

Using Computer Software
as a Virtual Lab for
Learning Structural
Stability

Ron Ziemian

NASCC
THE **STEEL** CONFERENCE



Stability Fun!

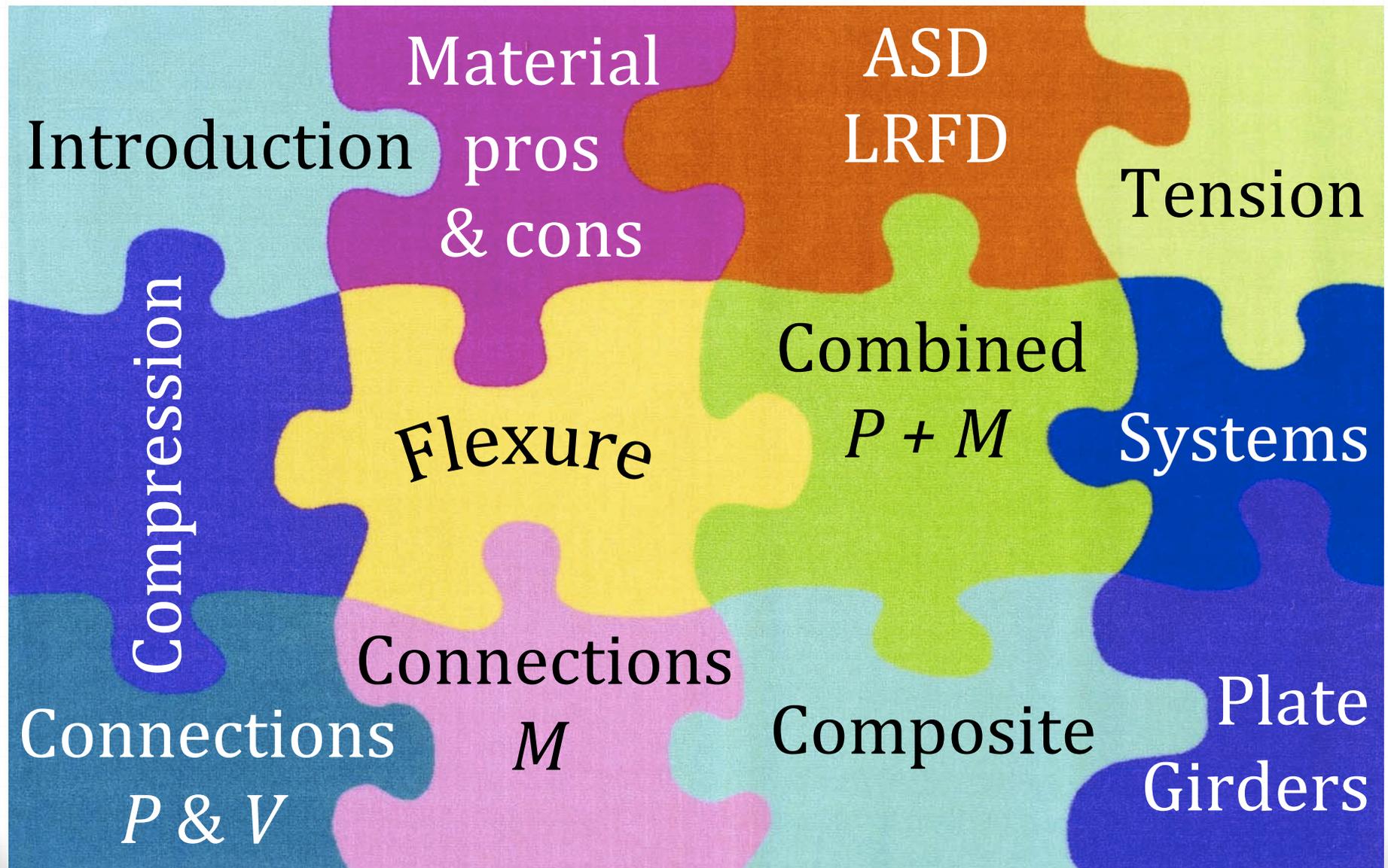
Annual Stability Conference
11 Sessions
35+ Papers
Rm. Texas 3-4



Overview

- ✓ Structure of Steel Courses
- ✓ Challenge of Designing Steel Structures
- ✓ Some History...1980's!
- ✓ Virtual Lab
- ✓ Overview of the Learning Modules
- ✓ Take an LM for a test drive...
- ✓ More details on the other LM's
- ✓ Summary

Structure of Steel Courses



Structure of Steel Courses

Behavior

Theory

Equations

Design
Charts

AISC
Specification

What does
the course

emphasize?



Structure of Steel Courses

Architecture

Structural
Engineering

Construction
Management

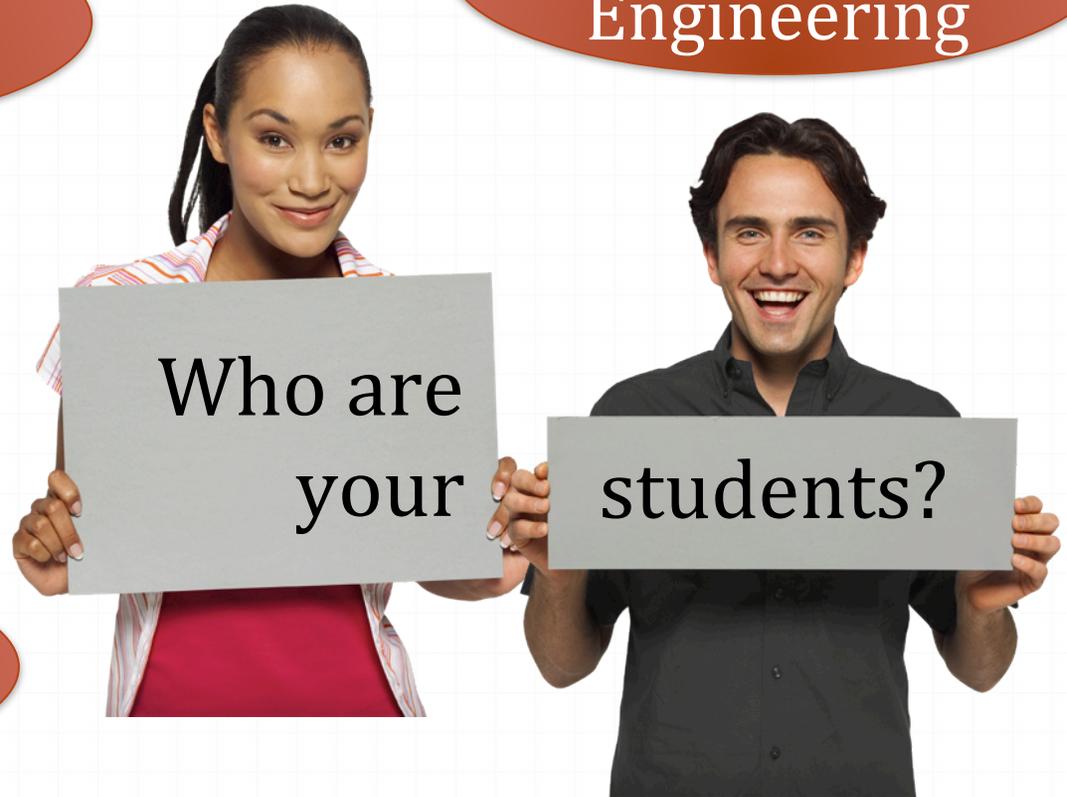
Architectural
Engineering

Who are
your

students?

Undergraduate

Graduate Student



Structure of Steel Courses

- ✓ So much to do, so little time...
- ✓ Today's lecture presents materials for use in any steel course that has some degree of focus on understanding the behavior of metal structures
- ✓ Emphasis is on stability
(wait, please don't run out...)

Challenge of Designing Steel Structures

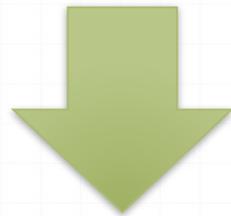
Strength/
Weight



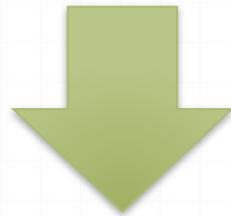
Stiffness/
Weight



Competitive
\$



Slender Members and Systems



Design for Stability!

Structural Stability & The Curse of the Differential Equation



Challenge of Designing Steel Structures

✓ Understanding Structural Stability

■ General Behavior

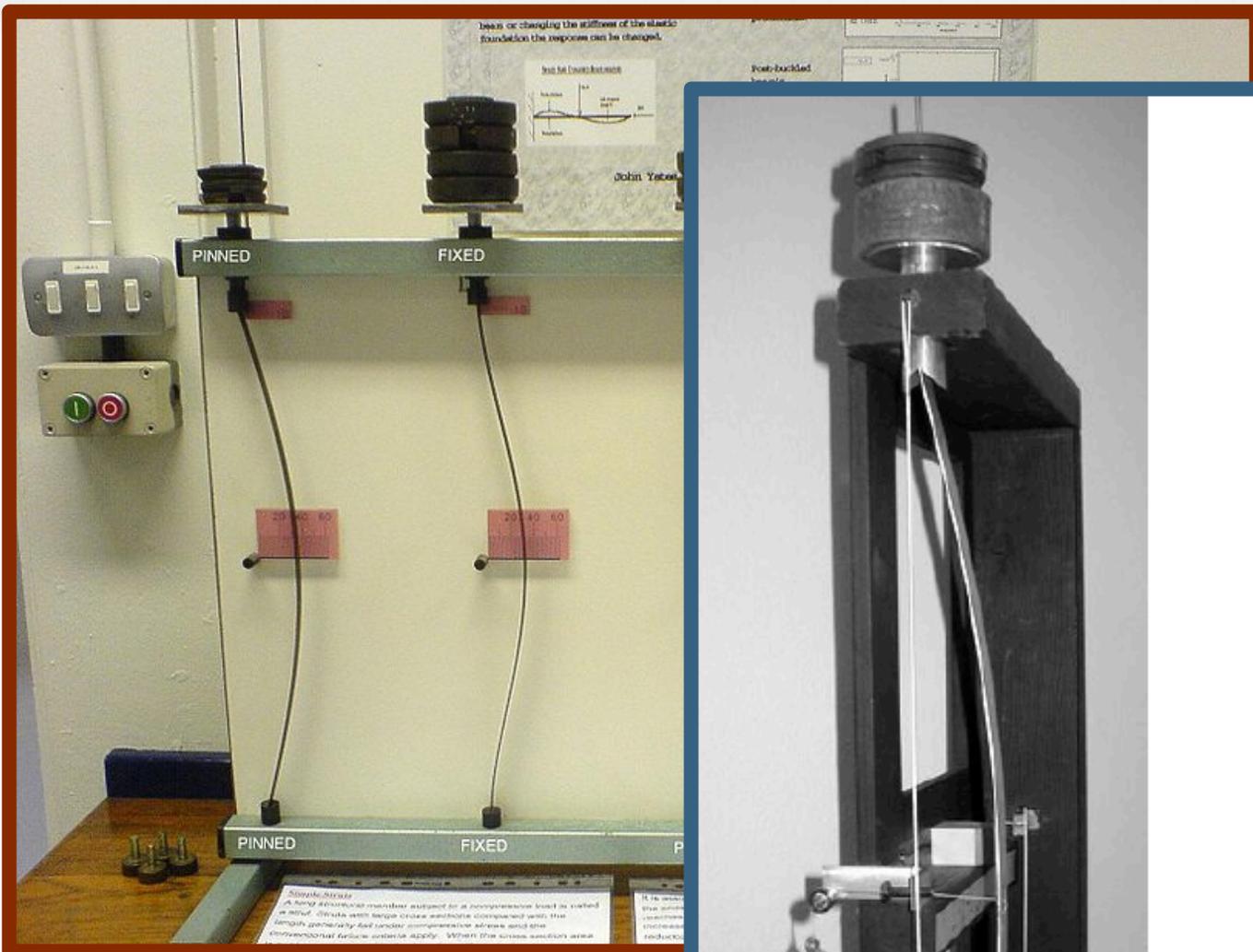
- Physical observations (go to the lab!)
- Virtual observations (go to the computer!)
- Hear it described in lecture
- Read about it in the book

■ “Exact” Solutions

- Differential Equations (limited by assumptions)
- Computational Analysis (much less limited)

✓ See the forest for the trees

✓ Engage the student - Active Learning



Physical Labs
would be ideal,
but...

Five Useful Stability Concepts
J. Yura

Some History...1980's!

- ✓ Product of educational software
 - BSCE '84, MENG '85, PhD '87-'91
- ✓ Cornell CEE Faculty led the way
 - McGuire, Abel, Ingraffea, Gergely, Deierlein
 - Developed GUI's to linear and nonlinear analysis software (state-of-the-art!)
 - GISMA, GISMO, PREPF, STAND, QUAND
 - Analysis software used extensively in all 3 steel design courses (McGuire)

Some History...1980's!

- ✓ McGuire's Steel Design Courses
 - Understand behavior through simulation
Virtual Laboratory
 - Active learning: effective and efficient
 - Not auto-design!
- ✓ Project SOCRETES: Goals to develop/distribute
 - educational software
 - learning modules
- ✓ Concept never to come full fruition
 - software was not portable to all platforms

Virtual Laboratory

- ✓ Fast forward to the late 90's
 - GUI for analysis software is the norm
 - Faculty developing software-based learning activities for understanding structural behavior (e.g., frame bending vs. story shear)
- ✓ “Easy to use” nonlinear analysis software not readily available
 - Requirement for simulating concepts related to structural stability

Virtual Laboratory

✓ In early 2000...

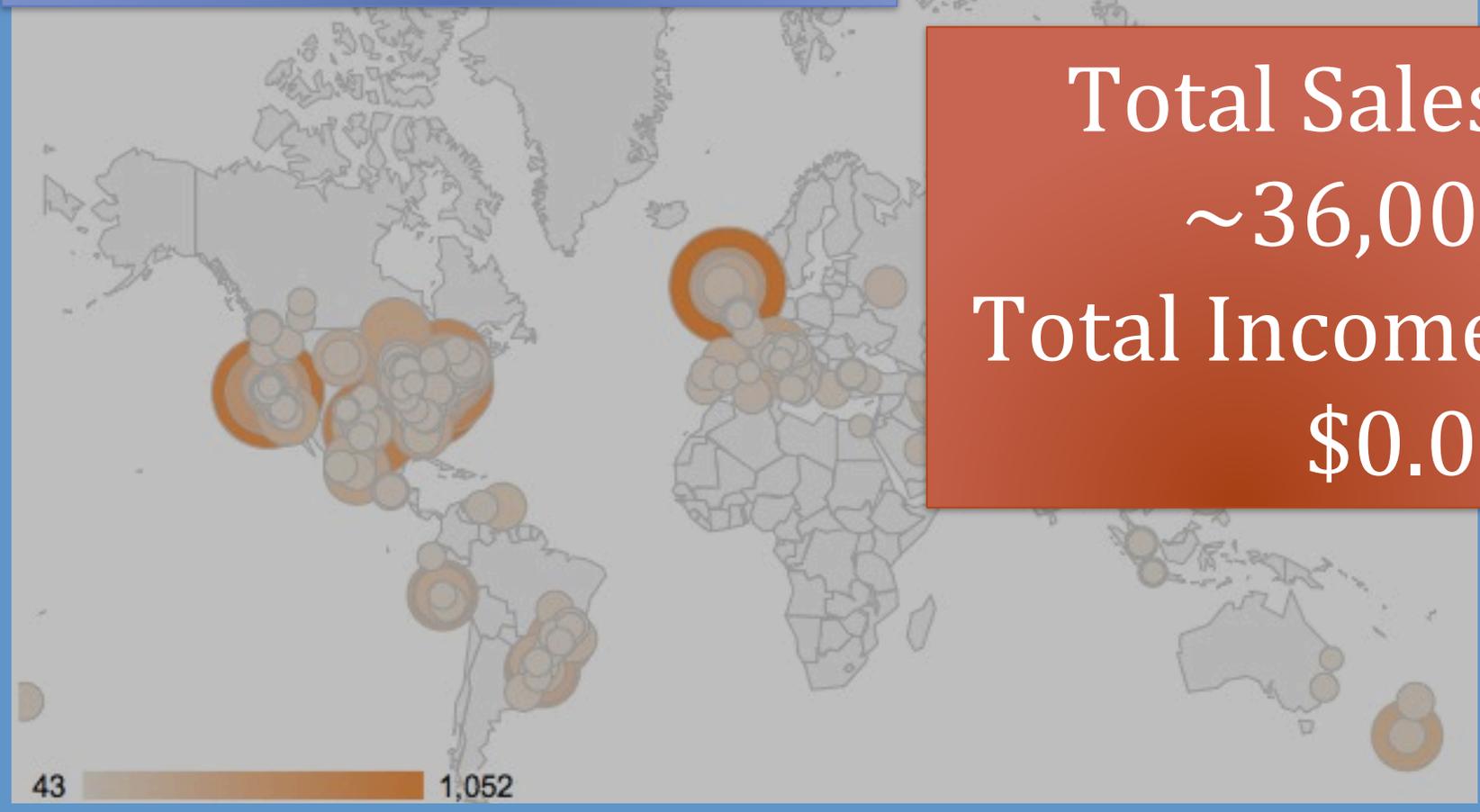
- *Matrix Structural Analysis*, McGuire, Gallagher, and Ziemian, 2nd ed., John Wiley & Sons.
- Rewritten to include new chapters on nonlinear analysis
- Educational software MASTAN2 developed and bundled with textbook
 - MATLAB-based, available on all platforms
 - Included suite of nonlinear analysis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

Virtual Laboratory

✓ 2000-2010...

- 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

Downloads since 2007:



12,948 Matlab Version
19,245 PC-version (stand-alone)
2,562 Mac-version (stand-alone)

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

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

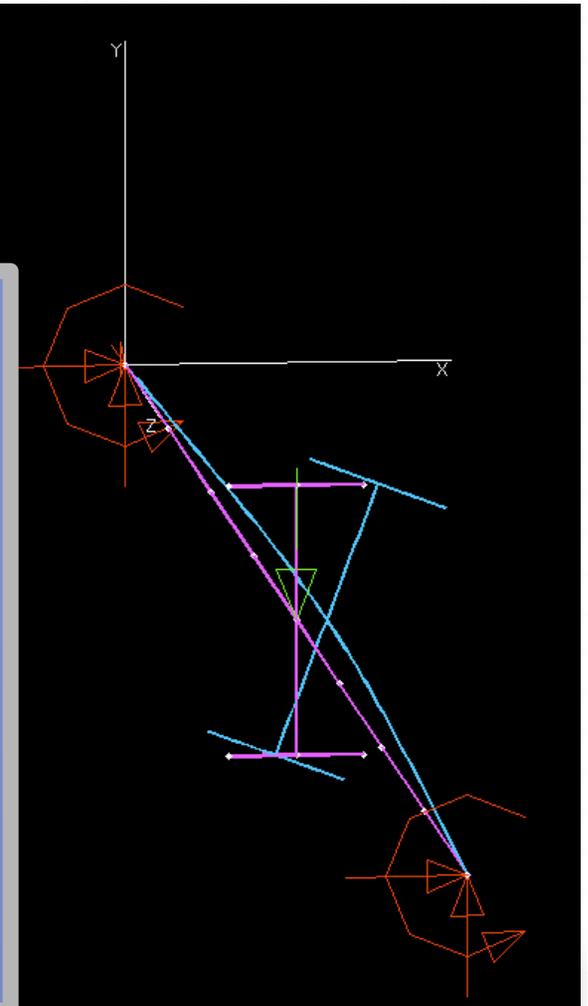
Virtual Lab for Stability Checklist		MASTAN2	Other
Stiffness	Axial, EA	yes	yes
	Flexural, EI	yes	yes
	Shear, GA_s	yes	yes
	St. Venant torsion, GJ	yes	yes
	Warping torsion, EC_w	yes	?
	Connection, k_{conn}	yes	?
Effects	Second-order including $P\Delta$, $P\delta$	yes	?
	Imperfections: system, member	yes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

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?



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 (see LM5 Handout)

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



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MASTAN2 - Learning Module 8

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MASTAN2

File View Geometry Properties Conditions Analysis Results

Deflected Shape: Incr # 1, Applied Load Ratio = 1

- Diagrams
 - Node Displacements
 - Node Reactions
- Element Forces
- Plastic Deformations
- Update Geometry
- MSAPlot

11:36 / 14:41

This video is public.

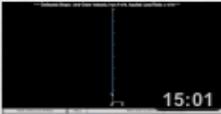
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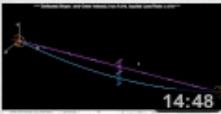
Published on Apr 2, 2012 by [ronziemian](#)

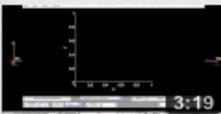
Strength of Beam-Columns

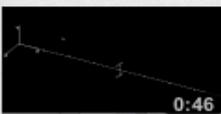
www.mastan2.com

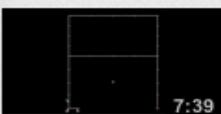
1 likes, 0 dislikes

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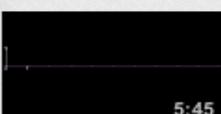
MASTAN2 - Learning Module 2
by ronziemian
1 view
- 

MASTAN2 - Learning Module 4
by ronziemian
4 views
- 

MASTAN2 - Plotting response curves
by ronziemian
1 view
- 

MASTAN2 - Warping Resistance
by ronziemian
2 views
- 

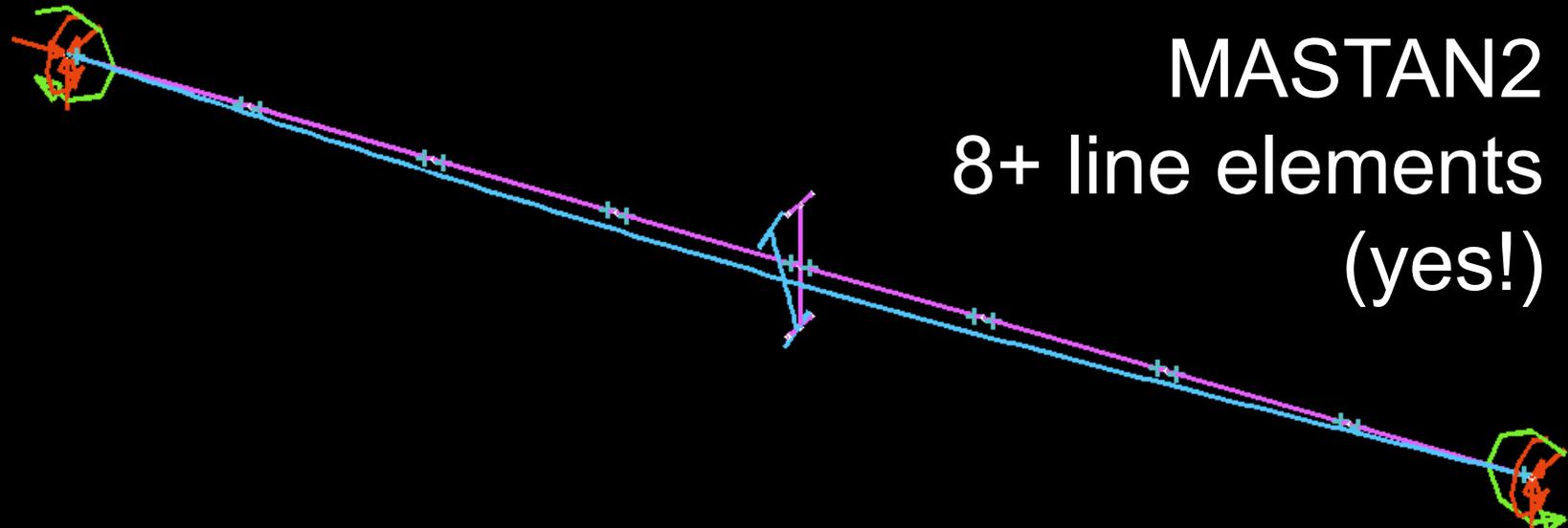
MASTAN2 - Sway Frame (out-of-plumb)
by ronziemian
No views
- 

MASTAN2 - Learning Module 9
by ronziemian
11 views
- 

MASTAN2 - Learning Module 7
by ronziemian
31 views

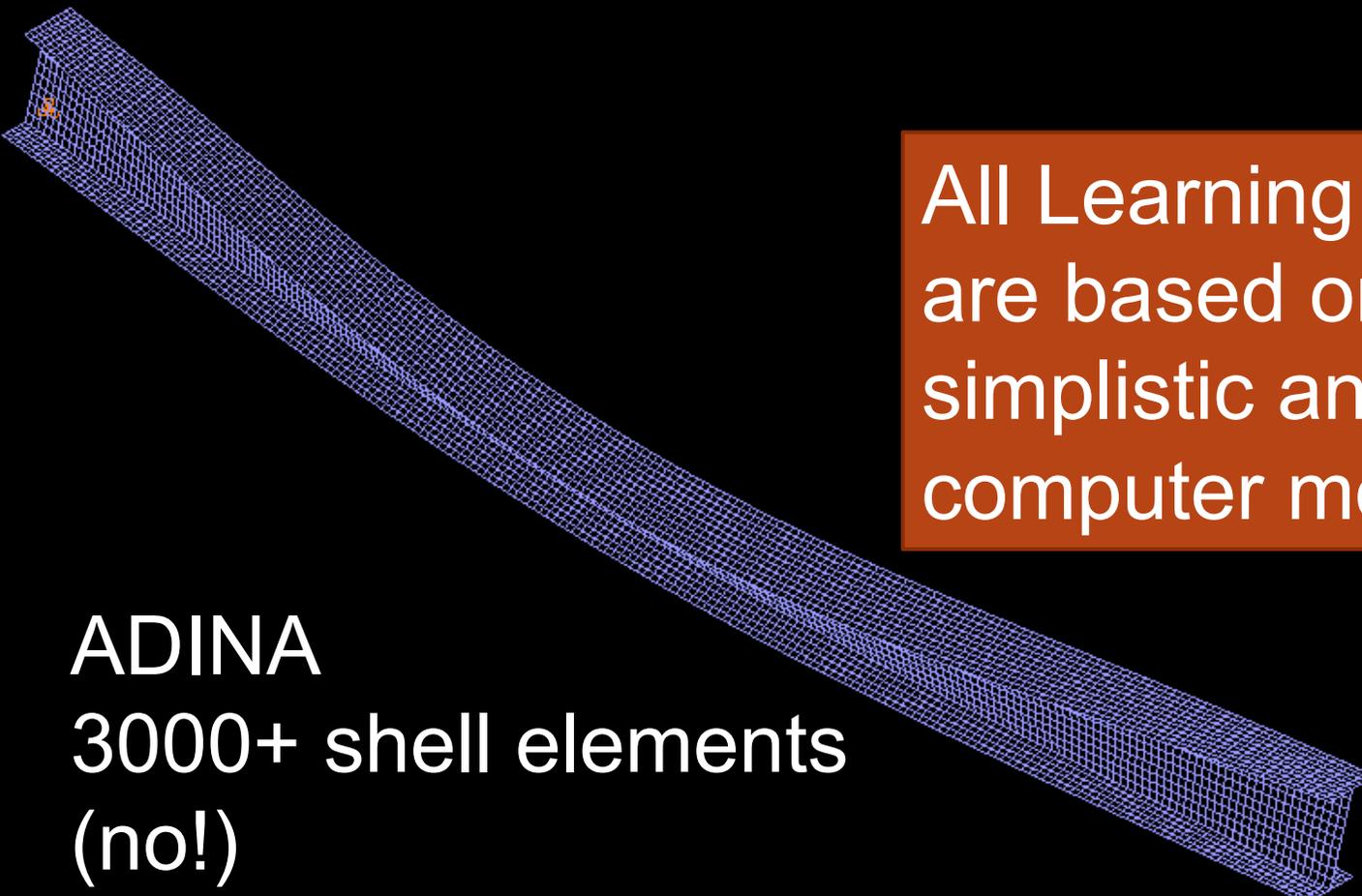
Overview of Learning Modules

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



MASTAN2
8+ line elements
(yes!)

All Learning Modules
are based on very
simplistic and accurate
computer models

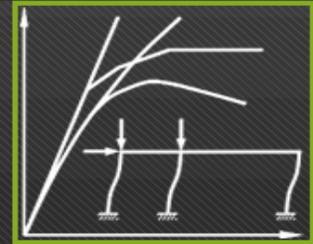


ADINA
3000+ shell elements
(no!)

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

MASTAN2 v3.3



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- About
- FAQ's
- Screenshots
- Tutorial
- Stability Fun**
- Download
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Designed By:
Projectdesigns.org
XHTML 1.0 Strict

Stability Fun

The nonlinear analysis capabilities of MASTAN2 provide students the opportunity to perform a wide range of investigations into the behavior of structural members and systems. With this in mind, the learning modules are intended for use in undergraduate level steel design or structural stability courses. The modules are also encouraged to continue the exercises.

Although the modules have been prepared in a format that can be used as Microsoft Word files or spreadsheets. In addition to the modules, for further study, these files are available for MASTAN2 in action. For those employing the modules, it is strongly encouraged before using the modules. Enjoy!

Learning Module 1 - Elastic Column Buckling and the Effect of End Restraint: Using a critical load analysis, the elastic flexural buckling strength of a column with various degrees of end restraint is investigated. [\[Click here for more details.\]](#) and [\[Click here to download module.\]](#)

Learning Module 2 - Factors Influencing the Flexural Buckling Strength of Compression Members: Using computational analysis as a virtual laboratory, the main factors that impact the flexural buckling strength of steel wide-flange sections with non-slender elements are investigated.

Availability/Distribution
www.mastan2.com

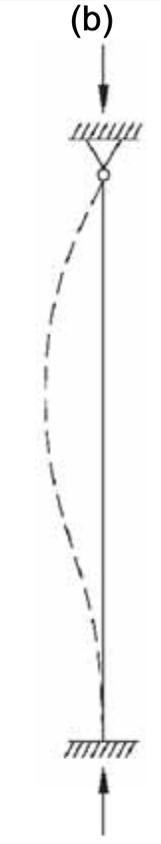
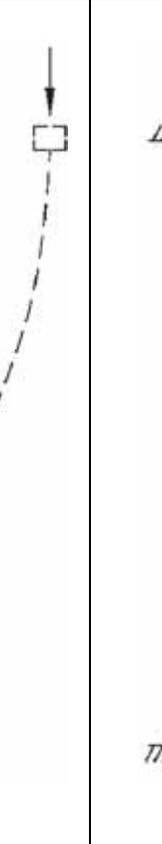
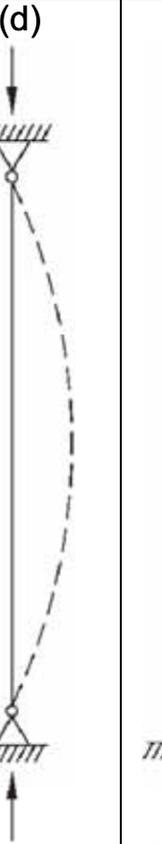
LM1. Elastic Column Buckling and the Effect of End Restraint

Learning Objectives

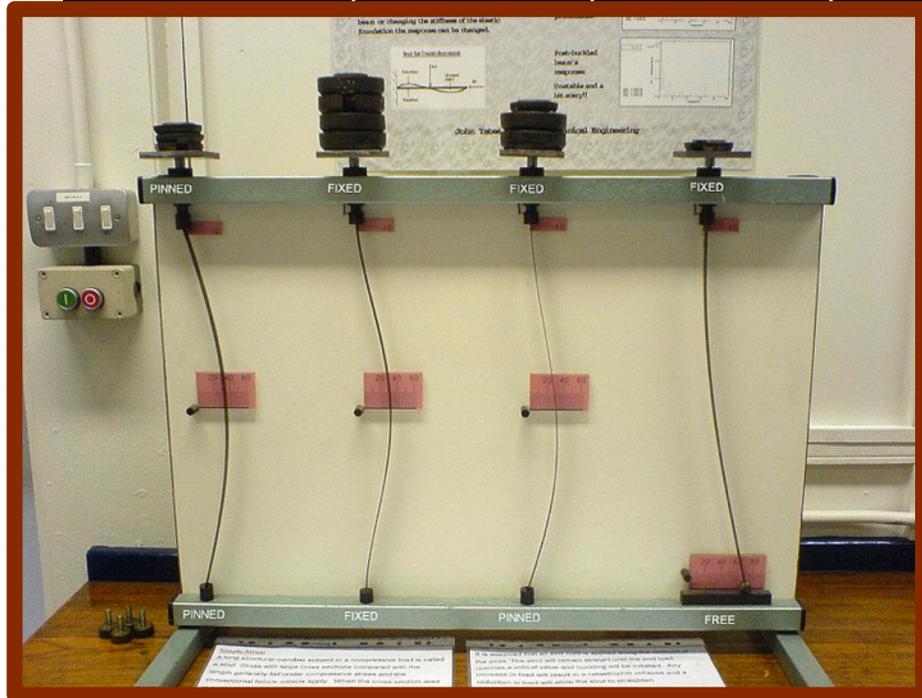
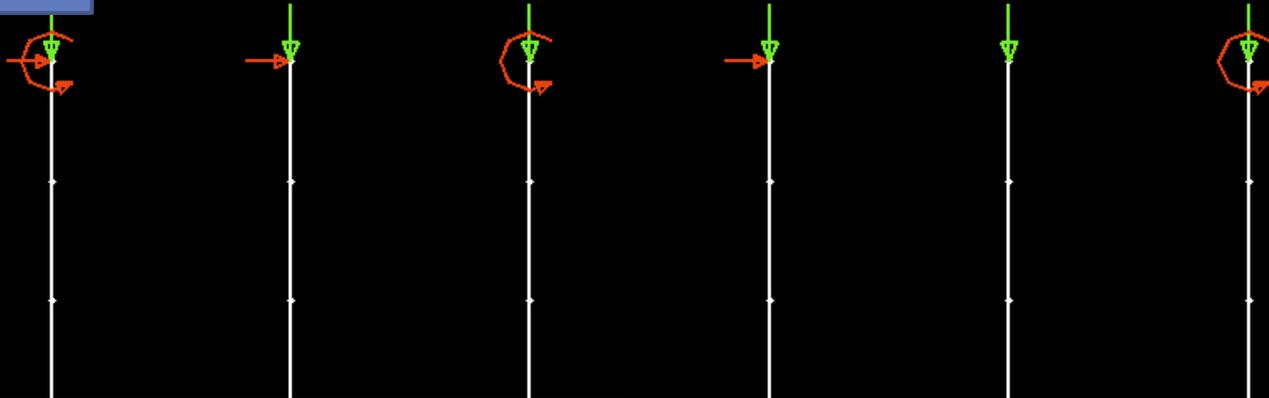
- Verify theoretical elastic column buckling solutions
- Observe impact of end restraint on capacity and buckled shape
- Confirm the K -factors appearing in AISC Table C-A-7.1

TABLE C-A-7.1

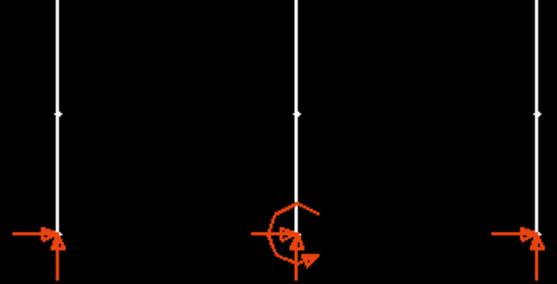
Approximate Values of Effective Length Factor, K

	(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

$$P = 1 \text{ k}$$



Compute 10 modes



Elastic Critical Load Analysis

Status

of Modes Calculated = 10 ----> Success: Analysis Complete

Analysis Type:

Planar Frame (xy)

Max. # of Modes:

< 10 >

Apply

Cancel

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

	(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 Status: Success: Deflection shown

Defl Line Type Scale # of pts Animate 1

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*

	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical <i>K</i> 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 Animate 2 Apply Cancel

Deflected Shape: Elastic Critical Load, Mode # 3, Applied Load Ratio = 1094.4739

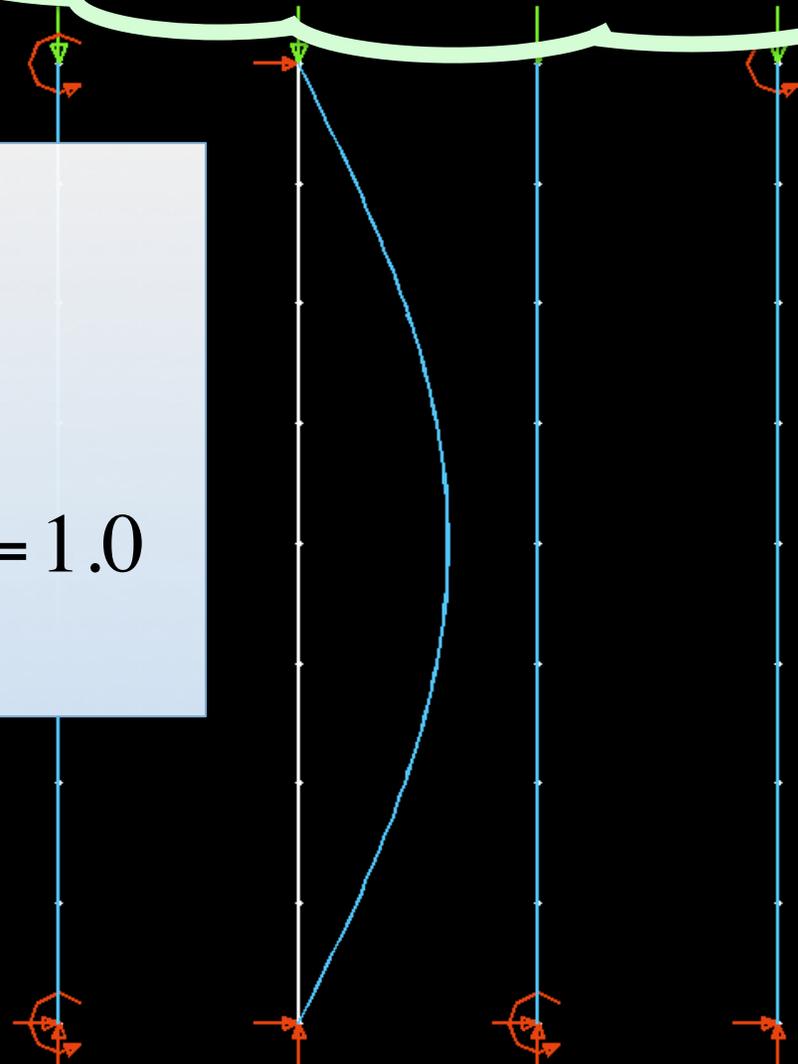
Mode 3:

$$P_{cr} = 1094.5$$

$$K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 1.0$$

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

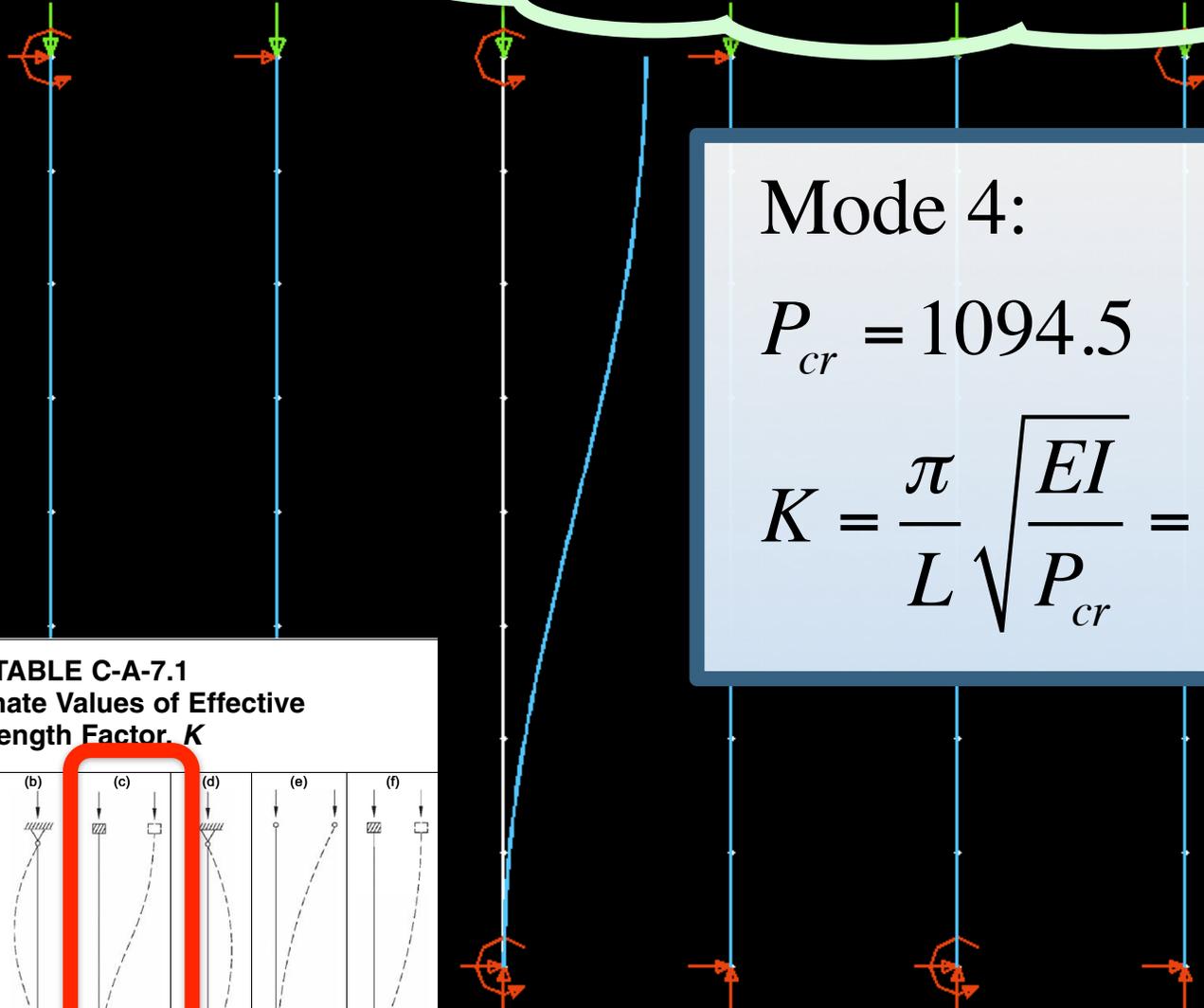
	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical <i>K</i> value	0.5	0.7	1.0	1.0	2.0	2.0



All All Clr Adv Status: Success: Deflection shown

Defl Line Type Solid Scale 75 # of pts 10 Animate 3 Apply Cancel

Deflected Shape: Elastic Critical Load, Mode # 4, Applied Load Ratio = 1094.4739



Mode 4:

$$P_{cr} = 1094.5$$

$$K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 1.0$$

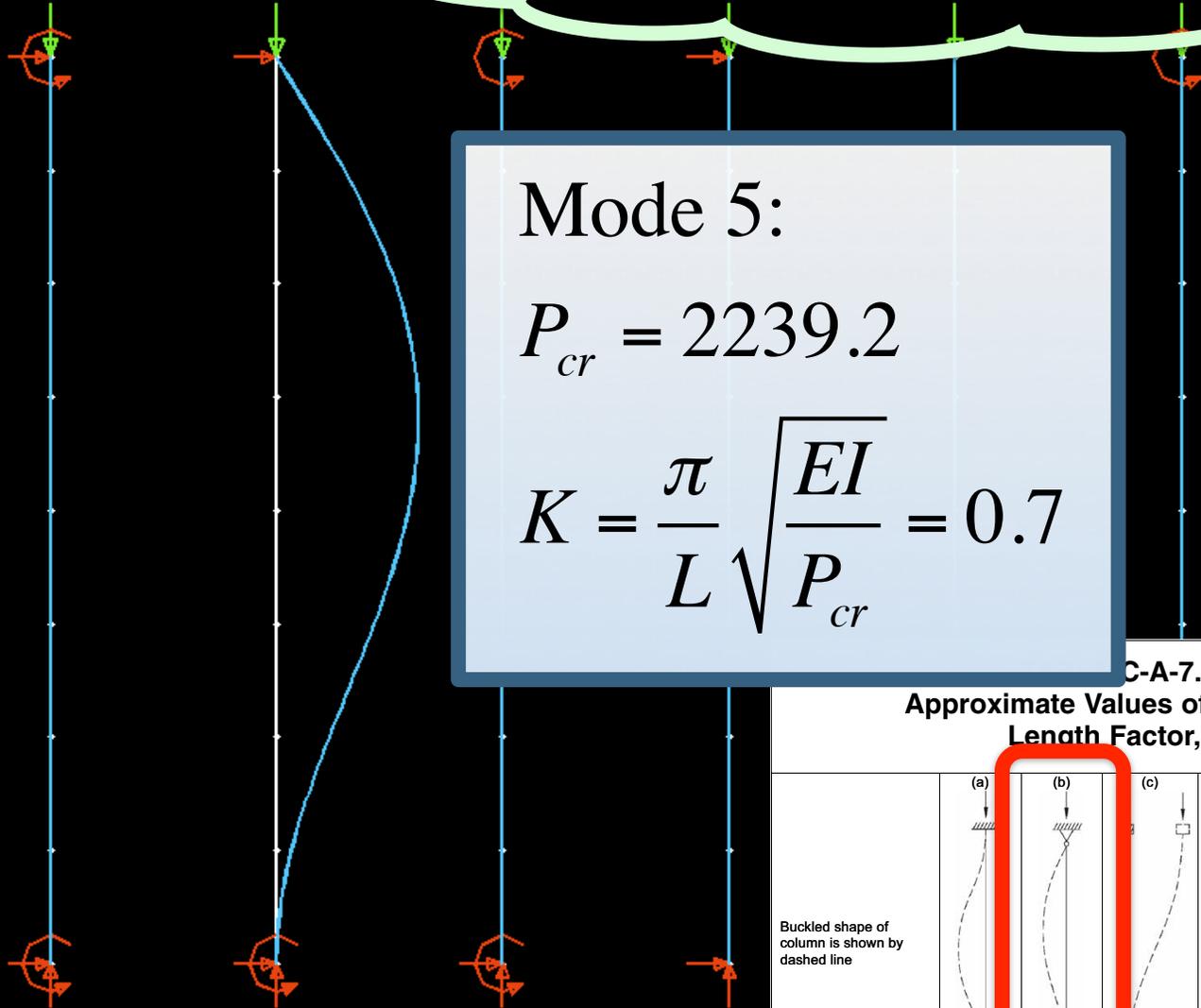
TABLE C-A-7.1
Approximate Values of Effective Length Factor, *K*

	(a)	(b)	(c)	(d)	(e)	(f)
Buckled shape of column is shown by dashed line						
Theoretical <i>K</i> 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 < 4 > Apply Cancel

Deflected Shape: Elastic Critical Load, Mode # 5, Applied Load Ratio = 2239.2487



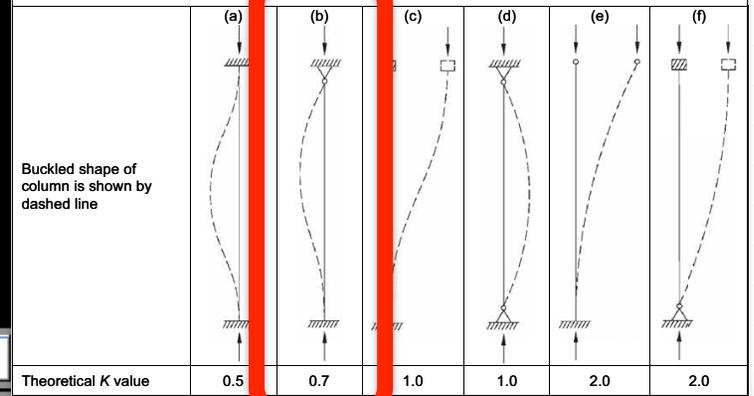
Mode 5:

$$P_{cr} = 2239.2$$

$$K = \frac{\pi}{L} \sqrt{\frac{EI}{P_{cr}}} = 0.7$$

C-A-7.1

Approximate Values of Effective Length Factor, K



Define element(s) and parameters Element(s): All All Clr

Defl Line Type Solid Scale 75 # of pts 10 Animate

< 5 > Apply Cancel

Deflected Shape: Elastic Critical Load, Mode # 6, Applied Load Ratio = 2462.89

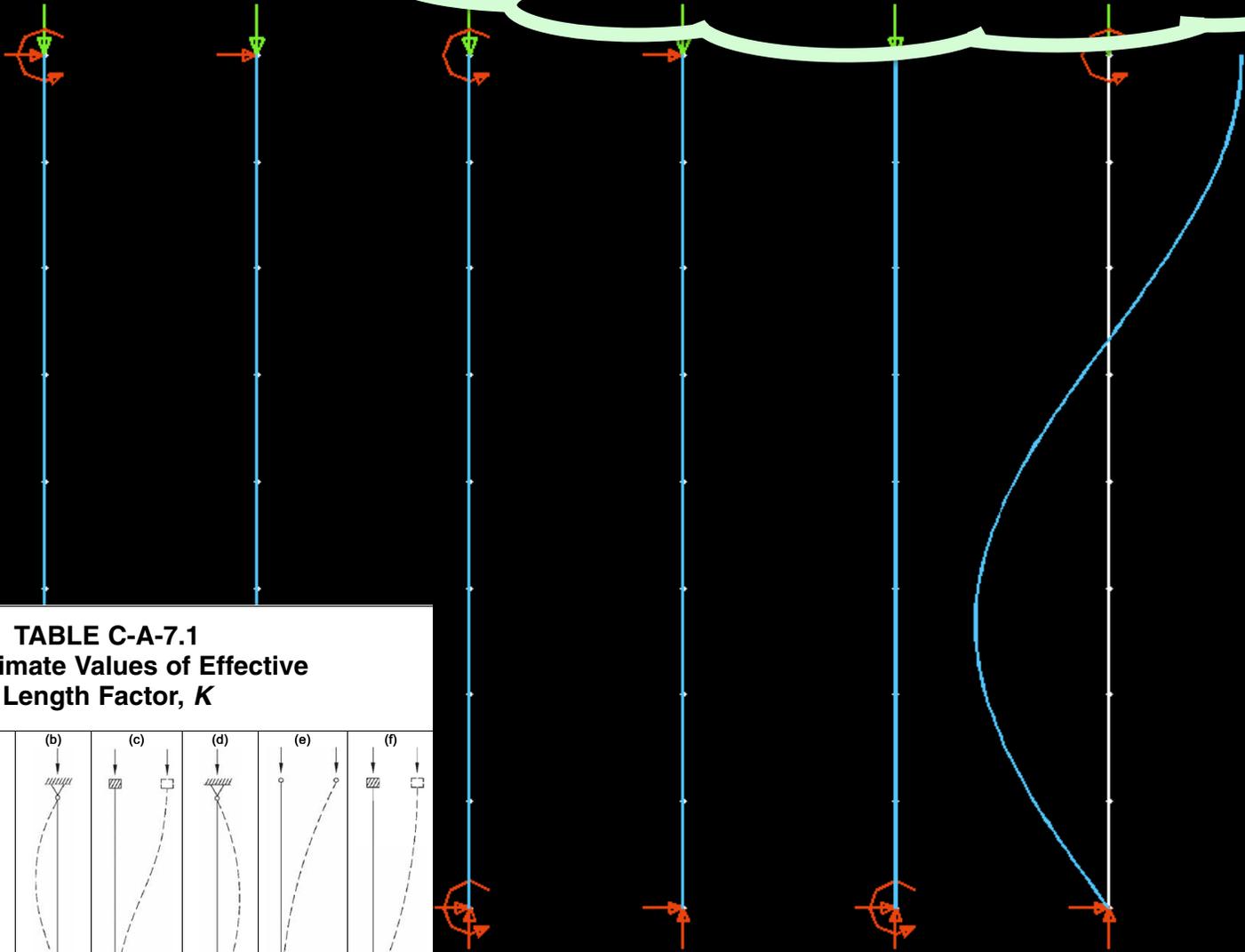


TABLE C-A-7.1
Approximate Values of Effective Length Factor, K

	(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

Deflected Shape: Elastic Critical Load, Mode # 7, Applied Load Ratio = 2462.89

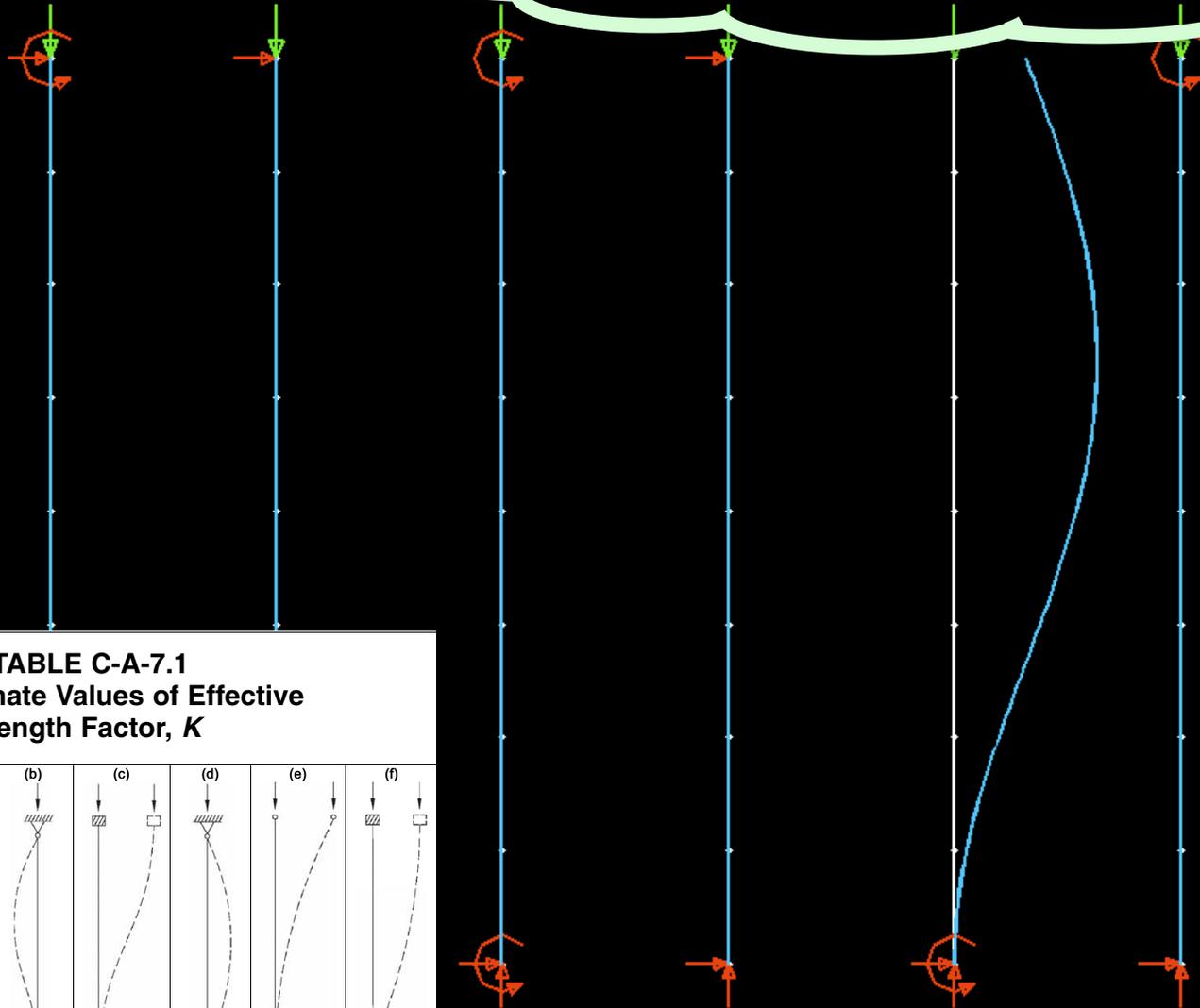


TABLE C-A-7.1
Approximate Values of Effective Length Factor, K

	(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

<

7

>

Apply

Cancel

Deflected Shape: Elastic Critical Load, Mode # 8, Applied Load Ratio = 4379.9942

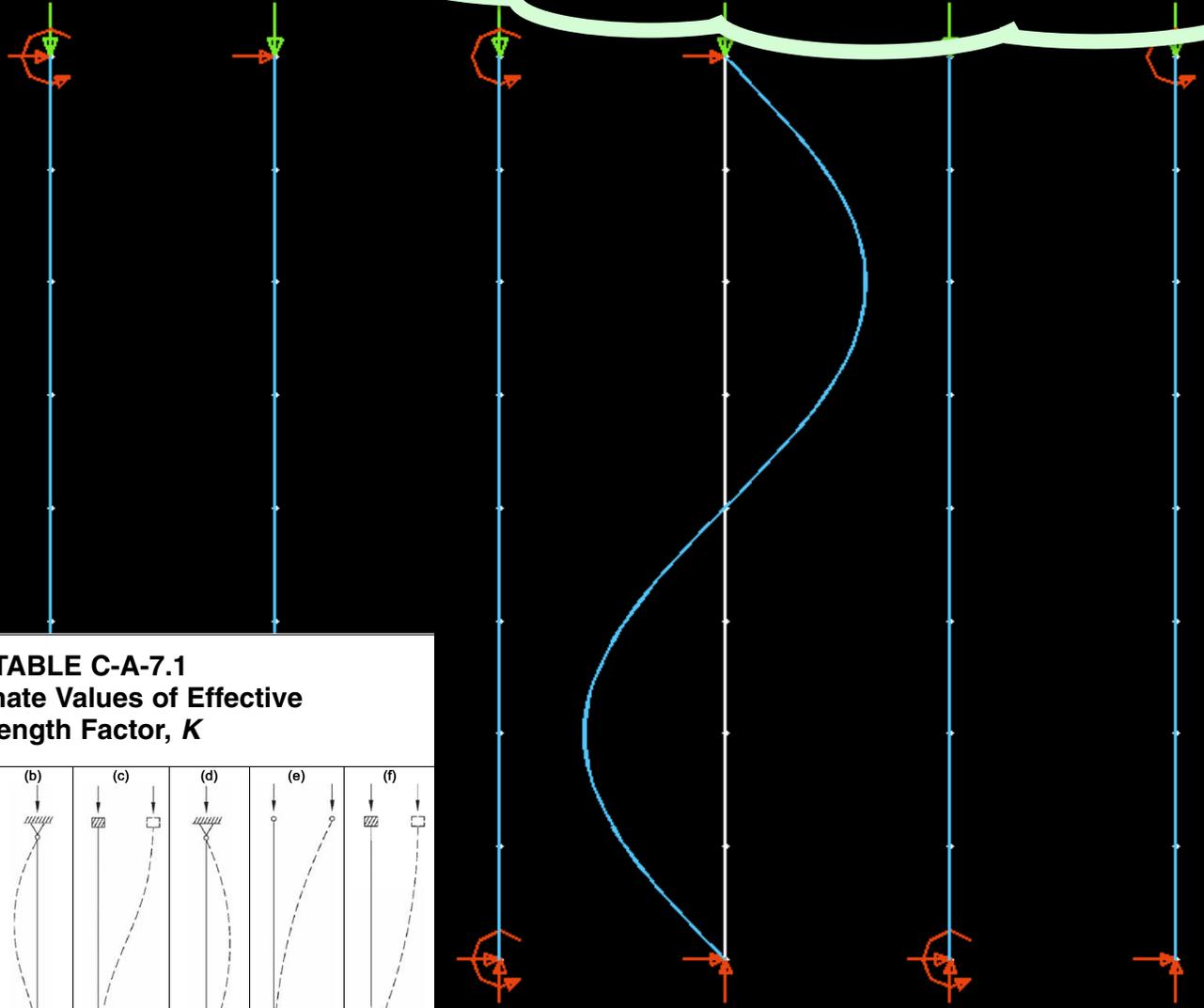


TABLE C-A-7.1
Approximate Values of Effective Length Factor, K

	(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 < 8 > Apply Cancel

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

	(a)	(b)	(c)	(d)	(e)	(f)
						
Theoretical K value	0.5	0.7	1.0	1.0	2.0	2.0

Buckled shape of column is shown by dashed line

Define element(s) and parameters

Element(s):

All

All

Clr

Defl Line Type

Solid

Scale

75

of pts

10

Animate

<

9

>

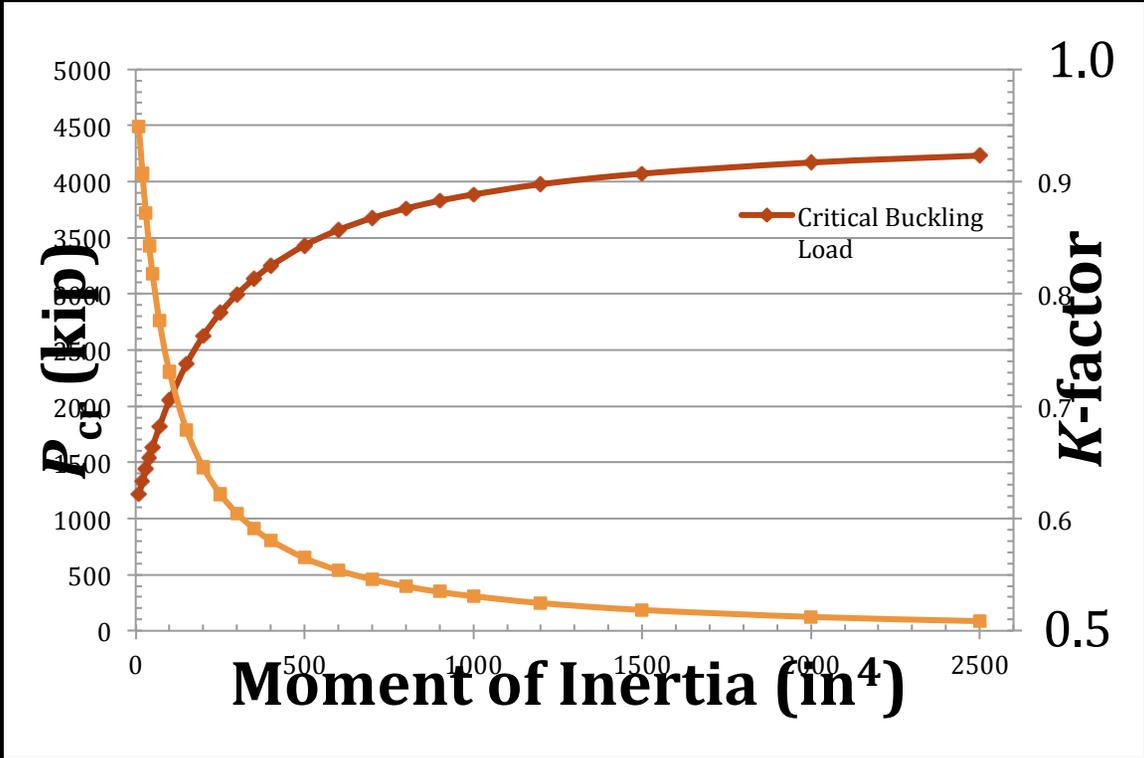
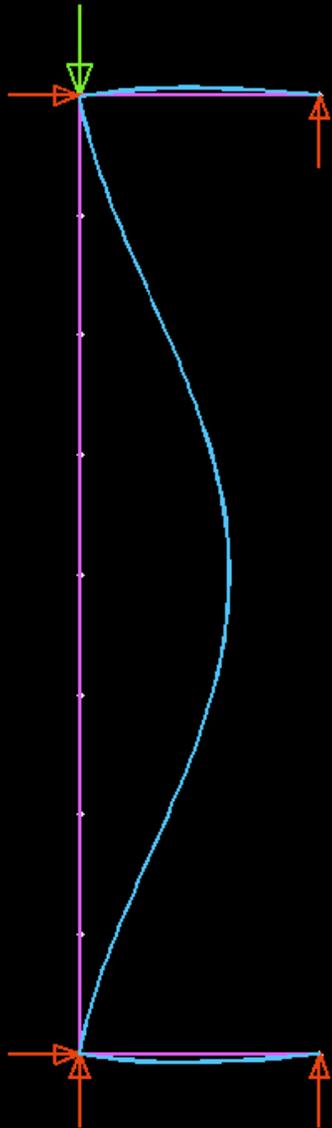
Apply

Cancel

Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio

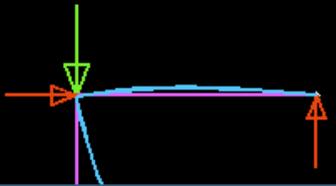
More Fun!

Vary beam size w/
 $I_{Top}^{Beam} = I_{Bottom}^{Beam}$

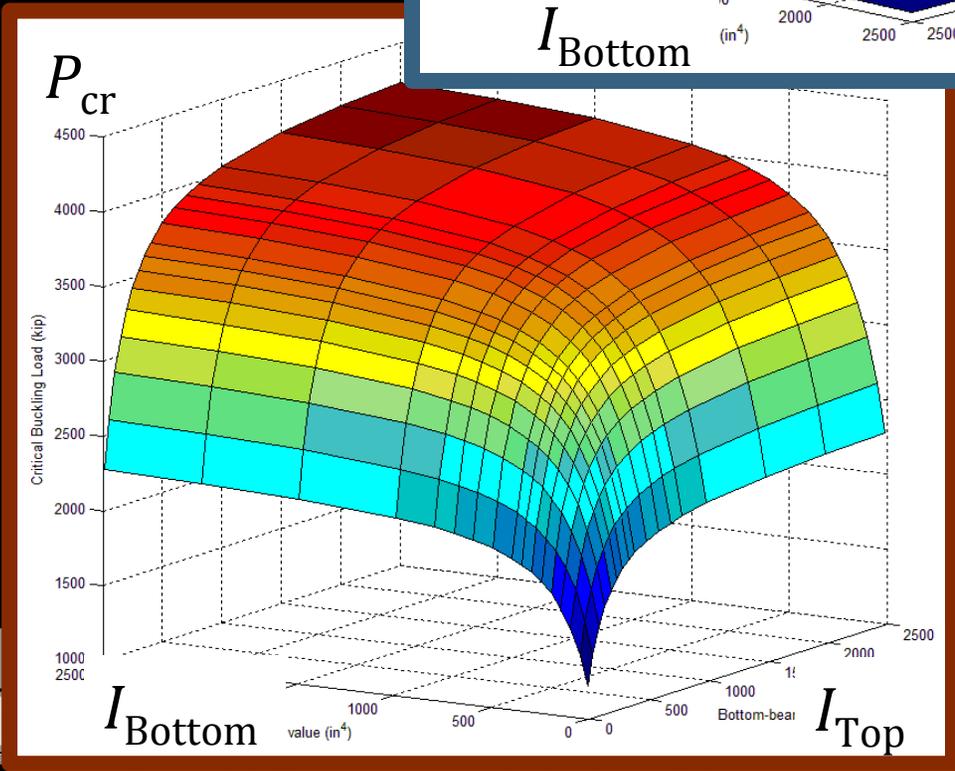
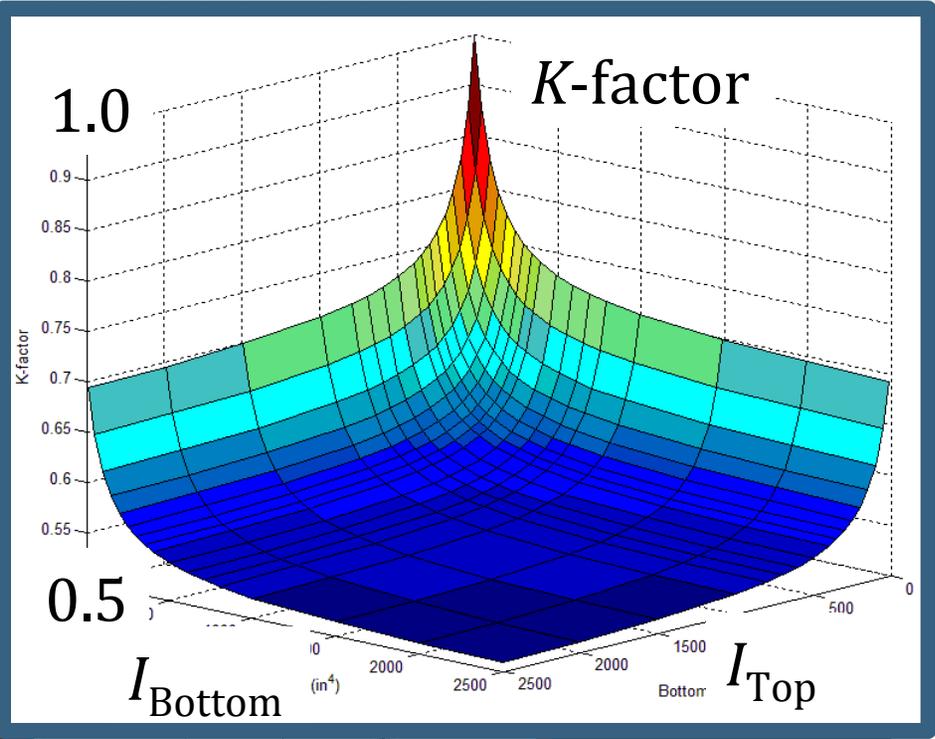
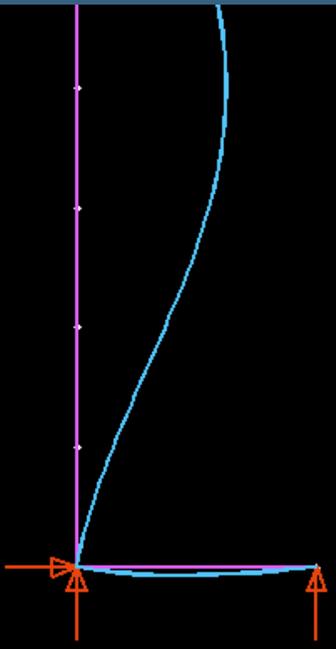


Thanks to Yue Hua

Deflected Shape: Elastic Critical Load, Mod



Vary beam sizes w/
 $I_{Top}^{Beam} \neq I_{Bottom}^{Beam}$



Message: Deflection shown

Apply Cancel

Thanks to
Yue Hua

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



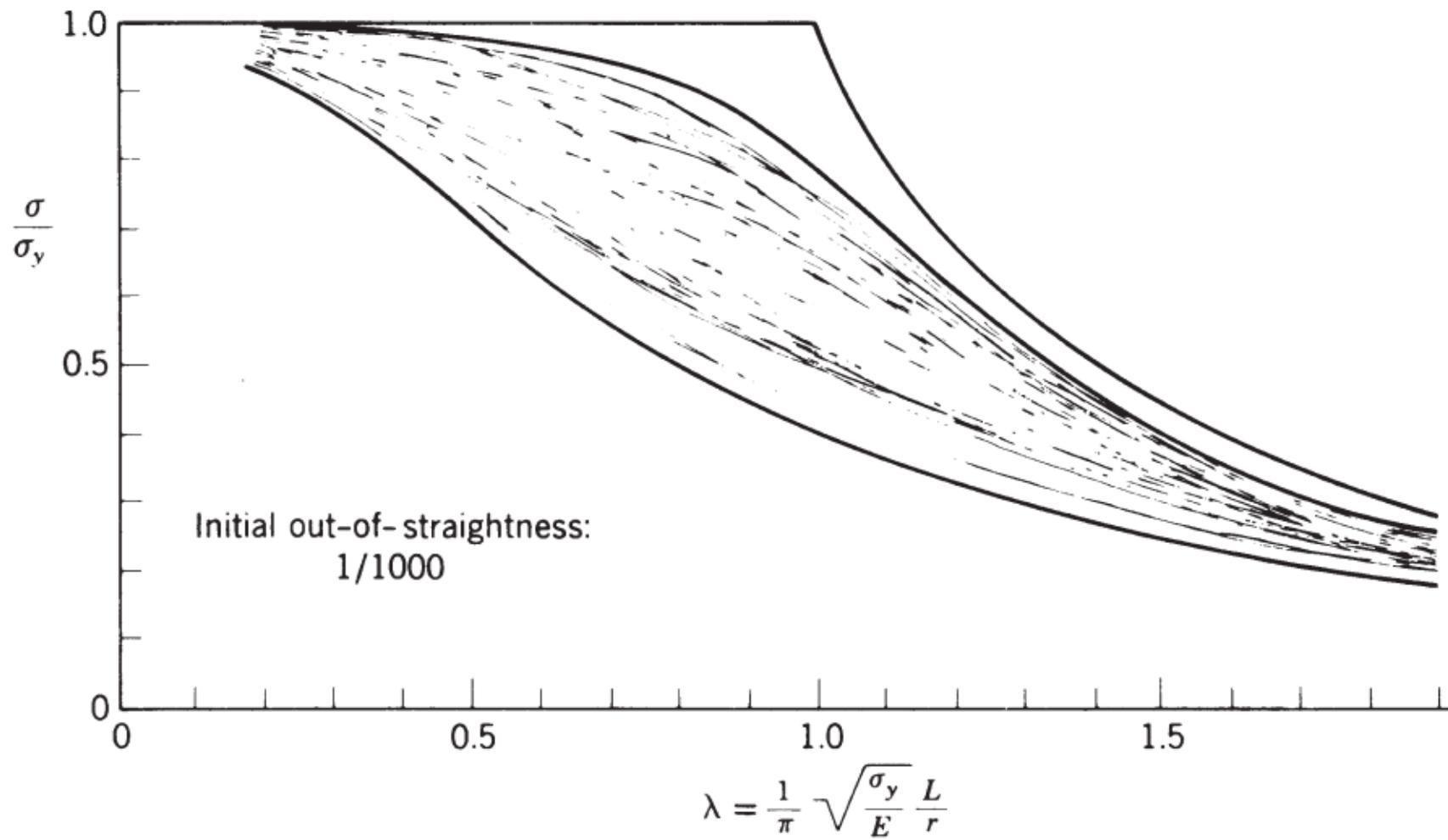
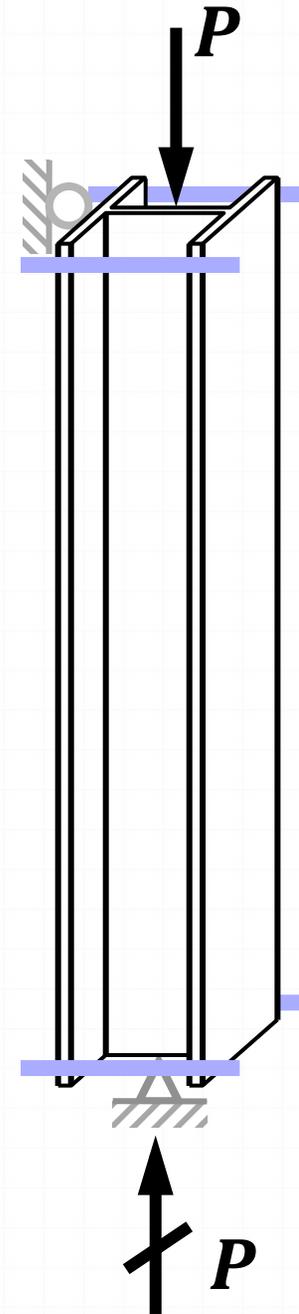


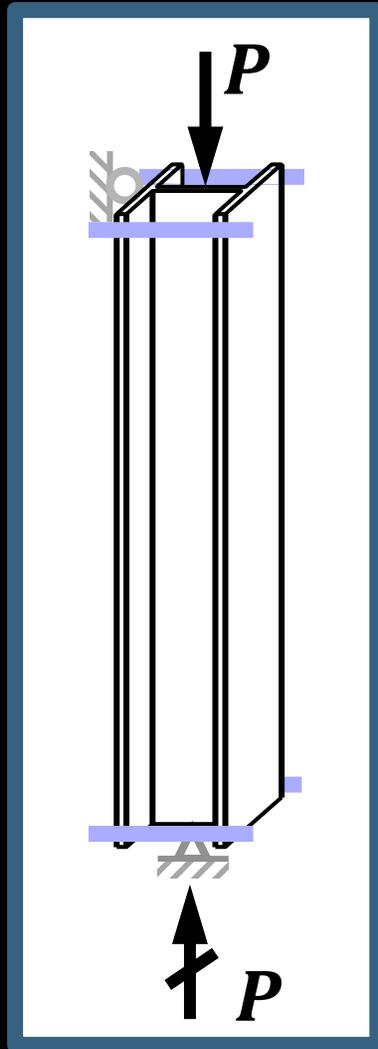
FIGURE 3.22 Maximum-strength column curves for a number of different column types (Bjorhovde, 1972).

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 δ_o / no σ_{res}
 - imperfection δ_o / no σ_{res}
 - no imperfection δ_o / σ_{res}
 - imperfection δ_o / σ_{res}
 - Critical Load (eigenvalue)
 - elastic
 - inelastic



**** Deflected Shape: 2nd-Order Inelastic, Incr # 384, Applied Load Ratio = 3.84 ****



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)

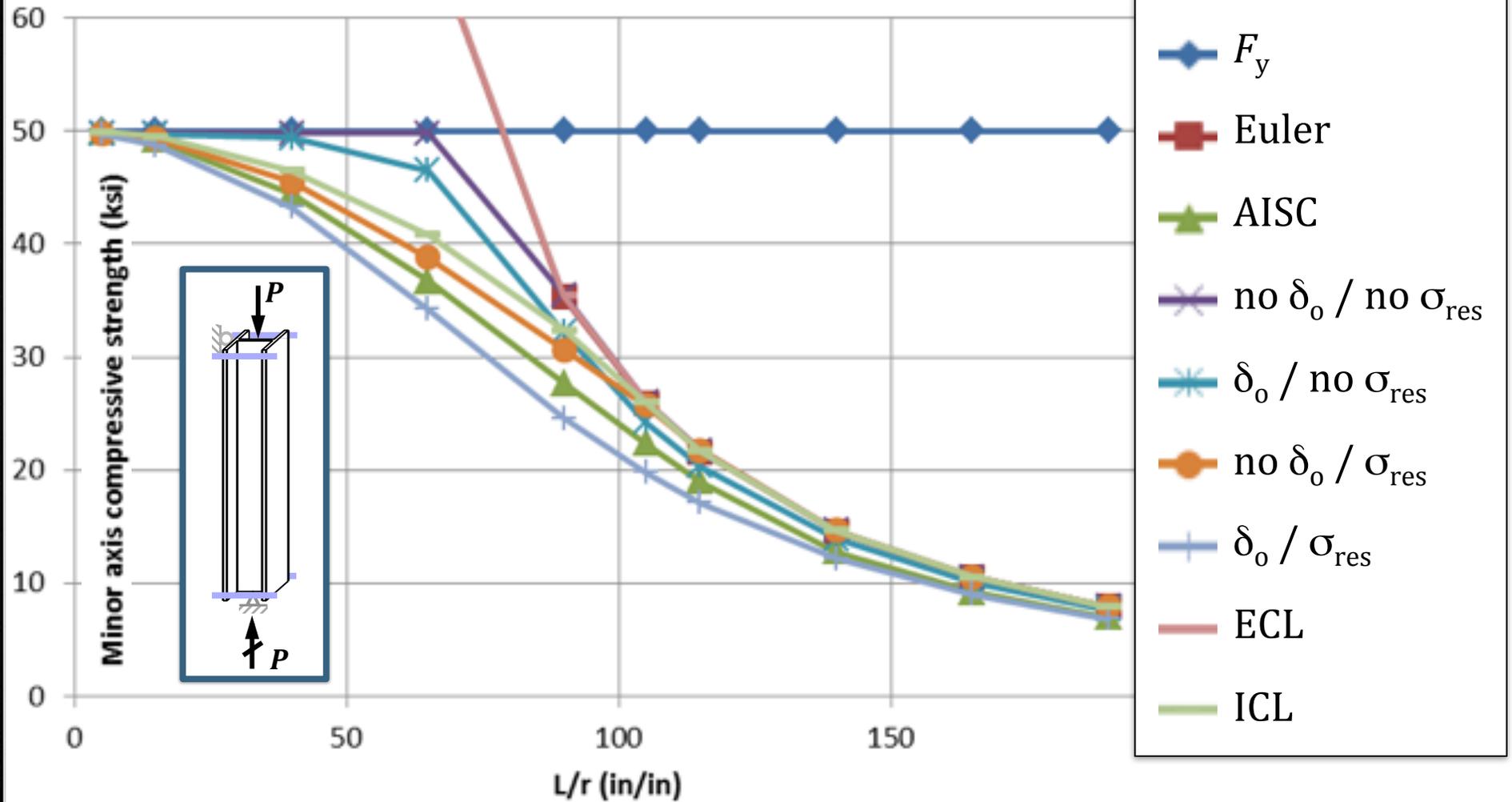
Modulus: Etm

Start New

Apply

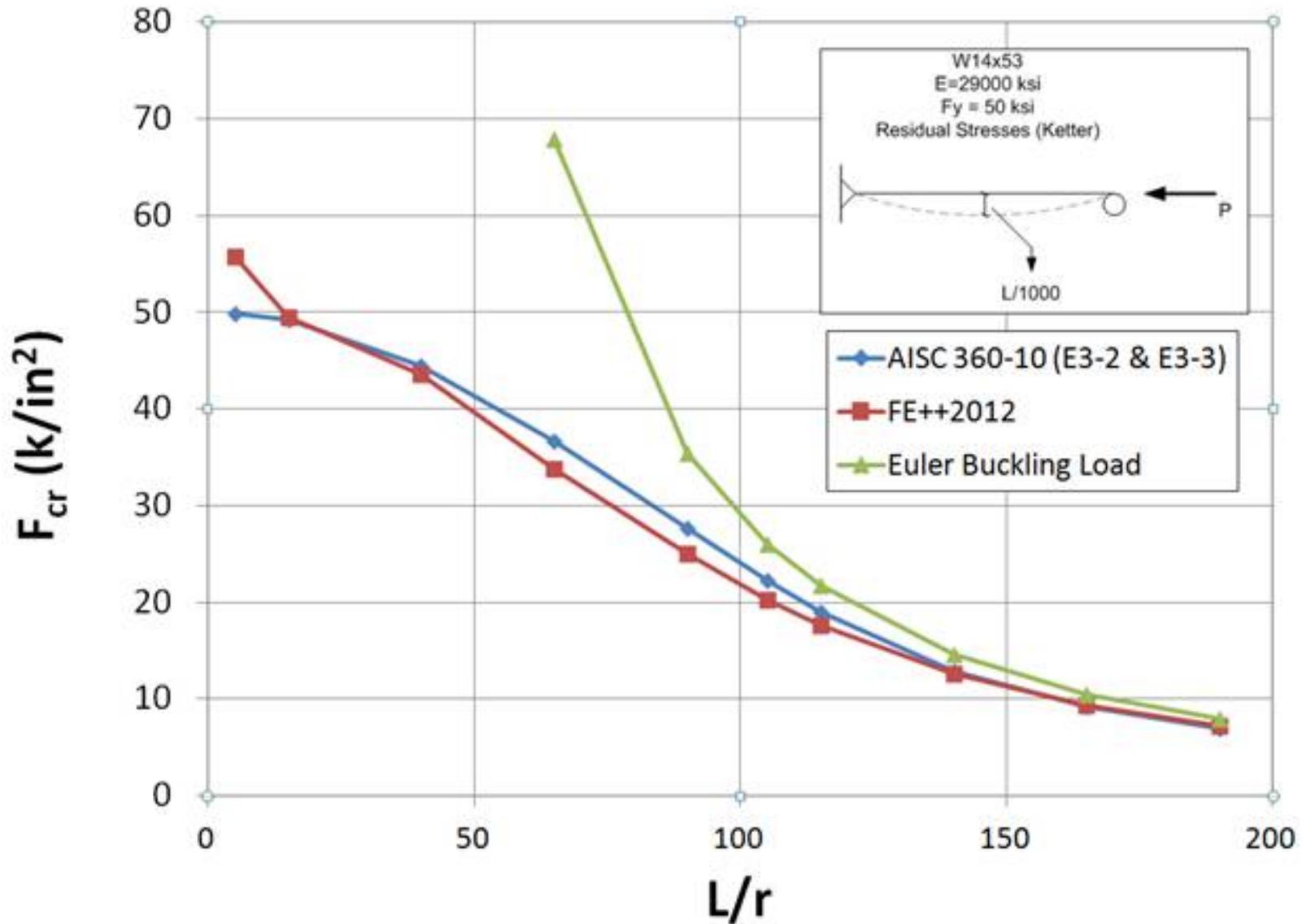
Cancel

Compr. Strength vs. L/r



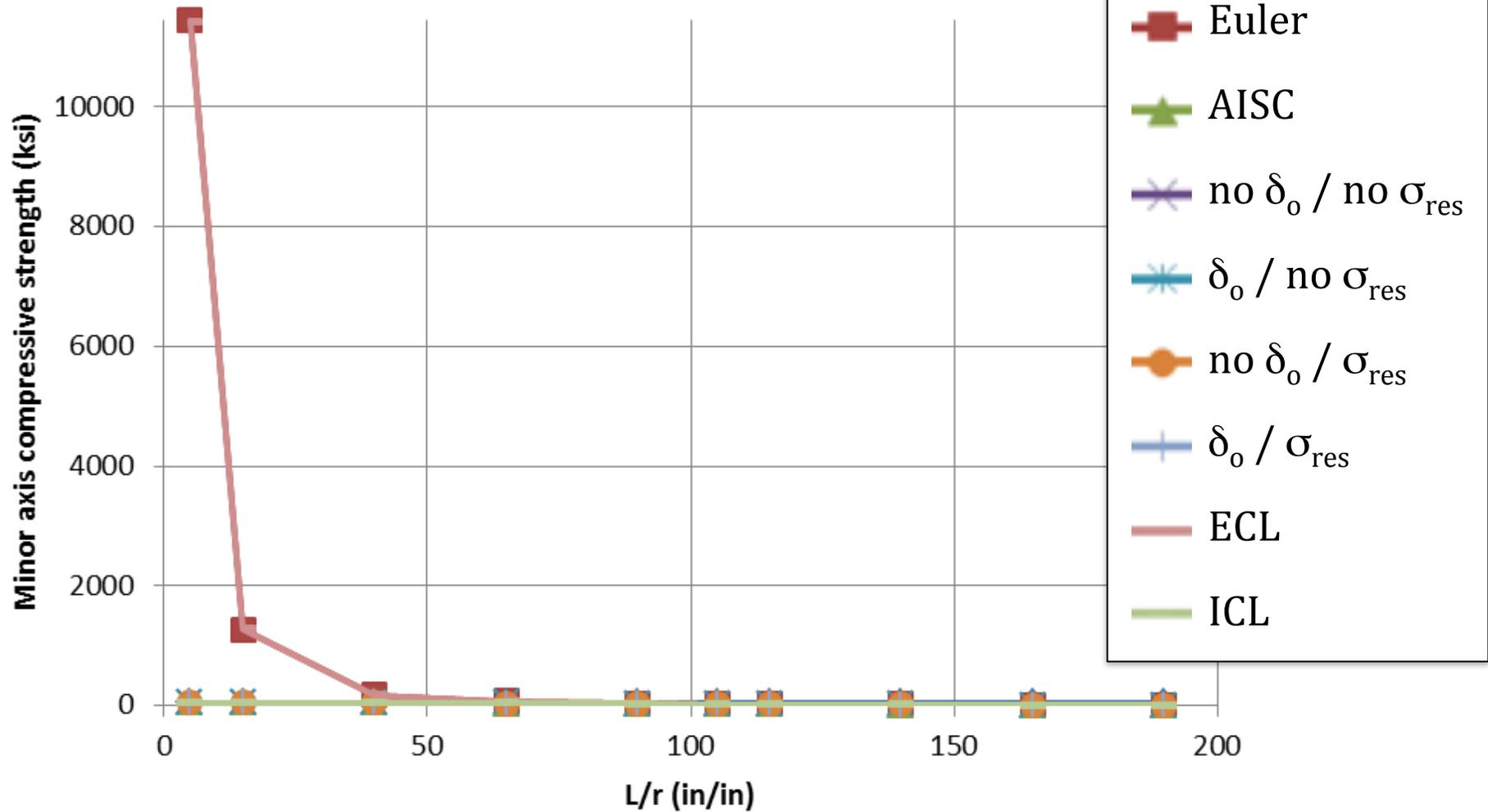
Thanks to Dan Tamarkin

Minor-Axis Column Study (W14x53)



Thanks to Bulent Alemdar at Bentley!

Compr. Strength vs. L/r



Thanks to Dan Tamarkin

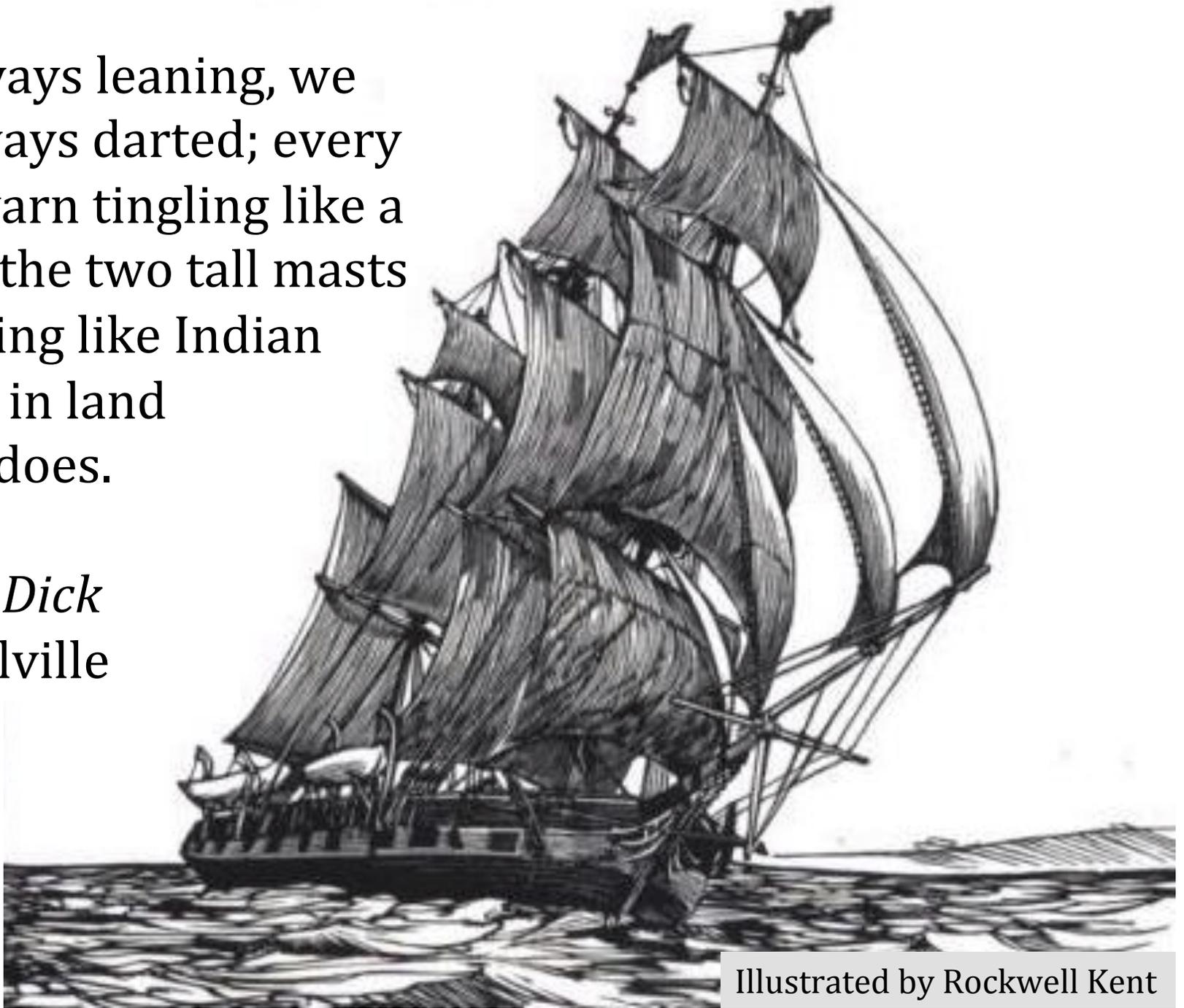
LM3. Effective Length K -factors for Frame Members

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

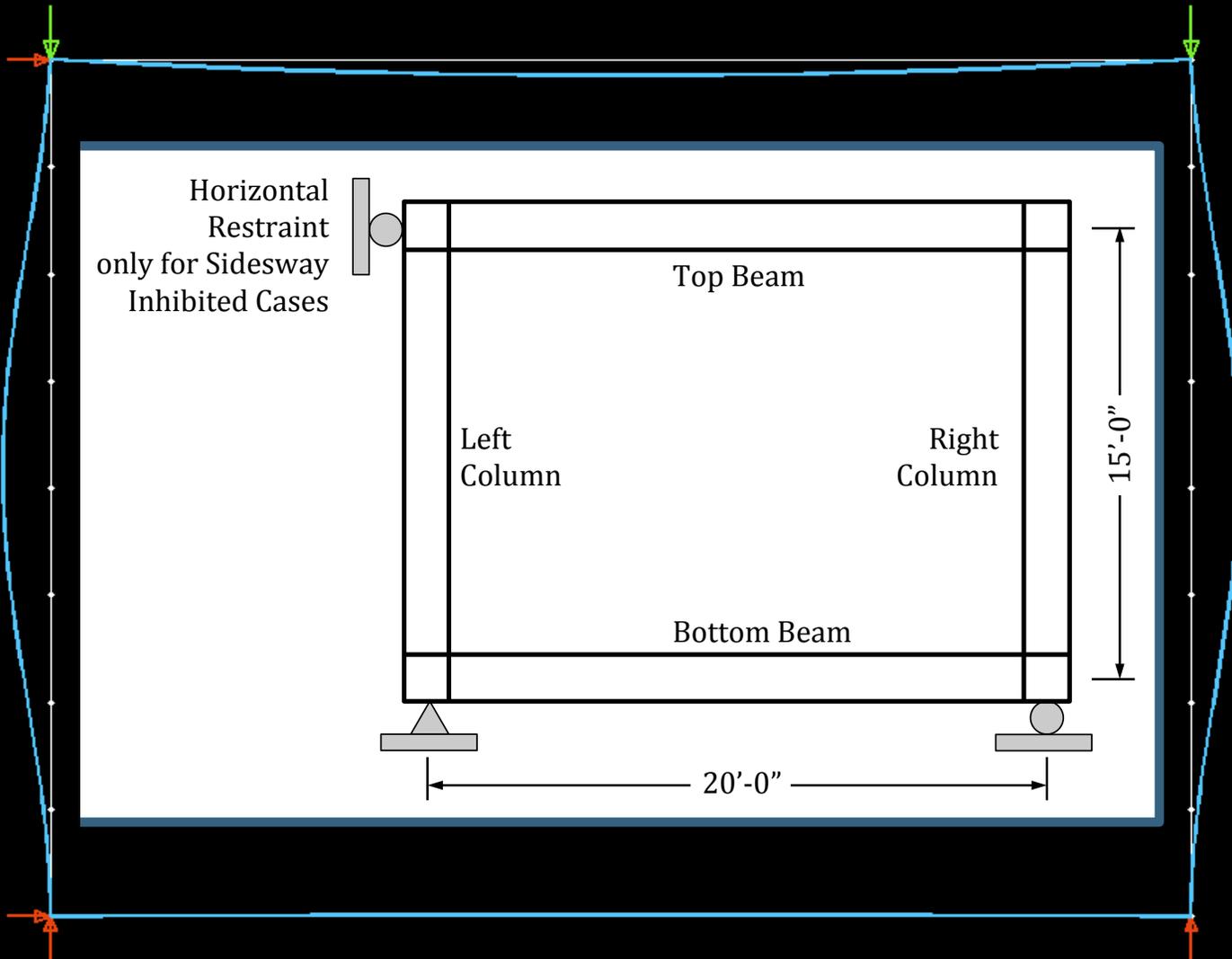
Sideways leaning, we
sideways darted; every
rope yarn tingling like a
wire; the two tall masts
buckling like Indian
canes in land
tornadoes.

Moby Dick
H. Melville
1851



Illustrated by Rockwell Kent

Deflected Shape: Inelastic Critical Load, Mode # 1, Applied Load Ratio = 434.1993



Inelastic Critical Load Analysis

Status:

Select Apply to perform an iterative eigenvalue analysis

Analysis Type:

Planar Frame (x-y)

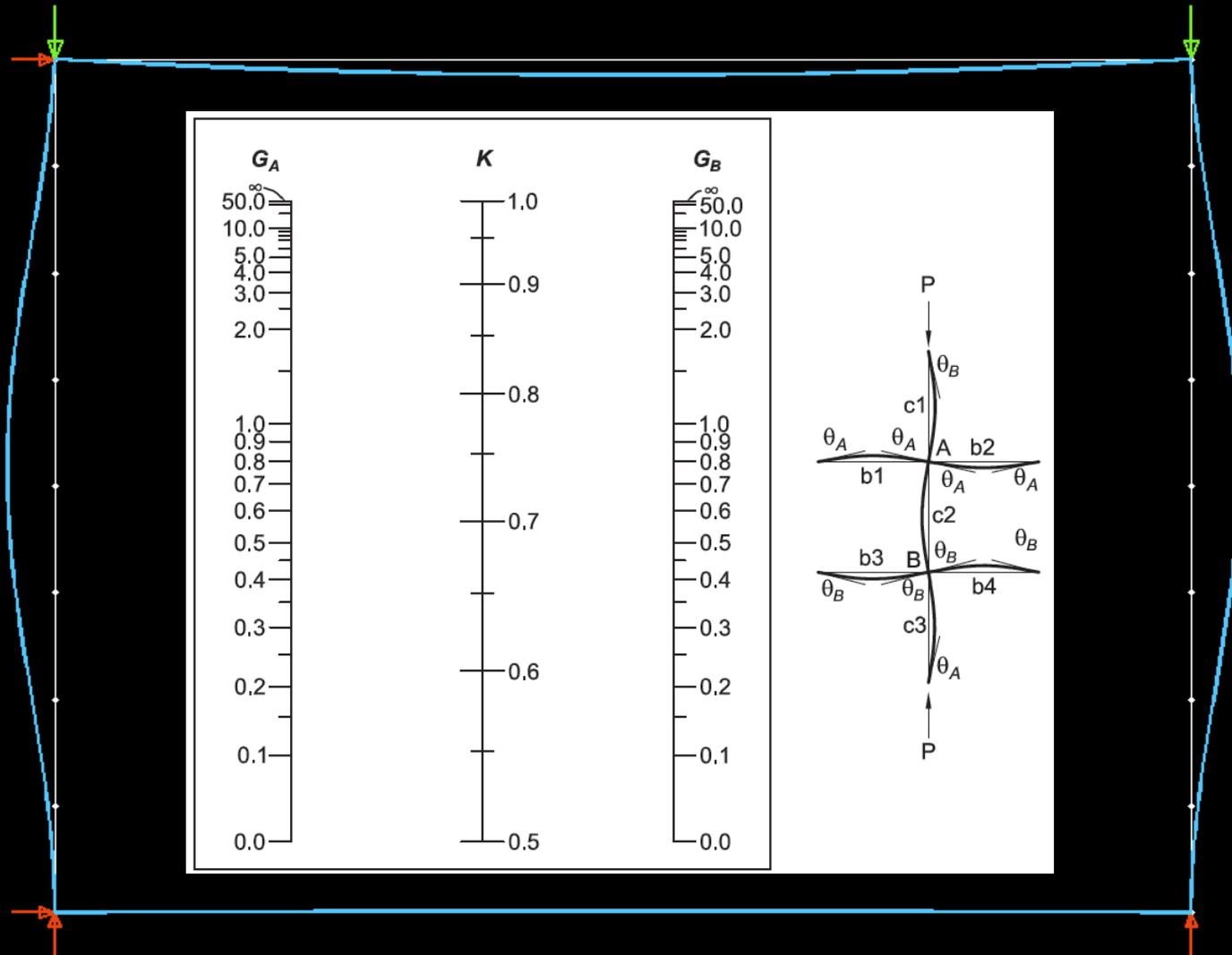
Max. # of Modes:

1

Apply

Cancel

Deflected Shape: Inelastic Critical Load, Mode # 1, Applied Load Ratio = 434.1993



Inelastic Critical Load Analysis

Status:

Select Apply to perform an iterative eigenvalue analysis

Analysis Type:

Planar Frame (x-y)

Max. # of Modes:

1

Apply

Cancel

Member Sizes					Sidesway Inhibited		Sidesway	
Case	Left	Right	Top	Bottom	Elastic	Inelastic	Elastic	Inelastic
	Column	Column	Beam	Beam	P_{cr}	P_{cr}	P_{cr}	P_{cr}
1	W10x33	W10x33	W12x14	W12x14	663.3	416.2	232.1	232.1
2	W10x33	W10x33	W24x68	W24x68	1227.6	439.1	317.5	299.9
3	W10x33	W10x33	W24x68	W12x14	892.5	429.9	269.9	267.2
4	W10x33	W10x33	W12x14	W24x68	892.5	429.9	269.9	267.2

Effective Length K-Factors							
	Case	Elastic	Elastic	Percent	Inelastic	Inelastic	Percent
		Critical	Alignmen		Critical	Alignmen	
		Load	Charts	Difference	Load	Charts	Difference
				(%)			(%)
Inhibited Sidesway	1	0.6982	0.70	0.26	0.6166	0.62	0.55
	2	0.5132	0.51	0.62	0.5046	0.51	1.08
	3	0.6019	0.60	0.31	0.5523	0.55	0.42
	4	0.6019	0.60	0.31	0.5523	0.55	0.42
Uninhibited Sidesway	1	1.1803	1.18	0.02	1.1803	1.18	0.02
	2	1.0091	1.00	0.90	1.0091	1.01	0.09
	3	1.0945	1.10	0.50	1.0944	1.09	0.40
	4	1.0945	1.10	0.50	1.0944	1.09	0.40

LM4. Factors Influencing the Strength of Flexural Members

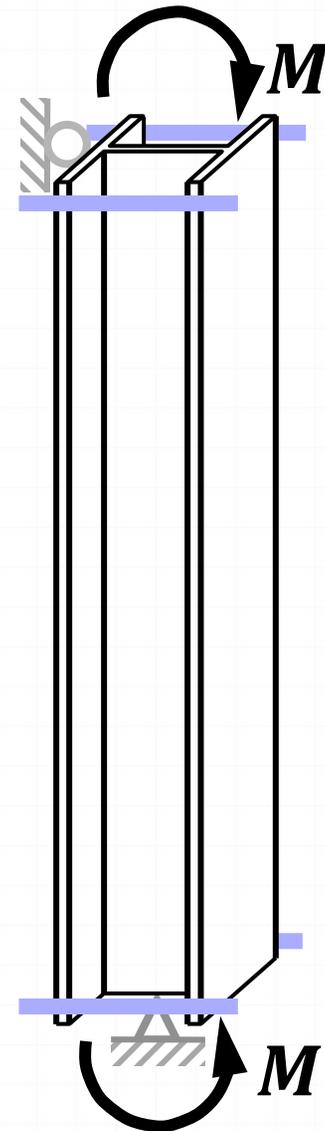
Learning Objectives

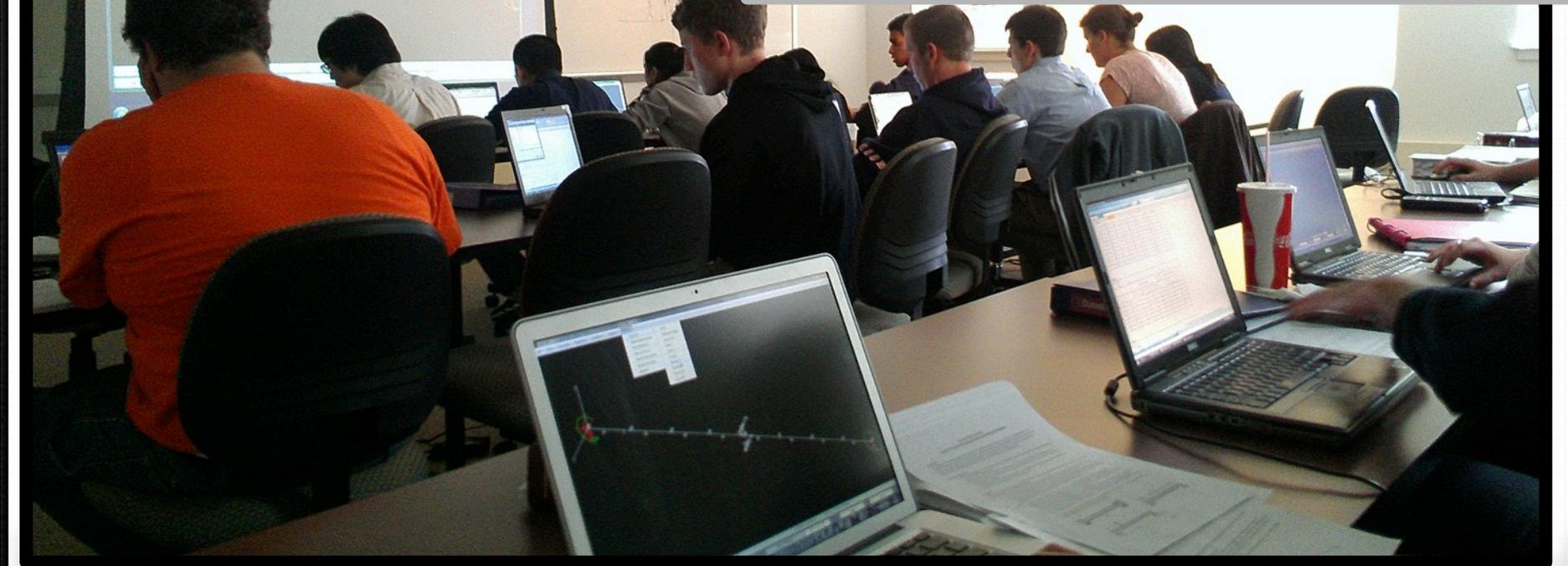
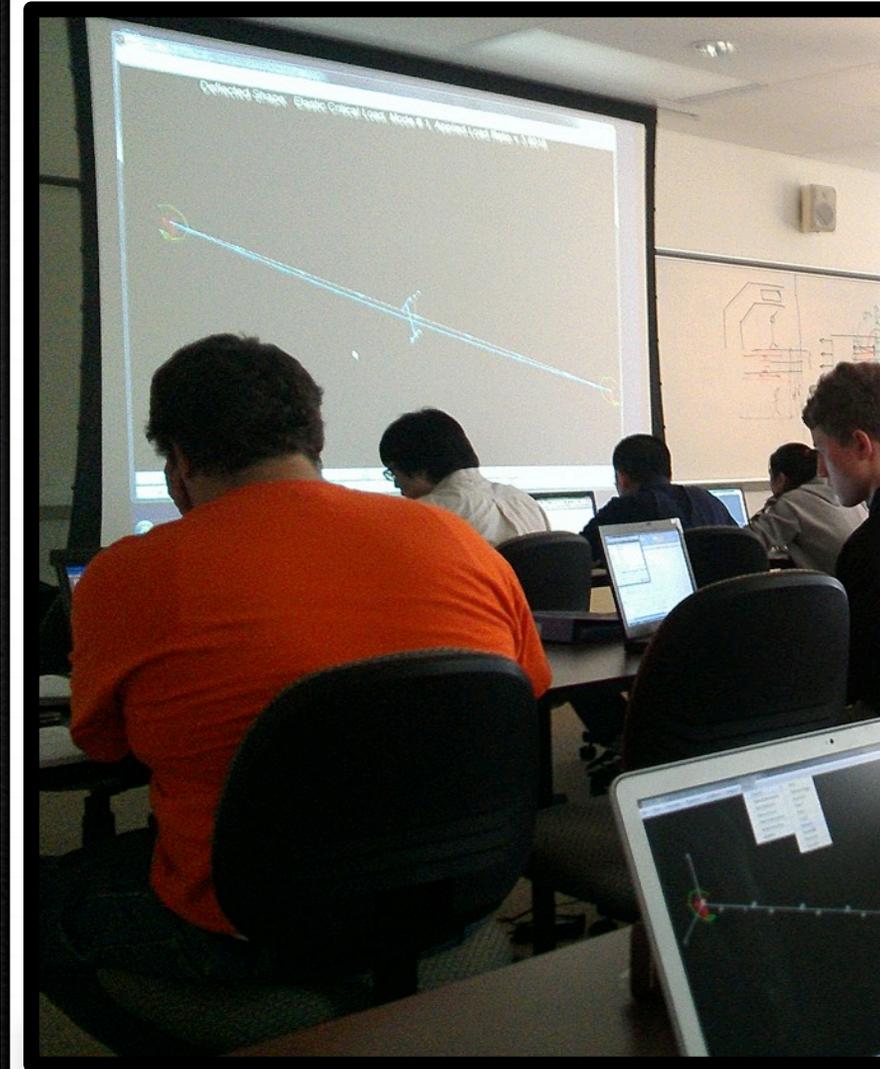
- Recognize limitations of the theoretical elastic lateral-torsional buckling solution
- Prepare beam strength curves (ϕM_n vs. L_b).
- Investigate the effect of local yielding/residual stress and out-of-straightness on elastic/inelastic LTB strength
- Compare with AISC beam strength curve

Sister to LM2....

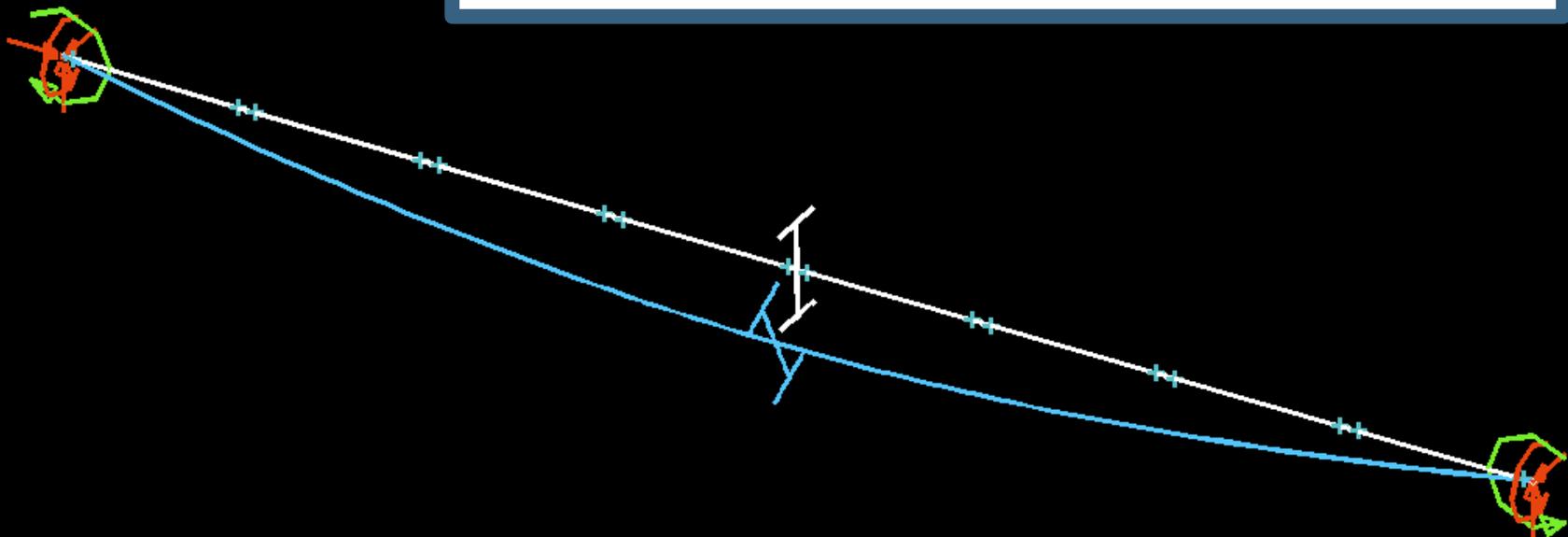
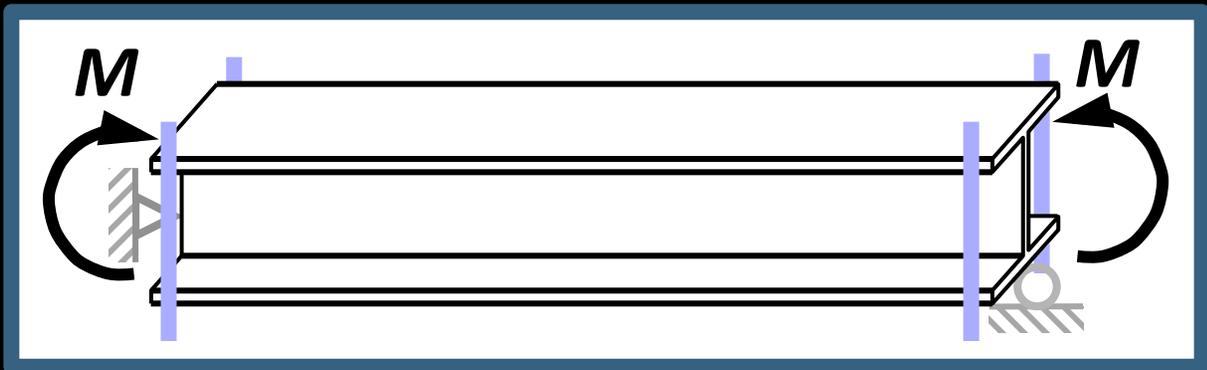
LM4

- ✓ 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 δ_o / no σ_{res}
 - imperfection δ_o / no σ_{res}
 - no imperfection δ_o / σ_{res}
 - imperfection δ_o / σ_{res}
 - Elastic critical load (eigenvalue)
 - FEA shell elements (ADINA)



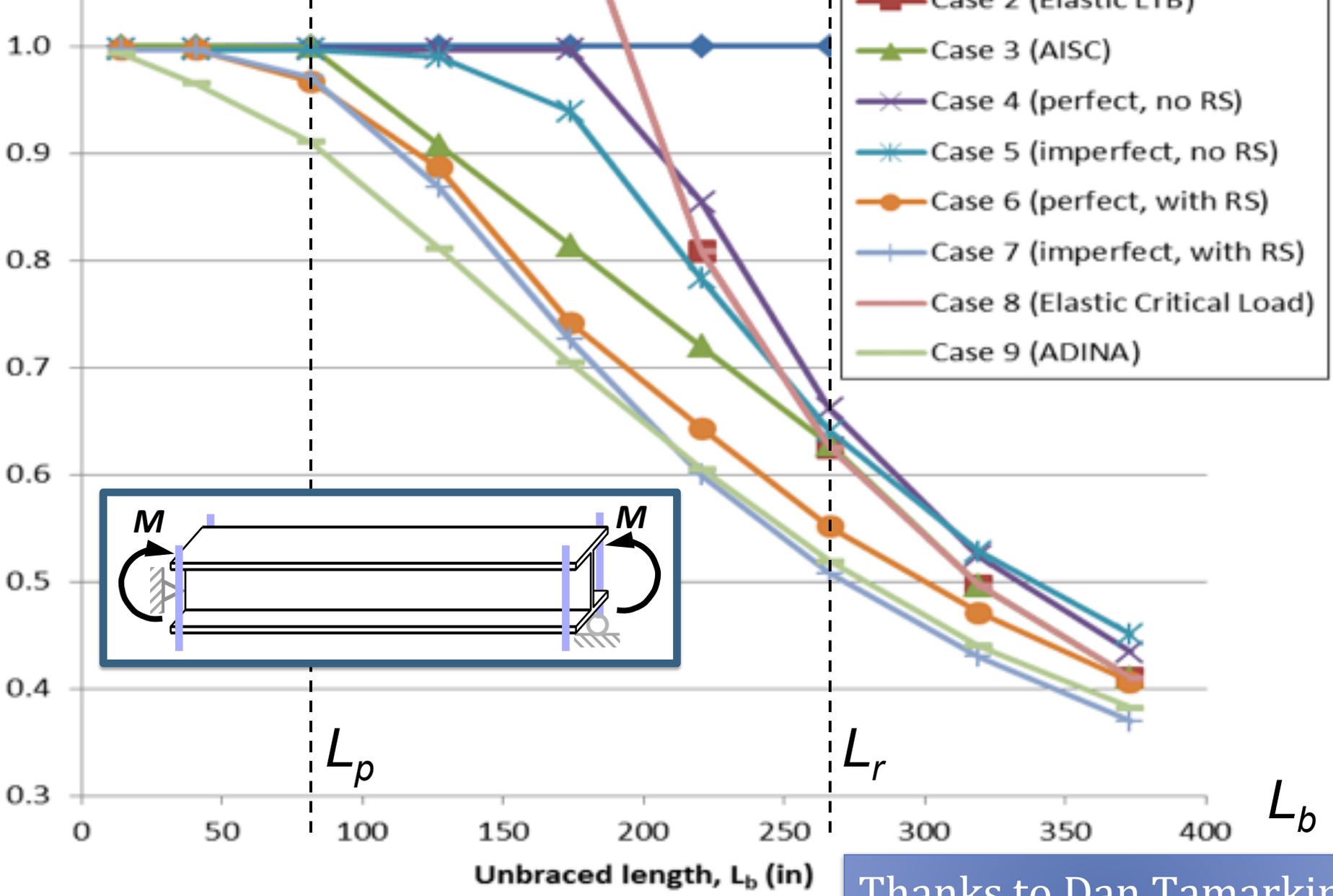


**** Deflected Shape: 2nd-Order Inelastic, Incr # 261, Applied Load Ratio = 2.61 ****



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	

M_n / M_p



Thanks to Dan Tamarkin

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

LM5

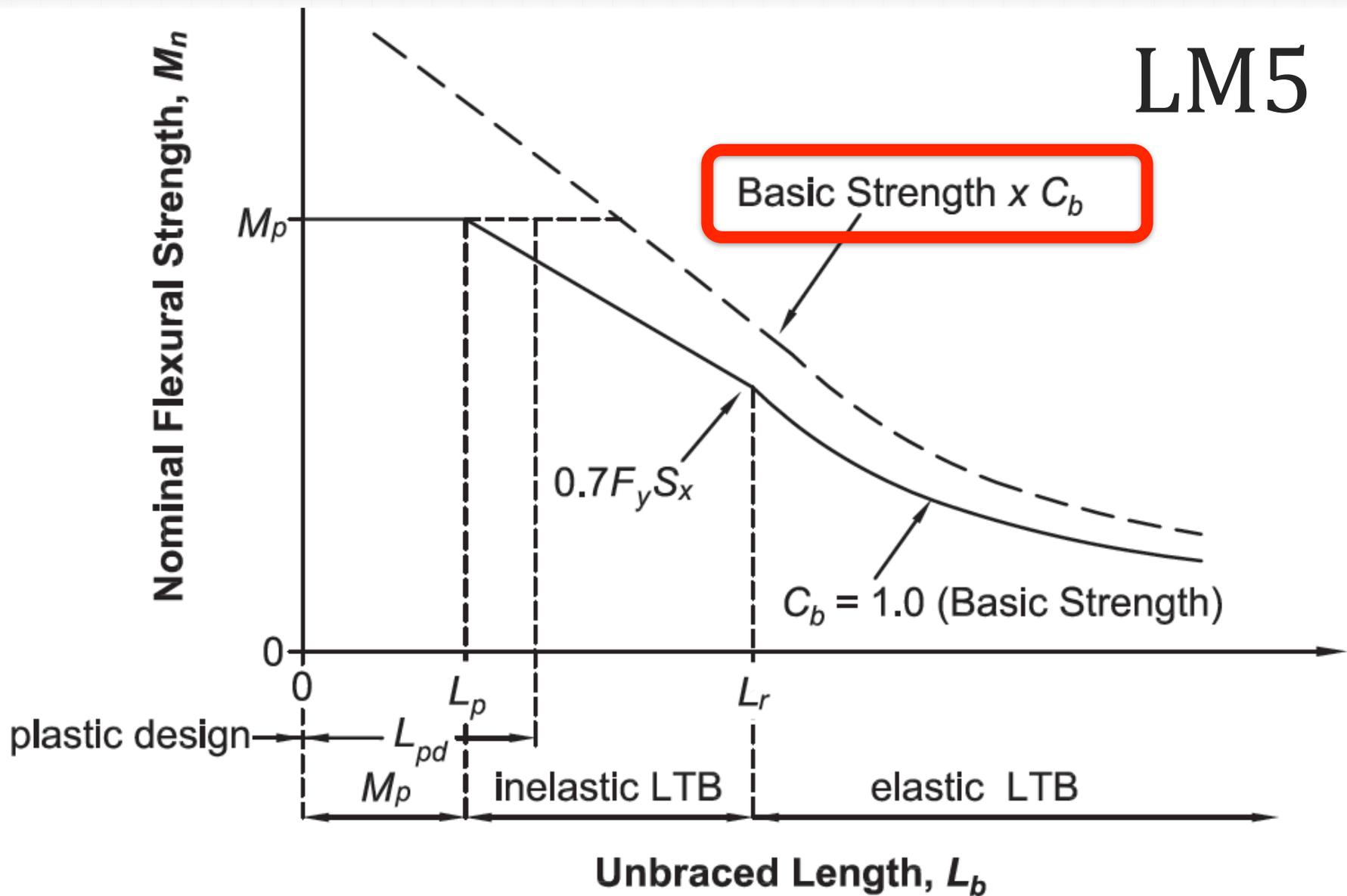
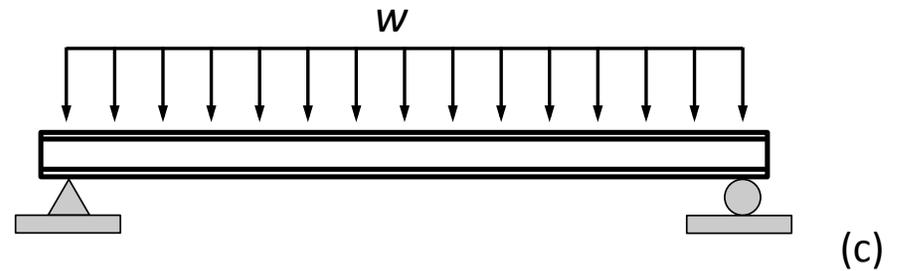
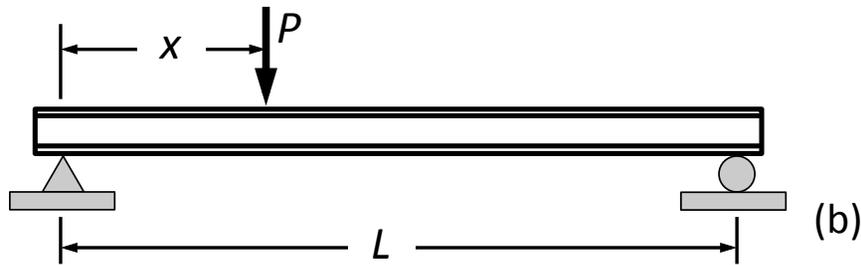


Fig. C-F1.2. Nominal flexural strength as a function of unbraced length and moment gradient.

LM5



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

Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio = 3.6018

$$M_1 = -1000 \text{ in-k}$$

$$M_{cr} = 3601.8 \text{ in-k}$$

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

$$M_2 = 1000 \text{ in-k}$$

Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio = 9.7873

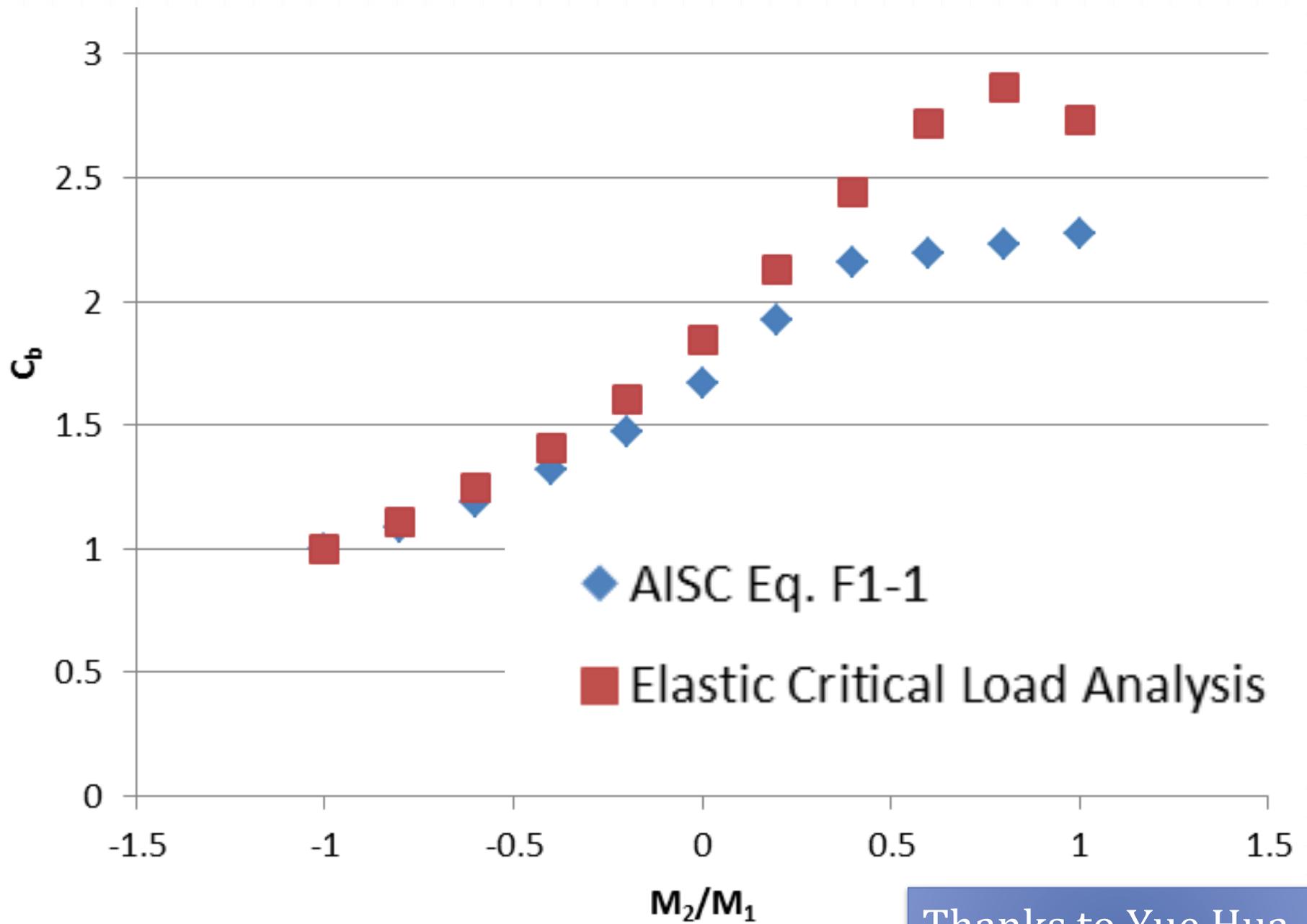
$$M_1 = -1000 \text{ in-k}$$

$$M_{cr} = 9787.3 \text{ in-k}$$

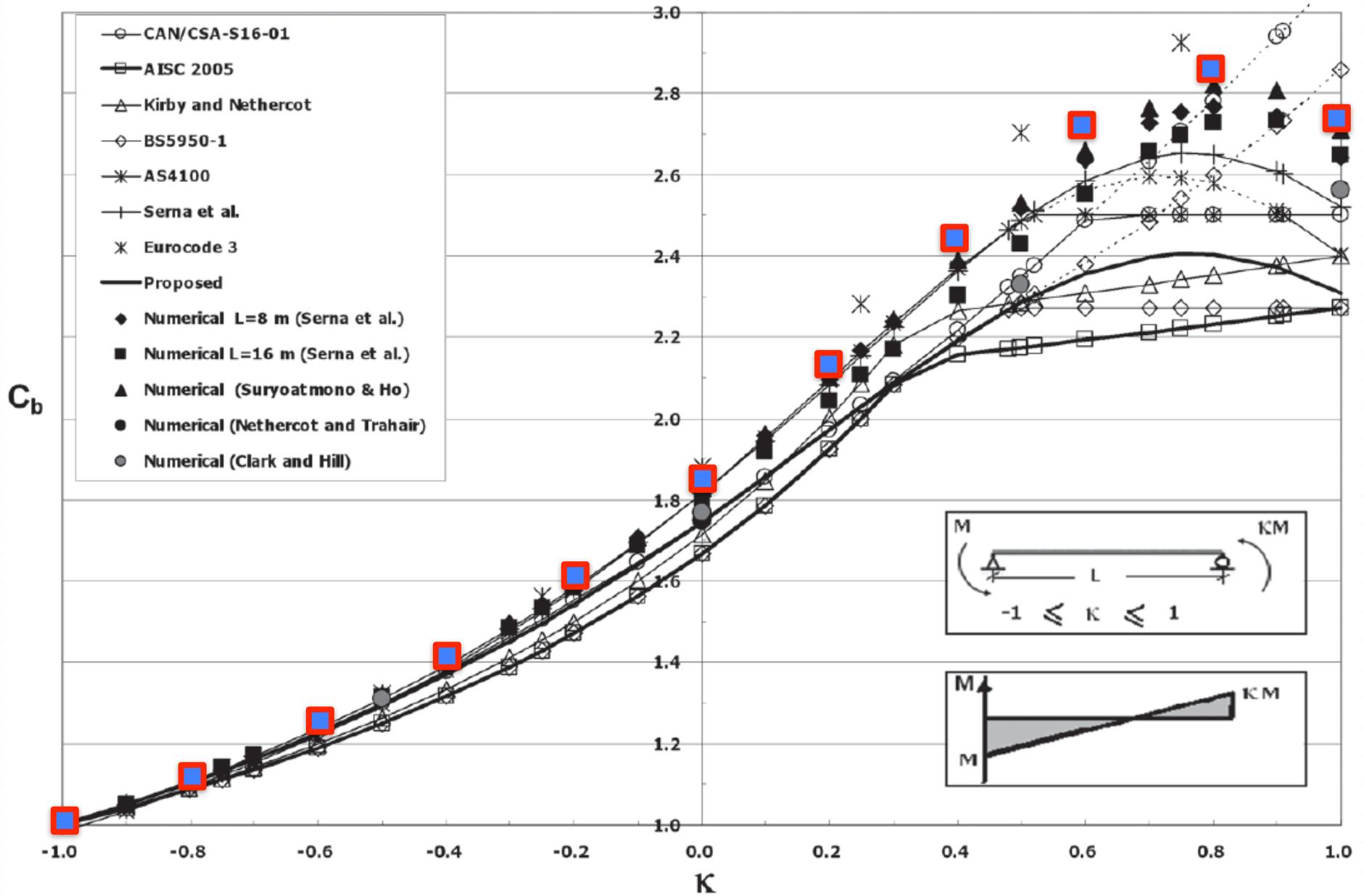
$$C_b^{MASTAN2} = \frac{9787.3}{3601.8} = 2.72$$

$$C_b^{AISC} = 2.19$$

$$M_2 = -600 \text{ in-k}$$



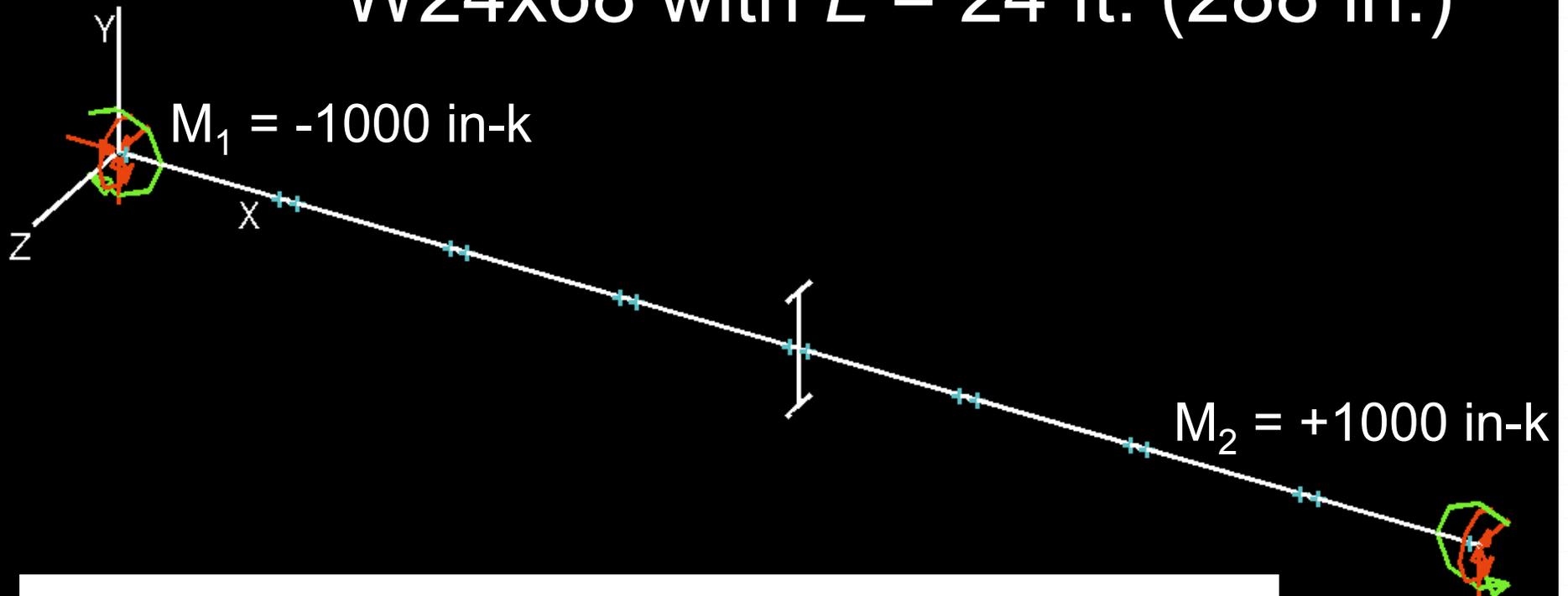
Thanks to Yue Hua



Wong and Driver, AISC EJ, 2010

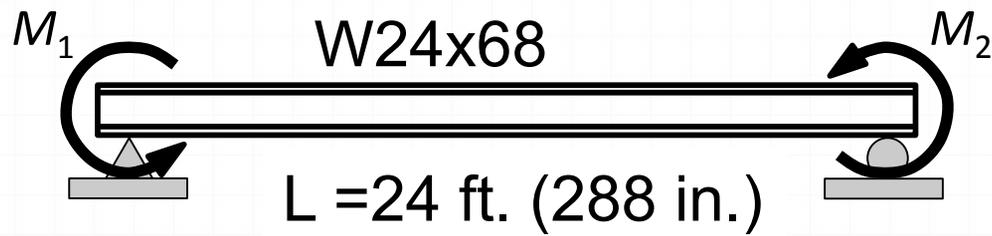
Time for you to take it for a spin...

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



$$M_{cr} = \frac{\pi}{L} \sqrt{EI_y GJ + \left(\frac{\pi E}{L}\right)^2 I_y C_w} = 3602 \text{ kip-in}$$

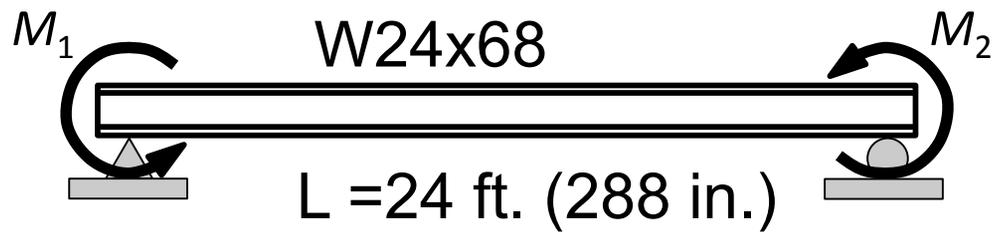
$$= 300 \text{ kip-ft}$$



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:



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	3.36
$M_1/M_2 = +1$	9,838	27,414	2.79
	2.73		

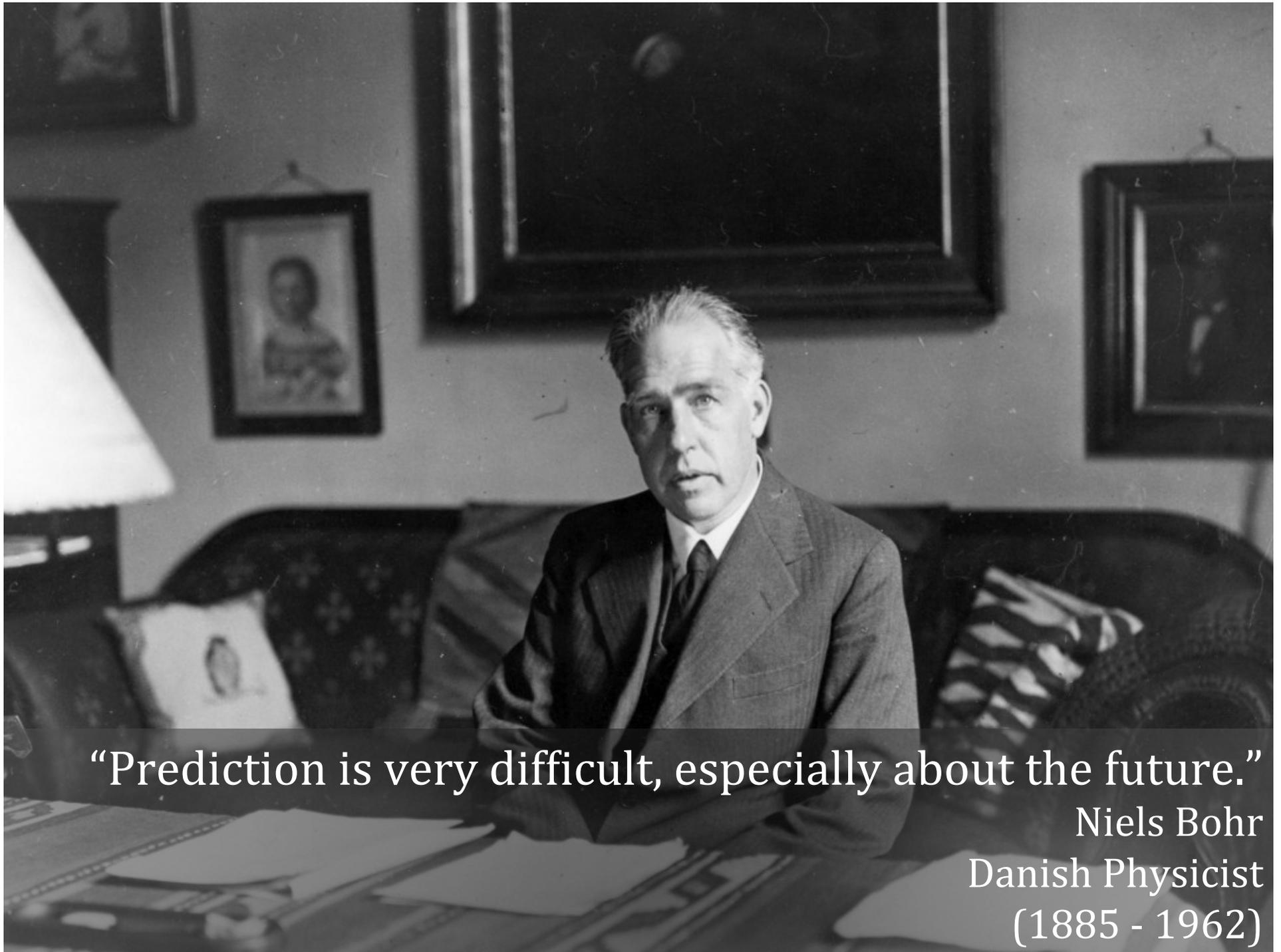
Observations:

- 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

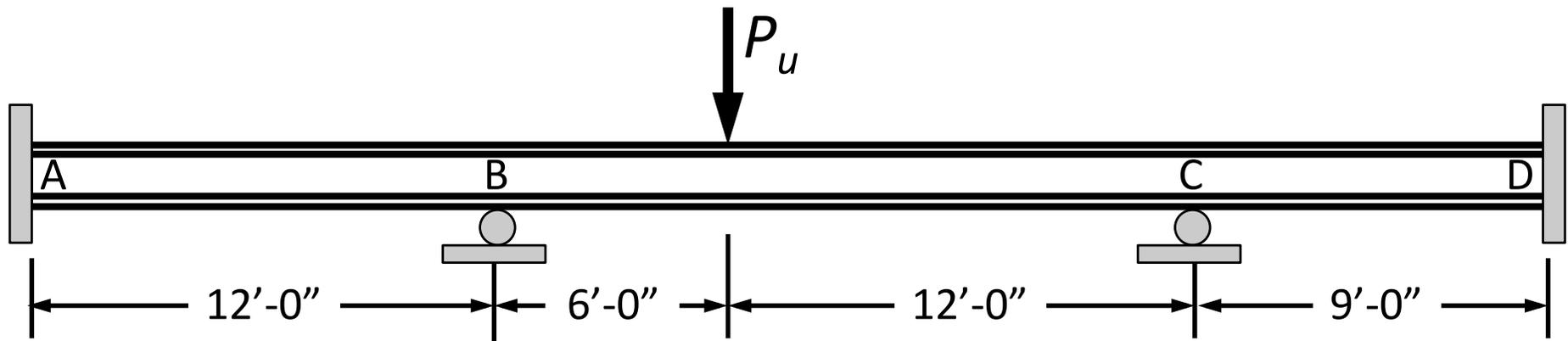
- Compare designs of continuous beams using elastic and inelastic analyses
- Observe pros and cons of each design method
- Employ AISC's 9/10^{ths} moment redistribution allowance
- Investigate force/moment redistribution that occurs as a result of member yielding.



“Prediction is very difficult, especially about the future.”

Niels Bohr
Danish Physicist
(1885 - 1962)

LM6: Elastic vs. Inelastic Design



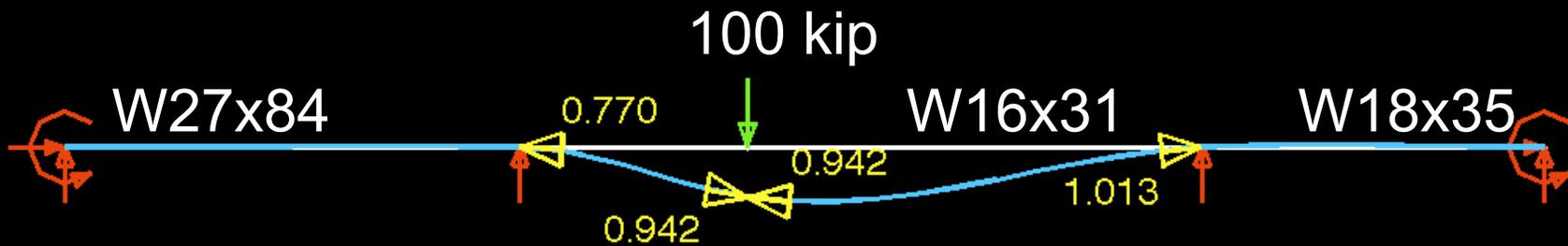
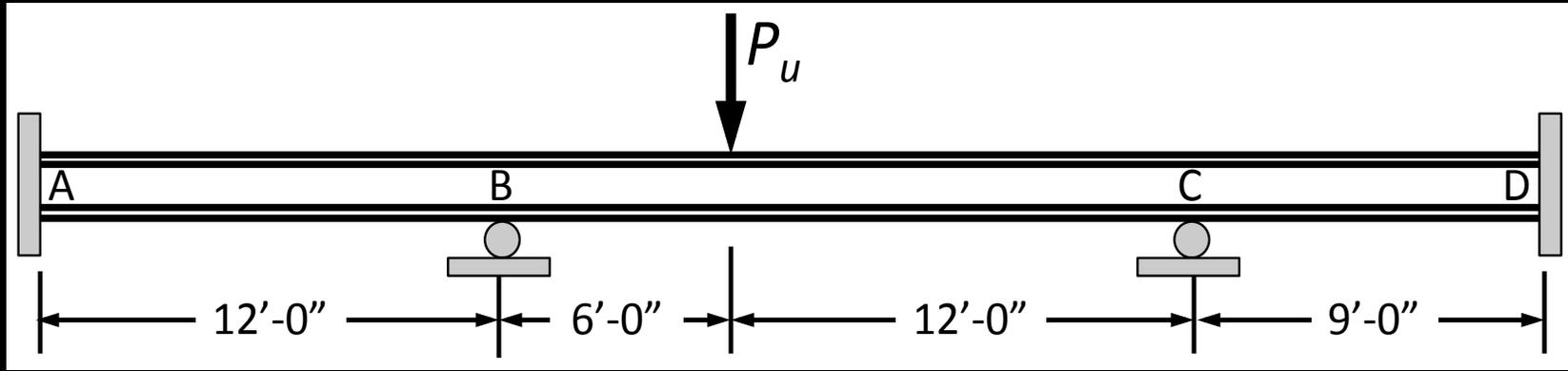
4 Cases:

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

**** Deflected Shape: 1st-Order Inelastic, Incr # 11, Applied Load Ratio = 1.0128 ****



Case 2: Inelastic Analysis

$$P_u = 101.3 \text{ kip}$$

$$Wt = 1.881 \text{ kip}$$

$$P_u / Wt = 53.84$$

First-Order Inelastic Analysis

Status:

Select Apply to perform analysis

Solution Type: Simple Step

Incr Size: 0.1

Max. # of Incrs: 100

Max. Appl. Ratio: 10

Analysis Type: Planar Frame (x-y)

Start New

Apply

Cancel

And the winner is...

	AISC Design Method	Member Lengths and Sizes			Weight kips	Ratio P_u / Wt
		AB 12'-0"	BC 18'-0"	CD 9'-0"		
Case 1	a. Elastic	W16x31	W16x31	W16x31	1.209	70.50
	b. Elastic 9/10 th	W16x31	W16x31	W16x31	1.209	78.33
	c. Inelastic	W16x31	W16x31	W16x31	1.209	83.79
Case 2	a. Elastic	W27x84	W16x31	W18x35	1.881	40.92
	b. Elastic 9/10 th	W27x84	W16x31	W18x35	1.881	45.47
	c. Inelastic	W27x84	W16x31	W18x35	1.881	53.84
Case 3	a. Elastic	W24x55	W24x55	W24x55	2.145	93.24
	b. Elastic 9/10 th	W21x55	W21x55	W21x55	2.145	93.24
	c. Inelastic	W21x50	W21x50	W21x50	1.950	102.56
Case 4	a. Elastic	W18x40	W24x62	W18x35	1.911	104.66
	b. Elastic 9/10 th	W18x35	W24x62	W14x26	1.770	112.99
	c. Inelastic	W10x15	W24x76	W10x15	1.683	118.84

Ratio P_u / Wt
70.50
78.33
83.79
40.92
45.47
53.84
93.24
93.24
102.56
104.66
112.99
118.84

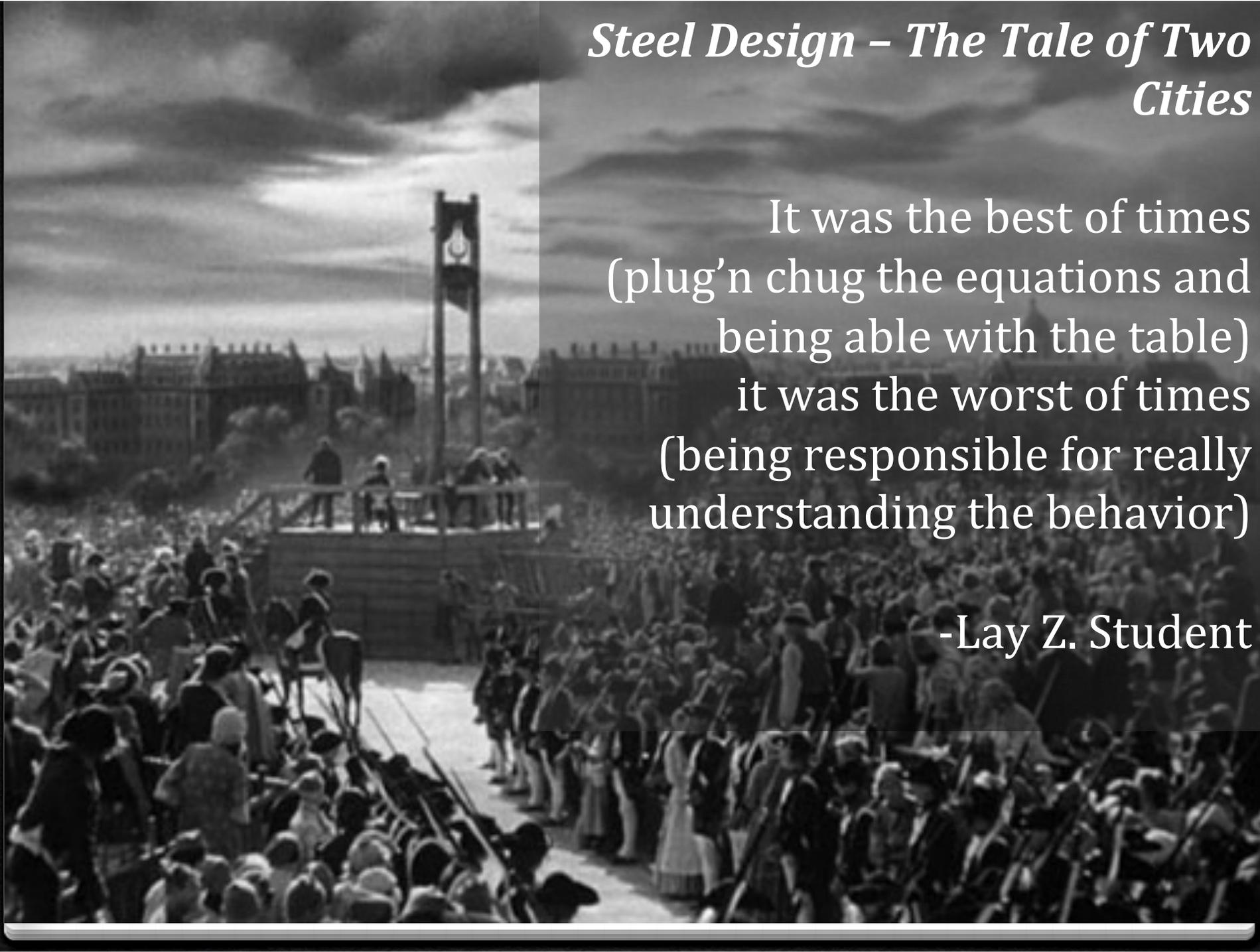
Ratio P_u / Wt
70.50
78.33
83.79
40.92
45.47
53.84
93.24
93.24
102.56
104.66
112.99
118.84

AISC Inelastic Design!

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



*Steel Design – The Tale of Two
Cities*

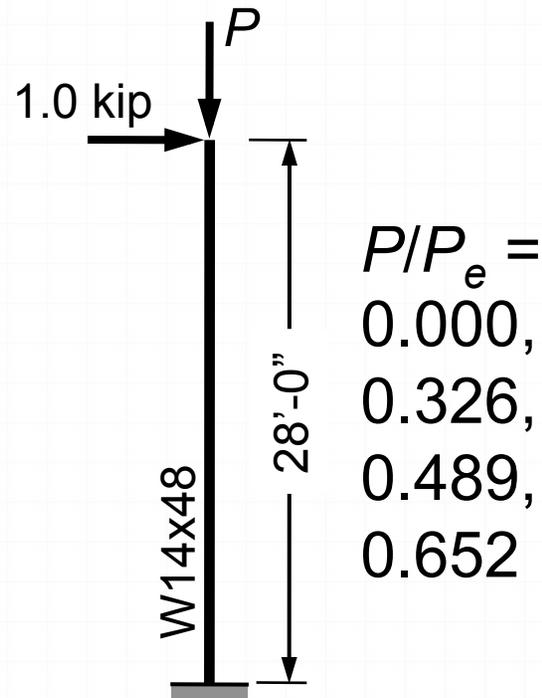
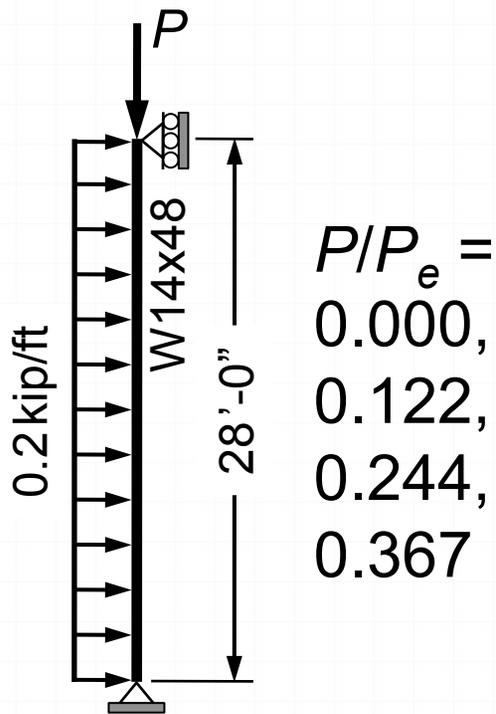
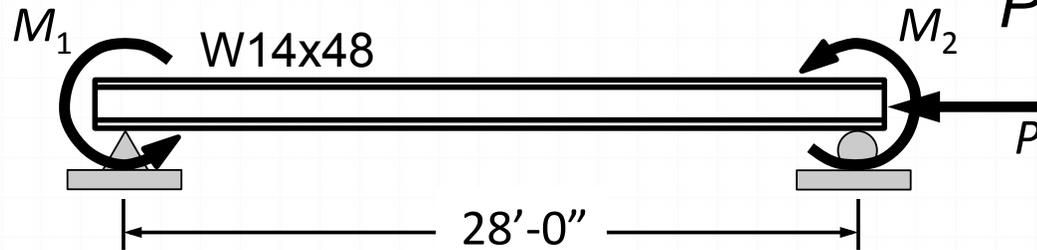
It was the best of times
(plug'n chug the equations and
being able with the table)
it was the worst of times
(being responsible for really
understanding the behavior)

-Lay Z. Student

1st-order vs. 2nd-order

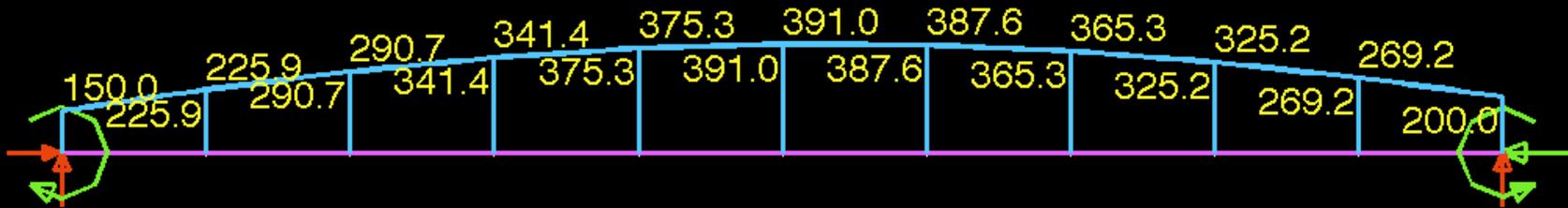
$$M_1/M_2 = +0.75, 0.0, -0.75$$

$$P/P_e = 0, 0.1, 0.2, \dots, 0.9$$



Rigorous
vs.
 B_1, B_2

**** Moment Z: 2nd-Order Elastic, Incr # 10, Applied Load Ratio = 1 ****



$$M_{\max}^{1st} = 200 \text{ k-in}$$

$$M_{\max}^{2nd} = 391 \text{ k-in}$$

$$B_1^{\text{Computation}} = \frac{391}{200} = 1.96$$

$$M_1^{1st} = -150 \text{ k-in}$$

$$M_2^{1st} = +200 \text{ k-in} (= M_{\max}^{1st})$$

$$C_m = 0.6 - 0.4(-150/+200) = 0.9$$

$$P/P_e = 0.5 \quad B_1^{\text{AISC}} = \frac{0.9}{1 - 0.5} = 1.8$$

$$M_{\max}^{2nd} = B_1^{\text{AISC}} M_{\max}^{1st}$$

$$M_{\max}^{2nd} = 1.8 \times 200 = 360 \text{ k-in}$$

Define element(s) and parameters

Element(s)

All

C

Moment Z

T

Scale

25.2

of pts

10

Fill

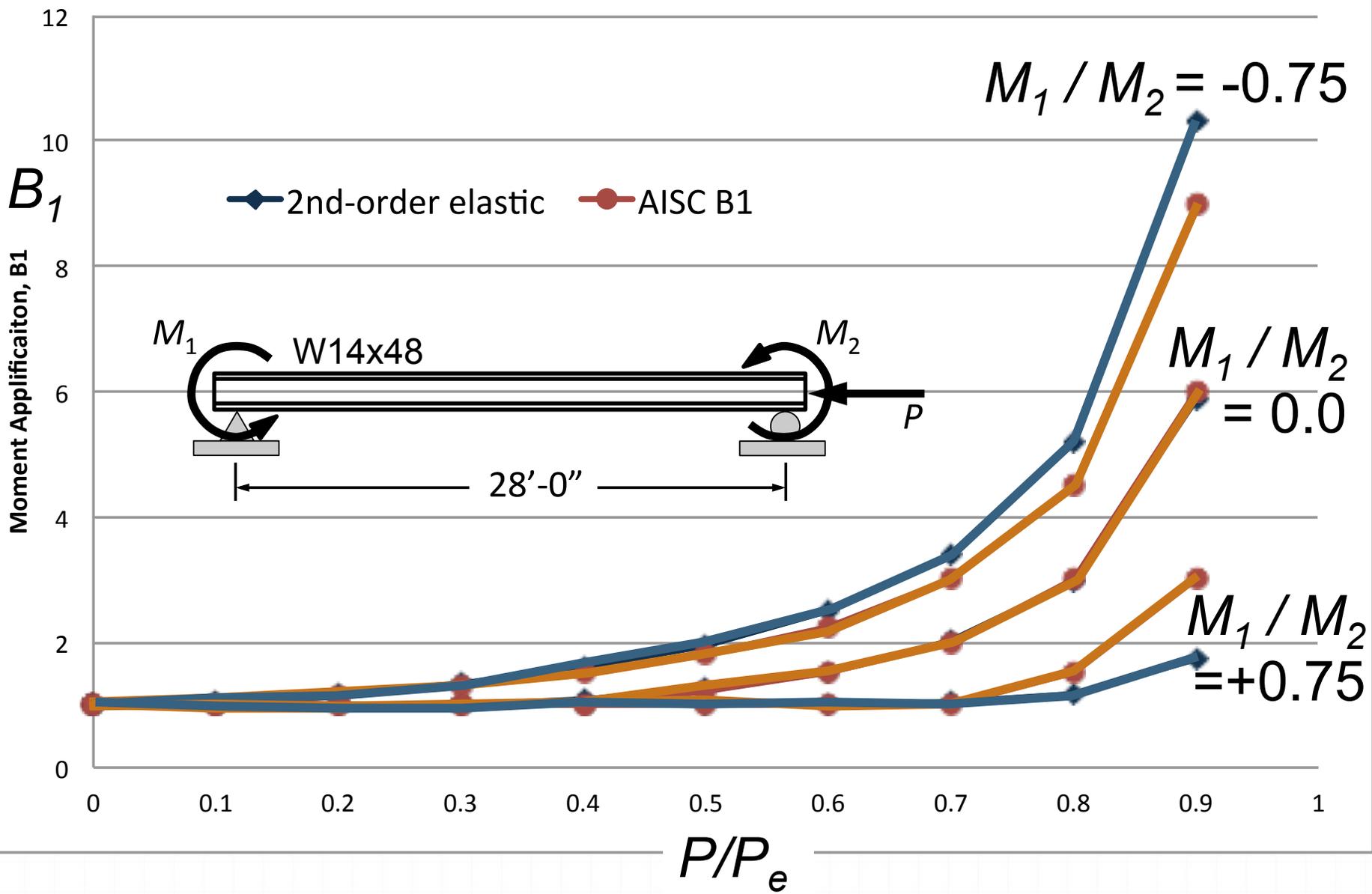
<

10

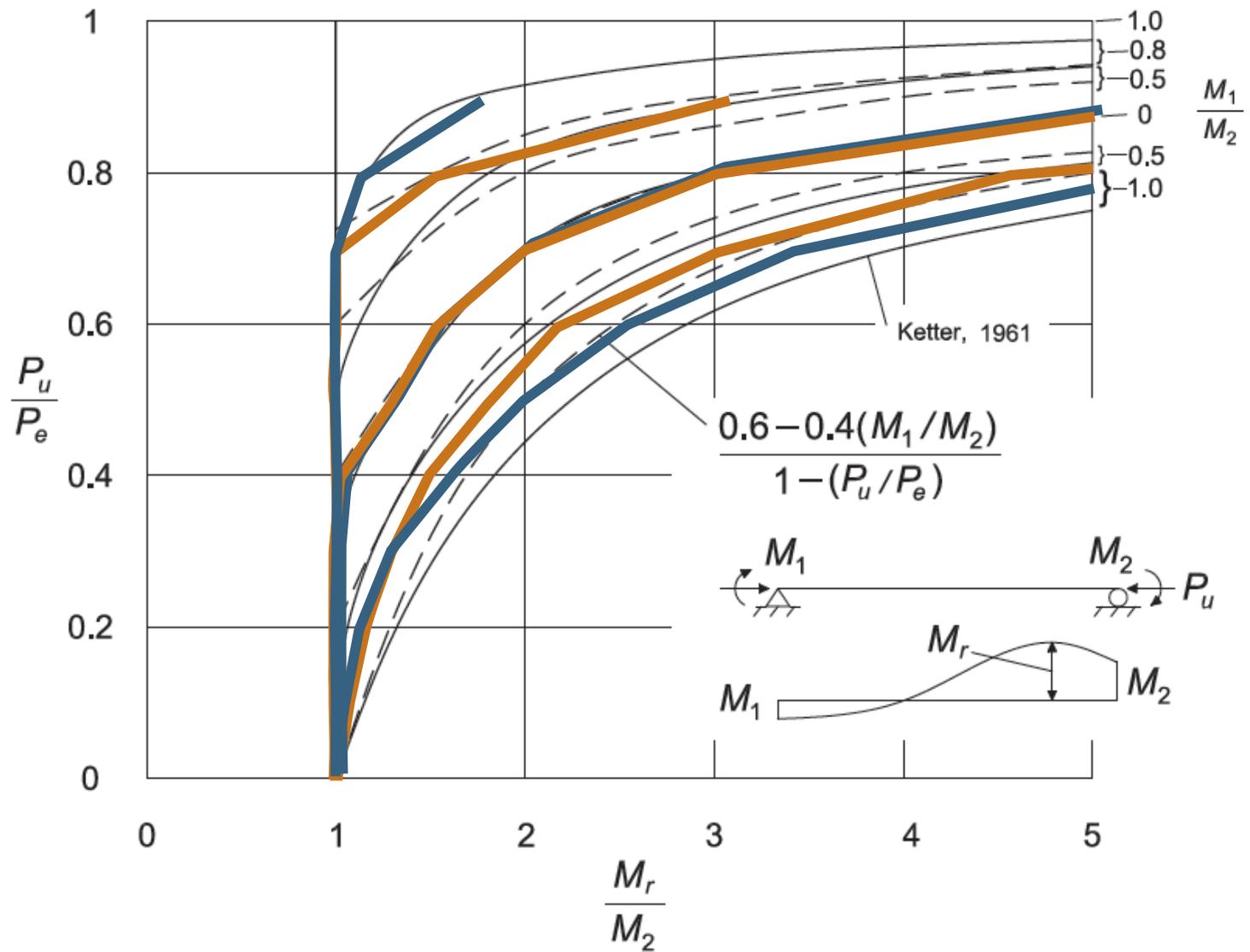
>

Apply

Cancel



Thanks to Dan Tamarkin



- Analytical Solution
- - - Approximate Solution [Austin (1961)]

LM8. Strength of Beam-Columns

Learning Objectives

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

Mother to LM2 and LM4...



The Second Part of Henry the Fourth,
Containing his Death : and the Coronation
of King Henry the Fift.

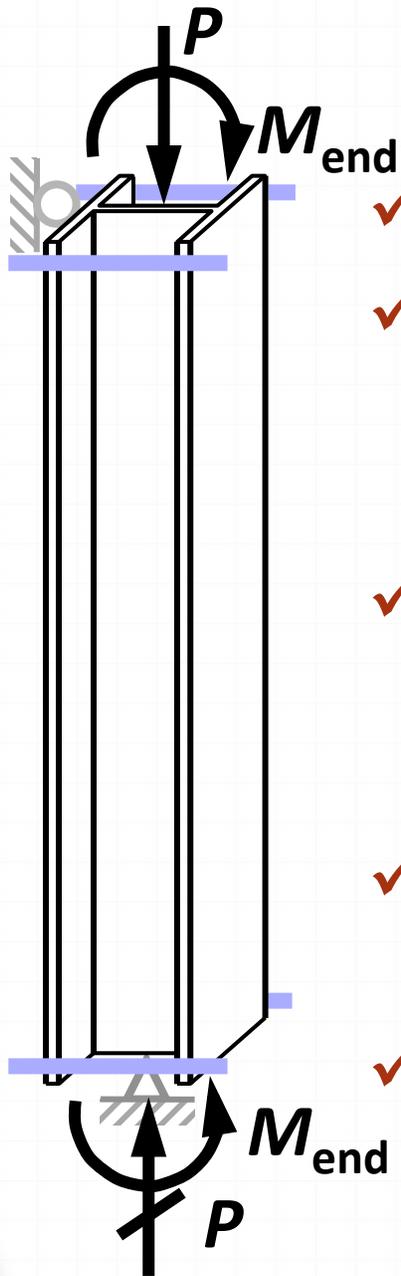
Actus Primus. Scena Prima.

Scena Secunda.

*And as the wretch, whose fever-weaken'd joints,
Like strengthless hinges, buckle under life,...*

Part II, King Henry the Fourth
W. Shakespeare
1599

LM8



✓ W14x53 (A992), $L_b = 15$ ft.

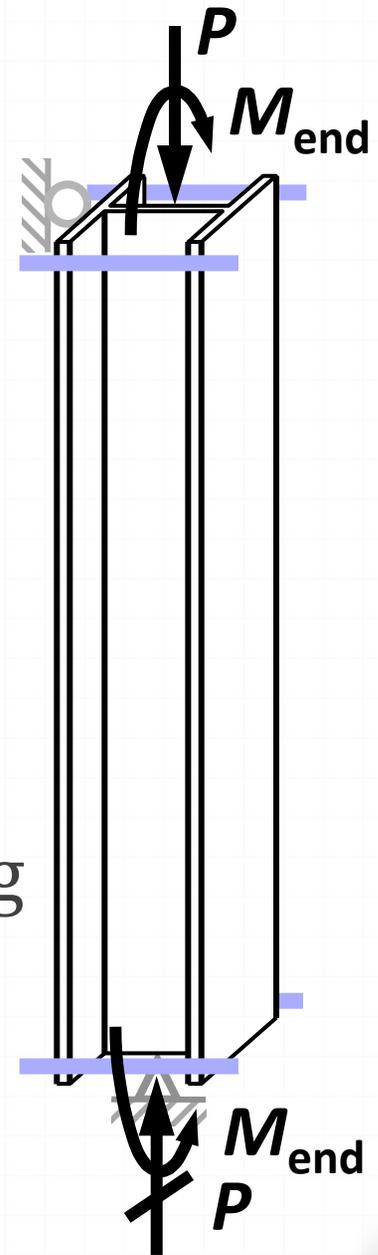
✓ Investigated:

- P - M_{major}
- P - M_{minor}

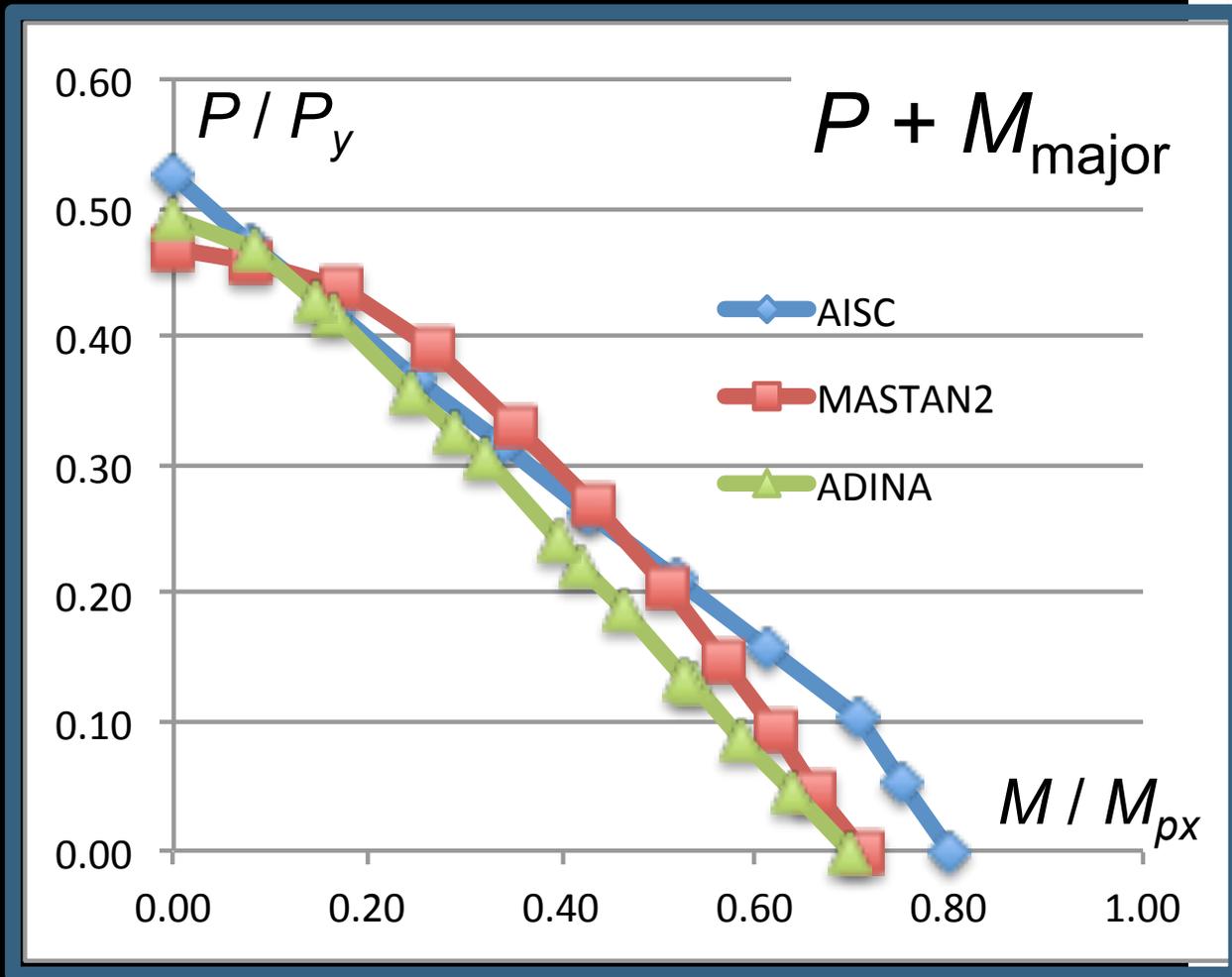
✓ Provided range of P - M_{end} 's that satisfy AISC interaction eq. H1-1 (student's to confirm)

✓ Determined strength according to 2nd-order inelastic analysis

✓ Wide range of failure modes including: full yielding, elastic/inelastic -LTB, -FTB



**** Deflected Shape: 2nd-Order Inelastic, Incr # 105, Applied Load Ratio = 1.05 ****

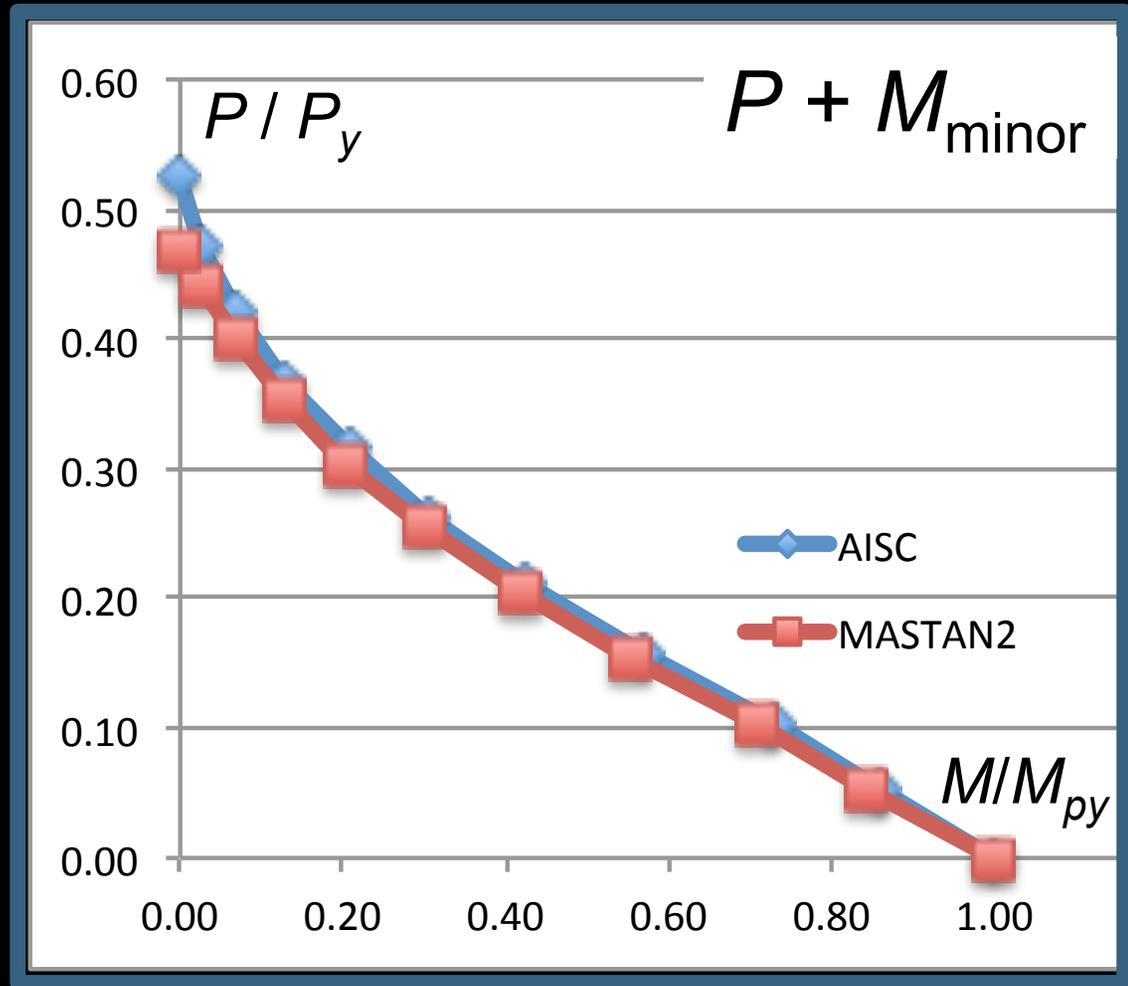
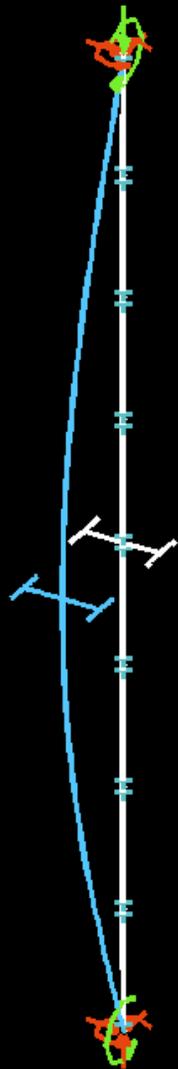


Second-Order Inelastic Analysis Status: Select Apply to perform analysis

Solution Type: Incr Size: Max. # of Incrs: Max. Appl. Ratio:

Analysis Type: Modulus: Start New:

**** Deflected Shape: 2nd-Order Inelastic, Incr # 96, Applied Load Ratio = 0.96 ****



Second-Order Inelastic Analysis Status: Select Apply to perform analysis

Solution Type: Incr Size: Max. # of Incrs: Max. Appl. Ratio:

Analysis Type: Modulus: Start New

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 Δ_o and τ_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.



AISC Specification Ch. C2.3

3. Adjustments to Stiffness

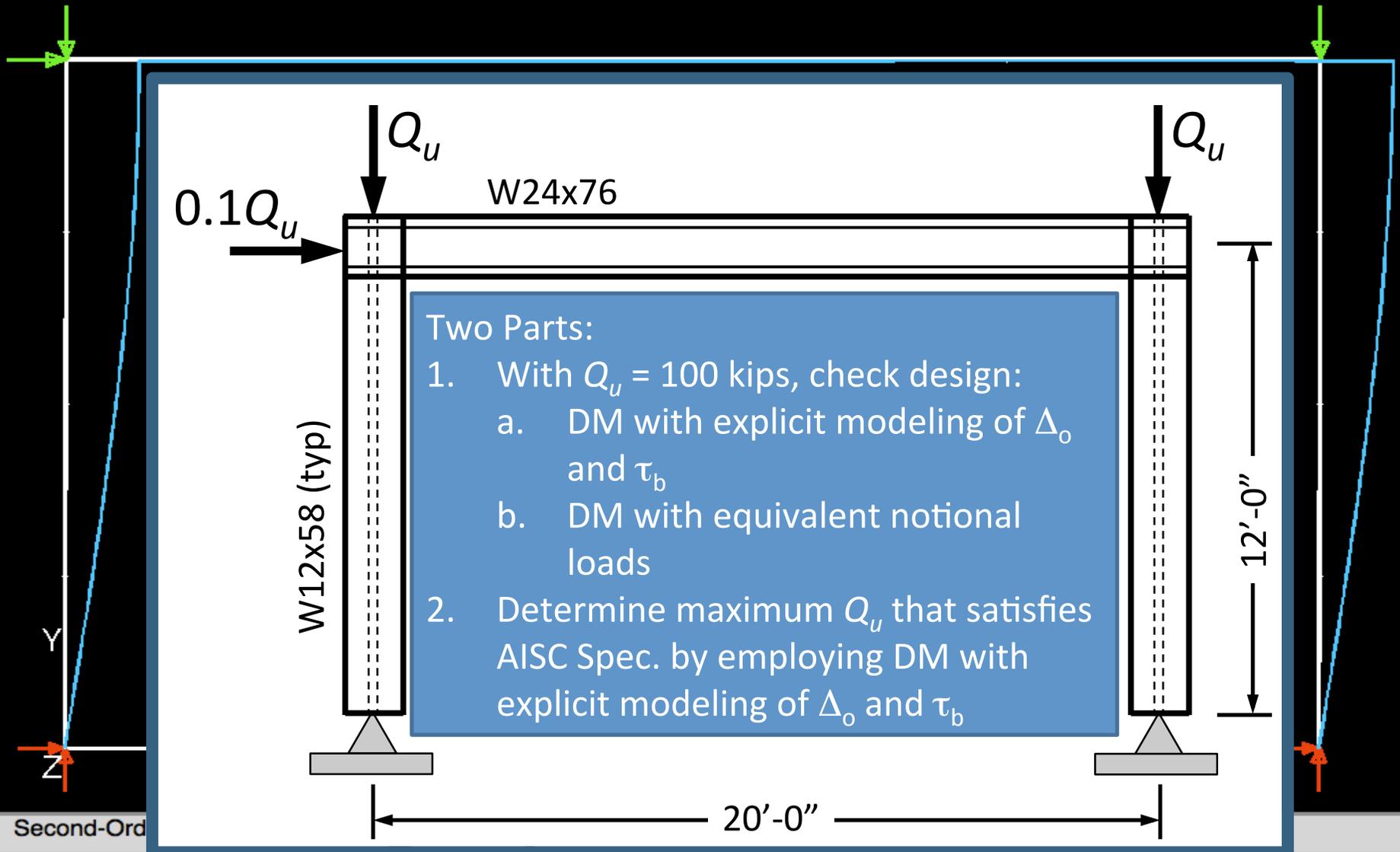
The analysis of the structure to determine the required strengths of components shall use reduced stiffnesses, as follows:

(1) A factor of 0.80 shall be applied to all stiffnesses that are considered to contribute to the stability of the structure



Perhaps I
should have
gone with trees
as the lateral
system...

**** Deflected Shape: 2nd-Order Inelastic, Incr # 10, Applied Load Ratio = 1 ****



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

LM9

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

1. Direct Analysis Method with imperfections modeled and τ_b included in analysis					0.8 E = ksi	
Gravity Load $Q_u = 100$ kips	Lateral Load $0.1Q_u = 10$ kips	Model includes lateral imperfection of H/500 = in.			Additional stiffness reduction modeled by use of τ_b included in the analysis	
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						

3. Direct Analysis Method with notional loads and no imperfections or τ_b included					0.8 E = ksi	
Gravity Load $Q_u = 100$ kips	Lateral Load $0.1Q_u = 10$ kips	Imperfection Notional Load $0.002\sum Q_u =$ kips	Stiffness Notional Load $0.001\sum Q_u =$ kips	Total Lateral Load = kips		
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						

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: $K = 1$, $P_n = 603\text{k}$ and ELF: $K = 2.1$, $P_n = 275\text{k}$)
- ✓ Very interesting comparisons...

Lessons Learned

- ✓ All modules fully tested in my CENG405-Design of Steel Structures course
- ✓ Students:
 - 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 structural analysis software
 - Benefited from the hands-on approach to learning structural stability

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

Plot Shape ?

separate window in-plane mode

2D 3D Undef. Scale 1

half-wavelength = 7

mode 1

file

CUFSM results

loaded files: Load another file

1 = CUFSM results

Plot Curve ?

dump to text

minima log scale classify

modes 1

files to be plotted 1

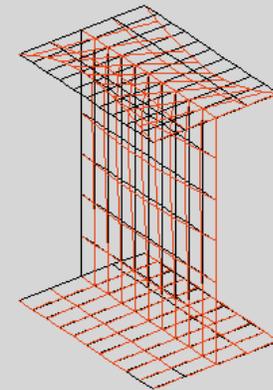
cFSM Modal Classification

Classify work norm

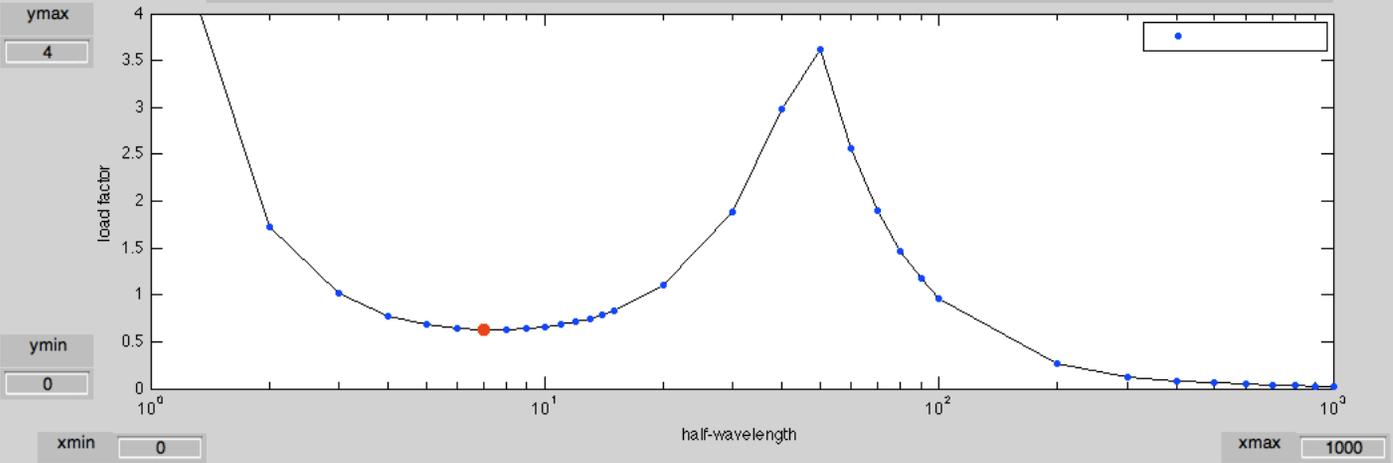
cFSM analysis is off

supplemental participation plot

CU-FSM



Buckled shape for CUFSM results
half-wavelength = 7 load factor = 0.62417 mode = 1
cFSM classification results: off



<http://www.ce.jhu.edu/bschafer/cufsm/>

Summary

- ✓ Virtual Laboratory
- ✓ Reviewed 9 Learning Modules related to structural stability
- ✓ 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!



Questions?