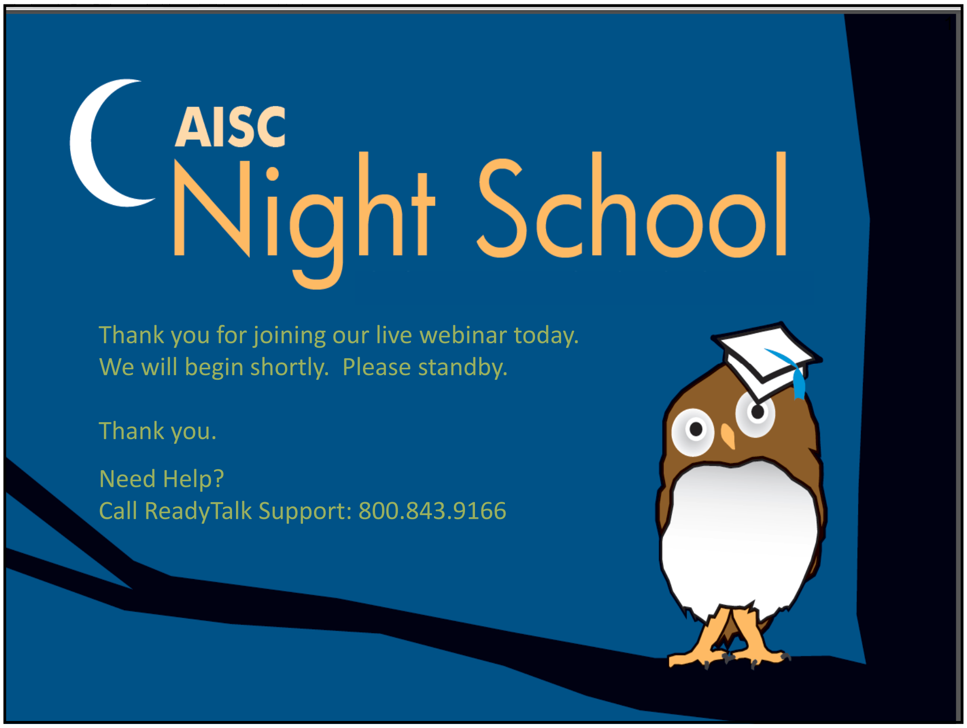


2

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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.

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## Copyright Materials



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## Course Description

**Modules for Learning Structural Stability**
February 9, 2015

With a basic understanding of linear and nonlinear analysis now in hand, it is time to explore and gain hands-on experience in understanding factors that are known to impact structural stability. As an alternative to experimental testing, nonlinear computational analysis can provide a virtual lab for investigating numerous important concepts related to the design for stability. An overview of several learning modules developed for a better understanding of topics such as elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects will be presented

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## Learning Objectives

- Become familiar with how non-linear computational analysis can help develop a better understanding of stability concepts.
- Gain hands-on experience in understanding factors that are known to impact structural stability through the use of structural analysis software.
- Become familiar with elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects.
- Develop a better understanding of elastic and inelastic flexural and lateral-torsional buckling, inelastic force redistribution, and second-order effects through design examples and structural analysis software demonstrations.

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# Stability Design of Steel Structures – Applying Modern Methods of Structural Analysis

There's always a solution in steel.

Session 3
**Modules for Learning Structural Stability**

Ronald D. Ziemian, P.E., Ph.D.

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# Course Overview

- Session Topics
  - Course Intro. and Modern Analysis (1 & 2)
  - Resources for Learning Stability by Analysis (3)
  - Second-Order Analysis (4)
  - Direct Analysis Method (5)
  - Low- and Medium-Rise Steel Buildings (6)
  - Advanced Application of Stability Design (7)
  - Design by Inelastic Analysis (8)
- Lectures by members of the Structural Stability Research Council (SSRC)
  - Don White and Ron Ziemian
  - Great to join AISC in this effort!

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**Impetus:**

AISC Ch. C: P-Δ, P-δ (DM)
App. 1.1: DM - DMMI
App. 1.2: Inelastic Design
Seismic: Pushover Analysis
Other: Progressive Collapse

Limit States Design

**Nonlinear Analysis**

Available Software:
MASTAN2

Research

Education:
Textbook and
Learning Modules

## Challenge of Designing Steel Structures

11

Strength/ Weight + Stiffness/ Weight + Competitive $

↓

Slender Members and Systems

↓

Design for Stability!

## Structural Stability & The Curse of the Differential Equation

13

# Challenge of Designing Steel Structures

- ✓Understanding Structural Stability
  - General Behavior
    - Physical observations (go to the lab!)
    - Virtual observations (go to the computer!)
    - Hear it described in lecture
    - Read about it in the book
  - "Exact" Solutions
    - Differential Equations (limited by assumptions)
    - Computational Analysis (much less limited)
- ✓See the forest for the tress
- ✓Engage the student - Active Learning

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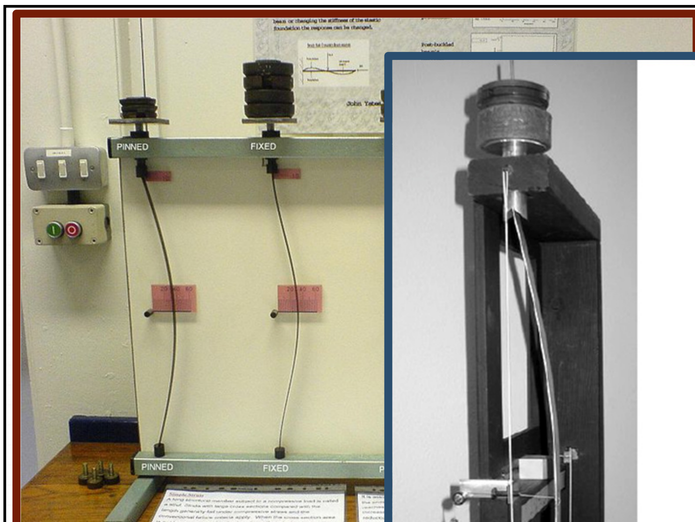


Physical Labs would be ideal, but…

15

# Virtual Laboratory

- ✓In early 2000…
  - *Matrix Structural Analysis*, McGuire, Gallagher, and Ziemian, 2nd ed., John Wiley & Sons.
  - Rewritten to include new chapters on nonlinear analysis
  - Educational software MASTAN2 developed and bundled with textbook
    - MATLAB-based, available on all platforms
    - Included suite of nonlinear analysis options
    - "Easy to use" GUI quickly led to MASTAN2 taking on a life independent of the textbook

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# Virtual Laboratory

- ✓2000-present…
  - Elastic nonlinear options become the norm in commercial analysis software
  - Other educational/research analysis software is developed that includes geometric and material nonlinear capabilities
  - MASTAN2 continues to develop
    - Standalone versions available on PC and Mac
    - Available at no cost over the web, www.mastan2.com
    - Adopted at many universities world-wide for use in undergraduate and graduate analysis and design courses

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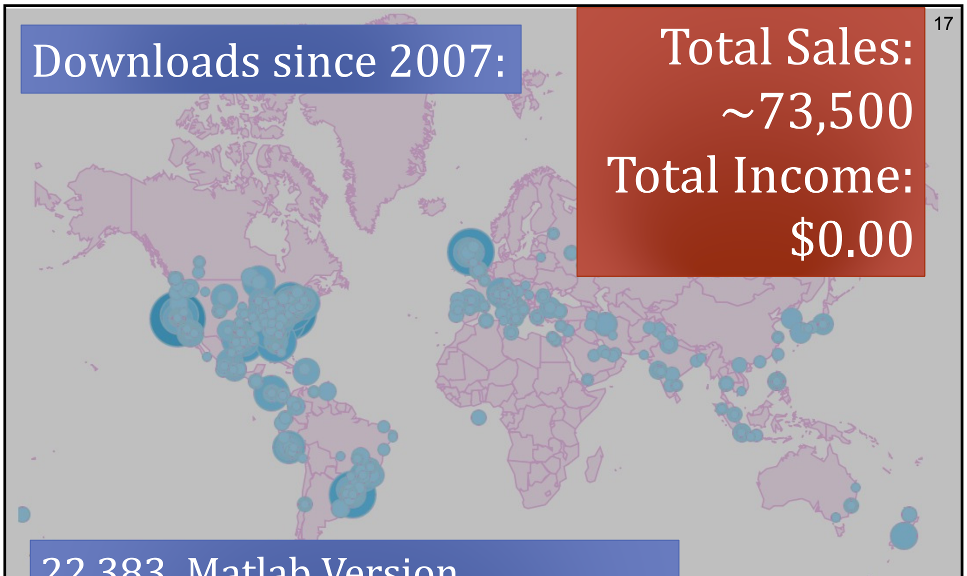
Downloads since 2007:

Total Sales: ~73,500
Total Income: $0.00



22,383 Matlab Version
45,066 PC-version (stand-alone)
6,173 Mac-version (stand-alone)

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# Virtual Laboratory

✓ Needs for simulating structural stability problems
- Partial yielding accentuated by residual stresses
- Full cross-section yielding, plastic hinge
- Local buckling, elastic/inelastic
- Flexural buckling, elastic/inelastic
- Torsional buckling, elastic/inelastic
- Lateral-torsional buckling, elastic/inelastic
- Flexural-torsional buckling, elastic/inelastic
- Above buckling strengths reduced by local buckling
- Account for initial imperfections
  out-of-plumb, out-of-straightness
- Second-order effects $P\Delta$, $P\delta$
- System instability, elastic/inelastic

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# Virtual Laboratory

- ✓Simulating Structural Stability
  - several analytical requirements
- ✓Possibilities
  - Commercial FEA software
    ABAQUS, ADINA, ANSYS, PERFORM3D, LARSA4D,…
  - Educational FEA software
    OpenSees, FE++2012, GT-SABRE, BASP, Arcade, Dr. Frame, GBTUL, MASTAN2, …
- ✓Considerations for making the choice
  - Price and availability
  - Ease of use--- Learning curve!
  - Experience

| | Virtual Lab for Stability Checklist | MASTAN2 | Other |
|---|---|---|---|
| Stiffness | Axial, $EA$ | yes | yes |
| | Flexural, $EI$ | yes | yes |
| | Shear, $GA_s$ | yes | yes |
| | St. Venant torsion, $GJ$ | yes | yes |
| | Warping torsion, $EC_w$ | yes | ? |
| | Connection, $k_{conn}$ | yes | ? |
| Effects | Second-order including $P\Delta$, $P\delta$ | yes | ? |
| | Imperfections: system, member | yes | ? |
| | Partial yielding including $\sigma_{res}$ | approx. | ? |
| | Plastic hinge: $P$, $M_x$, $M_y$ | yes | ? |
| Analysis | 2D/3D Incremental/iterative | yes | ? |
| | 2D/3D Critical load (eigenvalue) | yes | ? |

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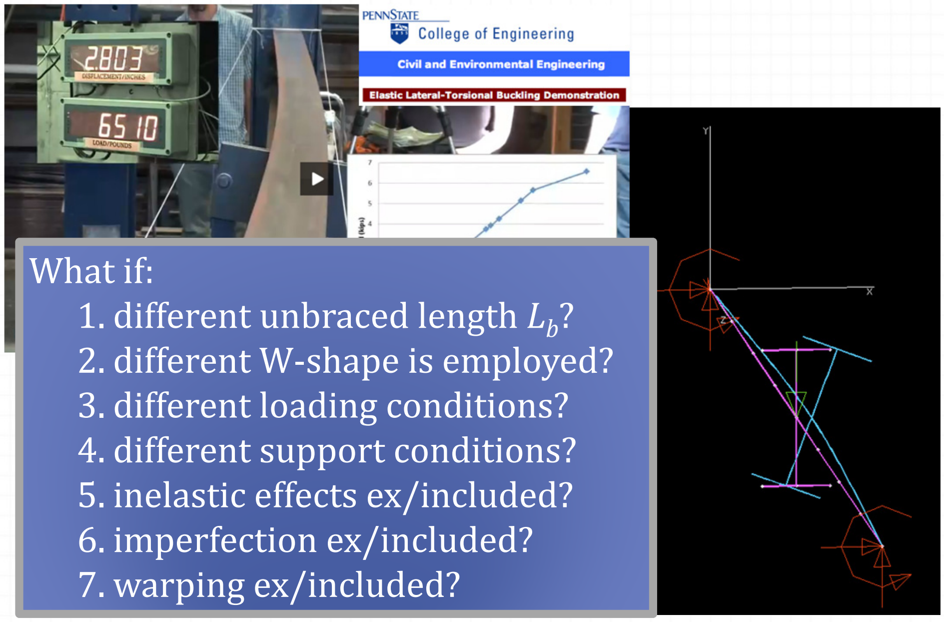
# Virtual Laboratory




What if:

1. different unbraced length $L_b$?
2. different W-shape is employed?
3. different loading conditions?
4. different support conditions?
5. inelastic effects ex/included?
6. imperfection ex/included?
7. warping ex/included?

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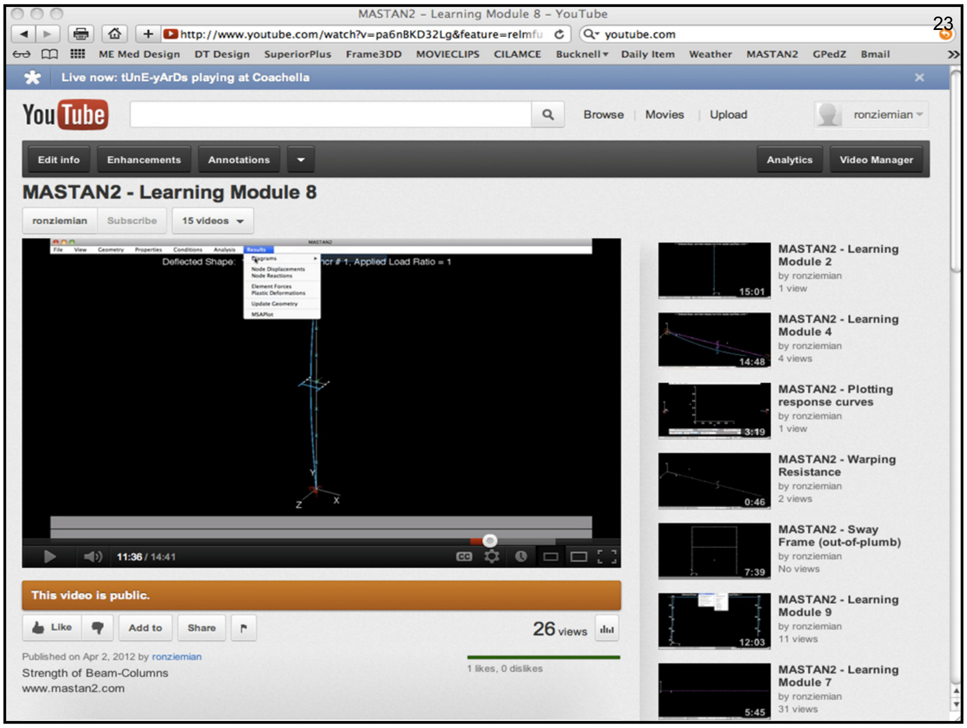
# Overview of Learning Modules

✓ Objectives

- Have "fun" focusing on the stability of members and systems (sorry, no local buckling; CU-FSM!)
- Alternative to experimental laboratory
- Hands-on ("active learning"); what if scenarios?
- Software independent

✓ Consistent format

- Overview
- Learning Objectives
- Method
- Hints
- Questions
- MASTAN2 details
- More fun!
- Resources:
  spreadsheets
  tutorial videos (~140 min)

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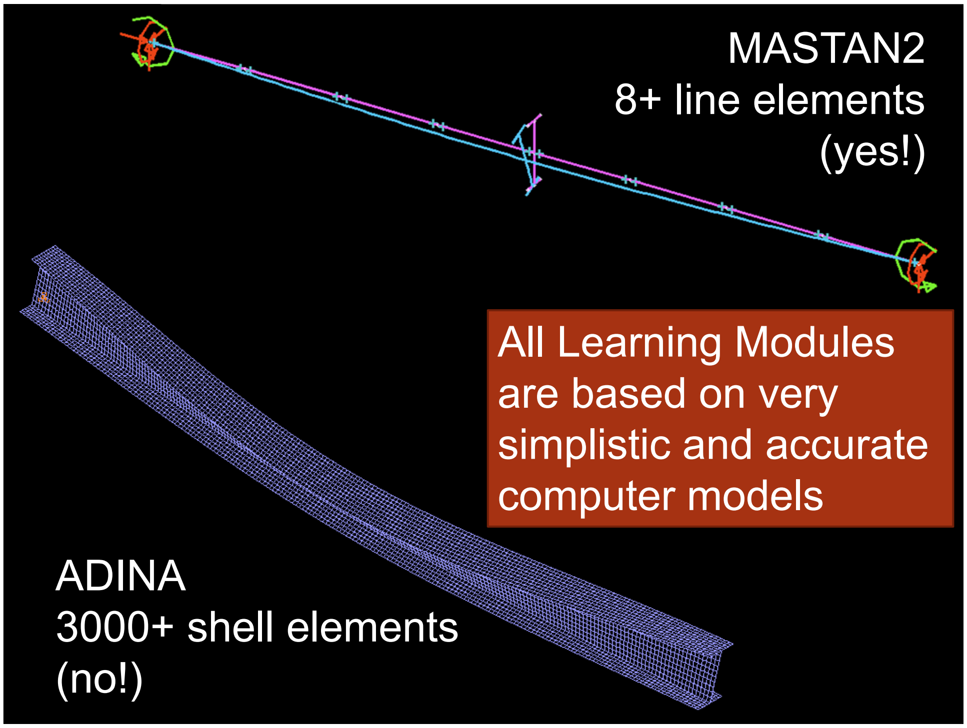
# Overview of Learning Modules

- ✓Students of all ages!
  - Undergraduates
  - Graduate students
  - Professionals
- ✓Courses of all types
  - Steel design / Behavior of metal structures
  - Structural stability
  - Workshops and AISC Night School!
- ✓Similar in concept to others
  - Prof. K. Martini, U.Va.-Architecture, Arcade
  - Prof. G. Miller, U.W.-CEE, Dr-Frame

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# Available Learning Modules

1. Elastic Column Buckling and the Effect of End Restraint
2. Factors Influencing the Flexural Buckling Strength of Compression Members
3. Effective Length *K*-factors for Frame Members
4. Factors Influencing the Strength of Flexural Members
5. Lateral-Torsional Buckling of Beams with Moment Gradient
6. Beam Design by Elastic and Inelastic Analyses
7. Second-order ($P$-$\Delta$ and $P$-$\delta$) Effects
8. Strength of Beam-Columns
9. Design by the Direct Analysis Method


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# LM1. Elastic Column Buckling and the Effect of End Restraint

## Learning Objectives

- Verify theoretical elastic column buckling solutions
- Observe impact of end restraint on capacity and buckled shape
- Confirm the *K*-factors appearing in AISC Table C-A-7.1

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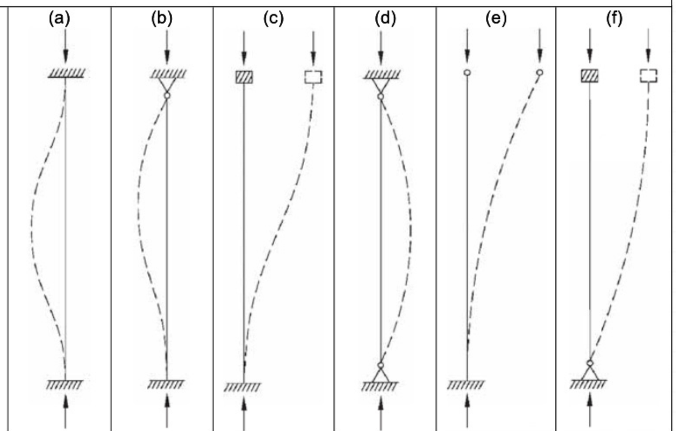
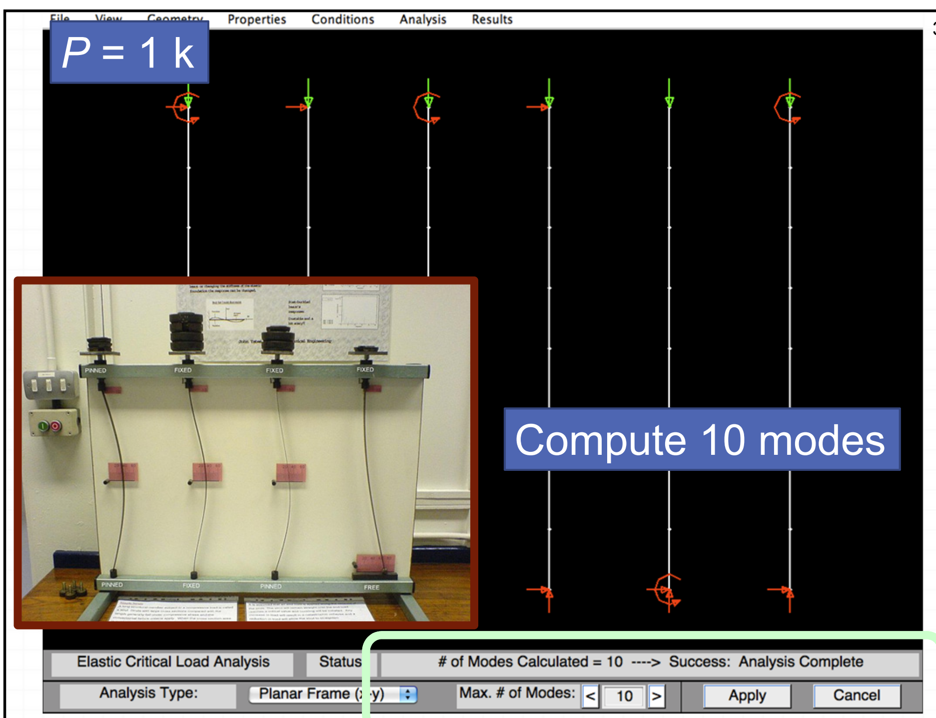
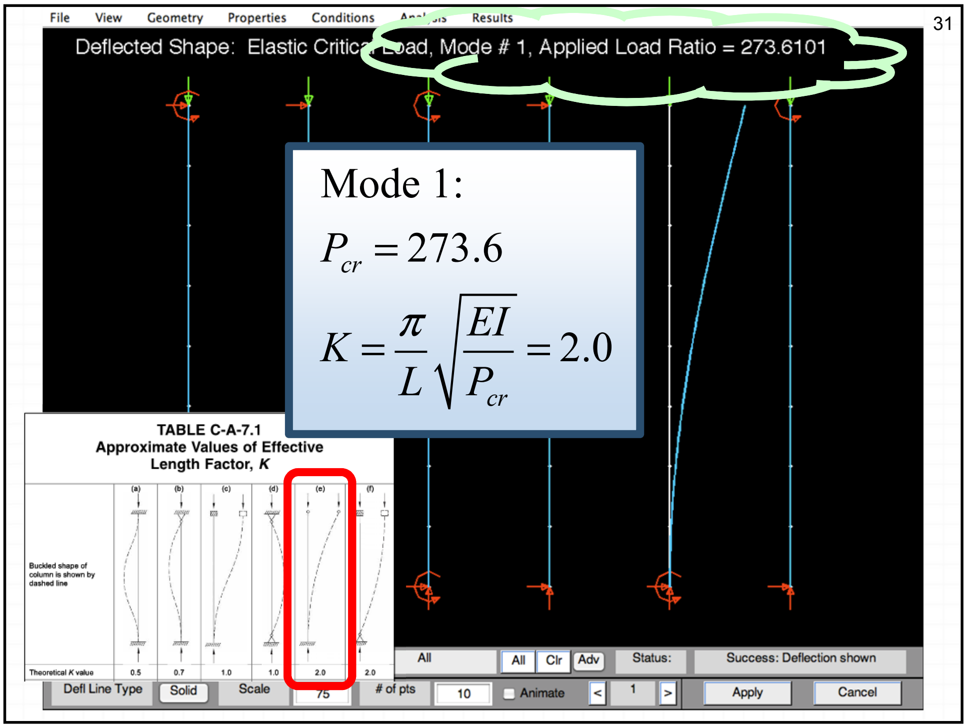
**TABLE C-A-7.1**
**Approximate Values of Effective Length Factor, *K***

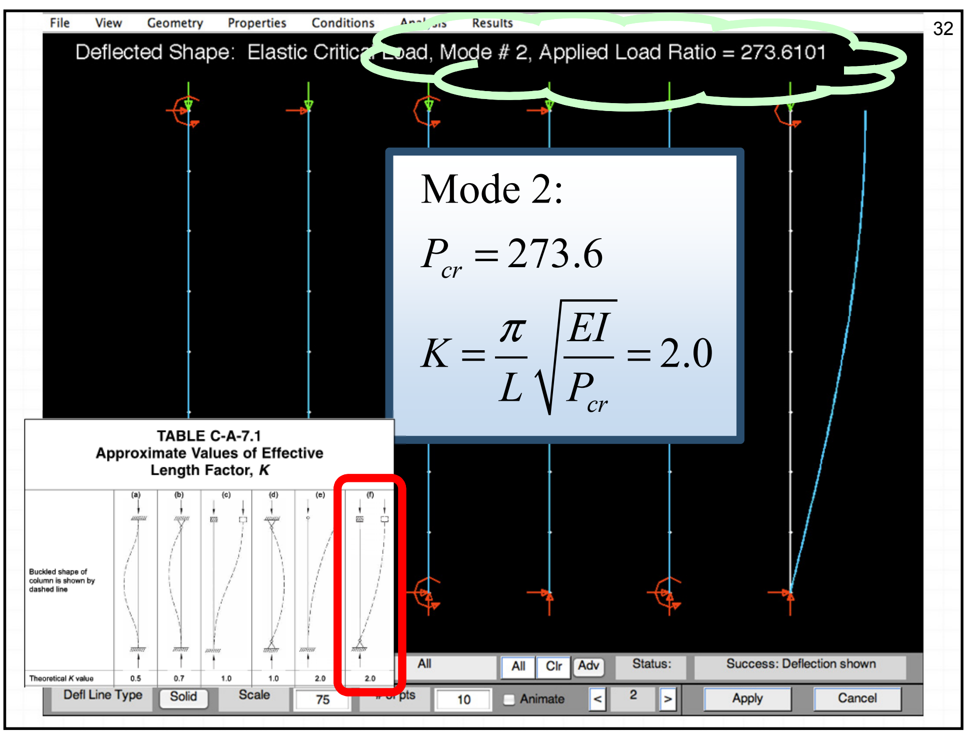
| | (a) | (b) | (c) | (d) | (e) | (f) |
|---|---|---|---|---|---|---|
| Buckled shape of column is shown by dashed line |  | | | | | |
| Theoretical *K* value | 0.5 | 0.7 | 1.0 | 1.0 | 2.0 | 2.0 |

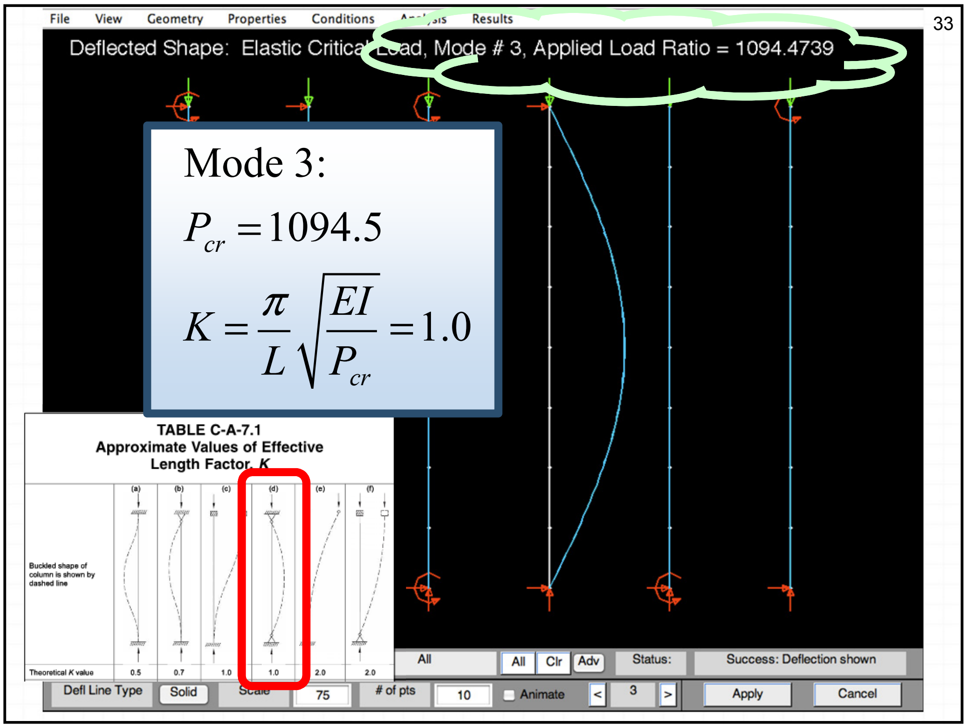
First big Q: # of elements to model compression member?

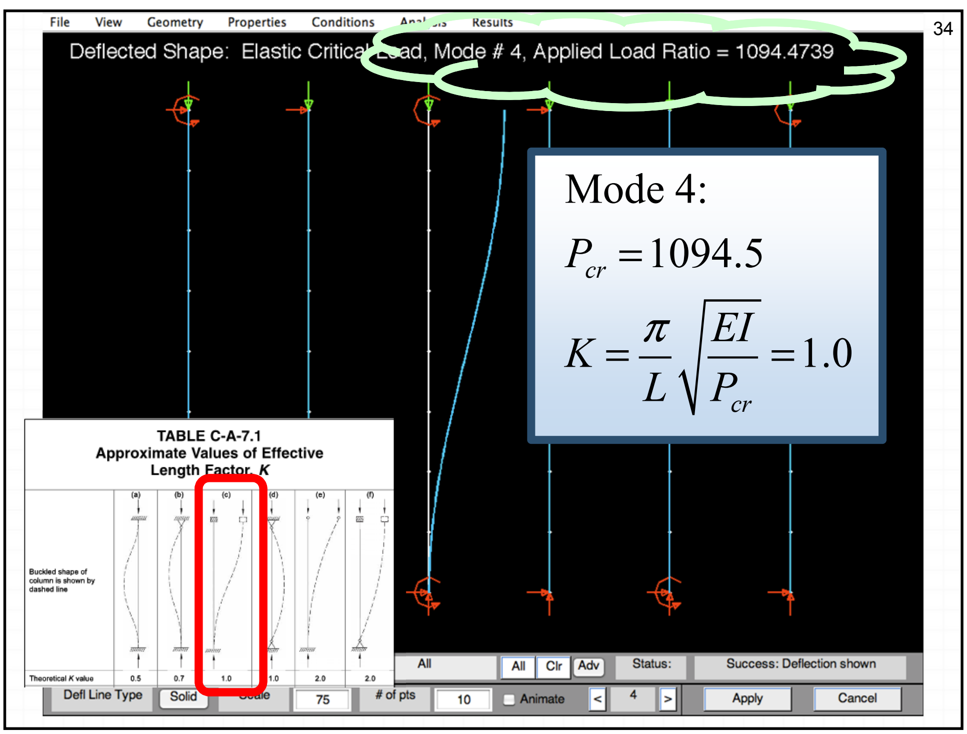
30

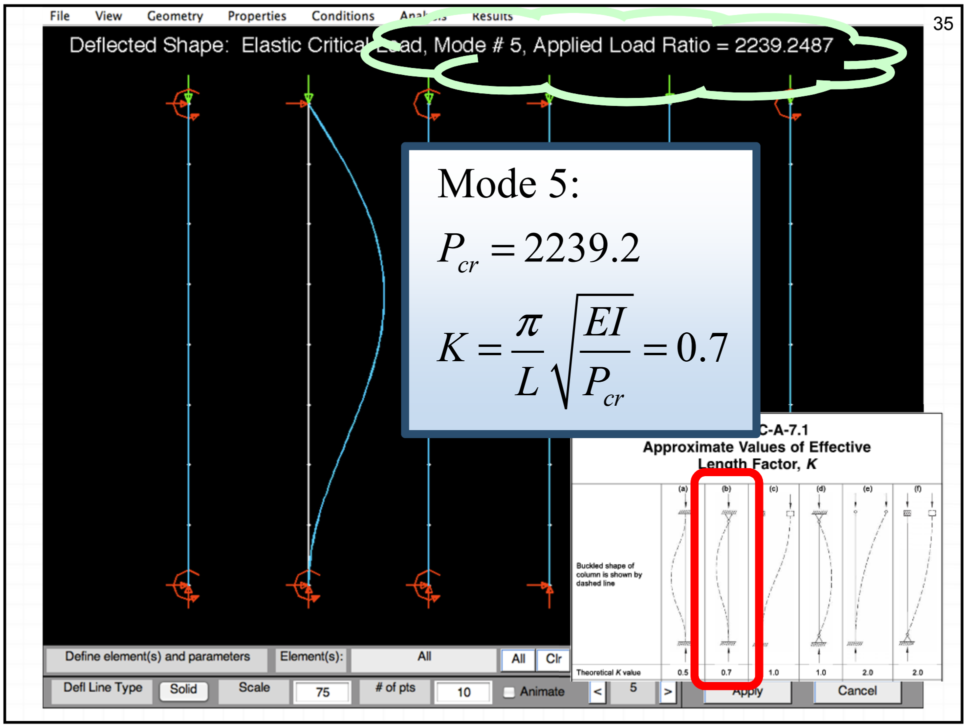


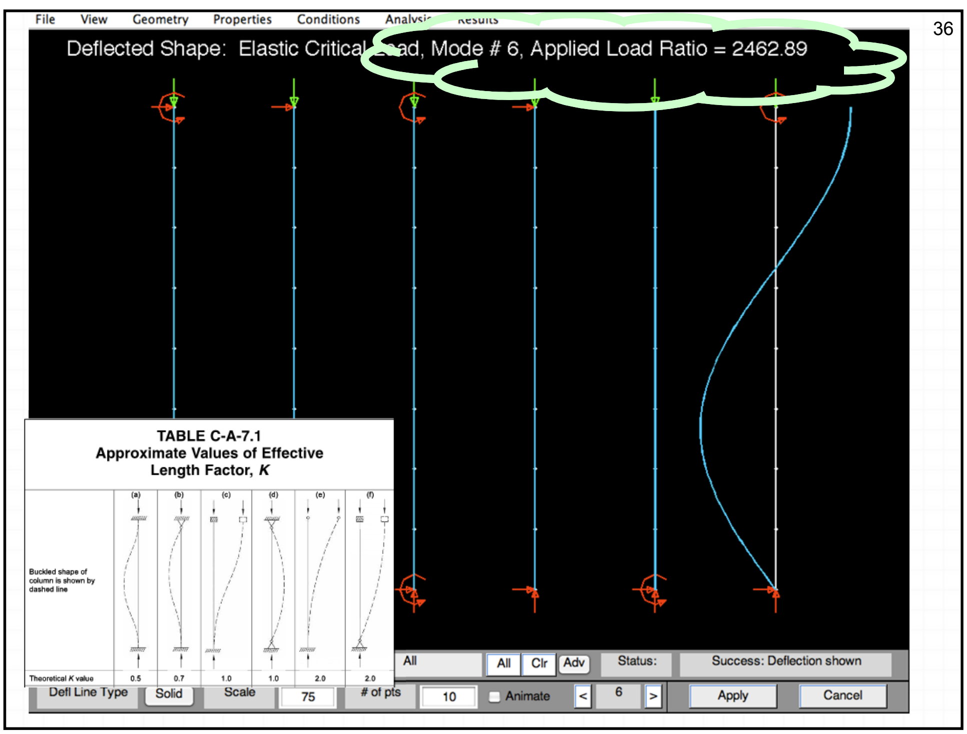

31
File
View
Geometry
Properties
Conditions
Results
Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio = 273.6101
Mode 1:
$P_{cr} = 273.6$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 2.0$
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value
0.5
0.7
1.0
1.0
2.0
2.0
All
Clr
Adv
Status:
Success: Deflection shown
Defl Line Type
Solid
Scale
75
# of pts
10
Animate
1
Apply
Cancel

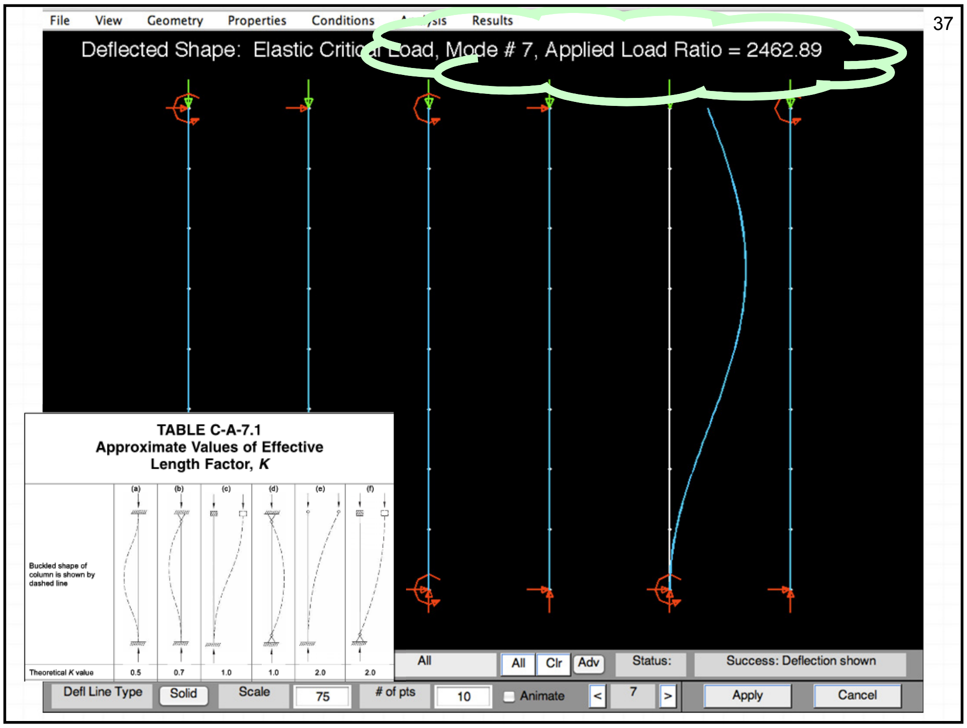

32
File
View
Geometry
Properties
Conditions
Results
Deflected Shape: Elastic Critical Load, Mode # 2, Applied Load Ratio = 273.6101
Mode 2:
$P_{cr} = 273.6$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 2.0$
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value
0.5
0.7
1.0
1.0
2.0
2.0
All
Clr
Adv
Status:
Success: Deflection shown
Defl Line Type
Solid
Scale
75
10
Animate
2
Apply
Cancel

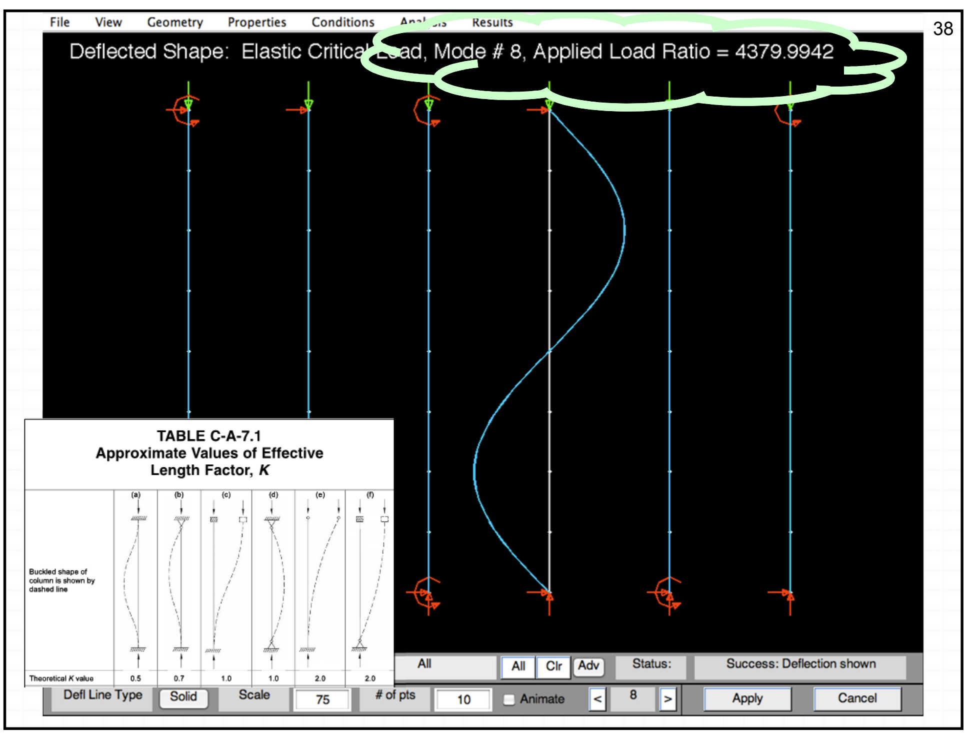

33
File View Geometry Properties Conditions Results
Deflected Shape: Elastic Critical Load, Mode # 3, Applied Load Ratio = 1094.4739
Mode 3:
$P_{cr} = 1094.5$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 1.0$
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
All Clr Adv Status: Success: Deflection shown
Defl Line Type Solid 75 # of pts 10 Animate 3 Apply Cancel

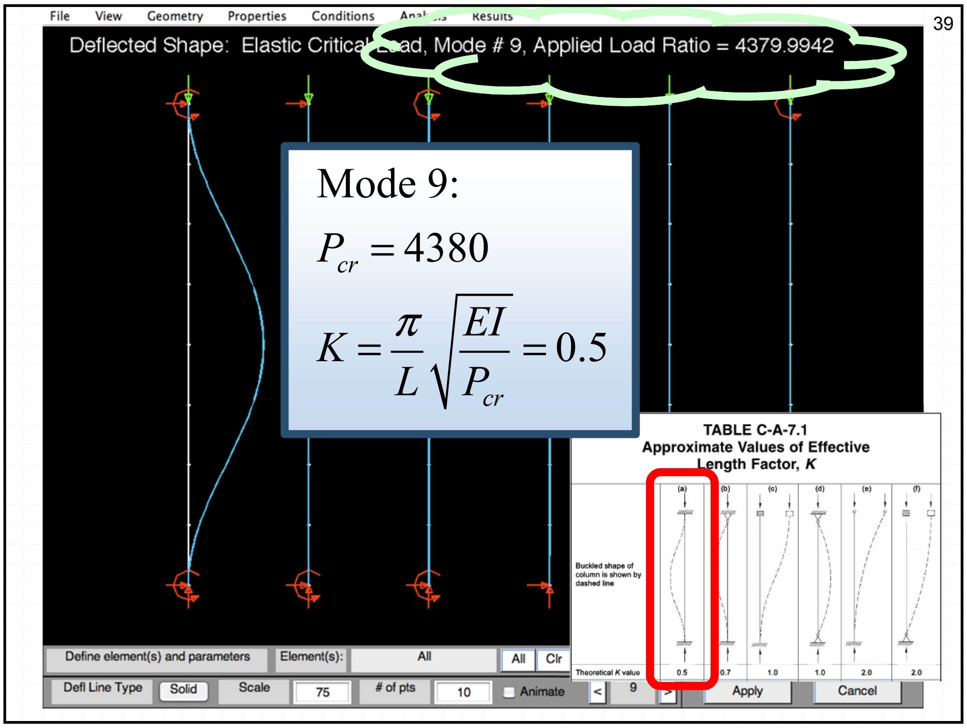

34
File View Geometry Properties Conditions Results
Deflected Shape: Elastic Critical Load, Mode # 4, Applied Load Ratio = 1094.4739
Mode 4:
$P_{cr} = 1094.5$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 1.0$
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
All Clr Adv Status: Success: Deflection shown
Defl Line Type Solid 75 # of pts 10 Animate 4 Apply Cancel

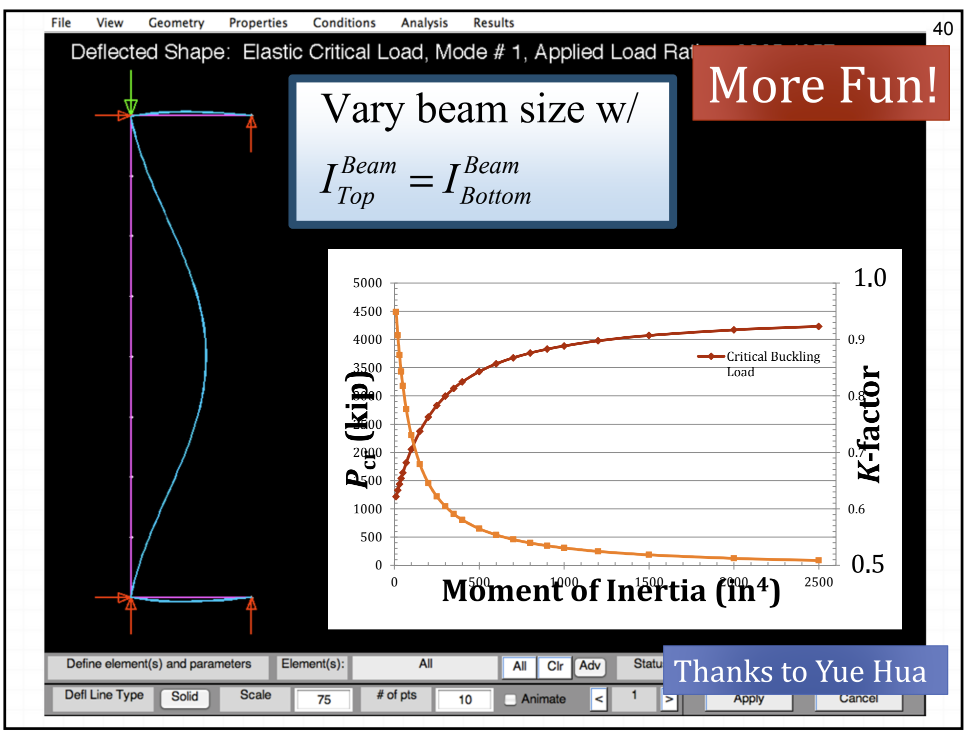

35
File View Geometry Properties Conditions Results
Deflected Shape: Elastic Critical
ad, Mode # 5, Applied Load Ratio = 2239.2487
Mode 5:
$P_{cr} = 2239.2$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 0.7$
C-A-7.1
Approximate Values of Effective
Length Factor, K
(a) (b) (c) (d) (e) (f)
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
Define element(s) and parameters
Element(s):
All
All
Clr
Defl Line Type
Solid
Scale
75
# of pts
10
Animate
5
Cancel

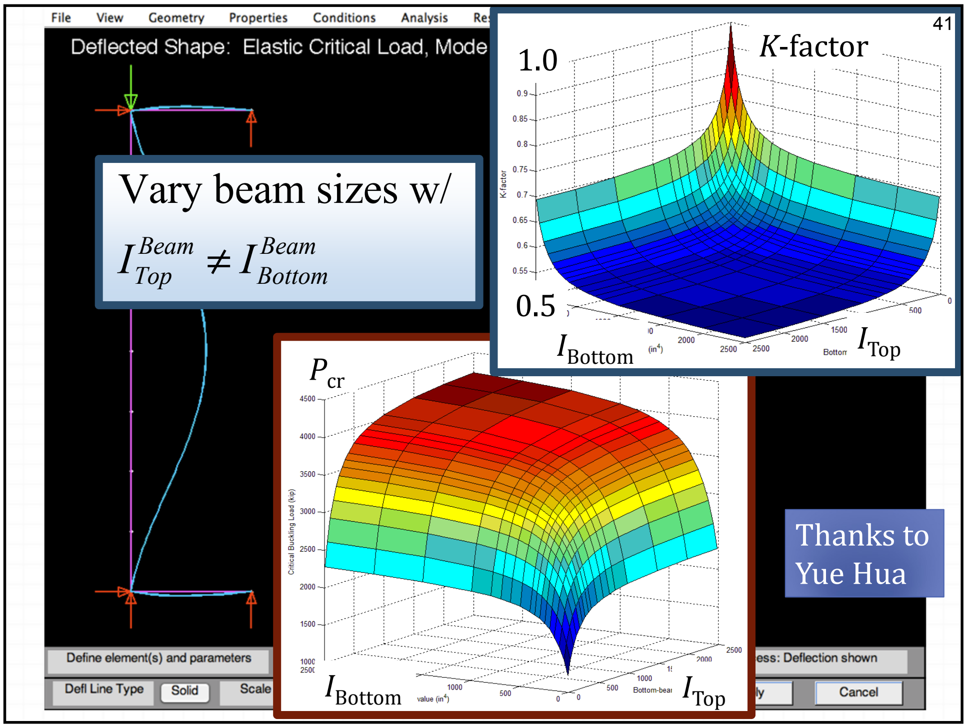

36
File View Geometry Properties Conditions
Deflected Shape: Elastic Critical
ad, Mode # 6, Applied Load Ratio = 2462.89
TABLE C-A-7.1
Approximate Values of Effective
Length Factor, K
(a) (b) (c) (d) (e) (f)
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
All
All
Clr
Adv
Status:
Success: Deflection shown
Defl Line Type
Solid
Scale
75
# of pts
10
Animate
6
Apply
Cancel


37
File View Geometry Properties Conditions Results
Deflected Shape: Elastic Critical Load, Mode # 7, Applied Load Ratio = 2462.89
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
All
All Clr Adv
Status:
Success: Deflection shown
Defl Line Type Solid Scale 75 # of pts 10 Animate 7
Apply
Cancel


38
File View Geometry Properties Conditions Results
Deflected Shape: Elastic Critical Load, Mode # 8, Applied Load Ratio = 4379.9942
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value 0.5 0.7 1.0 1.0 2.0 2.0
All
All Clr Adv
Status:
Success: Deflection shown
Defl Line Type Solid Scale 75 # of pts 10 Animate 8
Apply
Cancel


39
Deflected Shape: Elastic Critical Load, Mode # 9, Applied Load Ratio = 4379.9942
Mode 9:
$P_{cr} = 4380$
$K = \frac{\pi}{L}\sqrt{\frac{EI}{P_{cr}}} = 0.5$
TABLE C-A-7.1
Approximate Values of Effective Length Factor, K
Buckled shape of column is shown by dashed line
Theoretical K value
0.5
0.7
1.0
1.0
2.0
2.0
Define element(s) and parameters
Element(s):
All
Clr
Defl Line Type
Solid
Scale
75
# of pts
10
Animate
9
Apply
Cancel


40
Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Rat
More Fun!
Vary beam size w/
$I^{Beam}_{Top} = I^{Beam}_{Bottom}$
$P_{cr}$ (kip)
K-factor
Moment of Inertia (in$^4$)
Critical Buckling Load
1.0
0.5
Define element(s) and parameters
Element(s):
All
Clr
Adv
Defl Line Type
Solid
Scale
75
# of pts
10
Animate
1
Thanks to Yue Hua




42

# LM2. Factors Influencing the Flexural Buckling Strength of Compression Members

Learning Objectives

- Recognize limitations of theoretical Euler buckling solution
- Prepare column curves ($F_{cr}$ vs. $L/r$)
- Observe impact of initial imperfections and residual stresses
- Compare results to AISC column curve

43

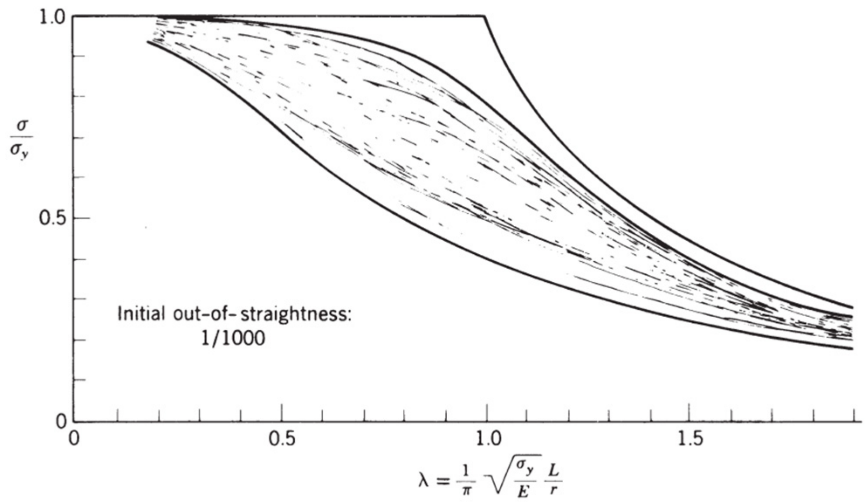
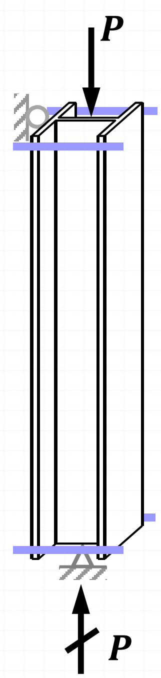


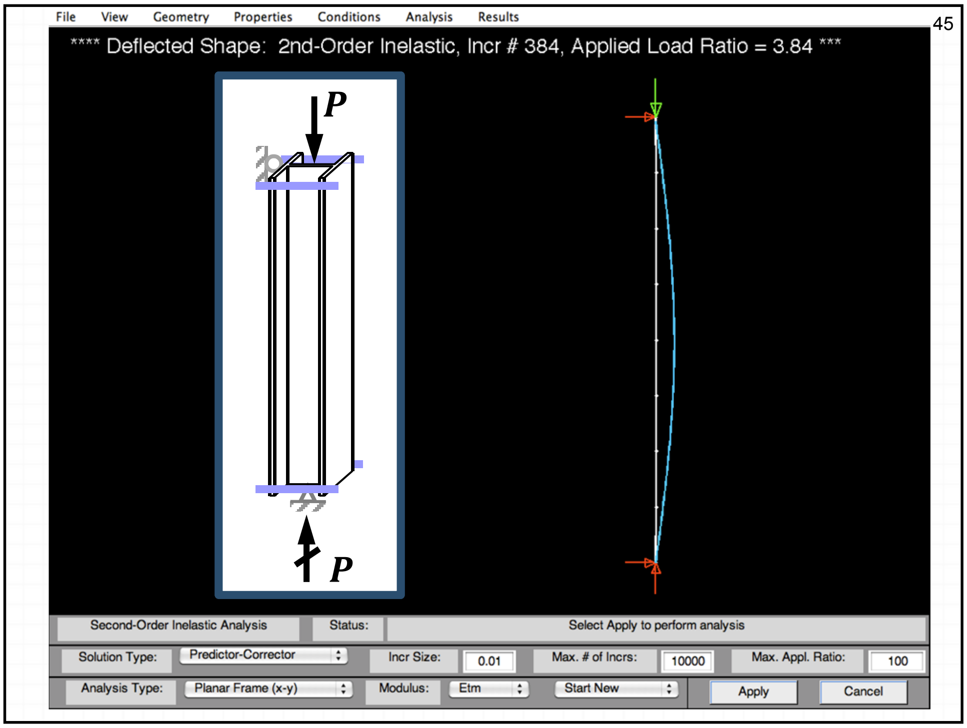

**FIGURE 3.22** Maximum-strength column curves for a number of different column types (Bjorhovde, 1972).

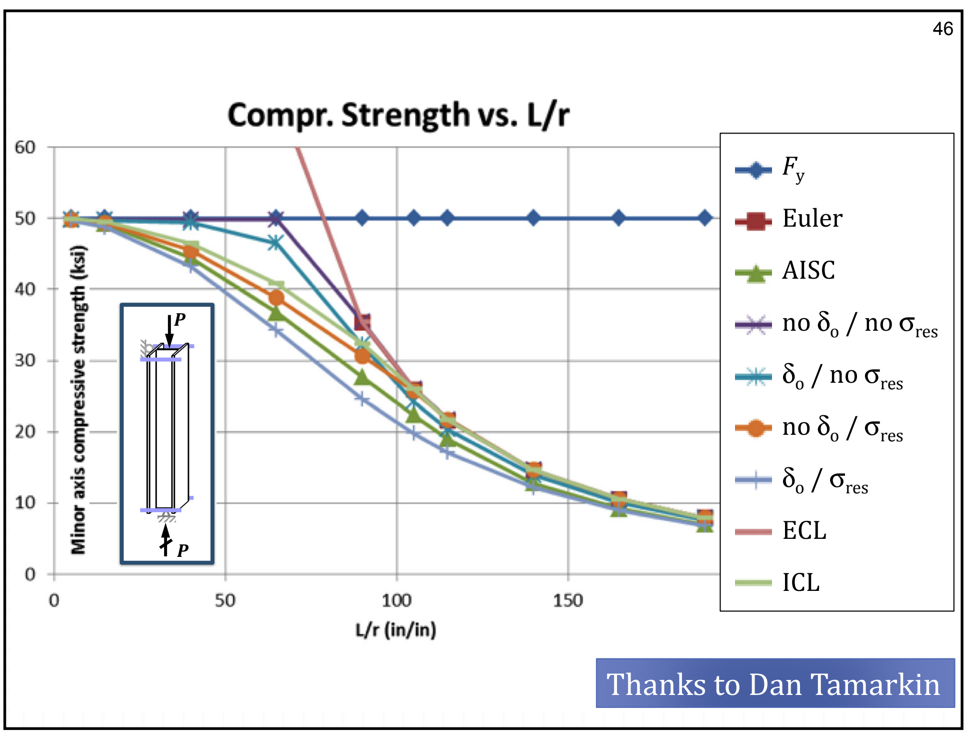
44

# LM2

- ✓W14x53 (A992)
- ✓$L/r_y$ = 5 to 190
- ✓For each $L/r_y$, investigate 9 cases:
  - Full yield
  - Euler
  - AISC
  - Computational analysis
    - Incremental
      - no imperfection $\delta_o$ / no $\sigma_{res}$
      - imperfection $\delta_o$ / no $\sigma_{res}$
      - no imperfection $\delta_o$ / $\sigma_{res}$
      - imperfection $\delta_o$ / $\sigma_{res}$
    - Critical Load (eigenvalue)
      - elastic
      - inelastic




45
File View Geometry Properties Conditions Analysis Results
**** Deflected Shape: 2nd-Order Inelastic, Incr # 384, Applied Load Ratio = 3.84 ***
P
P
Second-Order Inelastic Analysis
Status:
Select Apply to perform analysis
Solution Type:
Predictor-Corrector
Incr Size:
0.01
Max. # of Incrs:
10000
Max. Appl. Ratio:
100
Analysis Type:
Planar Frame (x-y)
Modulus:
Etm
Start New
Apply
Cancel


46
Compr. Strength vs. L/r
Minor axis compressive strength (ksi)
L/r (in/in)
0
10
20
30
40
50
60
0
50
100
150
P
P
$F_y$
Euler
AISC
no $\delta_o$ / no $\sigma_{res}$
$\delta_o$ / no $\sigma_{res}$
no $\delta_o$ / $\sigma_{res}$
$\delta_o$ / $\sigma_{res}$
ECL
ICL
Thanks to Dan Tamarkin

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# LM3. Effective Length *K*-factors for Frame Members

Learning Objectives

- Elastic/inelastic buckling of frames with sidesway inhibited/uninhibited
- Back-calculate *K*-factors from elastic/inelastic critical load analyses
- Employ alignment charts to obtain elastic/inelastic *K*-factors and assess alignment chart assumptions
- Compare alignment chart and computational results

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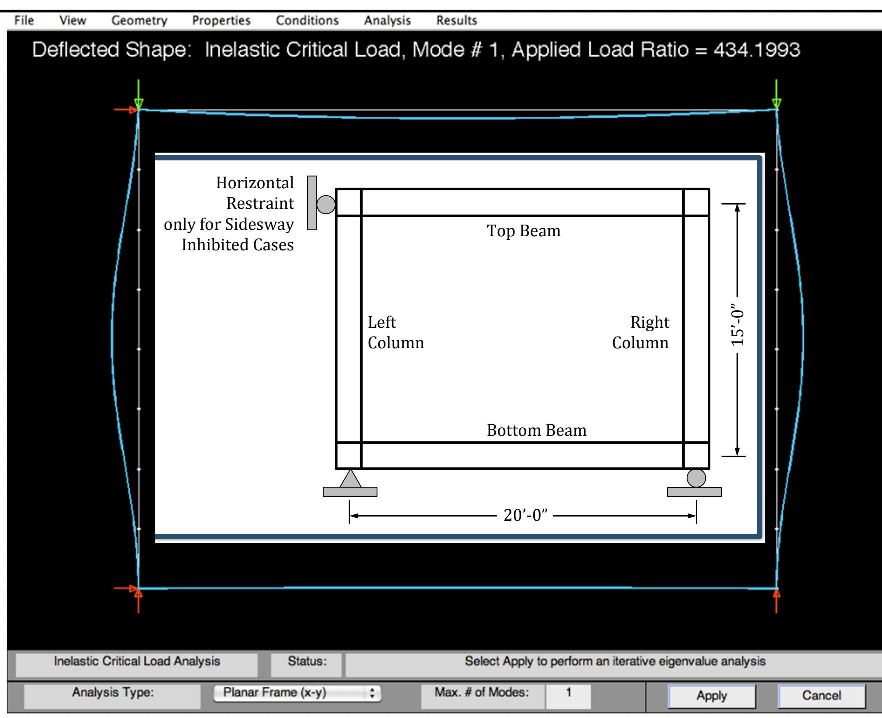

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# LM4. Factors Influencing the Strength of Flexural Members

Learning Objectives

- Recognize limitations of theoretical elastic lateral-torsional buckling solution
- Prepare beam curves ($M_n$ vs. $L_b$).
- Impact that partial yielding/residual stresses and out-of-straightness on elastic/inelastic LTB strength
- Compare with AISC beam strength curve

Sister to LM2…

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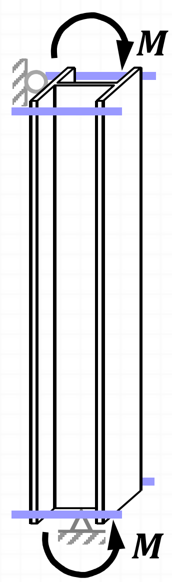
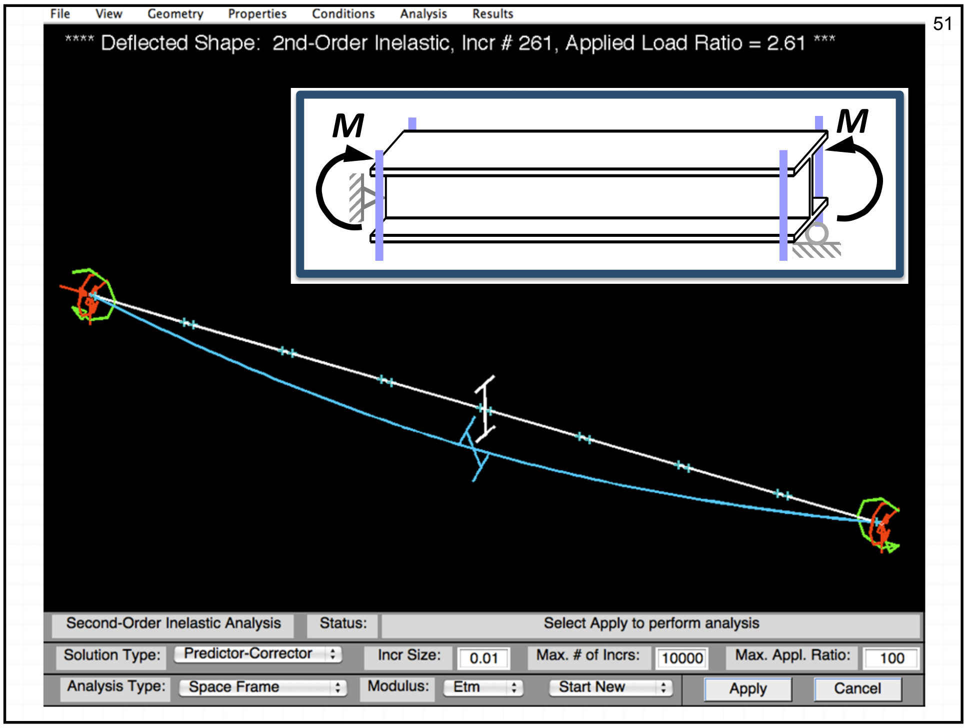
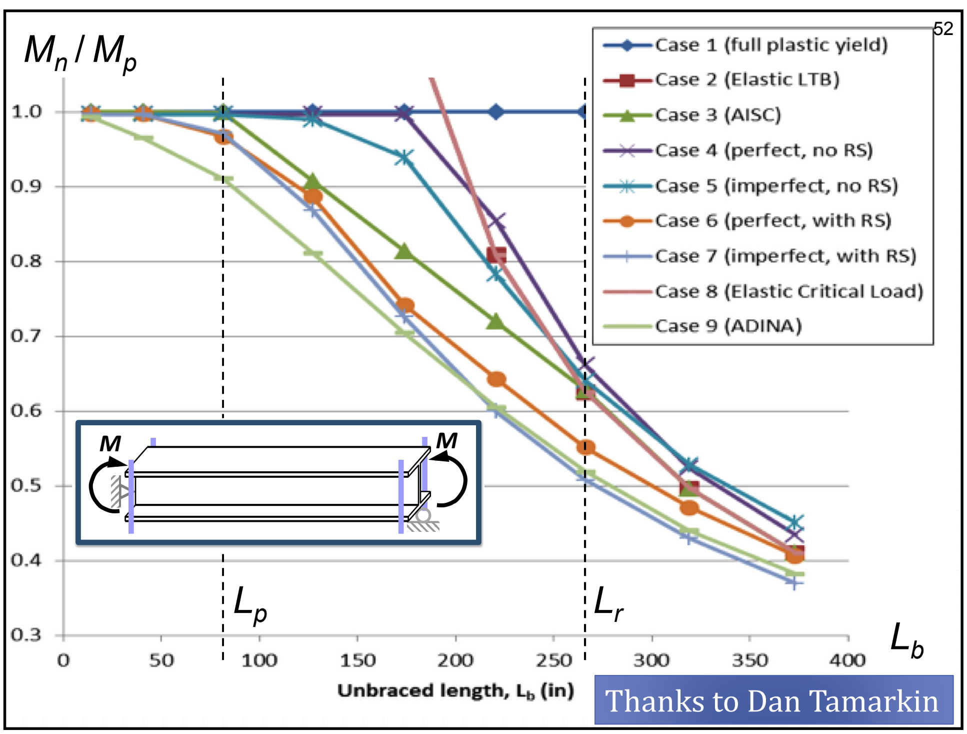
# LM4

- ✓W14x53 (A992)
- ✓$L_b$ = 1.2 to 31.1 ft.
- ✓For each $L_b$, investigate 9 cases:
  - Full yield
  - Theoretical elastic LTB
  - AISC
  - Computational analysis
    - Incremental
      - no imperfection $\delta_o$ / no $\sigma_{res}$
      - imperfection $\delta_o$ / no $\sigma_{res}$
      - no imperfection $\delta_o$ / $\sigma_{res}$
      - imperfection $\delta_o$ / $\sigma_{res}$
    - Elastic critical load (eigenvalue)
    - FEA shell elements (ADINA)




File
View
Geometry
Properties
Conditions
Analysis
Results
51
**** Deflected Shape: 2nd-Order Inelastic, Incr # 261, Applied Load Ratio = 2.61 ***
M
M
Second-Order Inelastic Analysis
Status:
Select Apply to perform analysis
Solution Type:
Predictor-Corrector
Incr Size:
0.01
Max. # of Incrs:
10000
Max. Appl. Ratio:
100
Analysis Type:
Space Frame
Modulus:
Etm
Start New
Apply
Cancel


52
Mn / Mp
Case 1 (full plastic yield)
Case 2 (Elastic LTB)
Case 3 (AISC)
Case 4 (perfect, no RS)
Case 5 (imperfect, no RS)
Case 6 (perfect, with RS)
Case 7 (imperfect, with RS)
Case 8 (Elastic Critical Load)
Case 9 (ADINA)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
M
M
Lp
Lr
Lb
0
50
100
150
200
250
300
350
400
Unbraced length, Lb (in)
Thanks to Dan Tamarkin

53

# LM5. Lateral-Torsional Buckling of Beams with Moment Gradient

Learning Objectives

- Effect of non-uniform moment distribution on elastic LTB strength
- Back-calculate $C_b$ from critical load analyses
- Compute $C_b$ from well-established equations and compare with computational results
- Investigate moment gradient distributions of linear, bi-linear, and parabolic
- Study impact of adding an interior brace point

54

## LM5

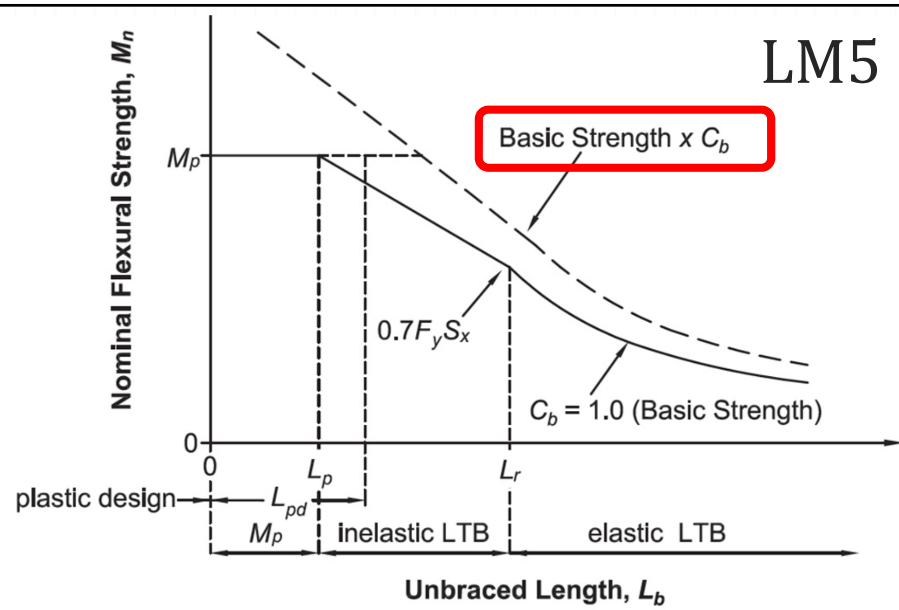
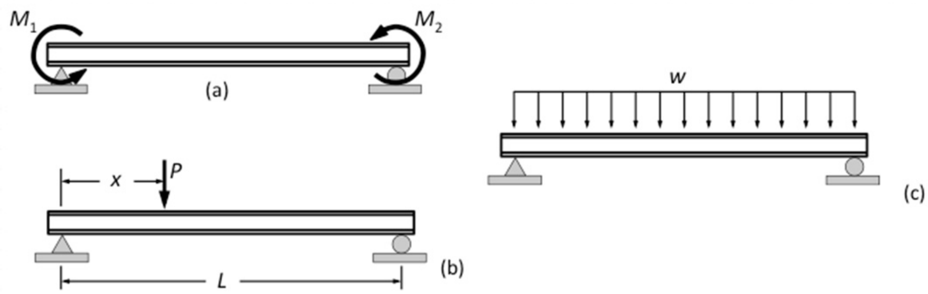



*Fig. C-F1.2. Nominal flexural strength as a function of unbraced length and moment gradient.*

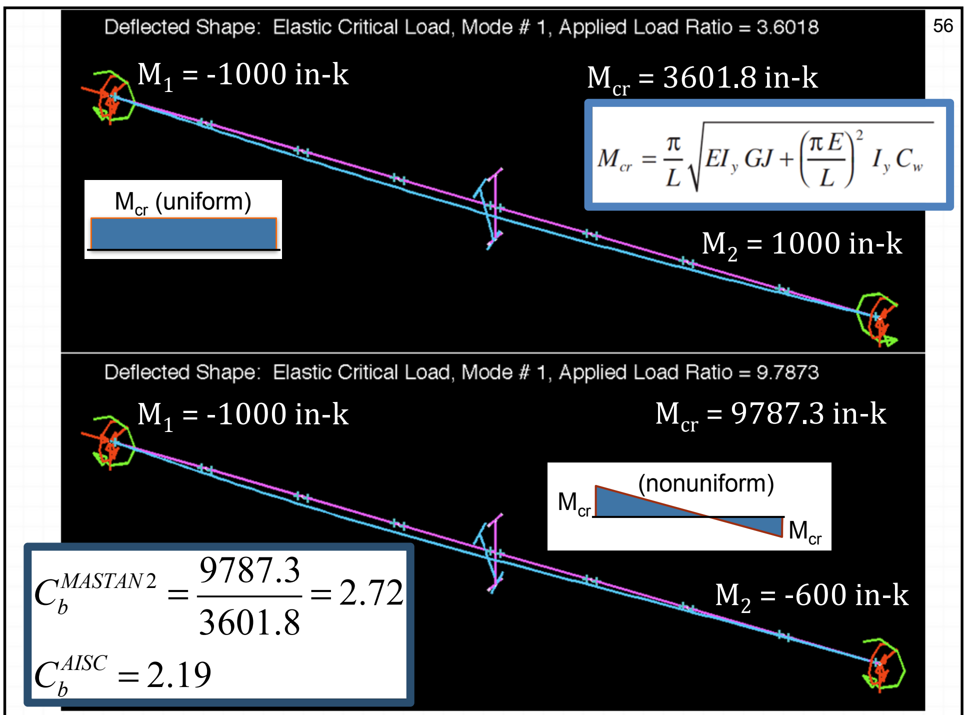
55

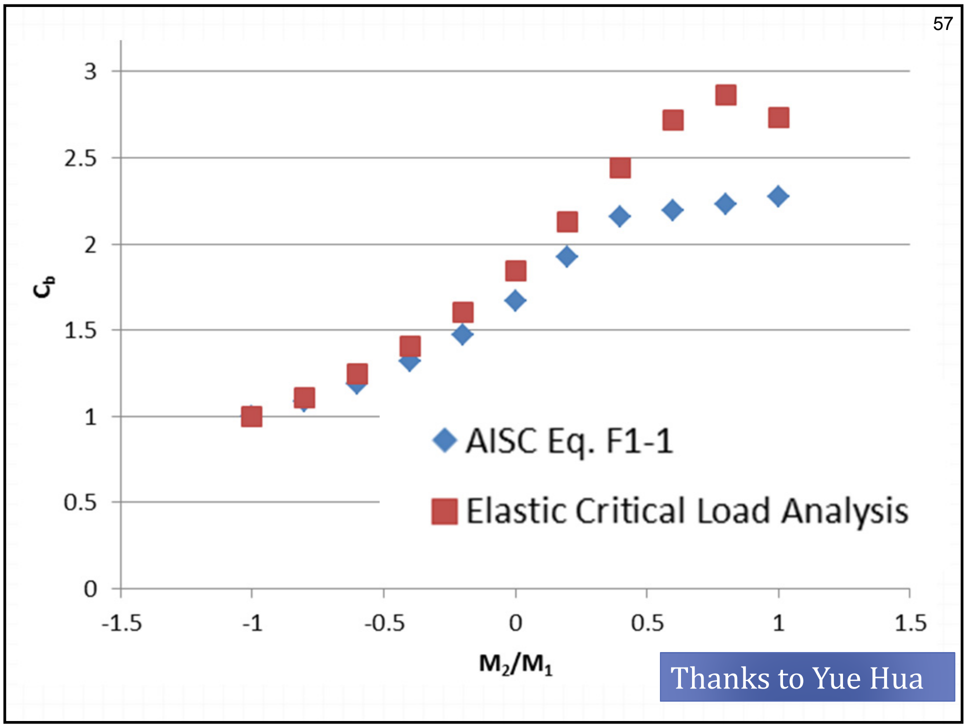
# LM5

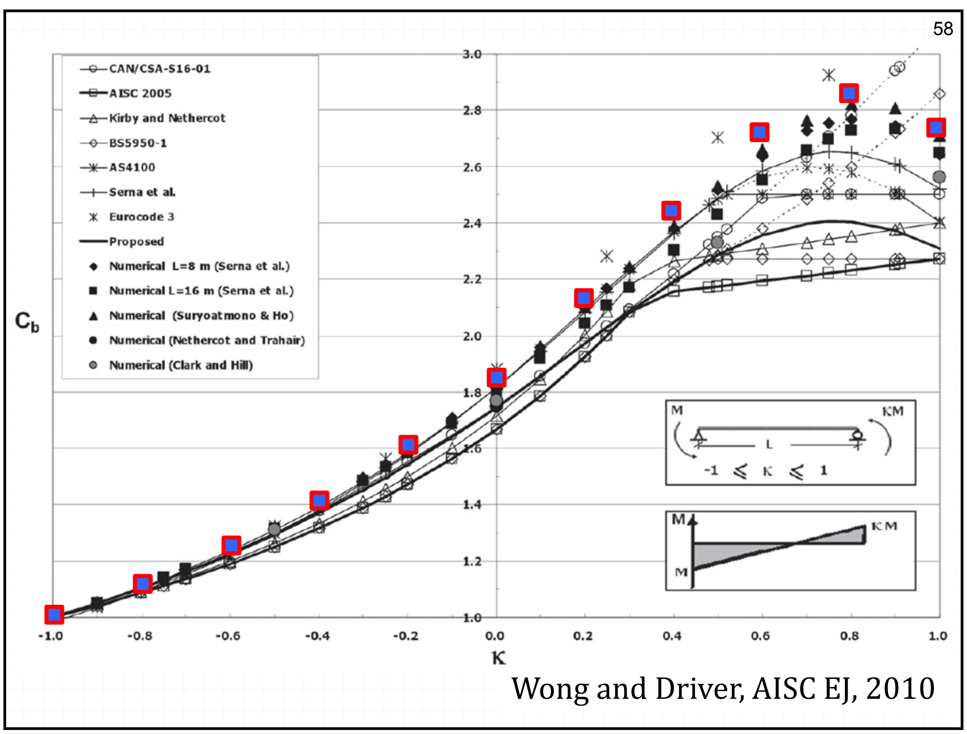



$$C_b = \frac{12.5M_{max}}{2.5M_{max} + 3M_A + 4M_B + 3M_C}$$

56



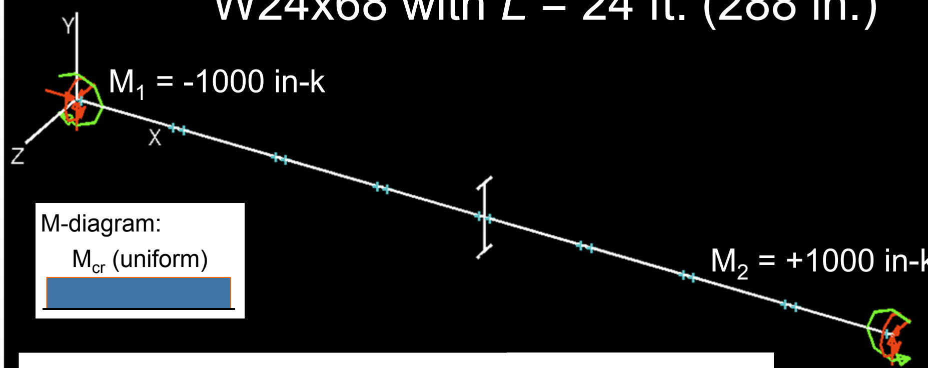

57
$C_b$
$M_2/M_1$
AISC Eq. F1-1
Elastic Critical Load Analysis
Thanks to Yue Hua


58
CAN/CSA-S16-01
AISC 2005
Kirby and Nethercot
BS5950-1
AS4100
Serna et al.
Eurocode 3
Proposed
Numerical L=8 m (Serna et al.)
Numerical L=16 m (Serna et al.)
Numerical (Suryoatmono & Ho)
Numerical (Nethercot and Trahair)
Numerical (Clark and Hill)
$C_b$
κ
Wong and Driver, AISC EJ, 2010

File View Geometry Properties Conditions Analysis Results

# Time for you to take it for a spin…

## W24x68 with $L$ = 24 ft. (288 in.)

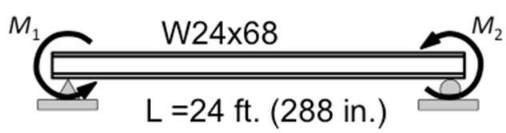



$$M_{cr} = \frac{\pi}{L}\sqrt{EI_y GJ + \left(\frac{\pi E}{L}\right)^2 I_y C_w}$$

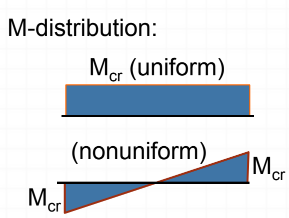
= 3602 kip-in
= 300 kip-ft

59

60

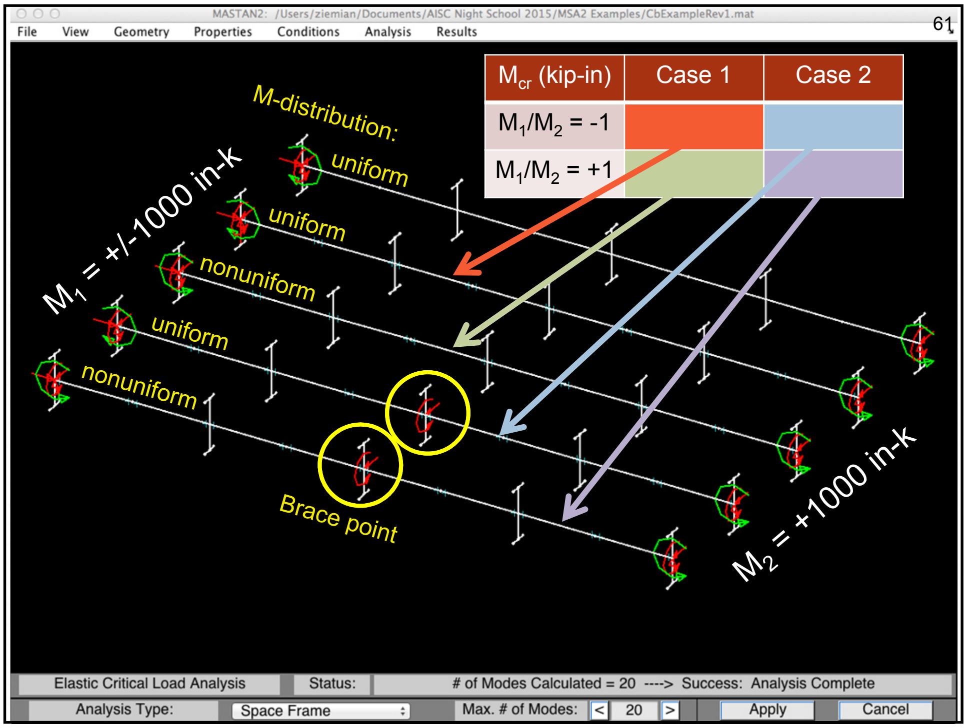


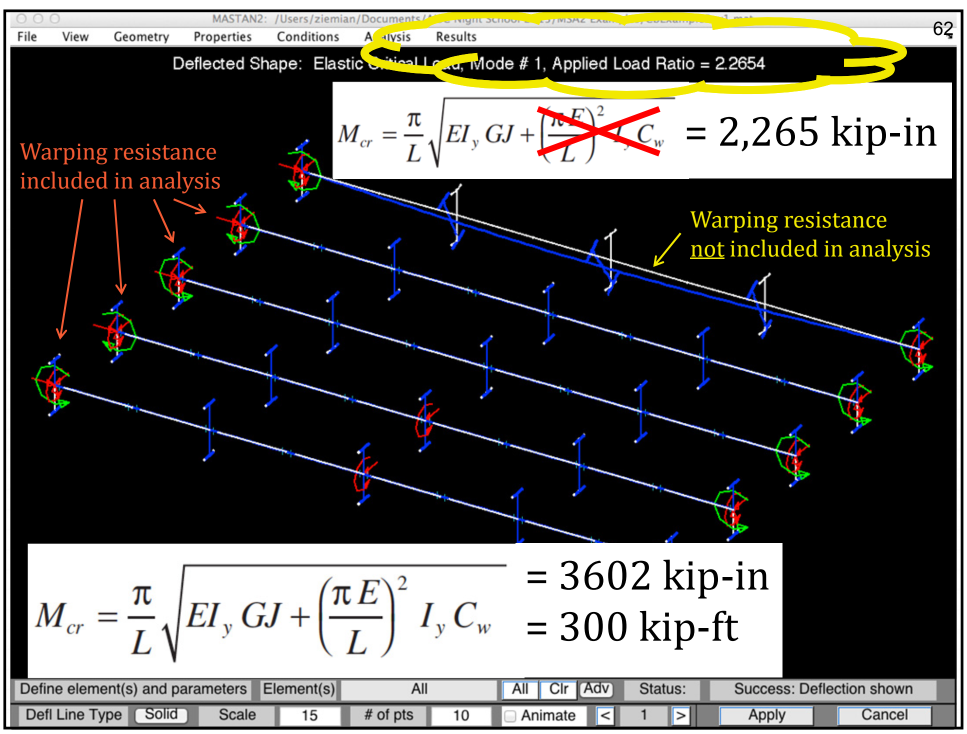

Case 1: Braces at ends
Case 2: Braces at ends and mid-span

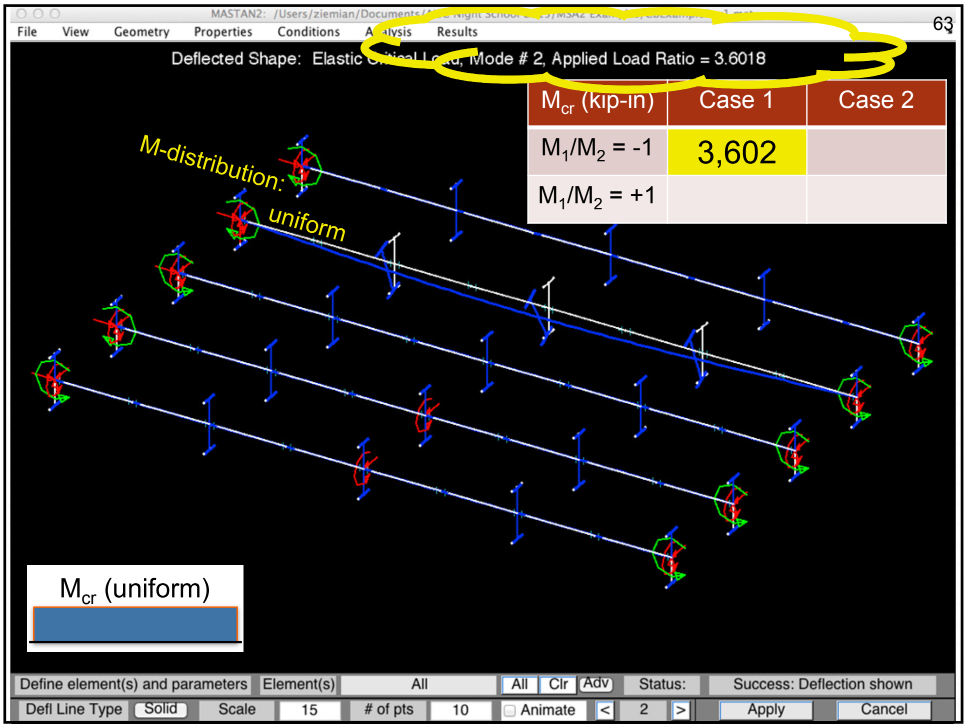


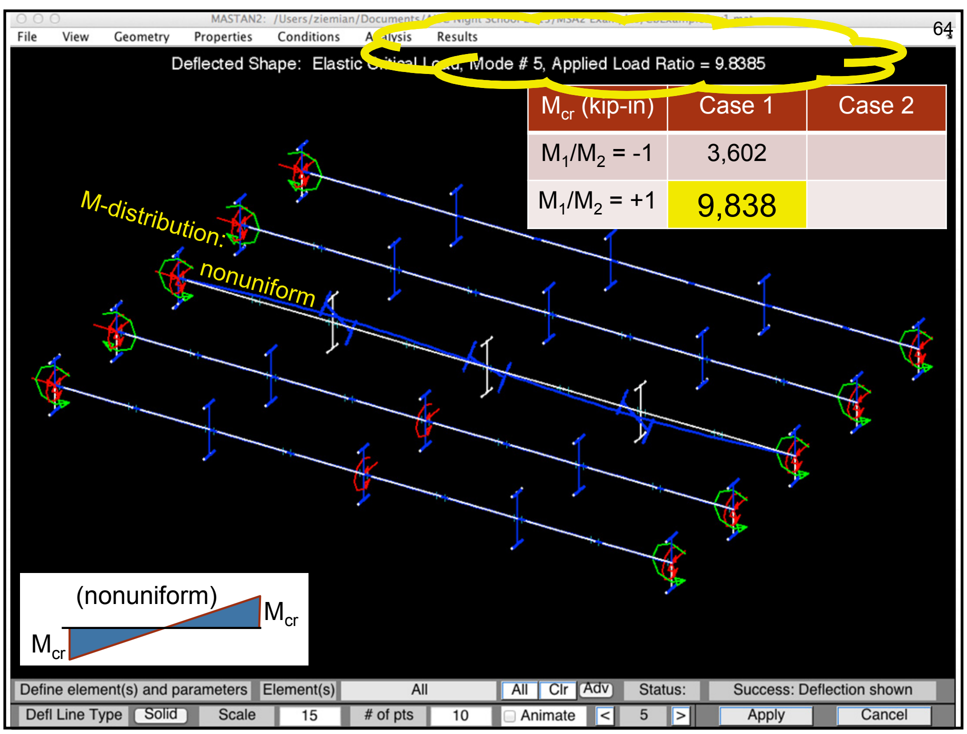

| $M_{cr}$ (kip-in) | Case 1 | Case 2 |
|---|---|---|
| $M_1/M_2$ = -1 | | |
| $M_1/M_2$ = +1 | | |

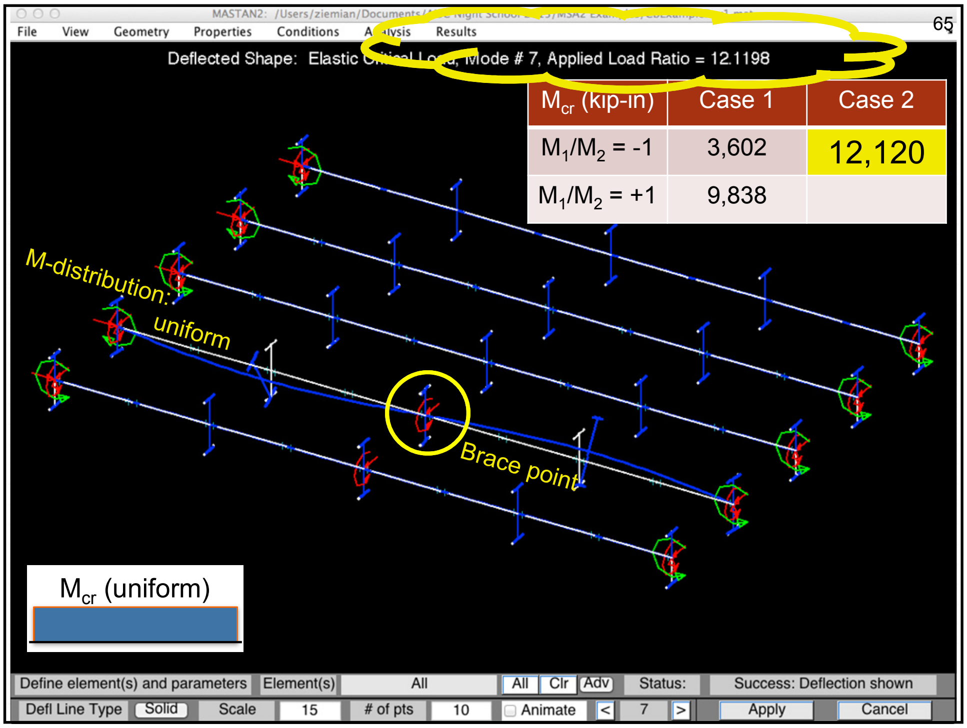
**Observations**:

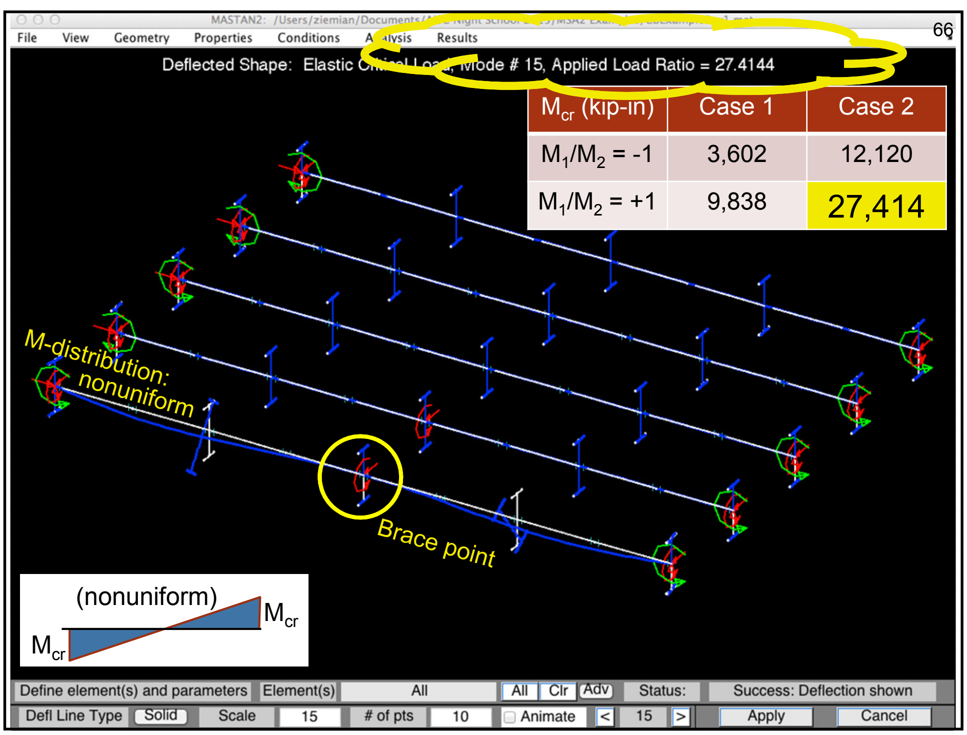

61
MASTAN2: /Users/ziemian/Documents/AISC Night School 2015/MSA2 Examples/CbExampleRev1.mat
File View Geometry Properties Conditions Analysis Results
$M_{cr}$ (kip-in) | Case 1 | Case 2
$M_1/M_2$ = -1
$M_1/M_2$ = +1
M-distribution:
uniform
uniform
nonuniform
uniform
nonuniform
$M_1$ = +/-1000 in-k
$M_2$ = +1000 in-k
Brace point
Elastic Critical Load Analysis
Status:
# of Modes Calculated = 20 ----> Success: Analysis Complete
Analysis Type:
Space Frame
Max. # of Modes:
20
Apply
Cancel

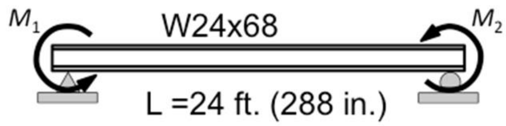

62
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio = 2.2654
$M_{cr} = \frac{\pi}{L}\sqrt{EI_y GJ + \cancel{\left(\frac{\pi E}{L}\right)^2 I_y C_w}}$ = 2,265 kip-in
Warping resistance included in analysis
Warping resistance not included in analysis
$M_{cr} = \frac{\pi}{L}\sqrt{EI_y GJ + \left(\frac{\pi E}{L}\right)^2 I_y C_w}$ = 3602 kip-in = 300 kip-ft
Define element(s) and parameters
Element(s)
All
Clr
Adv
Status:
Success: Deflection shown
Defl Line Type
Solid
Scale
15
# of pts
10
Animate
1
Apply
Cancel


63
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic
Mode # 2, Applied Load Ratio = 3.6018
$M_{cr}$ (kip-in) | Case 1 | Case 2
$M_1/M_2 = -1$ | 3,602
$M_1/M_2 = +1$
M-distribution:
uniform
$M_{cr}$ (uniform)
Define element(s) and parameters | Element(s) | All | All | Clr | Adv | Status: | Success: Deflection shown
Defl Line Type | Solid | Scale | 15 | # of pts | 10 | Animate | < | 2 | > | Apply | Cancel

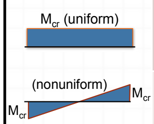

64
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic
Mode # 5, Applied Load Ratio = 9.8385
$M_{cr}$ (kip-in) | Case 1 | Case 2
$M_1/M_2 = -1$ | 3,602
$M_1/M_2 = +1$ | 9,838
M-distribution:
nonuniform
(nonuniform)
$M_{cr}$
$M_{cr}$
Define element(s) and parameters | Element(s) | All | All | Clr | Adv | Status: | Success: Deflection shown
Defl Line Type | Solid | Scale | 15 | # of pts | 10 | Animate | < | 5 | > | Apply | Cancel


65
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic Critical Load, Mode # 7, Applied Load Ratio = 12.1198
$M_{cr}$ (kip-in) | Case 1 | Case 2
$M_1/M_2$ = -1 | 3,602 | 12,120
$M_1/M_2$ = +1 | 9,838 |
M-distribution: uniform
Brace point
$M_{cr}$ (uniform)
Define element(s) and parameters | Element(s) | All | All | Clr | Adv | Status: | Success: Deflection shown
Defl Line Type | Solid | Scale | 15 | # of pts | 10 | Animate | < | 7 | > | Apply | Cancel


66
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic Critical Load, Mode # 15, Applied Load Ratio = 27.4144
$M_{cr}$ (kip-in) | Case 1 | Case 2
$M_1/M_2$ = -1 | 3,602 | 12,120
$M_1/M_2$ = +1 | 9,838 | 27,414
M-distribution: nonuniform
Brace point
(nonuniform)
$M_{cr}$
$M_{cr}$
Define element(s) and parameters | Element(s) | All | All | Clr | Adv | Status: | Success: Deflection shown
Defl Line Type | Solid | Scale | 15 | # of pts | 10 | Animate | < | 15 | > | Apply | Cancel




Case 1: Braces at ends
Case 2: Braces at ends and mid-span




| $M_{cr}$ (kip-in) | Case 1 | Case 2 |
|---|---|---|
| $M_1/M_2 = -1$ | 3,602 | 12,120 |
| $M_1/M_2 = +1$ | 9,838 | 27,414 |

3.36

2.73

7.61

**Observations**:

- $M_{cr}$ increases as $L_b$ is reduced
- $M_{cr}$ increases as moment gradient increases
- An inflection point is not a brace point!



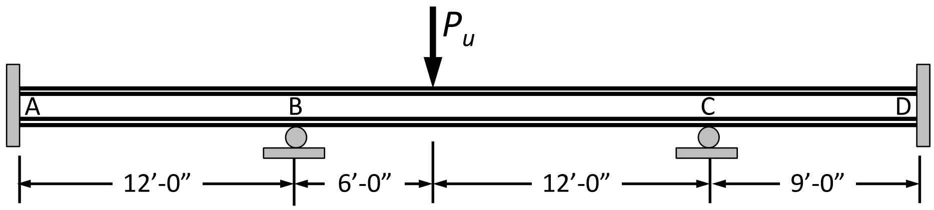
# LM6. Beam Design by Elastic and Inelastic Analyses

Learning Objectives

- Compare designs of continuous beams using elastic and inelastic analyses
- Observe pros and cons of each design method
- Employ AISC's 9/10$^{ths}$ moment redistribution allowance
- Investigate force/moment redistribution that occurs as a result of member yielding.

69

# LM6: Elastic vs. Inelastic Design



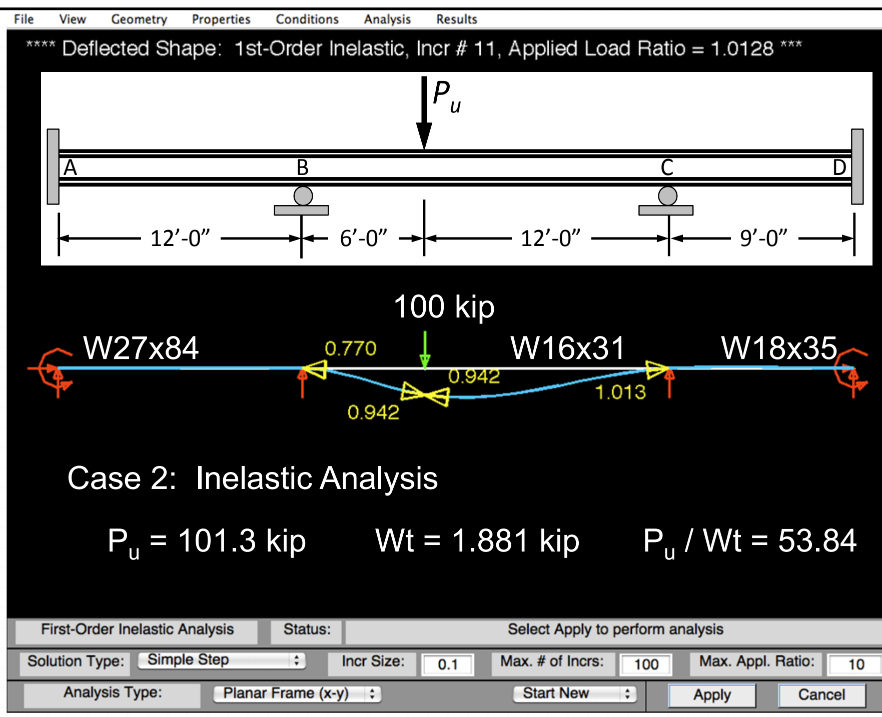

**4 Cases:**

1. All members W16x31, $P_u$ = ?
2. W27x84, W16x31, W18x35, $P_u$= ?
3. All members same size, $P_u$ = 200k, min. weight?
4. Members sizes may vary, $P_u$ = 200k, min. weight?

**3 AISC Designs:**

Elastic vs. Elastic 9/10 vs. Inelastic

70



# LM7. Second-order Effects ($P$-$\Delta$ and $P$-$\delta$) Effects

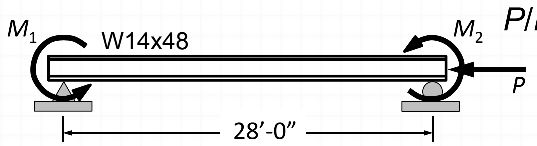
Learning Objectives

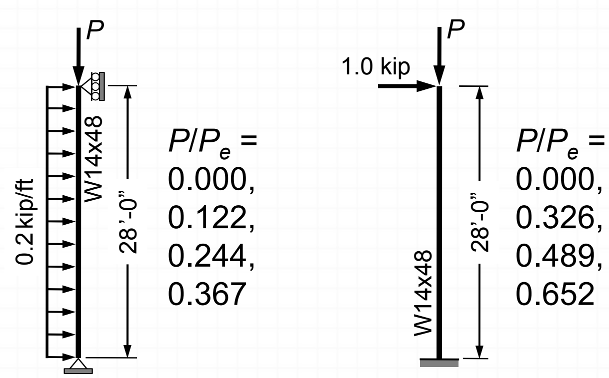
- Employ second-order elastic analysis
- Observe the relationship between extent of moment amplification and $P/P_e$
- Investigate the impact of single or double(reverse) curvature bending has on the degree of moment amplification
- Compute and assess the AISC moment amplification factor $B_1$ defined in App. 8



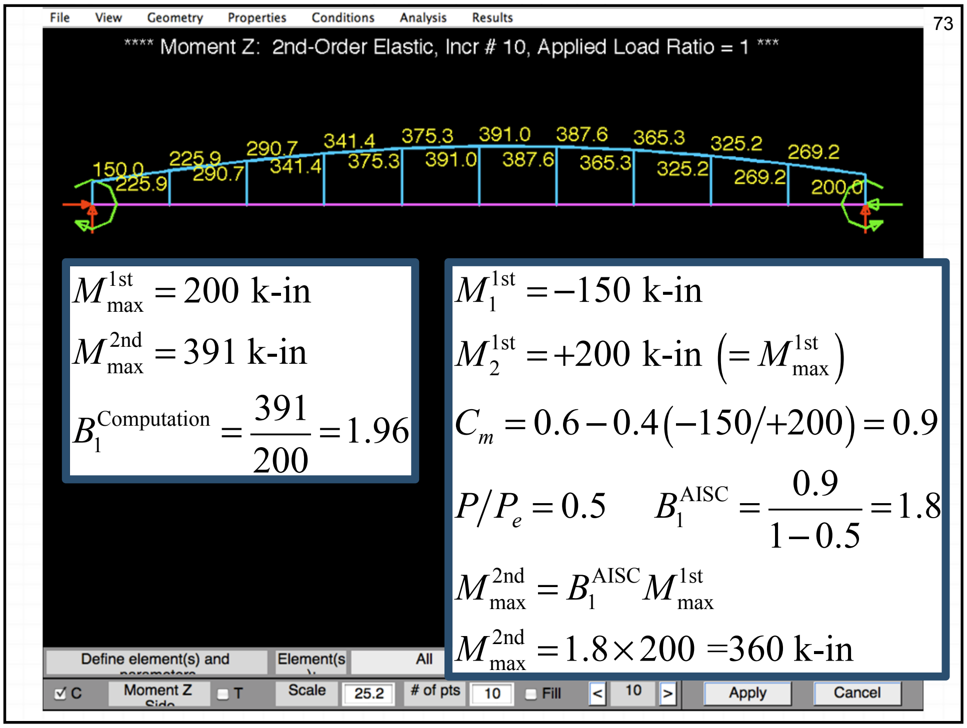
# 1st-order vs. 2nd-order

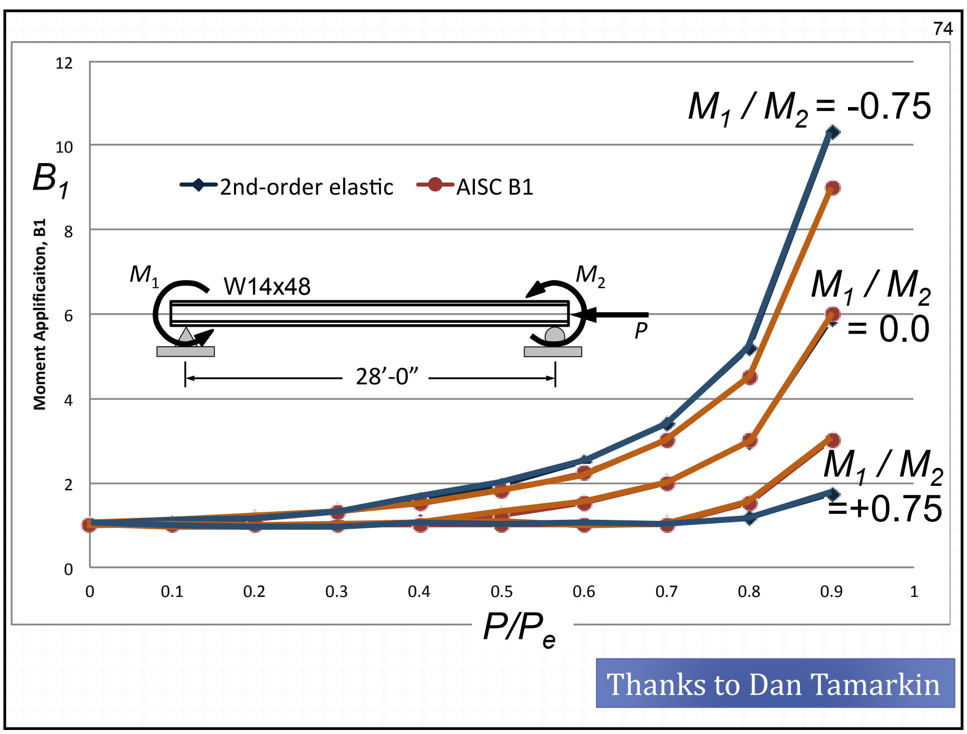
$M_1/M_2$ = +0.75, 0.0, -0.75
$P/P_e$ = 0, 0.1, 0.2,…,0.9



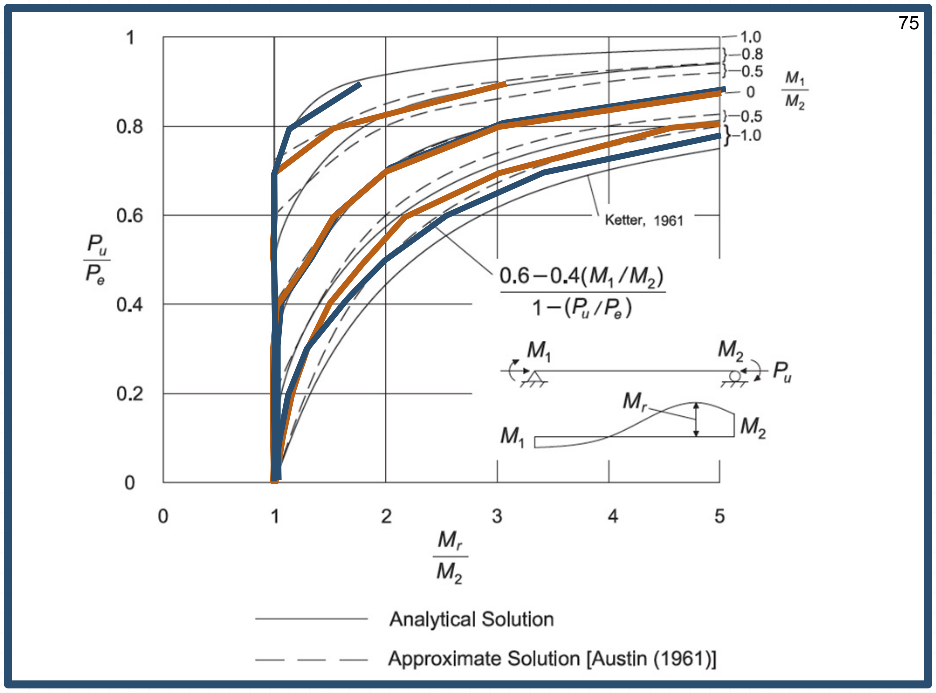




Rigorous
vs.
$B_1$, $B_2$


73
File View Geometry Properties Conditions Analysis Results
**** Moment Z: 2nd-Order Elastic, Incr # 10, Applied Load Ratio = 1 ***
150.0 225.9 225.9 290.7 290.7 341.4 341.4 375.3 375.3 391.0 391.0 387.6 387.6 365.3 365.3 325.2 325.2 269.2 269.2 200.0
$M_{\max}^{\text{1st}} = 200$ k-in
$M_{\max}^{\text{2nd}} = 391$ k-in
$B_1^{\text{Computation}} = \frac{391}{200} = 1.96$
$M_1^{\text{1st}} = -150$ k-in
$M_2^{\text{1st}} = +200$ k-in $\left(= M_{\max}^{\text{1st}}\right)$
$C_m = 0.6 - 0.4\left(-150/{+200}\right) = 0.9$
$P/P_e = 0.5 \quad B_1^{\text{AISC}} = \frac{0.9}{1-0.5} = 1.8$
$M_{\max}^{\text{2nd}} = B_1^{\text{AISC}} M_{\max}^{\text{1st}}$
$M_{\max}^{\text{2nd}} = 1.8 \times 200 = 360$ k-in
Define element(s) and parameters
Element(s)
All
C
Moment Z Side
T
Scale
25.2
# of pts
10
Fill
10
Apply
Cancel


74
$M_1 / M_2 = -0.75$
$B_1$
2nd-order elastic
AISC B1
Moment Applificaiton, B1
$M_1$
W14x48
$M_2$
P
28'-0"
$M_1 / M_2$ = 0.0
$M_1 / M_2$ =+0.75
0 2 4 6 8 10 12
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$P/P_e$
Thanks to Dan Tamarkin

75

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# LM8. Strength of Beam-Columns

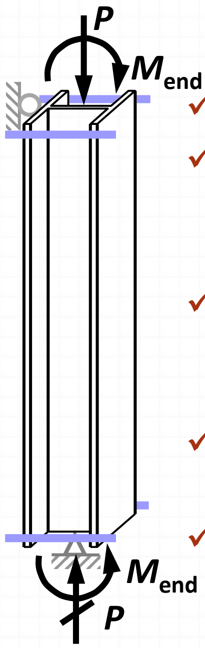
<u>Learning Objectives</u>

- Axial plus major- or minor-axis flexure
- Strength limit state behavior of beam-columns, including full yielding to elastic/inelastic flexural and lateral torsional buckling
- Prepare interaction curves ($P/P_y$ - $M/M_p$)
- Compare results of the AISC interaction equation and computational analysis

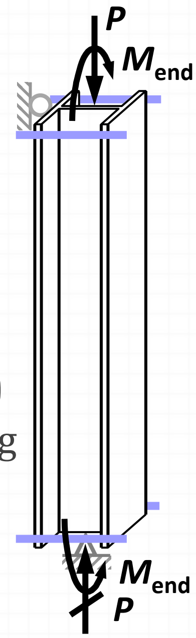
**Mother to LM2 and LM4…**

77

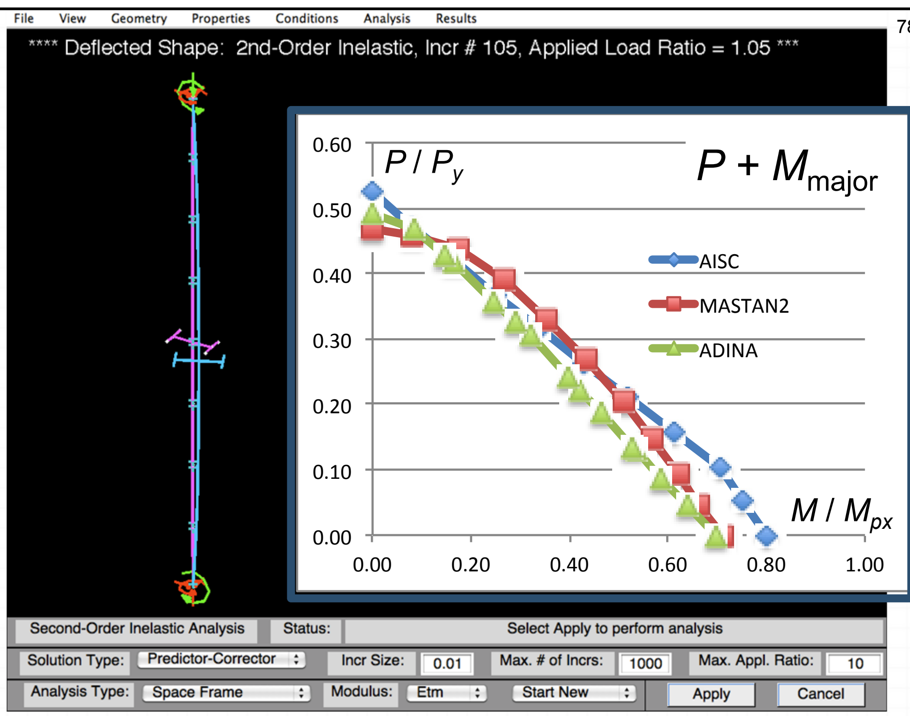
# LM8

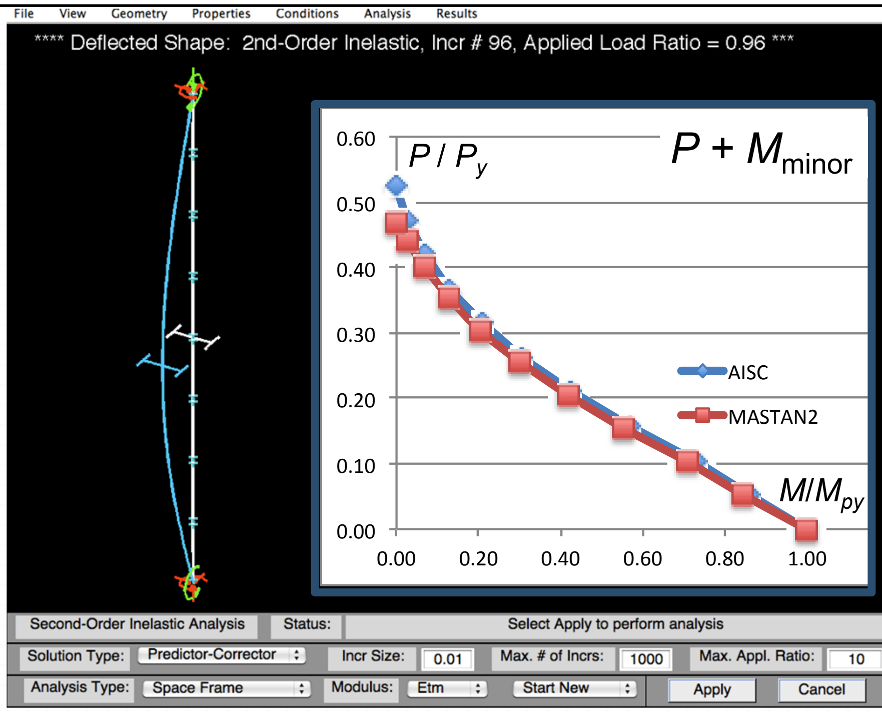



- ✓W14x53 (A992), $L_b$ = 15 ft.
- ✓Investigated:
  - *P-M*$_{major}$
  - *P-M*$_{minor}$
- ✓Provided range of *P-M*$_{end}$'s that satisfy AISC interaction eq. H1-1 (student's to confirm)
- ✓Determined strength according to 2$^{nd}$-order inelastic analysis
- ✓Wide range of failure modes including: full yielding, elastic/inelastic -LTB, -FTB




78



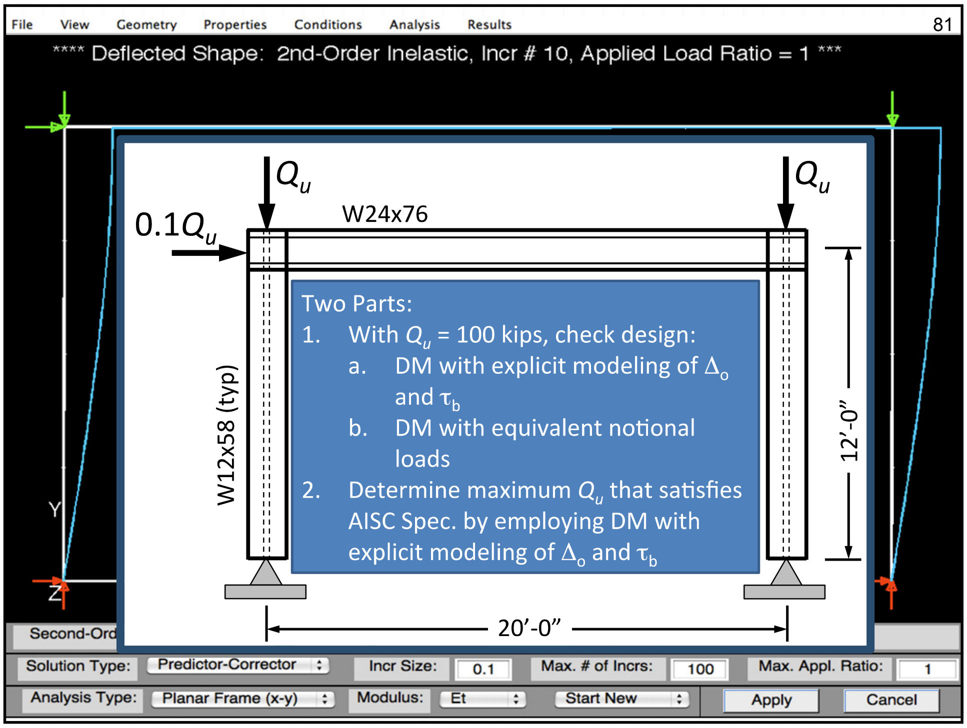


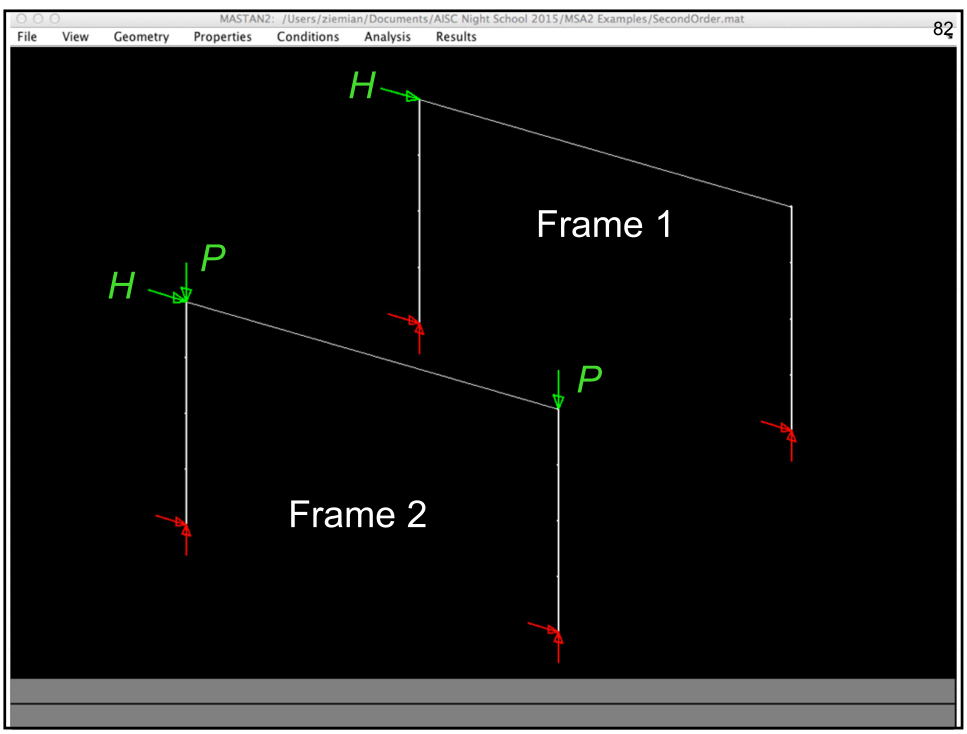

80

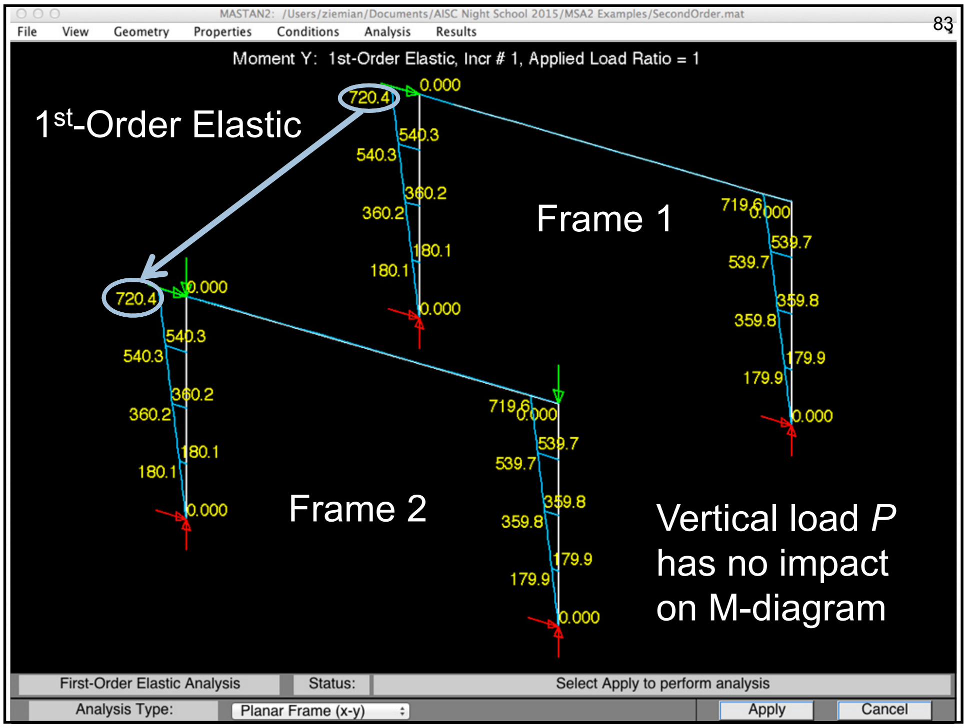
# LM9. Design by the Direct Analysis Method

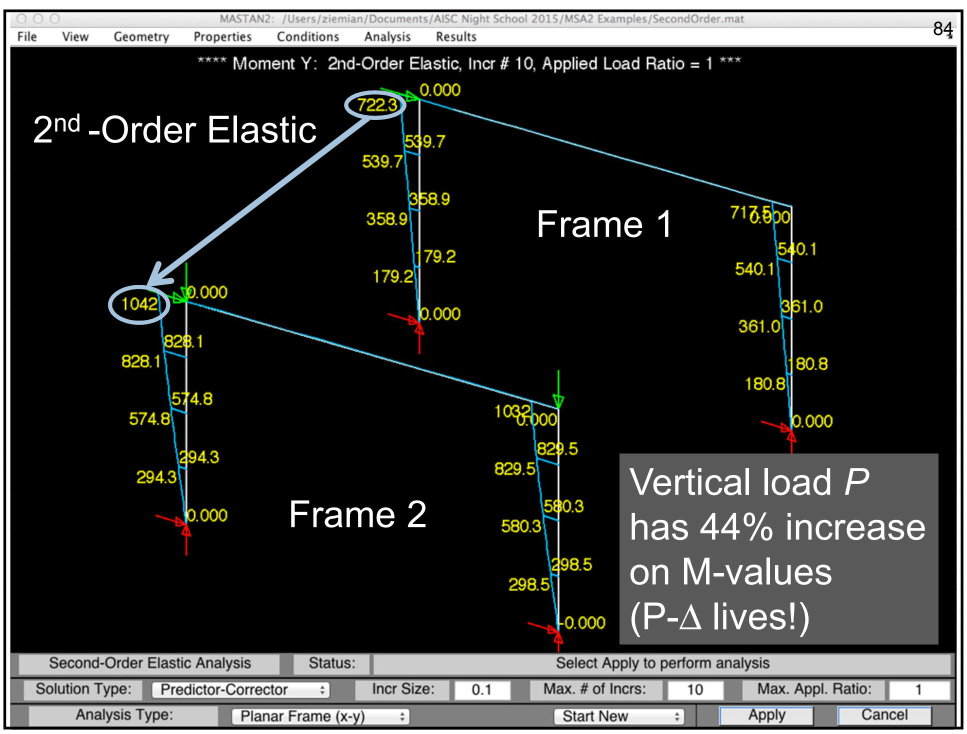
Learning Objectives

- Apply the Direct Analysis Method.
- 2nd-order analyses to determine $P_u$'s and $M_u$'s
- Utilize notional loads in place of direct modeling of $\Delta_o$ and $\tau_b$
- Practice with interaction equation
- Use the ratio of 2nd- to 1st-order drifts as an indicator of a system's sensitivity to 2nd-order effects.


File View Geometry Properties Conditions Analysis Results
81
**** Deflected Shape: 2nd-Order Inelastic, Incr # 10, Applied Load Ratio = 1 ***
$Q_u$
$Q_u$
$0.1Q_u$
W24x76
W12x58 (typ)
12'-0"
20'-0"
Two Parts:
1. With $Q_u$ = 100 kips, check design:
a. DM with explicit modeling of $\Delta_o$ and $\tau_b$
b. DM with equivalent notional loads
2. Determine maximum $Q_u$ that satisfies AISC Spec. by employing DM with explicit modeling of $\Delta_o$ and $\tau_b$
Second-Ord
Solution Type: Predictor-Corrector
Incr Size: 0.1
Max. # of Incrs: 100
Max. Appl. Ratio: 1
Analysis Type: Planar Frame (x-y)
Modulus: Et
Start New
Apply
Cancel


MASTAN2: /Users/ziemian/Documents/AISC Night School 2015/MSA2 Examples/SecondOrder.mat
File View Geometry Properties Conditions Analysis Results
82
H
H
P
P
Frame 1
Frame 2


83
File View Geometry Properties Conditions Analysis Results
Moment Y: 1st-Order Elastic, Incr # 1, Applied Load Ratio = 1
1st-Order Elastic
720.4
720.4
0.000
540.3
540.3
360.2
360.2
180.1
180.1
0.000
Frame 1
719.6
0.000
539.7
539.7
359.8
359.8
179.9
179.9
0.000
Frame 2
Vertical load P has no impact on M-diagram
First-Order Elastic Analysis
Status:
Select Apply to perform analysis
Analysis Type:
Planar Frame (x-y)
Apply
Cancel


84
File View Geometry Properties Conditions Analysis Results
**** Moment Y: 2nd-Order Elastic, Incr # 10, Applied Load Ratio = 1 ***
2nd -Order Elastic
722.3
0.000
539.7
539.7
358.9
358.9
179.2
179.2
0.000
Frame 1
717.5
0.000
540.1
540.1
361.0
361.0
180.8
180.8
0.000
1042
0.000
828.1
828.1
574.8
574.8
294.3
294.3
0.000
Frame 2
1032
0.000
829.5
829.5
580.3
580.3
298.5
298.5
0.000
Vertical load P has 44% increase on M-values (P-Δ lives!)
Second-Order Elastic Analysis
Status:
Select Apply to perform analysis
Solution Type:
Predictor-Corrector
Incr Size:
0.1
Max. # of Incrs:
10
Max. Appl. Ratio:
1
Analysis Type:
Planar Frame (x-y)
Start New
Apply
Cancel

85

## LM9

Guides student through a design check of a simple system using the Direct Analysis Method

| Member | $P_u$ (kips) | $\phi_c P_n$ (kips) | $M_u$ (kip-in) | $\phi_b M_n$ (kip-in) | AISC Eq. H1-1a/b | OK/NG? |
|---|---|---|---|---|---|---|
| Left Column | | | | | | |
| Right Column | | | | | | |
| Beam | | | | | | |

| Member | $P_u$ (kips) | $\phi_c P_n$ (kips) | $M_u$ (kip-in) | $\phi_b M_n$ (kip-in) | AISC Eq. H1-1a/b | OK/NG? |
|---|---|---|---|---|---|---|
| Left Column | | | | | | |
| Right Column | | | | | | |
| Beam | | | | | | |

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## LM9

- ✓Also includes making a comparison with 2nd-order inelastic analysis according to AISC Appendix 1 provisions.
- ✓More Fun!
  - Requests design check by Effective Length Method and 1st-Order Analysis Method, both appearing in AISC Appendix 7
    (DM: $K = 1$, $P_n = 603$k and ELF: $K = 2.1$, $P_n = 275$k)
- ✓Very interesting comparisons…

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# Lessons Learned

- ✓All modules fully tested in my CENG405-Design of Steel Structures course and now, many others worldwide…
- ✓Students (and Practitioners!):
  - Learn to read and follow instructions
  - Find MS Excel LM spreadsheets key to quickly prepare comparative tables
  - Enjoy the LM Tutorials available on YouTube.com
  - Welcome opportunity to employ nonlinear structural analysis software
  - Benefited from the hands-on approach to learning structural stability

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# Future Modules

- ✓Your suggestions!
  - e-mail me at ziemian@bucknell.edu
- ✓Yura's *Five Useful Stability Concepts*
  - leaning column
  - bracing (nearly complete!)
  - some already included in LM's…
- ✓Stability of slender cross-sections
  - CU-FSM

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# Summary

- ✓Virtual Laboratory
- ✓Reviewed 9 Learning Modules related to structural stability, 3 with MASTAN2
- ✓Each Module includes:
  - Assignment (PDF, MS Word)
  - MS Excel Spreadsheet of key tables
  - Links to LM tutorials on YouTube.com
- ✓Encourage you to try some or all…
- ✓Customizing of LM's permitted!

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# Up Next…

- Session 4: February 23 –
  **Second-Order Elastic Analysis – Getting it Right**
  by D.W. White, PhD
- Various methods of second-order elastic frame analysis, ranging from intelligent application of amplification factors with first-order analysis to three-dimensional matrix structural analysis models, are reviewed. Emphasis is on the sufficiency of the methods for different problems, methods of sanity checking and ensuring that the analysis is correct, and various essential concepts important for design application.





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# 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.

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**Access to the recording:** Information for accessing the recording will be emailed to you by this Wednesday. The recording will be available for two 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.

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# Thank You

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

structural STEEL