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Session Description

Session 3: Design of Horizontally Curved Members

July 2, 2018

The session addresses the treatment of horizontally-curved members. Topics include: flexural strength, torsional strength, combined flexural and torsional loads, serviceability, local strength and connections.

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Learning Objectives

- Identify the limit states for horizontally curved members.
- Identify 3 analysis methods and describe the preferred method.
- Describe the steps of designing a horizontally curved member for flexural and torsional strength.
- Describe the various connection considerations for horizontally curved members.

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There's always a solution in steel.

Design of Curved Members

Session 3: Design of Horizontally Curved Members

July 2, 2018

Presented by
Bo Dowswell, P.E., Ph.D.
ARC International, LLC
Birmingham, AL

structural STEEL

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Design of Horizontally-Curved Members

Session Description

Session Description

- Horizontally-Curved Members
  - Introduction
  - Structural analysis
  - Flexural strength
  - Torsional strength

(continued)

Photograph courtesy of the AISC Bender/Roller Committee

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Session Description

- Combined loads
- Serviceability
- Local strength
- Connections

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Design of Horizontally-Curved Members

Introduction

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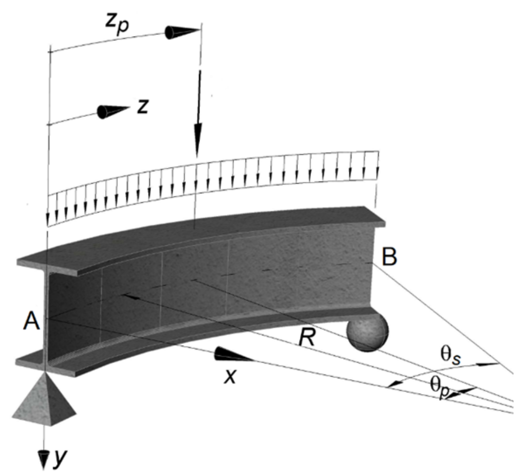
Introduction

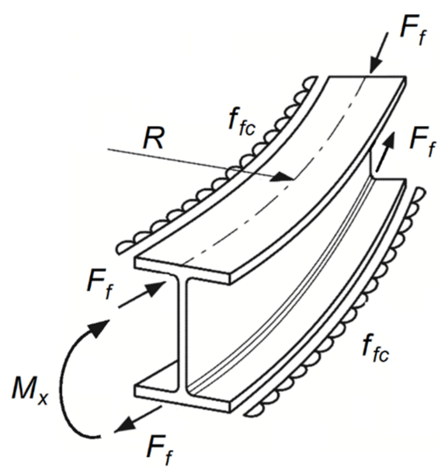
- Curved Members ≠ Straight Members
- Curved beam → Flexure + Torsion



Introduction

Deflected Shape

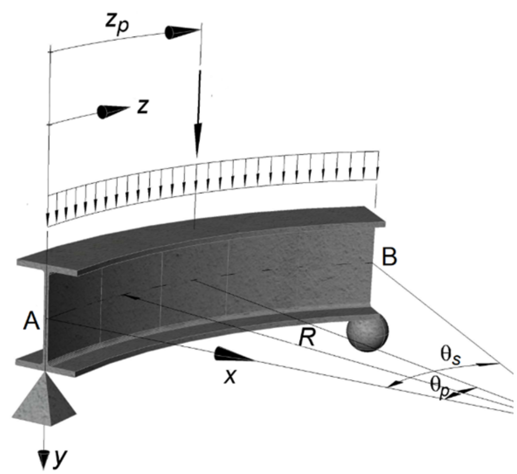
- Vertical translation
- Torsional rotation



Introduction

Typical Behavior

- Dependent on θ_s
  - $\theta_s < 1°$: Flexure (F)
  - $1° \leq \theta_s \leq 20°$: F + T
  - $20° < \theta_s$: Torsion (T)



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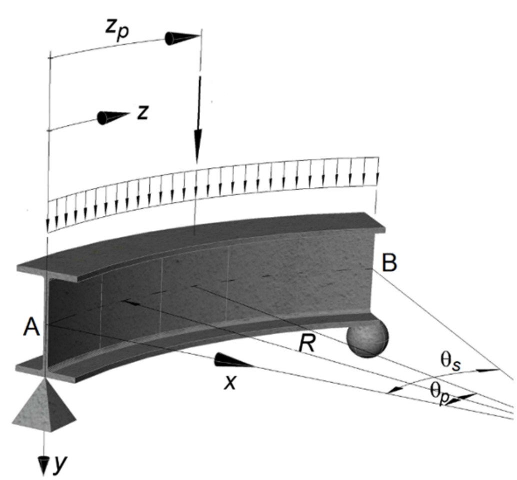
Introduction

Typical Limit States

- Excessive deformation
- Yielding



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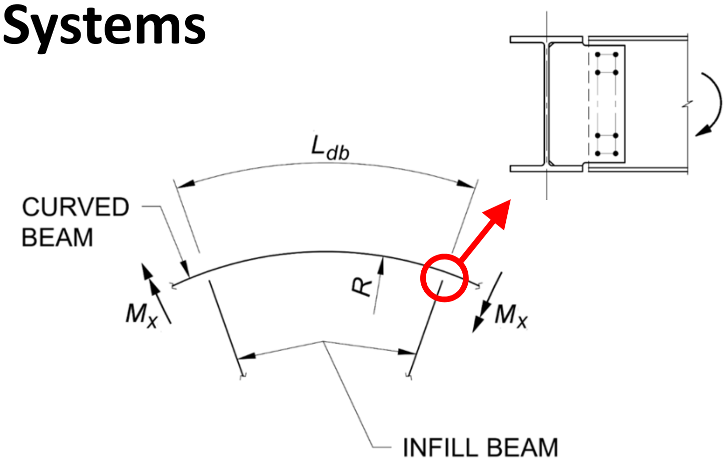
Introduction

Efficient Structural Systems

- Infill members restrain torsion



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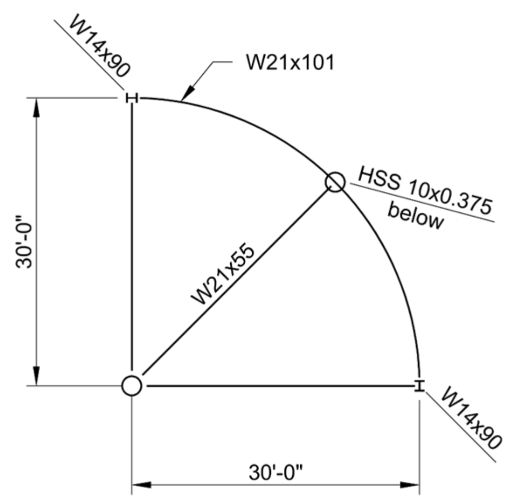
Introduction

Efficient Structural Systems

- Continuity
  - Flexure
  - Warping



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Design of Horizontally-Curved Members

Structural Analysis

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Structural Analysis

Analysis Methods

- Eccentric load method
- *M*/*R* method
- Finite element models

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Design of Horizontally-Curved Members

Structural Analysis

Eccentric Load Method

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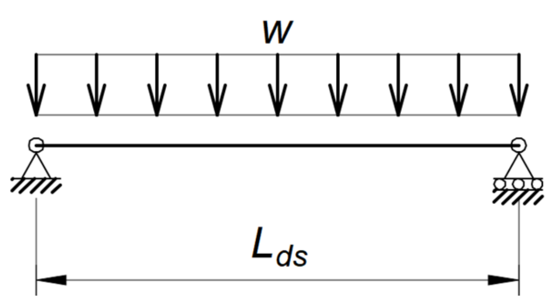
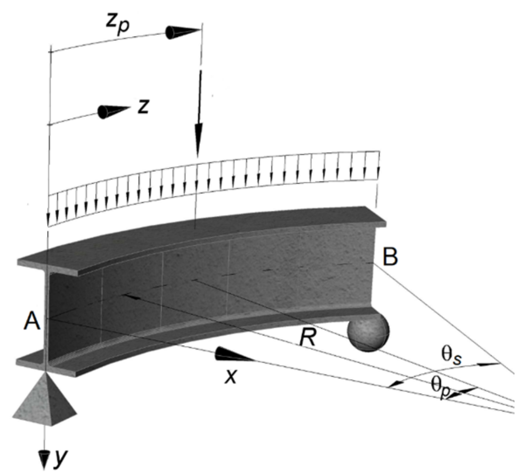
Eccentric Load Method

- Curved beam is modeled as straight member



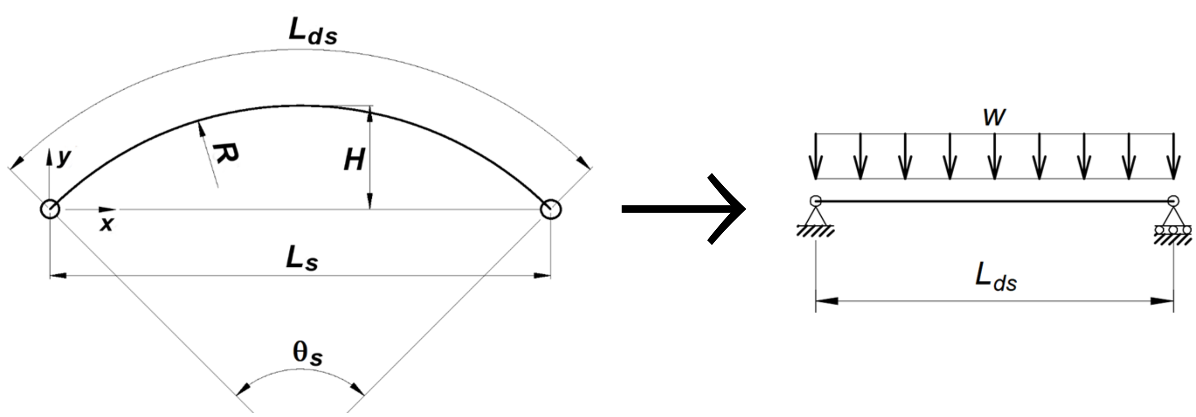
Eccentric Load Method

- Length is equal to the developed span length, $L_{ds} = R\theta_s$



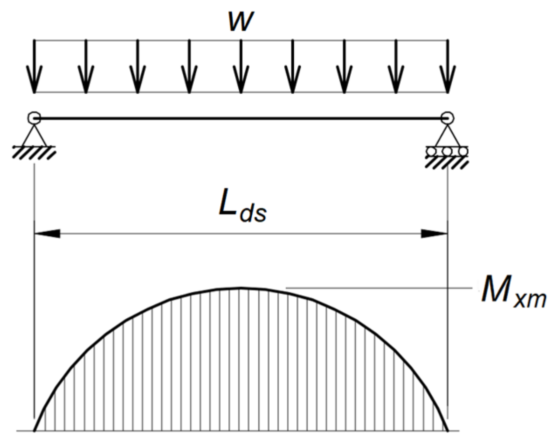
θ_s = span angle, rad

Eccentric Load Method



Eccentric Load Method

- Flexural (M_x) and shear (V) loads are calculated using the flexural support conditions



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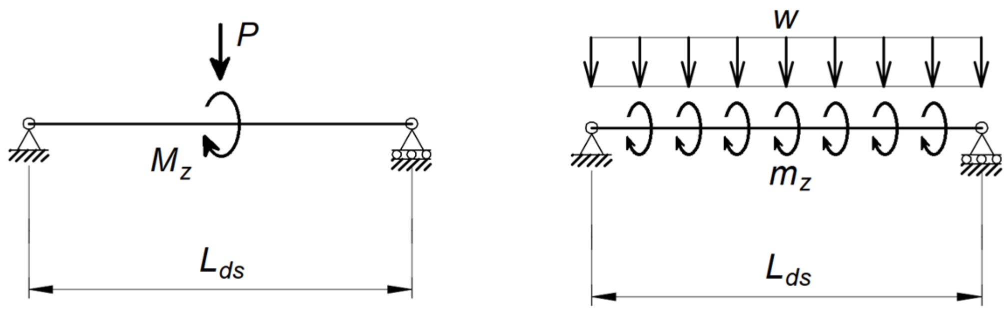
Eccentric Load Method

- Torsional moment = (vertical load) × (horizontal eccentricity)



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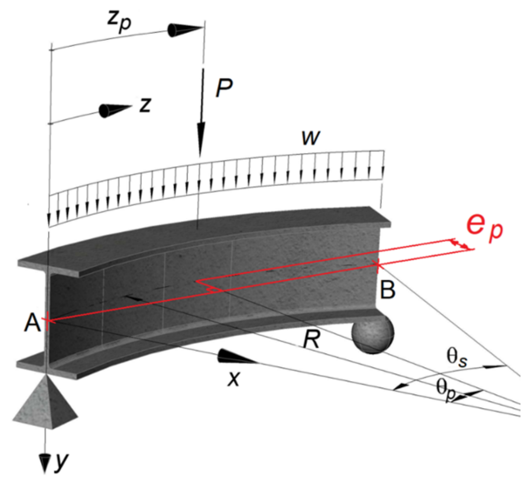
Eccentric Load Method

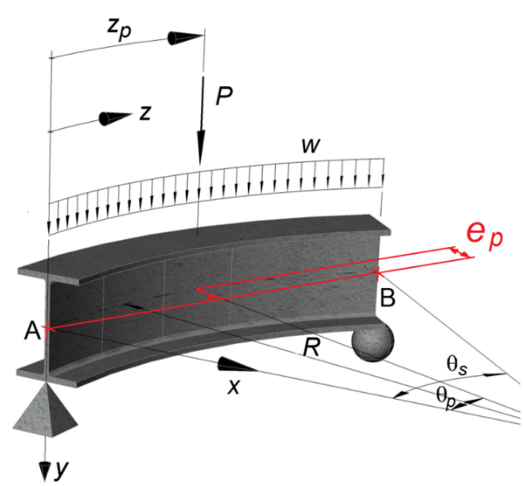
- Eccentricity = distance between the load centroid and the chord
- Chord = straight line drawn between supports



Eccentric Load Method

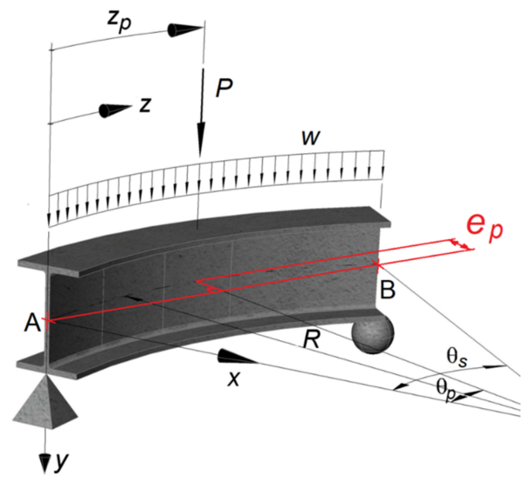
- For beams with a midspan concentrated load, the midspan concentrated torsion is

$$M_z = Pe_p$$



Eccentric Load Method

$$e_p = R\left[1-\cos\left(\frac{\theta_s}{2}\right)\right]$$



θ_s = span angle, rad

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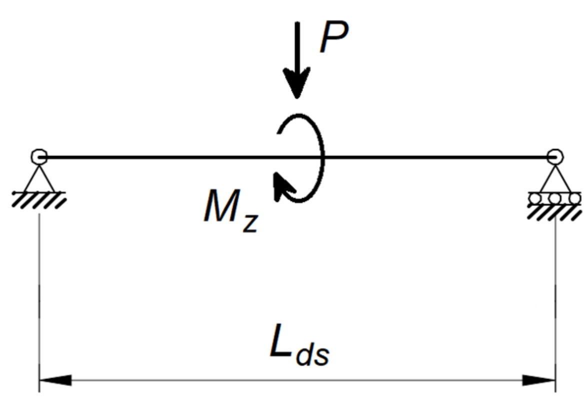
Eccentric Load Method



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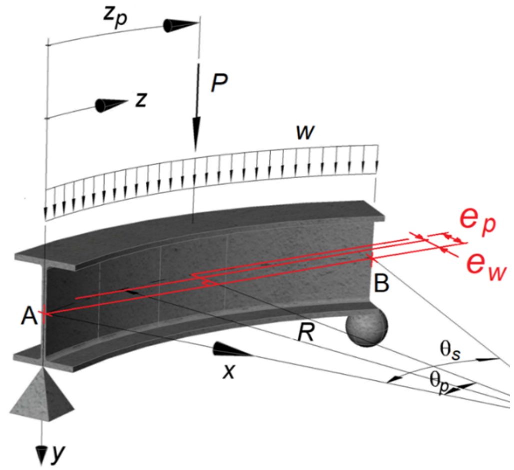
Eccentric Load Method

- For beams with a uniformly distributed load, the uniformly distributed torsion is

$$m_z = we_w$$



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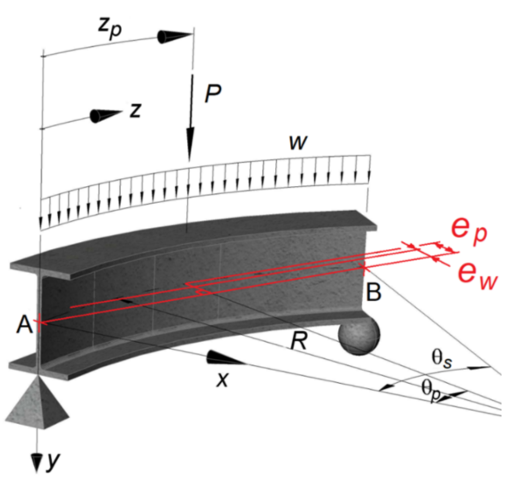
Eccentric Load Method



$$e_w = R\left[\cos\left(\frac{\theta_s}{4}\right) - \cos\left(\frac{\theta_s}{2}\right)\right]$$

θ_s = span angle, rad

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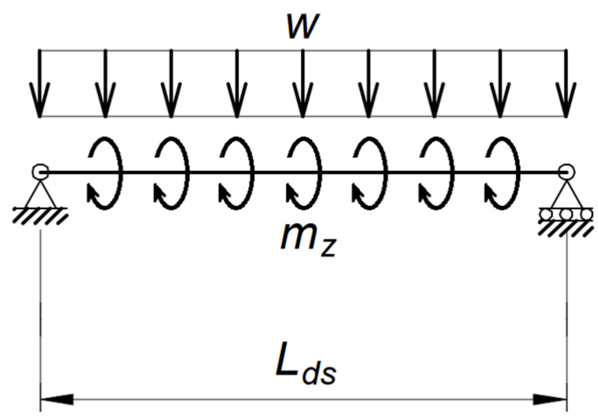
Eccentric Load Method



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Design of Horizontally-Curved Members

There's always a solution in steel.

Structural Analysis

M/*R* Method

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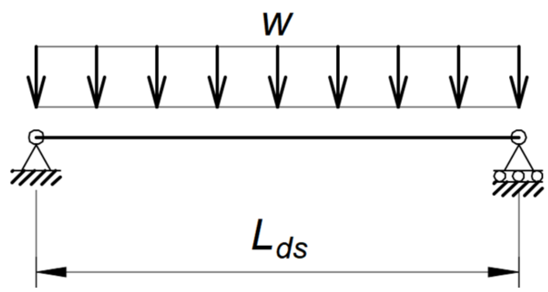
M/*R* Method

- Curved beam is modeled as straight member



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M/*R* Method

- Developed lengths
  - Span length: L_{ds}
  - Length between torsional restraints: L_{db}

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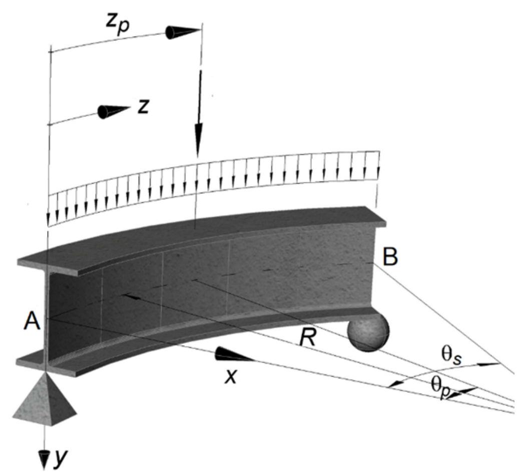
M/*R* Method

- Developed span length, $L_{ds} = R\theta_s$



θ_s = span angle, rad

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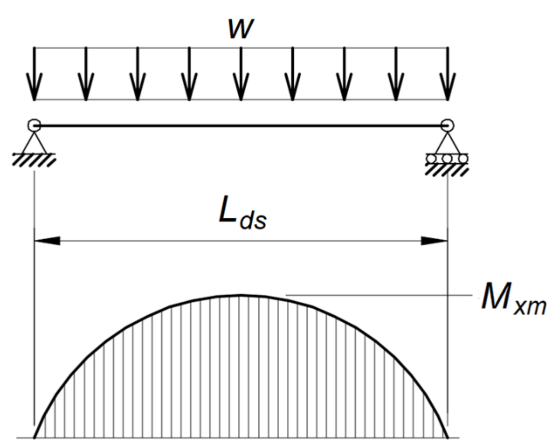
M/*R* Method

- Flexural (M_x) and shear (V) loads are calculated using L_{ds} with the flexural support conditions



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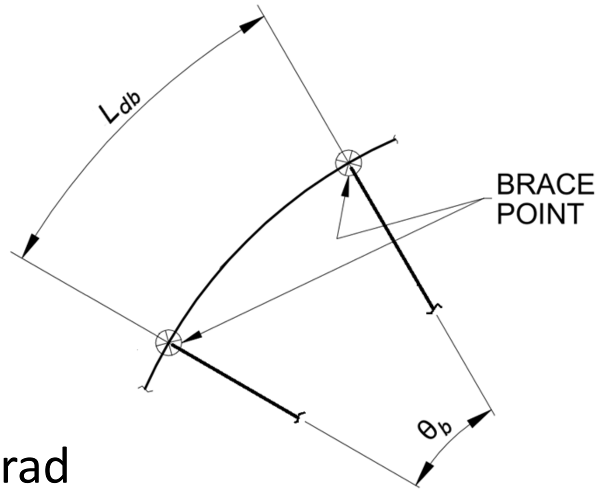
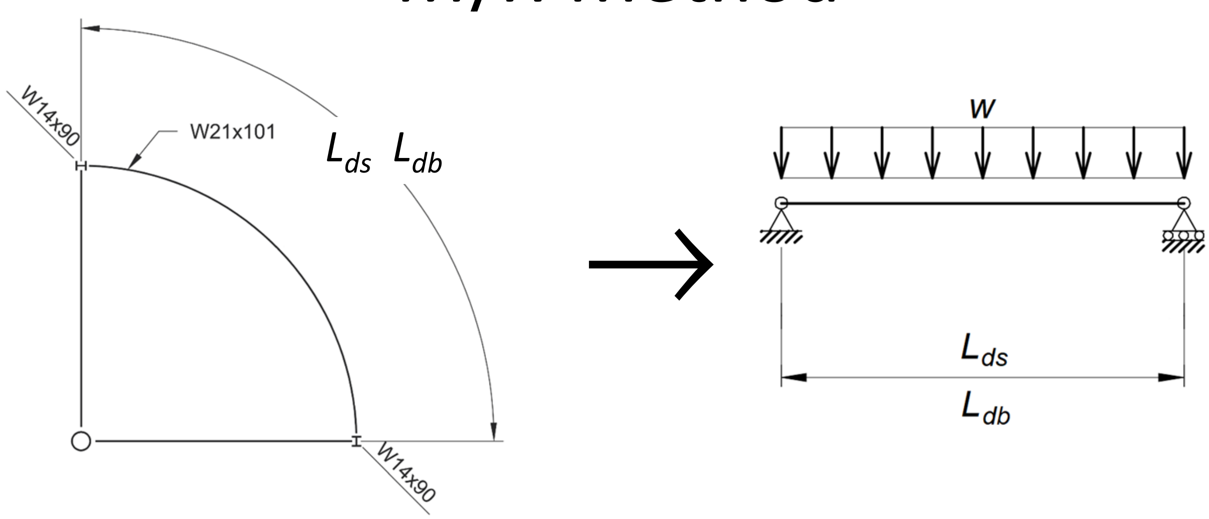
M/*R* Method

- Developed length between torsional restraints, $L_{db} = R\theta_b$

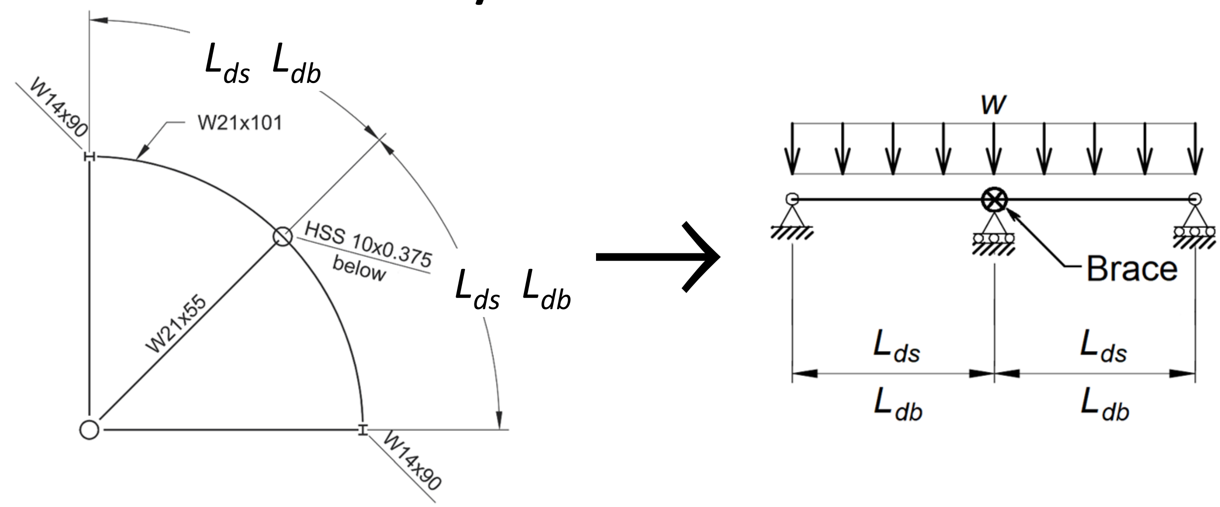


θ_b = angle between braces, rad

M/*R* Method



M/*R* Method



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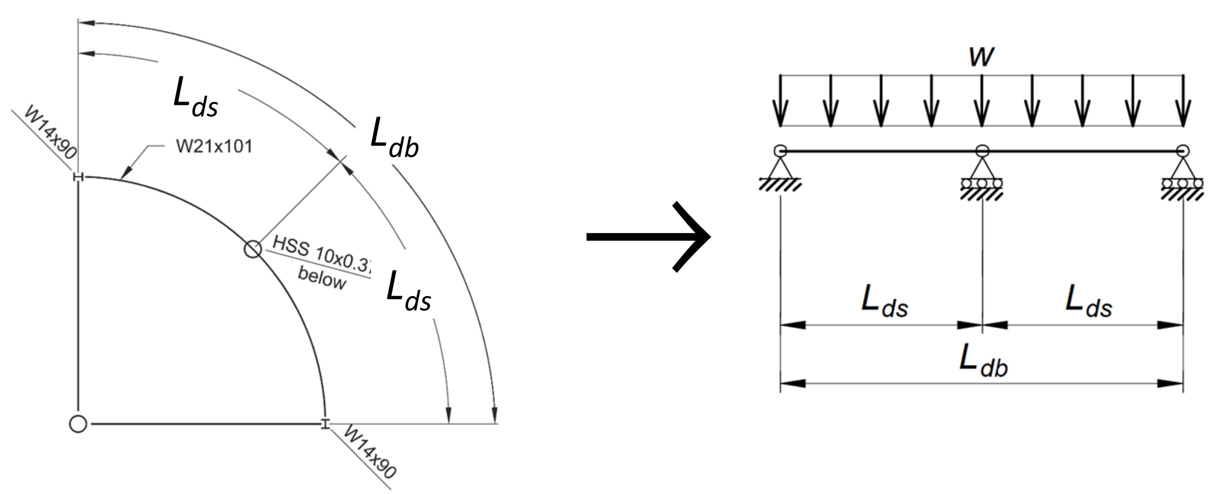
M/*R* Method



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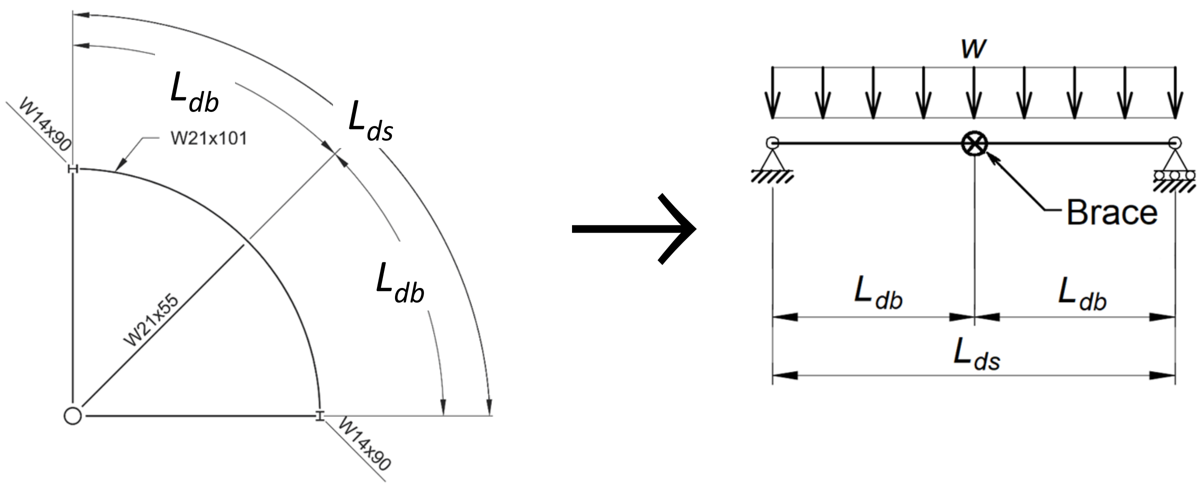
M/R Method



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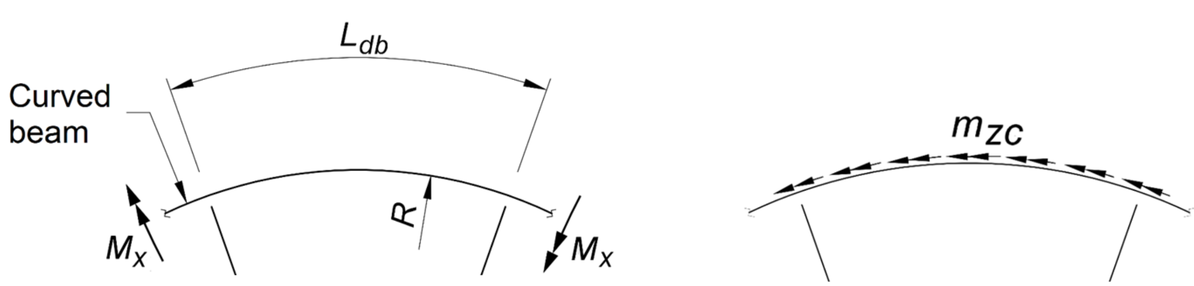
M/R Method

- Torsional moment per unit length: $m_{zc} = \dfrac{M_x}{R}$



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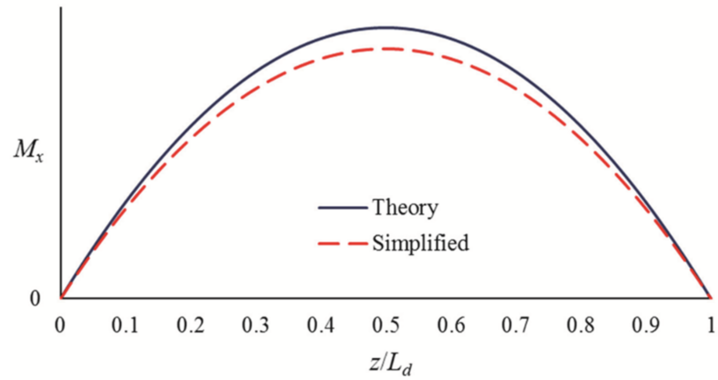
M/*R* Method

Moment Diagram (Uniform Load)



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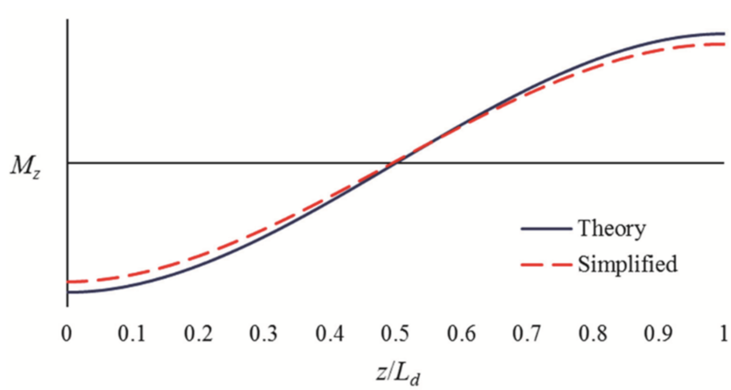
M/*R* Method

Torsion Diagram (Uniform Load)



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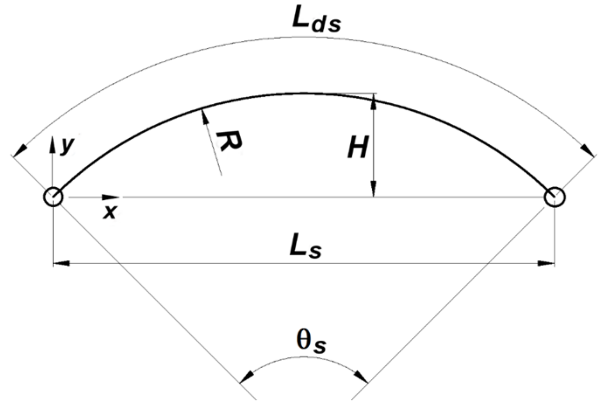
M/R Method

Corrected Moments

- Flexure: $M_{xc} = CM_x$
- Torsion: $M_{zc} = CM_z$

$$C = 1 - \frac{\theta_s}{30} + \frac{\theta_s^2}{6.2}$$



θ_s = span angle, rad

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Design of Horizontally-Curved Members

There's always a solution in steel.

Structural Analysis

Finite Element Models

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Finite Element Models

- Curved members are usually modeled by segmenting a series of straight elements
- Accuracy increases with the number of elements

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Finite Element Models

- ≈ 10 to 20 segments for semi-circular members
- For models with highly nonlinear behavior, a convergence study may be required

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Finite Element Models

- 2-D Models: cross section is a single beam element
- 3-D Models: cross section is comprised of multiple elements (beam, plate, solid)

Finite Element Models

2-D Models

- Basic beam finite element formulation
  - Used in most commercial finite element programs
  - Only St Venant stiffness
  - No warping stiffness
  - Over-estimates the rotation of open sections

Finite Element Models

2-D Models

- The additional stiffness from warping can be approximated with an equivalent torsion constant, J_e

Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3.

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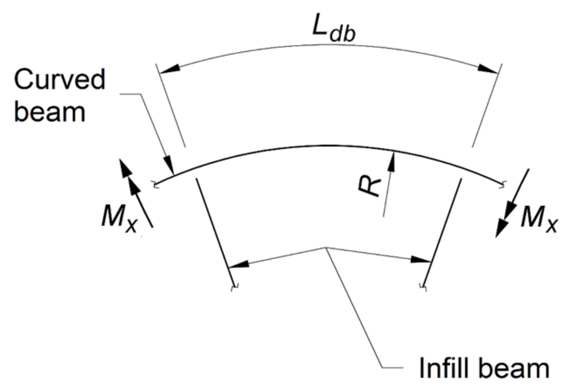
Finite Element Models

2-D Models

- Warping fixed at both ends of the span



Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3.

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Finite Element Models

2-D Models

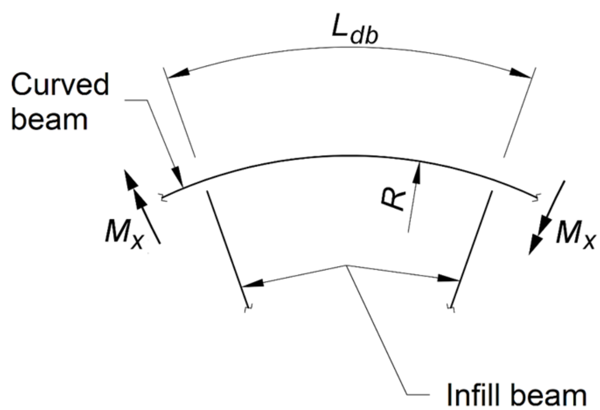
$$J_e = \frac{J}{1 - \frac{\sinh\gamma}{\gamma} + \frac{(\cosh\gamma - 1)^2}{\gamma\sinh\gamma}}$$

Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3.

Finite Element Models

2-D Models

$$\gamma = L_{db}\sqrt{\frac{GJ}{EC_w}}$$



C_w = warping constant

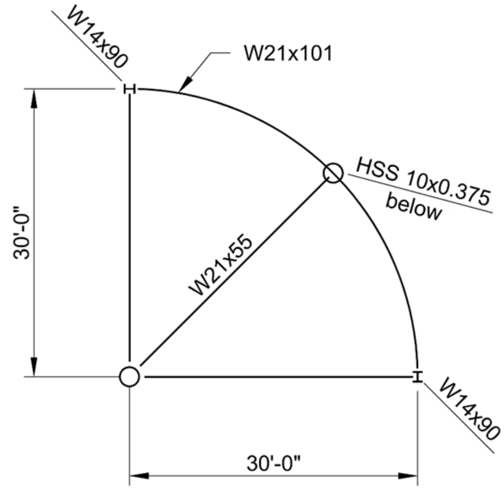
J = torsional constant

Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3.

Finite Element Models

2-D Models

- Warping fixed at one end and free at one end



Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3, January, pp 361-374.

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Finite Element Models

2-D Models

$$J_e = \frac{J}{1 - \dfrac{\sinh\gamma}{\gamma\cosh\gamma}}$$

Ahmed, M.Z and Weisgerber, F.E. (1996), "Torsion Constant for Matrix Analysis of Structures Including Warping Effect," *International Journal of Solids and Structures*, Vol. 33, No. 3, January, pp 361-374.

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Finite Element Models

3-D Models

- Cross section is comprised of multiple elements

Finite Element Models

3-D Models

- Webs of I-shape members
  - Typically modeled with plate elements
  - Can be modeled with solid elements

Finite Element Models

3-D Models

- Flanges of I-shape members
  – Typically modeled with beam elements
  – Can be modeled with plate or solid elements

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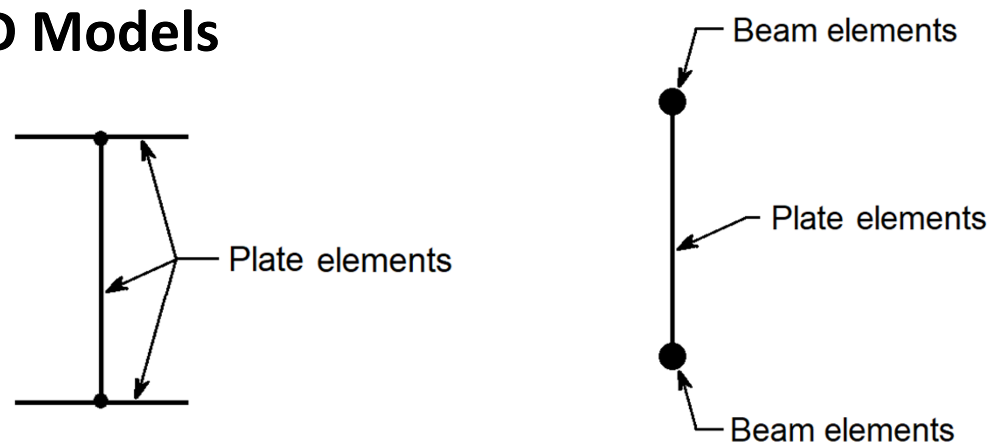
Finite Element Models

3-D Models



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Finite Element Models

3-D Models

- Infill members
  – Typically modeled with beam elements
  – Can be modeled with plate or solid elements

(continued)

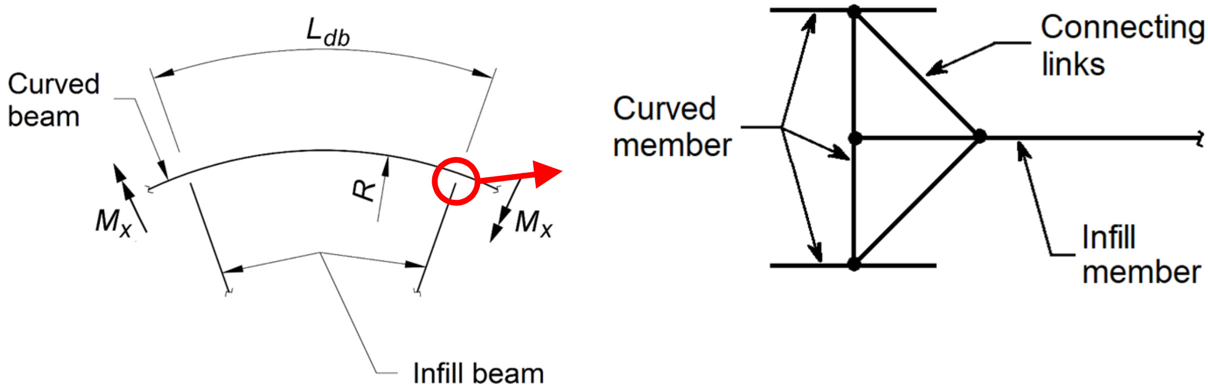
Finite Element Models

3-D Models

– If used to restrain torsion, connect to nodes at the top and bottom flanges of the curved member

Finite Element Models

3-D Models



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Design of Horizontally-Curved Members

Flexural Strength

There's always a solution in steel.

Flexural Strength

- Design as a straight beam
- AISC *Specification* Chapter F
- Unbraced length, $L_b \rightarrow L_{db}$
- Lateral-torsional buckling modification factor, $C_b \rightarrow C_{bo}$

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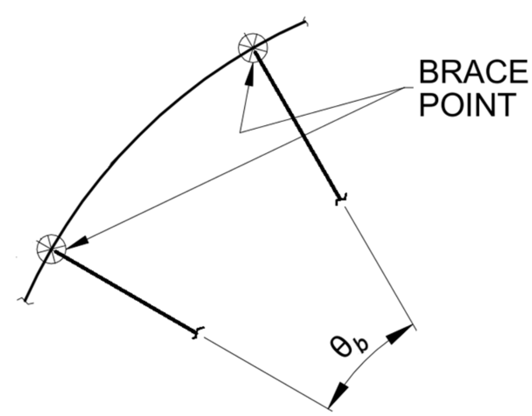
Flexural Strength

$$C_{bo} = C_{bs}\left[1-\left(\frac{\theta_b}{\pi}\right)^2\right]^2$$



θ_b = angle between braces, rad

C_{bs} = C_b for an equivalent straight member

Adapted from: Yoo, C.H., Kang, Y.J. and Davidson, J.S. (1996), "Buckling Analysis of Curved Beams by Finite-Element Discretization," *Journal of Engineering Mechanics*, ASCE, Vol. 122, No. 8.

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Design of Horizontally-Curved Members

Torsional Strength

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Torsional Strength

- Design as a straight beam
- Properly account for end conditions
  - Warping fixed
  - Warping free

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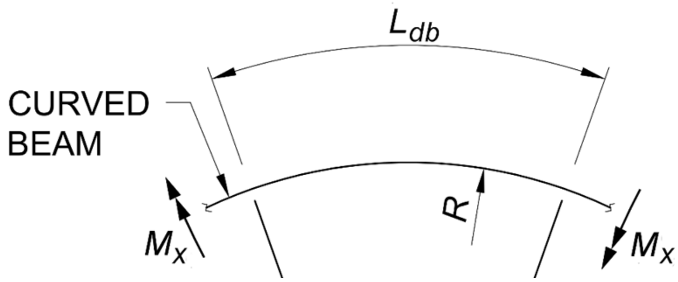
Torsional Strength

- Member length = developed length between torsional restraints, L_{db}



Torsional Strength

- Analysis Methods
  - Elastic method
  - Isolated flange method

There's always a solution in steel.

Design of Horizontally-Curved Members

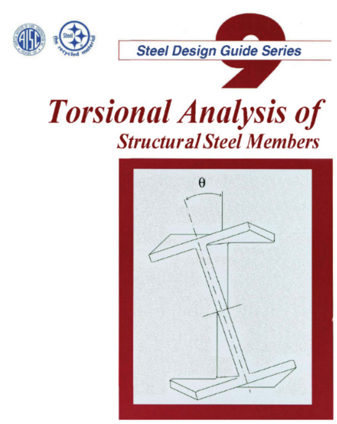
Torsional Strength

Elastic Method

structural
STEEL

Elastic Method

- AISC Design Guide 9
- Design charts in Appendix B



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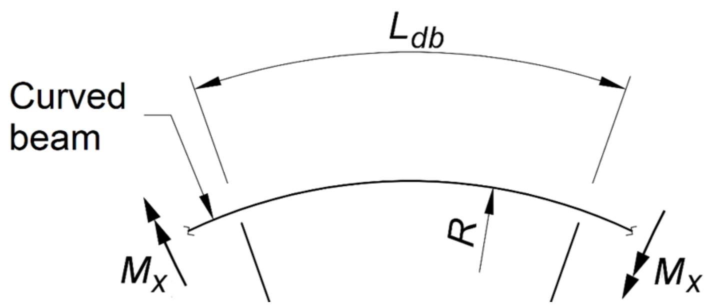
Elastic Method

Equal End Moments



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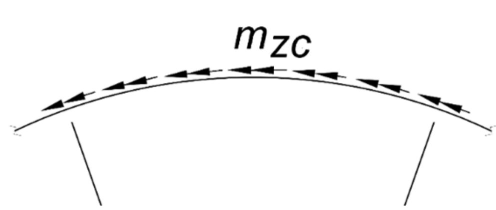
Elastic Method

Equal End Moments

- Results in a uniformly distributed torsional moment

$$m_{zc} = \frac{M_x}{R}$$



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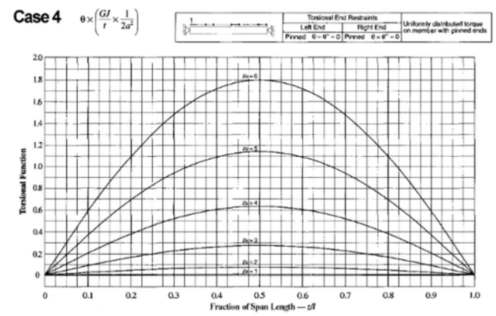
Elastic Method

Equal End Moments

- Design Guide 9 Charts
  - Warping free → Case 4
  - Warping fixed → Case 7
  - Warping fixed/free → Case 12



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Design of Horizontally-Curved Members

Torsional Strength

Isolated Flange Method

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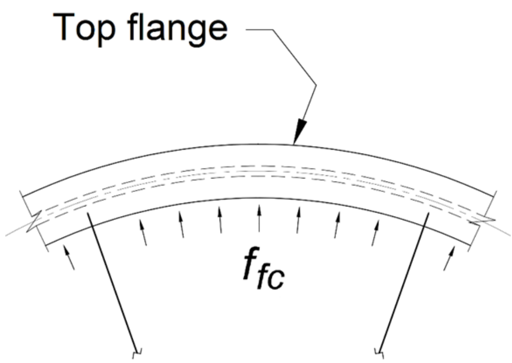
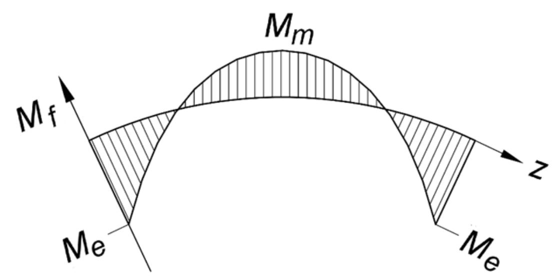
Isolated Flange Method

- I-shaped members
- Flanges are modeled as independent rectangular beams

Isolated Flange Method



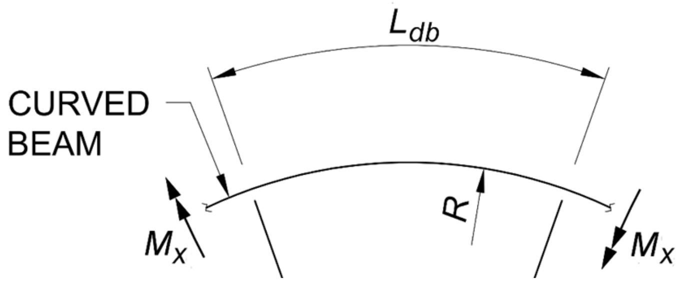
Radial Load



Moment Diagram

Isolated Flange Method

- Length of the isolated flange = developed (arc) length between torsional restraints, L_{db}

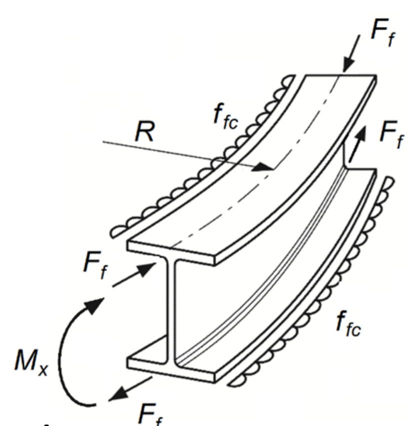


Isolated Flange Method

- Radial load, f_{fc}, is applied in the horizontal plane

$$f_{fc} = \frac{m_{zc}}{h_o} = \frac{M_x}{R h_o}$$

h_o = distance between flange centroids



Isolated Flange Method

- Flexural boundary conditions of the isolated flange are based on the warping boundary conditions of the curved member

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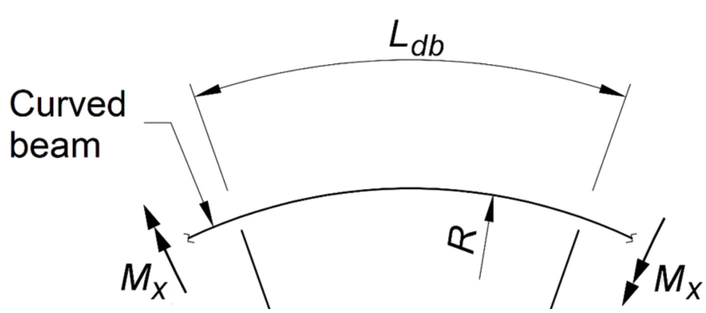
Isolated Flange Method

Equal End Moments



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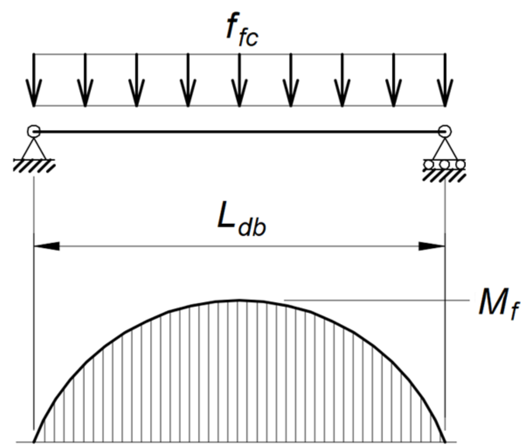
Isolated Flange Method

Equal End Moments

- Moment diagram for the isolated flange
- Warping free



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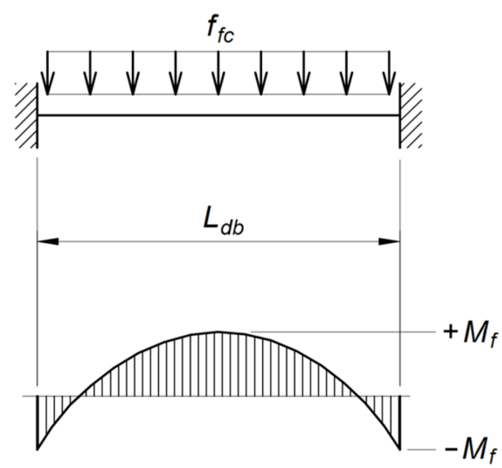
Isolated Flange Method

Equal End Moments

- Moment diagram for the isolated flange
- Warping fixed



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Isolated Flange Method

- Nominal flexural strength of the isolated flange: $M_{nw} = F_y Z_f$

$$Z_f = \frac{t_f b_f^2}{4}$$

b_f = flange width

t_f = flange thickness

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There's always a solution in steel.

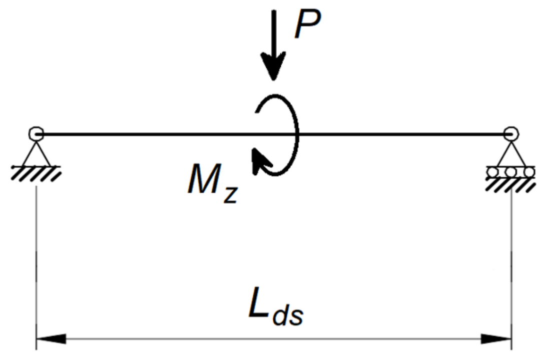
Design of Horizontally-Curved Members

Combined Loads

structural STEEL

Combined Loads

Flexure-torsion Interaction



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Design of Horizontally-Curved Members

There's always a solution in steel.

Combined Loads

Second-Order Effects

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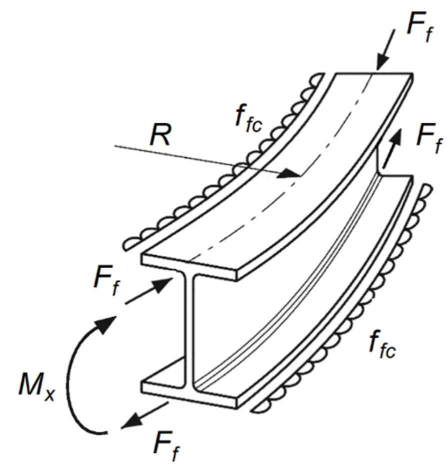
STEEL

Second-Order Effects

- Increase torsional moments and torsional rotations
- Isolated compression flange is analogous to a beam-column



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Second-Order Effects

- Rigorous second-order analysis
- Amplified first-order analysis

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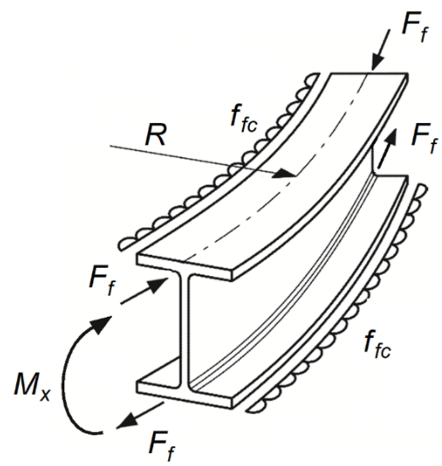
Second-Order Effects

Amplified First-Order Analysis

- Open sections subjected to torsion + strong-axis flexure



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Second-Order Effects

Amplified First-Order Analysis

- Second-order torsional rotation: $\theta_2 = B_o\theta_1$
- Second-order torsional moment: $M_{rz} = B_oM_z$

M_z = first-order torsional moment

θ_1 = first-order torsional rotation

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Second-Order Effects

Amplified First-Order Analysis

$$B_o = \frac{0.85}{1 - \alpha \frac{M_{ro}}{M_{eo}}} \geq 1.0$$

M_{eo} = elastic lateral-torsional buckling moment

M_{ro} = required strong-axis flexural moment (M_{rx})

α = 1.00 (LRFD); 1.60 (ASD)

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Design of Horizontally-Curved Members

There's always a solution in steel.

Combined Loads

Member Strength

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Member Strength

HSS and Box-Shaped Members

- Round and rectangular HSS
- Built-up box-shaped members
- *Specification* Section H3.2, Equation H3-6

Member Strength

HSS and Box-Shaped Members

$$\frac{M_{ro}}{M_{co}} + \left(\frac{V_r}{V_c} + \frac{M_{rz}}{M_{cz}} \right)^2 \leq 1.0$$

M_{co} M_{cz} V_c = available strengths: flexure, torsion, shear

M_{ro} M_{rz} V_r = required strengths: flexure, torsion, shear

Member Strength

I-Shaped Members

- Interaction method is based on the analysis method
  - Isolated flange method
  - Elastic method
  - FE model

Member Strength

I-Shaped Members: Isolated Flange Method

$$\frac{M_{ro}}{M_{co}} + \frac{8}{9}\frac{M_{rw}}{M_{cw}} \leq 1.0$$

M_{co} M_{cw} = available flexural strengths: member, flange

M_{ro} M_{rw} = required flexural strength: member, flange

Member Strength

I-Shaped Members: Elastic Method

$$\frac{\sigma_{ro}}{\sigma_{co}} + \frac{16}{27}\frac{\sigma_{rw}}{\sigma_{cw}} \leq 1.0$$

σ_{co} σ_{cw} = available stresses: flexure, warping

σ_{ro} σ_{rw} = required stresses: flexure, warping

Member Strength

I-Shaped Members: 2-D FE Model

- The required loads from the model can be compared with the available loads in the AISC *Specification* and AISC Design Guide 9

Member Strength

I-Shaped Members: 3-D FE Model

- Flange strength is evaluated using AISC *Specification* Section H1

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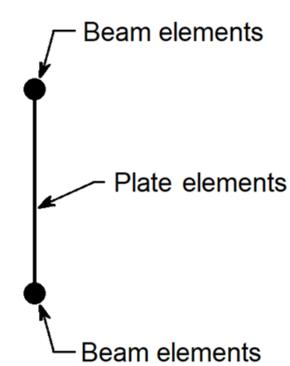
Member Strength

I-Shaped Members: 3-D FE Model

- Flanges modeled as rectangular beam elements: loads are used directly from the FE analysis



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Member Strength

I-Shaped Members: 3-D FE Model

- The available strengths in the AISC *Specification* were not developed to be compared to the results from finite element models built with plate or solid elements

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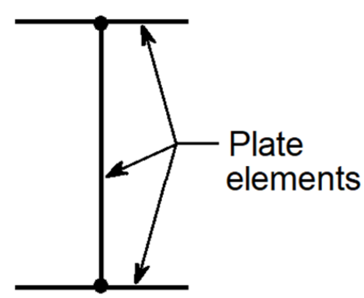
Member Strength

I-Shaped Members: 3-D FE Model

- Flanges modeled as plate or solid elements: loads are determined by summing stresses over the element



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Design of Horizontally-Curved Members

Serviceability

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Serviceability

- Large deformations at ultimate strength
- Member sizes are usually controlled by serviceability

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Serviceability

- Torsional rotation limits
  - Not in building codes
  - Some judgment may be required to define appropriate limits
  - Maintain geometry of the structure
  - Prevent damage to nonstructural elements

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Design of Horizontally-Curved Members

Local Strength

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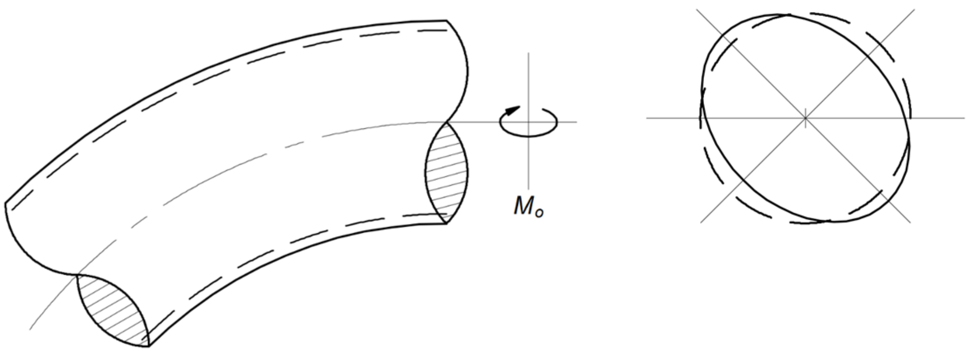
Local Strength

Out-of-Plane Moment



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Simplified Method

Effective Flexural Properties (Round HSS)

- Effective section modulus: $S_{eo} = k_{so} S$
- Effective plastic modulus: $Z_{eo} = k_{zo} Z$
- Effective moment of inertia: $I_e = k_i I$

I, S, Z = flexural properties of a straight member

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Simplified Method

Effective Flexural Properties (Round HSS)

$$k_{so} = 0.926 c_r^{2/3} \leq 1.00$$

$$c_r = \frac{4Rt}{(D-t)^2}$$

D = outside diameter

t = wall thickness

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Simplified Method

Effective Flexural Properties (Round HSS)

$$k_{zo} = \frac{1.2 c_r}{\sqrt{1 + c_r^2}}$$

$$k_i = \frac{1}{1 + \dfrac{9}{12 c_r^2 + 1}}$$

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Design of Horizontally-Curved Members

Connections

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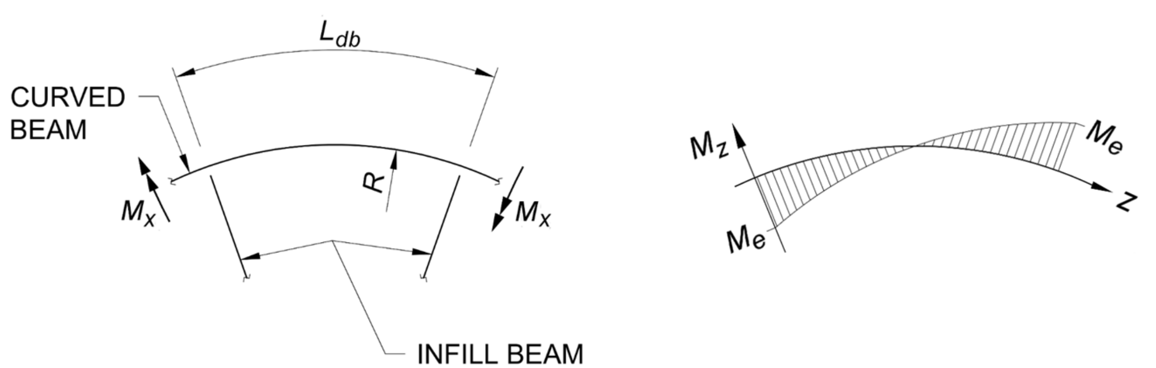
Connections

- Torsional resistance is required for equilibrium



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Connections

- Warping resistance is optional
  - Increased member twisting strength and stiffness
  - Dependent on connections
  - Often impractical due to connection requirements

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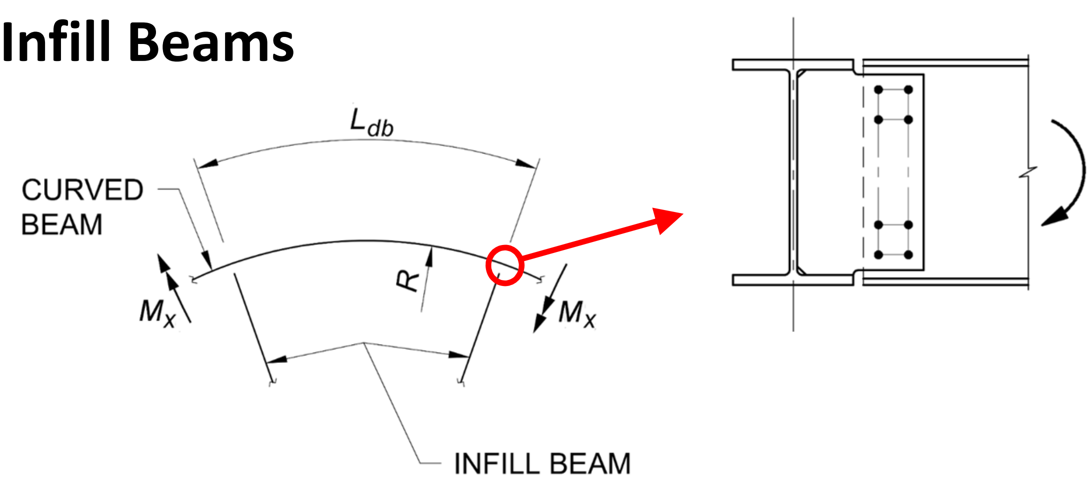
Connections

Infill Beams



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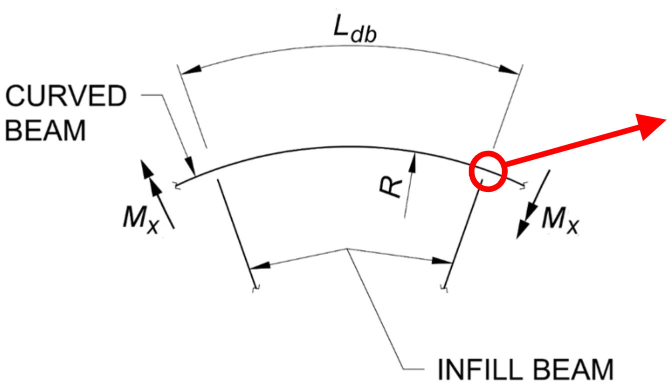
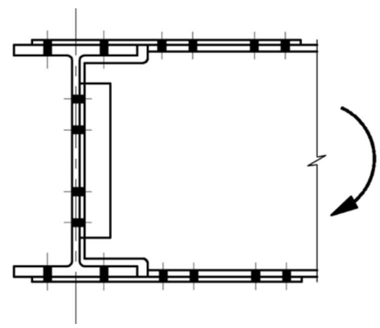
Connections

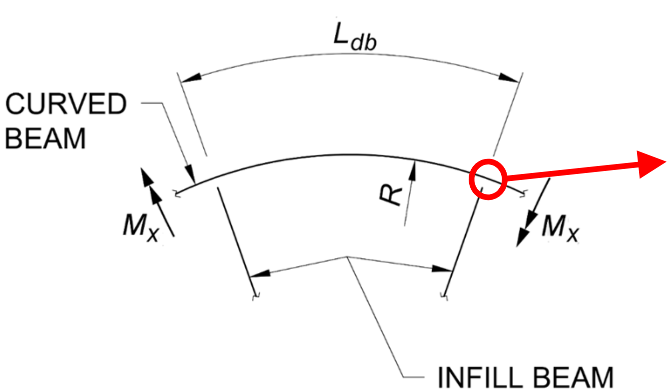
Infill Beams

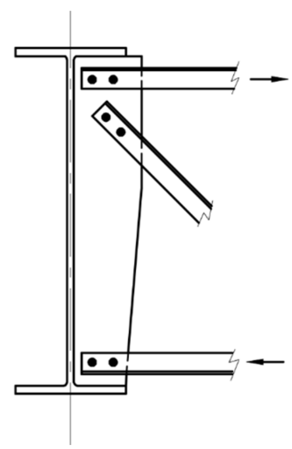




Connections

Infill Beams

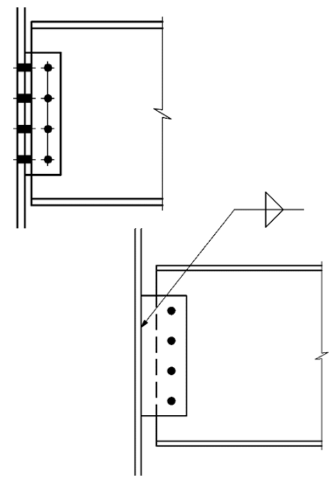




Connections

End Connections

- Simple shear connections
  → limited torsional resistance



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Connections

End Connections

- Flanges must be engaged to properly transfer torsional loads

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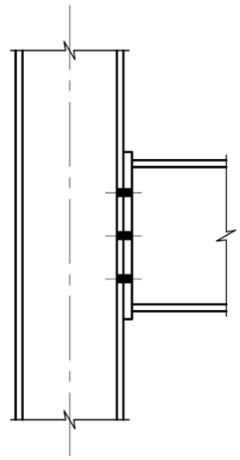
Connections

End Connections

- Warping free



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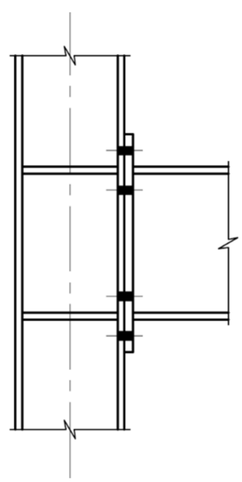
Connections

End Connections

- Warping fixed



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Question time

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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.

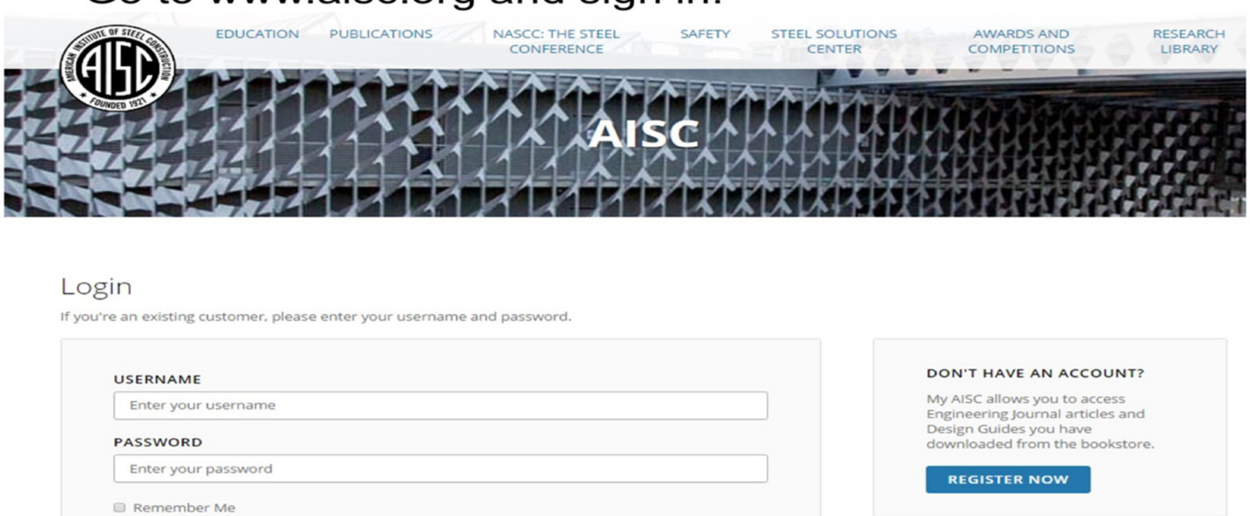
CEUs/PDHS – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

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

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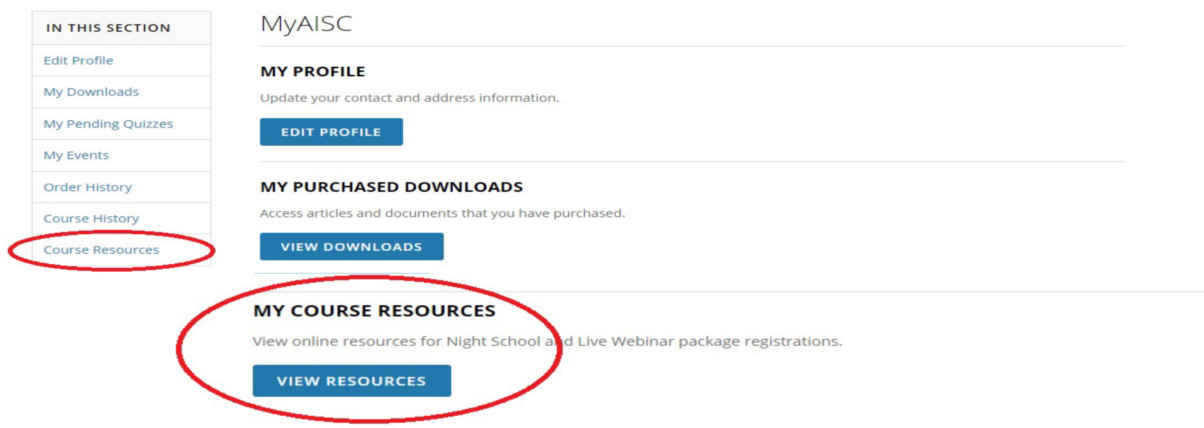

Night School Resources for 8-session package Registrants

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

Please give us your feedback!
Survey at conclusion of webinar.

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