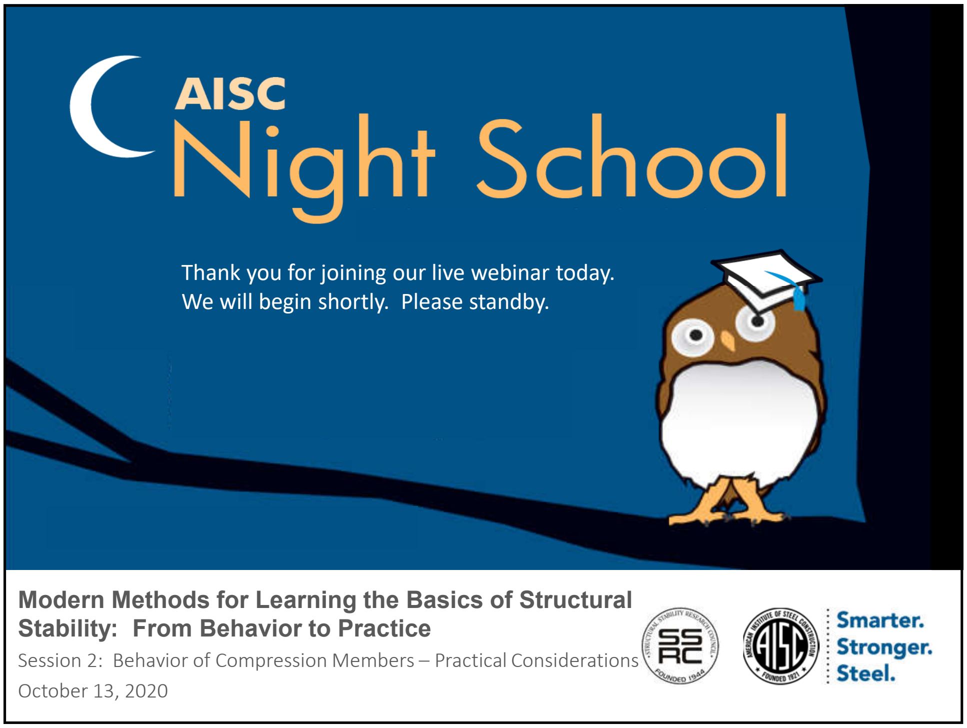

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Course Description

Behavior of Compression Members – Practical Considerations
October 13, 2020

In this session, the speakers will demonstrate and review/discuss the results of the first learning module on compression members and provide some advice for further exploration. They will then present a case study from practice involving the stability of compression members. They will close out the topic of compression members with some final lessons.

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Learning Objectives

- Explain how the behavior of a column is affected by slenderness.
- Describe how geometric and material nonlinearity impacts the buckling capacity of a column.
- Compare the column curve produced by structural analysis to what is codified in the AISC *Specification*.
- Identify why a shoring system may have a different capacity in the field than was found in the laboratory.

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Modern Methods for Learning The Basics of Structural Stability: From Behavior to Practice

Session 2: Behavior of Compression Members – Practical Considerations
October 13, 2020

Ronald D. Ziemian, PE, PhD
Professor
Bucknell University

Craig Quadrato, PE, PhD
Senior Associate
Wiss, Janney, Elstner Associates, Inc.

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Modern Methods for Learning The Basics of Structural Stability: From Behavior to Practice

Course Introduction

Compression Members – Sessions 1 & 2

Flexural Members – Session 3 & 4

Beam-Columns – Sessions 5 & 6

Systems – Session 7 & 8

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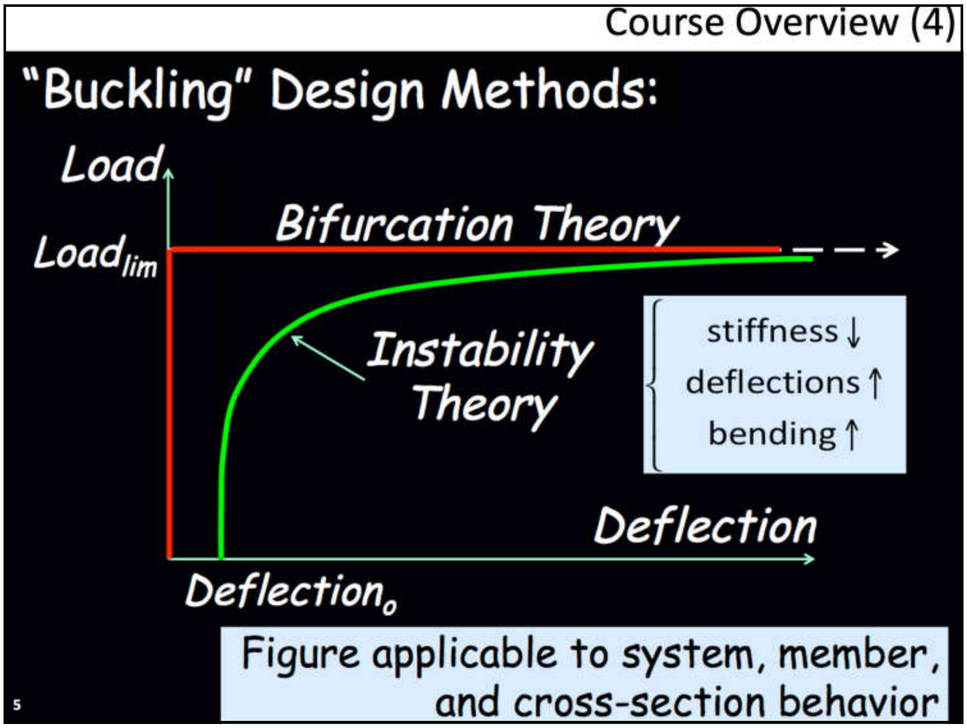
Course Overview (2)

Course Overview (3)

- Focus of the course is on fundamentals!
- Better understanding of behavior will result in improved design
- Key Definitions
  - **Stability:** Under load, component returns to current state after applying a small disturbance such as a deflection
  - **Bifurcation (critical load):** Theoretical point at which loading a component results in an instantaneous change from current state to significant deflection – two options: not buckled or buckled
  - **Instability:** Loading a component results in a realistic transition from small deflection to significant deflection – buckling preceded by deflection

4



Course Overview (5)

Analysis acronyms:

LBA: linear bucking analysis; elastic critical load analysis; elastic eigenvalue analysis; assumes bifurcation theory

GNA: geometric nonlinear analysis; 2nd-order elastic analysis; assumes equilibrium on the deformed shape and linear elastic material, with no initial imperfections

GNIA: same as GNA, but includes initial imperfections

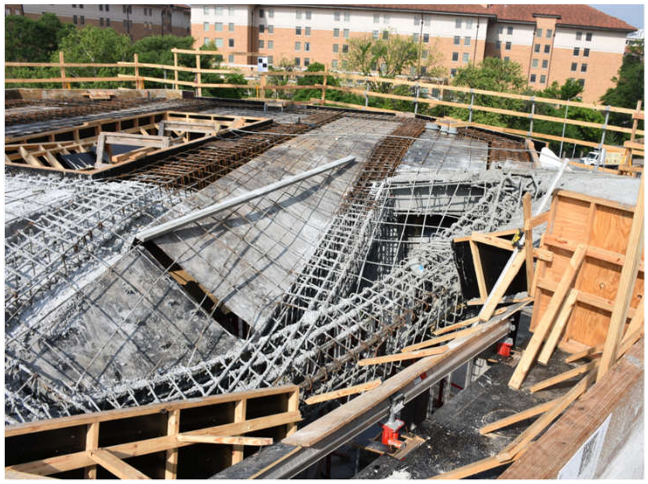
MNA: material nonlinear analysis; 1st-order inelastic analysis; assumes equilibrium on the undeformed shape and accounts for yielding, with no initial imperfections

GMNIA: geometric and material nonlinear analysis; 2nd-order inelastic analysis; assumes equilibrium on the deformed shape, accounts for yielding, and includes initial imperfections

6

Session 2

Compression Member Lab and Case Study



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Session Overview

- Review Learning Module (LM) 1
- Review LM2 Results
- Apply theory to case study from practice

8

LM1 Review

- Investigated various degrees of end restraint using elastic critical load analysis
- MASTAN2
  - Six Columns
  - 40 ft long
  - W14x82
  - C-A-7.1 boundary conditions
  - 1 kip load

AISC 360-16

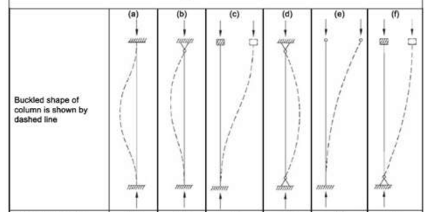

TABLE C-A-7.1
Approximate Values of Effective Length Factor, *K*

	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical *K* value	0.5	0.7	1.0	1.0	2.0	2.0
Recommended design value when ideal conditions are approximated	0.65	0.80	1.2	1.0	2.1	2.0
End condition code	Rotation fixed and translation fixed; Rotation free and translation fixed; Rotation fixed and translation free; Rotation free and translation free					

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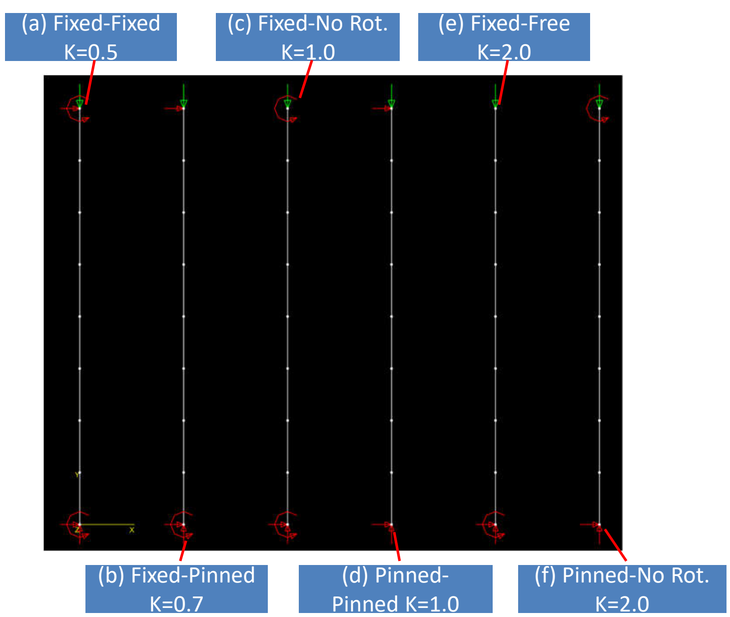
MASTAN2 Models



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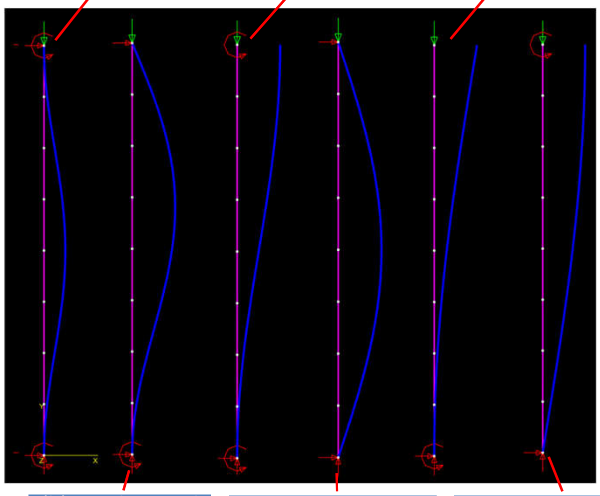
Applied Load Ratios (ALR)



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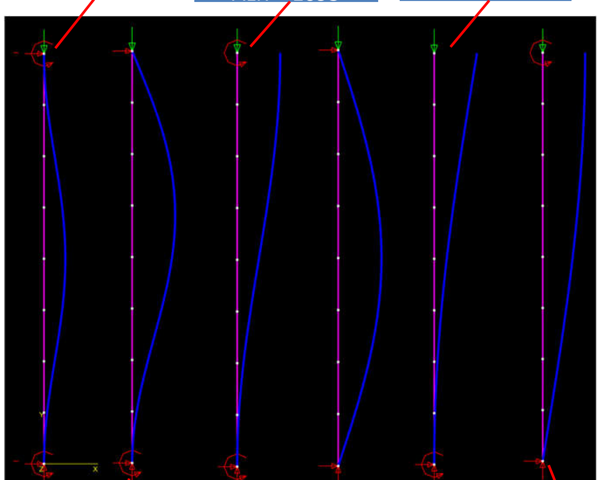
Applied Load Ratios (ALR)



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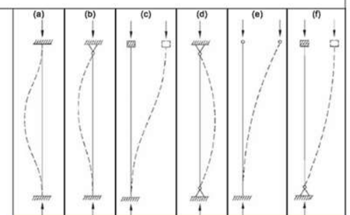
Results Summary

- If theoretical and analysis results are so close, why are recommended K values for design different?

AISC 360-16

TABLE C-A-7.1
Approximate Values of Effective Length Factor, *K*



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End condition code	Rotation fixed and translation fixed; Rotation free and translation fixed; Rotation fixed and translation free; Rotation free and translation free					
Analysis K	**0.5**	**0.7**	**1.0**	**1.0**	**2.0**	**2.0**

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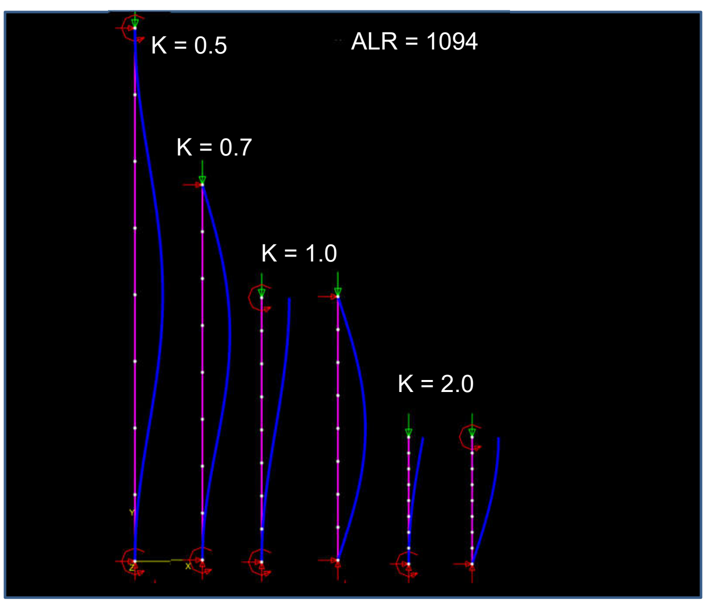
Applied Load Ratios (ALR)



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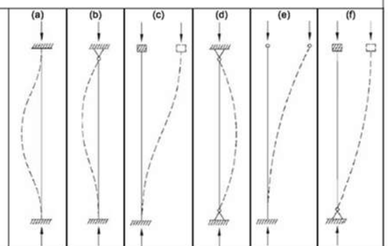
Results Summary

TABLE C-A-7.1
Approximate Values of Effective Length Factor, *K*



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End condition code	Rotation fixed and translation fixed; Rotation free and translation fixed; Rotation fixed and translation free; Rotation free and translation free					
Analysis K	**0.5**	**0.7**	**1.0**	**1.0**	**2.0**	**2.0**

AISC 360-16

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Recall Session 1

- Leonard Euler, 1744 and 1757
- Assumptions!
  - Prismatic member (I = constant)
  - Small deflections after buckling
  - No bending prior to bifurcation
    - Perfectly straight
    - Concentrically loaded
  - Linear elastic behavior (E = constant)
  - Pinned-roller supports (frictionless)

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LM2 Problem Statement

- Investigate the factors influencing the flexural buckling strength of compression members
  - Initial imperfections
  - Partial yielding
  - Support conditions

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Recall LM2 Objectives

- Recognize limitations of theoretical Euler buckling solution
- Prepare column curves that plot member slenderness versus compressive strength
- Observe the impact that initial imperfections and partial yielding have on column buckling strength
- Compare results to the AISC column curve

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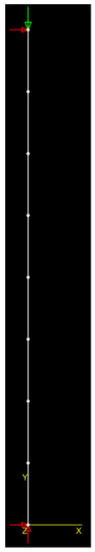
LM2 Modeling

Mastan2



AISC 360-16 Analytic

The nominal compressive strength, P_n, shall be determined based on the limit state of flexural buckling:

$$P_n = F_{cr} A_g \qquad \text{(E3-1)}$$

The critical stress, F_{cr}, is determined as follows:

(a) When $\frac{L_c}{r} \leq 4.71\sqrt{\frac{E}{F_y}}$ (or $\frac{F_y}{F_e} \leq 2.25$)

$$F_{cr} = \left(0.658^{\frac{F_y}{F_e}}\right) F_y \qquad \text{(E3-2)}$$

(b) When $\frac{L_c}{r} > 4.71\sqrt{\frac{E}{F_y}}$ (or $\frac{F_y}{F_e} > 2.25$)

$$F_{cr} = 0.877 F_e \qquad \text{(E3-3)}$$

- Variables
  - W14x53
  - L/r: 15, 65, 105, 140, and 190
  - Initial imperfection: 0 and L/1000
  - With and without partial yielding
  - Elastic and inelastic analysis

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Minor Axis Compressive Strength

- Investigate L/r = **190**, 105, 15
- What do we expect?
  - Elastic or inelastic buckling
  - AISC Column curve accuracy
  - Do residual stresses matter
  - Does initial imperfection matter
  - Do initial imperfections with partial yielding matter

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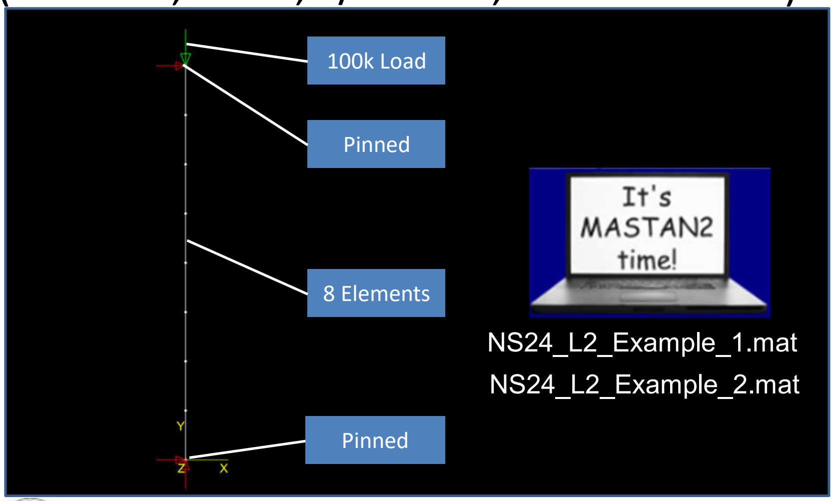
Minor Axis Compressive Strength (W14x53, A992, L/r = 190, AISC = 6.95ksi)



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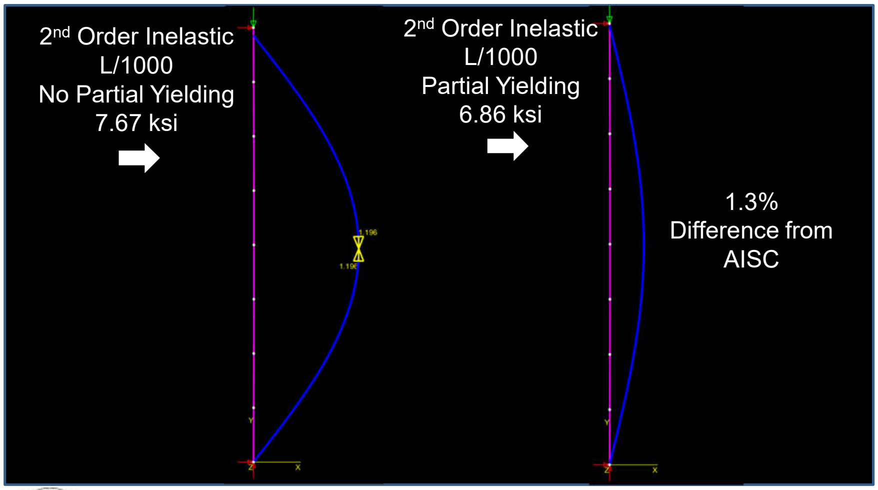
Minor Axis Compressive Strength (W14x53, A992, L/r = 190, AISC = 6.95ksi)

Axial Stresses (P_n/A) are reported

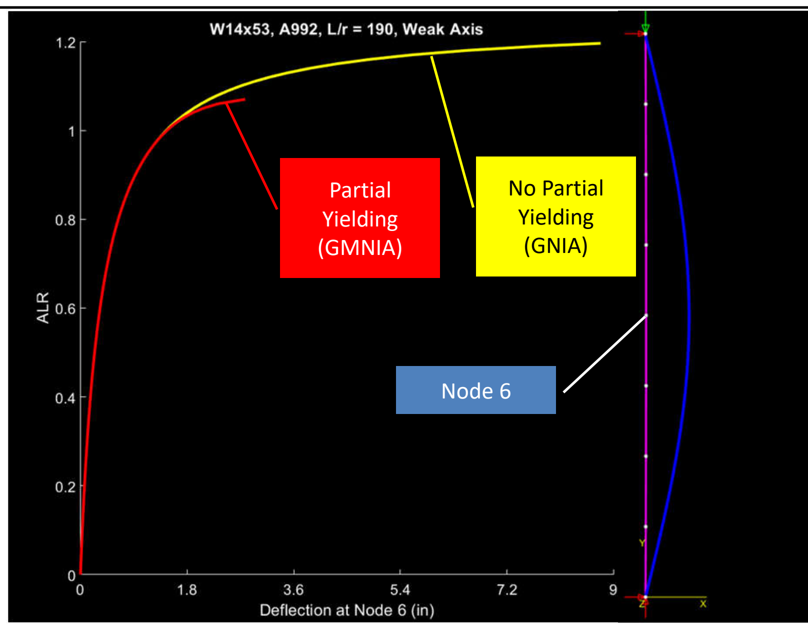
22

Minor Axis Compressive Strength
(W14x53, A992, L/r = 190, AISC = 6.95ksi)



Axial Stresses (P_n/A) are reported

23



Recall Session 1

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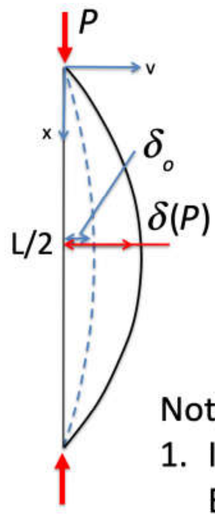
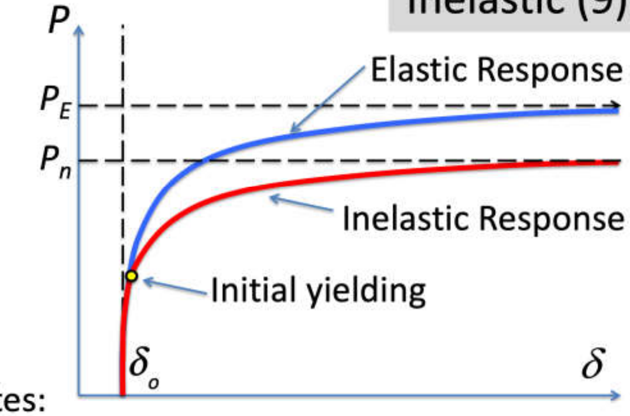
Inelastic (9)





Notes:

1. Inelastic instability occurs below the Euler critical load, i.e. $P_n < P_E$
2. The smaller the column slenderness L/r, the further P_n is below P_E ($L/r \downarrow \; P_E \Uparrow$)

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Session 1 Slide 48

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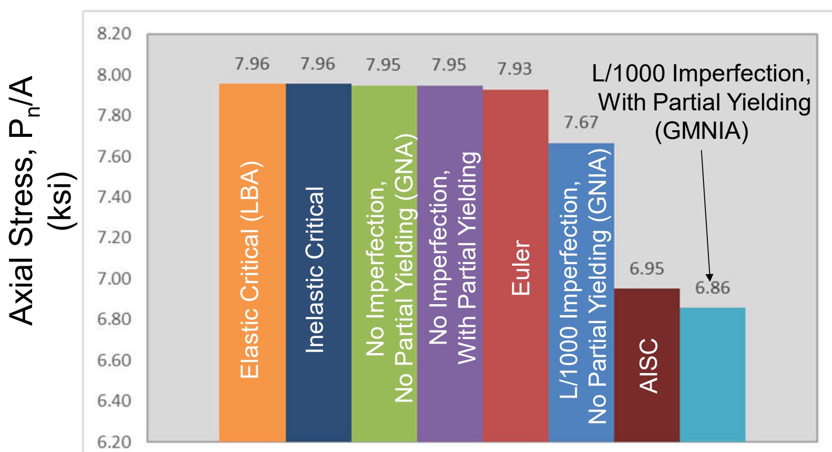
Minor Axis Compressive Strength (W14x53, A992, L/r = 190)



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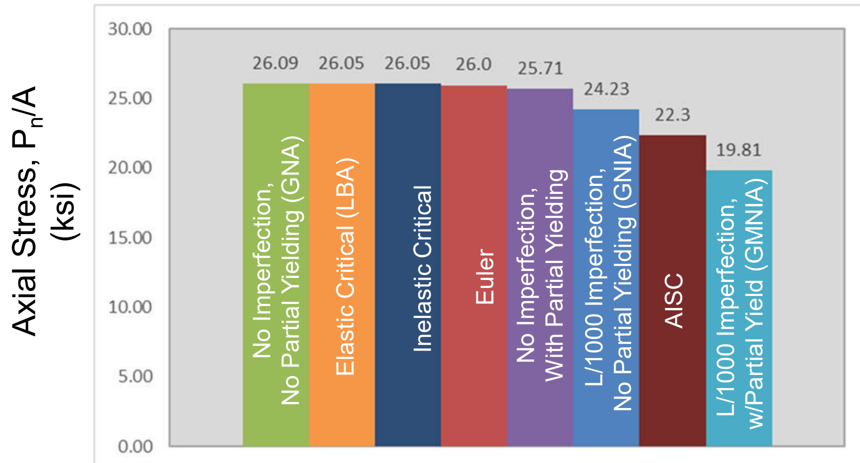
Minor Axis Compressive Strength (W14x53, A992, L/r = 105)



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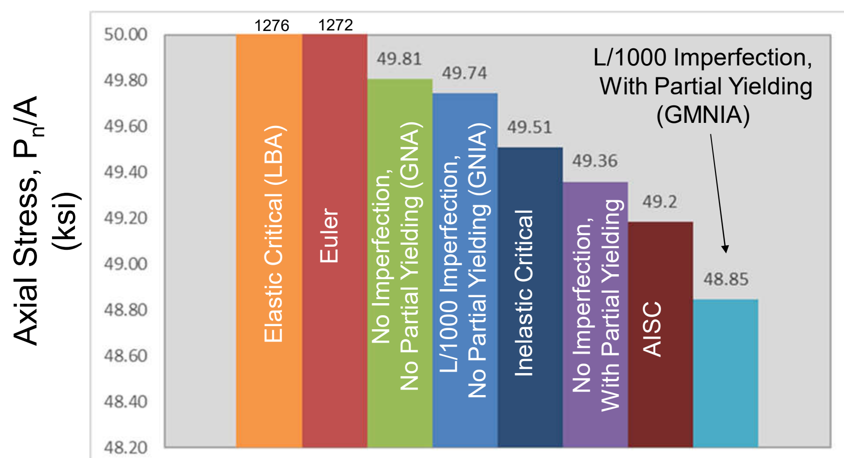
Minor Axis Compressive Strength (W14x53, A992, L/r = 15)



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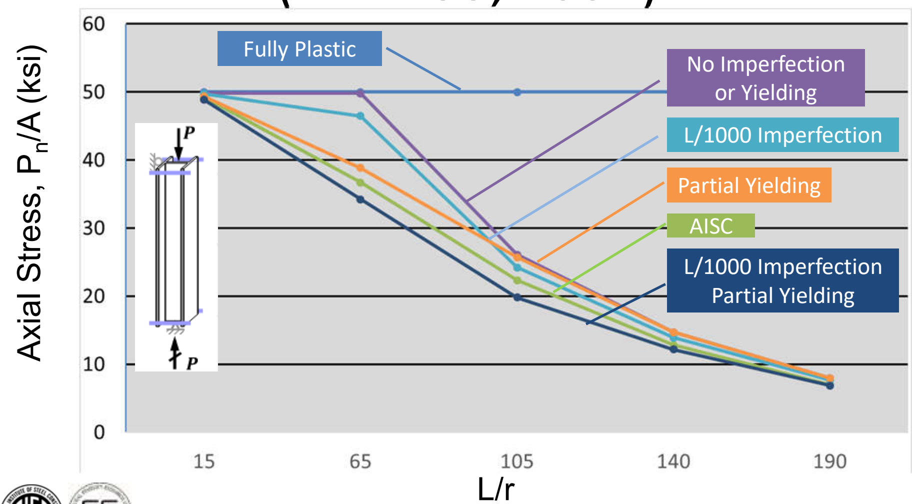
Minor Axis Compressive Strength (W14x53, A992)



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Major Axis Compressive Strength

- Investigate L/r = **190**, 105, 15
- What do we expect?
  – Elastic or inelastic buckling
  – AISC Column curve accuracy
  – Do residual stresses matter
  – Does initial imperfection matter
  – Do initial imperfections with partial yielding matter

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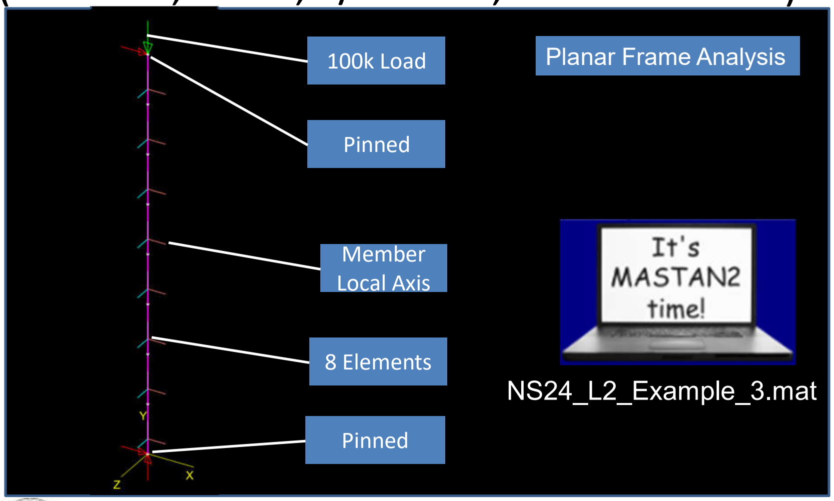
Major Axis Compressive Strength
(W14x53, A992, L/r = 190, AISC = 6.95ksi)



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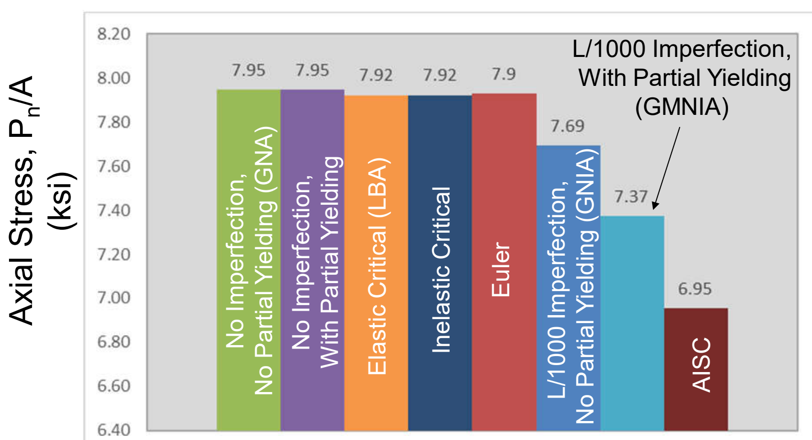
Major Axis Compressive Strength
(W14x53, A992, L/r = 190)



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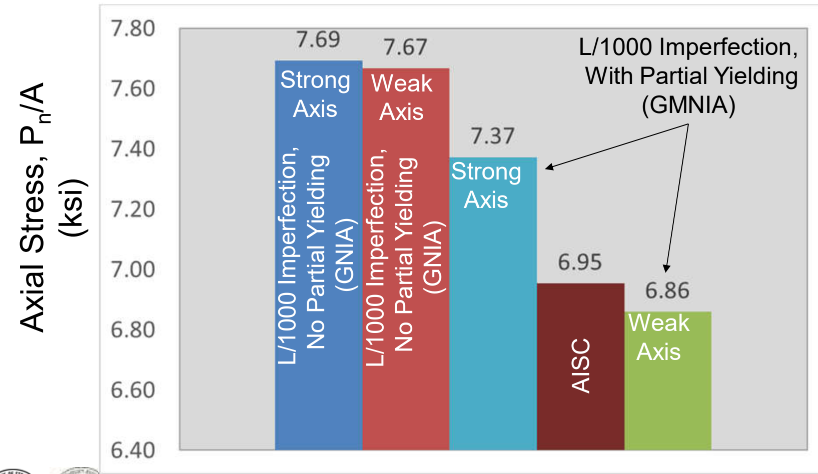
Major vs Minor Axis Compressive Strength (W14x53, A992, L/r = 190)



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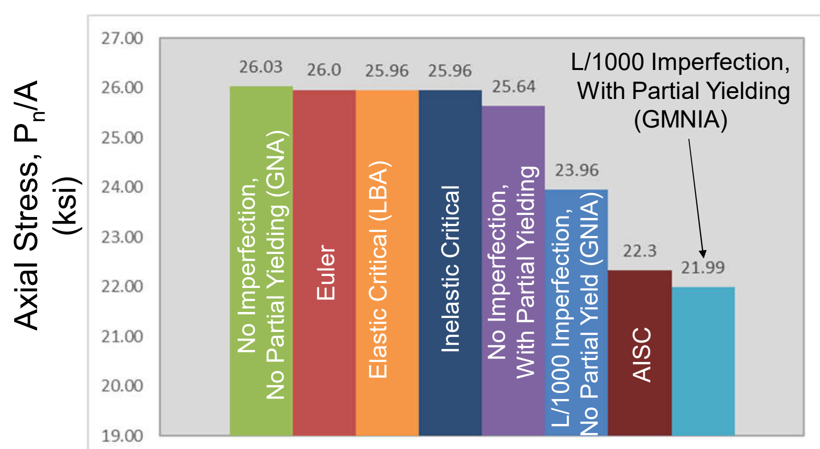
Major Axis Compressive Strength (W14x53, A992, L/r = 105)



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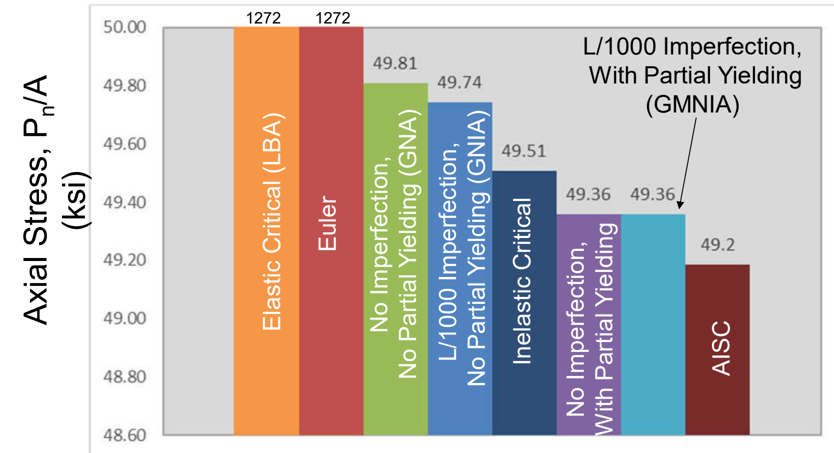
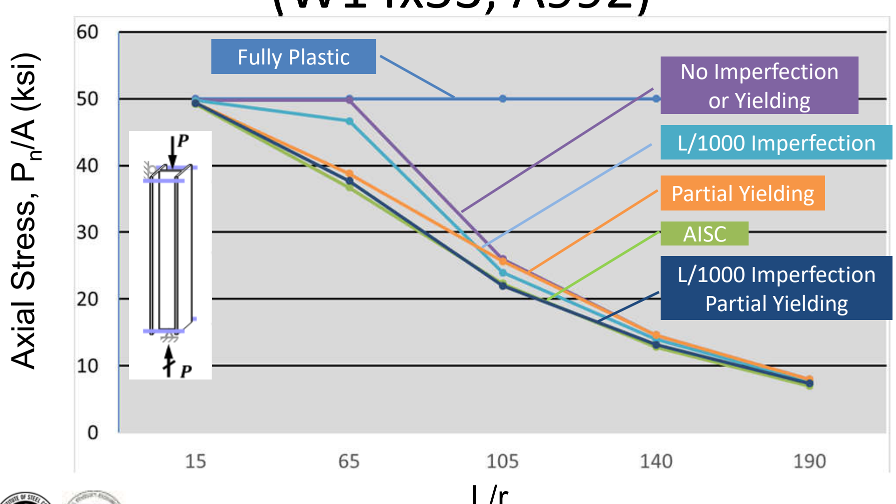
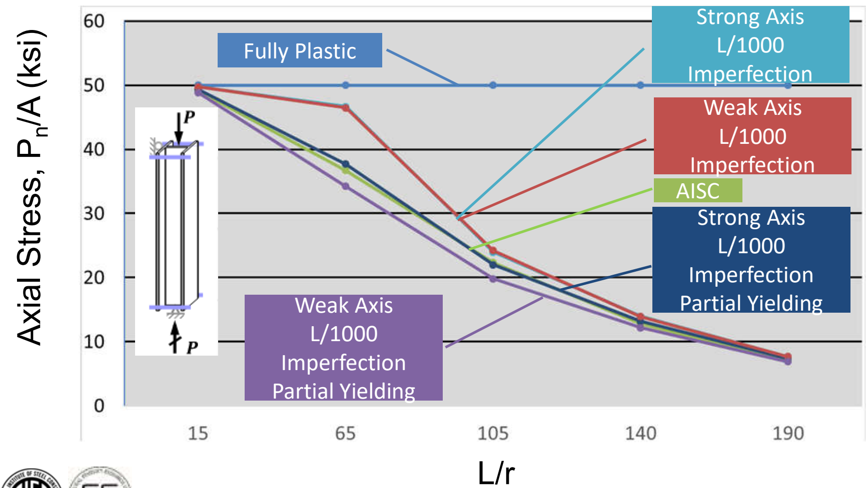
Major Axis Compressive Strength (W14x53, A992, L/r = 15)



Major Axis Compressive Strength (W14x53, A992)



Major vs. Minor Axis Compressive Strength (W14x53, A992)



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Compression Member Case Study

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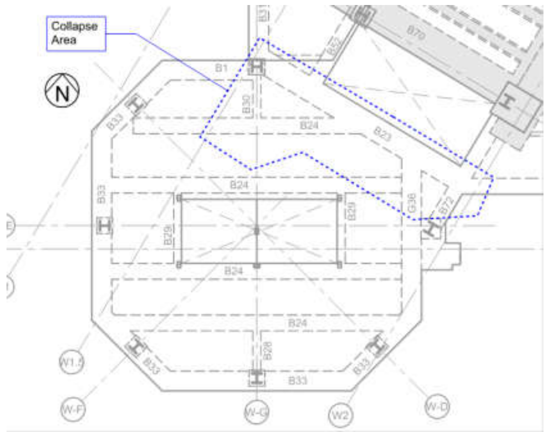
Collapse Affected Area

Collapse initiated at intersection of beam B23 and B24



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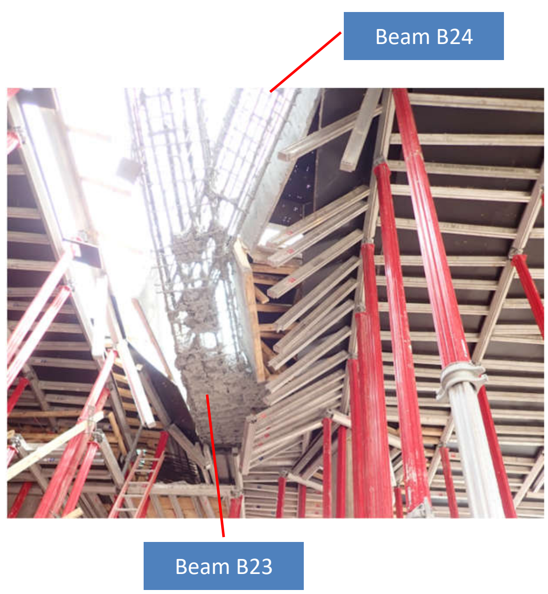
Ground Level View

Temporary shoring collapse during construction

5-inch thick slab

24-inch deep beams

Concrete approximately 19 inches deep at time of collapse



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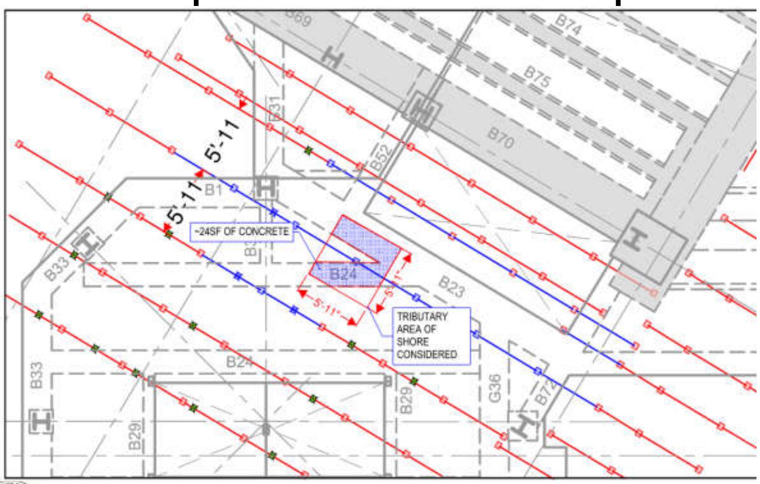
Most Heavily Loaded Shore
6.2 kips at time of collapse



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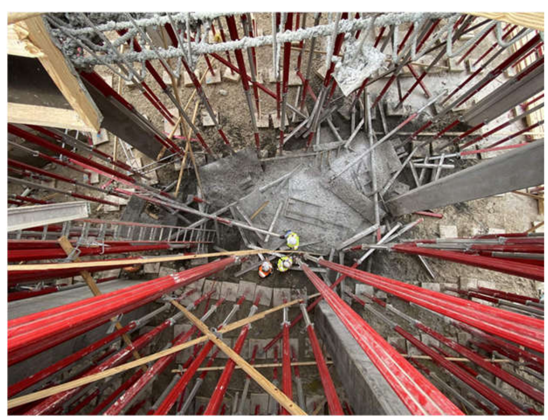
Looking down into collapse area

Shore post height 27'-7" in this area

L/r about 218



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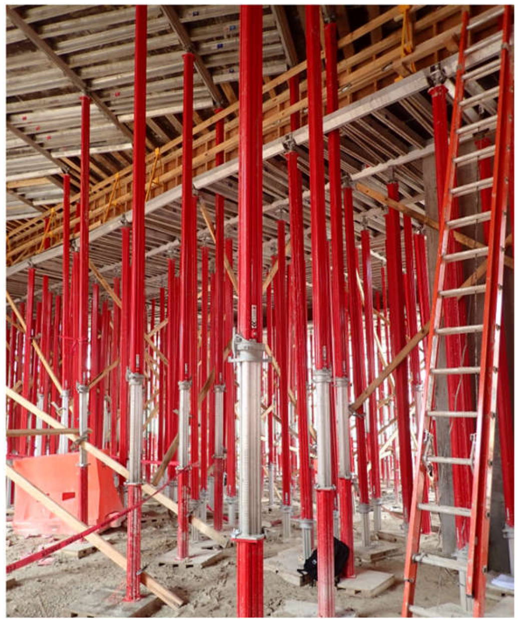
Shores still standing at edge of collapse area

Aluminum shoring system

Bases supported by wood dunnage on ground



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Typical Condition at Base

Wood dunnage on ground

Varying degrees of ground flatness

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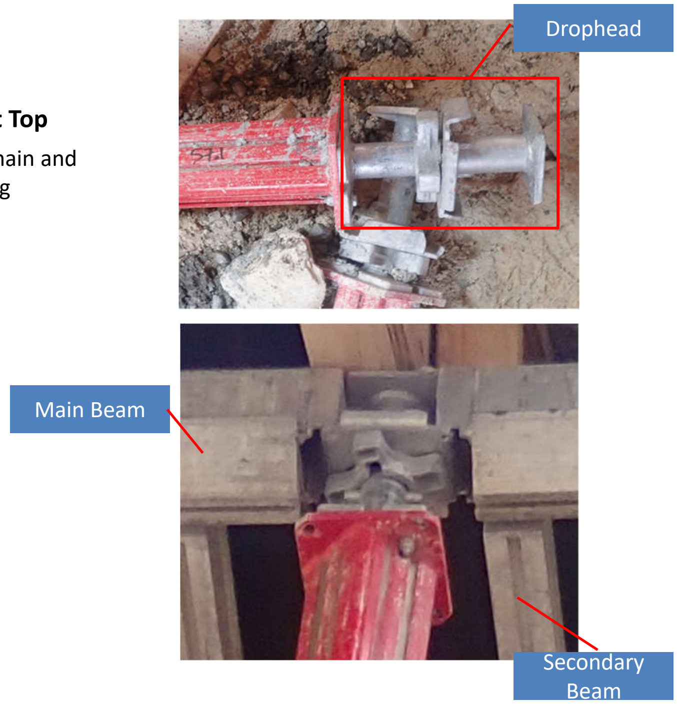
Typical Condition at Top

Shore posts clip into main and secondary beams using drophead



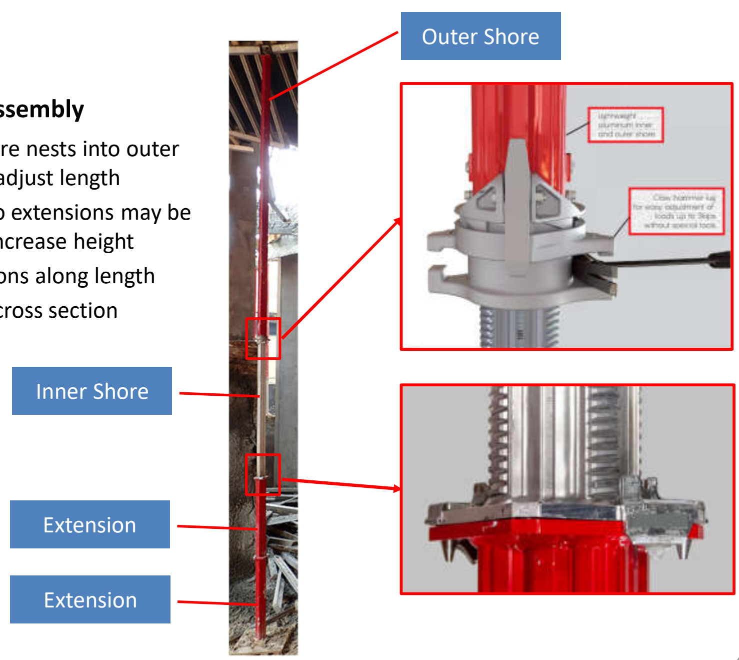
Shore Assembly

Inner shore nests into outer shore to adjust length

Up to two extensions may be used to increase height

Connections along length

Discrete cross section variation



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Anticipated Strengths

Supplier Lab Test (L = 27')

17.9 kip nominal load

7.1 kip allowable load (FS = 2.5)

Analytical Code (k = 1.0, prismatic outer shore cross section)

5.0 kip nominal load

3.1 kip allowable load (FS = 1.65)

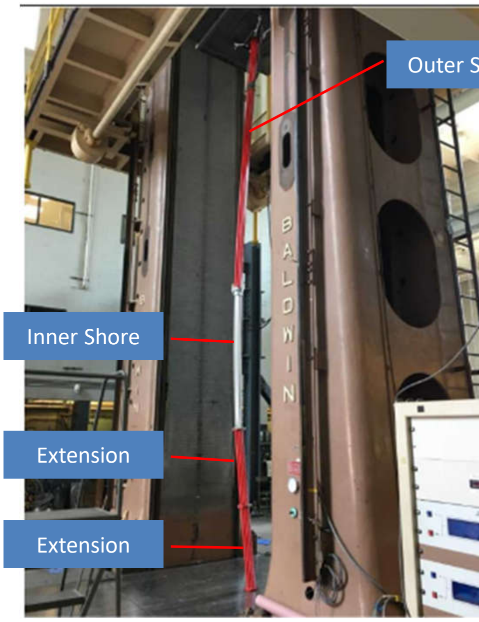
Analytical Code (k = 0.65 prismatic outer shore cross section)

11.9 kip nominal load

7.2 kip allowable load (FS = 1.65)

Lab specimen more closely matches fixed-fixed analytical solution.

But there are other differences too.



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Field Conditions

Similarities to laboratory specimen

-Inner shore fully extended

-Two Extensions

-Connections between segments

Differences from laboratory specimen

-Top pinned condition

-Base may not be level/completely stable

-Height 7" taller (drophead)

-Buckled at 6.2 kips (field estimate) vs. 17.2 kip nominal laboratory test load

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Issues

- Need to re-place concrete in collapse
- Still have another complete placement in less than a week
- Need to update shoring plan accounting for field conditions
- Need to provide updated capacities for shore posts of varying heights

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Mastan2 Model

Each segment subdivided into 4 elements

Neglect

-Weld affected zones

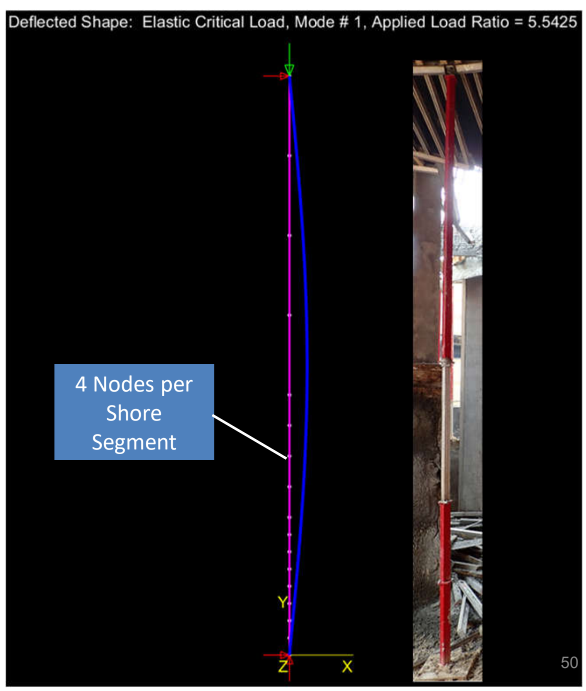
-Connections between segments

Investigate

-Variation in cross section

-End conditions

For project SAP2000 was used but Mastan2 used here



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Step 1 Validate Lab Model with Analytical Results

Pin-pin end condition 27' long

Model elastic critical load with prismatic outer shore cross section

-Critical Load = 5.54 kip

Analytical solution for prismatic outer shore cross section

-Nominal Load 5 kip/0.85 = 5.88 kip

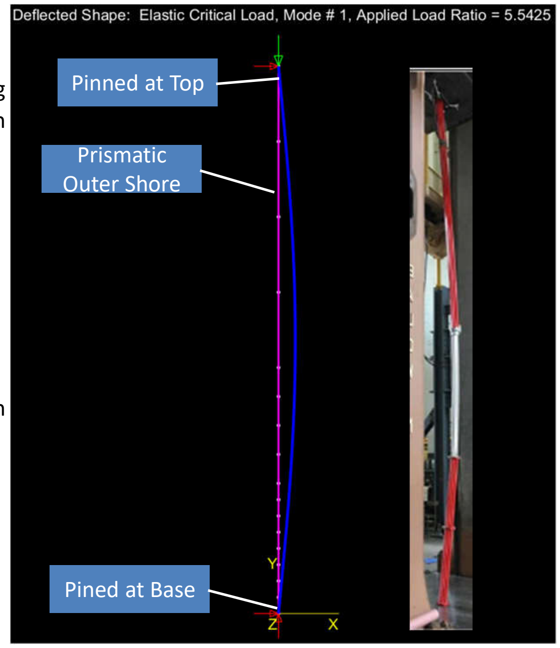
-Good agreement with model

Model elastic critical load with prismatic inner shore cross section (not shown)

-Critical Load = 3.54 kip

Model non-prismatic cross section (not shown)

-Critical Load = 4.66 kip



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Step 1 Validate Lab Model with Analytical Results

Fixed-fixed end condition

27' long

Model elastic critical load with prismatic outer shore cross section

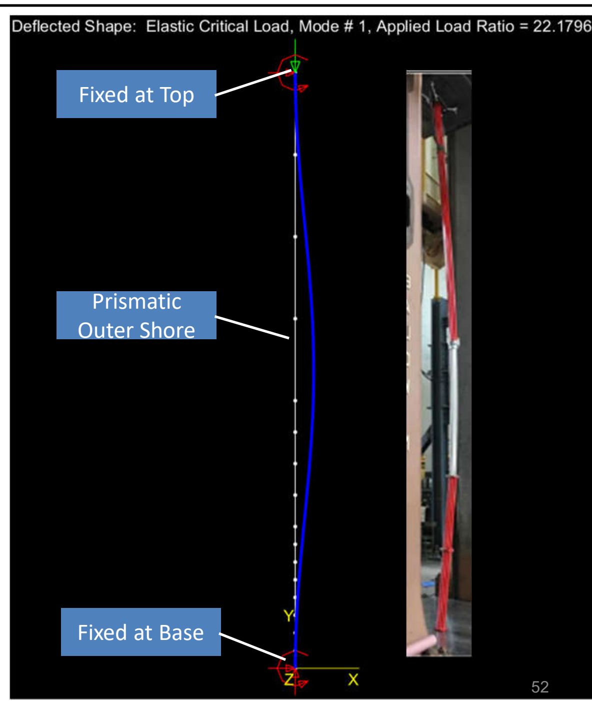
-Critical Load = 22.2 kip

Analytical solution for prismatic outer cross section

-Nominal Load = 20.1 kip

-Account for code initial imperfection 20.1kip/0.85 = 23.6 kip

-Good agreement with model



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Step 2 Validate Lab Model with Laboratory Specimen

Use fixed-fixed end conditions

Include non-prismatic cross section

Laboratory Model Elastic Critical Load

-Critical Load = 20.4 kip

Laboratory Specimen

-Nominal load 17.9 kip

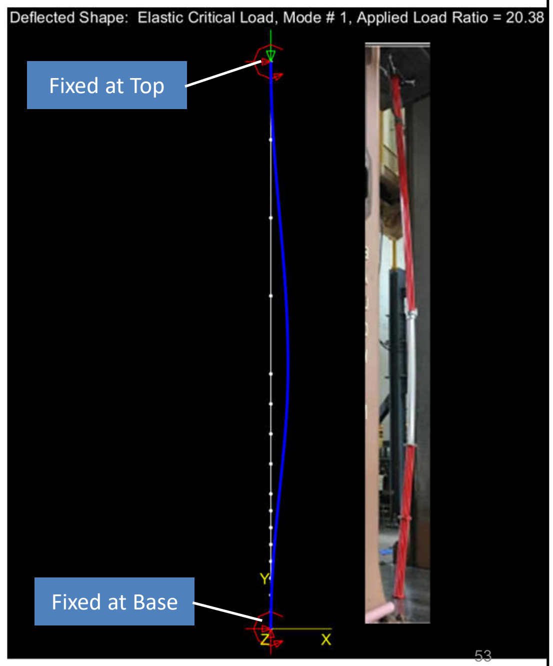
-Adjust for assumed code initial imperfection

17.9 kip/0.85 = 21.1 kip

-Good agreement with model

-Indicates restraint present at specimen ends

Attempt to model L/960 imperfection



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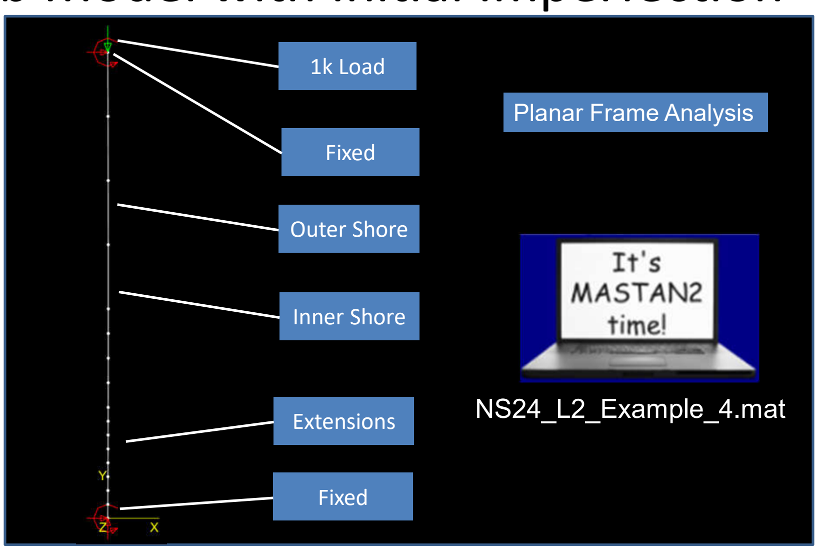
Lab Model with Initial Imperfection



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Step 2 Validate Model with Laboratory Specimen

Use fixed-fixed end conditions

Include non-prismatic cross section

Model Elastic Critical Load

-ALR= 20.4

Laboratory Specimen

-Nominal load = 17.9 kip

-Adjust for assumed code initial imperfection

17.9 kip/0.85 = 21.1 kip

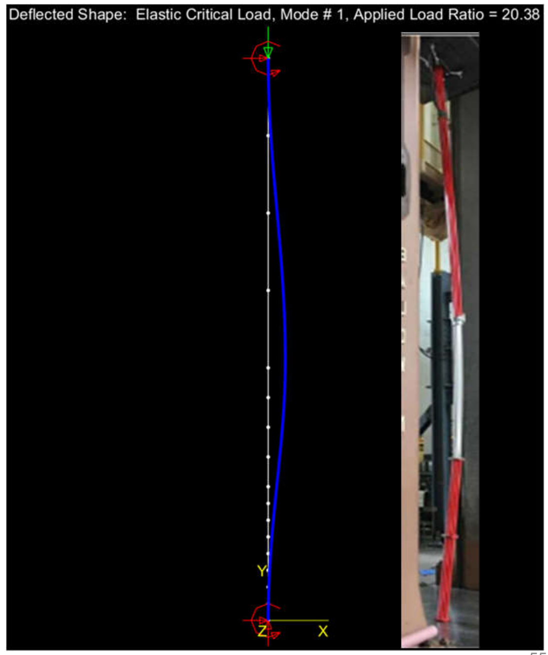
-Good agreement with model

Model with L/960 imperfection

-ALR = 45.3 (2nd Order Elastic)

-Shouldn't the buckling load decrease when an imperfection is added?

Let's look at the deflected shape



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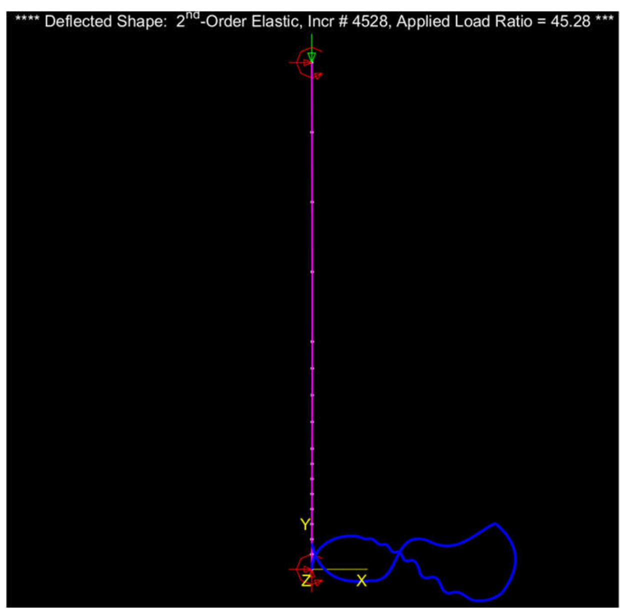
Step 2 Validate Model with Laboratory Results

Deflected shape is a mess, what is happening?

Investigate load displacement with MSA plot



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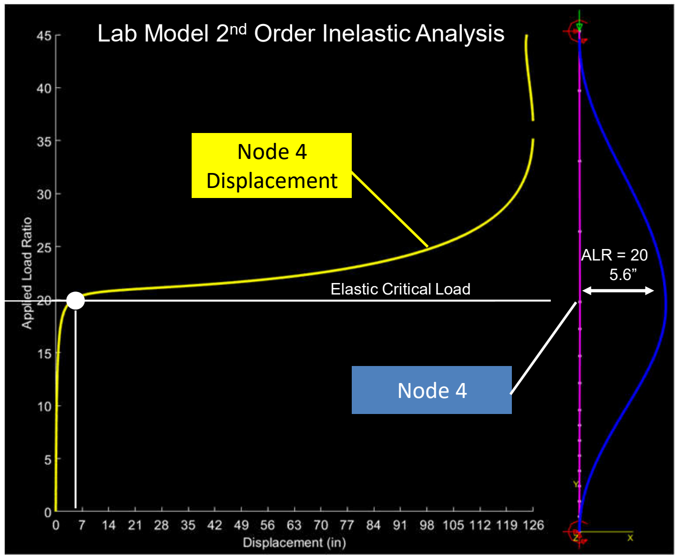
ALR vs. Displacement



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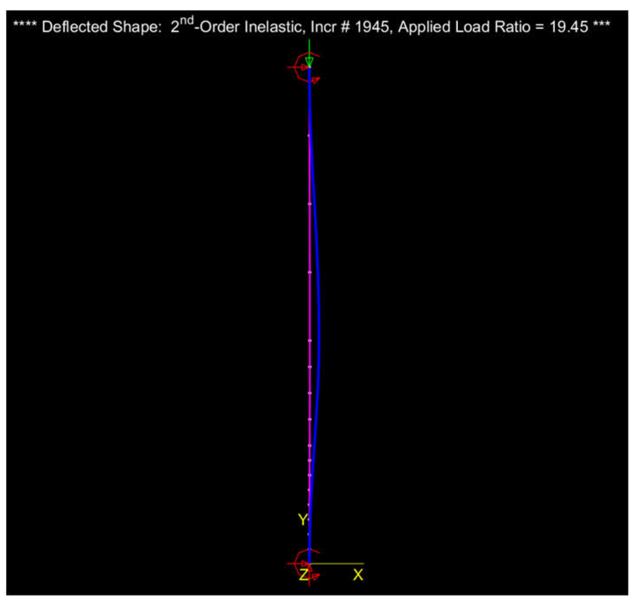
Step 2 Validate Model with Laboratory Results

Using an estimate of the plastic section modulus and 2nd Order Inelastic analysis gives applied load of 19.5 k

Recall **Laboratory Specimen**

-Nominal load = 17.9 kip

Good agreement with laboratory specimen



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Step 2 Validate Lab Model with Laboratory Results

In lieu of the second order inelastic analysis could we take 0.85 of the elastic critical load?

-accounts for out of straightness of L/960

Lab Model

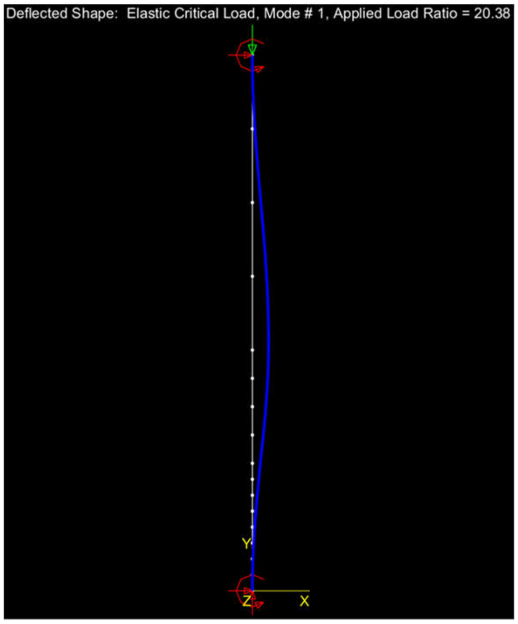
-Elastic critical load = 20.4 kip * 0.85 = 17.3 kip

-2nd order inelastic analysis = 19.5 kip

Doing so in this case is conservative

Recall **Laboratory Specimen**

-Nominal load = 17.9 kip



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Step 3 Validate Model with Field Data

Estimate pin-pin end condition

27'-7" long

Non-prismatic cross section

Field Specimen

-Estimated load at collapse = 6.2 kip

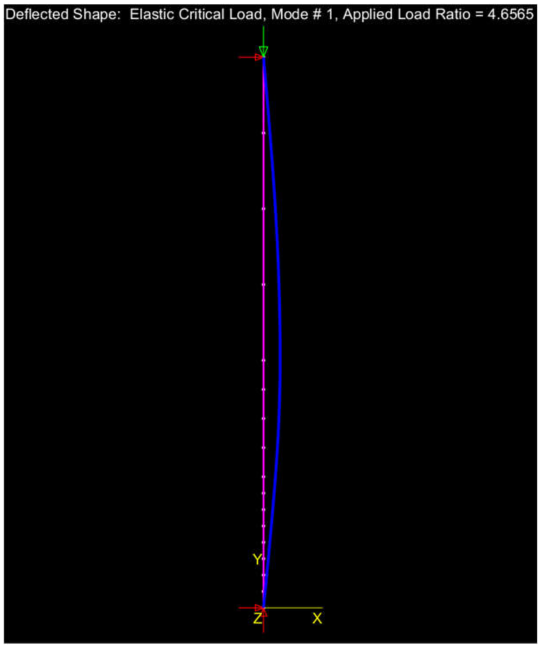
Field Model

-Elastic critical load = 4.65 kip

-75% of estimated load at collapse

-Base likely provides some stability

-Model fixed base



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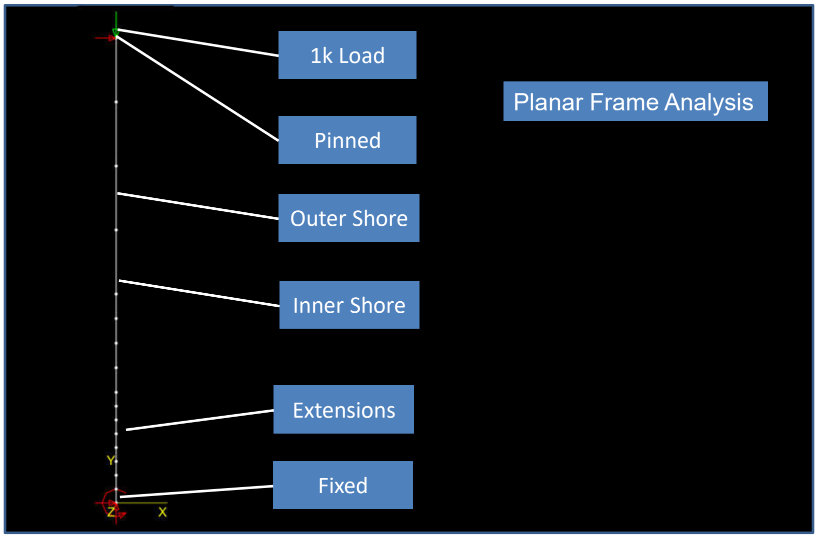
Field Model with Fixed Base



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Step 3 Compare Field Model to Field Specimen

Fixed-pin end condition

27’-7” long

Nonprismatic cross section

Field Specimen

-Estimated collapse load = 6.2 kip

Field Model

-Elastic critical load = 11.0 kip

-Adjust for code imperfection

11.0 kip * 0.85 = 9.35 kip

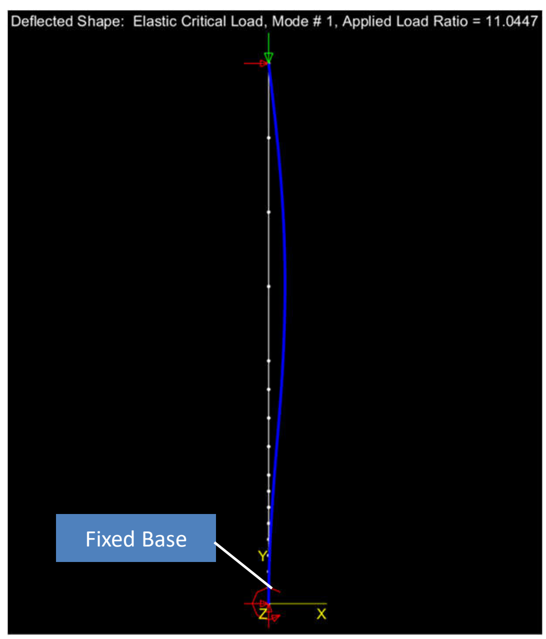
-150% of estimated field specimen

-2nd order inelastic analysis = 12.6 kips

Likely that

-Base was not fully fixed

-Connections played a role



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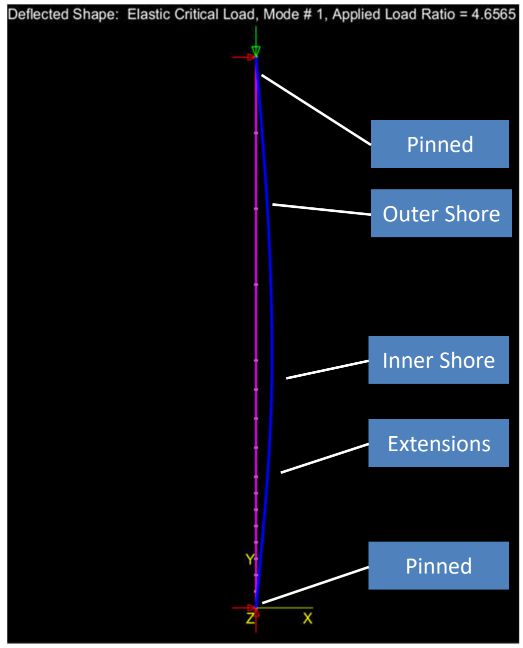
Step 4 Propose model for use

Model with
-Pin-pin end conditions
-Non-prismatic cross section
-Critical load at 27’ 7” was 4.65 kips

Recall
-Manufacturer allowable load = 7.1k (L=27’ & FS = 2.5)
-Estimated field load = 6.2k (L=27’ 7”)

Bracing shores was considered, but much easier just to add more shores where demand exceeded model allowable load

Some demand to capacity ratios were 1.2, but based on conservatism in model, this was deemed acceptable



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Summary

- Euler is a great mathematical solution
- Reality throws your compression members some curves
- Understanding behavior is key to knowing how and when to use computational modelling
- Laboratory test conditions may vary from field conditions

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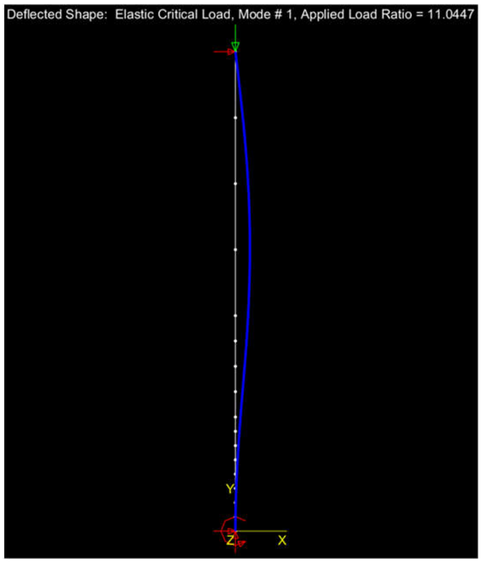

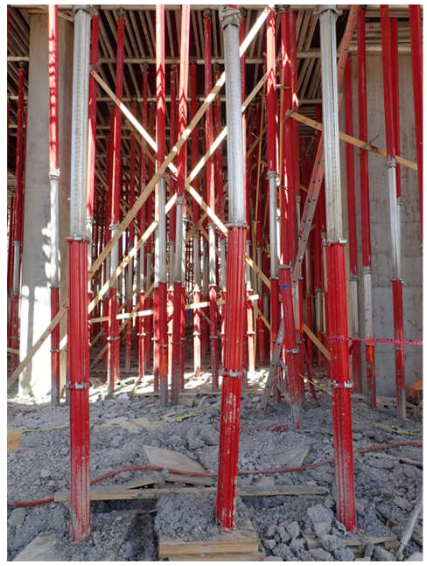

AISC | Questions?

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Single-Session Registrants

CEU / PDH Certificates

- 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!

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Single-Session Registrants

CEU / PDH Certificates

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.

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8-Session Registrants

CEU / PDH Certificates

One certificate will be issued at the conclusion of the course.

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Attendance and PDH Certificates

- You have two options to receive credit for a given session.
  - Option 1: Watch the live session. Credit for live attendance will be displayed on the Course Resources table within two days of the session.
  - Option 2: Watch the recording and pass the associated quiz.

Videos and Quizzes

- For each session, find access within two business days after the live air date. (An email will be sent from nightschool@aisc.org.)
- Reasons for quiz:
  - EEU – You must take all quizzes and the final exam to receive EEU.
  - PDHs – If you watch a recorded session, you must pass quiz for PDHs.
  - Reinforce what you learn in the lectures and get more out of the course!

Distribution of Certificates

All certificates will be issued after the course is completed. Only the registrant will receive a certificate for the course.

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Course Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information in one place!

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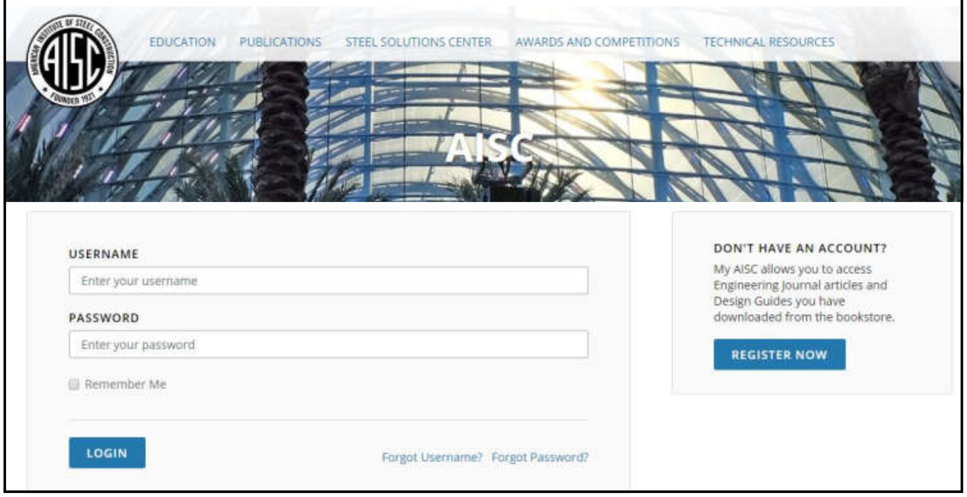
Course Resources

Go to www.aisc.org and sign in.



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Course Resources

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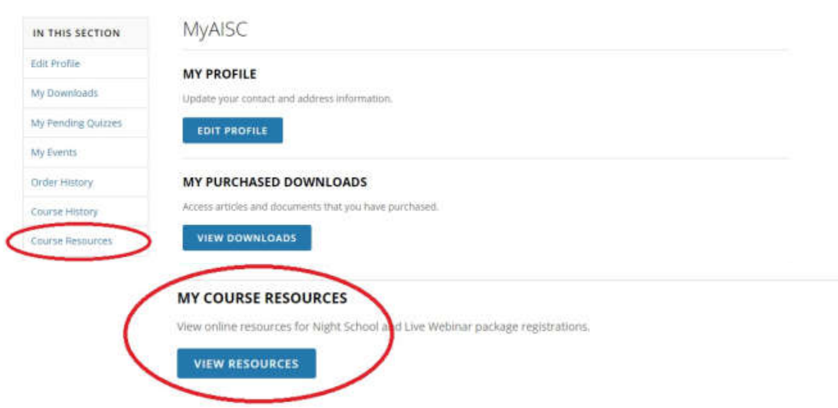

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Course Resources

AISC › MY ACCOUNT › COURSE RESOURCES

Course Resources

Event	Start Date
Seismic Design in Steel	1/1/1900 12:00:00 AM
4-Session Package-Design of Facade Attachments	5/9/2019 1:30:00 PM
NS 15 8-Session Package-Night School 15 - Fundamentals of Connection Design	10/3/2017 7:00:00 PM
NS 16 8-Session Package-Night School 16 - Seismic Design in Steel	2/5/2018 7:00:00 PM
NS 17 4-Session Package-Night School 17: Design of Facade Attachments	7/16/2018 7:00:00 PM
NS 18 8-Session Package-Night School 18: Steel Construction: Mill To Topping Out	10/15/2018 7:00:00 PM
NS 19 8-Session Package-Night School 19: Connection Design	2/4/2019 7:00:00 PM
NS 20 8-Session Package-Night School 20: Classical Methods of Structural Analysis	6/3/2019 7:00:00 PM
8-Session Package-Seismic Design in Steel - Concepts & Examples	7/16/2018 1:30:00 PM

8-Session Registrants

Course Resources

AISC › MY ACCOUNT › COURSE RESOURCES › NS24 8-SESSION PACKAGE RESOURCES

Night School 24: Modern Methods for Learning Structural Stability

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Video	Quiz	Attendance
NS24.1 - Compression Members - The Fundamentals	Oct 6 2020 7:00PM EDT	Handouts	Available 10/08/2020 5:00PM EDT	Available 10/08/2020 5:00PM EDT	Pending
NS24.2 - Compression Members - Practical Considerations	Oct 13 2020 7:00PM EDT	Handouts	Available 10/15/2020 5:00PM EDT	Available 10/15/2020 5:00PM EDT	Pending
NS24.3 - Behavior of Flexural Members - The Fundamentals	Oct 20 2020 7:00PM EDT	Handouts	Available 10/22/2020 5:00PM EDT	Available 10/22/2020 5:00PM EDT	Pending
NS24.4 - Flexural Members - Practical Considerations	Oct 27 2020 7:00PM EDT	Handouts	Available 10/29/2020 5:00PM EDT	Available 10/29/2020 5:00PM EDT	Pending
NS24.5 - Stability of Beam-Columns - The Fundamentals	Nov 10 2020 7:00PM EST	Handouts	Available 11/12/2020 5:00PM EST	No longer available	Pending
NS24.6 - Stability of Beam-Columns - Practical Consideration	Nov 17 2020 7:00PM EST	Handouts	Available 11/19/2020 5:00PM EST	No longer available	Pending
NS24.7 - Behavior of Structural Systems - The Fundamentals	Dec 1 2020 7:00PM EST	Handouts	Available 12/03/2020 5:00PM EST	No longer available	Pending
NS24.8 - Structural Systems - Practical Considerations	Dec 8 2020 7:00PM EST	Handouts	Available 12/10/2020 5:00PM EST	No longer available	Pending
NS24 - Final Exam	N/A			No longer available	


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