kip

M_u from analysis is 268,187 in-kip

The wall has the following gross section properties:

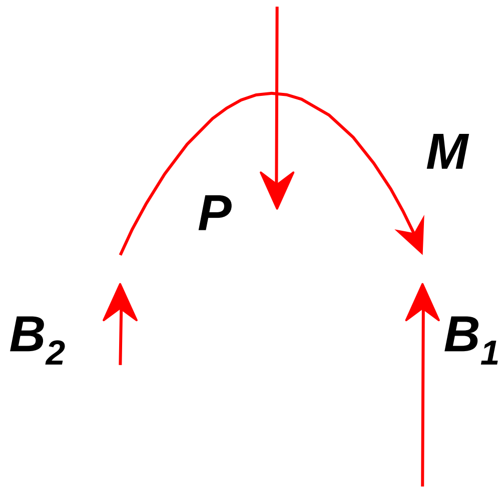
A = 4320 in^2 S = 261,600 in^3

f_c = 2.3 ksi = 38% of f'_c = 6 ksi

$\therefore$ **Need boundary element**

Boundary Element Design

Determine preliminary reinforcing ratio in boundary elements by assuming only boundary elements take compression



$M = 268{,}187$ in-k

$P = 5550$ k

$$B_1 = \frac{P}{2} + \frac{M}{240} = 3892 \text{ kip}$$

$$B_2 = \frac{P}{2} - \frac{M}{240} = 1658 \text{ kip}$$

Need $0.8P_o = 0.8(0.7)A_g\left[0.85\, f_c'(1-\rho) + \rho f_y\right] > 3892$ kip

For $A_g = 30(30) = 900$ in^2

For $f_c' = 4$ ksi $\Rightarrow$ $\rho = 7.06\%$ Too large

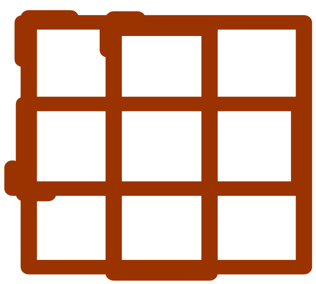
For $f_c' = 6$ ksi $\Rightarrow$ $\rho = 4.18\%$ Reasonable; 24 #11

Boundary Element Confinement

Transverse reinforcement in boundary elements is to be designed essentially like column transverse reinforcement

$$A_{sh} = 0.09\, s b_c \frac{f_c'}{f_y} = 1.08 \text{ in}^2 \text{ at } s = 4"$$

4 legs of #5



Shear Panel Reinforcement

$$V_n = A_{cv}\left(2\lambda\sqrt{f_c'} + \rho_t f_y\right)$$

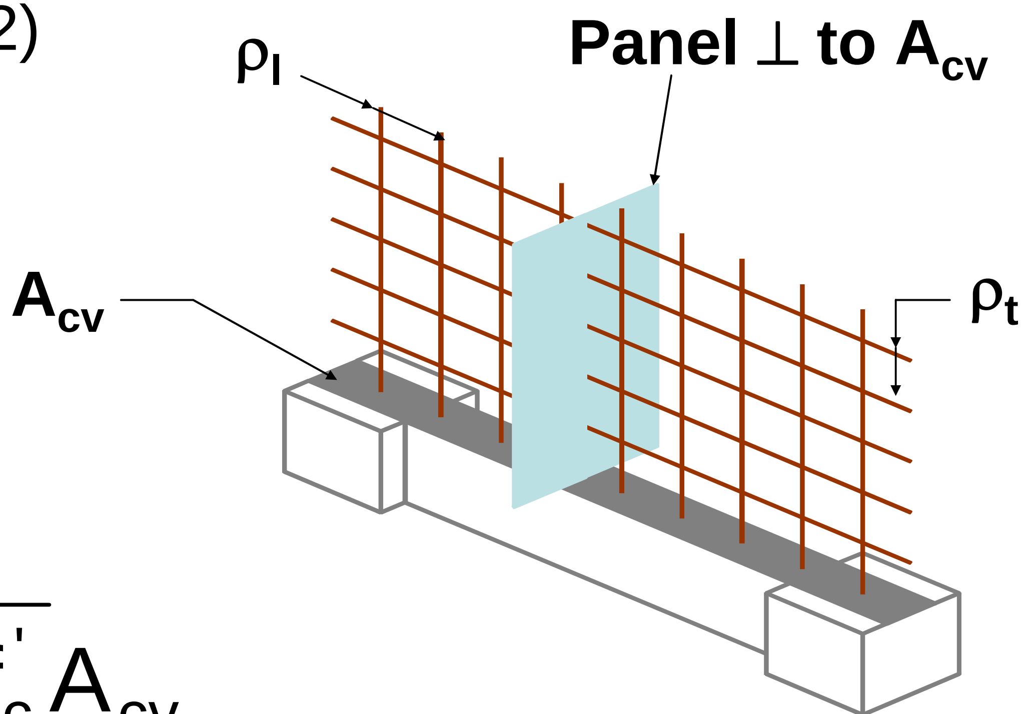
V_u = 539 kips (below level 2)

ϕ = 0.6 (per ACI 9.3.4(a))

ρ_t = 0.0036 for f_y = 40 ksi

Min ρ_ℓ (and ρ_t) = 0.0025

2 curtains if $V_u > 2\sqrt{f_c'}A_{cv}$



Shear Panel Reinforcement

Select transverse and longitudinal reinforcement:

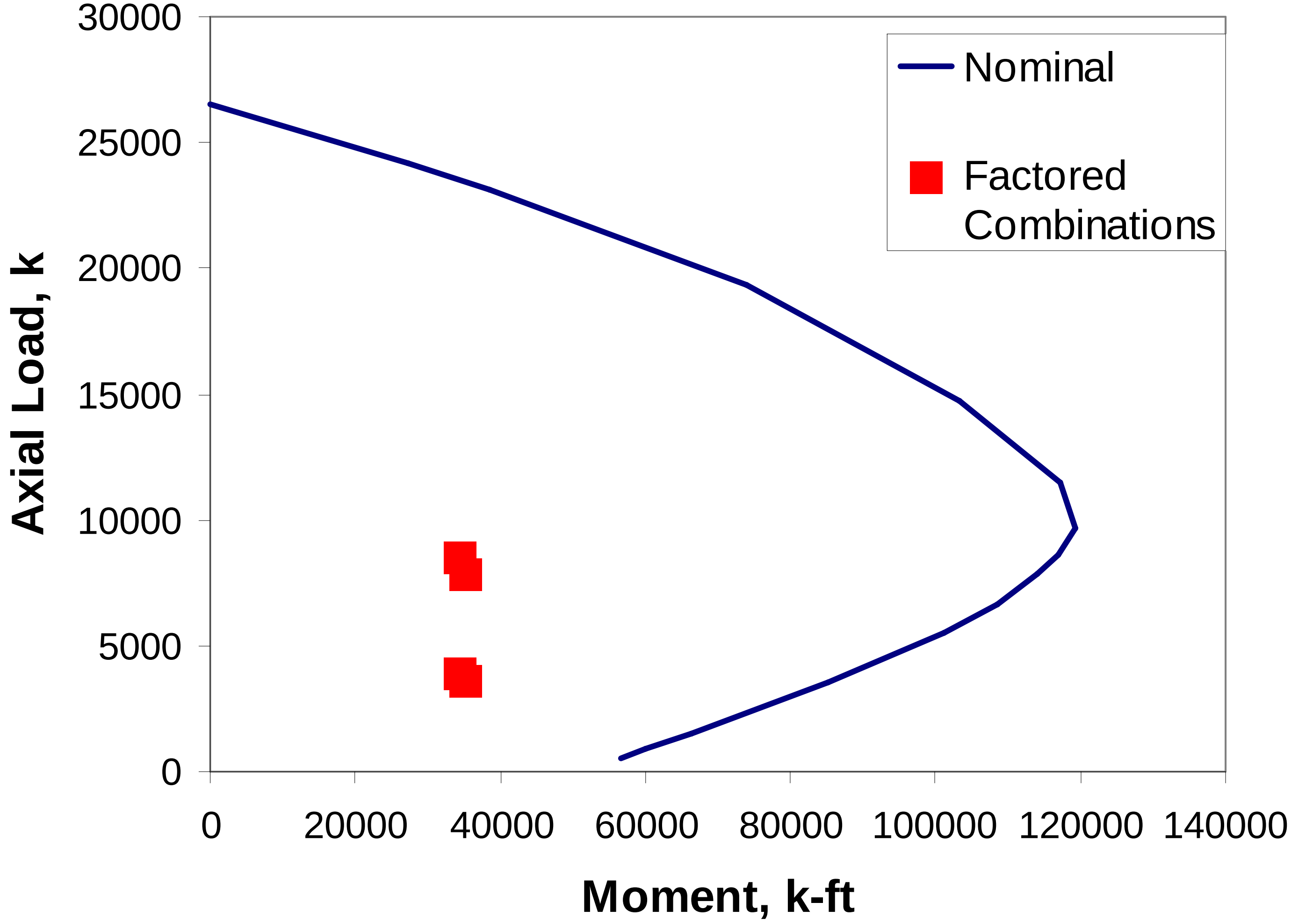
longitudinal:

$$\#4@12" \Rightarrow \frac{0.2 \cdot 2}{12 \cdot 12} = 0.0028 > 0.0025$$

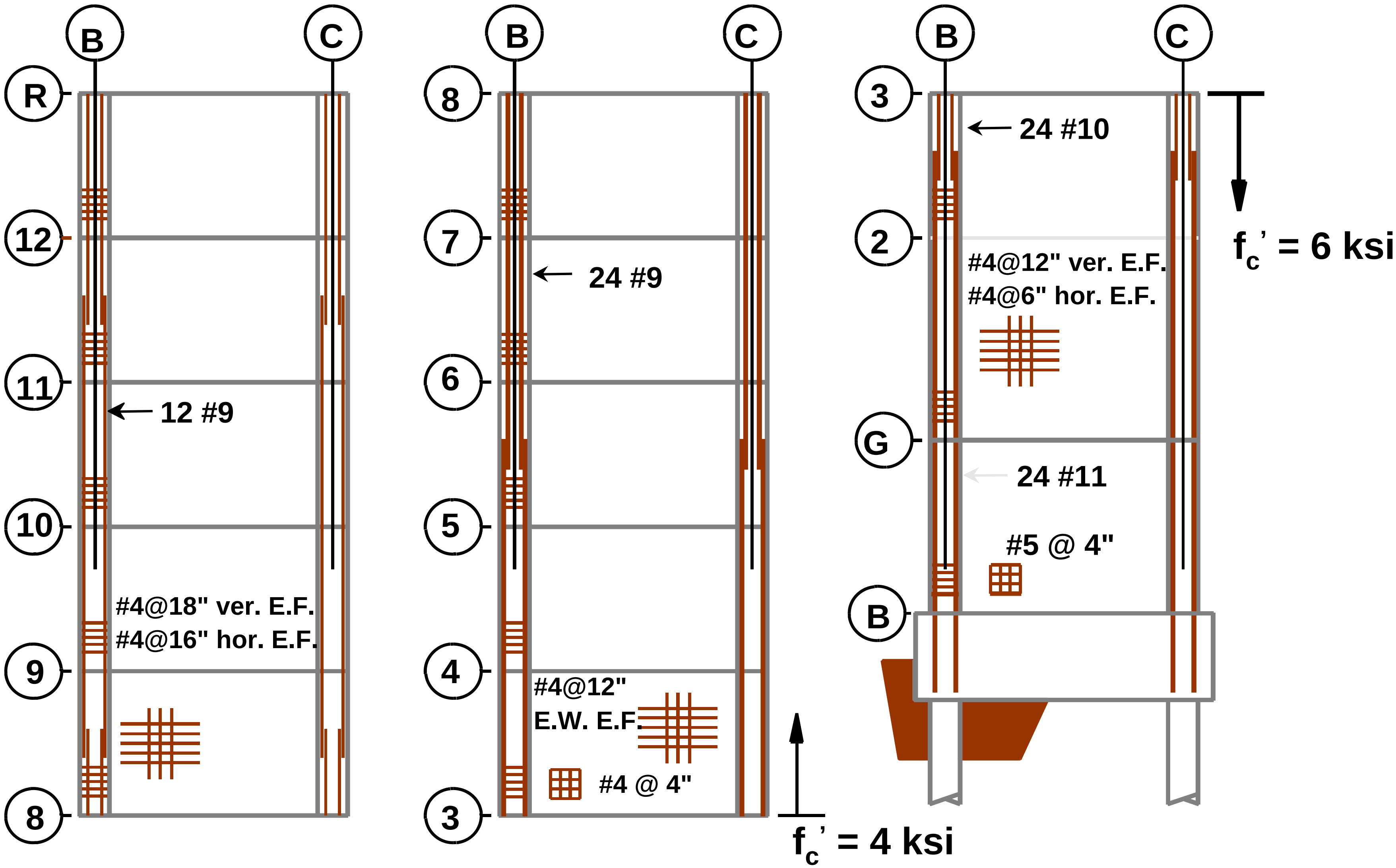
transverse:

$$\#4@9" \Rightarrow \frac{0.2 \cdot 2}{12 \cdot 9} = 0.0037 > 0.0036$$

Check Wall Design



Shear Wall Reinforcement



NEHRP Recommended Provisions Concrete Design

- **Context in the *Provisions***
- **Concrete behavior**
- **Reference standards**
- **Requirements by Seismic Design Category**
- **Moment resisting frames**
- **Shear walls**
- **Other topics**

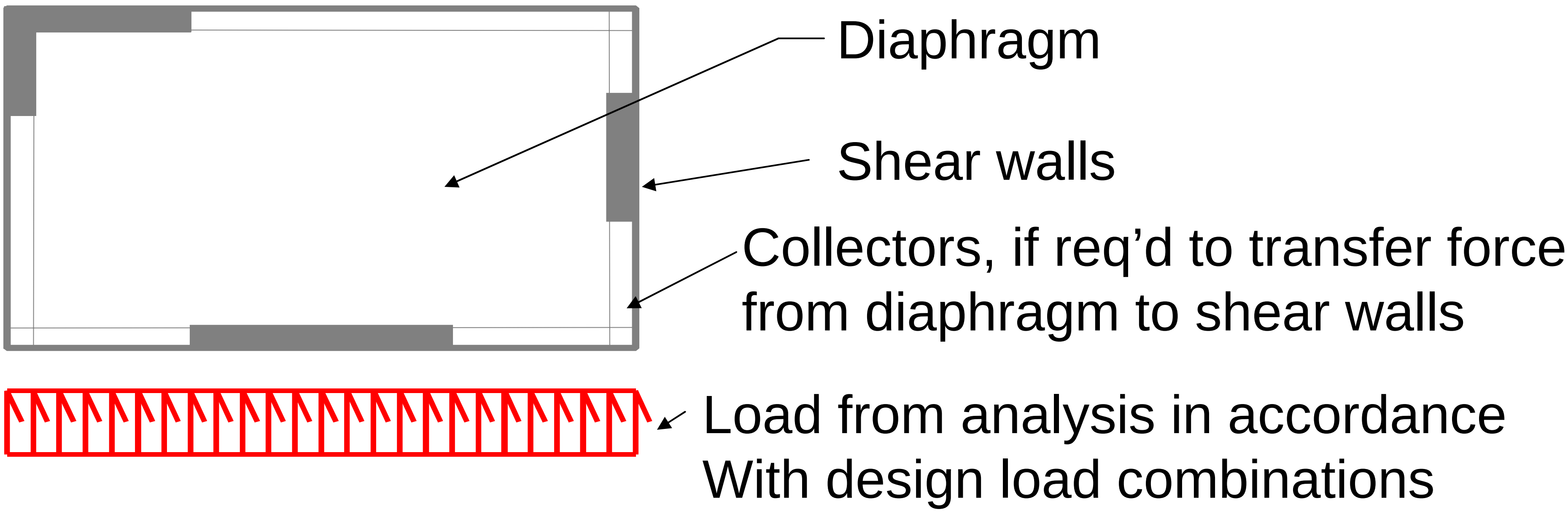
Members Not Part of SRS

- **In frame members not designated as part of the lateral-force-resisting system in regions of high seismic risk:**
  - Must be able to support gravity loads while subjected to the design displacement
  - Transverse reinforcement increases depending on:

    Forces induced by drift

    Axial force in member

Diaphragms



Check:

- Shear strength and reinforcement (min. slab reinf.)
- Chords (boundary members)

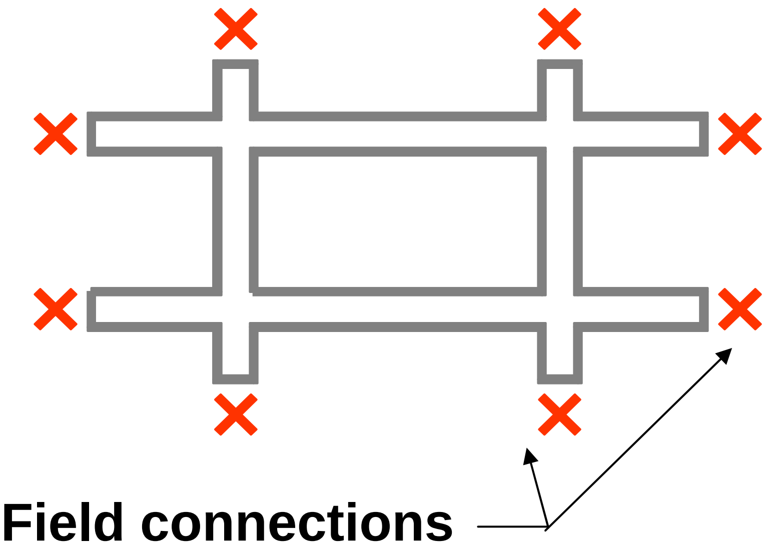
  - Force = M/d Reinforced for tension

  (Usually don't require boundary members)

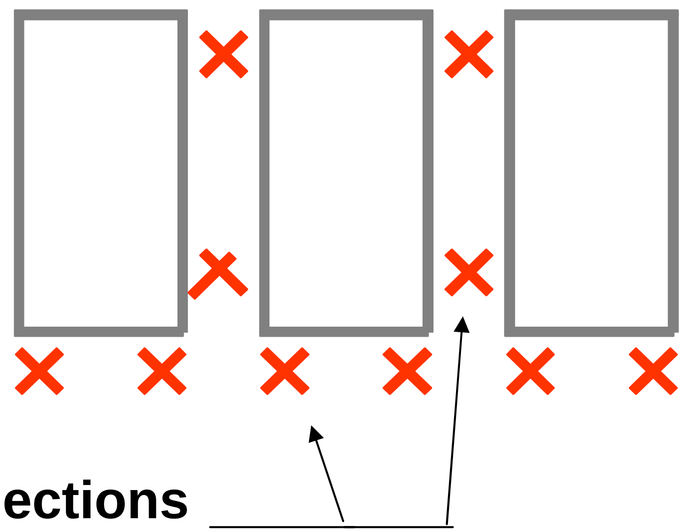
Struts and Trusses
performance objectives

- **All members have axial load (not flexure), so ductility is more difficult to achieve**
- **Full length confinement**

Precast performance objectives



Field connections at points of low stress



Field connections must yield

<u>Strong connections</u>

- Configure system so that hinges occur in factory cast members away from field splices

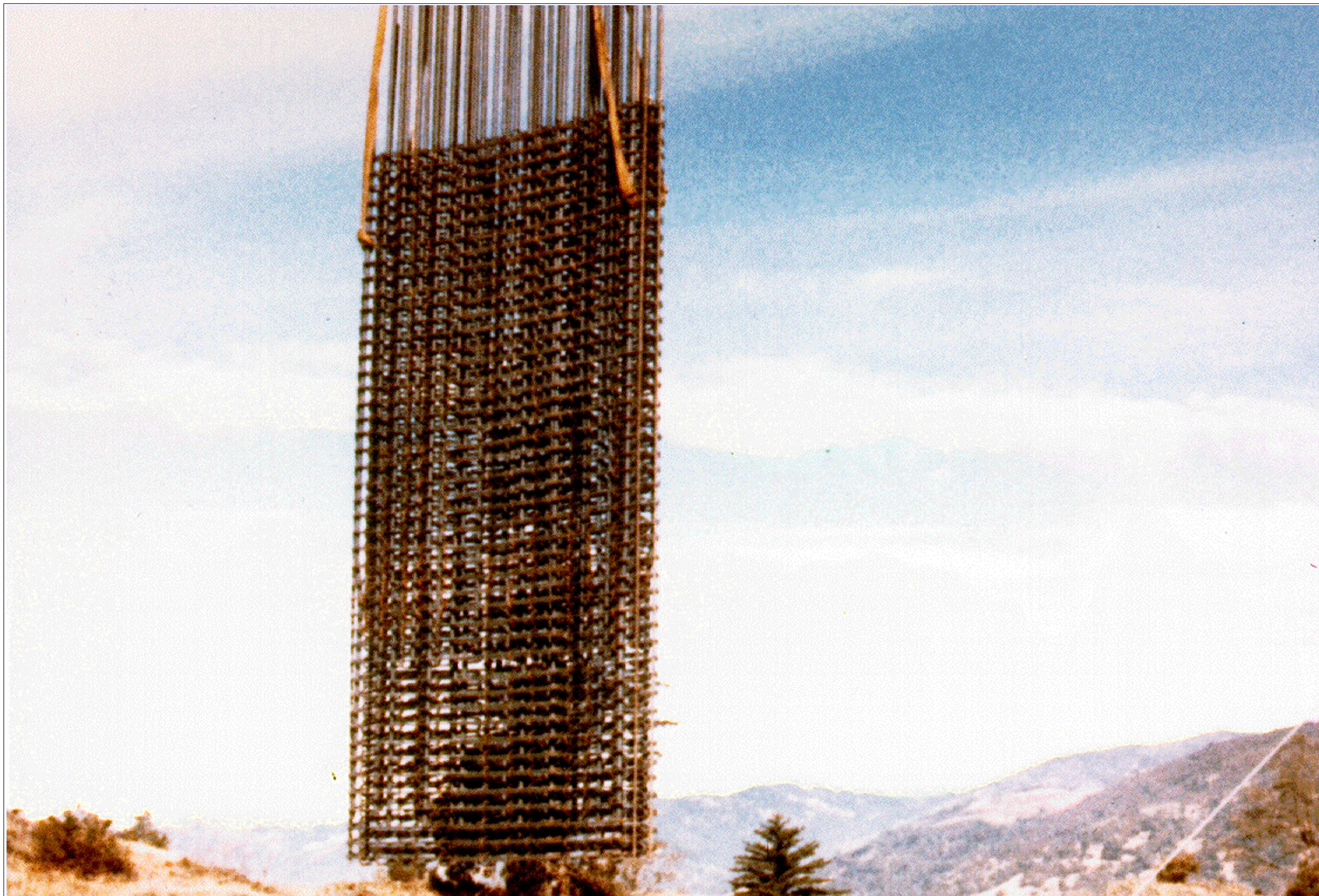
<u>Ductile connections</u>

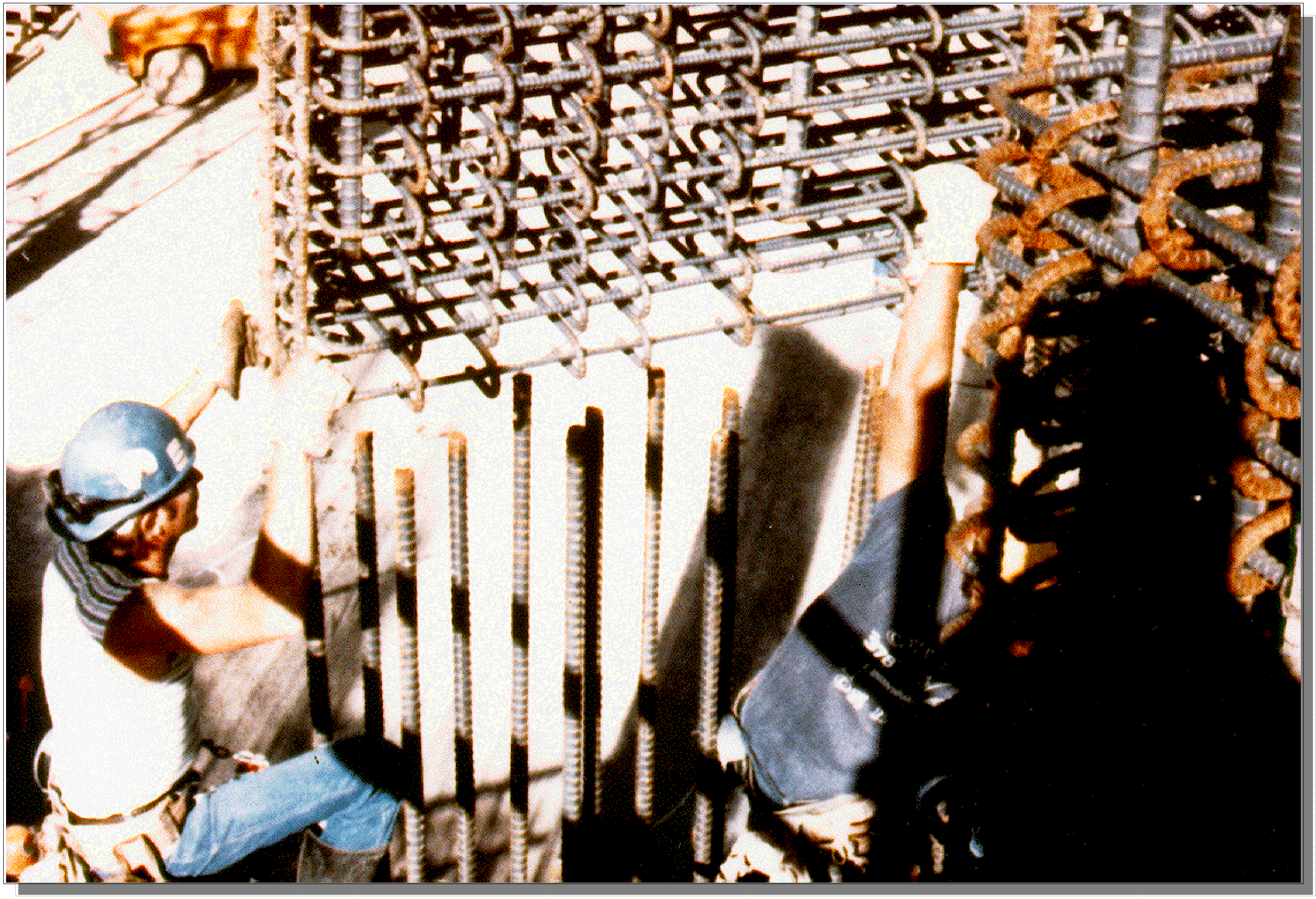
- Inelastic action at field splice

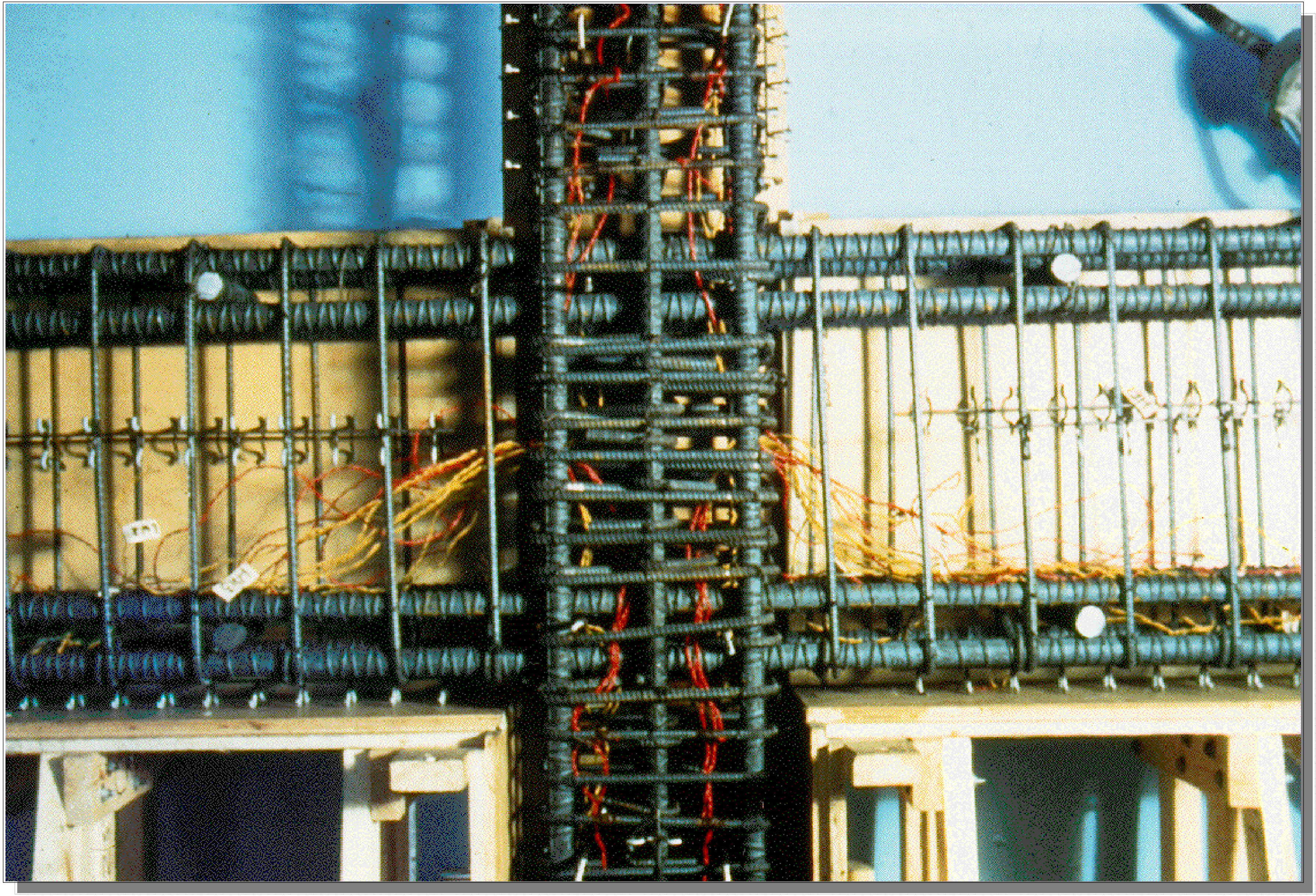
Quality Assurance Rebar Inspection

- **Continuous**
  - Welding of rebar
- **Periodic**
  - During and upon completion of placement for special moment frames, intermediate moment frames and shear walls

Shear panel reinforcement cage







Quality Assurance: Reinforcing Inspection - Prestressed

- **Periodic**
  - Placing of prestressing tendons (inspection required upon completion)
- **Continuous**
  - Stressing of tendons
  - Grouting of tendons

Quality Assurance: Concrete Placement Inspection

- **Continuous**
  - Prestressed elements
  - Drilled piers
  - Caissons
- **Periodic**
  - Frames
  - Shear walls

Quality Assurance: Precast Concrete (plant cast)

- **Manufacturer may serve as special inspector if plant's quality control program is approved by regulatory agency**
- **If no approved quality control program, independent special inspector is required**

Quality Assurance:
PCI Certification Program

- **Review of plant operations**
  - Scheduled and surprise visits
  - Qualified independent inspectors
  - Observed work of in-plant quality control
  - Check results of quality control procedures
  - Periodic – specific approvals requiring renewal

Quality Assurance: ACI Inspector Certification

- **Specialized training available for:**
  - Laboratory and in situ testing
  - Inspection of welding
  - Handling and placement of concrete
  - Others

Quality Assurance: Reinforcement Testing

- **Rebar**
  - Special and intermediate moment frames
  - Boundary elements
- **Prestressing steel**
- **Tests include**
  - Weldability
  - Elongation
  - Actual to specified yield strength
  - Actual to specified ultimate strength

Quality Assurance: Concrete Testing

- **Sample and test according to ACI 318-05**
  - Slump
  - Air content
  - 7 and 28 day strengths
  - Unit weight
- **Rate**
  - Once per day per class

NEHRP Recommended Provisions: Concrete Design

- Context in the *Provisions*
- Concrete behavior
- Reference standards
- Requirements by Seismic Design Category
- Moment resisting frames
- Shear walls
- Other topics
- Summary