





The logo features a white crescent moon to the left of the text "AISC Night School". "AISC" is in a bold, orange, sans-serif font, while "Night School" is in a larger, orange, serif font.

Thank you for joining our live webinar today.  
We will begin shortly. Please standby.

Thank you.

Need Help?  
Call ReadyTalk Support: 800.843.9166


A cartoon owl with brown feathers and a white belly, wearing a white graduation cap with a blue tassel. It is standing on a dark silhouette of a branch.


The logo features a white crescent moon to the left of the text "AISC Night School". "AISC" is in a bold, orange, sans-serif font, while "Night School" is in a larger, orange, serif font.

Today's audio will be broadcast through the internet.

Alternatively, to hear the audio through the phone, dial  
800-289-0459. Passcode: 316042

---



The AISC logo is a circular seal with "AMERICAN INSTITUTE OF STEEL CONSTRUCTION" around the top edge and "FOUNDED 1921" around the bottom edge. In the center, the letters "AISC" are prominently displayed.

2



Today's live webinar will begin shortly.  
Please standby.

As a reminder, all lines have been muted. Please type any questions or comments through the Chat feature on the left portion of your screen.

Today's audio will be broadcast through the internet.  
Alternatively, to hear the audio through the phone, dial  
800-289-0459. Passcode: 316042



3



*AISC is a Registered Provider with The American Institute of Architects Continuing Education Systems (AIA/CES). Credit(s) earned on completion of this program will be reported to AIA/CES for AIA members. Certificates of Completion for both AIA members and non-AIA members are available upon request.*

*This program is registered with AIA/CES for continuing professional education. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the AIA of any material of construction or any method or manner of handling, using, distributing, or dealing in any material or product.*

*Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.*



4





## Copyright Materials

This presentation is protected by US and International Copyright laws. Reproduction, distribution, display and use of the presentation without written permission of AISC is prohibited.

© The American Institute of Steel Construction 2018



5



## 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.



6





## 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.



7

# 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



There's always a solution in steel.



## Course Outline

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



9

## Course Outline

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



10



There's always a solution in steel.

# General Information on Curved Members

## Introduction



## Introduction

### Vertically-Curved Members



Photographs courtesy of the AISC Bender/Roller Committee



# Introduction

## Vertically-Curved Members



Photograph courtesy of the AISC Bender/Roller Committee



# Introduction

## Horizontally-Curved Members



Photograph courtesy of the AISC Bender/Roller Committee



# Introduction

## Horizontally-Curved Members



Photograph courtesy of the AISC Bender/Roller Committee



# Introduction

## Horizontally-Curved Members



Photograph courtesy of the AISC Bender/Roller Committee



There's always a solution in steel.

# General Information on Curved Members

## Session Description



## Session Description

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



Steel Design Guide 33  
Curved  
Member  
Design



## Session Description

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



19

## General Information on Curved Members

### Overview of Design Guide 33

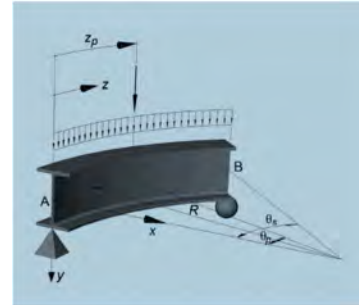
There's always a solution in steel.



## Design Guide Overview

### Purpose of Design Guide 33

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



Steel Design Guide 33  
Curved  
Member  
Design



## Design Guide Overview

- Practical information
  - Fabrication
  - Detailing



Steel Design Guide 33  
Curved  
Member  
Design



# 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



23

# 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



24

## Design Guide Overview

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



25

## Design Guide Overview

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



26



There's always a solution in steel.

# 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



28



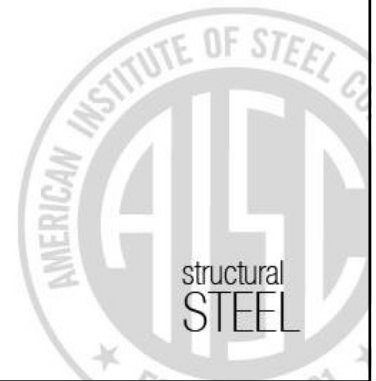
There's always a solution in steel.

# 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





# 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

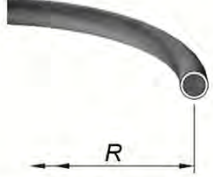





# Curve Geometries

Section	Orientation	
I-Shape	 <p>Hard Way</p>	 <p>Easy Way</p>


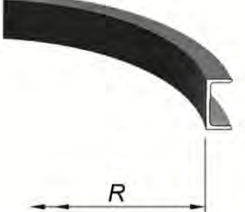
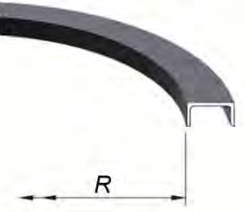


# Curve Geometries

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






# Curve Geometries

Section	Orientation		
Channel			
	Flanges In	Flanges Out	Hard Way



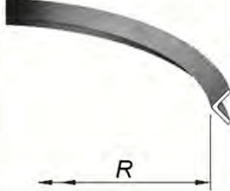



# Curve Geometries

Section	Orientation		
Tee			
	Stem In	Stem Out	Stem Up



# Curve Geometries

Section	Orientation			
Angle				
	Leg In	Leg Out	Heel In	Heel Out



There's always a solution in steel.

# 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



38



## Curve Geometries

### Off-Axis Bends



Photographs courtesy of the AISC Bender/Roller Committee

39

## Curve Geometries

### Off-Axis Bends

- Canopies
- Roofs



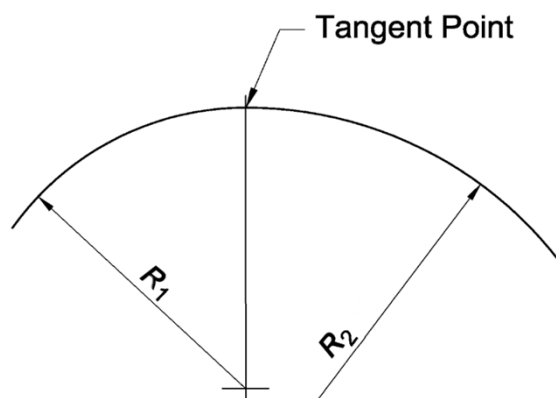
Photograph courtesy of the AISC Bender/Roller Committee

40

## Curve Geometries

### Compound Bends

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

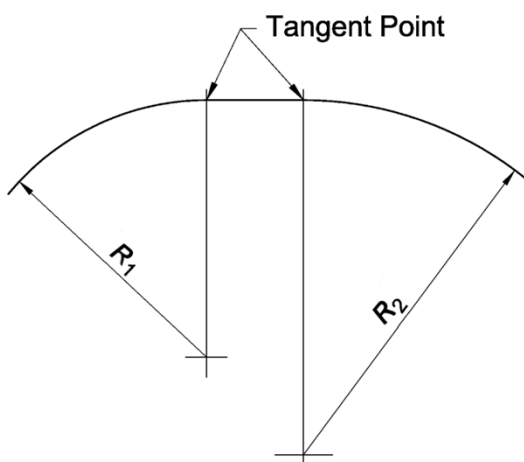


41

## Curve Geometries

### Compound Bends

- Can be fabricated with a straight segment between tangent points

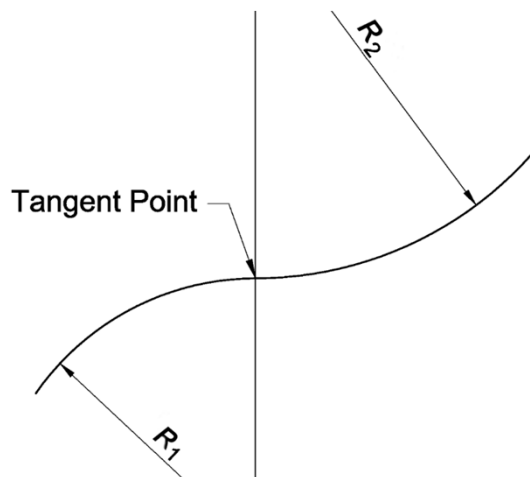


42

## Curve Geometries

### Reverse-Compound Bends

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



43

## Curve Geometries

### Reverse-Compound Bends



Photographs courtesy of the AISC Bender/Roller Committee



44

# Curve Geometries

## Compound and Reverse-Compound Bends

- Canopies
- Roofs
- Architectural features



45

# Curve Geometries

## Reverse-Compound Bends



Photographs courtesy of the AISC Bender/Roller Committee



46



## Curve Geometries

### Multi-Axis bends

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



47

## Curve Geometries

### Multi-Axis bends



Photographs courtesy of the AISC Bender/Roller Committee



48

## Curve Geometries

### Variable-Radius Bends

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



49

## Curve Geometries

### Variable-Radius Bends: Parabolic

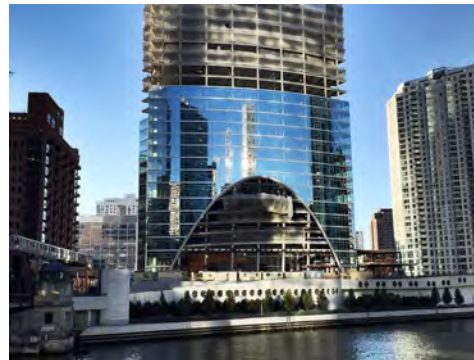
- Parabolic arches are efficient for resisting uniform gravity loads



50

## Curve Geometries

### Variable-Radius Bends: Parabolic



Photographs courtesy of the AISC Bender/Roller Committee



51

## 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



53

## Curve Geometries

### Spiral Bends

- Helical curve
- AKA sloped rolling or pitched rolling



Photograph courtesy of the AISC Bender/Roller Committee



54

## Curve Geometries

### Spiral Bends

- Spiral stairs
- Art sculptures



Photographs courtesy of the AISC Bender/Roller Committee



55

## General Information on Curved Members

### Curving Steel Members

### Bending Processes

There's always a solution in steel.



## 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



57

## Bending Processes

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



Photograph courtesy of the AISC Bender/Roller Committee

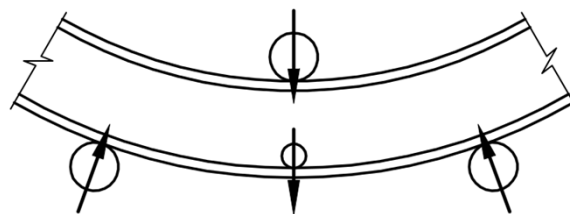


58

## Bending Processes

### Pyramid Roll Bending

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



59

## Bending Processes

### Pyramid Roll Bending



Photograph courtesy of the AISC Bender/Roller Committee

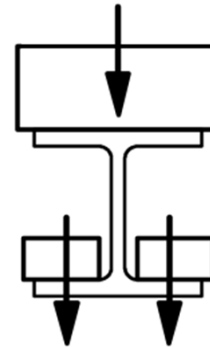


60

## Bending Processes

### Pyramid Roll Bending

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



61

## Bending Processes

### Pyramid Roll Bending

- Contoured rolls
  - Provide support during the bending operation



Photograph courtesy of the AISC Bender/Roller Committee



62

## Bending Processes

### Pyramid Roll Bending



Photograph courtesy of the AISC Bender/Roller Committee



63

## Bending Processes

### Pyramid Roll Bending

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



Photograph courtesy of the AISC Bender/Roller Committee



64

## Bending Processes

### Pyramid Roll Bending



Photograph courtesy of the AISC Bender/Roller Committee



65

## 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

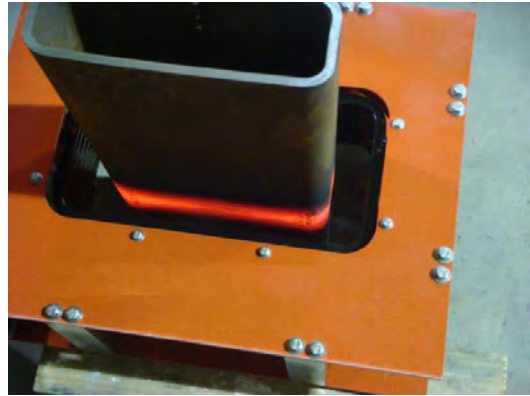


66

## 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

67

## Bending Processes

### Induction Bending

- After heating, the member is curved by force



Photograph courtesy of the AISC Bender/Roller Committee

68

## Bending Processes

### Induction Bending

- Equal thickness elements = uniform heating



Photograph courtesy of the AISC Bender/Roller Committee

69

## 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



71

## 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



72

There's always a solution in steel.

# General Information on Curved Members

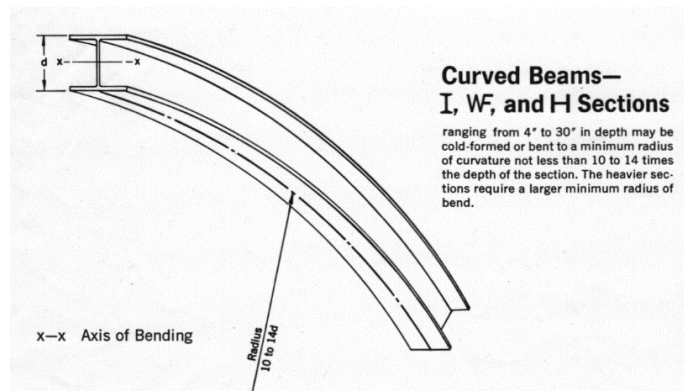
## Design for Bending



## Design for Bending

### What is the Minimum Cold-Bending Radius?

Rule of Thumb?



## 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)



75

## Design for Bending

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



76

## 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/](http://www.aisc.org/membership/bender-roller-committee/)



77

## Design for Bending

### Behavior During the Bending Operation

- Curving mechanics
- Fracture
- Cross-sectional distortion



78

There's always a solution in steel.

# General Information on Curved Members

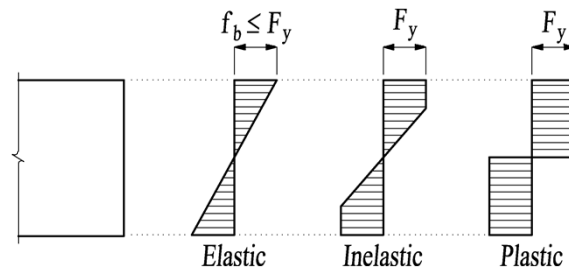
## Design for Bending

## Curving Mechanics



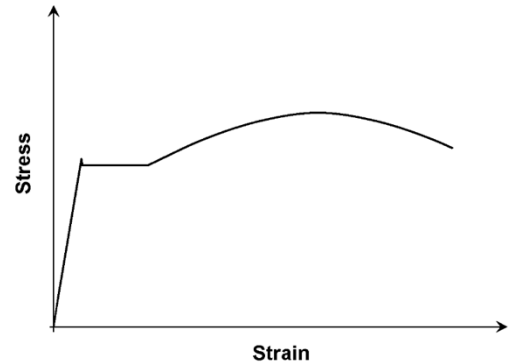
# Curving Mechanics

- Inelastic strain → permanent curvature



## Curving Mechanics

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

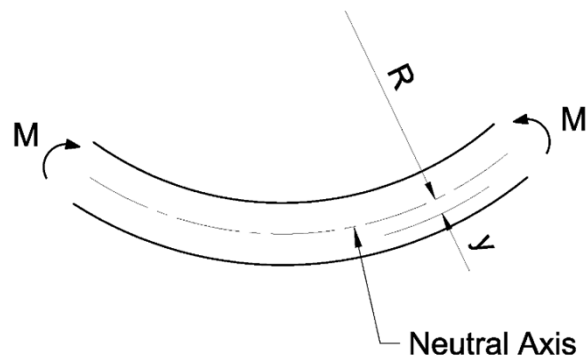


81

## Curving Mechanics

Maximum strain:

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



$R$  = centroidal radius of curvature

$y_o$  = distance from neutral axis to the outermost fiber

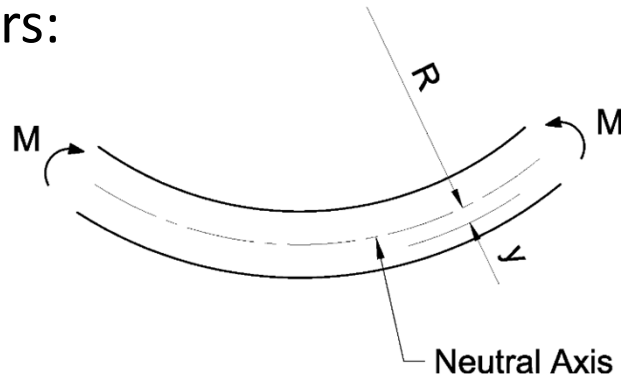


82

## Curving Mechanics

For symmetric members:

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



$D$  = member depth in the plane of curvature



83

## Curving Mechanics

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

$$\epsilon_{max} = \alpha \epsilon_y$$

$\alpha$  = strain ratio

$\epsilon_y$  = yield strain, =  $F_y/E$



84

## 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.

85

## Curving Mechanics

Description	$\alpha$	$R/D^b$ ( $F_y = 50$ 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
$\epsilon = 3\%$ ( $F_y = 50$ ksi)	17	16.7
$\epsilon = 5\%$ ( $F_y = 50$ ksi)	29	10.0
<sup>b</sup> For members that are symmetric about the axis of curvature		



There's always a solution in steel.

# General Information on Curved Members

Design for Bending

Fracture During the Bending Operation



## Fracture

### Risk Increased By:

- High  $\alpha$
- Low ductility



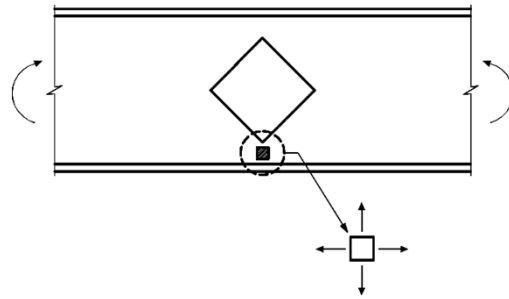
88



## Fracture

### Ductility is Decreased By:

- Holes
- Cuts
- Copes
- Welded fittings



89

## Fracture

### Tension Flange Bolt Holes

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



90

# Fracture

## Tension Flange Bolt Holes

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



91

# Fracture

## Tension Flange Bolt Holes

- Two limit states
  - Fracture
  - Excessive hole elongation



92

# 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



93

## General Information on Curved Members

Design for Bending

Distortion from the Bending Operation



There's always a solution in steel.



## 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



95

## Distortion

### Causes

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

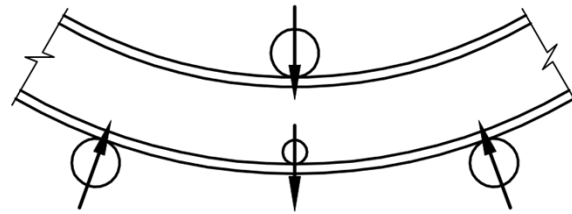


96

# Distortion

## Causes

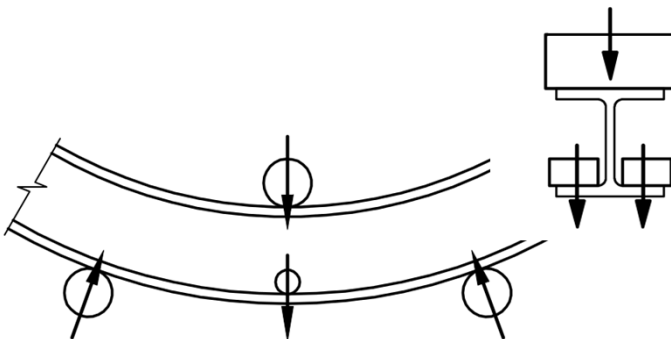
- Contact forces from the bending machine
  - Web crippling  
(continued)



97

# Distortion

- Flange bending

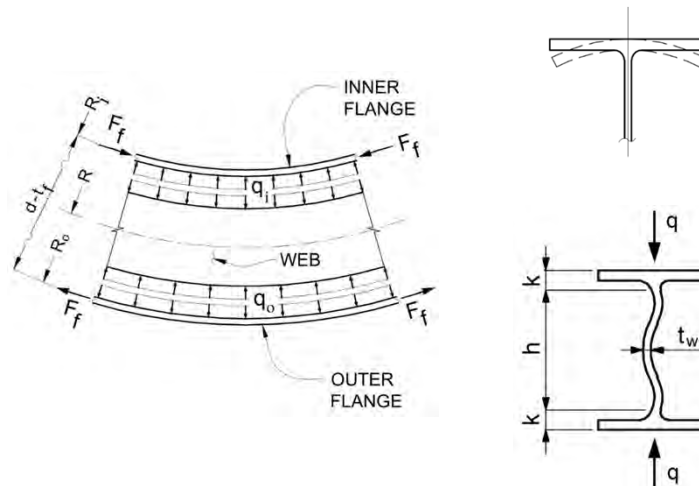


98

## Distortion

### Causes

- Radial forces
  - Flange bending
  - Web buckling



## Distortion

### Affected By:

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



## Distortion

### Affected By:

- Bending method/techniques
- Level of initial geometric imperfections



101

## 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)



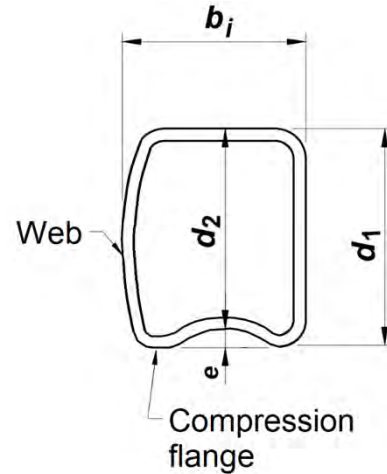
Photograph courtesy of Larry Kloiber

104

# Distortion

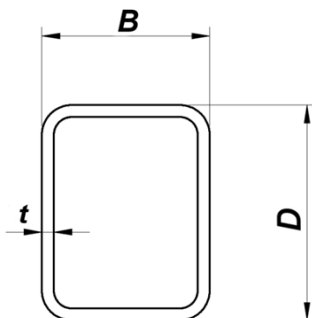
## Square and Rectangular HSS

- Concave compression flange
- Outward bowing of web



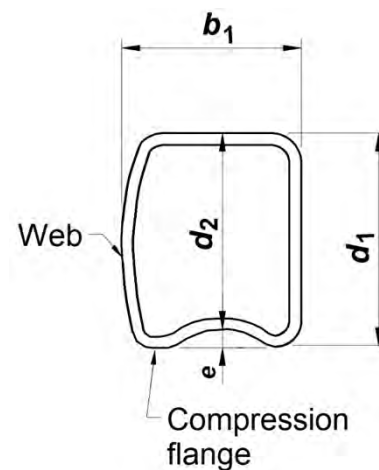
# Distortion

## Square and Rectangular HSS



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

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



# Distortion

## Square and Rectangular HSS



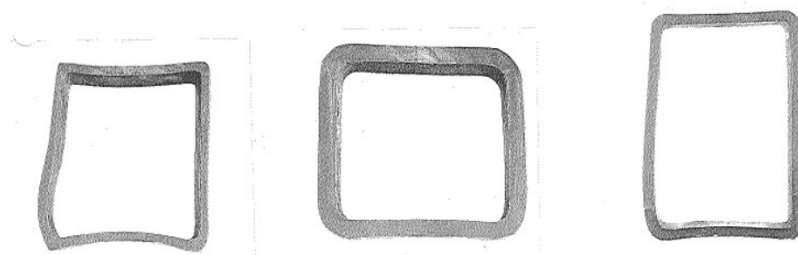
Photograph courtesy of Larry Kloiber



107

# Distortion

## Square and Rectangular HSS



Pyramid roll bending with no mandrel

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



108

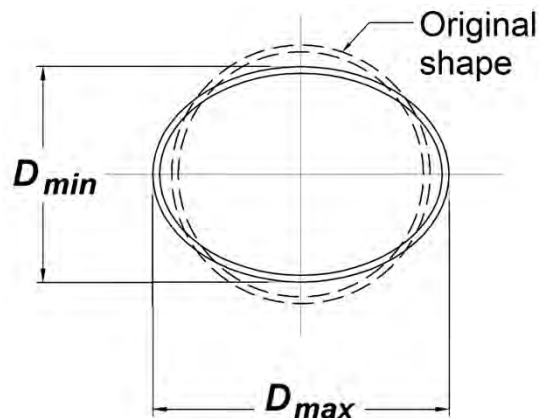
## Distortion

### Round HSS

- Ovalization

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

$D_n$  = nominal outside diameter

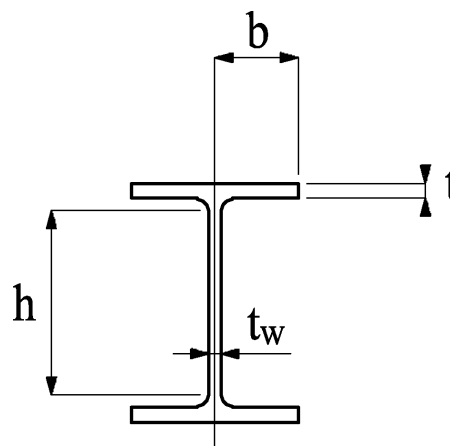


109

## Distortion

**Local buckling resistance  $\approx$   
distortion resistance**

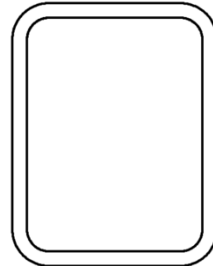
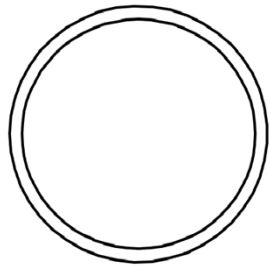
- Lower  $b/t$  = less distortion



110

## Distortion

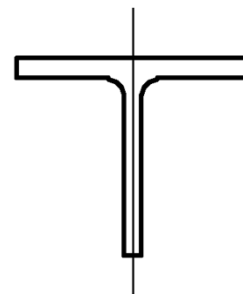
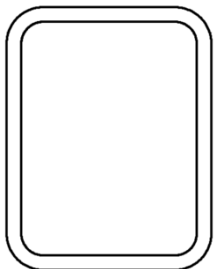
- Round elements perform better than rectangular elements



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



113

## Distortion

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



114

## Distortion

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



115

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](mailto: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](http://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](http://www.aisc.org) and sign in.



### Login

If you're an existing customer, please enter your username and password.

#### USERNAME

Enter your username

#### PASSWORD

Enter your password

Remember Me

#### DON'T HAVE AN ACCOUNT?

My AISC allows you to access Engineering Journal articles and Design Guides you have downloaded from the bookstore.

[REGISTER NOW](#)

## Night School Resources for 8-session package Registrants

Go to [www.aisc.org](http://www.aisc.org) and sign in.

**IN THIS SECTION**

- Edit Profile
- My Downloads
- My Pending Quizzes
- My Events
- Order History
- Course History
- Course Resources

**MyAISC**

**MY PROFILE**  
Update your contact and address information.  
[EDIT PROFILE](#)

**MY PURCHASED DOWNLOADS**  
Access articles and documents that you have purchased.  
[VIEW DOWNLOADS](#)

**MY COURSE RESOURCES**  
View online resources for Night School and Live Webinar package registrations.  
[VIEW RESOURCES](#)

FOUNDED 1921

## 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	<a href="#">Handouts</a>	<a href="#">View</a>	Pass Score: 80	Pending
NS13 - Economic Considerations	2/6/2017 7:00:00 PM	<a href="#">Handouts</a>	Passcode: NS13DSN	Available 02/08/2017 5pm EST	Pending
NS13 - Lateral Load Systems and Details	2/13/2017 7:00:00 PM	<a href="#">Handouts</a>	Available 02/15/2017 5pm EST	Available 02/15/2017 5pm EST	Pending
NS13 - Preliminary Design Procedures	2/27/2017 7:00:00 PM	<a href="#">Handouts</a>	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	<a href="#">Handouts</a>	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	<a href="#">Handouts</a>	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	<a href="#">Handouts</a>	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	<a href="#">Handouts</a>	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](http://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.



# Thank You

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

There's always a solution in steel.

