Observations in Shear Wall Strength in Tall Buildings

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Presented by StructurePoint
at ACI Spring 2012 Convention
in Dallas, Texas

Metropolitan Tower, New York City

- 68-story, 716 ft (218m) skyscraper

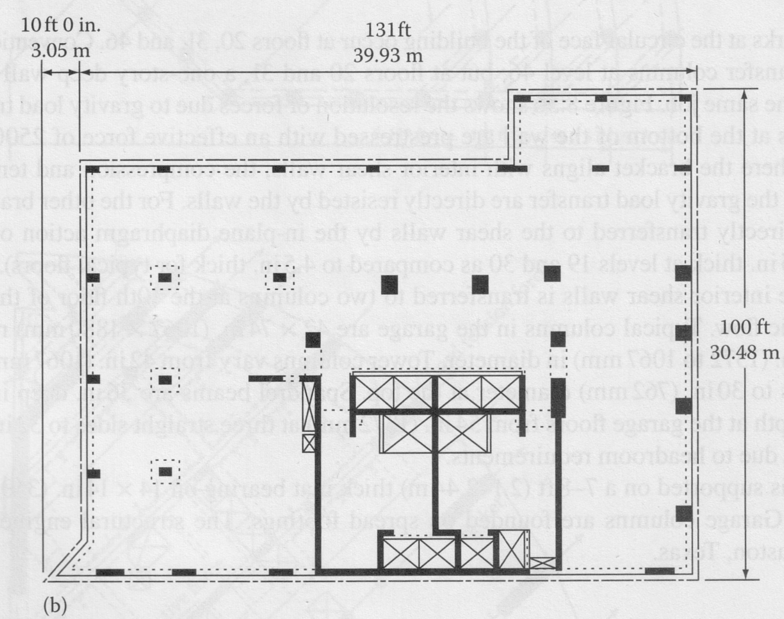
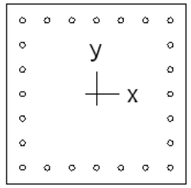


FIGURE 8.57 Metropolitan Tower, New York City. (a,b) Framing plans.

Reinforced Concrete Design of Tall Buildings by Bungale S. Taranath



48 x 48 in

Code: ACI 318-11

Units: English

Run axis: About X-axis

Run option: Investigation

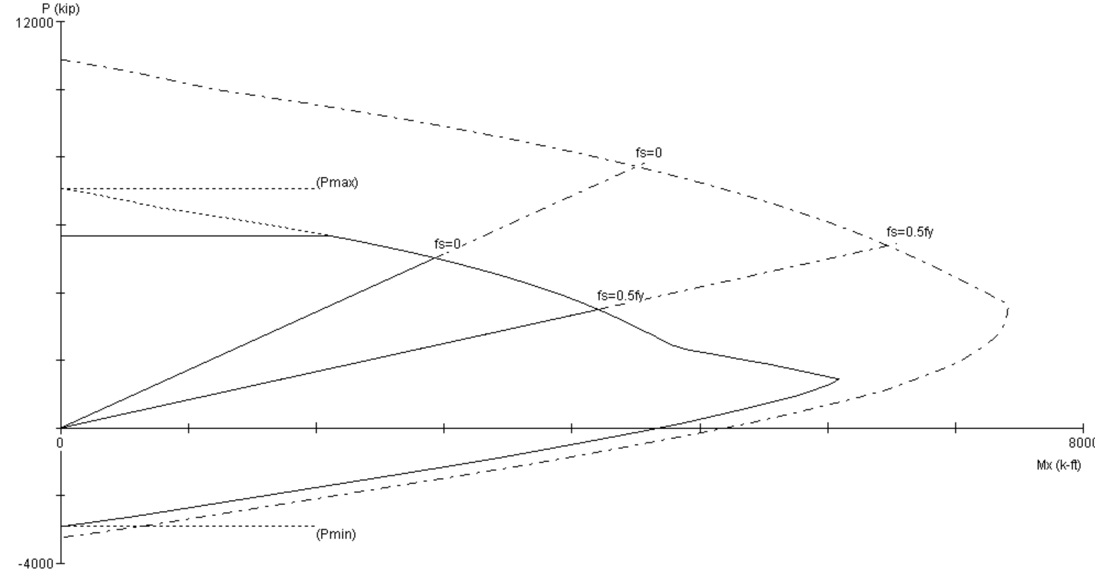
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 03/09/12

Time: 10:49:45



spColumn v4.80. Licensed to: StructurePoint. License ID: 00000-0000000-4-2A05D-2C8D0

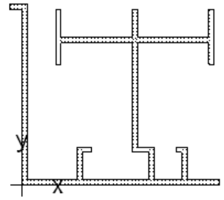
File: C:\Work\Projects\2012\ACI Convention - Dallas\Metropolitan Tower Column.col

Project:

Column:		Engineer:	
f'c = 4 ksi	fy = 60 ksi	Ag = 2304 in^2	24 #14 bars
Ec = 3605 ksi	Es = 29000 ksi	As = 54.00 in^2	rho = 2.34%
fc = 3.4 ksi		Xo = 0.00 in	Ix = 442368 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 442368 in^4
Beta1 = 0.85		Min clear spacing = 4.86 in	Clear cover = 3.50 in

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65



563 x 484 in

Code: ACI 318-11

Units: English

Run axis: Biaxial

Run option: Investigation

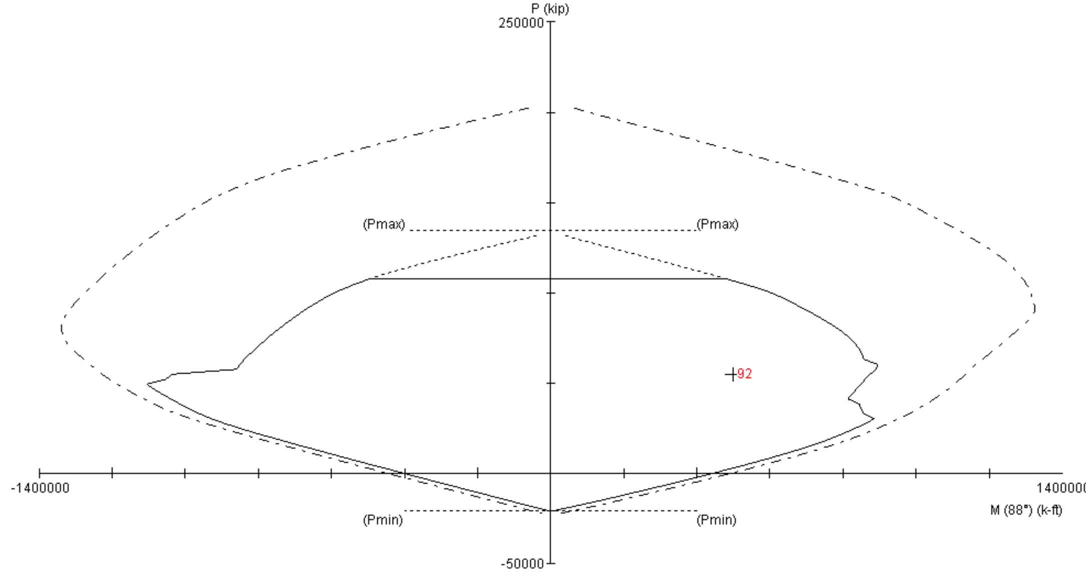
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 03/06/12

Time: 10:51:31



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Project:

Column:		Engineer:	
f'c = 6 ksi	fy = 60 ksi	Ag = 36270 in^2	496 #8 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 391.84 in^2	rho = 1.08%
fc = 5.1 ksi		Xo = 232.45 in	Ix = 1.04485e+009 in^4
e_u = 0.003 in/in		Yo = 219.32 in	Iy = 1.00942e+009 in^4
Beta1 = 0.75		Min clear spacing = 1.83 in	Clear cover = N/A

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65

Jin Mao Tower, Shanghai, China

- 88-story, 1381 ft (421m)

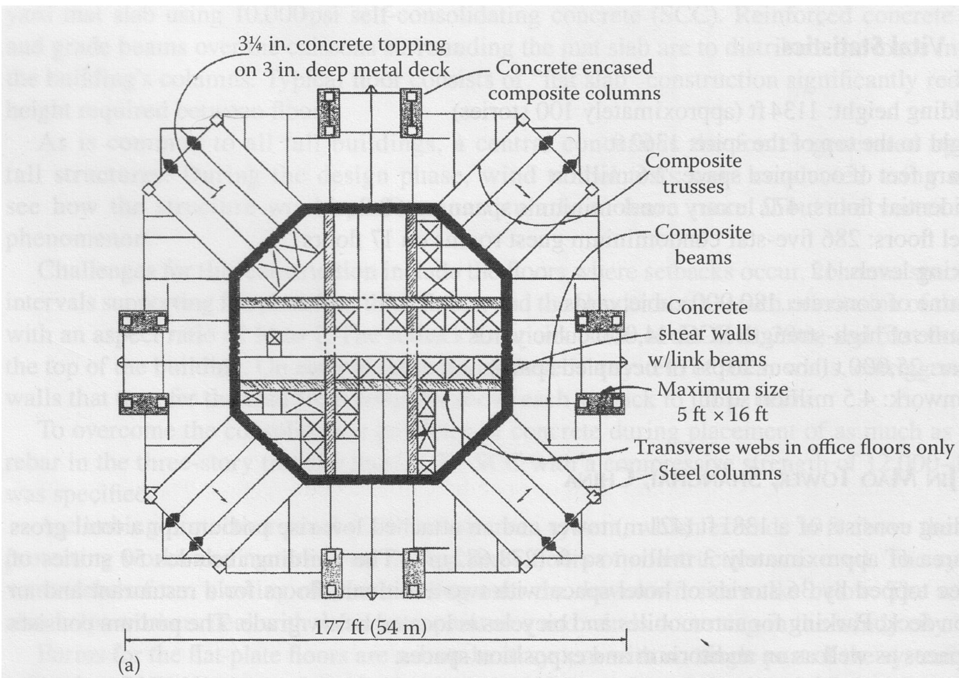
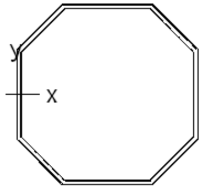


FIGURE 8.45 Jin Mao Tower, Shanghai, China: (a) typical office floor framing plan;



1200 x 1200 in

Code: ACI 318-11

Units: English

Run axis: Biaxial

Run option: Investigation

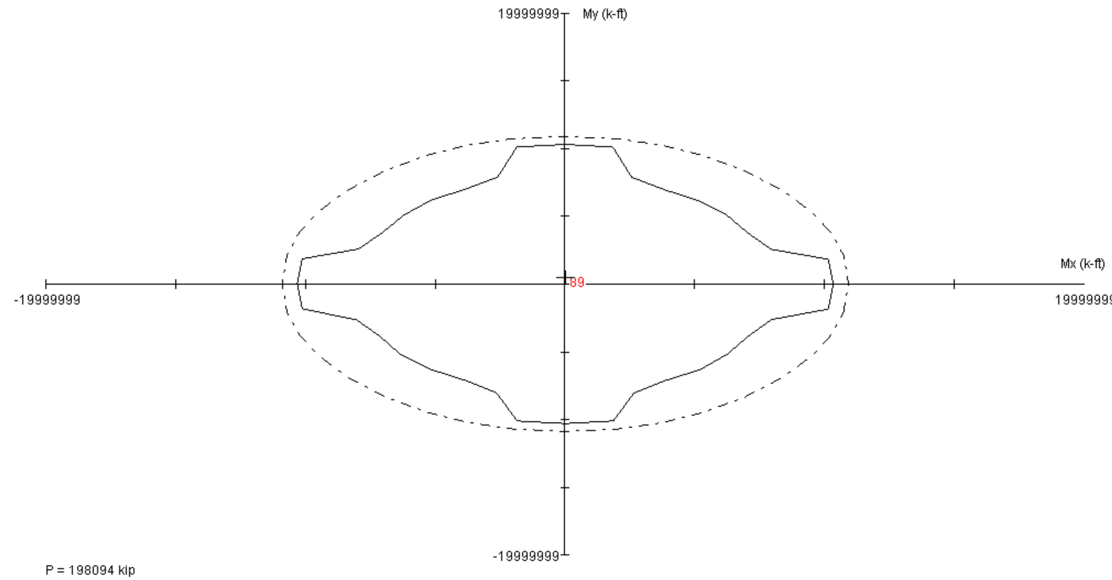
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 03/06/12

Time: 10:07:55



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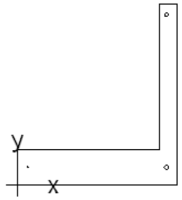
File: C:\Work\Projects\2012\ACI Convention - Dallas\Jin Mao Tower.col

Project:

Column:		Engineer:	
f'c = 6 ksi	fy = 60 ksi	Ag = 128600 in^2	1287 #8 bars
Ec = 4415 ksi	Es = 29000 ksi	As = 1016.72 in^2	rho = 0.79%
fc = 5.1 ksi		Xo = 600.00 in	Ix = 2.46235e+010 in^4
e_u = 0.003 in/in		Yo = 0.00 in	Iy = 2.46234e+010 in^4
Beta1 = 0.75		Min clear spacing = -1.00 in	Clear cover = N/A

Confinement: Tied

phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.65



90 x 102 in

Code: ACI 318-02

Units: English

Run axis: About Y-axis

Run option: Investigation

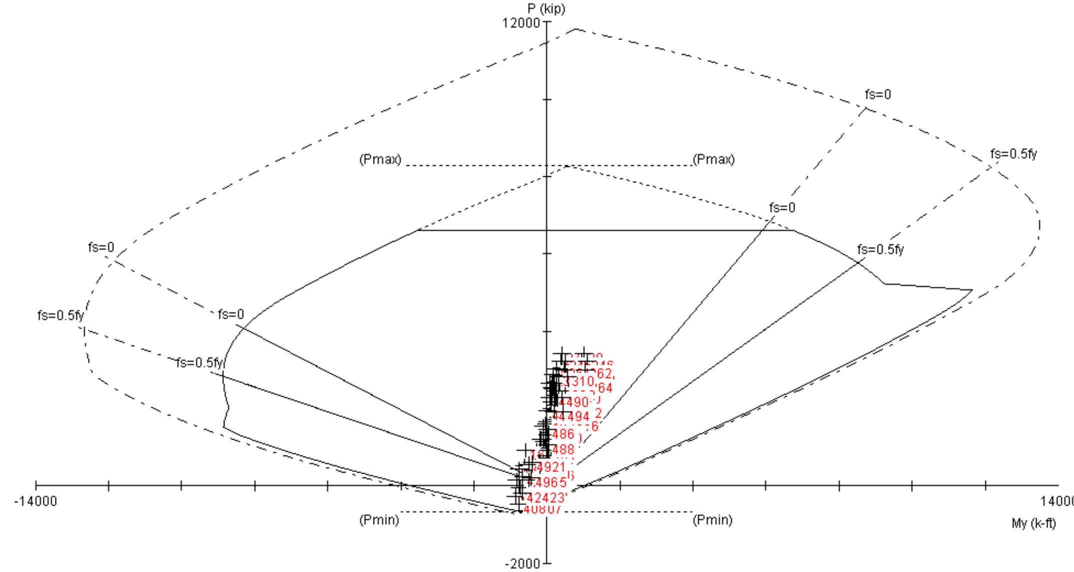
Slenderness: Not considered

Column type: Structural

Bars: ASTM A615

Date: 03/06/12

Time: 12:00:00



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File: C:\Work\Projects\2012\ACI Convention - Dallas\P3-05.col

Project: METRO THEATER

Column:		Engineer: PC	
f'c = 5 ksi	fy = 60 ksi	Ag = 2620 in^2	3 bars
Ec = 4031 ksi	Es = 29000 ksi	As = 12.24 in^2	rho = 0.47%
fc = 4.25 ksi		Xo = 57.52 in	Ix = 1.98477e+006 in^4
e_u = 0.003 in/in		Yo = 25.96 in	Iy = 2.12321e+006 in^4
Beta1 = 0.8		Min clear spacing = 75.79 in	Clear cover = N/A
Confinement: Other			
phi(a) = 0.8, phi(b) = 0.9, phi(c) = 0.7			

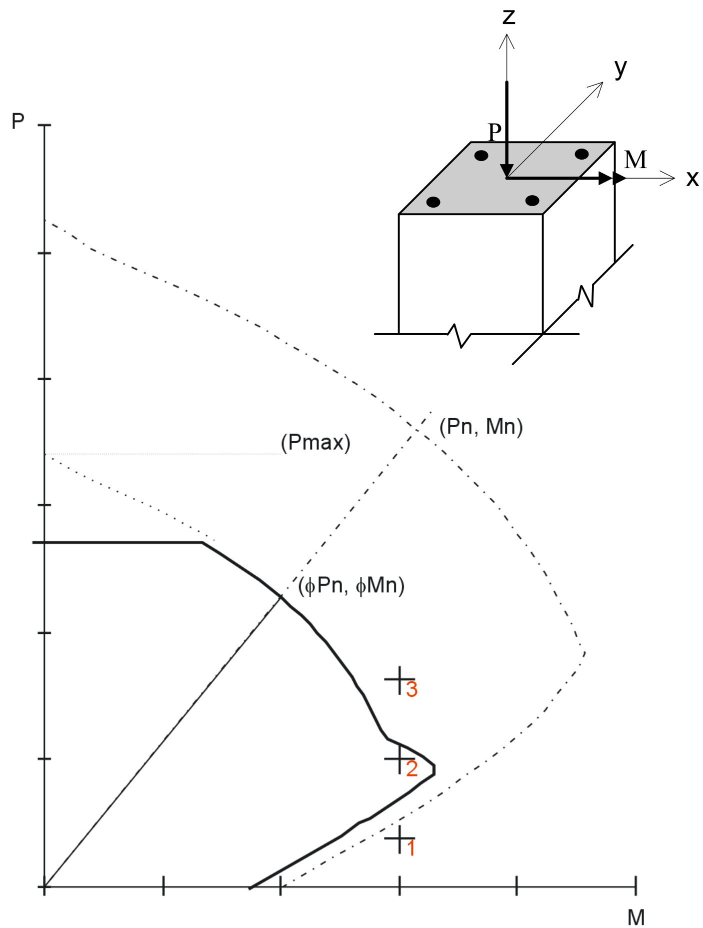
Motivation

- Sharing insight from detailed analysis and implementation of code provisions
- Sharing insight from members of ACI committees
- Sharing insight from wide base of spColumn users
- Raising awareness of irregularities and their impact on design
- Conclusions apply to all sections, but especially those of irregular shape and loaded with large number of load cases and combinations, e.g. Shear Walls

Outline

- Observations
  - P-M Diagram Irregularities
    - Symmetry/Asymmetry
    - Strength Reduction Factor
    - Uniaxial/Biaxial Bending
  - Moment Magnification Irregularities
- Conclusions

P-M Diagram



- Design
  - $(P_{u1}, M_{u1}) \rightarrow$ NG
  - $(P_{u2}, M_{u2}) \rightarrow$ OK
  - $(P_{u3}, M_{u3}) \rightarrow$ NG
  - Notice $P_{u1} < P_{u2} < P_{u3}$ with M_u=const
- One Quadrant OK if
  - $P_u \geq 0$ and $M_u \geq 0$
  - Section shape symmetrical
  - Reinforcement symmetrical

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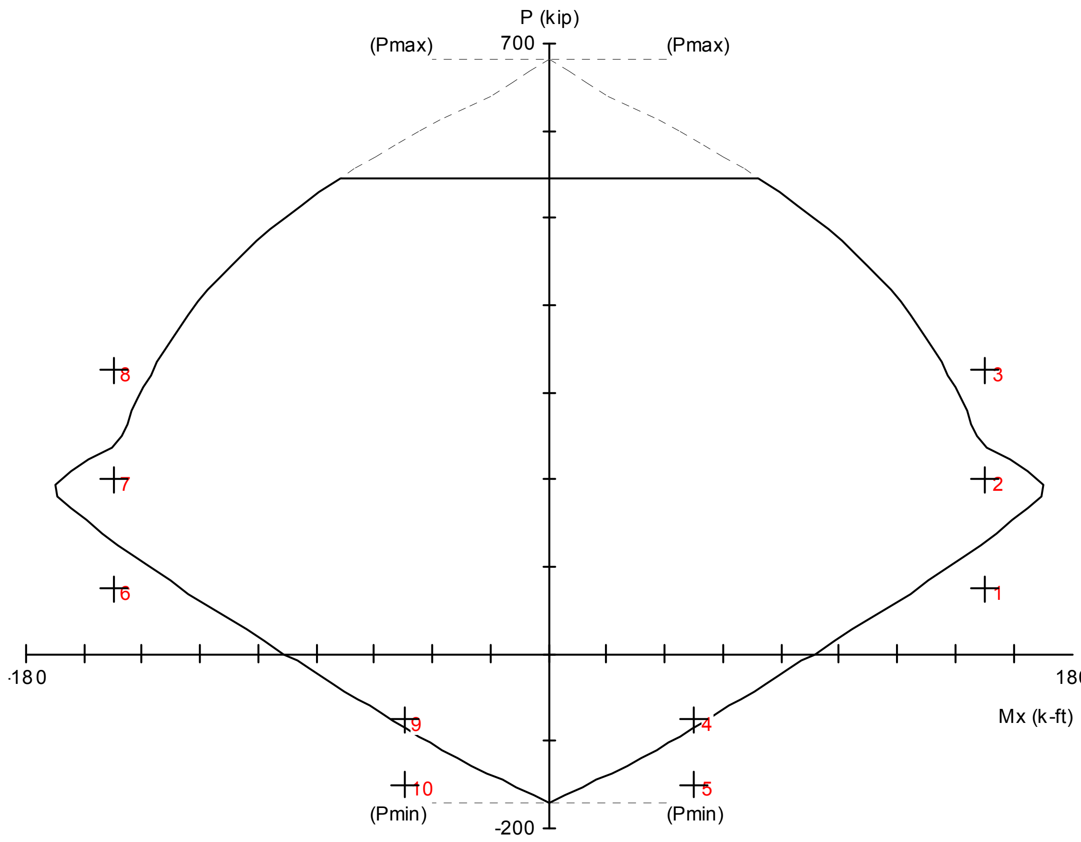
P-M Diagram – Pos./Neg. Load Signs

- All four quadrants are needed if loads change sign
  - If section shape and reinforcement are symmetrical then M- side is a mirror of M+ side



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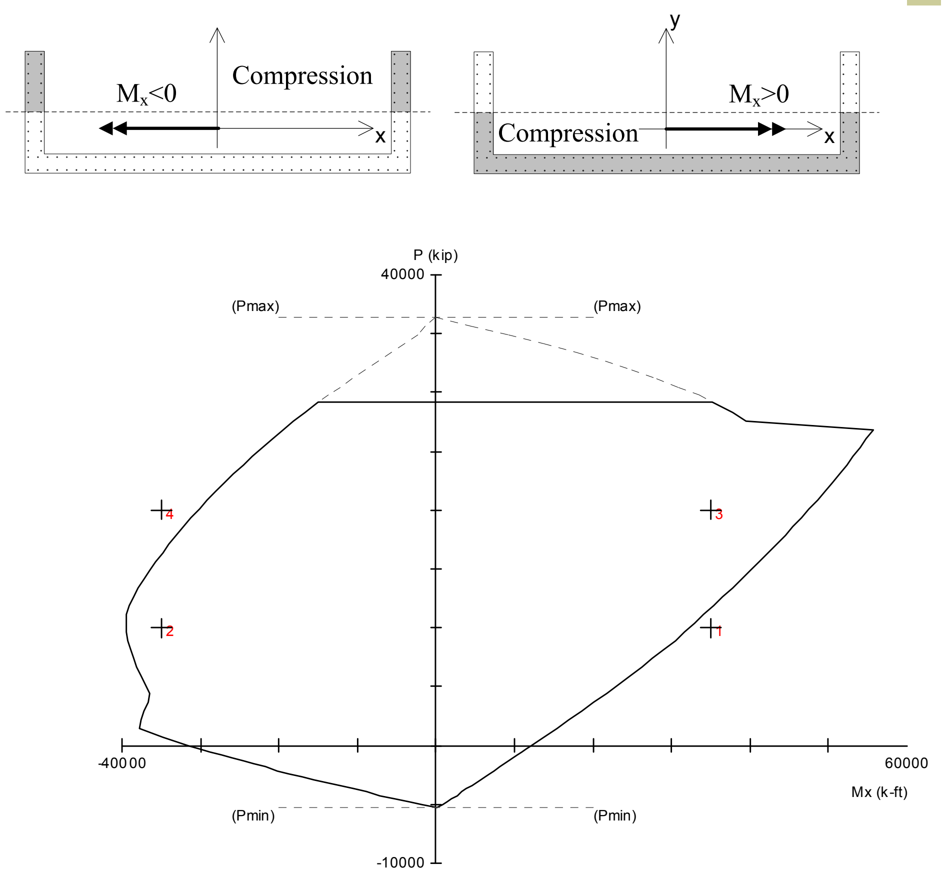
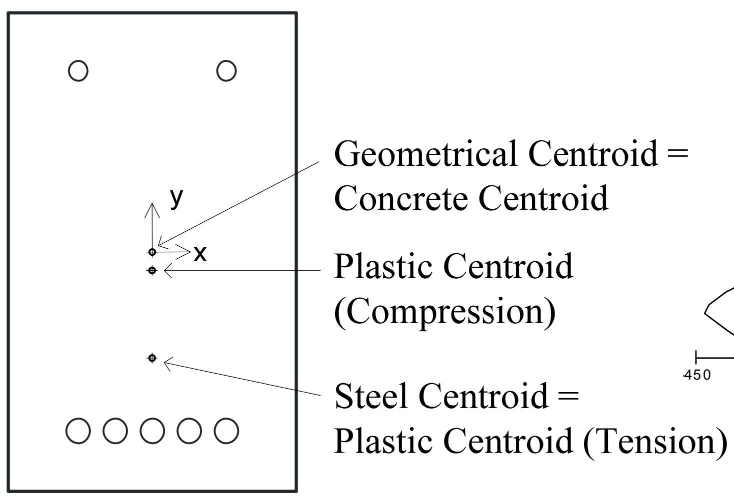
P-M Diagram – Asymmetric Section

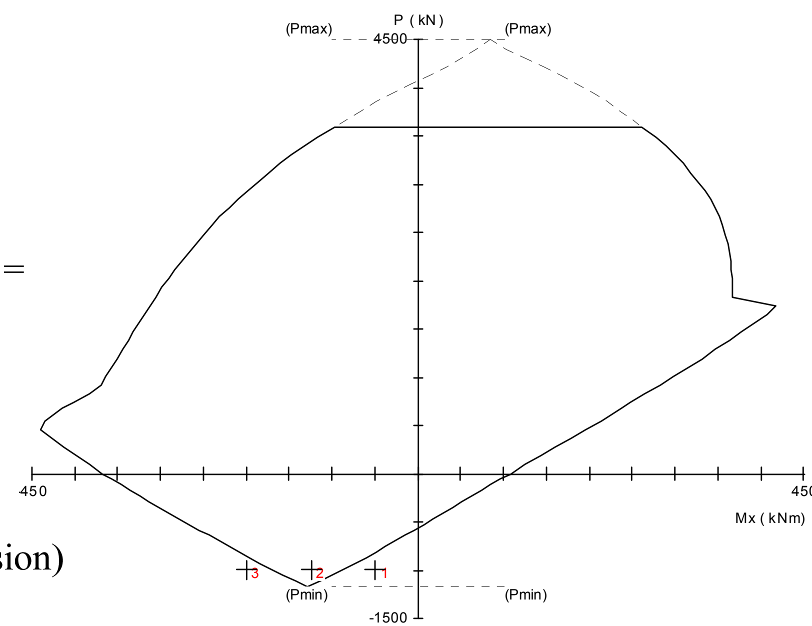


- Each quadrant different
  - $(P_{u1}, M_{u1}) \rightarrow$ NG
  - $(P_{u2}, M_{u2}) \rightarrow$ OK
  - $(P_{u3}, M_{u3}) \rightarrow$ OK
  - $(P_{u4}, M_{u4}) \rightarrow$ NG
  - Notice:
    - Absolute value of moments same on both sides
    - Larger axial force favorable on M+ side but unfavorable on M- side

P-M Diagram – Asymmetric Steel

- Skewed Diagram
  - Plastic Centroid ≠ Geometrical Centroid (Concrete Centroid ≠ Steel Centroid)
  - $(P_{u1}, M_{u1}) \rightarrow$ NG, $(P_{u2}, M_{u2}) \rightarrow$ OK, $(P_{u3}, M_{u3}) \rightarrow$ NG
    $|M_{u1}| < |M_{u2}| < |M_{u3}|$ with P_u = const

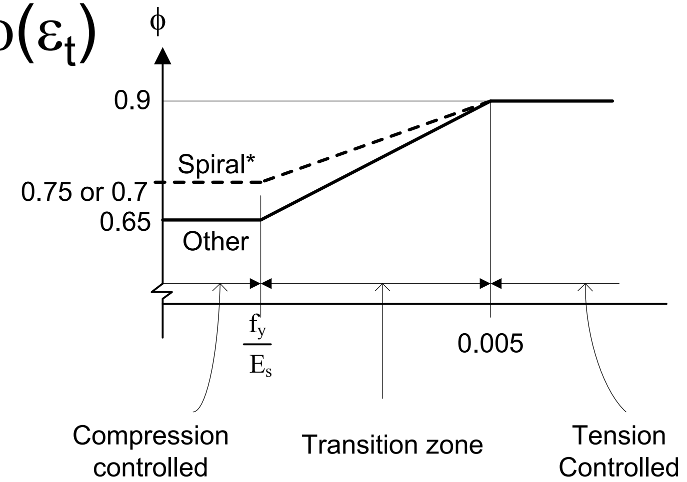


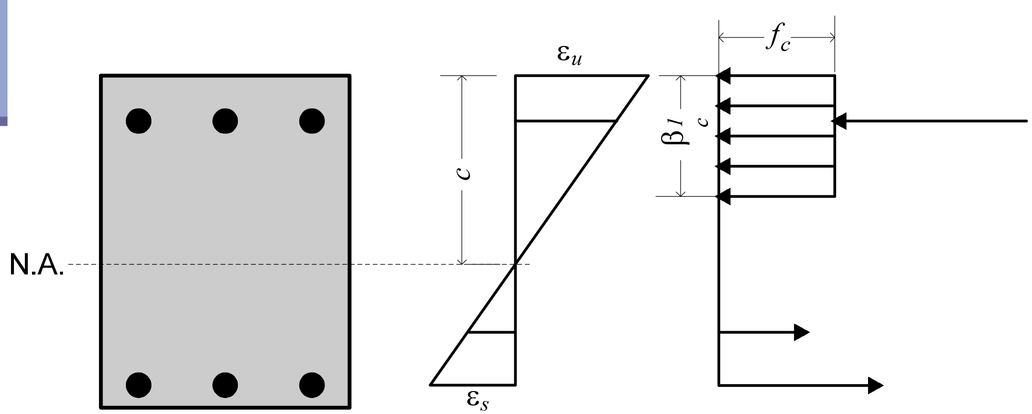


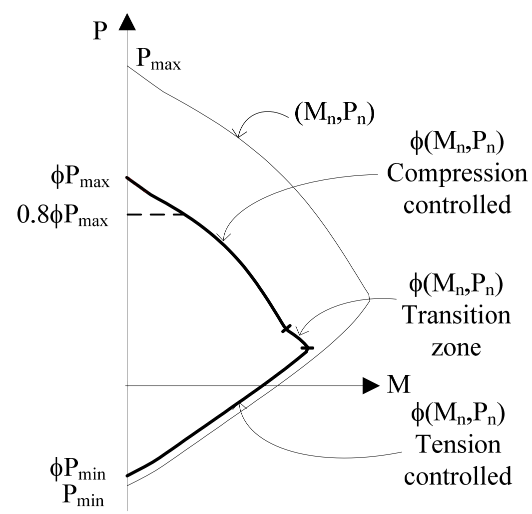
P-M Diagram – ϕ Factor

- Strength reduction factor $\phi = \phi(\varepsilon_t)$

$$(c \searrow) \rightarrow \begin{cases} \varepsilon_t \nearrow \\ \phi \nearrow \\ P_n \searrow \\ (\phi \cdot P_n) \begin{matrix} \text{usually} \searrow \\ \text{sometimes} \nearrow \end{matrix} \end{cases}$$







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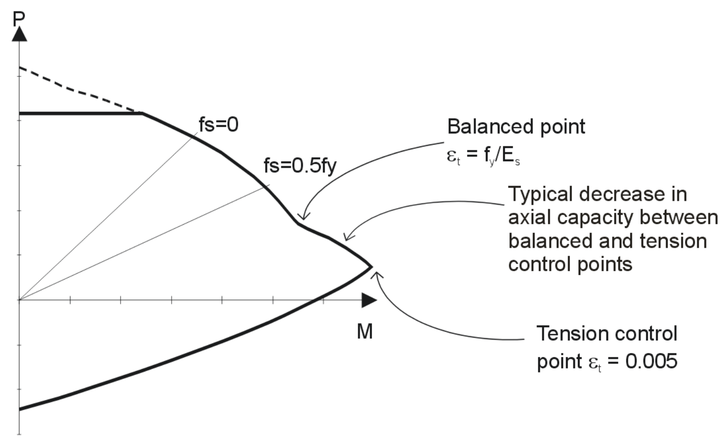
P-M Diagram – ϕ Factor

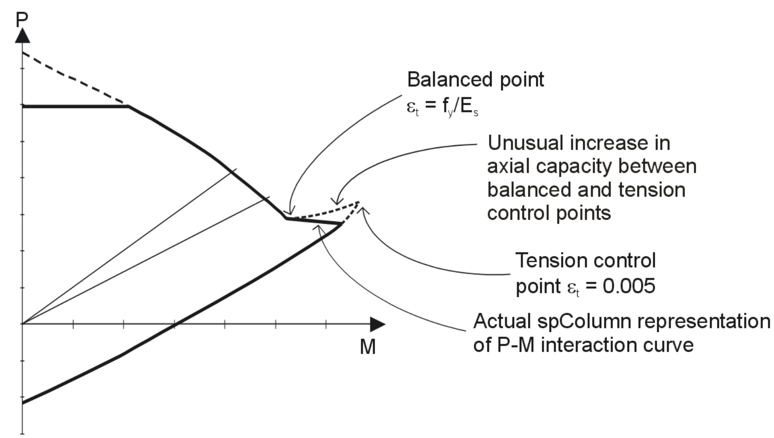
- Usually

$(c \searrow) \rightarrow (\phi \cdot P_n) \searrow$



- Sometimes

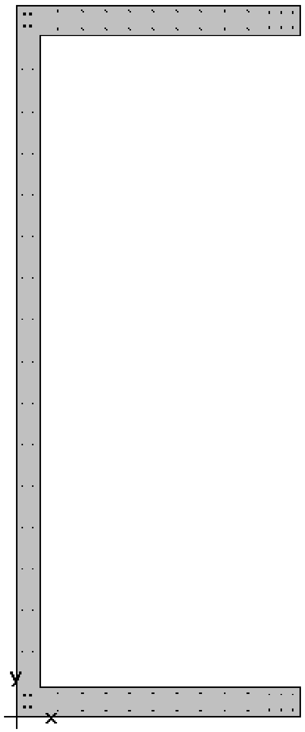
$(c \searrow) \rightarrow (\phi \cdot P_n) \nearrow$

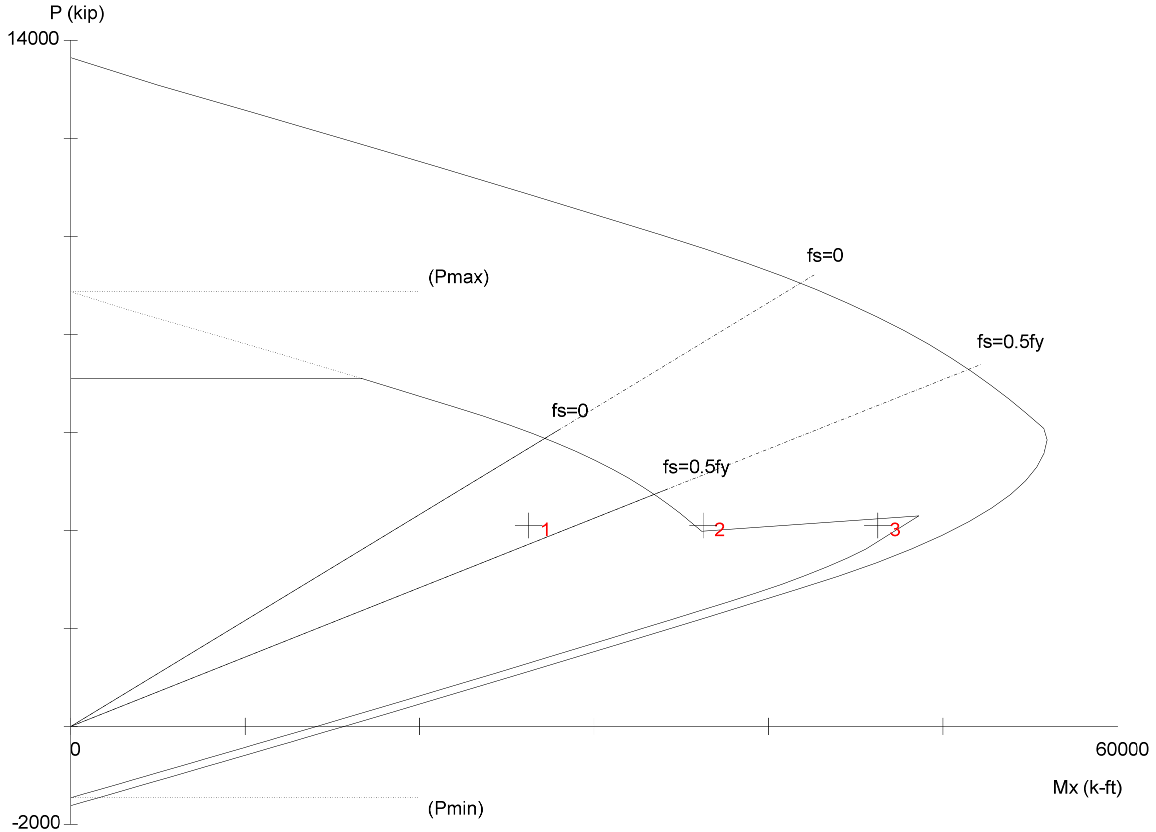


Sections with a narrow portion along height, e.g.: I, L, T, U, C-shaped or irregular sections

P-M Diagram – ϕ Factor

- $(P_{u1}, M_{u1}) \rightarrow$ OK, $(P_{u2}, M_{u2}) \rightarrow$ NG, $(P_{u3}, M_{u3}) \rightarrow$ OK
  $M_{u1} < M_{u2} < M_{u3}$ with P_u = const





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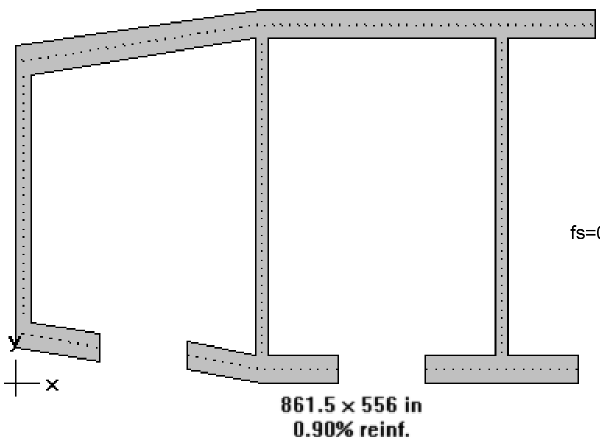
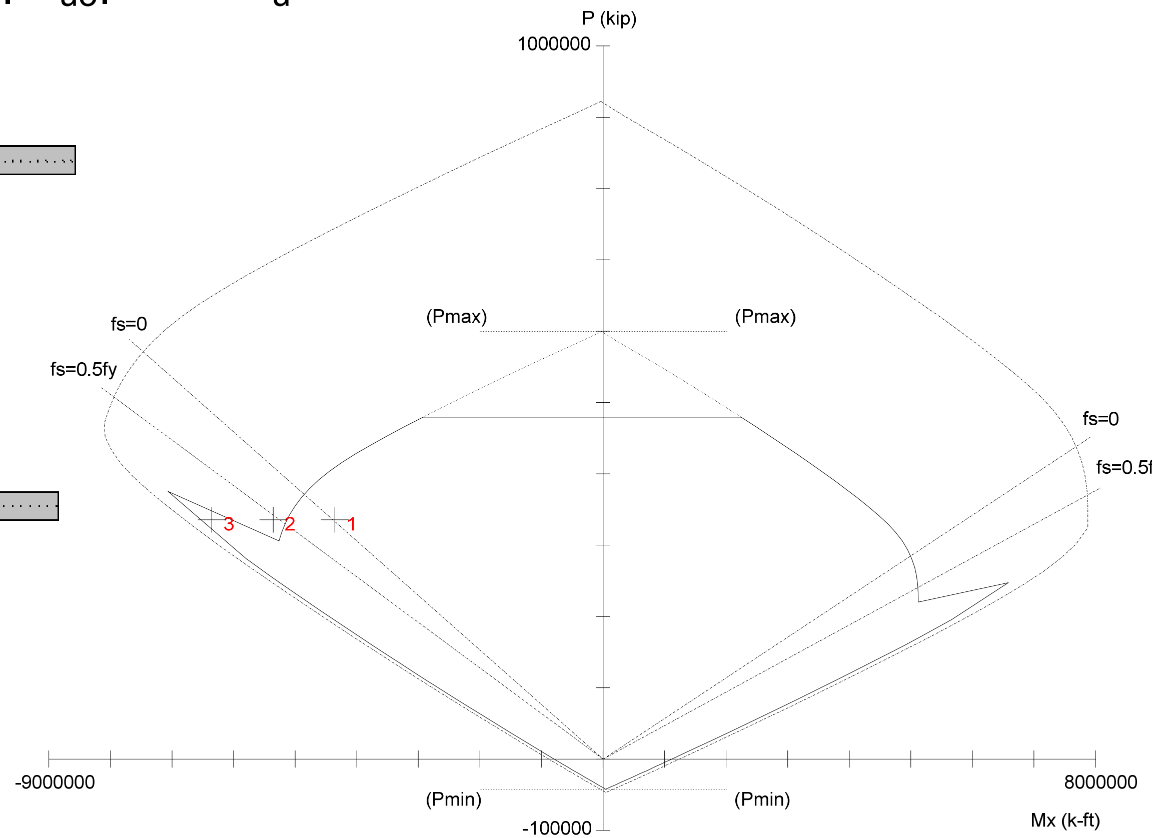
P-M Diagram – ϕ Factor

- $(P_{u1}, M_{u1}) \rightarrow$ OK, $(P_{u2}, M_{u2}) \rightarrow$ NG, $(P_{u3}, M_{u3}) \rightarrow$ OK
  $|M_{u1}| < |M_{u2}| < |M_{u3}|$ with P_u = const





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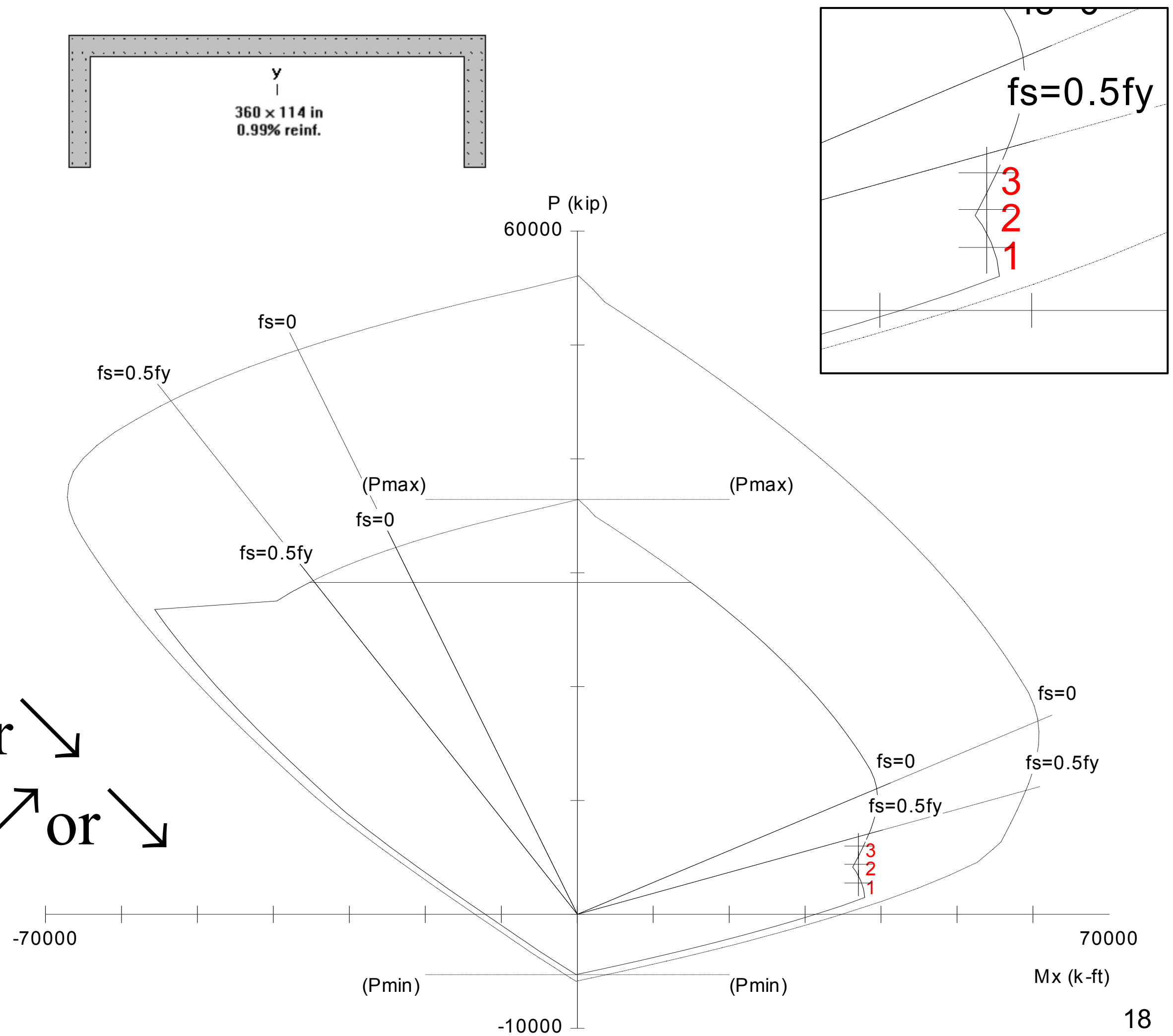
P-M Diagram – ϕ Factor

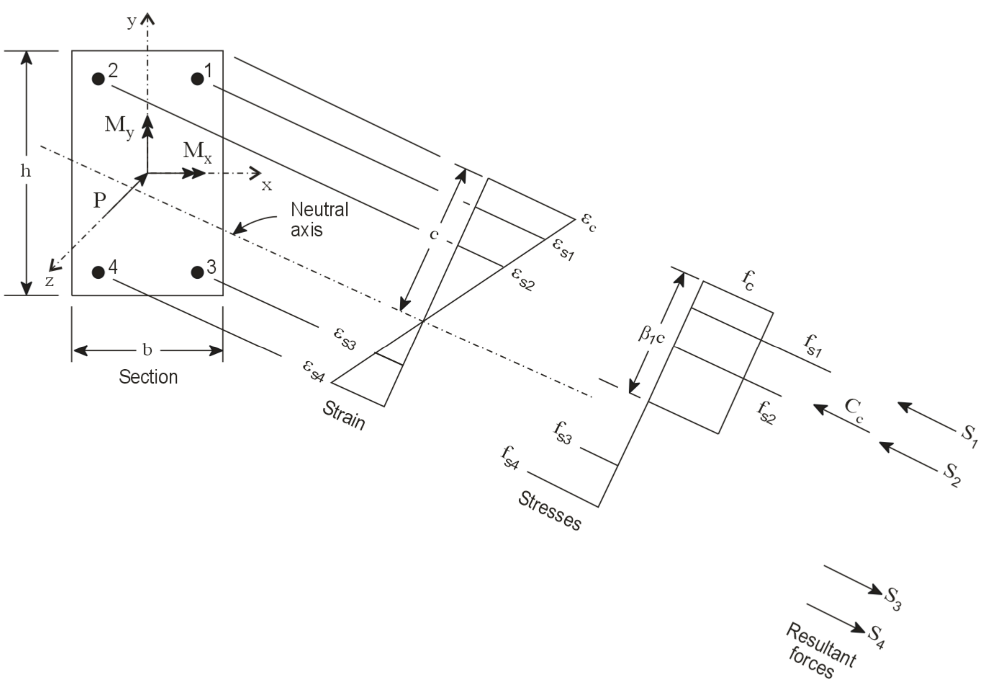
- $(P_{u1}, M_{u1}) \rightarrow$ OK
  $(P_{u2}, M_{u2}) \rightarrow$ NG
  $(P_{u3}, M_{u3}) \rightarrow$ OK
  $P_{u1} < P_{u2} < P_{u3}$
  with M_u = const

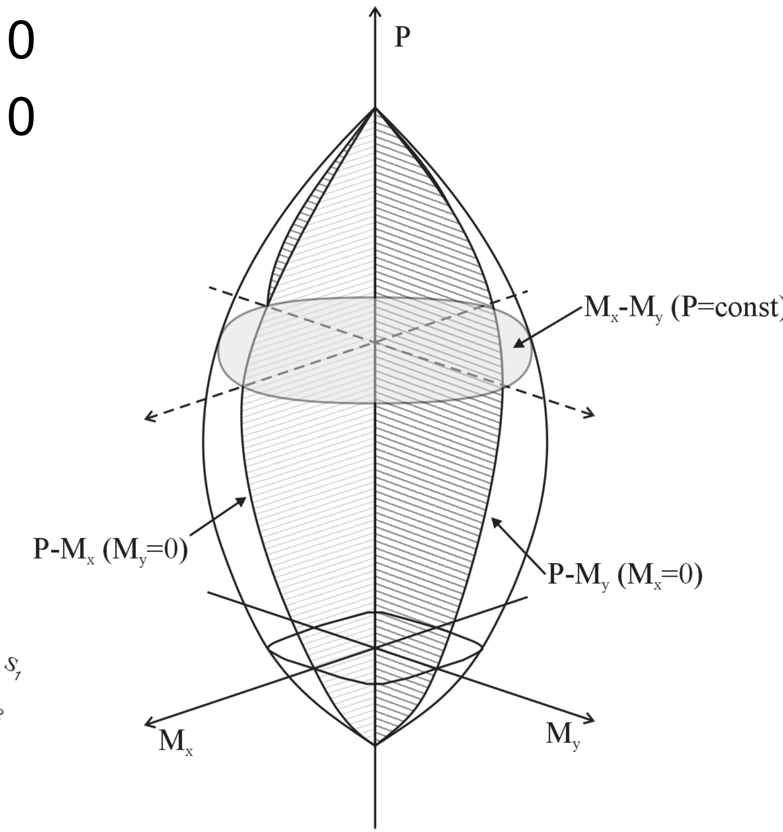
$$(c \searrow) \rightarrow \begin{cases} \varepsilon_t \nearrow \\ \phi \nearrow \\ M_n \nearrow \text{or} \searrow \\ (\phi \cdot M_n) \nearrow \text{or} \searrow \end{cases}$$



Uniaxial/Biaxial – Symmetric Case

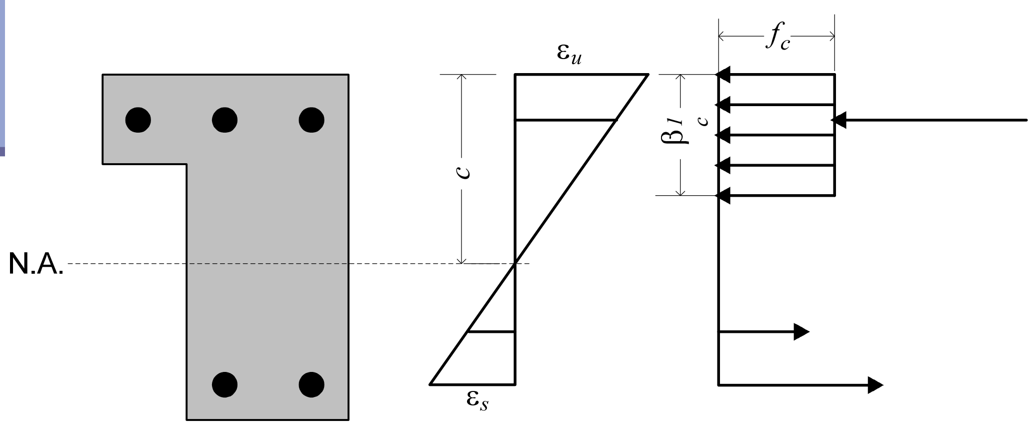
- 3D failure surface with tips directly on the P axis
- Uniaxial X = Biaxial P-M_x with M_y = 0
- Uniaxial Y = Biaxial P-M_y with M_x = 0

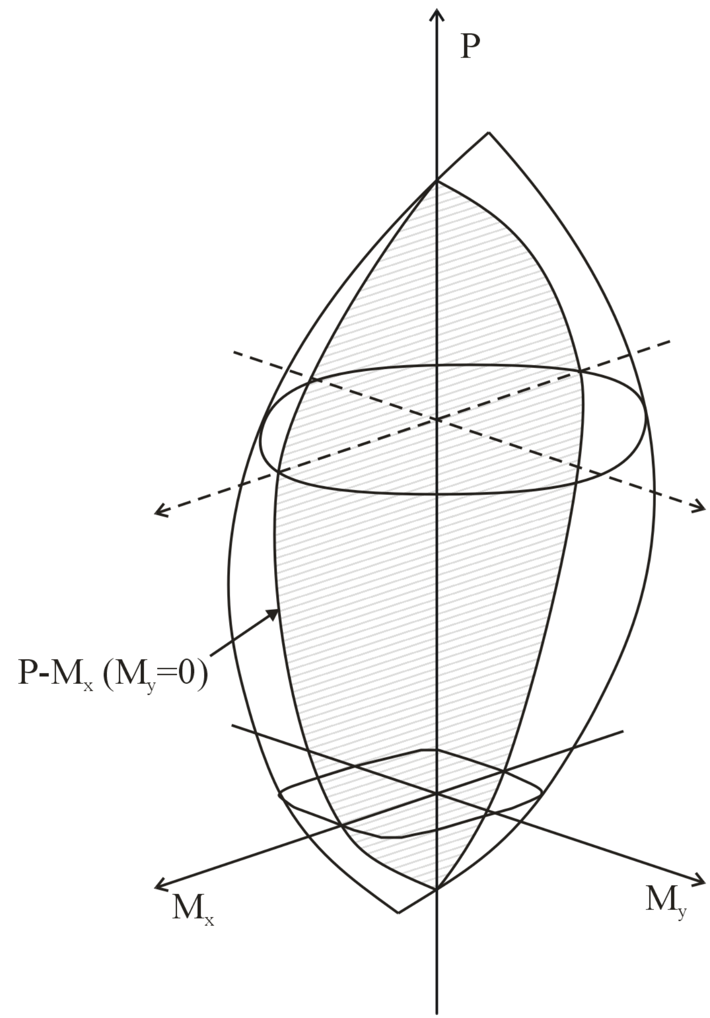




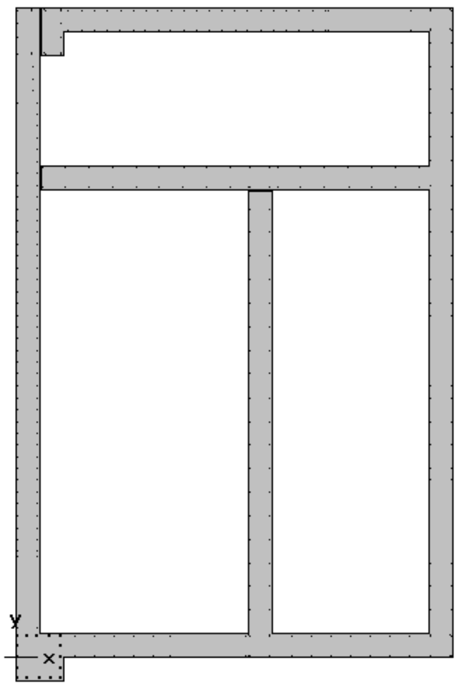
Uniaxial/Biaxial – Asymmetric case

- Tips of 3D failure surface may be off the P axis
- Uniaxial X means N.A. parallel to X axis but this produces $M_x \neq 0$ and $M_y \neq 0$
- Uniaxial X may be different than Biaxial P-M_x with $M_y = 0$

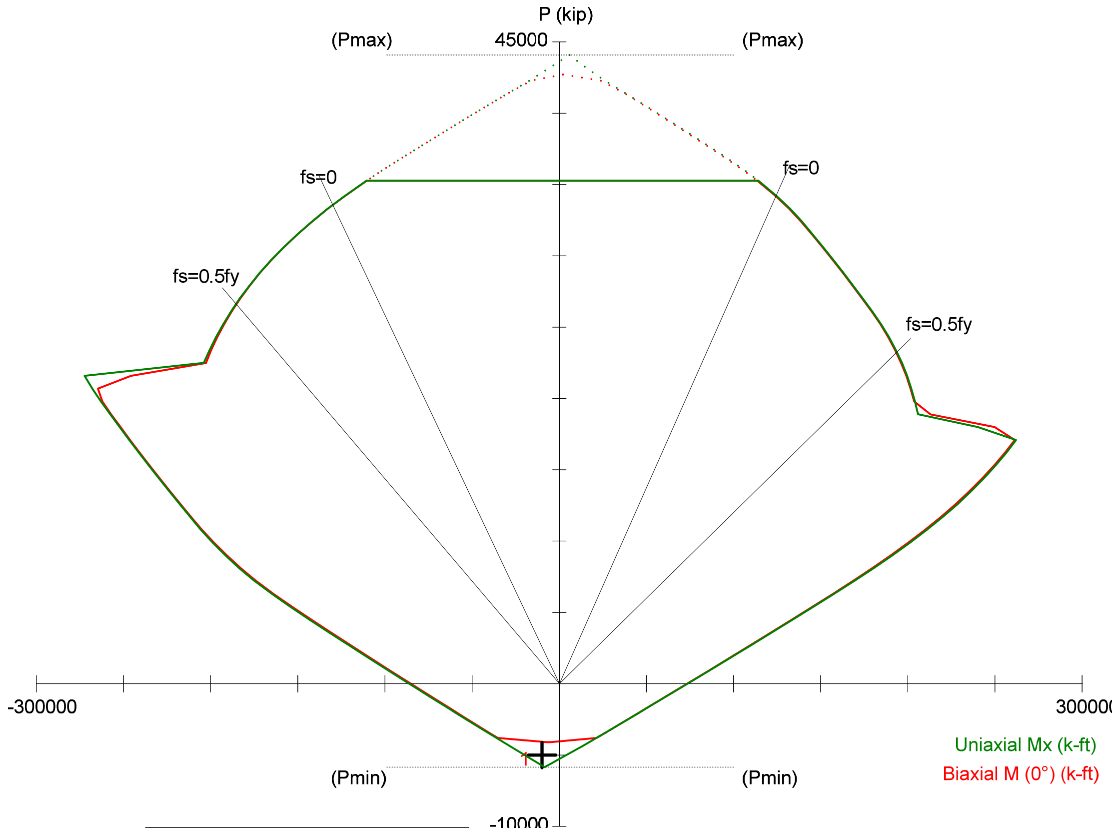


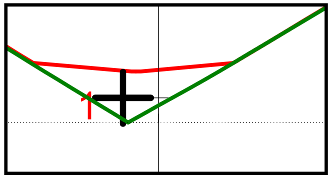


Uniaxial/Biaxial – Asymmetric Case



222 x 342 in
0.60% reinf.





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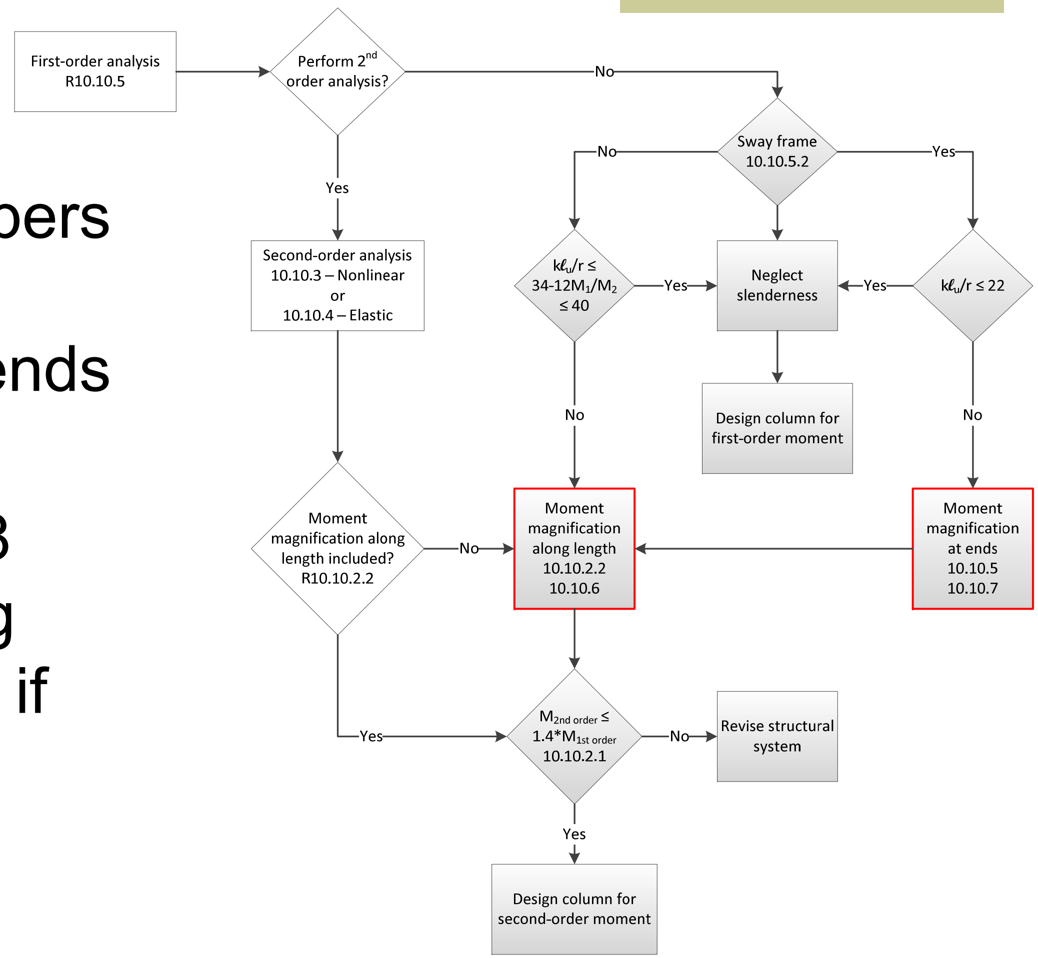
Moment Magnification – Sway Frames

- Magnification at column ends (Sway frames)
  - $M_2 = M_{2ns} + \delta_s M_{2s}$
  - If sign(M_{2ns}) = -sign(M_{2s}) then the magnified moment, M_2, is smaller than first order moment (M_{2ns}+M_{2s}) or it can even change sign, e.g.:
    - M_{2ns} = 16 k-ft, M_{2s} = -10.0 k-ft, δ = 1.2
      M_2 = 16 + 1.2 (-10.0) = 4.0 k-ft
      (M_{2ns}+M_{2s}) = 6.0 k-ft
    - M_{2ns} = 16 k-ft, M_{2s} = -14.4 k-ft, δ = 1.2
      M_2 = 16 + 1.2 (-14.4) = -1.28 k-ft
      (M_{2ns}+M_{2s}) = 1.6 k-ft
  - First-order moment may govern the design rather than second order-moment

Moment Magnification – Sway Frames

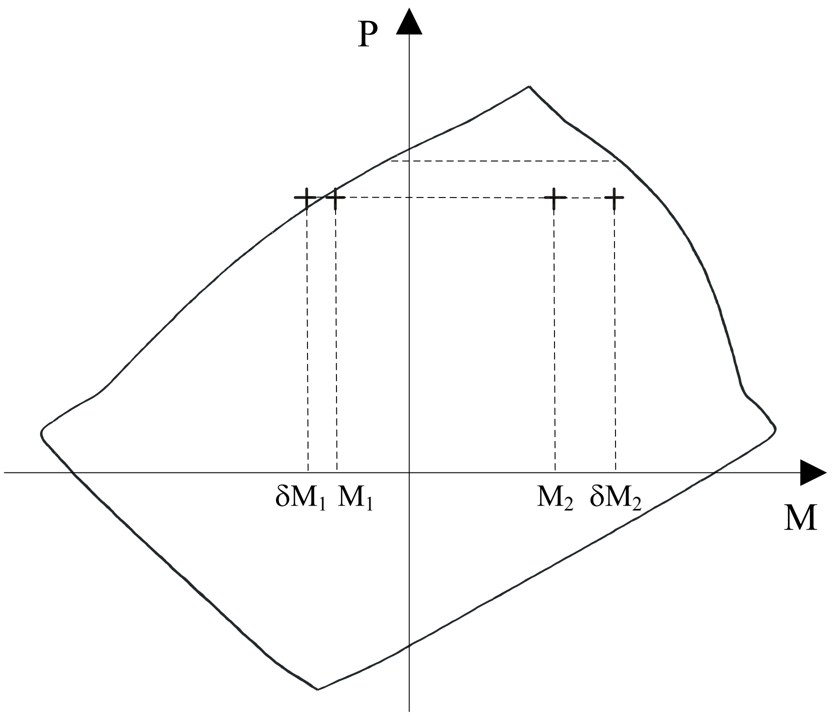
- Since ACI 318-08 moments in compression members in sway frames are magnified both at ends and along length
- Prior to ACI 318-08 magnification along length applied only if

$$\frac{\ell_u}{r} > \frac{35}{\sqrt{\frac{P_u}{f'_c A_g}}}$$



Moment Magnification – M_1

- M_1 may govern the design rather than M_2 even though $|M_2| > |M_1|$ and ACI 318, 10.10.6 provision stipulates that compression members shall be designed for $M_c = \delta M_2$. Consider:
  - Double curvature bending ($M_1/M_2 < 0$)
  - Asymmetric Section
  - $\delta M_2 \rightarrow$ OK but $\delta M_1 \rightarrow$ NG



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Moment Magnification – M^{2nd}/M^{1st}

- ACI 318-11, 10.10.2.1 limits ratio of second-order moment to first-order moments

$$M^{2nd}/M^{1st} < 1.4$$

- What if ratio is negative, e.g.:
  - $M^{1st} = M_{ns} + M_s = 10.0 + (-9.0) = 1.0$ k-ft
  - $M^{2nd} = \delta(M_{ns} + \delta_s M_s) = 1.05\ (10.0+1.3(-9.0)) = -1.78$ k-ft
  - $M^{2nd}/M^{1st} = -1.78 \rightarrow$ OK or NG ?

  - Check $|M^{2nd}/M^{1st}| = 1.78 > 1.4 \rightarrow$ NG

Moment Magnification – M^{2nd}/M^{1st}

- What if M^{1st} is very small, i.e. $M^{1st} < M_{min}$, e.g.:
  - $M^{1st} = M_2 = 0.1$ k-ft (Nonsway frame)
  - $M_{min} = P_u(0.6 + 0.03h) = 5$ k-ft
  - $M^{2nd} = M_c = \delta M_{min} = 1.1*5 = 5.5$ k-ft
  - $M^{2nd}/M^{1st} = 5.5/0.1 = 55 \rightarrow$ OK or NG ?
  - Check $M^{2nd}/M_{min} = 1.1 \rightarrow$ OK

Conclusions

- Summary
  - Irregular shapes of sections and reinforcement patterns lead to irregular and distorted interaction diagrams
  - Large number of load cases and load combinations lead to large number of load points potentially covering entire (P, M_x, M_y) space
  - Intuition may overlook unusual conditions in tall structures

Conclusions

- Recommendations
  - Do not eliminate load cases and combinations based on intuition
  - Run biaxial rather than uniaxial analysis for asymmetric sections
  - Run both 1st order and 2nd order analysis
  - Apply engineering judgment rather than following general code provisions literally
  - Use reliable software and verify its results

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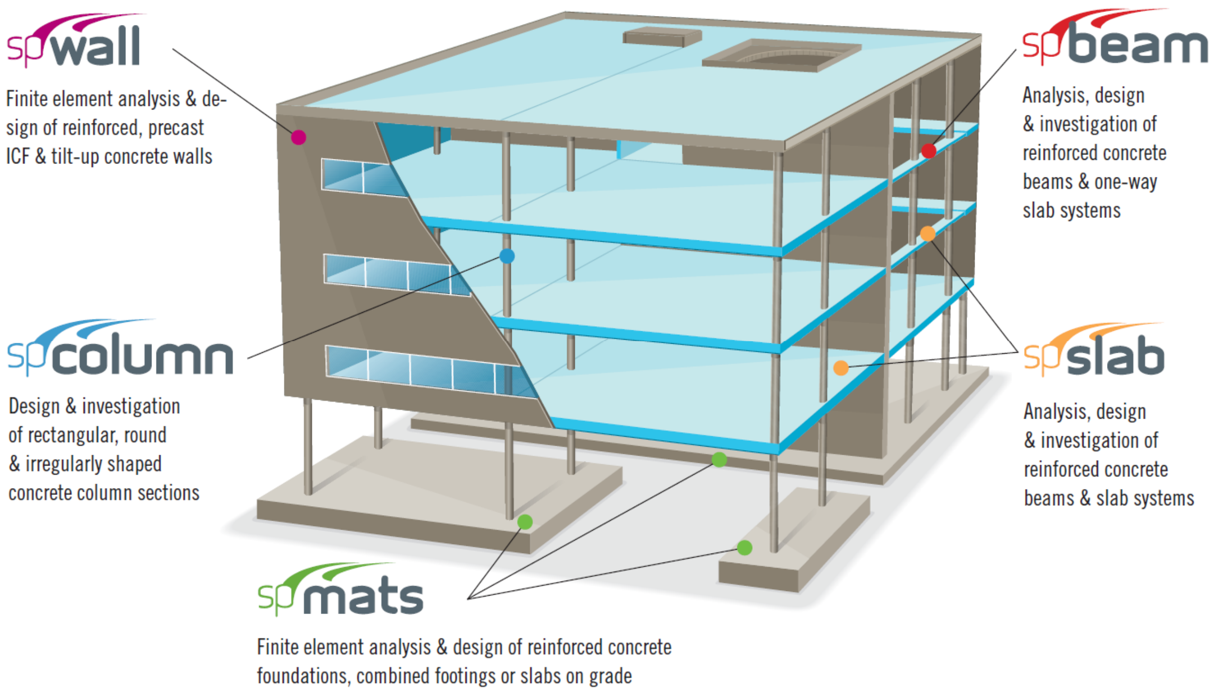

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