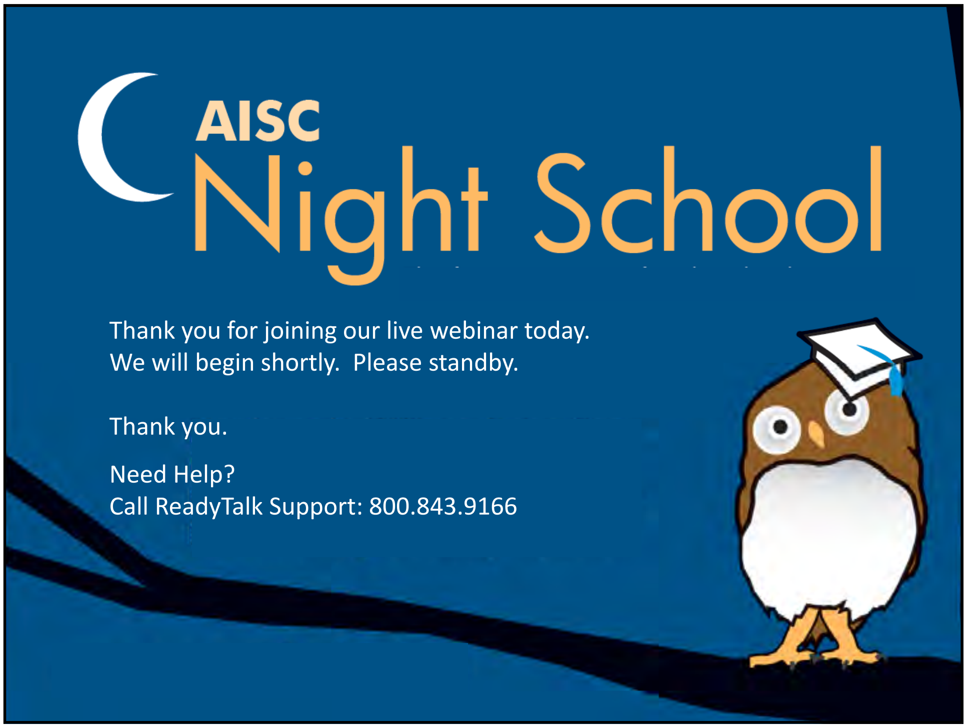

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Course Description

Course Overview and Behavior of Flexural Members
June 26, 2017

This lecture will begin with another brief overview of the 8-lecture course. Using an approach similar to that employed in Session 1, this lecture will then go on to present and dissect the solution to the differential equation that defines the elastic lateral torsional buckling (LTB) strength of beams. Related flexural and torsional concepts, including the benefits of warping resistance, will be briefly reviewed. The assumption of elastic behavior will then be relaxed to define the inelastic LTB and plastic moment capacities of flexural members. The strength of beams without slender elements will be covered and ultimately presented in the form of beam resistance curves.

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Learning Objectives

- Explain the limit state of full yielding.
- Explain the lateral torsional buckling strength of beams.
- Explain how the length between brace points of the compression flange of a member in flexure affects lateral torsional buckling.
- Explain the application of the lateral torsional buckling moment gradient factor, C_b.

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Fundamentals of Stability for Steel Design

Session 3: Course Overview and Behavior of Flexural Members

June 26, 2017

Presented by
Ronald D. Ziemian, Ph.D., P.E.
Professor
Bucknell University, Lewisburg, PA

Structural Stability Research Council · SSRC · Founded 1944

American Institute of Steel Construction

structural STEEL

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Fundamentals of Stability for Steel Design

Session 3
Course Overview and Behavior of Flexural Members

Ronald D. Ziemian, P.E., Ph.D.

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Course Overview

- Session Topics
  - Compression Members (1 & 2)
  - Flexural Members (3 & 4)
  - Systems / Beam-Columns (5 & 6)
  - Bracing (7 & 8)
- Topics in two parts
  - Behavior (1, 3, 5, 7)
  - Design (2, 4, 6, 8)
- Lectures by members of the Structural Stability Research Council (SSRC)
  - P.S. Green, T.A. Helwig, D.W. White, J.A. Yura, R.D. Ziemian
  - Great to join AISC in this effort!

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Course Overview (2)

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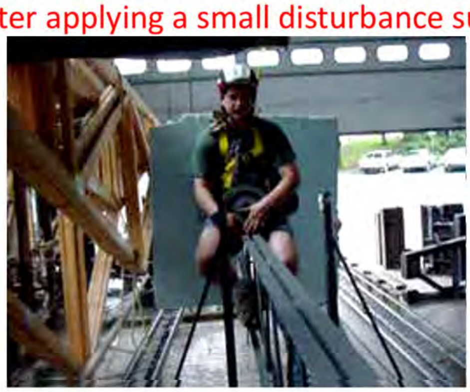
Course Overview (3)

- Focus of the course is on fundamentals!
- Better understanding of behavior will result in improved design
- Key Definitions
  - **Stability:** Under load, component returns to current state after applying a small disturbance such as a deflection



Thanks Matt!
(but he is not the only trained professional at buckling…)

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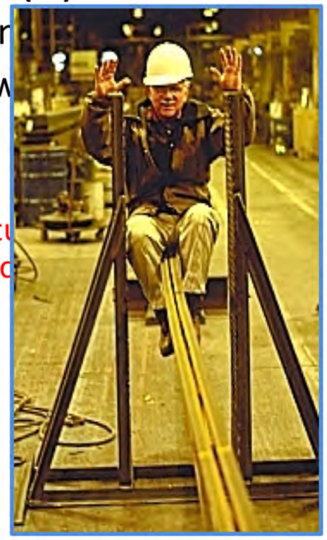
Course Overview (3)

- Focus of the course is on fundamen
- Better understanding of behavior w
  improved design
- Key Definitions
  - **Stability:** Under load, component retu
    after applying a small disturbance suc



Thanks Ted!

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Course Overview (3)

- Focus of the course is on fundamentals!
- Better understanding of behavior will result in improved design
- Key Definitions
  - **Stability:** Under load, component returns to current state after applying a small disturbance such as a deflection
  - **Bifurcation (critical load)**: Theoretical point at which loading a component results in an instantaneous change from current state to significant deflection – two options: not buckled or buckled
  - **Instability:** Loading a component results in an actual transition from small deflection to significant deflection – buckling preceded/defined by significant deflection

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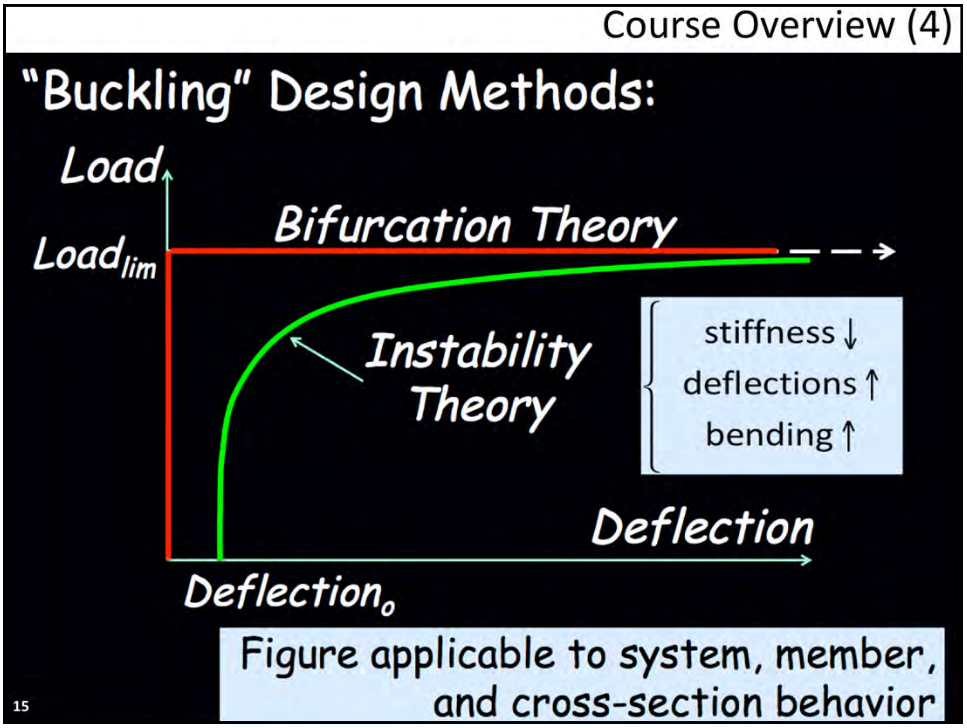

Course Overview (5)

ANSI/AISC 360-16
An American National Standard

Specification for Structural Steel Buildings

Let's continue to start at the end…

C1. GENERAL STABILITY REQUIREMENTS

Stability shall be provided for the structure as a whole and for each of its elements. The effects of all of the following on the stability of the structure and its elements shall be considered: (a) flexural, shear and axial member deformations, and all other component and connection deformations that contribute to the displacements of the structure; (b) second-order effects (including P-Δ and P-δ effects); (c) geometric imperfections; (d) stiffness reductions due to inelasticity, including the effect of partial yielding of the cross section which may be accentuated by the presence of residual stresses; and (e) uncertainty in system, member, and connection strength and stiffness. All load-dependent effe
sponding to LRFD load combinat

Why these for the Big 5?

Any rational method of design for stability that considers all of the listed effects is permitted; this includes the methods identified in Sections C1.1 and C1.2.

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Fundamentals of Stability for Steel Design

Session 3
Course Overview and
Behavior of Flexural Members

Ronald D. Ziemian, P.E., Ph.D.

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Limit States of Flexural Members

- Full yielding (today!)
- Instability
  - Along the member length (today!)
    - Lateral torsional buckling
      - elastic
      - inelastic
  - At the cross section
    - local buckling

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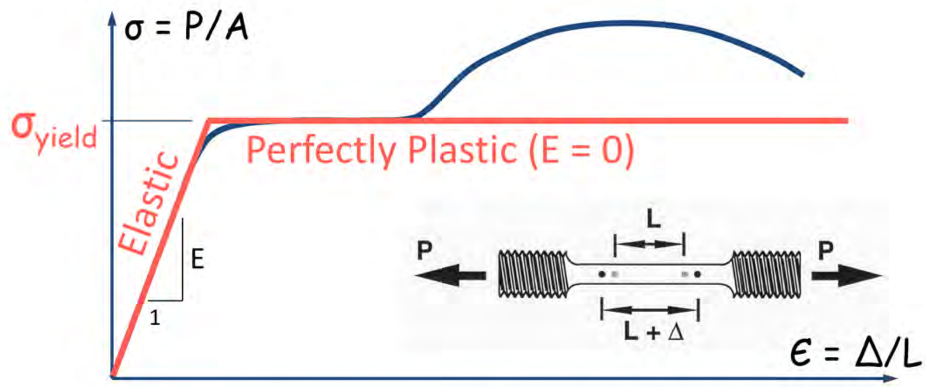
Full Yielding

- Tensile test



- Assume same response for compression
  - $\sigma_{y,compression} = \sigma_{y,tension} = \sigma_{yield}$
  - Neglect strain hardening (assume elastic-plastic)

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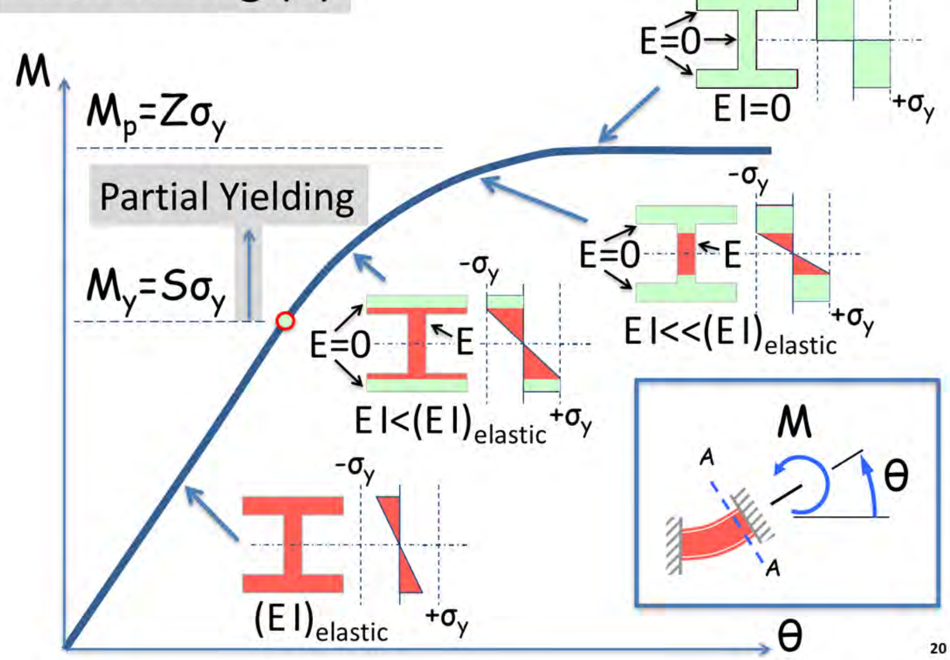
Full Yielding (2)



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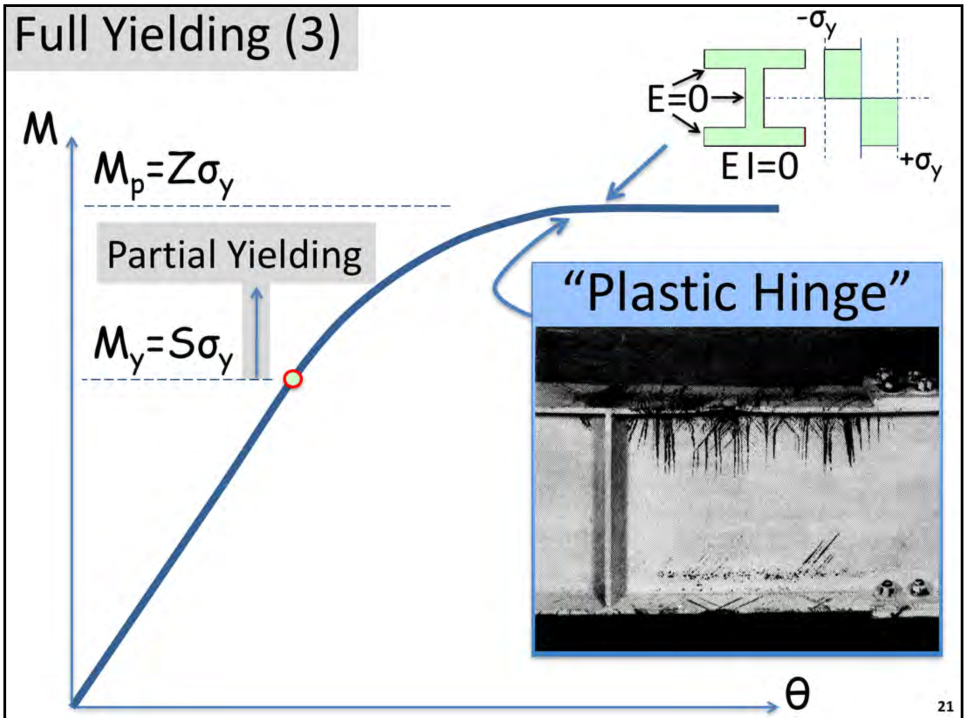
Full Yielding (3)



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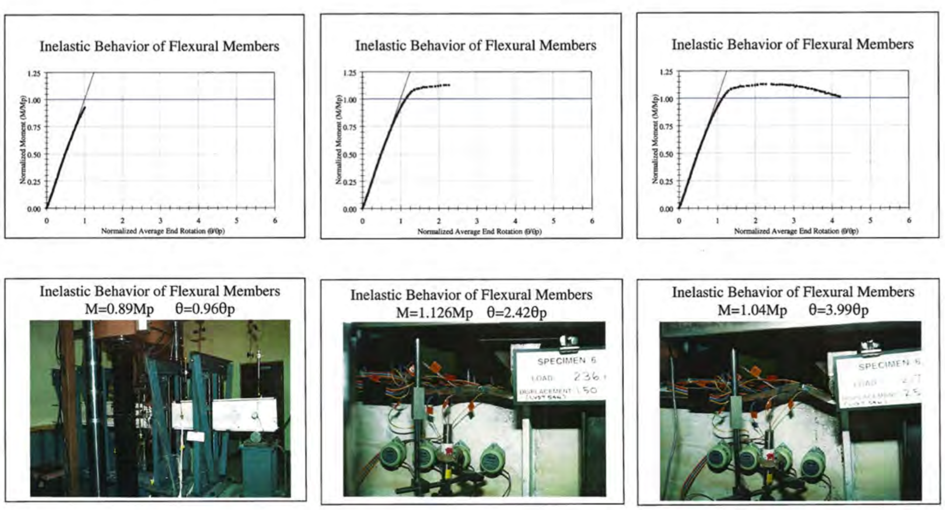
Full Yielding (4)

And, in the lab…



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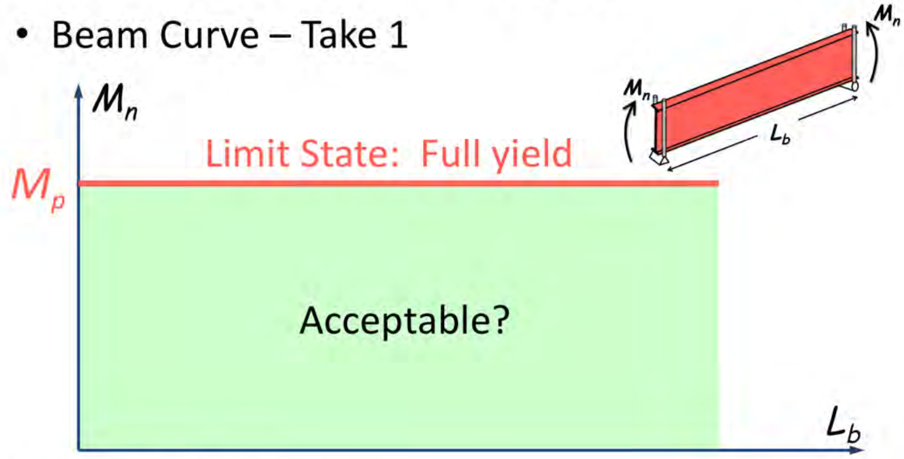
Full Yielding (5)

- Beam Curve – Take 1



- What about:
  - member instability ??? (today!)
  - cross section instability (local buckling) ???

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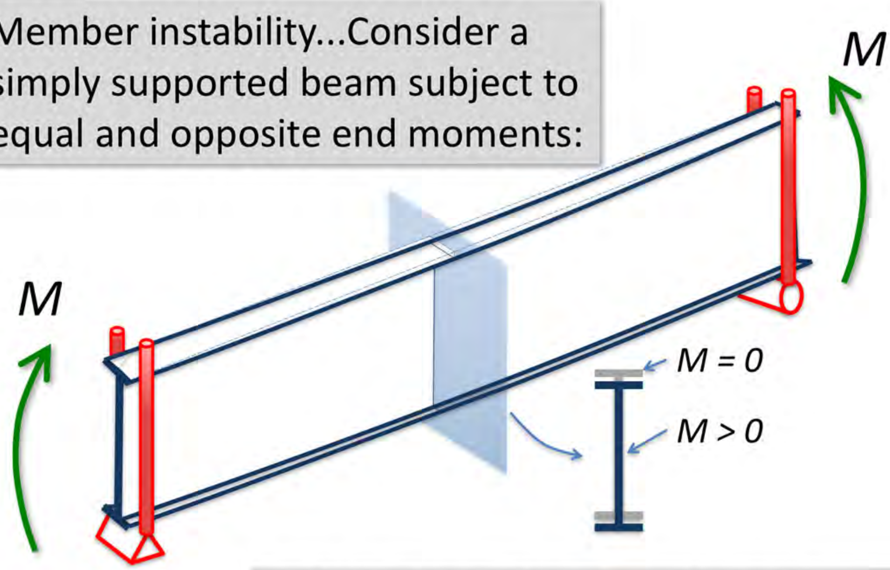
Member instability...Consider a simply supported beam subject to equal and opposite end moments:



Initially, beam bends downward resulting in only vertical deflection...

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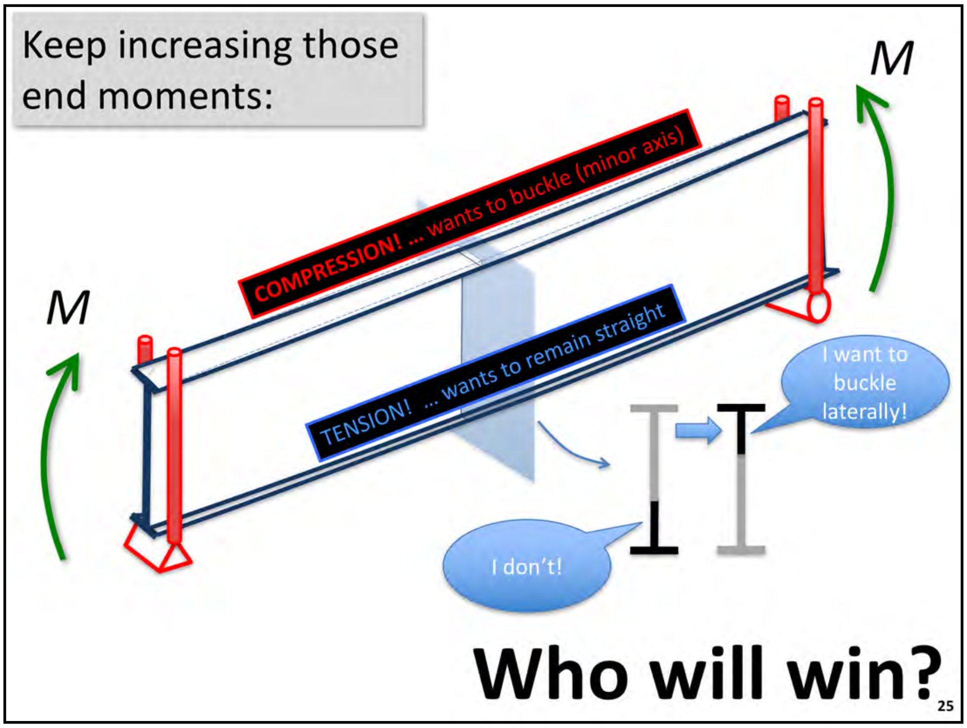
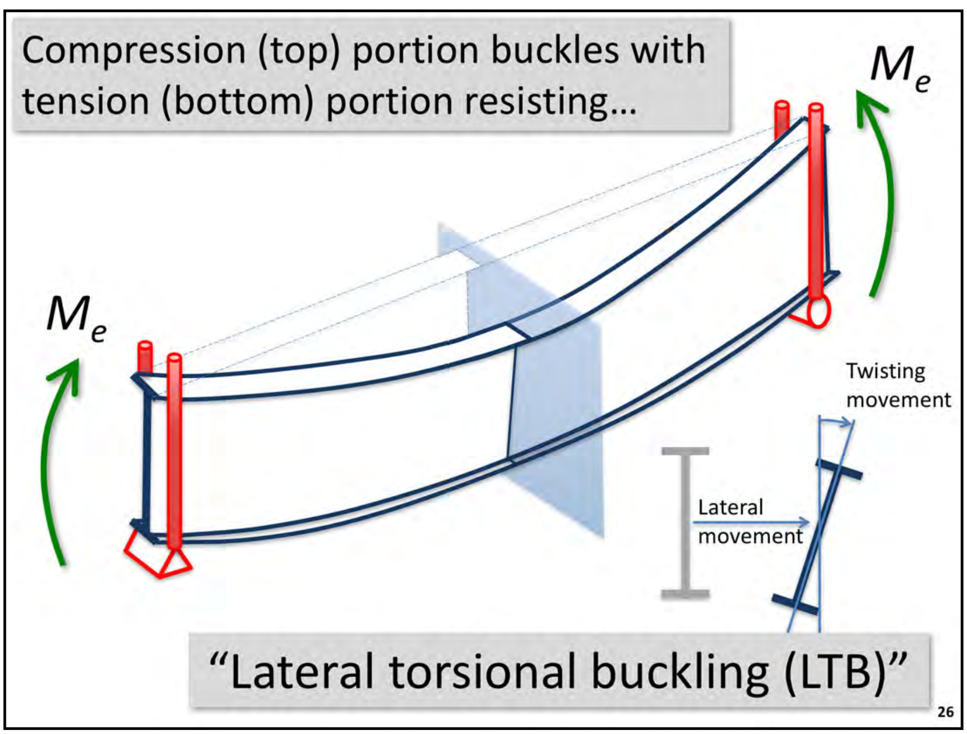
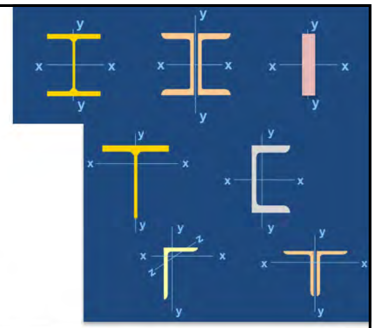

Keep increasing those end moments:
M
M
COMPRESSION! ... wants to buckle (minor axis)
TENSION! ... wants to remain straight
I want to buckle laterally!
I don't!
Who will win?
25


Compression (top) portion buckles with tension (bottom) portion resisting…
M_e
M_e
Twisting movement
Lateral movement
"Lateral torsional buckling (LTB)"
26

Member instability: Lateral Torsional Buckling



Some trouble in a power plant…

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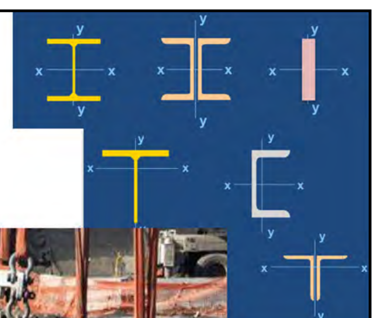
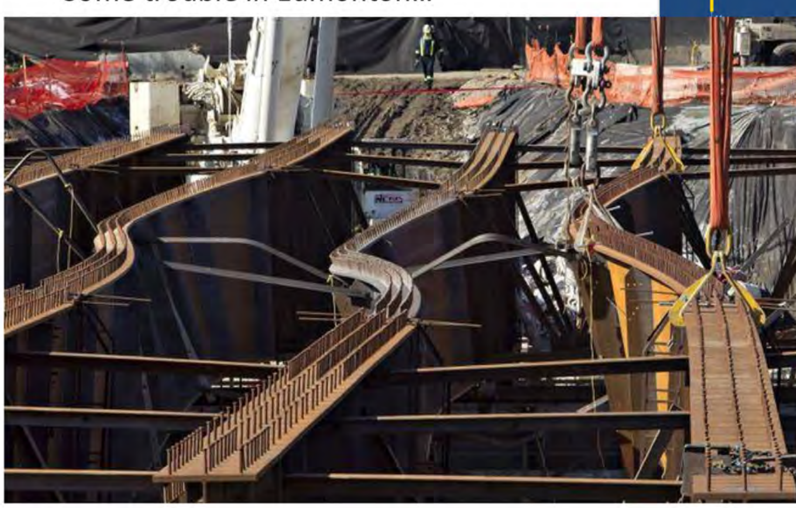
Member instability: Lateral Torsional Buckling



Some trouble in Edmonton…



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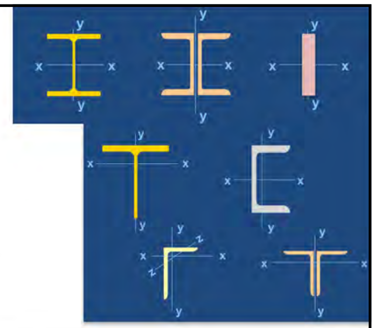
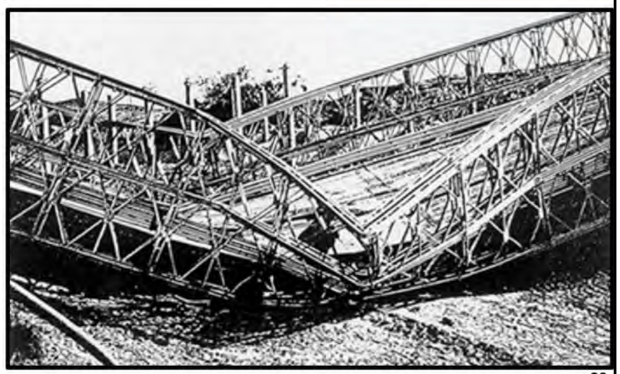
Member instability: Lateral Torsional Buckling



Some trouble in Santa Barbara County, CA…



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Lateral Torsional Buckling

- Theoretical bifurcation
  - solution
  - assumptions
- Undoing those assumptions (approaching reality)
  - not fully elastic, partial yielding
  - alternative loading and support conditions
- Beam curves
  - AISC
  - others

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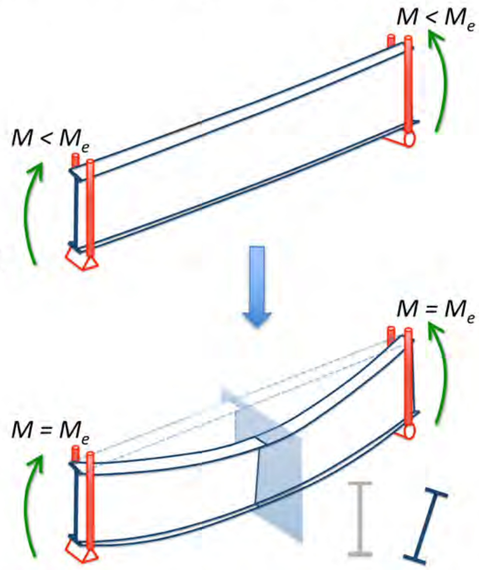
Lateral Torsional Buckling (LTB)

- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling
  - linear elastic behavior (E = constant)
  - uniform moment distribution
  - braced at the ends (frictionless)



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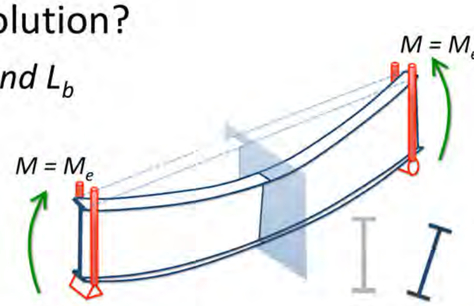
LTB (2)

- Before obtaining the theoretical solution for M_e, let's do a "parametric" analysis…
- Terms expected in the solution?
  - Minor axis buckling: EI_y *and* L_b
  - Torsion
    - St. Venant: GJ and L_b
    - Warping: EC_w and L_b
  - Others? π (of course!)
- What's their impact?



Terms in numerator → Material: $E\uparrow, G\uparrow \Rightarrow M_e\uparrow$

Terms in numerator → Section: $I_y\uparrow, J\uparrow, C_w\uparrow \Rightarrow M_e\uparrow$

Term in denominator → Unbraced length: $L_b\uparrow \Rightarrow M_e\downarrow$

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Wait…

- Minor axis buckling, we recall from Session 1

$$P_E = \frac{\pi^2 EI}{L^2}$$

- But, we may need a quick refresher on torsion!

St. Venant ?
Warping ????

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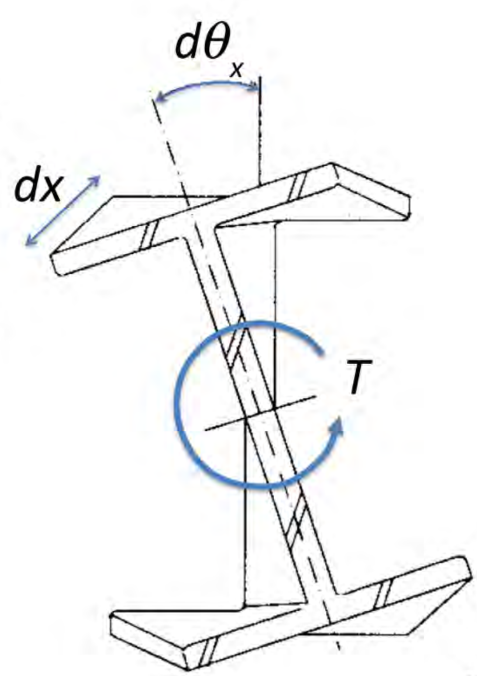
St. Venant Torsion

Consider a portion of the member of length *dx* subject to a torque *T*.
If we consider only St. Venant (uniform) torsion, the rotation per unit length is:

$$\frac{d\theta_x}{dx} = \frac{T}{GJ}$$



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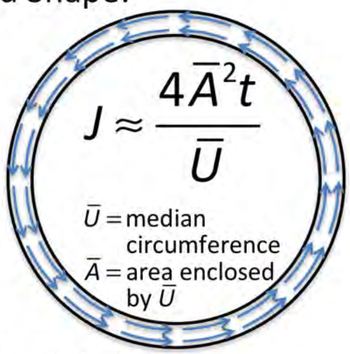
St. Venant Torsion (2)

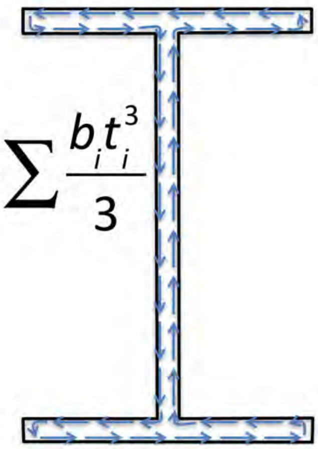
Closed Shape:



$$J \approx \frac{4\bar{A}^2 t}{\bar{U}}$$

$\bar{U}$ = median circumference
$\bar{A}$ = area enclosed by $\bar{U}$

Open Shape:



$$J \approx \sum \frac{b_i t_i^3}{3}$$

Circular Hollow Shape:
t = 0.25”, A = 3.84 in^2
$\bar{D} = A/(\pi t)$ = 4.90”

$$J = \frac{4(\pi \bar{D}^2/4)^2 t}{\pi \bar{D}} = 22.95 \text{ in}^4$$

W8x13 (t_f=0.23”, t_w=0.26”):
A = 3.84 in^2
J = 0.0871 in^4

Factor of 264…closed sections rule in torsion!

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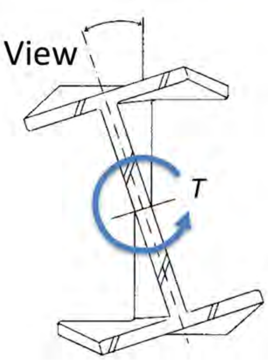
Warping Torsion (your new best friend!)

Top View

Notice that this torque T also causes the flanges to bend in opposite directions. This “cross flange” bending can also resist the applied torque.

End View



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Warping Torsion (2)

Relationship to rotation?

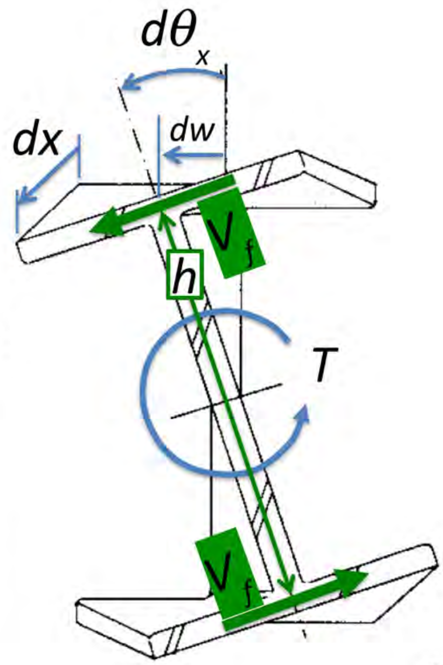
$$T = 2V_f \frac{h}{2} = V_f h$$

with $V_f = \frac{dM_f}{dx}$

$$M_f = -EI_f \frac{d^2 w}{dx^2}$$

$$dw = \frac{h}{2}\, d\theta_x$$

$$T = \left(-EI_f \frac{h}{2} \frac{d^3\theta_x}{dx^3} \right) h$$



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Warping Torsion (3)

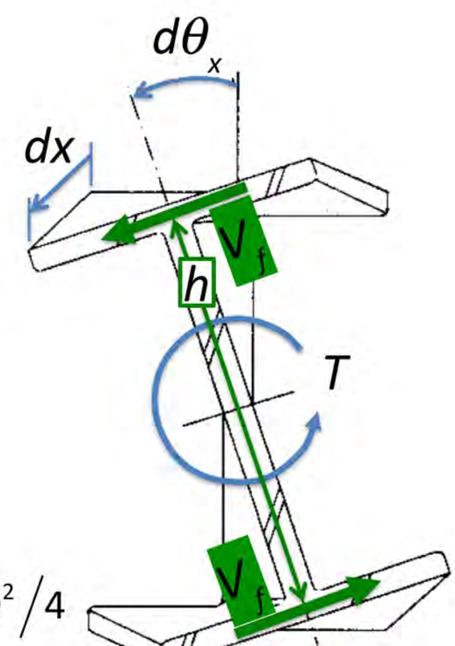
Relationship to rotation?

$$T = V_f h$$

$$T = \left(-EI_f \frac{h}{2} \frac{d^3\theta_x}{dx^3} \right) h$$

$$T = -EC_w \frac{d^3\theta_x}{dx^3}$$

with $I_f = I_y/2,\ C_w = I_y h^2/4$



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The twist on torsion

St. Venant (uniform):

$$T_{SV} = GJ\frac{d\theta_x}{dx}$$

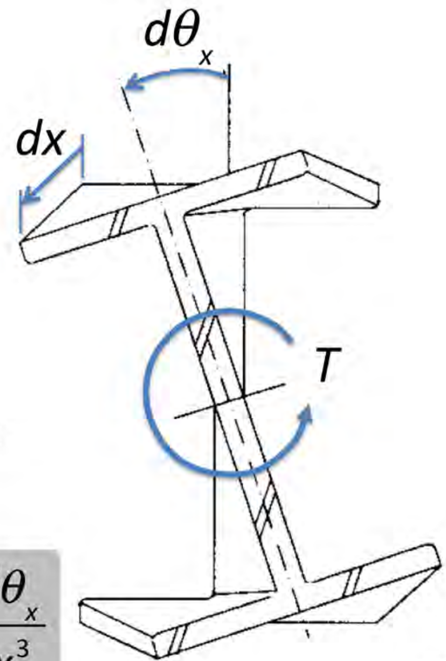
Warping(non-uniform):

$$T_w = -EC_w\frac{d^3\theta_x}{dx^3}$$

Total resisting torque:

$$T = T_{SV} + T_w$$

$$T = GJ\frac{d\theta_x}{dx} - EC_w\frac{d^3\theta_x}{dx^3}$$



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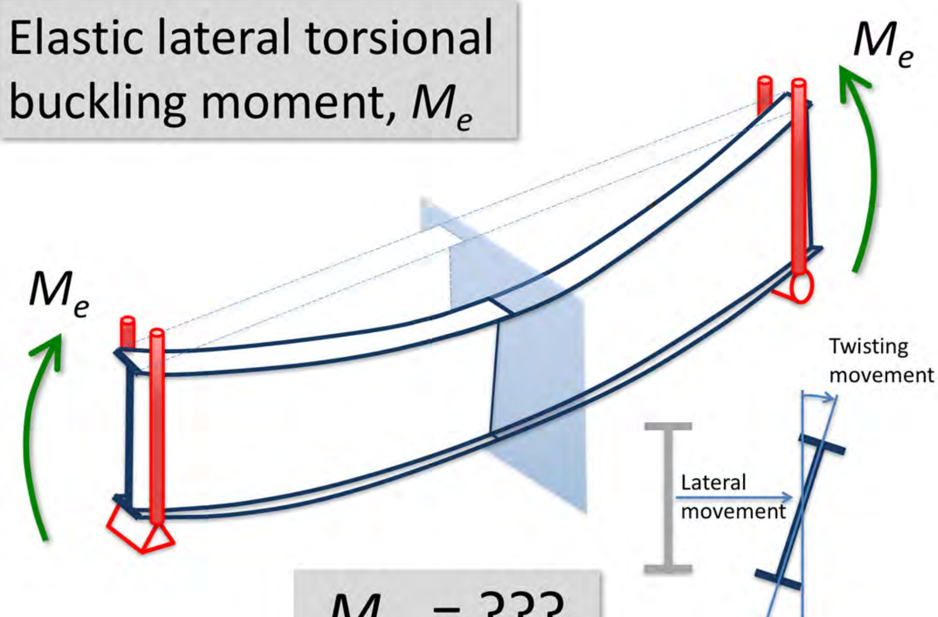
Elastic lateral torsional buckling moment, M_e



M_e = ???

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Elastic lateral torsional bu

M_e

Recall: Three Keys to an Analysis

1. Equilibrium
   (balance of forces and/or moments)
2. Compatibility
   (agreement of displacements and/or rotations)
3. Constitutive Relationship
   (relate forces and/or moments to displacements and/or rotations)

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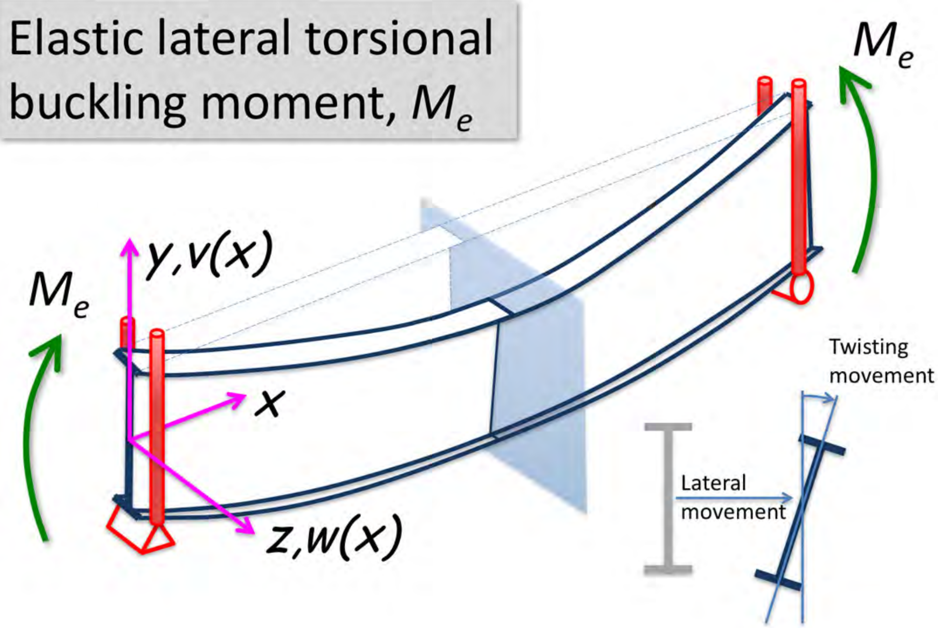
Elastic lateral torsional buckling moment, M_e



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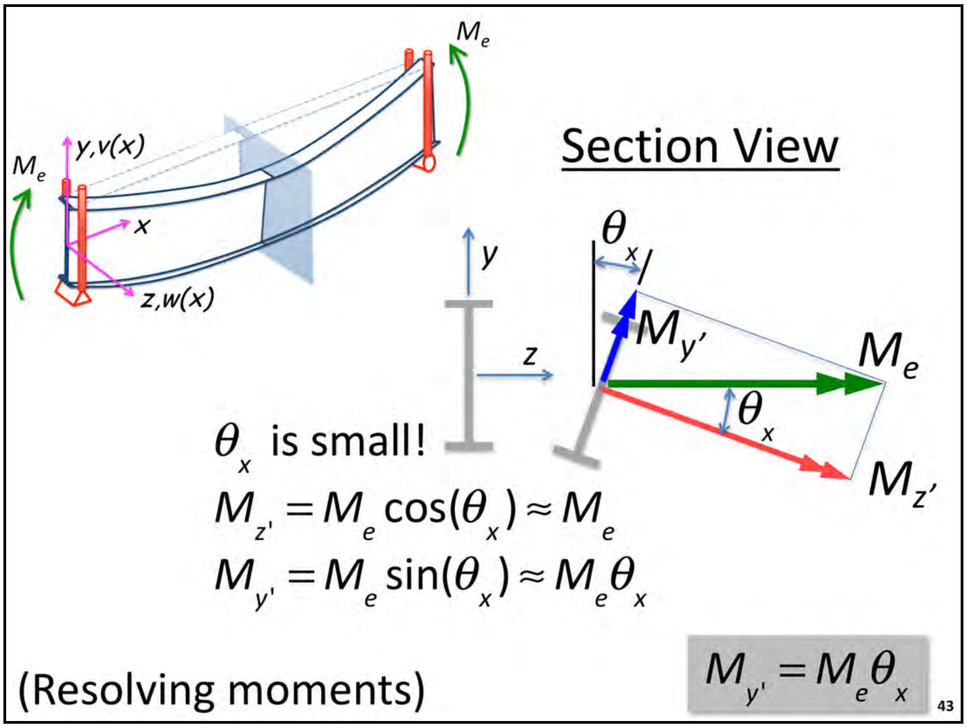
Section View
M_e
$y, v(x)$
x
$z, w(x)$
y
z
θ_x
$M_{y'}$
M_e
θ_x
$M_{z'}$
θ_x is small!
$M_{z'} = M_e \cos(\theta_x) \approx M_e$
$M_{y'} = M_e \sin(\theta_x) \approx M_e \theta_x$
(Resolving moments)
$M_{y'} = M_e \theta_x$
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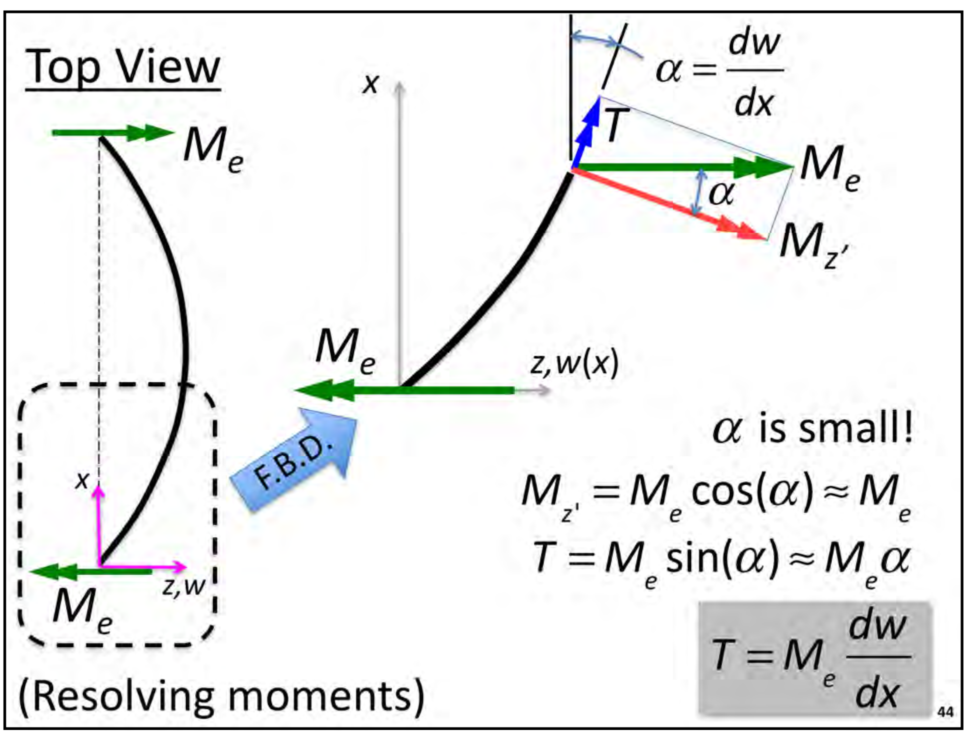
Top View
M_e
x
z, w
M_e
F.B.D.
x
$\alpha = \frac{dw}{dx}$
T
M_e
α
$M_{z'}$
M_e
$z, w(x)$
α is small!
$M_{z'} = M_e \cos(\alpha) \approx M_e$
$T = M_e \sin(\alpha) \approx M_e \alpha$
(Resolving moments)
$T = M_e \frac{dw}{dx}$
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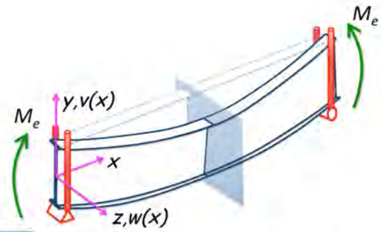
Summary



Equilibrium: $T = T_{SV} + T_w$

"applied" torque "resisting" torque

$$T = M_e \frac{dw}{dx} = GJ \frac{d\theta_x}{dx} - EC_w \frac{d^3\theta_x}{dx^3}$$ (Constitutive Relationship)

$$\frac{d}{dx}\left(M_e \frac{dw}{dx}\right) = \frac{d}{dx}\left(GJ \frac{d\theta_x}{dx} - EC_w \frac{d^3\theta_x}{dx^3}\right)$$

$$M_e \frac{d^2w}{dx^2} = GJ \frac{d^2\theta_x}{dx^2} - EC_w \frac{d^4\theta_x}{dx^4}$$

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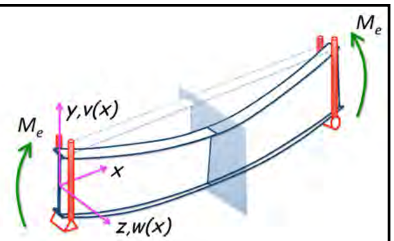
Summary (2)



$$M_e \frac{d^2w}{dx^2} = GJ \frac{d^2\theta_x}{dx^2} - EC_w \frac{d^4\theta_x}{dx^4}$$

Constitutive Relationship:

$$M_{y'} = M_e \theta_x = -EI_{y'} \frac{d^2w}{dx^2} \Rightarrow \frac{d^2w}{dx^2} = -\frac{M_e}{EI_{y'}}\theta_x$$

$$-\frac{M_e^2}{EI_{y'}}\theta_x = GJ \frac{d^2\theta_x}{dx^2} - EC_w \frac{d^4\theta_x}{dx^4}$$

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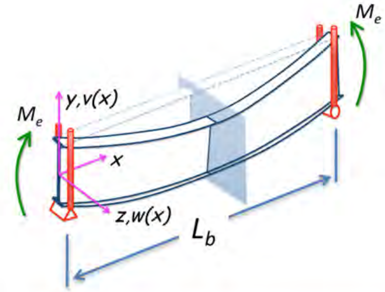
Summary (3)

Solve differential equation

$$EC_w \frac{d^4\theta_x}{dx^4} - GJ\frac{d^2\theta_x}{dx^2} - \frac{M_e^2}{EI_{y'}}\theta_x = 0$$



and apply boundary conditions (compatibility!)

$$\theta_x(x=0)=0,\ \theta_x(x=L_b)=0$$

$$\theta_x''(x=0)=0,\ \theta_x''(x=L_b)=0$$

Notes: (1) Ends are free to warp and (2) never had to assume that $w(x=0,L)=0$

Results in

$$M_e^2 = \left(\frac{\pi^2 EI_y}{L_b^2}\right)\left(GJ + \frac{\pi^2}{L_b^2}EC_w\right)$$

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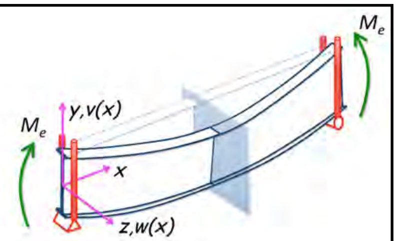
Summary (4)

This sort of makes sense!



$$M_e^2 = \left(\frac{\pi^2 EI_y}{L_b^2}\right)\left(GJ + \frac{\pi^2}{L_b^2}EC_w\right)$$

Top flange in compression trying to produce minor axis buckling

Bottom flange in tension resisting this minor axis buckling by creating a resisting torque, which includes both St. Venant and Warping components

which simplifies to:

$$M_e = \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$$

Also note that our earlier parametric study was spot on!

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Polling Question #1

In regard to the elastic lateral torsional buckling moment, which of the following is not true?

a. critical moment decreases as unbraced length increases.
b. critical moment increases as major axis moment of inertia increases.
c. critical moment decreases as minor axis moment of inertia decreases.
d. critical moment increases as warping resistance increases.
e. critical moment is related to the shear modulus (modulus of rigidity).

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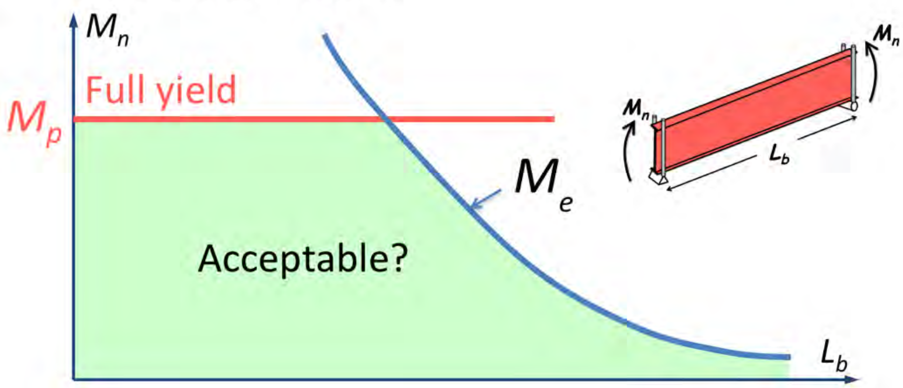
- Elastic lateral-torsional buckling

$$M_e = \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$$

- Beam Curve – Take 2



- What about those assumptions?

50

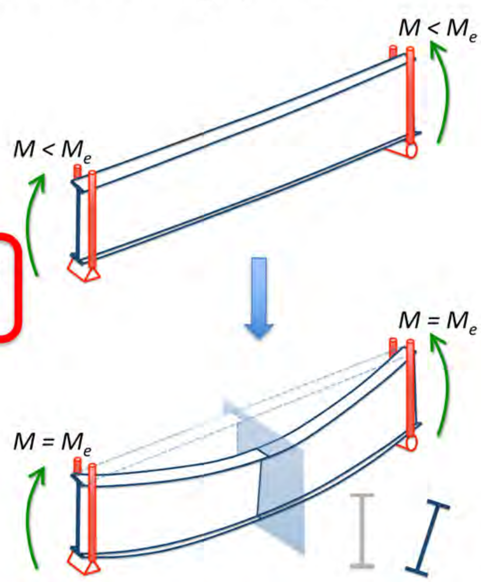
Lateral Torsional Buckling

- Theoretical bifurcation
  - solution
  - assumptions
- Undoing those assumptions (approaching reality)
  - not fully elastic, partial yielding
  - alternative loading and support conditions
- Beam curves
  - AISC
  - others

51

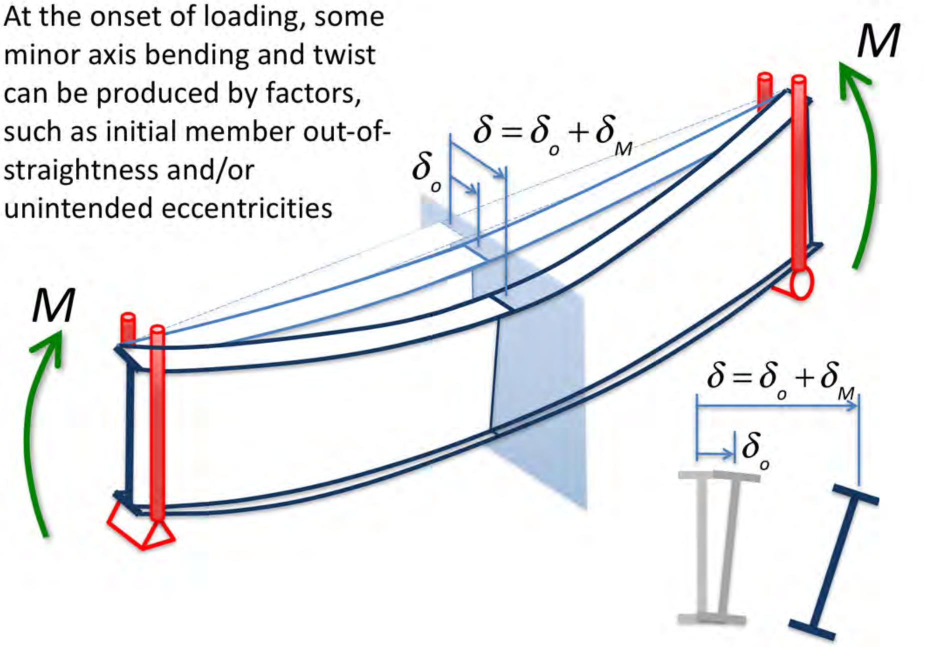
Lateral Torsional Buckling (LTB)

- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling
  - linear elastic behavior (E = constant)
  - uniform moment distribution
  - braced at the ends (frictionless)



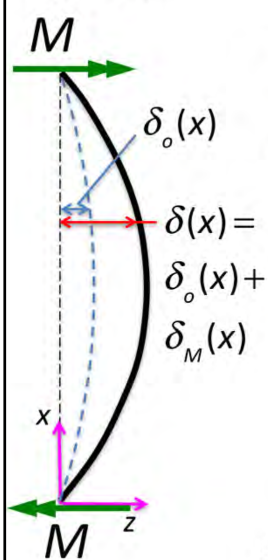
52

At the onset of loading, some minor axis bending and twist can be produced by factors, such as initial member out-of-straightness and/or unintended eccentricities

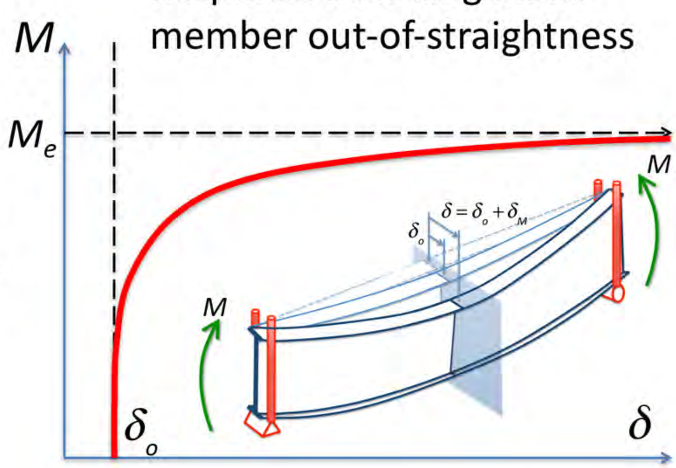


53

Top View:



Response including initial member out-of-straightness

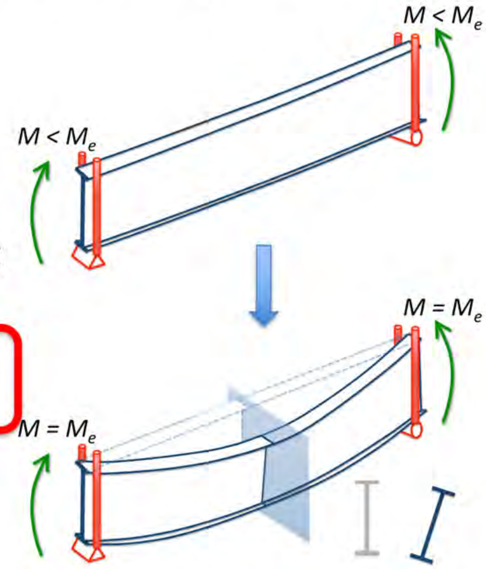


Elastic instability occurs as applied moment M approaches M_e

54

Lateral Torsional Buckling (LTB)

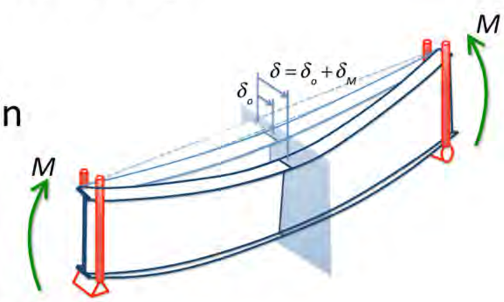
- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling
  - linear elastic behavior (E = constant)
  - uniform moment distribution
  - braced at the ends (frictionless)



55

Partial Yielding

- As loading is applied, cross section may begin to yield due to
  - major axis bending
  - minor axis bending
  - torsion (warping stresses)
- Yielding is accentuated by presence of residual stresses
- Yielding results in loss of stiffness, which may result in inelastic lateral torsional buckling.



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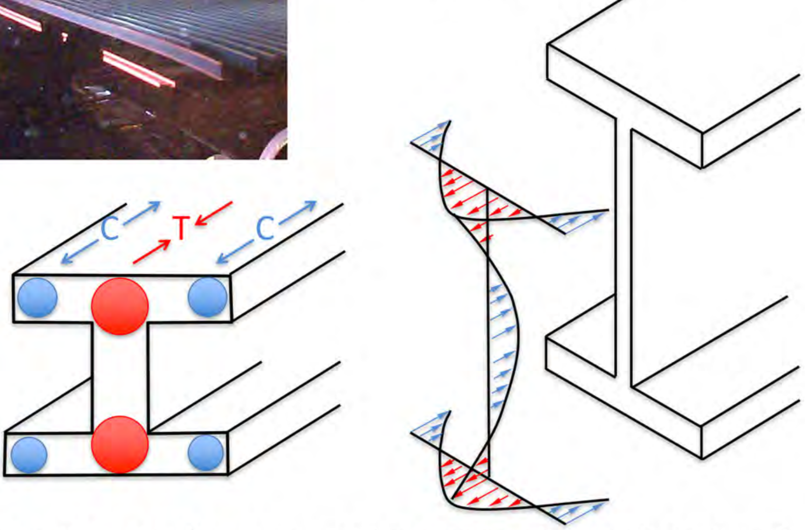
Reminder: Residual Stresses



Occur in rolled wide flange shapes because locations with high surface area (e.g., flange tips) cool well before locations with smaller surface area (flange-to-web intersections)

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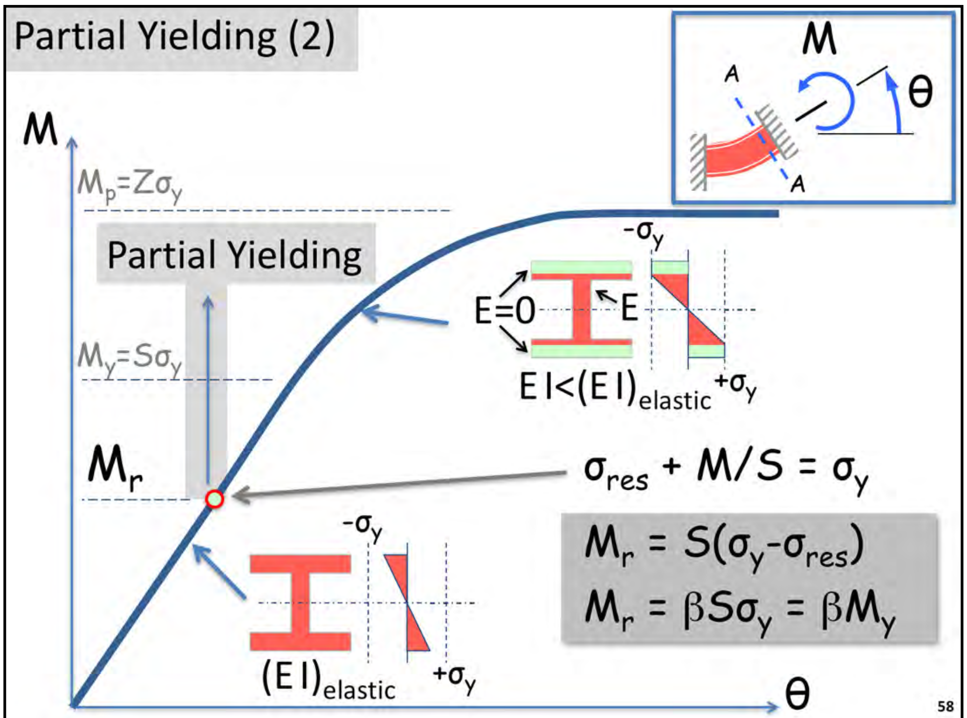
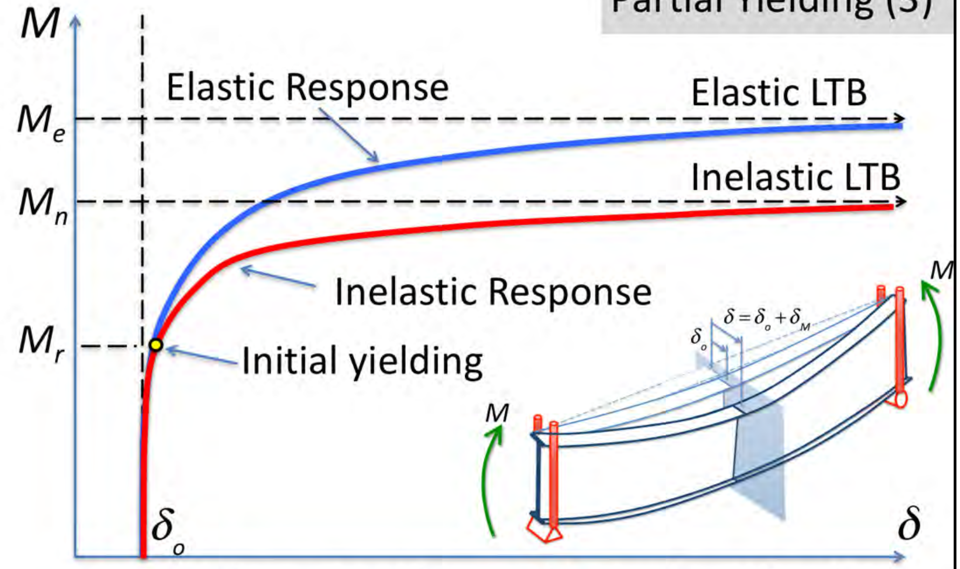
Partial Yielding (2)



58

Partial Yielding (3)

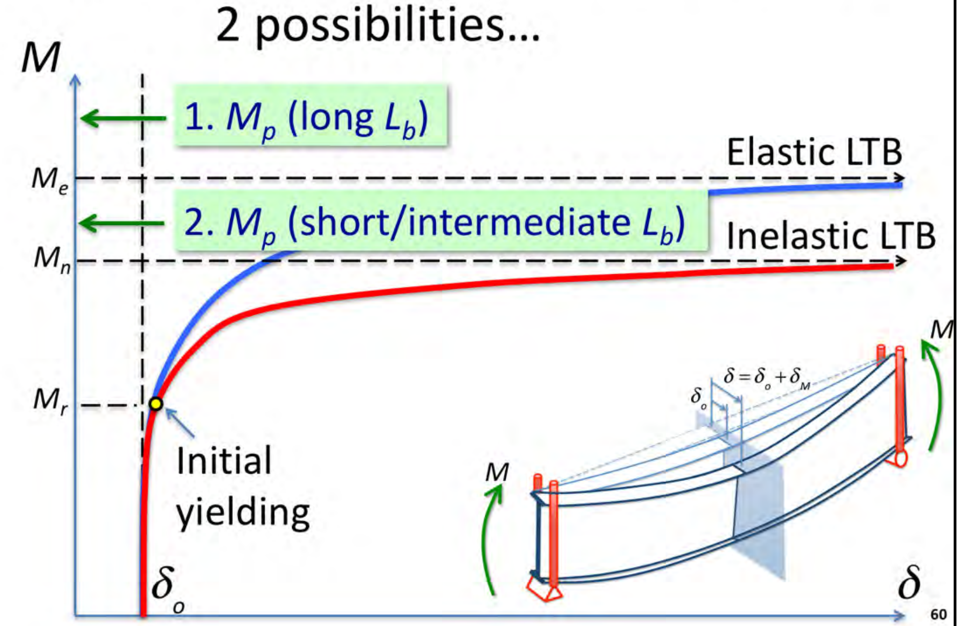


Depending on unbraced length, an inelastic instability can occur well below M_e

59

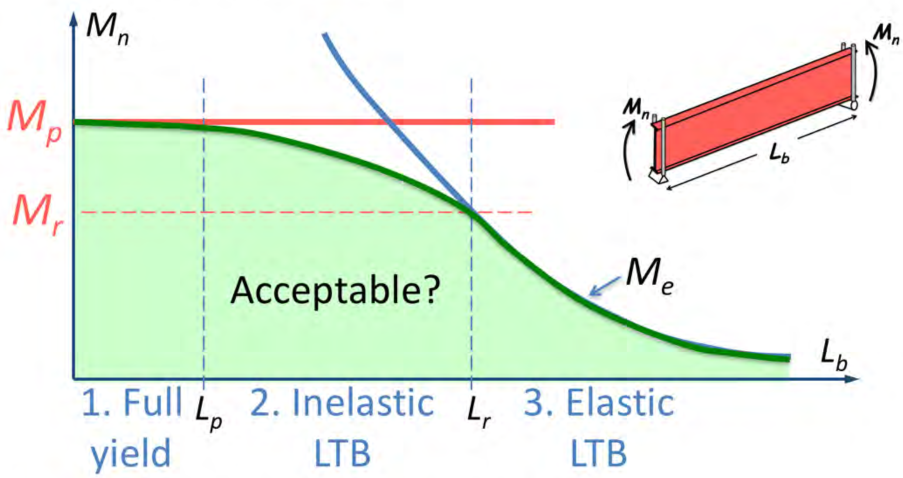
Partial Yielding (4)

Wait! Where's M_p?
2 possibilities…



60

- Beam Curve – Take 3



- Where did L_p and L_r come from?
- What about those assumptions?

61

- Where did L_r come from?
  - L_r is unbraced length at transition from inelastic to elastic LTB
  - Equate M_r (moment to produce first yield including residual stresses) with M_e (elastic LTB moment) …and solve for L_b

$$S(\sigma_y - \sigma_{res}) = \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$$

Yikes!!!

L_r, the limiting unbraced length for the limit state of inelastic lateral-torsional buckling, in. (mm), is:

$$L_r = 1.95 r_{ts}\frac{E}{0.7F_y}\sqrt{\frac{Jc}{S_x h_o} + \sqrt{\left(\frac{Jc}{S_x h_o}\right)^2 + 6.76\left(\frac{0.7F_y}{E}\right)^2}} \quad \text{(F2-6)}$$

where

r_y = radius of gyration about y-axis, in. (mm)

Note: $0.7F_y$'s

$$r_{ts}^2 = \frac{\sqrt{I_y C_w}}{S_x} \quad \text{(F2-7)}$$

and the coefficient c is determined as follows:

(1) For doubly symmetric I-shapes $c = 1$ (F2-8a)

62

- Where did L_p come from?
  - L_p is unbraced length at transition from full yielding to inelastic LTB
  - Game of darts in an AISC cigar filled room… …not quite!
  - Varies from code to code worldwide and is based on analytical and experimental studies
  - For a compact I-shaped member, AISC gives

$$L_p = 1.76 r_y \sqrt{E/F_y}$$

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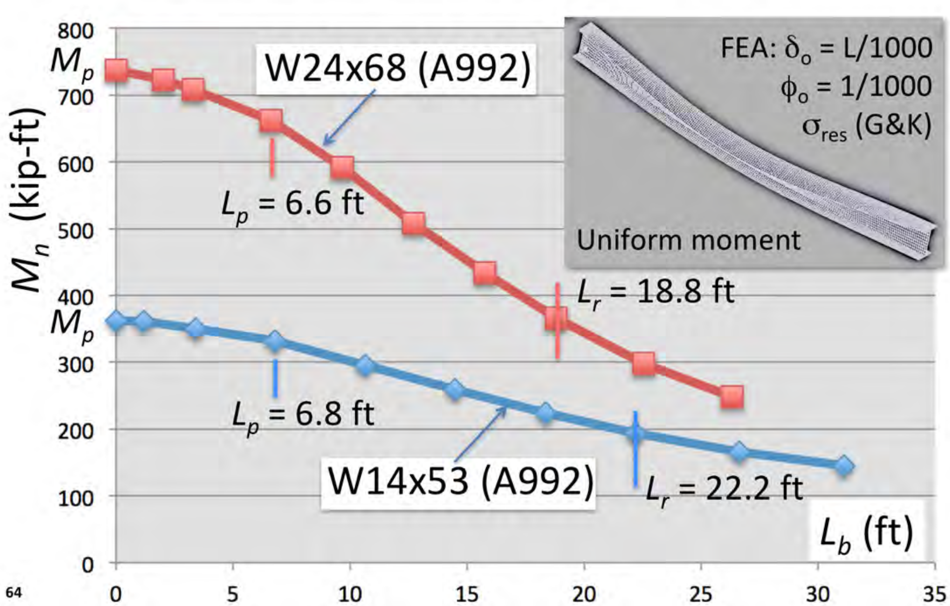
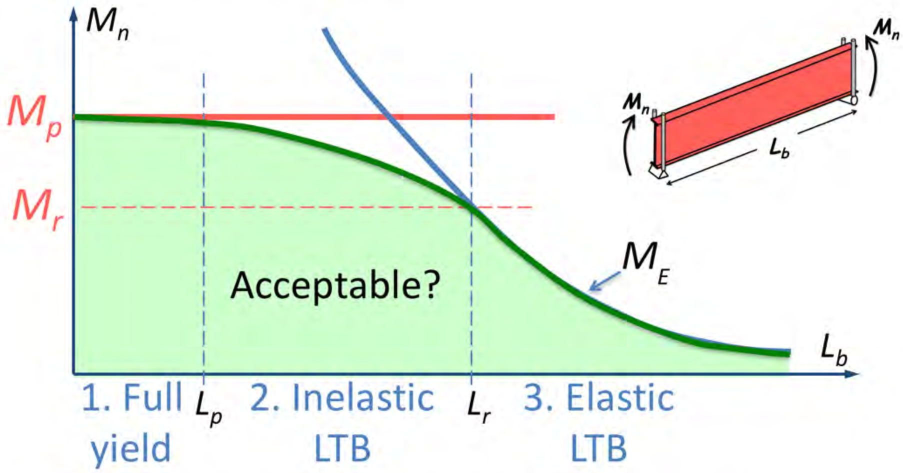
Flexural Strengths per FEA



64

- Beam Curve – Take 3

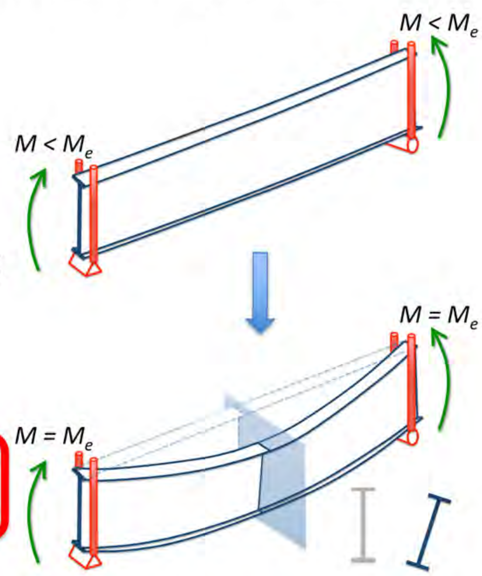


- Where did L_p and L_r come from? (done!)
- What about those assumptions? (hmmm…)

65

Lateral Torsional Buckling (LTB)

- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling
  - linear elastic behavior (E = constant)
  - uniform moment distribution
  - braced at the ends (frictionless)



66

Uniform Moment Distribution

- Provides for "simplest" differential equation and corresponding solution to the elastic LTB problem.
- Most conservative case
  - *M*(x) = constant
  - maximum compressive stress occurs along entire unbraced length
- In place of formulating and solving for other moment *M*(x) distributions, results can be adequately approximated by scaling the uniform moment LTB solution.

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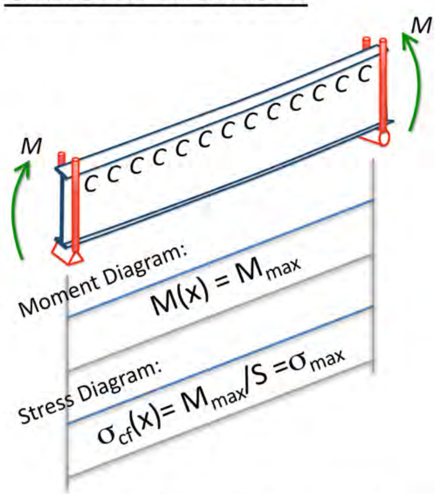
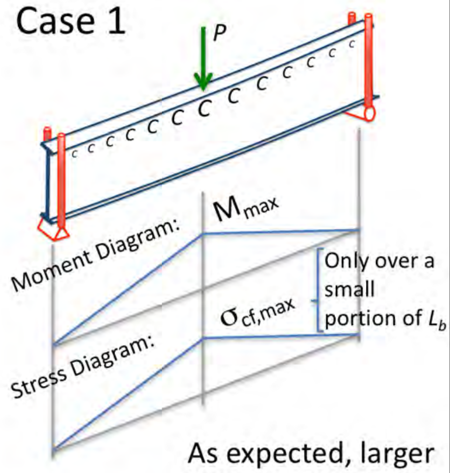
Uniform Moment



$$M_e = \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$$

Moment gradient

Case 1

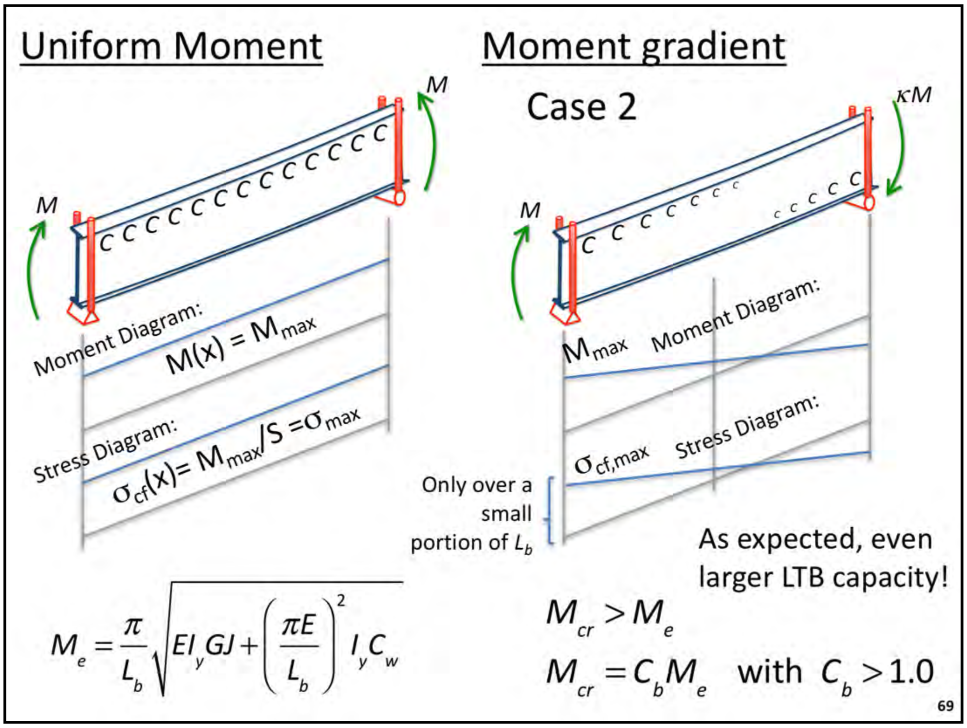


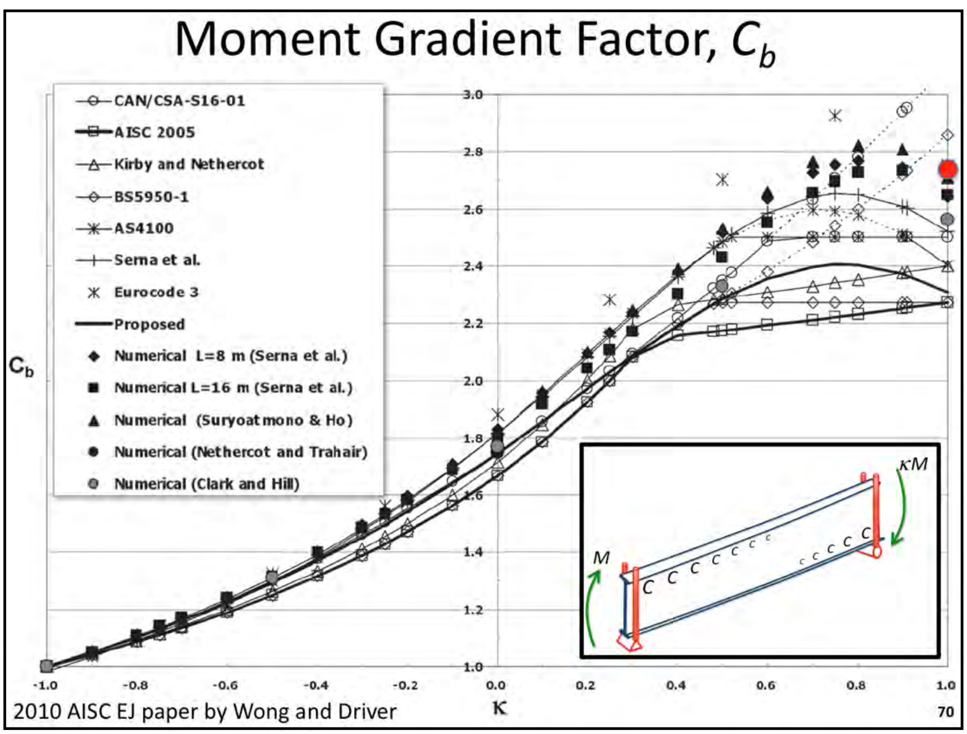
As expected, larger LTB capacity!

$M_{cr} > M_e$

$M_{cr} = C_b M_e$ with $C_b > 1.0$

68


Uniform Moment
Moment gradient
Case 2
M
κM
Moment Diagram:
M(x) = M_max
Stress Diagram:
σ_cf(x)= M_max/S =σ_max
M_max
σ_cf,max
Only over a small portion of L_b
As expected, even larger LTB capacity!
$M_e = \frac{\pi}{L_b}\sqrt{EI_yGJ + \left(\frac{\pi E}{L_b}\right)^2 I_yC_w}$
$M_{cr} > M_e$
$M_{cr} = C_bM_e$ with $C_b > 1.0$
69


Moment Gradient Factor, C_b
CAN/CSA-S16-01
AISC 2005
Kirby and Nethercot
BS5950-1
AS4100
Serna et al.
Eurocode 3
Proposed
Numerical L=8 m (Serna et al.)
Numerical L=16 m (Serna et al.)
Numerical (Suryoatmono & Ho)
Numerical (Nethercot and Trahair)
Numerical (Clark and Hill)
C_b
κ
κM
M
2010 AISC EJ paper by Wong and Driver
70

LTB Moment Gradient Factor, C_b

- LTB strength M_n adequately approximated by scaling the uniform moment LTB solution

$$M_n = C_b M_n^{C_b=1} \le M_p$$

- Under no conditions can M_n exceed M_p, regardless of moment gradient
- Many possibilities for C_b, AISC Spec. provides

$$C_b = \frac{12.5\left|M_{max}\right|}{2.5\left|M_{max}\right| + 3\left|M_{L_b/4}\right| + 4\left|M_{L_b/2}\right| + 3\left|M_{3L_b/4}\right|}$$

- But, be sure to see the AISC Commentary…
- See 2010 AISC EJ paper by Wong and Driver!

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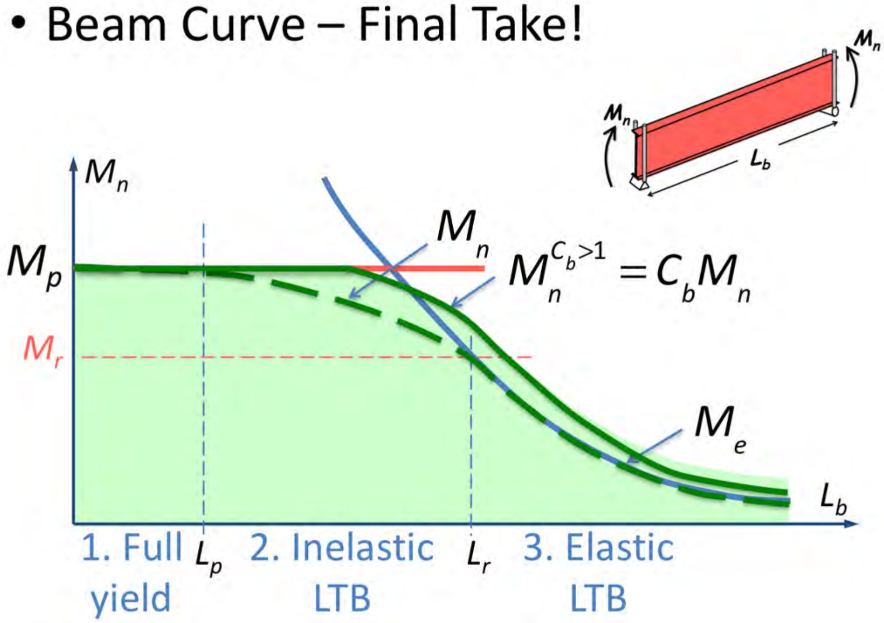
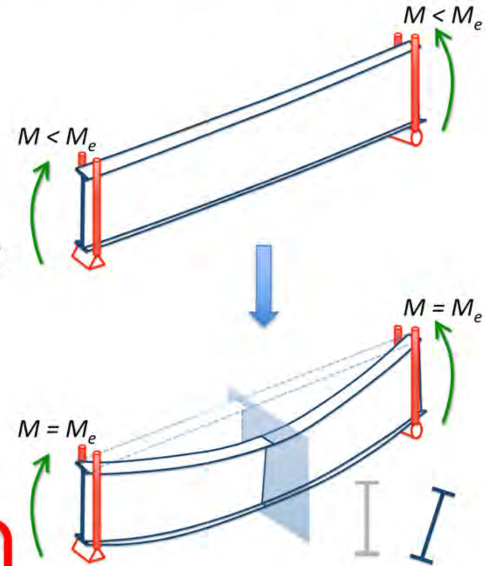
- Beam Curve – Final Take!



72

Lateral Torsional Buckling (LTB)

- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling
  - linear elastic behavior (E = constant)
  - uniform moment distribution
  - braced at the ends (frictionless)



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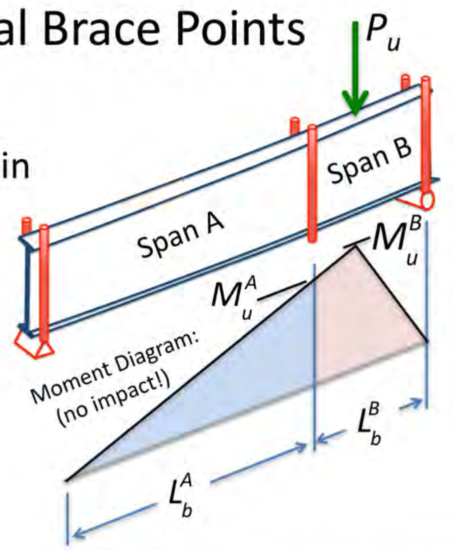
Providing Additional Brace Points

- Not vertical supports!
- Braces should either restrain
  - Twist (preferred)
  - lateral movement of compression flange
- All rules apply with L_b reduced to distance between brace points
- Must confirm strength within each unbraced span
- Design of braces!



$$L_b^A, C_b^A \Rightarrow M_n^A \qquad M_u^A \le \phi M_n^A$$

$$L_b^B, C_b^B \Rightarrow M_n^B \qquad M_u^B \le \phi M_n^B$$

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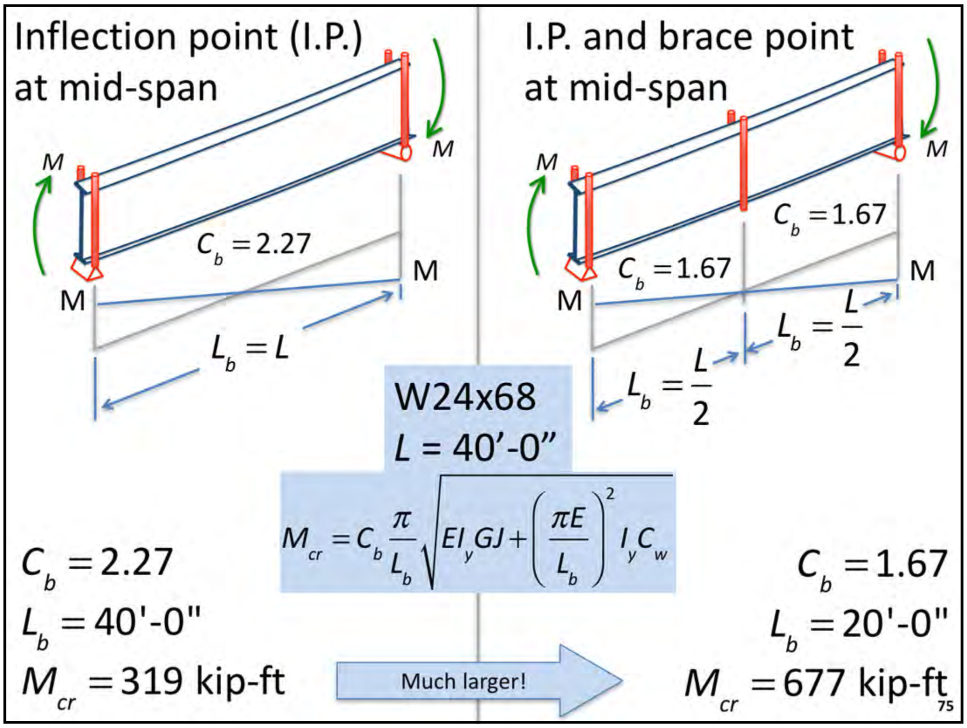
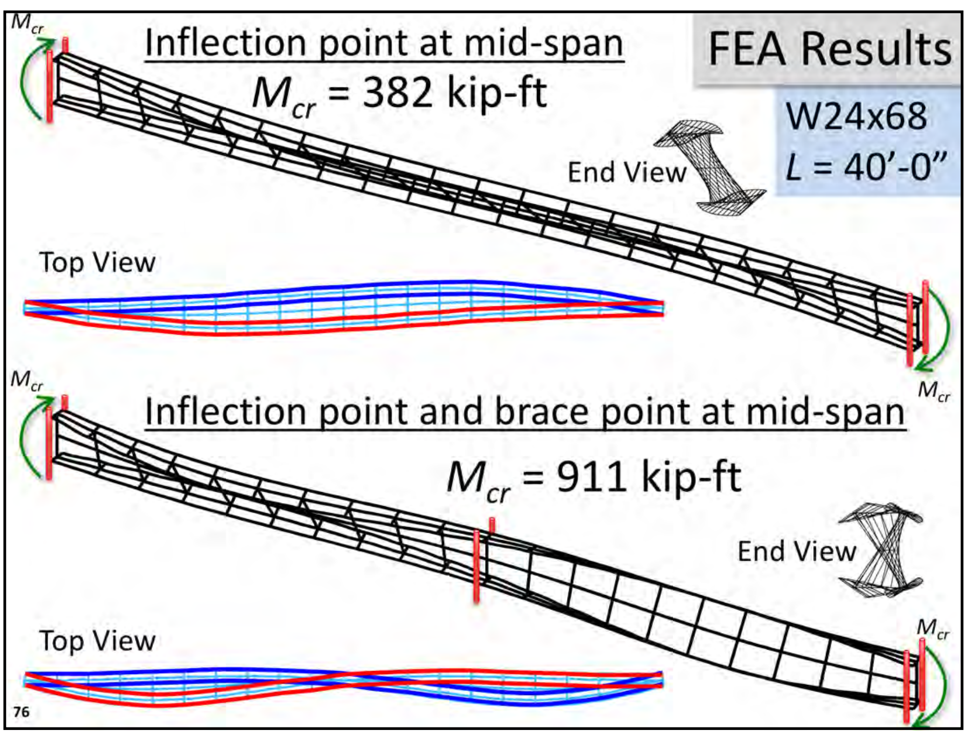
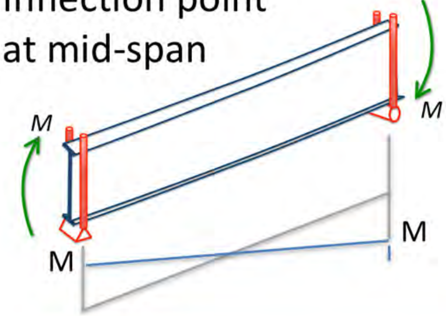
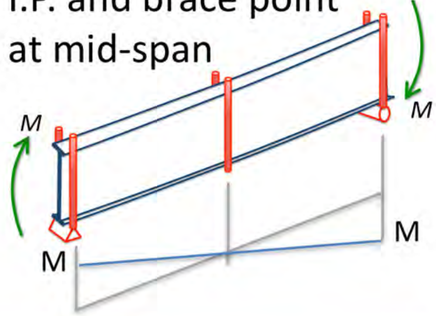

Inflection point (I.P.) at mid-span
I.P. and brace point at mid-span
M
M
$C_b = 2.27$
M
M
$L_b = L$
$C_b = 1.67$
$C_b = 1.67$
$L_b = \frac{L}{2}$
$L_b = \frac{L}{2}$
W24x68
L = 40'-0"
$M_{cr} = C_b \frac{\pi}{L_b} \sqrt{EI_y GJ + \left(\frac{\pi E}{L_b}\right)^2 I_y C_w}$
$C_b = 2.27$
$L_b = 40'\text{-}0"$
$M_{cr} = 319$ kip-ft
Much larger!
$C_b = 1.67$
$L_b = 20'\text{-}0"$
$M_{cr} = 677$ kip-ft
75


FEA Results
W24x68
L = 40'-0"
Inflection point at mid-span
M_{cr} = 382 kip-ft
End View
Top View
M_{cr}
Inflection point and brace point at mid-span
M_{cr} = 911 kip-ft
End View
Top View
76

Inflection point at mid-span



I.P. and brace point at mid-span



Inflection point is not a brace point!
(I.P. does not imply "no twist")

Why does FEA give a significantly higher M_{cr} for I.P. and B.P. case? $M_{cr}^{AISC} = 677$ vs. $M_{cr}^{FEA} = 911$

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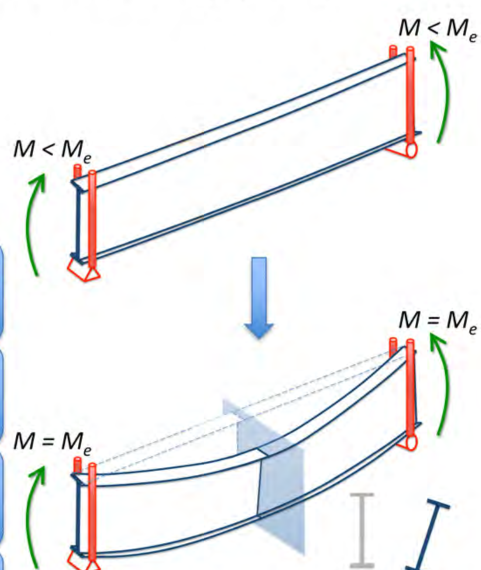
Lateral Torsional Buckling (LTB)

- Bifurcation solution
- Assumptions!
  - prismatic member (I = constant)
  - only major axis bending occurs before buckling — Undone
  - linear elastic behavior (E = constant) — Undone
  - uniform moment distribution — Undone
  - braced at the ends (frictionless) — Undone



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Lateral Torsional Buckling

- Theoretical bifurcation
  - solution
  - assumptions
- Undoing those assumptions (approaching reality)
  - not fully elastic, partial yielding
  - alternative loading and support conditions
- Beam curves
  - AISC
  - others

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AISC Flexural Strength (compact I-shapes)

- Initial yield
  - Moment, $M_r = S(\sigma_y - \sigma_{res}) = 0.7S\sigma_y = 0.7M_y$
  - setting $M_r = M_e$, back solve for unbraced length L_r
- For shorter unbraced lengths (full yielding)

$$L_b \le L_p,\ M_n = Z\sigma_y = M_p$$

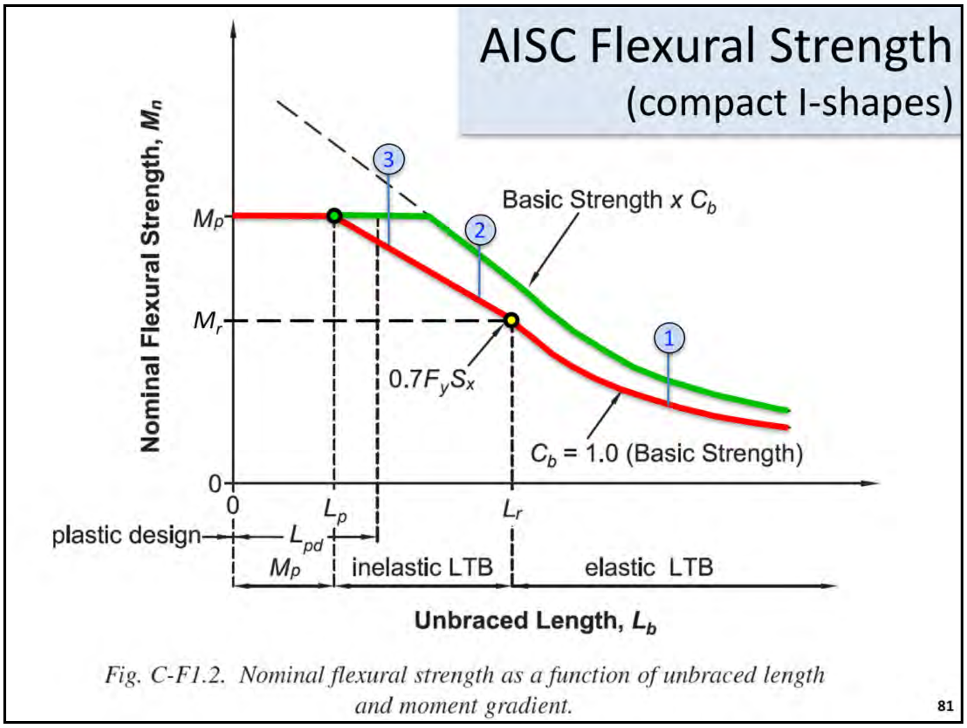
- For longer unbraced lengths (elastic LTB)

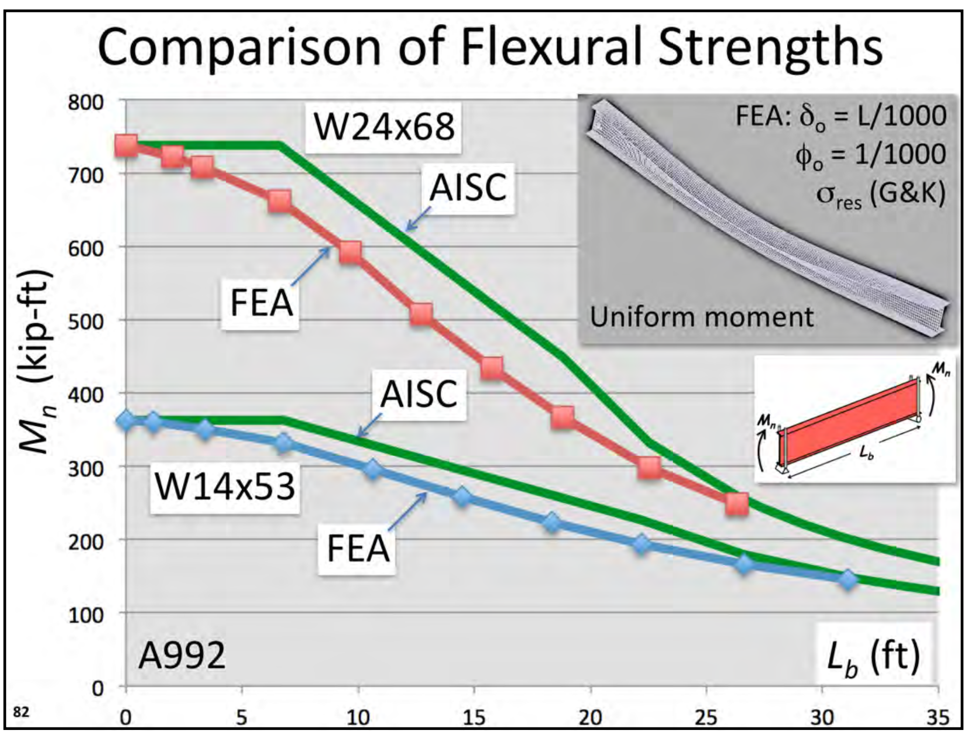
$$L_b \ge L_r,\ M_n = C_b M_e = C_b \frac{\pi}{L_b}\sqrt{EI_y GJ + \left(\pi E/L_b\right)^2 I_y C_w} \le M_p$$

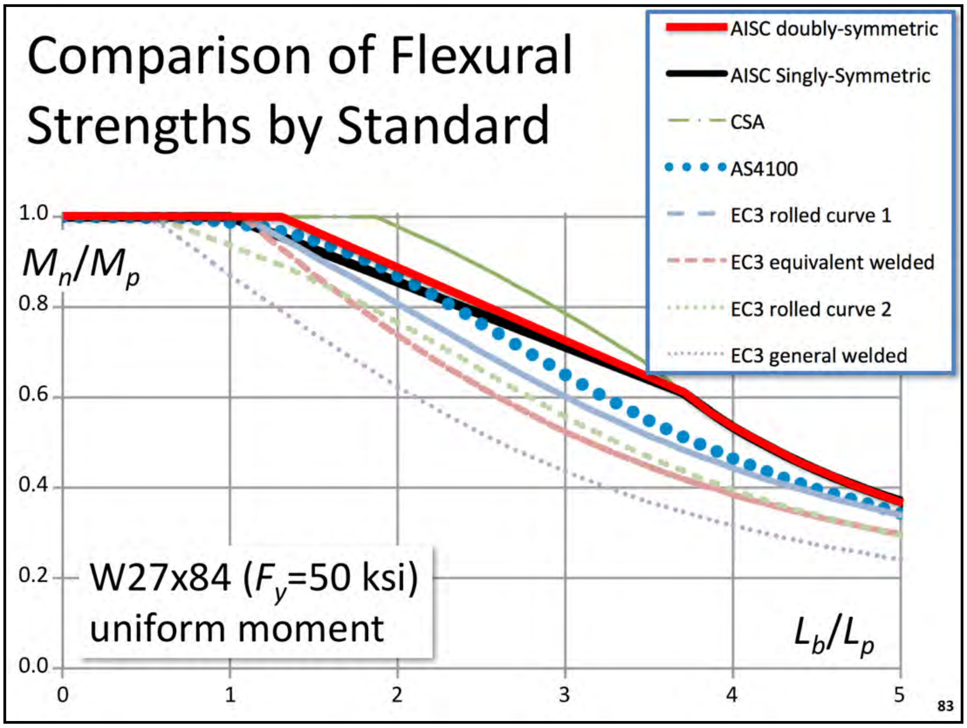
- For intermediate unbraced lengths (inelastic LTB)

$$L_p < L_b < L_r,\ M_n = C_b\left[M_p - (M_p - M_r)\left(\frac{L_b - L_p}{L_r - L_p}\right)\right] \le M_p$$

80


AISC Flexural Strength
(compact I-shapes)
Nominal Flexural Strength, M_n
M_p
M_r
0
3
2
1
Basic Strength x C_b
$0.7F_yS_x$
C_b = 1.0 (Basic Strength)
0
L_p
L_r
plastic design
L_{pd}
M_p
inelastic LTB
elastic LTB
Unbraced Length, L_b
Fig. C-F1.2. Nominal flexural strength as a function of unbraced length and moment gradient.
81


Comparison of Flexural Strengths
800
700
600
500
400
300
200
100
0
M_n (kip-ft)
W24x68
AISC
FEA
AISC
W14x53
FEA
FEA: δ_o = L/1000
ϕ_o = 1/1000
σ_{res} (G&K)
Uniform moment
M_n
M_n
L_b
A992
L_b (ft)
82
0
5
10
15
20
25
30
35



Polling Question #2

In regard to the C_b moment gradient factor, which of the following is true?

a. C_b is always less than or equal to unity.
b. a single expression for C_b covers all cases of moment distribution.
c. C_b modifies the B_1 factor to account for cases of moment gradient.
d. C_b is intended for beams with nonuniform moment distribution.
e. All of the above are true.

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Summary – Flexure

- Limit states of flexural members with focus on full yielding and lateral torsional buckling
- LTB Theory -to- Flexural Strength Beam Curve
- Beam curve accounts for:
  - full yielding
  - bending due to initial imperfection (out-of-straightness)
  - partial yielding accentuated by presence of residual stresses
  - moment gradient and brace points
- AISC and other standards

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Up Next…

- Session 4: July 10 – **Design of Flexural Members** by T.A. Helwig, PE, PhD
- This lecture will focus on the design of flexural members for the pertinent stability limit states. Solutions for the effects of moment gradient and load position will be covered including moment gradient factors for a variety of common design situations. This lecture will include material pertinent to both rolled sections as well as built-up members. Efficient use of the design aids in the AISC manual will be addressed as well as methods for the preliminary sizing of built-up girders.

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Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

- New reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.

8-Session Registrants

CEU/PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.

8-Session Registrants

Access to the quiz: Information for accessing the quiz will be emailed to you by Wednesday. It will contain a link to access the quiz. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG

Quiz and Attendance records: Posted Tuesday mornings.
www.aisc.org/nightschool - click on Current Course Details.

Reasons for quiz:

- EEU – must take all quizzes and final to receive EEU
- CEUs/PDHS – If you watch a recorded session you must take quiz for CEUs/PDHs.
- REINFORCEMENT – Reinforce what you learned tonight. Get more out of the course.

NOTE: If you attend the live presentation, you do not have to take the quizzes to receive CEUs/PDHs.

8-Session Registrants

Access to the recording: Information for accessing the recording will be emailed to you by this Wednesday. The recording will be available for three weeks. For 8-session registrants only. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

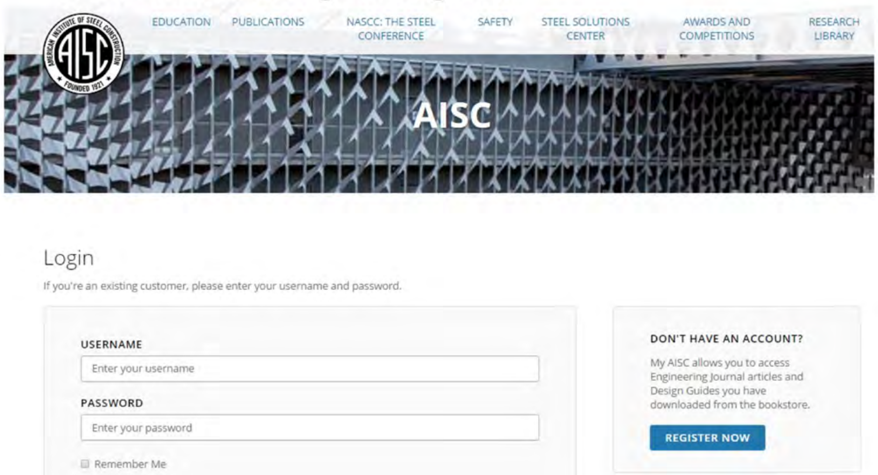
CEUs/PDHS – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

Night School Resources for 8-session package Registrants

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!

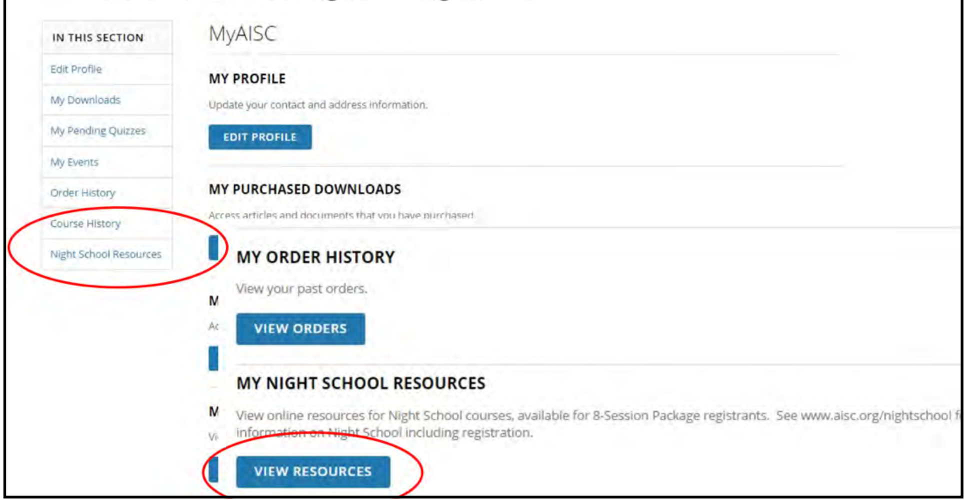
Night School Resources for 8-session package Registrants

Go to www.aisc.org and sign in.



Night School Resources for 8-session package Registrants

Go to www.aisc.org and sign in.

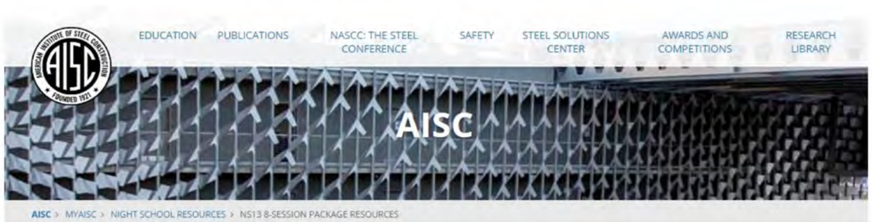


Night School Resources for 8-session package Registrants

Night School Resources

Event	Date
NS 13 8-Session Package	1/30/2017 7:00:00 PM

Night School Resources for 8-session package Registrants



Night School 13: Design of Industrial Buildings

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Video	Quiz	Attendance
NS13 - Design Criteria	1/30/2017 7:00:00 PM	Handouts	View Passcode: NS13DSN	Pass Score: 80	Pending
NS13 - Economic Considerations	2/6/2017 7:00:00 PM	Handouts	Available 02/08/2017 5pm EST	Available 02/08/2017 5pm EST	Pending
NS13 - Lateral Load Systems and Details	2/13/2017 7:00:00 PM	Handouts	Available 02/15/2017 5pm EST	Available 02/15/2017 5pm EST	Pending
NS13 - Preliminary Design Procedures	2/27/2017 7:00:00 PM	Handouts	Available 03/01/2017 5pm EST	Available 03/01/2017 5pm EST	Pending
NS13 - Crane Girder Design and Frame Analysis	3/6/2017 7:00:00 PM	Handouts	Available 03/08/2017 5pm EST	Available 03/08/2017 5pm EST	Pending
NS13 - Frame Member and Connection Design	3/13/2017 7:00:00 PM	Handouts	Available 03/15/2017 5pm EST	Available 03/15/2017 5pm EST	Pending
NS13 - Transfer Crane Girder & Longitudinal Bldg Bracing Dsn	3/27/2017 7:00:00 PM	Handouts	Available 03/29/2017 5pm EST	Available 03/29/2017 5pm EST	Pending
NS13 - Building Envelope and Bracing Design	4/3/2017 7:00:00 PM	Handouts	Available 04/05/2017 5pm EST	Available 04/05/2017 5pm EST	Pending
NS13 - Final Exam	4/10/2017 7:00:00 PM			Available 04/12/2017 5pm EST	

Night School Resources for 8-session package Registrants

- Weekly “quiz and recording” email.
- Weekly updates of the master Quiz and Attendance record found at www.aisc.org/nightschool. Scroll down to Quiz and Attendance records.
    - Updated on Tuesday mornings.

Night School Resources for 8-session package Registrants

- Webinar connection information:
    - Found in your registration confirmation/receipt.
    - Reminder email sent out Monday mornings.
- Link to handouts also found here.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Thank You
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Survey at conclusion of webinar.
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