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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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# 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

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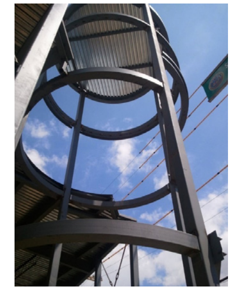
## Session Description

- 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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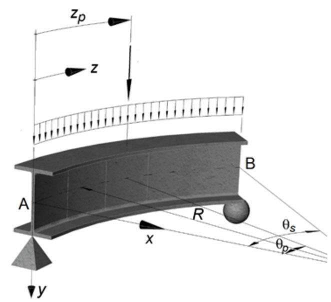
# Introduction

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

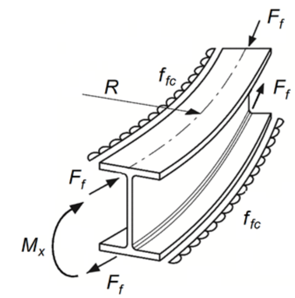





# Introduction

**Deflected Shape**

- Vertical translation
- Torsional rotation

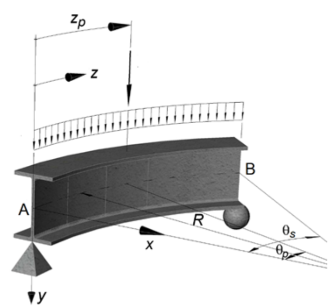





# Introduction

**Typical Behavior**

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

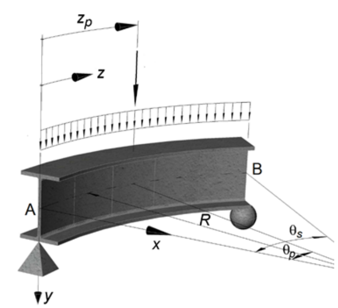





# Introduction

**Typical Limit States**

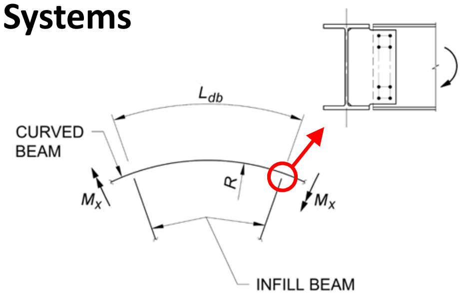
- Excessive deformation
- Yielding



# Introduction

**Efficient Structural Systems**

- Infill members restrain torsion

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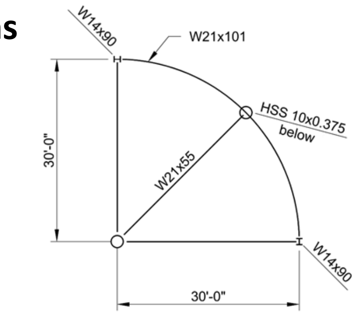
# Introduction

**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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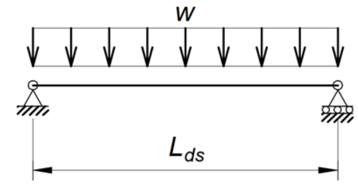
## Eccentric Load Method

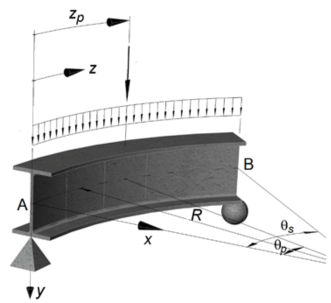
- Curved beam is modeled as straight member






## Eccentric Load Method

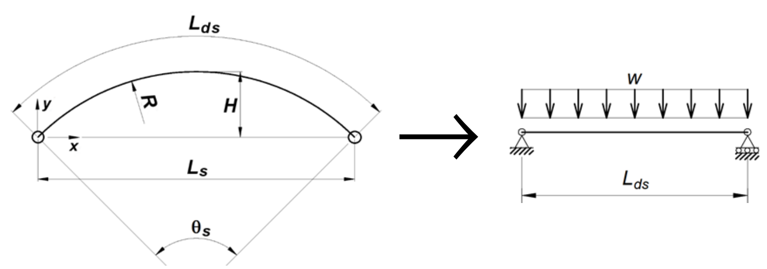
- Length is equal to the developed span length, $L_{ds} = R\theta_s$




$\theta_s$ = span angle, rad

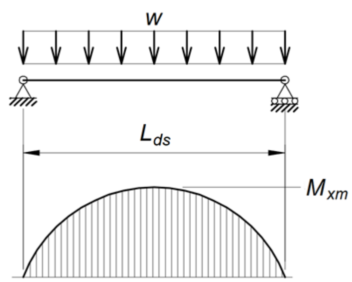


## Eccentric Load Method



## Eccentric Load Method

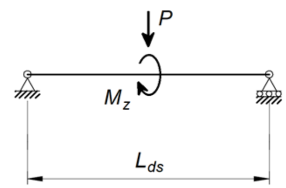
- Flexural ($M_x$) and shear ($V$) loads are calculated using the flexural support conditions

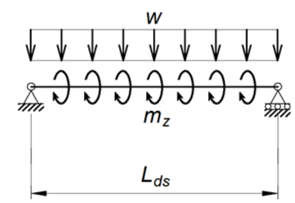





## Eccentric Load Method

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

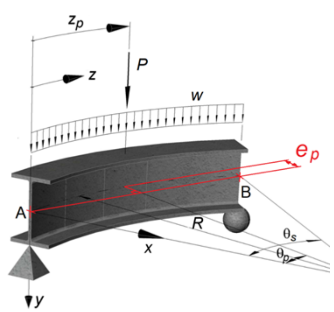





## Eccentric Load Method

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

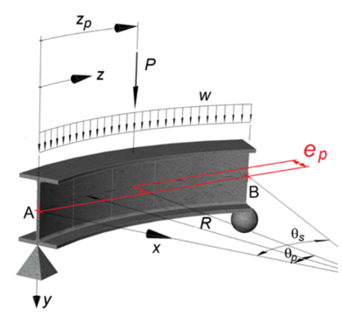





## Eccentric Load Method

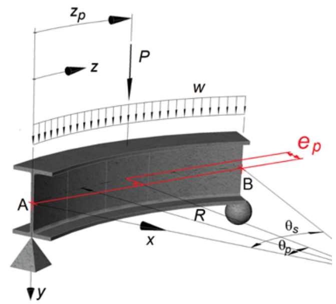
- For beams with a midspan concentrated load, the midspan concentrated torsion is

$$M_z = Pe_p$$



## Eccentric Load Method

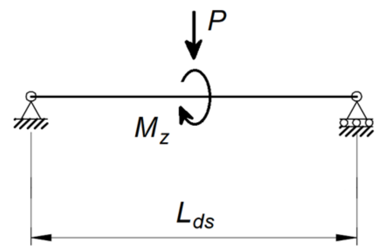
$$e_p = R\left[1 - \cos\left(\frac{\theta_s}{2}\right)\right]$$




$\theta_s$ = span angle, rad



## Eccentric Load Method

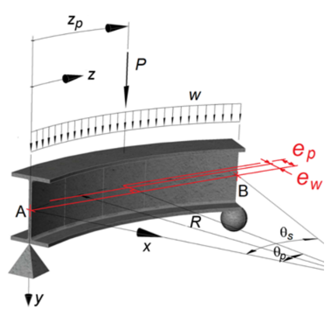





## Eccentric Load Method

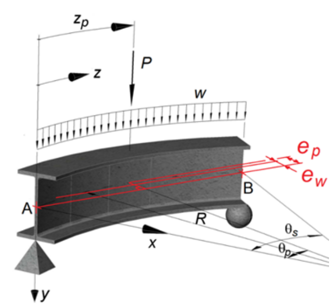
- For beams with a uniformly distributed load, the uniformly distributed torsion is

$$m_z = we_w$$





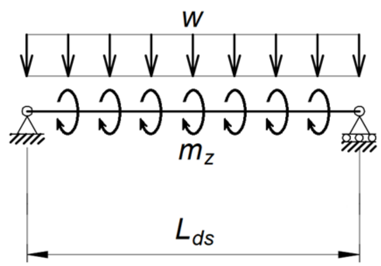

## Eccentric Load Method




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

$\theta_s$ = span angle, rad

## Eccentric Load Method

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## Design of Horizontally-Curved Members

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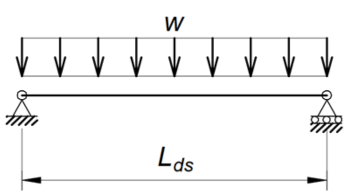
Structural Analysis

*M*/*R* Method

structural STEEL

## *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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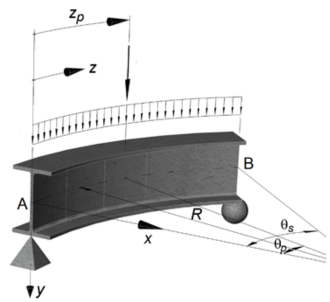
## *M*/*R* Method

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




$\theta_s$ = span angle, rad

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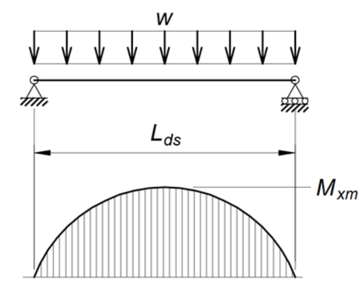
## *M*/*R* Method

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

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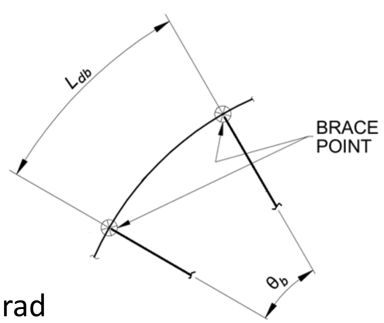
## *M*/*R* Method

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




$\theta_b$ = angle between braces, rad

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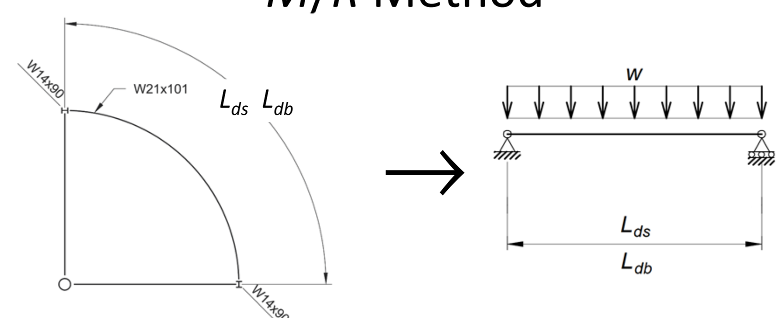
## *M*/*R* Method

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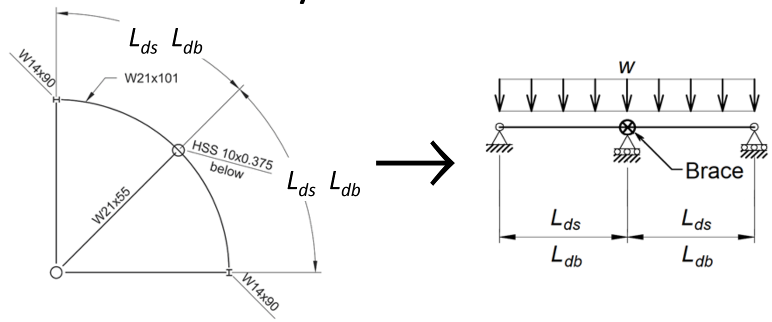
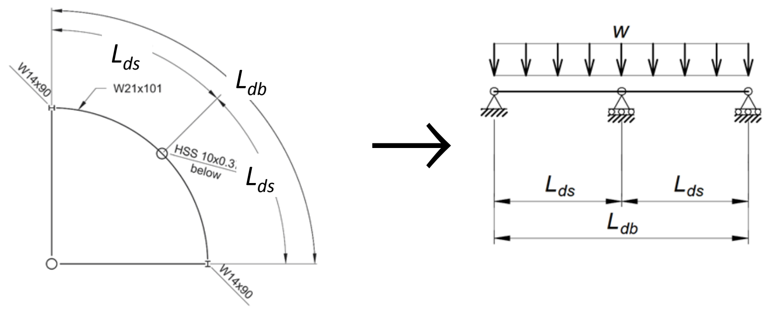
## *M*/*R* Method



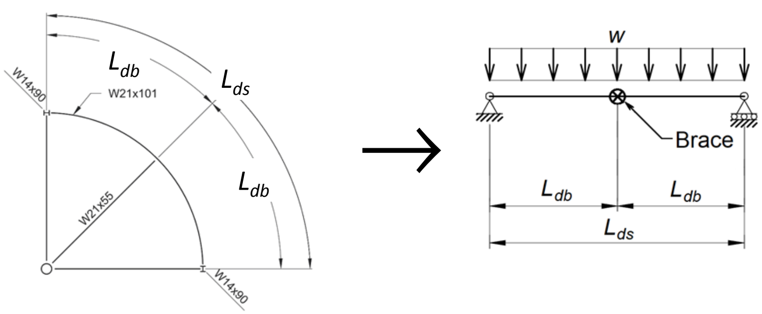



## *M*/*R* Method





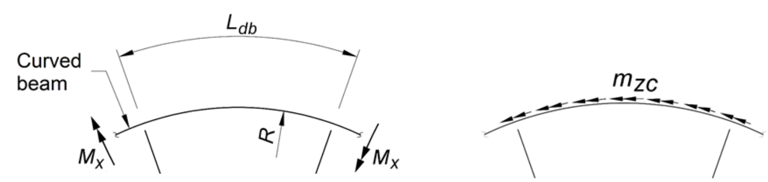

## *M*/*R* Method





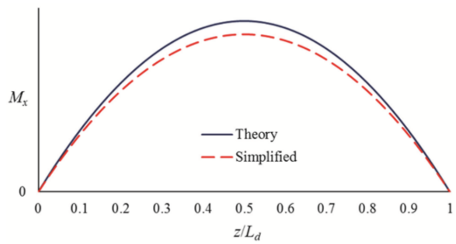

## *M*/*R* Method

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



# *M*/*R* Method

**Moment Diagram (Uniform Load)**

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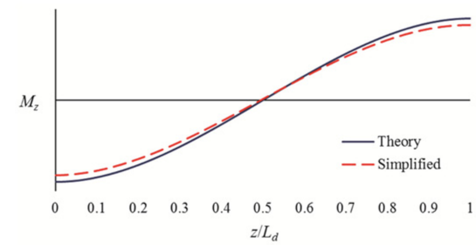
# *M*/*R* Method

**Torsion Diagram (Uniform Load)**

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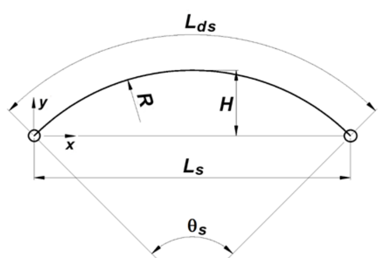
# *M*/*R* Method

**Corrected Moments**

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

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




$\theta_s$ = span angle, rad

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**Design of Horizontally-Curved Members**

Structural Analysis

Finite Element Models

## Finite Element Models

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



## Finite Element Models

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



## 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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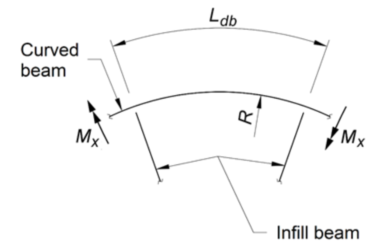
# Finite Element Models

**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.

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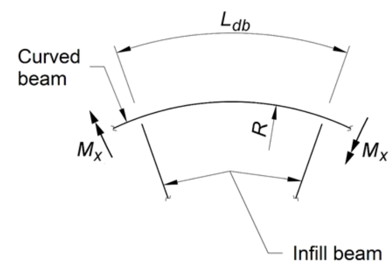
# Finite Element Models

**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.

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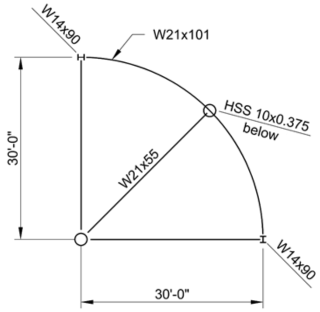
# Finite Element Models

**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.



# Finite Element Models

**2-D Models**

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

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.



# 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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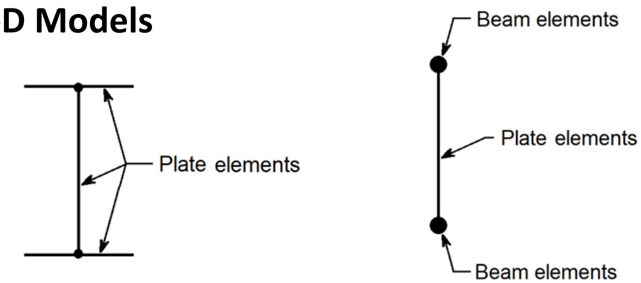
## Finite Element Models

**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)

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## Finite Element Models

**3-D Models**

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

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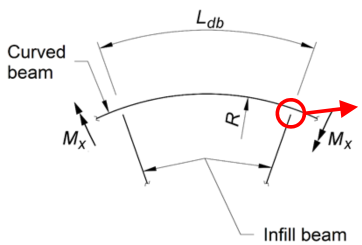
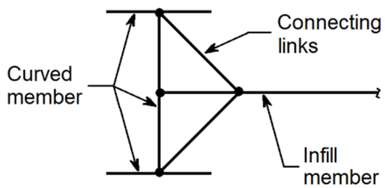
# Finite Element Models

**3-D Models**

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**Design of Horizontally-Curved Members**

Flexural Strength

# 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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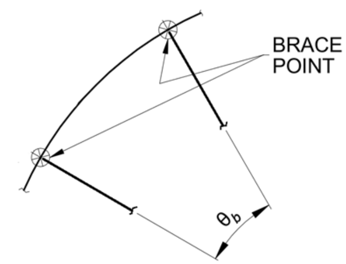
# Flexural Strength

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




$\theta_b$ = 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

structural STEEL

# Torsional Strength

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

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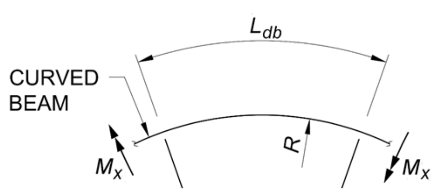
# Torsional Strength

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

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# Torsional Strength

- Analysis Methods
  - Elastic method
  - Isolated flange method

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**Design of Horizontally-Curved Members**

Torsional Strength

Elastic Method

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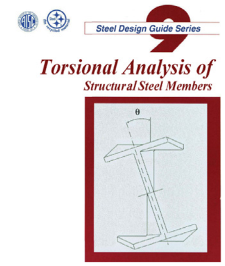
## Elastic Method

- AISC Design Guide 9
- Design charts in Appendix B

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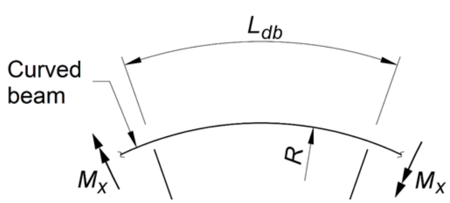
## Elastic Method

**Equal End Moments**

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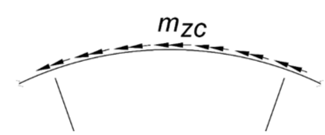
## Elastic Method

**Equal End Moments**

- Results in a uniformly distributed torsional moment

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

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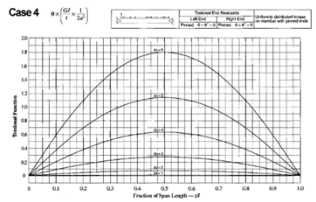
# Elastic Method

**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

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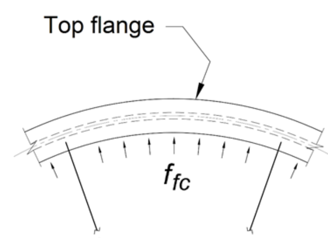
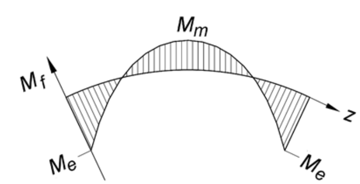
# Isolated Flange Method




Radial Load




Moment Diagram

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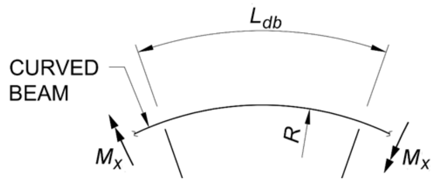
## Isolated Flange Method

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

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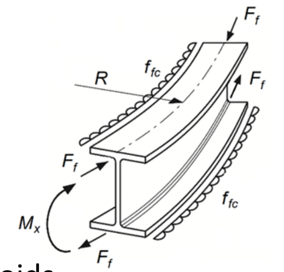
## Isolated Flange Method

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

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




$h_o$ = distance between flange centroids

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## 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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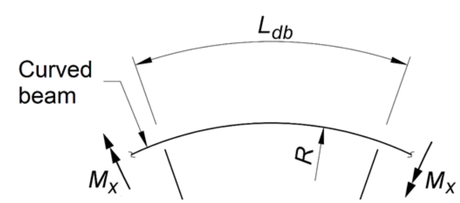
## Isolated Flange Method

**Equal End Moments**

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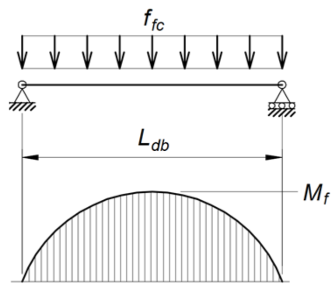
## Isolated Flange Method

**Equal End Moments**
- Moment diagram for the isolated flange
- Warping free

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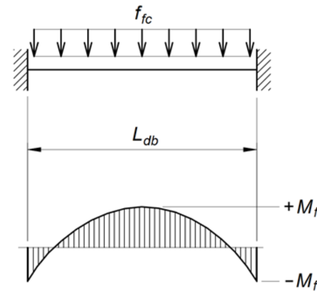
## Isolated Flange Method

**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.

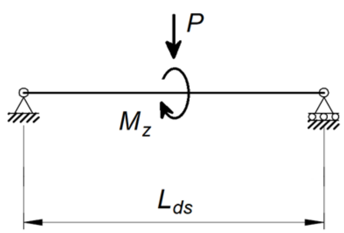
**Design of Horizontally-Curved Members**

Combined Loads

structural STEEL

# Combined Loads

**Flexure-torsion Interaction**

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**Design of Horizontally-Curved Members**

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Combined Loads

Second-Order Effects

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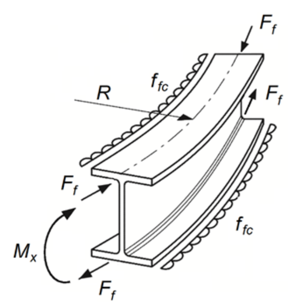
# Second-Order Effects

- 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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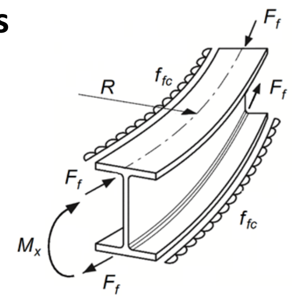
## Second-Order Effects

**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
$\theta_1$ = first-order torsional rotation

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## Second-Order Effects

**Amplified First-Order Analysis**

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

$M_{eo}$ = elastic lateral-torsional buckling moment
$M_{ro}$ = required strong-axis flexural moment ($M_{rx}$)
$\alpha$ = 1.00 (LRFD); 1.60 (ASD)

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**Design of Horizontally-Curved Members**

Combined Loads

Member Strength

structural STEEL

# Member Strength

**HSS and Box-Shaped Members**

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

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# 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

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# Member Strength

**I-Shaped Members**

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

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# 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

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# Member Strength

**I-Shaped Members: Elastic Method**

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

$\sigma_{co}$ $\sigma_{cw}$ = available stresses: flexure, warping

$\sigma_{ro}$ $\sigma_{rw}$ = required stresses: flexure, warping

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# 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

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# Member Strength

**I-Shaped Members: 3-D FE Model**

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

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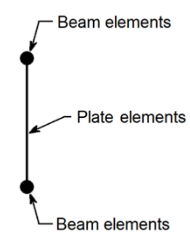
# Member Strength

**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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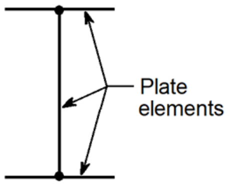
## Member Strength

**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

structural STEEL

## 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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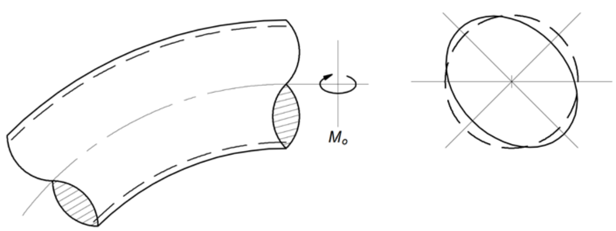
**Design of Horizontally-Curved Members**

Local Strength

structural STEEL

## 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)**

$$k_{so} = 0.926 c_r^{2/3} \leq 1.00 \qquad c_r = \frac{4Rt}{(D-t)^2}$$

*D* = outside diameter *t* = wall thickness

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# Simplified Method

**Effective Flexural Properties (Round HSS)**

$$k_{zo} = \frac{1.2 c_r}{\sqrt{1+c_r^2}} \qquad k_i = \frac{1}{1+\dfrac{9}{12c_r^2+1}}$$

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**Design of Horizontally-Curved Members**

Connections

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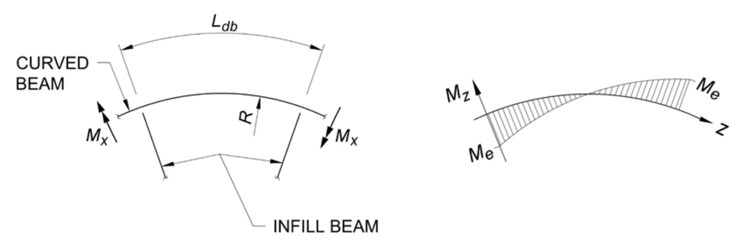
# Connections

- 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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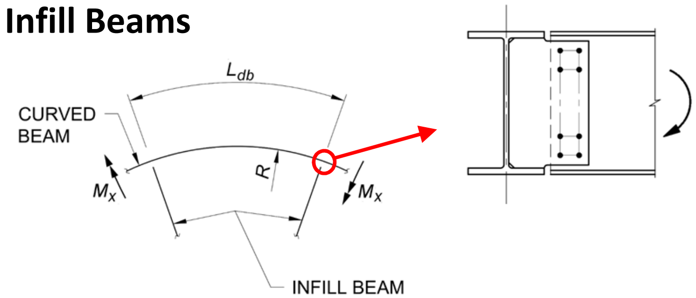
## Connections

**Infill Beams**

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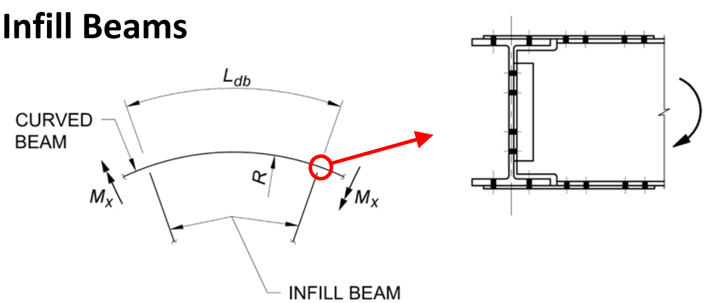
## Connections

**Infill Beams**

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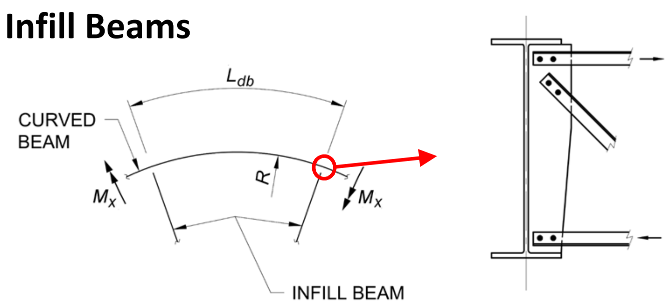
## Connections

**Infill Beams**

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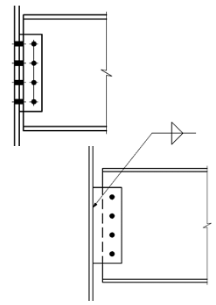
## Connections

**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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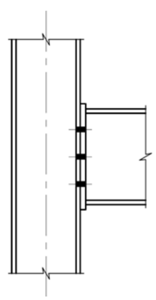
## Connections

**End Connections**

- Warping free



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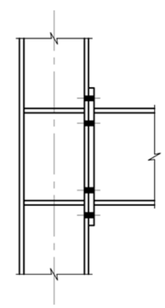
## Connections

**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.

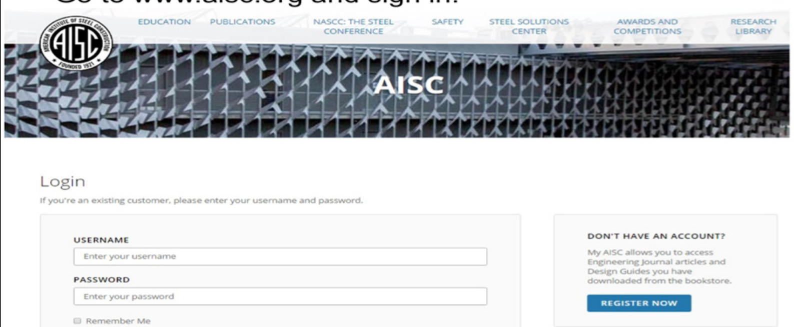
**CEUs/PDHS** – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

## 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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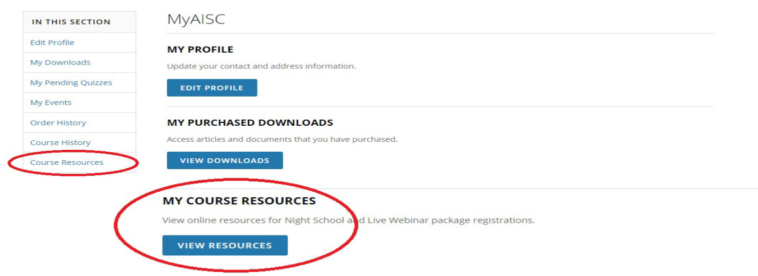



## Night School Resources for 8-session package Registrants


Night School 13: Design of Industrial Buildings

**8-SESSION PACKAGE RESOURCES**

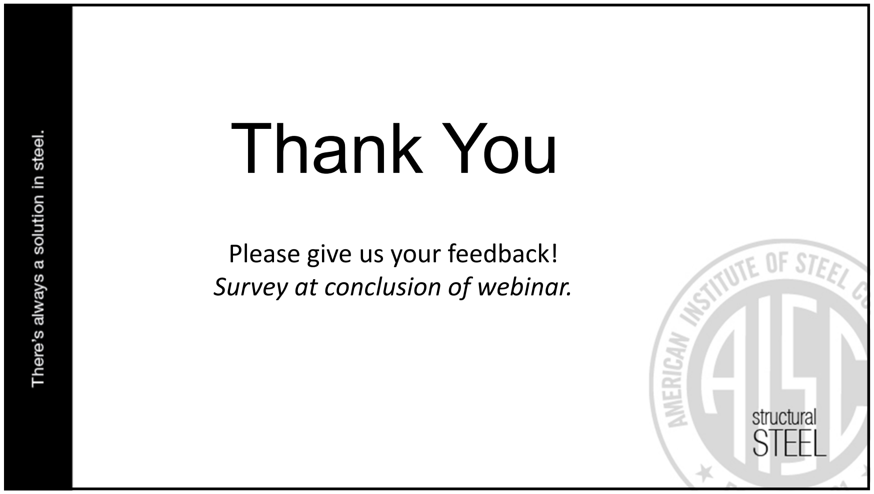
| Event | Date | Handouts | Video | Quiz | Attendance |
|---|---|---|---|---|---|
| NS13 - Design Criteria | 1/30/2017 7:00:00 PM | Handouts | View<br>Passcode: NS13DSN | Pass<br>Score: 80 | Pending |
| NS13 - Economic Considerations | 2/6/2017 7:00:00 PM | Handouts | Available 02/08/2017 5pm EST | Available 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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