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Session Description

Session 2: Design of Vertically Curved Members

June 25, 2018

This session first addresses general design considerations including architecturally exposed structural steel, tolerances and contract documents. The presentation then addresses the treatment vertically-curved members. Topics include axial strength, flexural strength, combined axial and flexural loads, local strength and connections.

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Learning Objectives

- Identify the 5 categories of Architecturally Exposed Structural Steel (AESS) stated in the 2016 AISC Code of Standard Practice.
- Identify the tolerances for curved steel members stated in the 2016 AISC Code of Standard Practice.
- Describe the design considerations for axial strength of vertically-curved members in terms of in-plane and out-of-plane strength.
- Describe the design considerations for flexural strength of vertically-curved members.

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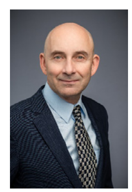
Design of Curved Members

Session 2: Design of Vertically Curved Members

June 25, 2018



Presented by
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structural STEEL

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General Information on Curved Members

Session Description

structural STEEL

Session Description

- General Design Considerations
  - Architecturally exposed members
  - Tolerances
  - Contract documents

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Design of Vertically-Curved Members

Session Description

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Session Description

- Vertically-curved members
  - Axial strength
  - Flexural strength
  - Combined loads

  (continued)

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Session Description

– Structural analysis
– Local strength
– Connections

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General Information on Curved Members

General Design Considerations

Architecturally Exposed (AESS) Members

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AESS Members

2016 AISC *Code of Standard Practice* (COSP)

- AISC Code of Standard Practice Section 10.1.1 defines five categories of AESS:
  – AESS 1: Basic elements
  – AESS 2: Feature elements viewed at > 20 ft

(continued)

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AESS Members

– AESS 3: Feature elements viewed at < 20 ft
– AESS 4: Showcase elements
– AESS C: Custom elements

The 2016 COSP is available for free download at: https://www.aisc.org/globalassets/aisc/publications/standards/code-of-standard-practice-june-15-2016.pdf

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AESS Members

- For further information on AESS, see the Nov. 2017 issue of *Modern Steel Construction*: https://www.aisc.org/globalassets/aisc/aess/all_about_aess_reprint.pdf
- Generally, the bending cost increases with increasing AESS category

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AESS Members

- Generally, the bending cost increases with increasing AESS category

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General Information on Curved Members

General Design Considerations

Tolerances

structural STEEL

Tolerances

2016 AISC *Code of Standard Practice* (COSP)

- Chord length tolerance
- Curvature tolerance
- Similar to those for straight members
- Tolerances for AESS are the same as non-AESS

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Tolerances

2016 AISC *Code of Standard Practice* (COSP)

- No cross-sectional distortion tolerance
- Tolerances that are not addressed in the COSP should be mutually agreed upon by the contractor and the owner

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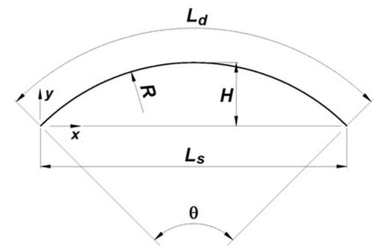
Tolerances

Chord Length Tolerance

- Tolerance on L_s
- COSP Section 6.4.2(b)



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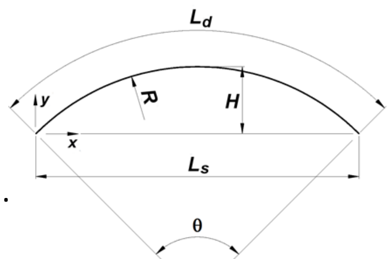
Tolerances

Chord Length Tolerance

- Members that frame to other structural steel elements:
  - For $L_s \leq 30$ ft: ± 1/16 in.
  - For $L_s > 30$ ft: ± 1/8 in.



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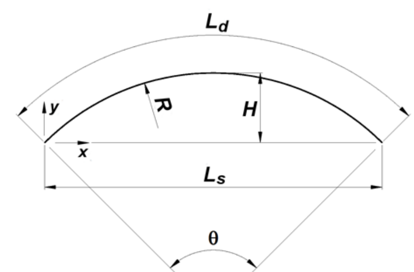
Tolerances

Curvature Tolerance

- Tolerance on H
- Non-AESS: COSP Section 6.4.2(b)
- AESS: COSP Section 10.4.4



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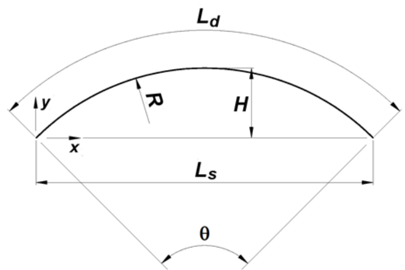
Tolerances

Curvature Tolerance

- Dependent on L_d



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Tolerances

Curvature Tolerance

- Equal to the camber and sweep tolerances for straight members in the applicable ASTM standard
- Sharp kinks or sharp bends are cause for rejection

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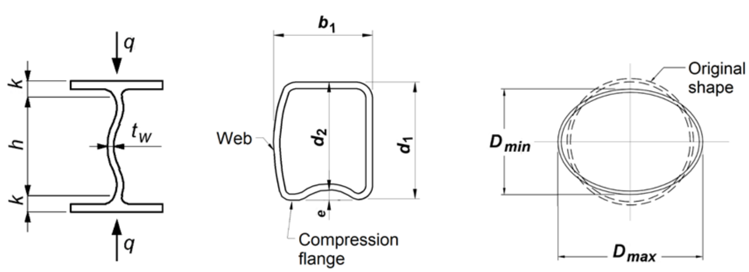
Tolerances

Distortion Tolerance



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Tolerances

Distortion Tolerance

- Should be based on:
  - The potential effect on structural performance
  - Any aesthetic requirements for AESS members
- Should be established with input from the bender/roller

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Tolerances

Distortion Tolerance: Structural Effects

- Reasonable cross-sectional distortions can be tolerated without a reduction in strength
- See Design Guide Section 5.5 for further information

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Tolerances

Distortion Tolerance: AESS

- Generally, AESS requirements are more stringent than strength requirements
- Members with large- and medium-radius bends are likely to be acceptable for AESS 1 and 2 without further consideration

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Tolerances

Distortion Tolerance

- Cross-sectional tolerances specified in ASTM A6, ASTM A53 and ASTM A500 are mill tolerances
- Initial geometric imperfections are amplified during the bending process

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Tolerances

Distortion Tolerance: Rectangular HSS

- The permissible cross-sectional variation for ASTM A500 rectangular HSS members larger than 5½ in. is 1% of the largest outside flat dimension

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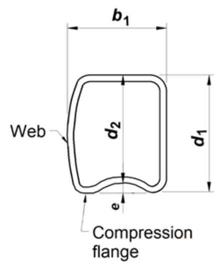
Tolerances

Distortion Tolerance: Rectangular HSS

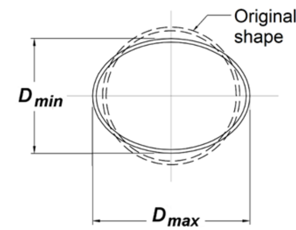
- Post-bending wall flatness tolerances (ρ_w and ρ_f) between 1% and 2% are common



Tolerances

Distortion Tolerance: Round HSS

- A post-bending ovality tolerance (ρ) of 5% is common



Tolerances

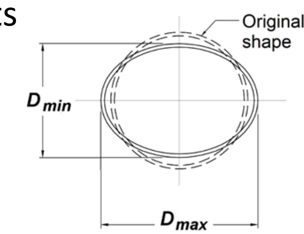
Distortion Tolerance: Round HSS

- Practical considerations may dictate more stringent tolerances

Tolerances

Distortion Tolerance: Round HSS

- Example: when two segments are connected with circumferential butt welds, proper wall alignment is essential



Tolerances

Distortion Tolerance: Round HSS

- For AESS, a 5% tolerance is likely to produce imperceptible ovalization distortions

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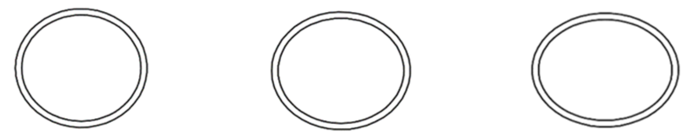
Tolerances

Distortion Tolerance: Round HSS



ρ = 5% ρ = 8% ρ = 12%

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General Information on Curved Members

General Design Considerations

Contract Documents

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Contract Documents

Member Sizes

- Often controlled by bending requirements rather than performance under service loads
- Member sizes shown on the design drawings should consider bending requirements

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Contract Documents

Architecturally Exposed (AESS) Members

- All AESS members must be identified in the contract documents
- AESS members must be assigned a category defined in AISC *Code of Standard Practice* Section 10.1.1

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Contract Documents

Distortion Tolerances

- Distortion tolerances should be specified in the contract documents

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Design of Vertically-Curved Members

Axial Strength

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Axial Strength

Arches

- Structurally efficient
- Loads carried primarily by compression

Photograph courtesy of the AISC Bender/Roller Committee

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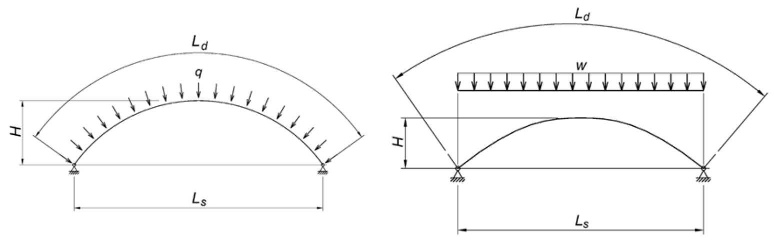
Axial Strength



Circular Parabolic

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Design of Vertically-Curved Members

Axial Strength

In-Plane Strength

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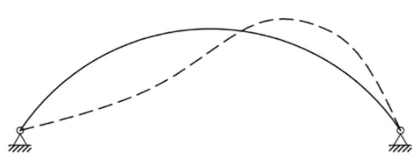
In-Plane Strength

- Curved Members ≠ Straight Members
- Buckled Shape



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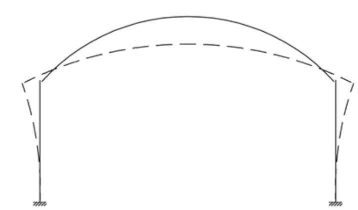
In-Plane Strength

- Support spreading
  - Increases deflection
  - Can lead to collapse



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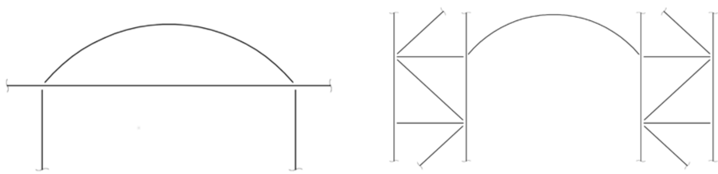
In-Plane Strength

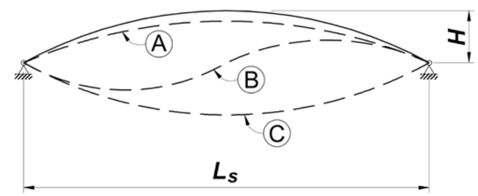
- Horizontal restraints



Tension Tie   Vertical Truss

In-Plane Strength

Snap-Through Buckling



A: Deflected shape
B: Antisymmetric mode
C: Symmetric mode

In-Plane Strength

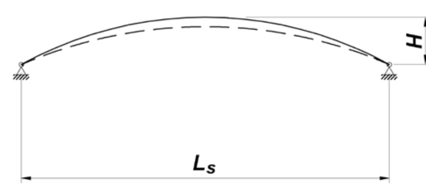
Snap-Through Buckling

- Sensitive to second-order effects
- Sensitive to support spreading
- Difficult to predict

In-Plane Strength

Snap-Through Buckling

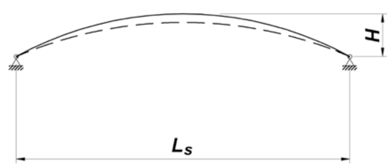
- Generally, not critical for arches with:
  - Rigid supports
  - $H/L_s > 0.2$



In-Plane Strength

Snap-Through Buckling

- When $H/L_s \leq 0.2$, L_s/r_i must exceed $(L_s/r_i)_{crit}$



r_i = in-plane radius of gyration

In-Plane Strength

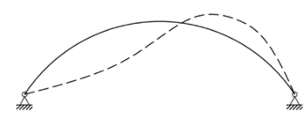
$(L_s/r_i)_{crit}$				
		H/L_s		
		0.10	0.15	0.20
End Conditions	Pinned	59	36	35
	Fixed	150	71	68

In-Plane Strength

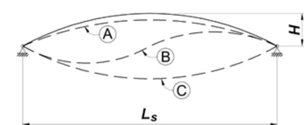
- Design as a straight column
- Flexural buckling provisions in AISC *Specification* Section E3

In-Plane Strength

- Applicable only for flexural buckling

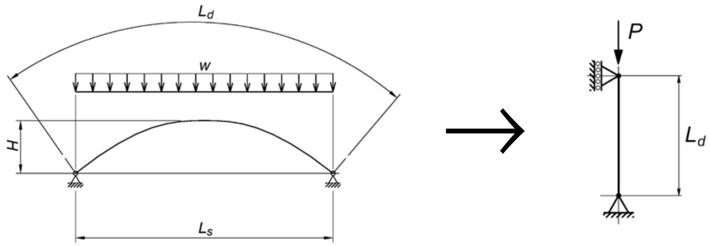


- Not valid for snap-through buckling



In-Plane Strength

- Unbraced length, $L \rightarrow L_d$



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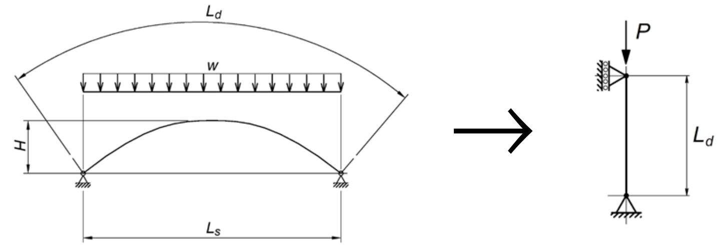
In-Plane Strength

- P = maximum axial load in the arch



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In-Plane Strength

In-plane effective length factor, K_i			
Arch Form	**End Conditions**	**H/L_s**	**K_i**
Circular	Pinned	$0.1 \leq H/L_s \leq 0.3$	0.55
		$0.3 \leq H/L_s \leq 0.5$	0.60
	Fixed	All	0.40
Parabolic	Pinned	All	0.50
	Fixed	$0.1 \leq H/L_s < 0.3$	0.40
		$0.3 \leq H/L_s \leq 1.0$	0.35

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Design of Vertically-Curved Members

Axial Strength

Out-of-Plane Strength

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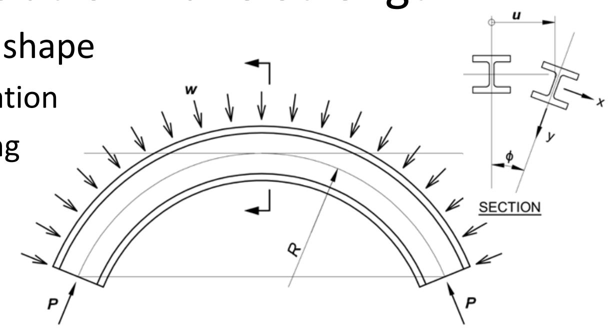
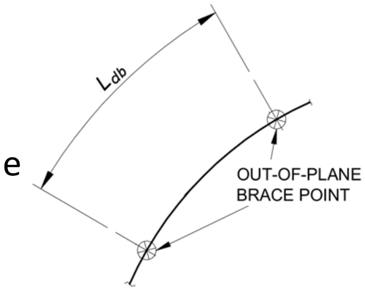
Out-of-Plane Strength

- Buckled shape
  - Translation
  - Twisting



Out-of-Plane Strength

- Most arches are braced against out-of-plane translation
- Each segment can buckle between brace points

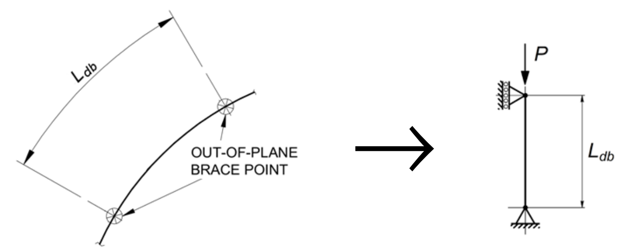


Out-of-Plane Strength

- Design as a straight column
- Flexural buckling provisions in AISC *Specification* Section E3

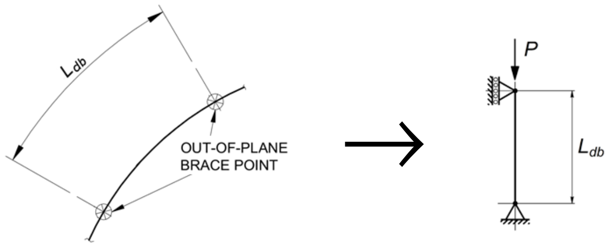
Out-of-Plane Strength

- Unbraced length, $L \rightarrow L_{db}$



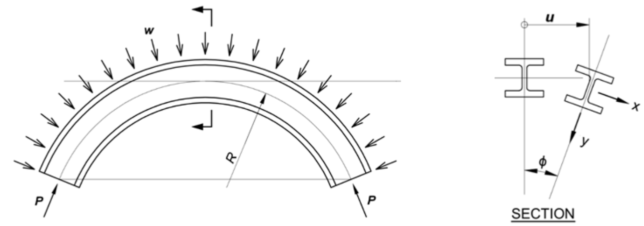
Out-of-Plane Strength

- P = maximum load in the segment



Out-of-Plane Strength

- Flexural-torsional buckling → flexural buckling

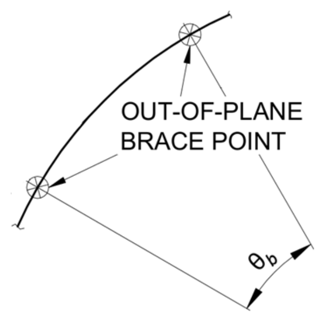


Out-of-Plane Strength

- Effective length factor, K_o: Circular doubly-symmetric segments

$$K_o = \frac{\sqrt{1+\frac{1}{C_o}\left(\frac{\theta_b}{\pi}\right)^2}}{1-\left(\frac{\theta_b}{\pi}\right)^2}$$

Out-of-Plane Strength



θ_b = angle between braces, rad

Out-of-Plane Strength

$$C_o = \frac{1}{I_o}\left[\frac{GJ}{E} + C_w\left(\frac{\pi}{L_{db}}\right)^2\right]$$

C_w = warping constant

J = torsional constant

I_o = moment of inertia ⊥ to the axis of curvature

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Design of Vertically-Curved Members

Flexural Strength

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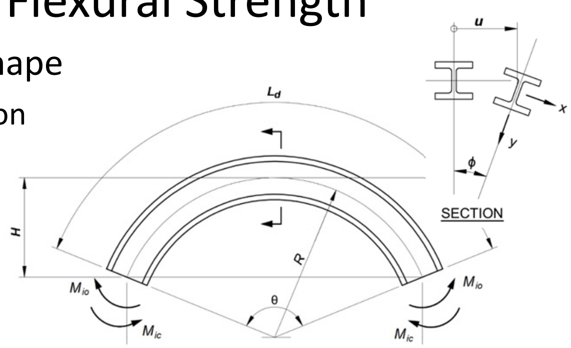
Flexural Strength

- Buckled shape
  - Translation
  - Twisting



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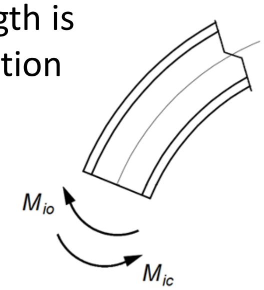
Flexural Strength

- Lateral-torsional buckling strength is dependent on the loading direction
  - Opening moment, M_{io}
  - Closing moment, M_{ic}



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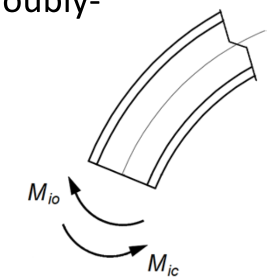
Flexural Strength

- Design as a straight beam
- Each unbraced segment is treated independently
- AISC *Specification* Chapter F
- Lateral-torsional buckling modification factor, $C_b \rightarrow C_{bi}$

Flexural Strength

Modification factor, C_{bi}: Circular doubly-symmetric segments

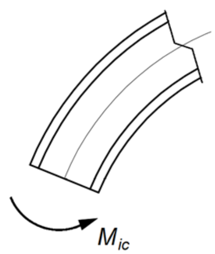
$$C_{bi} = C_{bs}\left(\sqrt{1+C_a^2-\frac{C_yC_z}{R^2M_{es}^2}} \pm C_a\right)$$



Flexural Strength

Closing moments → positive root

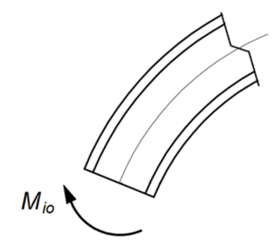
$$C_{bi} = C_{bs}\left(\sqrt{1+C_a^2-\frac{C_yC_z}{R^2M_{es}^2}} + C_a\right)$$



Flexural Strength

Opening moments → negative root

$$C_{bi} = C_{bs}\left(\sqrt{1+C_a^2-\frac{C_yC_z}{R^2M_{es}^2}} - C_a\right)$$



Flexural Strength

C_{bs} = C_b for an equivalent straight member (AISC *Specification* Equation F1-1)

$$C_b = \frac{12.5M_{max}}{2.5M_{max} + 3M_A + 4M_B + 3M_C}$$

M_{max} = absolute value of max. moment in the segment

$M_{A,B,C}$ = absolute value of moment at ¼, ½, ¾ points

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Flexural Strength

M_{es} = elastic lateral-torsional buckling moment of the equivalent straight member subjected to uniform moment with a length equal to L_{db}

$$M_{es} = \frac{\pi}{L_{db}}\sqrt{EI_o GJ + \left(\frac{\pi E}{L_{db}}\right)^2 I_o C_w}$$

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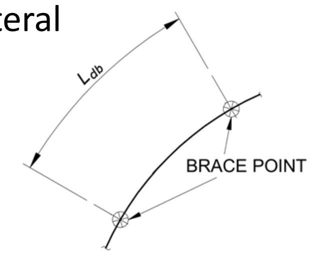
Flexural Strength

L_{db} = developed length between points that are either braced against lateral displacement of the compression flange or twisting of the cross section



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Flexural Strength

$$C_a = \frac{C_y + C_z}{2RM_{es}}$$

$$C_y = EI_o$$

$$C_z = GJ + \frac{\pi^2 EC_w}{L_{db}^2}$$

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Design of Vertically-Curved Members

Combined Loads

structural STEEL

Combined Loads

Axial-Flexure Interaction

- AISC *Specification* Section H1 for doubly-symmetric members

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Combined Loads

Axial-Flexure Interaction

- When $P_r/P_c \geq 0.2$

$$\frac{P_r}{P_c} + \frac{8}{9}\left(\frac{M_r}{M_c}\right) \leq 1.0$$

P_r M_r = required strengths P_c M_c = available strengths

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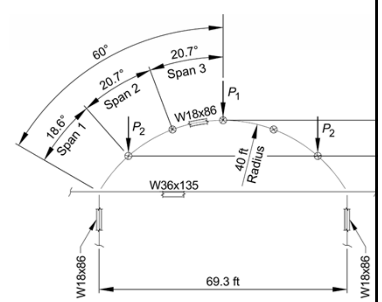
Combined Loads

Axial-Flexure Interaction

- Strength must be verified at each segment
- Use the minimum P_r/P_c ratio for each segment



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Combined Loads

Axial-Flexure Interaction

- In-plane buckling: P_r/P_c is constant for all segments
- Out-of-plane buckling: both P_r and P_c can vary between segments

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Combined Loads

Second-Order Effects

- Second-order analysis
- Amplified first-order moment: $M_{ri} = B_i M_{i1}$

M_{i1} = first-order moment about the axis of curvature

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Combined Loads

Second-Order Effects

$$B_i = \frac{1}{1 - \alpha \frac{P_r}{P_{ei}}}$$

α = 1.00 (LRFD)
= 1.60 (ASD)

P_r = maximum axial load in the arch

P_{ei} = elastic critical load for in-plane buckling

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Combined Loads

Second-Order Effects

$$P_{ei} = \frac{\pi^2 E I_i}{\left(K_i L_d\right)^2}$$

I_i = moment of inertia about the axis of curvature

K_i = effective length factor for in-plane buckling

L_d = developed length of the arch

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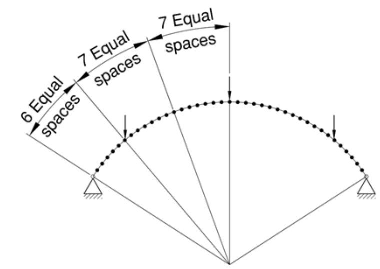
Design of Vertically-Curved Members

Structural Analysis

structural STEEL

Structural Analysis

- Curved Members
  - FE Models
  - 2-D beam elements
  - Segmented straight elements



90

Structural Analysis

- Accuracy increases with the number of elements
- ≈ 10 to 20 segments for semi-circular members
- For models with highly nonlinear behavior, a convergence study may be required

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Structural Analysis

- Where deflections are significant, a 2nd-order FE analysis is required
- 2nd-order effects are not captured with a traditional *P*-Δ FE analysis because arch deformations cause vertical, not horizontal, translation of the gravity loads

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Structural Analysis

- A 2nd-order FE analysis must properly consider in-plane deformations
  - member axial shortening
  - horizontal support flexibility

There's always a solution in steel.

Design of Vertically-Curved Members

Local Strength

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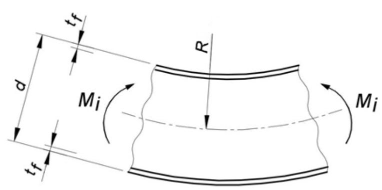
Local Strength

Cross-Sectional Distortion

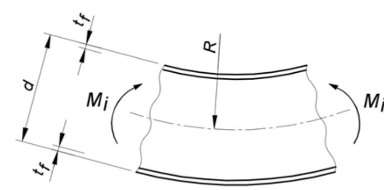
- Flexure in the plane of curvature



Local Strength

Cross-Sectional Distortion

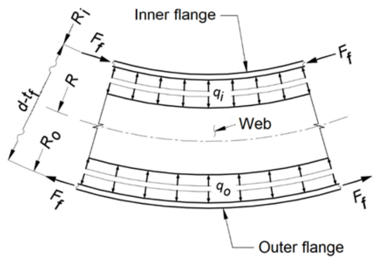
- Can reduce flexural strength and stiffness



Local Strength

Cross-Sectional Distortion

- Radial forces at web-to-flange interfaces



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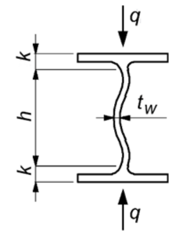
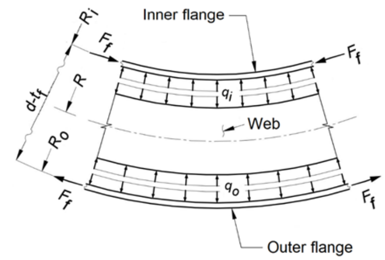
Local Strength

Web Bend-Buckling





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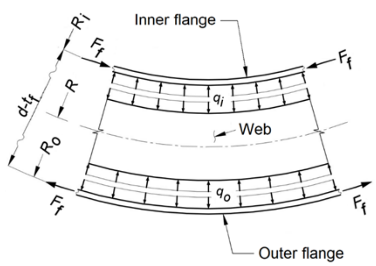
Local Strength

Element Local Bending



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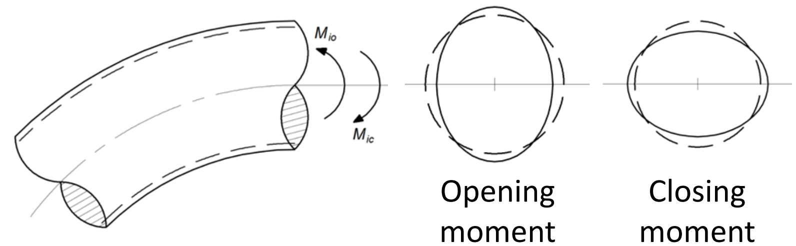
Local Strength

Ovalization



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Local Strength

Element Local Bending

Two design methods are available:

1. General method
   - Explicit calculation of the element local bending strength
   - Applicable to all flat elements

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Local Strength

Element Local Bending

2. Simplified method
   - Reduced flexural properties account for local bending
   - Applicable only to I-Shape and HSS Members

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There's always a solution in steel.

Design of Vertically-Curved Members

Local Strength

Simplified Method

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Simplified Method

Effective Flexural Properties (Flat Elements)

- Effective section modulus: $S_{ei} = k_f S_i$
- Effective plastic modulus: $Z_{ei} = k_f Z_i$
- Effective moment of inertia: $I_{ei} = k_f I_i$

I_i S_i Z_i = flexural properties of a straight member about the axis of curvature

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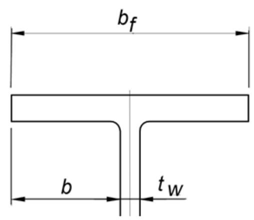
Simplified Method

Effective Flexural Properties

- I-shape members

$$k_f = \frac{9.20}{8.80 + \frac{b_f^2}{Rt_f}} \le 1.00$$

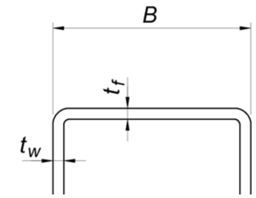


Simplified Method

Effective Flexural Properties

- Rectangular HSS members

$$k_f = \frac{8.24}{7.44 + \frac{(B - t_w)^2}{Rt_f}} \le 1.00$$



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Design of Vertically-Curved Members

Connections

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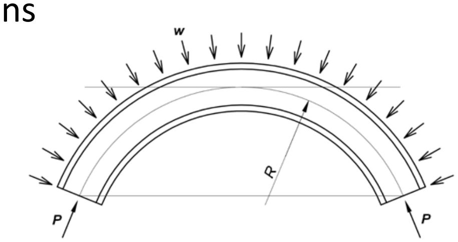
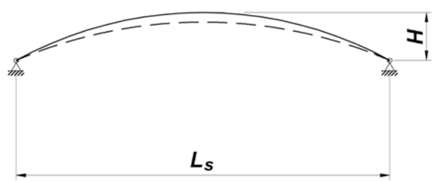
Connections

- Arch behavior produces large horizontal reactions



Connections

- Arch stability is dependent on horizontal connection rigidity



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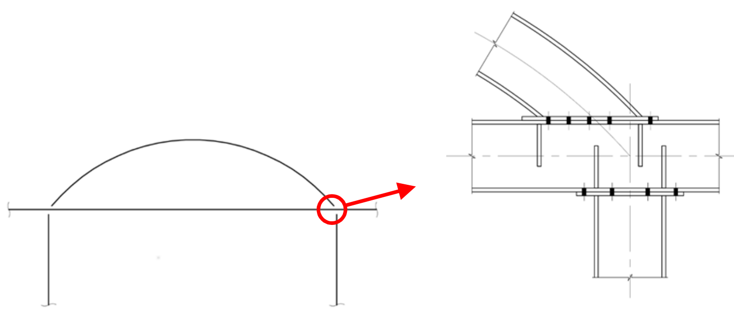
Connections

End Plate Connections

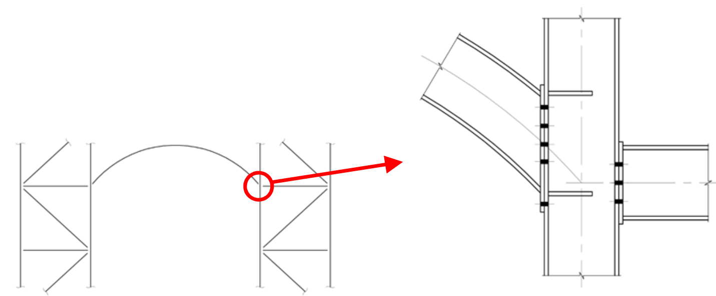
- Efficient for compression load transfer
- Member ends must be cut accurately to eliminate gaps

110

Connections



Connections



There's always a solution in steel.

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.

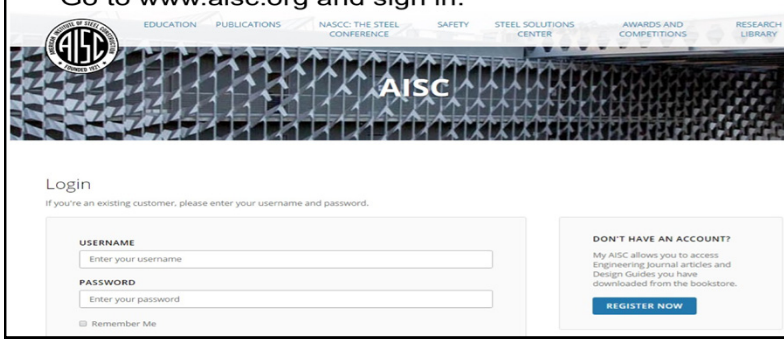
CEUs/PDHS – If you watch a recorded session you must take AND PASS the quiz for CEUs/PDHs.

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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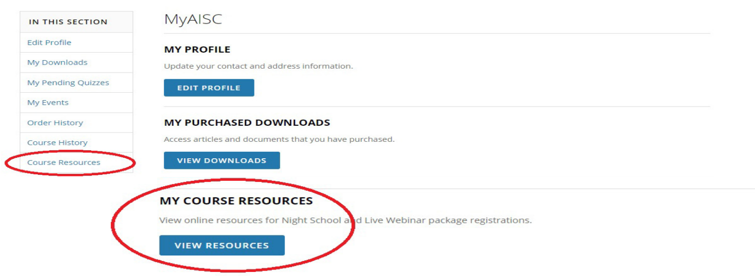
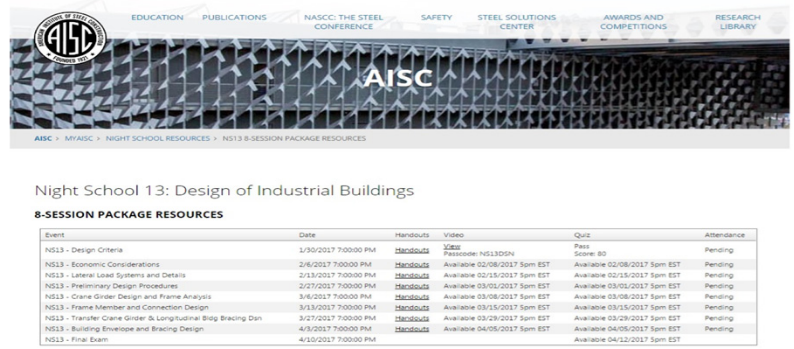


Night School Resources for 8-session package Registrants



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

Night School Resources for 8-session package Registrants

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

Night School Resources for 8-session package Registrants

- Webinar connection information:
  - Found in your registration confirmation/receipt.
  - Reminder email sent out Monday mornings.
- Link to handouts also found here.

There's always a solution in steel.

Thank You

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