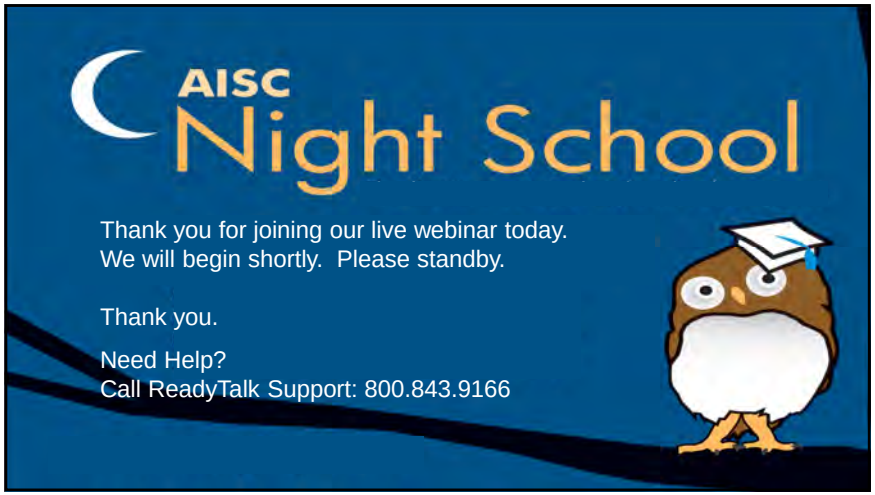

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Copyright Materials

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AISC Night School

Session Description

Session 1: General Information on Curved Members

June 18, 2018

This session presents general information on curved members including an overview to the coming soon AISC Design Guide. The session will introduce the attendees to bending geometries, bending processes, and considerations for design for bending: curving mechanics, fracture during bending and distortion. Additional design considerations, tolerances contract documents and more, are also discussed.

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AISC Night School

Learning Objectives

- Identify curve geometries and differences between standard bends and specialty bends.
- Identify the various bending processes and the differences between cold bending and hot bending.
- Describe curving mechanics when designing for bending.
- Describe fracture and distortion issues during the bending operation.

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There's always a solution in steel.

Design of Curved Members

Session 1: General Information on Curved Members

June 18, 2018

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

structural STEEL

Course Outline

- Session 1
  - General information on curved members
  - June 18
- Session 2
  - Design of vertically-curved members
  - June 25

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Course Outline

- Session 3
  - Design of horizontally-curved members
  - July 2
- Session 4
  - Design examples
  - July 9

10

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General Information on Curved Members

Introduction

Introduction

Vertically-Curved Members

Photographs courtesy of the AISC Bender/Roller Committee

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Introduction

Vertically-Curved Members

Photograph courtesy of the AISC Bender/Roller Committee

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Introduction

Horizontally-Curved Members

Photograph courtesy of the AISC Bender/Roller Committee

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Introduction

Horizontally-Curved Members

Photograph courtesy of the AISC Bender/Roller Committee

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Introduction

Horizontally-Curved Members

Photograph courtesy of the AISC Bender/Roller Committee

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General Information on Curved Members

Session Description

Session Description

- Overview of AISC Design Guide 33
- Curving steel members
  - Curve geometries
  - Bending processes

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Session Description

- Design for bending
  - Curving mechanics
  - Fracture during the bending operation
  - Distortion from the bending operation

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General Information on Curved Members

Overview of Design Guide 33

Design Guide Overview

Purpose of Design Guide 33

- Design guidance
  - Vertically-curved members
  - Horizontally-curved members
  - Connections

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Design Guide Overview

- Practical information
  - Fabrication
  - Detailing

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Design Guide Overview

Contents of Design Guide 33

- Chapter 1: Introduction
  - Typical applications of curved members
- Chapter 2: Curving Steel Members
  - Bending geometries and processes

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Design Guide Overview

Contents of Design Guide 33

- Chapter 3: Design for Bending
  - Preventing fracture and distortion during the bending operation
- Chapter 4: Fabrication and Detailing
  - Tolerances, fabrication and detailing

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Design Guide Overview

- Chapter 5: General Design Issues
  - Material properties, contract documents, etc.
- Chapter 6: Vertically-Curved Members
- Chapter 7: Horizontally-Curved Members

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Design Guide Overview

- Chapter 8: Design Examples
- Glossary
- List of bender-roller companies

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General Information on Curved Members

Curving Steel Members

Curve Geometries

Curve Geometries

- Standard Bends
- Specialty Bends
  - Off-Axis, Compound, Reverse-Compound, Multi-Axis, Variable-Radius, Spiral

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General Information on Curved Members

Curving Steel Members

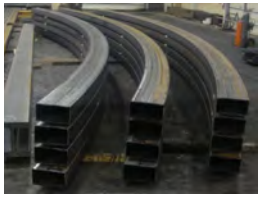
Curve Geometries

Standard Bends

Curve Geometries

Standard Bends

- Single-radius curvature



Photographs courtesy of the AISC Bender/Roller Committee

30

Curve Geometries

Standard Bends

- Bending about a principal or geometric axis
  - Hard way: bending about the strong axis
  - Easy way: bending about the weak axis

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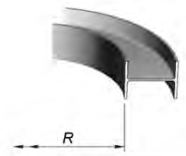
Curve Geometries

Section	Orientation	
I-Shape		
	Hard Way	Easy Way

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Curve Geometries

Section	Orientation			
HSS				
	Round	Square	Rectangular-Hard Way	Rectangular-Easy Way

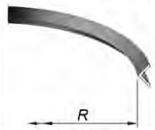
Curve Geometries

Section	Orientation		
Channel			
	Flanges In	Flanges Out	Hard Way

Curve Geometries

Section	Orientation		
Tee			
	Stem In	Stem Out	Stem Up

Curve Geometries

Section	Orientation			
Angle				
	Leg In	Leg Out	Heel In	Heel Out

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General Information on Curved Members

Curving Steel Members

Curve Geometries

Specialty Bends

Curve Geometries

Off-Axis Bends

- Bending about a non-principal or non-geometric axis
- AKA conical rolling

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Curve Geometries

Off-Axis Bends

Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Off-Axis Bends

- Canopies
- Roofs

Photograph courtesy of the AISC Bender/Roller Committee

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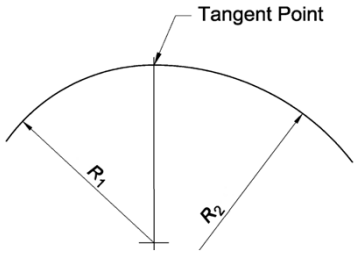
Curve Geometries

Compound Bends

- Two or more arcs in the same plane
- No reversal of curvature



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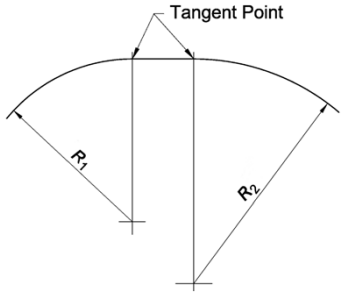
Curve Geometries

Compound Bends

- Can be fabricated with a straight segment between tangent points



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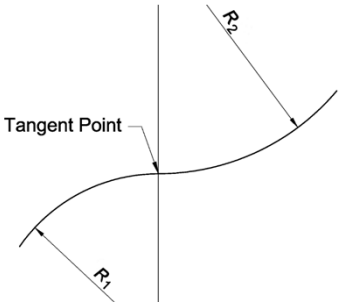
Curve Geometries

Reverse-Compound Bends

- Compound bend with reversal of curvature
- AKA S-curve



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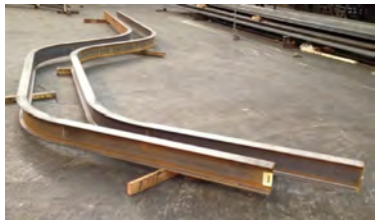
Curve Geometries

Reverse-Compound Bends



Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Compound and Reverse-Compound Bends

- Canopies
- Roofs
- Architectural features

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Curve Geometries

Reverse-Compound Bends

Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Multi-Axis bends

- Curvature about more than one axis
- AKA multi-plane bending

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Curve Geometries

Multi-Axis bends

Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Variable-Radius Bends

- Any non-circular bend
- AKA multi-radius bends

49

Curve Geometries

Variable-Radius Bends: Parabolic

- Parabolic arches are efficient for resisting uniform gravity loads

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Curve Geometries

Variable-Radius Bends: Parabolic

Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Variable-Radius Bends: Elliptical

- Elliptical bends can be required where a curved plane interfaces with a skewed plane

52

Curve Geometries

Variable-Radius Bends: Elliptical

Photographs courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Spiral Bends

- Helical curve
- AKA sloped rolling or pitched rolling

Photograph courtesy of the AISC Bender/Roller Committee

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Curve Geometries

Spiral Bends

- Spiral stairs
- Art sculptures

Photographs courtesy of the AISC Bender/Roller Committee

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General Information on Curved Members

Curving Steel Members

Bending Processes

Bending Processes

- Cold bending
  - Room temperature
  - Usually more economical than hot bending
- Hot Bending
  - Heating lowers the material yield strength
  - Smaller forces required by the bending machine

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Bending Processes

- Pyramid roll bending
- Incremental step bending
- Induction bending
- Other processes

Photograph courtesy of the AISC Bender/Roller Committee

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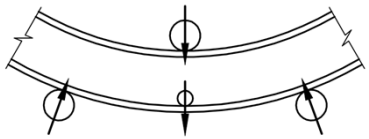
Bending Processes

Pyramid Roll Bending

- Member is repeatedly passed through a set of rolls
- Cold-bending method



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Bending Processes

Pyramid Roll Bending

Photograph courtesy of the AISC Bender/Roller Committee

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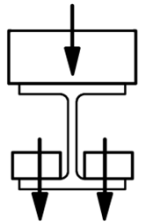
Bending Processes

Pyramid Roll Bending

- Supplementary rolls
  - Tension force applied to the tension flange
  - Control web distortion



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Bending Processes

Pyramid Roll Bending

- Contoured rolls
  - Provide support during the bending operation

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Pyramid Roll Bending

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Pyramid Roll Bending

- Special rolls
  - Stabilize cross-sectional elements
  - Reduce distortion

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Pyramid Roll Bending

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Incremental Step Bending

- Forces applied at several discrete locations along the member length
- Cold-bending method

Photograph courtesy of the AISC Bender/Roller Committee

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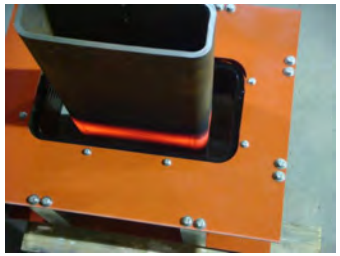
Bending Processes

Induction Bending

- Hot-Bending Method
- Electric induction coil heats a narrow band around the member circumference



Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Induction Bending

- After heating, the member is curved by force

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Induction Bending

- Equal thickness elements = uniform heating

Photograph courtesy of the AISC Bender/Roller Committee

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Bending Processes

Induction Bending

- Usually costs more than cold-bending
- Capable of small-radius bends with low cross-sectional distortion
- With proper control of the essential variables, material properties can be enhanced

70

Bending Processes

Induction Bending

- Heavy shapes
  - Hollow shapes with wall thicknesses up to 6 in. have been successfully bent

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Bending Processes

- Each bending method has advantages and disadvantages
- The capabilities of each bender/roller can vary significantly
- Involve a bender/roller early in the design process

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General Information on Curved Members

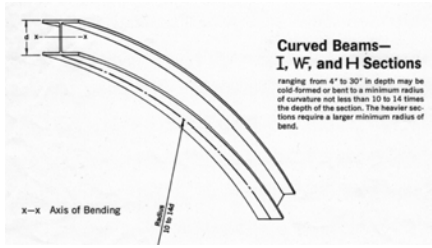
Design for Bending

structural STEEL

Design for Bending

What is the Minimum Cold-Bending Radius?

Rule of Thumb?



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Design for Bending

Rigid Guidelines Are Not Available

- Minimum radius is dependent on:
  - Bending axis
  - Shape of the cross-section
  - Slenderness of the cross-sectional elements

(continued)

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Design for Bending

- Bending method and equipment
- Level of acceptable cross-sectional distortion
- Level of acceptable cold-working of the material

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Design for Bending

- Bending requirements should be discussed with the bender-roller who will provide the service
- A list of bender-rollers is on the AISC website at www.aisc.org/membership/bender-roller-committee/

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Design for Bending

Behavior During the Bending Operation

- Curving mechanics
- Fracture
- Cross-sectional distortion

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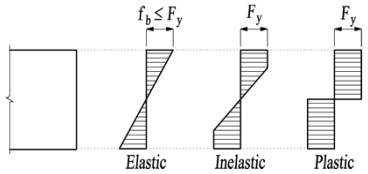
General Information on Curved Members

Design for Bending

Curving Mechanics

Curving Mechanics

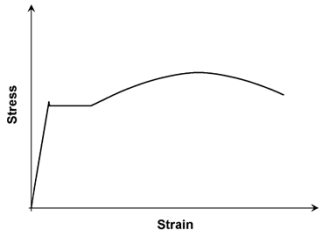
- Inelastic strain → permanent curvature



80

Curving Mechanics

- Low curvature → yield plateau
- High curvature → strain hardening



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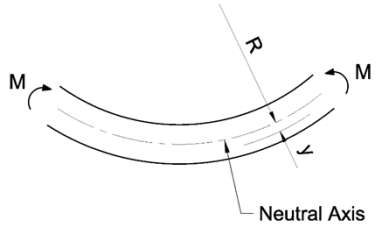
Curving Mechanics

Maximum strain:

$$\varepsilon_{max} = \frac{y_o}{R}$$



R = centroidal radius of curvature

y_o = distance from neutral axis to the outermost fiber

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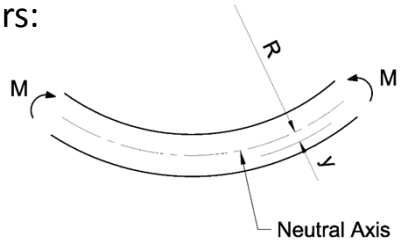
Curving Mechanics

For symmetric members:

$$\varepsilon_{max} = \frac{D}{2R}$$



D = member depth in the plane of curvature

83

Curving Mechanics

The maximum strain can be defined as a multiple of the yield strain

$$\varepsilon_{max} = \alpha\varepsilon_y$$

α = strain ratio

ε_y = yield strain, = F_y/E

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Curving Mechanics

For $\alpha > 12$, precautions may be necessary to ensure quality of the curved member (Bjorhovde, 2006).

Bjorhovde, R. (2006), "Cold Bending of Wide-Flange Shapes for Construction," *Engineering Journal*, AISC, Vol. 43, No. 4, pp. 271–286.

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Curving Mechanics

Description	α	R/D^b (F_y = 50 ksi)
97% of M_p for W-Shape bent the hard way	2.0	145
97% of M_p for W-Shape bent the easy way	3.5	83.1
Strain hardening (F_y = 50 ksi)	8.7	33.3
Conservative limit	12	24.2
ε = 3% (F_y = 50 ksi)	17	16.7
ε = 5% (F_y = 50 ksi)	29	10.0
[b]For members that are symmetric about the axis of curvature		

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General Information on Curved Members

Design for Bending

Fracture During the Bending Operation

Fracture

Risk Increased By:

- High α
- Low ductility

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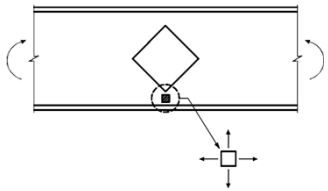
Fracture

Ductility is Decreased By:

- Holes
- Cuts
- Copes
- Welded fittings



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Fracture

Tension Flange Bolt Holes

- Holes formed before bending
  - Beam line = economical
  - Acceptable at large-radius bends

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Fracture

Tension Flange Bolt Holes

- Holes formed after bending
  - Manual fabrication = expensive
  - Necessary at small-radius bends

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Fracture

Tension Flange Bolt Holes

- Two limit states
  - Fracture
  - Excessive hole elongation

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Fracture

Tension Flange Bolt Holes

- Suggested limit if holes are formed before bending: $F_u A_{fn} \geq 1.1 F_y A_{fg}$

A_{fg} = gross area of the tension flange

A_{fn} = net area of the tension flange

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General Information on Curved Members

Design for Bending

Distortion from the Bending Operation

Distortion

- A deviation from the original cross-sectional shape
- Occurs in every bent member to some degree
- A single half-wave or a series of wrinkles along the entire bend length
- AKA waving or wrinkling

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Distortion

Causes

- Flexural compression
  - Flange local buckling
  - Web local buckling
- Shear
  - Web shear buckling

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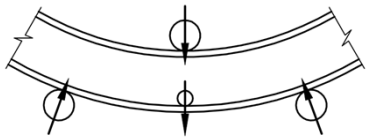
Distortion

Causes

- Contact forces from the bending machine
  - Web crippling
  (continued)



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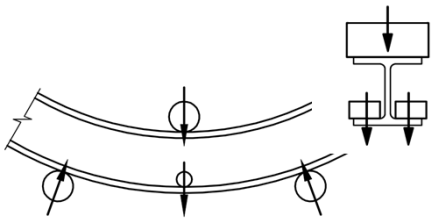
Distortion

- Flange bending



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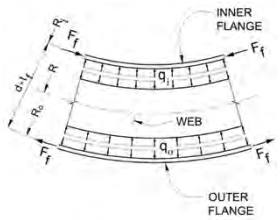
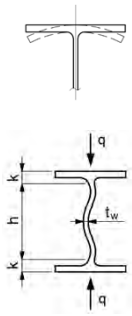
Distortion

Causes

- Radial forces
  - Flange bending
  - Web buckling





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Distortion

Affected By:

- Bending radius
- Cross-sectional shape of the member
- Cross-sectional dimensions of the member
- Bending axis

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Distortion

Affected By:

- Bending method/techniques
- Level of initial geometric imperfections

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Distortion

Affected By:

- Cross-sectional support (special rolls)

Photograph courtesy of the AISC Bender/Roller Committee

102

Distortion

Affected By:

- Cross-sectional support (supplementary rolls)

Photograph courtesy of the AISC Bender/Roller Committee

103

Distortion

Affected By:

- Cross-sectional support (mandrel or other support)

Photograph courtesy of Larry Kloiber

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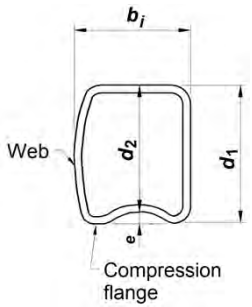
Distortion

Square and Rectangular HSS

- Concave compression flange
- Outward bowing of web



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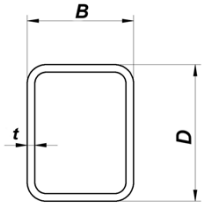
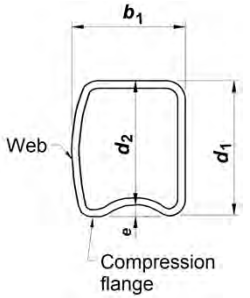
Distortion

Square and Rectangular HSS



$$\rho_w = \frac{b_1 - B}{B}$$

$$\rho_f = \frac{e}{D}$$



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Distortion

Square and Rectangular HSS

Photograph courtesy of Larry Kloiber

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Distortion

Square and Rectangular HSS

Pyramid roll bending with no mandrel

(REF: CIDECT Report 11C-88/14E)

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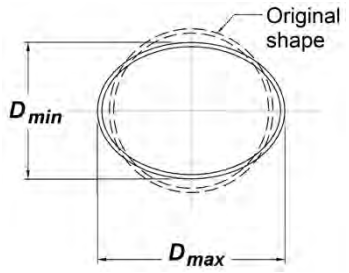
Distortion

Round HSS

- Ovalization

$$\rho = \frac{D_{max} - D_{min}}{D_n}$$



D_n = nominal outside diameter

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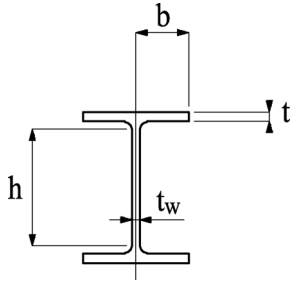
Distortion

Local buckling resistance ≈ distortion resistance

- Lower b/t = less distortion



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Distortion

- Round elements perform better than rectangular elements

111

Distortion

- Stiffened elements perform better than unstiffened elements

112

Distortion

- The bending operation often requires a lower b/t than required for strength under service loads

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Distortion

- Compact elements per AISC *Specification* Section B4.1: $\lambda \le \lambda_p$
  - Medium-radius bends
  - Sufficient for a minimum of $\alpha = 4$
  - Usually sufficient for $\alpha = 9$
  - α can be much higher for restrained elements

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Distortion

- Highly-ductile elements per AISC *Seismic Provisions* Section D1.1b: $\lambda \le \lambda_{hd}$
  - Small-radius bends
  - Bender/roller may suggest more stringent width-to-thickness ratios

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There's always a solution in steel.

Question time

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.

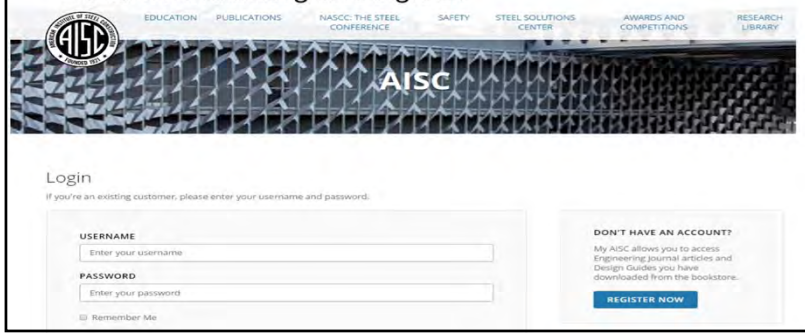
CEUs/PDHS – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

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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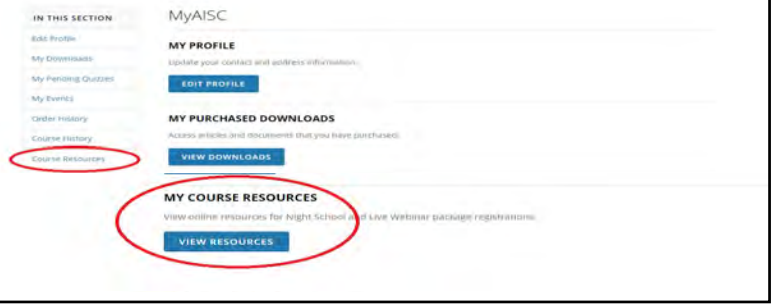

Night School Resources for 8-session package Registrants

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	Video 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.

There's always a solution in steel.

Thank You

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