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Course Description

Modern Methods of Structural Analysis, from Linear to Nonlinear – Part II
February 2, 2015

Time to go nonlinear! Using the approach provided in Lecture 1, the participants will receive a basic introduction to nonlinear methods of structural analysis. This session will give an overview of how material nonlinear behavior and/or second-order effects can be included in modern structural analysis software.

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Learning Objectives

- Become familiar with the basic principles of structural stability.
- Gain an understanding of nonlinear analysis methods.
- Gain an understanding of material nonlinear behavior and second order effects.
- Become familiar with how material nonlinear behavior and/or second-order effects can be included in modern structural analysis computer software.

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

Session 2
Course Introduction and Modern Methods of Structural Analysis, from Linear to Nonlinear – Part II

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

structural STEEL

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!

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

<u>Session 2</u>

Modern Methods of Structural Analysis, from Linear to Nonlinear – Part II

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Key Points from Session 1

- Reviewed the "Direct Stiffness Method"
  - Equilibrium → Translator F(Δ) → Compatibility
- Response of structure controlled by stiffness of members (a.k.a. springs)
- First-order elastic stiffness of member function of:
  - Material Property (E)
  - Geometric Properties (A, I, L, and orientation)
- Time to go nonlinear…
  let's begin with material nonlinear

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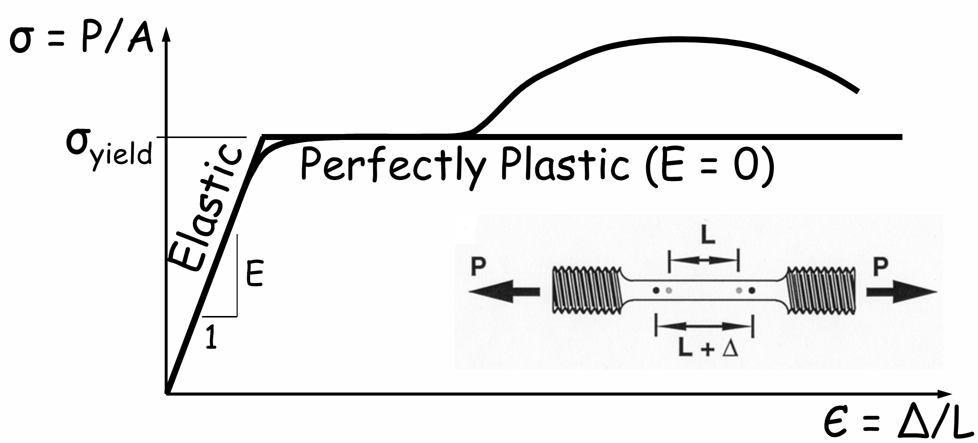
Material Nonlinear (Inelastic)

- Best place to start is with a tensile test



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Normal Stress: Structural Members

- For typical structural steel members (L/d>10), elastic/inelastic behavior controlled by normal stresses σ's acting along the length axis of the member.
- Normal stress produced by:
  - Axial force (P/A)
  - Major and/or minor axis flexure (Mc/I)
  - Combination of above effects (i.e. P/A + Mc/I)
  - Warping (not today!)
- We will assume elastic-perfectly-plastic material (often done for steel)

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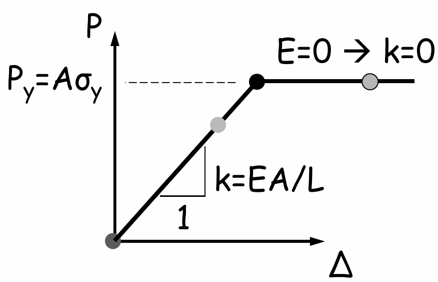
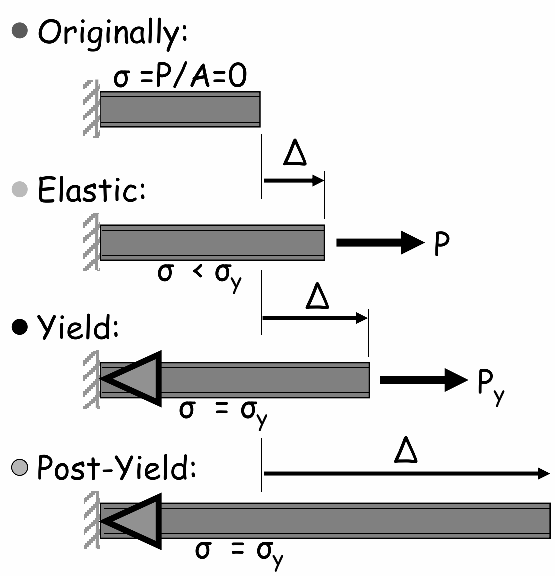
Inelastic Behavior: Axial Force





Plastic Hinge ◁
at $P = P_y$ or
when $P/P_y = 1.0$

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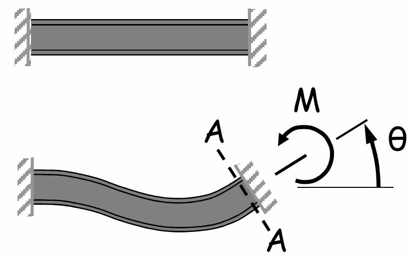
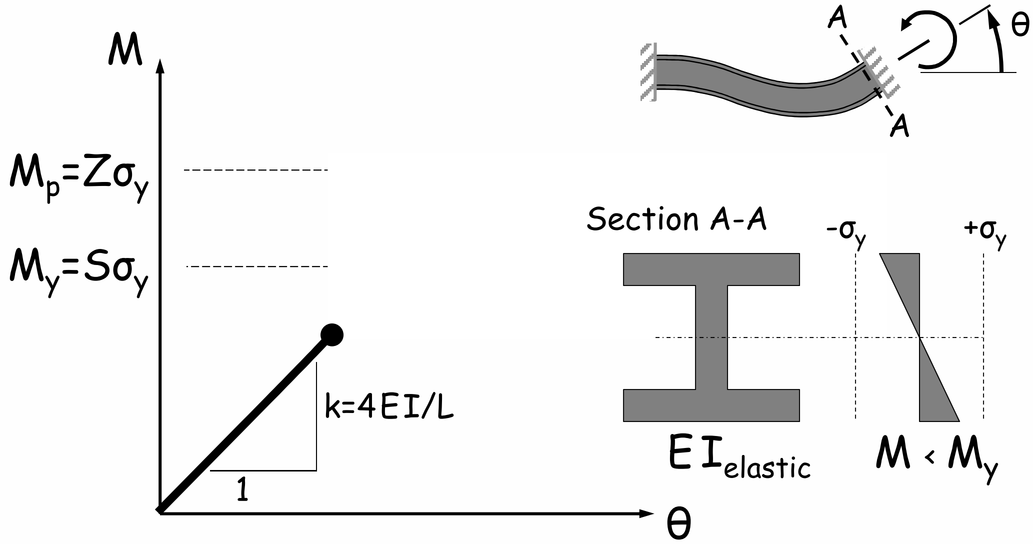
Inelastic Behavior: Flexure





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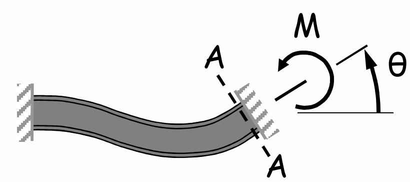
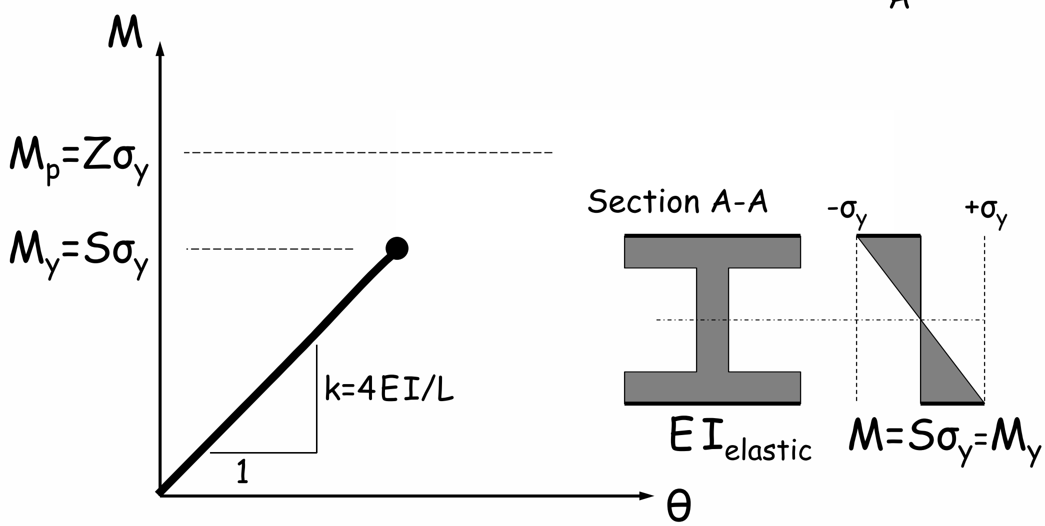
Inelastic Behavior: Flexure (cont.)





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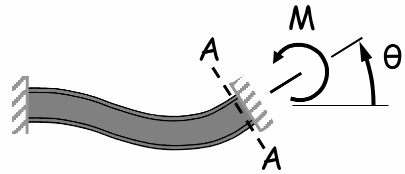
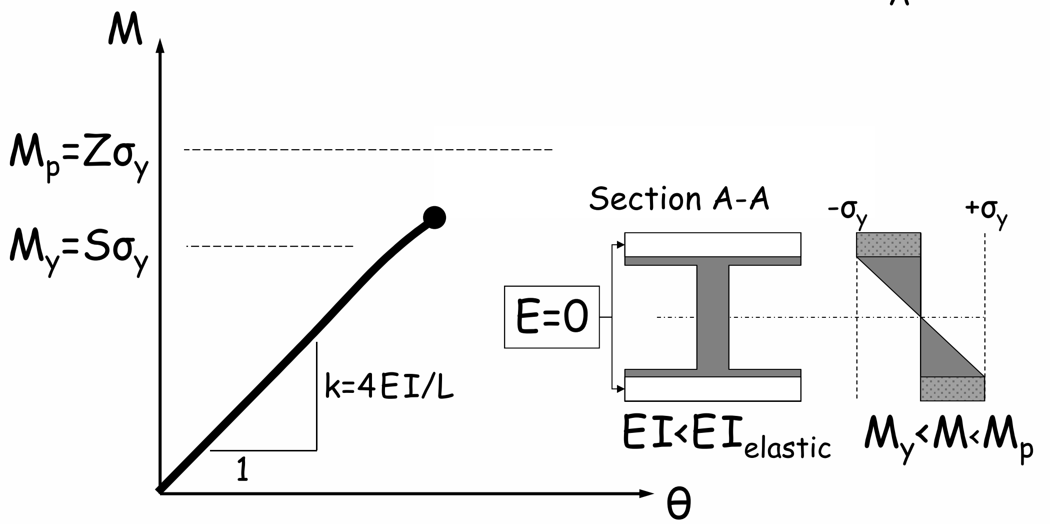
Inelastic Behavior: Flexure (cont.)





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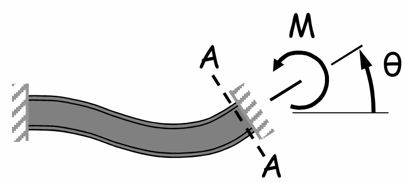
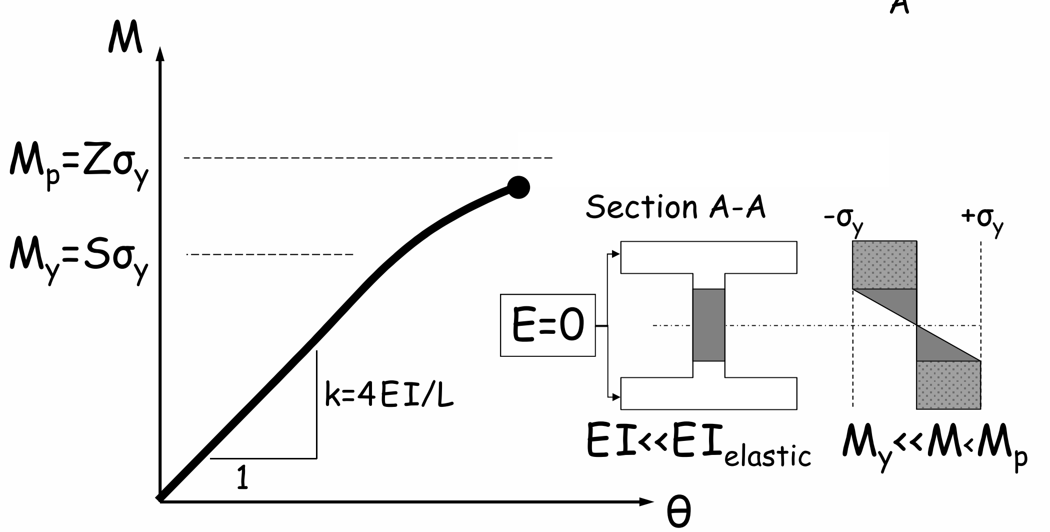
Inelastic Behavior: Flexure (cont.)





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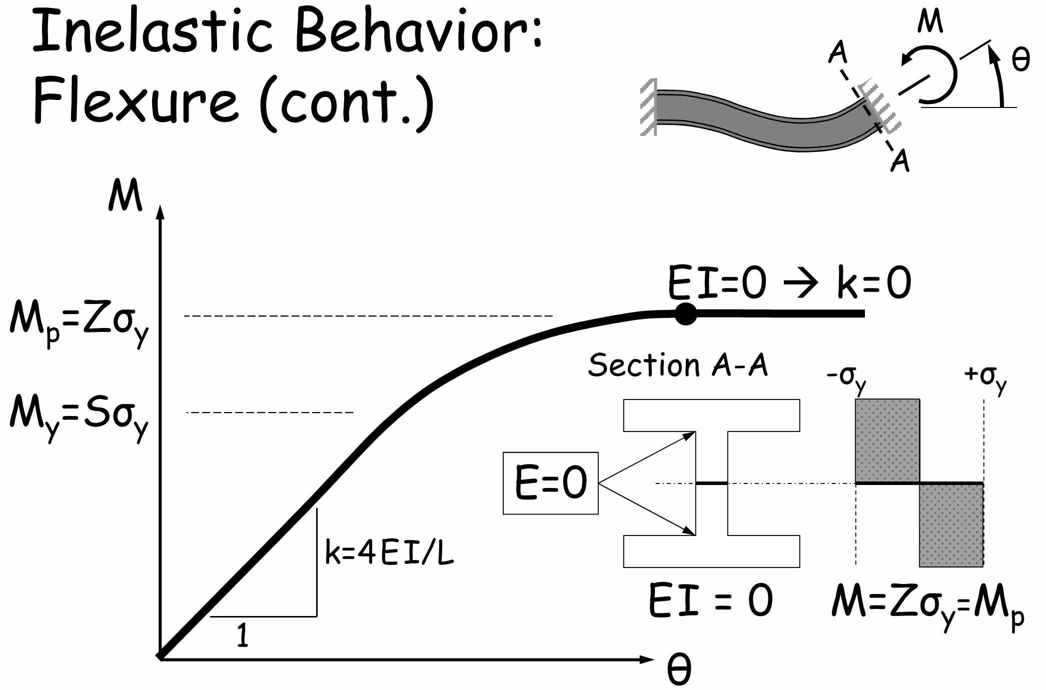
Inelastic Behavior: Flexure (cont.)



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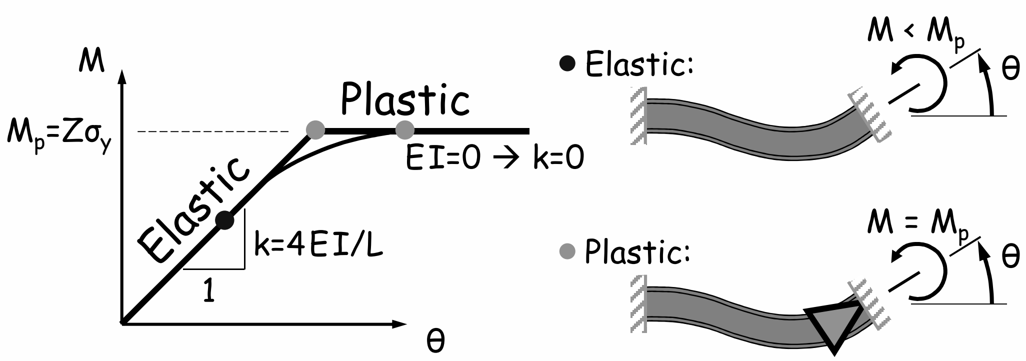
Inelastic Behavior: Flexure



- Plastic Hinge Model – Assume section as fully elastic or fully plastic (neglect partial yielding)
- Plastic Hinge at $M = M_p$ or when $M/M_p = 1.0$

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Types of inelastic models

- We will employ a plastic hinge model
  - A.K.A. "Concentrated Plasticity"
  - Section is fully elastic or fully yielded
  - Plastic hinges only at element ends
  - www.mastan2.com (software/textbook at no cost)
- Distributed plasticity (still line elements)
  - A.K.A. "Plastic Zone"
  - Captures gradual yielding through depth and along length
  - More accurate, but computationally more $$
- Finite element with continuum elements ($$$$)

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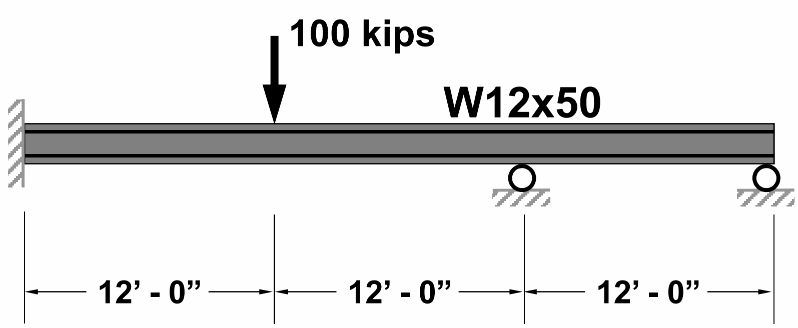
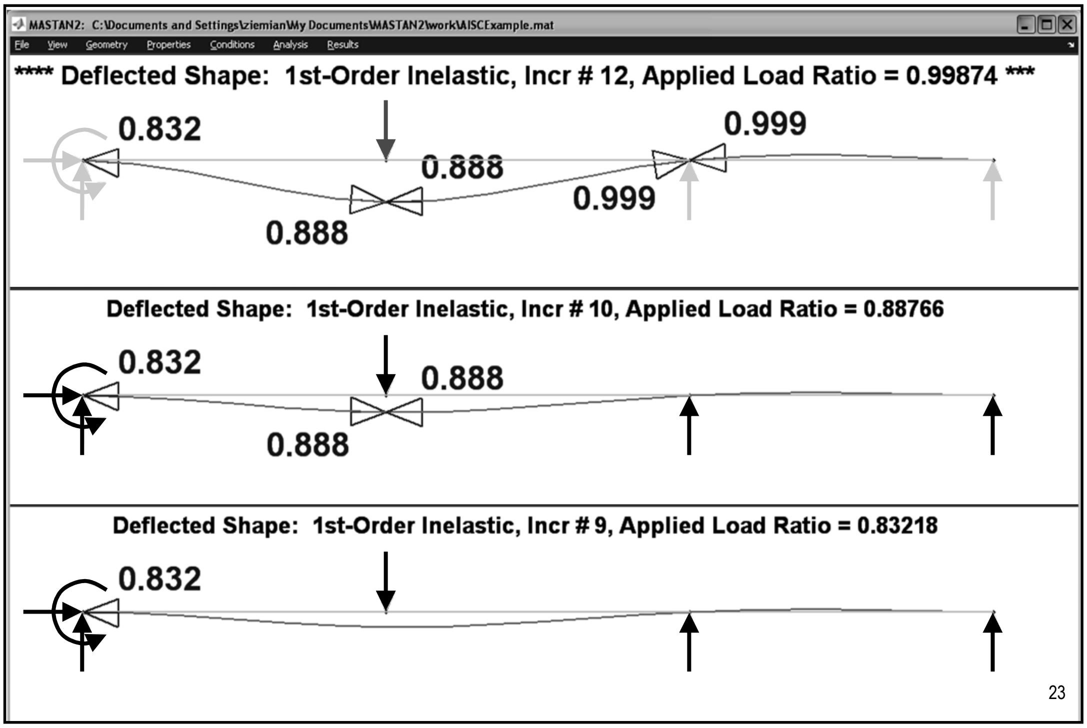
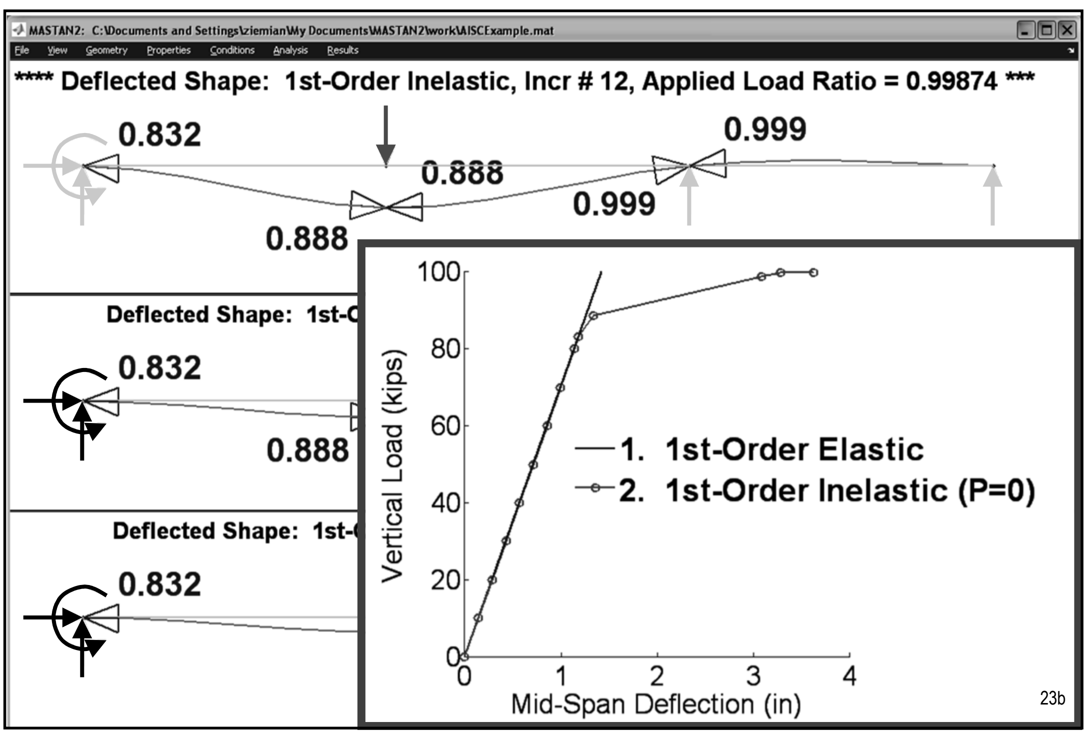
Simple Example:



E = 29,000 ksi
σ_y = 50 ksi


MASTAN2: C:\Documents and Settings\ziemian\My Documents\MASTAN2\work\AISCExample.mat
File View Geometry Properties Conditions Analysis Results
**** Deflected Shape: 1st-Order Inelastic, Incr # 12, Applied Load Ratio = 0.99874 ***
0.832
0.888
0.888
0.999
0.999
Deflected Shape: 1st-Order Inelastic, Incr # 10, Applied Load Ratio = 0.88766
0.832
0.888
0.888
Deflected Shape: 1st-Order Inelastic, Incr # 9, Applied Load Ratio = 0.83218
0.832
23


MASTAN2: C:\Documents and Settings\ziemian\My Documents\MASTAN2\work\AISCExample.mat
File View Geometry Properties Conditions Analysis Results
**** Deflected Shape: 1st-Order Inelastic, Incr # 12, Applied Load Ratio = 0.99874 ***
0.832
0.888
0.888
0.999
0.999
Deflected Shape: 1st-O
Deflected Shape: 1st-O
Vertical Load (kips)
Mid-Span Deflection (in)
1. 1st-Order Elastic
2. 1st-Order Inelastic (P=0)
0 20 40 60 80 100
0 1 2 3 4
23b

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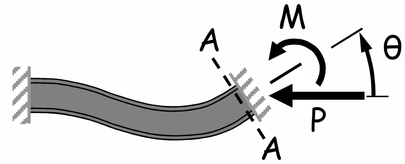
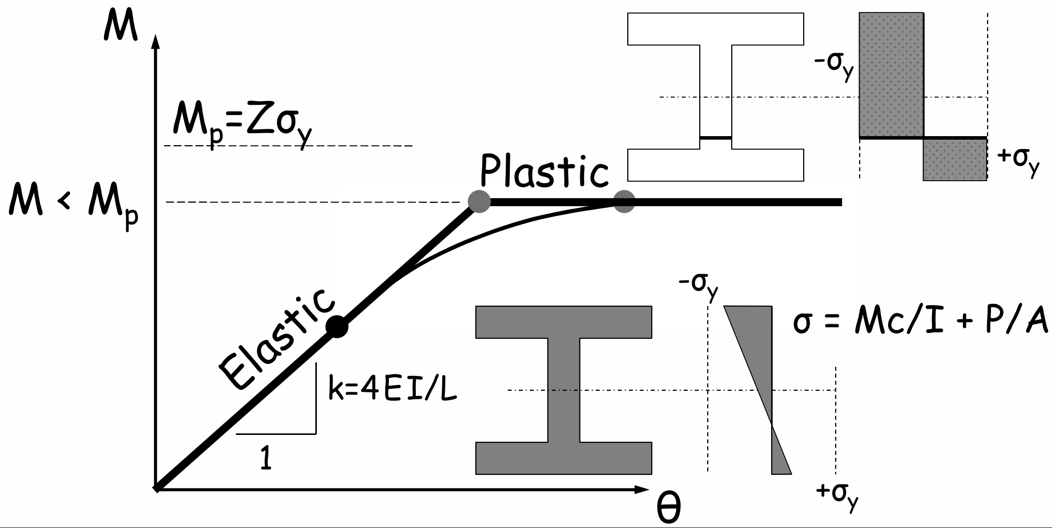
Inelastic Behavior: Combination P & M





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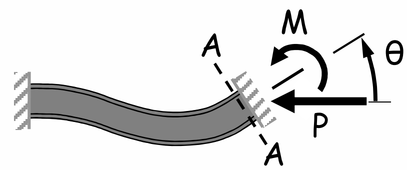
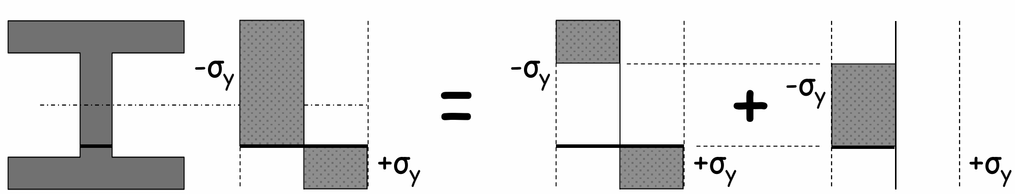
Inelastic Behavior: Combination P & M for Plastic Hinge





Fully yielded section when:	$M < M_p$ $M/M_p < 1$	$P < P_y$ $P/P_y < 1$

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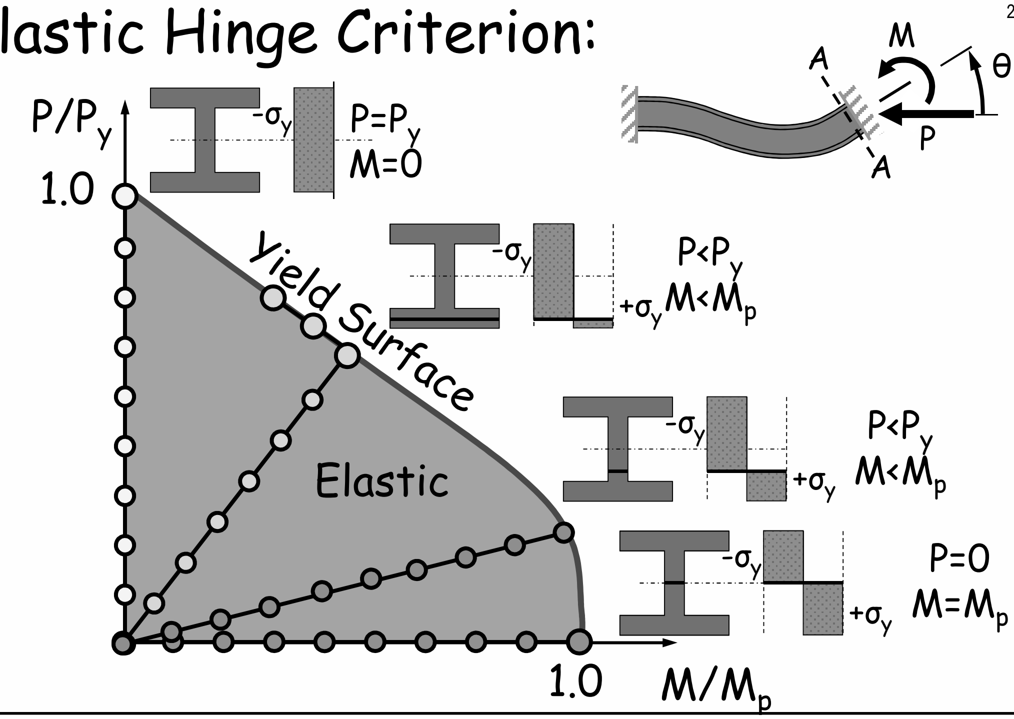
Plastic Hinge Criterion:



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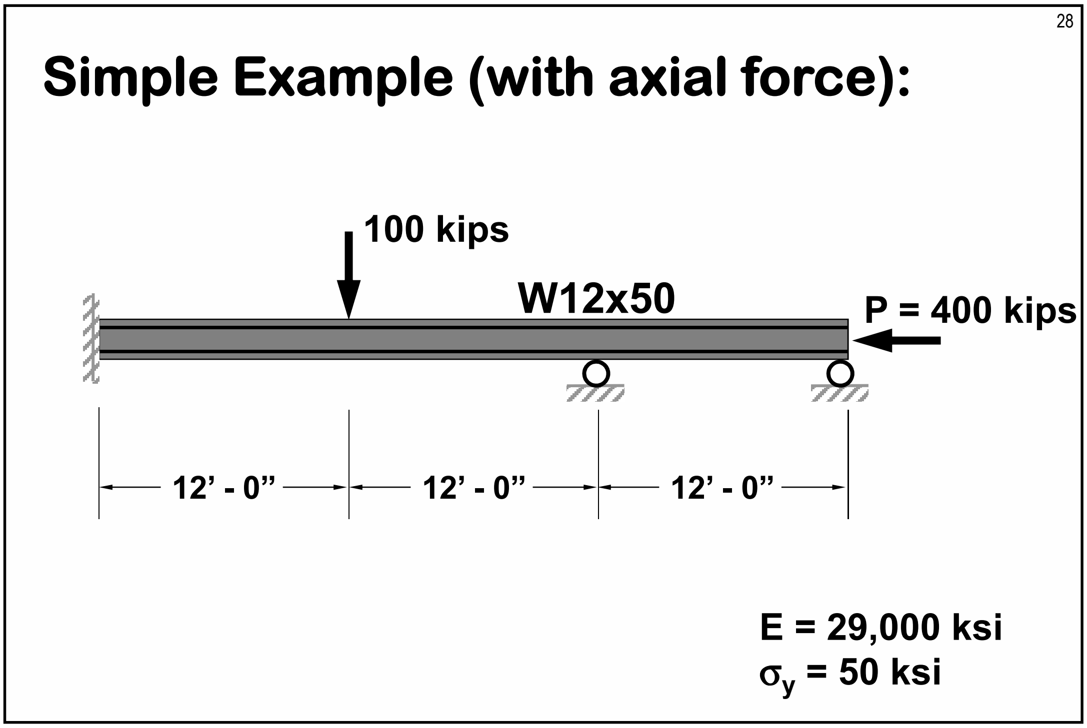
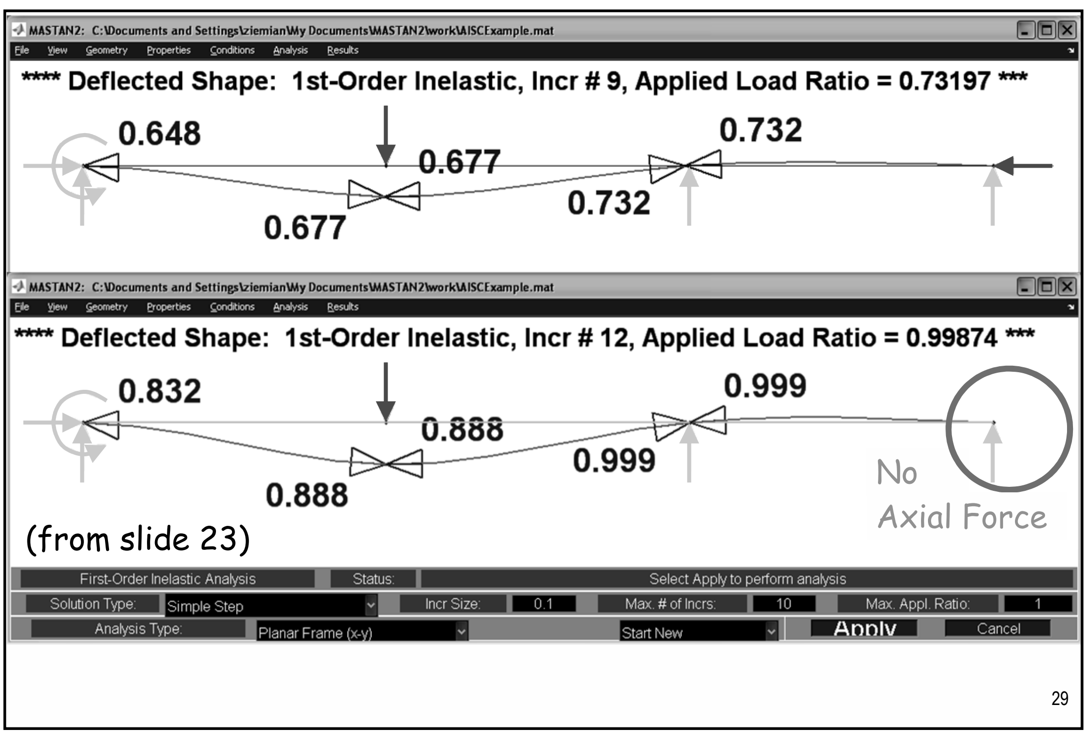
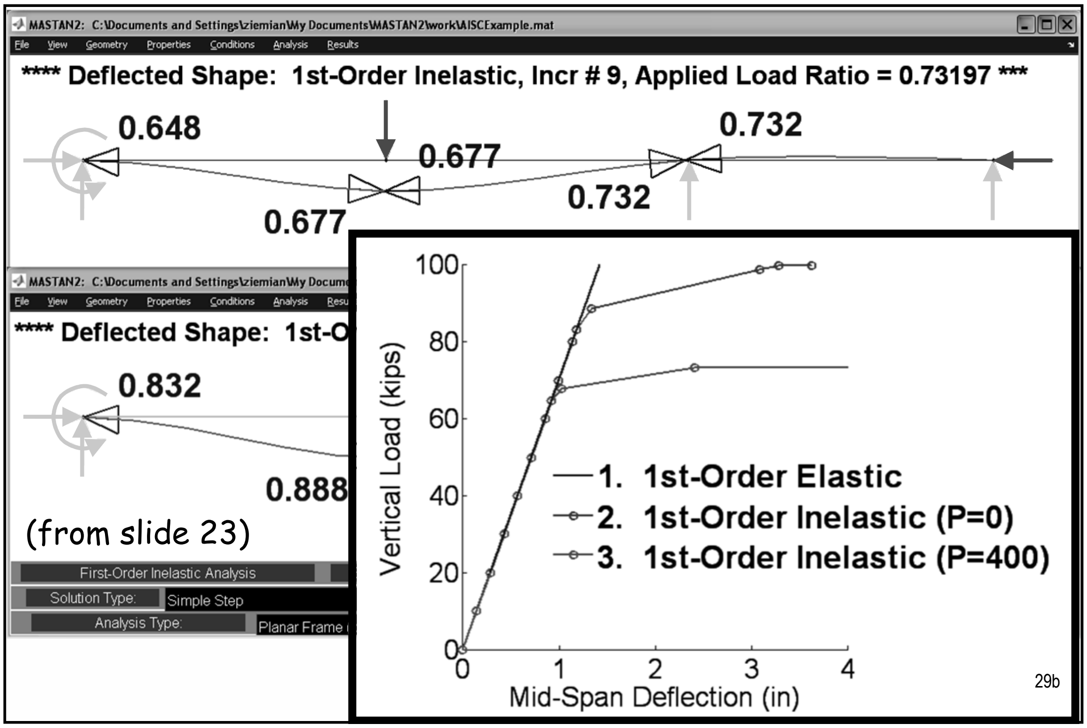
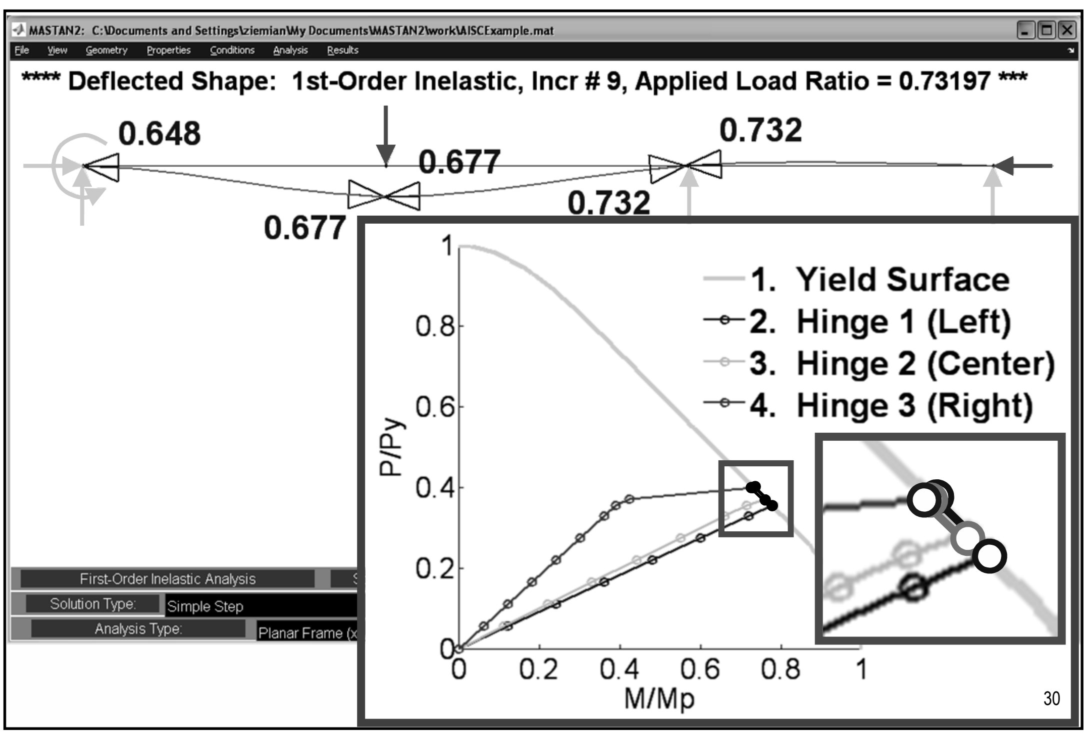
Material Nonlinear Analysis

- Employ “Direct Stiffness Method” applying loads in increments: [K]{dΔ} = {dF}
- During the load increment, check to see if plastic hinge(s) form. If so, scale back load increment accordingly.
- Reduce stiffness of yielded members and continue load increments
  - $k = k_{elastic} + k_{plastic}$ with $k_{plastic}$ = plastic reduction
- Continue to accumulate results of load increments until all of load is applied or a plastic mechanism forms.


28
Simple Example (with axial force):
100 kips
W12x50
P = 400 kips
12' - 0"
12' - 0"
12' - 0"
E = 29,000 ksi
σy = 50 ksi


**** Deflected Shape: 1st-Order Inelastic, Incr # 9, Applied Load Ratio = 0.73197 ***
0.648
0.677
0.677
0.732
0.732
**** Deflected Shape: 1st-Order Inelastic, Incr # 12, Applied Load Ratio = 0.99874 ***
0.832
0.888
0.888
0.999
0.999
No Axial Force
(from slide 23)
First-Order Inelastic Analysis
Status:
Select Apply to perform analysis
Solution Type:
Simple Step
Incr Size:
0.1
Max. # of Incrs:
10
Max. Appl. Ratio:
1
Analysis Type:
Planar Frame (x-y)
Start New
Apply
Cancel
29


MASTAN2: C:\Documents and Settings\ziemian\My Documents\MASTAN2\work\AISCExample.mat
**** Deflected Shape: 1st-Order Inelastic, Incr # 9, Applied Load Ratio = 0.73197 ***
0.648
0.677
0.677
0.732
0.732
**** Deflected Shape: 1st-O
0.832
0.888
(from slide 23)
First-Order Inelastic Analysis
Solution Type: Simple Step
Analysis Type: Planar Frame
Vertical Load (kips)
Mid-Span Deflection (in)
1. 1st-Order Elastic
2. 1st-Order Inelastic (P=0)
3. 1st-Order Inelastic (P=400)
29b


MASTAN2: C:\Documents and Settings\ziemian\My Documents\MASTAN2\work\AISCExample.mat
**** Deflected Shape: 1st-Order Inelastic, Incr # 9, Applied Load Ratio = 0.73197 ***
0.648
0.677
0.677
0.732
0.732
First-Order Inelastic Analysis
Solution Type: Simple Step
Analysis Type: Planar Frame (x
P/Py
M/Mp
1. Yield Surface
2. Hinge 1 (Left)
3. Hinge 2 (Center)
4. Hinge 3 (Right)
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Second-Order Effects

- A.K.A. "Geometric Nonlinear Behavior"
- Equilibrium Equations
  - Reality: Should be formulated on deformed shape
  - Difficulty: Deformed shape (deformations) is a function of the member forces, which are in turn a function of the deformations (Chicken 'n Egg)
  - Remedy: Perform a series of analyses with loads applied in small increments and update geometry after each load increment.

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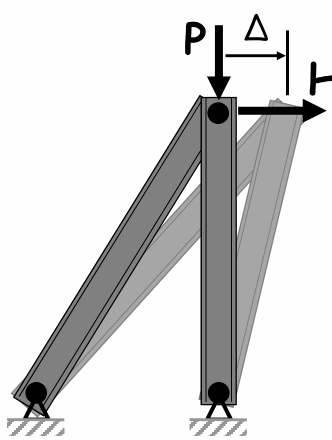
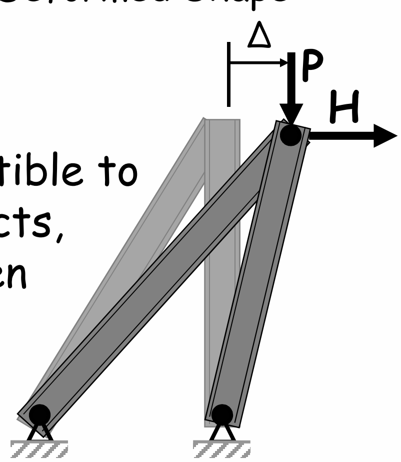
Equilibrium Equations

- Formulated on Undeformed Shape
- Formulated on Deformed Shape



Truss is susceptible to 2^{nd}-Order effects, luckily Δ is often quite small.



Different reactions and member forces.

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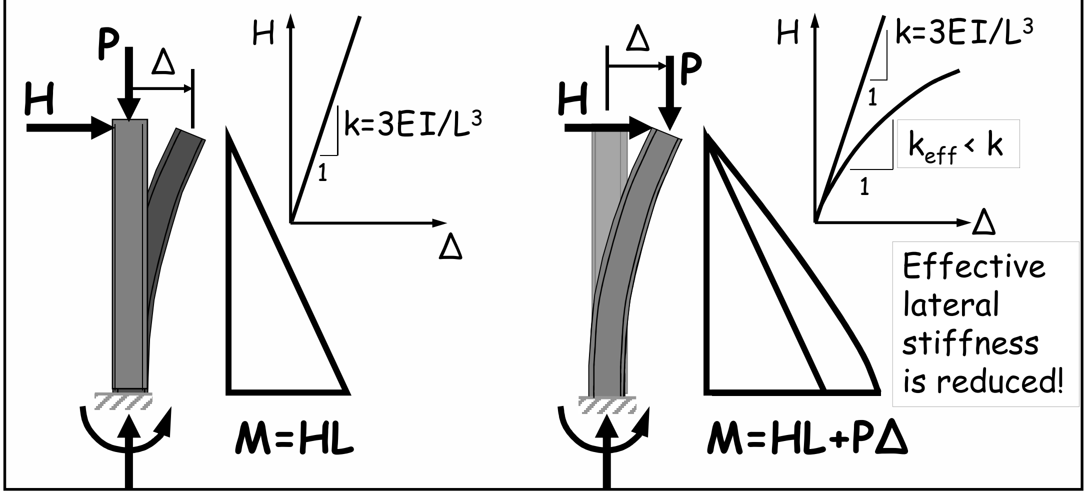
Equilibrium Equations

- Formulated on Undeformed Shape
- Formulated on Deformed Shape



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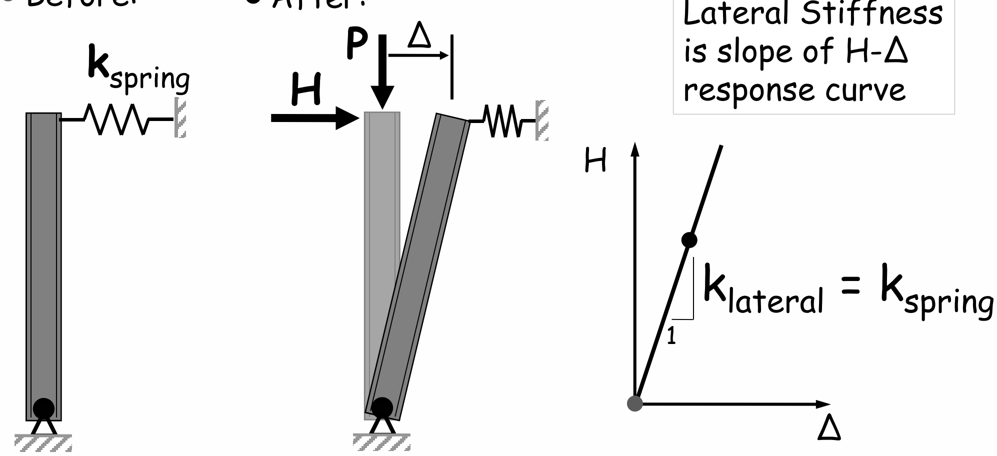
Focus on Lateral Stiffness

- Formulated on Undeformed Shape: <u>Linear Response</u>

- Before:
- After:



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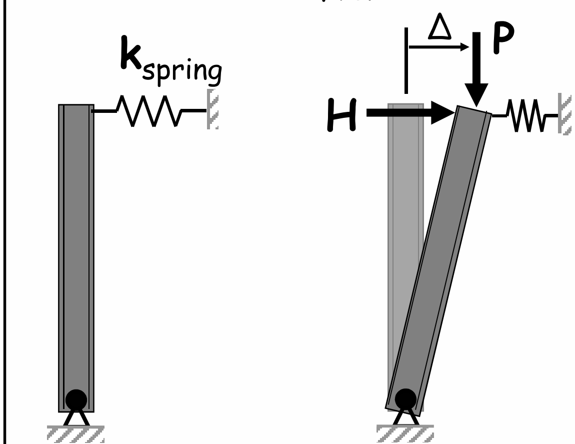
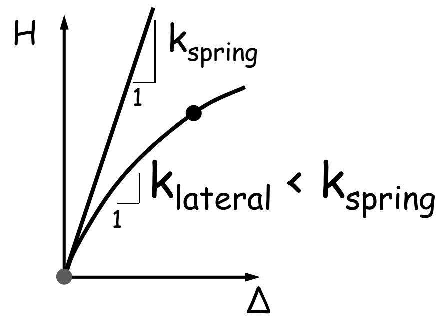
Focus on Lateral Stiffness (cont.)

❖ Formulated on Deformed Shape: Nonlinear Response

- Before:
- After:



Effective lateral stiffness is reduced



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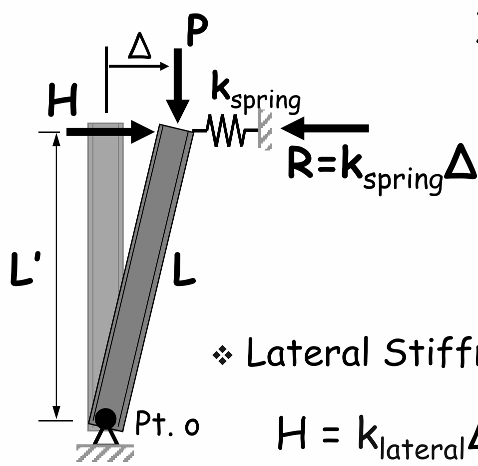
Focus on Lateral Stiffness (cont.)

❖ Equilibrium Formulated on Deformed Shape

Let's start by assuming $L' \approx L$,



$$\Sigma M_o = 0 \quad RL = HL + P\Delta$$

$$R = H + P\Delta/L$$

$$k_{spring}\Delta = H + P\Delta/L$$

$$H = k_{spring}\Delta - P\Delta/L$$

$$H = (k_{spring} - P/L)\,\Delta$$

❖ Lateral Stiffness (slope of response curve)

$$H = k_{lateral}\Delta \quad \text{with} \quad \boxed{k_{lateral} = k_{spring} - P/L}$$

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Some thoughts here…

- This simple analysis becomes less "accurate" as Δ/L becomes large (i.e. $\Delta/L >> 1/5$)
  - Remedy: Perform an incremental analysis and update geometry after each load increment…hence, limit Δ/L in each step to some small amount
  - Keep in mind serviceability limits are often something like $\Delta/L < 1/400$
- Most importantly, $k_{lateral} = k_{spring} - P/L$ takes on the form:

$$k_{2nd\text{-}Order\ El.} = k_{1st\text{-}Order\ El.} + k_g$$

Geometric Stiffness

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Geometric Stiffness

- Effective lateral stiffness of a member:
  - decreases as a member is compressed
    - k_g is negative for compressive P
    - backpacker example
  - increases when subjected to tension
    - k_g is positive for tensile P
    - guitar string example
- Employing geometric stiffness approach
  - Other methods exist (i.e. stability functions)

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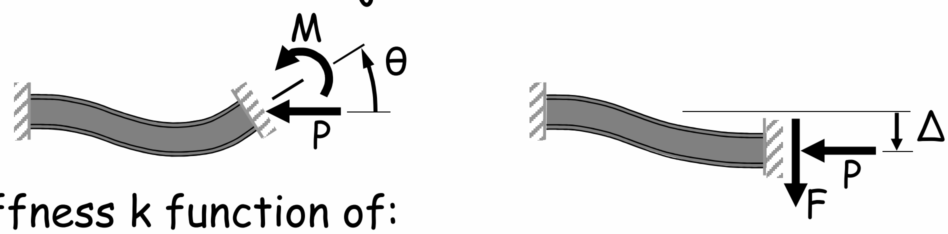
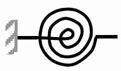
How about real members? (recall…)

- Flexural members subjected to axial force



- Stiffness k function of:
  - **Geometry**: Moment of Inertia & Length (I↑,k↑& L↑, k↓)
  - **Material**: Elastic Modulus (E ↑,k↑)
  - **Axial Force**: Compressive (P↑, k↓)



$M = k(I,L,E,P)\ \theta$

$F = k(I,L,E,P)\ \Delta$

40

Closer look at stiffness terms…

- Flexural members subjected to axial force

$M = k(I,L,E,P)\ \theta$ with
$k = 4EI/L - 2PL/15$

$F = k(I,L,E,P)\Delta$ with
$k = 12EI/L^3 - 6P/5L$

Again, basic form:

$$k_{\text{2nd-Order El.}} = k_{\text{1st-Order El.}} + k_g$$

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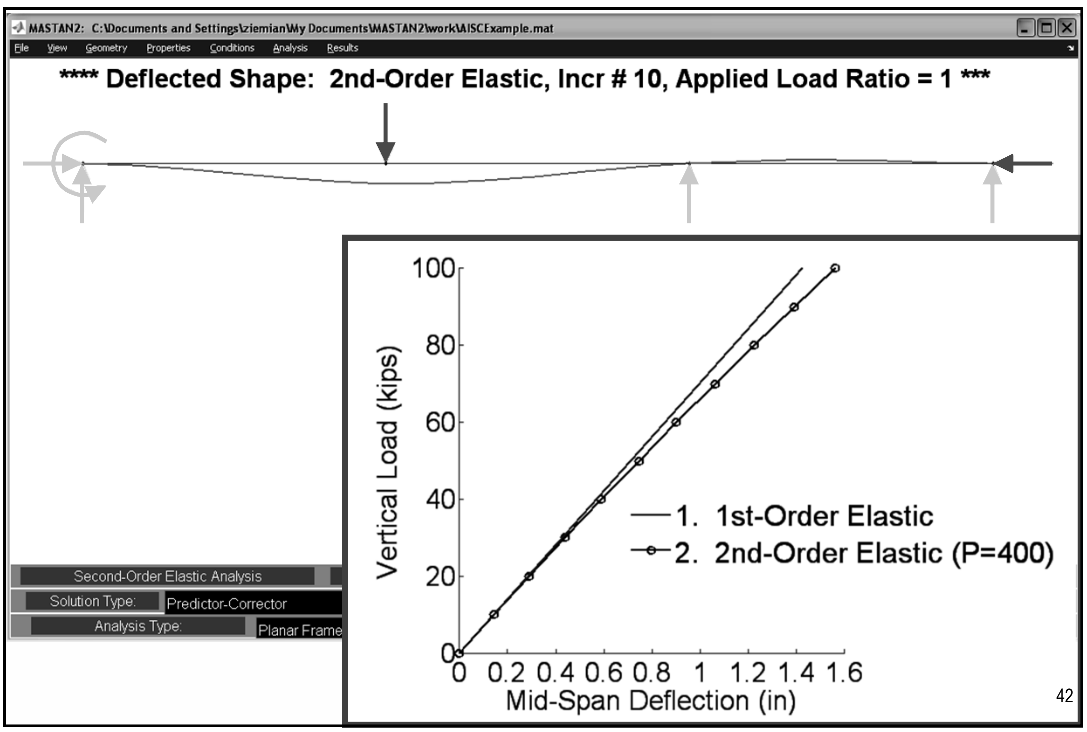
Geometric Nonlinear Analysis

- Employ "Direct Stiffness Method" applying loads in increments: Solve Equil. Eqs. $\{dF\} = [K]\{d\Delta\}$
- At start of increment, modify member stiffness to account for presence of member forces (such as axial force):
  - $k = k_{elastic} + k_g$ with k_g = geometric stiffness
- At end of increment, update model of structural geometry to include displacements
- Continue to accumulate results of load increments ($\Delta_i = \Delta_{i-1} + d\Delta$ and $f_i = f_{i-1} + df$) until all of load is applied or elastic instability is detected.



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Comparison: 1st- and 2nd-Order Analysis Results

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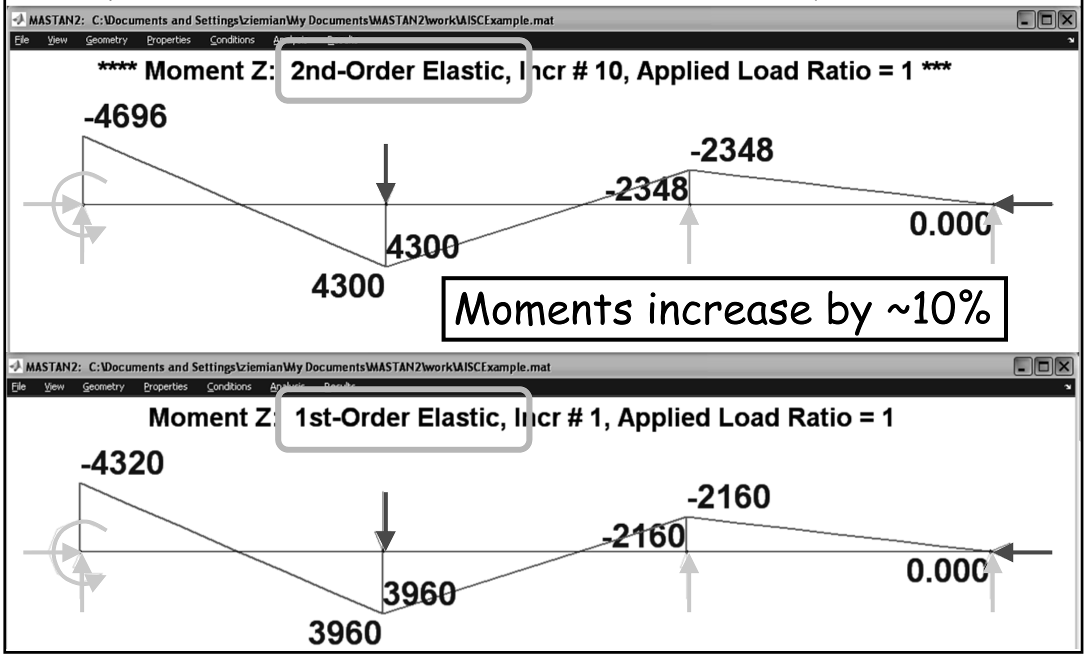

2nd-Order Inelastic Analysis

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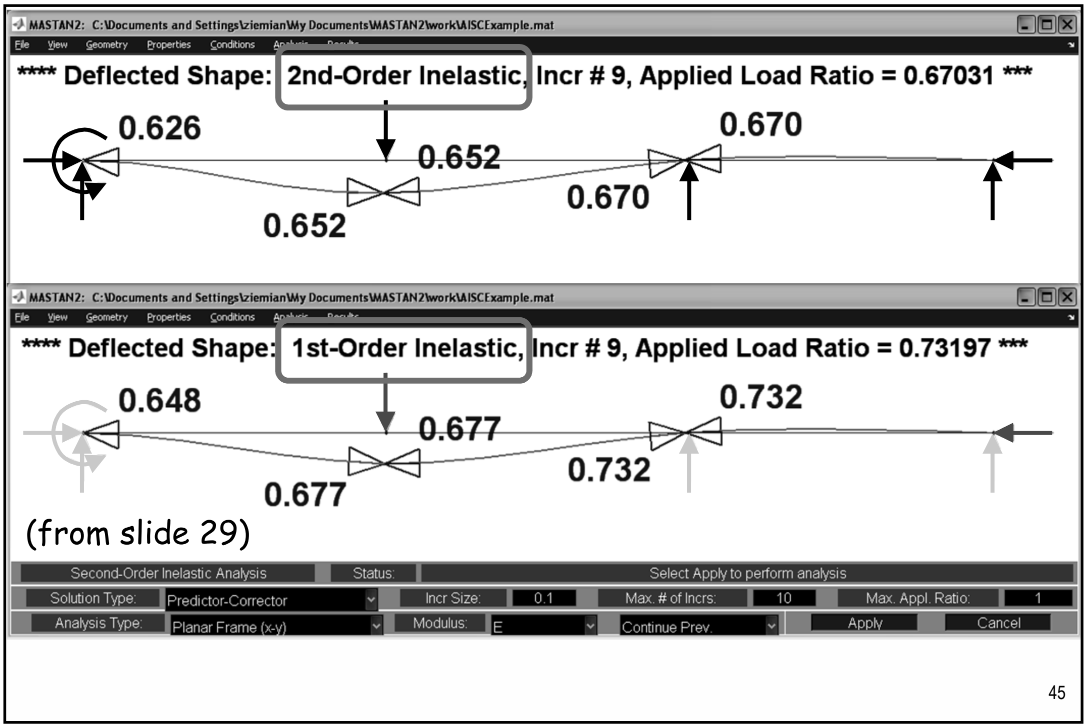
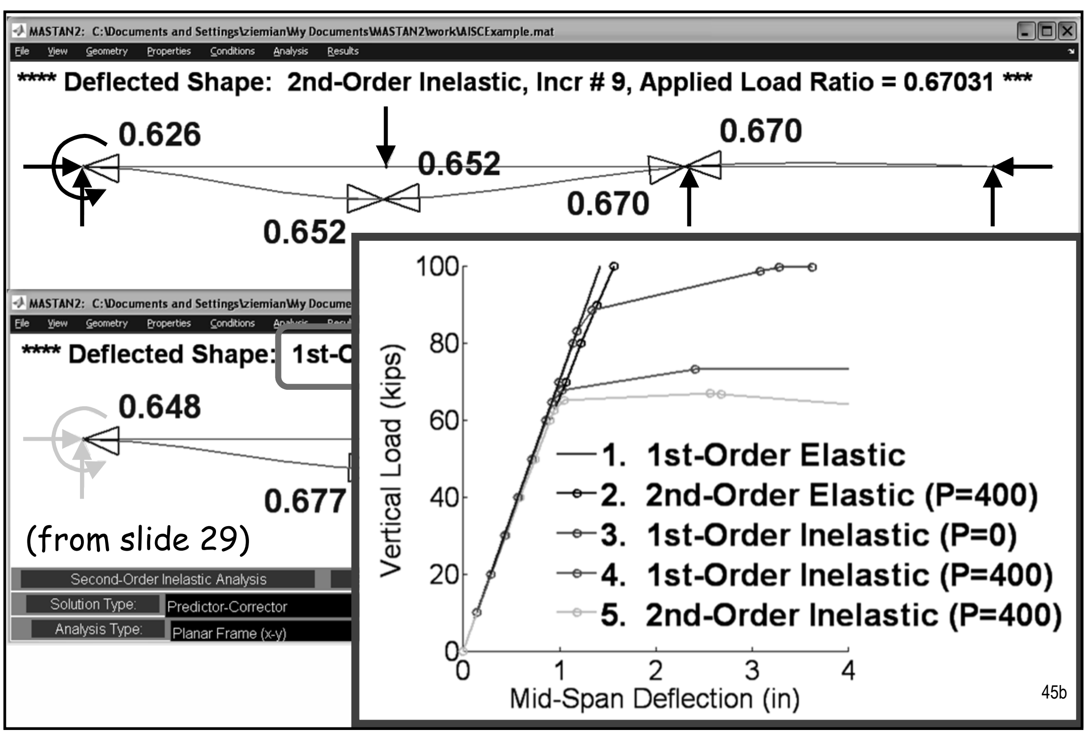
- Employ "Direct Stiffness Method" applying loads in increments: Solve Equil. Eqs. $\{dF\} = [K]\{d\Delta\}$
- At start of increment, modify member stiffness to account for presence of member forces and any yielding:

$$k = k_{elastic} + k_{geometric} + k_{plastic}$$

- At end of increment, update model of structural geometry to include displacements
- Continue to accumulate results of load increments ($\Delta_i = \Delta_{i-1} + d\Delta$ and $f_i = f_{i-1} + df$) until all of load is applied or inelastic instability is detected.

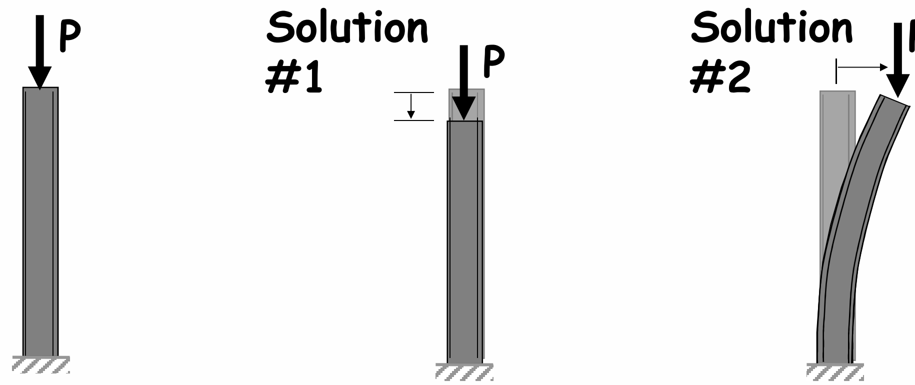

MASTAN2: C:\Documents and Settings\ziemian\My Documents\MASTAN2\work\AISCExample.mat
**** Deflected Shape: 2nd-Order Inelastic, Incr # 9, Applied Load Ratio = 0.67031 ***
0.626
0.652
0.652
0.670
0.670
**** Deflected Shape: 1st-Order Inelastic, Incr # 9, Applied Load Ratio = 0.73197 ***
0.648
0.677
0.677
0.732
0.732
(from slide 29)
Second-Order Inelastic 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)
Modulus:
E
Continue Prev.
Apply
Cancel
45


**** Deflected Shape: 2nd-Order Inelastic, Incr # 9, Applied Load Ratio = 0.67031 ***
0.626
0.652
0.652
0.670
0.670
0.648
0.677
(from slide 29)
Vertical Load (kips)
Mid-Span Deflection (in)
1. 1st-Order Elastic
2. 2nd-Order Elastic (P=400)
3. 1st-Order Inelastic (P=0)
4. 1st-Order Inelastic (P=400)
5. 2nd-Order Inelastic (P=400)
45b

Critical Load Analysis (Basics)

46

- Definition: Critical or buckling load is the load at which equilibrium may be satisfied by more than one deformed shape.



Big Q: How does computer software calculate this?

Critical Load Analysis (Background)

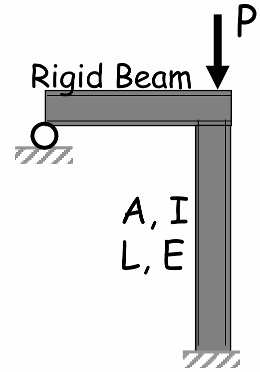
47

- Elastic stiffness of a member $k = k_{el} + k_g$
  - k_{el} is f(A or I, L, and E)
  - k_g is f(P,L), also note directly proportional to P
- Elastic stiffness of structure $[K] = \Sigma k$
  - $[K] = [K_{el}] + [K_g]$
  - $[K_g]$ directly proportional to applied force
    - i.e. Double applied forces, hence, double internal force distribution and double $[K_g]$
- To the computer, “buckling” will occur when our equilibrium equations $\{F\} = [K]\{\Delta\}$ permit non-unique solutions, e.g. $\det[K] = 0$.

48

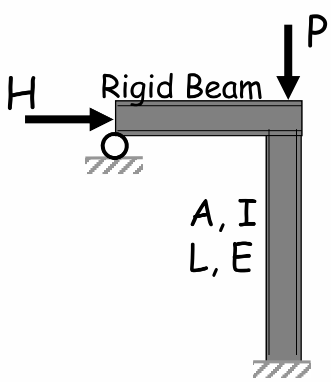
Example

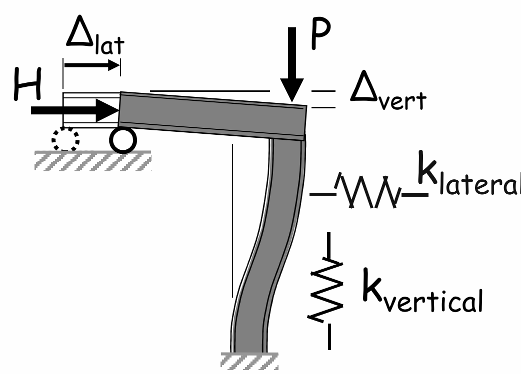
Demonstrate computational method for calculating the elastic critical load (buckling load) for the structural system shown.



49

Example: Key Stiffness Terms





Vertical Stiffness:

$P = k_{vertical}\,\Delta_{vert}$

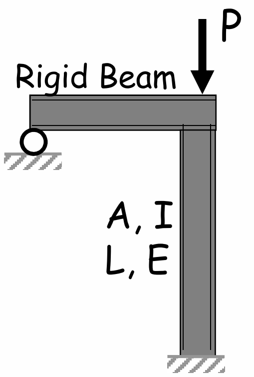
Lateral Stiffness:

$H = k_{lateral}\,\Delta_{lat}$

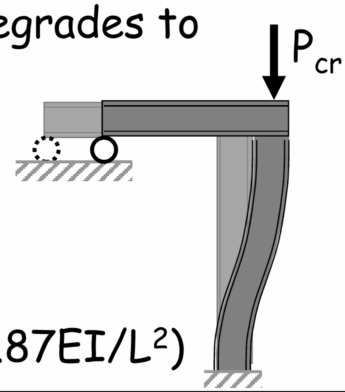
$k_{lateral} = 12EI/L^3 - 6P/5L$

Example: Solution

50



1. Apply reference load, and use 1st-order elastic analysis to obtain internal force distribution.
2. Determine load factor λ at which system stiffness degrades to permit buckling.

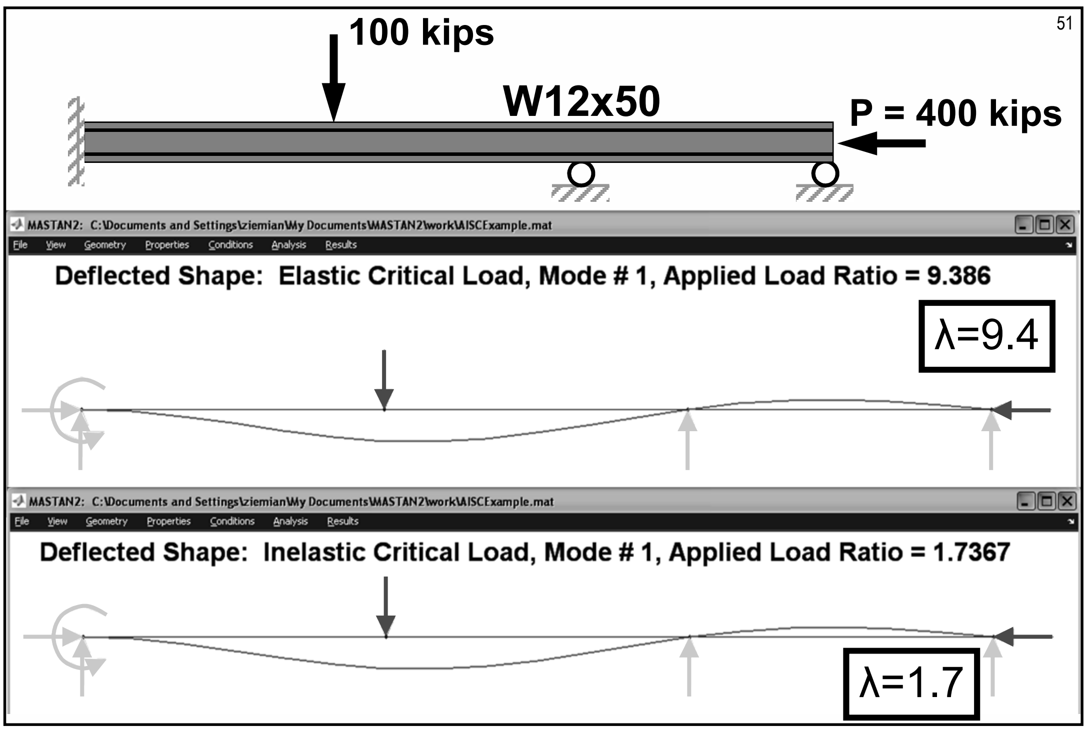


$k_{lateral} = 12EI/L^3 - 6\lambda P/5L$

$k_{lateral} = 0$ when $\lambda P = 10EI/L^2$

$P_{cr} = \lambda P = 10EI/L^2$ ($P_{theory}=9.87EI/L^2$)

51



52

Thoughts on Critical Load Analysis

- Computer analysis for a large system:
  - First, apply reference and perform analysis
    - Solve equilibrium eqs. $\{F_{ref}\} = [K]\{\Delta\}$
    - With displacements solve for member forces
  - Second, assemble $[K_{el}]$ and $[K_g]$ based on $\{F_{ref}\}$
  - Finally, determine load factor λ causing instability; computationally this means find load factor λ at which $[K]=[K_{el}]+\lambda[K_g]$ becomes singular
    - Determine λ at which $\det([K_{el}]+\lambda[K_g]) = 0$
    - "Eigenvalue" problem: Eigenvalues = Critical Load Factors, λ's
      Eigenvectors = Buckling modes
- Accuracy increases with more elements per compression members (2 often adequate)

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Basic Introduction Complete

- Where do I go from here? (Learning to drive)
  - Review the slides (Read the driver's manual)
  - Acquire nonlinear software (Borrow a friend's car)
  - Work lots of examples (Go for a drive, scary at first…)
  - Apply nonlinear analysis in design (NASCAR? not quite)

Acquire nonlinear analysis software
  - Commercial programs
  - Educational software (i.e. MASTAN2)

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MASTAN2:

- Educational software
- GUI similar to commercial programs
- Limited # of pre- and post-processing options to reduce learning curve
- Suite of linear and nonlinear 2D and 3D analysis routines
- Available online with textbook at no cost

www.mastan2.com

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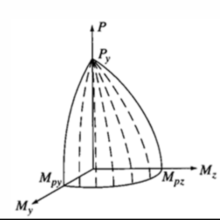
MASTAN2

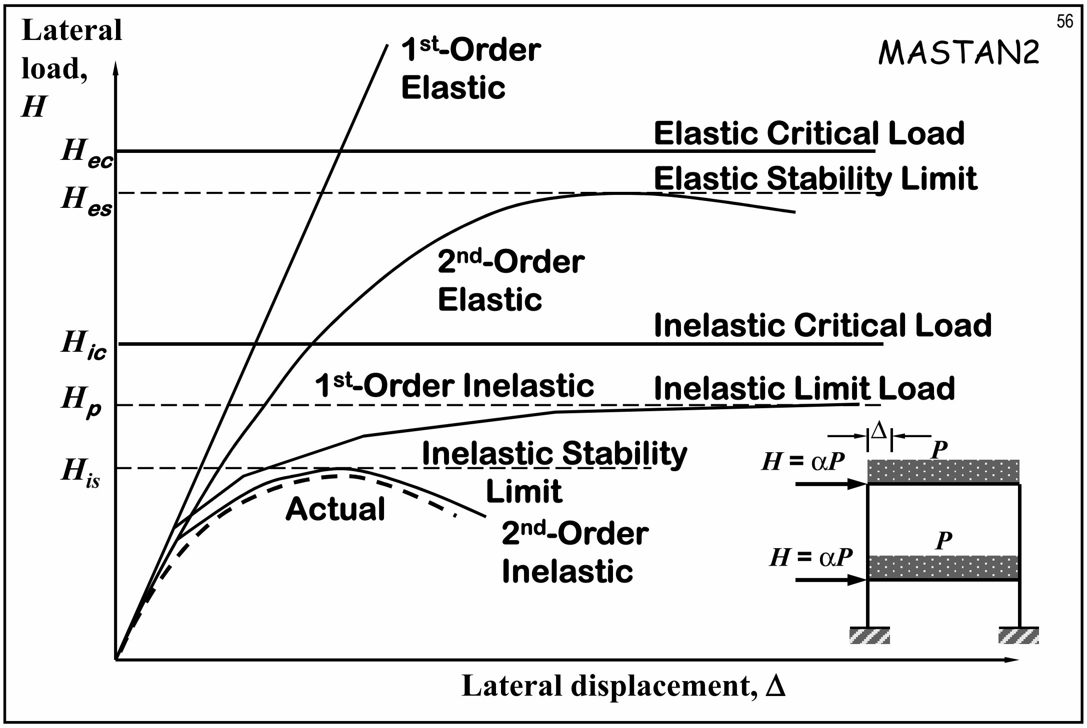
Levels of Analysis:

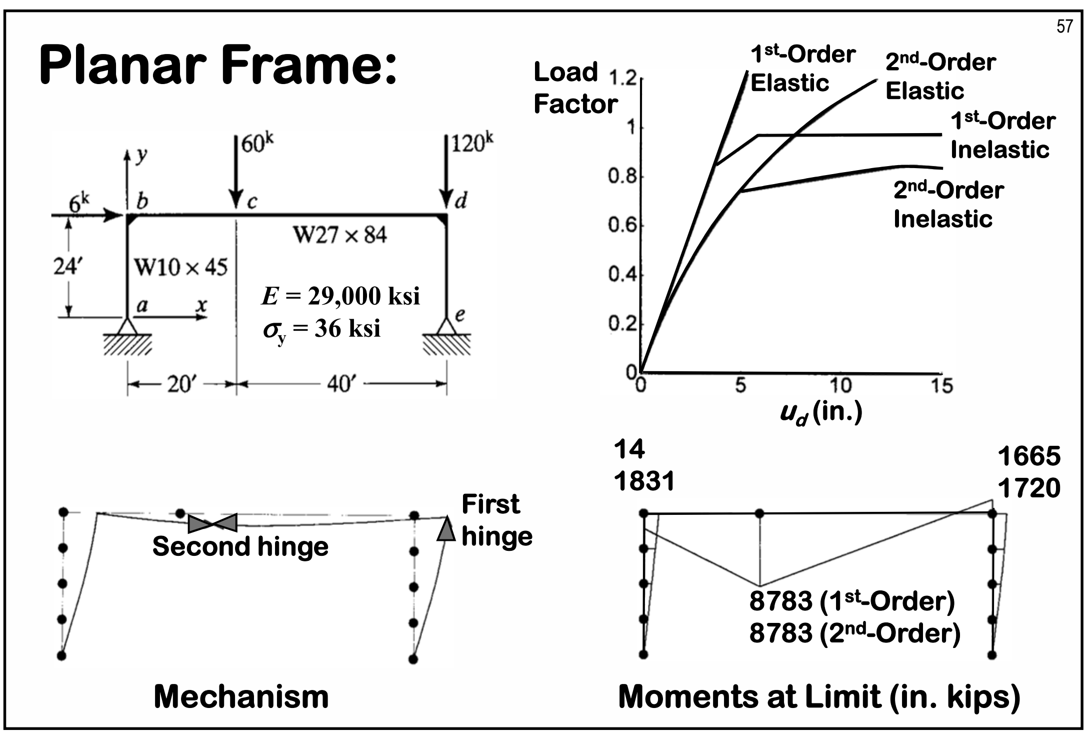
1^{st}-Order Elastic:	$[K_e]\{\Delta\}=\{F\}$
2^{nd}-Order Elastic:	$[K_e + K_g]\{d\Delta\}=\{dF\}$
1^{st}-Order Inelastic:	$[K_e + K_p]\{d\Delta\}=\{dF\}$
2^{nd}-Order Inelastic:	$[K_e + K_g + K_p]\{d\Delta\}=\{dF\}$
Critical Load:	$[K_e + \lambda K_g]\{d\Delta\}=\{0\}$

Yield Surface:

Function of P, M_{major}, and M_{minor}




56
MASTAN2
Lateral load, H
1st-Order Elastic
Elastic Critical Load
Elastic Stability Limit
2nd-Order Elastic
Inelastic Critical Load
1st-Order Inelastic
Inelastic Limit Load
Inelastic Stability Limit
Actual
2nd-Order Inelastic
H = αP
P
Δ
Lateral displacement, Δ


57
Planar Frame:
60k
120k
6k
24′
W10 × 45
W27 × 84
E = 29,000 ksi
σy = 36 ksi
20′
40′
Load Factor
1st-Order Elastic
2nd-Order Elastic
1st-Order Inelastic
2nd-Order Inelastic
ud (in.)
Second hinge
First hinge
Mechanism
14
1831
1665
1720
8783 (1st-Order)
8783 (2nd-Order)
Moments at Limit (in. kips)

58

Summary and Conclusions

- Provided an introduction to nonlinear analysis
  - Review of direct stiffness method
  - Material nonlinear analysis (Inelastic hinge)
  - Geometric nonlinear analysis (2^{nd}-Order)
  - 2^{nd}-Order inelastic analysis (combine above)
  - Critical load analysis ("eigenvalue analysis")
- Nonlinear…think modifying member stiffness!
- Overview and availability of MASTAN2
- Now, it's your turn to take it for a spin…

Up Next…

- Session 3: February 9 –
  Modules for Learning Structural Stability
  by R.D. Ziemian, PE, PhD
- 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. Modern computer software makes it easy to use non-linear computational analysis as a virtual lab for learning many important concepts related to designing 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. Course attendees will be encouraged to download a simple analysis software package (at no charge) and work the examples and modules at the conclusion of the lecture.

There's always a solution in Steel

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

There's always a solution in Steel

Individual Webinar Registrants

CEU/PDH Certificates

Within 2 business days…

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!

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CEU/PDH Certificates

Within 2 business days…

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

There's always a solution in Steel

8-Session Registrants

CEU/PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.

There's always a solution in Steel

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.

There's always a solution in Steel

8-Session Registrants

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

There's always a solution in Steel

There's always a solution in steel.

Thank You

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

structural STEEL

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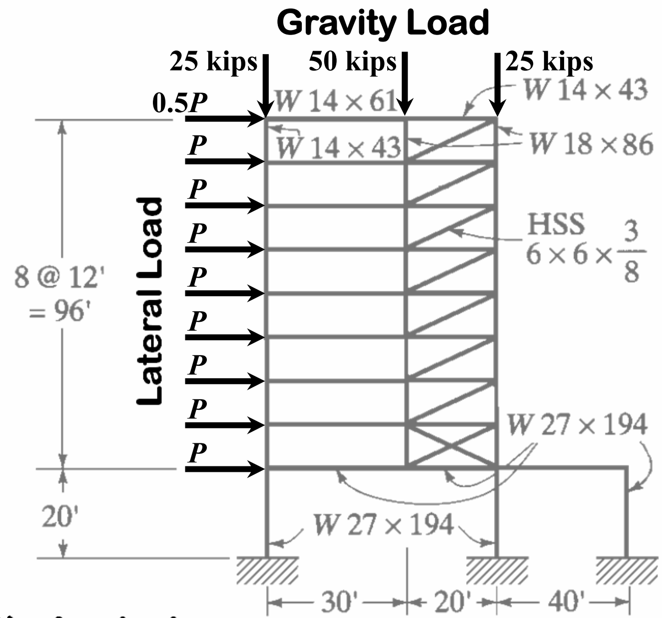
Appendix

- Several examples to try out
- Solutions by MASTAN2
- Need a reference text with many examples? see Matrix Structural Analysis, 2nd Ed., by McGuire, Gallagher, and Ziemian (Wiley, 2000)
- See tutorial that comes with MASTAN2
- OK, time to jump in and start driving…

68

Multi-story Frame:

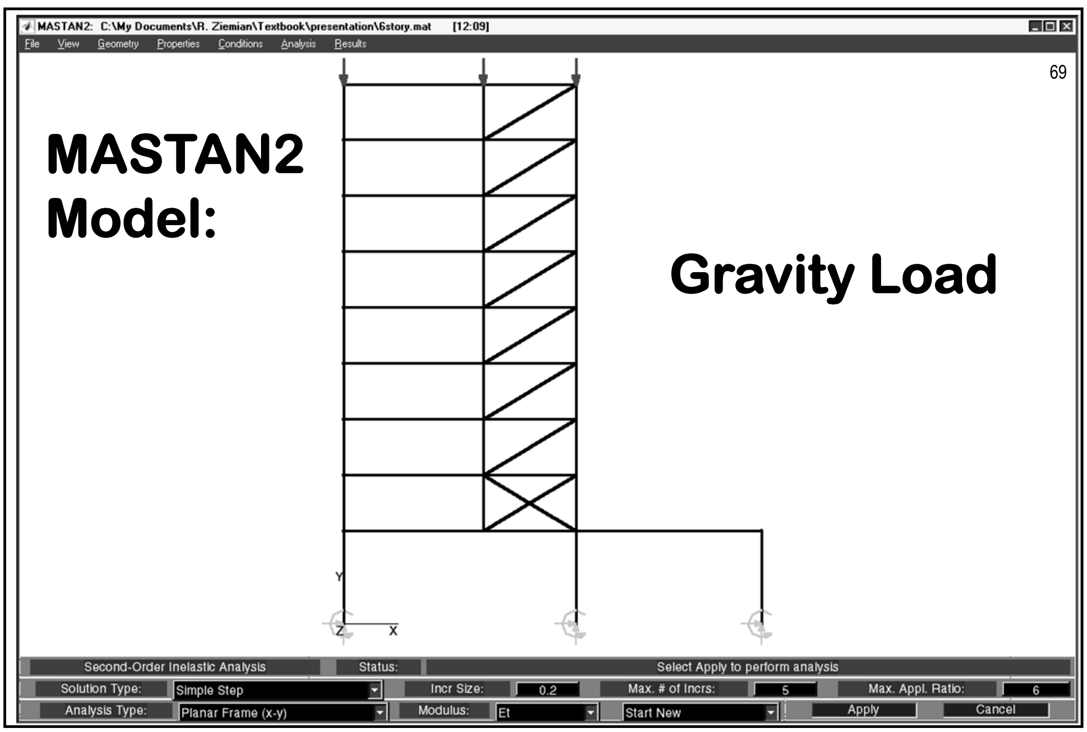


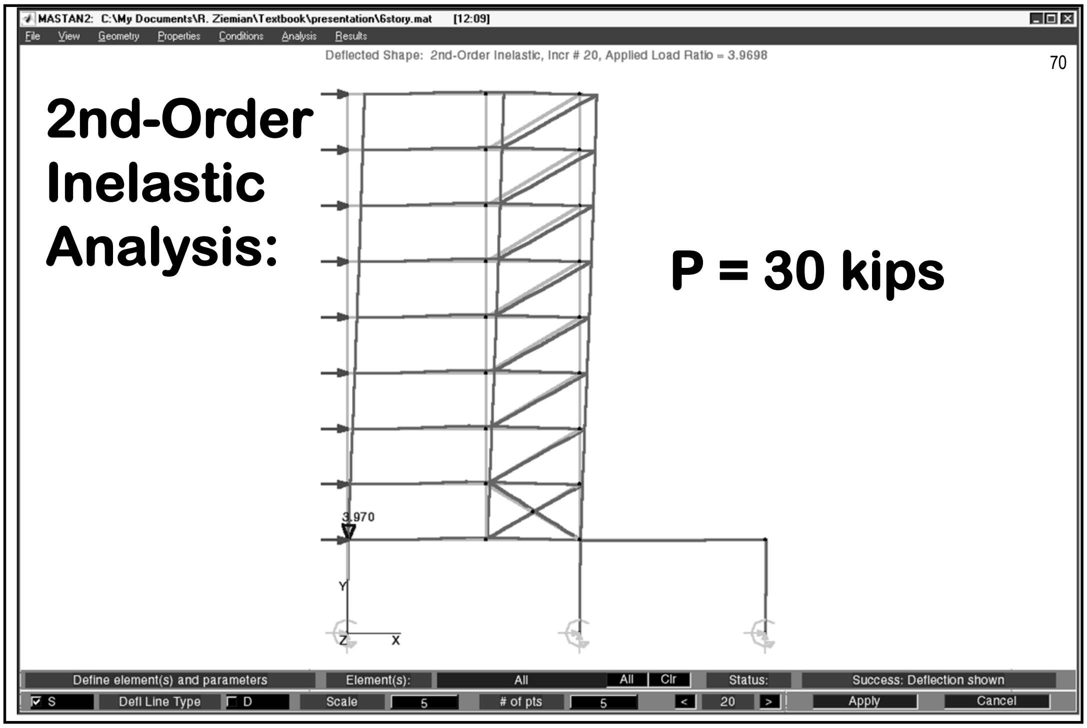
Demonstrate:

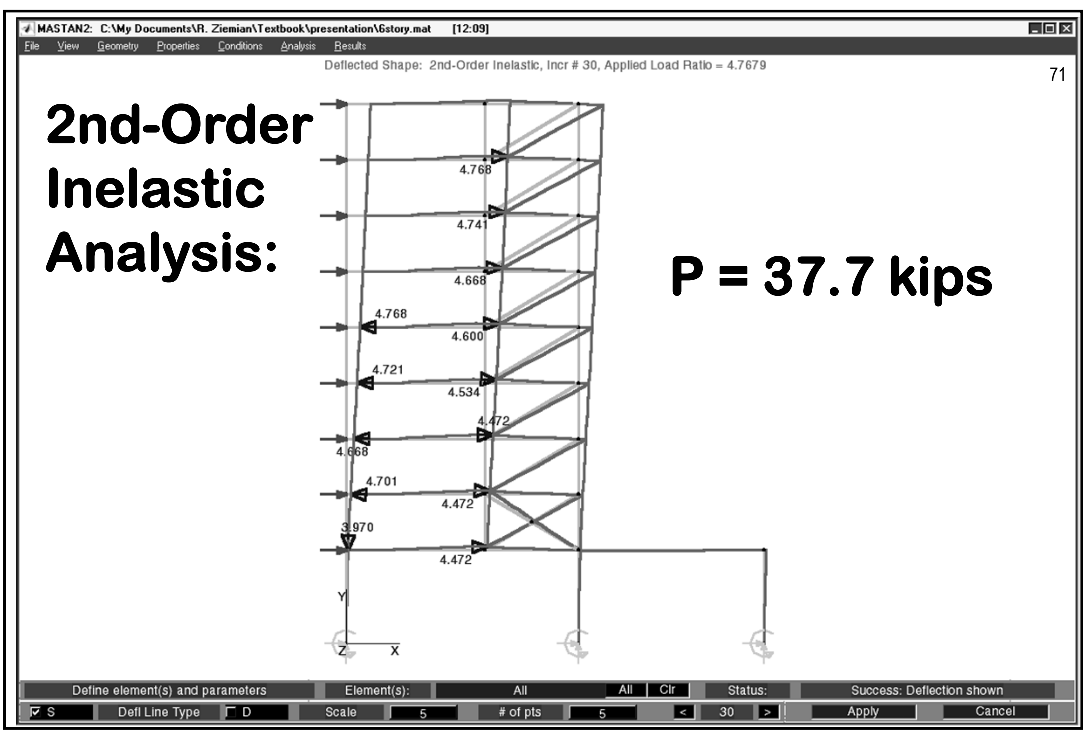
- **2nd-Order Inelastic Analysis**
- **Non-proportional loading**

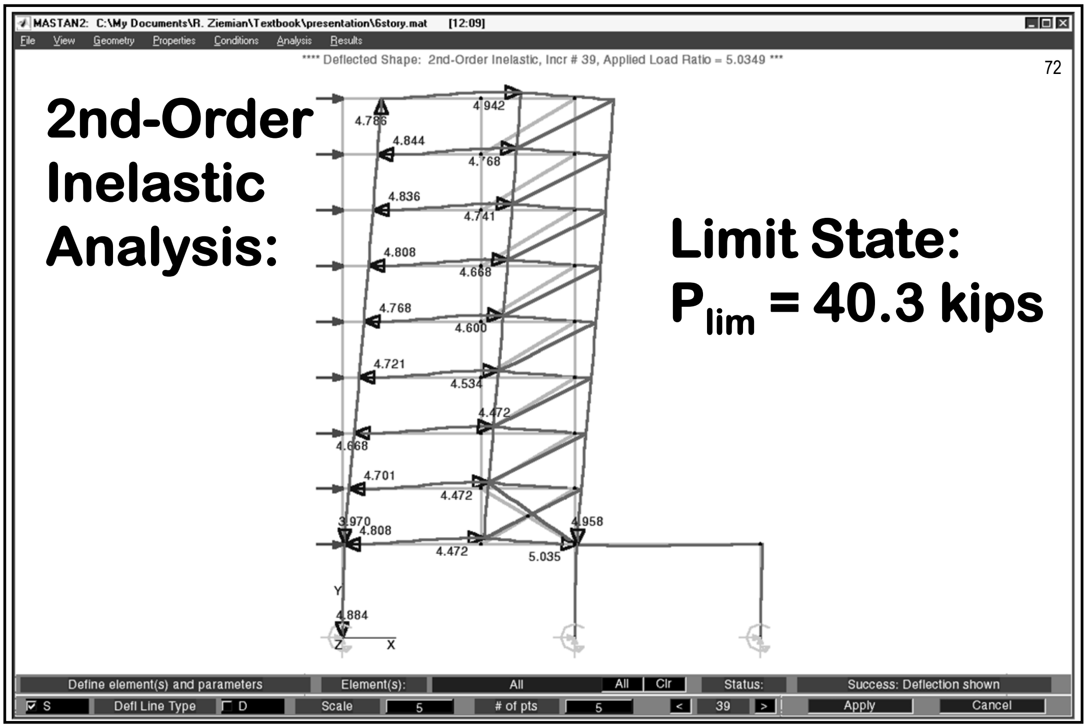
E = 29,000 ksi
σ_y = 36 ksi

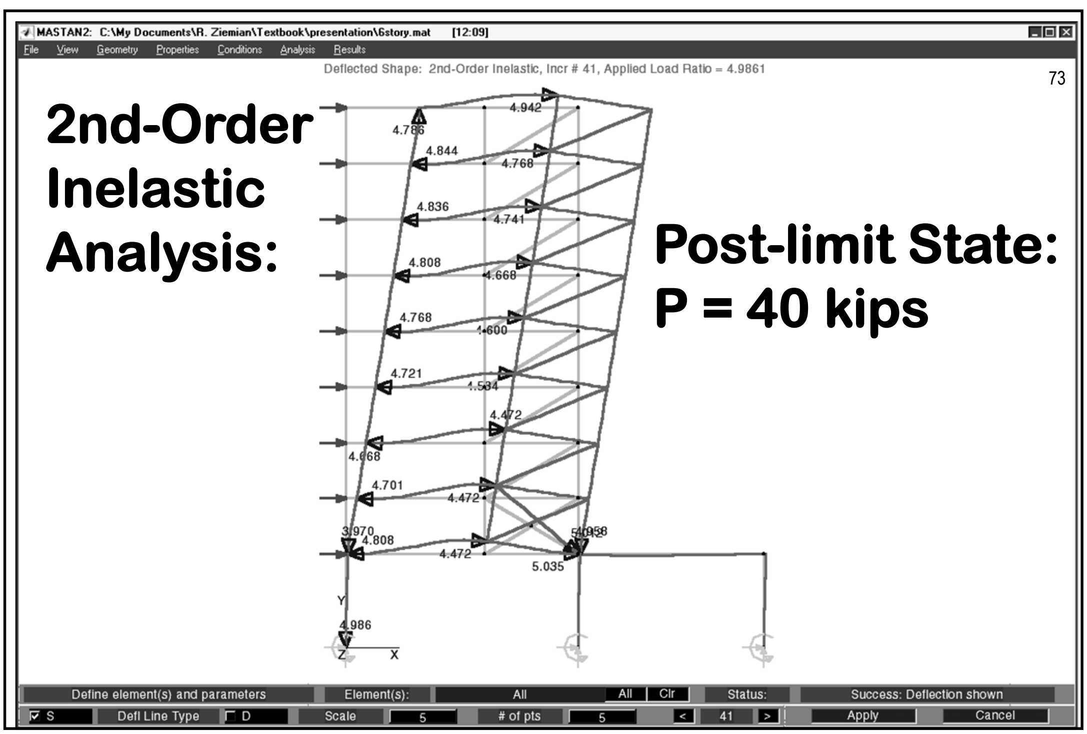
69

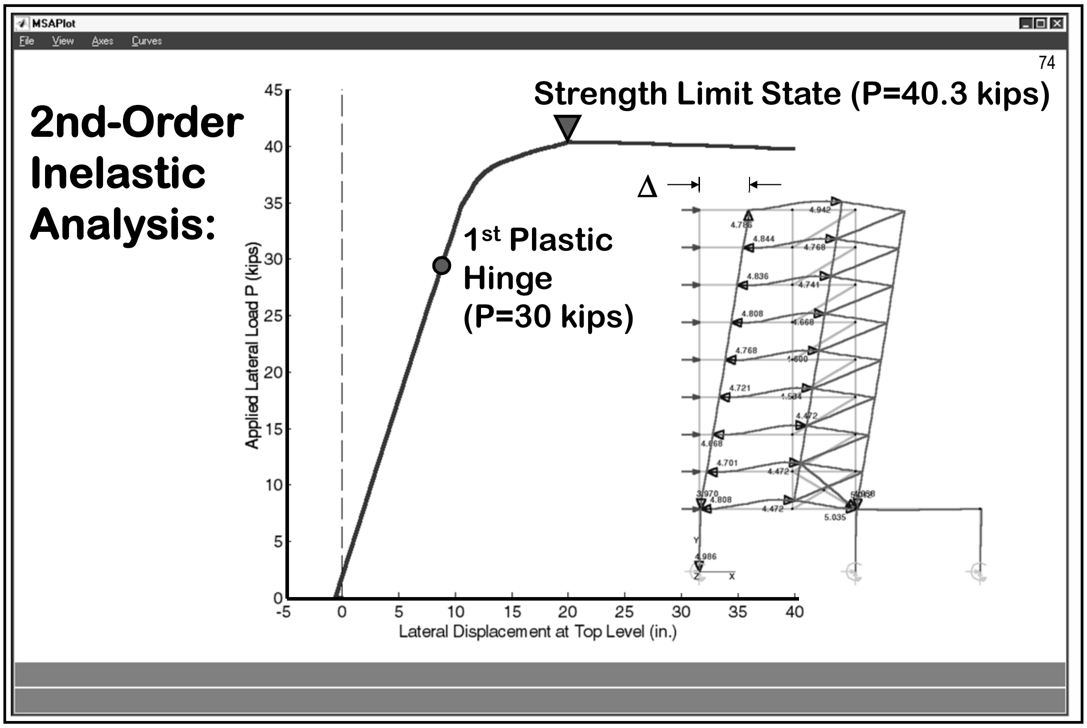



MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\6story.mat [12:09]
Deflected Shape: 2nd-Order Inelastic, Incr # 20, Applied Load Ratio = 3.9698
70
2nd-Order Inelastic Analysis:
P = 30 kips
3.970
Define element(s) and parameters
Element(s):
All
Status:
Success: Deflection shown
Defl Line Type
Scale
# of pts
Apply
Cancel


MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\6story.mat [12:09]
Deflected Shape: 2nd-Order Inelastic, Incr # 30, Applied Load Ratio = 4.7679
71
2nd-Order Inelastic Analysis:
P = 37.7 kips
4.768
4.741
4.668
4.768
4.600
4.721
4.534
4.472
4.668
4.701
4.472
3.970
4.472
Define element(s) and parameters
Element(s):
All
Status:
Success: Deflection shown
Defl Line Type
Scale
# of pts
Apply
Cancel

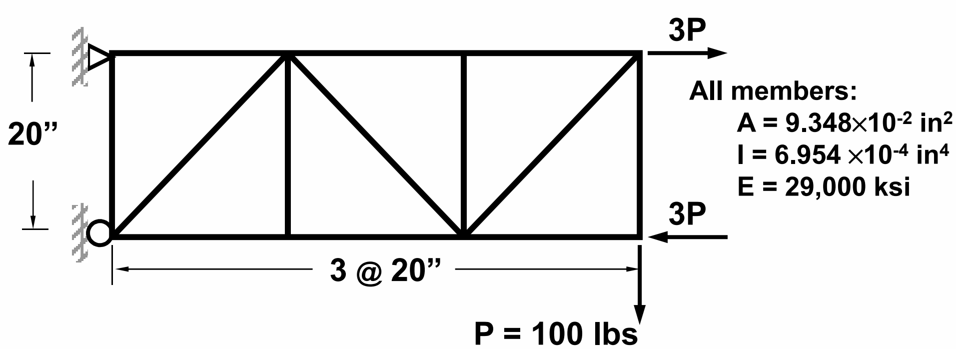

MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\6story.mat [12:09]
**** Deflected Shape: 2nd-Order Inelastic, Incr # 39, Applied Load Ratio = 5.0349 ***
72
2nd-Order Inelastic Analysis:
Limit State:
P_{lim} = 40.3 kips


MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\6story.mat [12:09]
Deflected Shape: 2nd-Order Inelastic, Incr # 41, Applied Load Ratio = 4.9861
73
2nd-Order Inelastic Analysis:
Post-limit State:
P = 40 kips



75

Truss (Hoff et al.):

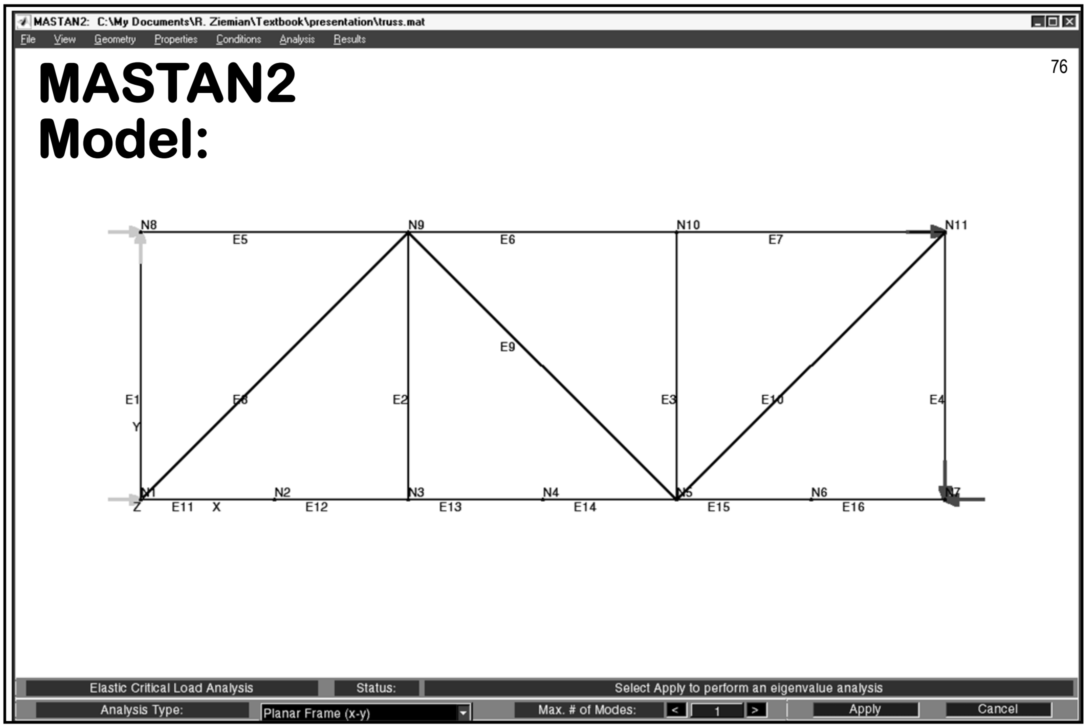


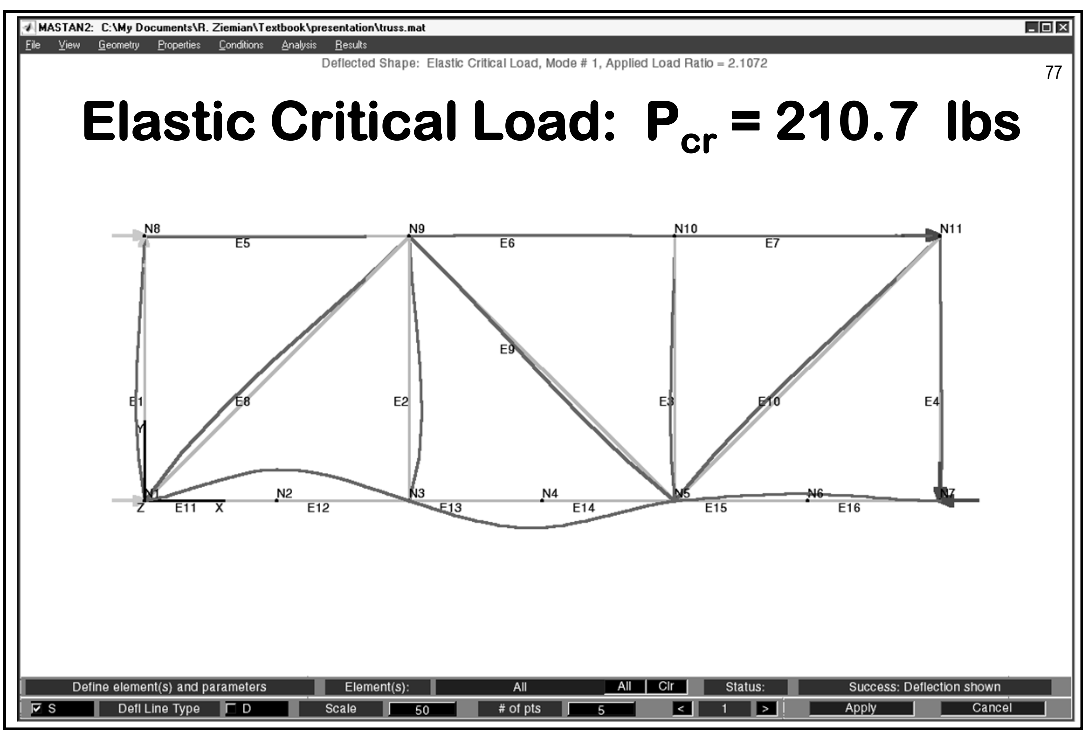
Demonstrate:

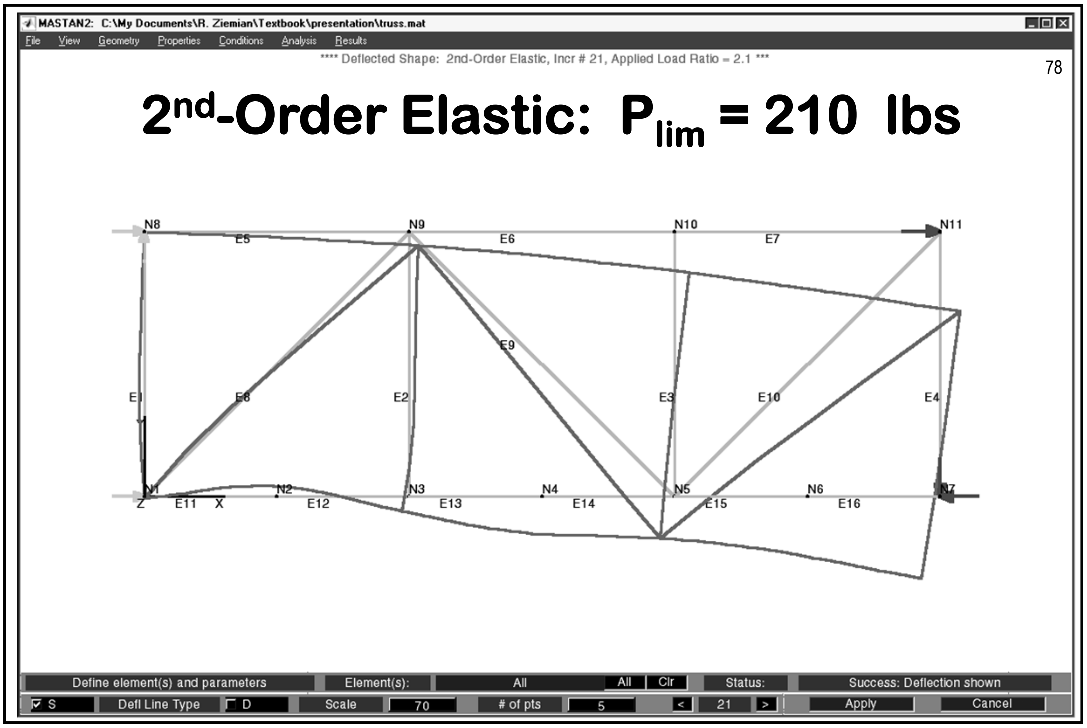
Elastic Critical Load

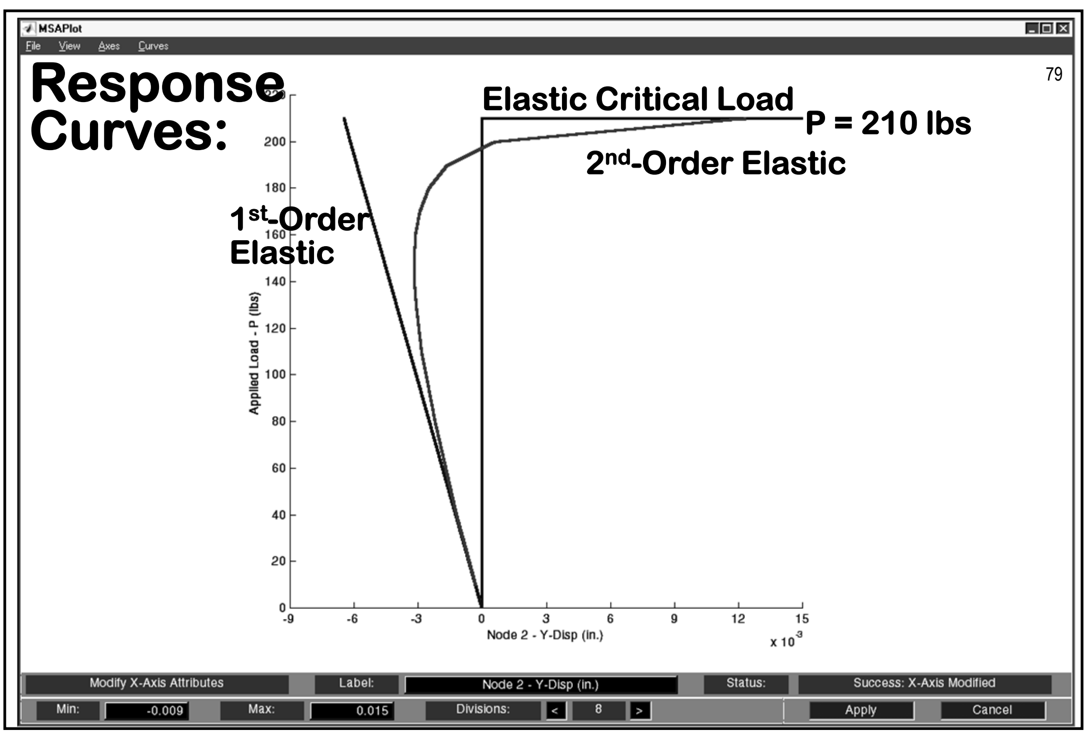
2nd-Order Elastic

Experimental (P_{limit}=220 lbs)


MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\truss.mat
File View Geometry Properties Conditions Analysis Results
76
MASTAN2
Model:
N8 N9 N10 N11
E5 E6 E7
E9
E1 E8 E2 E3 E10 E4
Y
N1 N2 N3 N4 N5 N6 N7
Z E11 X E12 E13 E14 E15 E16
Elastic Critical Load Analysis
Status:
Select Apply to perform an eigenvalue analysis
Analysis Type:
Planar Frame (x-y)
Max. # of Modes:
1
Apply
Cancel


MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\truss.mat
File View Geometry Properties Conditions Analysis Results
Deflected Shape: Elastic Critical Load, Mode # 1, Applied Load Ratio = 2.1072
77
Elastic Critical Load: P_{cr} = 210.7 lbs
N8 N9 N10 N11
E5 E6 E7
E9
E1 E8 E2 E3 E10 E4
Y
N1 N2 N3 N4 N5 N6 N7
Z E11 X E12 E13 E14 E15 E16
Define element(s) and parameters
Element(s):
All
All Clr
Status:
Success: Deflection shown
S
Defl Line Type
D
Scale
50
# of pts
5
1
Apply
Cancel

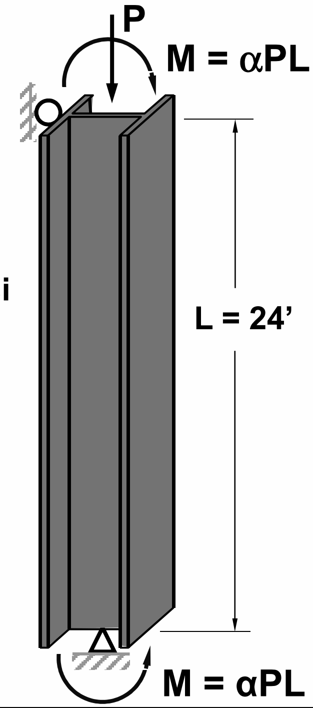

MASTAN2: C:\My Documents\R. Ziemian\Textbook\presentation\truss.mat
**** Deflected Shape: 2nd-Order Elastic, Incr # 21, Applied Load Ratio = 2.1 ***
78
2nd-Order Elastic: Plim = 210 lbs
N8
N9
N10
N11
E5
E6
E7
E9
E1
E8
E2
E3
E10
E4
N1
N2
N3
N4
N5
N6
N7
E11
E12
E13
E14
E15
E16
Define element(s) and parameters
Element(s):
All
Status:
Success: Deflection shown
Defl Line Type
Scale
70
# of pts
5
21
Apply
Cancel


MSAPlot
79
Response Curves:
Elastic Critical Load
P = 210 lbs
2nd-Order Elastic
1st-Order Elastic
Applied Load - P (lbs)
Node 2 - Y-Disp (in.)
x 10^-3
Modify X-Axis Attributes
Label:
Node 2 - Y-Disp (in.)
Status:
Success: X-Axis Modified
Min:
-0.009
Max:
0.015
Divisions:
8
Apply
Cancel

80

Beam-Column:

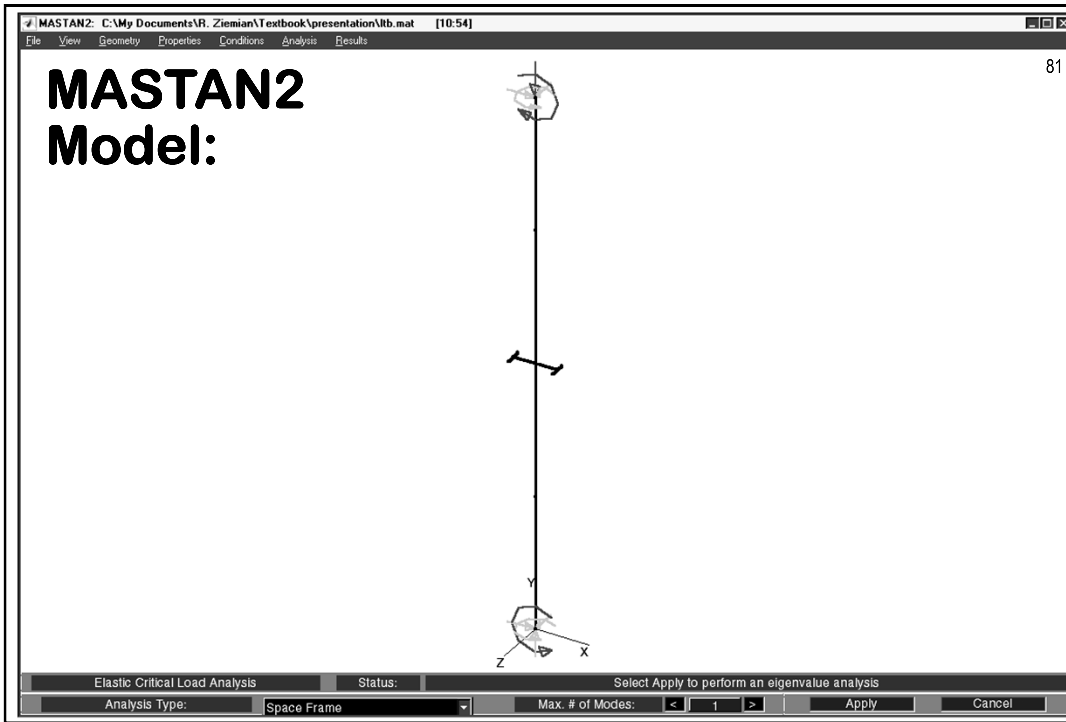
W24x76
E = 29,000 ksi



Demonstrate:
- **Elastic Critical Load Analysis**
- **1. Flexural Buckling (α=0.0)**
- **2. Torsional Flexural Buckling (α=0.04)**

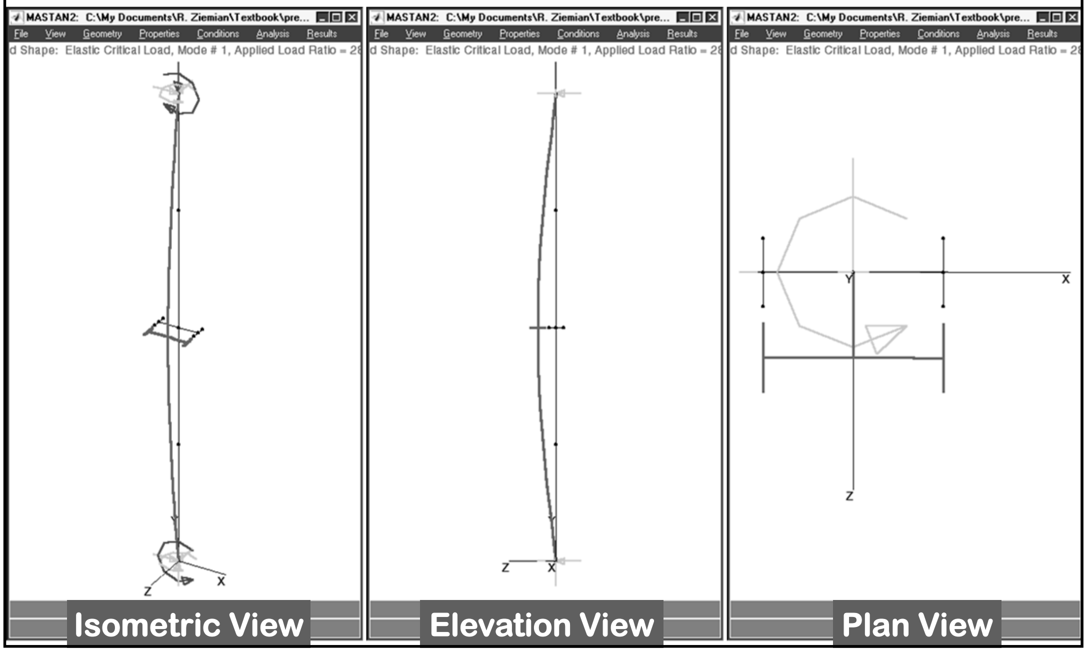
81

MASTAN2 Model:



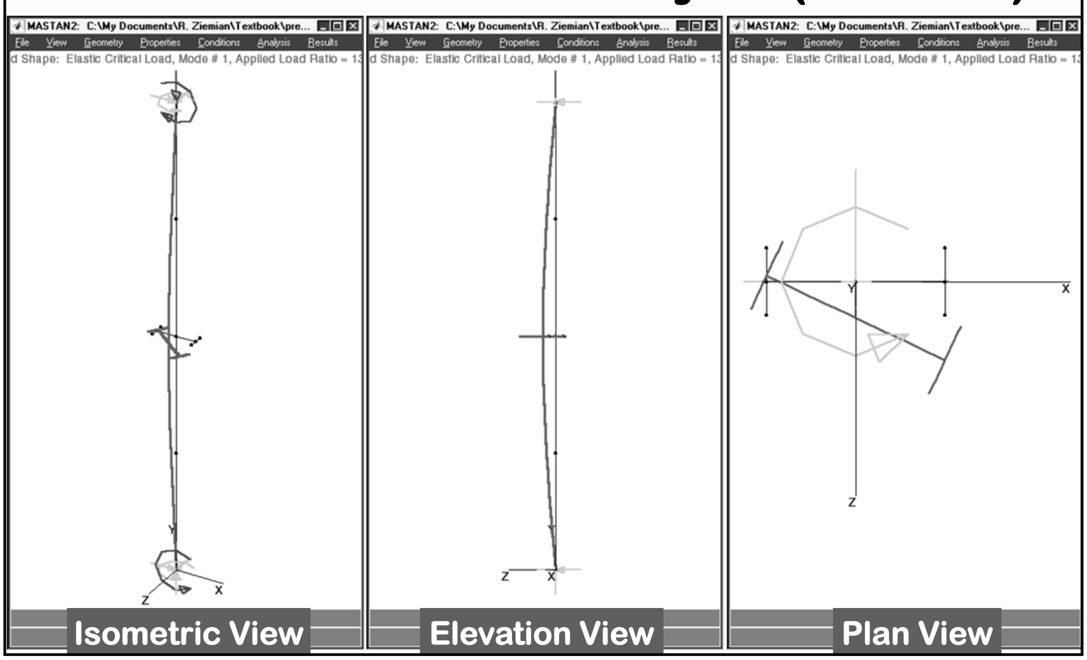
Elastic Critical Load ($\alpha = 0.0$)

82



Elastic Critical Load Analysis ($\alpha = 0.04$)

83



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Suspension System: